Electroweak and BSM Physics Working Group Update

- weak mixing angle
- electroweak interference (γZ) structure functions
- leptoquarks

- also looking into: SMEFT analysis, dark photon and axion searches

Neutral Current Inclusive Physics

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

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

$$\left[g_1^\gamma, g_1^{\gamma Z}, g_1^Z\right] = \frac{1}{2}\sum_q \left[e_q^2, 2e_q g_V^q, g_V^{q\,2} + g_A^{q\,2}\right](\Delta q+\Delta\bar{q}),$$

$$\left[g_5^\gamma, g_5^{\gamma Z}, g_5^Z\right] = \sum_q \left[0, e_q g_A^q, g_V^q g_A^q\right](\Delta q-\Delta\bar{q}),$$

Inclusive NC cross sections:

$$\frac{d^2\sigma}{dxdy} = \frac{d^2\sigma_0}{dxdy} + P_e\frac{d^2\sigma_e}{dxdy} + P_p\frac{d^2\sigma_p}{dxdy} + P_eP_p\frac{d^2\sigma_{ep}}{dxdy}$$

Neglecting target-mass corrections:

$$\begin{aligned}\frac{d^2\sigma_0}{dxdy} &= \frac{4\pi\alpha^2}{xyQ^2}\Big\{(1-y)\left[F_2^\gamma - g_V^e\eta_{\gamma Z}F_2^{\gamma Z} + (g_V^{e\,2}+g_A^{e\,2})\eta_Z F_2^Z\right] \\ &\quad + xy^2\left[F_1^\gamma - g_V^e\eta_{\gamma Z}F_1^{\gamma Z} + (g_V^{e\,2}+g_A^{e\,2})\eta_Z F_1^Z\right] - \frac{xy}{2}(2-y)\left[g_A^e\eta_{\gamma Z}F_3^{\gamma Z} - 2g_V^e g_A^e\eta_Z F_3^Z\right]\Big\} \quad (2)\end{aligned}$$

$$\begin{aligned}\frac{d^2\sigma_e}{dxdy} &= \frac{4\pi\alpha^2}{xyQ^2}\Big\{(1-y)\left[g_A^e\eta_{\gamma Z}F_2^{\gamma Z} - 2g_V^e g_A^e\eta_Z F_2^Z\right] + xy^2\left[g_A^e\eta_{\gamma Z}F_1^{\gamma Z} - 2g_V^e g_A^e\eta_Z F_1^Z\right] \\ &\quad + \frac{xy}{2}(2-y)\left[g_V^e\eta_{\gamma Z}F_3^{\gamma Z} - (g_V^{e\,2}+g_A^{e\,2})\eta_Z F_3^Z\right]\Big\}\,, \quad (3)\end{aligned}$$

$$\begin{aligned}\frac{d^2\sigma_p}{dxdy} &= \frac{4\pi\alpha^2}{xyQ^2}\Big\{y\,(2-y)\left[g_A^e\eta_{\gamma Z}g_1^{\gamma Z} - 2g_V^e g_A^e\eta_Z g_1^Z\right] + (1-y)\left[-g_V^e\eta_{\gamma Z}g_4^{\gamma Z} + (g_V^{e\,2}+g_A^{e\,2})\eta_Z g_4^Z\right] \\ &\quad + xy^2\left[-g_V^e\eta_{\gamma Z}g_5^{\gamma Z} + (g_V^{e\,2}+g_A^{e\,2})\eta_Z g_5^Z\right]\Big\}\,, \quad (4)\end{aligned}$$

$$\begin{aligned}\frac{d^2\sigma_{ep}}{dxdy} &= \frac{4\pi\alpha^2}{xyQ^2}\Big\{y\,(2-y)\left[g_1^\gamma - g_V^e\eta_{\gamma Z}g_1^{\gamma Z} + (g_V^{e\,2}+g_A^{e\,2})\eta_Z g_1^Z\right] \\ &\quad + (1-y)\left[g_A^e\eta_{\gamma Z}g_4^{\gamma Z} - 2g_V^e g_A^e\eta_Z g_4^Z\right] + xy^2\left[g_A^e\eta_{\gamma Z}g_5^{\gamma Z} - 2g_V^e g_A^e\eta_Z g_5^Z\right]\Big\}\,, \quad (5)\end{aligned}$$

fermion	Q_f	g_A^f	g_V^f
ν_e, ν_μ, ν_τ	0	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W \approx -0.03$
u, c, t	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W \approx 0.19$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \approx -0.34$

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

Simulation

- Due to the high statistics needed for electroweak study (assuming 100 fb^{-1}), we used Djangoh.4.6.16 to generate 10M events and combined with fast smearing (Tyler Kutz /inclusive group, June concept for today, July concept upcoming)

- Used calculated cross sections to project expected statistics in a certain (x,Q2) bin

- Unfolded counts from detected (x,Q2) to leptonic (x,Q2), including uncertainty of dApv

- Extracting physics:

