Center for Frontiers in Nuclear Science

Elastic Electron (Positron) – Proton Scattering at the EIC

Barak Schmookler

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Main Supervisor: Abhay Deshpande

Stony Brook University

Electron-Proton Cross Section

Differential Cross Section in the **Nucleon Rest Frame**:

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

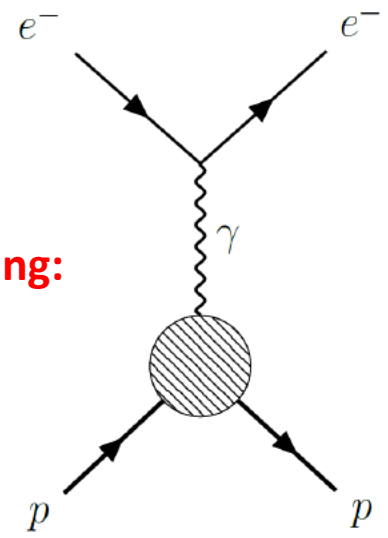
$$\left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E_e^2 \sin^4\left(\frac{\theta_e}{2}\right)} \frac{E_e'}{E_e}$$

$$\sigma_R = \epsilon G_E^2 + \tau G_M^2$$

$$\tau \equiv \frac{Q^2}{4M_p^2}$$

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

Electron-Proton Elastic Scattering:



Electron-Proton Cross Section **at EIC Energies**

Lorentz Invariant Differential Cross Section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2 + \tau G_M^2}{(1+\tau)}\left(1 - y - \frac{M^2 y^2}{Q^2}\right) + \frac{1}{2}y^2 G_M^2\right]$$

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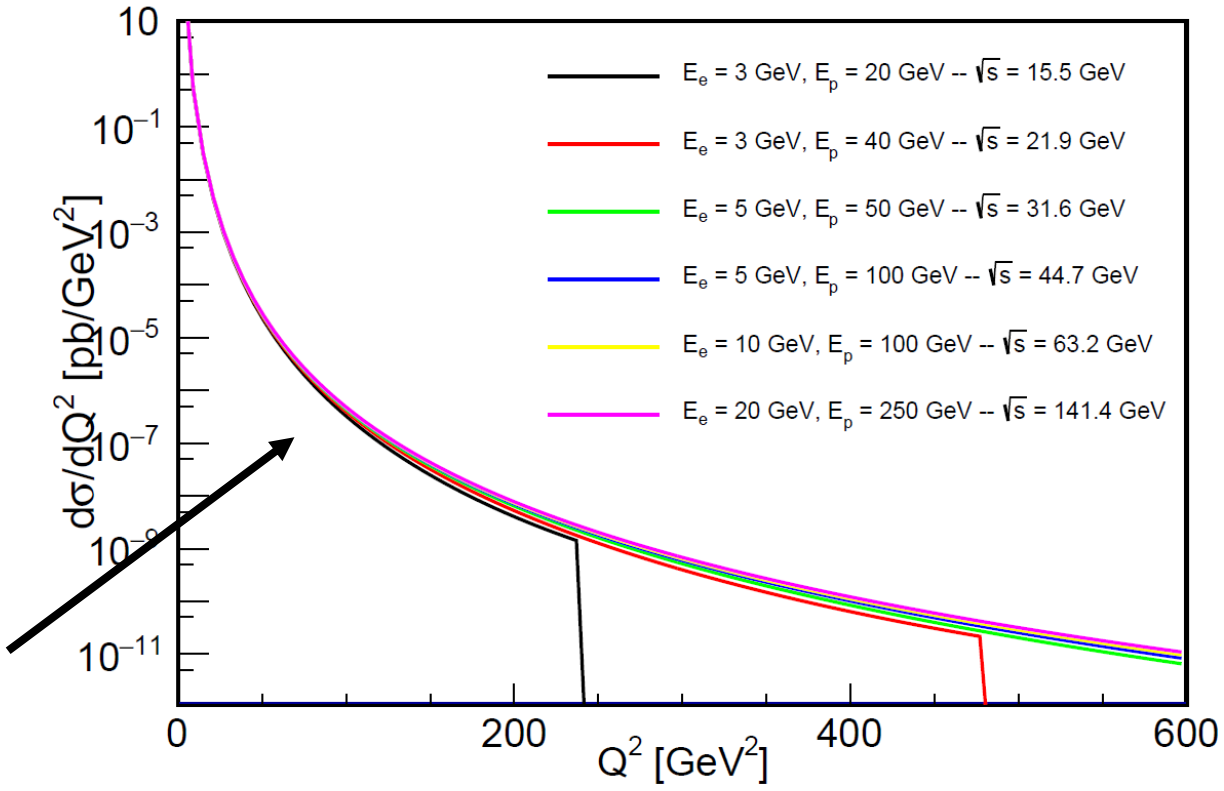
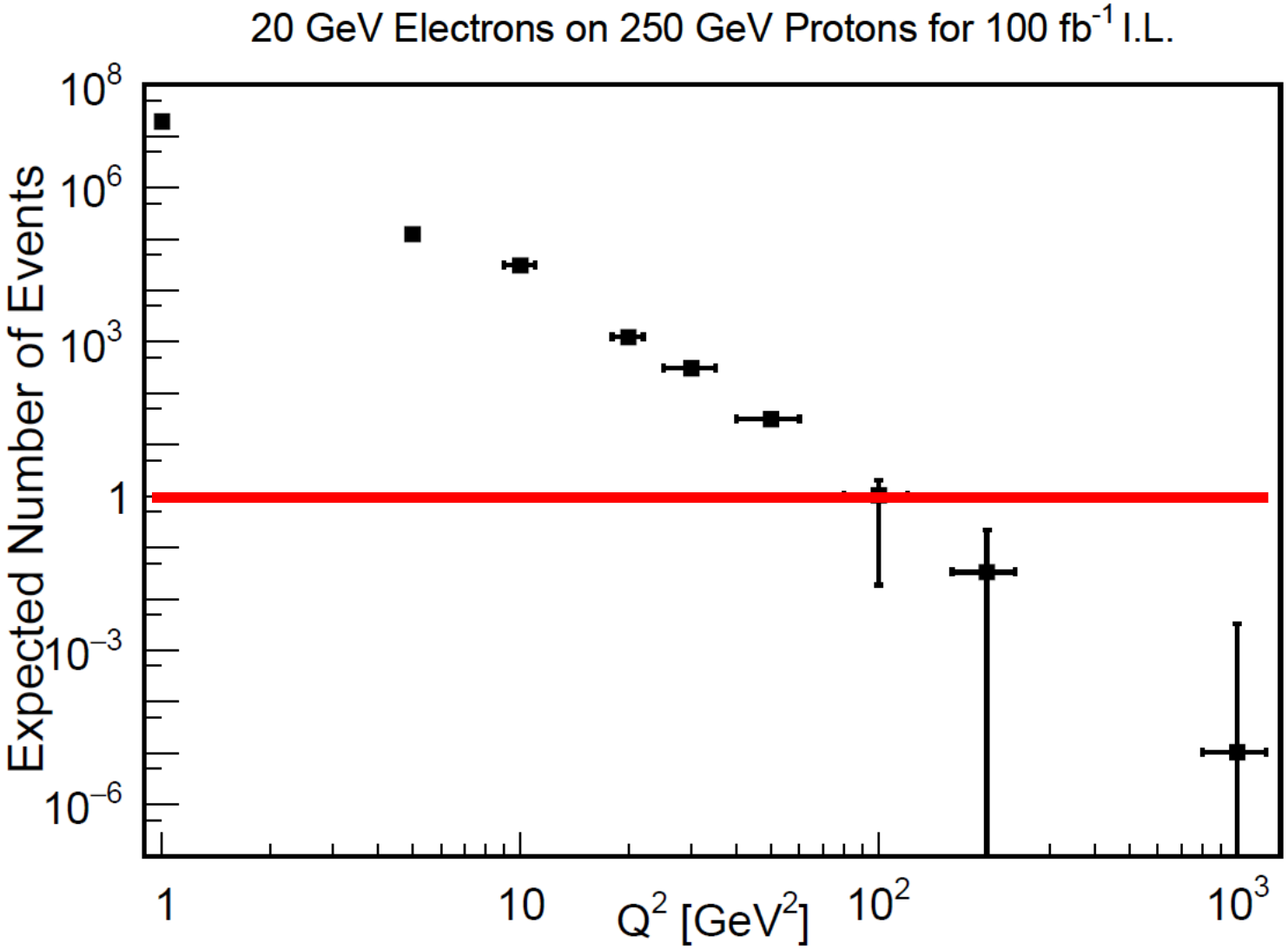


