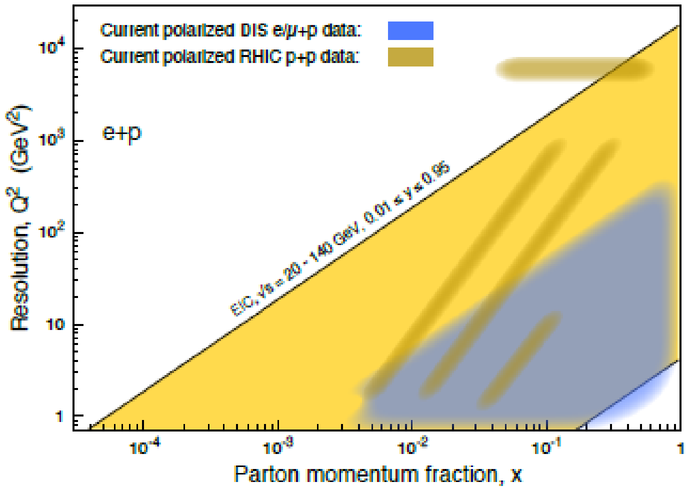
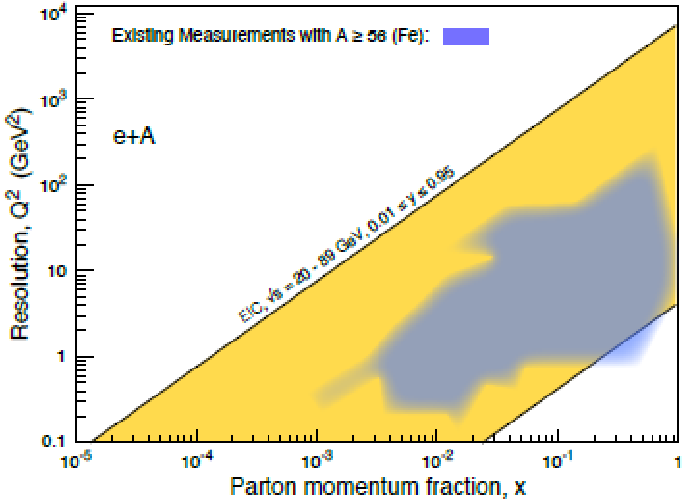
Inclusive physics at the EIC: opportunities and requirements

Barak Schmookler

Inclusive scattering at the EIC

Measurement	Physics Topic/goal
$\boldsymbol{\sigma}_{red,NC(CC)}(x,Q^2) \rightarrow F_2, F_L$	Proton PDFs $q(x,Q^2)$, $g(x, Q^2)$
$\boldsymbol{\sigma}_{red,NC(CC)}(x,Q^2) \rightarrow F_2, F_L$	Nuclear PDFs $q(x,Q^2)$, $g(x, Q^2)$ Non-linear QCD dynamics
Inclusive $A_{\|\|}$ / $A_{\perp}$ for proton, deuterium, ^3He	Gluon & Quark Helicity $\Delta g(x,Q^2)$, Δu^+, Δd^+
Inclusive A_{PV}	Strange Pol and Unpolarized $\Delta s^+(x,Q^2)$, $s^+(x,Q^2)$ BSM & Precision EW ($\sin^2\boldsymbol{\theta}_W$)





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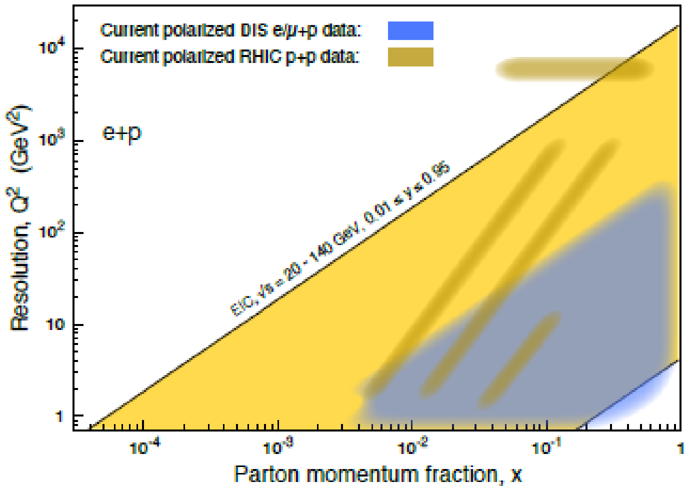
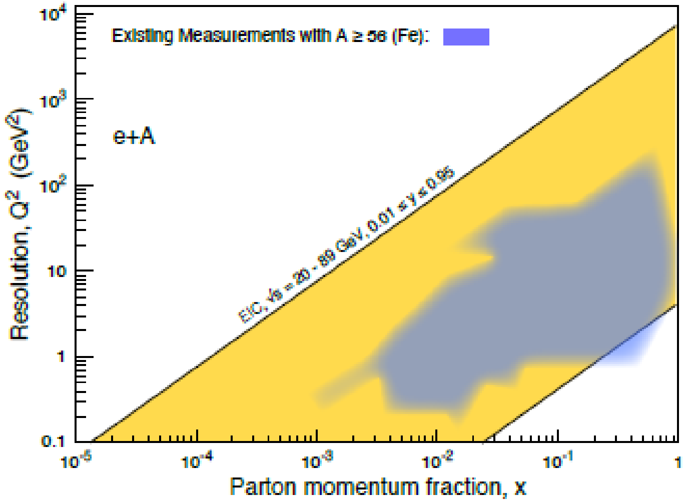
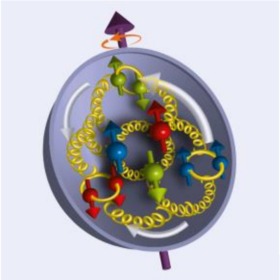




Polarized PDFs and the Spin of the Proton

Proton spin

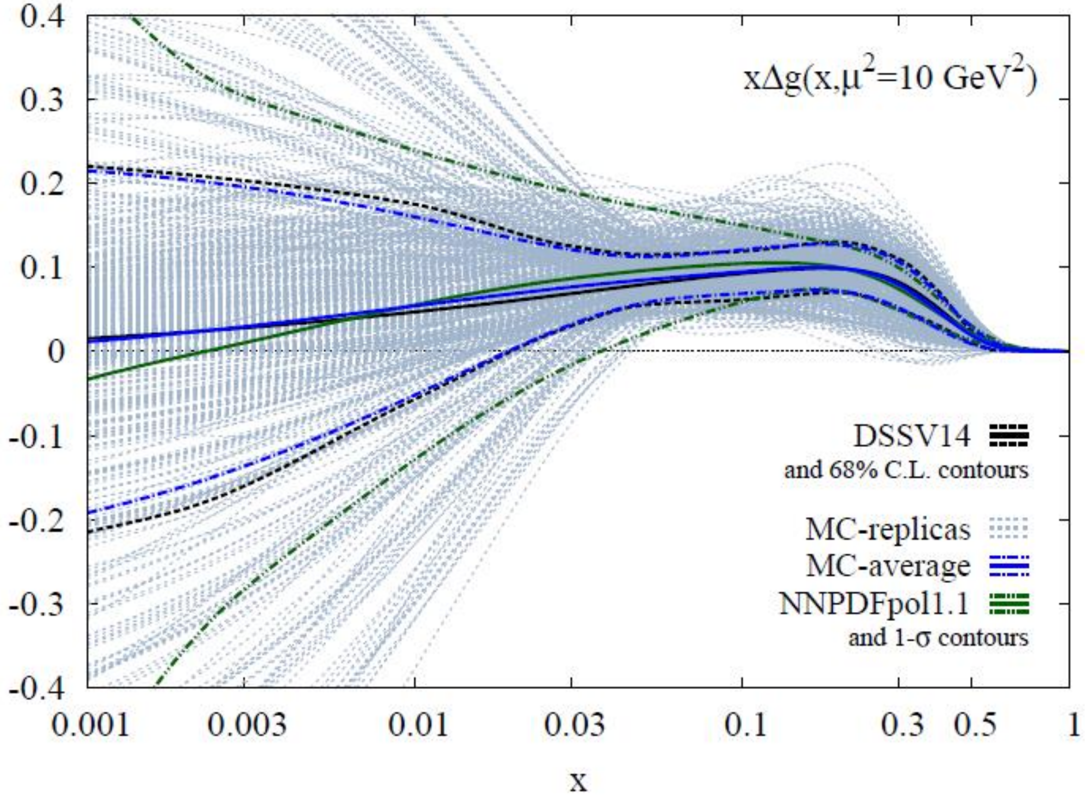


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \ldots$$

$$\Delta q = q^{\uparrow} - q^{\downarrow} \qquad \Delta q = \int \Delta q(x)dx$$

Phys. Rev. D **100**, 114027

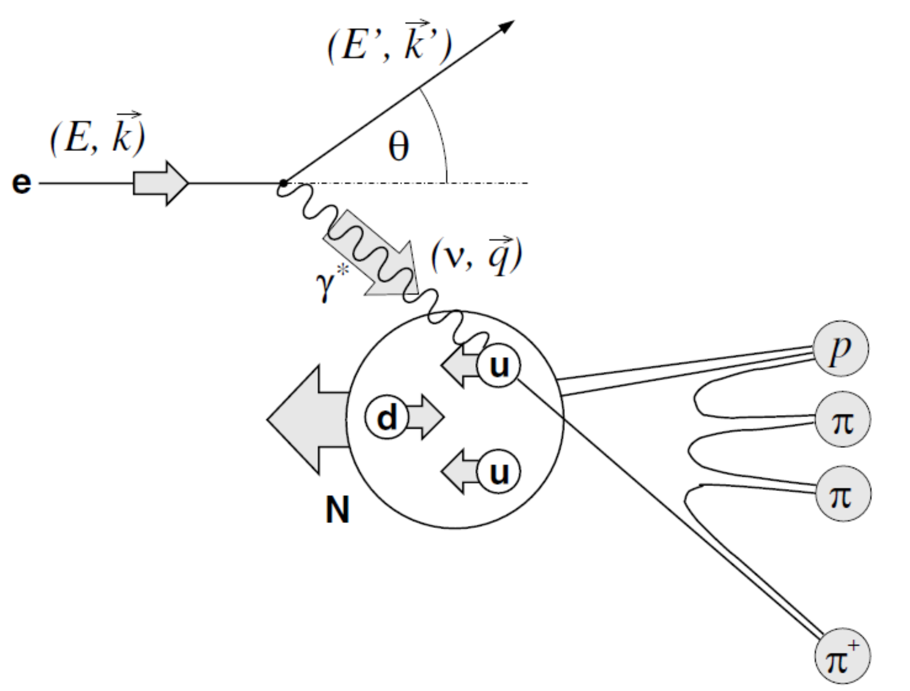


Quark spin only accounts for a portion of the proton's spin

Large uncertainty on polarized gluon PDF

Experimental channels for studying Polarized PDFs

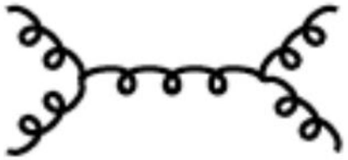
Inclusive and semi-inclusive lepton-proton (light nucleus) scattering, with longitudinally polarized proton (or light nucleus)



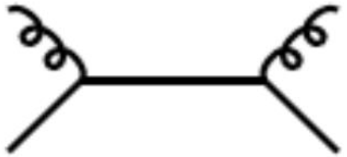
Hard proton-proton scattering with longitudinally polarized proton beams

$$p + p \to \pi + X$$

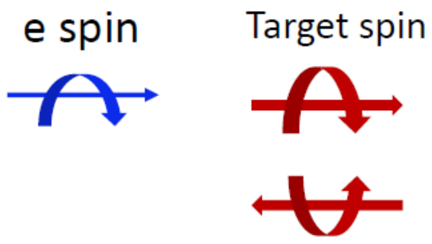
$$g + g \to g + g$$



$$q + g \to q + g$$



NC e-p cross section with Longitudinally Polarized Protons



At high Q^2, for electron-proton scattering:

$$\Delta\sigma = \frac{d^2\sigma}{dxdQ^2}(\lambda_n = -1, \lambda_l) - \frac{d^2\sigma}{dxdQ^2}(\lambda_n = +1, \lambda_l) = \frac{4\pi\alpha^2}{Q^4 x}\left[-Y_+ g_4 + Y_- 2x g_1 + y^2 g_L\right]$$

$$g_1 = -\lambda_l g_1^{\gamma} + \eta_z\left(\lambda_l g_v^e - g_A^e\right) g_1^{\gamma z} + \eta_z^2\left[-\lambda_l\left((g_v^e)^2 + (g_A^e)^2\right) + 2 g_A^e g_v^e\right] g_1^z$$

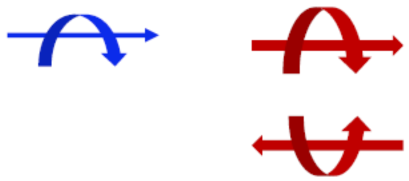
$$g_{4,5} = \eta_z\left(g_v^e - \lambda_l g_A^e\right) g_{4,5}^{\gamma z} + \eta_z^2\left[-(g_v^e)^2 - (g_A^e)^2 + 2\lambda_l g_A^e g_v^e\right] g_{4,5}^z$$

$$\begin{cases} Y_\pm = 1 \pm (1-y)^2 \\ g_L = g_4 - 2x g_5 \end{cases}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

NC e-p cross section with Longitudinally Polarized Protons

e spin Target spin



At high Q², for electron-proton scattering:

$$\Delta\sigma = \frac{d^2\sigma}{dxdQ^2}(\lambda_n=-1,\lambda_l)-\frac{d^2\sigma}{dxdQ^2}(\lambda_n=+1,\lambda_l) = \frac{4\pi\alpha^2}{Q^4x}\left[-Y_+g_4+Y_-2xg_1+y^2g_L\right]$$

$$g_1 = -\lambda \boxed{g_1^\gamma} + \eta_z\left(\lambda_l g_v^e - g_A^e\right)g_1^{\gamma z} + \eta_z^2\left[-\lambda_l\left((g_v^e)^2+(g_A^e)^2\right)+2g_A^e g_v^e\right]g_1^z$$

For non-zero electron beam polarization, this term dominates

$$g_{4,5} = \eta_z\left(g_v^e - \lambda_l g_A^e\right)g_{4,5}^{\gamma z} + \eta_z^2\left[-(g_v^e)^2-(g_A^e)^2+2\lambda_l g_A^e g_v^e\right]g_{4,5}^z$$

$$\begin{cases} Y_\pm = 1 \pm (1-y)^2 \\ g_L = g_4 - 2xg_5 \end{cases}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Measuring the g_1 structure function

At high Q^2, for an electron with λ=-1:

$$\Delta\sigma \approx \frac{4\pi\alpha^2}{Q^4 x}\left(Y_{-} 2 x g_1^{\gamma}\right)$$

$$A_{||} = \frac{\sigma\left(\lambda_n = -1, \lambda_l = -1\right) - \sigma\left(\lambda_n = +1, \lambda_l = -1\right)}{\sigma\left(\lambda_n = -1, \lambda_l = -1\right) + \sigma\left(\lambda_n = +1, \lambda_l = -1\right)} \approx \boxed{\frac{Y_-}{Y_+}} A_1$$

Depolarization factor

$$A_{\gamma * p} = A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1^{\gamma}}{F_1^{\gamma}}$$

Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

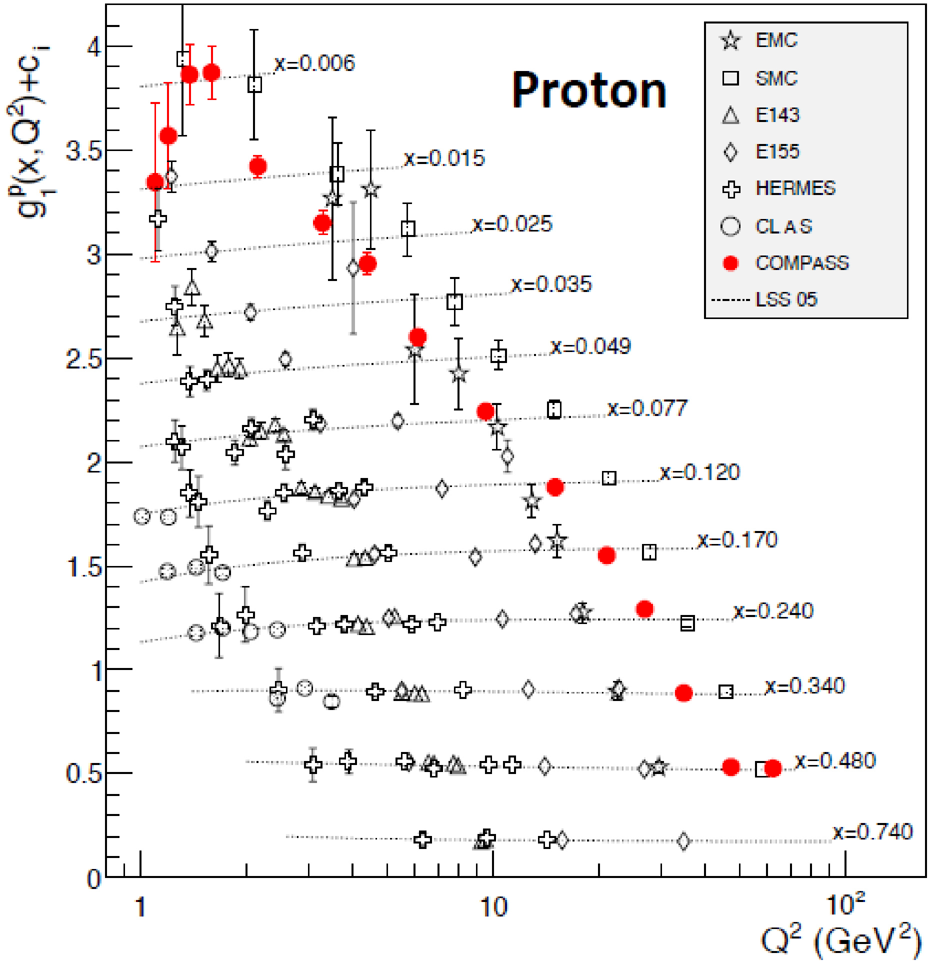
Extraction of polarized PDFs from g_1

Aidala et al.1209.2803v2

$$g_1^{\gamma}\left(x,Q^2\right) = \sum_{i=q,g} C_i \otimes \Delta f_i$$

$$= \frac{1}{2}\sum_q e_q^2\left[\Delta q\left(x,Q^2\right) + \Delta \bar{q}\left(x,Q^2\right)\right] \quad \textbf{at LO}$$

$$\frac{\partial \Delta f_{i=q,g}}{\partial\, lnQ^2} = \sum_j P_{i,j} \otimes \Delta f_j \qquad \textbf{DGLAP evolution}$$



Need measurements at a wide variety of x values and scales (Q^2 values) to constrain the polarized quark and gluon PDFs