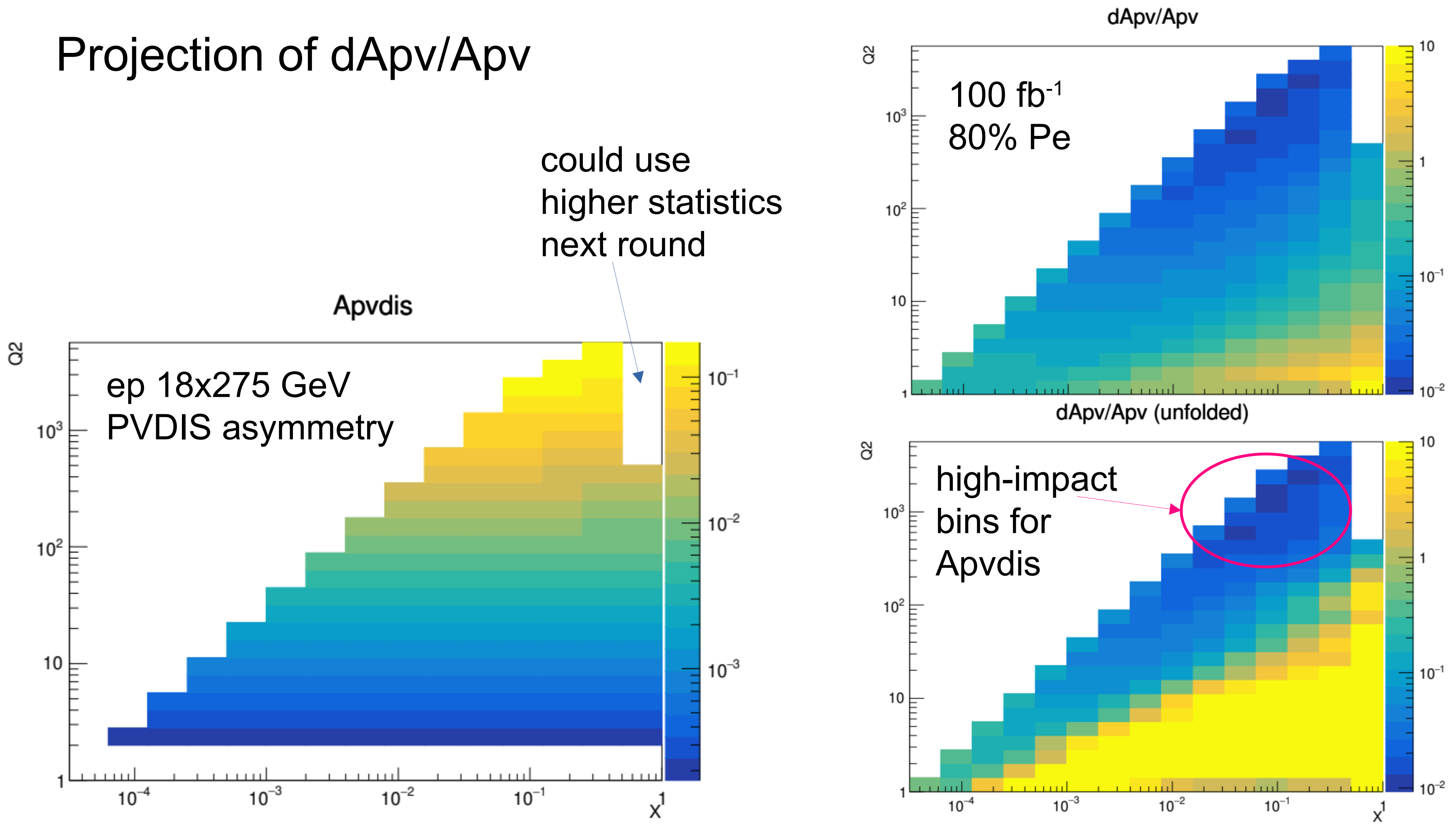
$$A_{PVDIS} \equiv \frac{\sigma_e}{\sigma_0}$$

  - Use calculated asymmetries to project dApv/Apv

  - Use unfolded counts to project cross section uncertainties and structure function results

