Measuring the light quark couplings to Z in HERA

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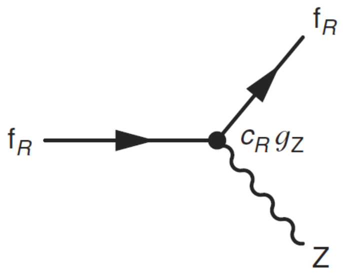
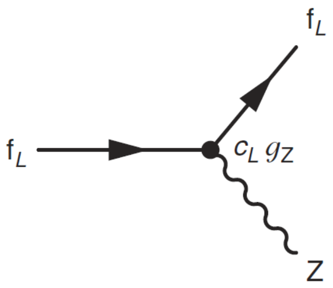
10/20/21

Particle Physics Seminar 290E

Z-fermion coupling

Coupling of Z to fermions **completely** determined by SM





This is seen in the SM Z current term:

$$j_Z^\mu = -\tfrac{1}{2} g' \sin\theta_W [Y_{f_L} \overline{u}_L \gamma^\mu u_L + Y_{f_R} \overline{u}_R \gamma^\mu u_R] + I_W^{(3)} g_W \cos\theta_W [\overline{u}_L \gamma^\mu u_L]$$

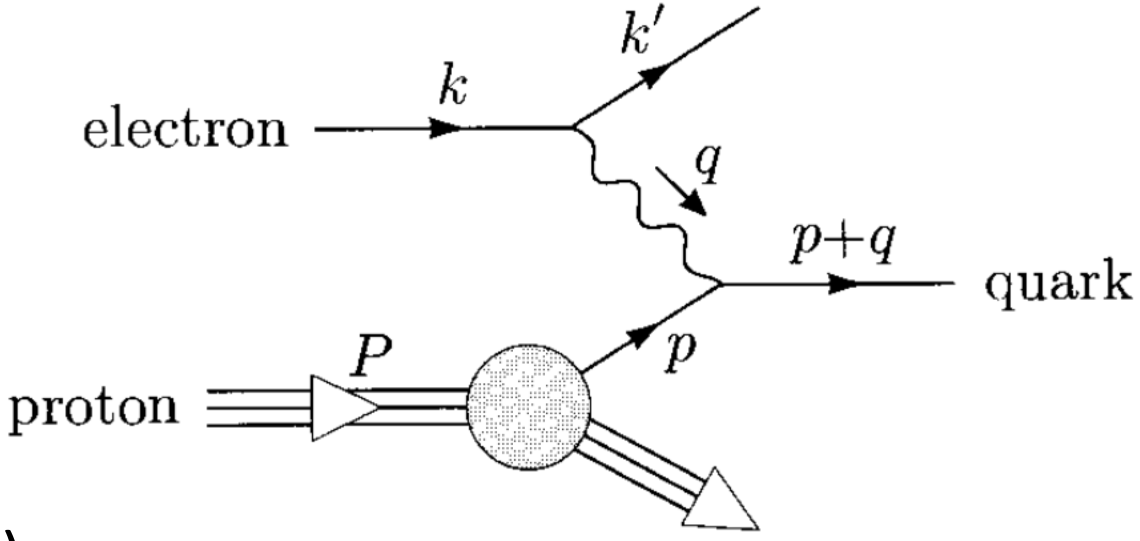
Which can be rearranged to:

$$j_Z^\mu = \tfrac{1}{2} g_Z \overline{u} \left(c_V \gamma^\mu - c_A \gamma^\mu \gamma^5 \right) u$$

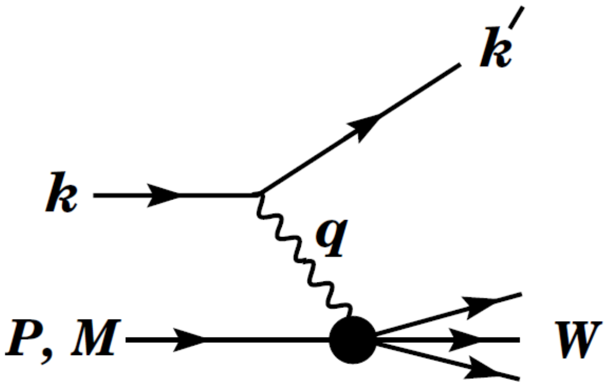
$$c_V = (c_L + c_R) = I_W^{(3)} - 2Q \sin^2\theta_W$$
$$c_A = (c_L - c_R) = I_W^{(3)}$$

$e^- p^+$ Scattering

- The structure of the proton can be probed by using a lepton
- Low energy photon exchange cannot resolve the inner structure but gives a measure of the proton size (**elastic scattering**)
- For $q^2 \sim m_p^2$ you create hadrons, but proton remain intact (**inelastic scattering**)
- For $q^2 \gg m_p^2$, proton completely dissociates (**deep inelastic scattering**)



Deep Inelastic Scattering



- W is the invariant mass of the hadronic system
- In lab frame: $P = (M, 0)$
- In any frame, $k = k' + q$, $W = p + q$
- Invariants of the problem:

$$\begin{aligned} Q^2 &= -q^2 = -(k-k')^2 \\ &= 2EE'(1-\cos\theta) \;\; \text{[in lab]} \\ P\cdot q &= P\cdot(k-k') \\ &= M(E-E') \;\; \text{[in lab]} \end{aligned}$$

$$\frac{d^2\sigma^{ep}}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

- Define $\nu \equiv E - E'$ (in lab frame) so $P\cdot q = m\nu$ and

$$\begin{aligned} W^2 &= (P+q)^2 \\ &= (P-Q)^2 \\ &= M^2 + 2P\cdot q - Q^2 \\ &= M^2 + 2M\nu - Q^2 \end{aligned}$$

where $Q^2 = -q^2$

- Elastic scattering corresponds to $W^2 = P^2 = M^2$
  - $Q^2 = 2M\nu$ elastic scattering
- We can define 2 indep dimensionless parameters

$$\begin{aligned} x &\equiv Q^2/2M\nu; \quad (0 < x \leq 1) \\ y &\equiv \frac{P\cdot q}{P\cdot k} = 1 - E'/E; \quad (0 < y \leq 1) \end{aligned}$$

Blatantly stolen from Marjorie's Lecture Notes

Neutral Current DIS

If we work out specifically the NC cross-section we get:

$$\sigma_{r,\mathrm{NC}}^{e^\pm p} = \frac{x_{\mathrm{Bj}} Q^4}{2\pi\alpha_0^2}\frac{1}{Y_+}\frac{d^2\sigma(e^\pm p)}{dx_{\mathrm{Bj}}dQ^2} = \tilde{F}_2(x_{\mathrm{Bj}},Q^2) \mp \frac{Y_-}{Y_+}x\tilde{F}_3(x_{\mathrm{Bj}},Q^2) - \frac{y^2}{Y_+}F_L(x_{\mathrm{Bj}},Q^2)$$

Decomposed into Z/γ components:

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z$$

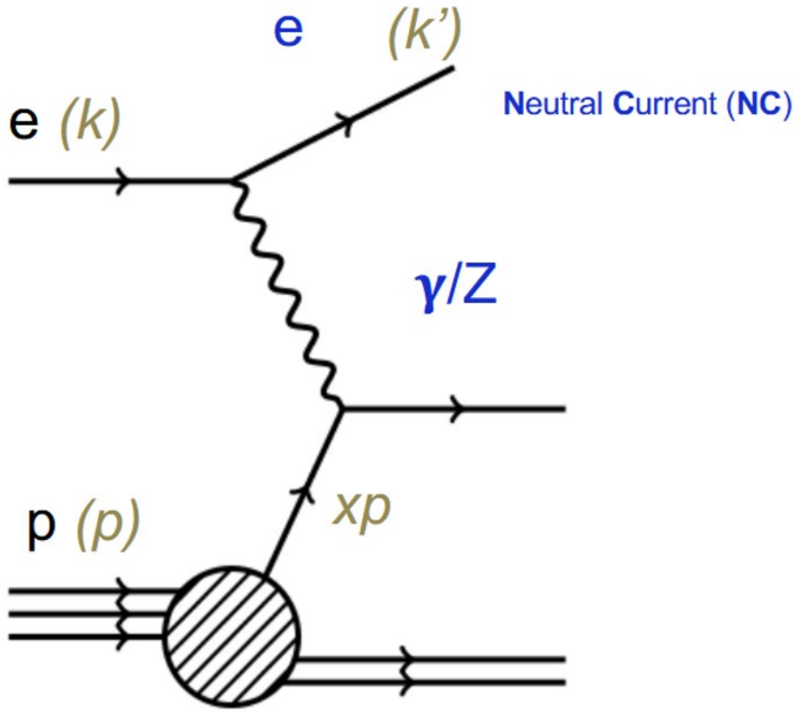
$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 x F_3^Z$$

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

Where the Form factors can be written as:

$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2]x(q+\bar{q})$$

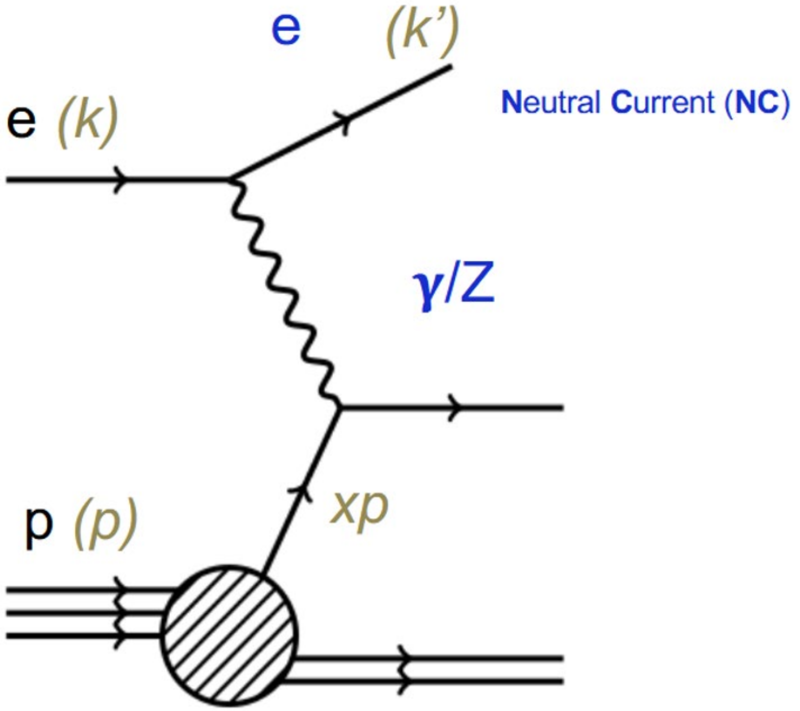
$$[xF_3^{\gamma Z}, xF_3^Z] = \sum_q [e_q a_q, v_q a_q]2x(q-\bar{q})$$