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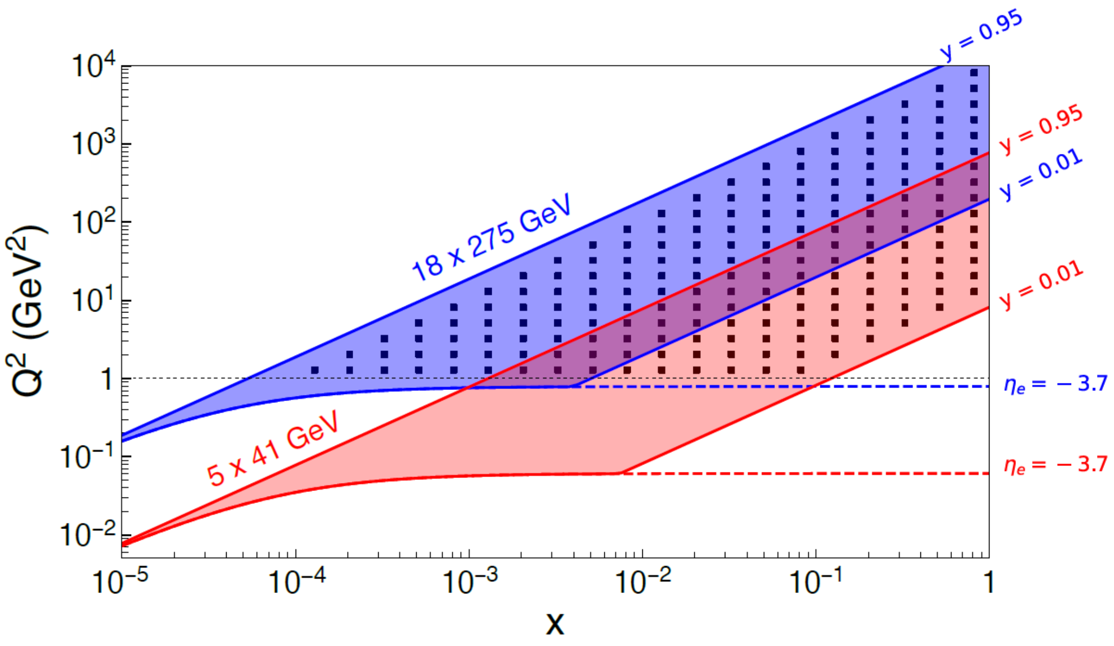
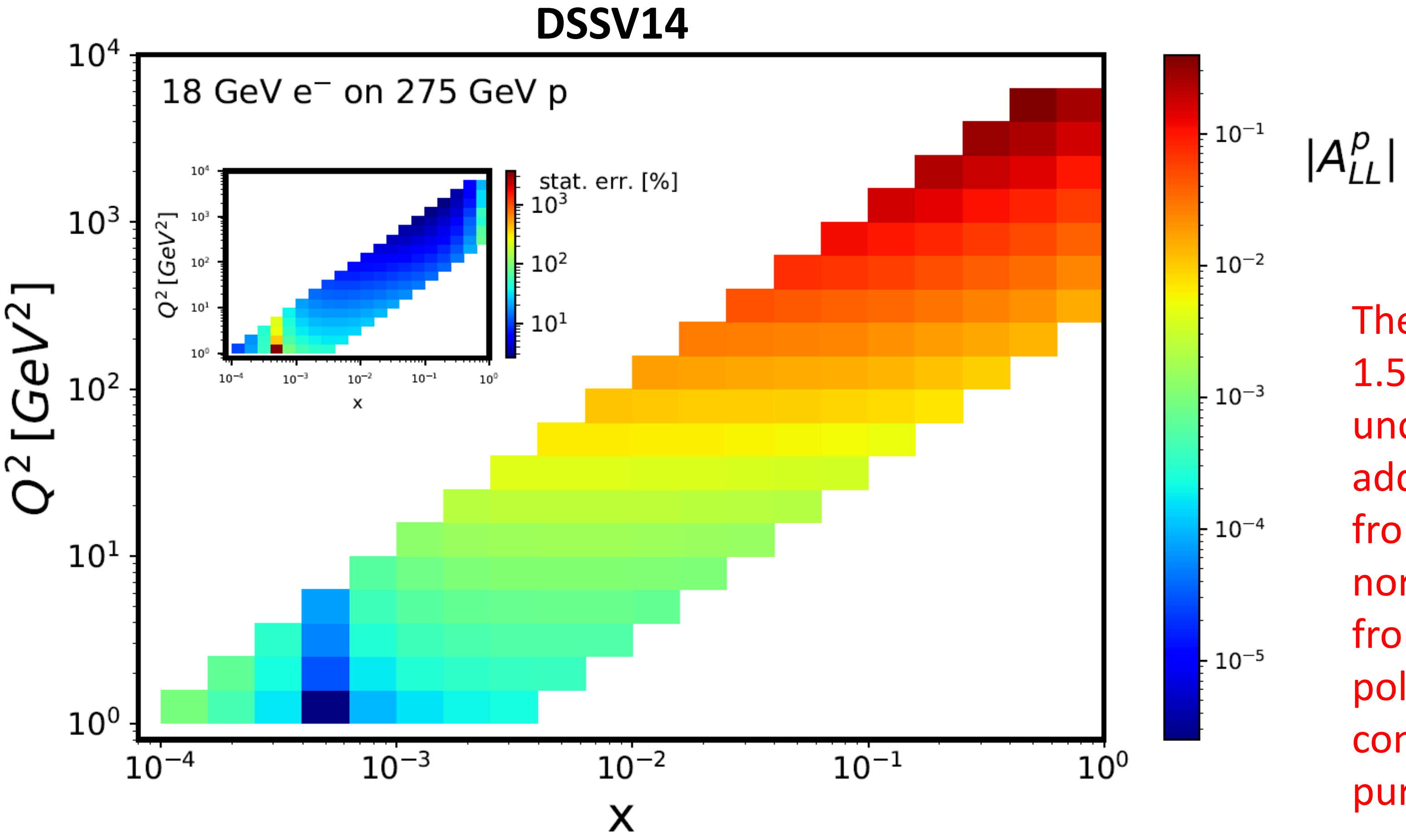
EIC kinematic coverage



e-beam E	p-beam E	$\sqrt{s}$ (GeV)	inte. Lumi. (fb^{-1})
18	275	140	15.4
10	275	105	100.0
10	100	63	79.0
5	100	45	61.0
5	41	29	4.4

- ❑ Different center-of-mass energies allow coverage in different x,Q^2 ranges.
- ❑ Standard binning of 5 bins per decade in both x and Q^2. Kinematic coverage considered is $Q^2 > 1$ GeV^2, $0.01 < y < 0.95$.

Statistical and systematic uncertainties

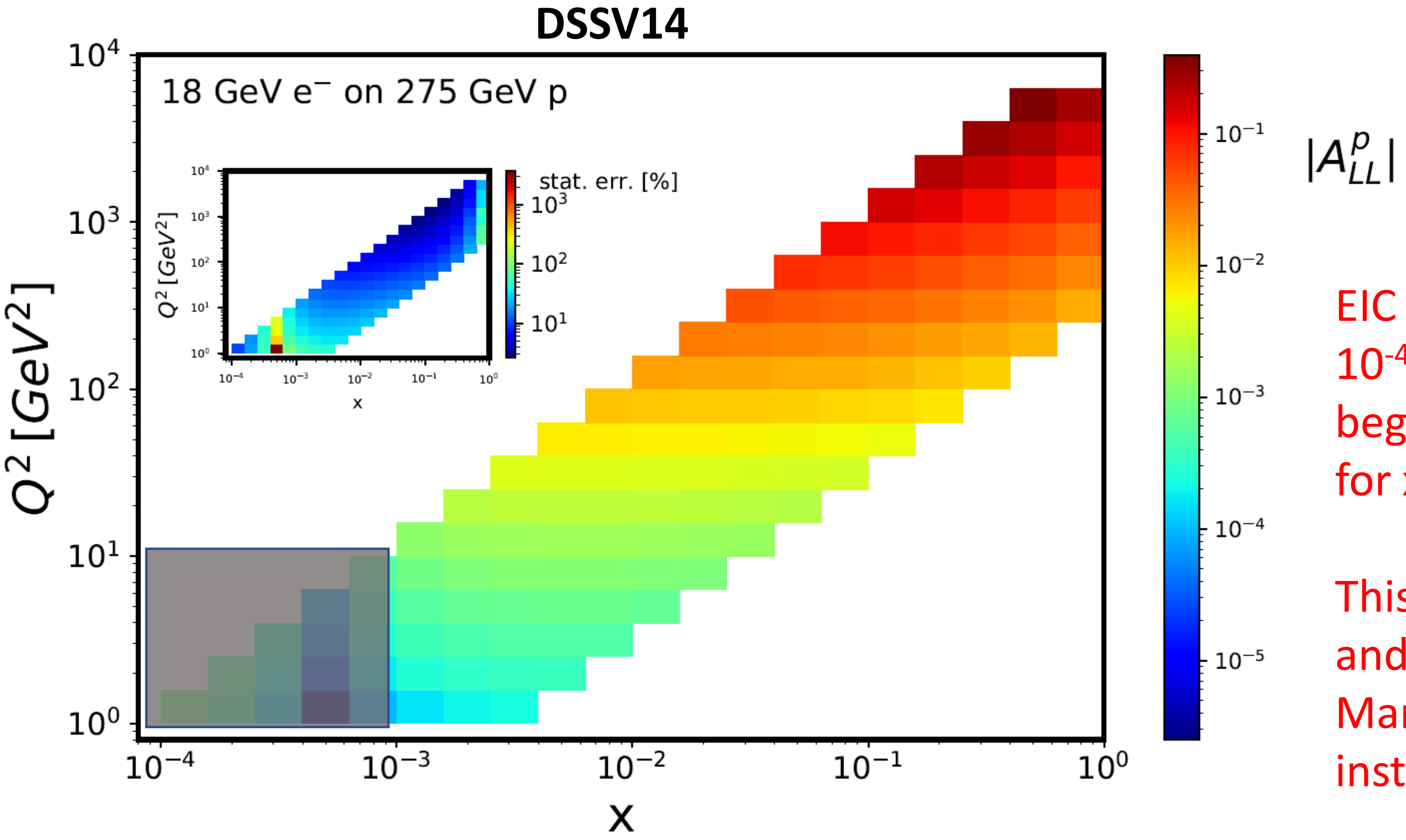


The systematic uncertainty estimation includes 1.5% point-by-point uncorrelated systematic uncertainty, 5% normalization uncertainty, and an additional systematic (shift) uncertainty of 10^{-4} from relative luminosity. The conservative 5% normalization uncertainty includes contributions from electron beam polarization (2%), proton polarization (2%), uncertainty related with pion contamination (3%, assuming 90% electron purity), and 1-2% on detector effects.

Statistical uncertainty on asymmetry measurement:

$$\sigma_{A_{LL}} = \frac{\sqrt{1 - A^2_{LL,meas}}}{P_e P_p \sqrt{N}} \approx \frac{1}{P_e P_p \sqrt{N}}$$

Statistical and systematic uncertainties



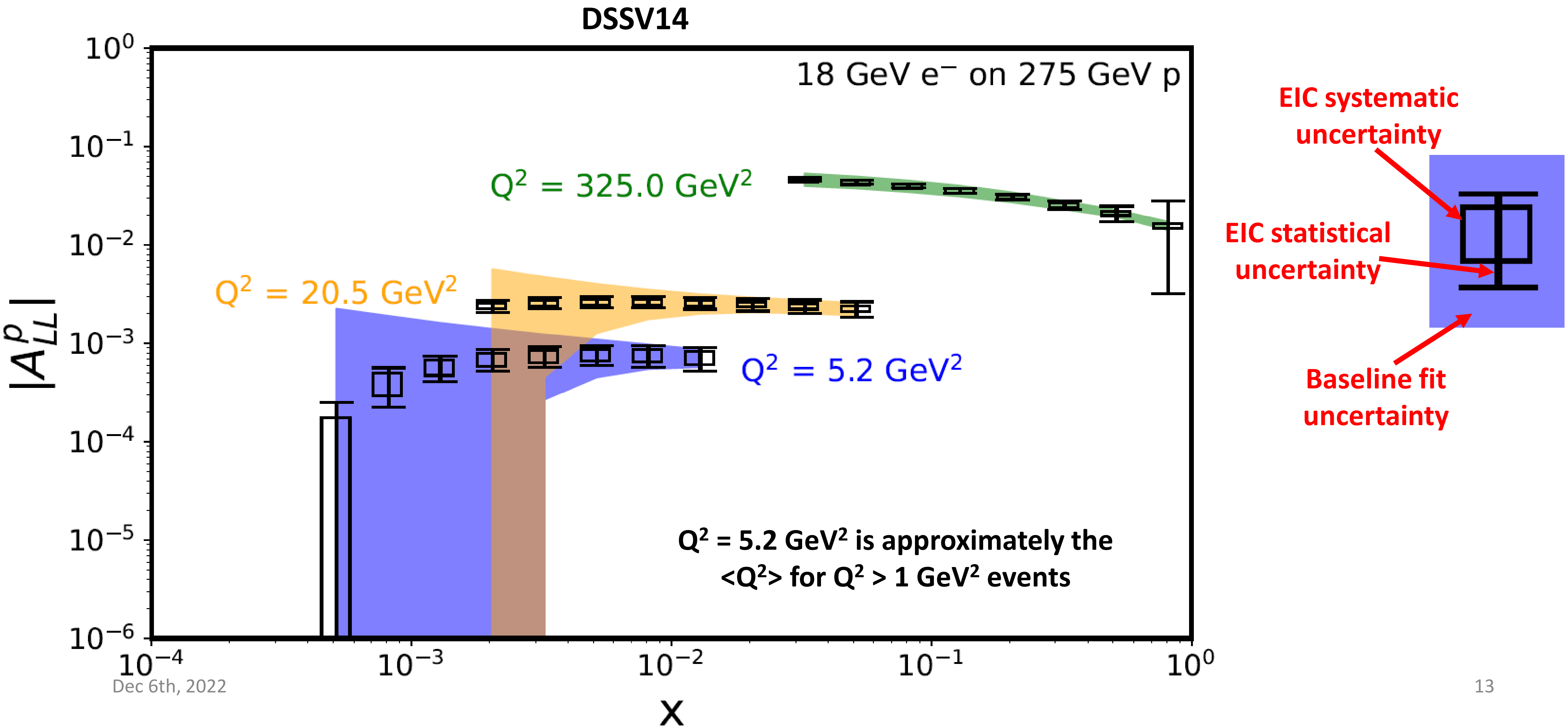
EIC kinematic coverage extends down to x of 10^{-4} for $Q^2 > 1$ GeV^2 …but statistical error begins to approach 100% of the asymmetry for $x < 10^{-3}$.

This assumes ~15 fb^{-1} integrated luminosity and 70-80% electron and proton polarization. Many years of running with high instantaneous luminosity can help.

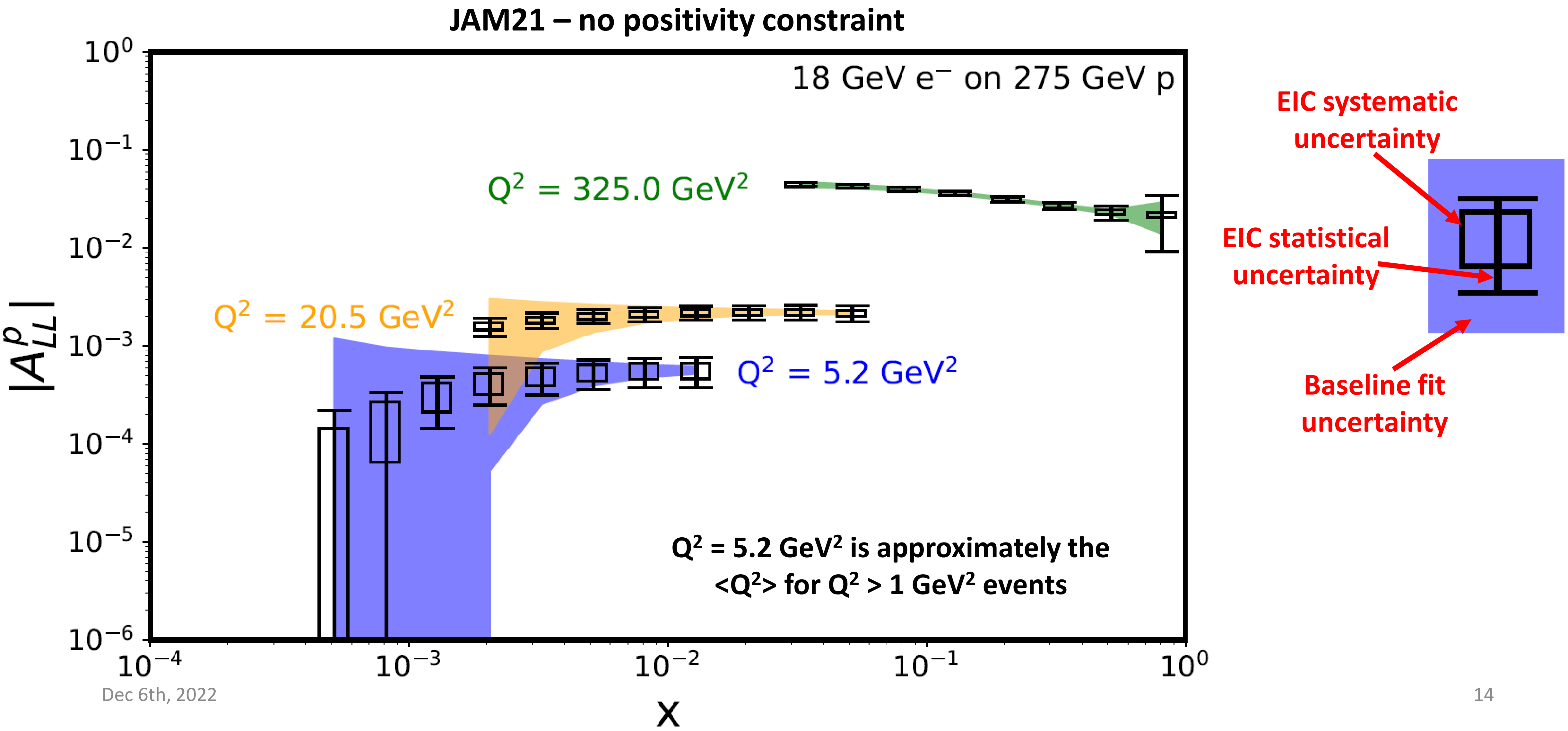
Statistical uncertainty on asymmetry measurement:

$$\sigma_{A_{LL}} = \frac{\sqrt{1 - A^2_{LL,meas}}}{P_e P_p \sqrt{N}} \approx \frac{1}{P_e P_p \sqrt{N}}$$

