# Electroweak Interactions and Nucleon Structure

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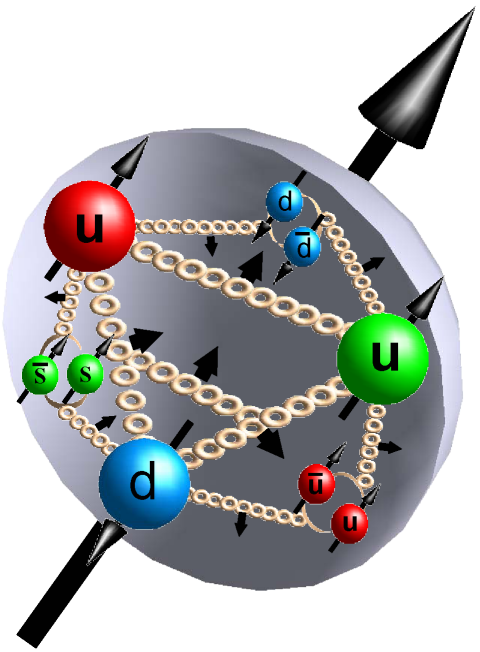
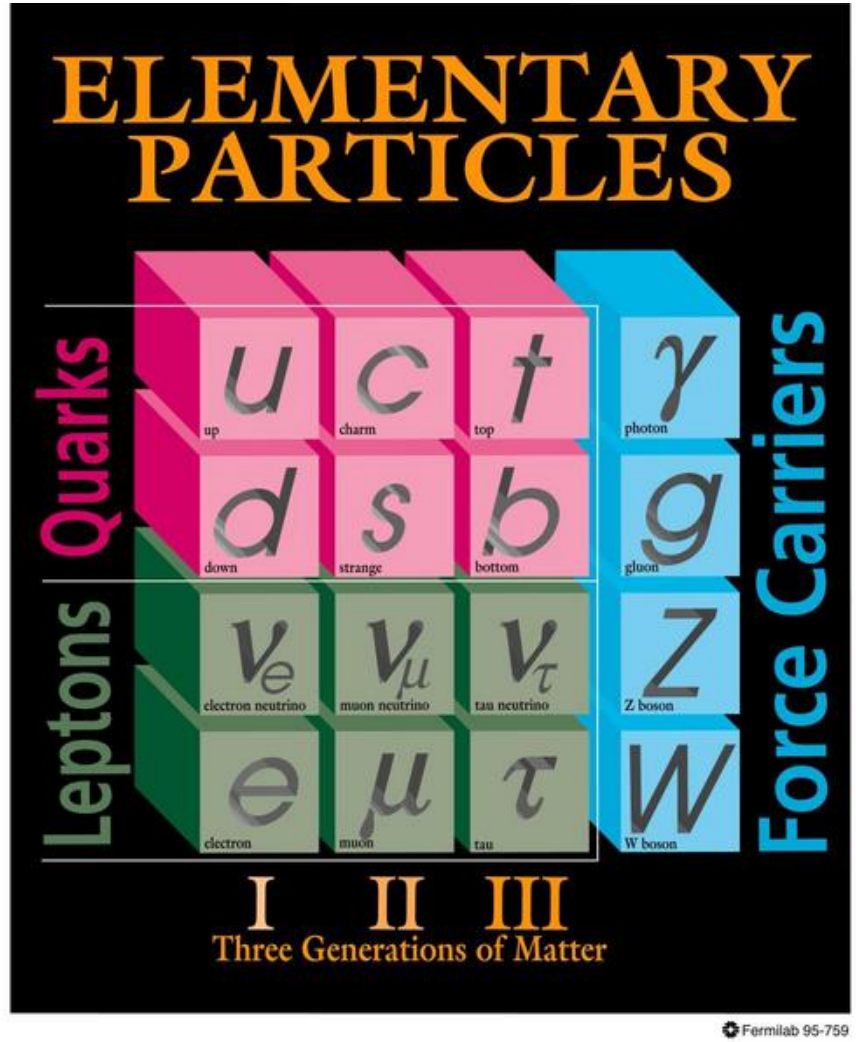
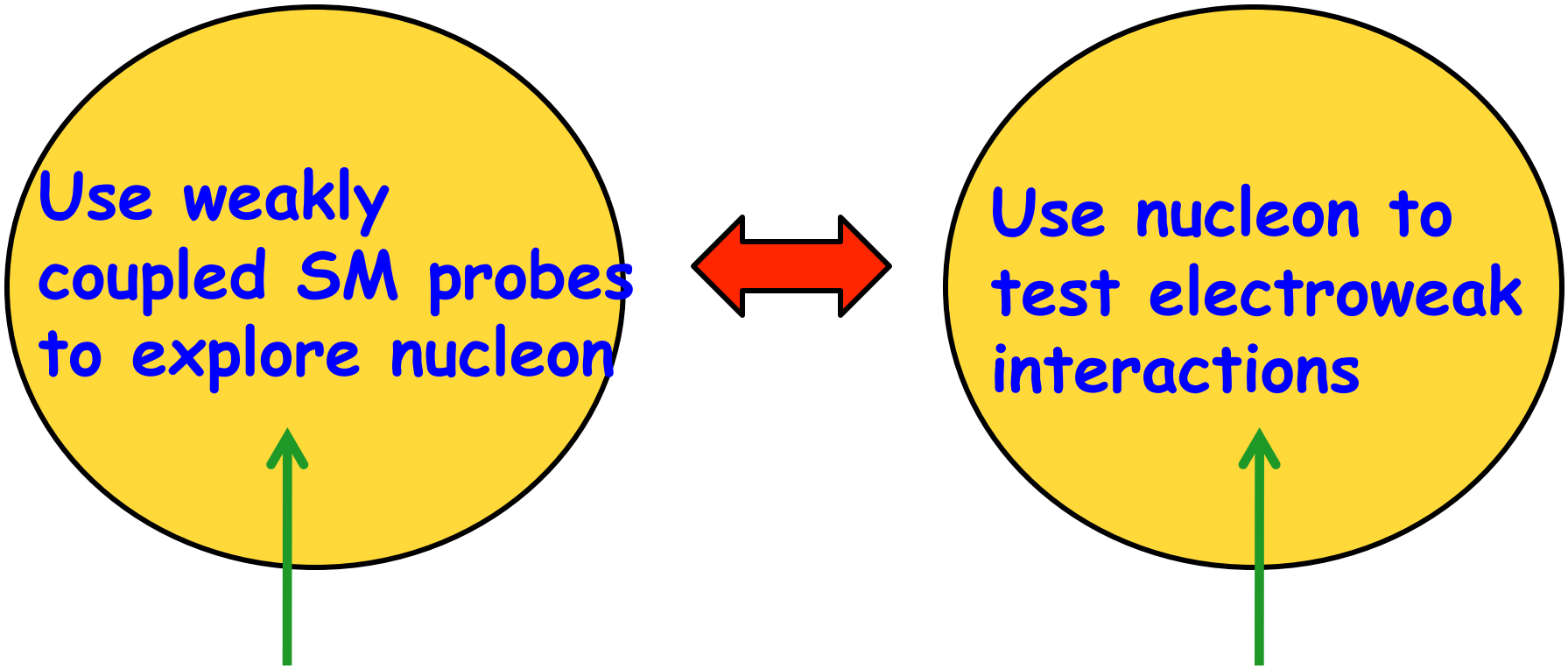
Washington DC, 07/29/2010

Quarks participate in all known fundamental interactions !



Offers tremendous opportunity:




For aspects of nucleon where we have "little knowledge"

Find observables where nucleon structure / QCD is *very* well known, or cancels

# Outline:

- Basic electroweak interaction
- Partons, hadronic scattering, and QCD
- EW applications for unpolarized nucleons
- EW applications for polarized nucleons

Disclaimer: will not be able to cover all aspects …
(Sorry for your favorite omission !)

# I. Basic electroweak interaction

- one of the most profound insights in theoretical physics is that interactions are dictated by symmetry principles

- we believe that all particle interactions are dictated by "local gauge (phase) invariance"

- intimately related to local conservation of charges (e.m. charge, color, …)

- example: Quantum Electro Dynamics (QED)

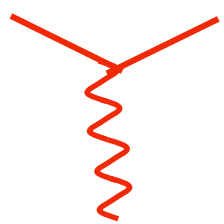
$$\mathcal{L} = \bar{\psi}\,(\,i\partial^{\mu}\gamma_{\mu} - m\,)\,\psi + e\,\bar{\psi}\gamma^{\mu}\psi\,A_{\mu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

where $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

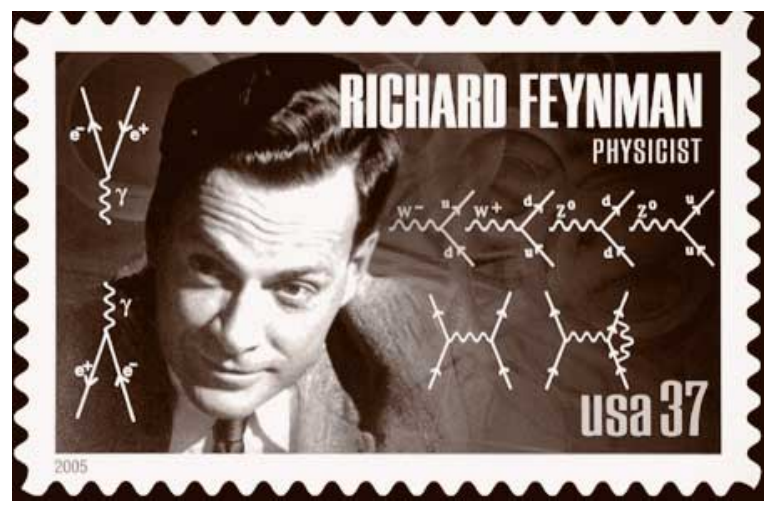
- $\mathcal{L}$ unchanged under U(1) local gauge transformation

$$\psi(x) \rightarrow \mathrm{e}^{i\alpha(x)}\,\psi(x) \qquad A_{\mu}(x) \rightarrow A_{\mu}(x) + \frac{1}{e}\partial_{\mu}\alpha(x)$$

$$e\,\bar{\psi}\gamma^{\mu}\psi\,A_{\mu}$$



is interaction between electron and photon



- one of the biggest achievements in 20th century: electromagnetic and weak interactions unified based on gauge group SU(2) x U(1)
  (Glashow, Salam, Weinberg)

- cornerstone of Standard Model

$$\mathcal{L}_{\rm int} = -\frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \psi_i$$

charged currents

$$- e \sum_i q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$

e.m. interaction

$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \, \gamma^\mu (g_V^i - g_A^i \gamma^5) \, \psi_i \, Z_\mu$$

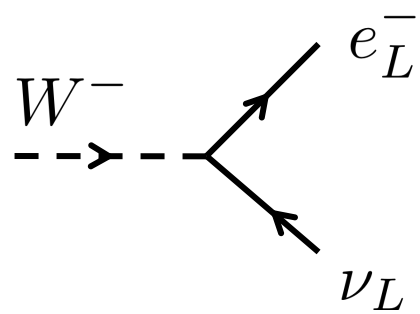
weak neutral current

$$-\frac{g}{2\sqrt{2}}\sum_i \overline{\psi}_i\,\gamma^\mu\,(1-\gamma^5)(T^+\,W_\mu^+ + T^-\,W_\mu^-)\,\psi_i$$

- Fermion fields are doublets, e.g. $\psi_i = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$

$$-\frac{e}{2\sqrt{2}\sin\theta_W}\left[W_\mu^-\,\overline{e}\,\gamma^\mu(1-\gamma^5)\nu + W_\mu^+\,\overline{\nu}\,\gamma^\mu\,(1-\gamma^5)e\right]$$

$$\sim\; W_\mu^-\,\bar{e}_L\gamma^\mu\nu_L \;+\; W_\mu^+\,\bar{\nu}_L\gamma^\mu e_L$$




- (maximal) violation of parity

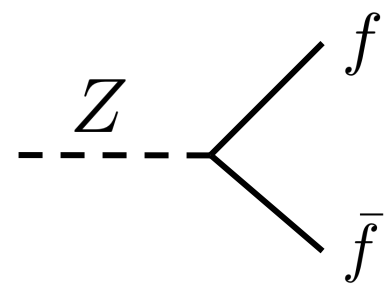
$$-e\sum_i q_i\,\overline{\psi}_i\,\gamma^\mu\,\psi_i\,A_\mu\;-\frac{g}{2\cos\theta_W}\sum_i\overline{\psi}_i\,\gamma^\mu(g_V^i-g_A^i\gamma^5)\,\psi_i\,Z_\mu$$

- Neutral currents in SU(2) and U(1) mix to produce physical photon and Z boson:

$$\begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix}$$

$\theta_W$ "weak mixing" / Weinberg angle" $\sin^2\theta_W = \dfrac{g'^2}{g^2+g'^2}$

- Specifies couplings to fermions:




$$g_V^i \equiv t_{3L}(i) - 2q_i\sin^2\theta_W$$
$$g_A^i \equiv t_{3L}(i)$$

$$t_{3L} = \begin{cases} +\frac{1}{2} & u_i, \nu_i \\ -\frac{1}{2} & d_i, e_i \end{cases}$$

- Weak bosons are massive thanks to spontaneous symmetry breaking and the Higgs mechanism:

$$M_W = 80.398 \pm 0.025 \text{ GeV}$$

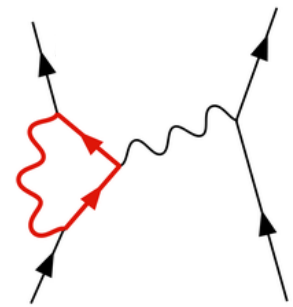
$$M_Z = 91.1876 \pm 0.0021 \text{ GeV}$$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$ at tree level

- Theory is renormalizable

  ('t Hooft, Veltman)

