Inclusive processes – IR2 Meeting

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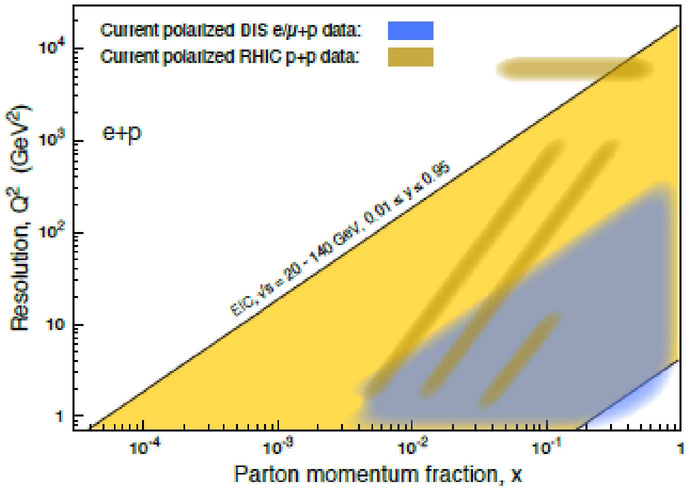
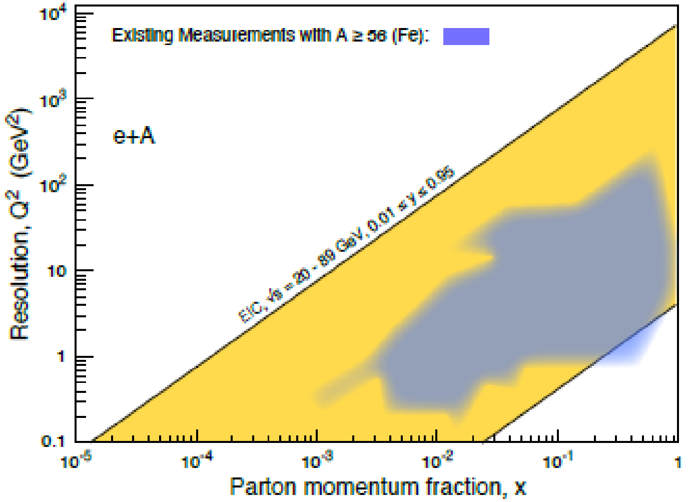
Inclusive scattering at the EIC

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, ^{3}He	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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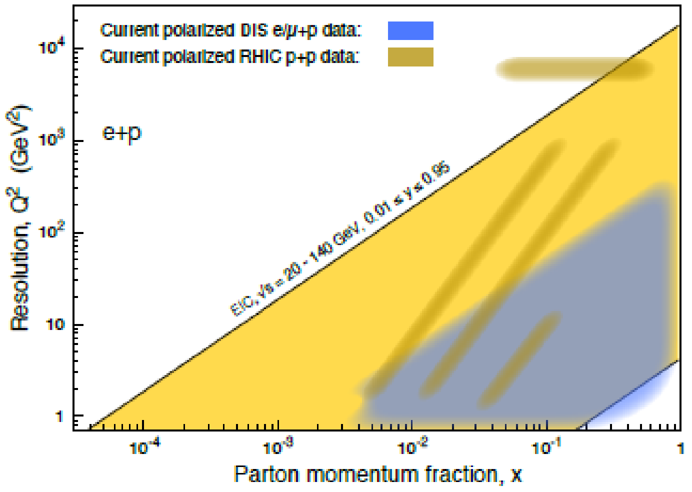
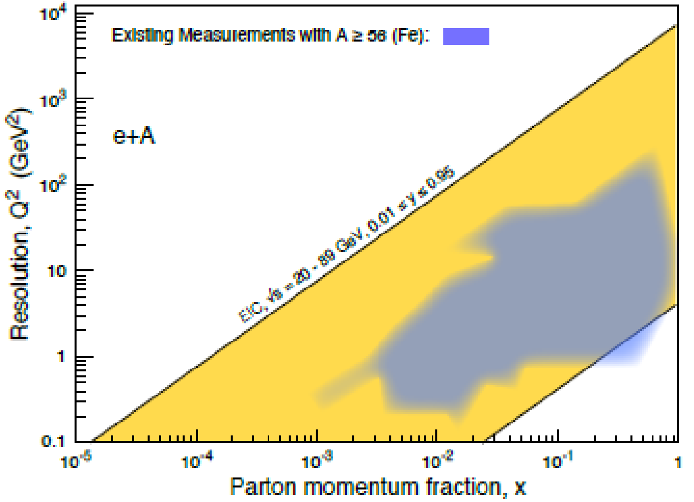
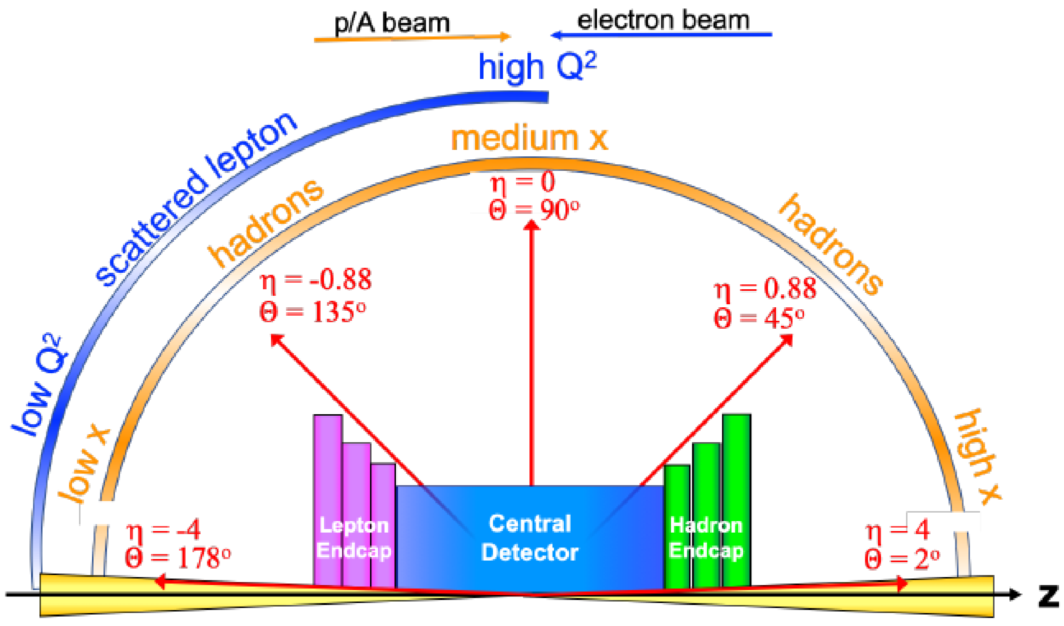
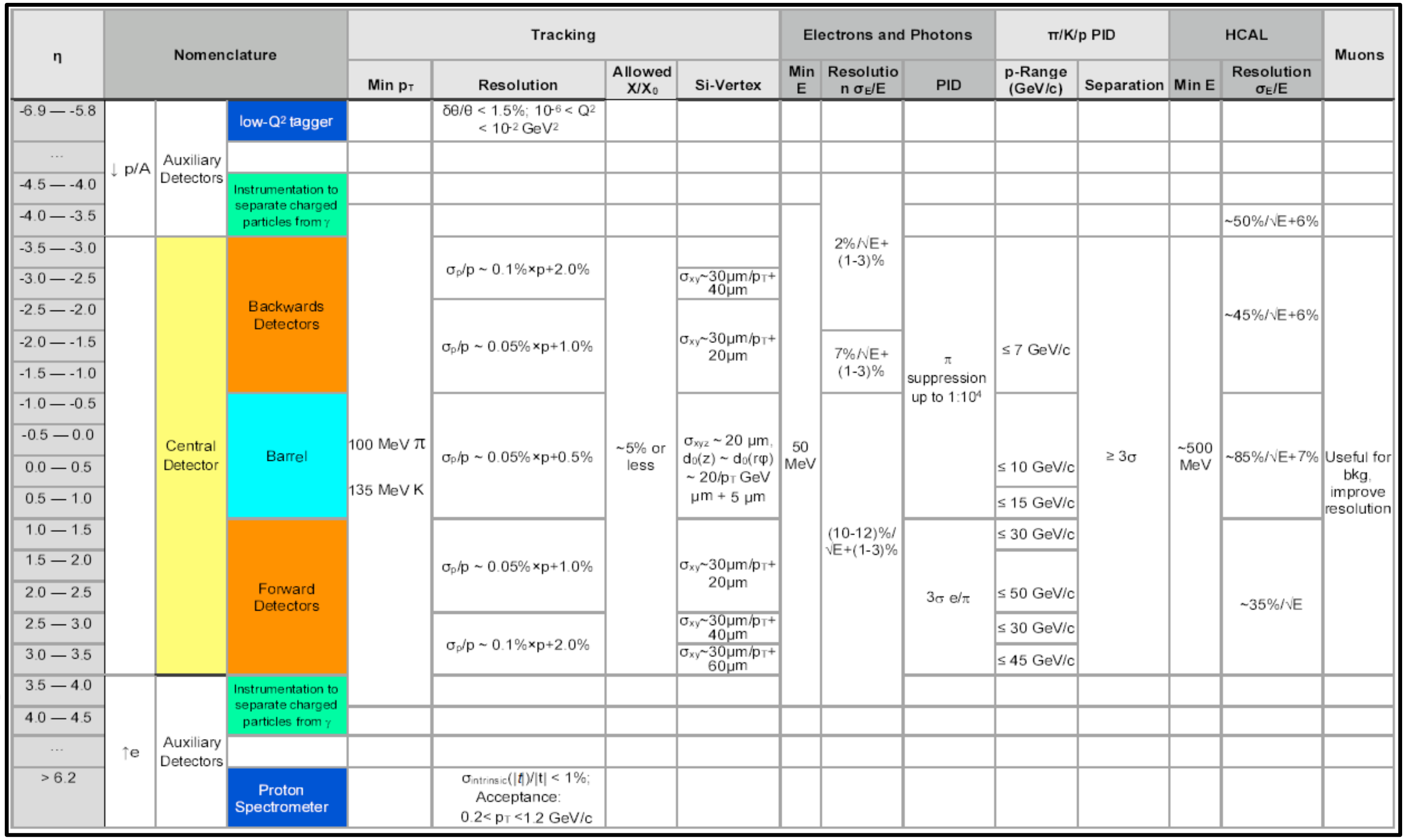




