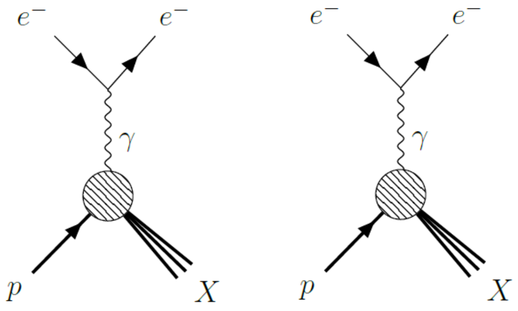
Unpolarized e-p NC Cross Section at the EIC

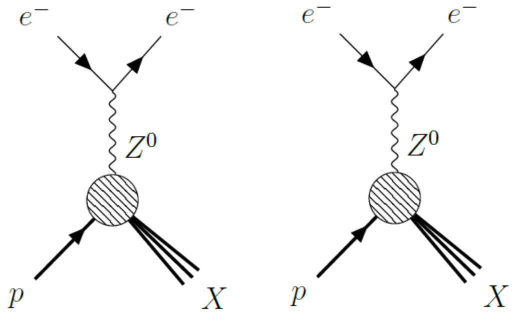
Barak Schmookler

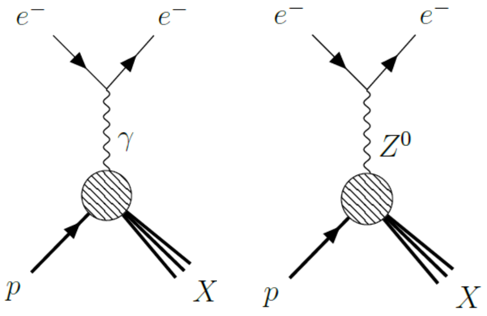
Inclusive Physics of Interest

Measurement	Main Detector Requirements	Anticipated Plot	Physics Topic/goal	Responsible persons
inclusive $A_{\|\|}$ / $A_{\perp}$ for proton, deuterium, ^{3}He	Standard inclusive	$A_{\|\|}(x,y,Q^2), A_{\perp}$ $g_1(x)$, $g_{2/T}(x)$ vs Q^2 $\Delta g(Q^2)$ vs x	Gluon & Quark Helicity $\Delta g(x,Q^2)$, Δu^+, Δd^+	
inclusive A_{PV}	Standard inclusive	A_{PV} vs x for $W^{+/-}$ $g^W{}_5(x)$ vs Q^2 $\Delta s^+(Q^2)$, $s^+(Q^2)$ vs x	Strange Pol and Unpolarized $\Delta s^+(x,Q^2)$, $s^+(x,Q^2)$	
$\boldsymbol{\sigma}_{red}(x,Q^2)$, $\boldsymbol{\sigma}^{c/b}{}_{red}(x,Q^2) \rightarrow F_2, F_L, F_2{}^{c/b}$	Standard inclusive + heavy quark tag	$\boldsymbol{\sigma}_{red}(x,y)$ vs Q^2 $\boldsymbol{\sigma}^{c/b}{}_{red}(x,y)$ vs Q^2 $g(Q^2)$ vs x	Proton PDFs $q(x,Q^2)$, $g(x, Q^2)$	
$\boldsymbol{\sigma}_{red}(x,Q^2)$, $\boldsymbol{\sigma}^{c/b}{}_{red}(x,Q^2) \rightarrow F_2, F_L, F_2{}^{c/b}$	Standard inclusive + heavy quark tag	$\boldsymbol{\sigma}_{red}(x,y)$ vs Q^2 $\boldsymbol{\sigma}^{c/b}{}_{red}(x,y)$ vs Q^2 $F_L(Q^2)$ vs x $F^{c/b}{}_L(Q^2)$ vs x	Nuclear PDFs $q(x,Q^2)$, $g(x, Q^2)$	
$\boldsymbol{\sigma}_{red}(x,Q^2)$, $\boldsymbol{\sigma}^{c/b}{}_{red}(x,Q^2) \rightarrow F_2, F_L, F_2{}^{c/b}$	Standard inclusive + heavy quark tag	$\boldsymbol{\sigma}_{red}(x)$ vs Q^2 $\boldsymbol{\sigma}^{c/b}{}_{red}(x)$ vs Q^2 $\Delta F_L/F_L$ vs x, Q^2	Non-linear QCD dynamics	
EW inclusive A_{PV}	Standard inclusive	$A_{PV}(y)$ vs Q^2 $\sin^2\boldsymbol{\theta}_w$ vs Q^2	BSM & Precision EW ($\sin^2\boldsymbol{\theta}_w$)	
$\frac{d\sigma^{NC}}{dxdyd\phi}$ Triply differential NC X-sec	Standard inclusive	Updated Fig.6 in ***PhysRevD.98.115018*** for CM energies smearing.	Lorentz and CPT Violating Effects	

Electron-Proton Neutral Current (NC) Scattering

$\sigma_{NC} \propto$ 

$+$ 

$+$ 

Electron-Proton Neutral Current (NC) Scattering

For high Q^2 and unpolarized proton:

$$\sigma_{r,NC}^{e^{\pm}p\to e^{\pm}X} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \times \frac{d^2\sigma_{NC}^{e^{\pm}p\to e^{\pm}X}}{dx dQ^2} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L$$

$$F_L = F_2 - 2xF_1 \qquad Y_{\pm} = 1 \pm (1-y)^2$$

Electron-Proton Neutral Current (NC) Scattering

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Reduced cross section – contains the proton structure information

$$F_L = F_2 - 2xF_1 \qquad Y_{\pm} = 1 \pm (1-y)^2$$

Electron-Proton Neutral Current (NC) Scattering

For high Q^2 and unpolarized proton:

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= 0 in the quark-parton model (Callan-Gross Relation)

$$F_L = F_2 - 2xF_1 \qquad Y_\pm = 1 \pm (1-y)^2$$

NC Structure Functions

$$F_{1,2}^{\pm} = F_{1,2}^{\gamma} + \eta_z \left(-g_v^e \mp \langle\lambda\rangle g_A^e\right) F_{1,2}^{\gamma z} + \eta_z^2 \left[(g_v^e)^2 + (g_A^e)^2 \pm 2\langle\lambda\rangle g_A^e g_v^e\right] F_{1,2}^{z}$$

$$xF_3^{\pm} = \eta_z \left(\pm g_A^e + \langle\lambda\rangle g_v^e\right) xF_3^{\gamma z} + \eta_z^2 \left[\mp 2 g_v^e g_A^e - \langle\lambda\rangle \left((g_v^e)^2 + (g_A^e)^2\right)\right] xF_3^{z}$$

$\langle\lambda\rangle$: Polarization of Electron Beam [-1,1]

$$\eta_z = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2+M_Z^2}\right)$$

$$g_v^e = -\frac{1}{2} + 2\sin^2\theta_w \approx -0.05$$

$$g_A^e = -\frac{1}{2}$$

NC Structure Functions

Only important term for unpolarized leptons at low to moderate Q^2

$$F_{1,2}^{\pm} = \boxed{F_{1,2}^{\gamma}} + \eta_z \left(-g_v^e \mp \langle\lambda\rangle g_A^e\right) F_{1,2}^{\gamma z} + \eta_z^2 \left[\left(g_v^e\right)^2 + \left(g_A^e\right)^2 \pm 2\langle\lambda\rangle g_A^e g_v^e\right] F_{1,2}^{z}$$

$$xF_3^{\pm} = \eta_z \left(\pm g_A^e + \langle\lambda\rangle g_v^e\right) xF_3^{\gamma z} + \eta_z^2 \left[\mp 2 g_v^e g_A^e - \langle\lambda\rangle \left(\left(g_v^e\right)^2 + \left(g_A^e\right)^2\right)\right] xF_3^{z}$$

$\langle\lambda\rangle$: Polarization of Electron Beam [-1,1]

$$\eta_z = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

$$g_v^e = -\frac{1}{2} + 2\sin^2\theta_w \approx -0.05$$

$$g_A^e = -\frac{1}{2}$$

NC Structure Functions in the Quark-Parton Model

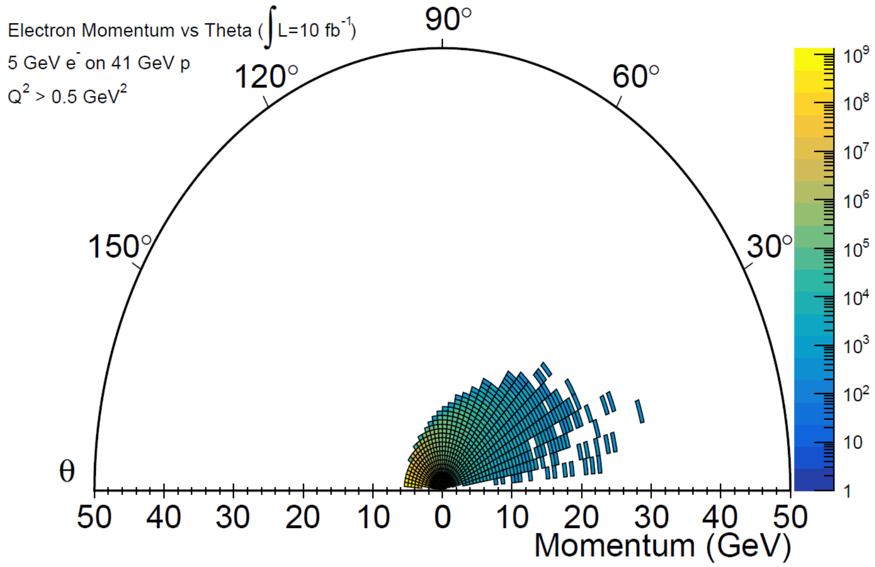
$$[F_2^\gamma, F_2^{\gamma z}, F_2^z] = x \sum_q \left[e_q^2, 2e_q g_v^q, (g_v^q)^2 + \left(g_A^q\right)^2\right](q + \bar{q})$$

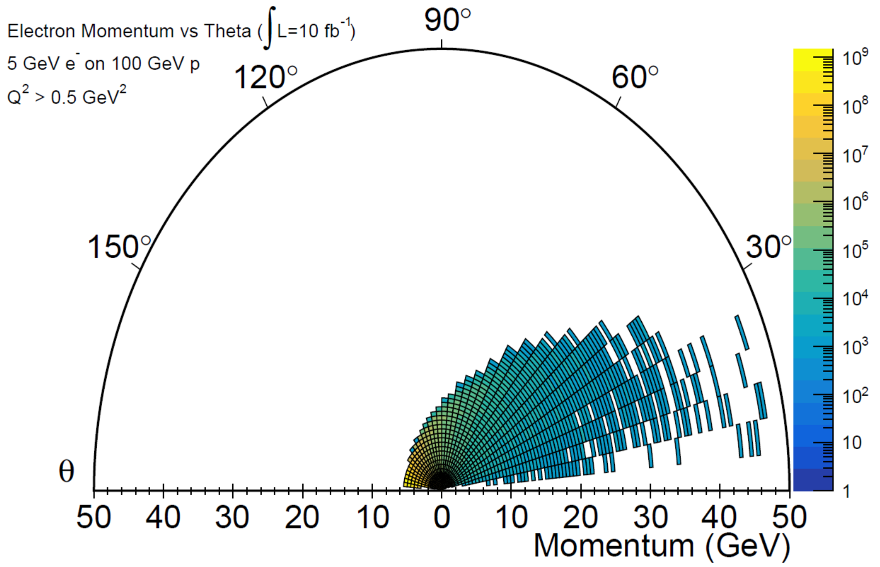
$$[F_3^\gamma, F_3^{\gamma z}, F_3^z] = \sum_q \left[0, 2e_q g_A^q, 2g_v^q g_A^q\right](q - \bar{q})$$