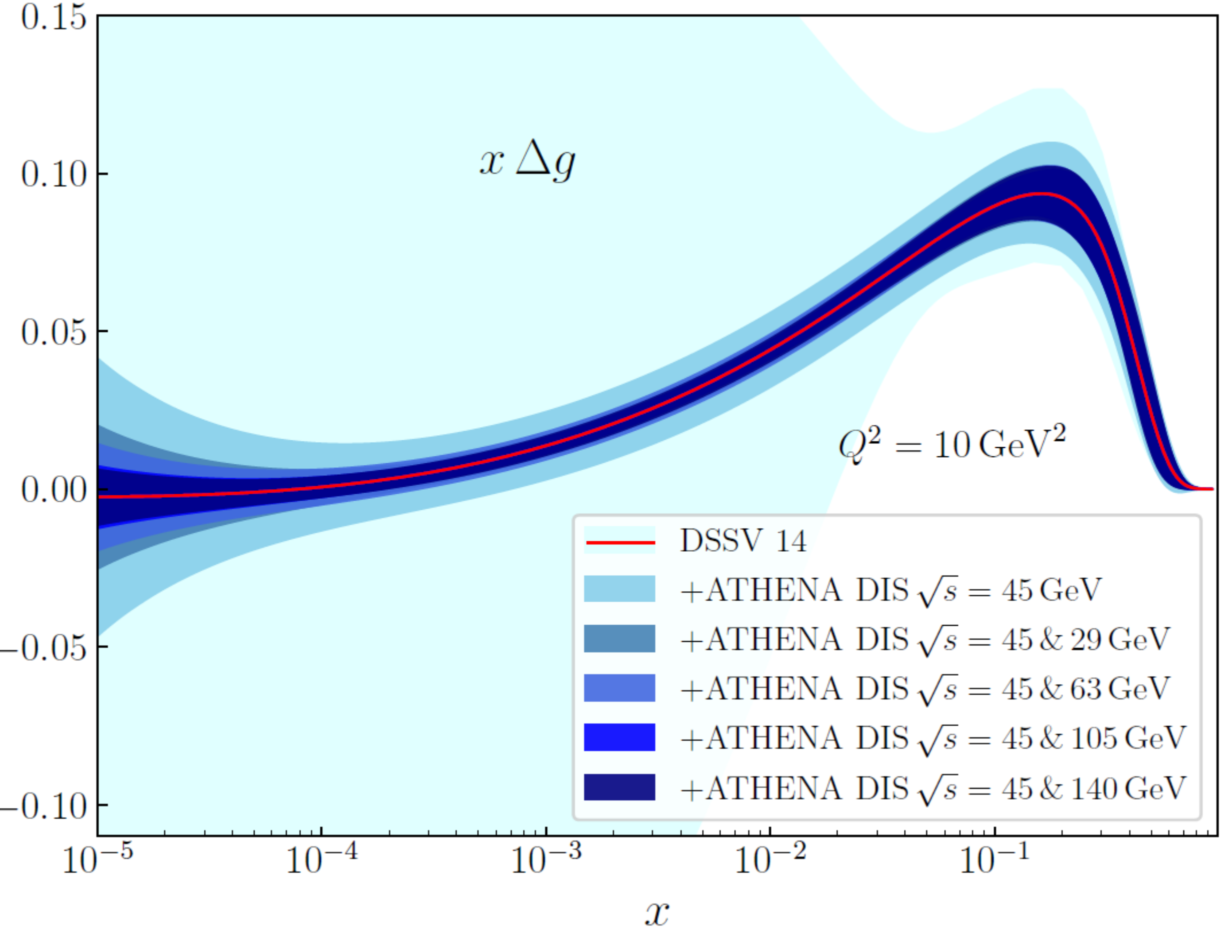
Expected EIC experimental precision

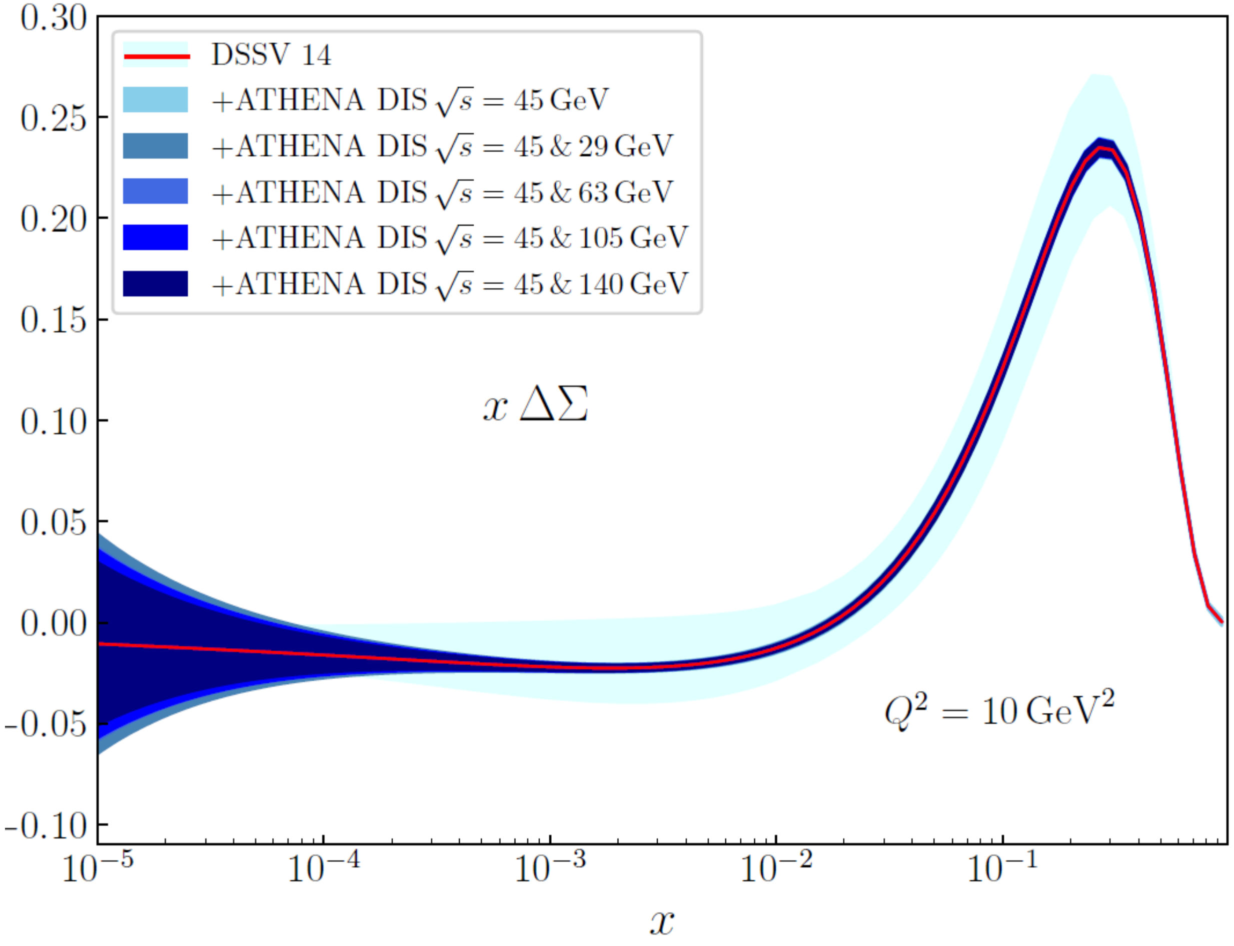


Expected EIC experimental precision



Impact of the EIC on polarized PDFs: **DSSV**





Very significant impact on polarized gluon and quark singlet PDFs using inclusive e-p only!

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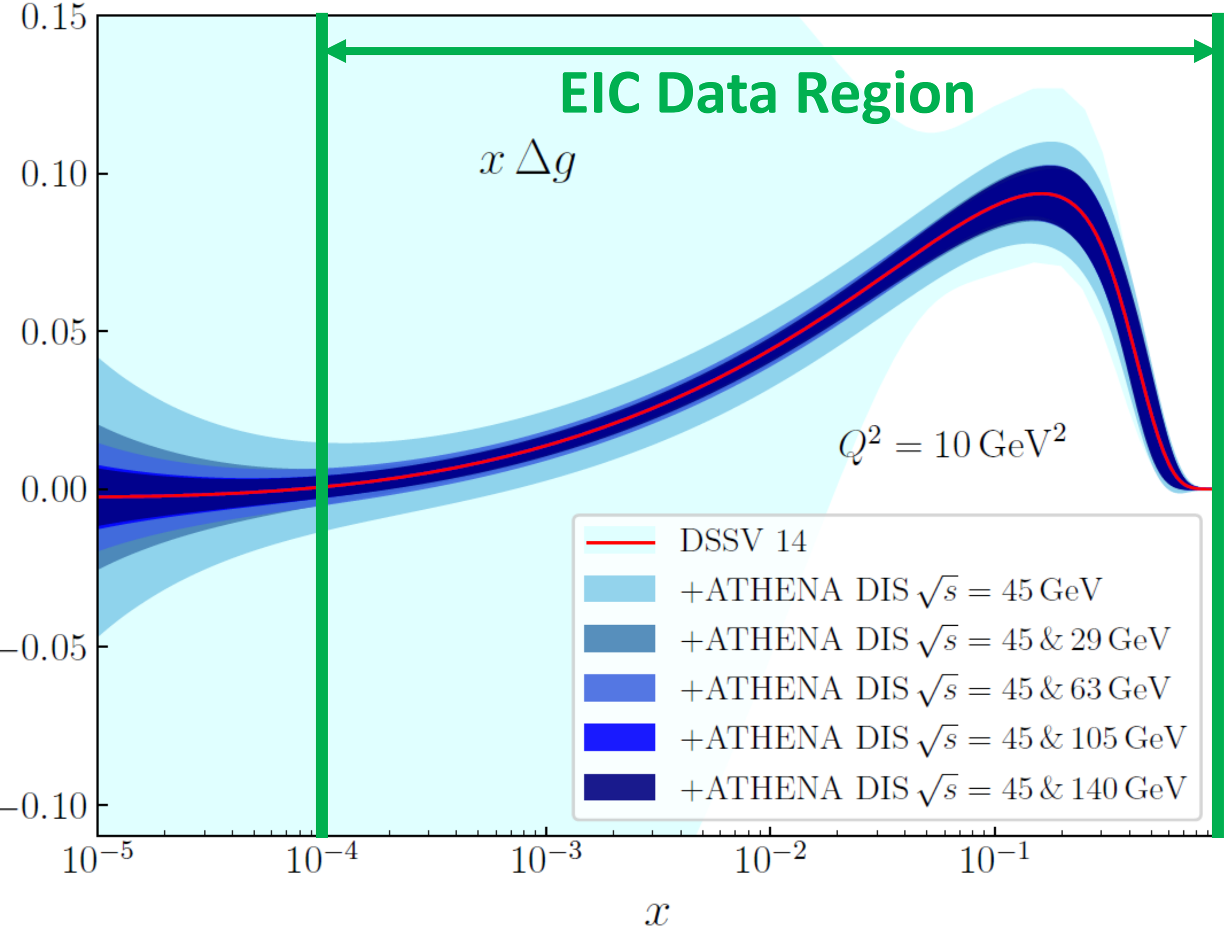

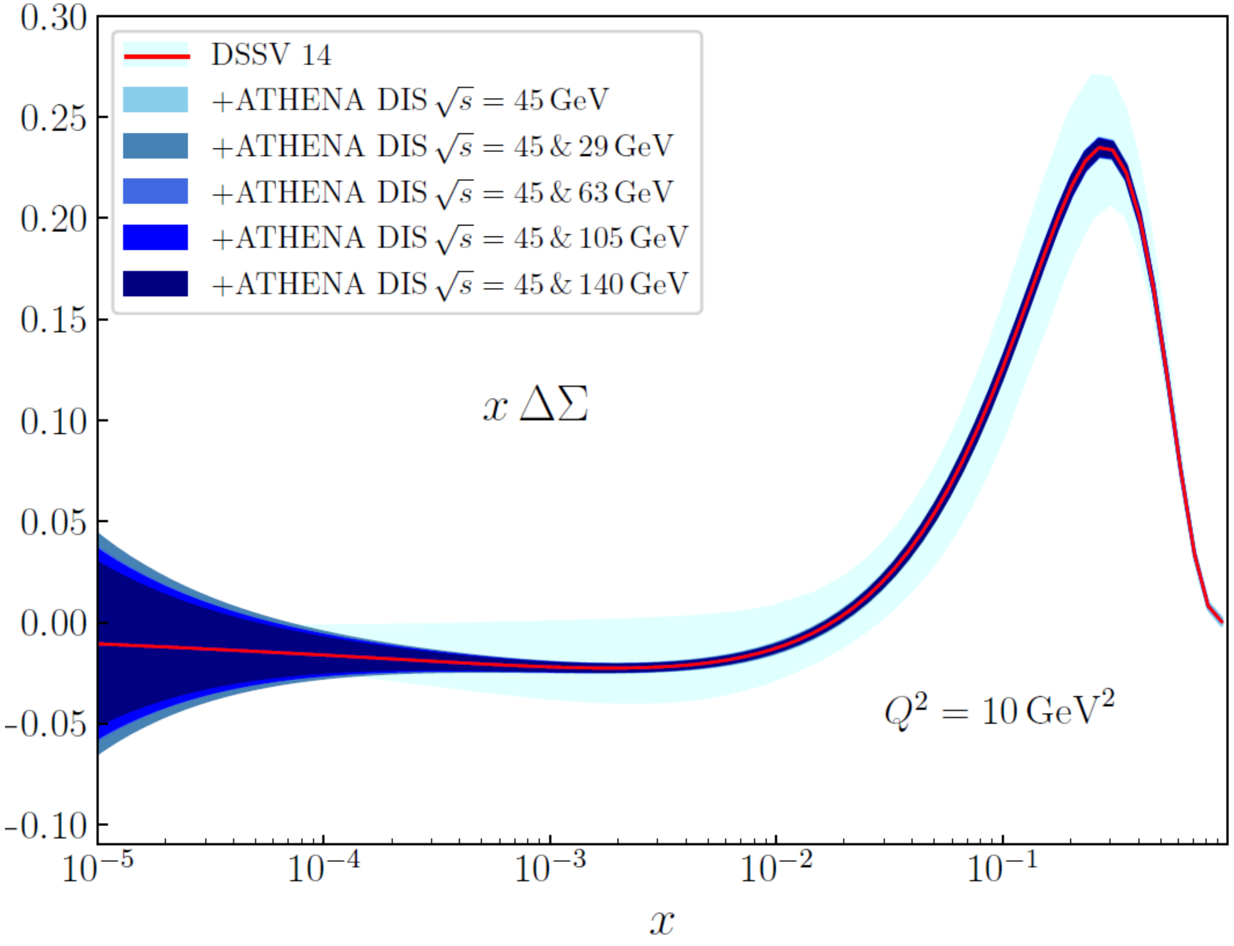

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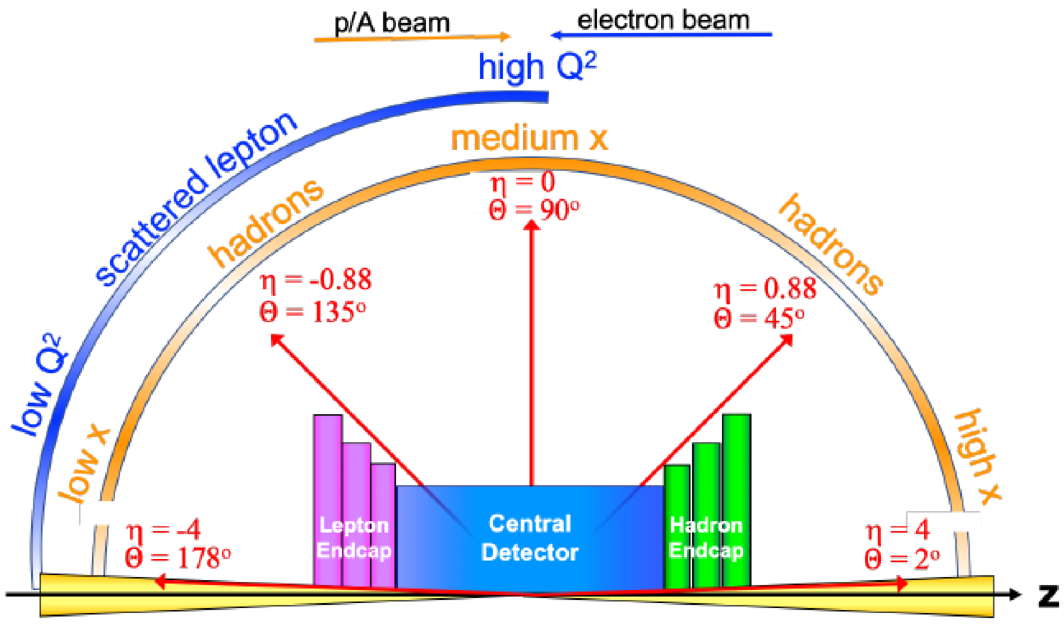
Detector requirements and associated challenges



Detector requirements from EIC Yellow report

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8			low-Q^2 tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2										
...	↓ p/A	Auxiliary Detectors													
-4.5 — -4.0			Instrumentation to separate charged particles from γ												
-4.0 — -3.5														~50%/√E+6%	
-3.5 — -3.0									2%/√E+(1-3)%						
-3.0 — -2.5					$\sigma_p/p \sim 0.1\% \times p + 2.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$								
-2.5 — -2.0			Backwards Detectors											~45%/√E+6%	
-2.0 — -1.5					$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$		7%/√E+(1-3)%		≤ 7 GeV/c				
-1.5 — -1.0										π suppression up to 1:10^4					
-1.0 — -0.5															
-0.5 — 0.0															
0.0 — 0.5		Central Detector	Barrel	100 MeV π 135 MeV K	$\sigma_p/p \sim 0.05\% \times p + 0.5\%$	~5% or less	$\sigma_{xyz} \sim 20$ μm, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV μm + 5 μm	50 MeV			≤ 10 GeV/c	≥ 3σ	~500 MeV	~85%/√E+7%	Useful for bkg, improve resolution
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5									(10-12)%/√E+(1-3)%		≤ 30 GeV/c				
1.5 — 2.0					$\sigma_p/p \sim 0.05\% \times p + 1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$								
2.0 — 2.5			Forward Detectors							3σ e/π	≤ 50 GeV/c			~35%/√E	
2.5 — 3.0							$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$				≤ 30 GeV/c				
3.0 — 3.5					$\sigma_p/p \sim 0.1\% \times p + 2.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 60\mu m$				≤ 45 GeV/c				
3.5 — 4.0			Instrumentation to separate charged particles from γ												
4.0 — 4.5															
...	↑e	Auxiliary Detectors													
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t \rvert)/\lvert t \rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										

Detector requirements and associated challenges

- Hermetic coverage for scattered electron – leave no gaps in EMcal coverage while also incorporating PID readout
- Scattered electron momentum resolution in backward direction – design trackers to optimize momentum resolution when the particle has a large component parallel to the solenoid field; use combined information from tracker and EMcal for reconstruction
- Scattered electron purity in the backwards direction and barrel – high-precision EMcals and additional detectors for low momentum
- Remove large ISR events and reduce photoproduction background – good measurement of total E-p_z of all particles.
- Forward detection – want good energy resolution for hadronic reconstruction methods at low y