Detector requirements and associated challenges



Detector requirements from EIC Yellow report

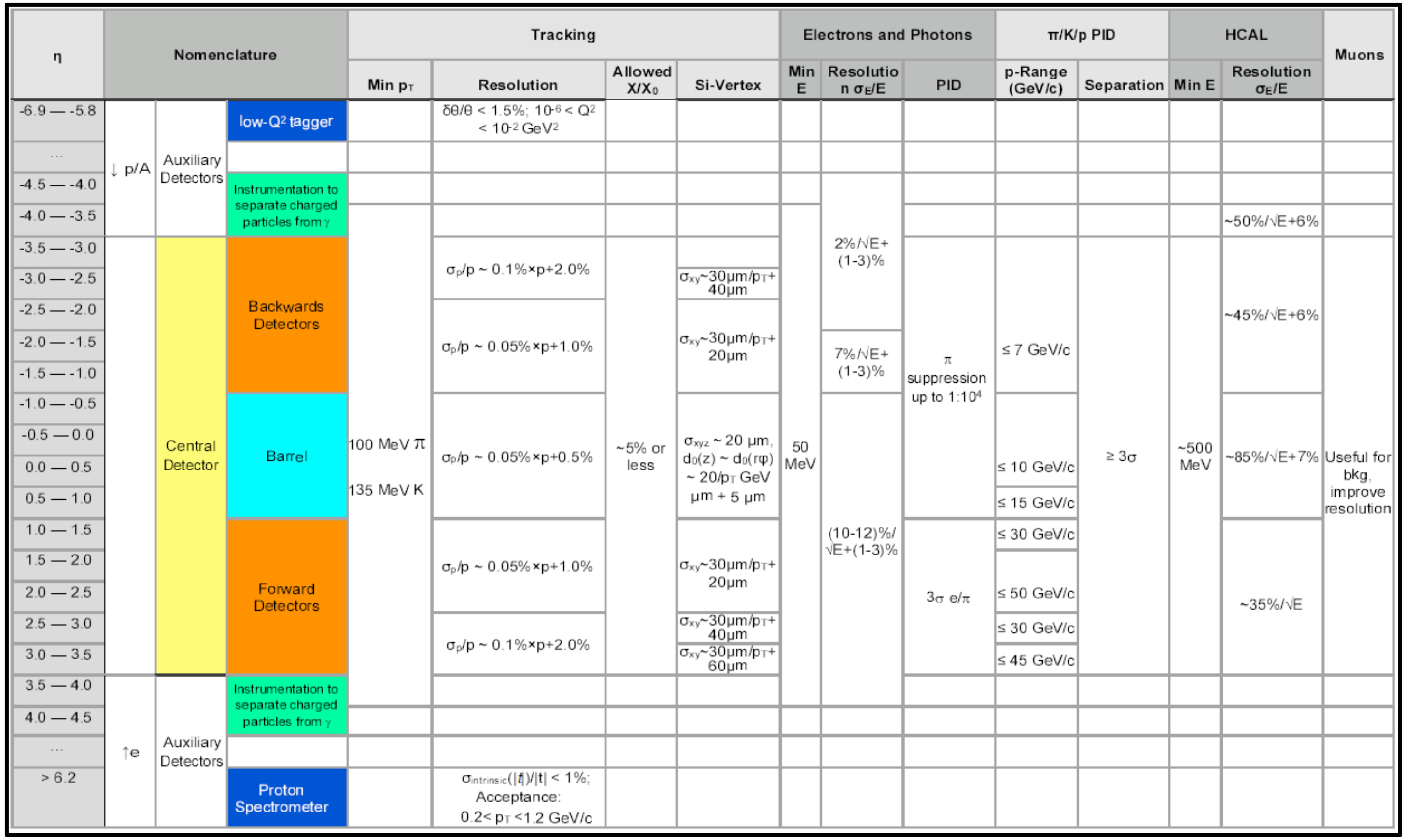


η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q² tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV²										
...															
-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						$\sim 50\%/\sqrt{E}+6\%$	
-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 1:10⁴	≤ 7 GeV/c	≥ 3σ	~500 MeV	$\sim 45\%/\sqrt{E}+6\%$	Useful for bkg, improve resolution
-3.0 — -2.5							$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$								
-2.5 — -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 — -1.5									$7\%/\sqrt{E}+(1\text{-}3)\%$						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		$\sigma_{xyz} \sim 20\ \mu m$, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV μm + 5 μm		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			$\sim 85\%/\sqrt{E}+7\%$	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p+1.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 20\mu m$			3σ e/π	≤ 30 GeV/c			$\sim 35\%/\sqrt{E}$	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p+2.0\%$		$\sigma_{xy} \sim 30\mu m/p_T + 40\mu m$				≤ 30 GeV/c				
3.0 — 3.5							$\sigma_{xy} \sim 30\mu m/p_T + 60\mu m$				≤ 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		$\sigma_{intrinsic}(\|t\|)/\|t\| < 1\%$; 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



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-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		$\sigma_{xyz} \sim 20$ μm, $d_0(z) \sim d_0(r\varphi) \sim 20/p_T$ GeV μm + 5 μm		$(10\text{-}12)\%/\sqrt{E}+(1\text{-}3)\%$		≤ 10 GeV/c			$\sim 85\%/\sqrt{E}+7\%$	
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Scattered electron requirements

- Given the importance of measuring the scattered electron, I'll focus on that for the next several slides.
- For the scattered electron, the requirements can be divided into three categories: angular and momentum acceptance; momentum (energy) resolution; and electron purity.

Electron Acceptance

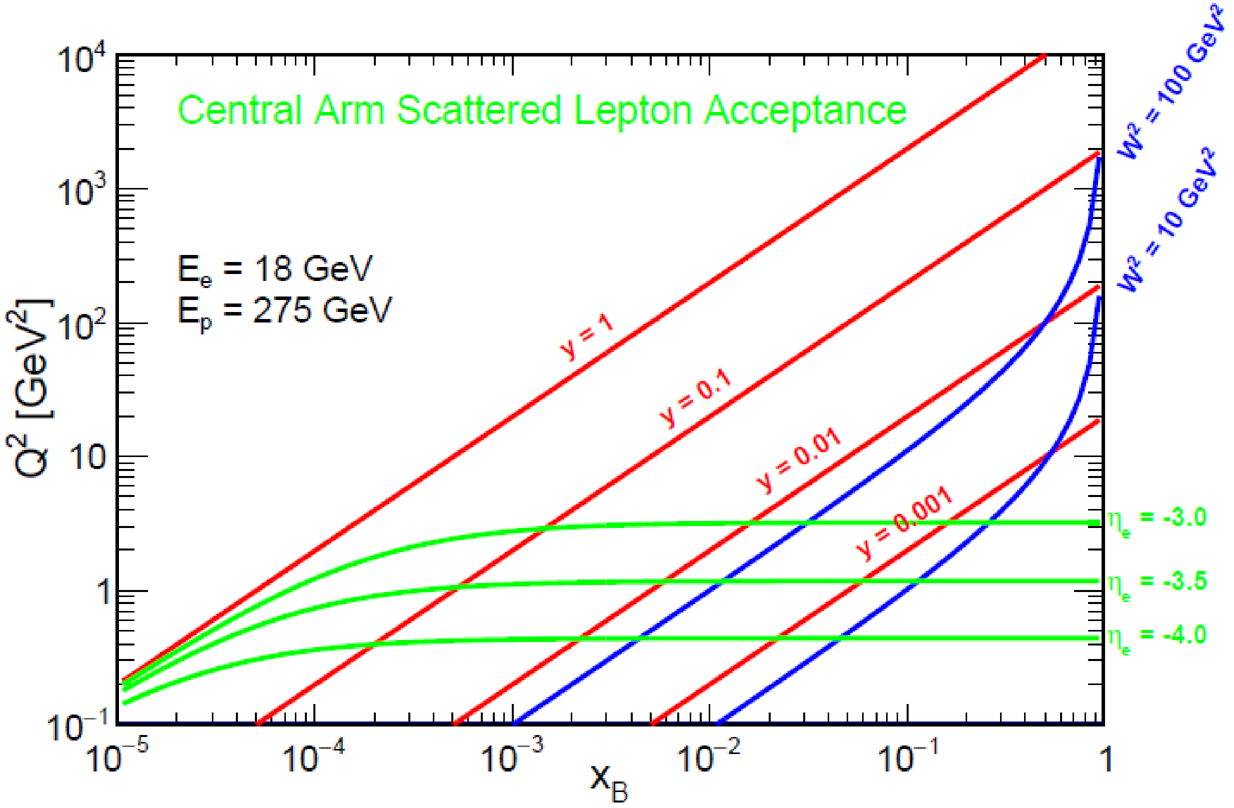
- For the beam energies that will be used at the EIC and considering scattered electrons in the pseudo-rapidity range of $-4 < \eta < 4$ (where $Q^2 \gg m_e^2$), we can relate the inclusive kinematic variables to the scattered electron angles and energies as

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

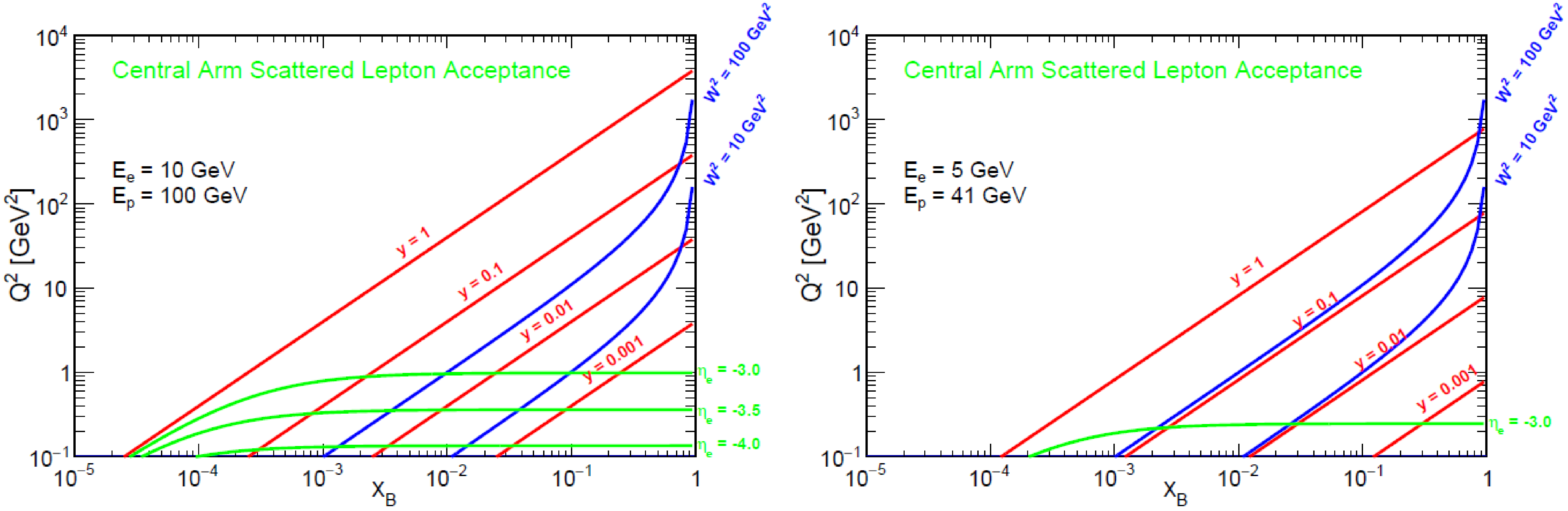
- Note how neither Q^2 nor y depend explicitly on the proton beam energy.