Calculated assuming dipole form factors

Expected Number of Elastic Events at the *EIC*

A luminosity of 10^{-34} cm^{-2} s^{-1} -> 100 fb^{-1} per year

Expected Number of Elastic Events at the *EIC*



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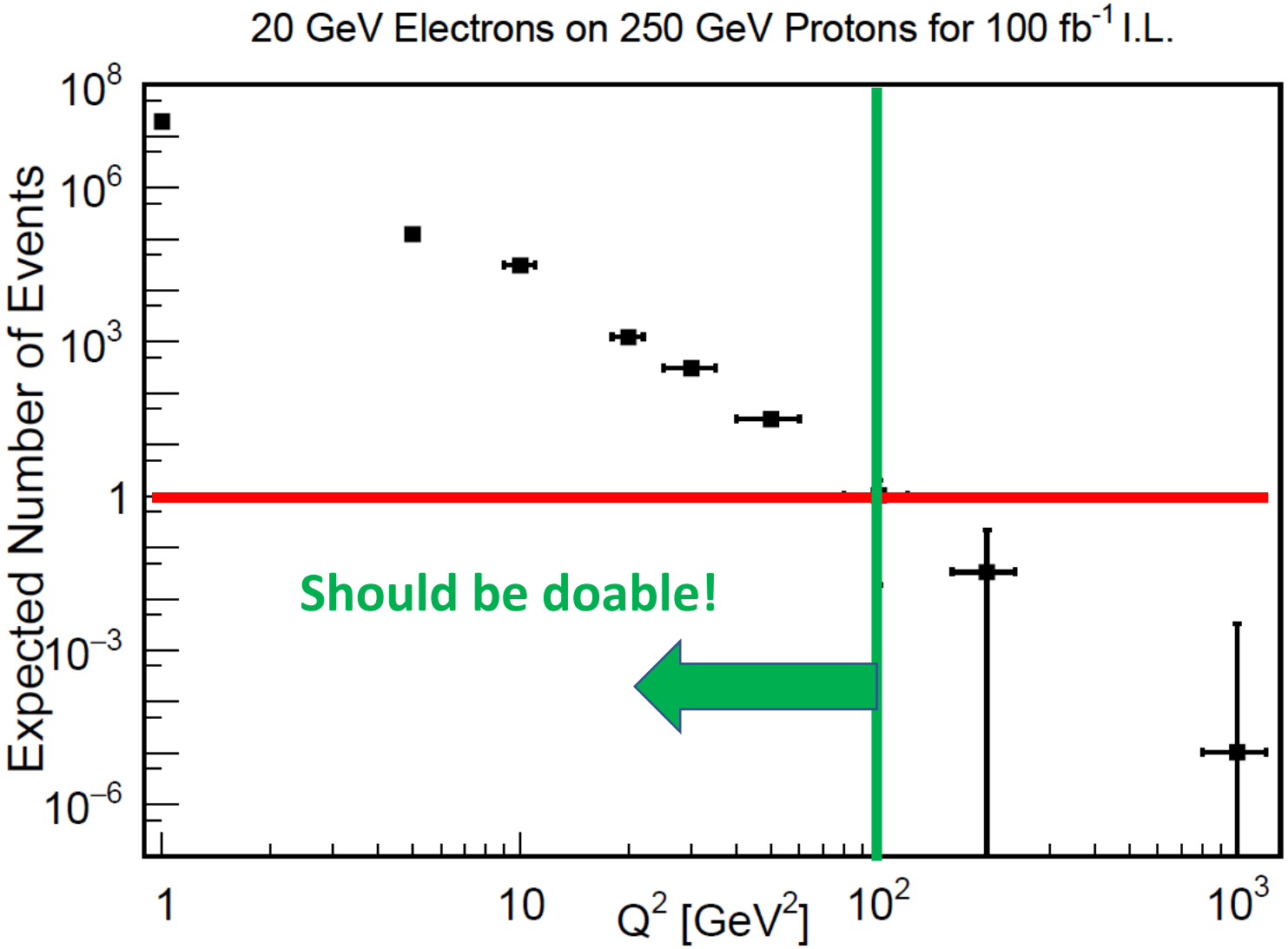
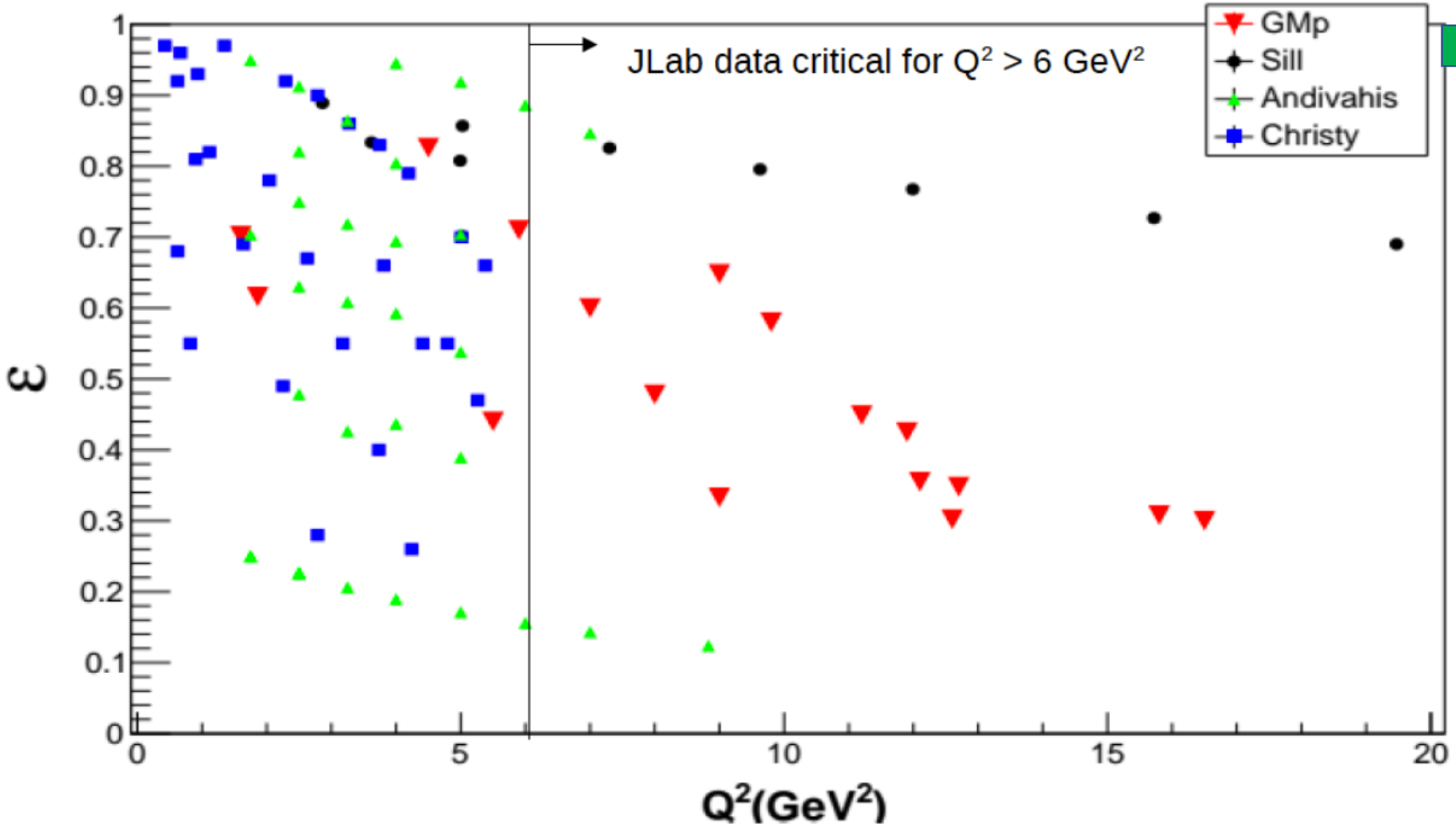
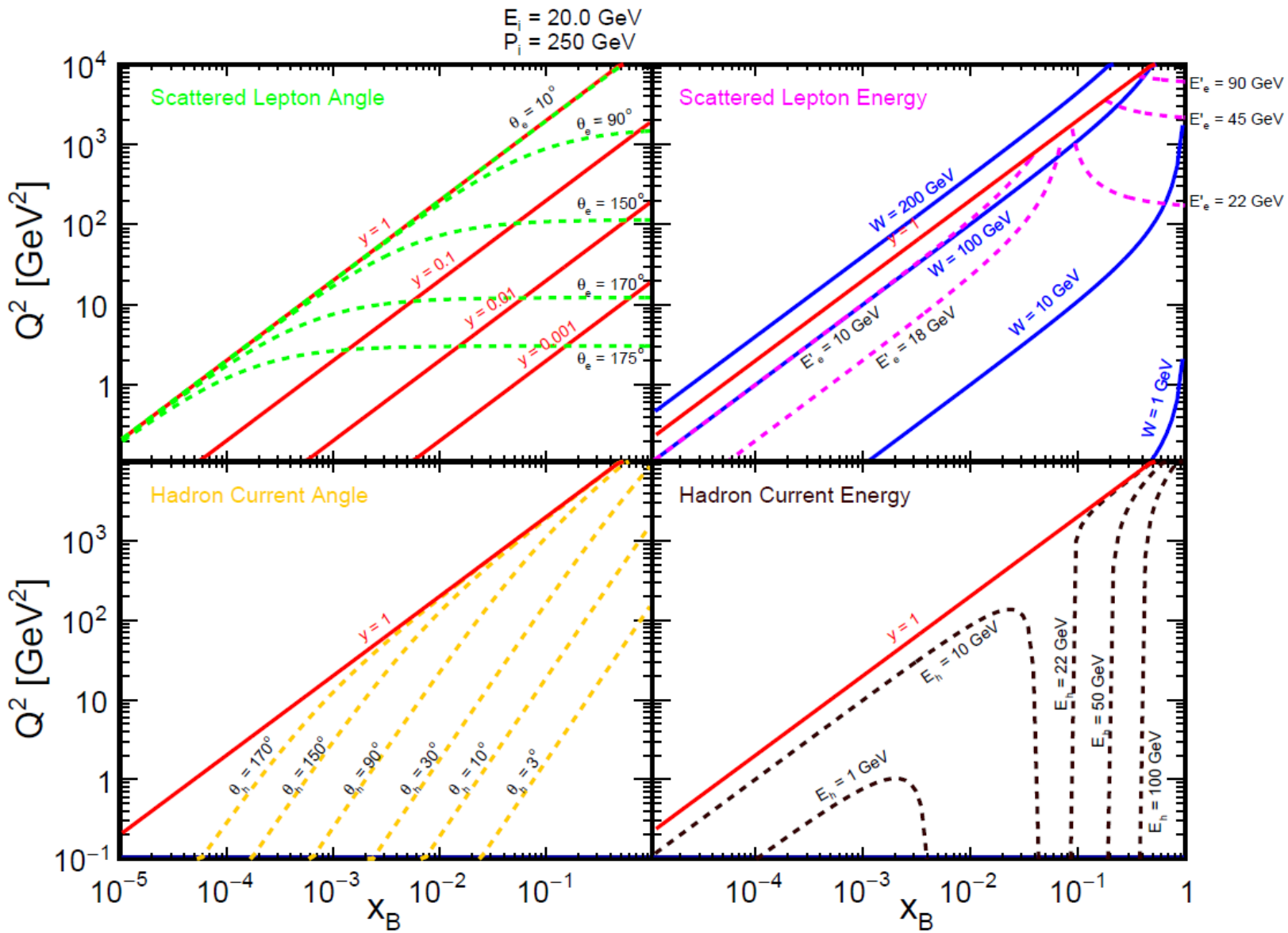


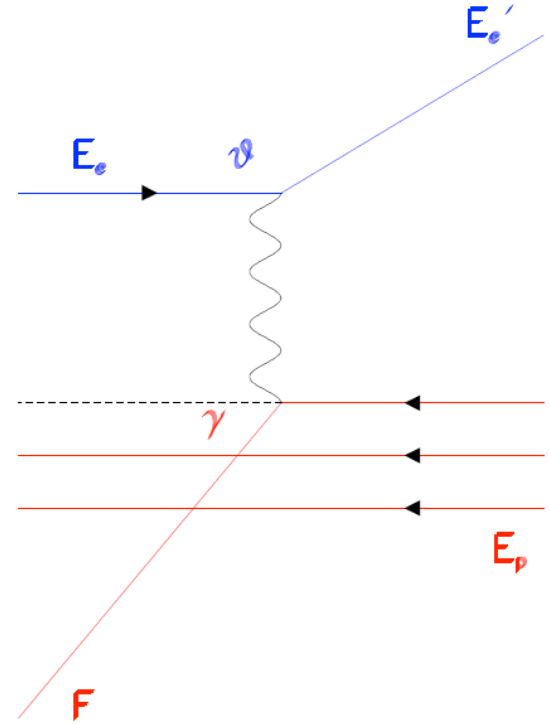
The *EIC* will allow us to probe the highest-ever values of Q^2



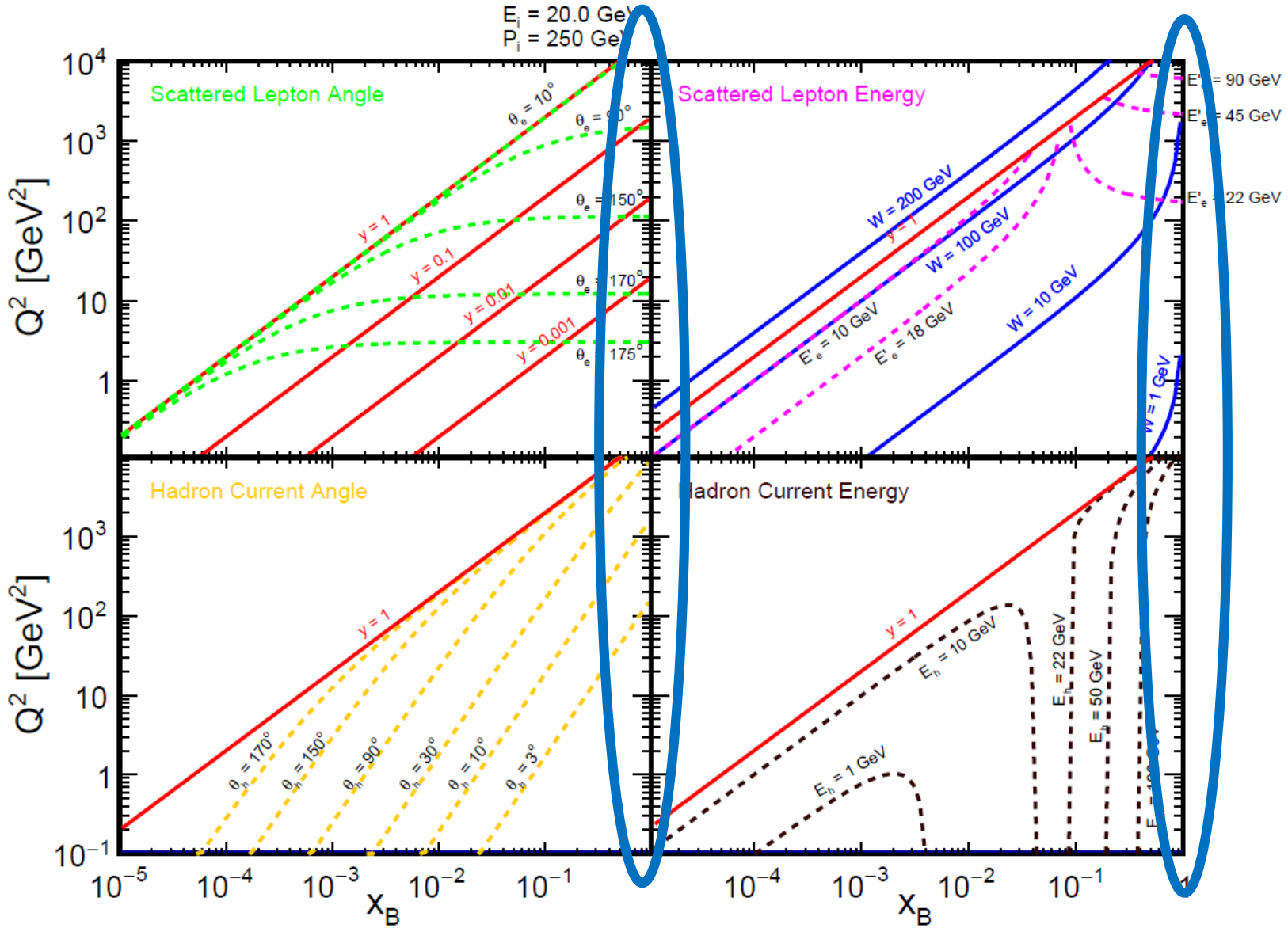
Up to Q^2 ~50 GeV^2 or higher at the EIC – all at high ε

