Elastic Electron-Deuteron Scattering for Tensor Polarization Determination

Barak Schmookler

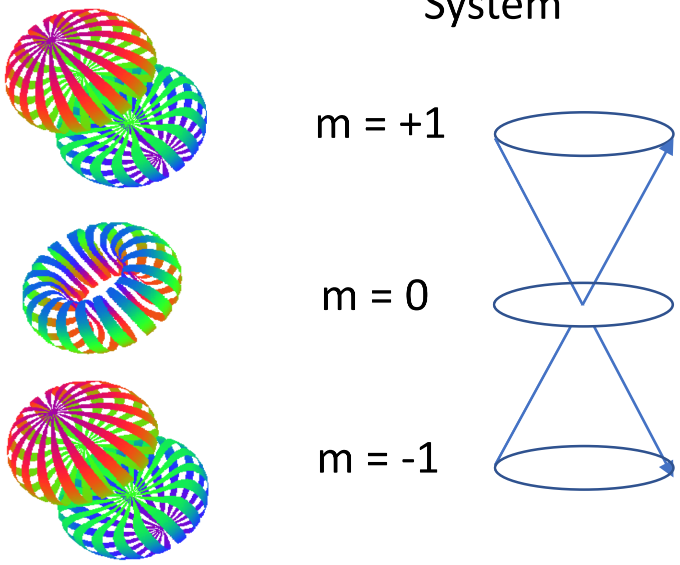
(+ Douglas Higinbotham

Andrew Puckett

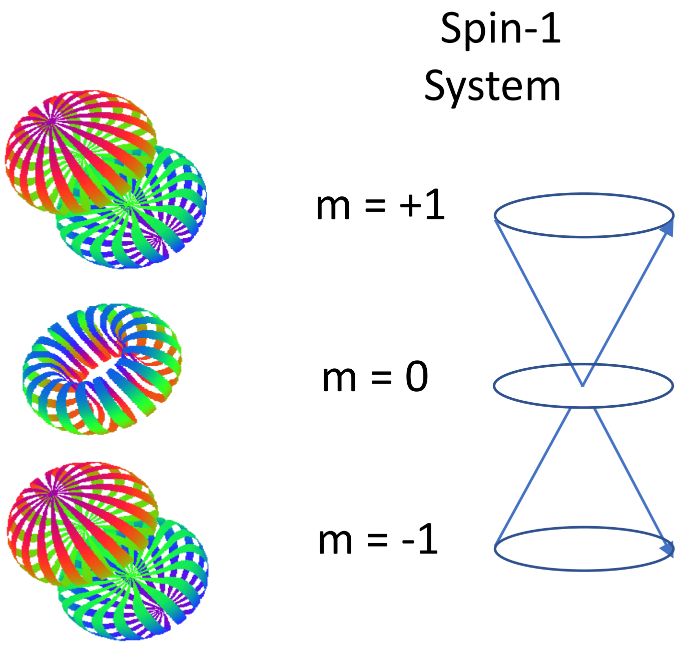
Elena Long)

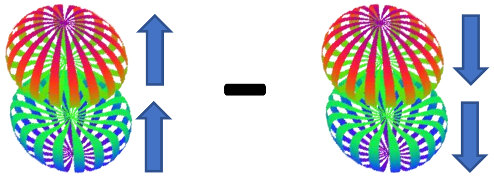
Tensor Polarization – Briefly

Spin-1
System



Tensor Polarization – Briefly

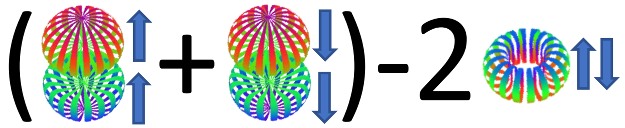




Vector Polarization:

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

$$-1 \leq P_z \leq 1$$



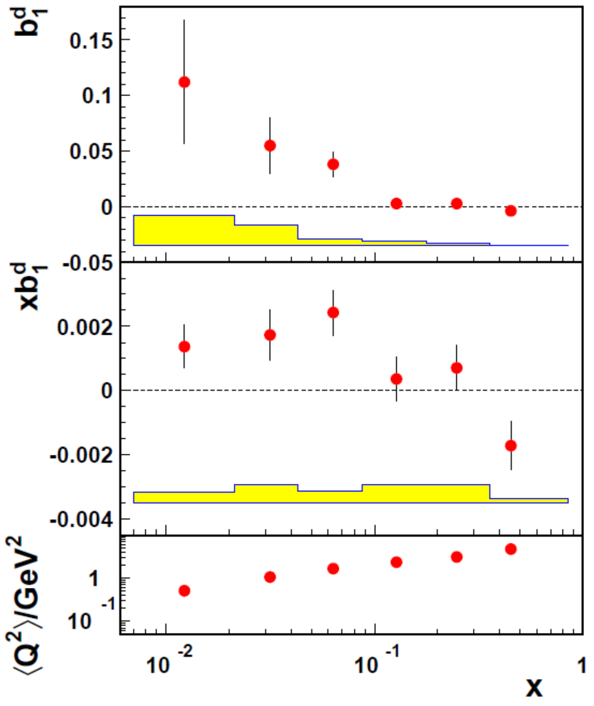
Tensor Polarization:

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

$$-2 \leq P_{zz} \leq 1$$

Why do we care about Tensor-Polarized Deuterium?

Potential measurement of b_1^d structure function at low x with the EIC



Data from the *HERMES* Collaboration

Phys. Rev. Lett. **95**, 242001

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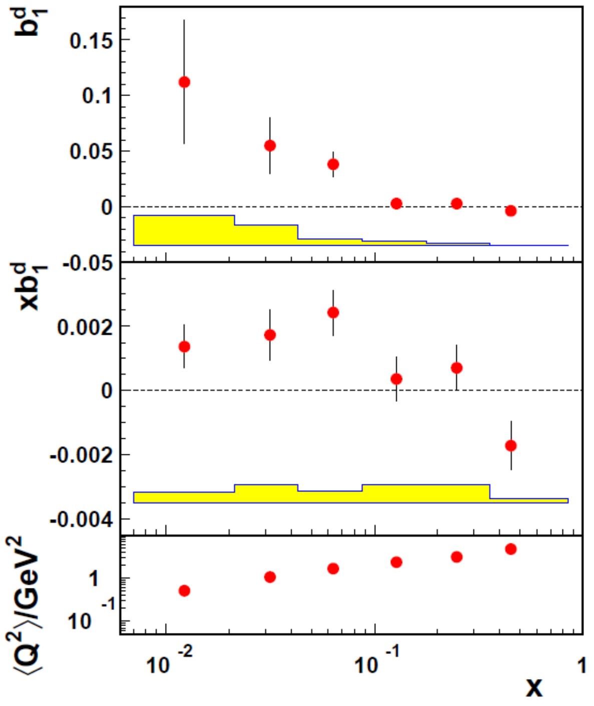

Data from the *HERMES* Collaboration

Possible contamination of g_1^d structure function measurements due to non-zero tensor polarization

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

$$\frac{g_1^d}{F_1^d} \simeq A_1^d \simeq \frac{c_{zz}}{|P_z P_B| D}\,\frac{(\sigma^{\leftrightarrows} - \sigma^{\rightrightarrows})}{(\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows})}$$

$$c_{zz} = \frac{(\sigma^{\leftrightarrows} + \sigma^{\rightrightarrows})}{2\sigma_U} = 1 + \frac{(P_{zz}^{\leftrightarrows} + P_{zz}^{\rightrightarrows})}{4} A_{zz}^d$$

Phys. Rev. Lett. **95**, 242001

Elastic Electron-Deuteron Scattering

Let’s start with unpolarized scattering…

The elastic deuteron structure is described in terms of three form factors: charge monopole $G_C(Q^2)$, charge quadrupole $G_Q(Q^2)$, and magnetic dipole $G_M(Q^2)$

Elastic Electron-Deuteron Scattering

Let's start with unpolarized scattering…

The elastic deuteron structure is described in terms of three form factors: charge monopole $G_C(Q^2)$, charge quadrupole $G_Q(Q^2)$, and magnetic dipole $G_M(Q^2)$

The cross section (in the deuteron rest frame) is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{Z}^2\alpha^2\cos^2(\frac{\theta_\mathrm{e}}{2})}{4E_\mathrm{e}^2\sin^4(\frac{\theta_\mathrm{e}}{2})} \times \frac{1}{1+\frac{2E_\mathrm{e}}{M_\mathrm{d}}\sin^2(\frac{\theta_\mathrm{e}}{2})} \times [A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta_\mathrm{e}}{2}\right)]$$

Elastic Electron-Deuteron Scattering – Still Unpolarized

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2\cos^2(\frac{\theta_e}{2})}{4E_e^2\sin^4(\frac{\theta_e}{2})} \times \frac{1}{1+\frac{2E_e}{M_d}\sin^2(\frac{\theta_e}{2})} \times [A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)]$$

Elastic Electron-Deuteron Scattering – Still Unpolarized

$$\frac{d\sigma}{d\Omega} = \underbrace{\frac{Z^2\alpha^2\cos^2(\frac{\theta_e}{2})}{4E_e^2\sin^4(\frac{\theta_e}{2})}}_{\text{Mott Cross Section}} \times \underbrace{\frac{1}{1+\frac{2E_e}{M_d}\sin^2(\frac{\theta_e}{2})}}_{\text{Recoil Term}} \times \underbrace{[A(Q^2)+B(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)]}_{\text{Reduced Cross Section}}$$

Mott Cross Section

Recoil Term

Reduced Cross Section

Elastic Electron-Deuteron Scattering – Still Unpolarized

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2\cos^2(\frac{\theta_e}{2})}{4E_e^2\sin^4(\frac{\theta_e}{2})} \times \frac{1}{1+\frac{2E_e}{M_d}\sin^2(\frac{\theta_e}{2})} \times [A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)]$$