Gauge theories are plagued by infinities



These can be absorbed in a well-defined way
into the "renormalized" (measurable) couplings and masses

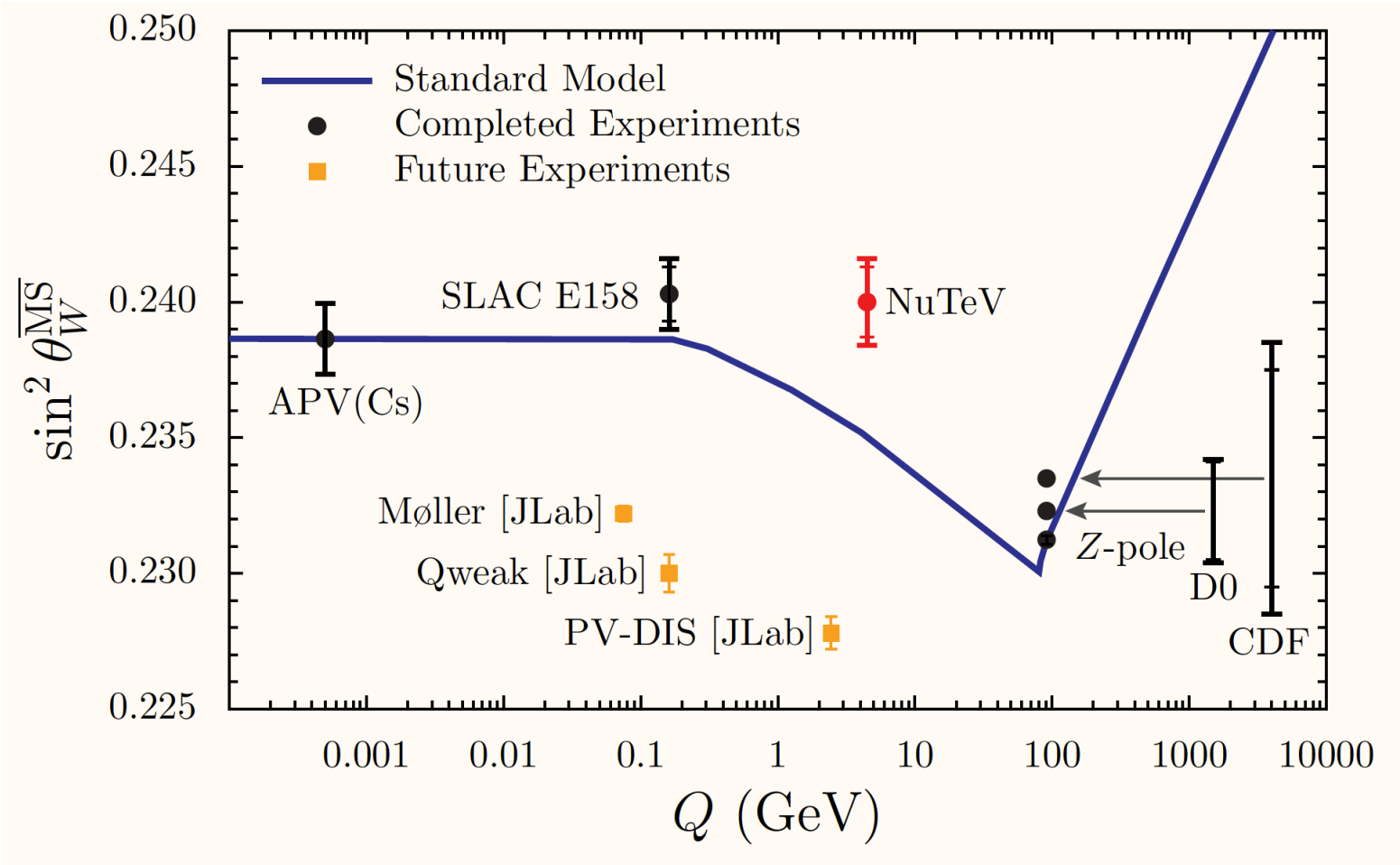
- renormalization -> "running couplings"

e.g.

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log\left(\frac{Q^2}{\mu^2}\right)}$$

**Running QED coupling**

# Running Weinberg angle:



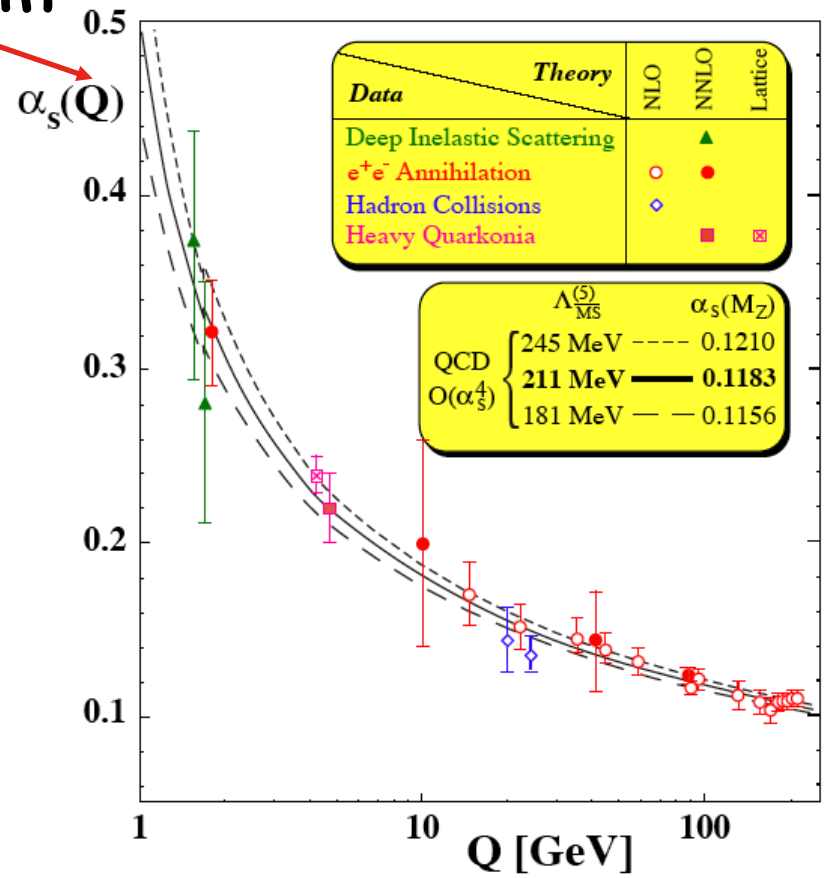

Tests theory at loop level !

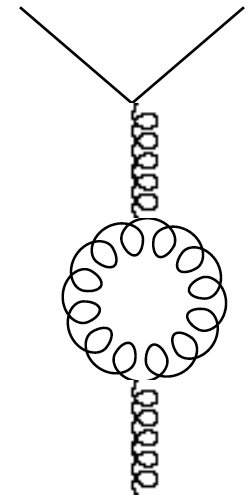
# II. Partons, hadronic scattering, and QCD

- another famous example of a running coupling: **QCD**

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)\log\left(\frac{Q^2}{\mu^2}\right)}$$

**"Confinement"**



**"Asymptotic Freedom"**

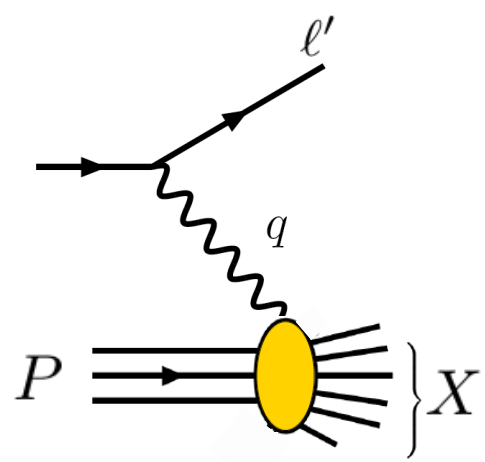
Gross, Wilczek; Politzer

- "IR safe" cross sections: insensitive to long-distance physics. Perturb. theory useful. Example: $e^+e^- \to \text{hadrons}$

- There is a class of cross sections that are not IR safe, but for which pQCD makes powerful predictions

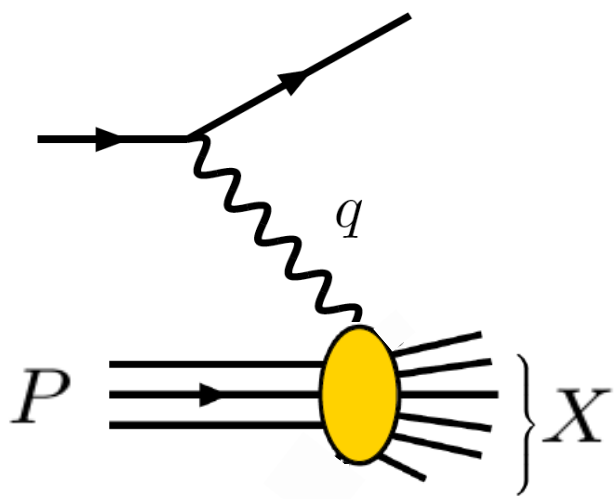
- These are the factorizable cross sections, for which long-distance and short-distance phenomena may be systematically separated (today's talk)

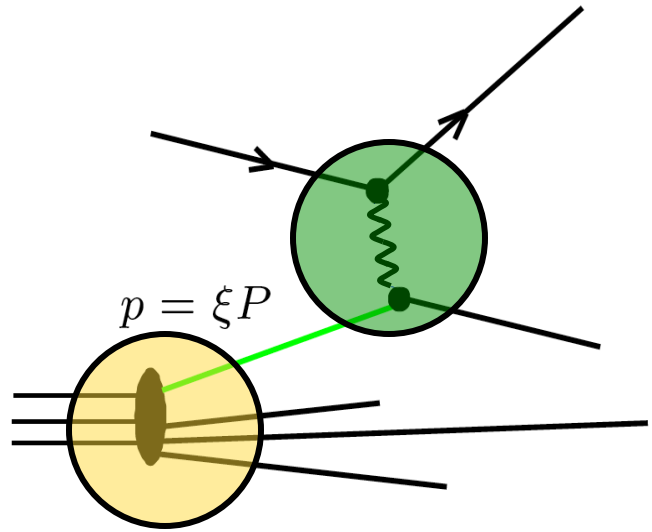
- Classic example: Deep-inelastic scattering



# Parton Model :

Feynman; Bjorken, Paschos



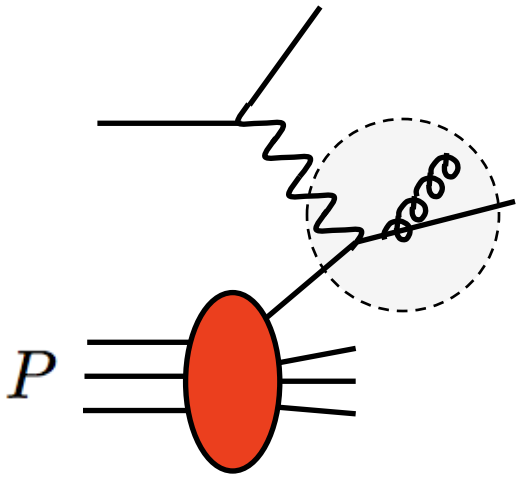

$$x = \frac{Q^2}{2P\cdot q}$$

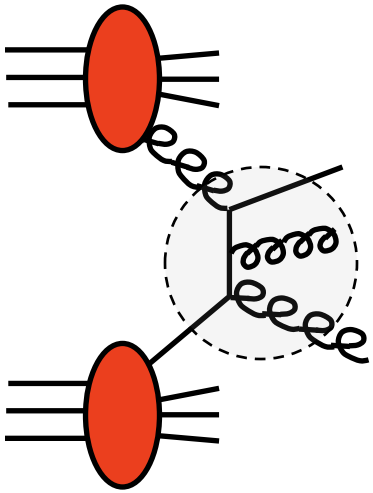
$$\xi = x$$

# QCD factorization

**DIS:**

HERA
NuTeV
JLab
EIC



Tevatron
RHIC
LHC

$$d\sigma_{\rm DIS} = \sum_{f=q,\bar{q},g} \int dx\, f(\xi, Q^2)\, d\hat{\sigma}^{\gamma^* f}(\xi P, \alpha_s(Q^2)) \; + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

universal pdf's

$$d\sigma_{\rm pp} = \sum_{a,b=q,\bar{q},g} \int d\xi_a\, f_a(\xi_a, p_T^2) \int d\xi_b\, f_b(\xi_b, p_T^2)\, d\hat{\sigma}^{ab}(\xi_a P, \xi_b P', \alpha_s(p_T^2)) + \mathcal{O}\left(\frac{1}{p_T^k}\right)$$

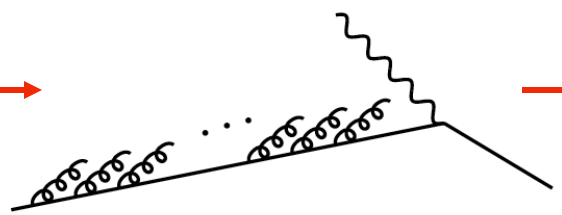
$$d\hat{\sigma} = d\hat{\sigma}_{\rm LO} + \alpha_s d\hat{\sigma}_{\rm NLO} + \ldots$$

- Evolution equations

$$Q^2 \frac{\mathrm{d}}{\mathrm{d}Q^2} \begin{pmatrix} q(x,Q^2) \\ g(x,Q^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix} \begin{pmatrix} q \\ g \end{pmatrix} \left(\frac{x}{z}, Q^2\right)$$