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

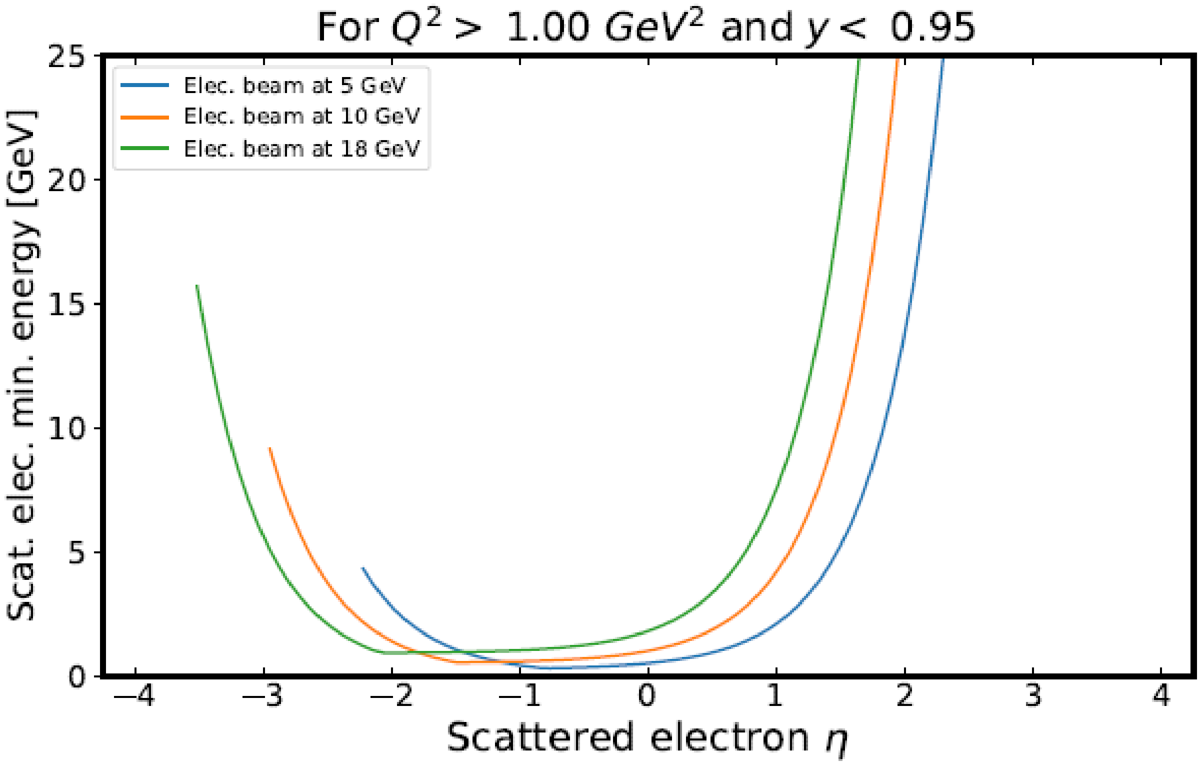


Electron Minimum momentum (energy)

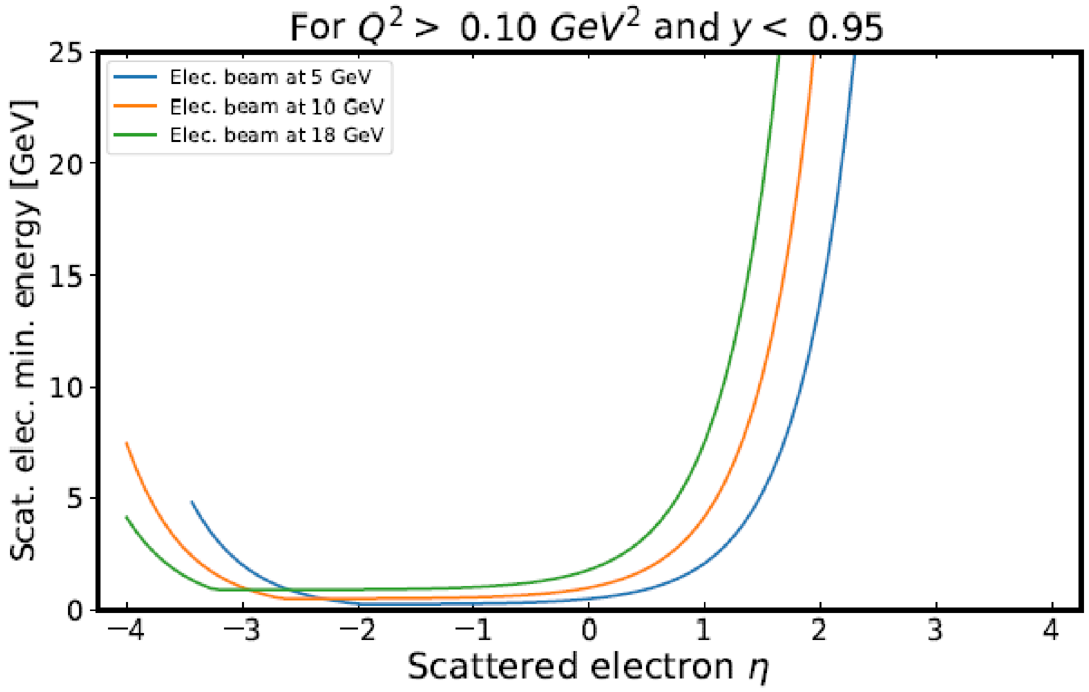
- For a fixed electron beam energy and scattered electron angle, Q^2 increases as the energy of the scattered electron increases, while y decreases.
- For all physics analyses, a cut of $y < 0.95$ will be applied. The minimum energy is also affected by the minimum Q^2 which needs to be measured. These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

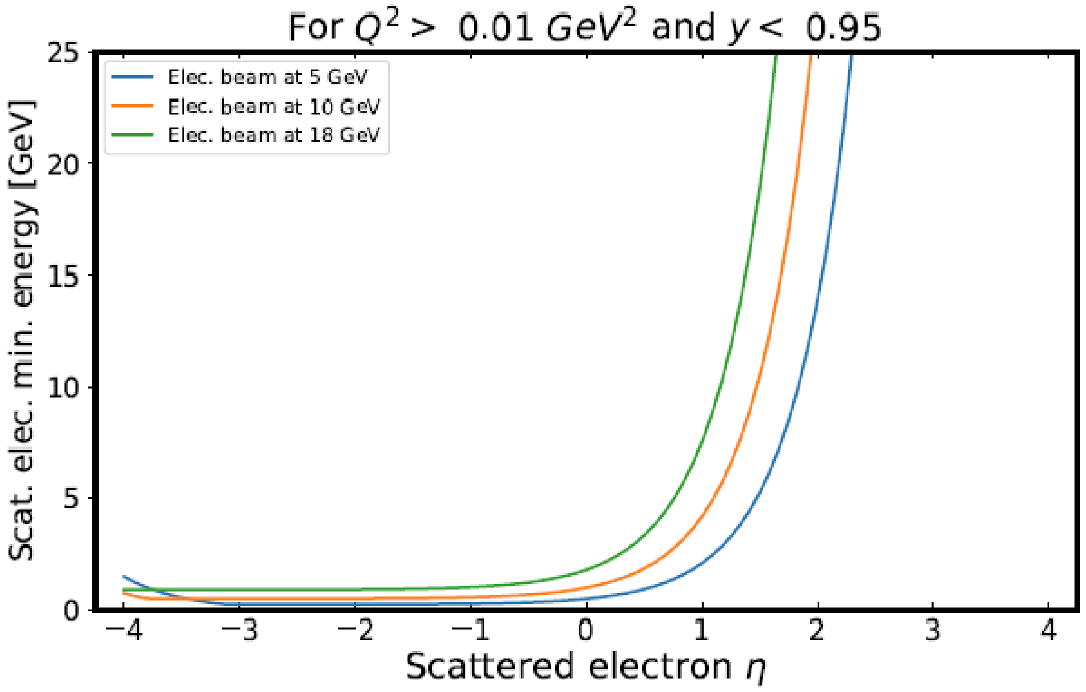
Electron Minimum momentum (energy)

- 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).