Mott Cross Section | Recoil Term | Reduced Cross Section

$$A(Q^2) = G_C^2(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{2}{3}\eta G_M^2(Q^2)$$

$$B(Q^2) = \frac{4}{3}\eta(1+\eta)G_M^2(Q^2)$$

$$\eta = \frac{Q^2}{4M_d^2}$$

Electron-Deuteron Cross Section with polarized deuteron…and unpolarized electron

$$\frac{\sigma}{\sigma_0} = 1 + (P_{zz}/\sqrt{2})\left(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}}\sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}}\sin^2\theta^* \cos 2\phi^* T_{22}\right)$$

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Ratio of polarized to unpolarized cross section

Electron-Deuteron Cross Section with polarized deuteron…and unpolarized electron

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Deuteron tensor polarization

Electron-Deuteron Cross Section with polarized deuteron…and unpolarized electron

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Tensor Analyzing Powers (i.e. Polarization Observables)

$$T_{20} = -(\sqrt{2}\eta/3S)\left[4G_C G_Q + \frac{4\eta}{3}G_Q^2 + \left(\frac{1}{2} + \varepsilon\right)G_M^2\right]$$

$$T_{21} = \frac{2}{S}\sqrt{\frac{\eta^3(1+\varepsilon)}{3}}G_Q G_M \qquad T_{22} = [\eta/(2\sqrt{3}S)]G_M^2$$

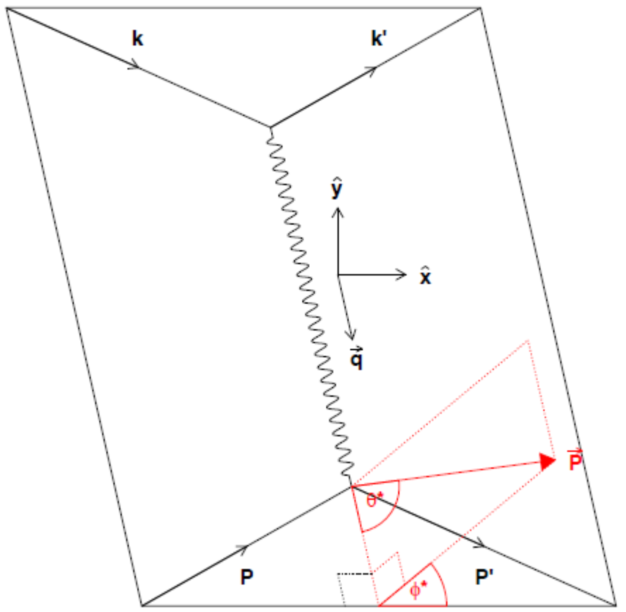
$$\eta = \frac{Q^2}{4M_d^2}$$

$$\varepsilon = (1 + \eta)\tan^2(\theta_e/2)$$

$$S \equiv A + \tan^2(\theta_e/2)B$$

Electron-Deuteron Cross Section with polarized deuteron…and unpolarized electron

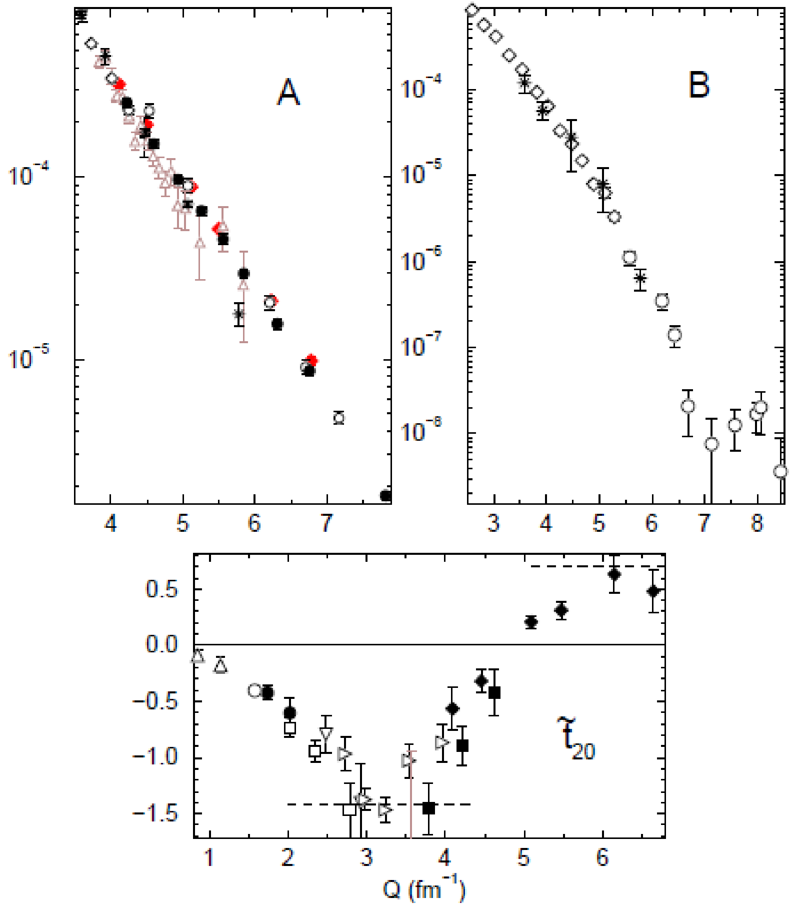
$$\frac{\sigma}{\sigma_0} = 1 + (P_{zz}/\sqrt{2})\left(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}}\sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}}\sin^2\theta^* \cos 2\phi^* T_{22}\right)$$

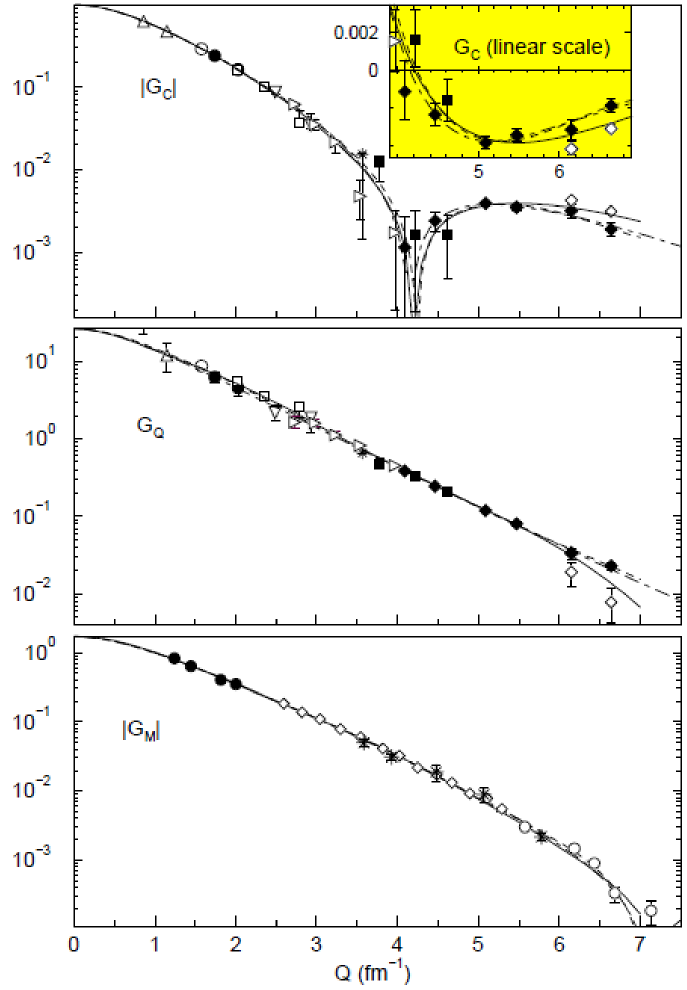


$\vec{P}$ ≡ Target polarization

θ* and ϕ* give the polarization orientation with respect to the momentum transfer. The terms here are proportional to the real part of the corresponding spherical harmonic.

We can use the measurements of the deuteron form factors at low-Q^2 to measure the tensor polarization