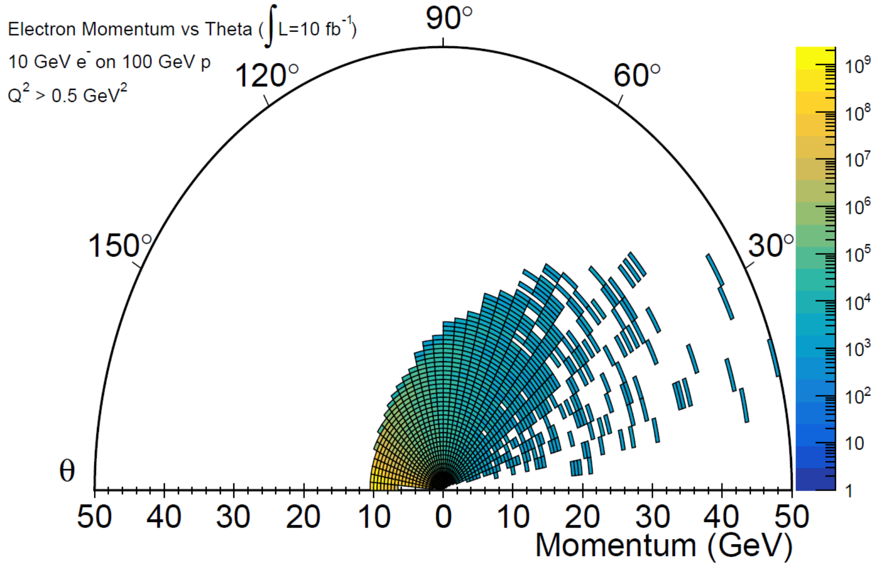
$$g_v^q = \pm\frac{1}{2} - 2e_q \sin^2\theta_w$$

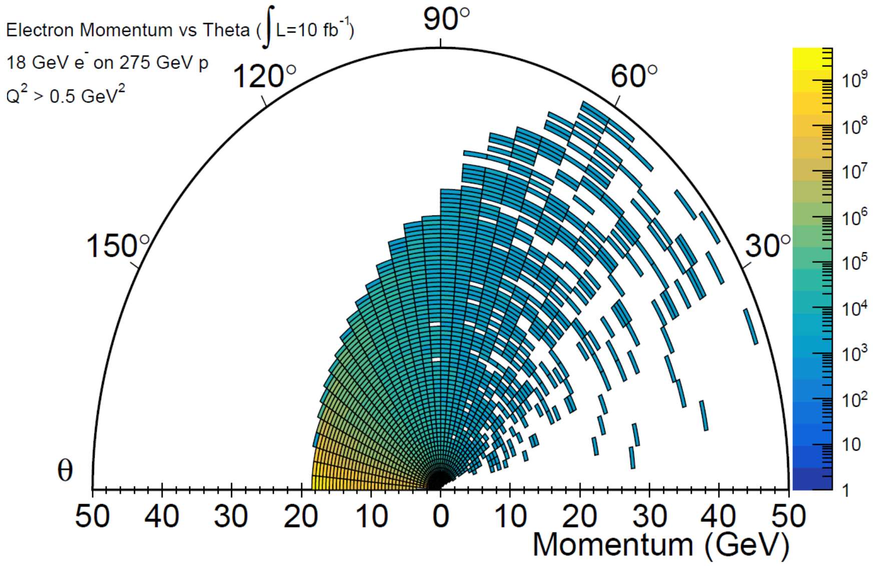
$$g_A^q = \pm\frac{1}{2}$$

Last Time

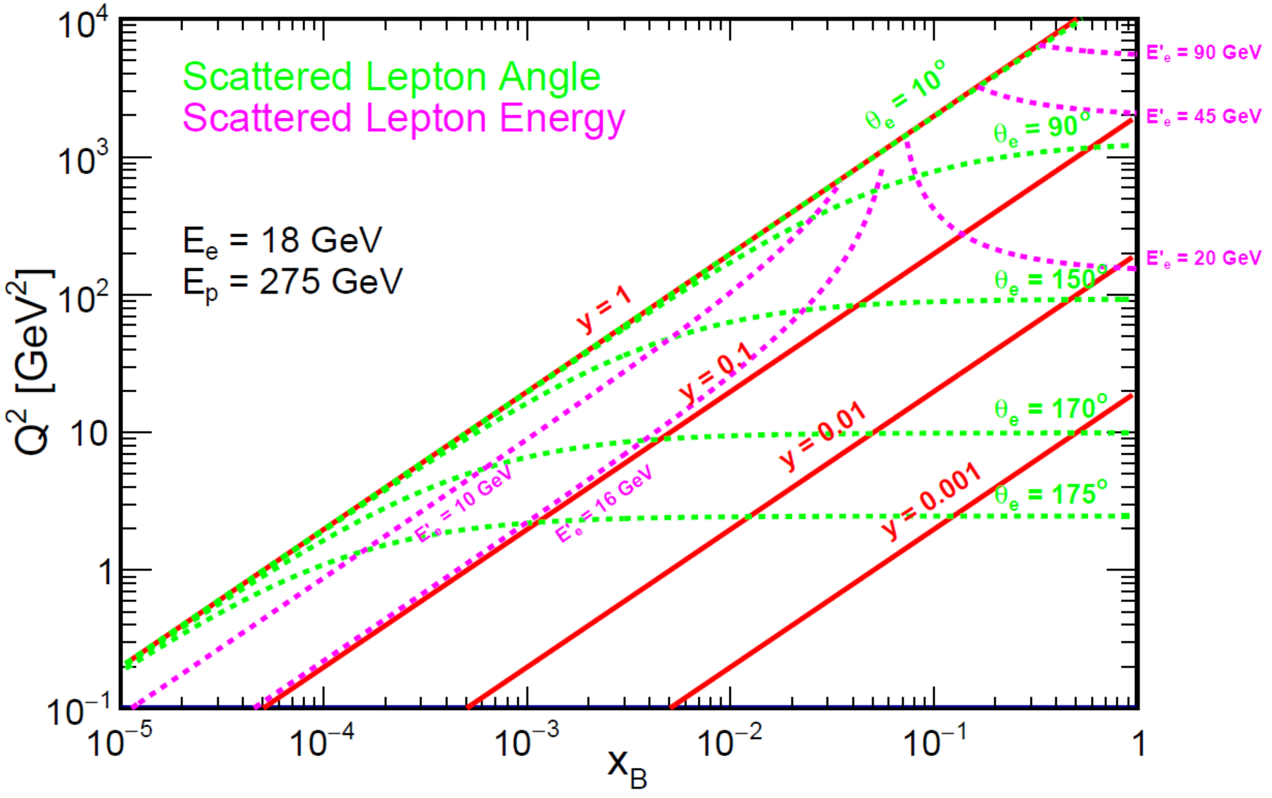

Electron Momentum vs Theta ($\int$L=10 fb^{-1})
5 GeV e$^-$ on 41 GeV p
Q^2 > 0.5 GeV^2
90°
120°
60°
150°
30°
θ
50 40 30 20 10 0 10 20 30 40 50
Momentum (GeV)
1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

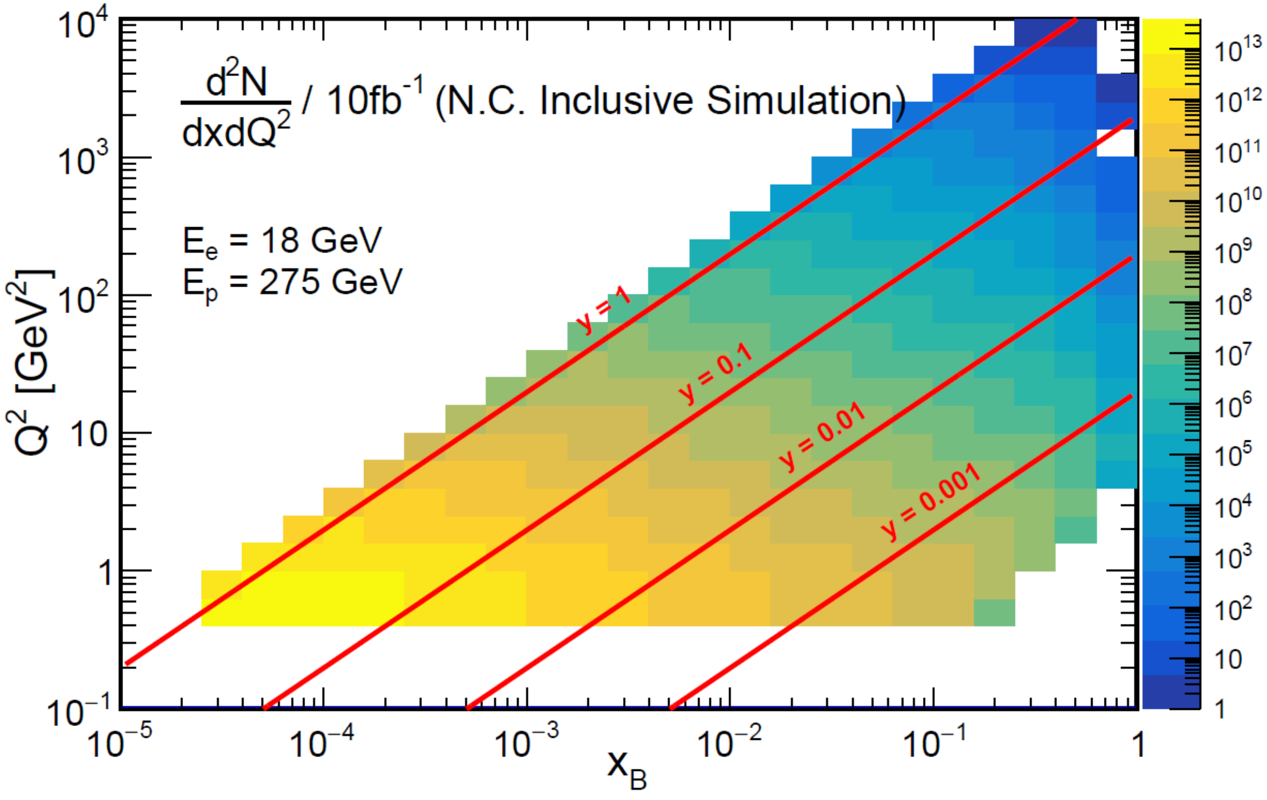

Electron Momentum vs Theta ($\int$L=10 fb^{-1})
5 GeV e$^-$ on 100 GeV p
Q^2 > 0.5 GeV^2
90°
120°
60°
150°
30°
θ
50 40 30 20 10 0 10 20 30 40 50
Momentum (GeV)
1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9


Electron Momentum vs Theta ($\int$L=10 fb^{-1})
10 GeV e$^-$ on 100 GeV p
Q^2 > 0.5 GeV^2
90°
120°
60°
150°
30°
θ
50 40 30 20 10 0 10 20 30 40 50
Momentum (GeV)
1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

