Elastic Electron-Proton and Electron-Deuteron Scattering at the EIC

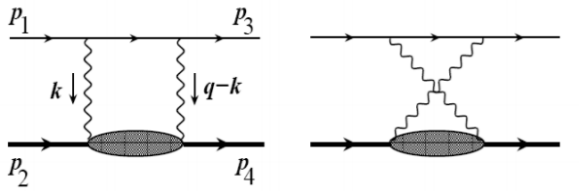
Barak Schmookler
(+ Douglas Higinbotham
Andrew Puckett
Elena Long)

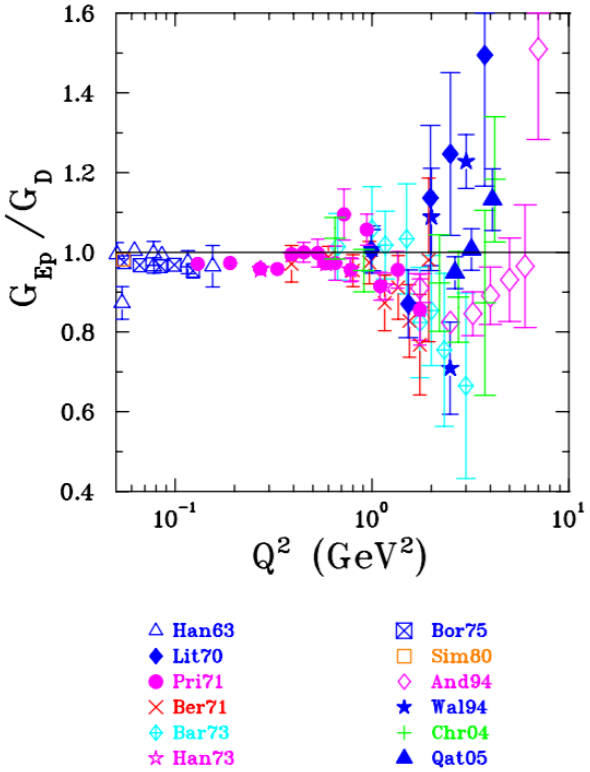
Part I: Elastic Electron-Proton Scattering

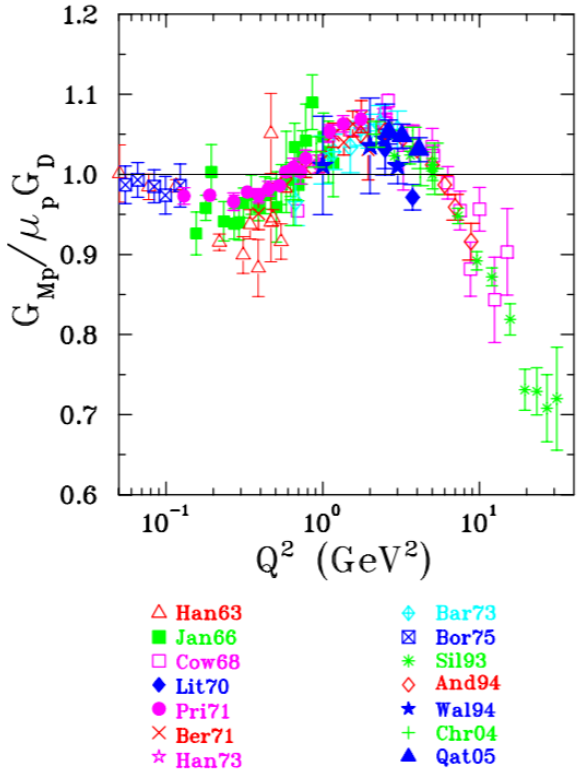
Elastic Electron-Proton Scattering at the EIC

Elastic electron-proton scattering at high Q^2 can be interesting in itself:

- 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

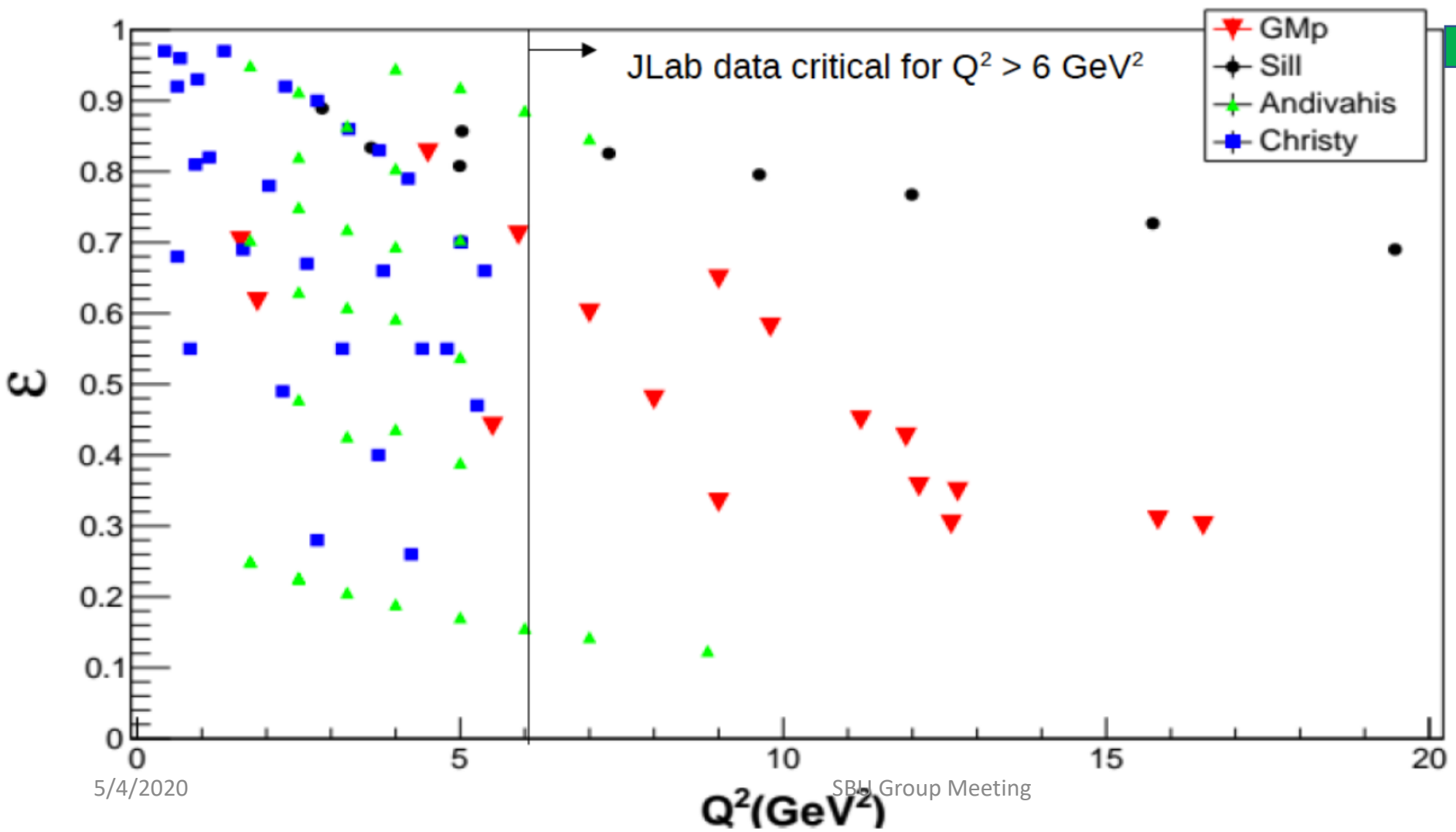






C.F Perdrisat, V. Punjabi, M. Vanderhaeghen, *Progress in Particle and Nuclear Physics 59 (2007) 694–764*

For ep elastic scattering, the *EIC* will allow us to probe the highest-ever values of Q^2



Up to Q^2 ~40 GeV^2 or higher at the EIC – all at high ε

Description of rest-frame Elastic generator with anti-parallel beams

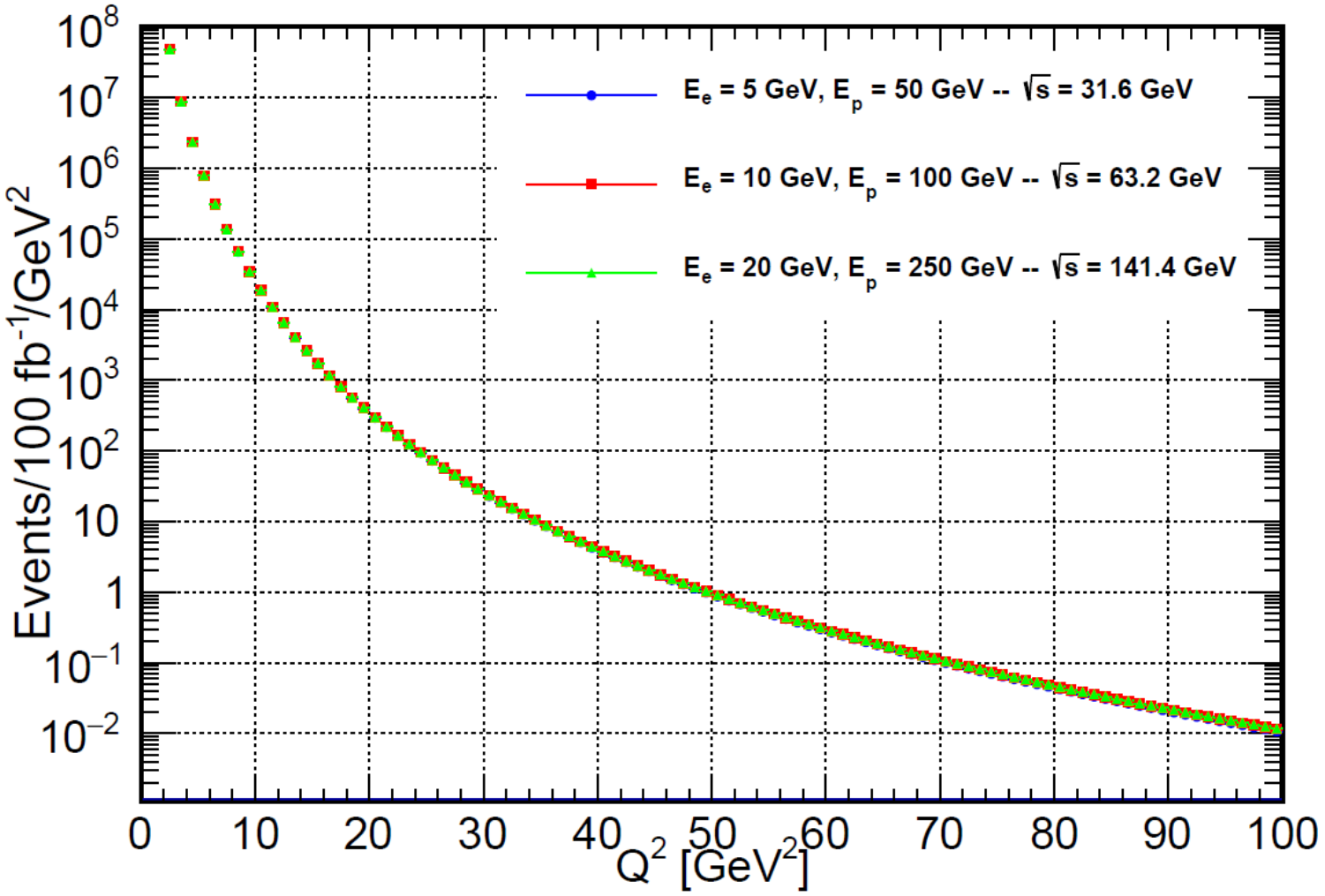
1. Boost from lab frame to proton's rest frame
2. Generate events according to Born cross section below
3. Form factor parameterization comes from *Kelly (*PHYSICAL REVIEW C **70**, 068202 2004, Phys. Rev. C **96**, 055203).
4. We choose to generate 100 fb^{-1} worth of simulation data