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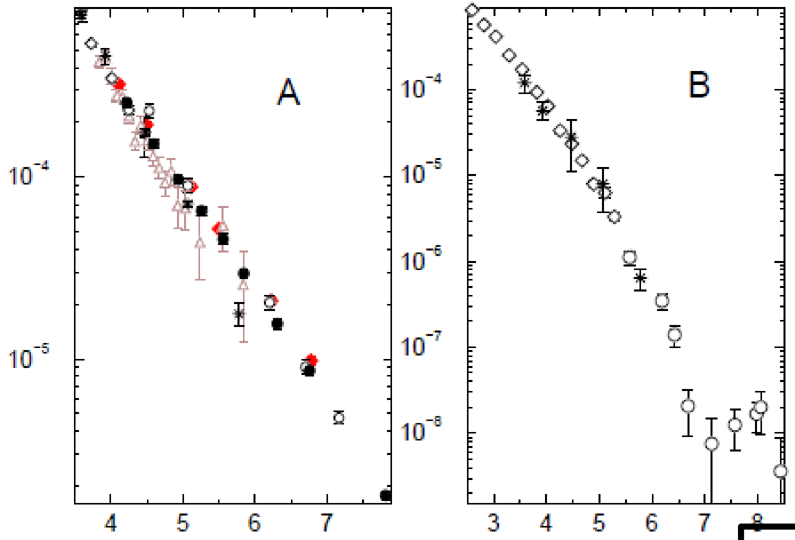
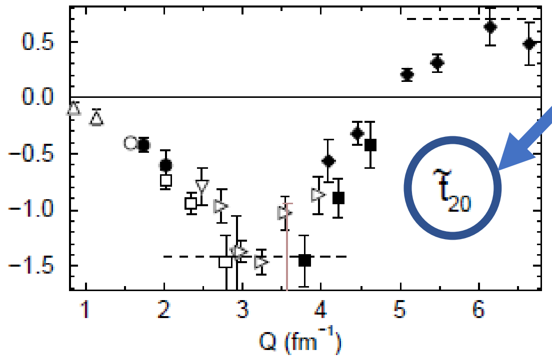
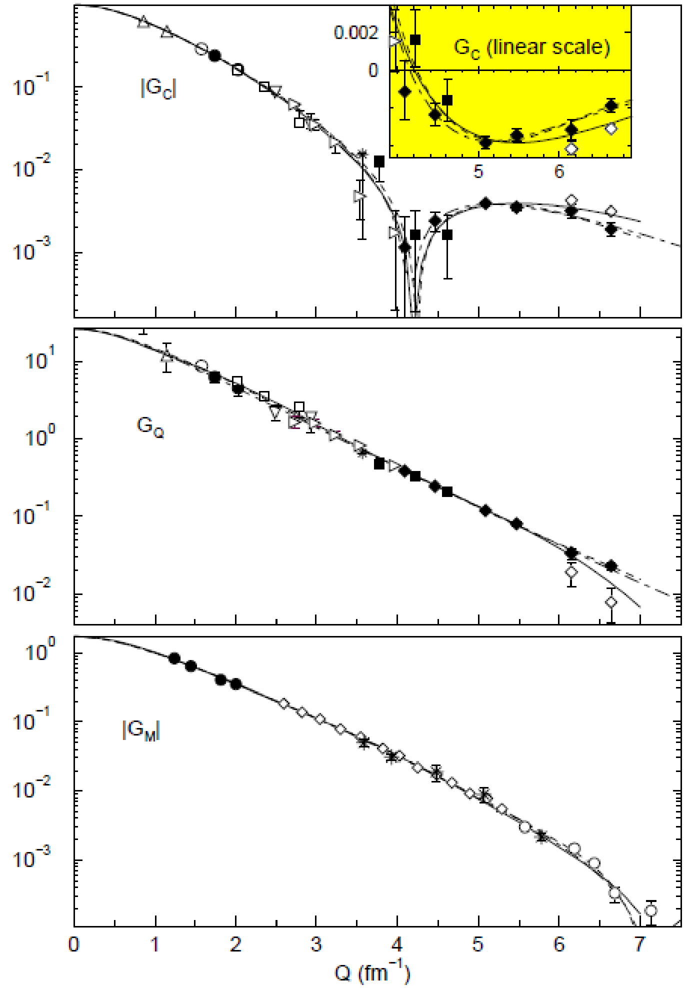




Slightly modified version of t_{20}.



Also, note that the tensor analyzing powers are equivalent to the recoil deuteron polarizations…

We can use the measurements of the deuteron form factors at low-Q^2 to determine the tensor polarization

Measurement of the Tensor Analyzing Powers T_{20} and T_{21} in Elastic Electron-Deuteron Scattering

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The tensor analyzing power components T_{20} and T_{21} have been measured in elastic electron-deuteron scattering at the 2 GeV electron storage ring VEPP-3, Novosibirsk, in a four-momentum transfer range from 8.4 to 21.6 fm^{-2}. A new polarized internal gas target with an intense cryogenic atomic beam source was used. The new data determine the deuteron form factors G_C and G_Q in an important range of momentum transfer where the first node of the deuteron monopole charge form factor is located. The new results are compared with previous data and with some theoretical predictions.

We can use the measurements of the deuteron form factors at low-Q^2 to determine the tensor polarization

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where N^+ and N^- are the event counts of a detector when the target polarization is P_{zz}^+ and P_{zz}^-, respectively. N^+ and N^- are normalized to the electron beam charge. In accordance with Eq. (1), A^t can be written as a linear combination of tensor analyzing powers (right formula). We assume that depolarization processes occur identically in both polarization states; therefore P_{zz}^- / P_{zz}^+ is close to -2 (the same as for the ABS beam; see also [9]).

The value of A^t measured by the LQP can be used to calculate the target polarization if the tensor analyzing power is known at small Q^2. At present, the measure-

We can use the measurements of the deuteron form factors at low-Q^2 to determine the tensor polarization

$$A^t = \sqrt{2}\frac{(N^+ - N^-)}{(N^- P_{zz}^+ - N^+ P_{zz}^-)}$$

$$= \left(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}} \sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}} \sin^2\theta^* \cos 2\phi^* T_{22}\right)$$

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$$= \left(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}}\sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}}\sin^2\theta^* \cos 2\phi^* T_{22}\right)$$

The procedure can be as follows:

1. Bin data in Q^2
2. For each bin, use the form factor parameterizations to calculate A^t. Note that if the polarization axis is parallel to the initial electron and deuteron momentum direction, ϕ*=0 (or 180^o) and θ* is a function of Q^2.
3. For each bin, calculate the charge normalized yields (i.e. N$^+$ & N$^-$) which correspond to the tensor polarization orientations (i.e. P_{zz}^+ & P_{zz}^-)
4. Using the information from steps 2 and 3, extract P_{zz}^+ & P_{zz}^-

Question: Can something be gained by rotating the polarization axis? Is this possible?

We can use the measurements of the deuteron form factors at low-Q^2 to determine the tensor polarization

$$A^t = \sqrt{2}\frac{(N^+ - N^-)}{(N^- P_{zz}^+ - N^+ P_{zz}^-)}$$

$$= \left(\frac{3\cos^2\theta^* - 1}{2} T_{20} - \sqrt{\frac{3}{2}} \sin 2\theta^* \cos\phi^* T_{21} + \sqrt{\frac{3}{2}} \sin^2\theta^* \cos 2\phi^* T_{22}\right)$$

Other option: Use high precision measurements of T_{20} at a single (or a few) Q^2 values. (Phys. Rev. Lett. **77**, 2630) No parameterization of form factors would have to be assumed here – but we need to make sure θ* is small so T_{20} dominates the asymmetry. We would also need to take data with $P_{zz} = 0$ if we want both P_{zz}^+ & P_{zz}^-.

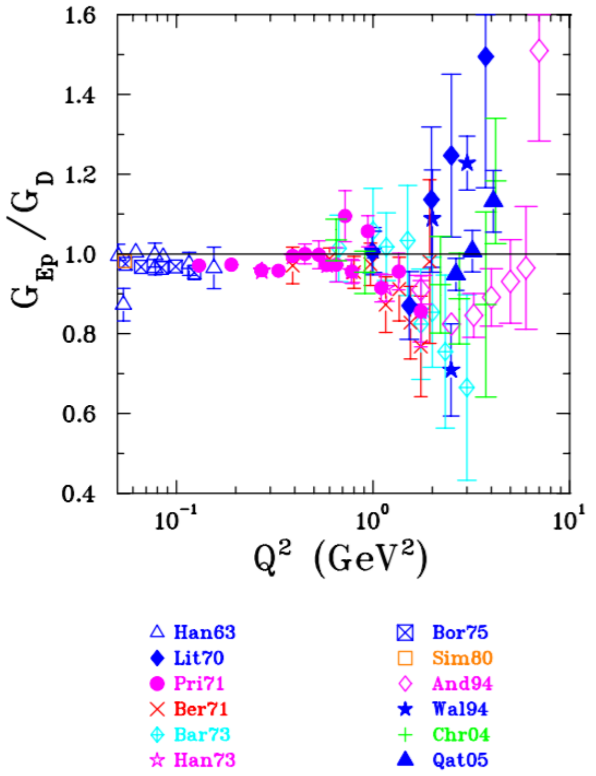
Plan for this month

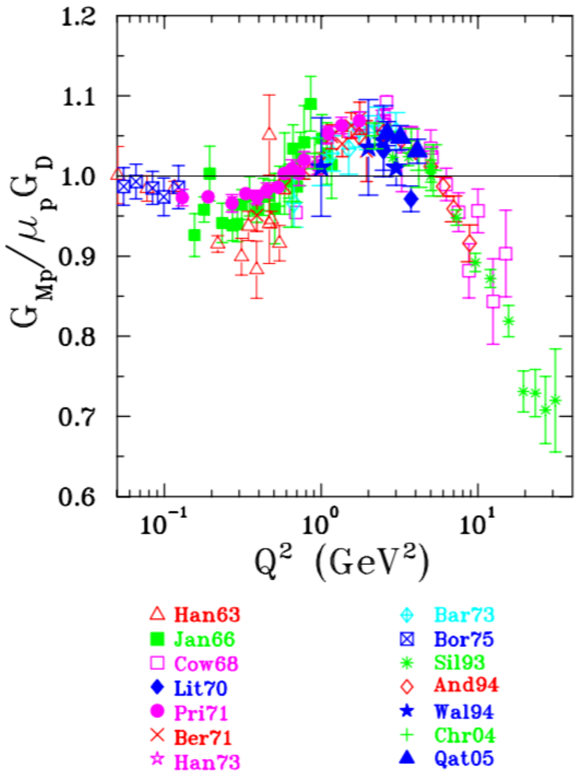
- Generate electron-deuteron elastic events for various beam energy combinations to see the angles and energies of the scattered electron and deuteron in the collider frame
- Mix these elastic events with minimum-bias deuterium DIS events (perhaps using *BeAGLE*) to see if the elastic events can be isolated
- Calculated expected asymmetries as a function of Q^2

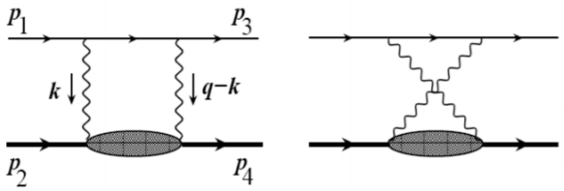
We've already done some similar work for elastic electron-proton scattering