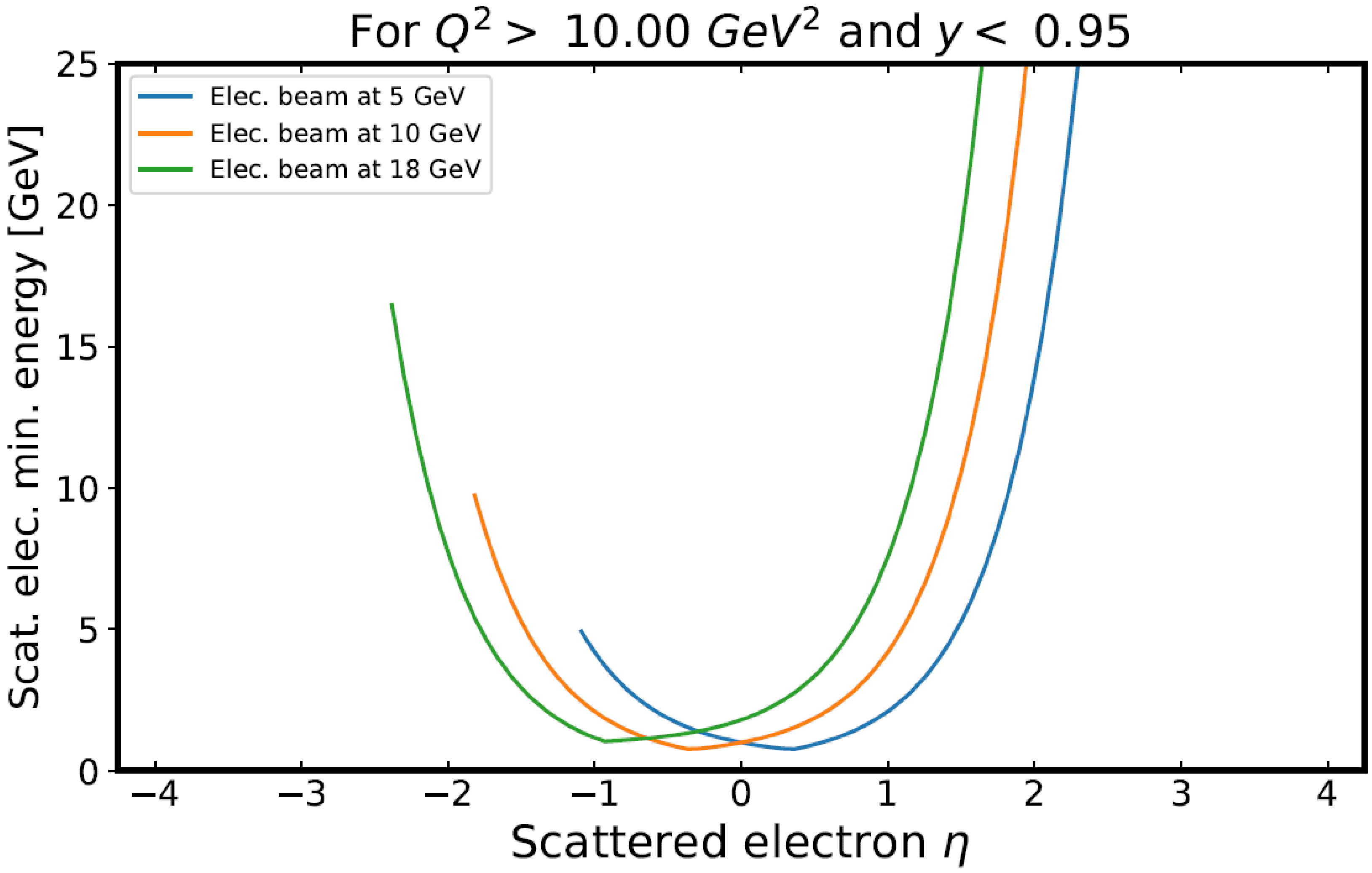


Electron Minimum momentum (energy) – lower minimum Q^2



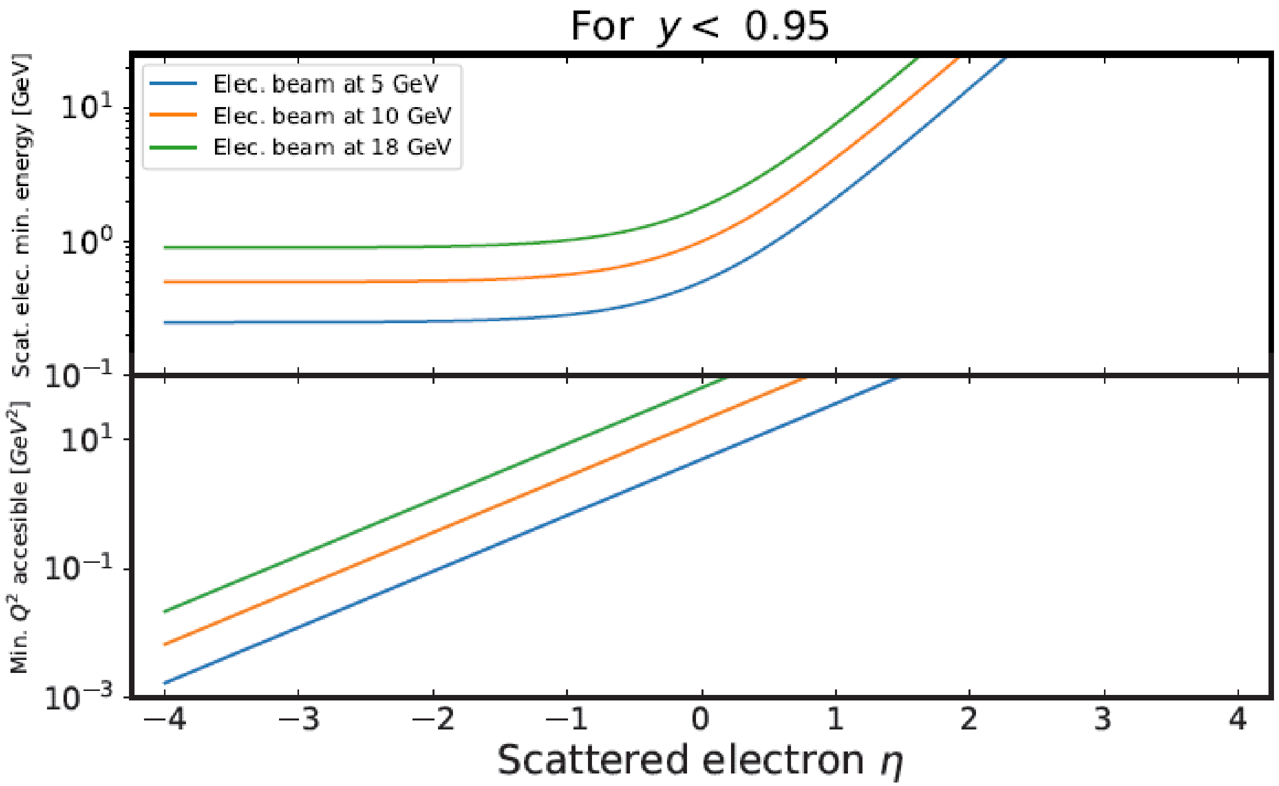


Electron Minimum momentum (energy) – higher minimum Q^2



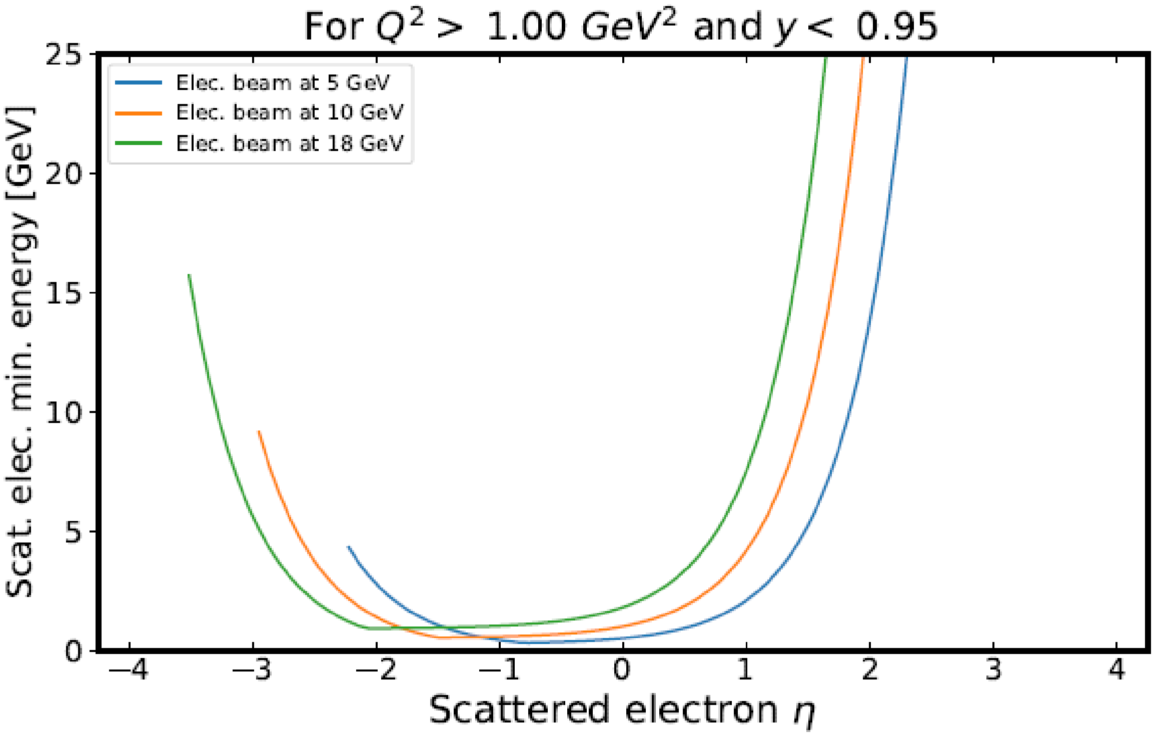
Electron Minimum momentum (energy) – no minimum Q^2

- 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 $Q^2 \approx 10^{-3}$.



Electron Momentum (energy) resolution

- The momentum (energy) resolution requirements for the scattered electron given in the yellow report are sufficient for all inclusive measurements.
- One important consideration is how best to perform the momentum (energy) reconstruction for the scattered electron in the electron endcap.
- If we consider again the case where we are interested in physics processes with $Q^2 > 1$ GeV^2, we see from the plot above that we only need to measure scattered electrons with energy greater than 5 GeV for $\eta < -3.0$.
- The higher Q^2 electron momentum reconstruction at these backwards angles will therefore rely on the EEMC detector, as can be seen in the right plot.