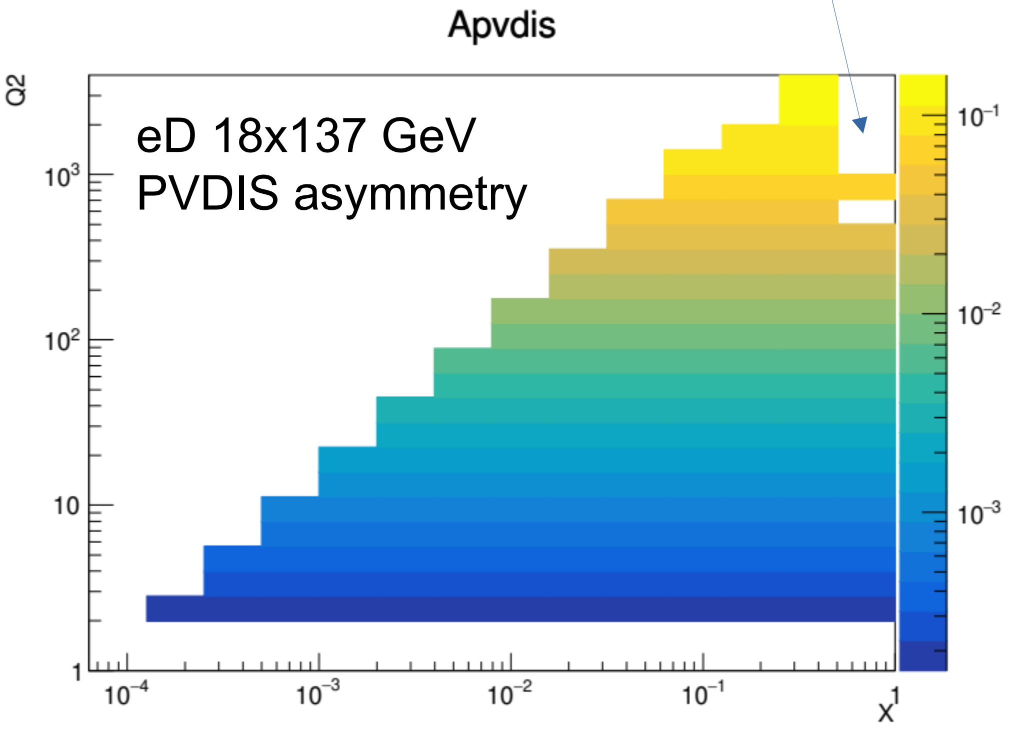
Projection of dApv/Apv

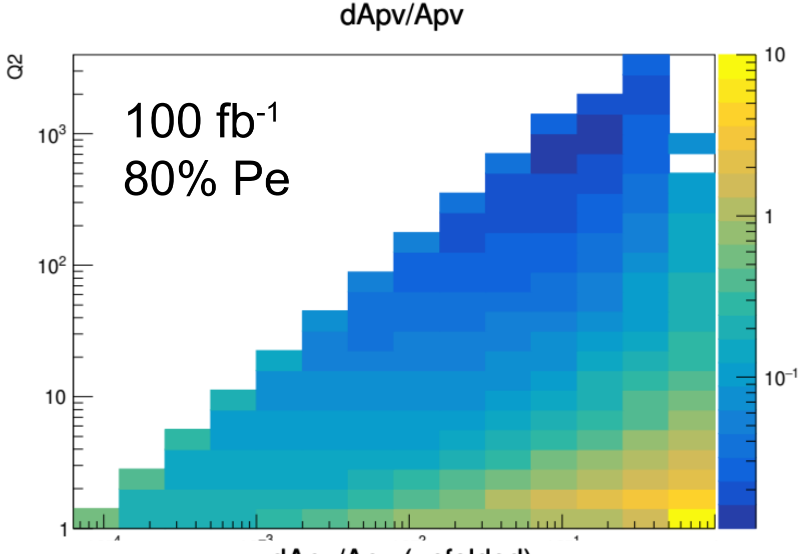
could use higher statistics next round

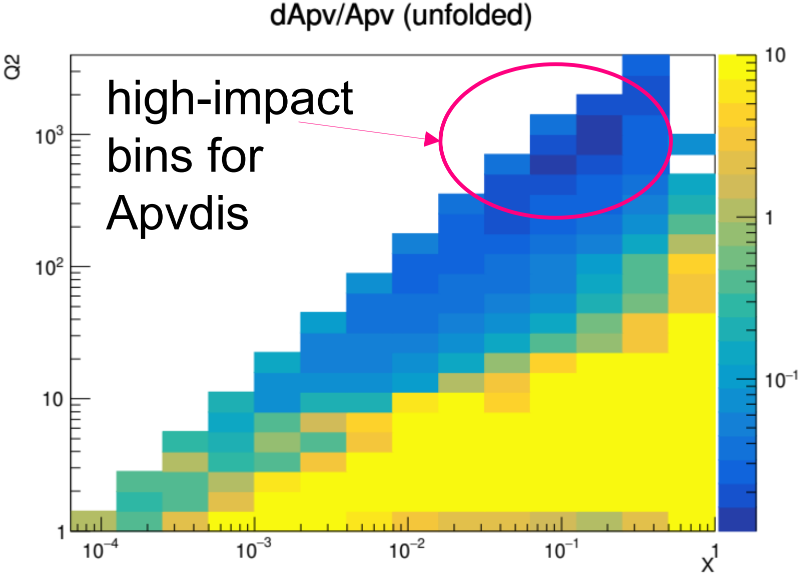


Projection of dApv/Apv

could use higher statistics next round







Fitting of Weak Mixing Angle

$$A_{RL}^{e^-} = \frac{\eta_{\gamma Z}\left[g_A^e\, 2y F_1^{\gamma Z} + g_A^e F_2^{\gamma Z}\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2}\right) + g_V^e (2-y) F_3^{\gamma Z}\right]}{2y F_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2}\right) F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e\, 2y F_1^{\gamma Z} + g_V^e \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2 xy}{Q^2}\right) F_2^{\gamma Z} + g_A^e (2-y) F_3^{\gamma Z}\right]}$$

- using both ep and eD data sets (smaller xmin), LO SF calculation
- PDF uncertainties evaluated by re-fitting pseudo data N times with N eigensets
- What remains to be done (next round):
  - Include Z terms (a few percent effect):
  - adding RGE (running)

going beyond previous (Stony Brook) analysis (which used eD low-energy approximation with cuts x>0.2, y>0.1)

Fitting of Weak Mixing Angle

(Alex Emmert/UVA)

- Caveat 1: no kinematic cut (yet), (x,Q2) cut should cause minimal change, but background cut will reduce useful data set by significant amount (see next slide);
- Caveat 2: simulation used 0.231, fitted result is 0.227 (mismatch in formula?)

	ep 18x275	eD 18x137
Luminosity	100 fb^{-1}	100 fb^{-1} (times nucleon xsection)
$d(\sin^2\theta_W)$ stat before unfolding	0.000375	0.000496
$d(\sin^2\theta_W)$ stat after unfolding	0.000406	0.000551
$d(\sin^2\theta_W)$ PDF using MSHT20nlo_as118 (68% CL)	0.000476	0.000215
Total (after unfolding + PDF)	0.000626	0.000593

YR ("read" from the graph, 100fb^{-1} ep 18x275 + 10fb^{-1} eD 18x100): <u>0.23495+/- 0.000974</u>

Adding some background effect

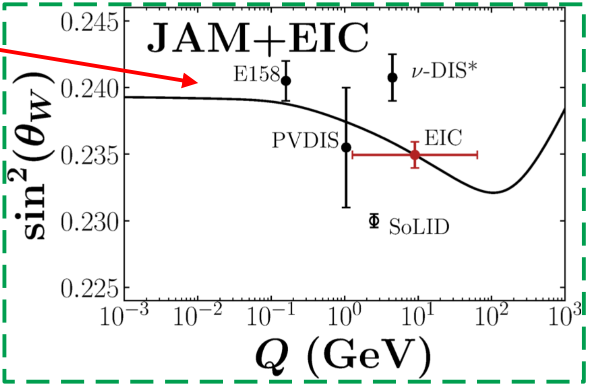
- Assuming we reject 50% of DIS data due to detector acceptance, high background region, etc