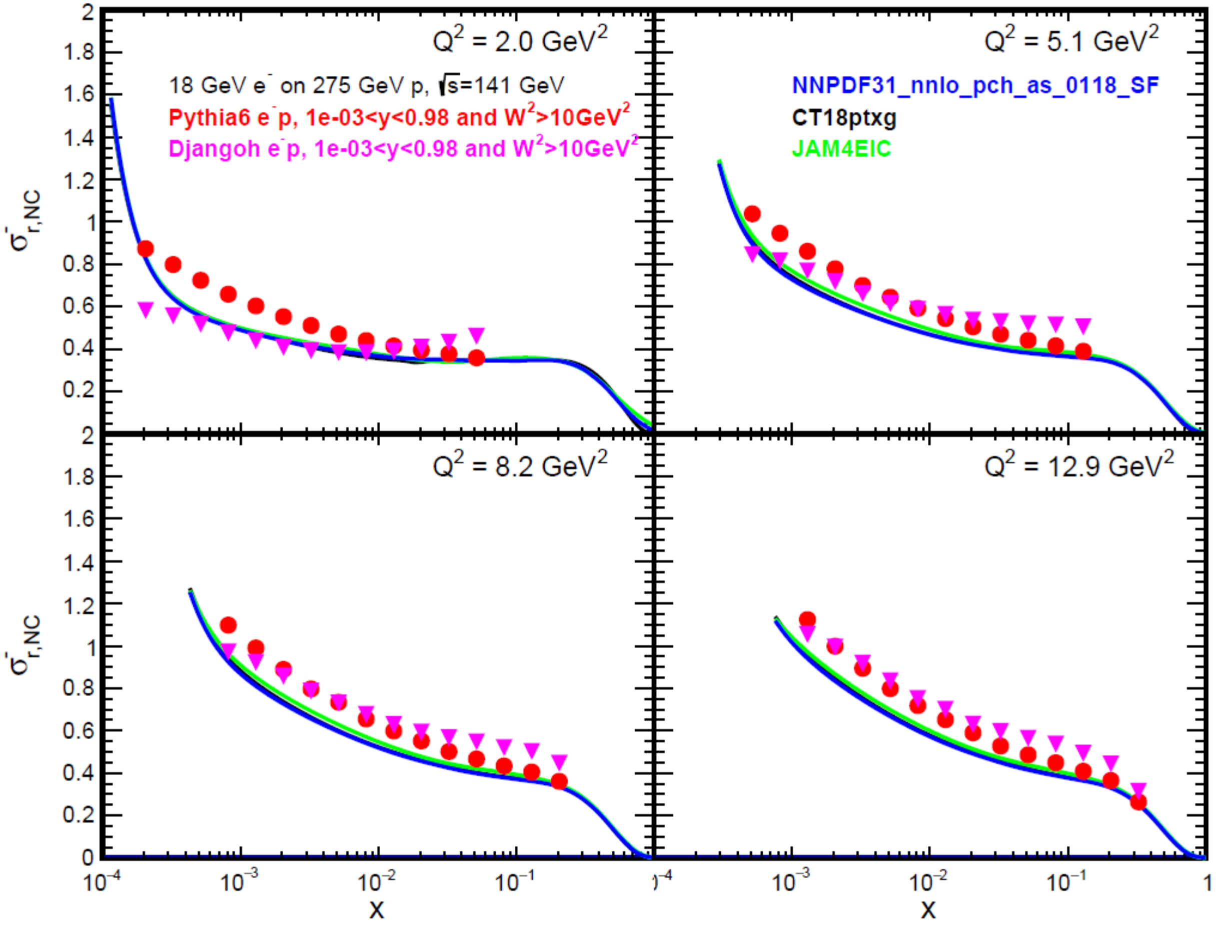

Electron Momentum vs Theta ($\int$L=10 fb^{-1})
18 GeV e$^-$ on 275 GeV p
Q^2 > 0.5 GeV^2
90°
120°
60°
150°
30°
θ
50 40 30 20 10 0 10 20 30 40 50
Momentum (GeV)
1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9

Last Time

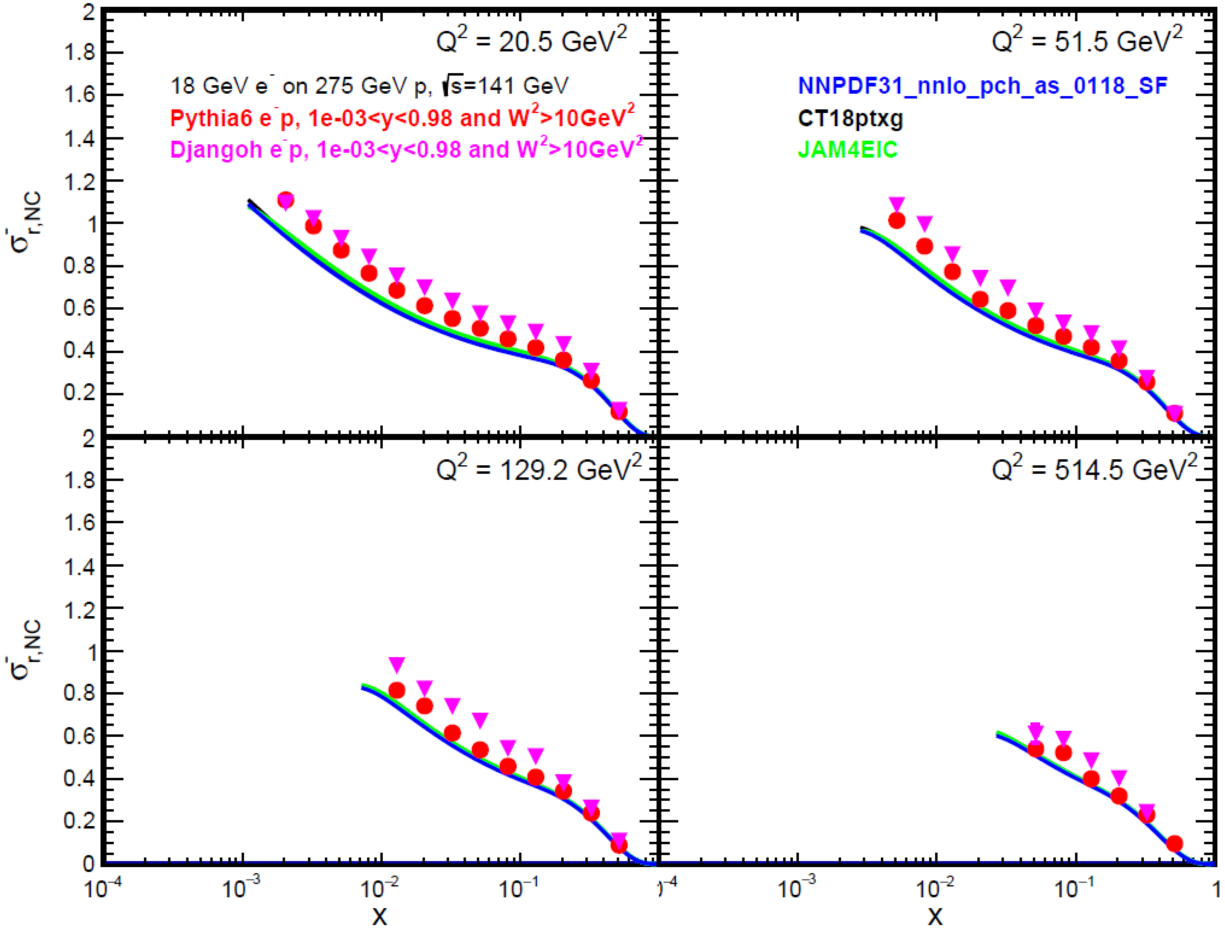

Scattered Lepton Angle
Scattered Lepton Energy
E_e = 18 GeV
E_p = 275 GeV
θ_e = 10°
θ_e = 90°
θ_e = 150°
θ_e = 170°
θ_e = 175°
E'_e = 90 GeV
E'_e = 45 GeV
E'_e = 20 GeV
E'_e = 10 GeV
E'_e = 16 GeV
y = 1
y = 0.1
y = 0.01
y = 0.001
Q^2 [GeV^2]
x_B


d^2N/dxdQ^2 / 10fb^-1 (N.C. Inclusive Simulation)
E_e = 18 GeV
E_p = 275 GeV
y = 1
y = 0.1
y = 0.01
y = 0.001
Q^2 [GeV^2]
x_B

Last Time



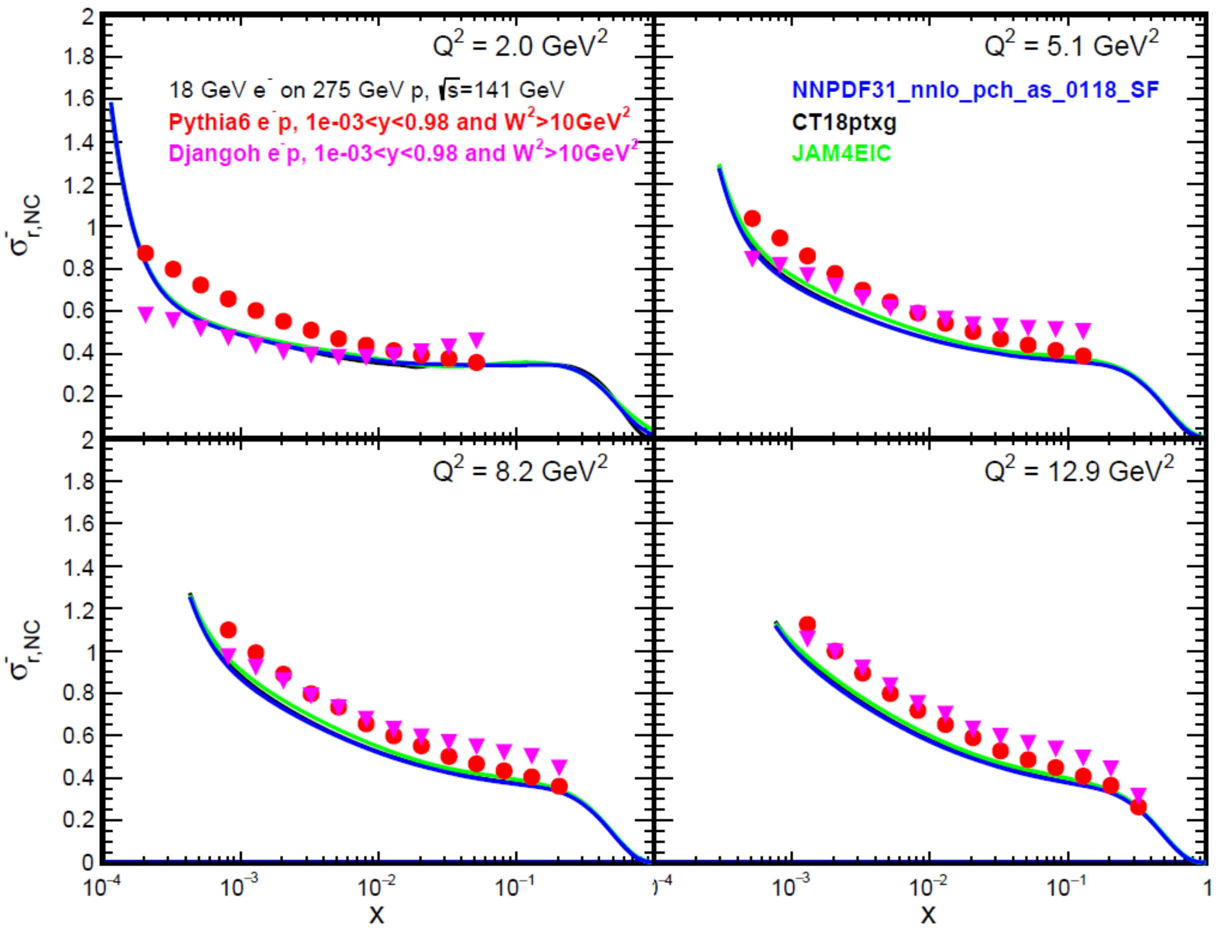
Q^2 = 2.0 GeV^2
18 GeV e- on 275 GeV p, √s=141 GeV
Pythia6 e-p, 1e-03<y<0.98 and W^2>10GeV^2
Djangoh e-p, 1e-03<y<0.98 and W^2>10GeV^2
Q^2 = 5.1 GeV^2
NNPDF31_nnlo_pch_as_0118_SF
CT18ptxg
JAM4EIC
Q^2 = 8.2 GeV^2
Q^2 = 12.9 GeV^2
σ̃r,NC
x