Detector requirements from EIC Yellow report

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV^2										
...															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						$2\%/\sqrt{E}+(1\text{-}3)\%$						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~$50\%/\sqrt{E}+6\%$	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p+2.0\%$	~5% or less				π suppression up to 1:10^4	≤ 7 GeV/c	≥ 3σ	~500 MeV	~$45\%/\sqrt{E}+6\%$	Useful for bkg, improve resolution
-3.0 — -2.5							σ_{xy}~30μm/p_T+ 40μm								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+ 20μm								
-2.0 — -1.5									$7\%/\sqrt{E}+(1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		σ_{xyz} ~ 20 μm, $d_0(z) \sim d_0(r\varphi)$ ~ 20/p_T GeV μm + 5 μm		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			~$85\%/\sqrt{E}+7\%$	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+ 20μm			3σ e/π	≤ 30 GeV/c			~$35\%/\sqrt{E}$	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p+2.0\%$		σ_{xy}~30μm/p_T+ 40μm				≤ 30 GeV/c				
3.0 — 3.5							σ_{xy}~30μm/p_T+ 60μm				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
...															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: 0.2< p_T <1.2 GeV/c										

Scattered Electron Acceptance

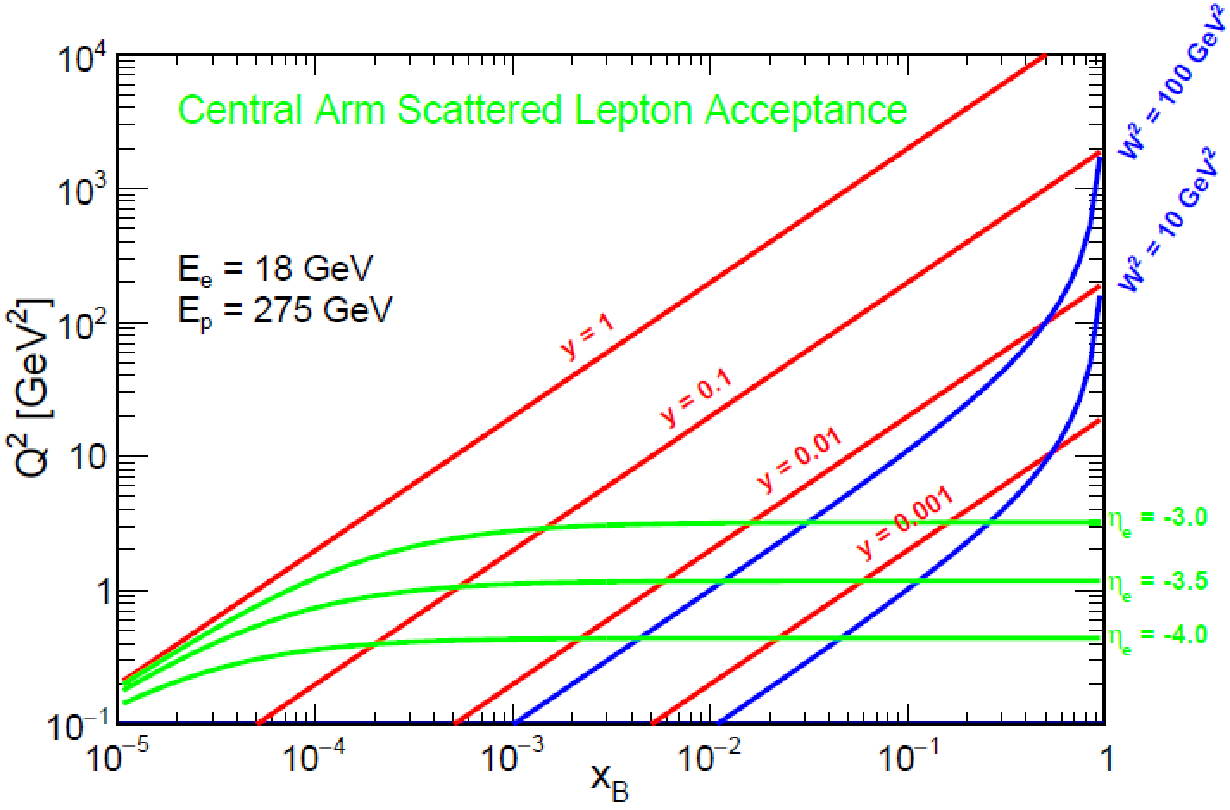
- For the beam energies that will be used at the EIC and considering scattered electrons in the pseudo-rapidity range of $-4 < \eta < 4$ (where $Q^2 \gg m_e{}^2$), we can relate the inclusive kinematic variables to the scattered electron angles and energies as

$$y_e = 1 - \frac{E'_e}{2E_e}(1 - \cos\theta_e) \ ,$$
$$Q^2_e = 4E_e E'_e \cos^2(\theta_e/2) \ ,$$
$$x_e = \frac{Q^2_e}{s y_e} \ .$$

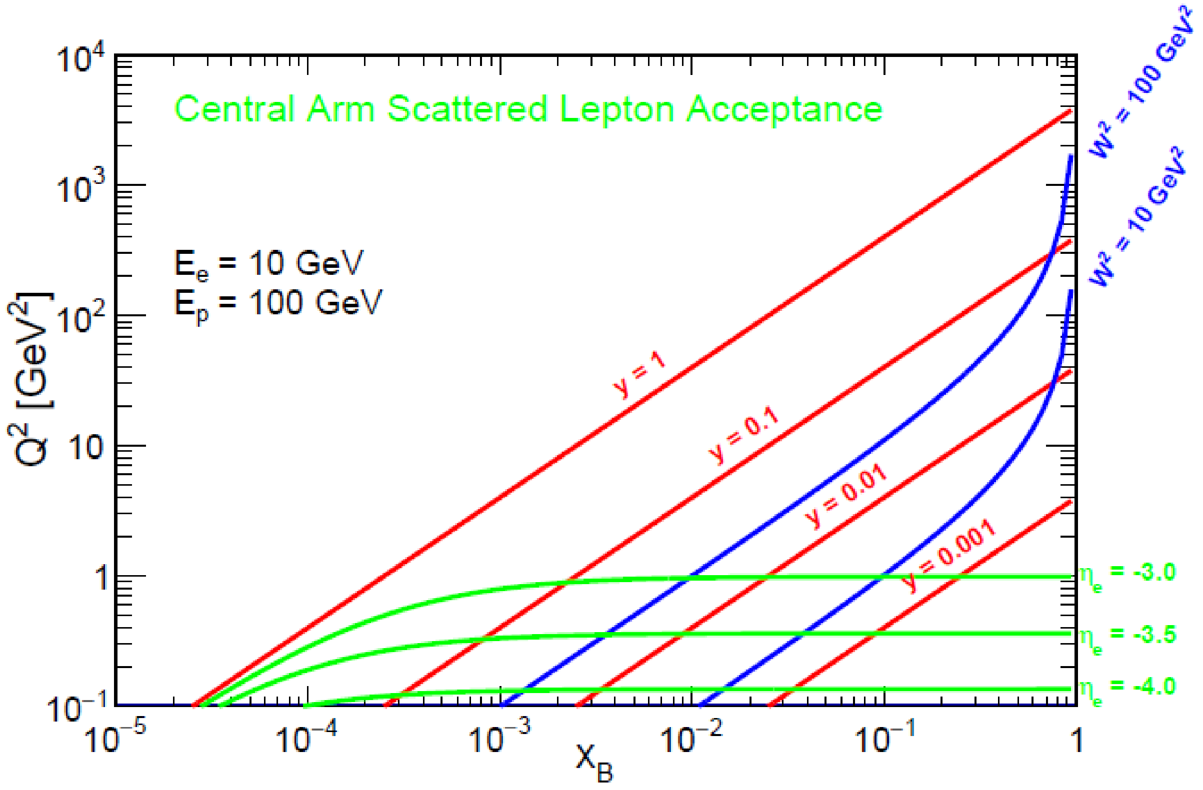
- Note how neither Q^2 nor y depend explicitly on the proton beam energy.

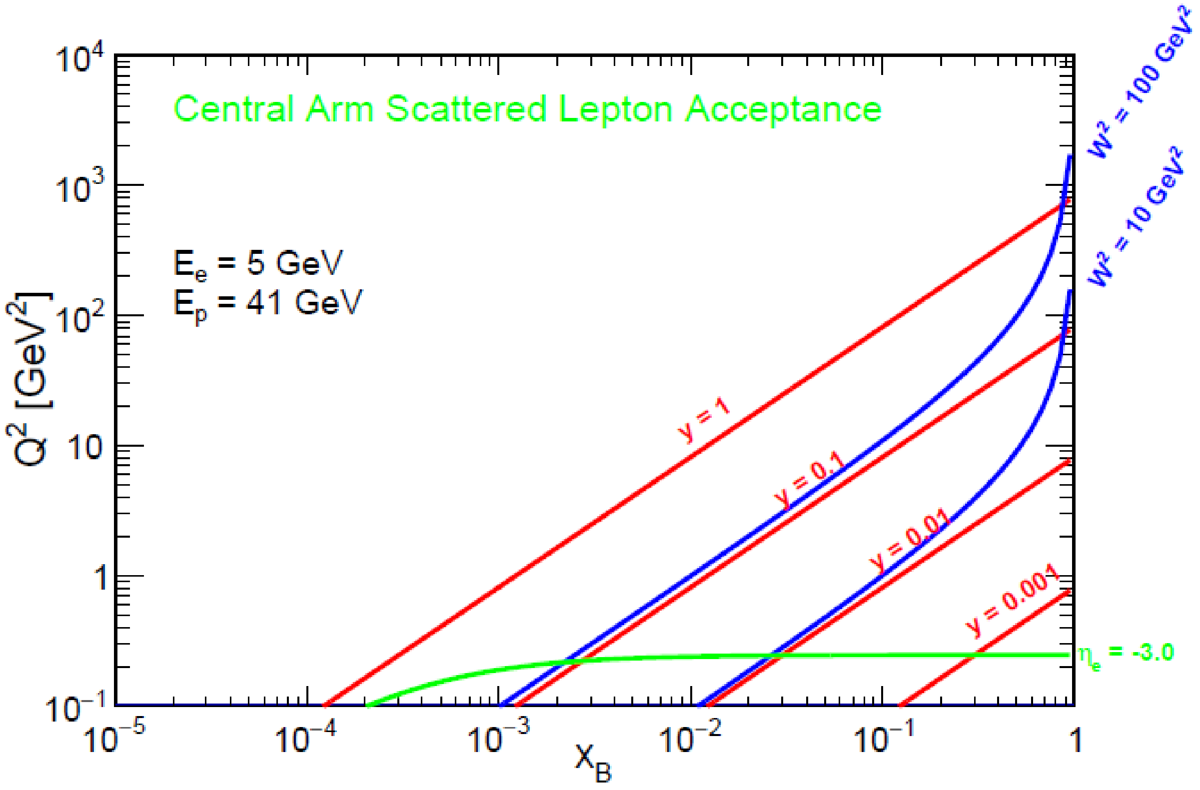
Electron Angular Acceptance

- For many EIC physics processes which have a requirement that $Q^2 > 1$ GeV^2, an angular acceptance of $\eta \gtrapprox -3.6$ will allow full coverage at the highest EIC beam energy setting. At lower energies, this same acceptance coverage would allow access to lower values of Q^2 (see next slide).
- Any processes which require $Q^2 < 1$ GeV^2 at the highest energy setting will need an extended acceptance below $\eta \approx -3.6$.
- For inclusive physics, coverage below $Q^2 = 1$ GeV^2 has strong motivations: to study the perturbative to non-perturbative transition; to give access to lowest possible x, which is well-aligned with the central EIC physics aims to study mass generation and dense systems of gluons; and to minimize the 'gap' in Q^2 coverage between the central detector and the far-backwards low-Q^2 tagger.



Electron Angular Acceptance



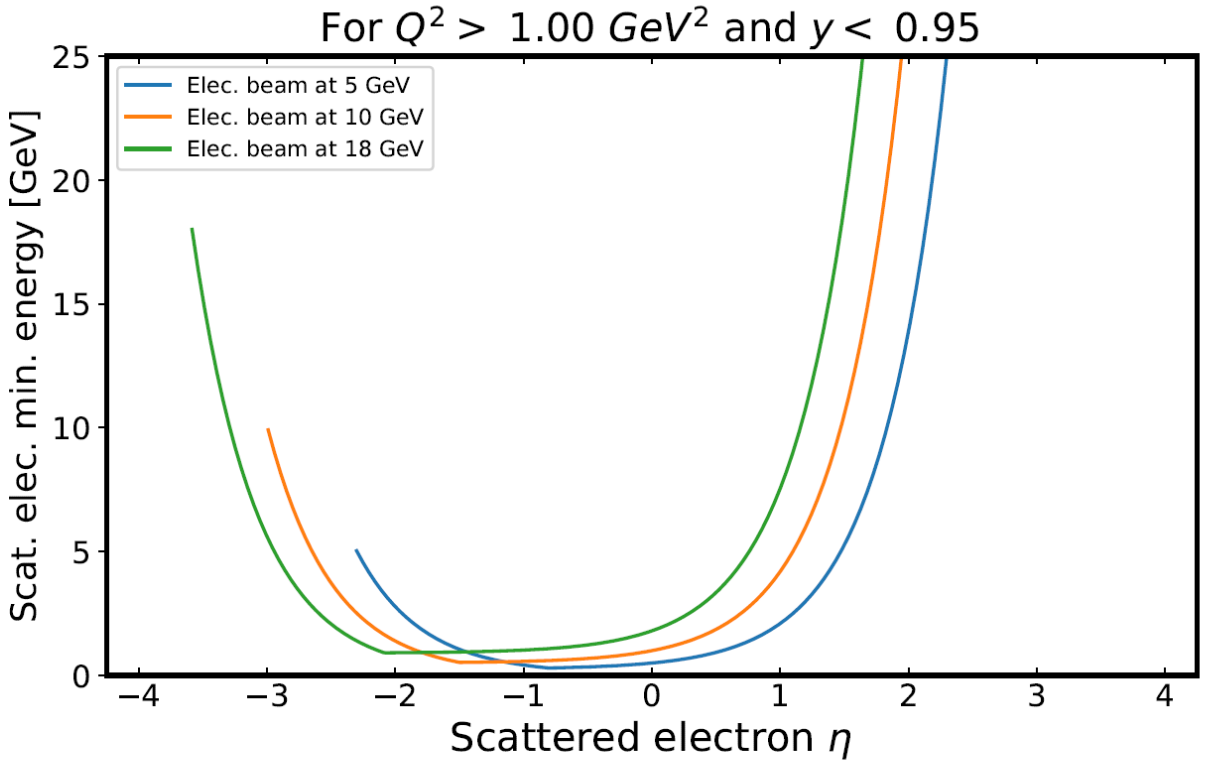


Electron Minimum momentum (energy)

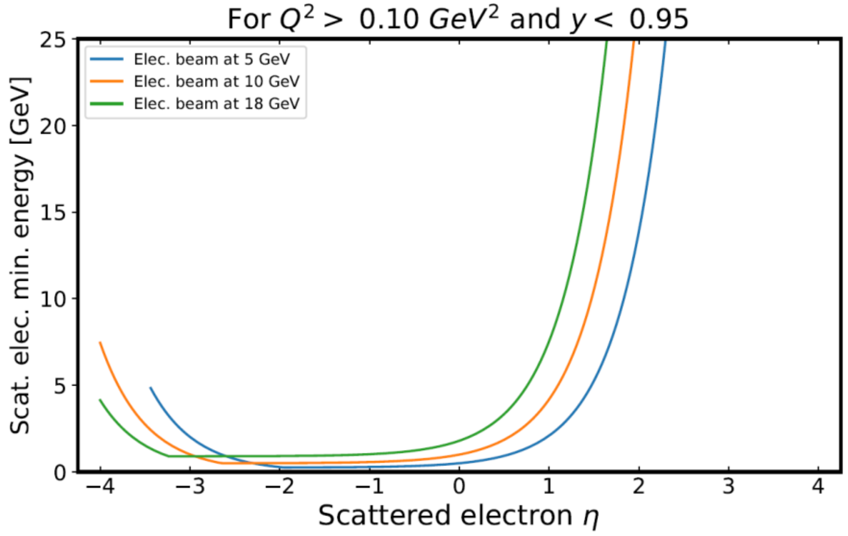
- For a fixed electron beam energy and scattered electron angle, Q^2 increases as the energy of the scattered electron increases, while y decreases.
- For all physics analyses, a cut of $y < 0.95$ will be applied. The minimum energy is also affected by the minimum Q^2 which needs to be measured. These two requirements place a minimum-energy threshold on the scattered electron energy, above which full acceptance is needed.