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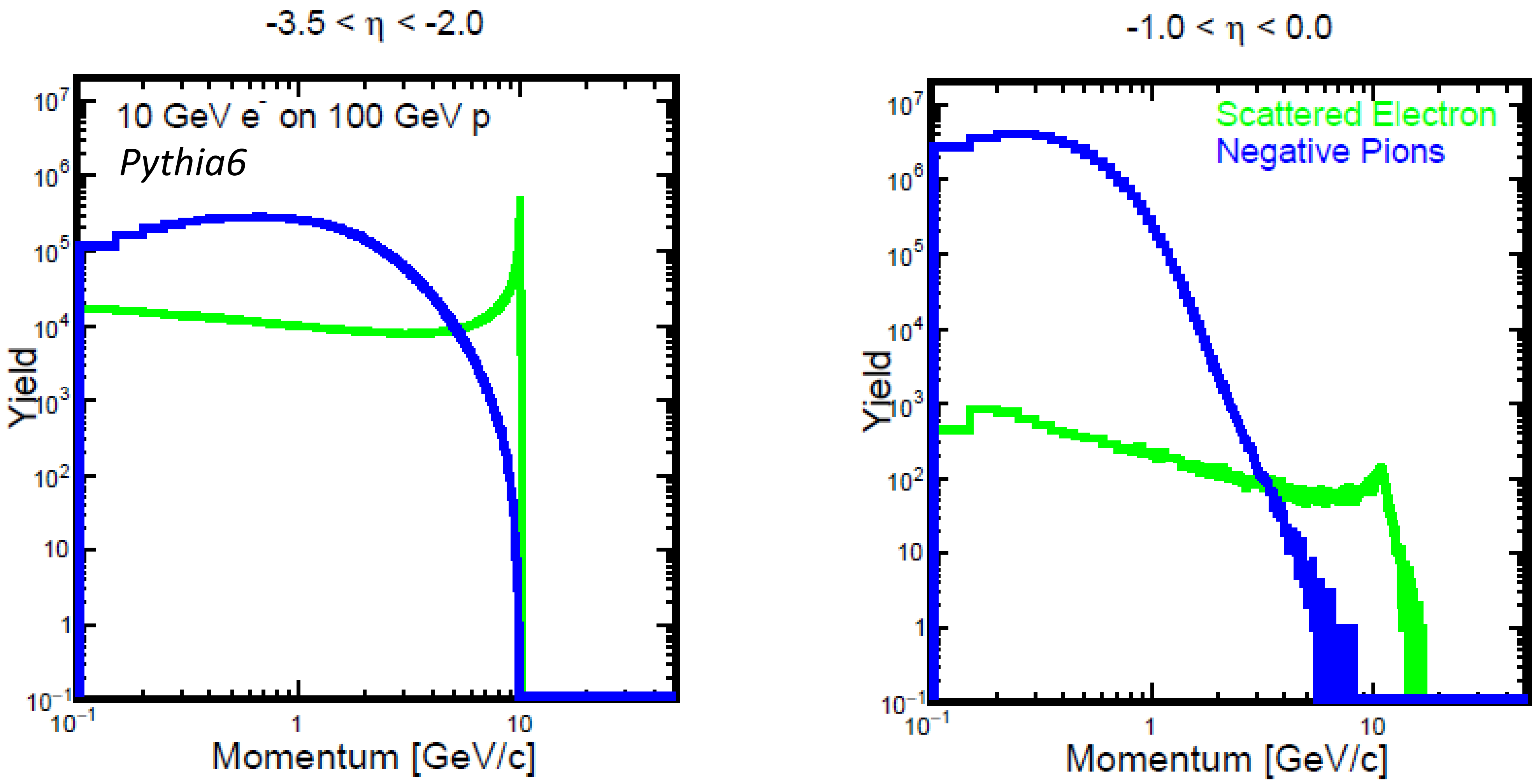
- The higher Q^2 electron momentum reconstruction at these backwards angles will therefore rely on the EEMC detector, as can be seen in the right plot.
- If the lower-energy scattered electrons mentioned above can be measured, their reconstruction would of course use the tracker. The measurement of the scattered electron polar and azimuthal angles will also probably rely on the tracking detector for all scattered electron energies.
- Even when the electron momentum reconstruction is done primarily using the EEMC, it is important to maintain a reasonable tracking resolution for electron identification cuts (i.e. E-over-p cuts). However, it is difficult to quantify the tracker momentum resolution requirement in this case since the electron efficiency and purity are functions of the integrated detector response.

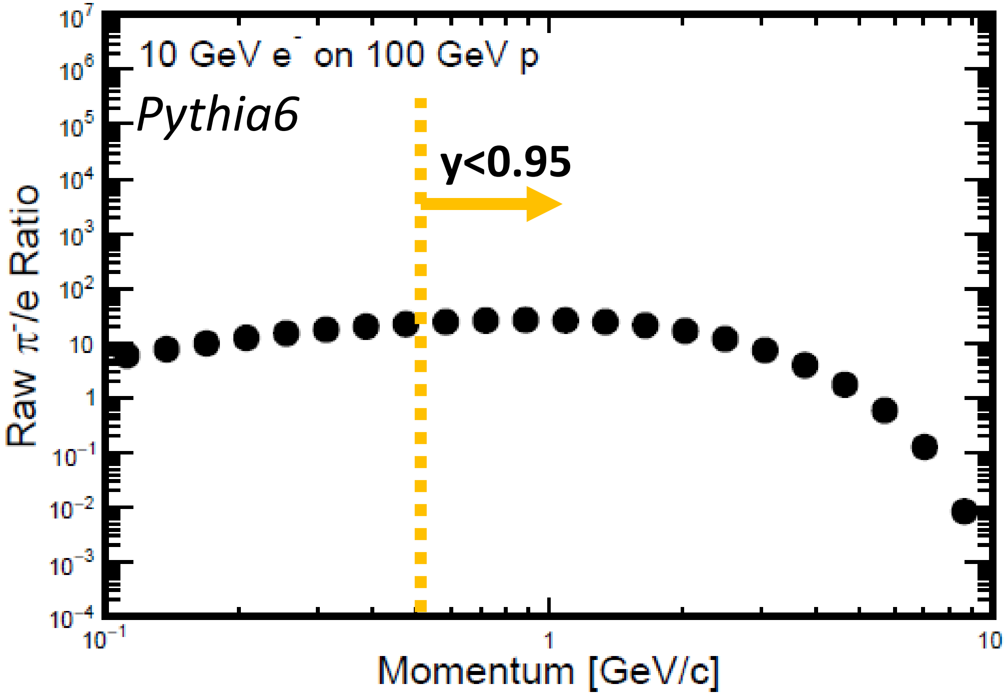
Electron purity

- Requirements on the scattered electron purity were determined by the inclusive working group during the yellow report. The requirement is given as 99% electron purity over the entire detector. This requirement is quite stringent and can be relaxed in certain regions of kinematic phase space, but there are a few good reasons to initially try to achieve this most stringent requirement:
    1. The most challenging place to meet the electron purity requirement is in the barrel region (see next slides). This has to do with the cross-section dependence on Q^2, the momentum distribution of the negative pion background and the fact that, for $Q^2 > 1$ GeV^2 for example, lower momentum electrons only need to be reconstructed for more central pseudo-rapidities.
    2. As demonstrated in all the detector proposals − albeit using parameterized detector responses − the combination of tracking, EmCal, PID, and kinematic cuts can significantly remove the negative pion background. This suggests the more stringent requirement may be achievable. Once an adequate ‘electron finder’ algorithm is in place, electron purity will be a useful benchmark to compare detector configurations.

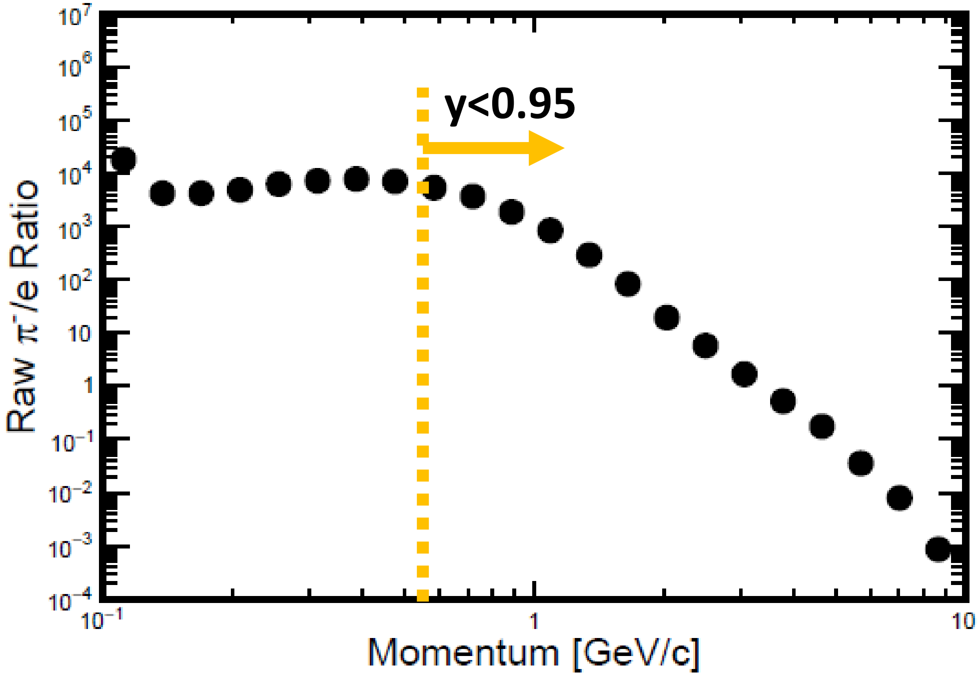
Electron purity



Electron purity



-3.5 < η < -2.0

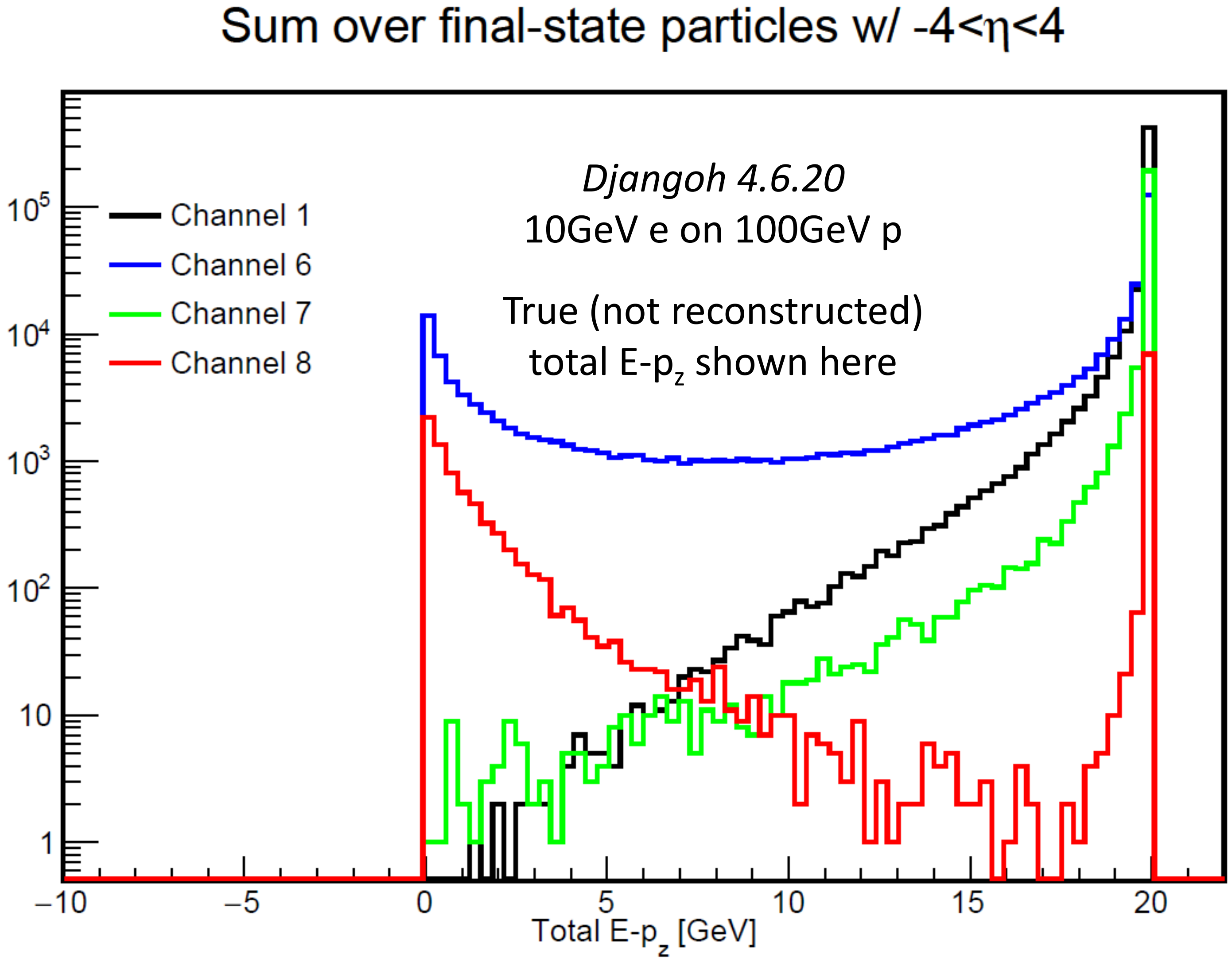


-1.0 < η < 0.0

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)