Neutral Current DIS

That was a lot, but to summarize, the NC DIS cross section can be written:

$$\sigma_{NC}^{e^{\pm}p} \propto \tilde{F}(x, Q^2)$$



These form factors in turn can be expanded to:

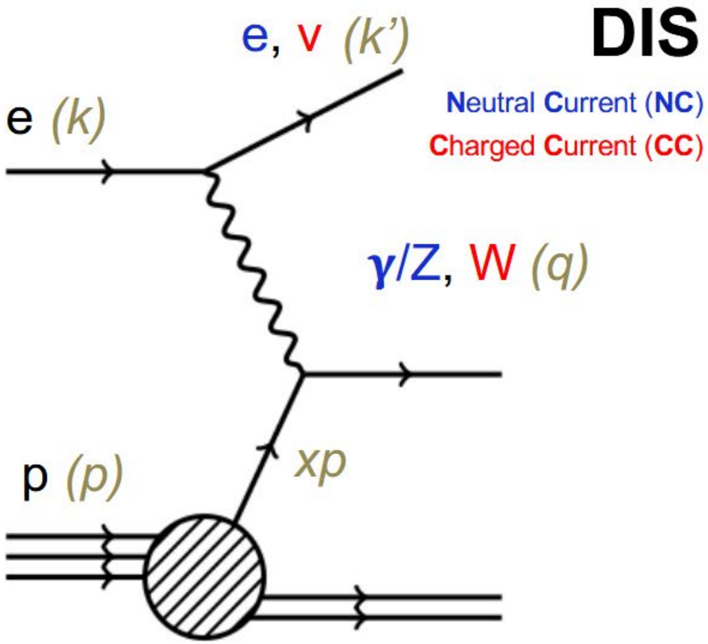
$$\tilde{F} \propto F^{\gamma}, F^{\gamma Z}, F^{Z}$$

And these process specific form factors are written:

$$F^{\gamma,\gamma Z,Z} \propto c_V^q, c_A^q$$

By measuring the cross-sections, you measure the **Z-quark coupling**!!

HERA: the world's only ep collider



HERA (1992–2007): √s = 252–**318** GeV

(Ee = 27.5 GeV; Ep = **920**, 820, 575, 460 GeV)

two general purpose detectors, **H1 and ZEUS**

collected 0.5 fb^{-1} per experiment, equally between e$^+$ and e$^-$

HERA-II (02–07): polarised lepton beams;

crucial for electroweak measurements

$Q^2 = -q^2 = -(k - k')^2$ Virtuality of the exchanged boson

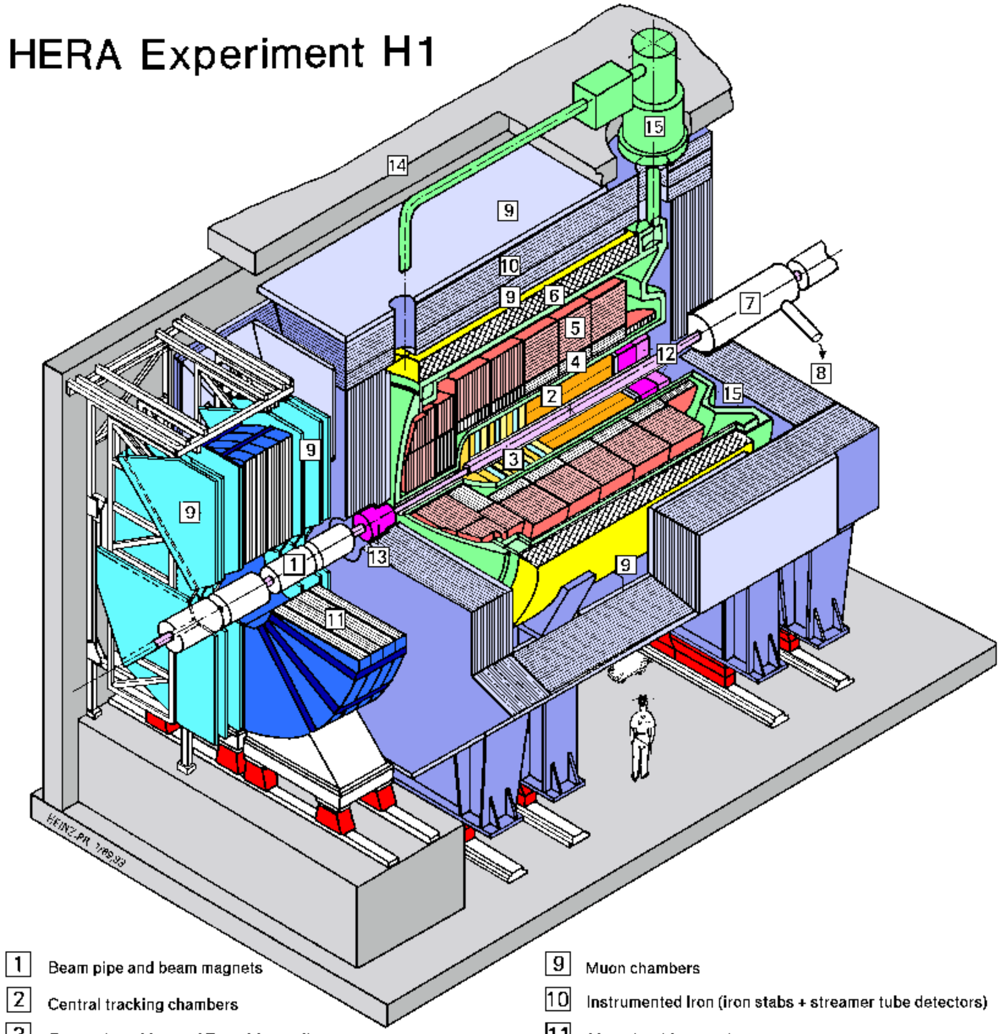
$x = \frac{Q^2}{2p \cdot q}$ Bjorken scaling parameter

$y = \frac{p \cdot q}{p \cdot k}$ Inelasticity parameter

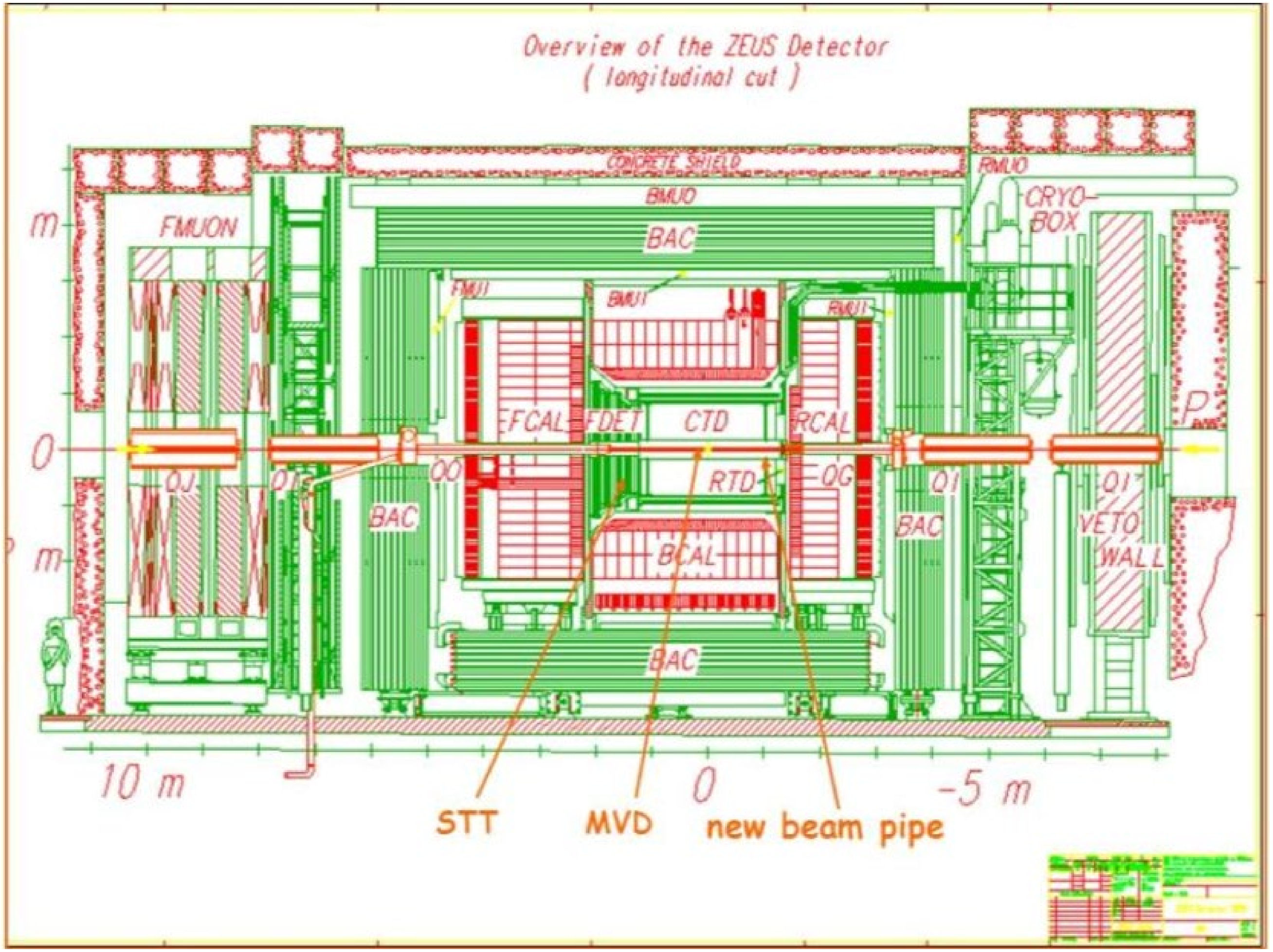
$s = (k + p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