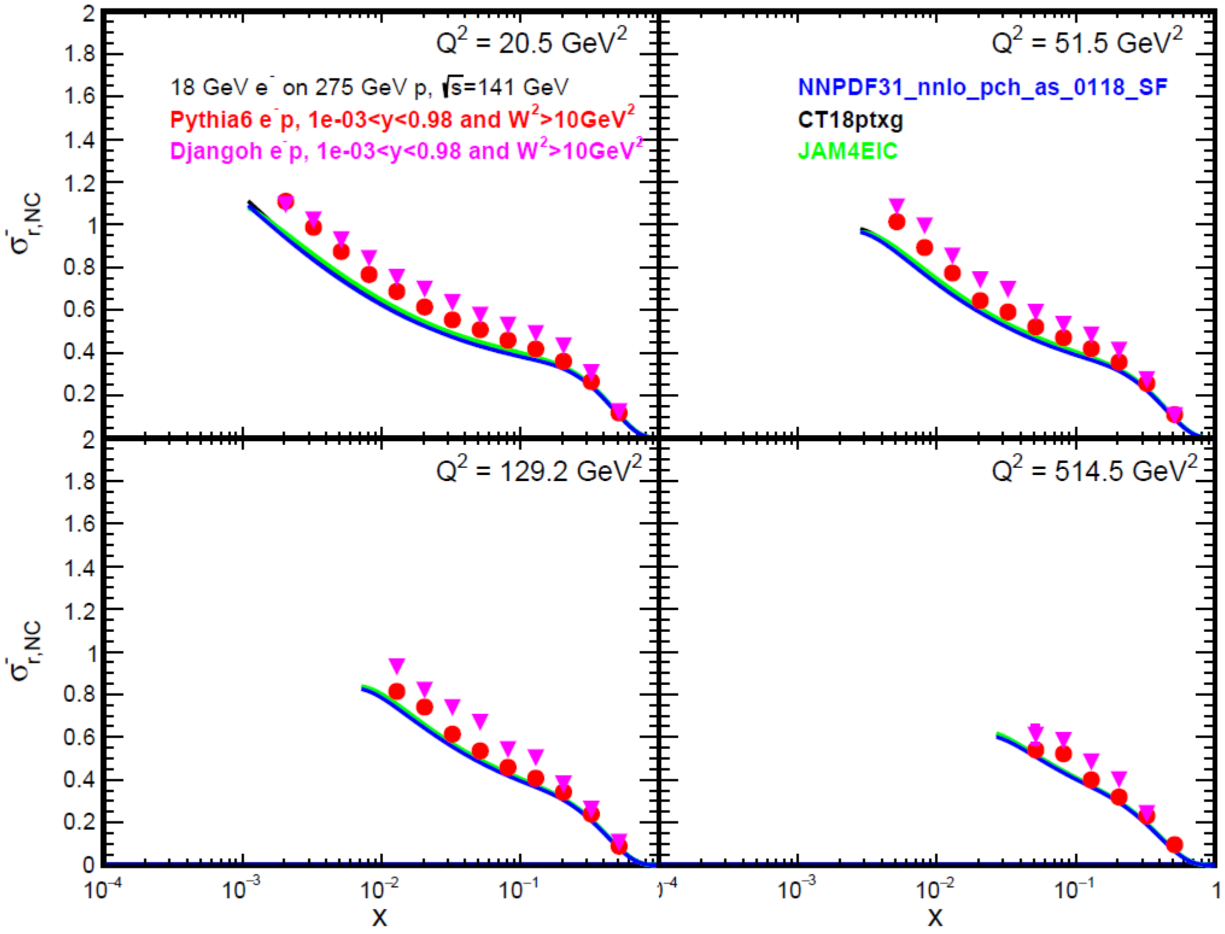


Q^2 = 20.5 GeV^2
18 GeV e- on 275 GeV p, √s=141 GeV
Pythia6 e-p, 1e-03<y<0.98 and W^2>10GeV^2
Djangoh e-p, 1e-03<y<0.98 and W^2>10GeV^2
Q^2 = 51.5 GeV^2
NNPDF31_nnlo_pch_as_0118_SF
CT18ptxg
JAM4EIC
Q^2 = 129.2 GeV^2
Q^2 = 514.5 GeV^2
σ̃r,NC
x

Last Time

Pythia6 and *Djangoh* events generated with QED radiative effects OFF, and perfect detector acceptance and resolution.





Cross Section Measurement

We want to measure:

$$\sigma_{r,NC}^{e^{\pm}p\rightarrow e^{\pm}X} = \frac{Q^4 x}{2\pi\alpha^2 Y_+} \times \frac{d^2\sigma_{NC}^{e^{\pm}p\rightarrow e^{\pm}X}}{dx dQ^2} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L \qquad Y_{\pm} = 1 \pm (1-y)^2$$

We actually measure:

$$\left(\frac{d\sigma}{dx dQ^2}\right)_{meas} = \frac{N_{bin}}{\mathcal{L}\Delta x \Delta Q^2}$$

Cross Section Measurement

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We should apply a bin-centering correction factor:

(assuming QED radiative effects are OFF in event generator)

$$\left(\frac{d\sigma^{Born}}{dxdQ^2}\right)^{corr}_{meas} = \left(\frac{d\sigma}{dxdQ^2}\right)_{meas} \times \frac{\sigma^{Model,Born}_{Center}}{\sigma^{Model,Born}_{Average}}$$

Cross Section Measurement

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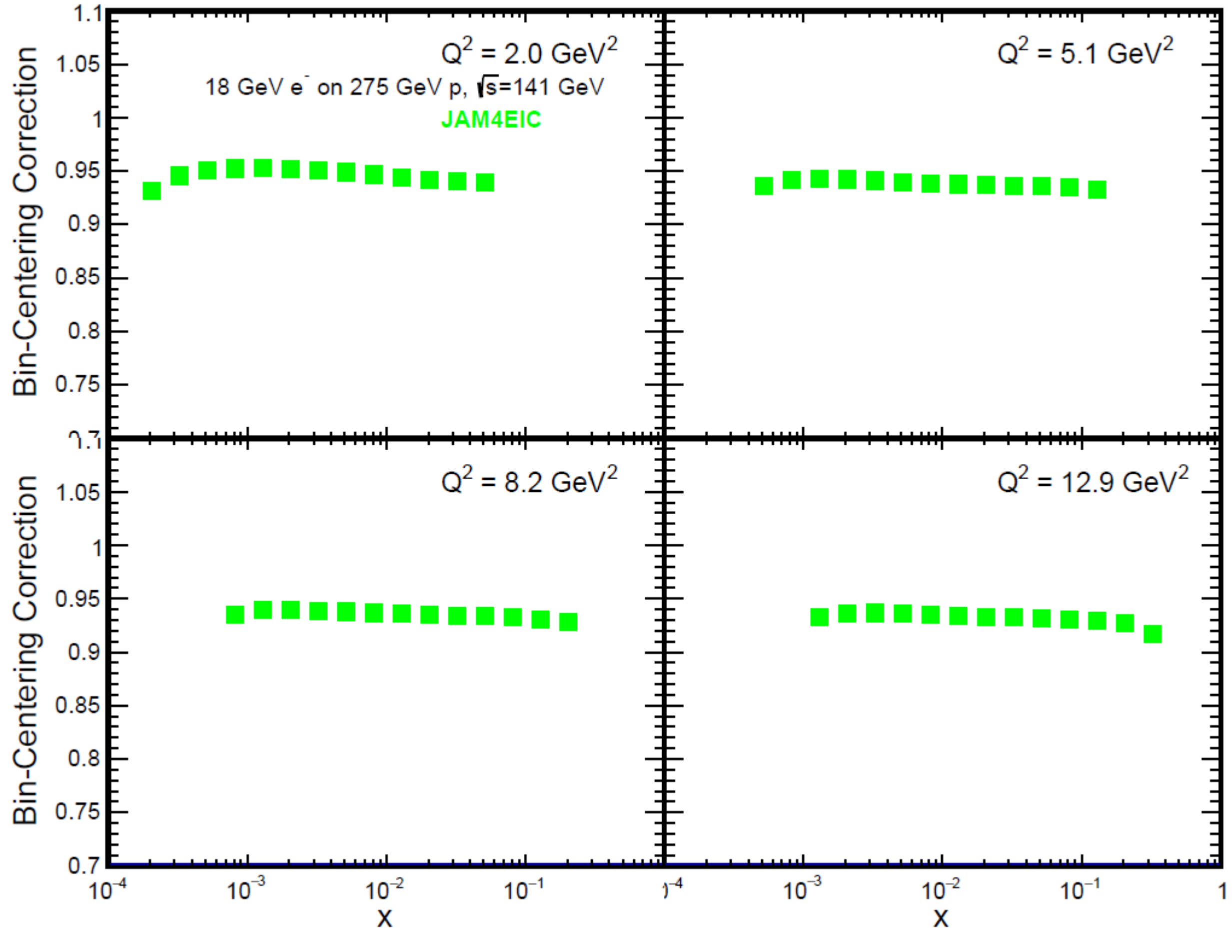
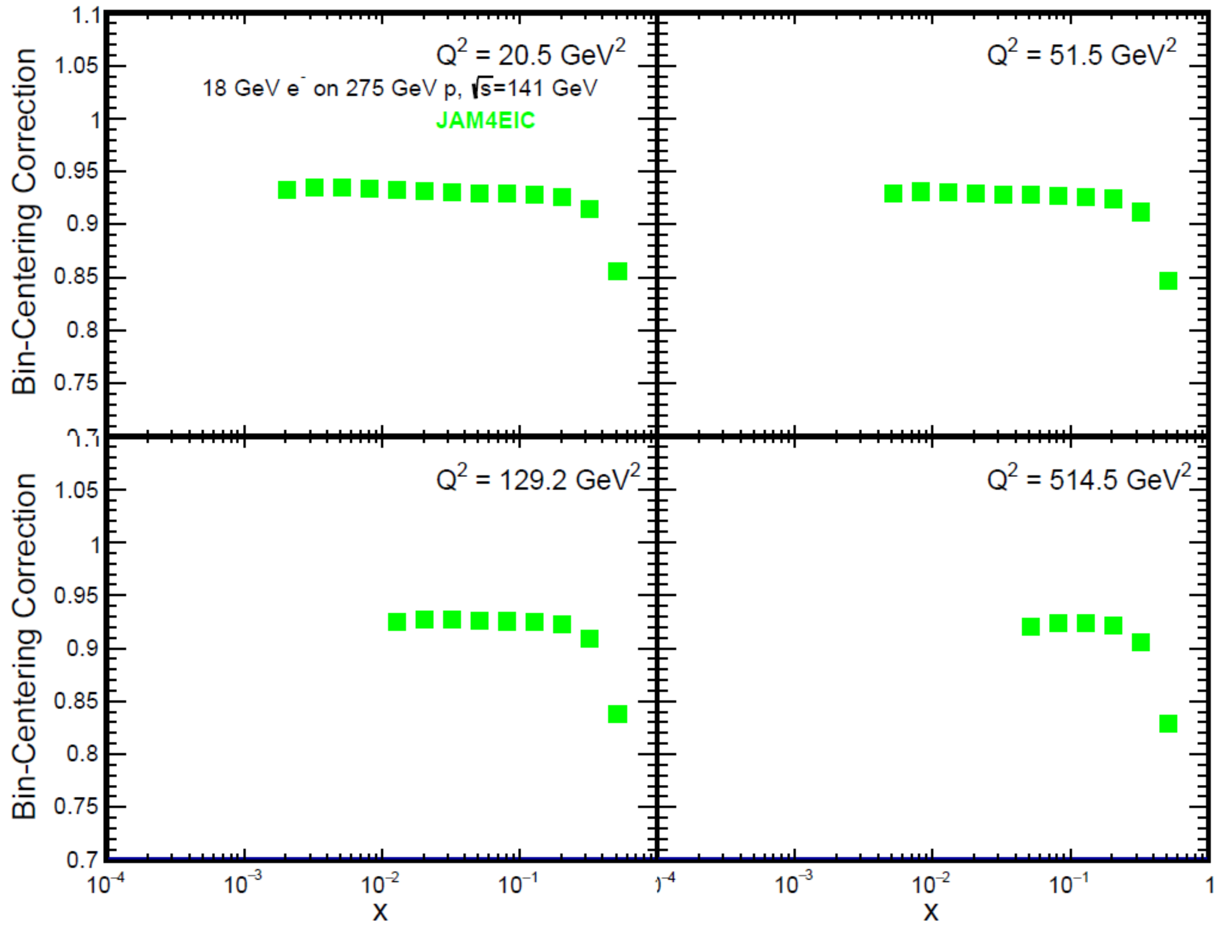
BC Correction Factor