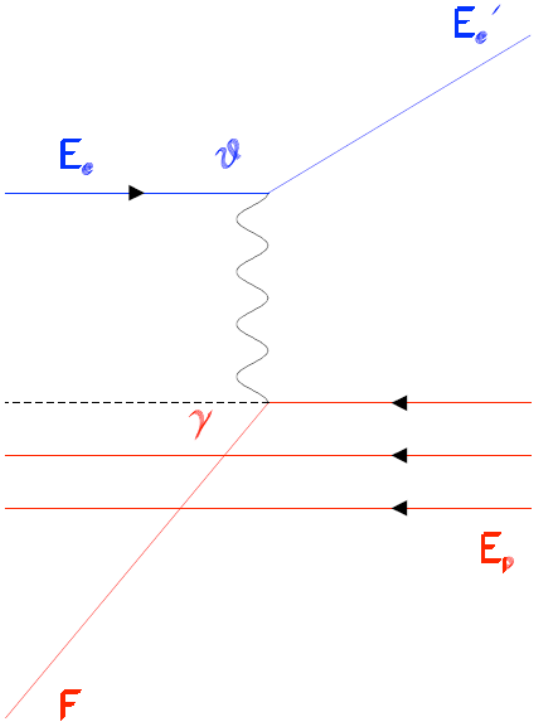
Kinematics


E_i = 20.0 GeV
P_i = 250 GeV
Scattered Lepton Angle
θ_e = 10°
θ_e = 90°
θ_e = 150°
θ_e = 170°
θ_e = 175°
y = 1
y = 0.1
y = 0.01
y = 0.001
Scattered Lepton Energy
E'_e = 90 GeV
E'_e = 45 GeV
E'_e = 22 GeV
W = 200 GeV
W = 100 GeV
W = 10 GeV
W = 1 GeV
E'_e = 10 GeV
E'_e = 18 GeV
Hadron Current Angle
θ_h = 170°
θ_h = 150°
θ_h = 90°
θ_h = 30°
θ_h = 10°
θ_h = 3°
Hadron Current Energy
E_h = 10 GeV
E_h = 22 GeV
E_h = 50 GeV
E_h = 100 GeV
E_h = 1 GeV
Q² [GeV²]
x_B


E_e'
E_e
ϑ
γ
E_p
F

Kinematics

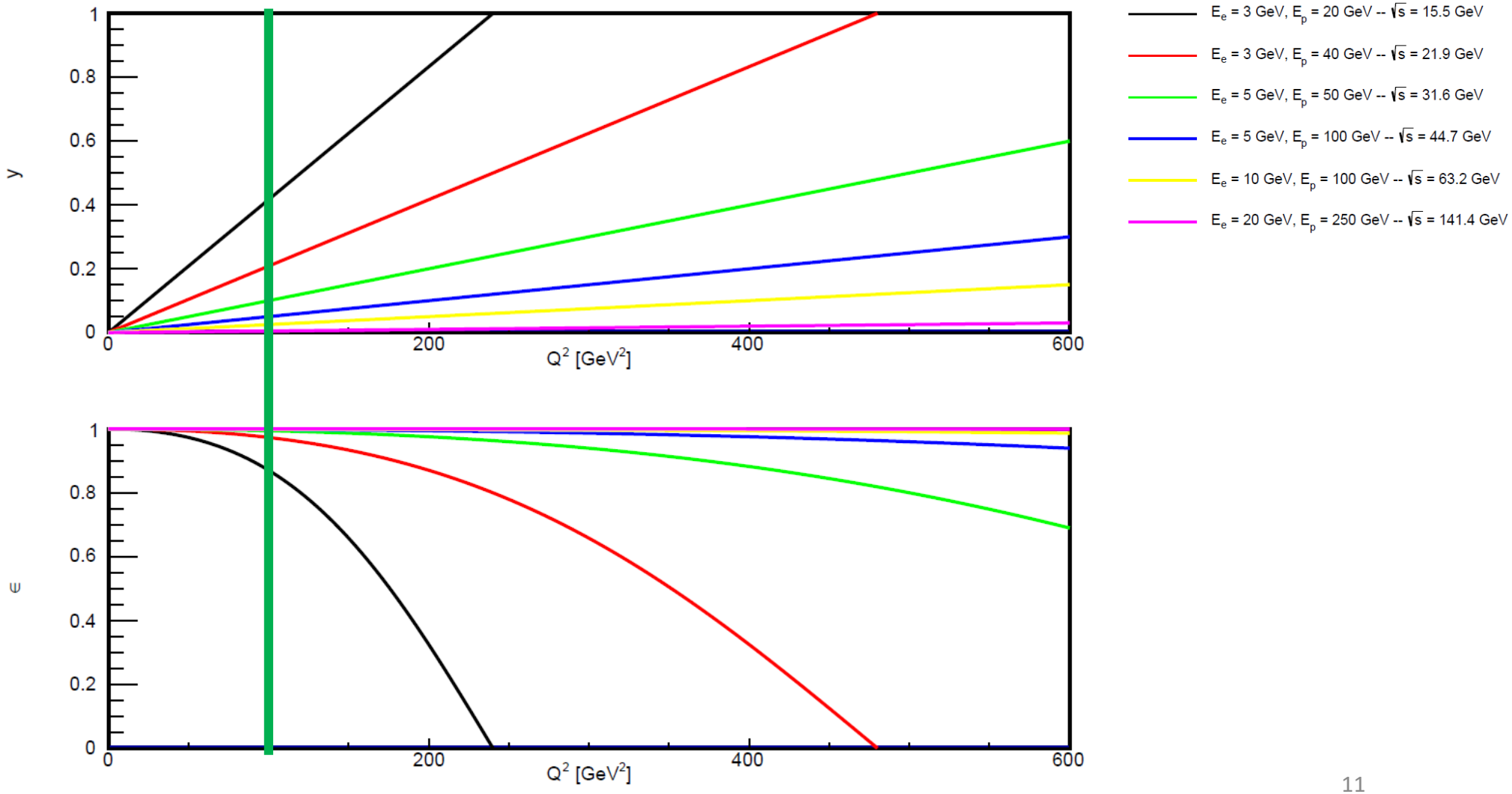




Elastic at x = 1

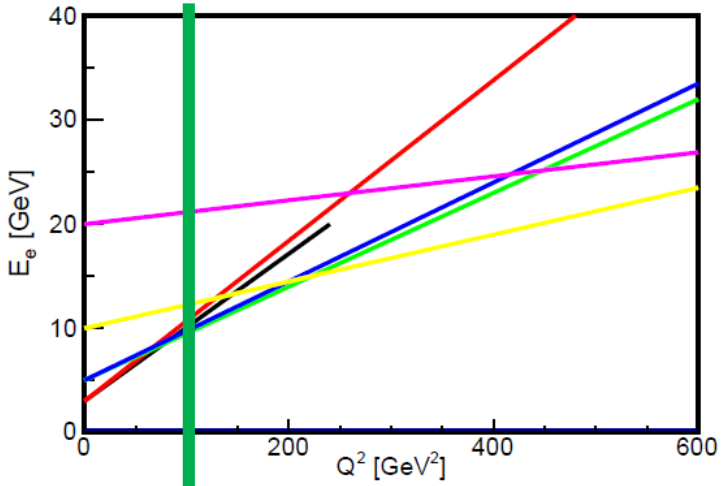
Kinematics

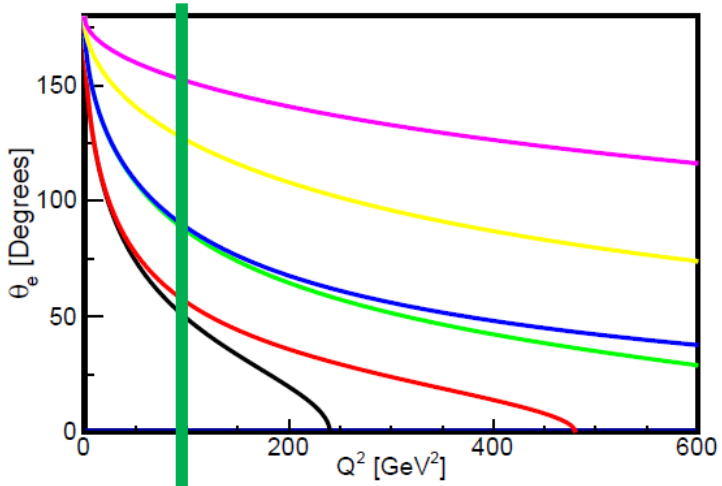
Events will be close to ε = 1



Kinematics

Scattered Electron Energy

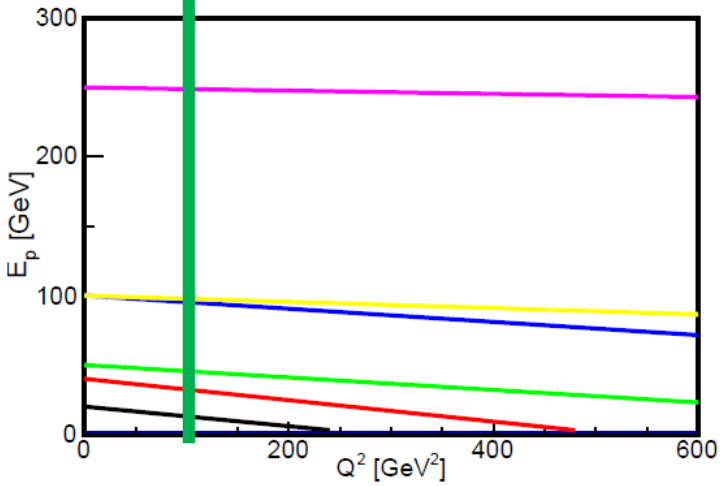


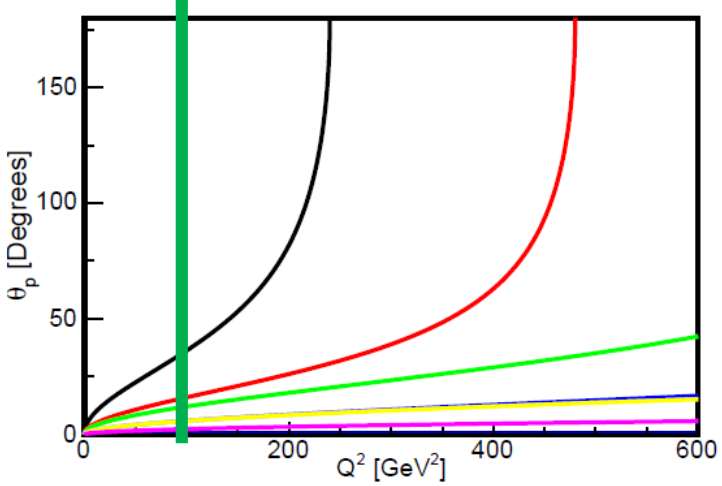


E_e = 3 GeV, E_p = 20 GeV -- $\sqrt{s}$ = 15.5 GeV
E_e = 3 GeV, E_p = 40 GeV -- $\sqrt{s}$ = 21.9 GeV
E_e = 5 GeV, E_p = 50 GeV -- $\sqrt{s}$ = 31.6 GeV
E_e = 5 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 44.7 GeV
E_e = 10 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 63.2 GeV
E_e = 20 GeV, E_p = 250 GeV -- $\sqrt{s}$ = 141.4 GeV