Taken from Claire Gwenlan's talk

H1 and Zeus Detectors

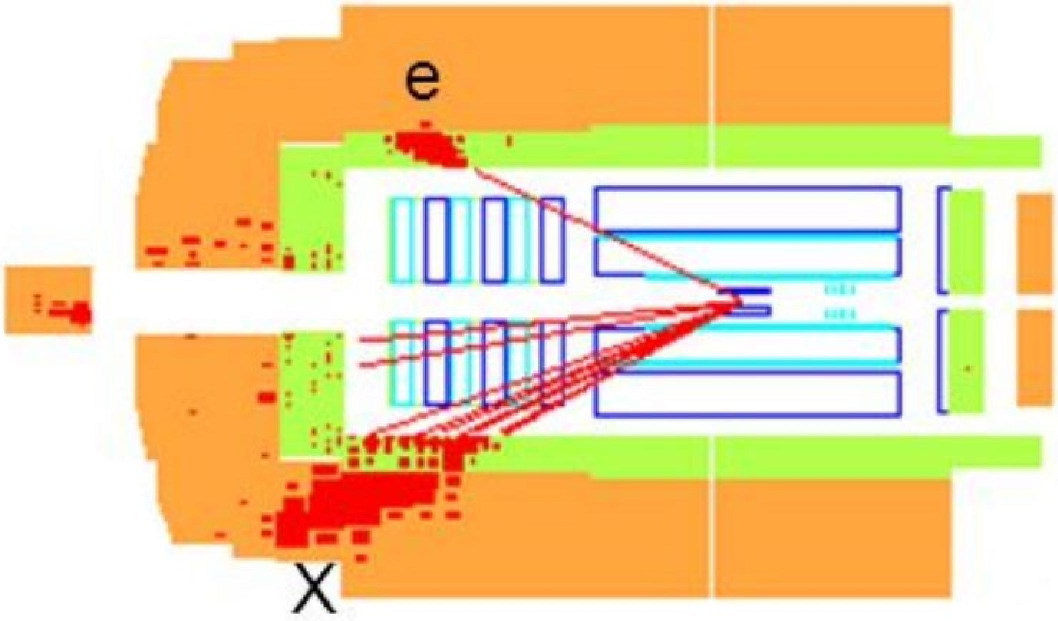


1 Beam pipe and beam magnets
2 Central tracking chambers
3 Forward tracking and Transition radiators
4 Electromagnetic Calorimeter (lead) } Liquid Argon
5 Hadronic Calorimeter (stainless steel) } Liquid Argon
6 Superconducting coil (1.2T)
7 Compensating magnet
8 Helium cryogenics
9 Muon chambers
10 Instrumented Iron (iron stabs + streamer tube detectors)
11 Muon toroid magnet
12 Warm electromagnetic calorimeter
13 Plug calorimeter (Cu, Si)
14 Concrete shielding
15 Liquid Argon cryostat



Event Selection

- Well reconstructed interaction vertex
- Isolated electron in calorimeter
- Low MET requirement
- $E - P_z \sim 2E_e$
- Hadronic angle γ_h large enough that you don't have lost hadronic activity to beam pipe



H1 Run 122145 Event 69506

Results

Before we wrote:

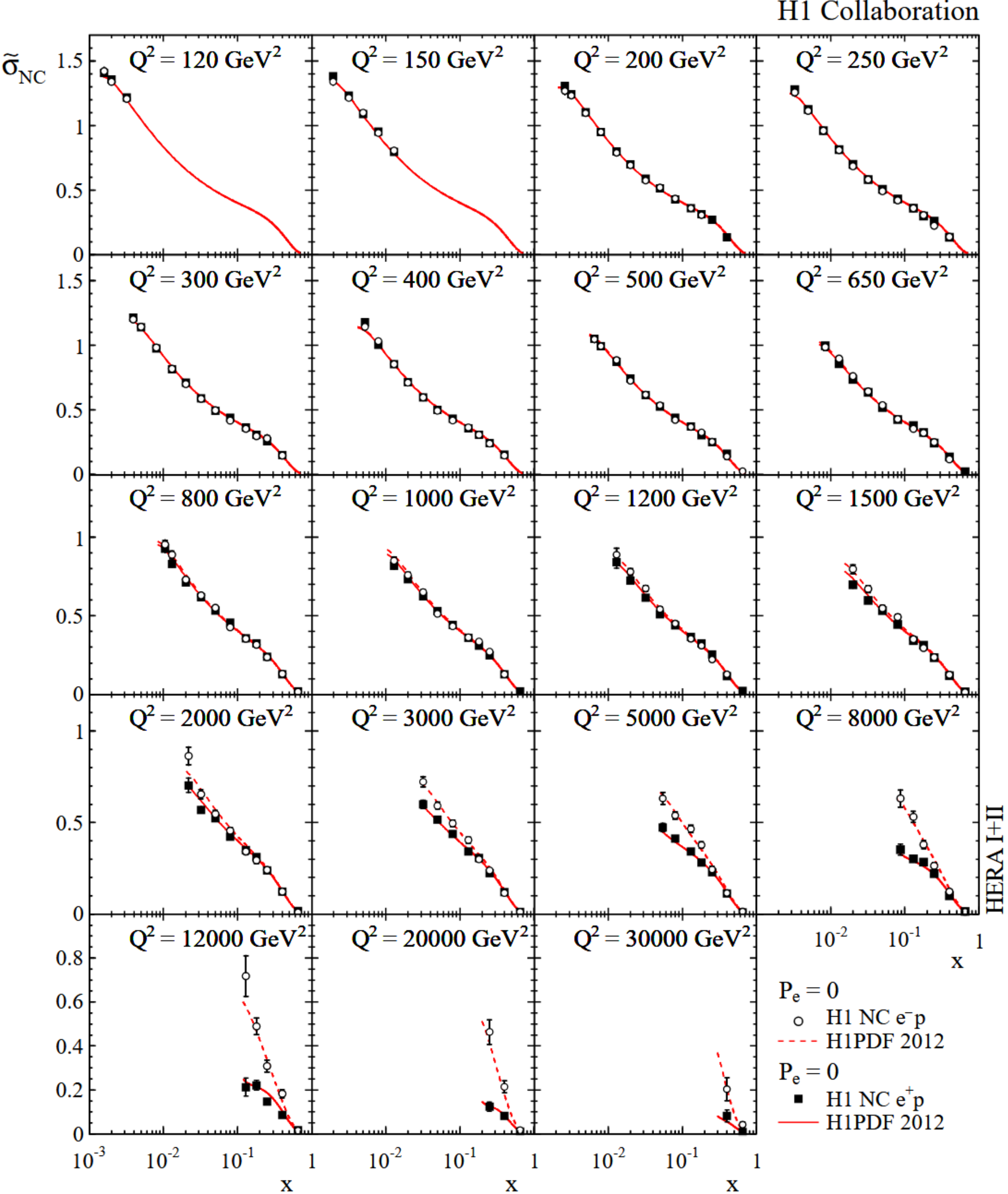
$$\sigma \propto c_V^q, c_A^q$$

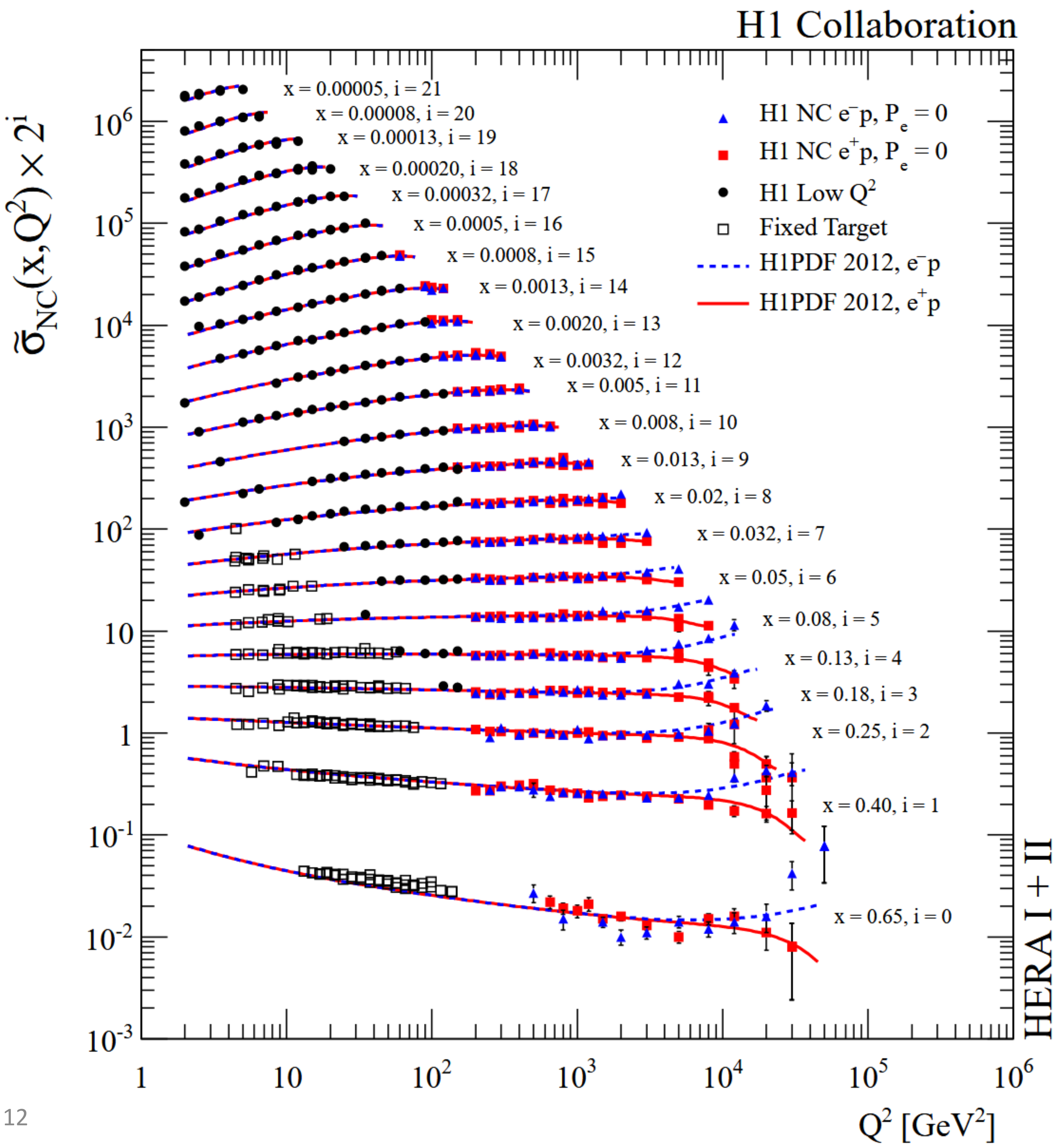
How do we get a cross-section?