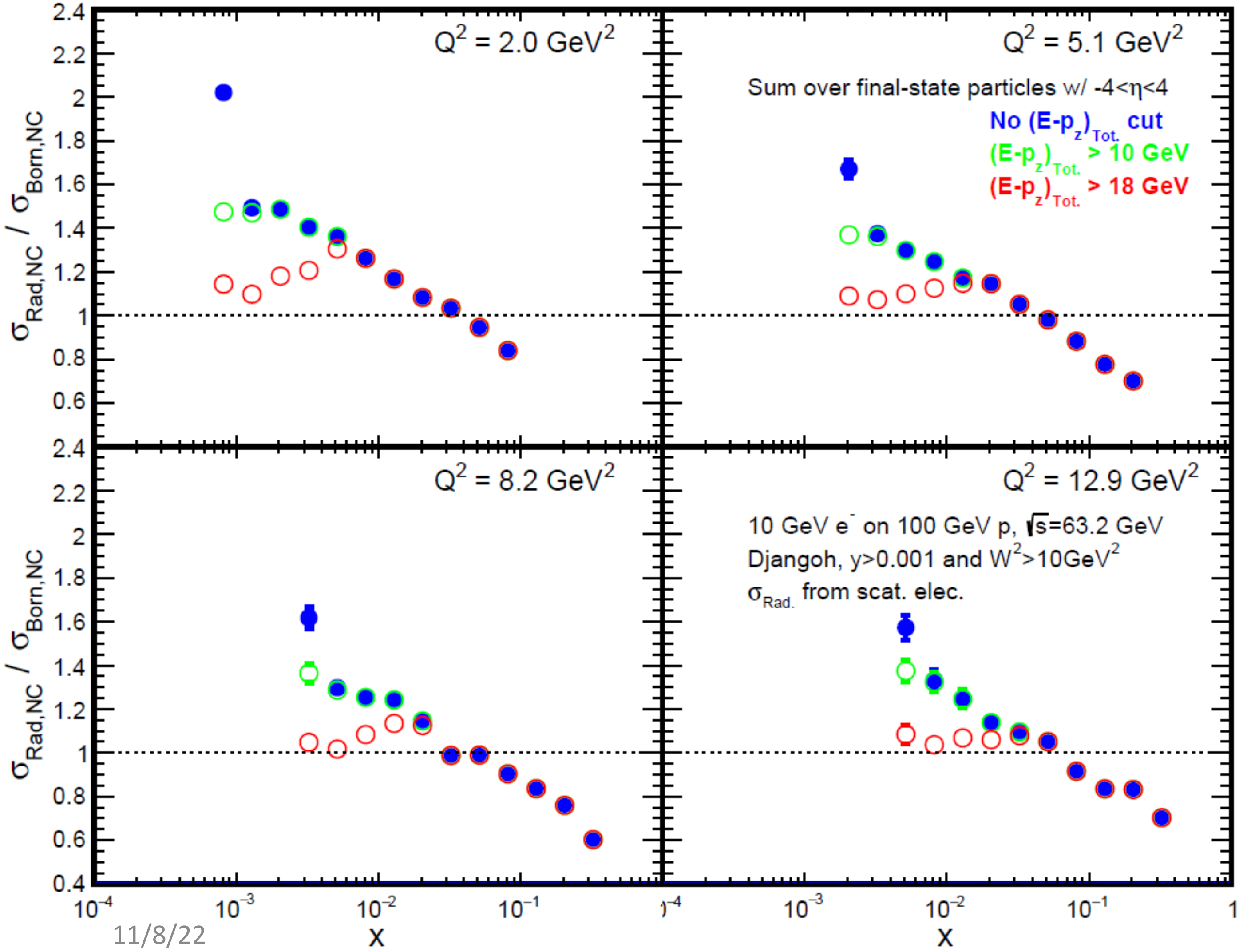
If all particles are detected, the total E-p_z will be twice the electron beam energy (20 GeV here).


Sum over final-state particles w/ $-4<\eta<4$

Djangoh 4.6.20
10GeV e on 100GeV p

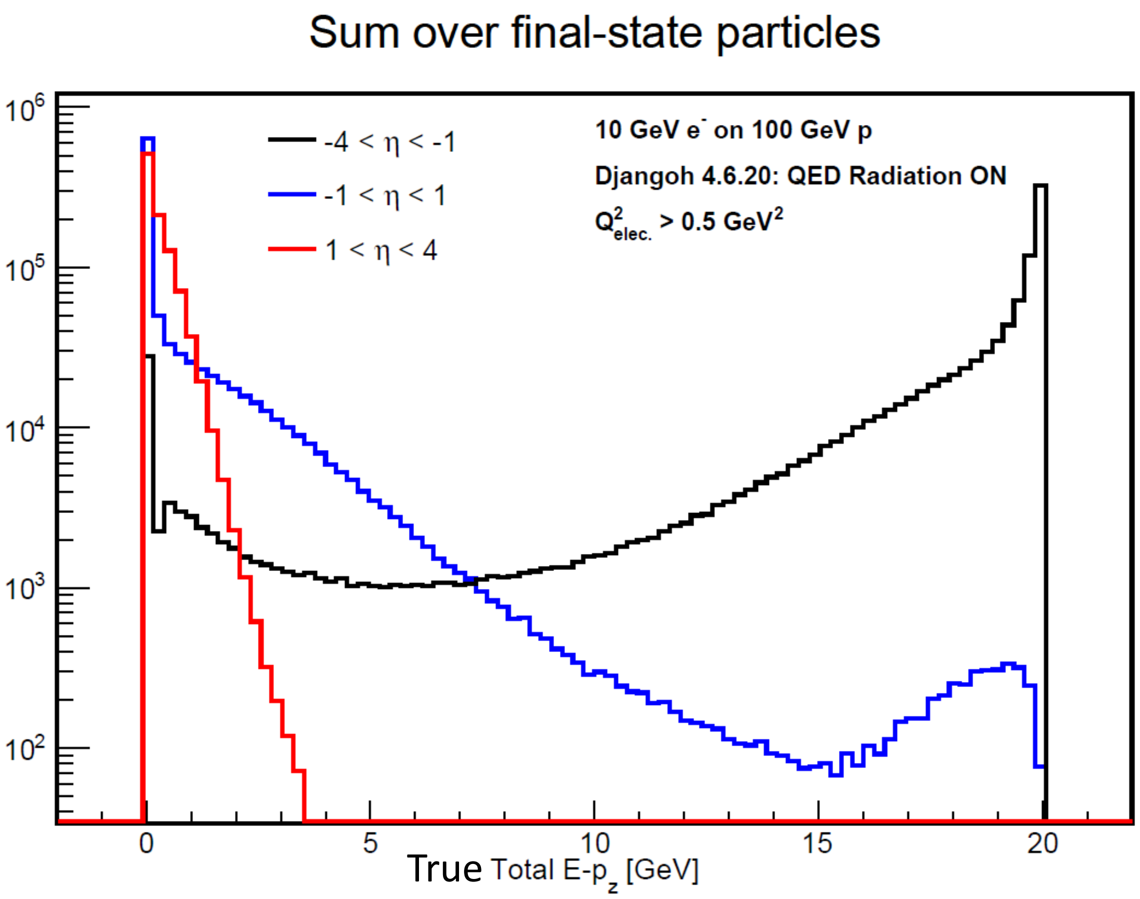
True (not reconstructed) total E-p_z shown here

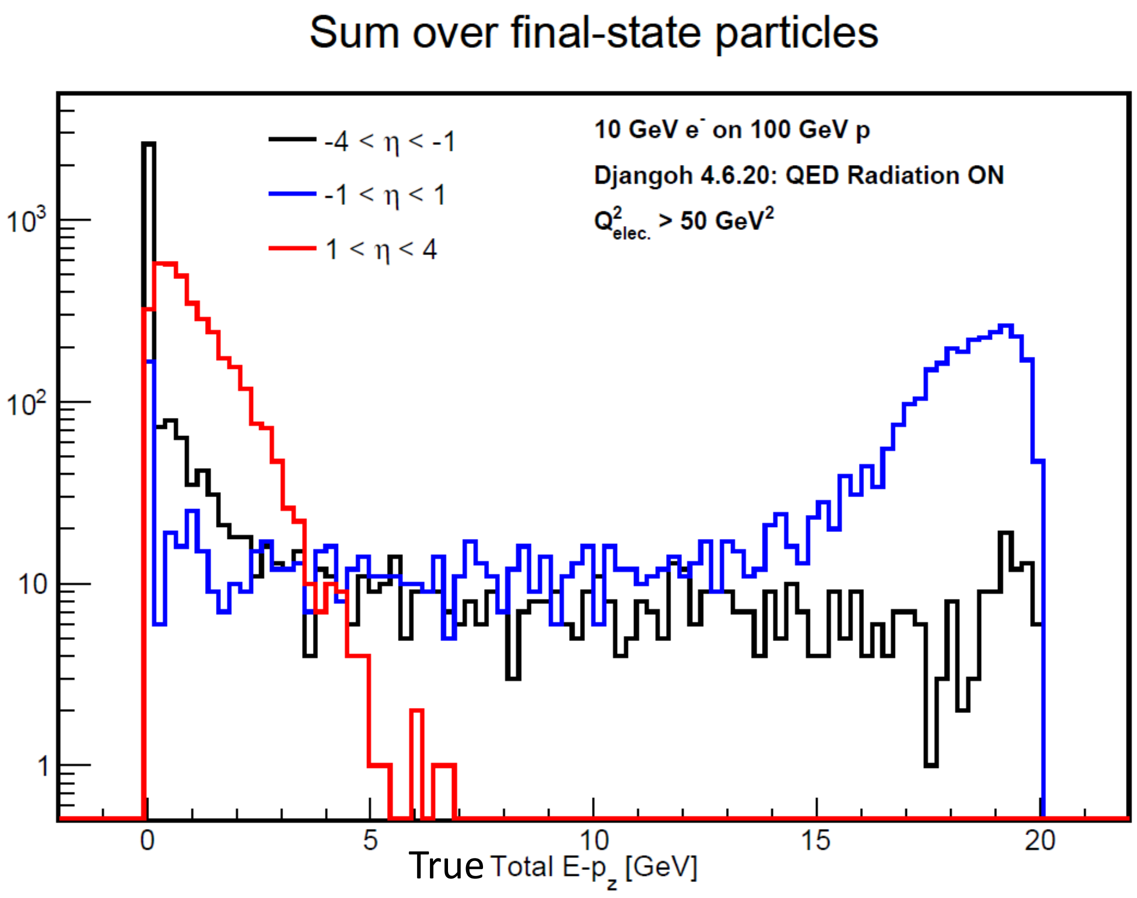
Importance of total E-p_z cut for reducing radiative correction