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)} \qquad \tau \equiv \frac{Q^2}{4M_p^2}$$

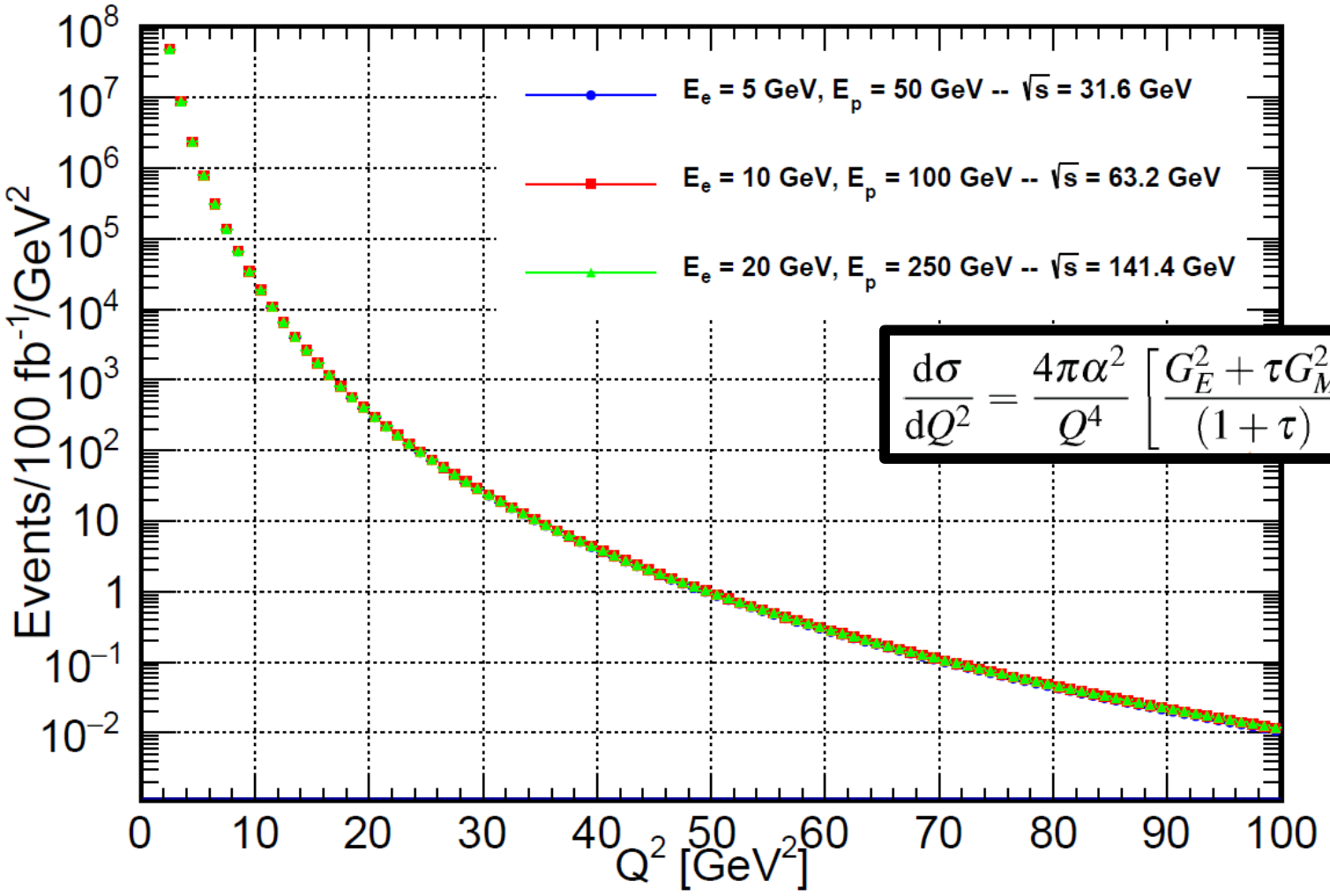
$$\left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} = \frac{\alpha^2 \cos^2\left(\frac{\theta_e}{2}\right)}{4E_e^2 \sin^4\left(\frac{\theta_e}{2}\right)} \frac{E_e'}{E_e} \qquad \epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

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

Electron-Proton Elastic scattering expected yields



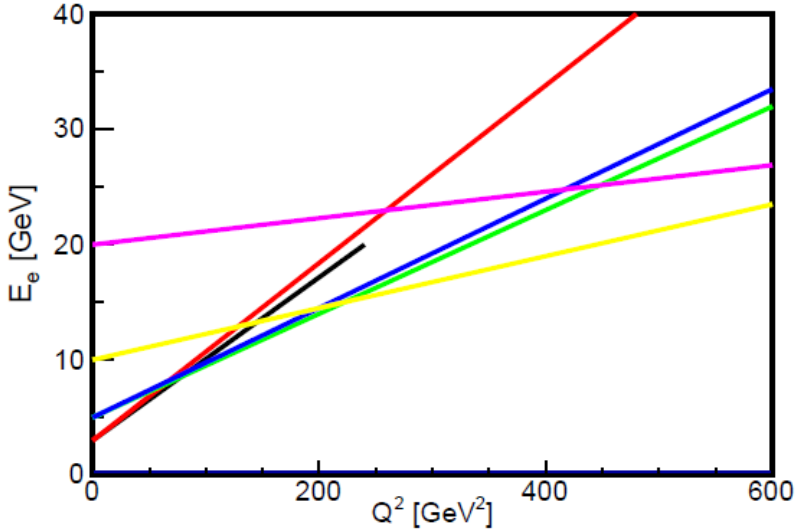
Electron-Proton Elastic scattering expected yields

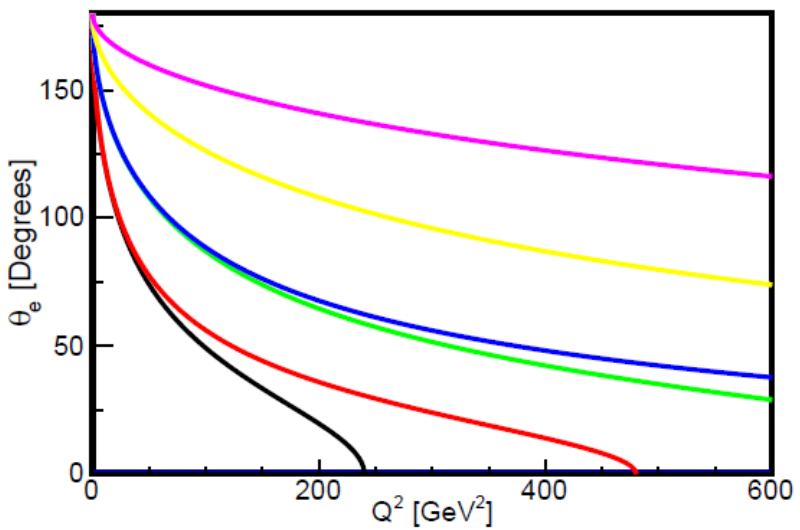


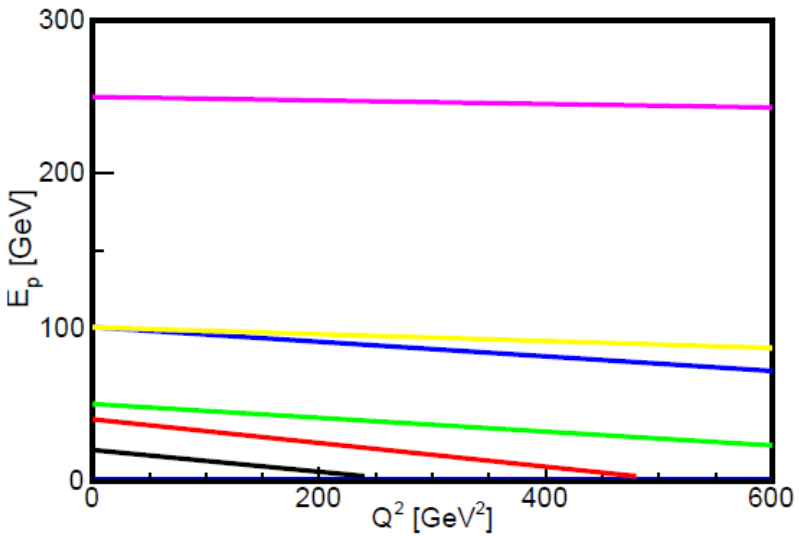
$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2 + \tau G_M^2}{(1+\tau)}\left(1 - y - \frac{M^2 y^2}{Q^2}\right) + \frac{1}{2}y^2 G_M^2\right]$$