Dokshitzer, Gribov, Lipatov; Altarelli, Parisi

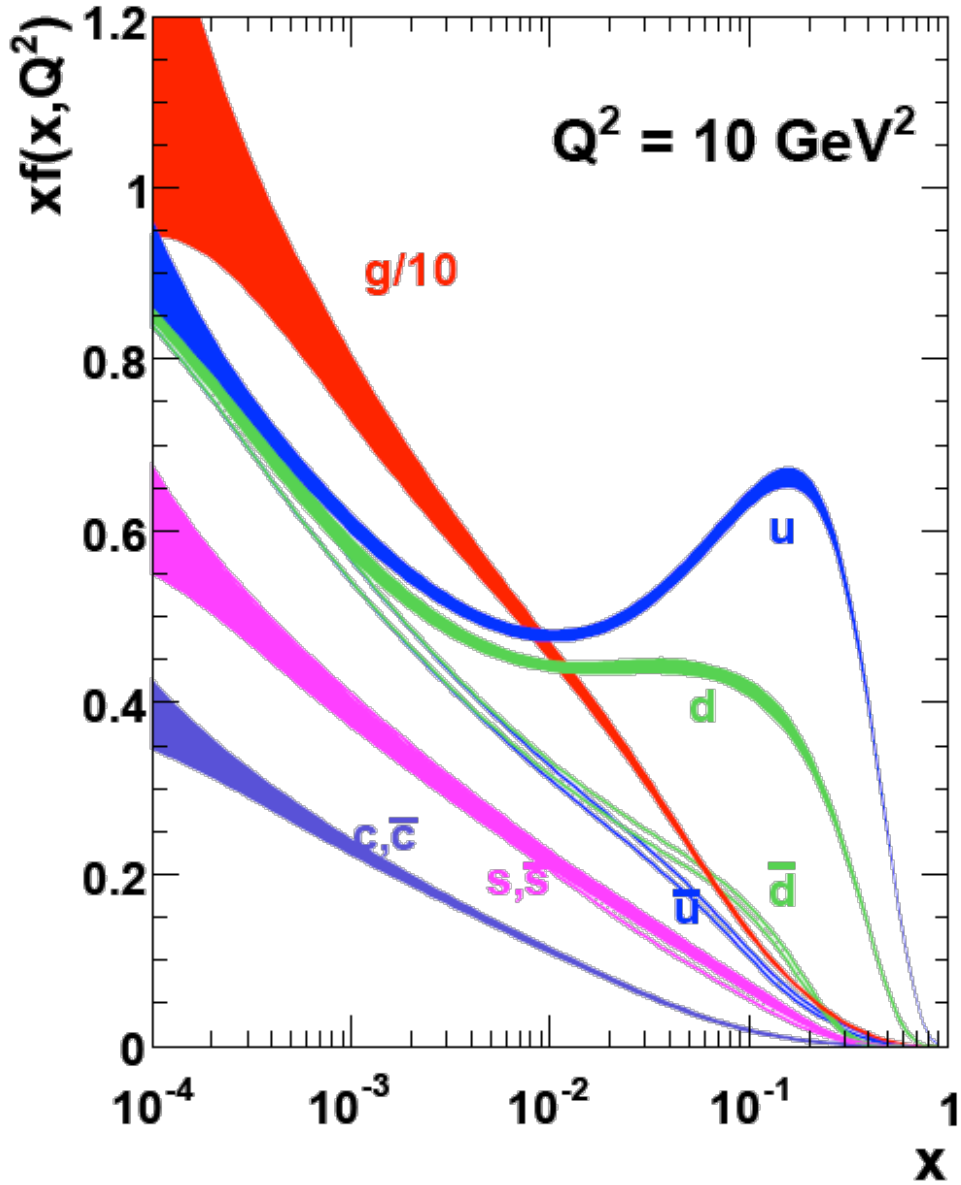
$q(\mu_0)$ →



→ $q(\mu \sim Q)$

resums terms $\alpha_s^k \log^k(Q/\mu_0)$

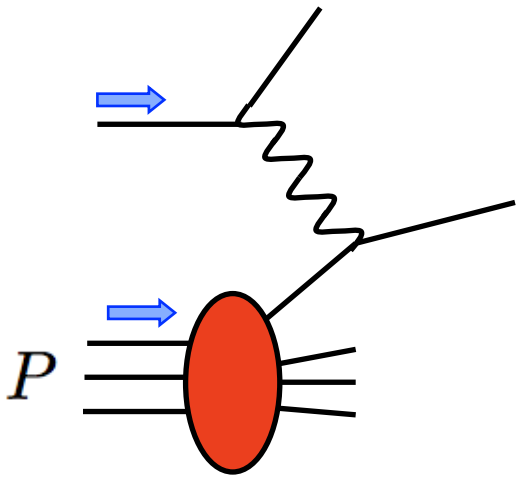
Martin, Stirling, Thorne, Watt

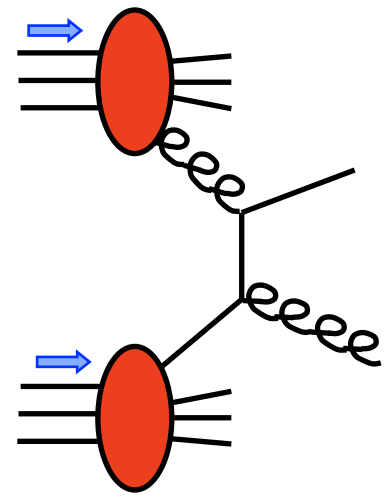



Crucial input for LHC !

# Also for *polarized* nucleons:

SLAC
HERMES
COMPASS
Jlab
EIC



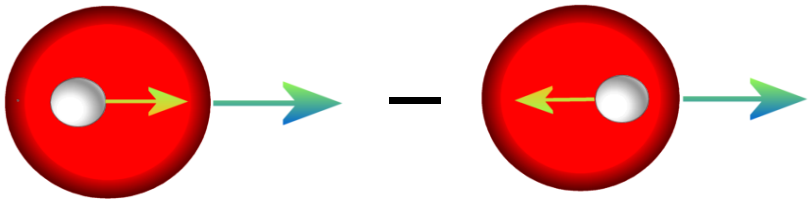



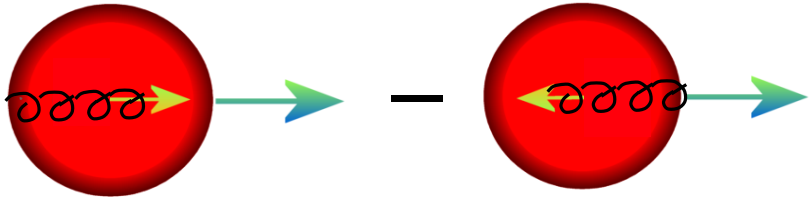
RHIC

$$d\Delta\sigma_{\rm DIS} = \sum_{f=q,\bar{q},g} \int dx \;\; \Delta f(\xi, Q^2) \; d\Delta\hat{\sigma}^{\gamma^* f}(\xi P, \alpha_s(Q^2)) + \ldots$$

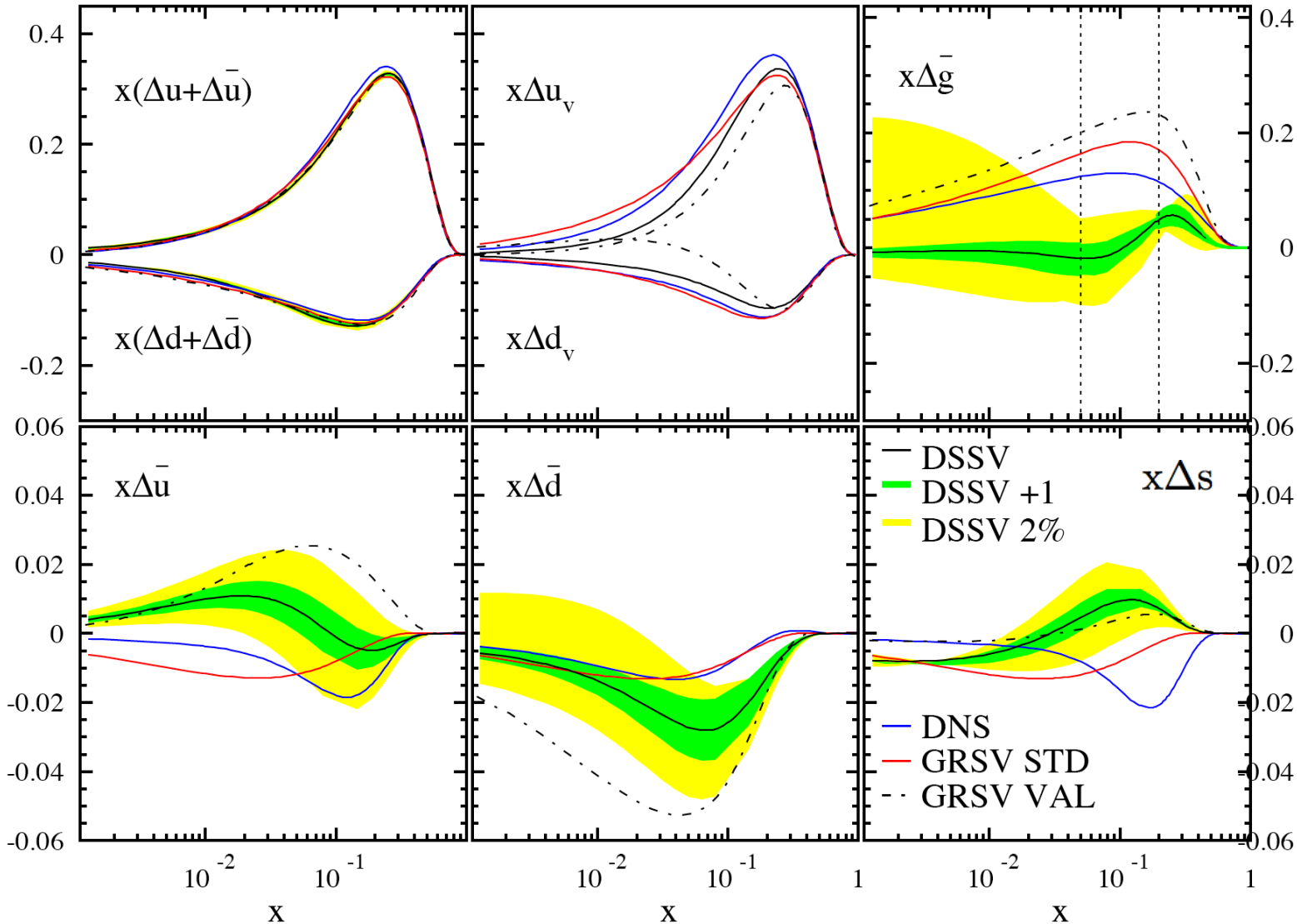
$$d\Delta\sigma_{\rm pp} = \sum_{a,b=q,\bar{q},g} \int d\xi_a \;\; \Delta f_a(\xi_a, p_T^2) \int d\xi_b \;\; \Delta f_b(\xi_b, p_T^2) \, \Delta\hat{\sigma}^{ab}(\xi_a P, \xi_b P', \alpha_s(p_T^2)) \; + \ldots$$

$\Delta q, \Delta g$ **carry spin information:**

$\Delta q(x) =$ 

$\Delta g(x) =$ 

# Current status of helicity parton distributions:




$Q^2 = 10\ \mathrm{GeV}^2$

de Florian, Sassot, Stratmann, WV

- give q and g spin contributions to proton spin:

Jaffe, Manohar; Ji, Hoodbhoy;
Jaffe, Bashinsky; Brodsky; Chen et al.

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

$$\Delta\Sigma = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x)$$

$$\Delta G = \int_0^1 dx\, \Delta g(x)$$

- proton "spin crisis":

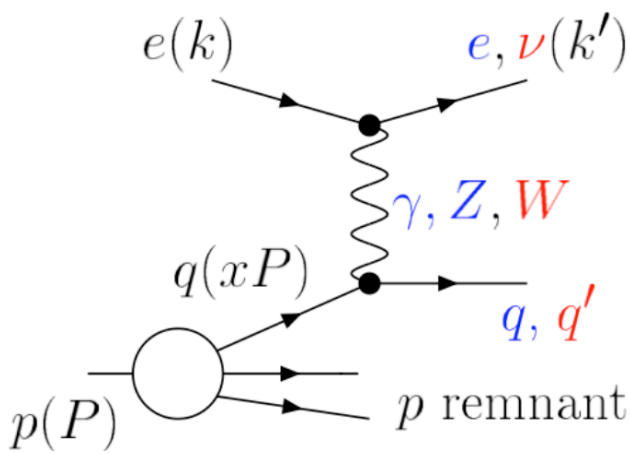
$$\Delta\Sigma \sim 0.25 \ll 1$$

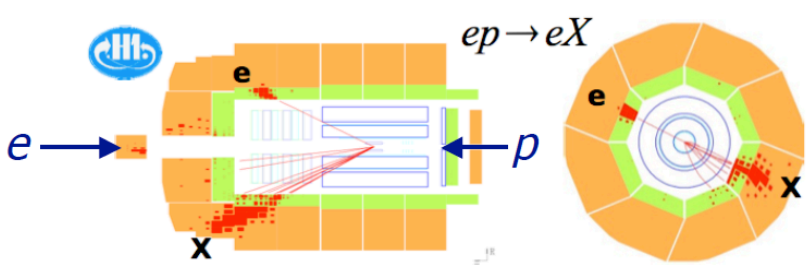
We are now ready to look at some examples for the interplay of

Electroweak physics and Nucleon Structure !