Scattered Electron Angle

Scattered Proton Energy

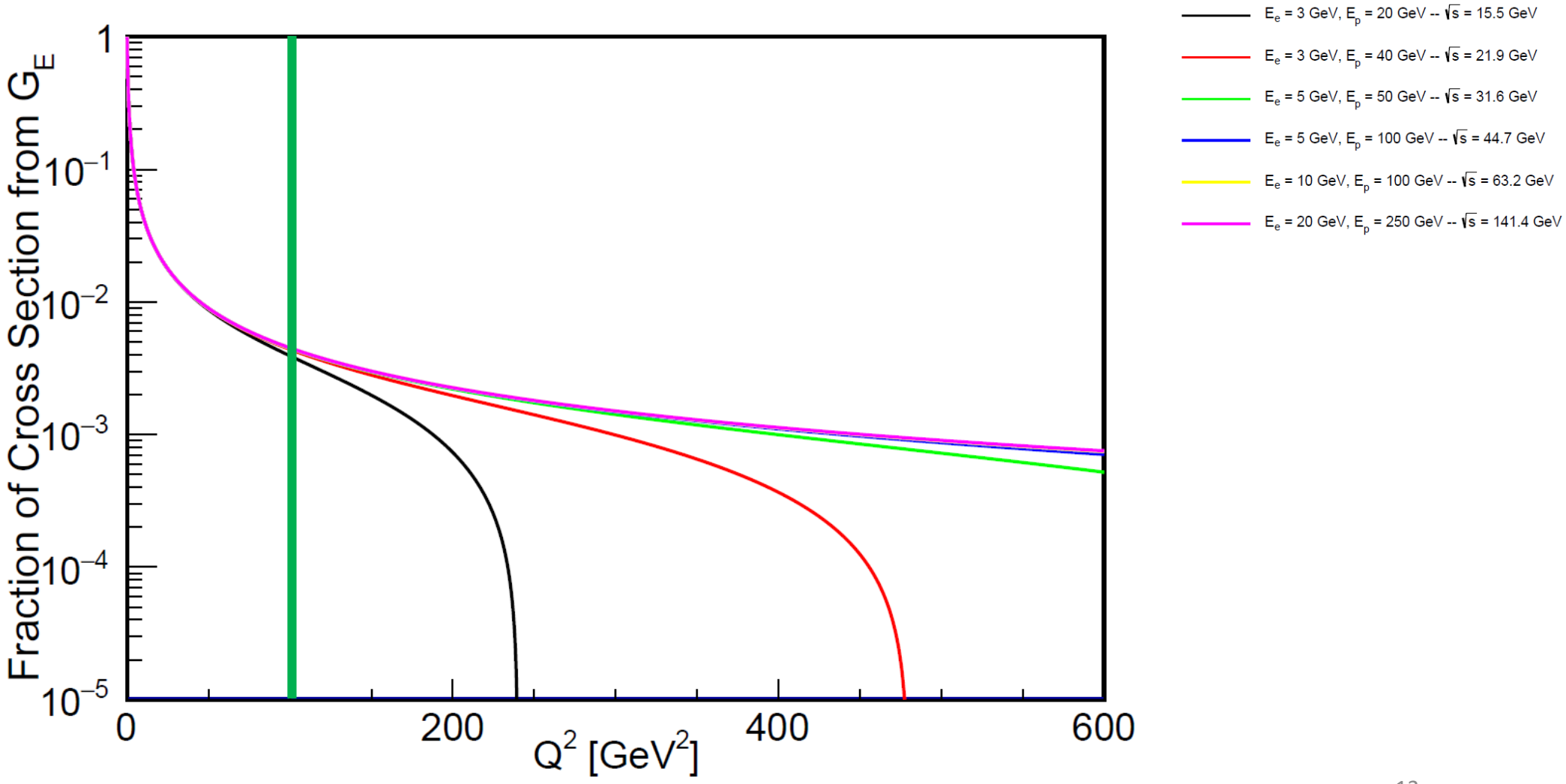




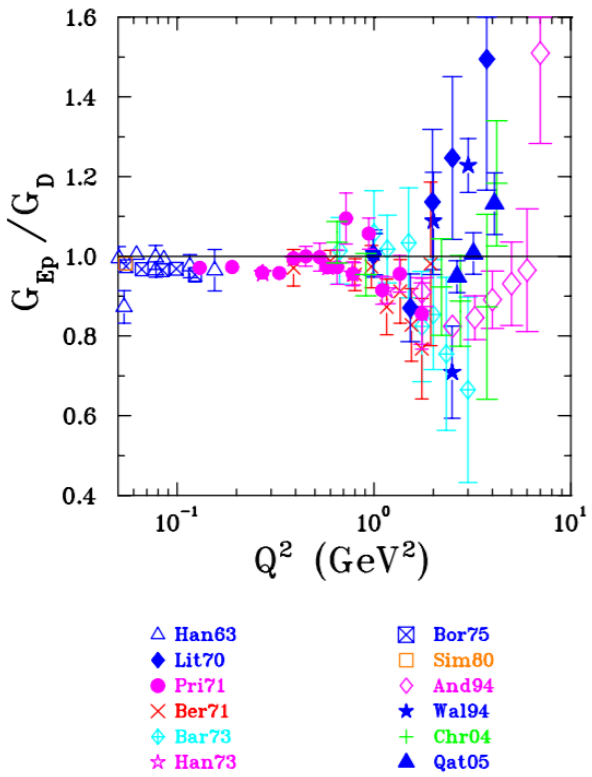
Scattered Proton Angle

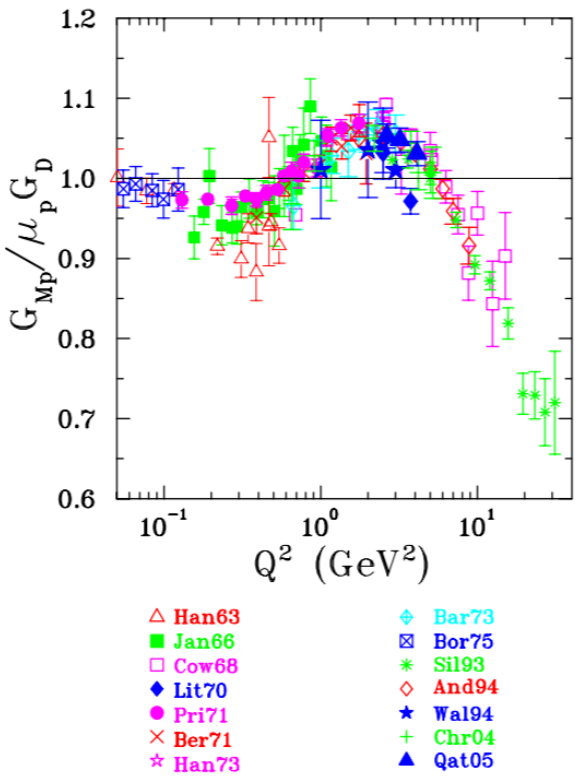
Kinematics

Magnetic Form Factor contribution will dominate at High Q^2

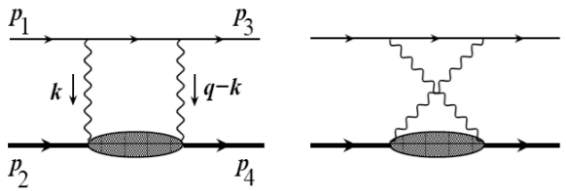


So we probably can do this…but what will we learn?





- Precision G_M required to study approach of QCD scaling in Dirac F_1 Form Factor
- Constraints on GPDs at high-x & high-t via sum rules
- Possible increased sensitivity to hard two-photon exchange effects



C.F Perdrisat, V. Punjabi, M. Vanderhaeghen, *Progress in Particle and Nuclear Physics 59 (2007) 694–764*

What we are doing for *EIC* simulations

1. Create an elastic generator that we'll mix with some minimum bias DIS events and run through detector simulations ✓
2. Add non-zero crossing angle to generator for both *eRHIC* and *JLEIC* ✓

Elastic Generator

1. Generate events in nucleon rest frame
   - Either generate uniformly and weight events…
   - …Or generate according to cross section
2. Boost to lab frame for analysis

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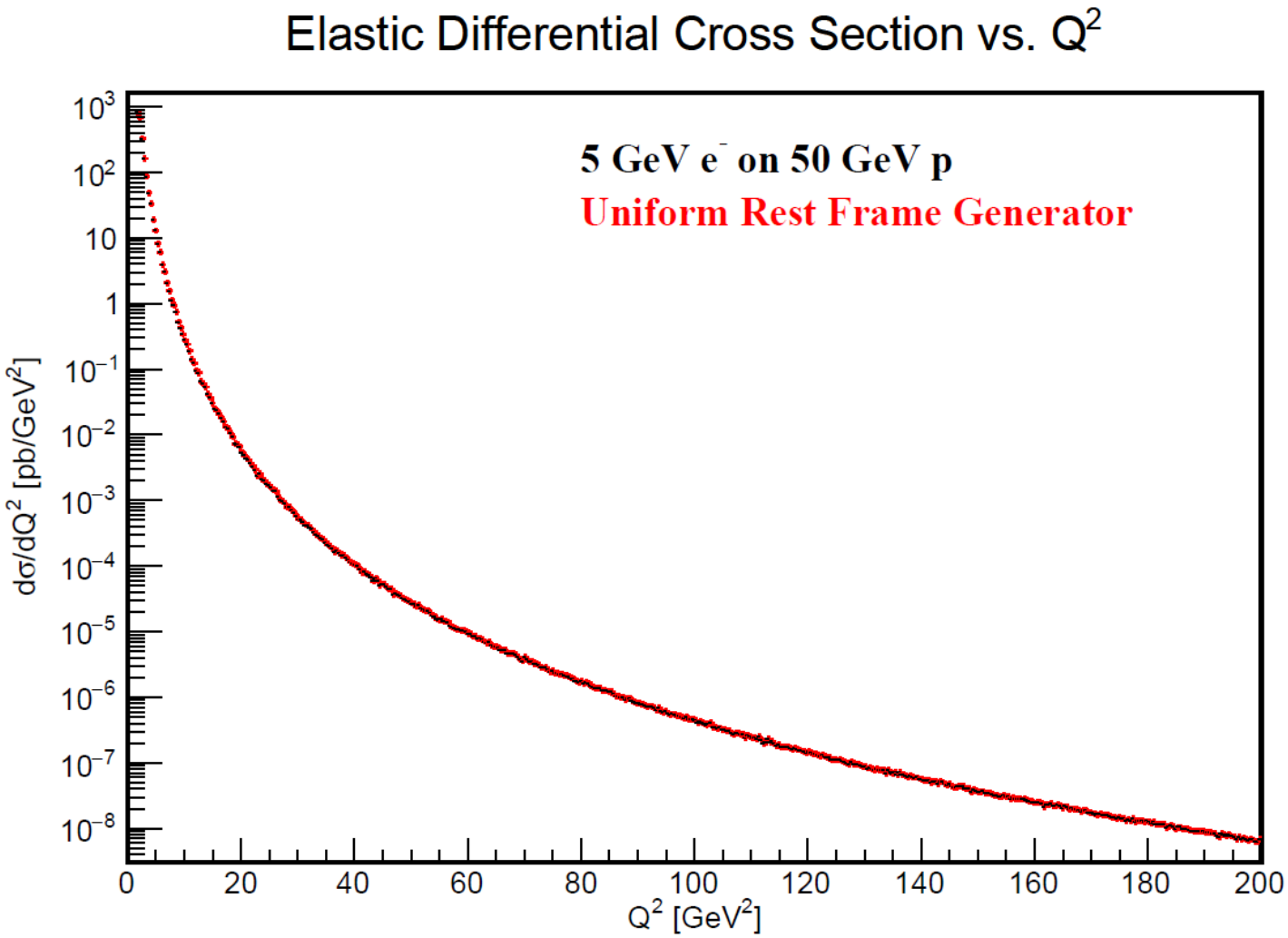
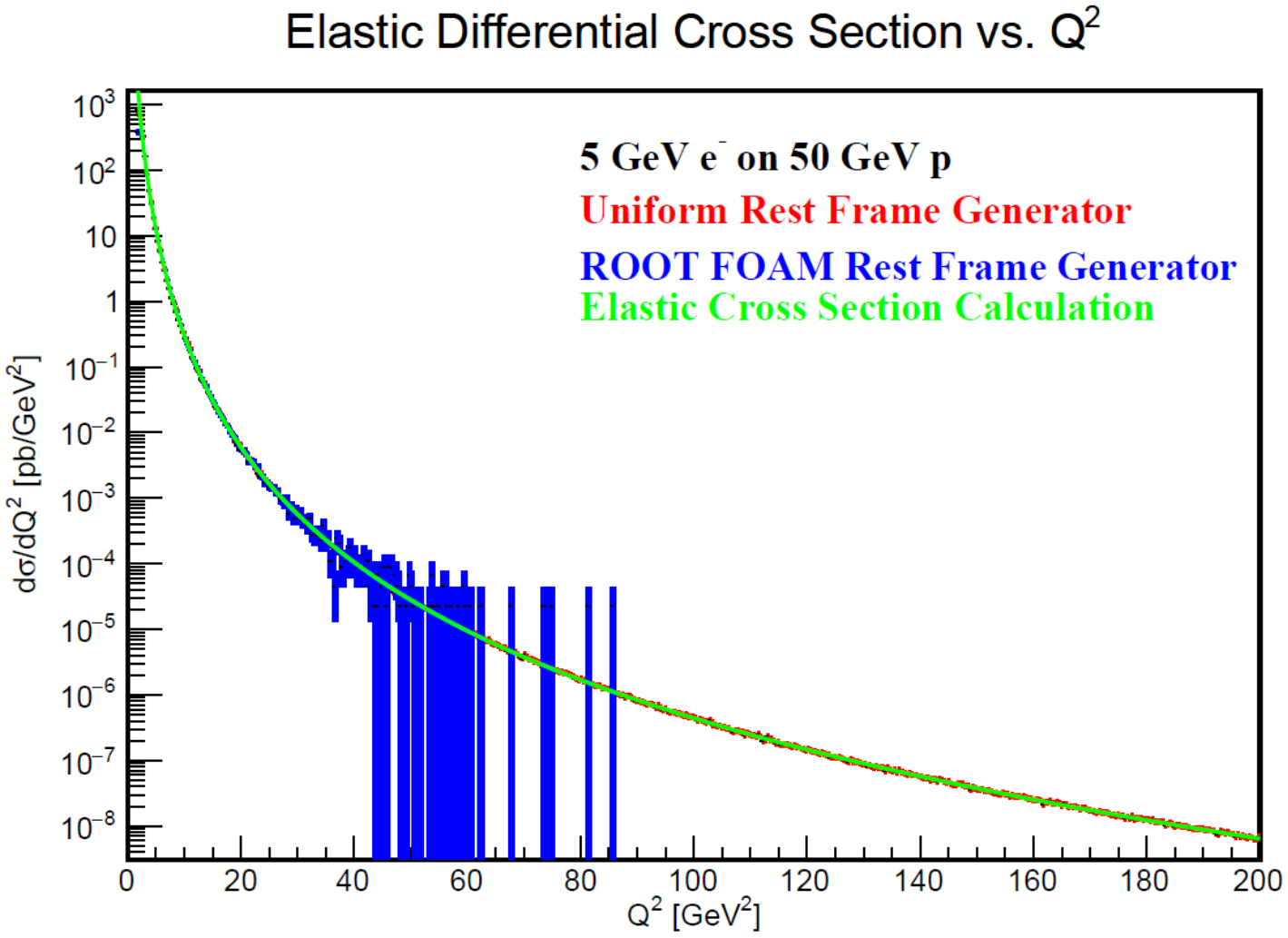