$$\sigma(x, Q^2) = \frac{N - B}{\mathcal{L} \cdot A} \cdot \mathcal{C} \cdot (1 + \Delta^{QED})$$

As is customary, this is really a counting experiment

Q^2 (GeV^2)	x	$\tilde{\sigma}_{NC}$	δ_{tot} (%)	δ_{stat} (%)	δ_{unc} (%)	δ^{E}_{unc} (%)	δ^{h}_{unc} (%)	δ_{cor} (%)	δ^{E+}_{cor} (%)	$\delta^{\theta+}_{cor}$ (%)	δ^{h+}_{cor} (%)	δ^{N+}_{cor} (%)	δ^{B+}_{cor} (%)
120	0.0020	1.312	1.73	0.87	1.02	0.54	0.09	1.09	−0.36	−0.61	0.02	0.18	−0.81
120	0.0032	1.182	1.89	1.24	1.21	0.77	0.05	0.75	−0.35	−0.62	0.02	0.19	−0.16
150	0.0032	1.195	1.43	0.73	0.91	0.43	0.06	0.81	−0.32	−0.59	0.02	0.19	−0.41
150	0.0050	1.071	1.74	0.88	1.20	0.86	0.00	0.90	−0.55	−0.71	0.00	0.04	−0.04
150	0.0080	0.9197	2.54	1.20	1.85	1.24	1.02	1.26	−0.79	−0.80	−0.27	−0.50	−0.08
150	0.0130	0.7984	4.03	1.68	3.09	2.78	0.82	1.96	−1.61	−0.64	−0.28	−0.85	−0.09
200	0.0032	1.222	1.81	1.35	0.94	0.18	0.07	0.75	0.18	−0.50	0.01	0.15	−0.51
200	0.0050	1.079	1.57	0.96	0.99	0.54	0.02	0.75	−0.44	−0.58	0.01	0.14	−0.08
200	0.0080	0.9389	1.93	0.99	1.39	1.10	0.00	0.91	−0.60	−0.69	0.00	0.00	0.00
200	0.0130	0.7669	1.62	1.14	0.89	0.19	0.03	0.72	−0.04	−0.46	−0.02	0.55	0.00
200	0.0200	0.6800	1.81	1.23	1.14	0.68	0.19	0.70	−0.47	−0.39	−0.08	0.32	−0.01
200	0.0320	0.5735	2.21	1.38	1.51	1.07	0.51	0.85	−0.60	−0.56	−0.19	0.09	0.00
200	0.0500	0.5107	2.97	1.63	1.78	1.47	0.02	1.73	−0.89	−0.79	−0.18	1.24	0.00
200	0.0800	0.4341	3.41	1.73	2.19	1.90	0.19	1.96	−1.13	−0.86	−0.07	1.35	−0.01
200	0.1300	0.3521	3.54	2.09	2.21	1.36	1.09	1.81	−0.80	−1.02	−0.27	−1.23	0.00
200	0.1800	0.2987	4.40	2.71	2.82	1.17	1.97	2.01	−0.83	−1.23	−0.49	−1.26	0.00
250	0.0050	1.096	1.56	1.12	0.89	0.30	0.06	0.60	−0.29	−0.42	0.02	0.18	−0.27
250	0.0080	0.9512	1.67	1.10	1.01	0.55	0.00	0.76	−0.50	−0.57	0.00	0.04	0.00
250	0.0130	0.8042	2.08	1.20	1.25	0.89	0.18	1.15	0.50	−0.66	0.03	0.79	−0.02
250	0.0200	0.6806	2.10	1.23	1.31	0.93	0.26	1.10	0.35	−0.57	0.07	0.87	0.00
250	0.0320	0.5813	2.19	1.30	1.42	1.10	0.11	1.06	0.52	−0.63	−0.08	0.67	0.00
250	0.0500	0.4968	2.44	1.48	1.46	1.12	0.16	1.27	0.45	−0.57	−0.12	1.03	−0.01
250	0.0800	0.4166	2.94	1.52	1.11	0.41	0.34	2.26	0.18	−0.45	−0.02	2.21	0.00
250	0.1300	0.3560	2.55	1.54	1.82	1.08	0.76	0.92	0.51	−0.56	−0.22	−0.46	0.00
250	0.1800	0.3035	4.11	2.11	2.69	1.59	1.59	2.28	1.02	−0.80	−0.38	−1.84	0.00
300	0.0050	1.110	2.23	1.89	1.00	0.17	0.08	0.63	−0.17	−0.46	0.03	0.15	−0.38
300	0.0080	0.9626	1.71	1.28	0.92	0.35	0.02	0.65	−0.35	−0.53	0.01	0.10	−0.08
300	0.0130	0.8029	1.97	1.28	1.18	0.80	0.00	0.93	−0.79	−0.50	0.00	0.00	0.00
300	0.0200	0.6884	2.00	1.42	1.07	0.57	0.17	0.91	0.43	−0.53	0.03	0.61	−0.02
300	0.0320	0.5748	2.15	1.50	1.20	0.79	0.03	0.97	0.46	−0.55	−0.03	0.65	0.00
300	0.0500	0.4892	2.57	1.62	1.45	1.10	0.18	1.38	0.60	−0.66	−0.10	1.05	0.00
300	0.0800	0.4164	3.12	1.72	1.48	1.09	0.18	2.14	0.47	−0.69	−0.06	1.97	−0.01
300	0.1300	0.3547	2.76	1.71	1.89	1.35	0.42	1.07	0.66	−0.69	−0.17	0.45	0.00
300	0.1800	0.2961	4.67	2.26	3.02	2.14	1.53	2.76	1.31	−0.88	−0.36	−2.23	0.00
300	0.4000	0.1439	6.67	2.75	3.63	2.38	1.99	4.88	1.39	−1.03	−0.41	−4.55	0.00
400	0.0080	1.025	1.91	1.54	0.96	0.38	0.04	0.59	−0.33	−0.41	0.01	0.16	−0.22
400	0.0130	0.8439	1.93	1.50	0.97	0.42	0.00	0.72	−0.41	−0.59	0.00	0.03	−0.02
400	0.0200	0.7106	2.25	1.54	1.28	0.91	0.00	1.03	−0.90	−0.50	0.00	0.00	0.00
400	0.0320	0.5984	2.15	1.63	1.02	0.46	0.09	0.95	0.45	−0.48	−0.02	0.69	−0.01
400	0.0500	0.4846	2.32	1.84	1.12	0.51	0.34	0.85	0.50	−0.36	−0.13	0.58	−0.01
400	0.0800	0.4188	2.74	1.91	1.05	0.27	0.23	1.67	0.22	−0.33	0.05	1.62	0.00
400	0.1300	0.3598	2.65	1.93	1.42	0.64	0.16	1.12	0.55	−0.49	−0.10	0.85	0.00
400	0.1800	0.2991	4.47	2.43	2.57	1.14	1.78	2.73	1.06	−0.54	−0.48	−2.41	0.00
400	0.4000	0.1438	7.28	3.09	3.24	1.27	2.22	5.74	1.18	−0.56	−0.31	−5.58	0.00
500	0.0080	0.9879	2.83	2.57	1.05	0.16	0.07	0.52	−0.24	−0.39	0.02	0.16	−0.20
500	0.0130	0.8903	2.15	1.85	0.96	0.31	0.03	0.56	−0.25	−0.49	0.00	0.08	−0.06
500	0.0200	0.7270	2.31	1.83	1.15	0.69	0.00	0.80	−0.69	−0.40	0.00	0.00	0.00
500	0.0320	0.6232	2.35	1.87	1.09	0.50	0.25	0.91	0.52	−0.38	−0.03	0.65	0.00
500	0.0500	0.5411	2.44	1.99	1.12	0.56	0.18	0.84	0.56	−0.32	−0.06	0.54	0.00
500	0.0800	0.4169	2.96	2.27	1.17	0.60	0.07	1.49	0.60	−0.52	−0.02	1.26	0.00
500	0.1300	0.3658	3.21	2.54	1.38	0.44	0.07	1.41	0.44	−0.38	−0.11	1.28	0.00
500	0.1800	0.3299	3.63	2.86	1.95	0.90	0.92	1.11	0.90	−0.53	−0.30	−0.18	0.00
500	0.2500	0.2529	5.34	3.32	2.54	0.99	1.69	3.32	0.99	−0.53	−0.44	−3.09	0.00
650	0.0130	0.8832	2.38	2.08	1.06	0.48	0.05	0.49	−0.32	−0.31	0.01	0.14	−0.13
650	0.0200	0.7582	2.48	2.14	1.06	0.41	0.00	0.70	−0.47	−0.52	0.00	0.03	0.00
650	0.0320	0.6334	2.84	2.23	1.43	1.01	0.00	1.04	−0.94	−0.45	0.00	0.00	0.00
650	0.0500	0.5229	2.82	2.35	1.24	0.68	0.15	0.94	0.75	−0.43	−0.12	0.34	0.00
650	0.0800	0.4300	3.14	2.66	1.16	0.41	0.08	1.22	0.47	−0.30	0.07	1.08	0.00
650	0.1300	0.3599	3.64	2.94	1.55	0.70	0.21	1.48	0.72	−0.51	−0.06	1.19	0.00
650	0.1800	0.3140	3.77	3.18	1.78	0.79	0.46	0.93	0.82	−0.37	−0.17	0.17	0.00
650	0.2500	0.2471	5.56	4.13	2.44	1.09	1.40	2.82	1.06	−0.44	−0.34	−2.55	0.00
650	0.4000	0.1222	8.53	6.14	3.78	1.65	2.42	4.56	1.67	−0.71	−0.63	−4.13	0.00