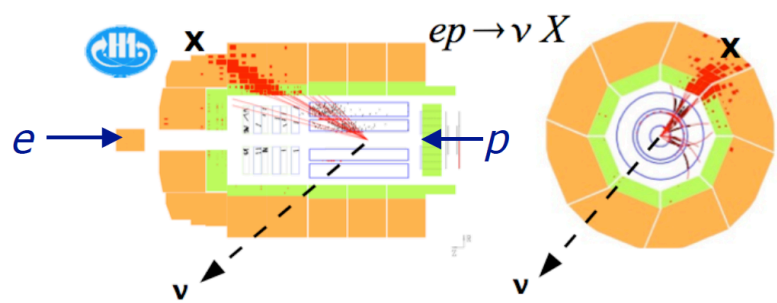
# III. EW applications for unpolarized nucleons (emphasis: testing electroweak theory)

# (1) HERA




*Neutral Current* interaction




*Charged Current* interaction

## e.g.

$$\frac{d^2\sigma^{NC}}{dx dQ^2} = \frac{2\pi^2\alpha^2}{Q^4 x}\left[Y_+ \hat{F}_2 + Y_- x\hat{F}_3 - y^2 \hat{F}_L\right] \qquad Y_\pm \equiv 1 \pm (1-y)^2$$

**$F_{2,3,L}$ depend on the lepton charge (±) & polarization P and e-w parameters ($a_i$, $v_i$, $\varkappa$)**

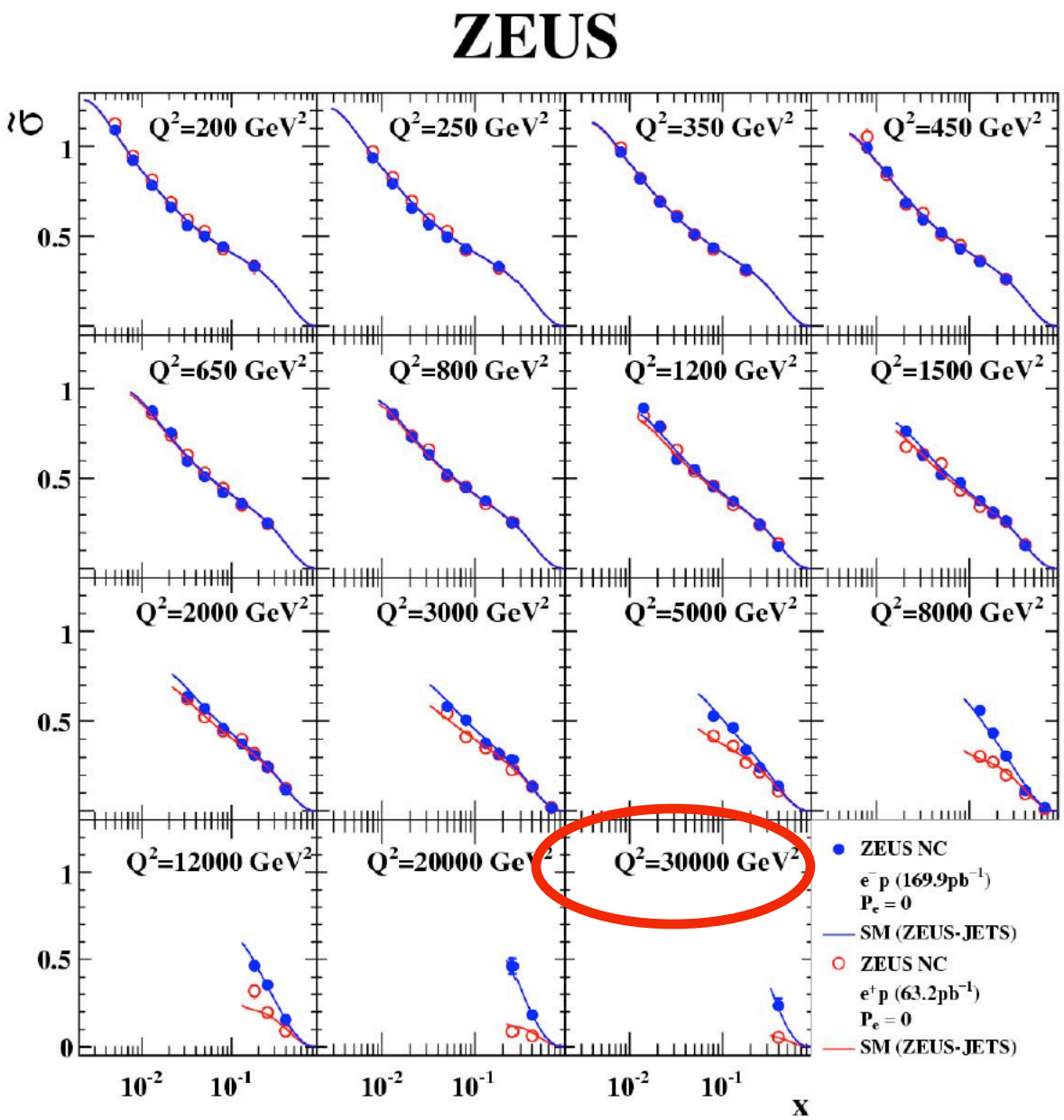
$$\begin{aligned}
\hat{F}_2^\pm &= F_2 + \kappa(-v_e \mp P a_e) F_2^{\gamma Z} + \kappa^2(v_e^2 + a_e^2 \pm P v_e a_e) F_2^Z \\
x\hat{F}_3^\pm &= 0 + \kappa(\pm a_e + P v_e) x F_3^{\gamma Z} + \kappa^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2)) x F_3^Z
\end{aligned}$$

**to $O(\alpha_s^0)$ one finds**

$$\begin{aligned}
(F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\
(xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q})
\end{aligned}$$

$$\kappa = \frac{Q^2}{(Q^2 + M_Z^2)(4\sin^2\theta_W \cos^2\theta_W)}$$

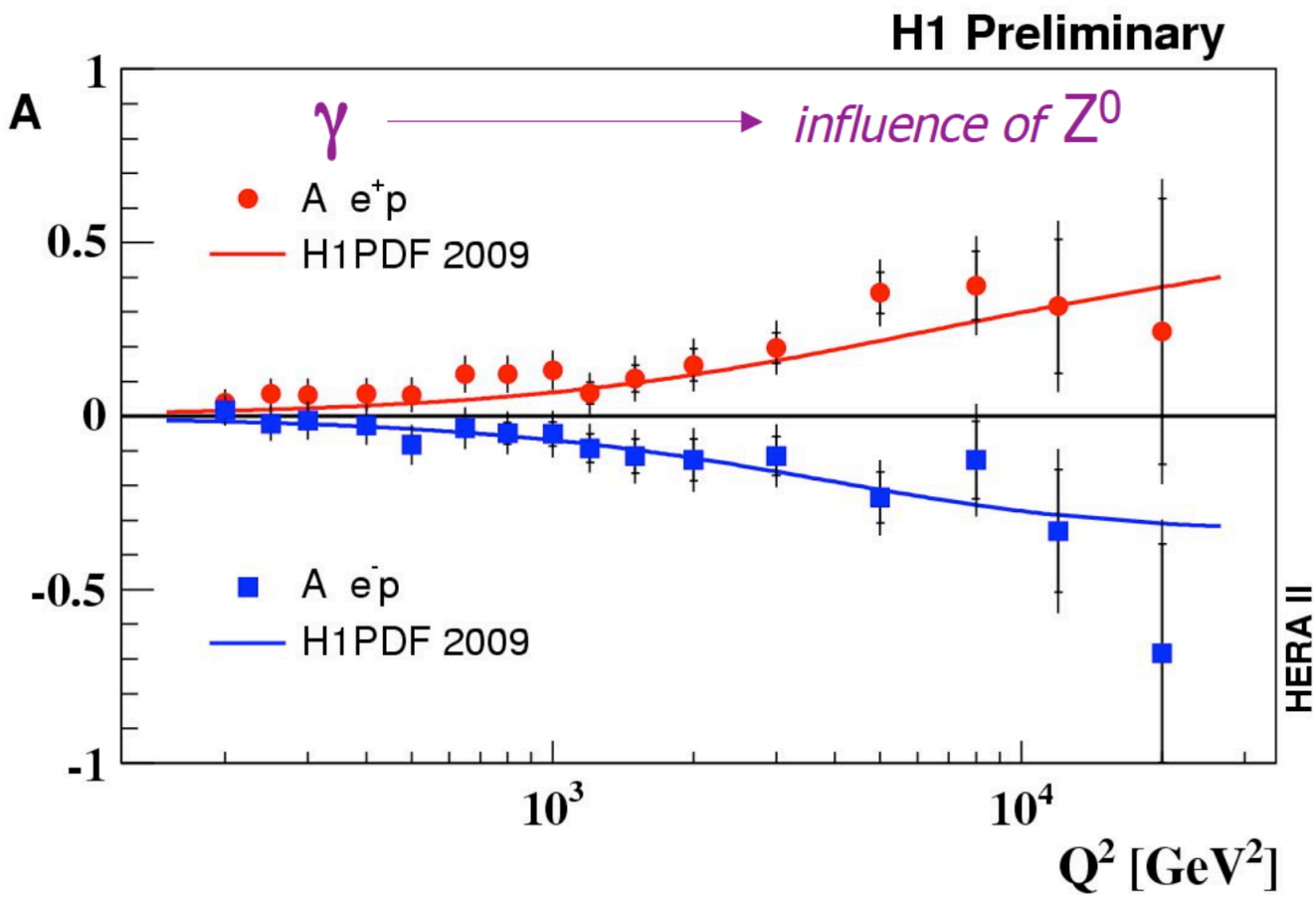
# Neutral current interactions:



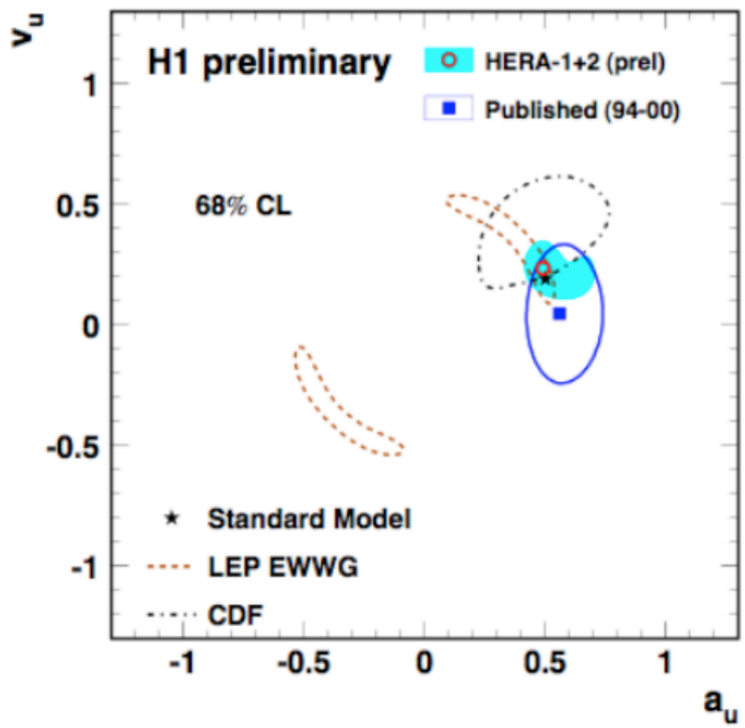

See onset of $\gamma Z$ interference

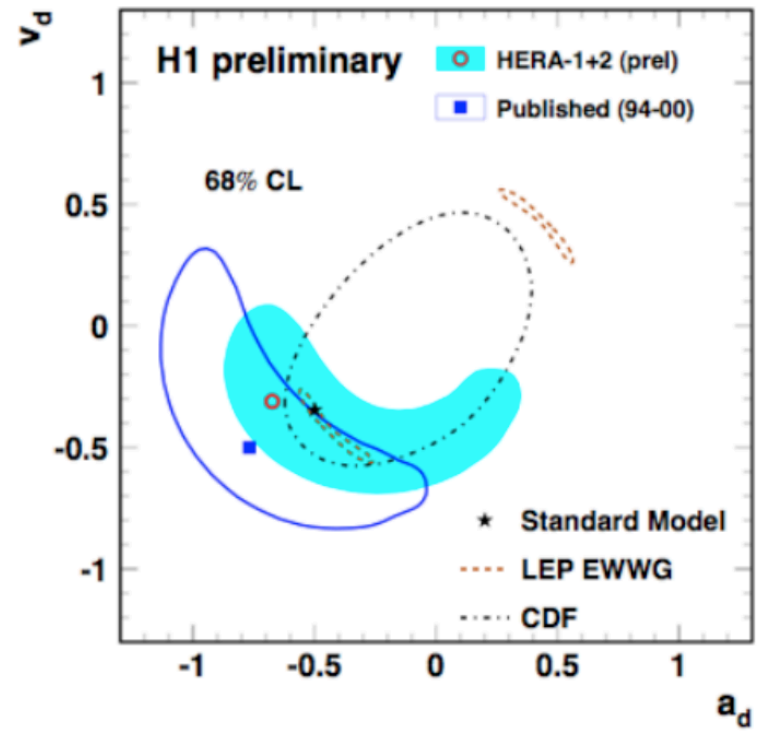
## With polarized leptons:

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



# Access to electroweak parameters:




$a_q$ mainly constrained by $xF_3^{\gamma Z}$

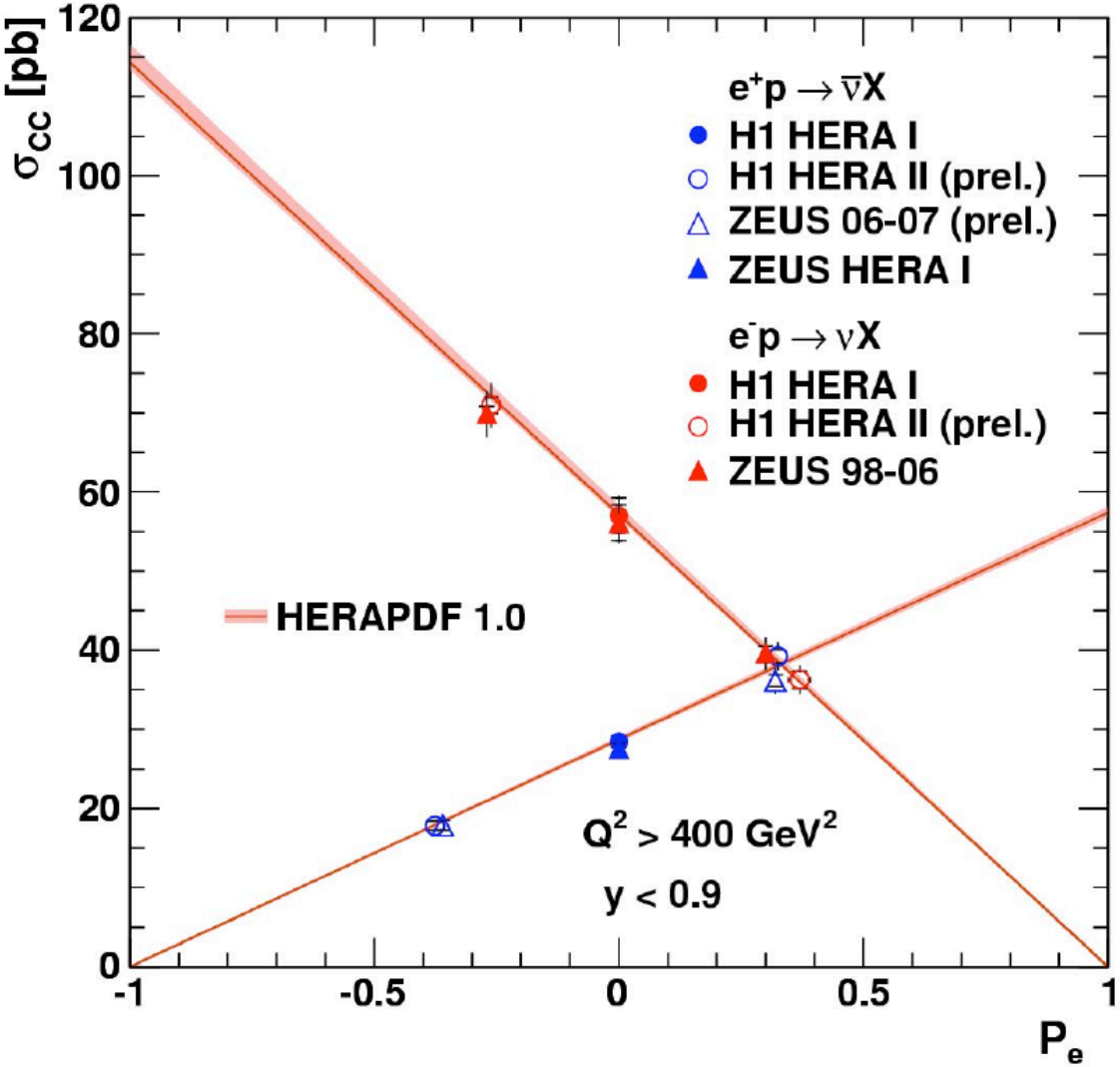
$v_q$ mainly constrained by $F_2^Z$

## Charged current interactions

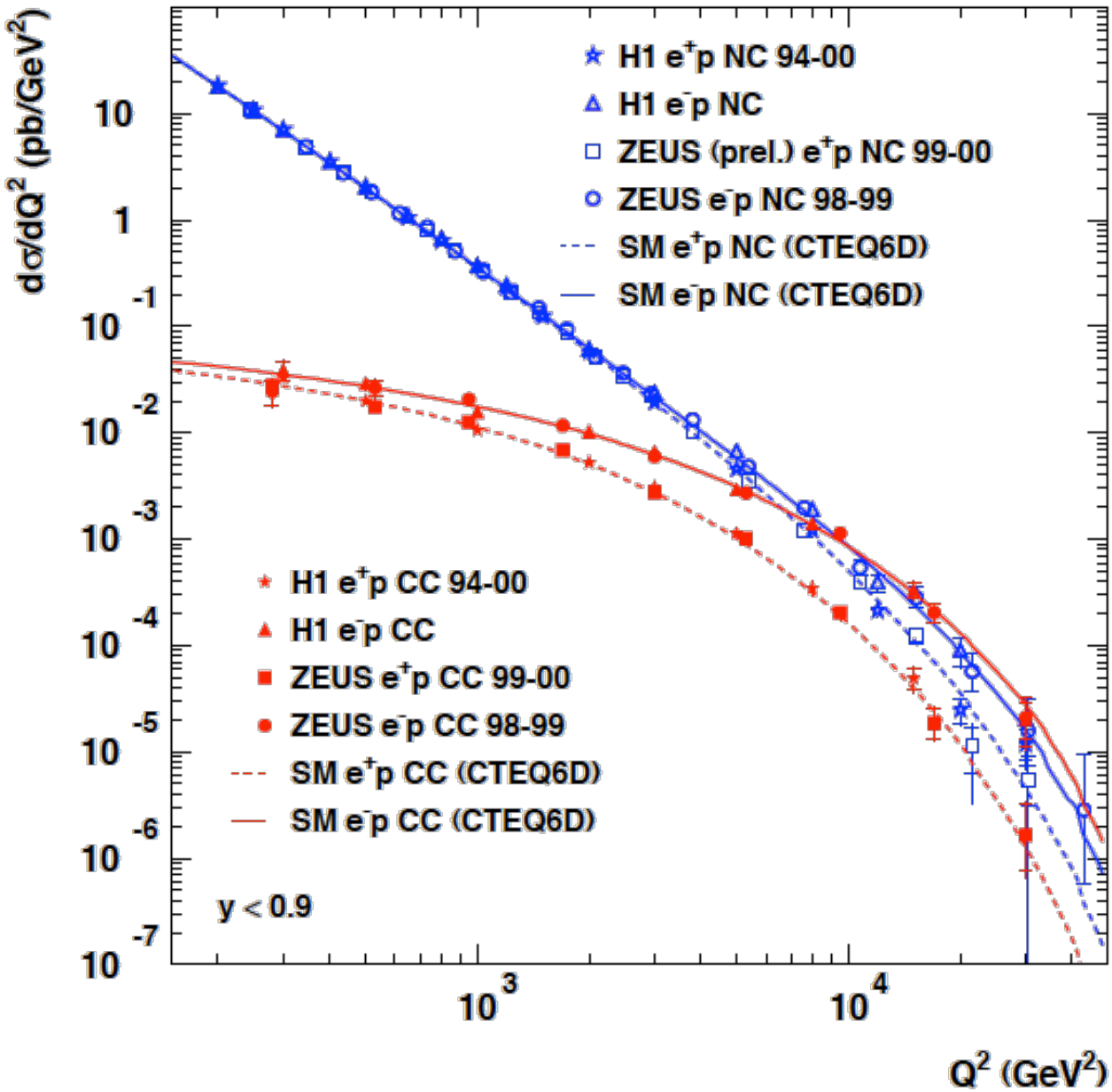
$$\frac{d^2\sigma^{CC}(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[\bar{u}+\bar{c}+(1-y)^2(d+s)\right]$$

$$\frac{d^2\sigma^{CC}(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2\left[u+c+(1-y)^2(\bar{d}+\bar{s})\right]$$

$$\sigma_{CC}^{e^\pm p}(P_e) = (1 \pm P_e)\cdot\sigma_{CC}^{e^\pm p}(P_e = 0)$$


$\sigma_{CC}$ [pb]
120
100
80
60
40
20
0
-1
-0.5
0
0.5
1
$P_e$
$e^+p \to \bar{\nu}X$
H1 HERA I
H1 HERA II (prel.)
ZEUS 06-07 (prel.)
ZEUS HERA I
$e^-p \to \nu X$
H1 HERA I
H1 HERA II (prel.)
ZEUS 98-06
HERAPDF 1.0
$Q^2 > 400$ GeV$^2$
$y < 0.9$

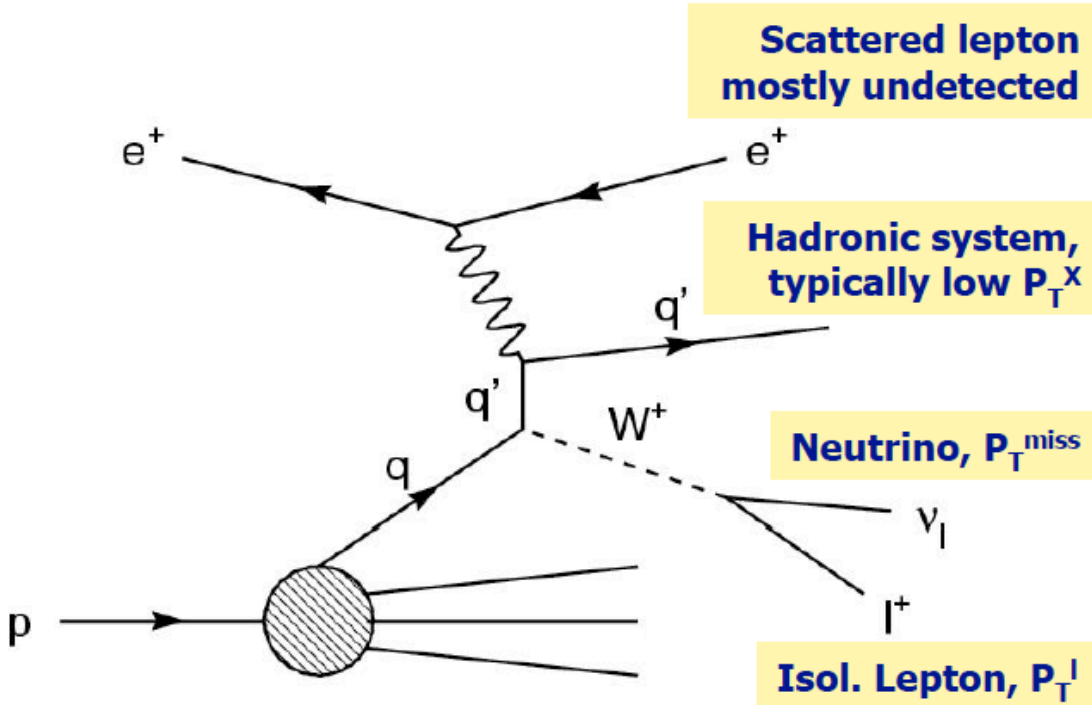
# Neutral vs. charged current interactions




$$\sigma(e^- p) \simeq u$$

$$> \sigma(e^+ p) \simeq d$$

## A lot more coming…

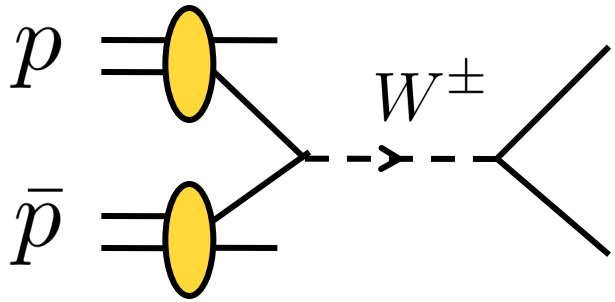



$$\sigma_{\mathrm{H1+ZEUS}} = 1.06 \pm 0.16 \pm 0.07 \text{ pb}$$

$$\sigma_{\mathrm{SM}} = 1.26 \pm 0.19 \text{ pb}$$

**Sets high bar for EW physics at an EIC !**

## (2) Tevatron:
(one example)

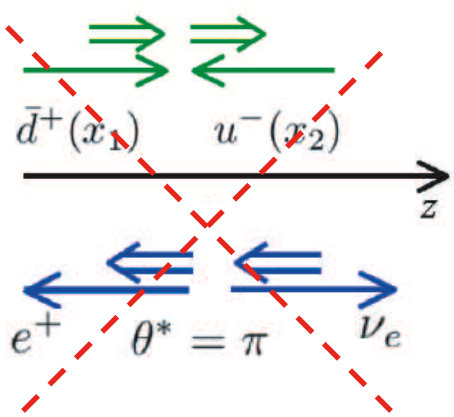



+ QCD

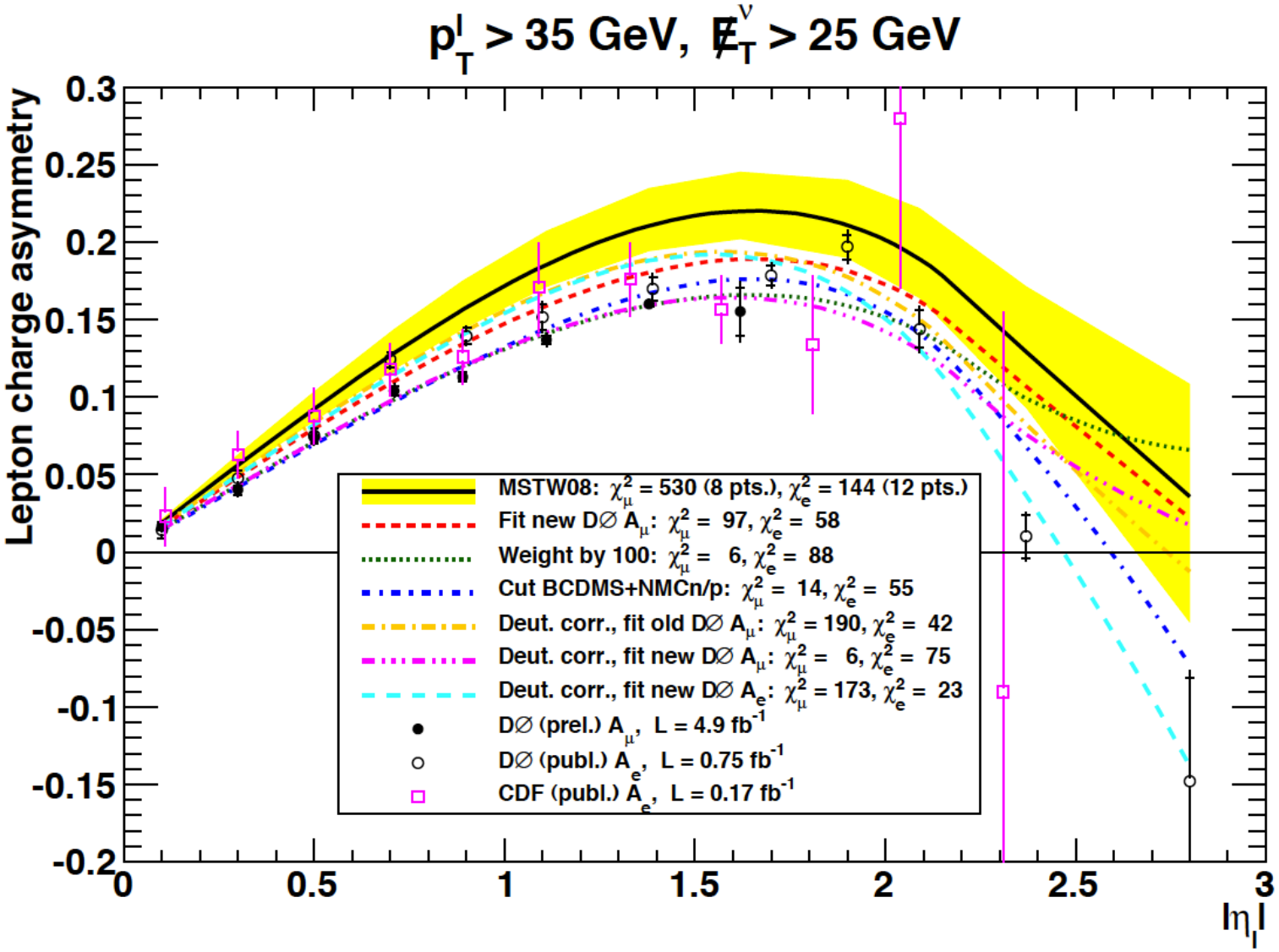
$$A(\eta_\ell) = \frac{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell - \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}{\mathrm{d}\sigma(\ell^+)/\mathrm{d}\eta_\ell + \mathrm{d}\sigma(\ell^-)/\mathrm{d}\eta_\ell}$$