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

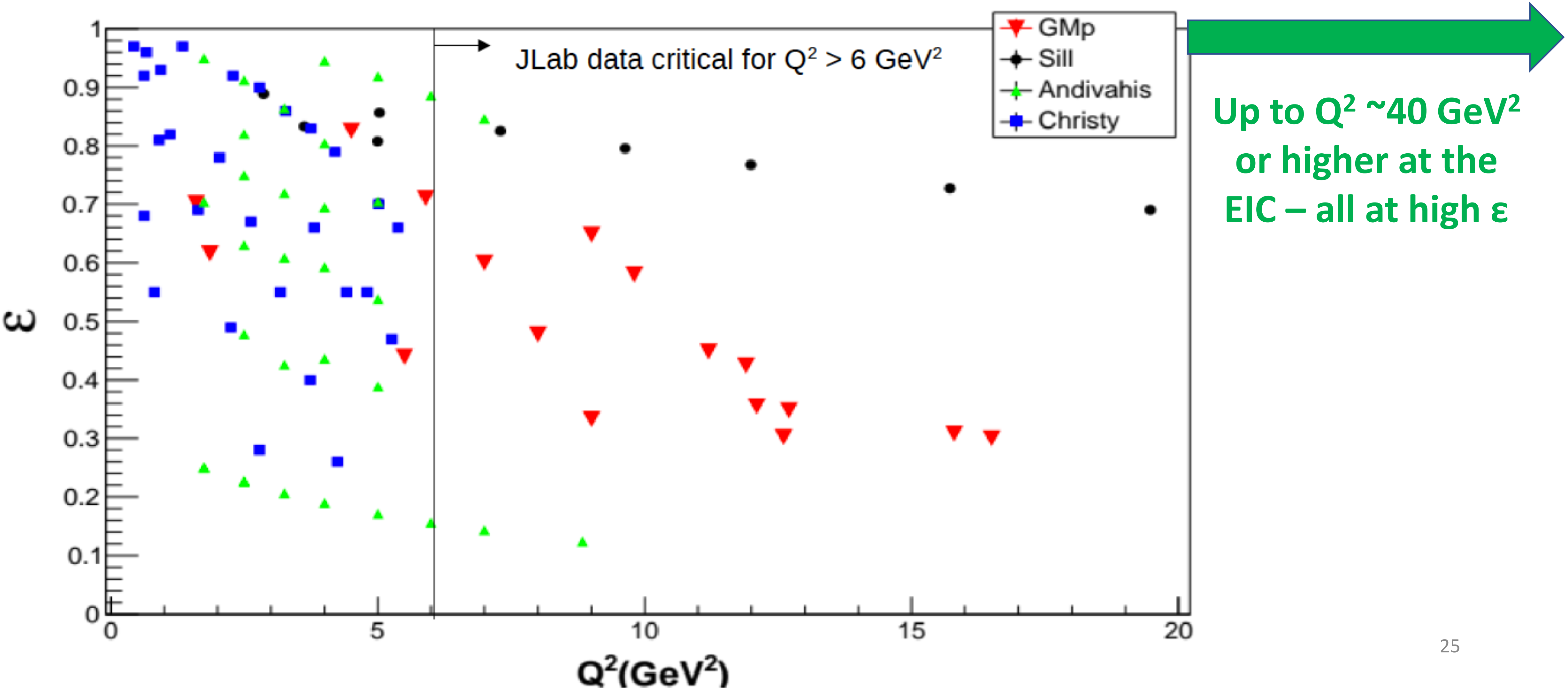






C.F Perdrisat, V. Punjabi, M. Vanderhaeghen, *Progress in Particle and Nuclear Physics 59 (2007) 694–764*

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 uniformly in electron's solid angle in the proton rest frame
3. Weight each event using the rest-frame cross section equation shown below. Form factor parameterization comes from *Kelly (*PHYSICAL REVIEW C **70**, 068202 2004, Phys. Rev. C **96**, 055203).
4. Bin data in Q^2, for example, and scale to total luminosity to get expected yield. (See equation on next slide.)

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

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

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

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

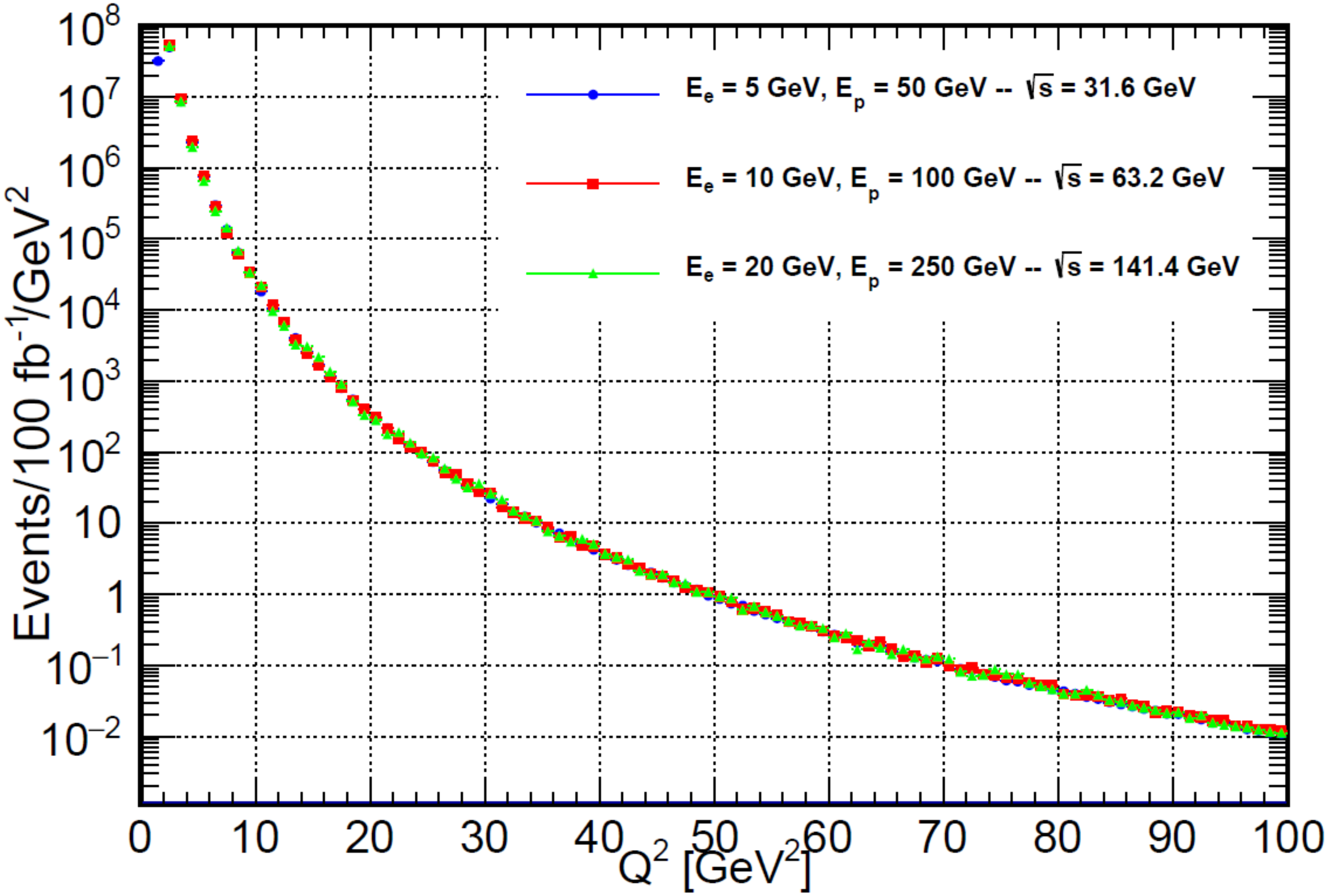
$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