H1 Collaboration
$\tilde{\sigma}_{NC}$
$Q^2 = 120\ GeV^2$
$Q^2 = 150\ GeV^2$
$Q^2 = 200\ GeV^2$
$Q^2 = 250\ GeV^2$
$Q^2 = 300\ GeV^2$
$Q^2 = 400\ GeV^2$
$Q^2 = 500\ GeV^2$
$Q^2 = 650\ GeV^2$
$Q^2 = 800\ GeV^2$
$Q^2 = 1000\ GeV^2$
$Q^2 = 1200\ GeV^2$
$Q^2 = 1500\ GeV^2$
$Q^2 = 2000\ GeV^2$
$Q^2 = 3000\ GeV^2$
$Q^2 = 5000\ GeV^2$
$Q^2 = 8000\ GeV^2$
$Q^2 = 12000\ GeV^2$
$Q^2 = 20000\ GeV^2$
$Q^2 = 30000\ GeV^2$
HERA I+II
$P_e = 0$
H1 NC e^-p
H1PDF 2012
$P_e = 0$
H1 NC e^+p
H1PDF 2012
x


H1 Collaboration
$\tilde{\sigma}_{NC}(x,Q^2) \times 2^i$
x = 0.00005, i = 21
x = 0.00008, i = 20
x = 0.00013, i = 19
x = 0.00020, i = 18
x = 0.00032, i = 17
x = 0.0005, i = 16
x = 0.0008, i = 15
x = 0.0013, i = 14
x = 0.0020, i = 13
x = 0.0032, i = 12
x = 0.005, i = 11
x = 0.008, i = 10
x = 0.013, i = 9
x = 0.02, i = 8
x = 0.032, i = 7
x = 0.05, i = 6
x = 0.08, i = 5
x = 0.13, i = 4
x = 0.18, i = 3
x = 0.25, i = 2
x = 0.40, i = 1
x = 0.65, i = 0
H1 NC e^-p, $P_e = 0$
H1 NC e^+p, $P_e = 0$
H1 Low Q^2
Fixed Target
H1PDF 2012, e^-p
H1PDF 2012, e^+p
HERA I + II
$Q^2\ [GeV^2]$

Measuring the Structure Functions

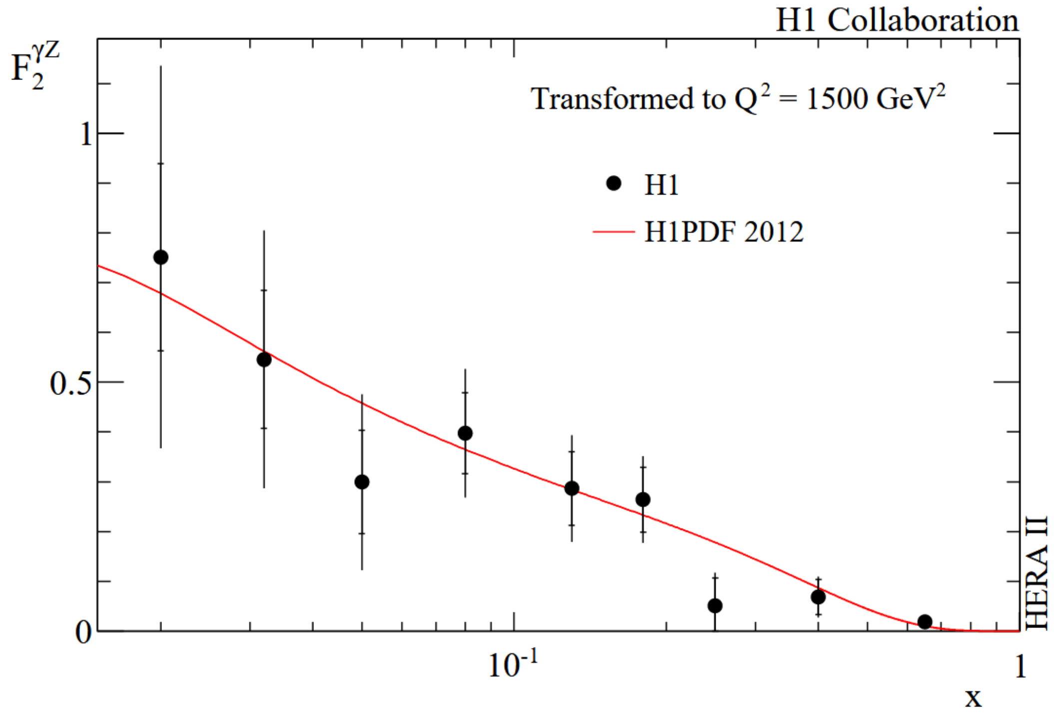
So now we have the cross-section, use this to derive $\tilde{F}$'s

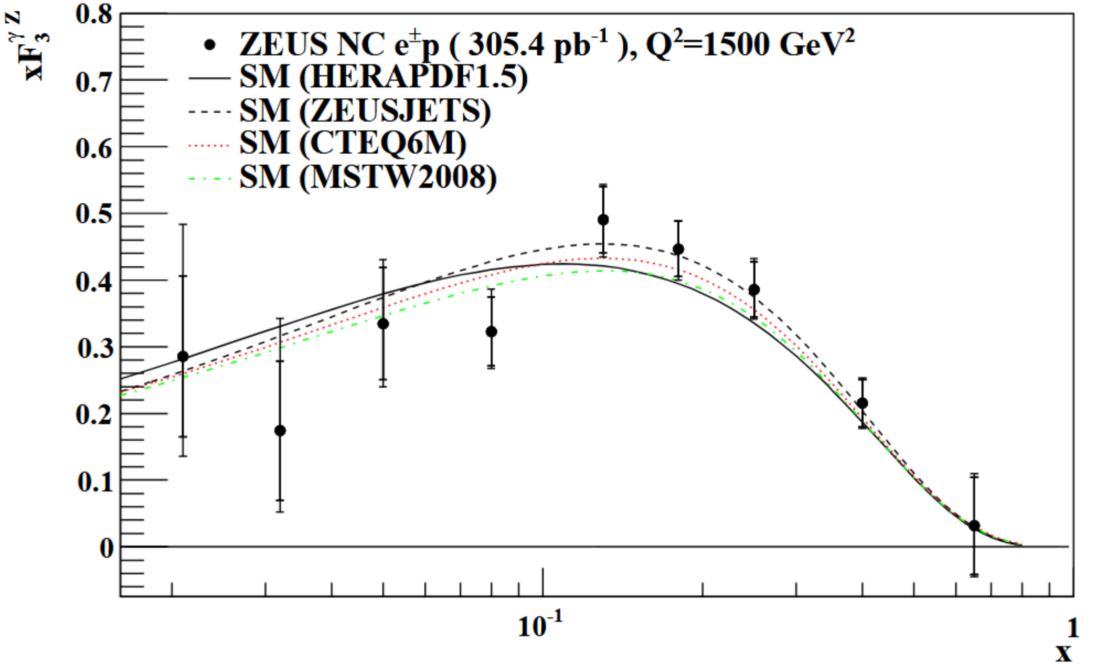
$$\sigma \propto F^{\gamma}, F^{\gamma Z}, \mathrm{F}^{Z}$$

Then in turn, we can use these structure functions to calculate coupling constants!

$$F_2^{\gamma Z} = \sum_q 2e_q \boldsymbol{c_V^q} x(q + \bar{q})$$

$$xF_3^{\gamma Z} = \sum_q 2e_q \boldsymbol{c_A^q} x(q - \bar{q})$$





Finally! The Coupling Constants

- HERA calculated the up and down quark couplings to Z
- Agrees with SM EW predictions

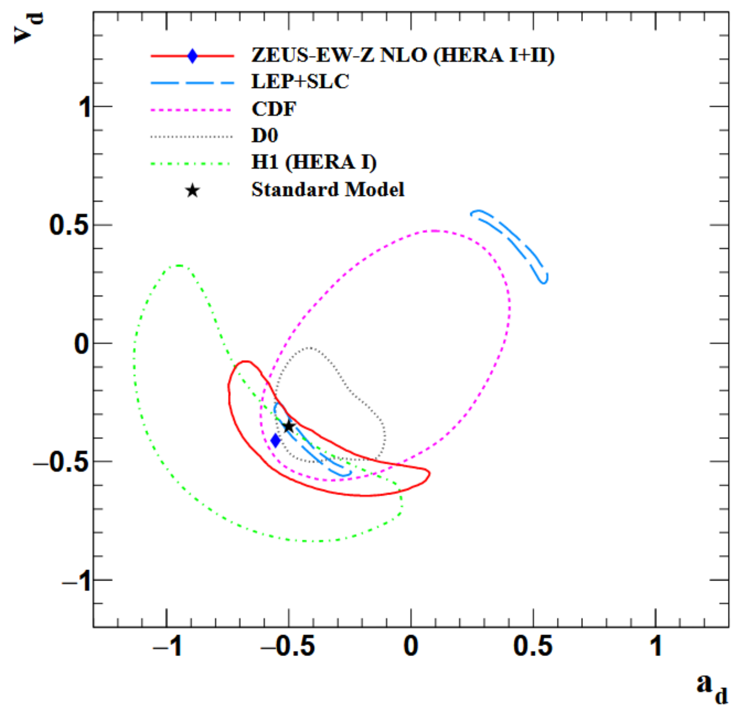
$$c_V = (c_L + c_R) = I_W^{(3)} - 2Q\sin^2\theta_W$$
$$c_A = (c_L - c_R) = I_W^{(3)}$$