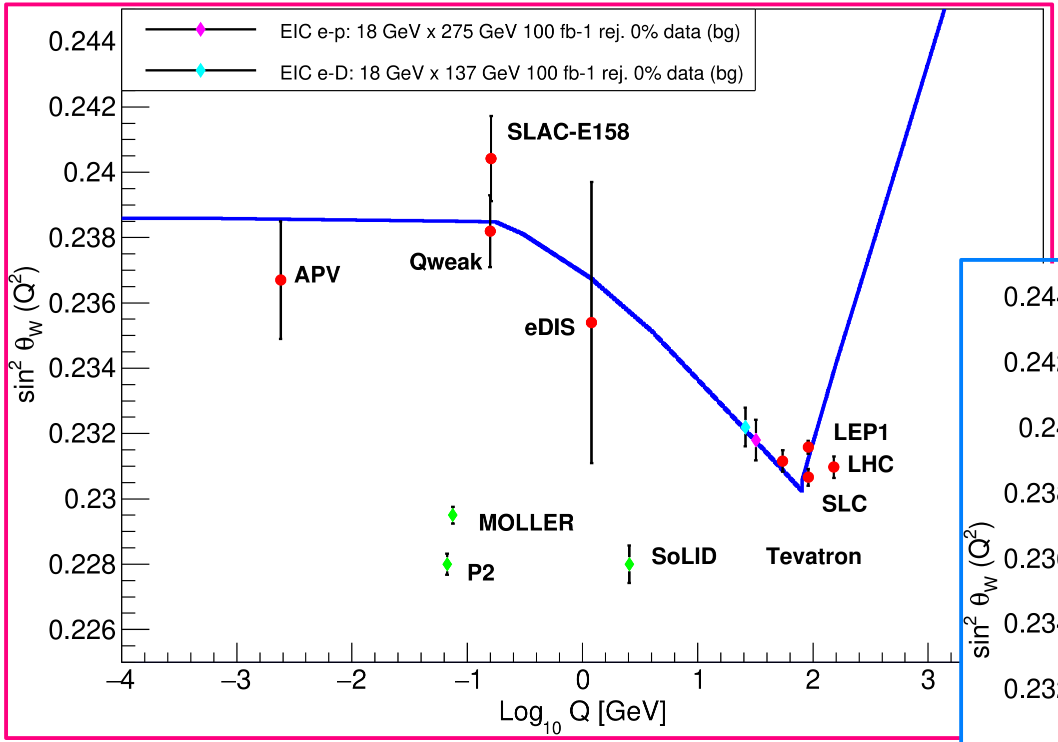
	ep 18x275	eD 18x137
Luminosity	100 fb-1	100 fb-1 (times nucleon xsection)
d($\sin^2\theta_W$) stat before unfolding	0.000375 * sqrt(2)	0.000496 * sqrt(2)
d($\sin^2\theta_W$) stat after unfolding	0.000406 * sqrt(2)	0.000551 * sqrt(2)
d($\sin^2\theta_W$) PDF using MSHT20nlo_as118 (68% CL)	0.000476	0.000215
Total (after unfolding + PDF)	0.000746	0.000810

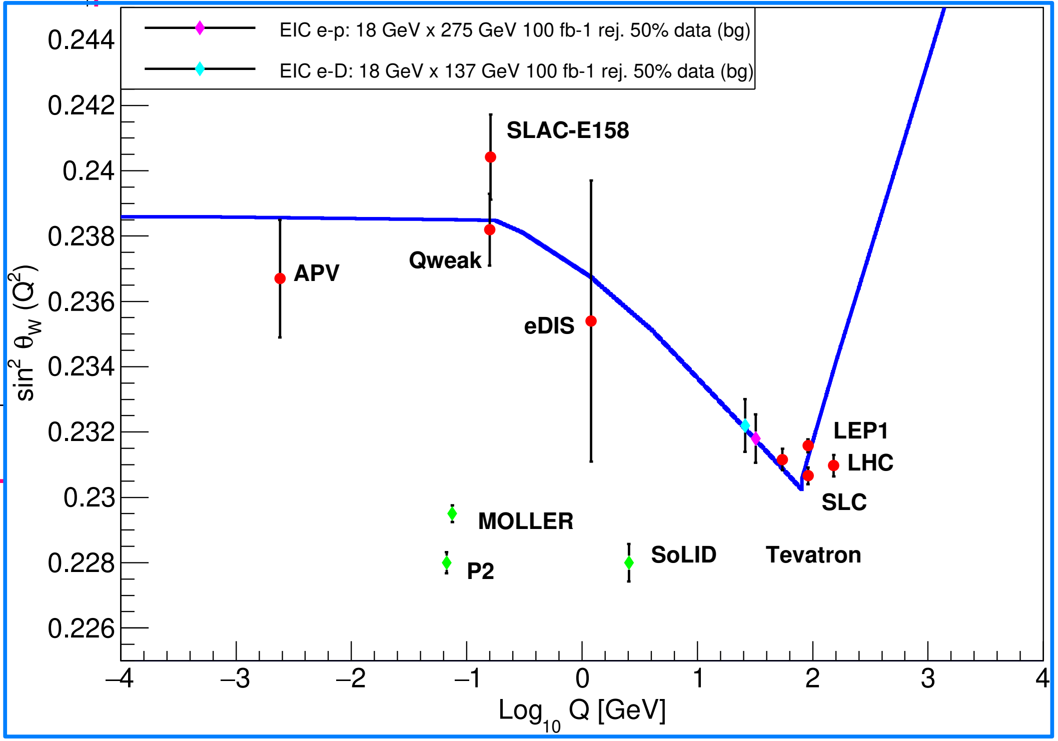
YR (“read” from the graph, 100fb^{-1} ep 18x275 + 10fb^{-1} eD 18x100): 0.23495+/- 0.000974

Fitting of Weak Mixing Angle

YR (cuts? bg?)