charge *asymmetry*

$$\sim\ u(x_1)d(x_2)(1-\cos\theta^*)^2 + \bar{d}(x_1)\bar{u}(x_2)(1+\cos\theta^*)^2$$
$$-d(x_1)u(x_2)(1+\cos\theta^*)^2 - \bar{u}(x_1)\bar{d}(x_2)(1-\cos\theta^*)^2$$




Probe of valence distrib.,
but also involves sea quarks

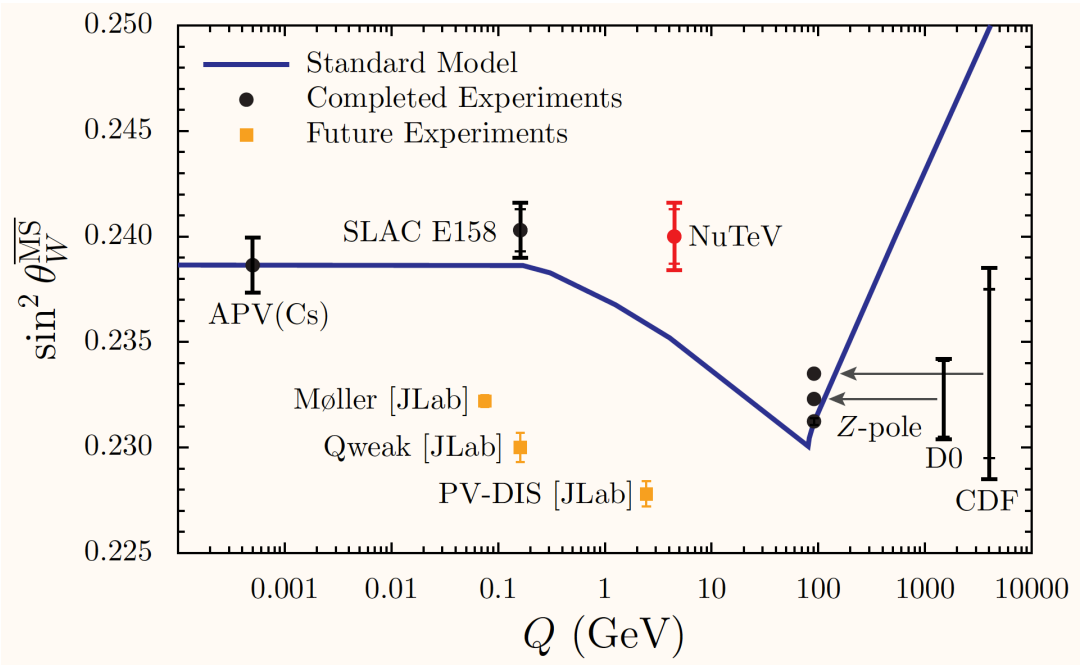



Martin, Stirling, Thorne, Watts

New light on nuclear corrections in deuterium DIS ?

10% increase of d(x) at x~0.4 and $Q^2=10^4$ $GeV^2$

# (3) The "NuTeV warning" …




**NuTeV:**

DIS $\overset{(-)}{\nu}_\mu$ Fe

**Motivation: Paschos-Wolfenstein ratio**

$$R^- \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} \approx \frac{1}{2} - \sin^2\theta_W$$

**Derived for isoscalar target, with further assumptions**

Look more closely:

Kretzer et al., MSTW, CTEQ; Cloet et al.; Moch, McFarland;…

Even for pure isoscalar target, one has:

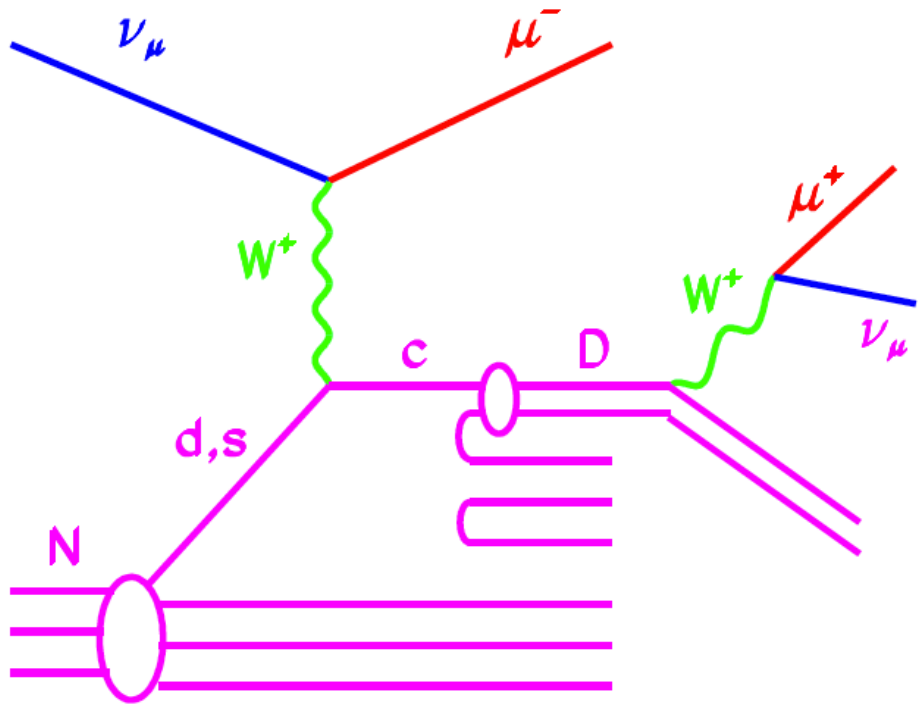
$$R^- \approx \frac{1}{2} - \sin^2\theta_W$$

$$+ \ (1 - \frac{7}{3}\sin^2\theta_W)\frac{\int_0^1 \mathrm{d}x\ x\,[(u_v^p - d_v^n) - (d_v^p - u_v^n)]}{2\int_0^1 \mathrm{d}x\ x(u_v + d_v)}$$

$$- \ (1 - \frac{7}{3}\sin^2\theta_W)\frac{\int_0^1 \mathrm{d}x\ x(s - \bar{s})}{\int_0^1 \mathrm{d}x\ x(u_v + d_v)}$$

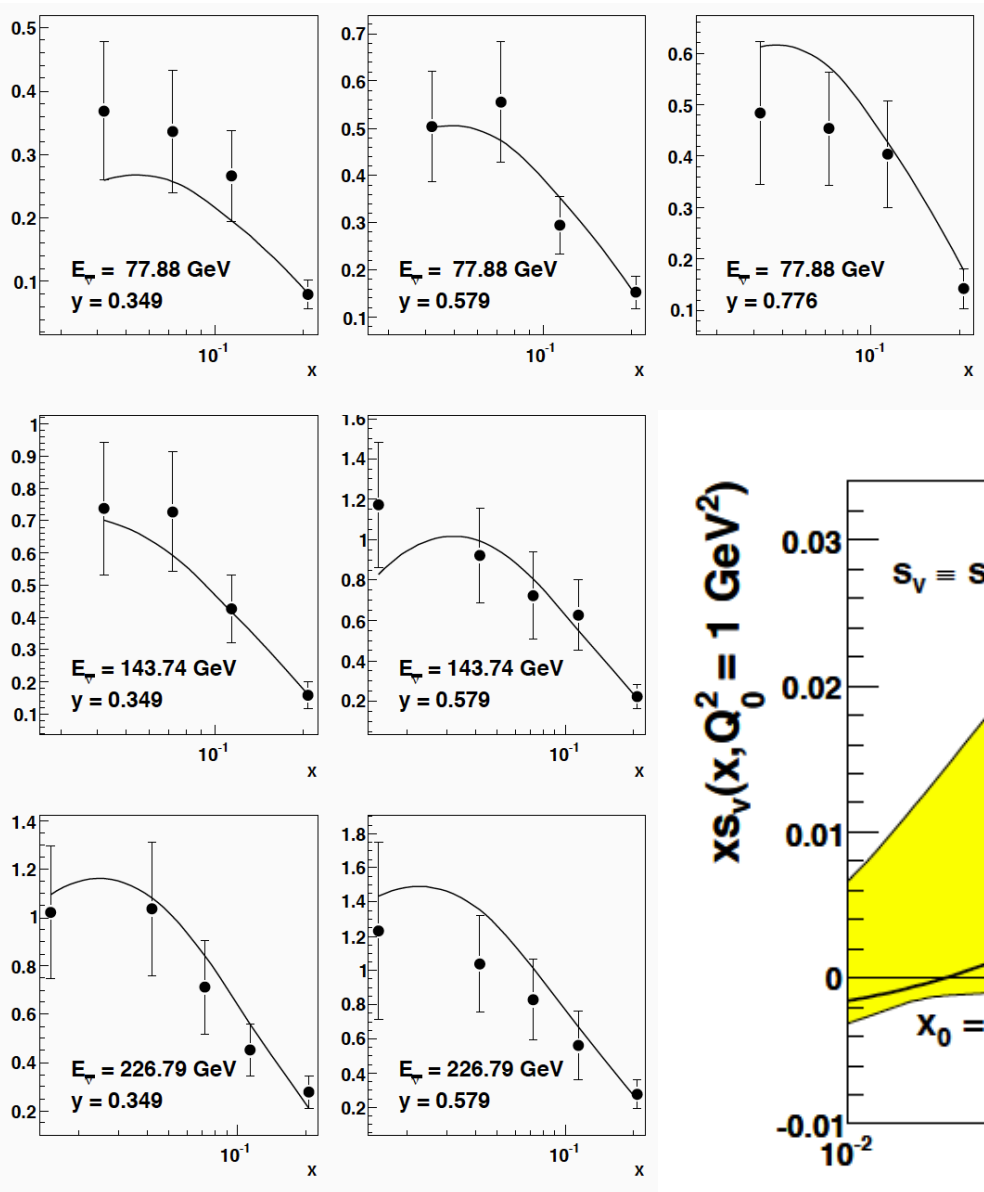
While there is no universally accepted picture, it is likely that these effects are responsible

Dimuon cross sections constrain strangeness:
(CCFR, NuTeV)



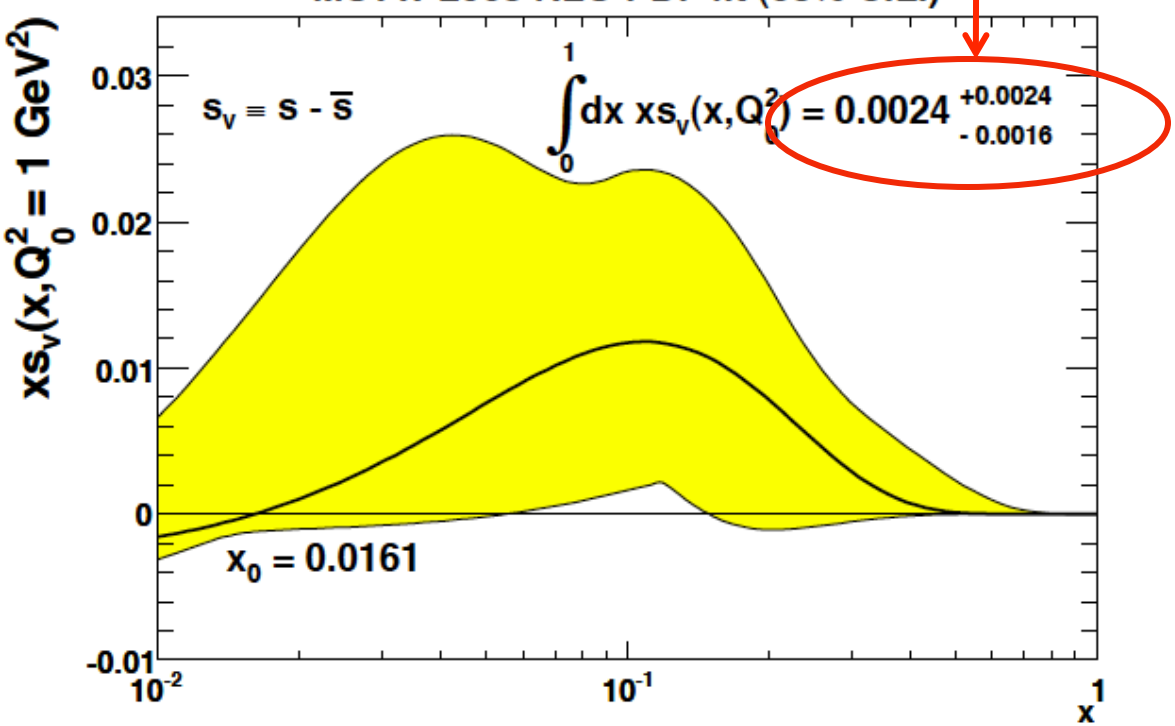
$$\text{NuTeV}\ \frac{100\pi}{G_F^2 M_N E_{\bar{\nu}}}\frac{d\sigma}{dxdy}(\bar{\nu}_\mu N \to \mu^+\mu^- X)\ \text{in GeV}^{-2}$$

MSTW 2008 NNLO PDF fit, $\chi^2 = 32$ for 19 DOF




~ 1/3 of "needed" value

MSTW 2008 NLO PDF fit (68% C.L.)