Elastic Generator normalization

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

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

Electron-Proton Elastic scattering expected yields



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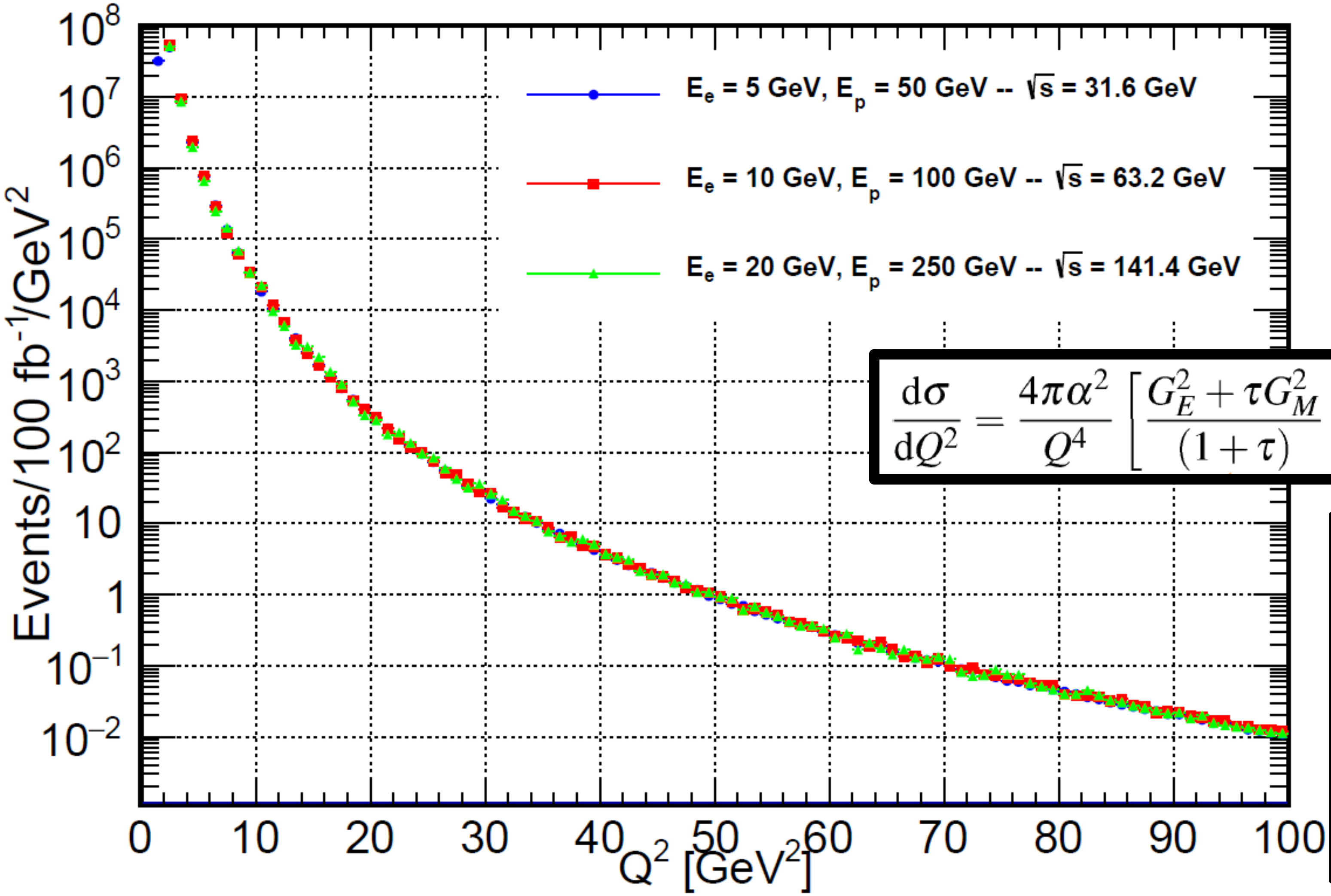
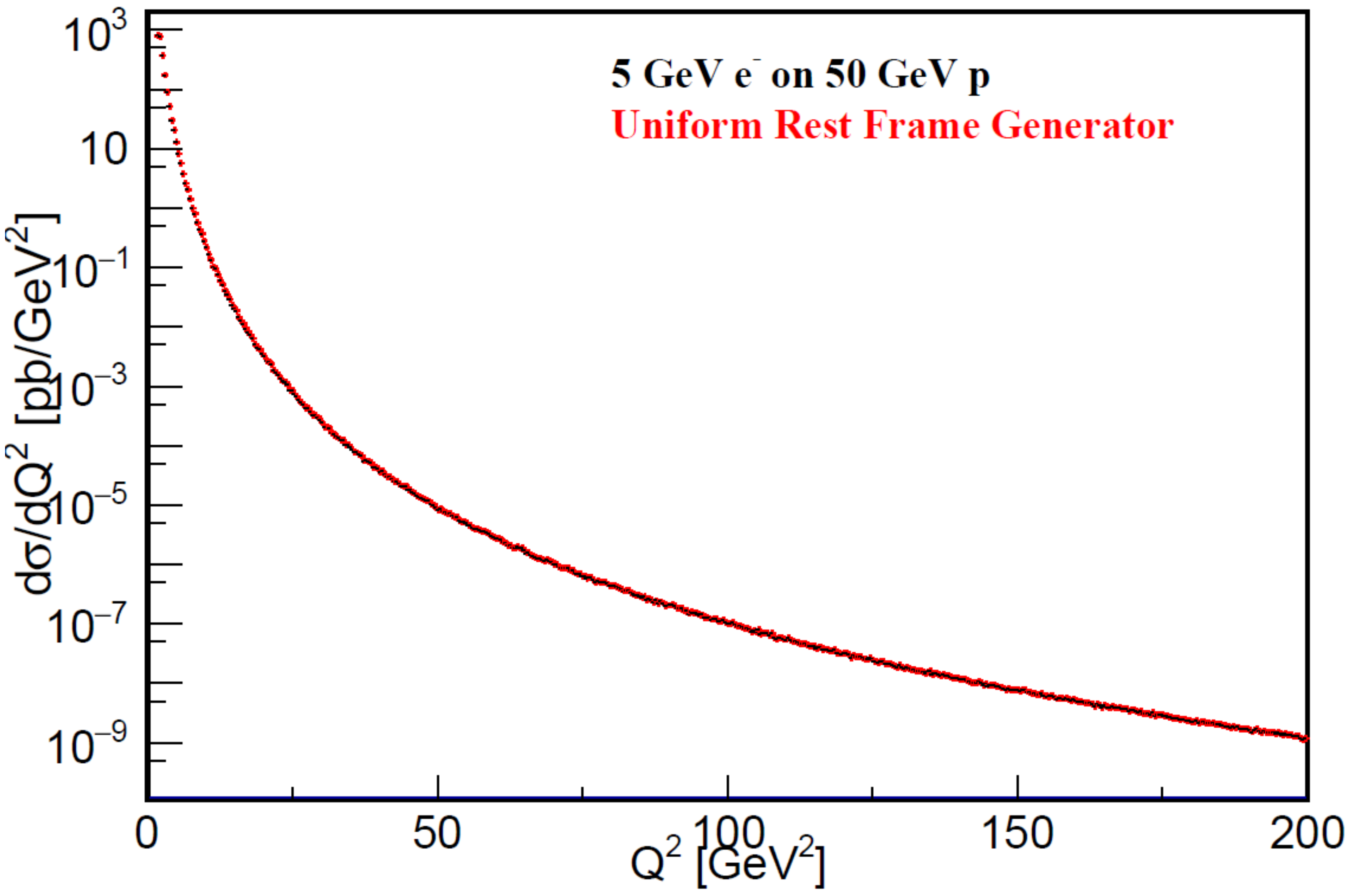


$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2+\tau G_M^2}{(1+\tau)}\left(1-y-\frac{M^2y^2}{Q^2}\right)+\frac{1}{2}y^2G_M^2\right]$$