Bin-Centering Correction Factor

$$\frac{\sigma^{Model,Born}_{Center}}{\sigma^{Model,Born}_{Average}}$$

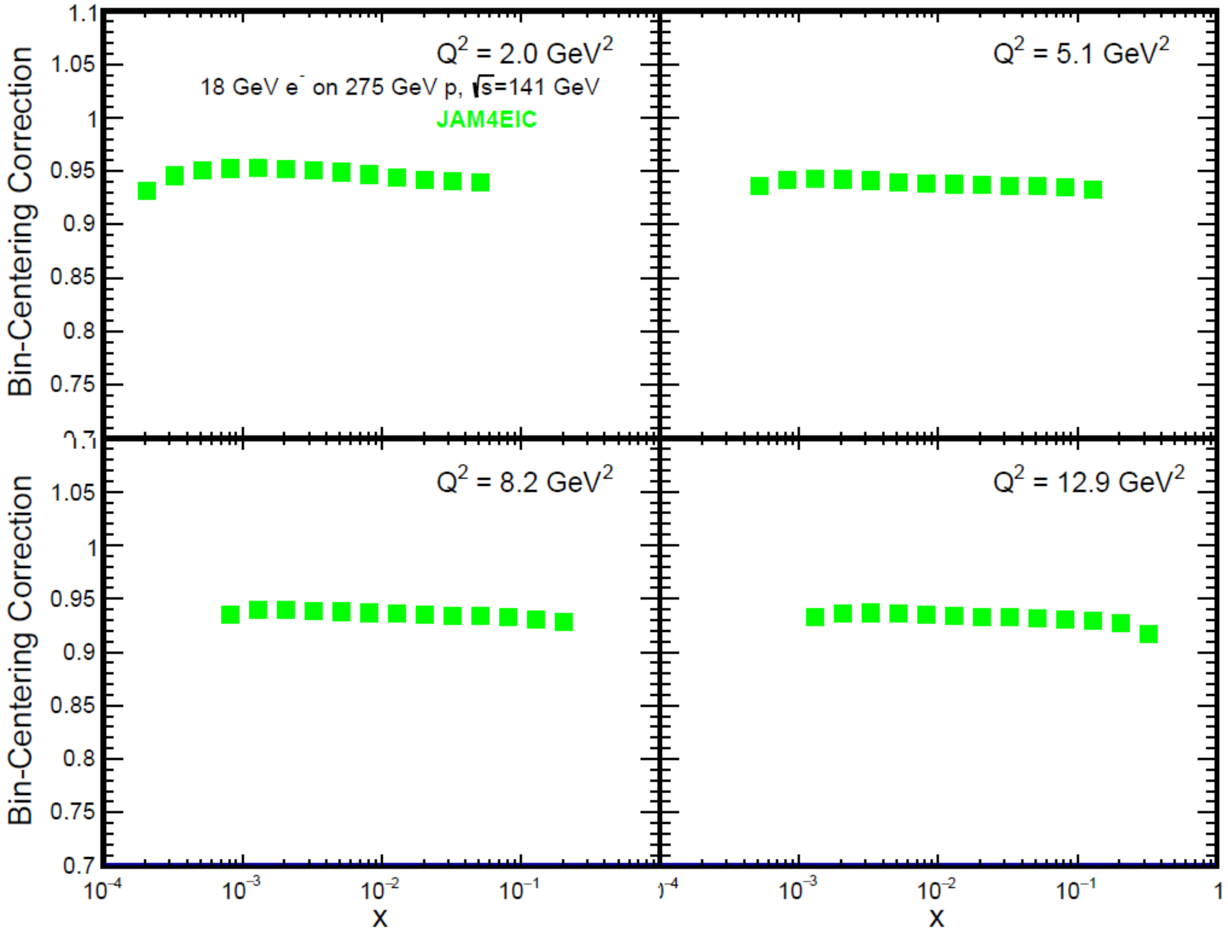


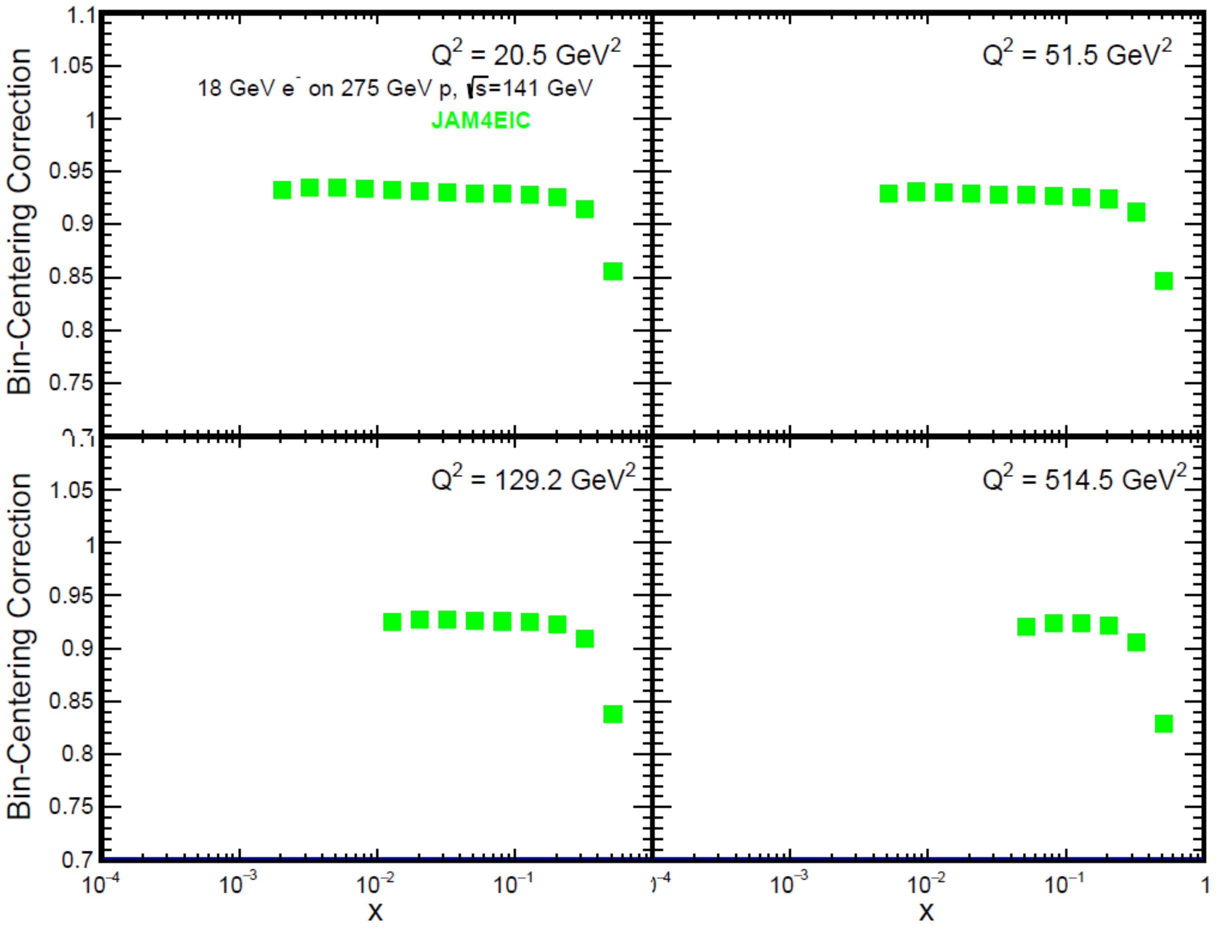


Bin-Centering Correction Factor

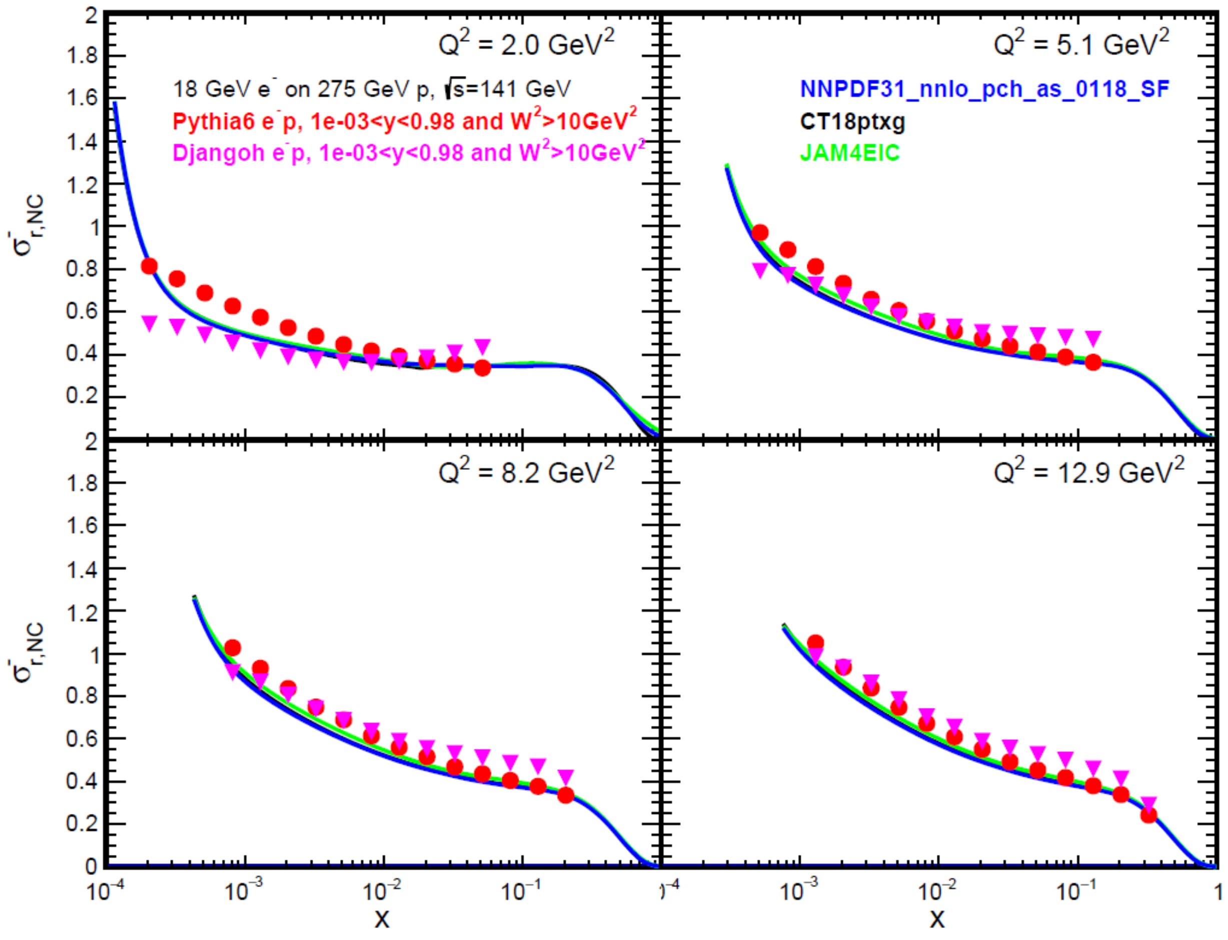
$$\frac{\sigma^{Model,Born}_{Center}}{\sigma^{Model,Born}_{Average}}$$

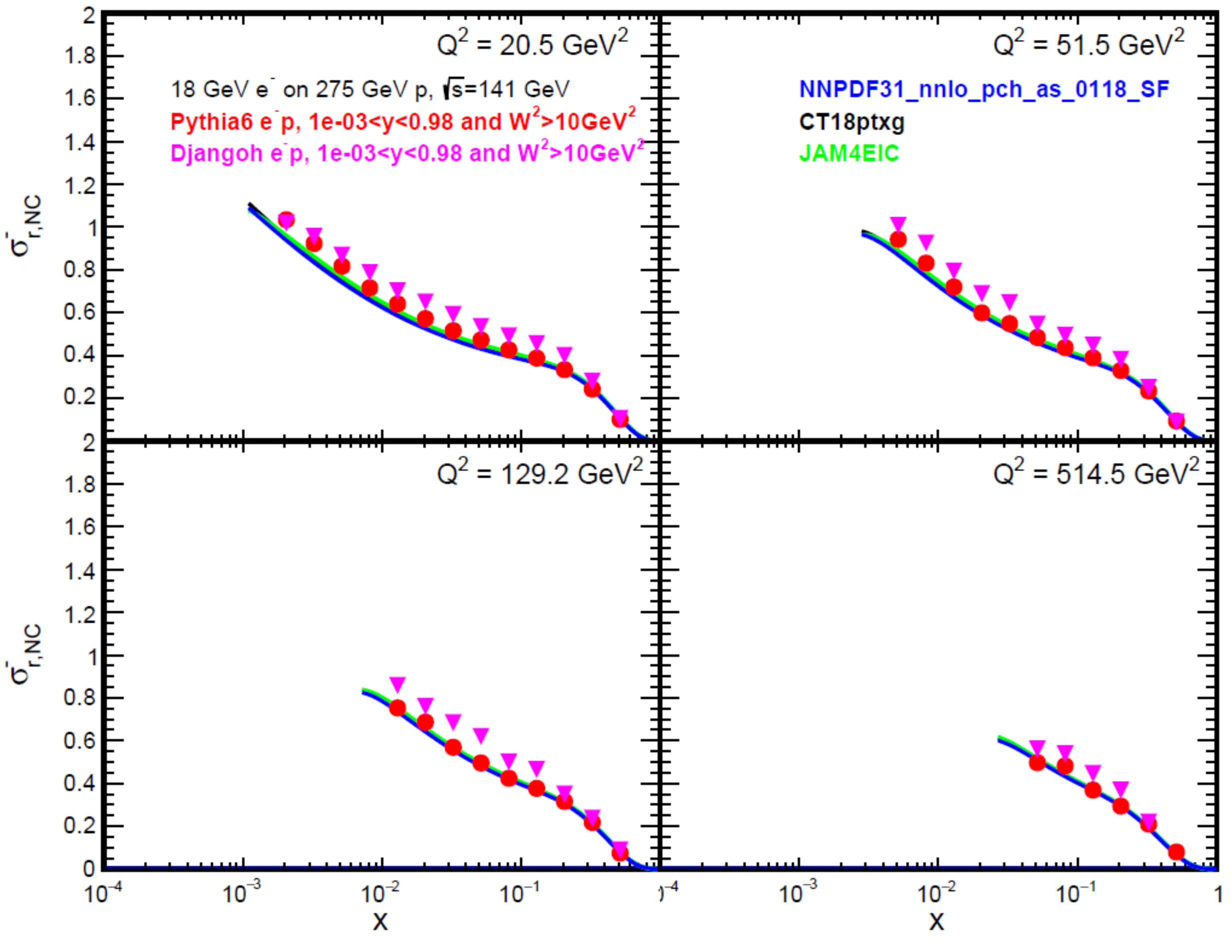
Correction is about 5-8% for the chosen binning