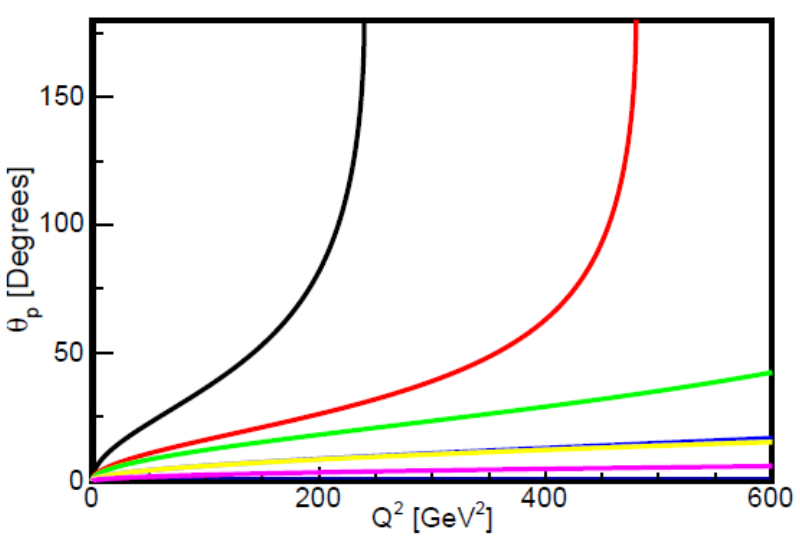
Lack of dependence on beam energy seen here is expected at the EIC since the data will all be at y~0 (ε~1). See the Lorentz-invariant cross section formula above

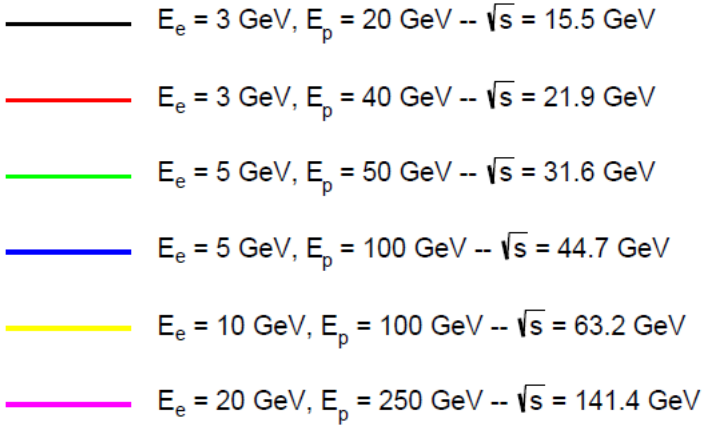
Kinematics


40
30
20
10
0
0
200
400
600
E_e [GeV]
Q^2 [GeV^2]

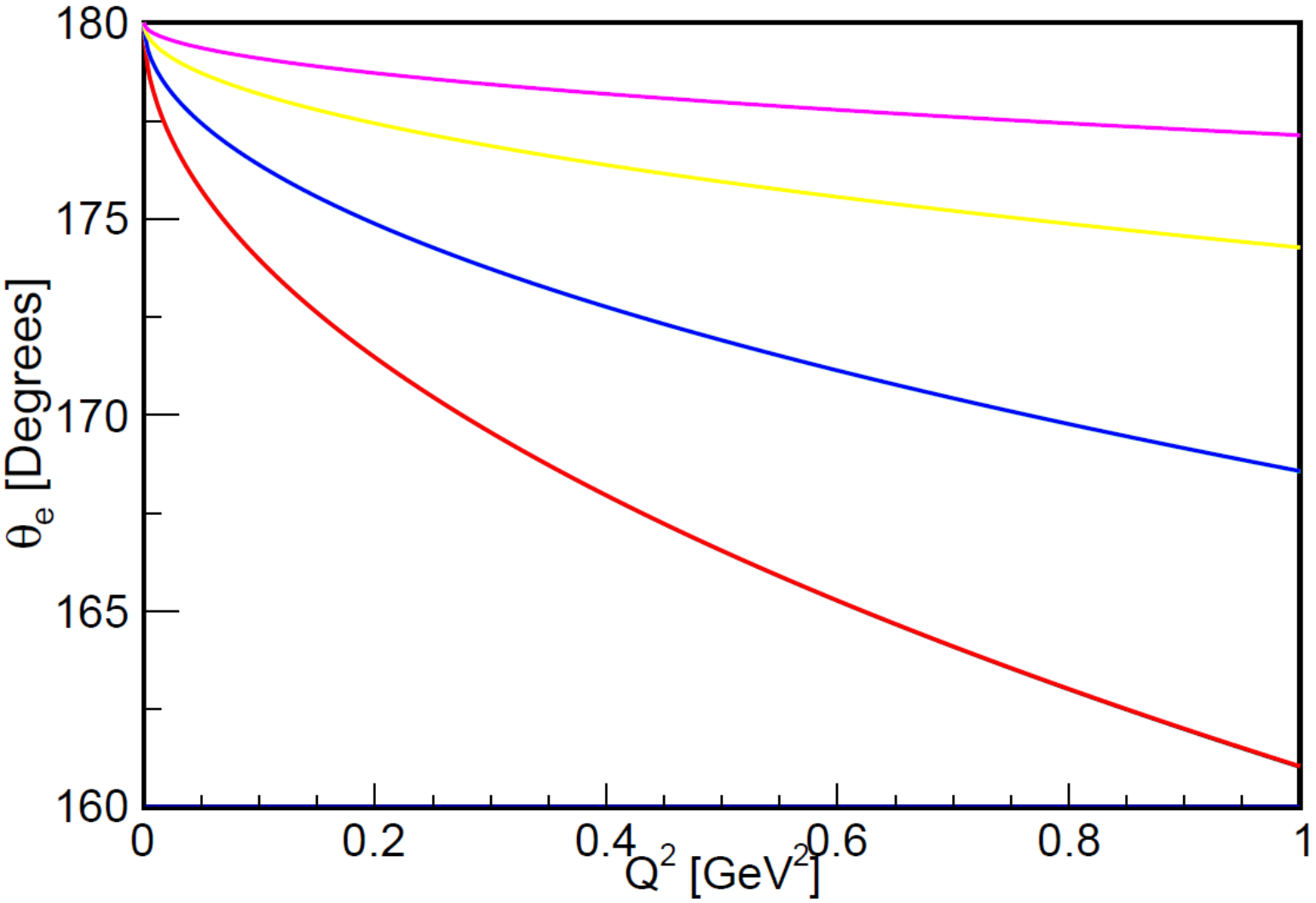

150
100
50
0
0
200
400
600
θ_e [Degrees]
Q^2 [GeV^2]

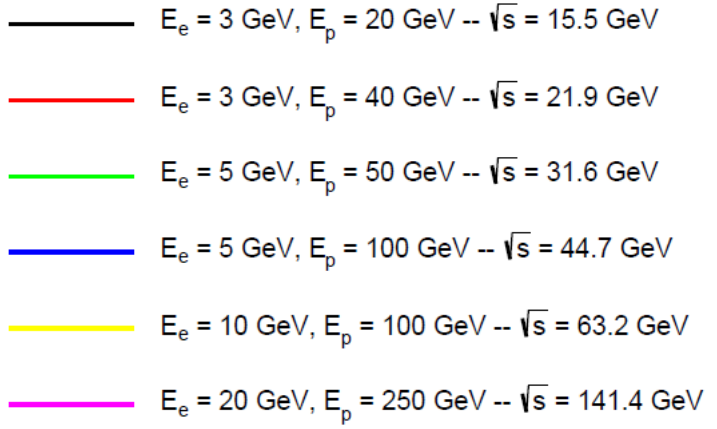

300
200
100
0
0
200
400
600
E_p [GeV]
Q^2 [GeV^2]


150
100
50
0
0
200
400
600
θ_p [Degrees]
Q^2 [GeV^2]