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

Generator agrees with cross section calculation



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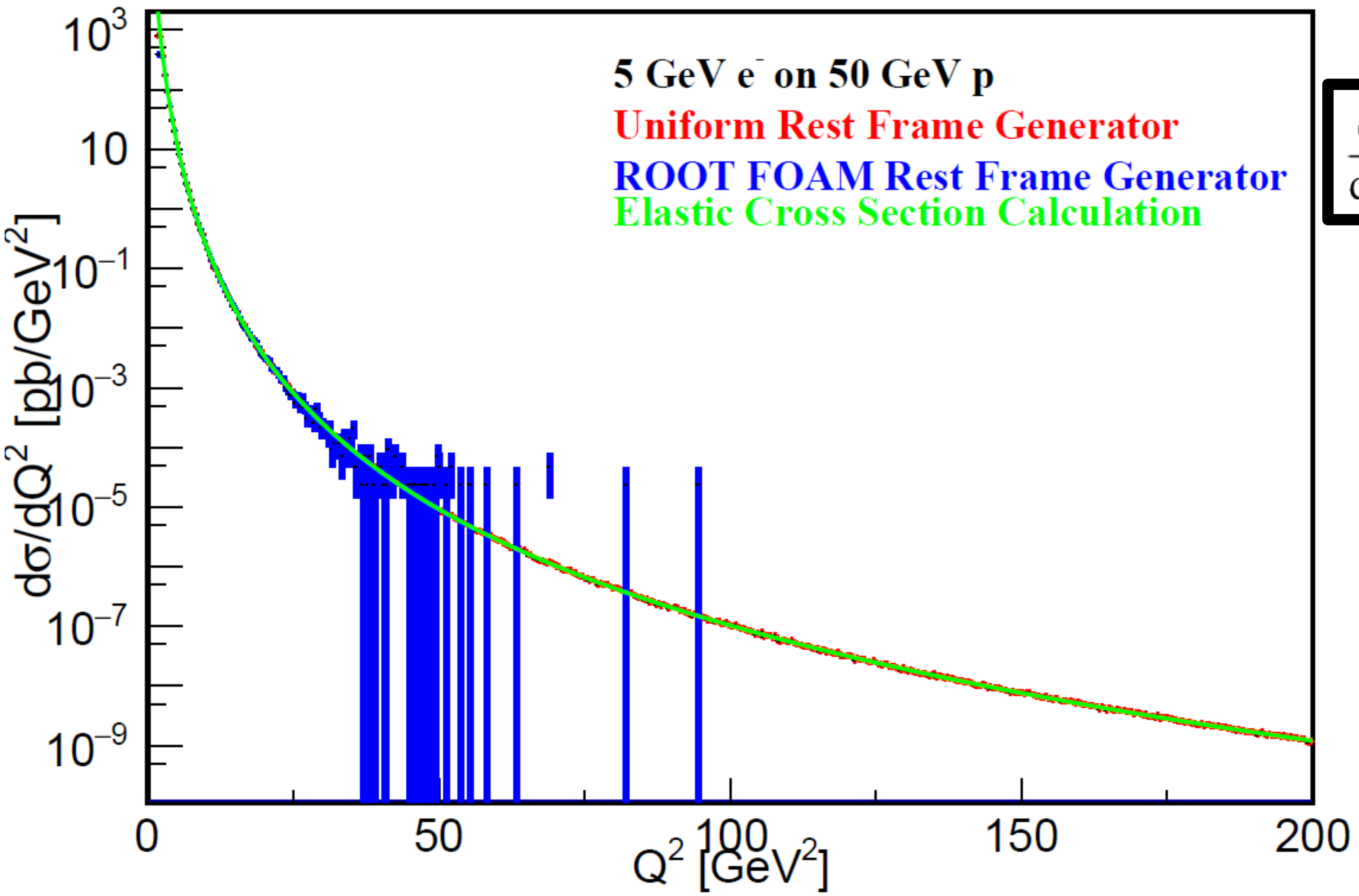
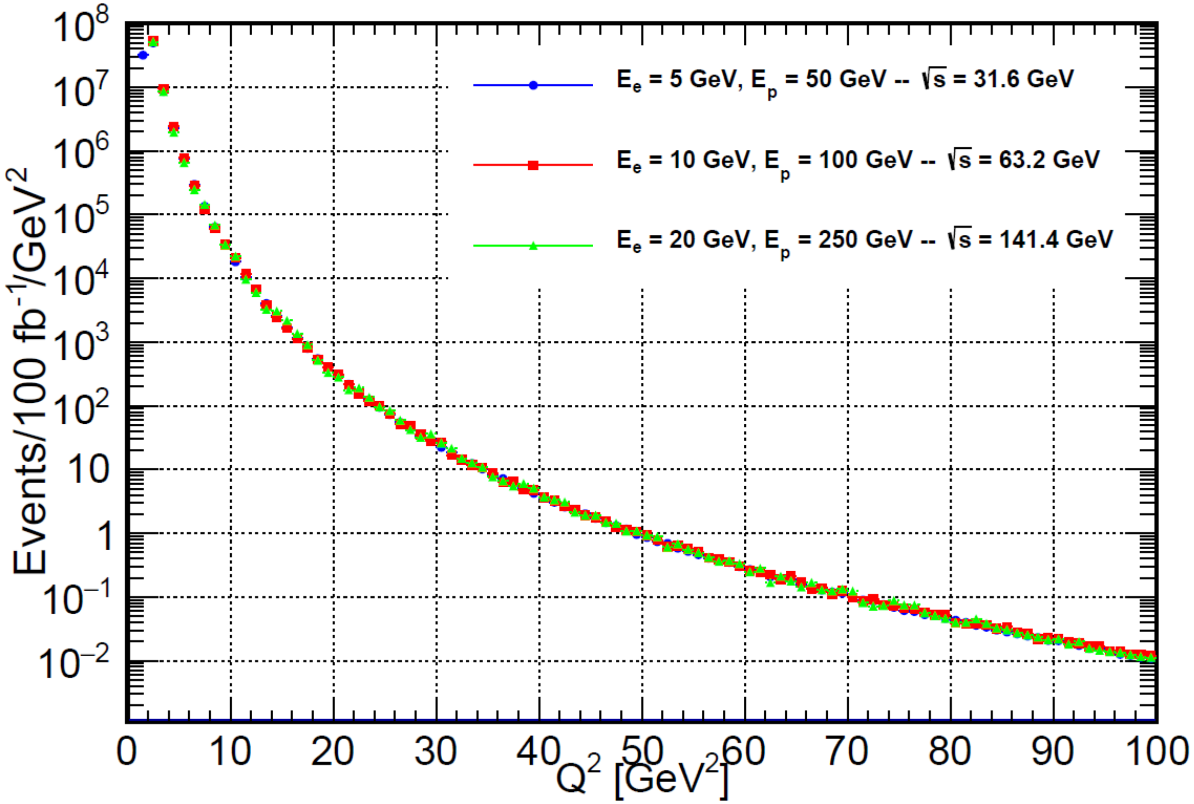


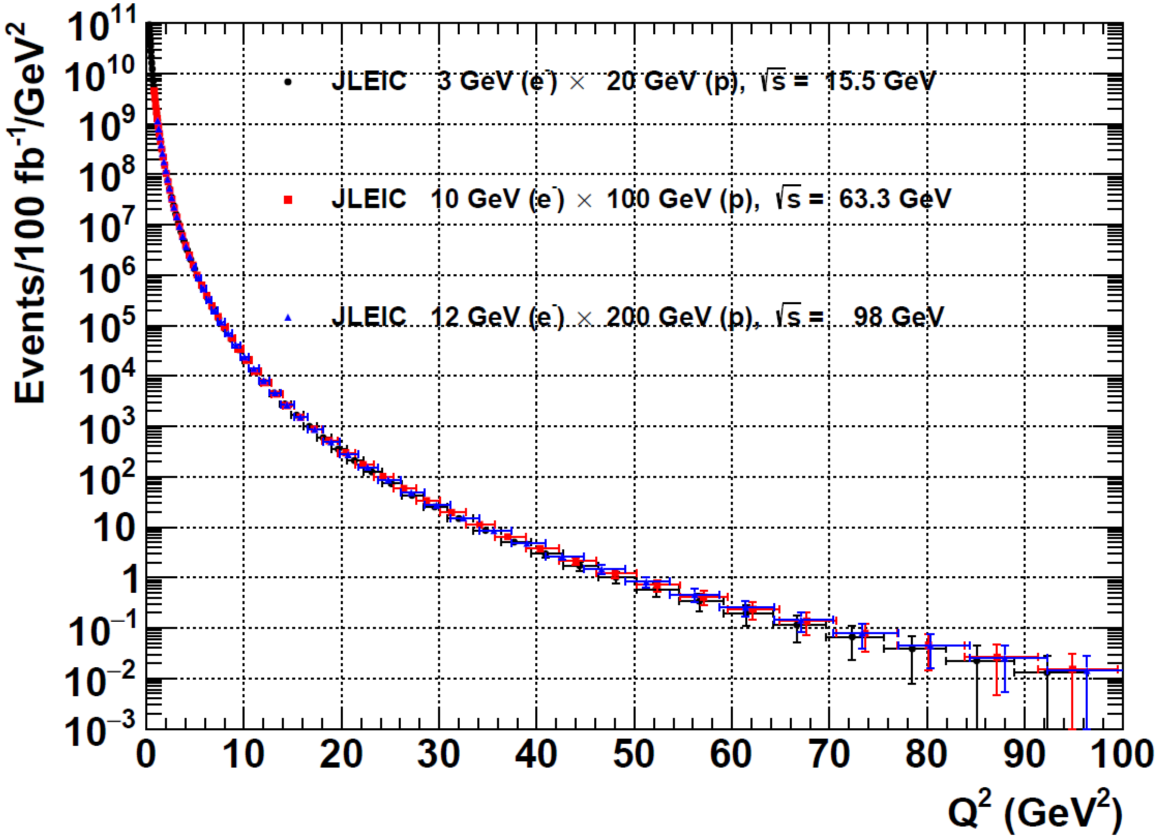
$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2} = \frac{4\pi\alpha^2}{Q^4}\left[\frac{G_E^2+\tau G_M^2}{(1+\tau)}\left(1-y-\frac{M^2y^2}{Q^2}\right)+\frac{1}{2}y^2G_M^2\right]$$