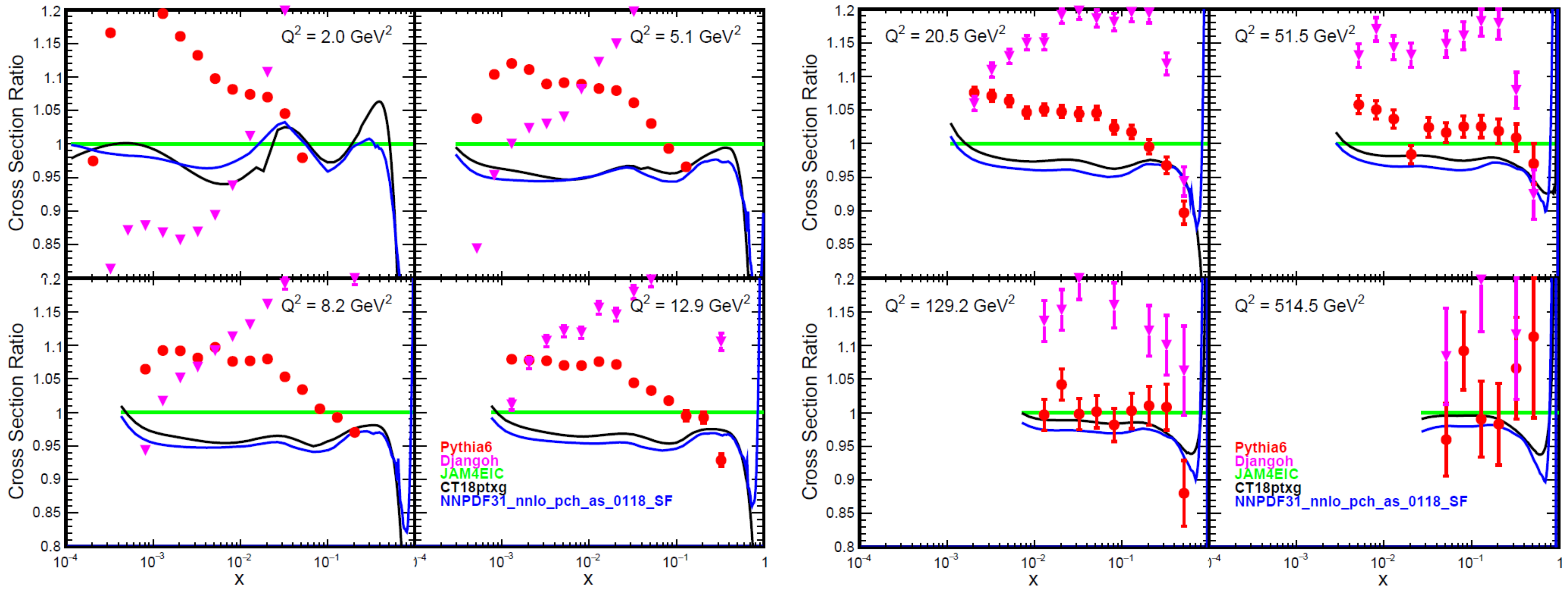
Cross Section with B.C. Correction





Cross Section Ratios

Uncertainties are based on the number of events generated – not scaled to any particular luminosity



The central values for the 3 theory curves can vary by 3-5%. But JAM was extracted at NLO, while the other 2 models are at NNLO.

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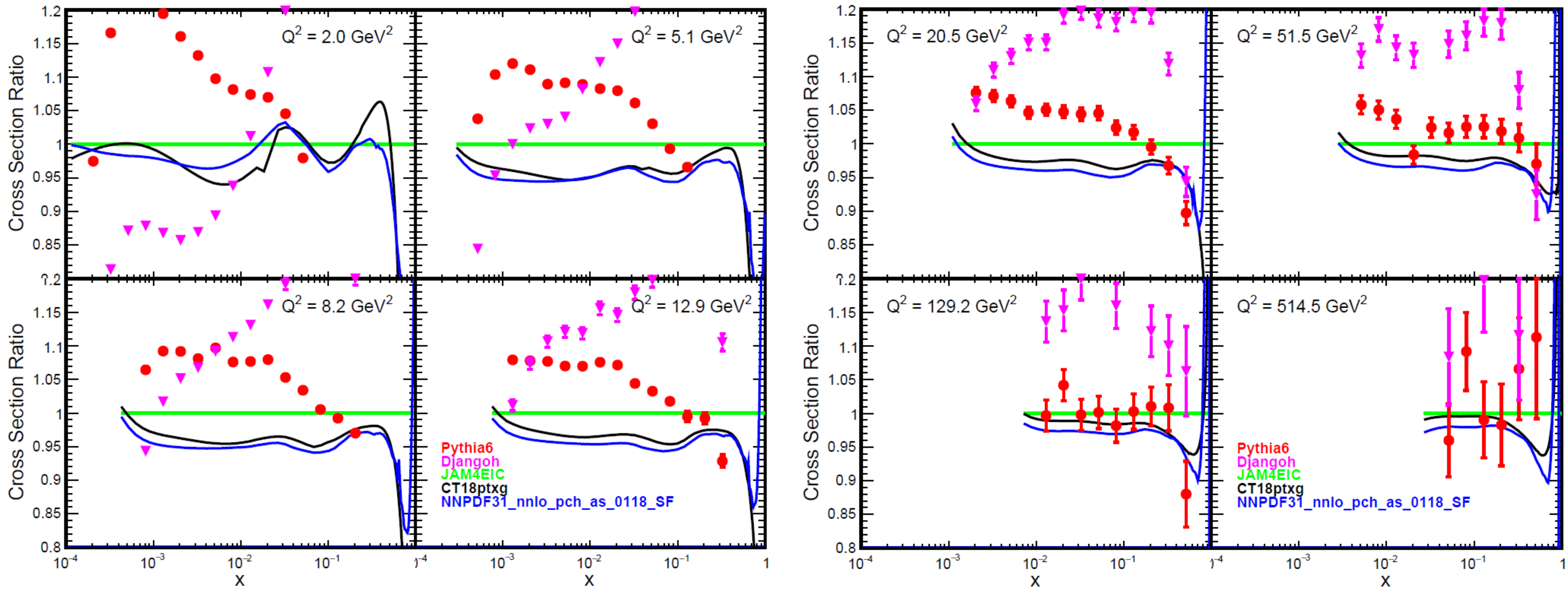
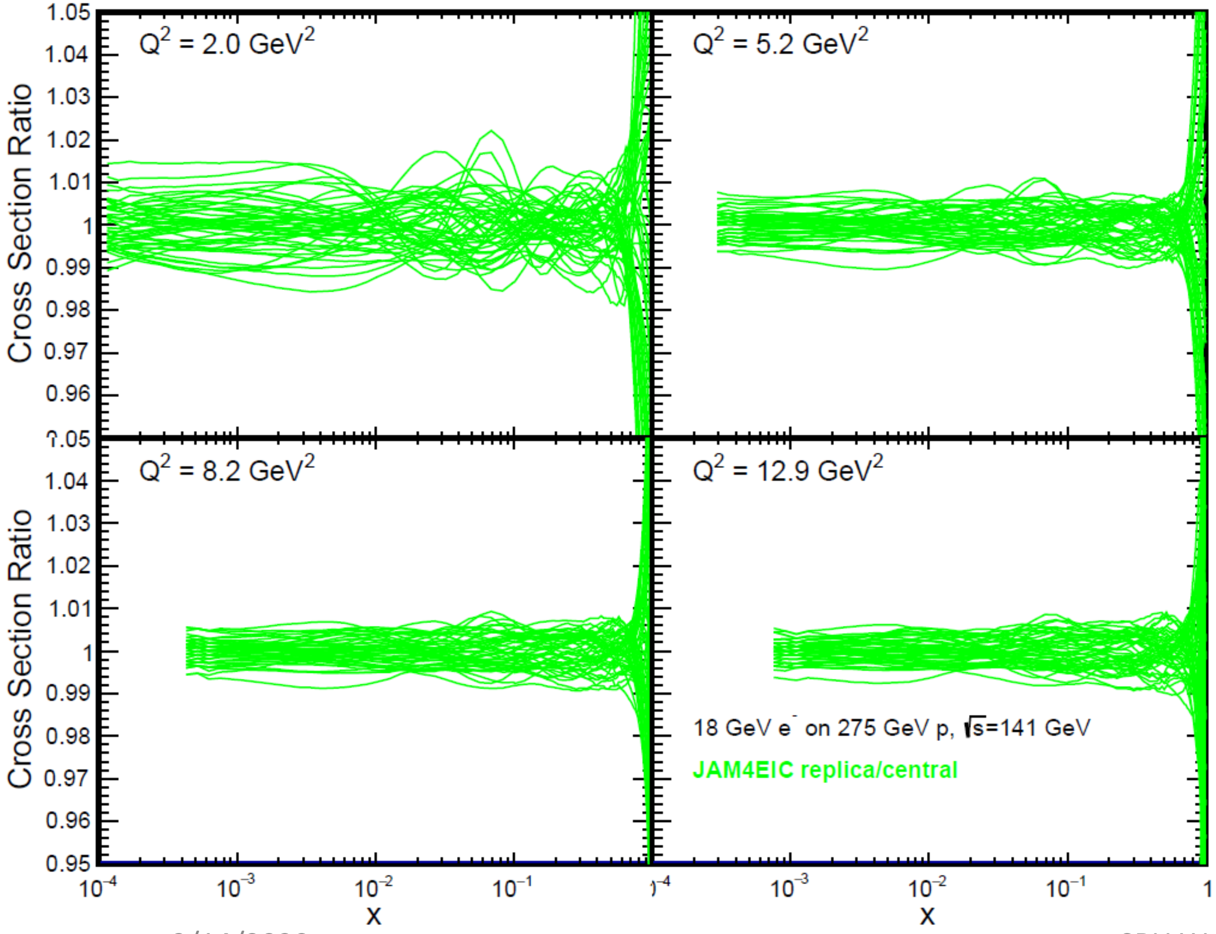
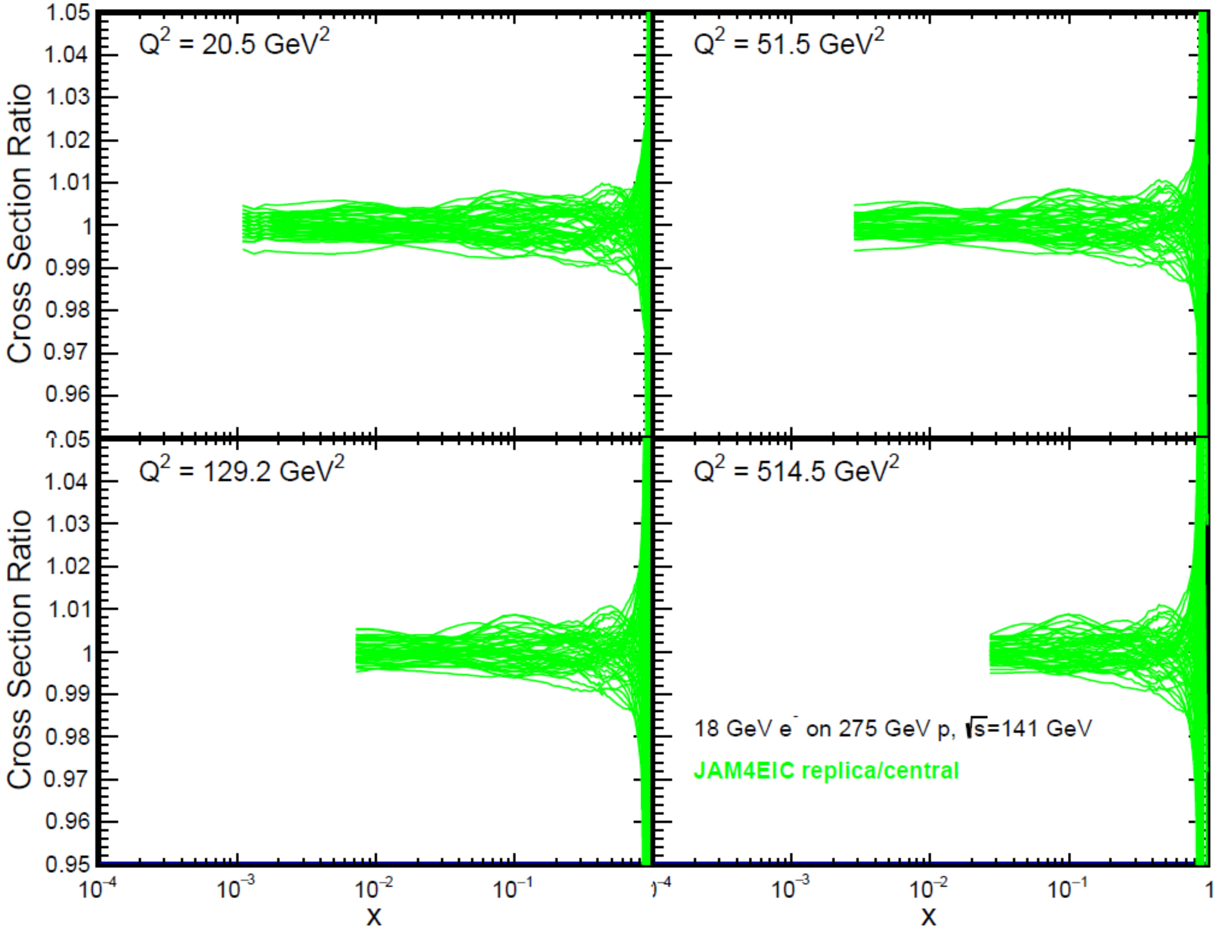