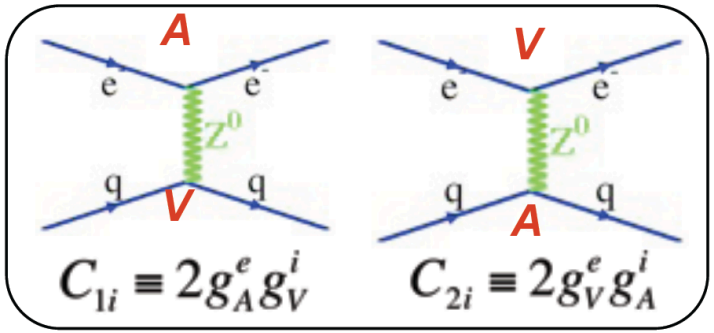


## (4) The future: Jlab (PVDIS)

**$A_{PV}$ in Electron-Nucleon DIS:**

*polarized* electron, *unpolarized* hadron

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$



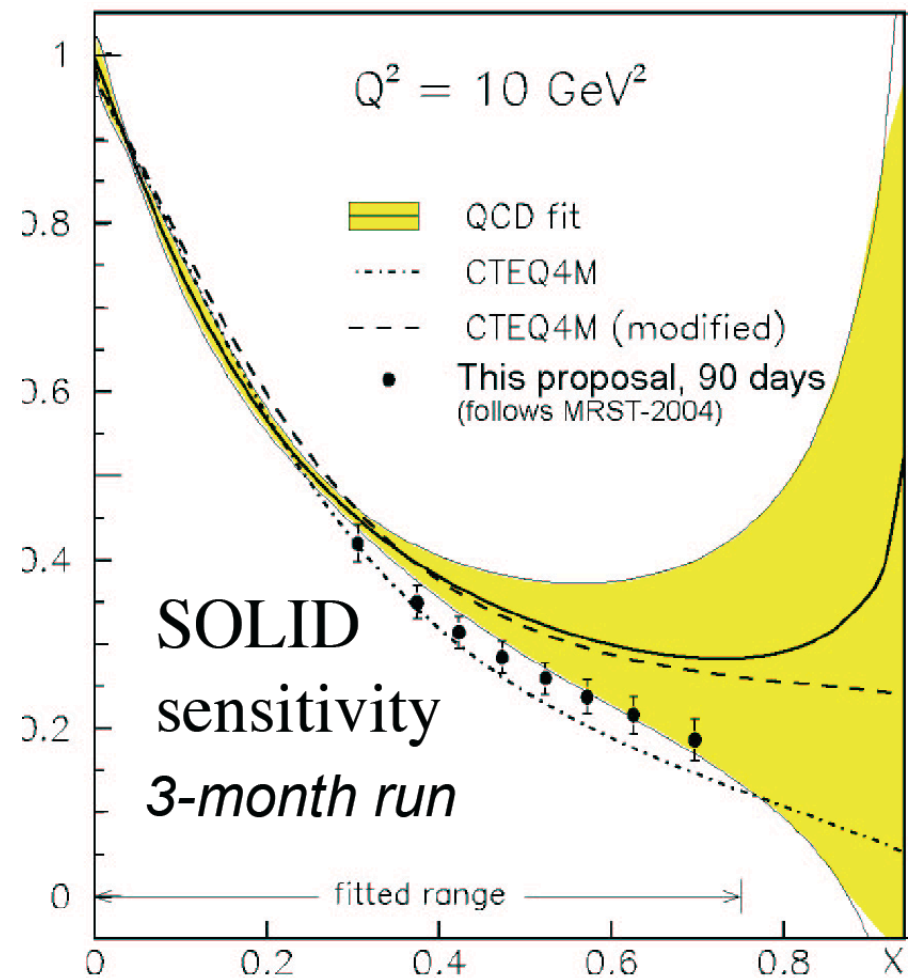

**Cahn-Gilman formula for deuteron:**

$$A_{\rm PV} \approx -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\left(1-\frac{20}{9}\sin^2\theta_W\right)+\left(1-4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

**Corrections from sea quarks, higher twist, isospin violation**

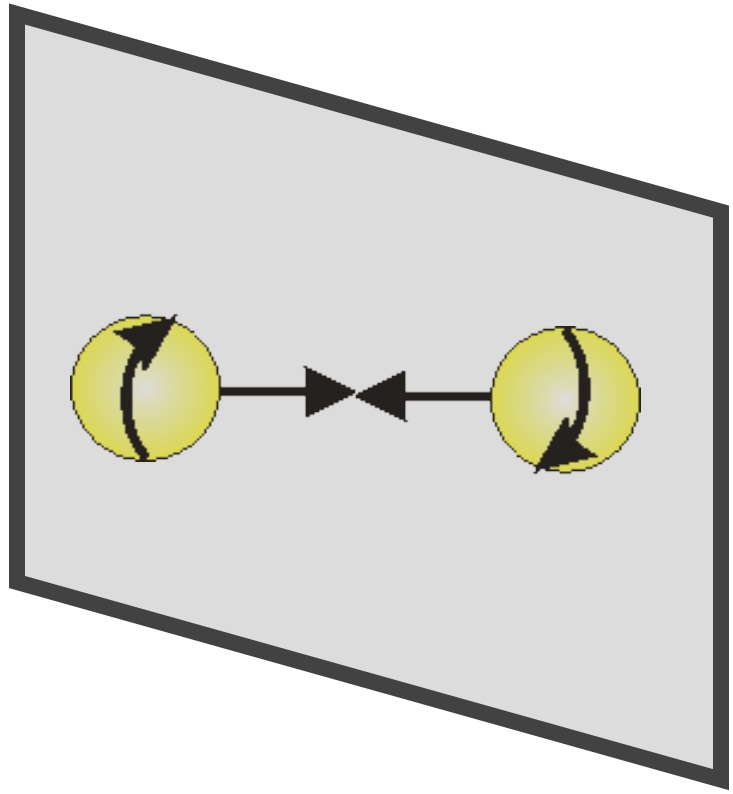
## For proton target:

$$\frac{F_1^{\gamma Z}}{F_1^{\gamma}} \sim \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$



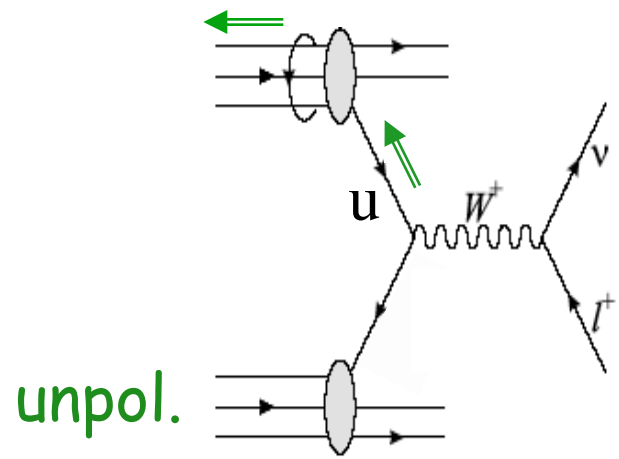
# IV. EW applications for *polarized* nucleons (emphasis: exploring the proton)

## (1) W-bosons at RHIC



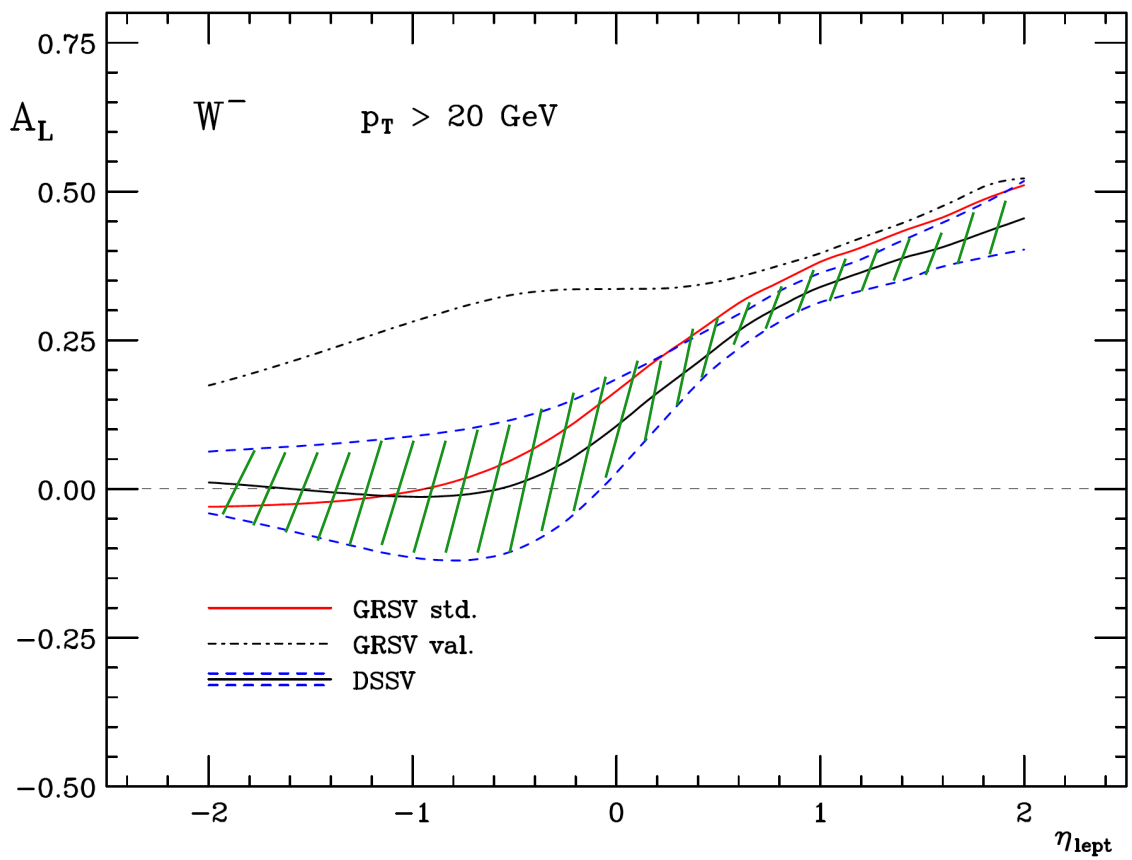
**Parity violation:** can have

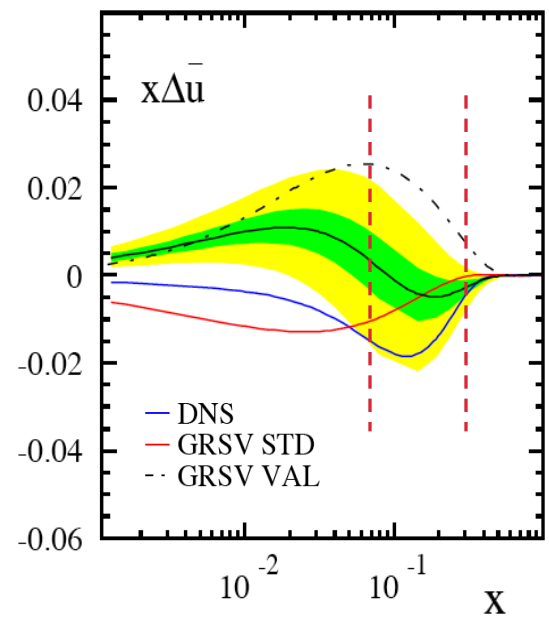
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$