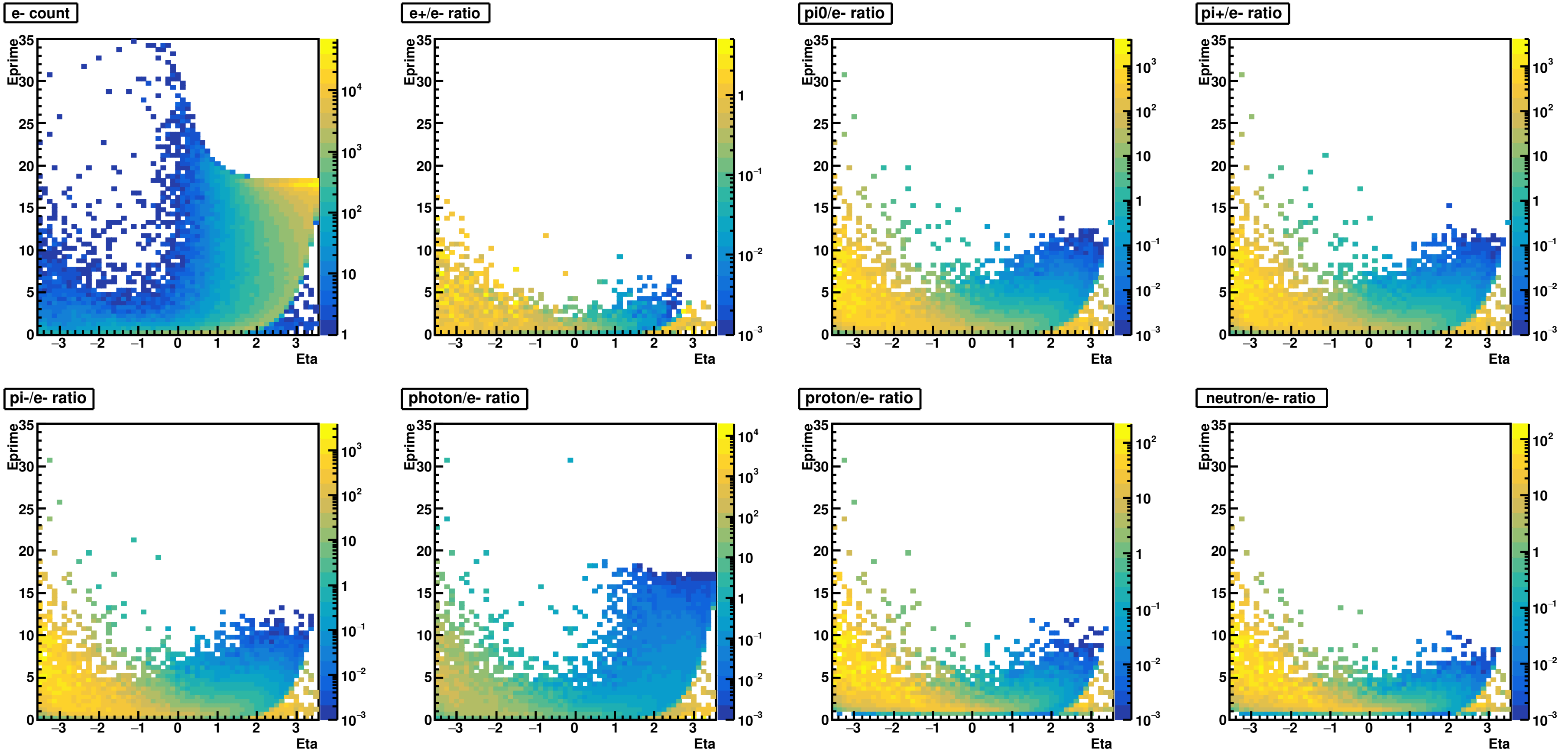


Photoproduction Background

- using Djangoh output (Q2min = 1.0 GeV^2), study particle background from hadronization (but only electron is smeared)

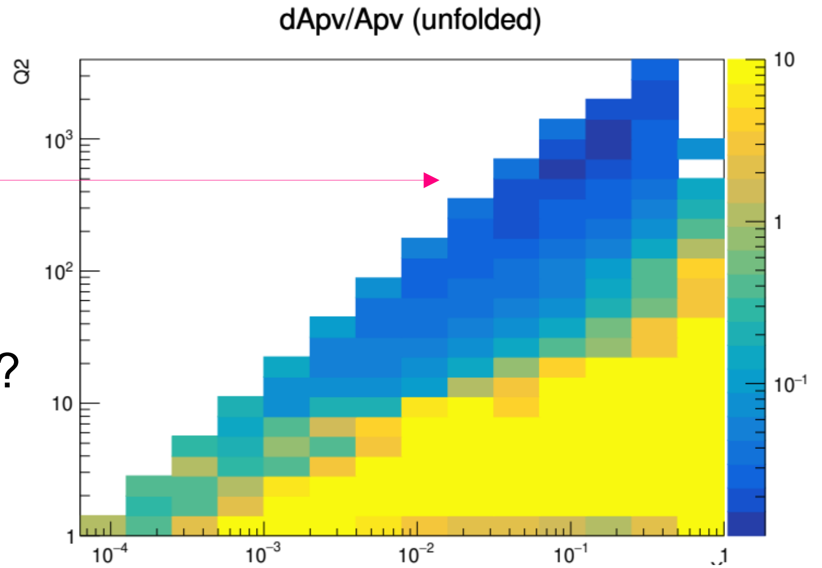
(Cameron Cotton/UVA)