What really matters is how much the data can help constrain the uncertainty in a specific model. Here we see the replicas vary by 1-2% from the central value. Note, however, this does not necessarily mean we need to make measurements better than 2% to make an impact – we need to make fits.

Cross Section Ratios

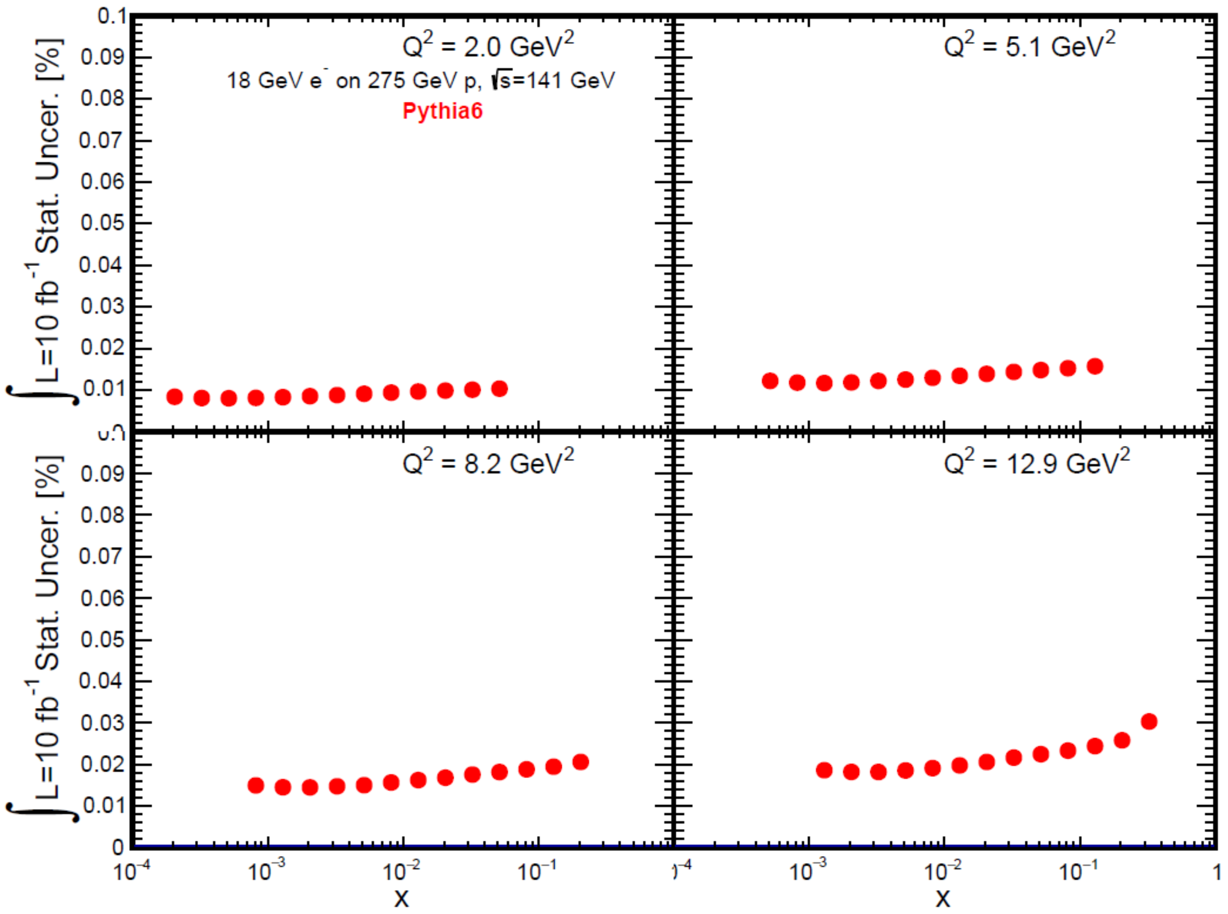


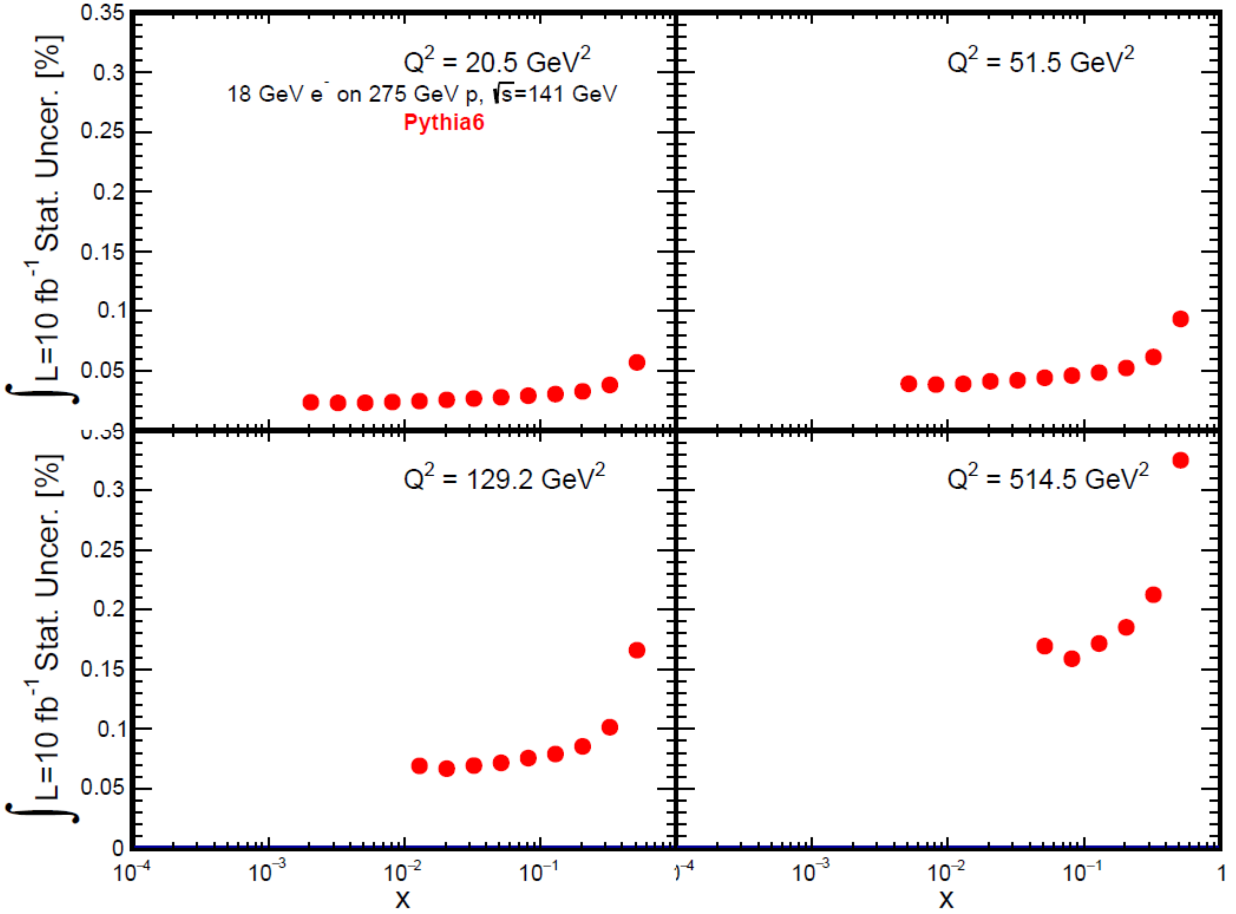


Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})		

Cross Section Uncertainties – Statistics





Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})	0.01-0.35	-

Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})	0.01-0.35	-
Luminosity	-	~1
Electron Purity	-	~1 (for 90% purity)

Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
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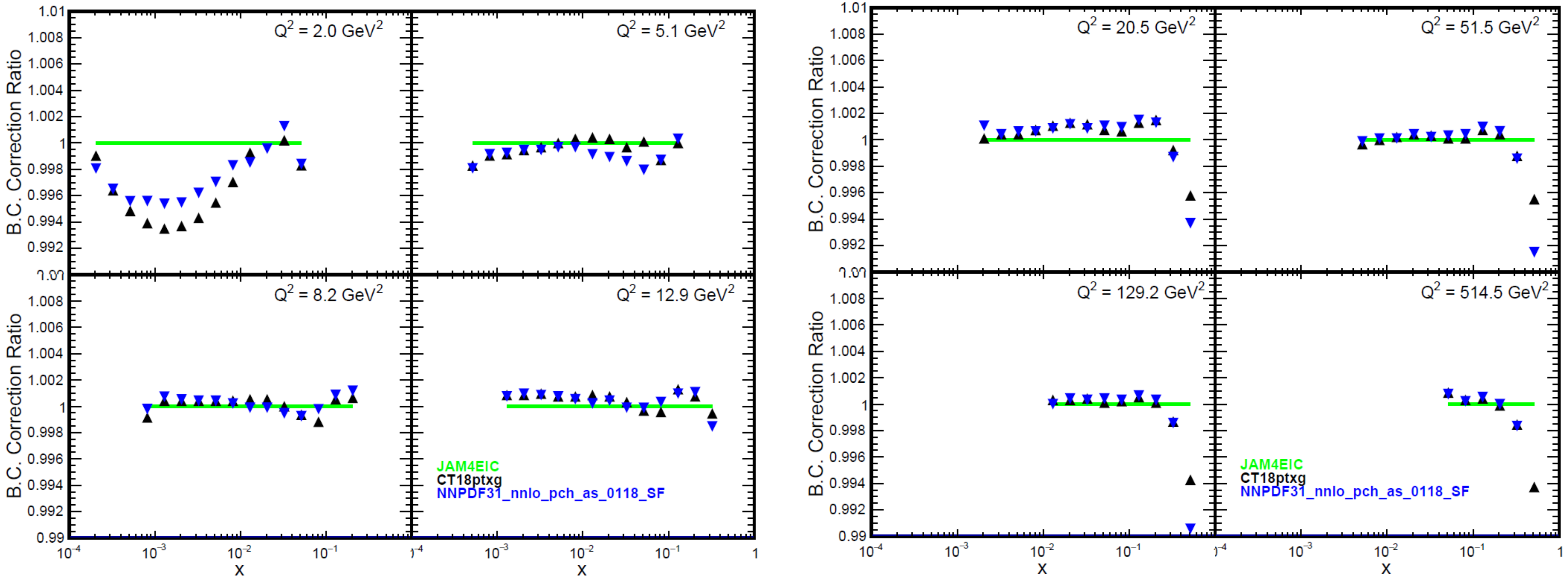
Bin-Centering		