Weight each event by:

$$\frac{\frac{d\sigma}{d\Omega_i}\left(Q_{hi}^2 - Q_{low}^2\right)}{N_{tot}\,\Delta Q_i^2}$$

Elastic Generator



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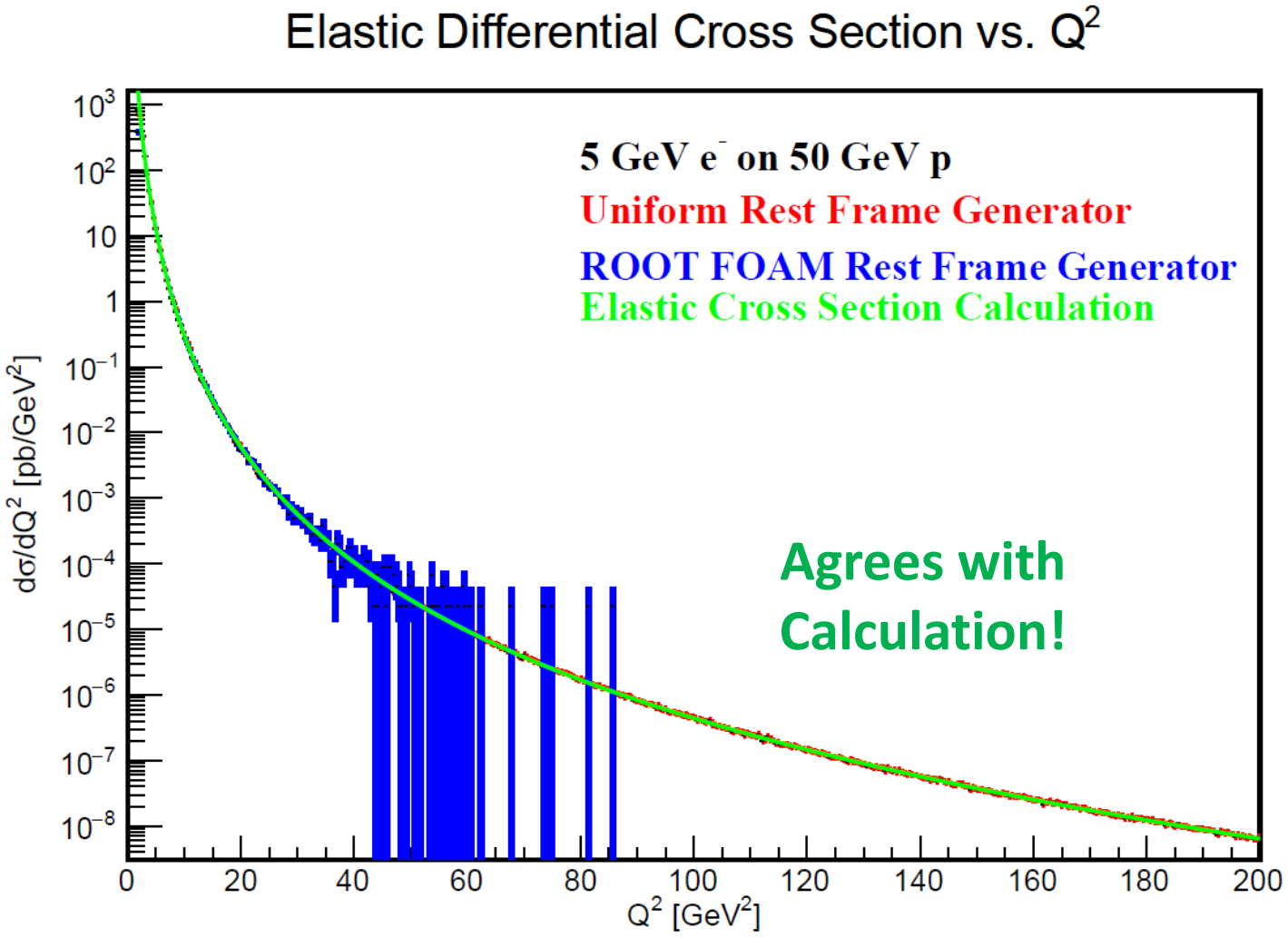

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3. Perform similar studies for elastic scattering on the deuteron – can we use this to measure tensor polarization of deuteron beam?

$$P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0}$$

$$P_{zz} = \frac{n^+ + n^- - 2n^0}{n^+ + n^- + n^0}$$

$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{\sigma_M}{1 + \frac{2E}{M_d}\sin^2\frac{\theta}{2}} \times \left[A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}\right] \\ &\times \left[1 + \rho_{20}\cdot t_{20}(Q^2,\theta) + 2Re\rho_{21}\cdot t_{21}(Q^2,\theta) + 2Re\rho_{22}\cdot t_{22}(Q^2,\theta)\right. \\ &\left. + h\rho_{10}\cdot t_{10}(Q^2,\theta) + 2hRe\rho_{11}\cdot t_{11}(Q^2,\theta)\right]\end{aligned}$$

Garçon M., Van Orden J.W. (2001), *The Deuteron: Structure and Form Factors*

What we are doing for *EIC* simulations

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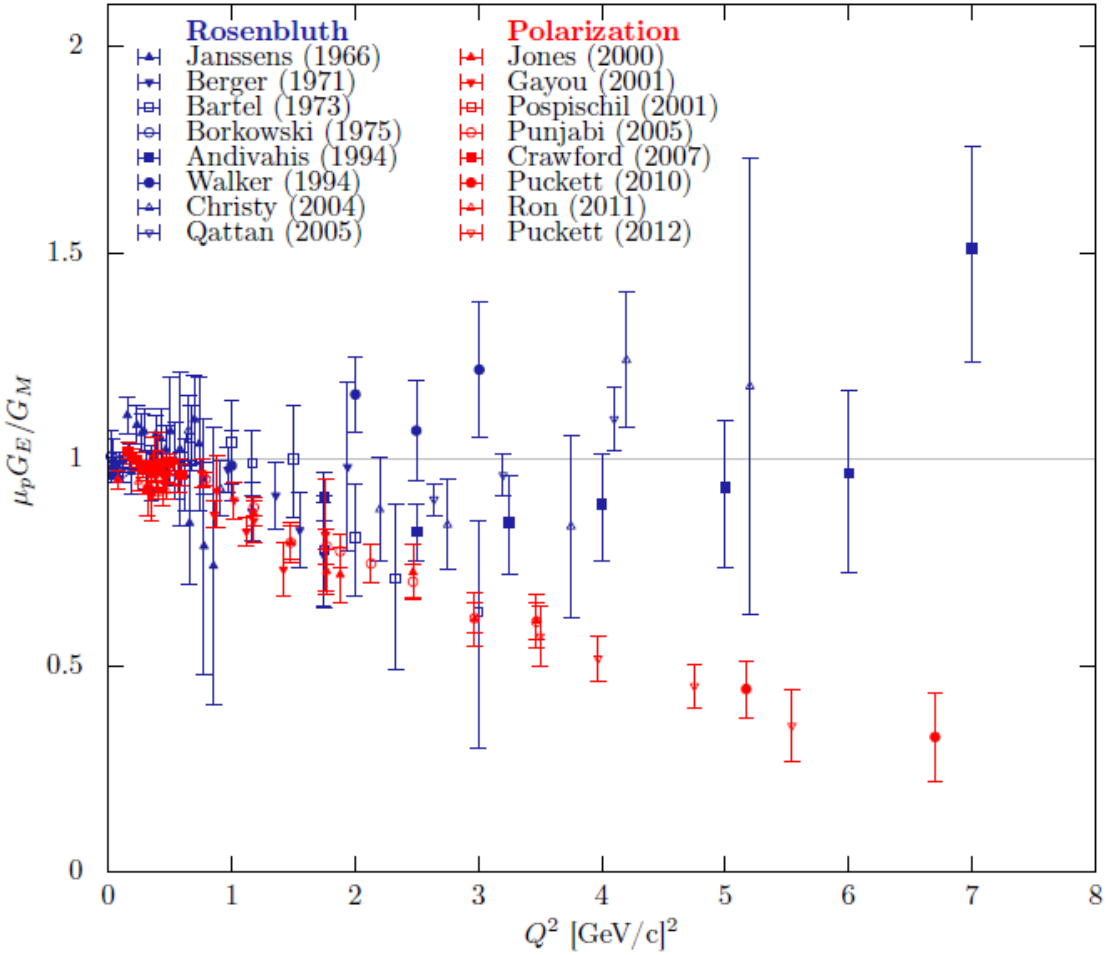
2. Add non-zero crossing angle to generator for both *eRHIC* and *JLEIC* ✓
3. Perform similar studies for elastic scattering on the deuteron – can we use this to measure tensor polarization of deuteron beam?
4. Look at the possibility of polarization transfer measurements at the *EIC*
5. Hard two-photon exchange with positrons?