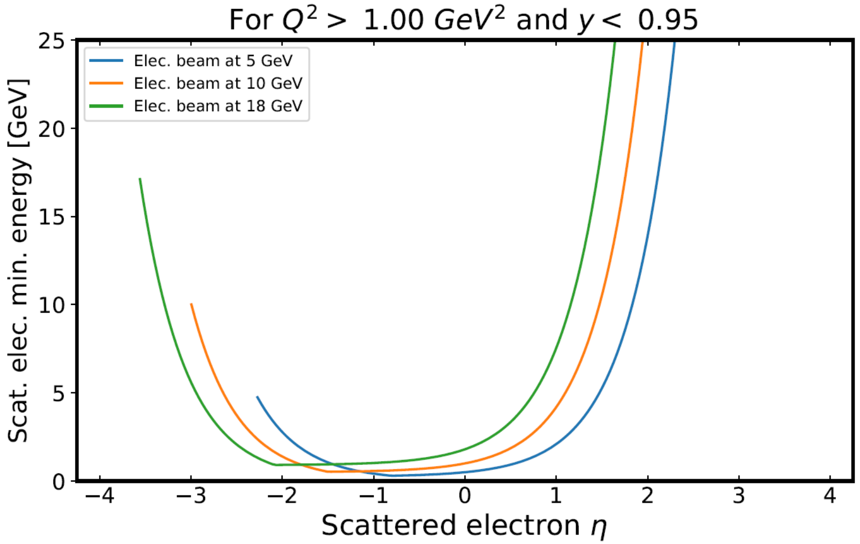
Electron Minimum momentum (energy)

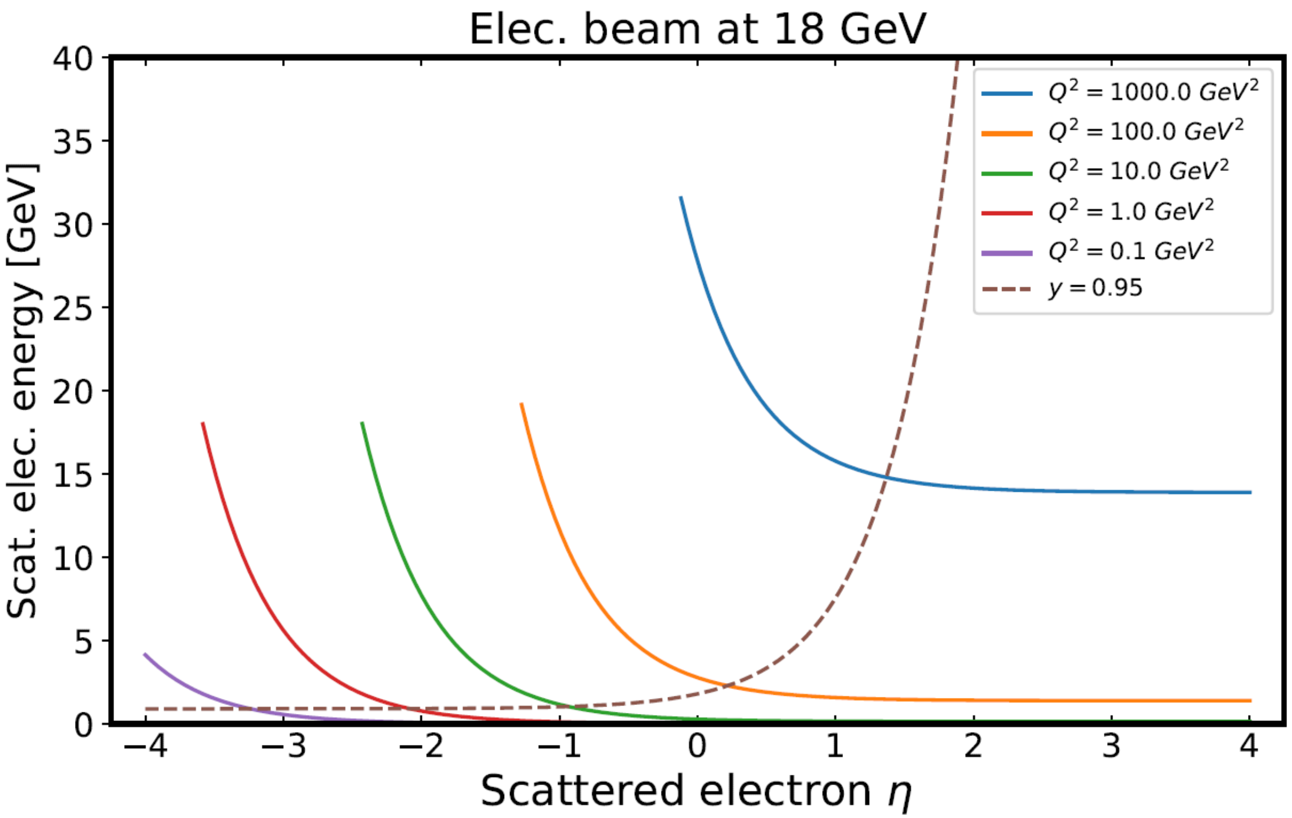
- Consider the case where the physics requires $Q^2 > 1$ GeV^2. The plot on the right shows as a function of η the minimum electron energy that satisfies both the $Q^2 > 1$ GeV^2 requirement and the $y < 0.95$ requirement.
- There are a few important features of this plot:
  1. The curves do not extend to the lowest possible values of pseudo-rapidities. This is because at the most negative values of η, the scattered electron can not be created at $Q^2 = 1$ GeV^2, only at lower values of Q^2.
  2. Starting at the most negative η value that is allowed, each minimum energy curve decreases towards more positive values of η. For this left part of the curve, the minimum energy is exactly at the $Q^2 = 1$ GeV^2 limit (while still satisfying the $y < 0.95$ requirement).
  3. Moving towards more positive values of η, each minimum energy curve reaches a global minimum value and then begins to grow. Once the curve begins to increase towards more positive values of η, the minimum energy of the scattered electron is at the $y = 0.95$ limit (while still satisfying the $Q^2 > 1$ GeV^2 requirement).



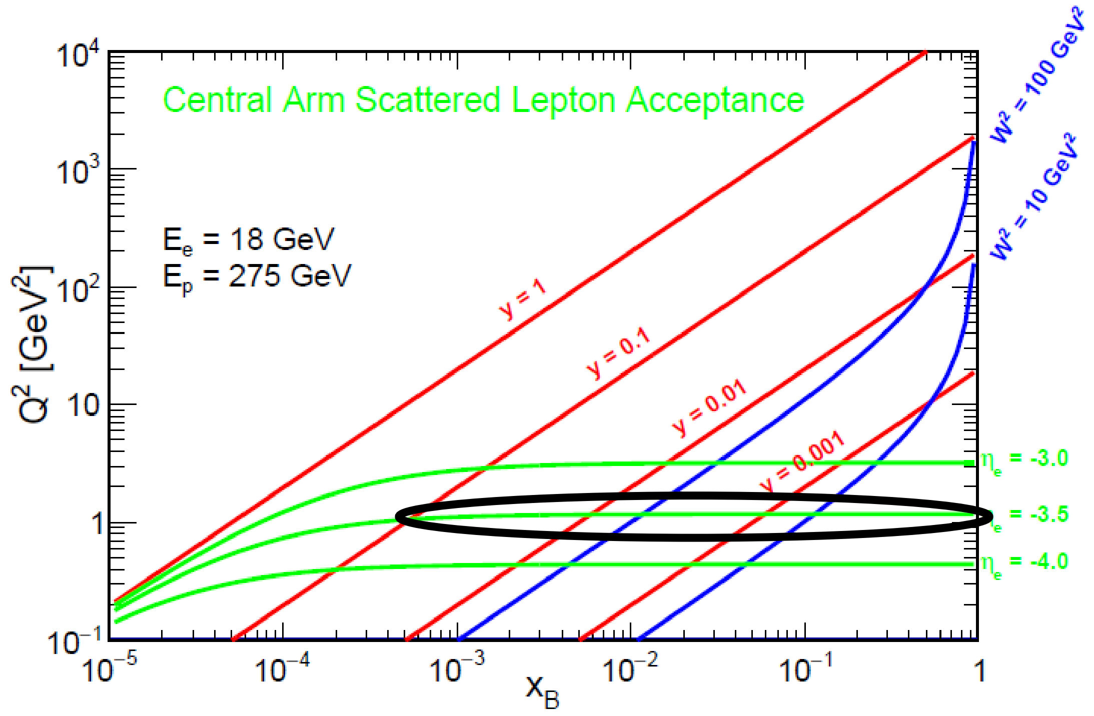
Scattered electron energy in backwards direction is quite large unless at very low Q^2

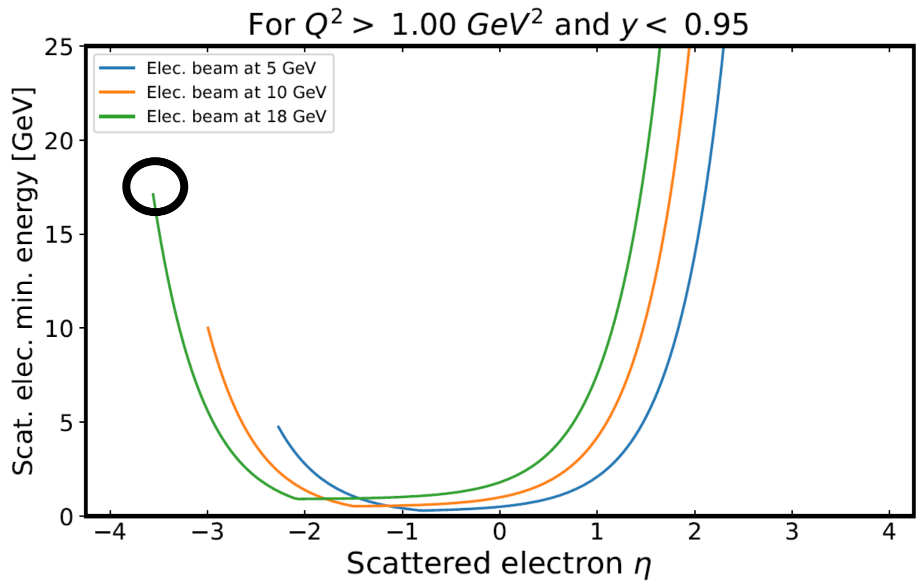


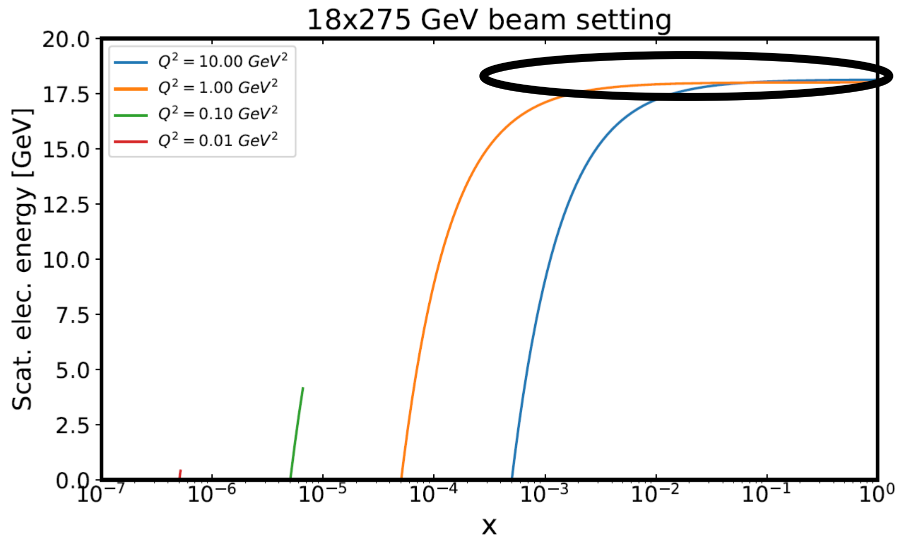




scattered electron energy and x_B



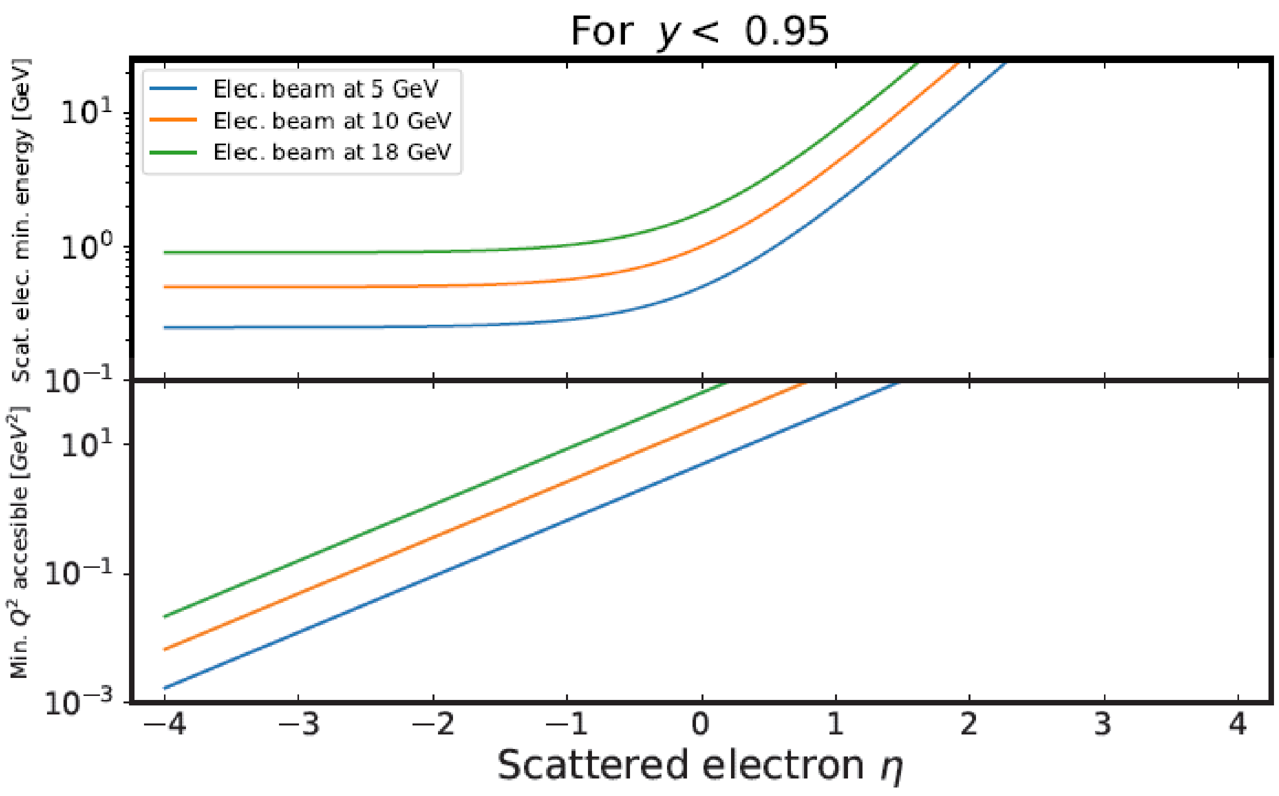




- For $Q^2 = 1$ GeV^2, the scattered electron energy is at almost a fixed energy for a large range of x. Reconstruction of x using the scattered electron is impossible here.
- Note how more central rapidities correspond to lower x at a fixed Q^2.

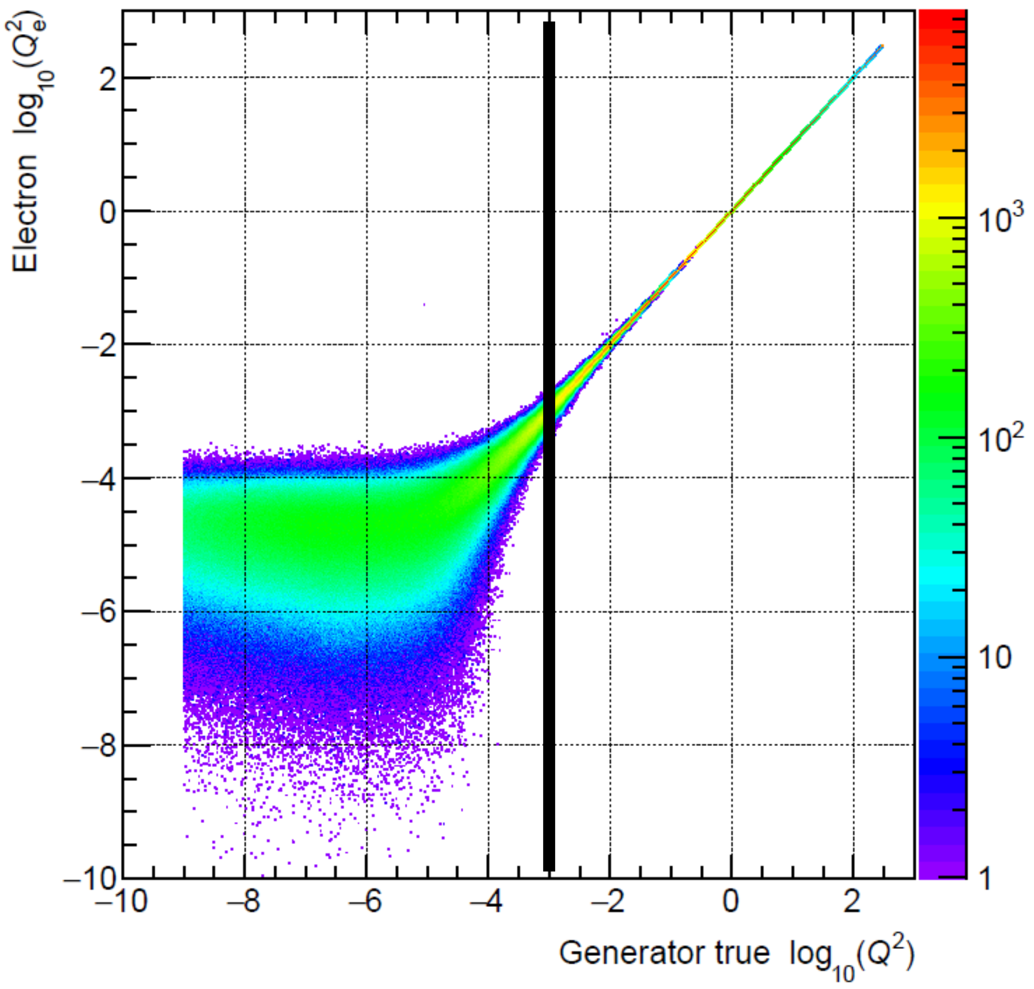
Electrons at low Q^2 in the main detector

- By applying the $y < 0.95$ requirement only, we can consider the minimum possible scattered electron energy that would need to be measured. This is shown in the top panel of the right plot.
- The bottom panel then shows the Q^2 that is measured at that scattered electron energy. Note that since this minimum Q^2 is at the $y = 0.95$ limit, the measurement will be also be at the lowest x accessible.
- For example, in the case of a 5 GeV electron beam, being able to identify and reconstruct 250 MeV electrons at $\eta = -4$ would allow measurements down to $Q^2 \approx 10^{-3}$.