- Fun4all output shows similar results → in progress

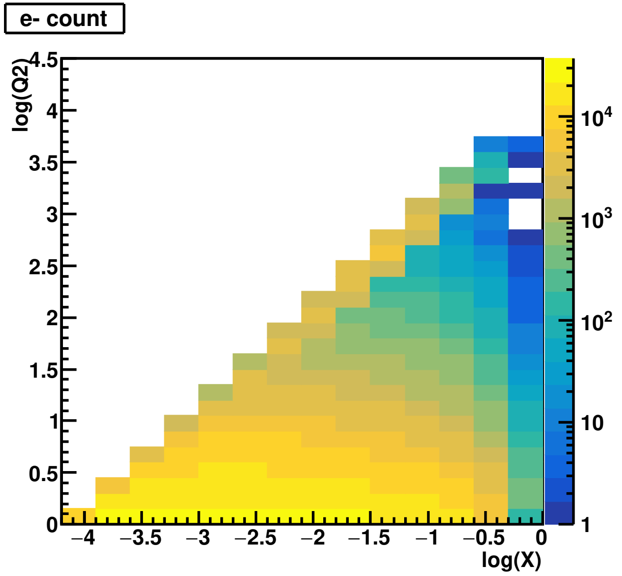


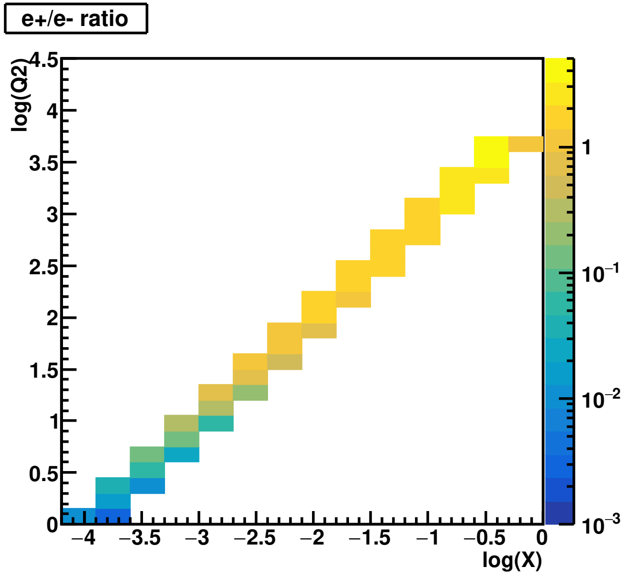
Photoproduction Background

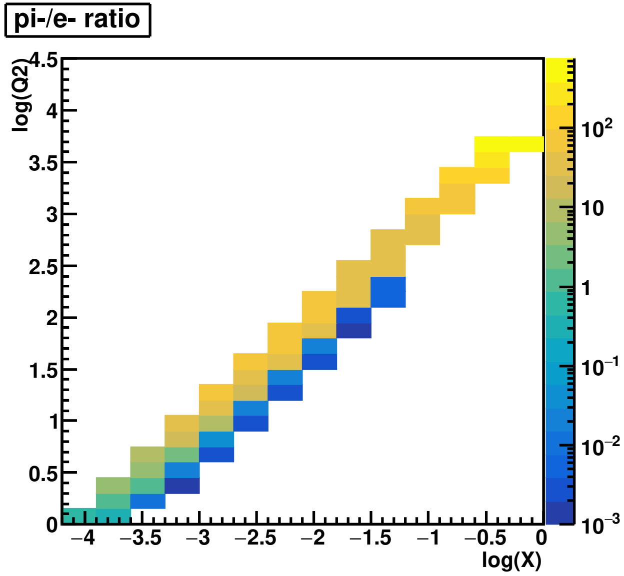
- high background overlaps with high physics-impact region, pair (e+) more problematic than pi-;
- Is Djangoh accurate enough? (low stat anyways)
- Need dedicated photoproduction background simulation?



(Cameron Cotton/UVA)