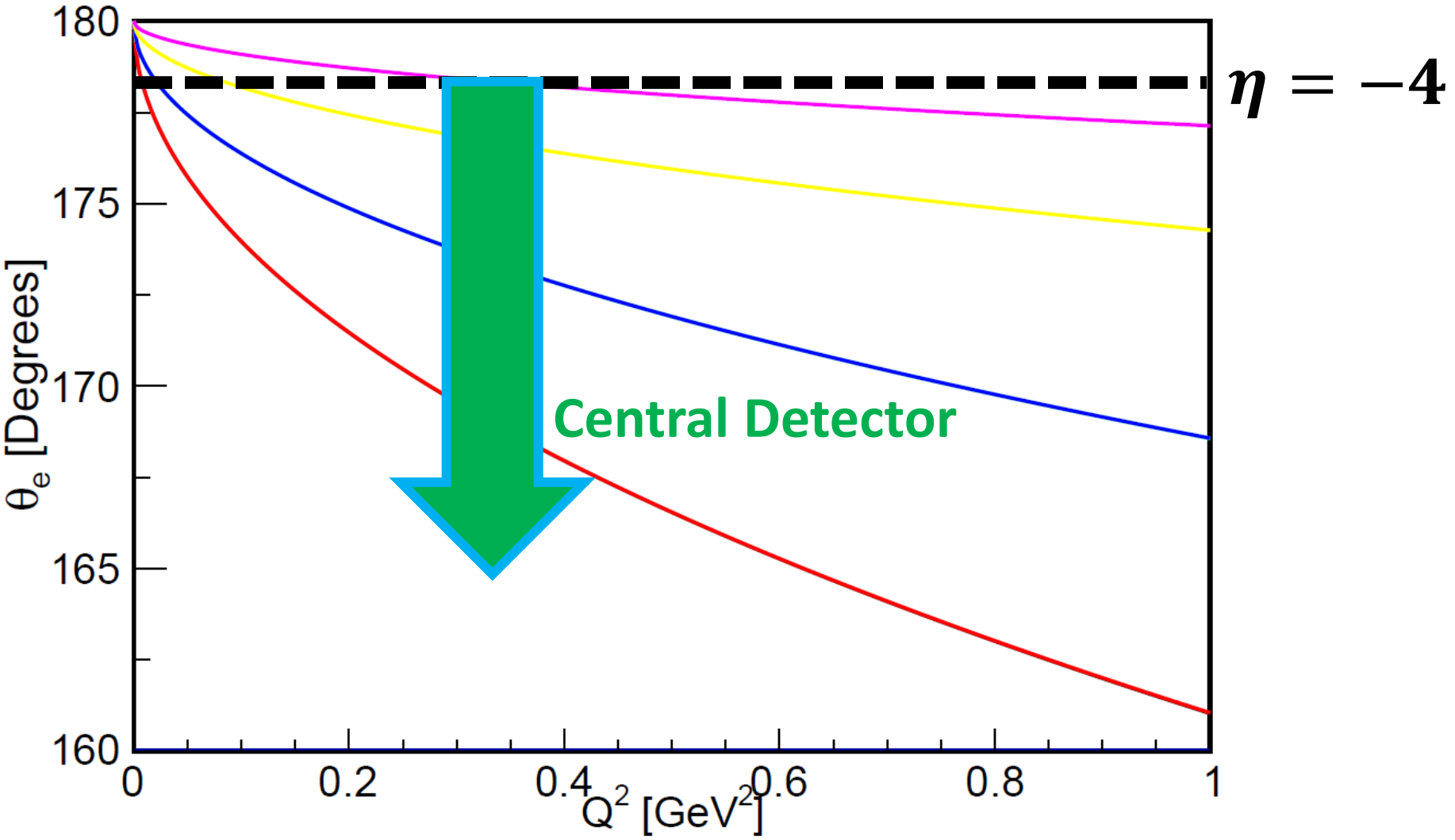

E_e = 3 GeV, E_p = 20 GeV -- $\sqrt{s}$ = 15.5 GeV
E_e = 3 GeV, E_p = 40 GeV -- $\sqrt{s}$ = 21.9 GeV
E_e = 5 GeV, E_p = 50 GeV -- $\sqrt{s}$ = 31.6 GeV
E_e = 5 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 44.7 GeV
E_e = 10 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 63.2 GeV
E_e = 20 GeV, E_p = 250 GeV -- $\sqrt{s}$ =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

Kinematics: Low Q^2 Electron Angle





Kinematics: Low Q^2 Electron Angle



$\eta = -4$

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

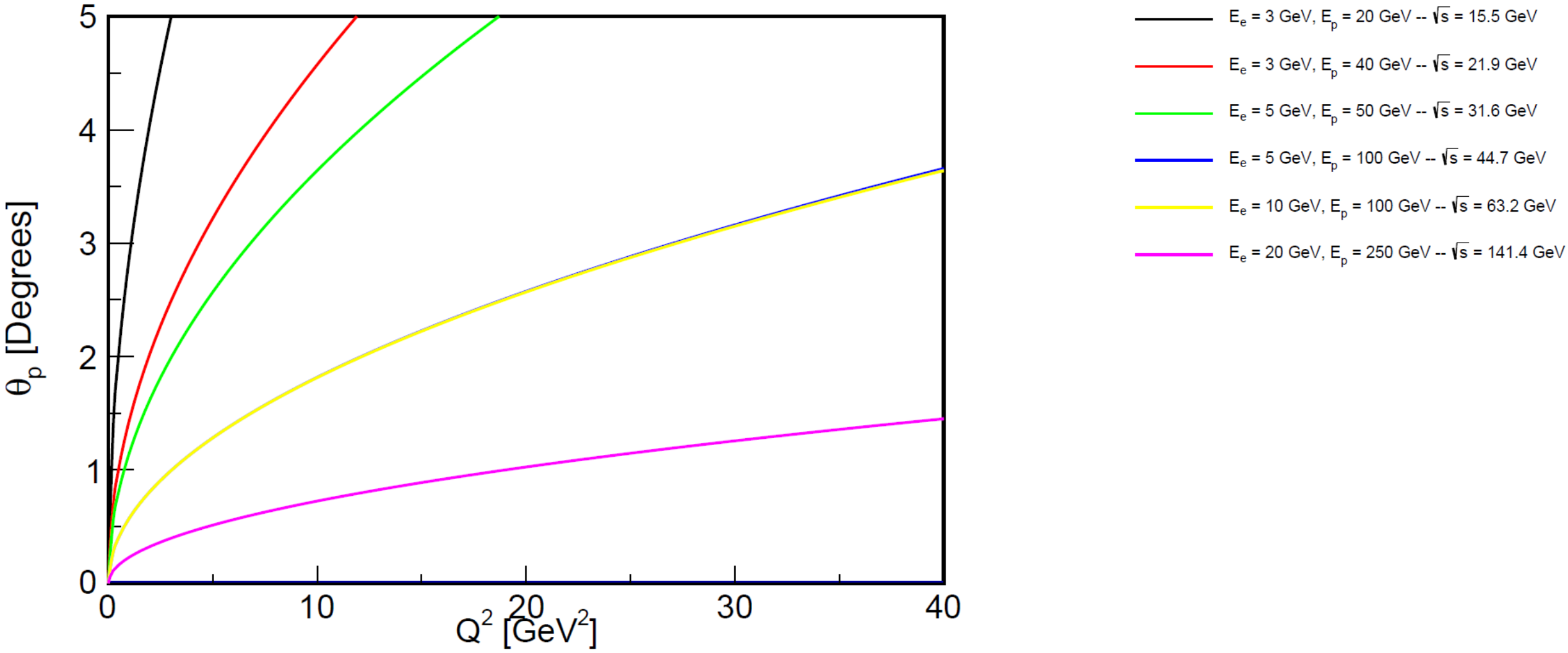
E_e = 5 GeV, E_p = 50 GeV -- $\sqrt{s}$ = 31.6 GeV

E_e = 5 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 44.7 GeV

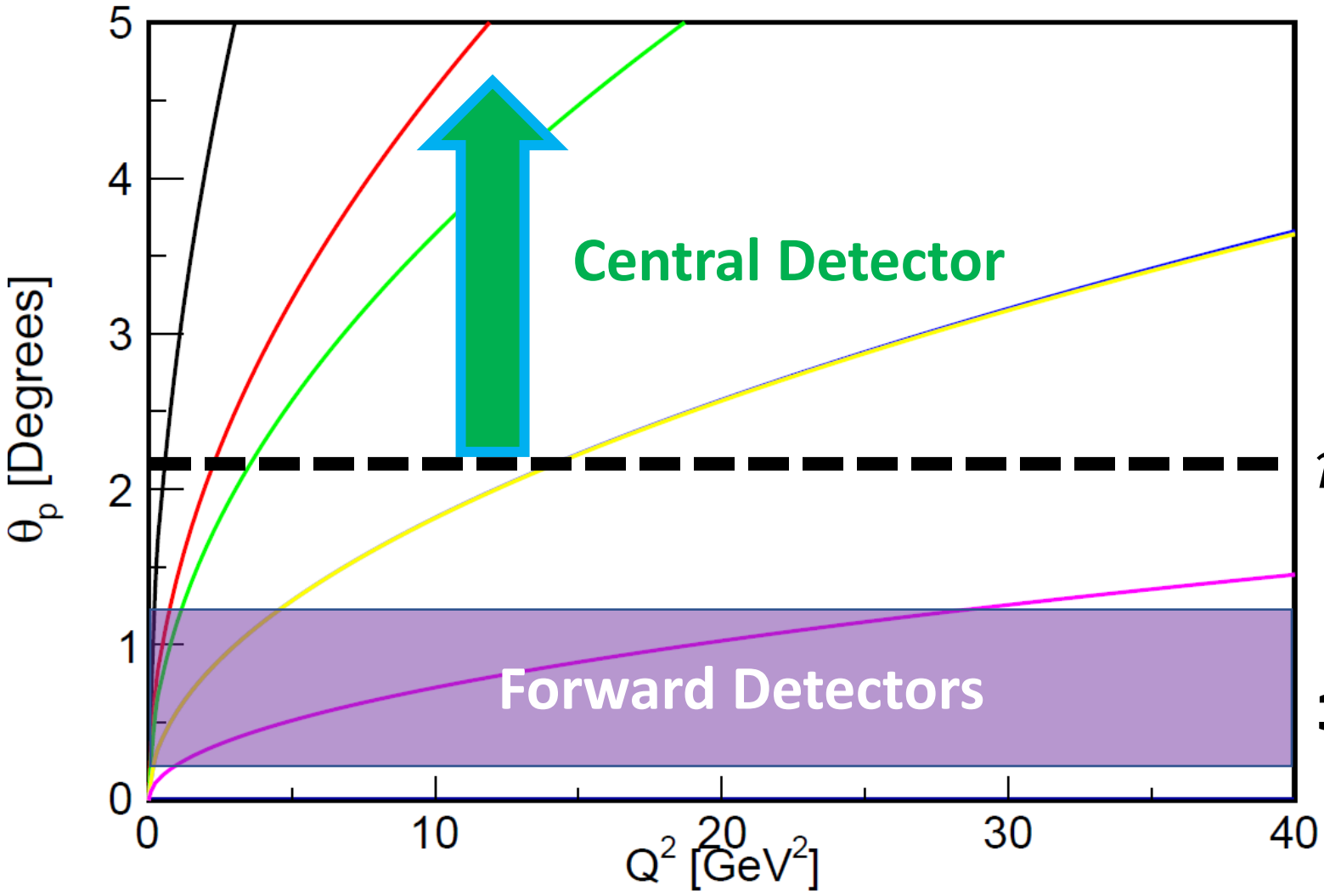
E_e = 10 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 63.2 GeV