Proton Form Factor Discrepancy

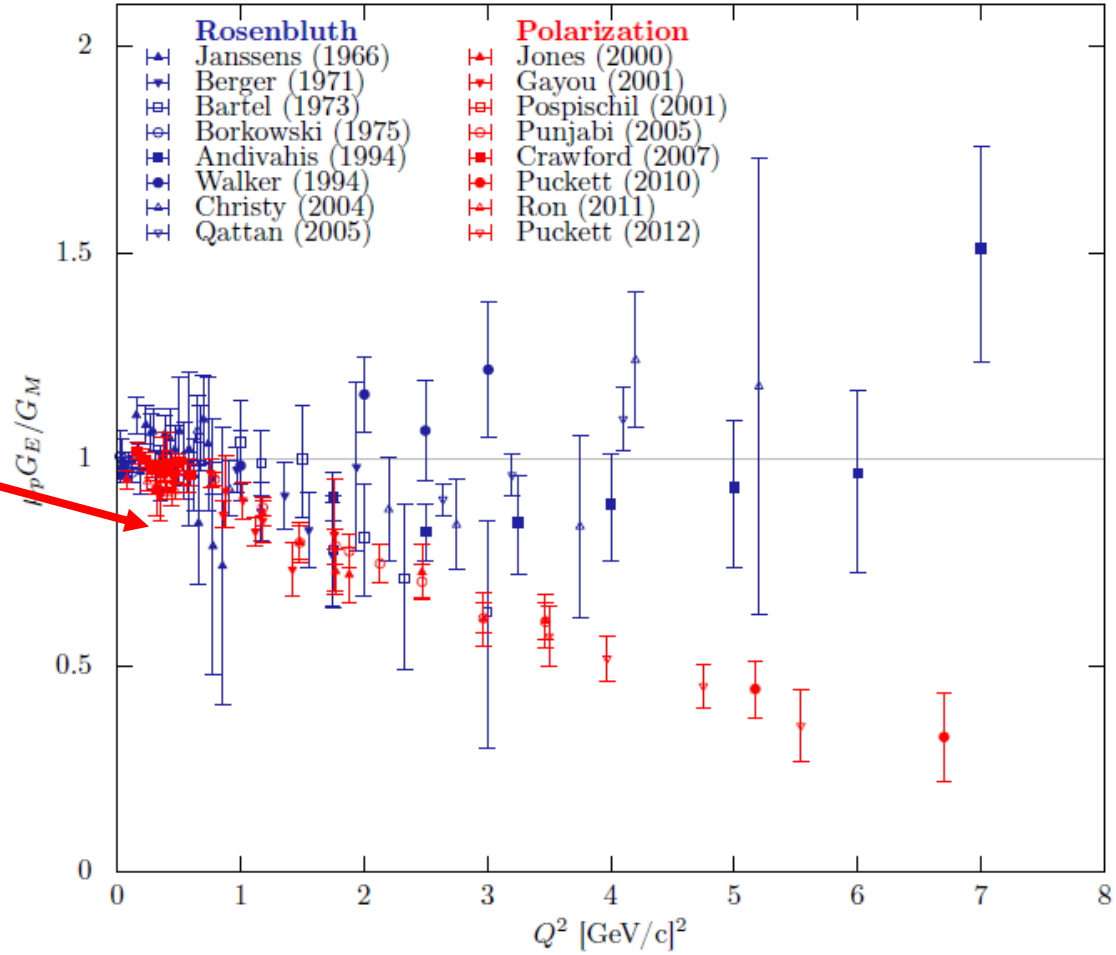


If discrepancy is due to hard two-photon exchange, we should observe an asymmetry between the electron-proton and positron-proton elastic cross sections

A. Schmidt, *Measuring the lepton sign asymmetry in elastic electron-proton scattering with OLYMPUS*

Proton Form Factor Discrepancy

$$R = 1 - 0.12 \times Q^2$$



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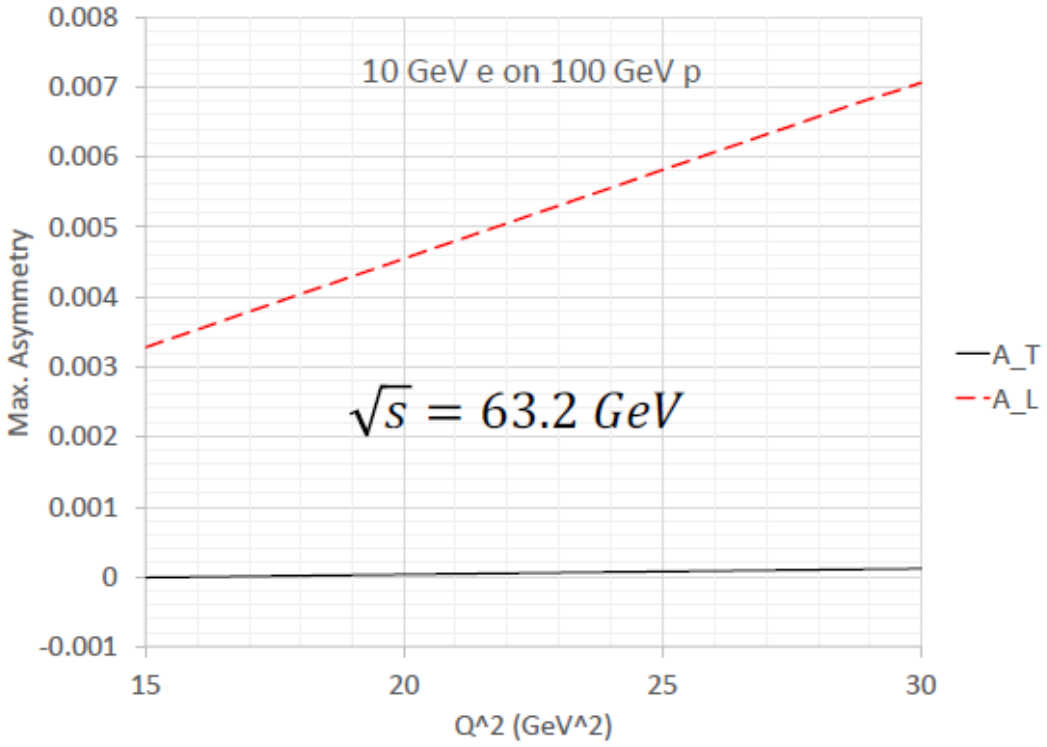
Possibility of Polarization Transfer Measurements at the *EIC*

Figure courtesy of A. Puckett



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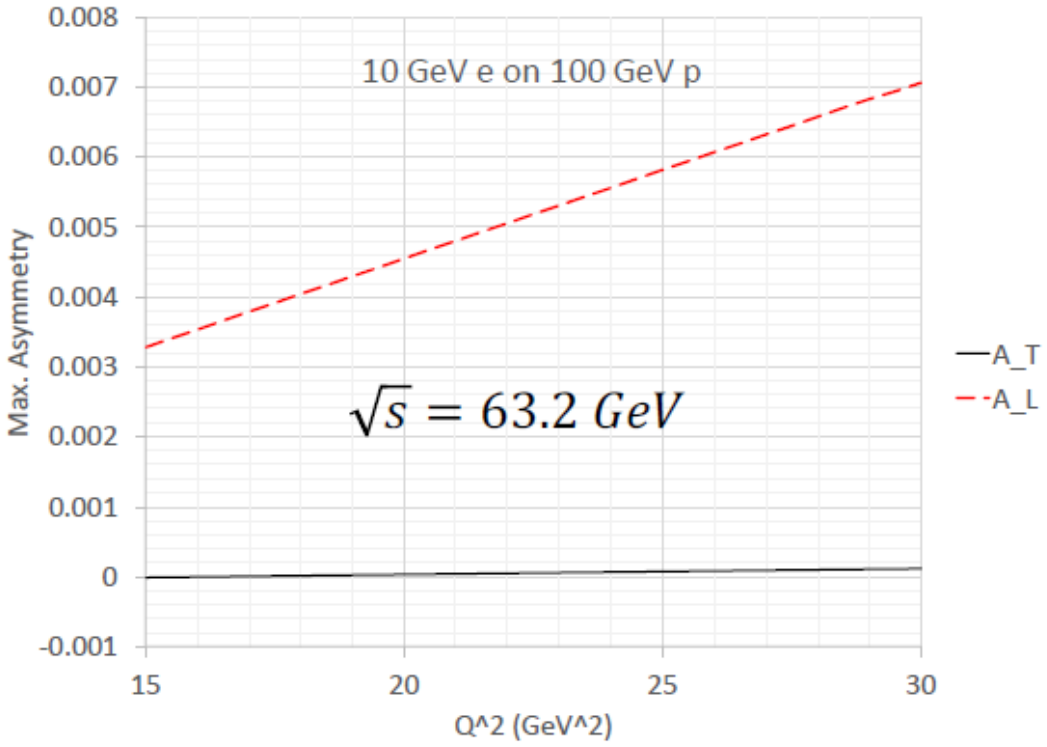
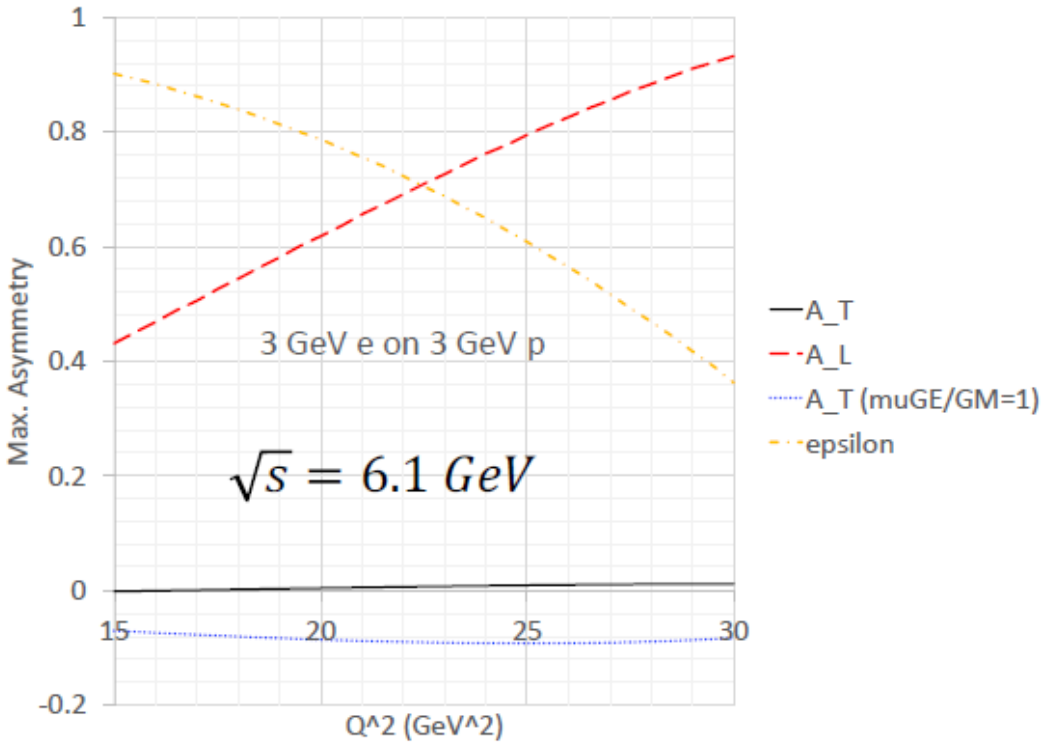