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

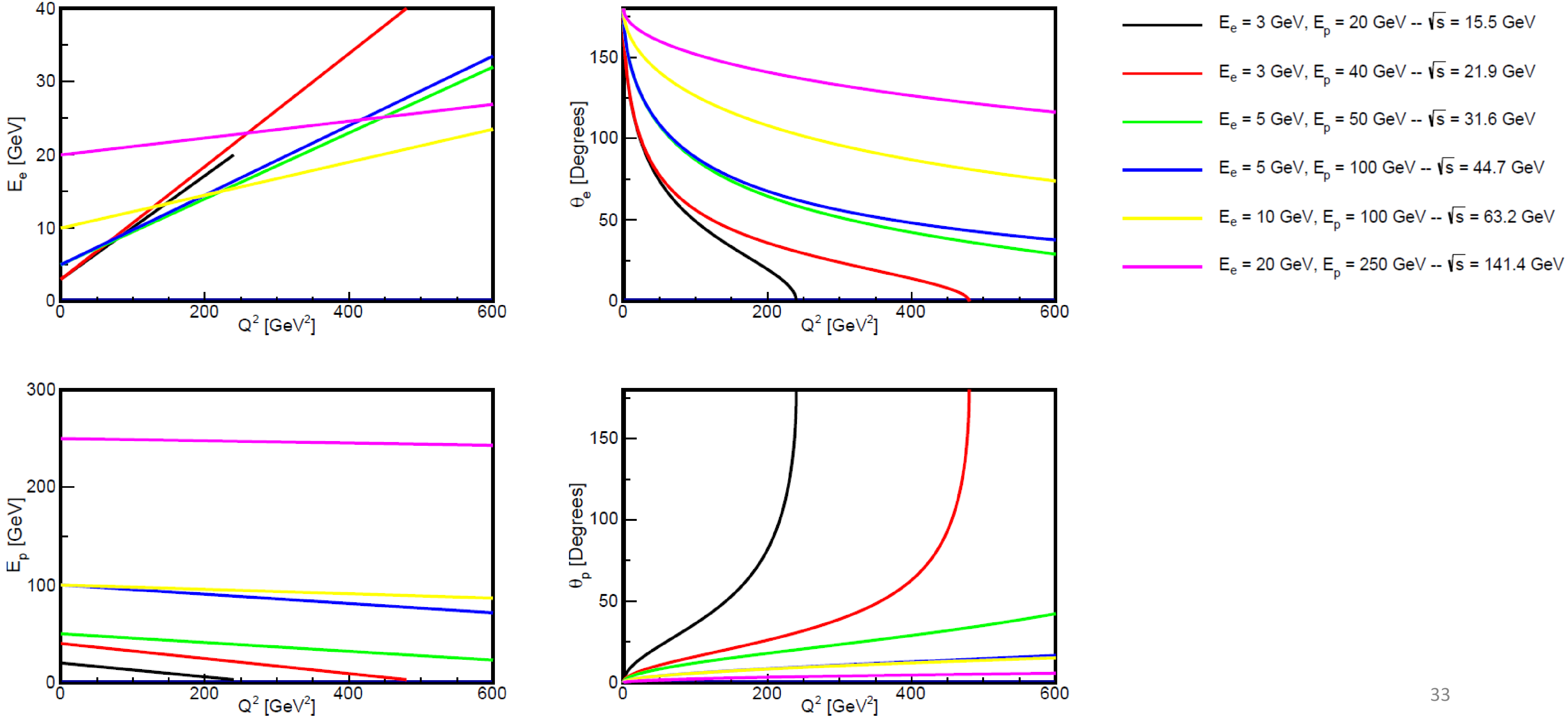
Rest Frame Generator



Lab Frame Generator

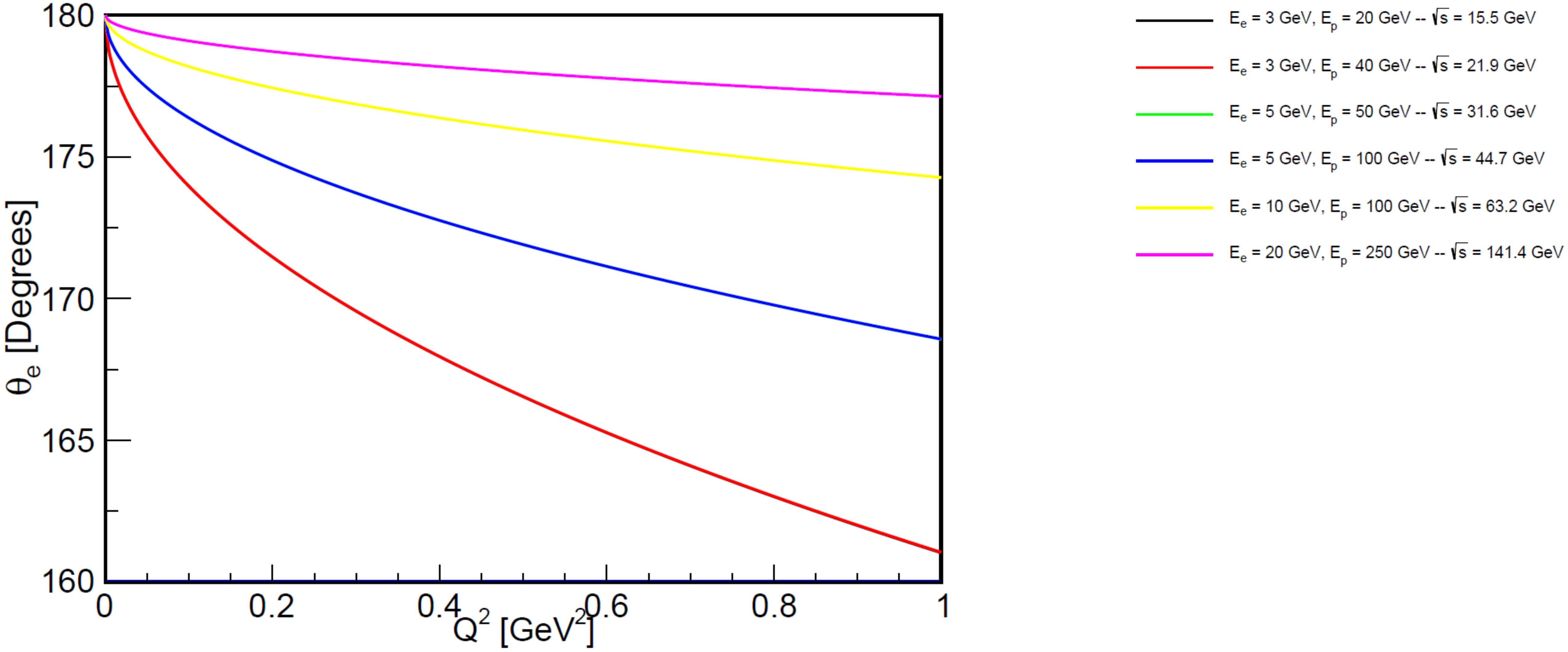


Kinematics

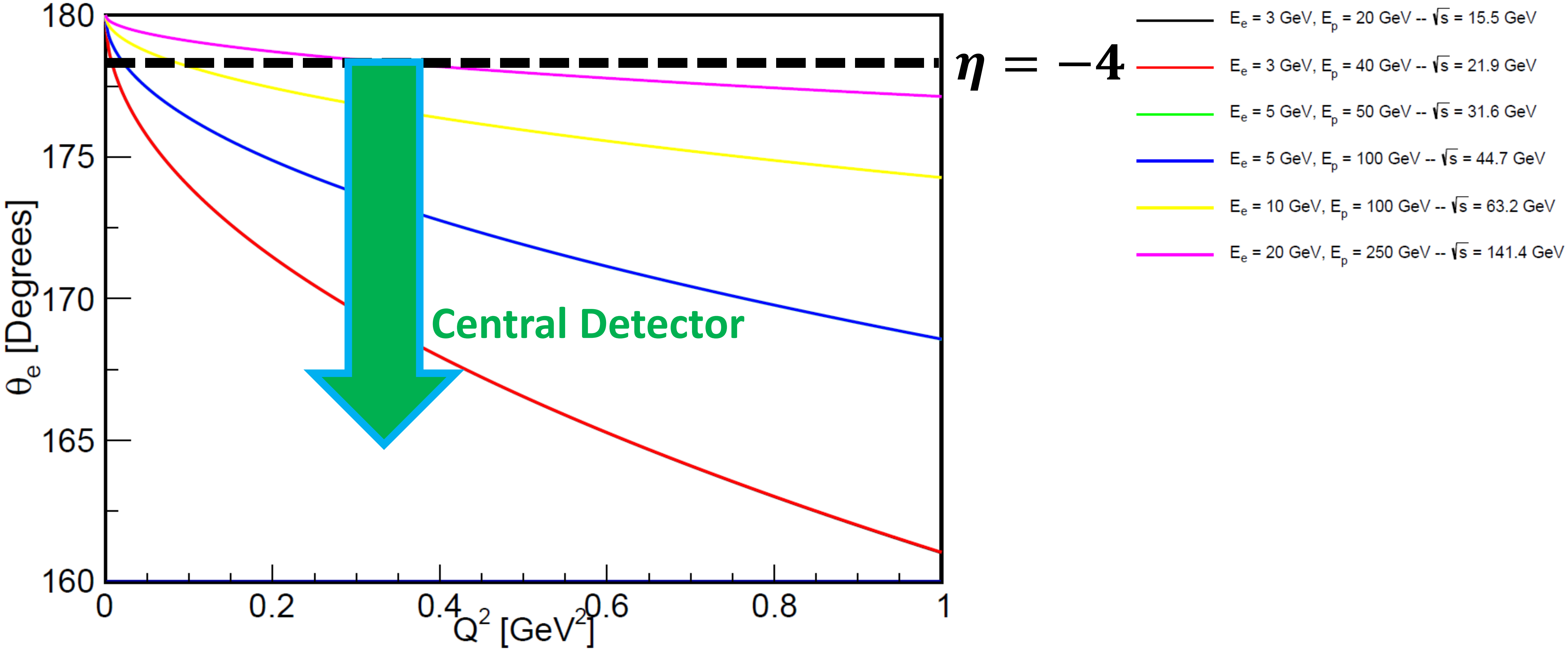


E_e [GeV]
Q^2 [GeV^2]
0
10
20
30
40
200
400
600
θ_e [Degrees]
50
100
150
E_p [GeV]
300
θ_p [Degrees]
E_e = 3 GeV, E_p = 20 GeV -- $\sqrt{s}$ = 15.5 GeV
E_e = 3 GeV, E_p = 40 GeV -- $\sqrt{s}$ = 21.9 GeV
E_e = 5 GeV, E_p = 50 GeV -- $\sqrt{s}$ = 31.6 GeV
E_e = 5 GeV, E_p = 100 GeV -- $\sqrt{s}$ = 44.7 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