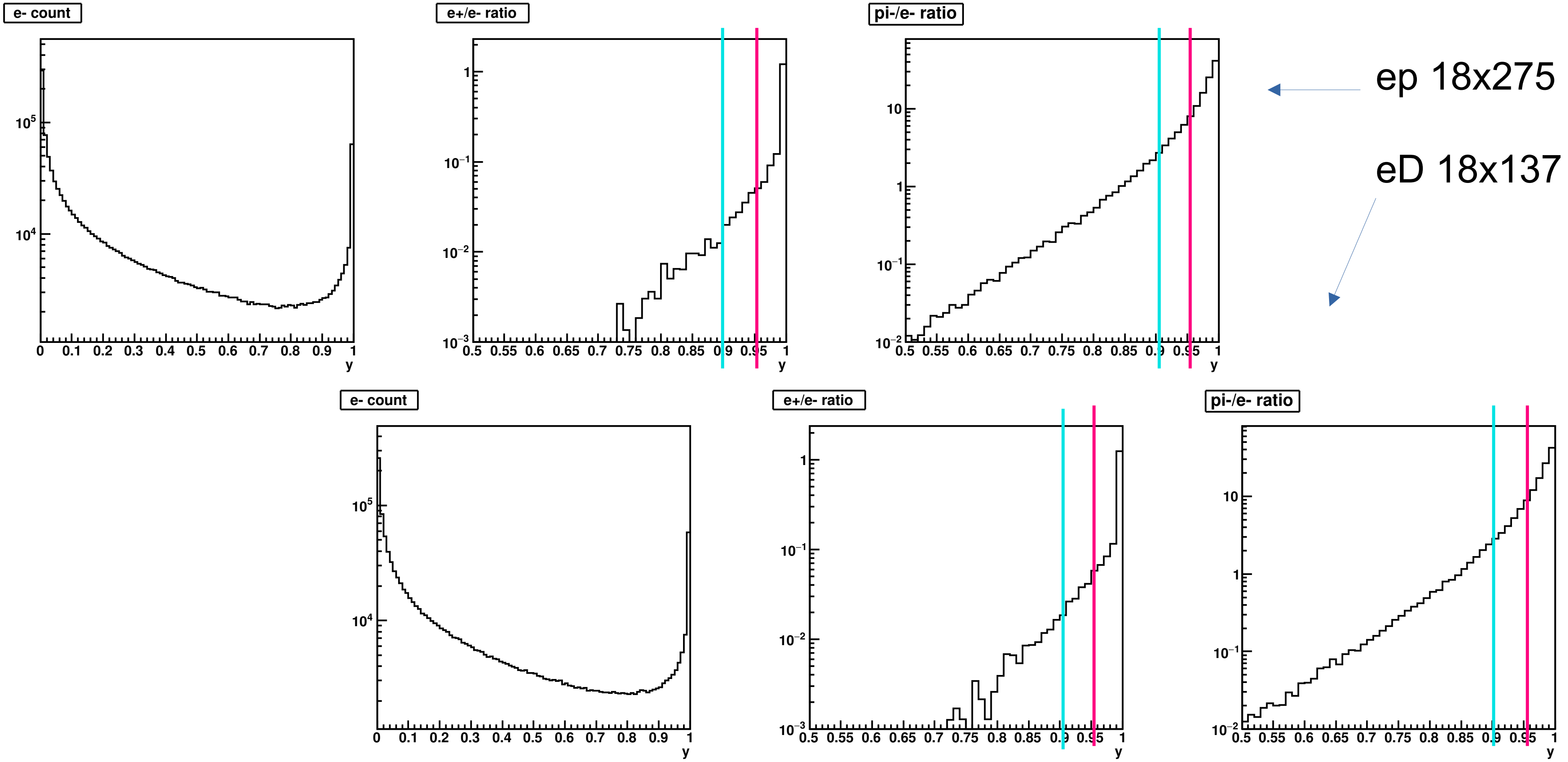






Photoproduction Background

- HERA used y<0.95, is it good enough for EIC? (will reject 1/3 to ½ of our bins)



Structure Functions

$$\frac{d^2\sigma_0}{dxdy}=\frac{4\pi\alpha^2}{xyQ^2}\left\{(1-y)\left[F_2^{\gamma}-g_V^e\,\eta_{\gamma Z}F_2^{\gamma Z}+(g_V^e g_V^e+g_A^e g_A^e)\,\eta F_2^Z\right]+xy^2\left[F_1^{\gamma}-g_V^e\,\eta_{\gamma Z}F_1^{\gamma Z}+(g_V^e g_V^e+g_A^e g_A^e)\,\eta_Z F_1^Z\right]-\frac{xy(2-y)}{2}\left[g_A^e\,\eta_{\gamma Z}F_3^{\gamma Z}-2g_V^e g_A^e\,\eta_Z F_3^Z\right]\right\}$$

$$\frac{d^2\sigma_e}{dxdy}=\frac{4\pi\alpha^2}{xyQ^2}\left\{(1-y)\left[g_A^e\,\eta_{\gamma Z}F_2^{\gamma Z}-2g_V^e g_A^e\,\eta F_2^Z\right]+xy^2\left[g_A^e\,\eta_{\gamma Z}F_1^{\gamma Z}-2g_V^e g_A^e\,\eta_Z F_1^Z\right]+\frac{xy(2-y)}{2}\left[g_V^e\,\eta_{\gamma Z}F_3^{\gamma Z}-(g_V^e g_V^e+g_A^e g_A^3)\,\eta_Z F_3^Z\right]\right\}$$

- Strategy: combine low, medium, and high energy settings, use y-dependence to separate the 3 terms; ignore either F_L or F_3 where they are small.