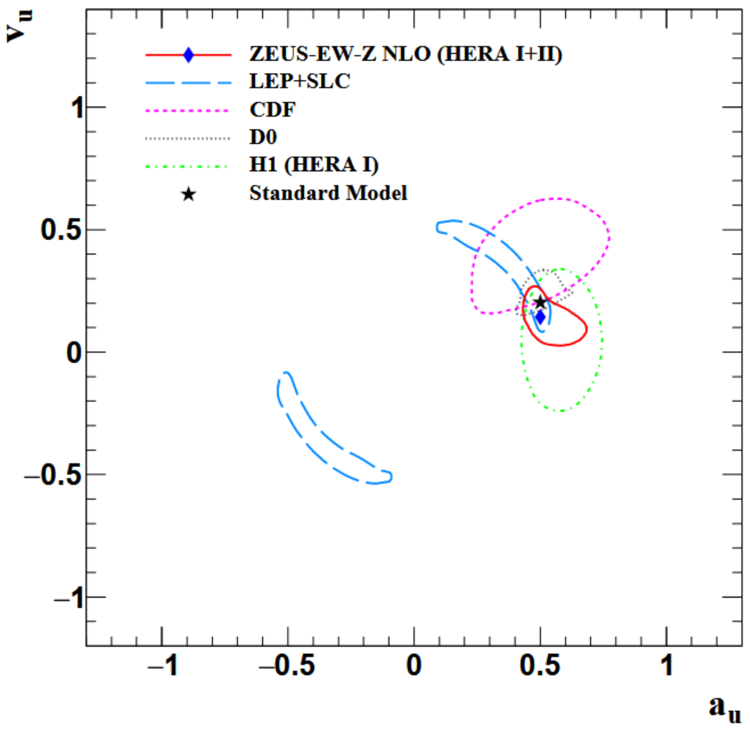
$$a_u = +0.532\ ^{+0.081}_{-0.058}\ \text{(experimental/fit)}\ ^{+0.036}_{-0.022}\ \text{(model)}\ ^{+0.060}_{-0.008}\ \text{(parameterisation)}$$
$$a_d = -0.409\ ^{+0.327}_{-0.199}\ \text{(experimental/fit)}\ ^{+0.112}_{-0.071}\ \text{(model)}\ ^{+0.140}_{-0.026}\ \text{(parameterisation)}$$
$$v_u = +0.144\ ^{+0.065}_{-0.050}\ \text{(experimental/fit)}\ ^{+0.013}_{-0.014}\ \text{(model)}\ ^{+0.002}_{-0.025}\ \text{(parameterisation)}$$
$$v_d = -0.503\ ^{+0.168}_{-0.093}\ \text{(experimental/fit)}\ ^{+0.031}_{-0.028}\ \text{(model)}\ ^{+0.006}_{-0.036}\ \text{(parameterisation)}$$

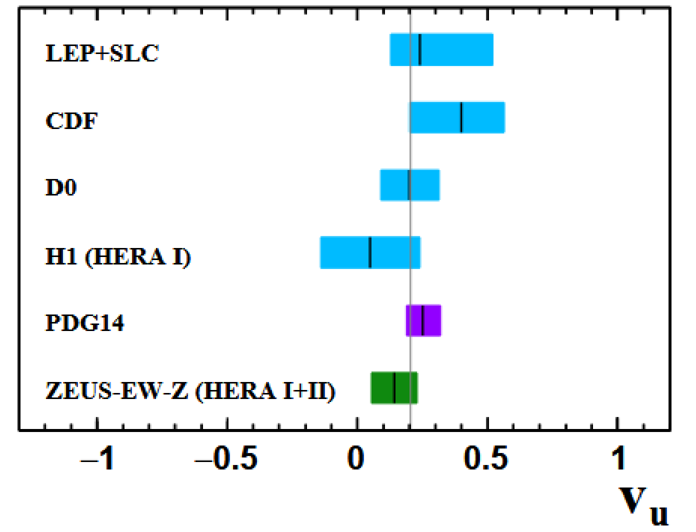
Table 15.1 The charge, $I_W^{(3)}$ and weak hypercharge assignments of the fundamental fermions and their couplings to the Z assuming $\sin^2\theta_W = 0.231\,46$.

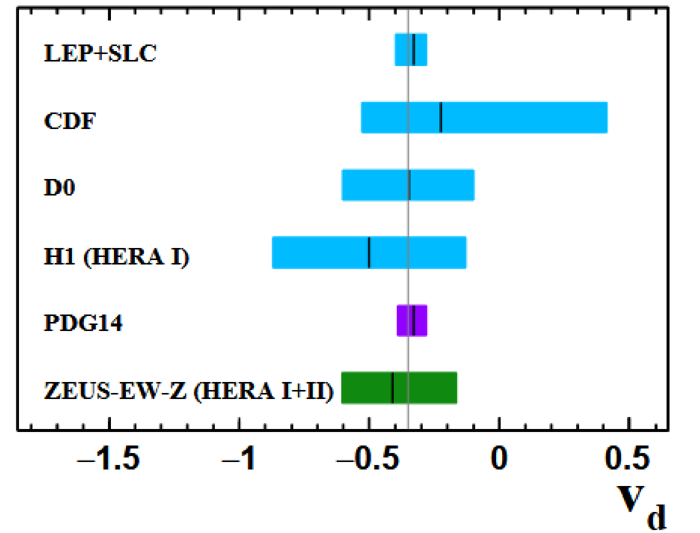
fermion	Q_f	$I_W^{(3)}$	Y_L	Y_R	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	-1	0	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-1	-2	-0.27	$+0.23$	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	$+\frac{4}{3}$	$+0.35$	-0.15	$+0.19$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	$-\frac{2}{3}$	-0.42	$+0.08$	-0.35	$-\frac{1}{2}$

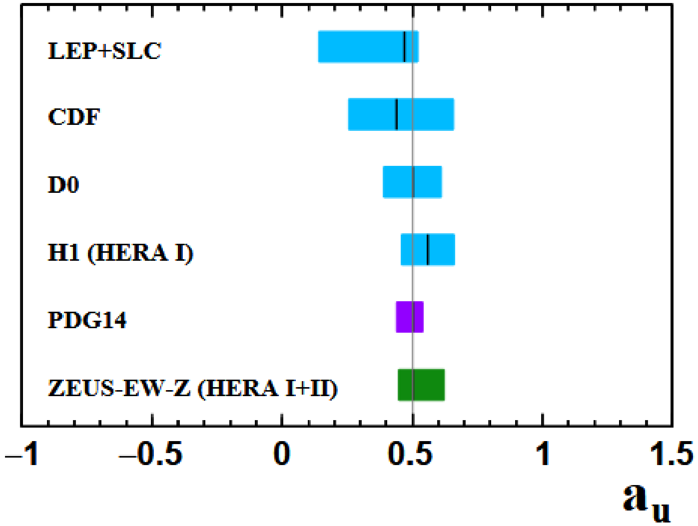
Coupling Constants

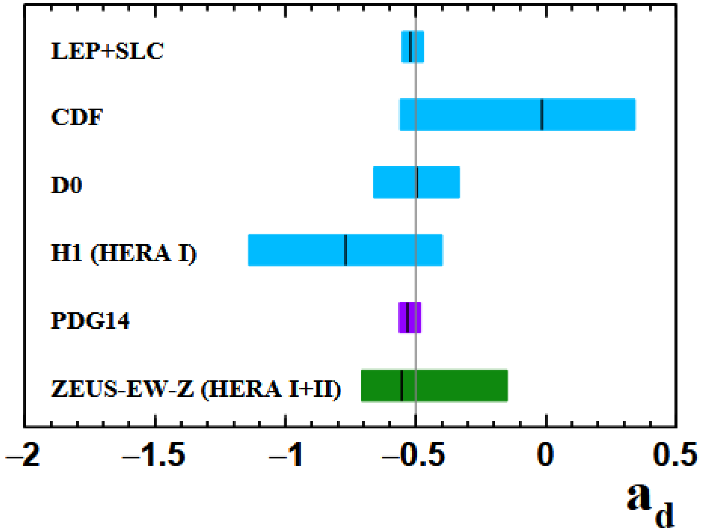












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- Zeus Collaboration, “*The Zeus Detector: Status Report 1993*” (https://www-zeus.desy.de/bluebook/scanned_bluebook.pdf)
- H1 Collaboration, “*The H1 Detector at HERA*” (https://www.physics.mcgill.ca/~corriveau/projects/620B/HERA/h1_detector_1.pdf)
- H1 Collaboration, “*Inclusive Deep Inelastic Scattering at High Q2 with Longitudinally Polarised Lepton Beams at HERA*”, arXiv:1206.7007v1
- Zeus Collaboration, “*Measurement of high-Q2 neutral current deep inelastic e+p scattering cross sections with a longitudinally polarised positron beam at HERA*”, arXiv:1208.6138v2