- 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.**

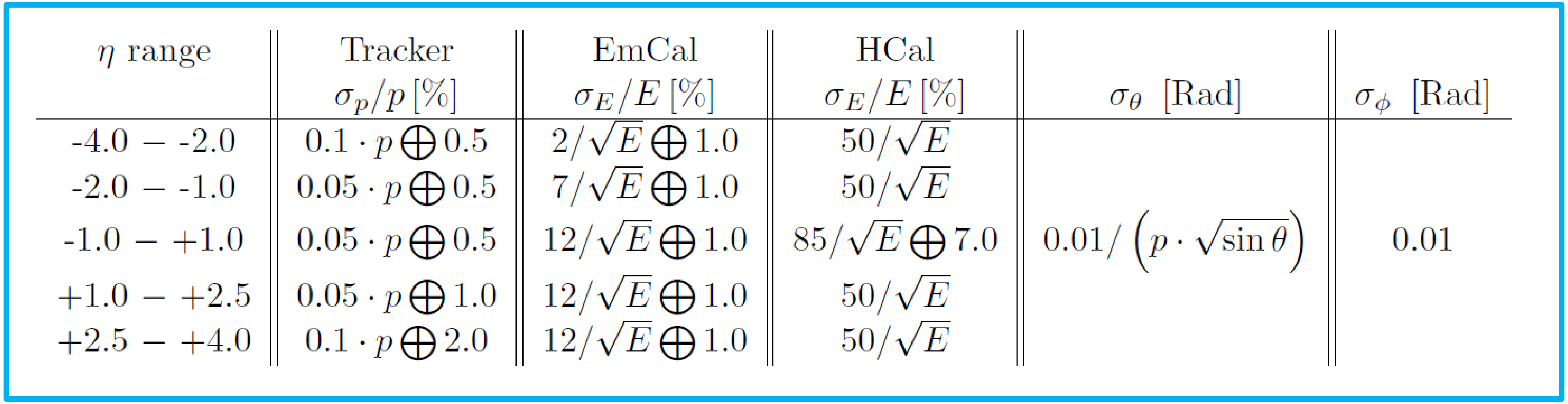
Where in the detector does most of the total E-p_z go?





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

Fast simulation detector parameterization

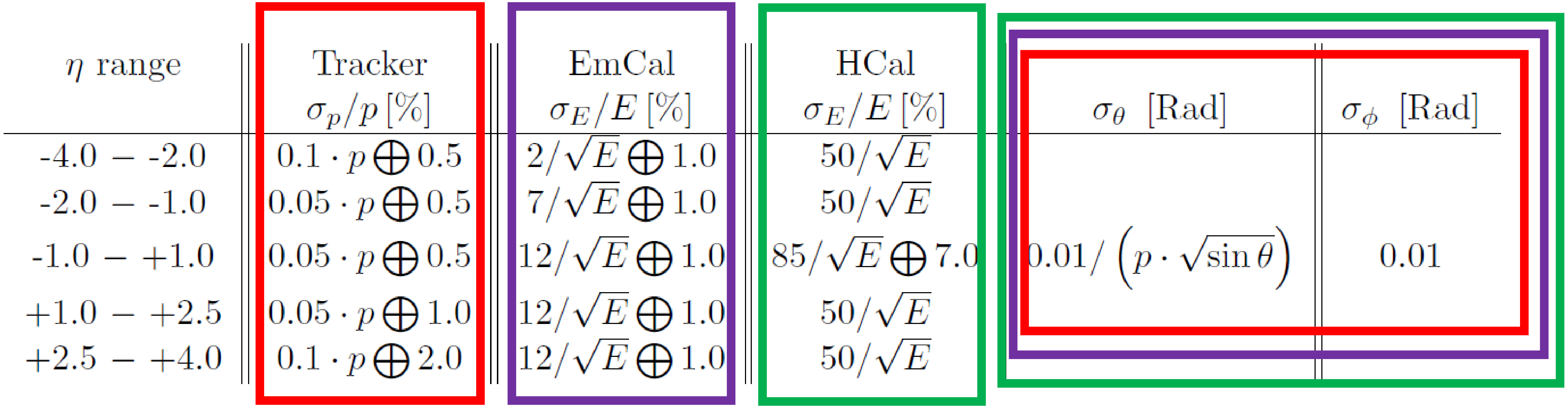


η range	Tracker σ_p/p [%]	EmCal σ_E/E [%]	HCal σ_E/E [%]	σ_θ [Rad]	σ_ϕ [Rad]
-4.0 – -2.0	$0.1 \cdot p \bigoplus 0.5$	$2/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$	$0.01/\left(p \cdot \sqrt{\sin\theta}\right)$	0.01
-2.0 – -1.0	$0.05 \cdot p \bigoplus 0.5$	$7/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-1.0 – +1.0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



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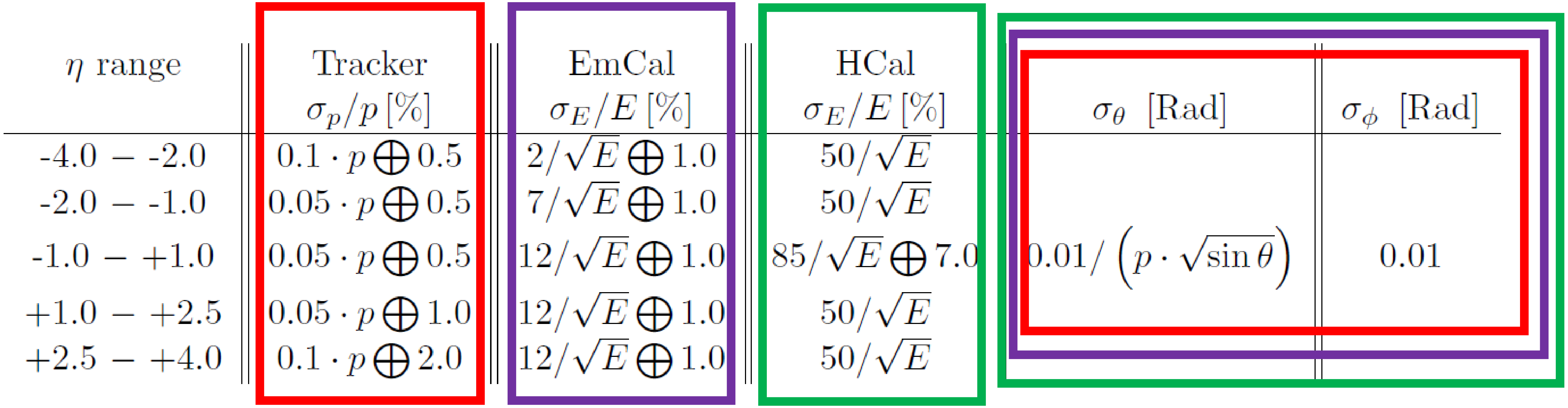
Charged particles
Photons
Neutral hadrons

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	$0.1 \cdot p \bigoplus 0.5$	$2/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$	$0.01/\left(p \cdot \sqrt{\sin\theta}\right)$	0.01
-2.0 – -1.0	$0.05 \cdot p \bigoplus 0.5$	$7/\sqrt{E} \bigoplus 1.0$	$50/\sqrt{E}$		
-1.0 – +1.0	$0.05 \cdot p \bigoplus 0.5$	$12/\sqrt{E} \bigoplus 1.0$	$85/\sqrt{E} \bigoplus 7.0$		
+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

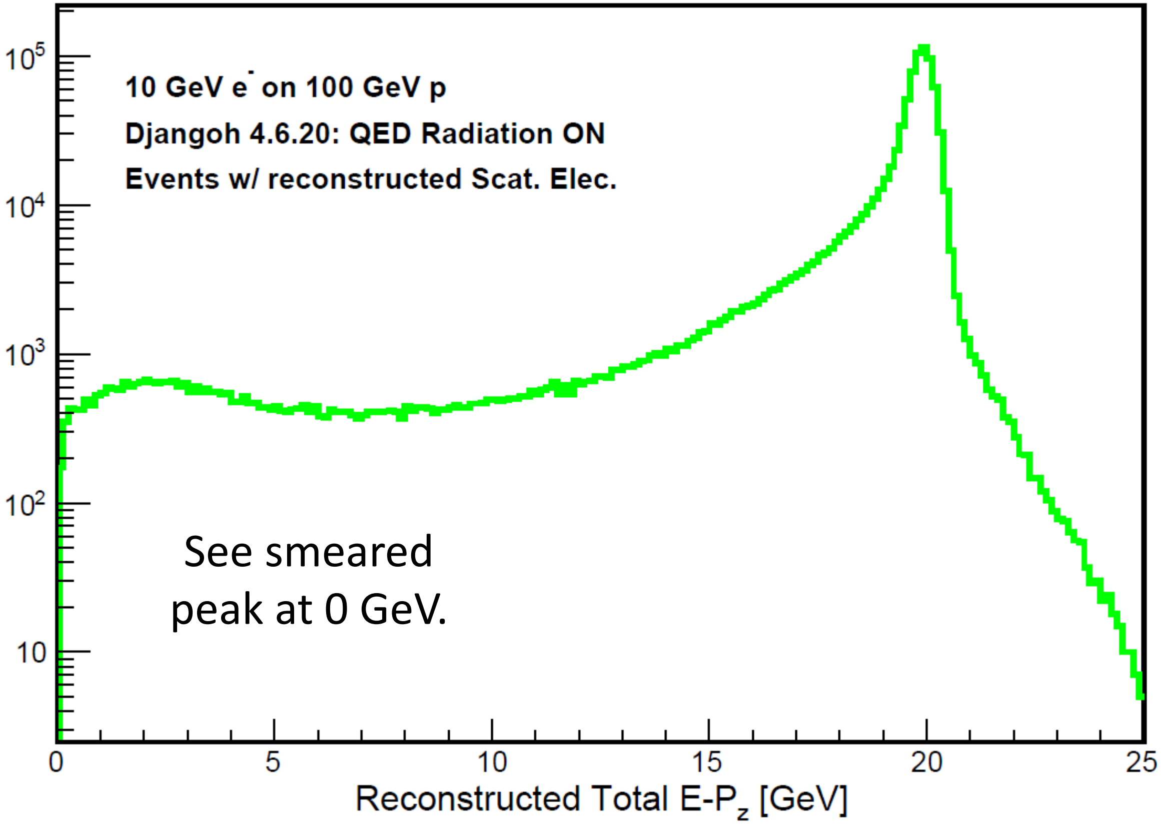
Neutral hadrons

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.