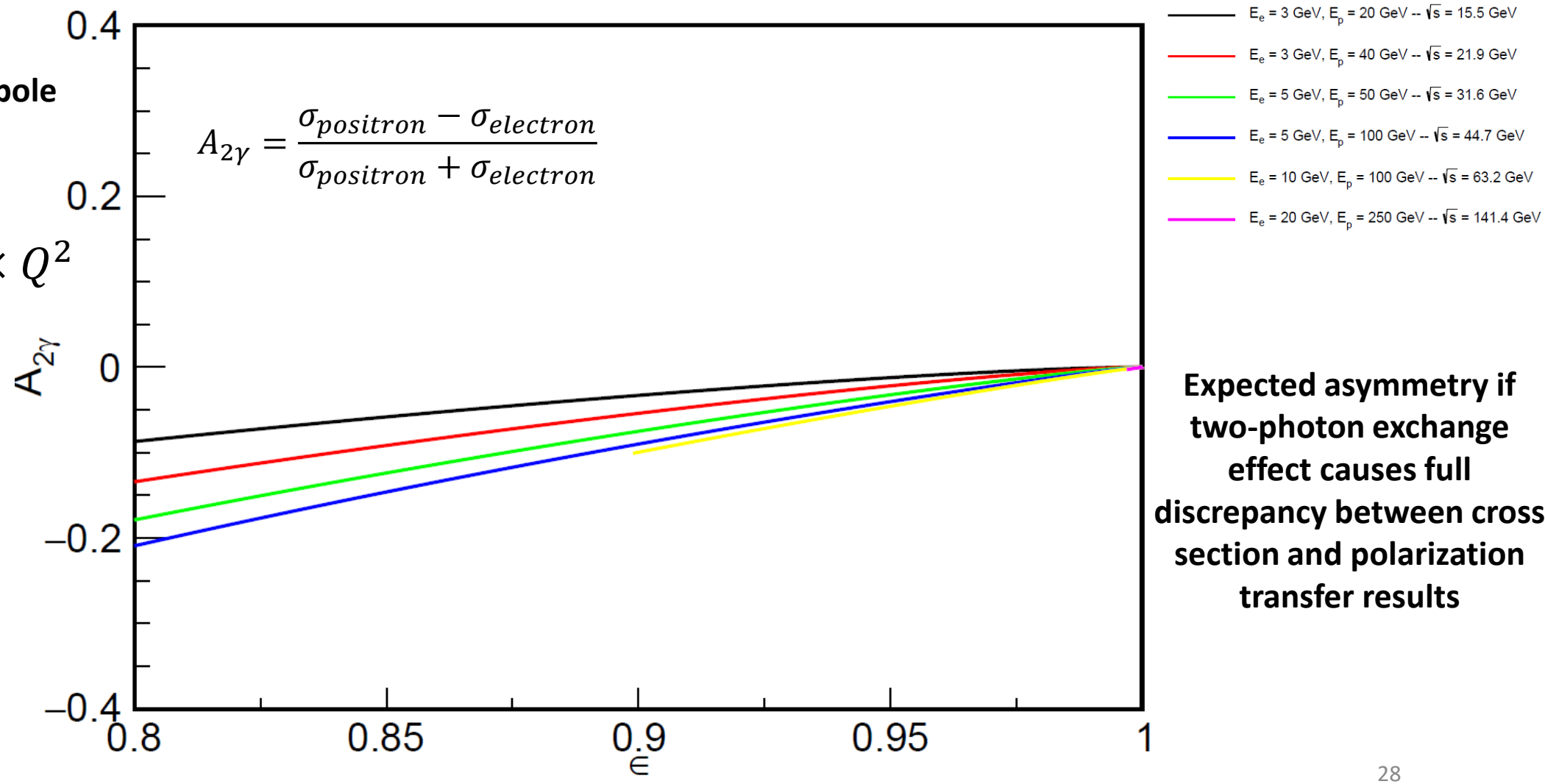


It appears much lower beam energies would be needed to make these measurements

What about electron-positron asymmetry?

Again, assuming dipole form factors…

$$R = 1 - 0.12 \times Q^2$$



Expected asymmetry if two-photon exchange effect causes full discrepancy between cross section and polarization transfer results

Summary: Elastic Scattering

- We think it will be possible to measure elastic electron-proton cross sections at high Q^2 at the EIC
- We are currently conducting simulation studies on this topic
- We are starting to investigate the possibilities with elastic electron-deuteron scattering

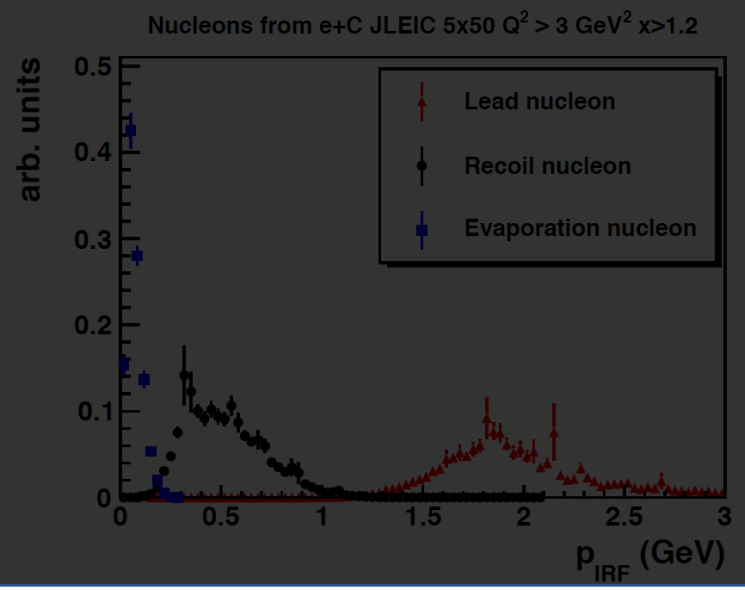
Other EIC Physics Topics

Kinematic Reconstruction for electron-nucleus DIS

- We usually use the scattered electron to reconstruct the standard kinematic variables (e.g. x, y, Q^2). But in certain cases we cannot:
  - The scattered electron is not detected
  - There is no scattered electron (i.e. charged-current events)
  - The scattered electron is reconstructed poorly
- In these cases, we must use the final hadronic state.
- Well-established methods have been developed for electron-proton scattering.
- We are using various event generators to look at reconstruction for electron-nucleus scattering

Studies of Short-Range Correlations (SRCs) at the EIC

- Working to combine an SRC quasi-elastic generator with the *BeAGLE* generator
- Look at the possibility of studying SRC events at the EIC



LDRD Proposal: Tagged Short-Range Correlations for medium to heavy ions at JLEIC

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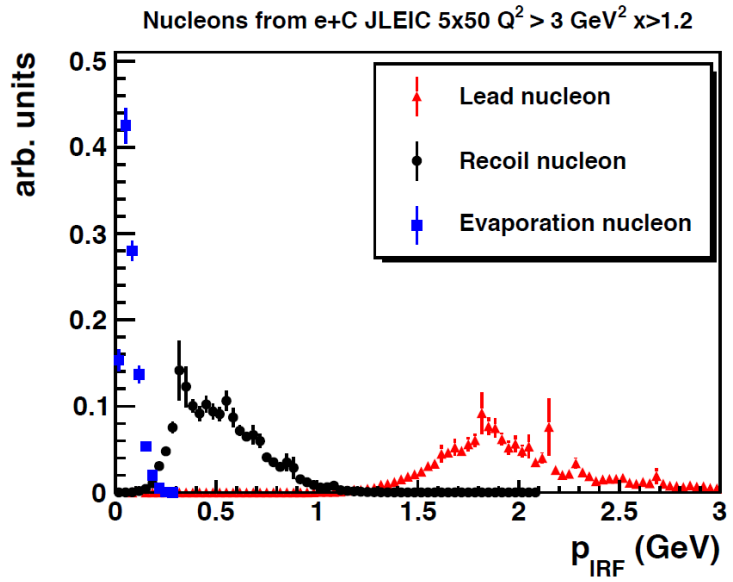

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Other EIC Physics Topics

Decay Angular Distribution in DVMP

- See talk later today by Athira Vijayakumar!

Spin Structure Function Studies

- Use models/fits of g_1^p and g_1^n to estimate expected double-spin asymmetries as a function of x and Q^2 for proton and deuteron beams.
- Possibility of measuring tensor spin structure function b_1^d?

$$\frac{\mathrm{d}^2\sigma_P}{\mathrm{d}x\mathrm{d}Q^2} \simeq \frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2}\left[1 - P_z P_B D A_1^{\mathrm{d}} + \frac{1}{2}P_{zz}A_{zz}^{\mathrm{d}}\right]$$

$$A_{zz}^{\mathrm{d}} = \frac{2\sigma^1 - 2\sigma^0}{3\sigma_U P_{zz}^{\mathrm{eff}}}$$

$$b_1^{\mathrm{d}} = -\frac{3}{2}A_{zz}^{\mathrm{d}}\, F_1^{\mathrm{d}}$$

The HERMES Collaboration: First Measurement of the Tensor Structure Function b_1 of the Deuteron.

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Papers and Talks

- Papers:
  - “Modified structure of protons and neutrons in correlated pairs”. Nature 566, 354-358 (2019)
- Talks:
  - BNL Seminar: March 2019
  - CFNS Workshop on Forward Physics: September 2019
  - DNP Meeting: October 2019

BACKUP SLIDES

Kinematics (ignoring electron and proton masses)

$$Q^2 = x\,s\,y \qquad s = 4E_eE_p$$

$$\varepsilon \simeq \frac{1-y}{1-y+y^2/2}$$

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Final State Electron Angle and Energy:

$$E_e' = (1-y)\,E_e + x\,y\,E_p$$
$$\cos\theta_e' = [x\,y\,E_p - (1-y)\,E_e] / [x\,y\,E_p + (1-y)\,E_e]$$
$$E_e'^2 \sin^2\theta_e' = 4\,x\,y\,(1-y)\,E_e\,E_p$$

Final State Proton Angle and Energy:

$$E_j = y\,E_e + x\,(1-y)\,E_p$$
$$\cos\theta_j = [-y\,E_e + (1-y)\,x\,E_p] / [y\,E_e + (1-y)\,x\,E_p]$$
$$E_j^2 \sin^2\theta_j = 4\,x\,y\,(1-y)\,E_e\,E_p = Q^2\,(1-y)$$

Kinematics (ignoring electron and proton masses)

$$Q^2 = \cancel{x}\, s\, y \qquad s = 4E_e E_p$$

= 1 for elastic

$$\varepsilon \simeq \frac{1-y}{1-y+y^2/2}$$

Final State Electron Angle and Energy:

$$E_e' = (1-y)\,E_e + \cancel{x}\,y\,E_p$$
$$\cos\theta_e' = [\cancel{x}\,y\,E_p - (1-y)\,E_e] / [\cancel{x}\,y\,E_p + (1-y)\,E_e]$$
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Final State Proton Angle and Energy:

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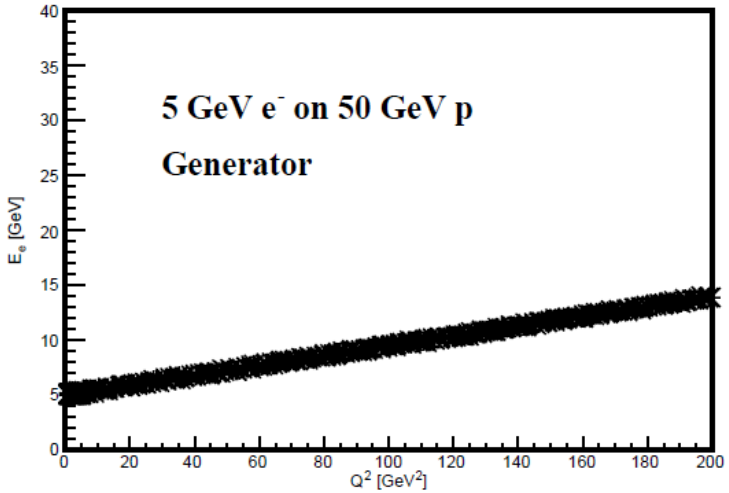
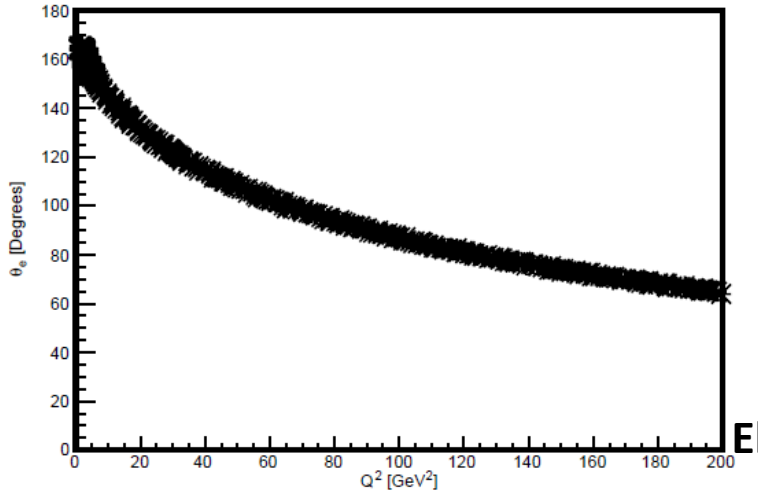
$$\cos\theta_j = [-y\,E_e + (1-y)\cancel{x}\,E_p] / [y\,E_e + (1-y)\cancel{x}\,E_p]$$
$$E_j^2 \sin^2\theta_j = 4\cancel{x}\,y\,(1-y)\,E_e\,E_p = Q^2\,(1-y)$$