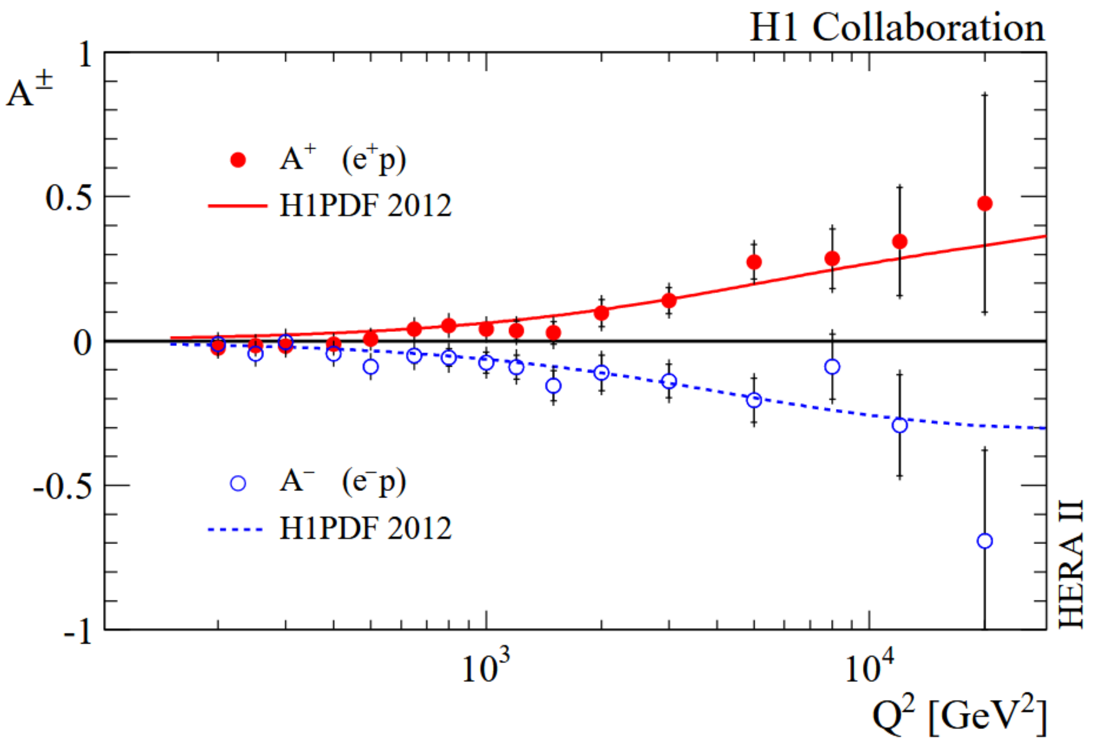
Backup Slides

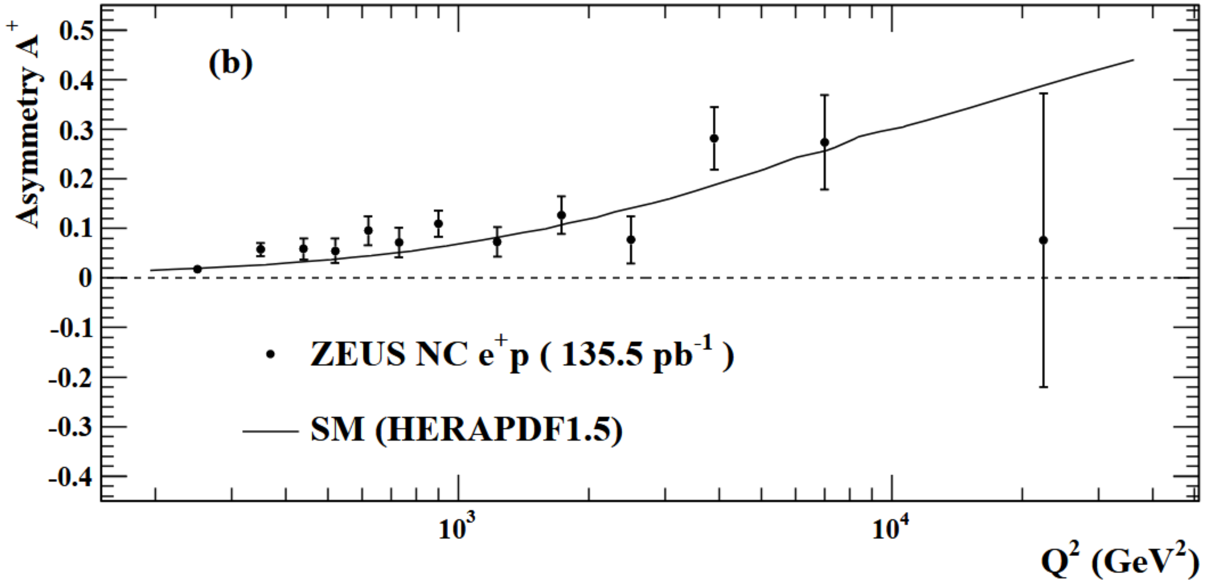
Measuring L/R Asymmetry

- Parity violation built into SM
- Can calculate this through the Z quark couplings via L/R cross-sections

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

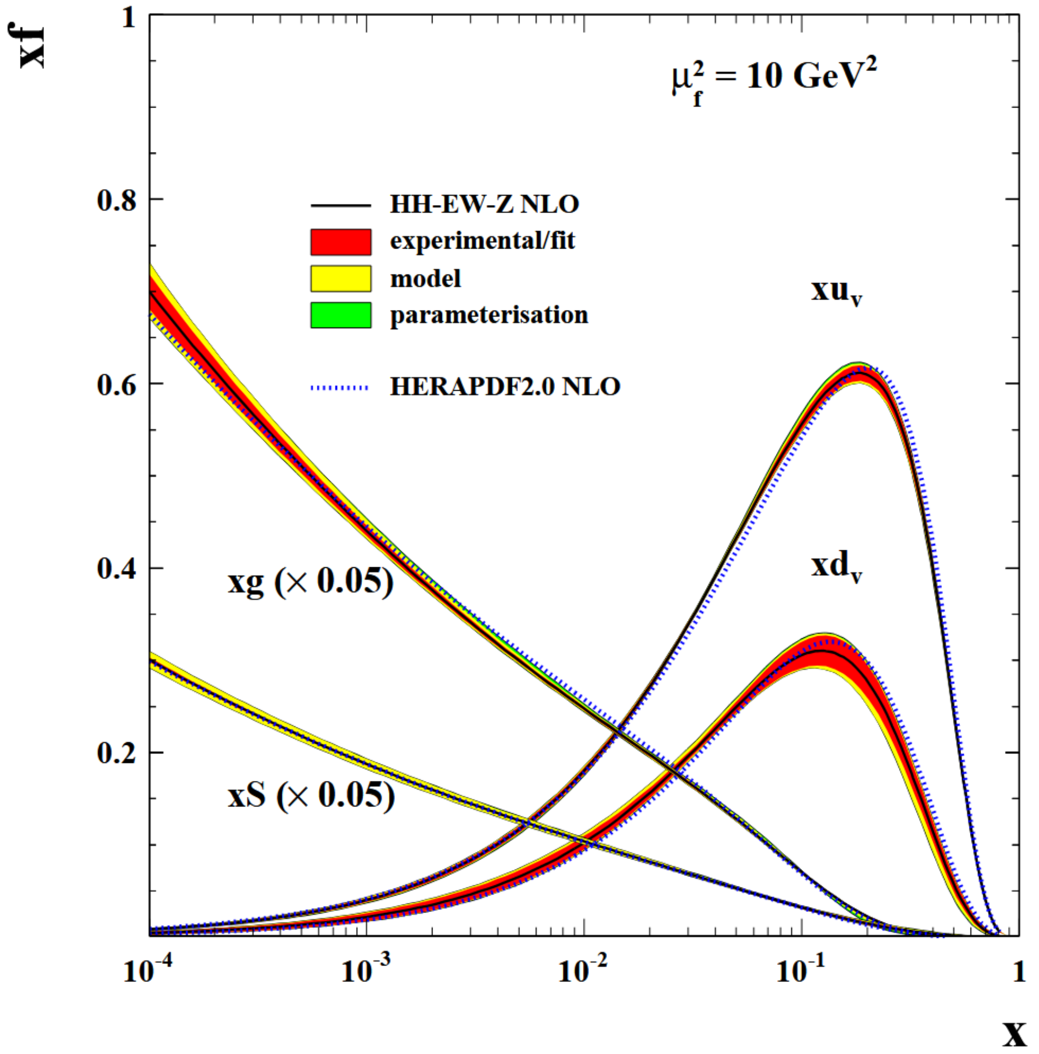
- Asymmetry matches well with SM prediction





Calculating Proton PDF

- Cross-sections can also be used to measure proton PDFs
- 13 parameter fit for PDFs performed
- Combination of HERA I+II give more stringent PDF values

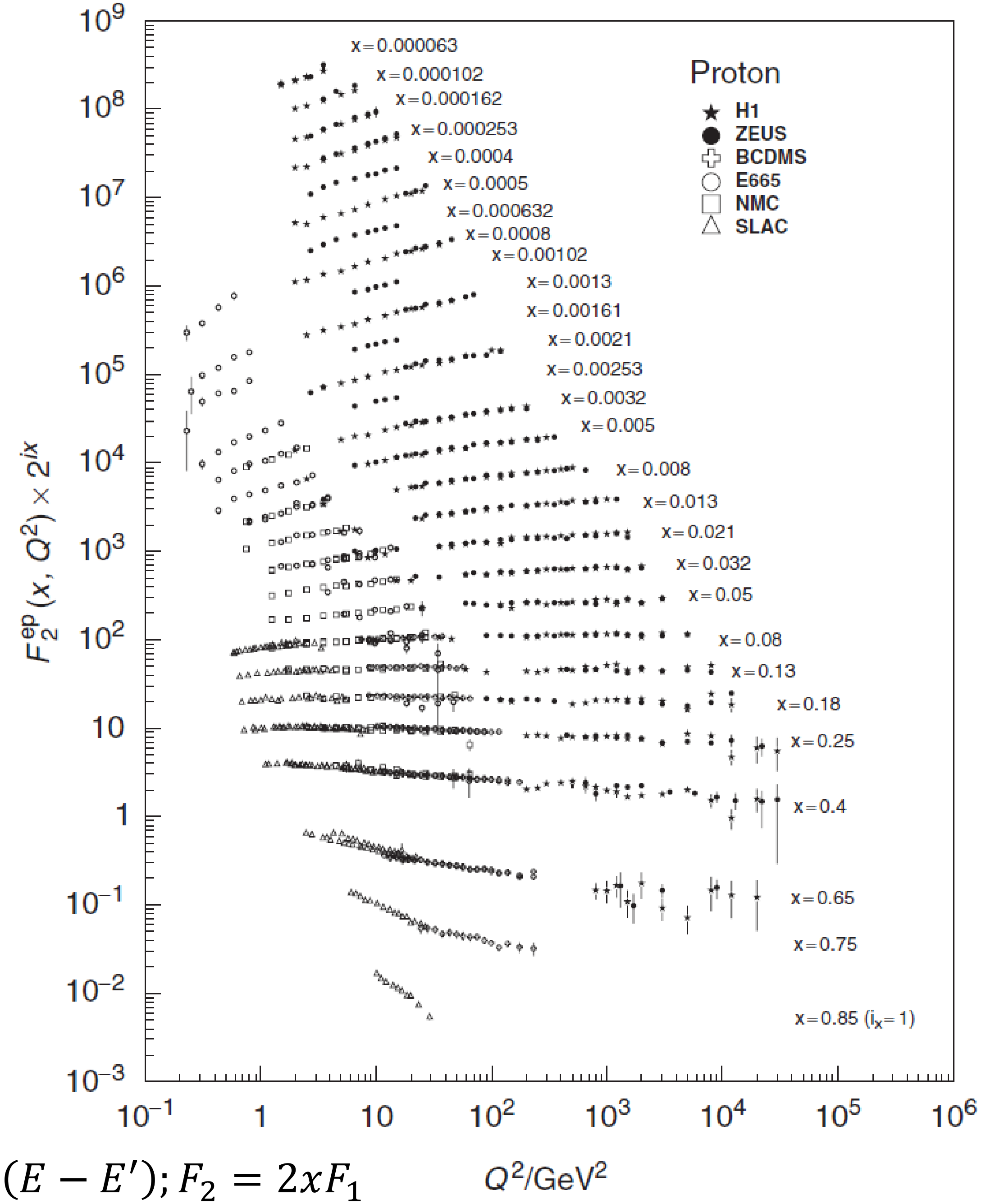


Deep Inelastic Scattering

- Due to the high energy exchange, the interaction is between the electron and the parton inside the proton
- Cross-section of electron-parton scattering given by:

$$\left(\frac{d\sigma}{d\Omega\, dE'}\right)_{\text{lab}} = \frac{\alpha_e^2}{8\pi E^2 \sin^4\frac{\theta}{2}}\left[\frac{m_p}{2}W_2(x,Q)\cos^2\frac{\theta}{2} + \frac{1}{m_p}W_1(x,Q)\sin^2\frac{\theta}{2}\right]$$