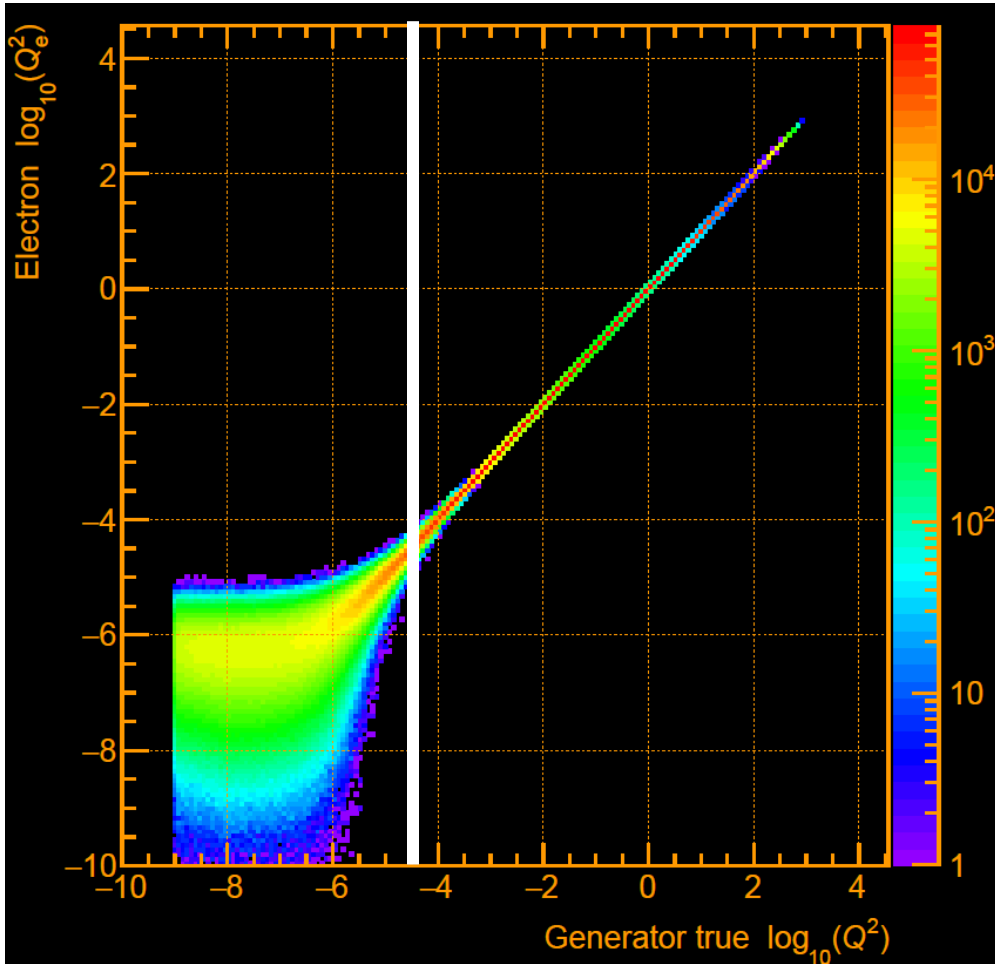
Beam divergence effects at low Q^2

18x275 GeV IP6 high-divergence setting



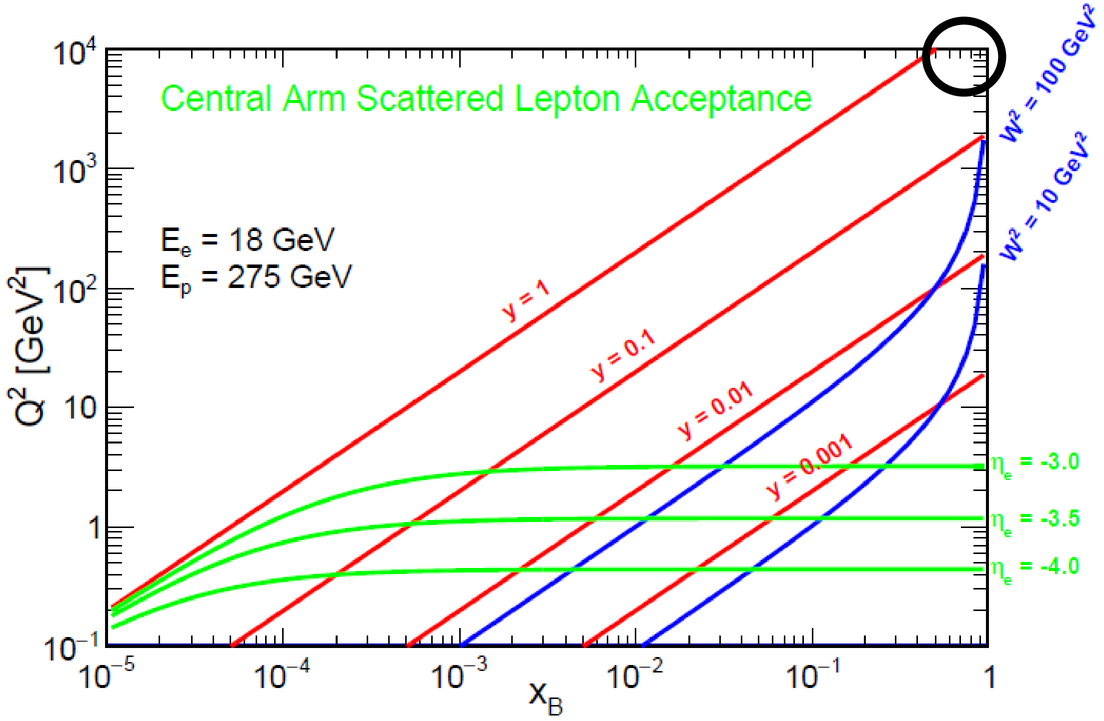
YR figure 11.121

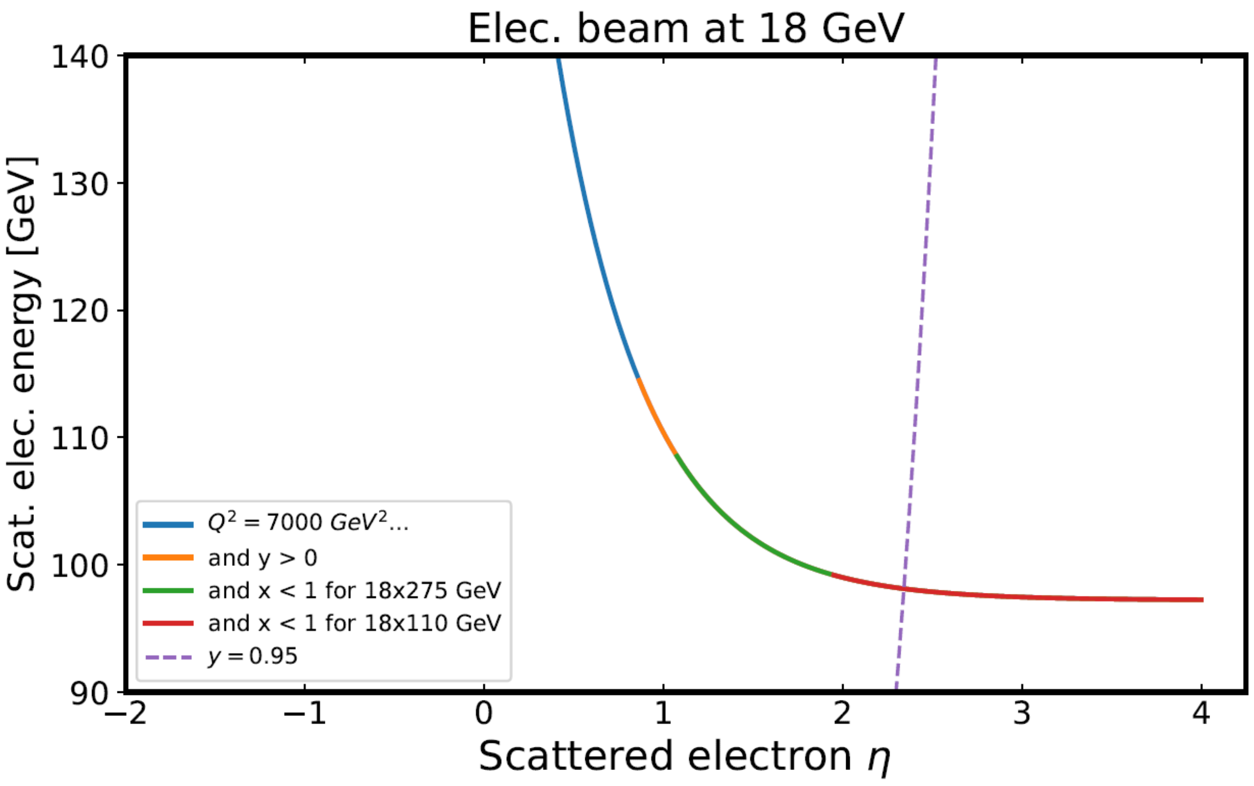
5x41 GeV IP6 high-divergence setting



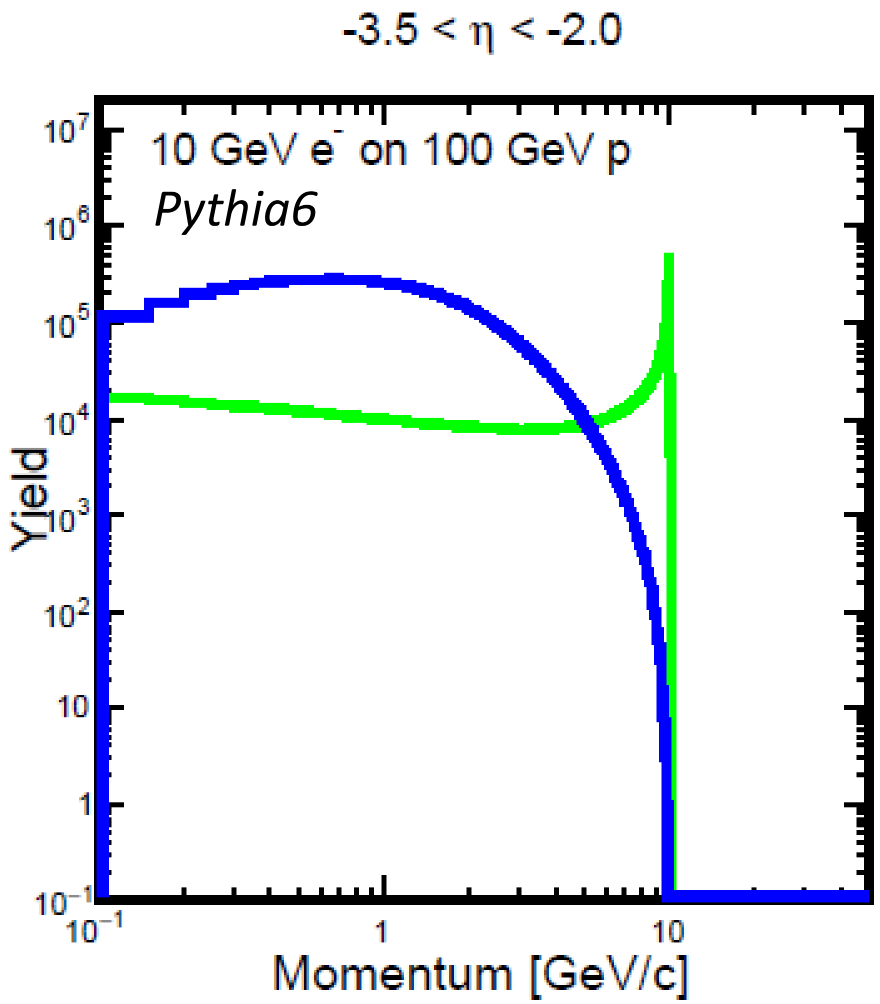
Plot courtesy of Jaroslav Adam

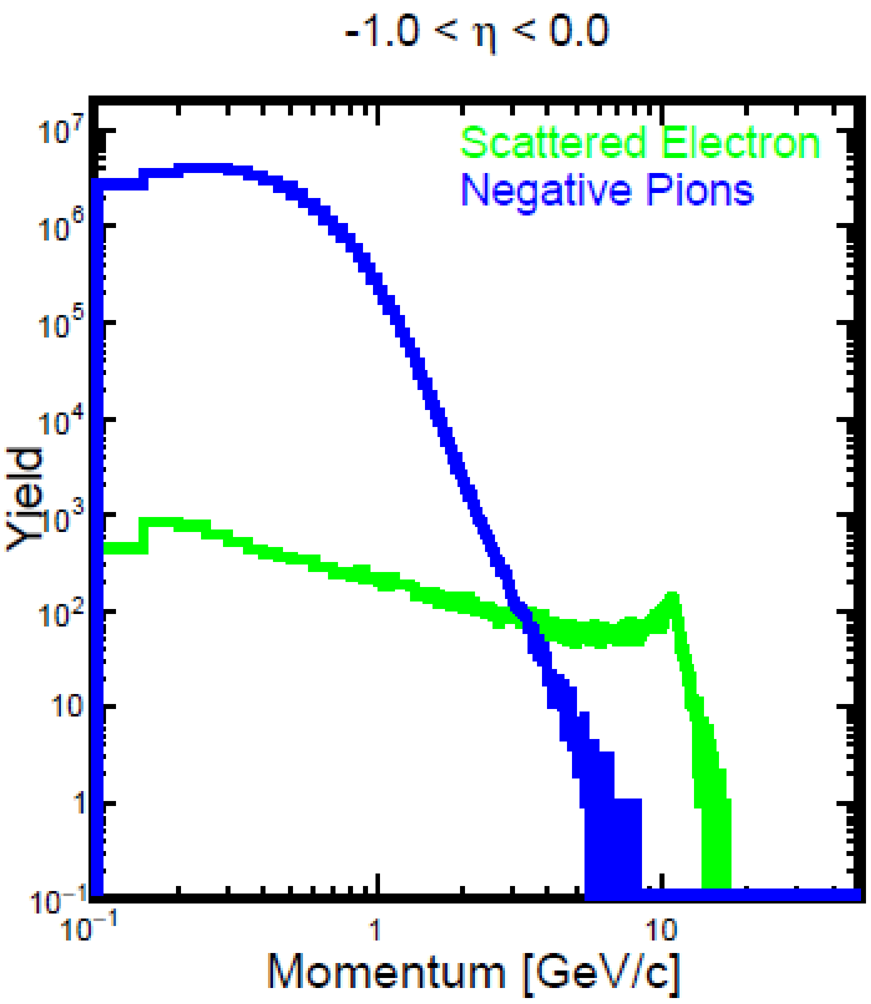
Electrons at very high Q^2



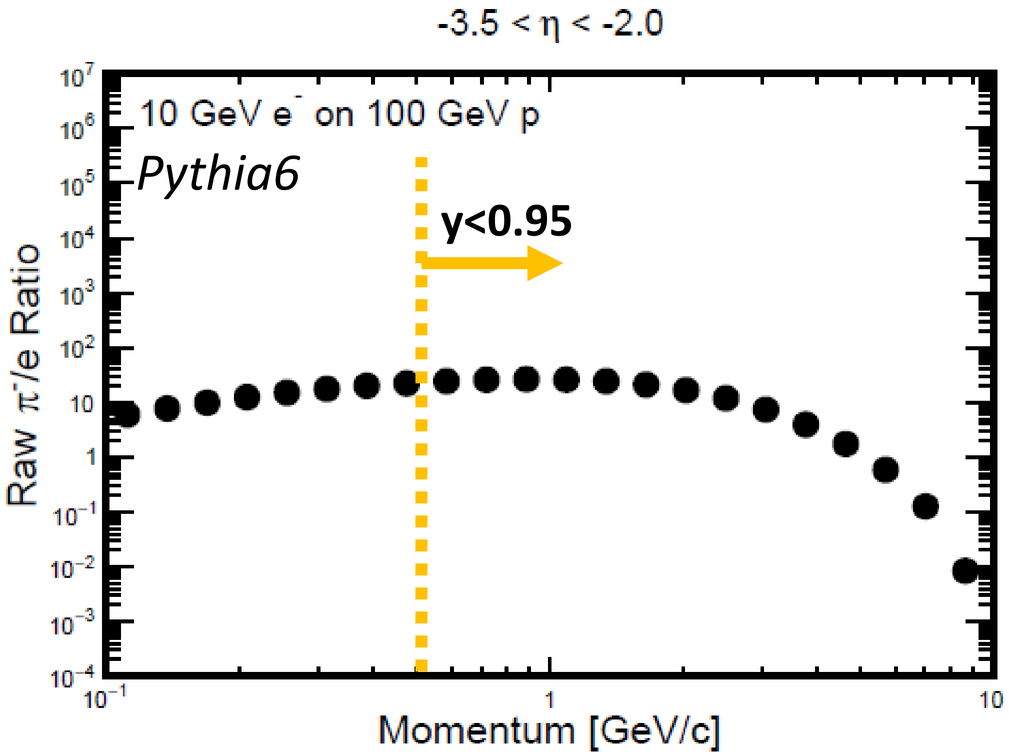


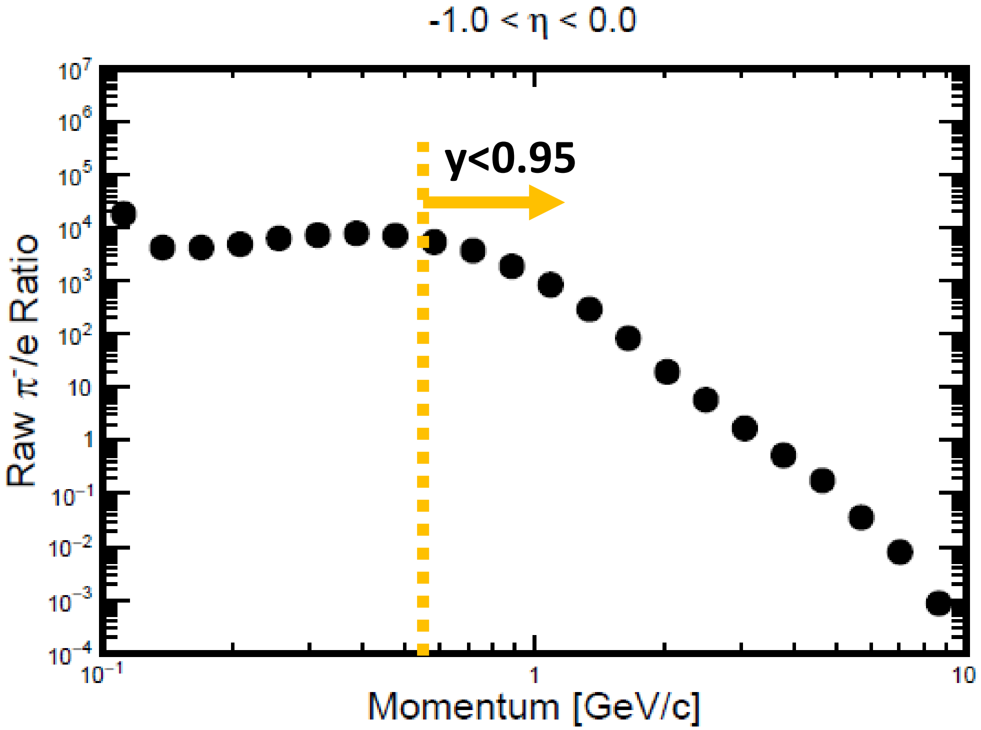
Electron purity





Electron purity

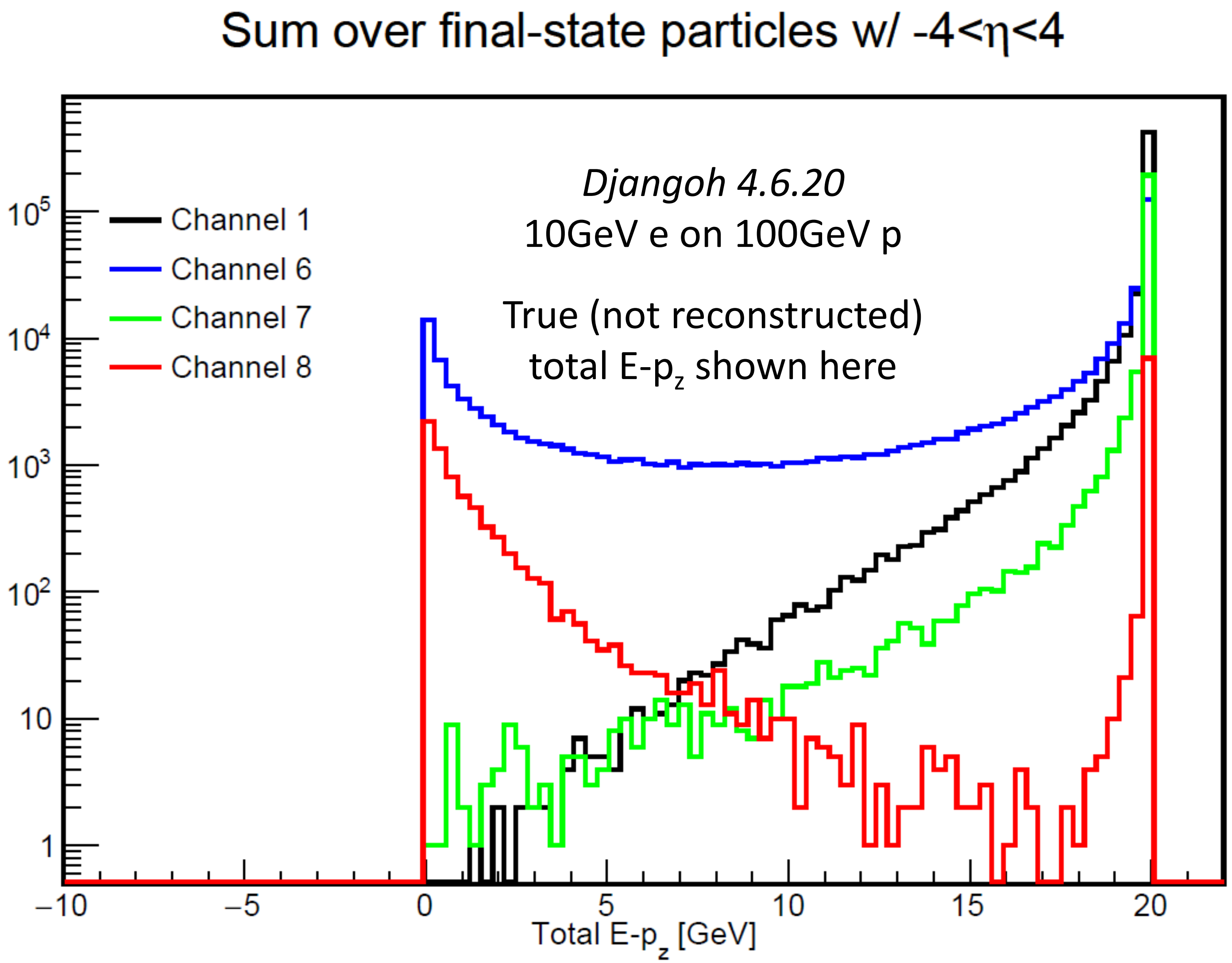




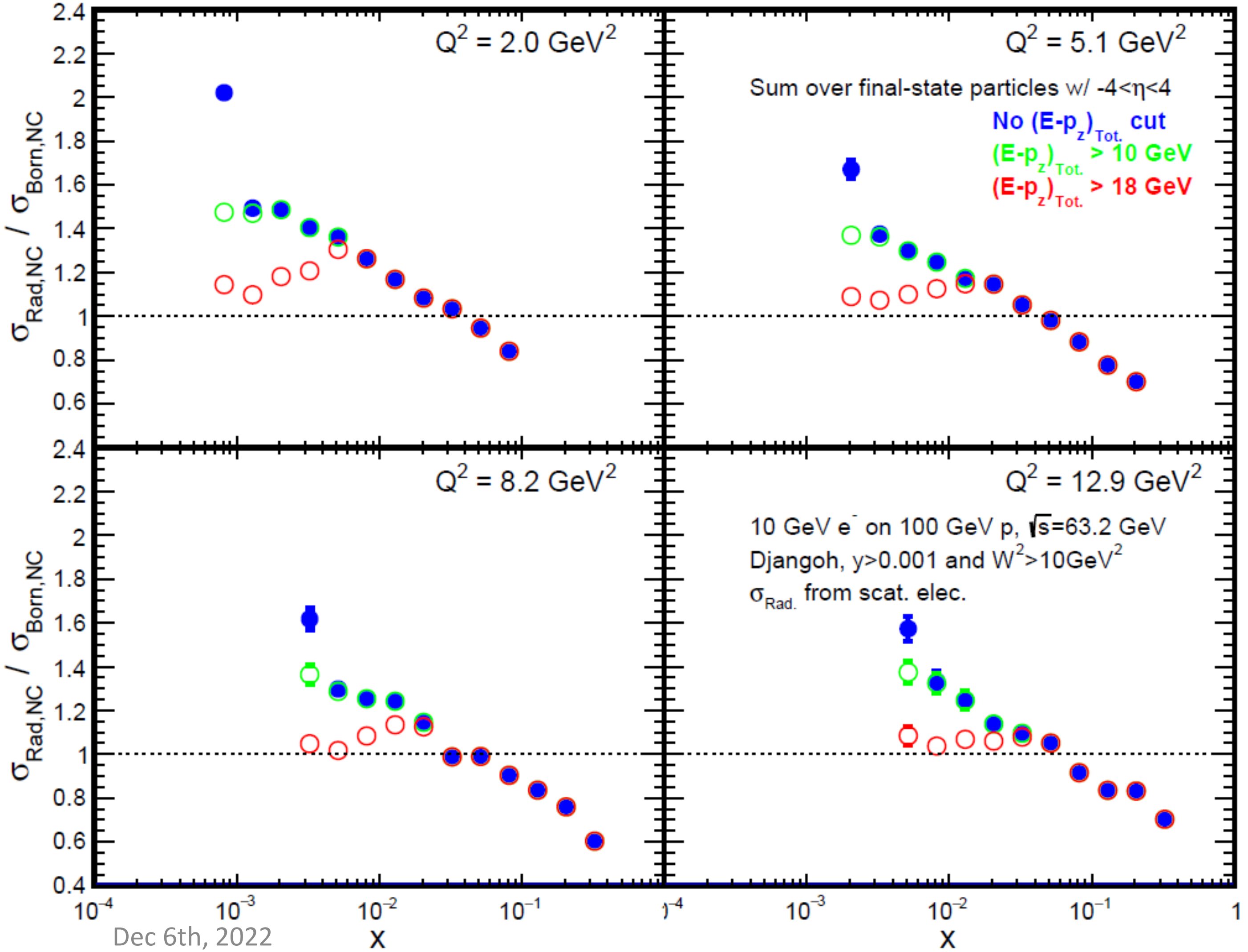
Importance of total E-p_z cut for reducing radiative correction

- Channel 1: No radiation – Born term, virtual corrections, and integration of soft photon radiation
- Channel 6 – ISR radiation
- Channel 7 – FSR radiation
- Channel 8 – ISR radiation at low Q^2 (sometimes referred to as Compton)

If all particles are detected, the total E-p_z will be twice the electron beam energy (20 GeV here).



Importance of total E-p_z cut for reducing radiative correction



- The radiative correction at low x and low Q^2 can be very large and 'positive' when reconstructing using the scattered electron. It can also be large and 'negative' at higher x (low y), but here methods other than the scattered electron method are generally relied upon.