Elastic Generator

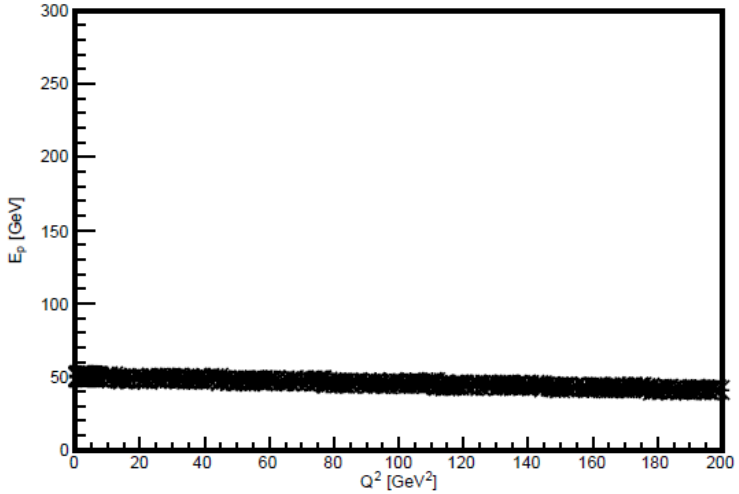
Scattered Electron Energy

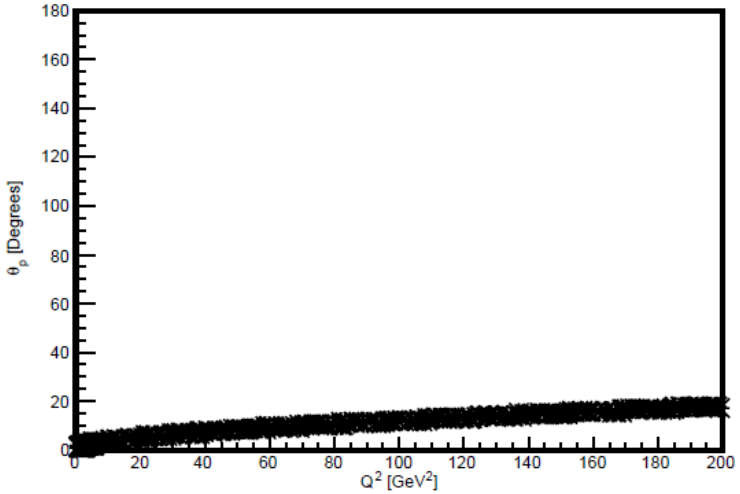




Scattered Electron Angle

Scattered Proton Energy

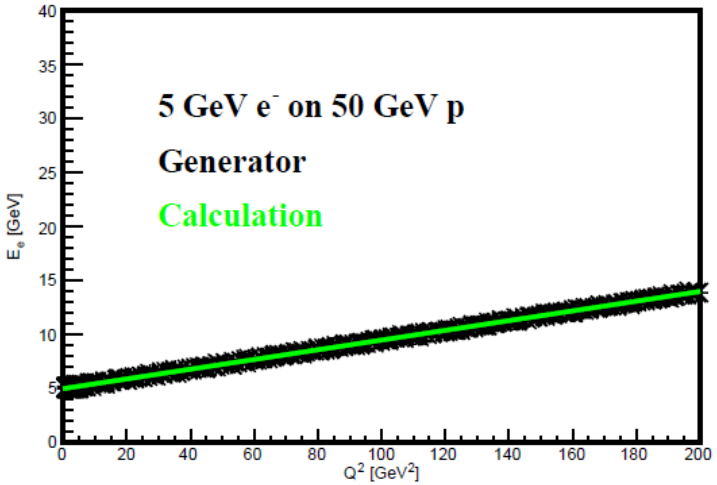


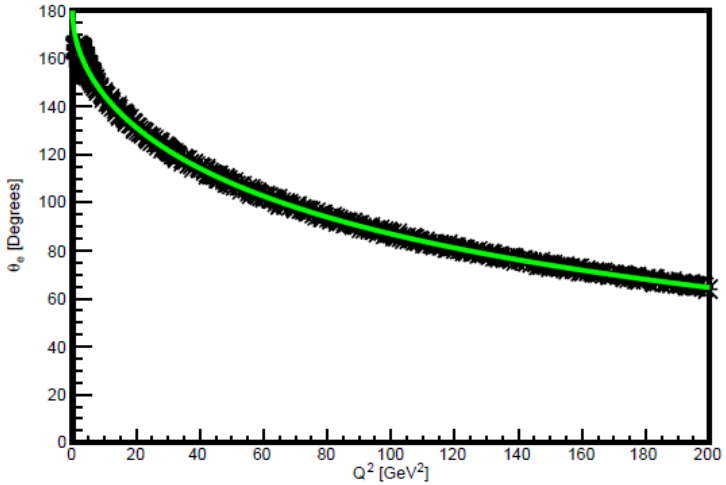


Scattered Proton Angle

Elastic Generator

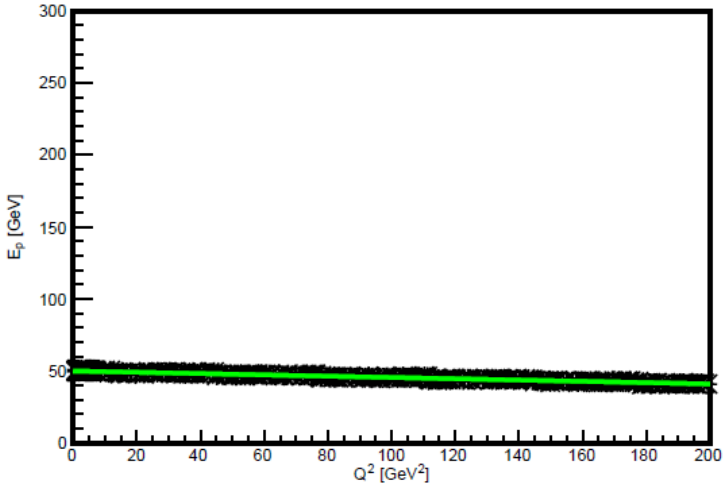
Scattered Electron Energy

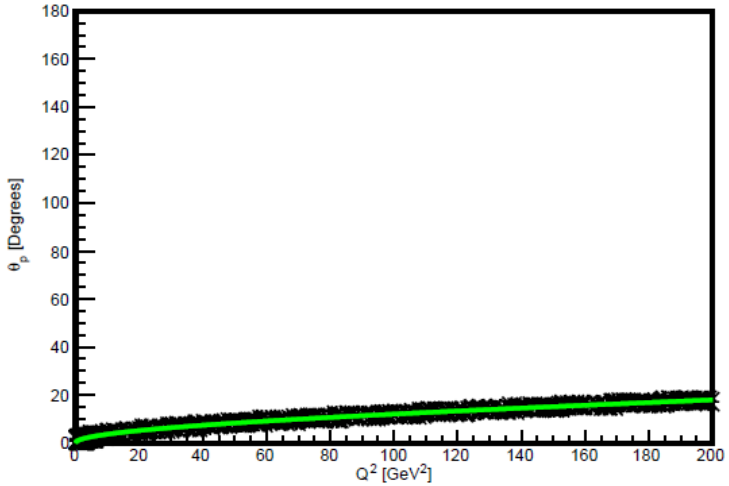




Scattered Electron Angle

Scattered Proton Energy

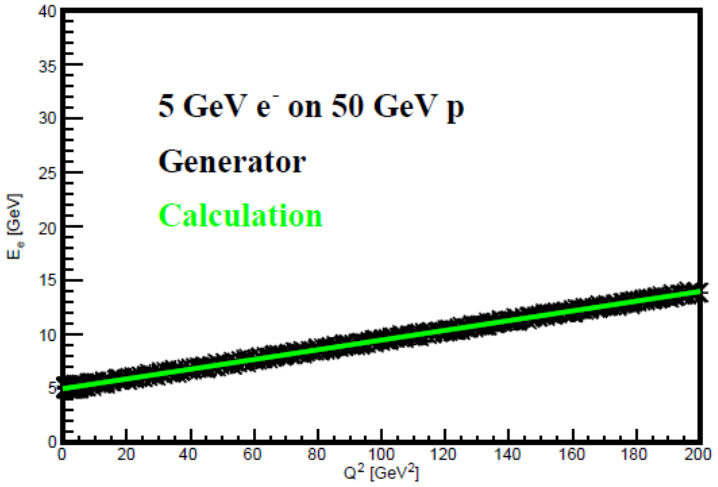


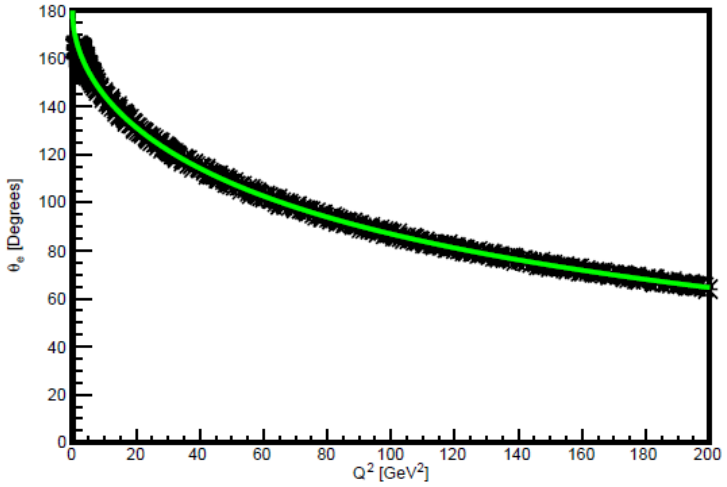


Scattered Proton Angle

Elastic Generator

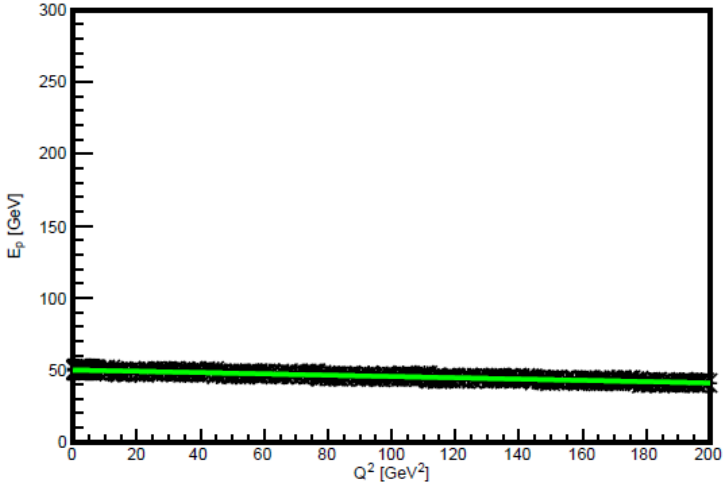
Scattered Electron Energy

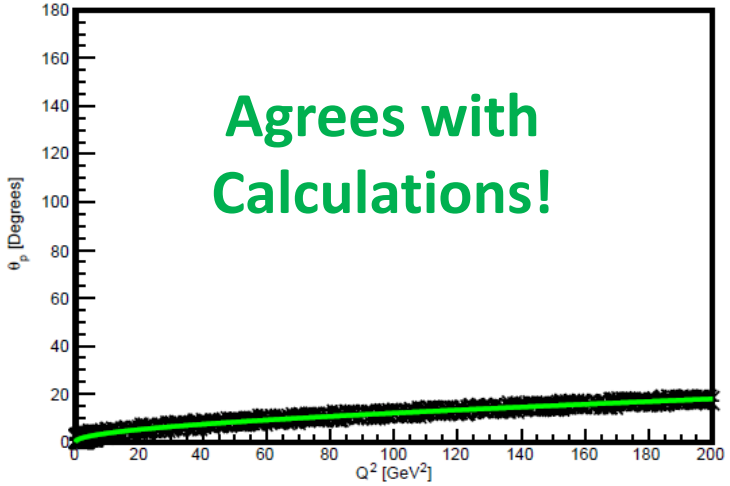




Scattered Electron Angle

Scattered Proton Energy





Scattered Proton Angle