E_e = 20 GeV, E_p = 250 GeV -- $\sqrt{s}$ = 141.4 GeV

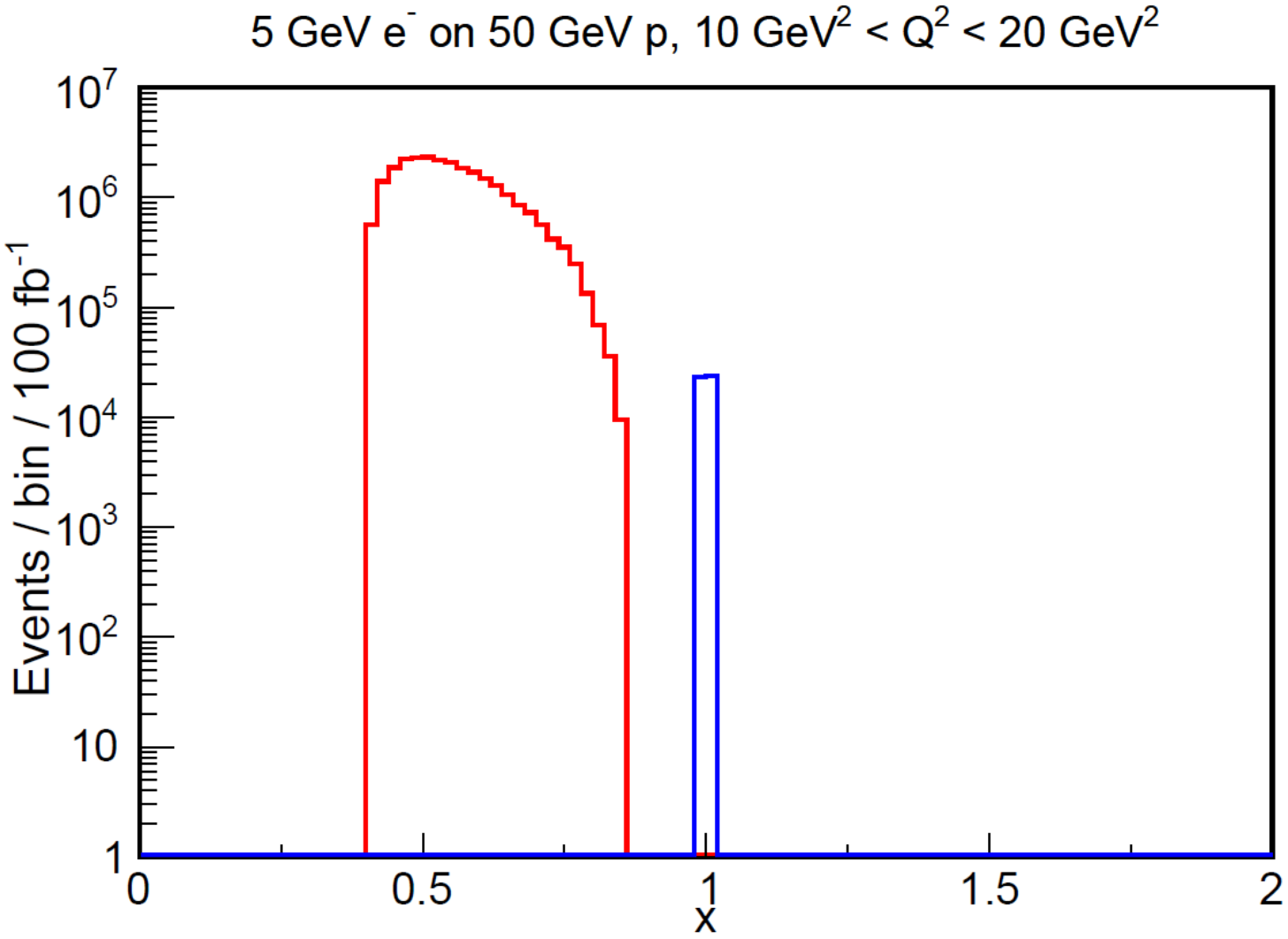
Kinematics: Proton Angle



Kinematics: Proton Angle



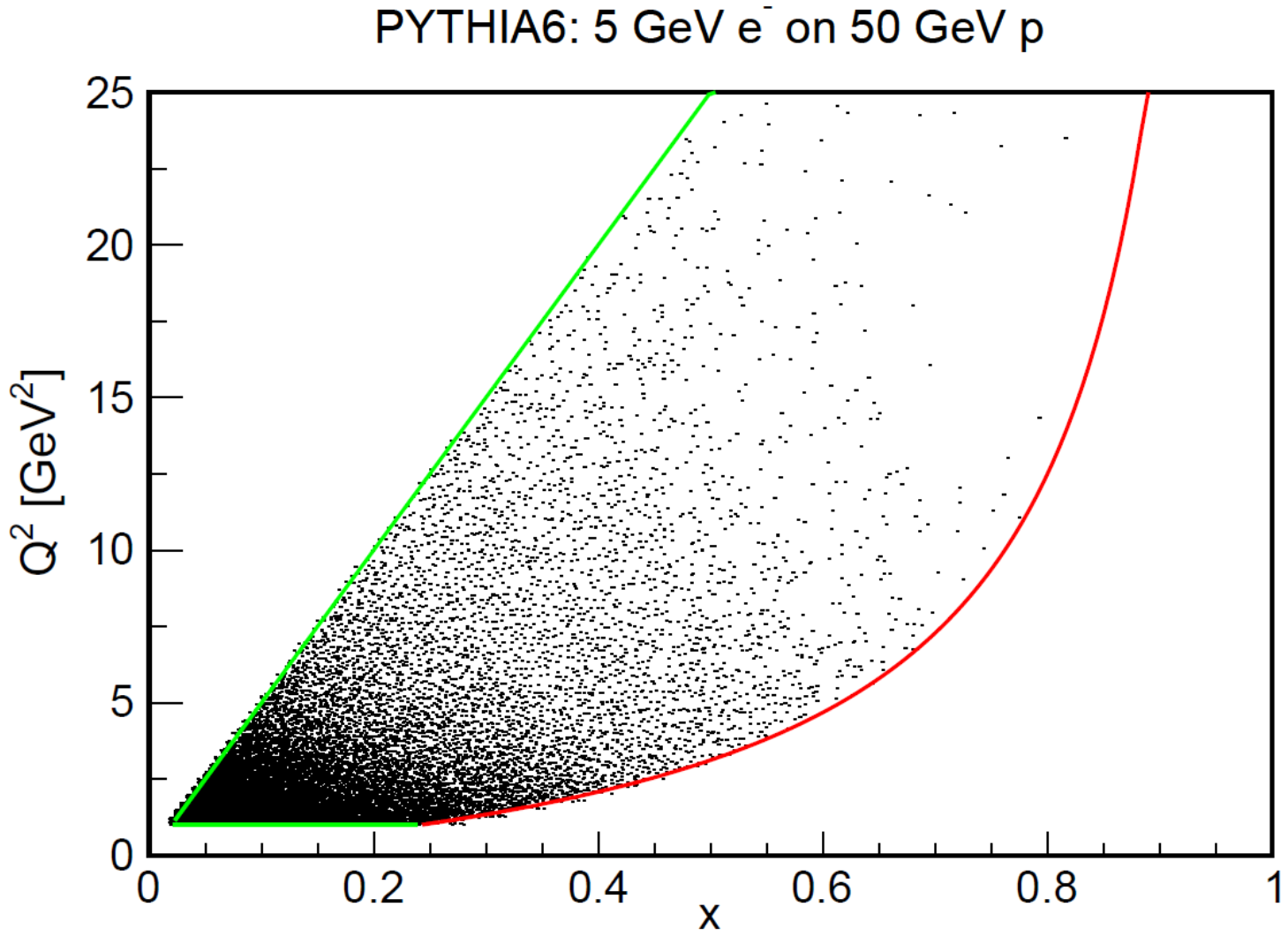
Mix With *Pythia6* Events – Generator Level



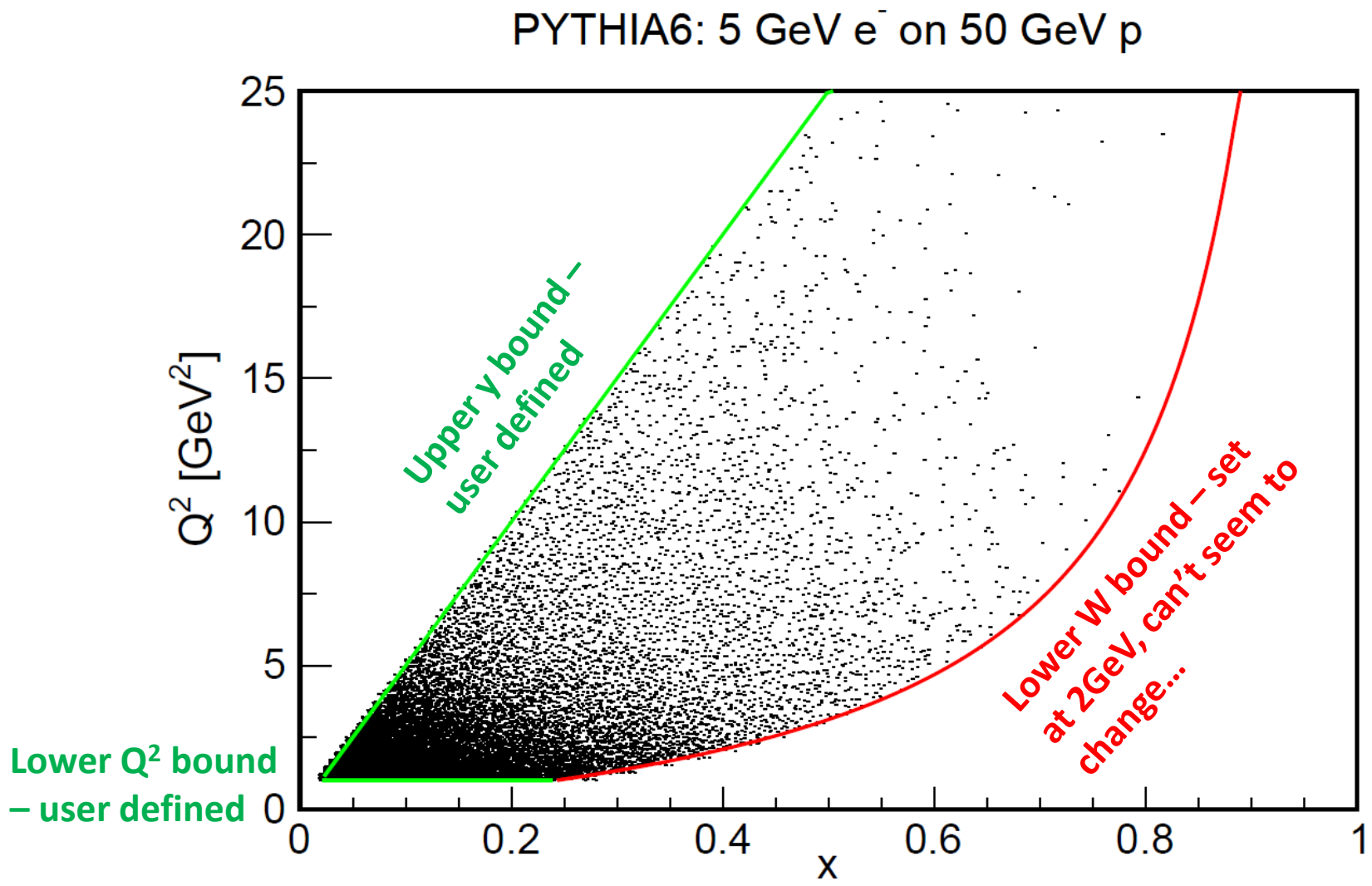
PYTHIA6 Events

Elastic Events

Aside: *Pythia6* at high x



Aside: *Pythia6* at high x



A Simple Central Detector

```
  Smear::Device energy(Smear::kE,"0.2 * TMath::Sqrt(E)");
  Smear::Device momentum(Smear::kP,"0.01 * P");
  Smear::Device theta(Smear::kTheta,"0.01 / ( P * TMath::Sqrt(TMath::Sin(theta)) )");
  Smear::Device phi(Smear::kPhi,"0.01");
  }

//Detector Acceptance
Smear::Acceptance::Zone central(etaToTheta(4.),etaToTheta(-4.));
```