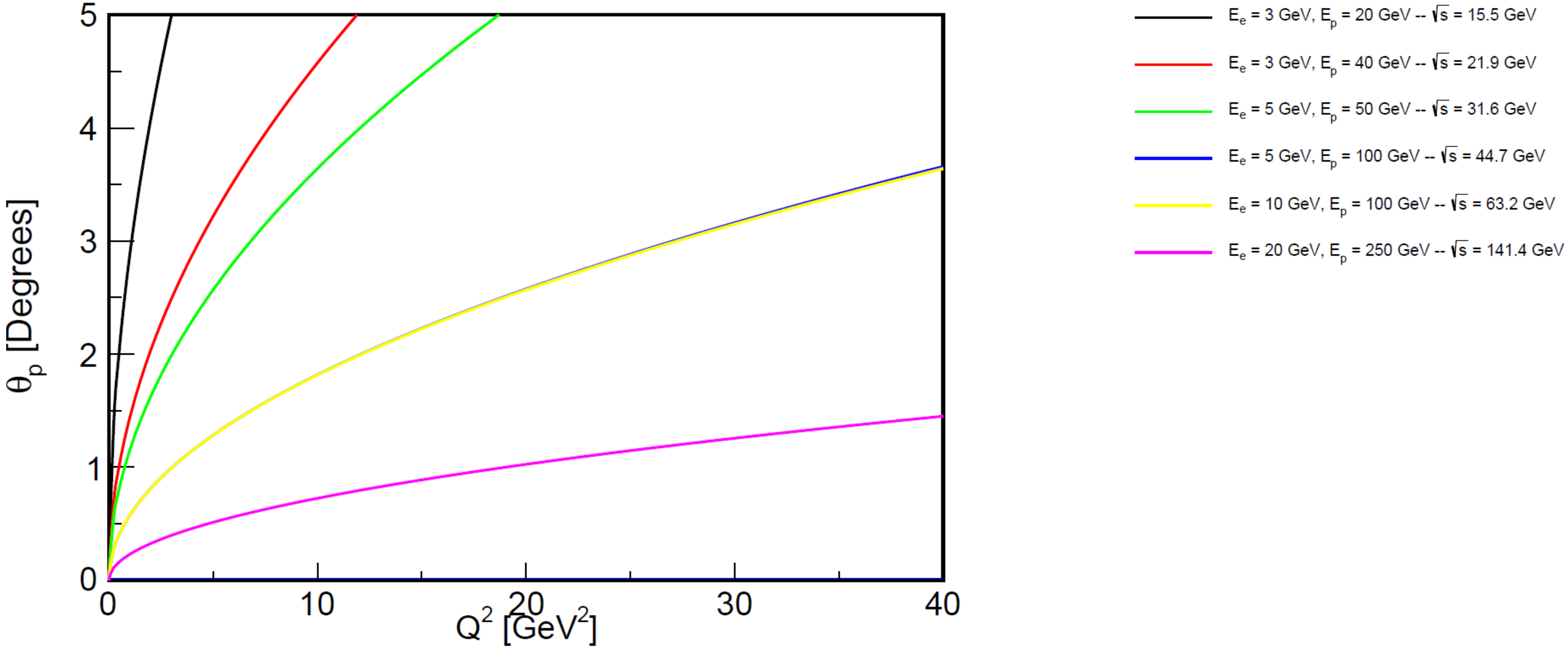
Kinematics: Low Q^2 Electron Angle



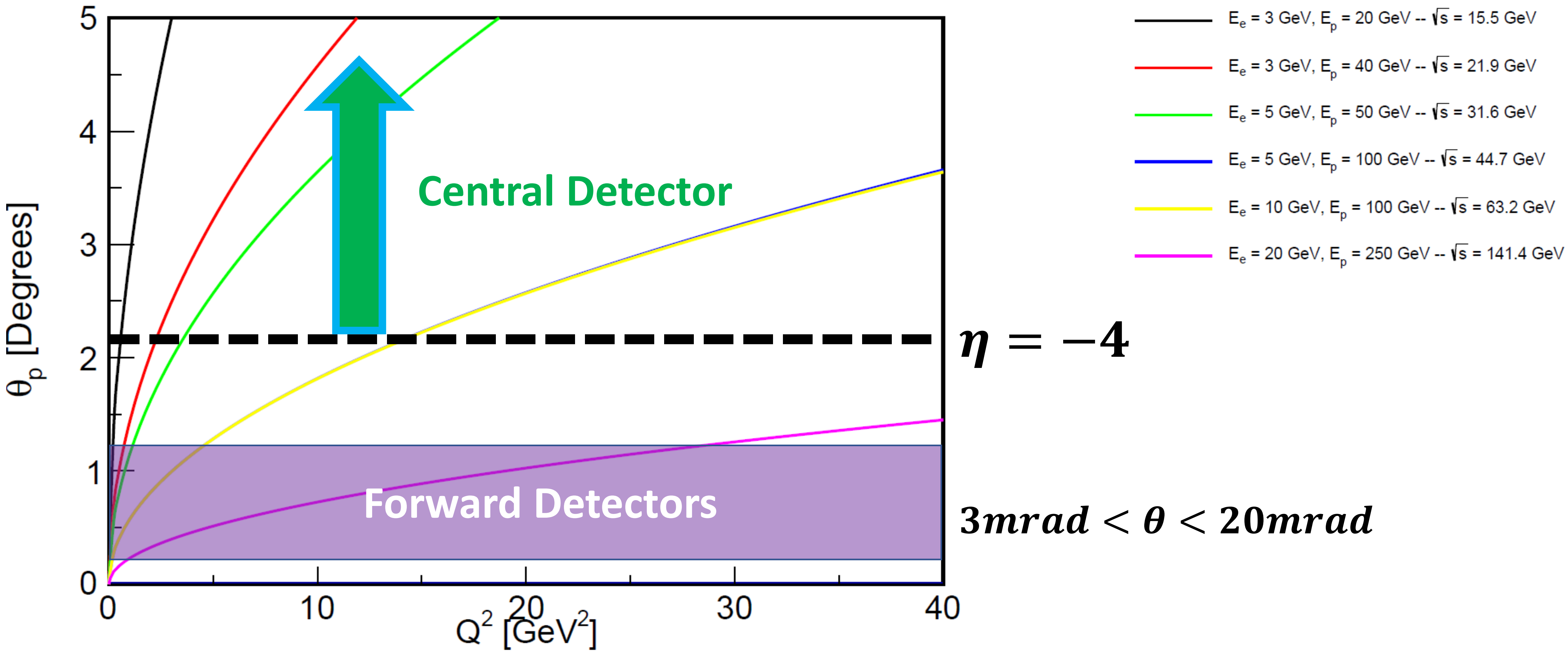
Kinematics: Low Q^2 Electron Angle



Kinematics: Proton Angle



Kinematics: Proton Angle



$\boldsymbol{\eta = -4}$

$\boldsymbol{3mrad < \theta < 20mrad}$

Polarized Electron-Proton Elastic Scattering Asymmetry Measurements

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

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

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

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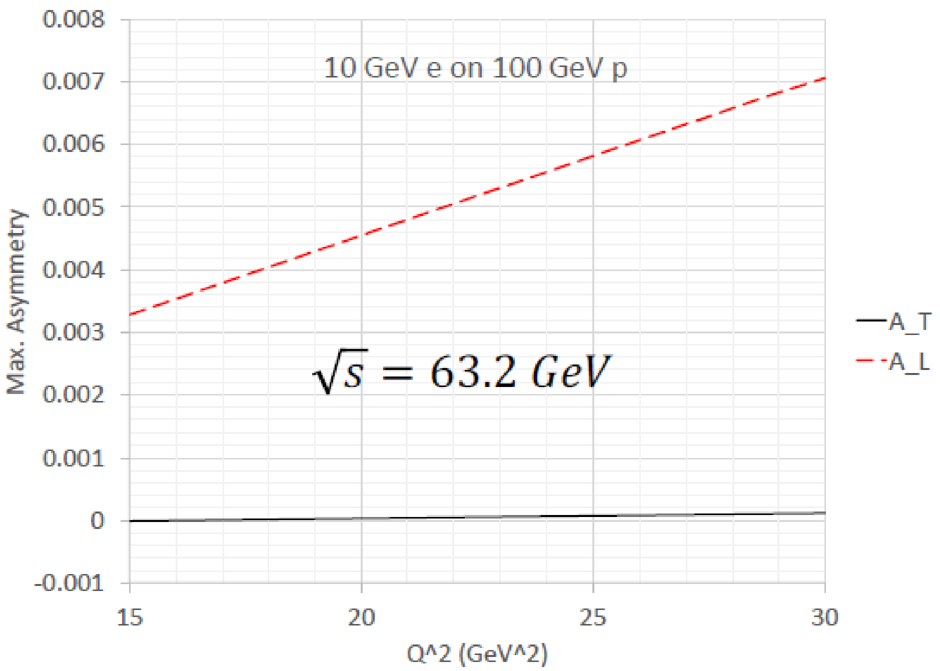

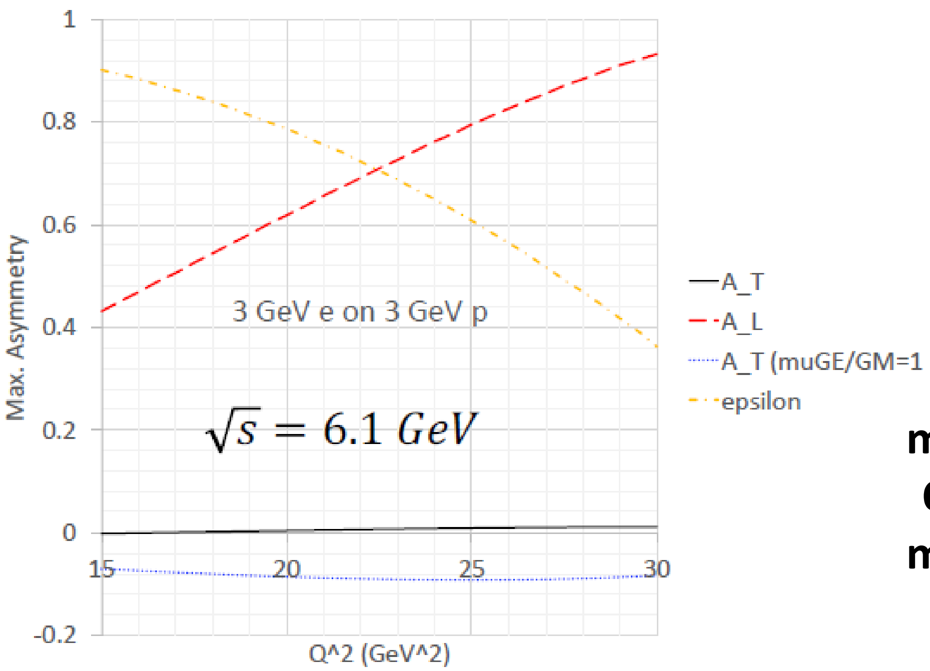

To make reasonable measurements in this higher Q^2 range, we would need a much lower energy than will be provided by the *EIC*

Summary

- We presented a potential technique to extract the deuteron tensor polarization using elastic electron-deuteron scattering.
- We are beginning to conduct simulation studies on this topic.
- 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*.