Cross Section Uncertainties – Bin-Centering



Cross Section Uncertainties

	Point-to-Point (%)	Normalization (%)
Statistics (10 fb^{-1})	0.01-0.35	-
Luminosity	-	~1
Electron Purity	-	~1 (for 90% purity)
Bin-Centering	<0.5	<0.5

Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})	0.01-0.35	-
Luminosity	-	~1
Electron Purity	-	~1 (for 90% purity)
Bin-Centering	<0.5	<0.5
Radiative Corrections		
Acceptance / Bin-Migration		
Total		

Cross Section Measurement: Simple 'Unfolding'

For real data – or for an event generator with QED radiative effects and detector resolution/acceptance effects – we can extract the true cross section as follows:

$$\left(\frac{d\sigma^{Born}}{dxdQ^2}\right)^{corr}_{meas} = \left(\frac{d\sigma}{dxdQ^2}\right)_{meas} \times \frac{N^{Rad}_{gen}}{N^{Rad}_{rec}} \times \frac{\sigma^{Model,Born}_{Average}}{\sigma^{Model,Rad}_{Average}} \times \frac{\sigma^{Model,Born}_{Center}}{\sigma^{Model,Born}_{Average}}$$

$$\left(\frac{d\sigma}{dxdQ^2}\right)_{meas} = \frac{N_{bin}}{\mathcal{L}\Delta x \Delta Q^2}$$

Cross Section Measurement: Simple ‘Unfolding’

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All detector acceptance and resolution effects are accounted for here. It is the ratio of the number of events generated divided by the number reconstructed in a given bin, calculated using an event generator including QED radiative effects. Note that the scattered electron should be used to calculate the kinematic variables in the numerator, rather than the (true) virtual Boson. To wit, the ratio goes to 1 (i.e. no correction) for a detector with perfect acceptance and resolution.

$$\left(\frac{d\sigma}{dxdQ^2}\right)_{meas} = \frac{N_{bin}}{\mathcal{L}\Delta x \Delta Q^2}$$

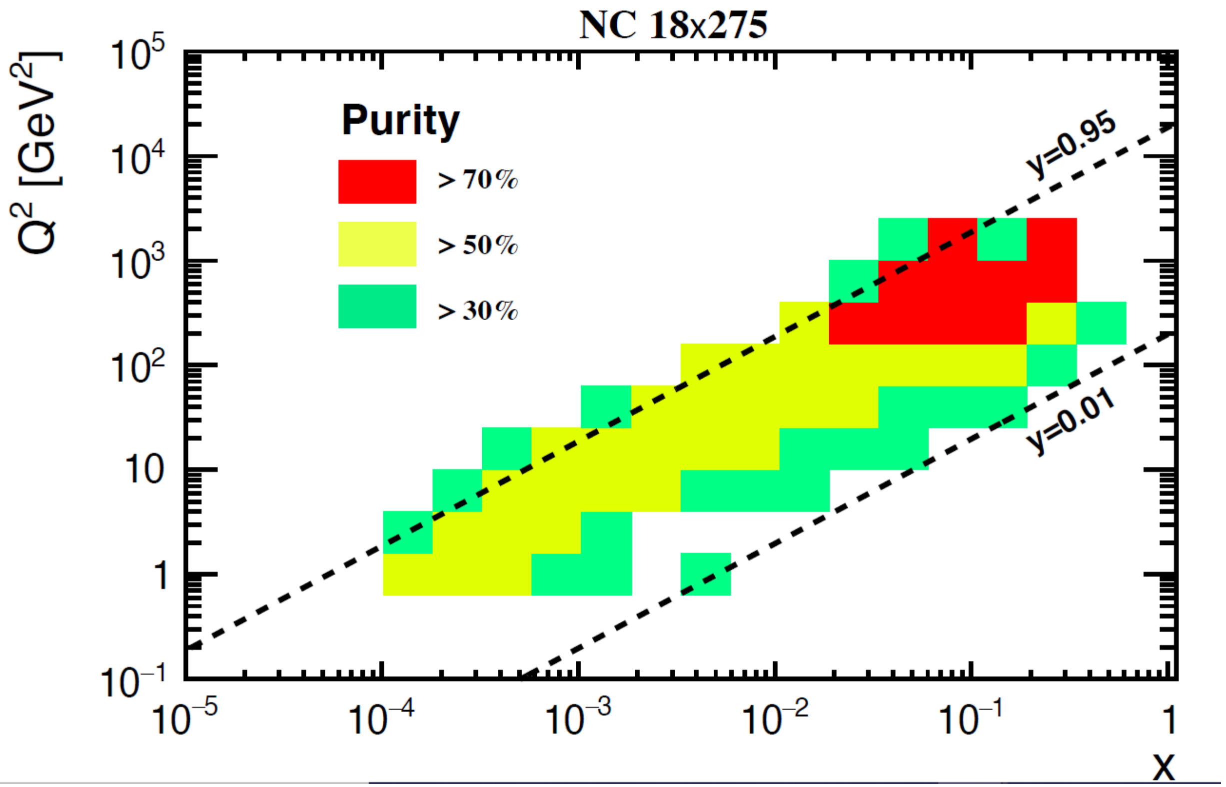
Standard Detector Matrix

η	Nomenclature			Tracking			Electrons		π/K/p		HCAL	Muons	
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Resolution σ_E/E		
-6.9 to -5.8	↓ p/A	Auxiliary Detectors	low-Q2 tagger	σθ/θ < 1.5%; 10-6 < Q2 < 10-2 GeV2									
...													
-4.5 to -4.0			Instrumentation to separate charged particles from photons				2%/√E						
-4.0 to -3.5													
-3.5 to -3.0		Central Detector		σp/p ~ 0.1%⊕0.5%									
-3.0 to -2.5			Backward Detector										
-2.5 to -2.0				σp/p 0.1%⊕0.5%		TBD	2%/√E		≤ 7 GeV/c		~50%/√E		
-2.0 to -1.5					~5% or less X_0 cannot evaluate without full detector simulations. Critical that this is minimized		7%/√E	π suppression up to 1:104					
-1.5 to -1.0				σp/p 0.05%⊕0.5%			7%/√E						
-1.0 to -0.5						σxyz ~ 20 μm, d0(z) ~ d0(rφ) ~ 20/pTGeV μm + 5 μm							
-0.5 to 0.0			Barrel	σp/p ~0.05%×p+0.5%					≤ 5 GeV/c	≥ 3σ		TBD	
0.0 to 0.5													
0.5 to 1.0													
1.0 to 1.5													
1.5 to 2.0				σp/p ~0.05%×p+1.0%					≤ 8 GeV/c				
2.0 to 2.5			Forward Detectors			TBD			≤ 20 GeV/c		~50%/√E		
2.5 to 3.0				σp/p ~ 0.1%×p+2.0%			(10-12)%/√E						
3.0 to 3.5									≤ 45				
3.5 to 4.0	↑ e	Auxiliary Detectors	Instrumentation to separate charged particles from photons	Coverage as far forward as possible is critical for JB reconstruction							Coverage as far forward as possible is critical for JB reconstruction		
4.0 to 4.5													
...			Neutron Detection										
> 6.2			Proton Spectrometer	σintrinsic(|t|)/|t| < 1%; Acceptance: 0.2 < pt < 1.2 GeV/c									

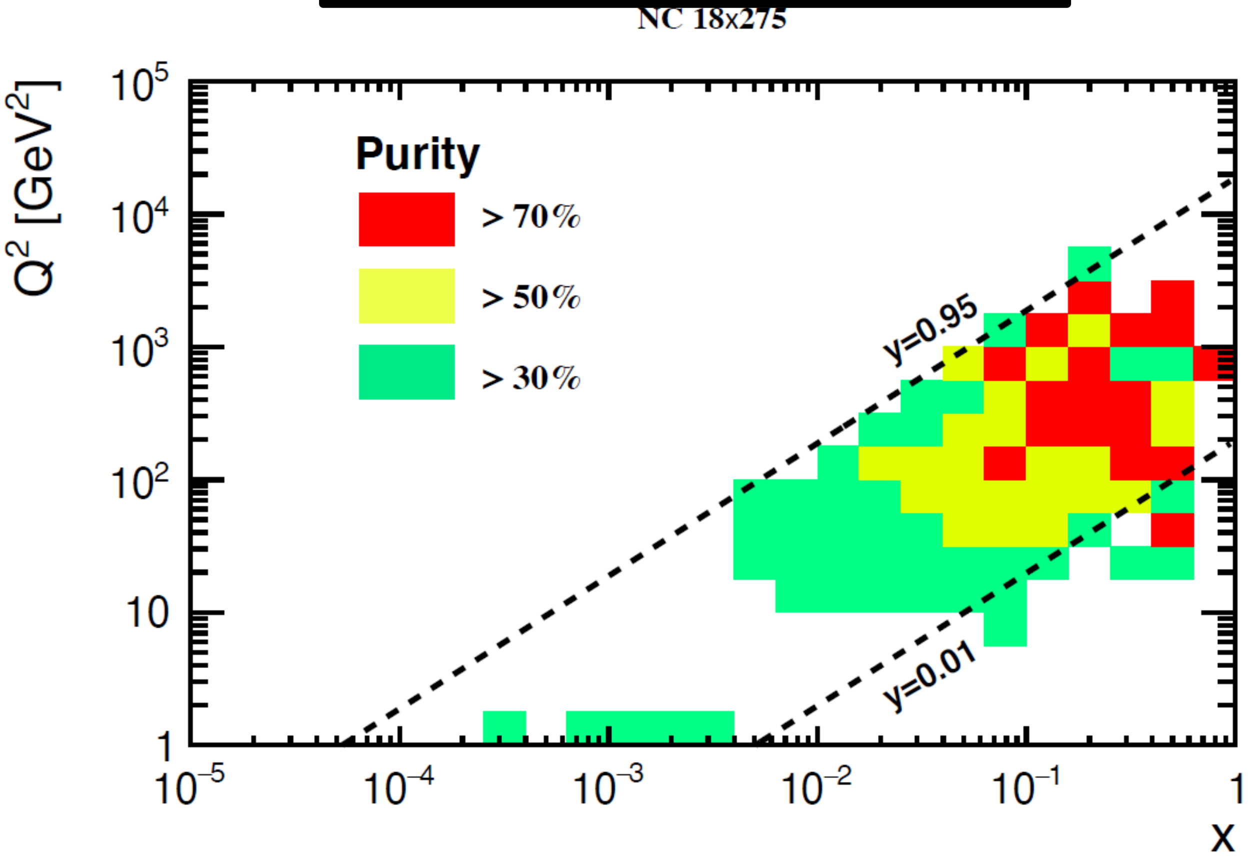
Plots by Xiaoxuan Chu

Standard Detector Matrix

Electron Reconstruction



J.B. Reconstruction



Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})	0.01-0.35	-
Luminosity	-	~1
Electron Purity	-	~1 (for 90% purity)
Bin-Centering	<0.5	<0.5
Radiative Corrections (*HERA*)	1	-
Acceptance / Bin-Migration		
Total		

Cross Section Uncertainties

	Point-to-Point (%)	**Normalization (%)**
Statistics (10 fb^{-1})	0.01-0.35	-
Luminosity	-	~1
Electron Purity	-	~1 (for 90% purity)
Bin-Centering	<0.5	<0.5
Radiative Corrections (*HERA*)	1	-
Acceptance / Bin-Migration + Trigger & Tracking Eff. + Charge-Symmetric Background	1-2	2-4
Additional uncertainty for y<0.01 bins	2	-
Total	1.5-2.3 (2.5-3 for y<0.01)	2.5-4.3

Assessing the Impact – In Progress

1. Full fits – potentially in next few months
2. Statistical t-type tests – Theorists in the Inclusive group
3. Reweighting studies – My current work