A Simple Central Detector

Smearing

```
Smear::Device energy(Smear::kE,"0.2 * TMath::Sqrt(E)");
Smear::Device momentum(Smear::kP,"0.01 * P");
Smear::Device theta(Smear::kTheta,"0.01 / ( P * TMath::Sqrt(TMath::Sin(theta)) )");
Smear::Device phi(Smear::kPhi,"0.01");
}
```

```
//Detector Acceptance
Smear::Acceptance::Zone central(etaToTheta(4.),etaToTheta(-4.));
```

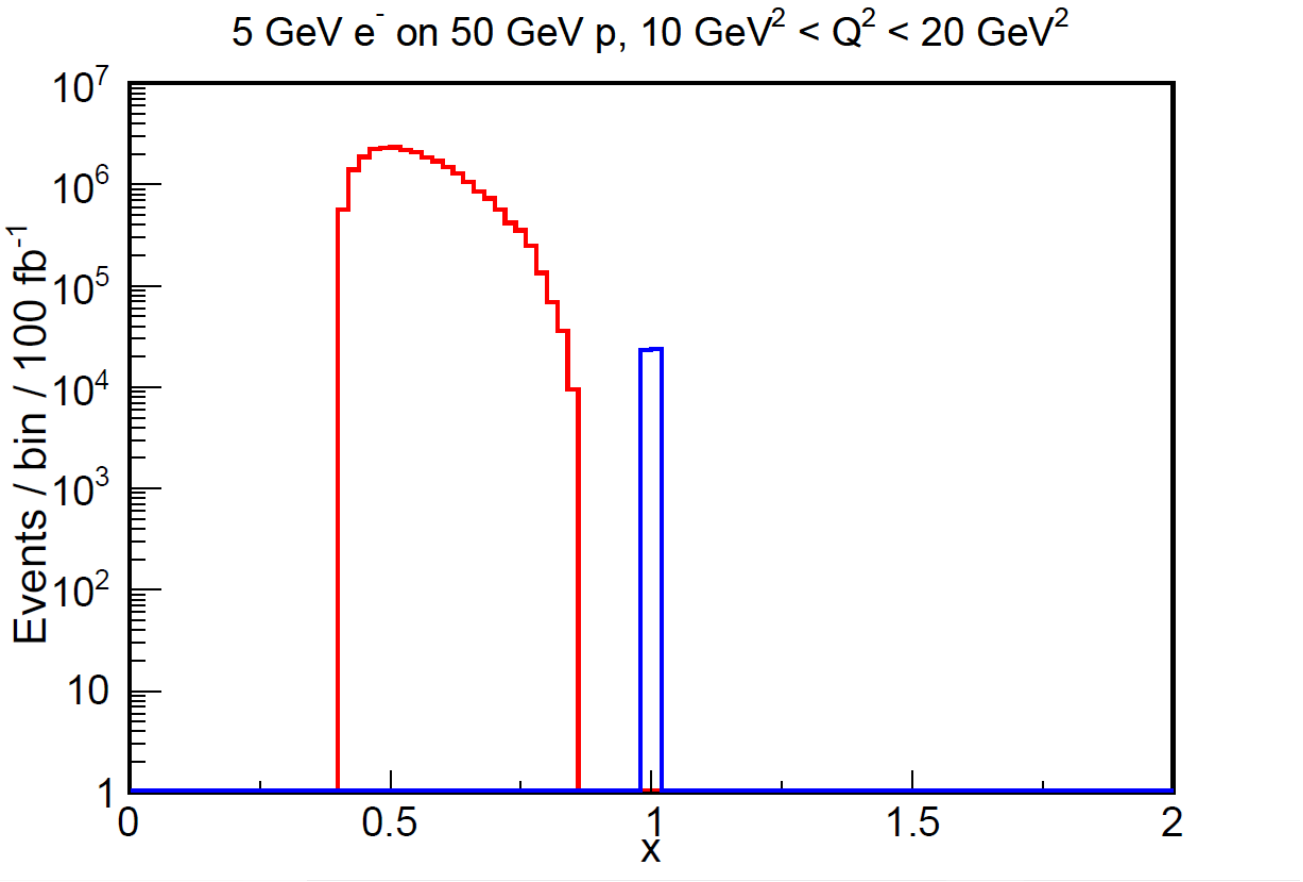
A Simple Central Detector

```
Smear::Device energy(Smear::kE,"0.2 * TMath::Sqrt(E)");
Smear::Device momentum(Smear::kP,"0.01 * P");
Smear::Device theta(Smear::kTheta,"0.01 / ( P * TMath::Sqrt(TMath::Sin(theta)) )");
Smear::Device phi(Smear::kPhi,"0.01");
}

//Detector Acceptance
Smear::Acceptance::Zone central(etaToTheta(4.),etaToTheta(-4.));
```

Acceptance

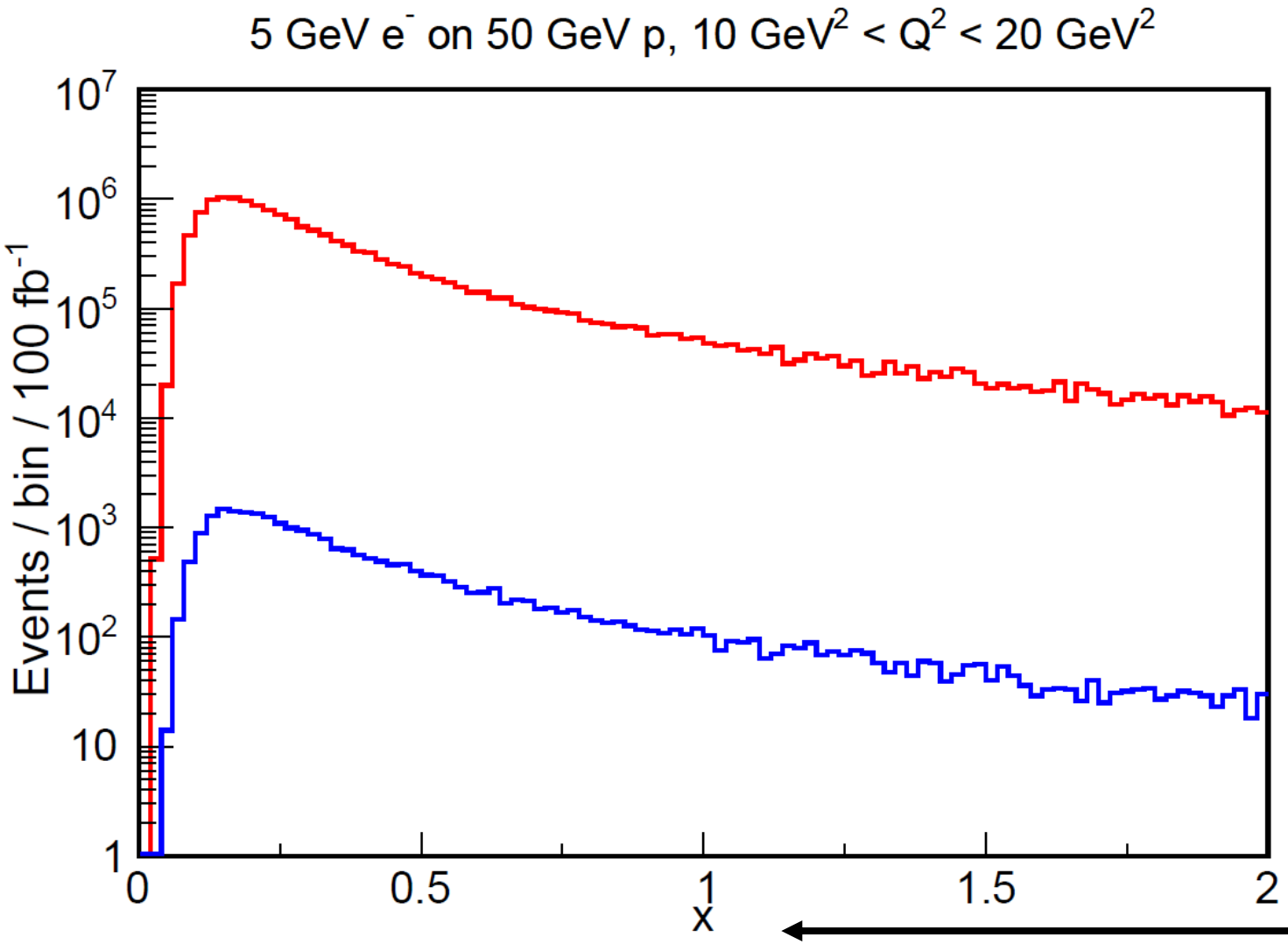
Mix With *Pythia6* Events – Generator Level