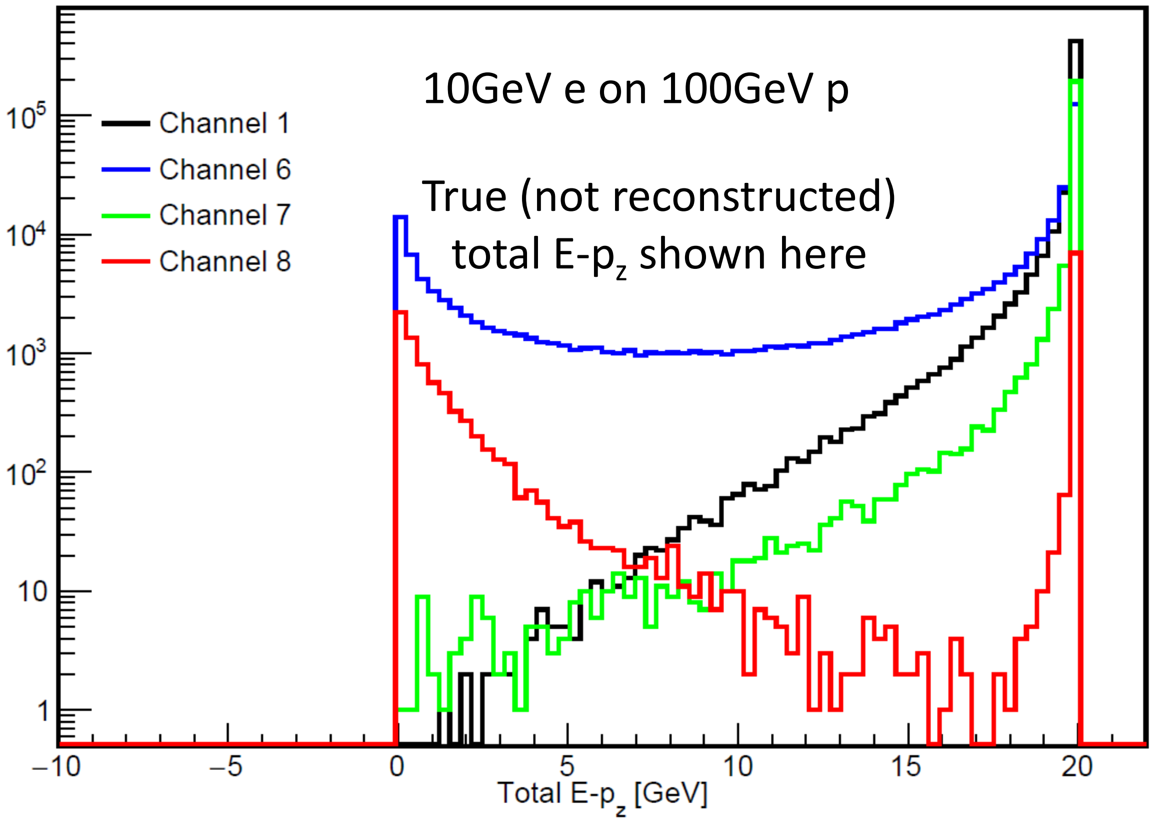
Reconstruction results – QED radiation ON

Perfect PID



See smeared peak at 0 GeV.

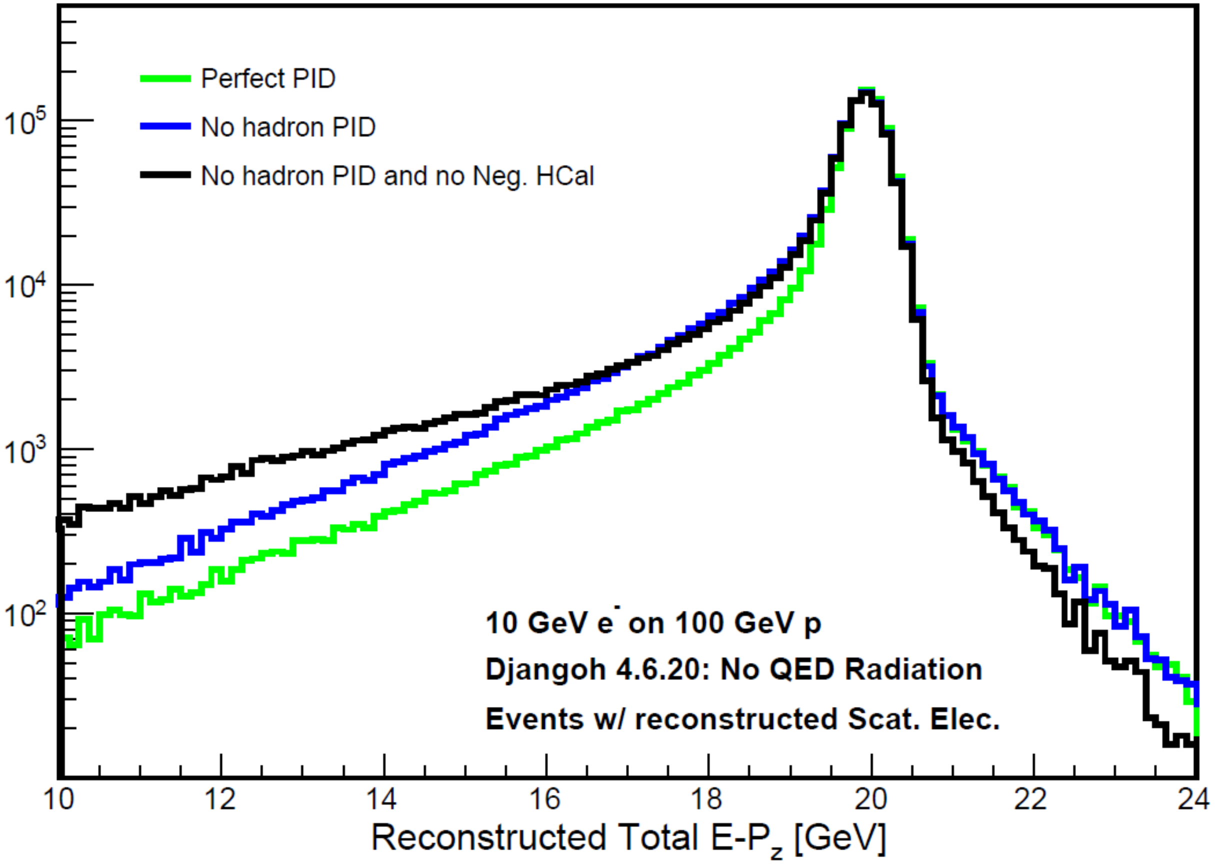
Sum over final-state particles w/ $-4<\eta<4$



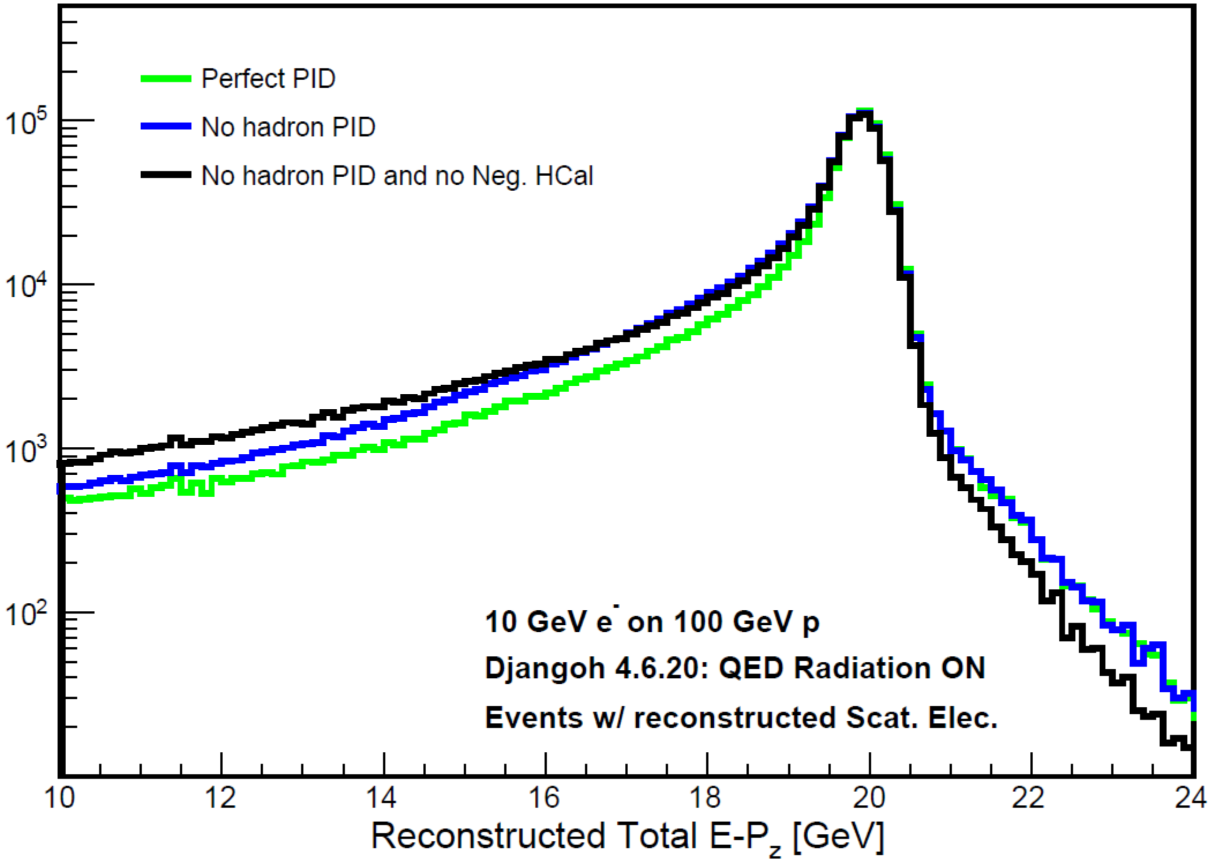
True (not reconstructed) total E-p_z shown here

Reconstruction results – all

No QED effects included



QED effects turned ON



Summary

- Key inclusive measurements are the unpolarized nuclear cross section and double-spin asymmetry.
- These measurements will require very good electron and total E-p_z reconstruction.