- Limiting the size of the correction is necessary for high precision measurements.
- A cut on the total E-p_z can reduce the correction factor significantly.
- Of course, we should not cut into the main peak of the total E-p_z distribution, only in the tail. **So, the resolution on the total E-pz distribution is a very important consideration for EIC measurements.**

Inclusive PWG for *EPIC* (Detector 1)

- **Conveners:**
  - Claire Gwenlan (claire.gwenlan@physics.ox.ac.uk)
  - Tyler Kutz (tkutz@mit.edu)
  - Paul Newman (paul.newman@cern.ch)
  - Barak Schmookler (baraks@ucr.edu)

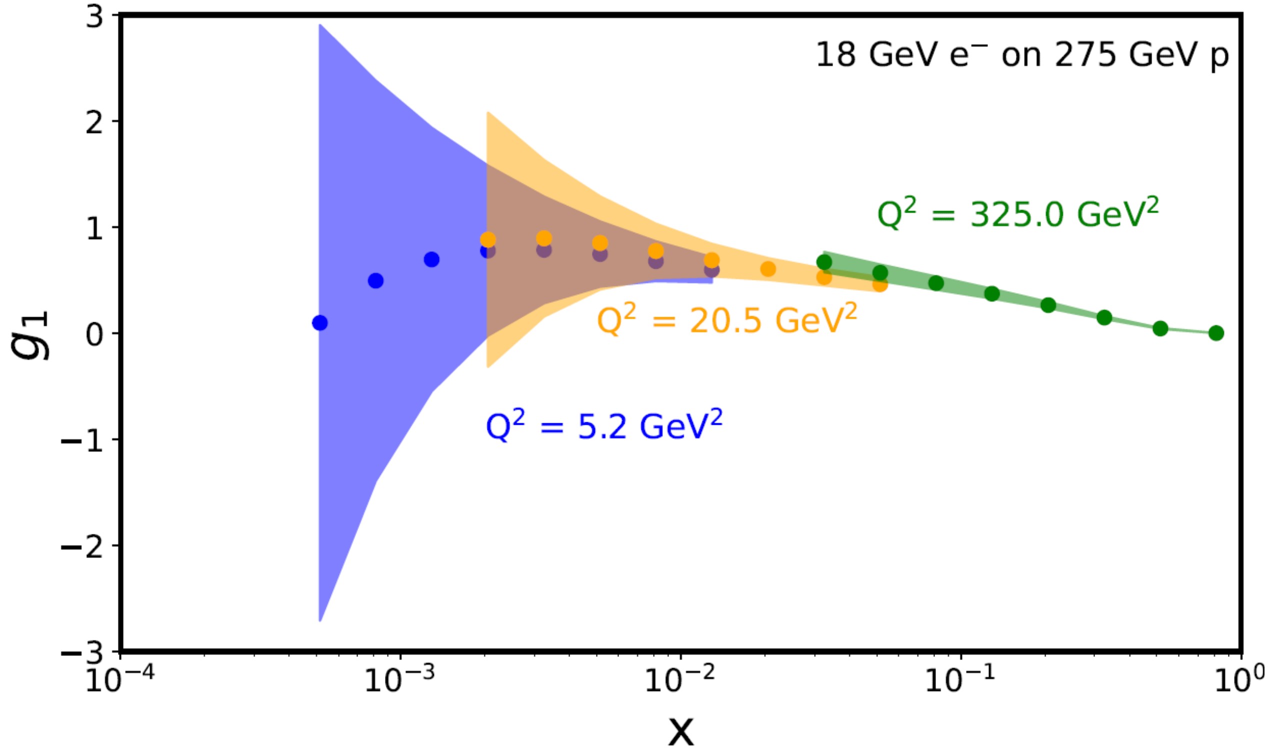
- **Meetings:** (INDICO) Mondays @ 12:00pm Eastern Time

Summary

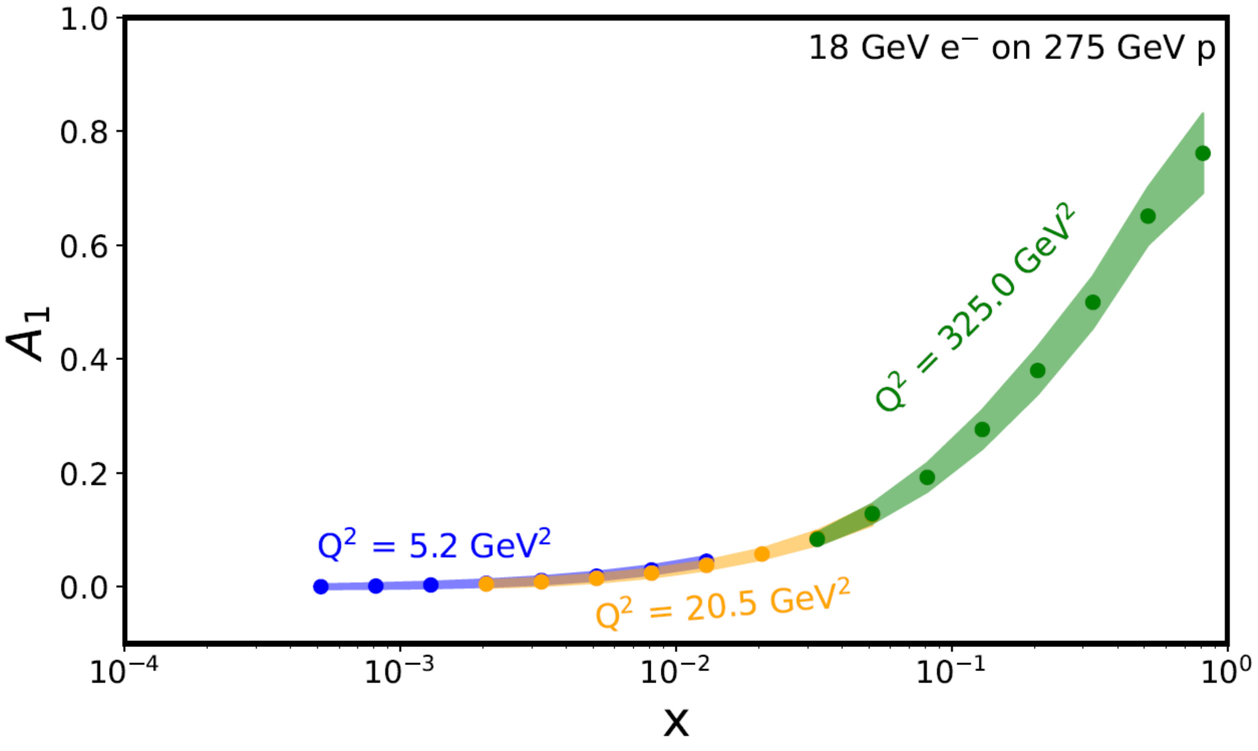
- Key inclusive measurements are the unpolarized nuclear cross section and double-spin asymmetry.
- These measurements will benefit from the high luminosity, the adjustable center-of-mass energy, and the variety of beam ions available at the EIC.
- For NC inclusive measurements, identification and reconstruction of the scattered electron is most important. (For CC measurements, the hadronic final state will be used.)
- Keeping pion contamination and radiative corrections small will require very good total $E\text{-}p_z$ reconstruction.

BACKUP

g_1, A_1



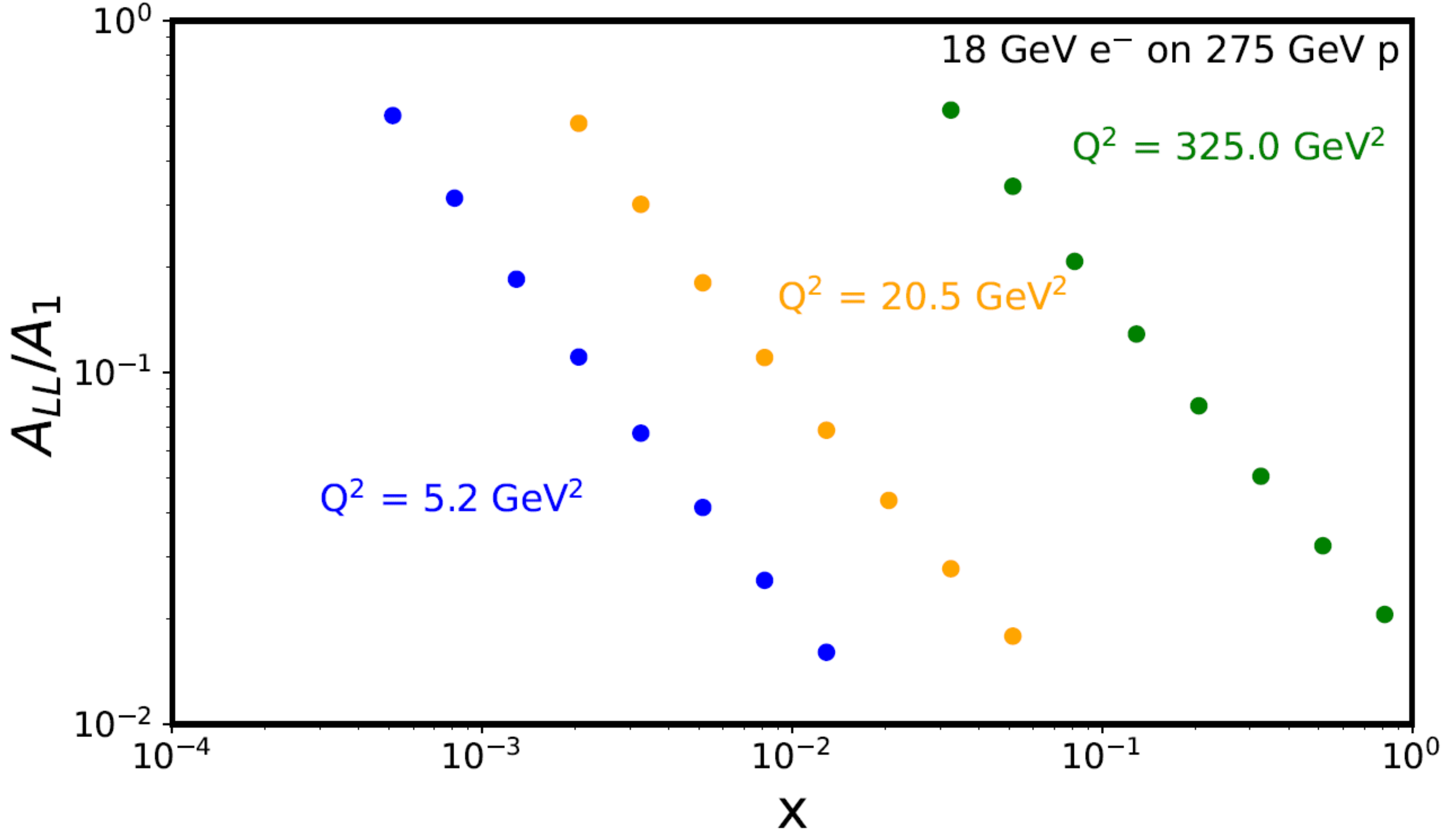
18 GeV e⁻ on 275 GeV p
Q² = 325.0 GeV²
Q² = 20.5 GeV²
Q² = 5.2 GeV²
g₁
x