PYTHIA6 Events

Elastic Events

Mix With *Pythia6* Events – Detector Level

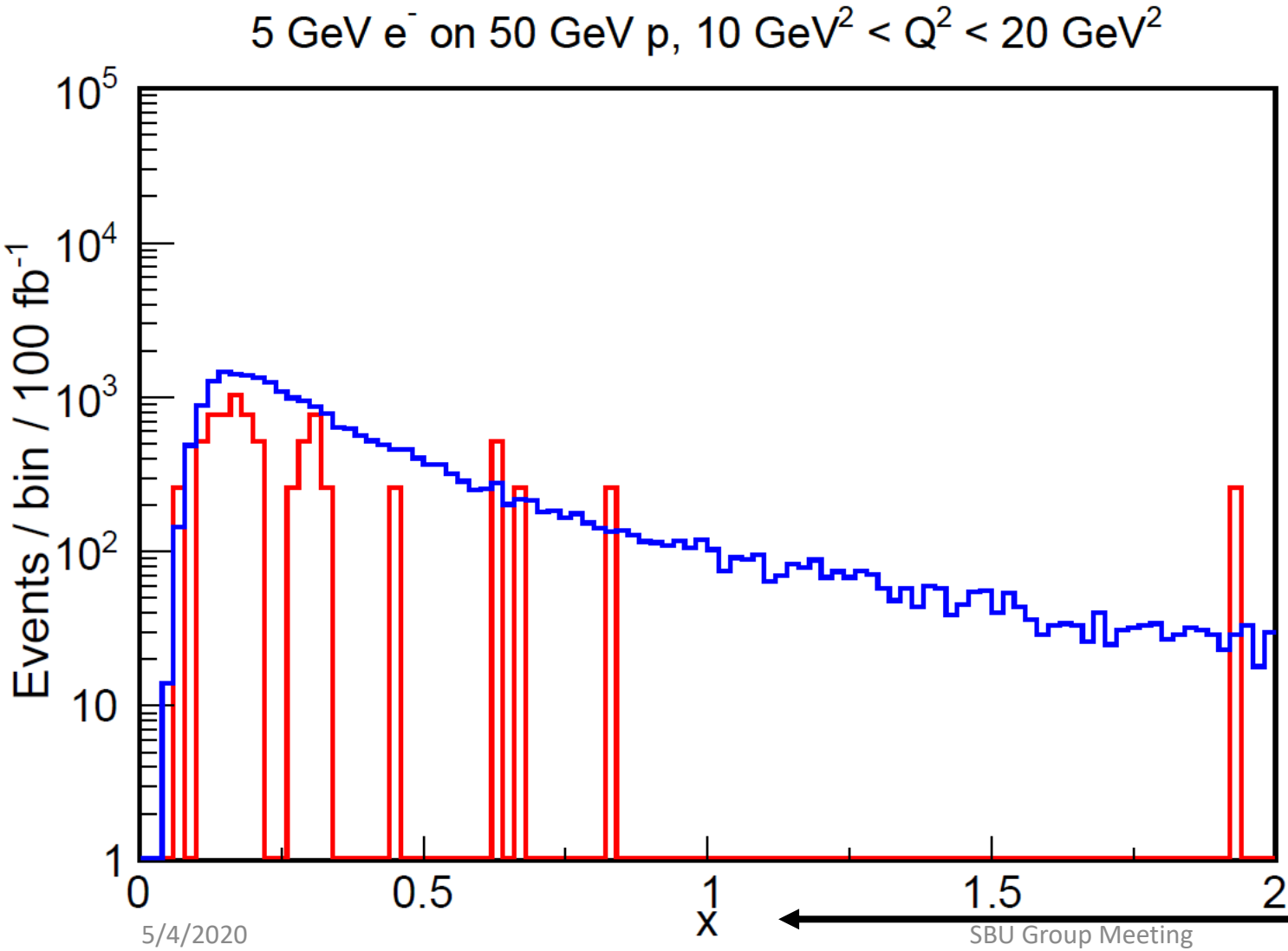


PYTHIA6 Events

Elastic Events

Reconstructed x using the scattered electron here…bad electron resolution at low y

Mix With *Pythia6* Events – Detector Level…but only an electron and proton are detected in central detector



PYTHIA6 Events

Elastic Events

Reconstructed x using the scattered electron here

Polarized Electron-Proton Elastic Scattering Asymmetry Measurements

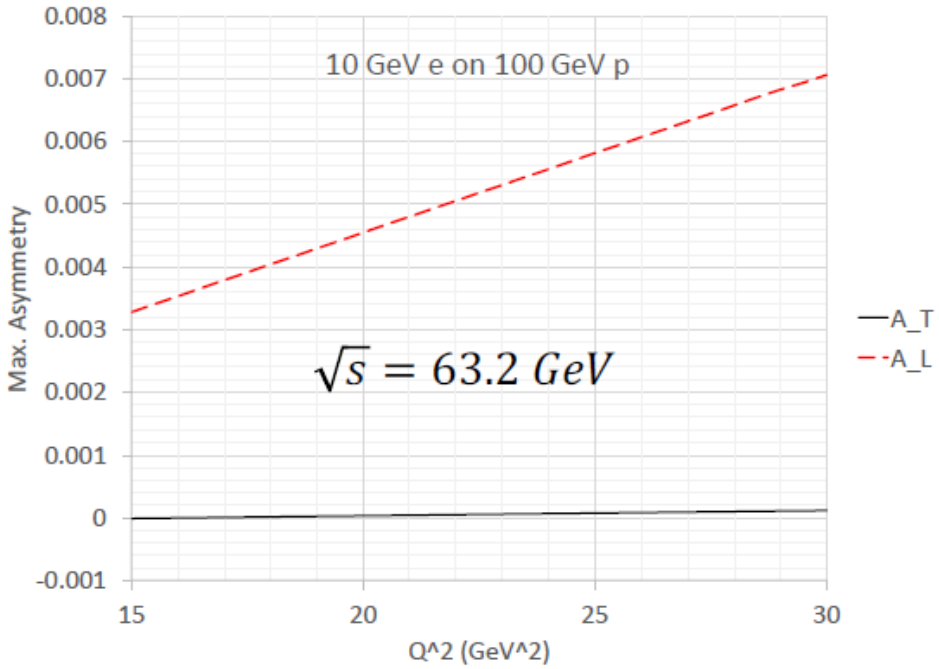
$$
\begin{aligned}
A_{eN} &= -\frac{P_{beam}P_{target}}{1+\frac{\epsilon}{\tau}r^2}\left[\left(\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\sin\theta^*\cos\phi^*\right)r+\sqrt{1-\epsilon^2}\cos\theta^*\right] \\
&\equiv P_{target}\left[A_t\sin\theta^*\cos\phi^*+A_\ell\cos\theta^*\right]
\end{aligned}
\qquad\qquad
r \equiv \frac{G_E}{G_M}
$$

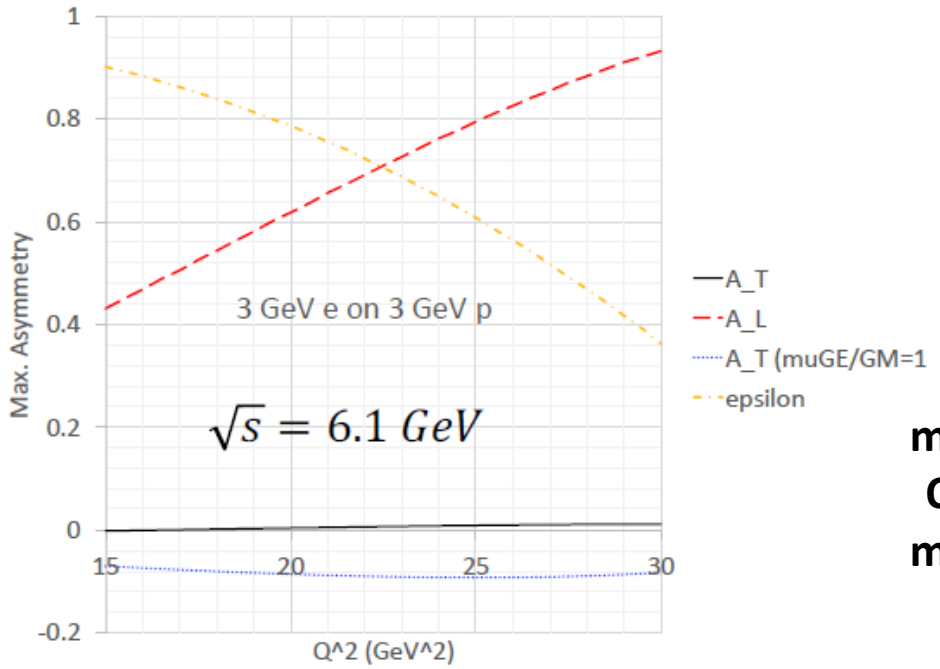
Polarized Electron-Proton Elastic Scattering Asymmetry Measurements

$$A_{eN} = -\frac{P_{beam}P_{target}}{1+\frac{\epsilon}{\tau}r^2}\left[\left(\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\sin\theta^*\cos\phi^*\right)r+\sqrt{1-\epsilon^2}\cos\theta^*\right]$$

$$\equiv P_{target}\left[A_t\sin\theta^*\cos\phi^*+A_\ell\cos\theta^*\right]$$

$$r \equiv \frac{G_E}{G_M}$$





To make reasonable measurements in this higher Q^2 range, we would need a much lower energy than will be provided by the *EIC*

Summary

- For unpolarized electron-proton scattering, we see the possibility of making high Q^2 measurements. We need to see how easily elastic events can be separated from high-x inelastic events.
- We will most likely be unable to make useful beam-target double-spin asymmetry measurements at high Q^2 using the *EIC*.