- Where W_1 and W_2 are **structure functions** which are dependent on the energy of the photon exchanged (Q), the fractional energy of the parton (x), and the **parton distribution function**

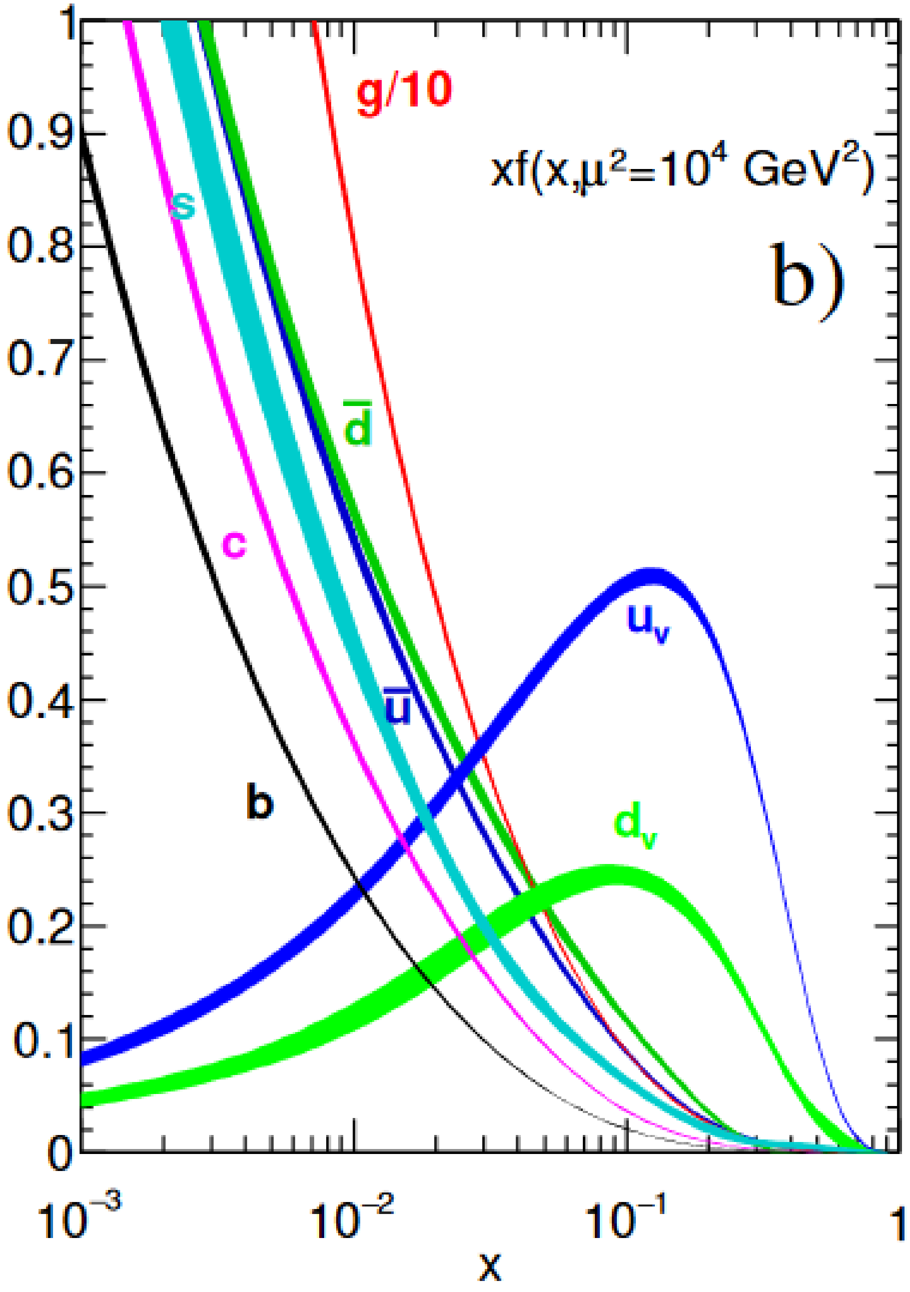


$F_2 = W_2 * (E - E'); F_2 = 2xF_1$

Beringer, J. *et al*. (Particle Data Group). 2012. *Phys. Rev.*, **D86**, 010001

Parton Distribution Functions (PDF)

- Parton distribution function written,
    - $f_i^{(H_j)}(x_i, \mu)$
- is the probability of finding parton i in hadron j with x_i fraction of momentum at scale μ
- Due to large mass of the charm and strange quarks, their respective pdfs are much harder to probe than the valence quark pdfs
- High energy protons allow for easier probe of these tougher pdfs



R. D. Ballet al.(NNPDF), JHEP04, 040 (2015), [arXiv:1410.8849]

Parton Distribution Functions (PDF)

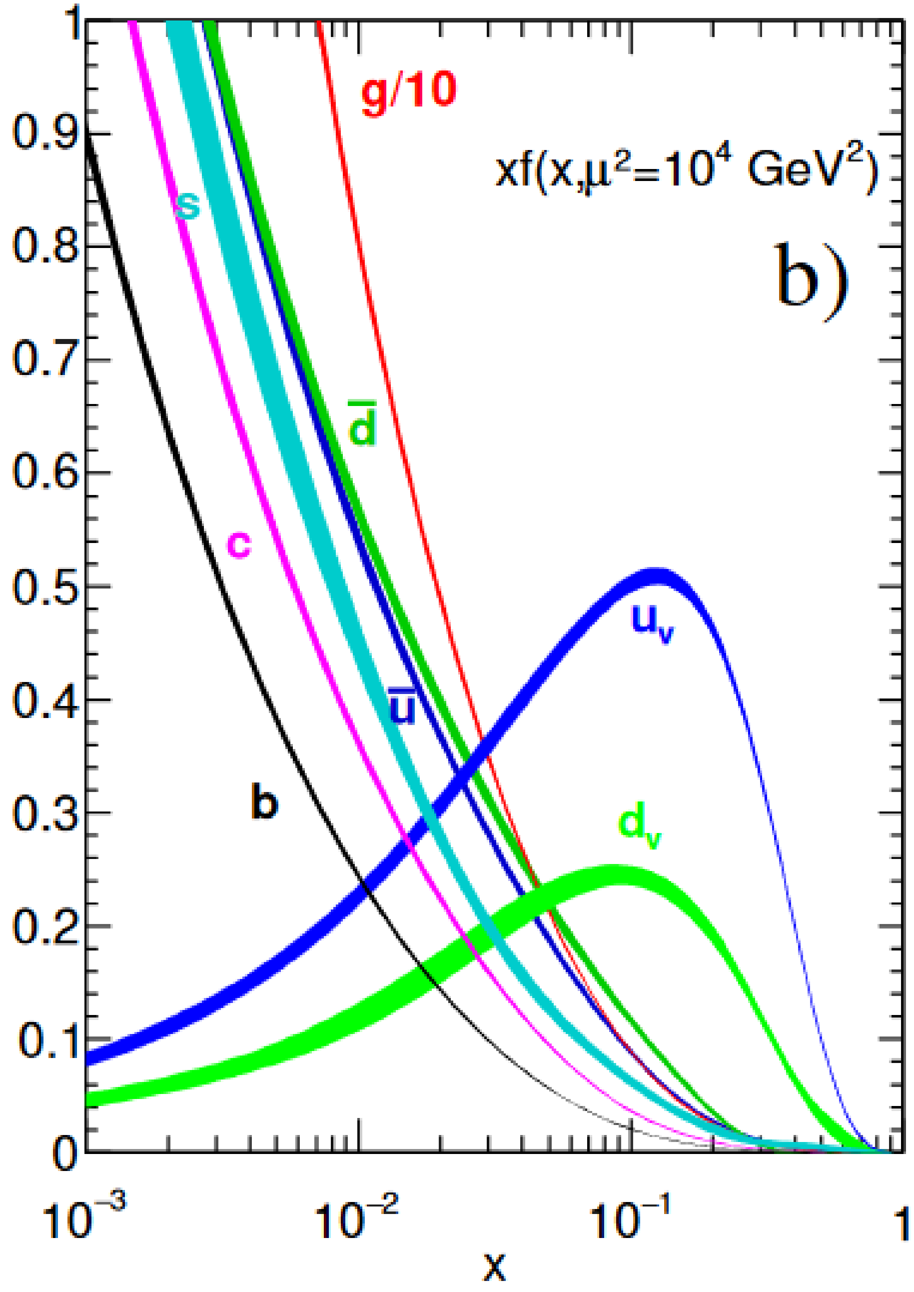
Energy conservation: momentum sum rule

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} \left[q_i((x,Q^2) + \bar{q}_i(x,Q^2) \right] + g(x,Q^2) \right) = 1$$

Quark number conservation: valence sum rules

$$\int_0^1 dx\, \left(u(x,Q^2) + \bar{u}(x,Q^2) \right) = 2$$

- Sum rules give constraints on the different gluon and quark pdf values in the proton
- Better measure of one pdf makes a difference in others



R. D. Ballet al.(NNPDF), JHEP04, 040 (2015), [arXiv:1410.8849]