18 GeV e⁻ on 275 GeV p
Q² = 325.0 GeV²
Q² = 5.2 GeV²
Q² = 20.5 GeV²
A₁
x

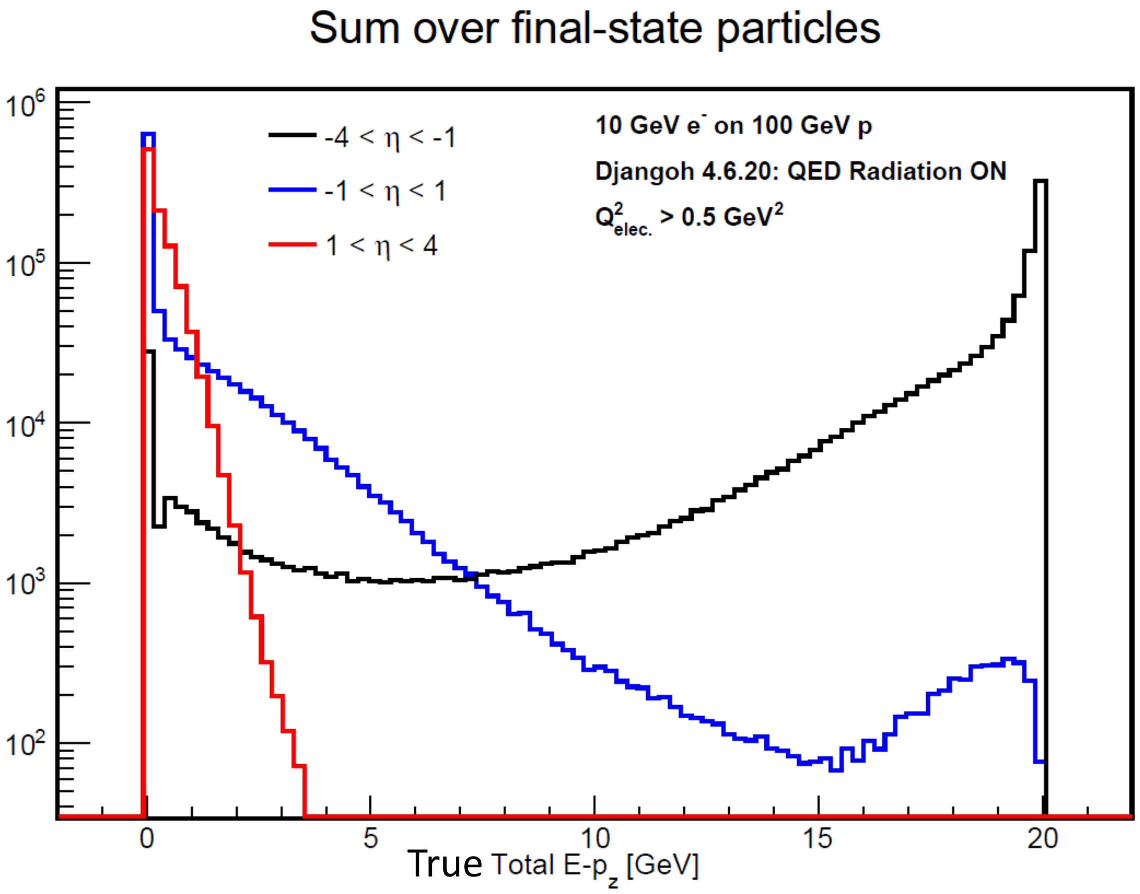
DSSV14

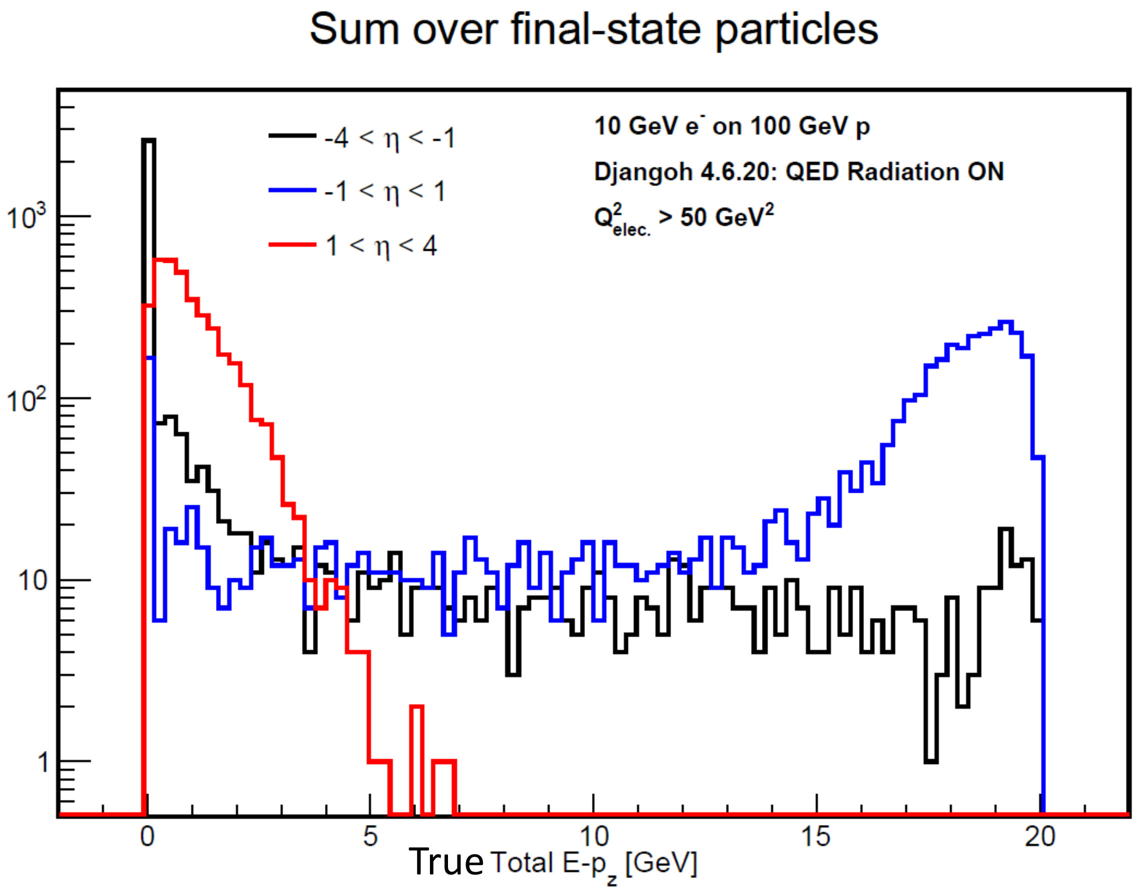
Depolarization factor



DSSV14

Where in the detector does most of the total E-p_z go?





Distribution of the total E-p_z in the detector depends strongly on the scattered electron kinematics.

Fast simulation detector parameterization

η range	Tracker σ_p/p [%]	EmCal σ_E/E [%]	HCal σ_E/E [%]	σ_θ [Rad]	σ_ϕ [Rad]
-4.0 – -2.0	$0.1 \cdot p \bigoplus 0.5$	$2/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-2.0 – -1.0	$0.05 \cdot p \bigoplus 0.5$	$7/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-1.0 – +1.0	$0.05 \cdot p \bigoplus 0.5$	$12/\sqrt{E} \bigoplus 1.0$	$85/\sqrt{E} \bigoplus 7.0$	$0.01/\left(p \cdot \sqrt{\sin\theta}\right)$	0.01
+1.0 – +2.5	$0.05 \cdot p \bigoplus 1.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
+2.5 – +4.0	$0.1 \cdot p \bigoplus 2.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		

The above is based on the EIC Yellow Report detector matrix, with a few modifications:

1. Extend acceptance from [-3.5,3.5] to [-4,4]
2. Added non-zero angular resolutions (important for realistic scattered electron Q^2 resolution)
3. Added a barrel HCal (based on CMS detector, I think)
4. Added 1% constant terms to all the EmCal resolutions
5. For all particles (both charged and neutral, added a minimum P_t acceptance of $P_t > 0.25$ GeV/c.

Fast simulation for reconstruction of total E-p_z

η range	Tracker σ_p/p [%]	EmCal σ_E/E [%]	HCal σ_E/E [%]	σ_θ [Rad]	σ_ϕ [Rad]
-4.0 – -2.0	$0.1 \cdot p \bigoplus 0.5$	$2/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-2.0 – -1.0	$0.05 \cdot p \bigoplus 0.5$	$7/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-1.0 – +1.0	$0.05 \cdot p \bigoplus 0.5$	$12/\sqrt{E} \bigoplus 1.0$	$85/\sqrt{E} \bigoplus 7.0$	$0.01/\left(p \cdot \sqrt{\sin\theta}\right)$	0.01
+1.0 – +2.5	$0.05 \cdot p \bigoplus 1.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
+2.5 – +4.0	$0.1 \cdot p \bigoplus 2.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		

Charged particles
Photons
Neutral hadrons

General comments:

1. We only study events where the scattered electron is reconstructed.
2. We use the tracker to reconstruct the momentum (energy) of the scattered electron for this study.
3. When the radiated photon is within the detector acceptance, we assume it is separated from the scattered electron and can be treated as any other photon.
4. As mentioned above, for all particles, we use a minimum P_t acceptance of P_t > 0.25 GeV/c.

Fast simulation for reconstruction of total E-p_z

η range	Tracker σ_p/p [%]	EmCal σ_E/E [%]	HCal σ_E/E [%]	σ_θ [Rad]	σ_ϕ [Rad]
-4.0 – -2.0	$0.1 \cdot p \bigoplus 0.5$	$2/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-2.0 – -1.0	$0.05 \cdot p \bigoplus 0.5$	$7/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-1.0 – +1.0	$0.05 \cdot p \bigoplus 0.5$	$12/\sqrt{E} \bigoplus 1.0$	$85/\sqrt{E} \bigoplus 7.0$	$0.01/\left(p \cdot \sqrt{\sin\theta}\right)$	0.01
+1.0 – +2.5	$0.05 \cdot p \bigoplus 1.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
+2.5 – +4.0	$0.1 \cdot p \bigoplus 2.0$	$12/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		

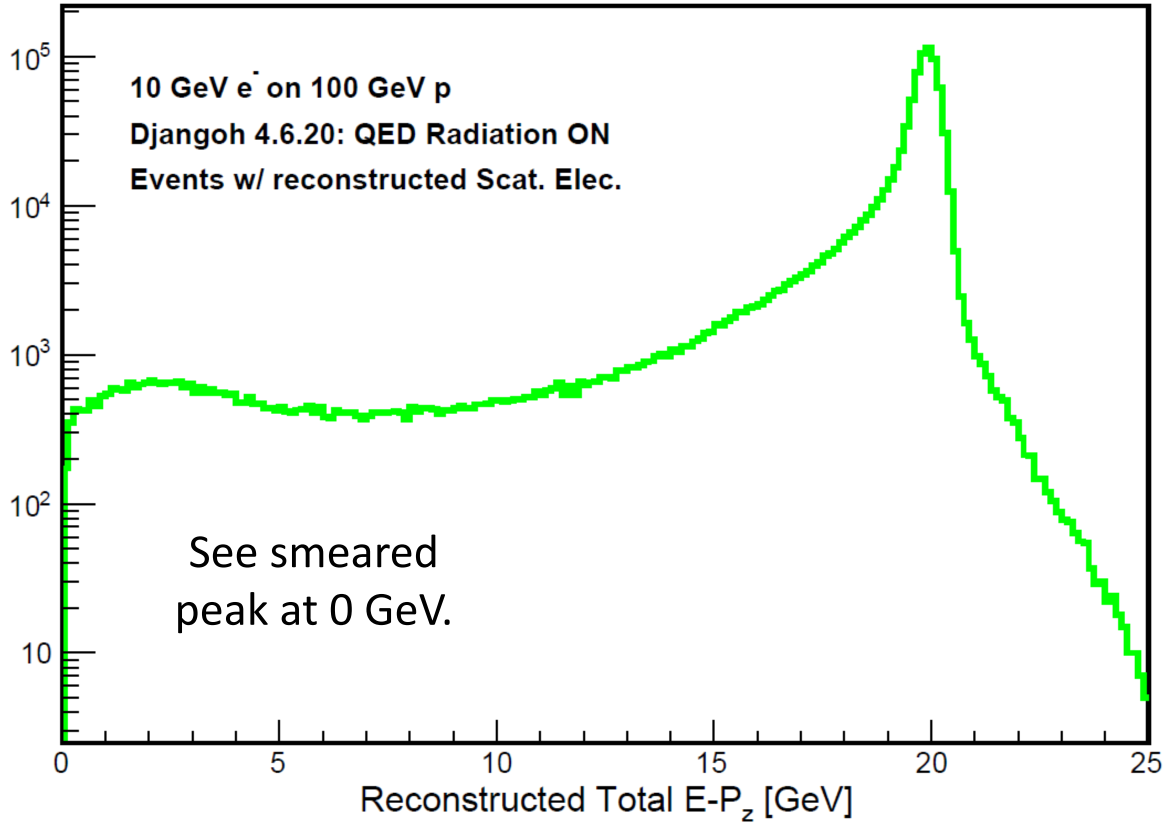
Charged particles
Photons
Neutral hadrons

We studied three different detector settings within the above detector configuration:

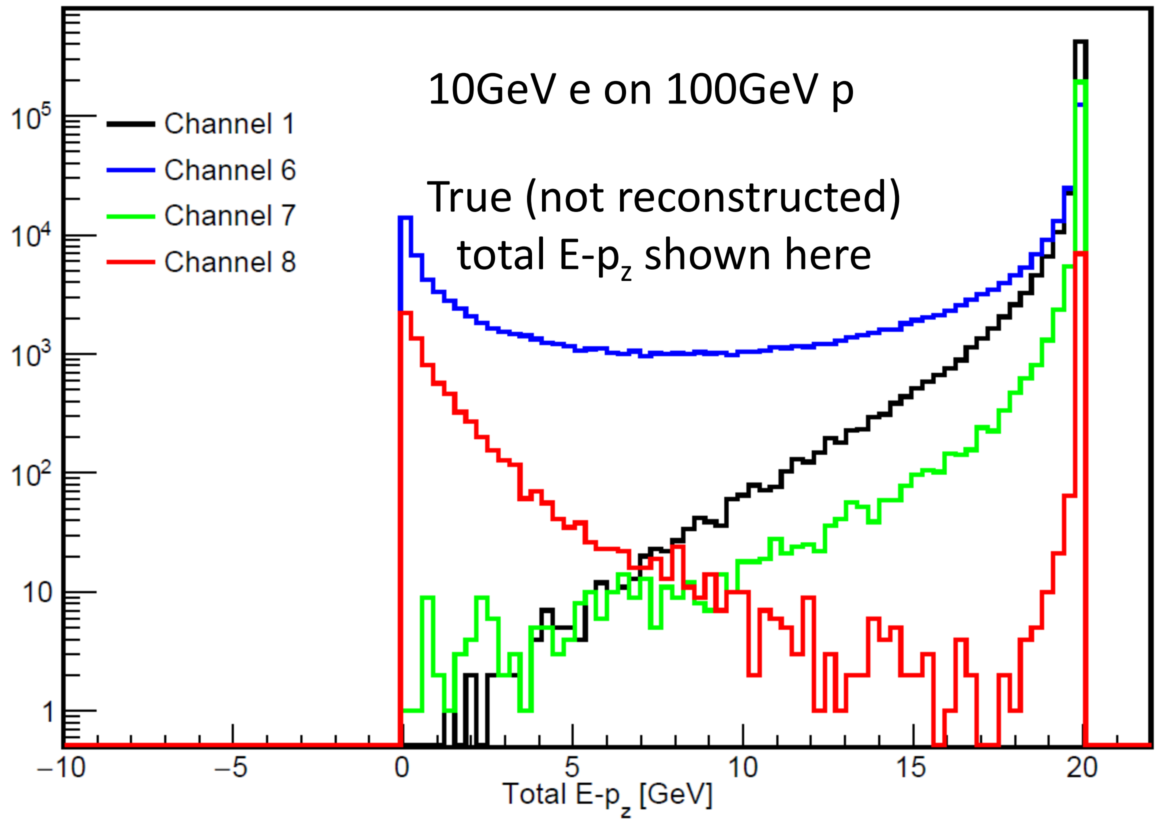
1. Perfect PID for all reconstructed particles.
2. No hadronic PID: for charged particles other than electrons and positrons, reconstruct particle using charged pion mass; for neutral hadrons, reconstruct using zero mass.
3. No hadronic PID and no backwards HCal: same as setting 2, with HCal from -4 < eta < -1 removed.

Reconstruction results – QED radiation ON

Perfect PID

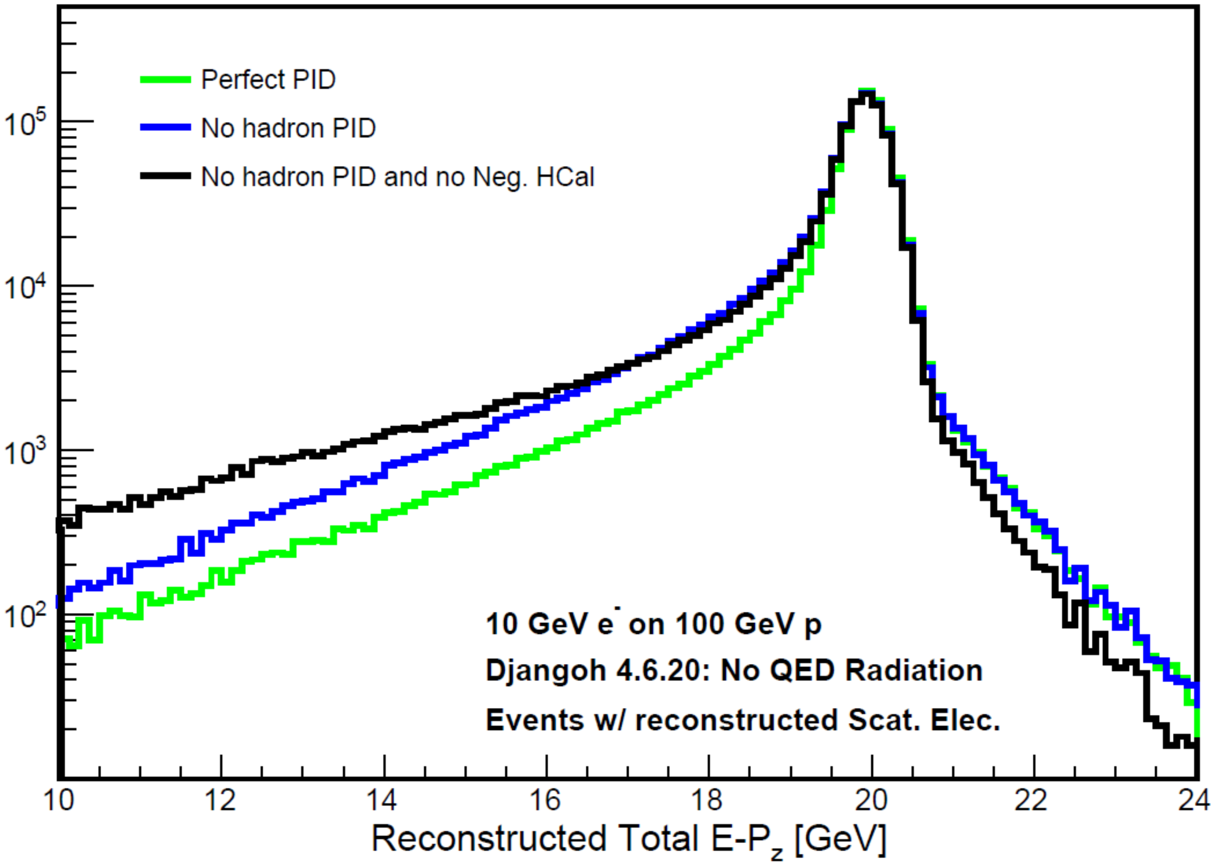


Sum over final-state particles w/ -4<η<4



Reconstruction results – all

No QED effects included



QED effects turned ON