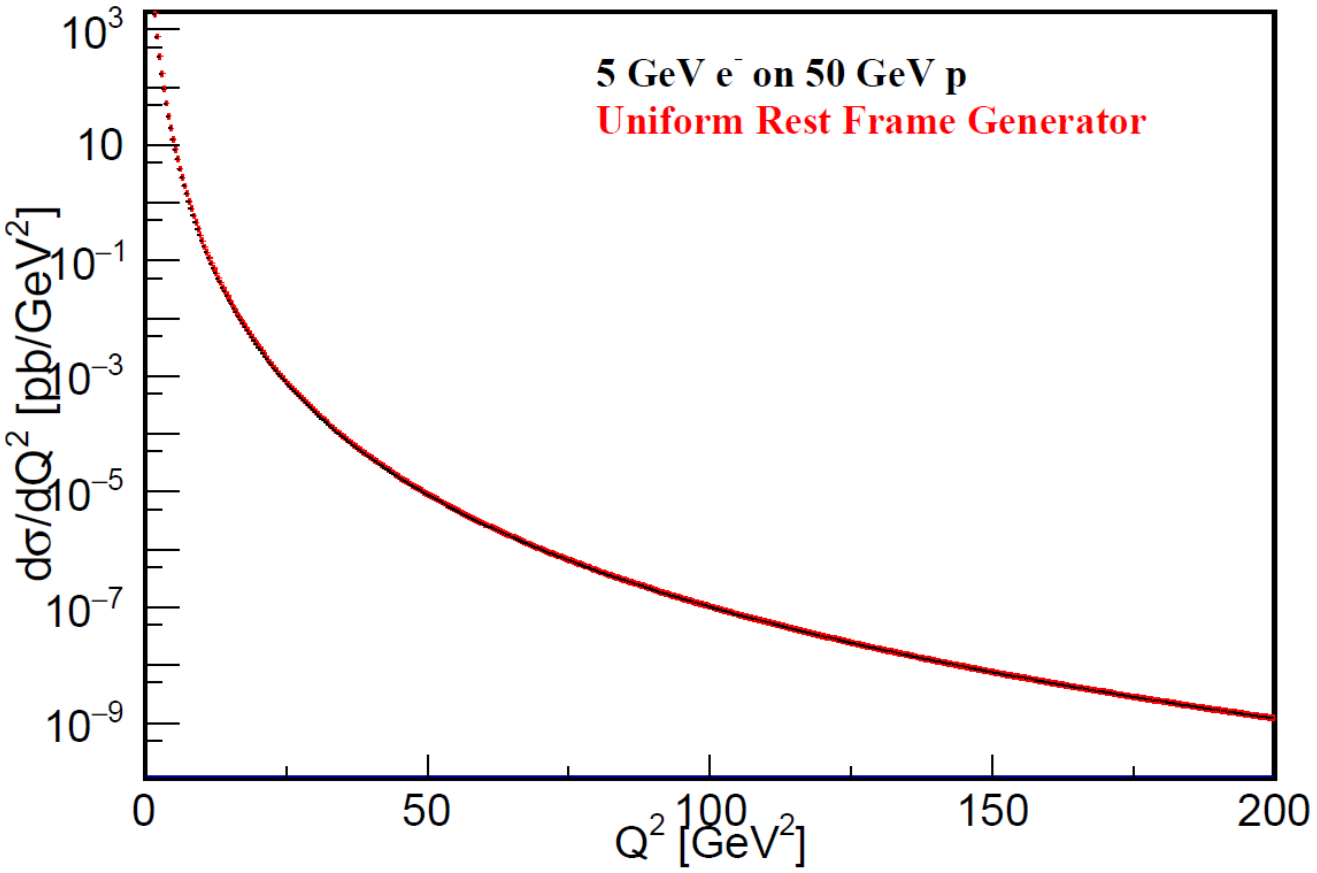
BACKUP

Elastic Generator normalization for uniform generator

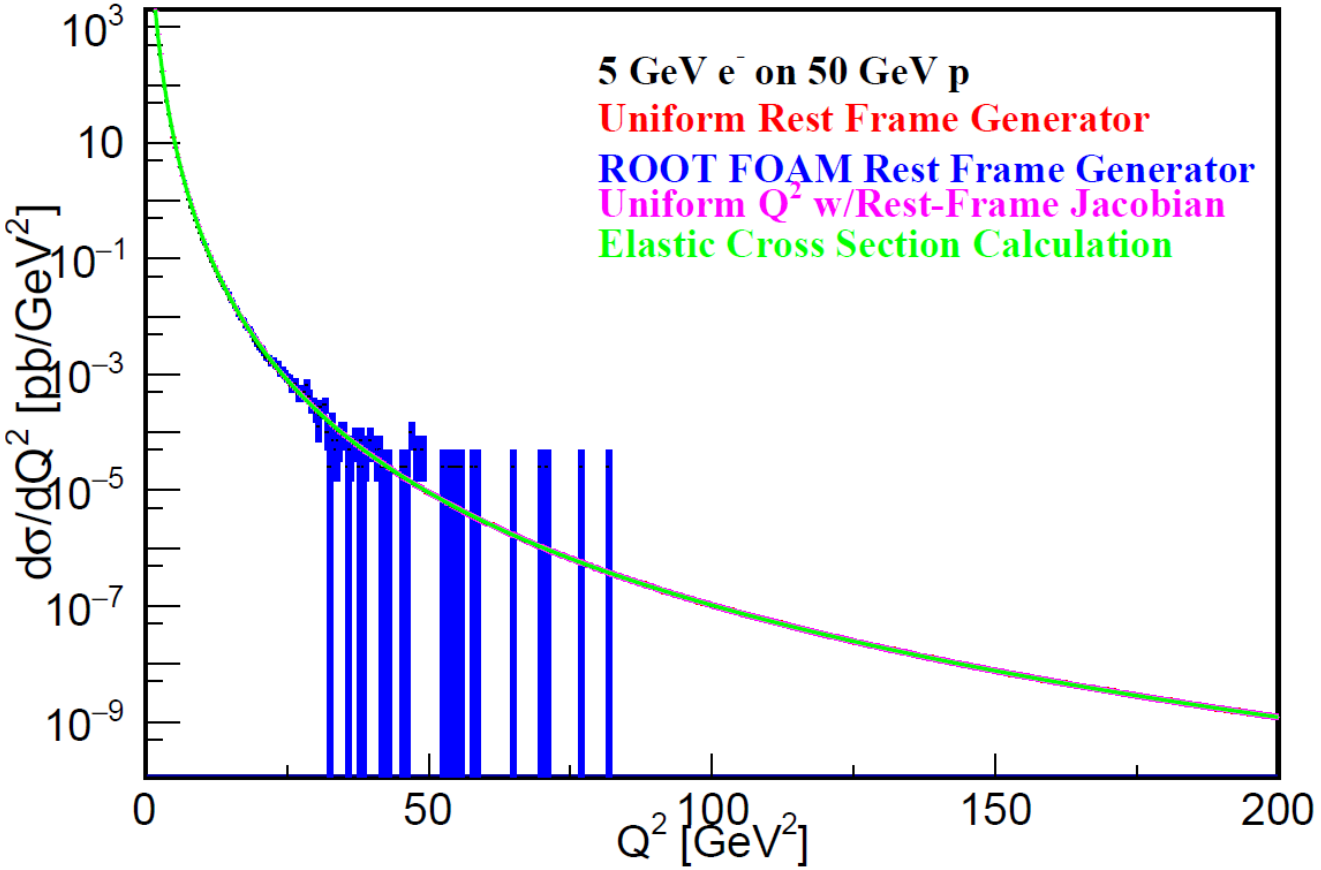
For Uniform Generator, to get expected yield (in bins of Q^2, for example), weight each event by:

$$\frac{\frac{d\sigma}{d\Omega_i}\ (\Omega_{tot})}{N_{tot}\ \Delta Q_i^2} \times luminosity$$

Generator agrees with cross section calculation



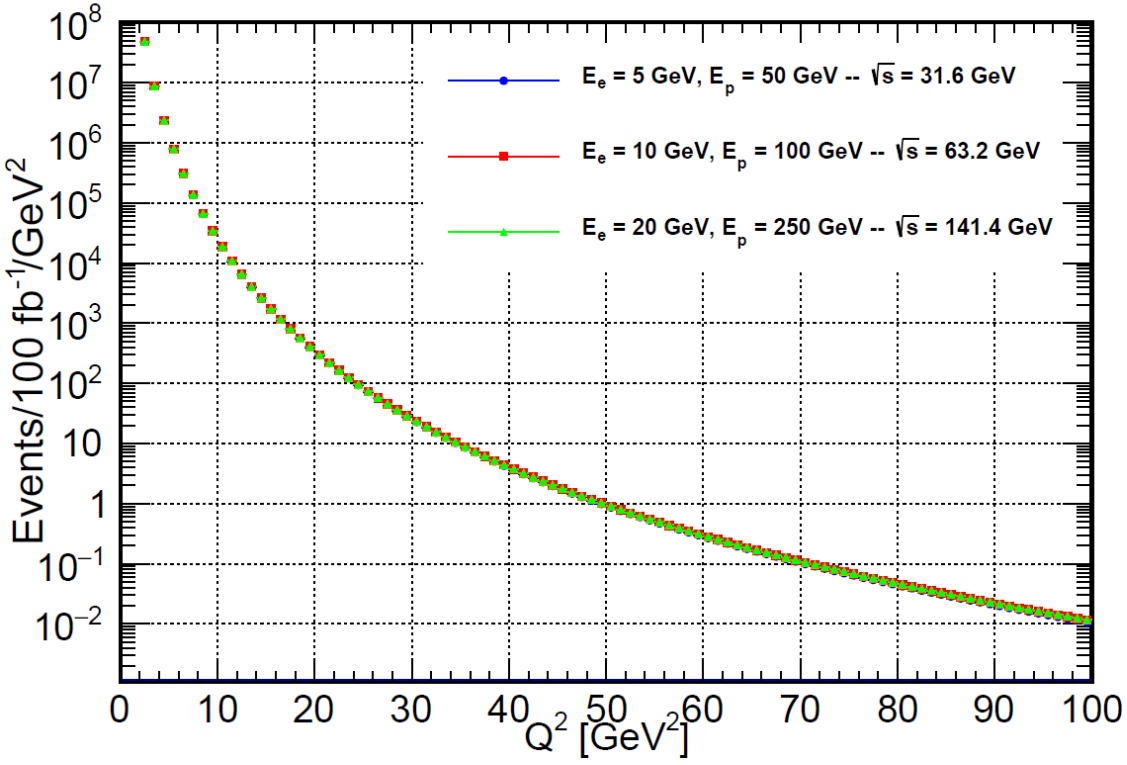
Generator agrees with cross section calculation



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

Generating in the proton rest frame and the lab frame also gives consistent results

Rest Frame Generator



Lab Frame Generator