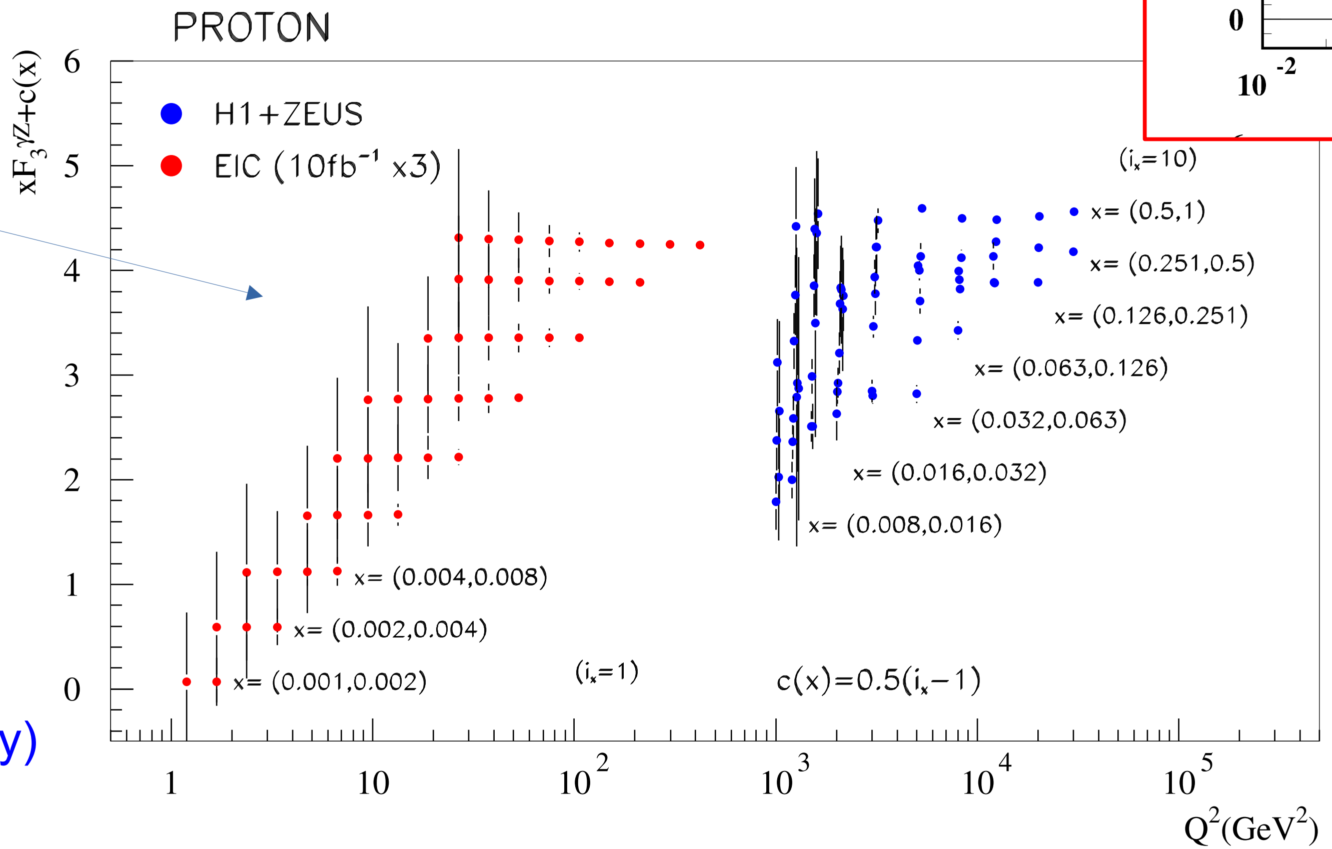
- Use σ_0 for F_2^{NC}, F_L^{NC}, F_3^{NC}
- Use σ_e for $F_2^{\gamma Z+Z}$, $F_L^{\gamma Z+Z}$ (ignore F_3 term or use calculation)
- Focus probably will be in F_3^{NC}

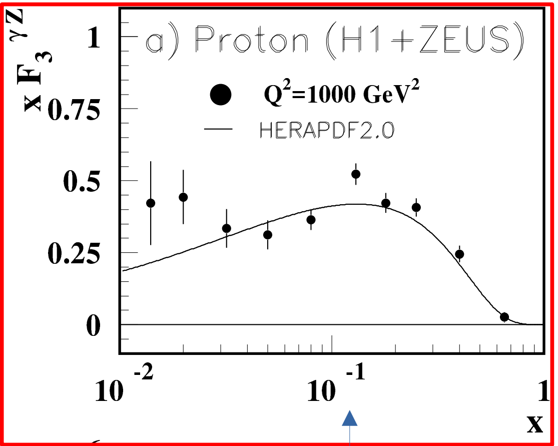
going beyond previous analysis (low-energy approximation and fitting $F_1^{\gamma Z}$ vs. $F_3^{\gamma Z}$ from asymmetries)

Structure Functions

- Using σ_0 with 10fb^{-1} each of ep 5x41, 10x100, 18x275 GeV

projection exists but error bar too large





maybe combine all Q^2 bins is better

(Sonny Mantry)

Summary

- machinery setup for fitting weak mixing angle
- at next round, will
  - dedicate more high Q^2 fast smearing data
  - reject high-background region (eta, E', y cuts, expect large effect)
  - add kinematic cuts ($x>0.01$, $Q^2>50$, expect small effect)
  - add Z-terms to fitting (expect small effect) and cross-check all fitting
- structure function analysis in progress – focus will be $F_3^{\gamma Z}$
- leptoquark analysis in progress

analysis note in progress: https://www.overleaf.com/read/nppbbjmrjmgs

Backup Slides

pion background:

assuming one takes pion (or any hadron) trigger and measure their asymmetry and correct it using

$$A_{DIS} = (1+f) A_{total} - f A_{bg}$$

the net effect of pion contamination in an increase in the statistical precision of the DIS asymmetry:

$$(\Delta A_{\rm DIS})^2_{\pi\ bg} = \frac{1}{N_{\rm DIS}} + \frac{f_{\pi/e}}{\eta_\pi N_{\rm DIS}/PS} + (A_{\rm total} - A_\pi)^2 (\Delta f_{\pi/e})^2$$

where

- N_{DIS} is the total count of DIS events, so the 1st term is the pure statistical precision we expect,
- η_π is pion rejection factor of PID detectors,
- $f_{\pi/e}$ is the final pion contamination ,i.e. 1-purity,
- A_{total} is total measured asymmetry,
- A_π is the pion trigger asymmetry,
- PS is a “prescale” factor assuming one does not take all pion triggers for whatever reason,
- $\Delta f_{\pi/e}$ is the uncertainty in $f_{\pi/e}$

$$\left(\frac{\Delta f_{\pi/e}}{\Delta A/A}\right)^2 \text{ need } \ll 1$$