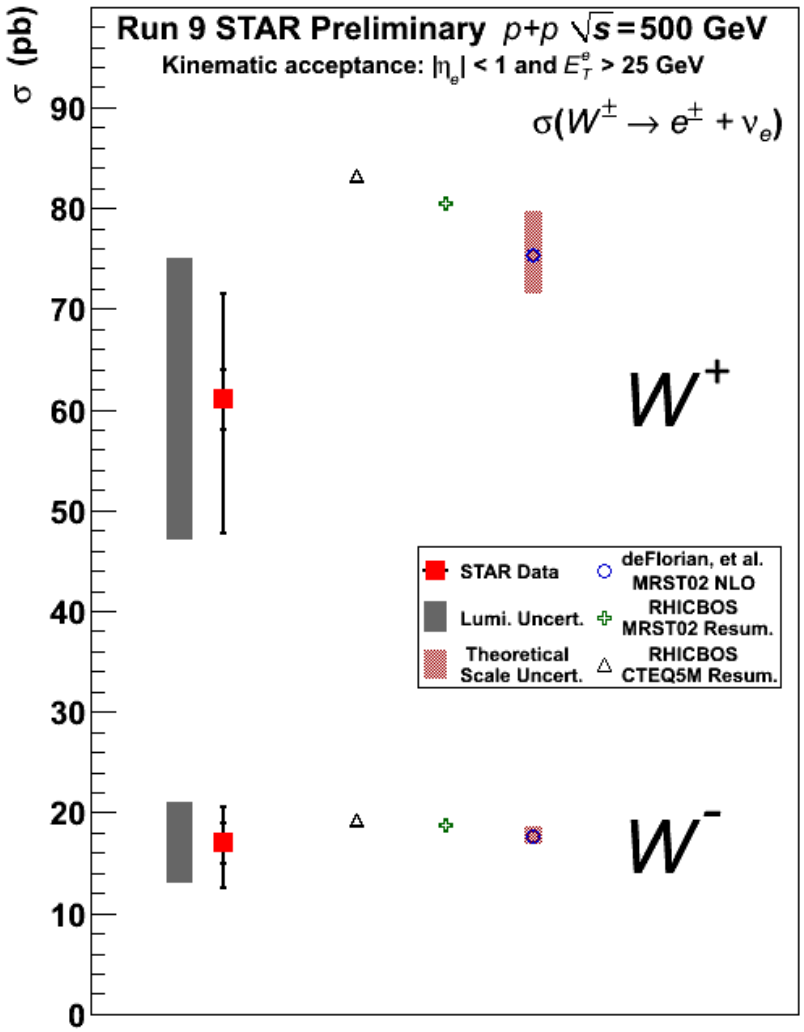
$$\Delta\sigma^{W^-} \sim \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2$$

$\Delta\bar{u}(x_1)\, d(x_2)$ $\Delta d(x_1)\, \bar{u}(x_2)$



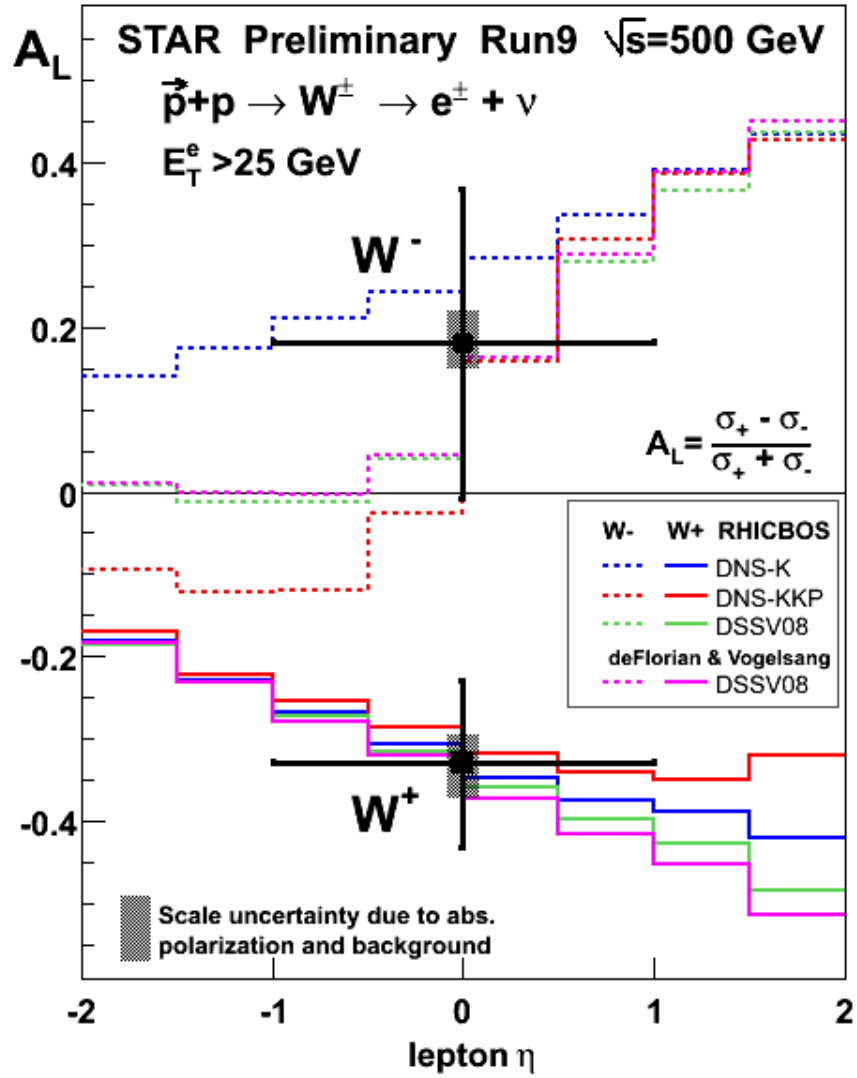

**NLO:**
**de Florian, WV**




**Run 9 STAR Preliminary (p+p 500 GeV)**

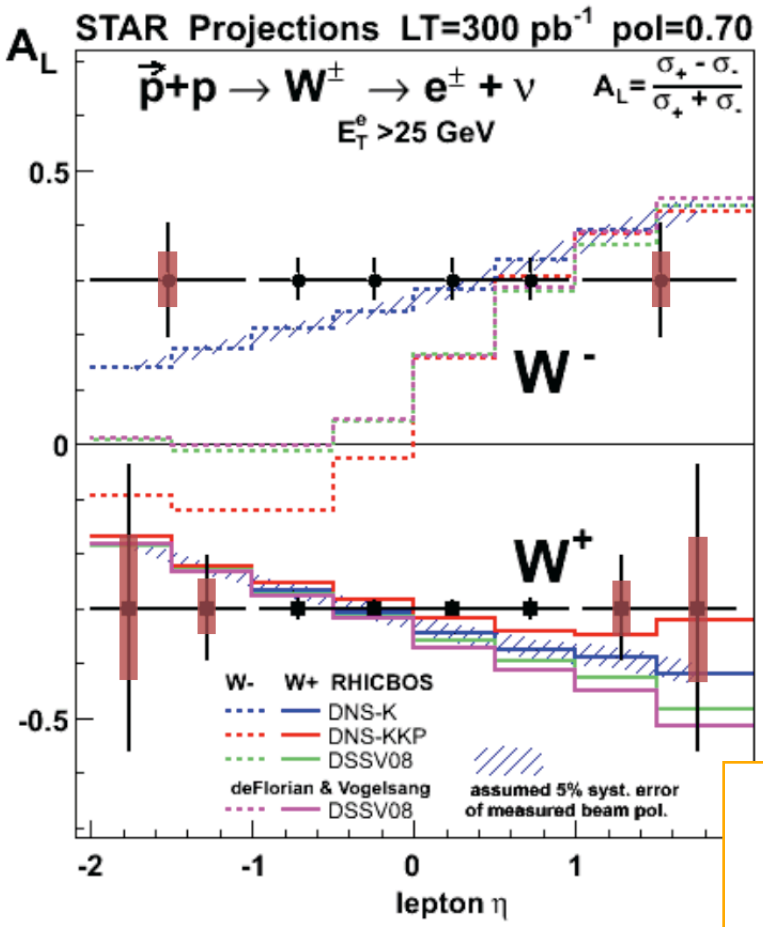
$$\sigma_{W^+\to e^+ + \nu} = 61 \pm 3\,(\text{stat.})\ ^{+10}_{-13}\,(\text{syst.}) \pm 14\,(\text{lumi.})\ \text{pb}$$

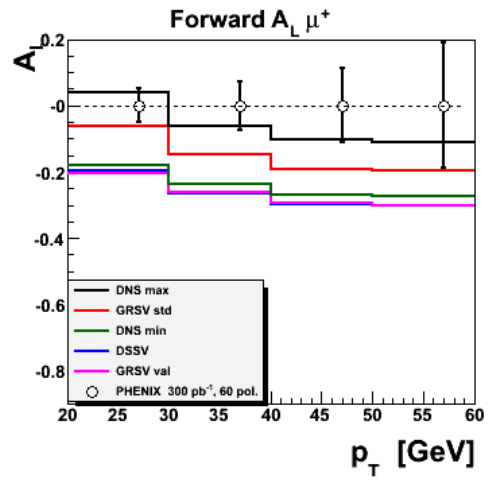
$$\sigma_{W^-\to e^- + \bar{\nu}} = 17 \pm 2\,(\text{stat.})\ ^{+3}_{-4}\,(\text{syst.}) \pm 4\,(\text{lumi.})\ \text{pb}$$

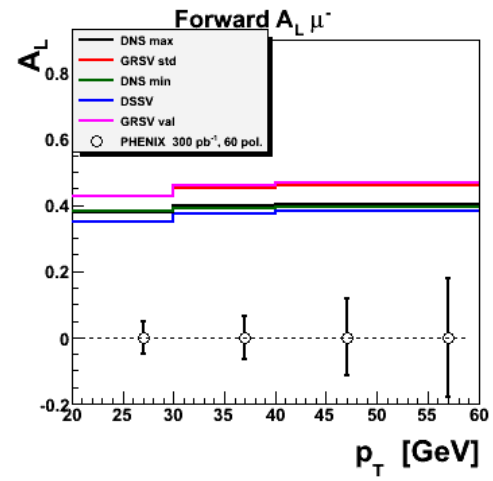


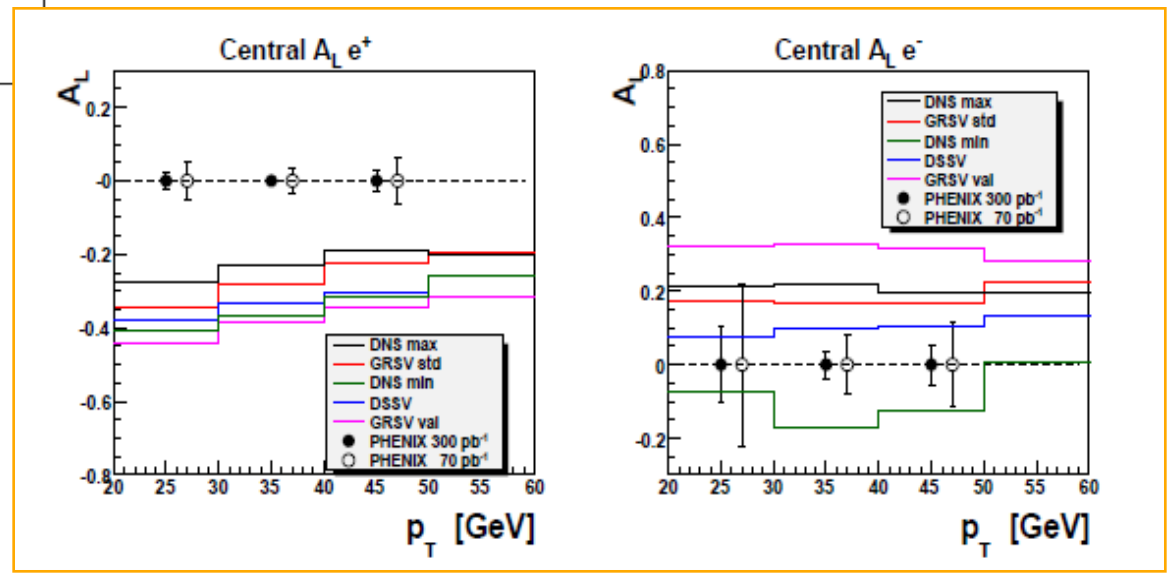

STAR, prel.

# STAR & Phenix projections

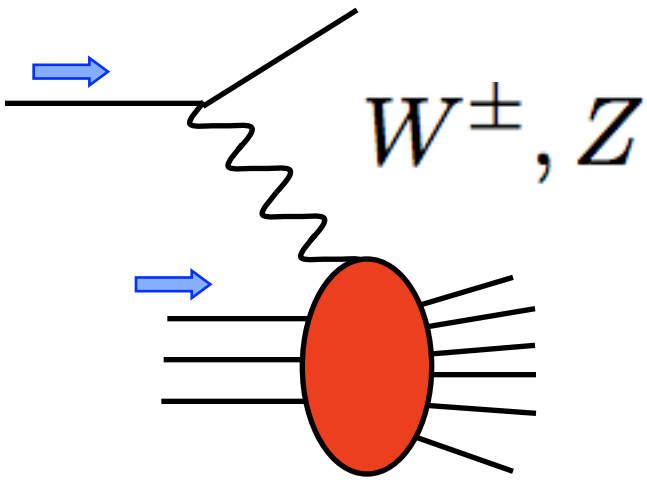


# (2) Polarized el.weak DIS at an EIC




Wray, Derman, Ahmed Ross, Lampe,
Weber Stratmann WV
Ji, Anselmino Gambino Kalinowski, …

## e.g. charged current:

$$\frac{d^2\sigma_{cc}^{\ell^{\mp}p}}{dx\,dQ^2}(\lambda, S_L) = \frac{G^2 M_W^4}{4\pi}\frac{(1\mp\lambda)}{(Q^2+M_W^2)^2}\Big\{(y^2-2y+2)F_1^{W^{\mp}} - \lambda\,\frac{y(2-y)}{2}F_3^{W^{\mp}} - \lambda y(2-y)\,g_1^{W^{\mp}} + (y^2-2y+2)\,g_5^{W^{\mp}}\Big\}$$

$$g_1^{W^-} = \Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s}$$
$$g_5^{W^-} = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s}$$
$$g_1^{W^+} = \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{c}$$
$$g_5^{W^+} = \Delta d + \Delta s - \Delta \bar{u} - \Delta \bar{c}$$

$$g_1^{W^-} + g_1^{W^+} = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} + \Delta c + \Delta \bar{c}$$

- **neutrons ??**

$$g_1^{W^-}(n) = \Delta d + \Delta c + \Delta \bar{u} + \Delta \bar{s}$$
$$g_5^{W^-}(n) = \Delta d + \Delta c - \Delta \bar{u} - \Delta \bar{s}$$
$$\ldots$$

- many more combinations for neutral current int.

$$g_1^{\gamma Z} = \sum_q e_q (g_V)_q (\Delta q + \Delta \bar{q})$$

$$g_5^{\gamma Z} = \sum_q e_q (g_A)_q (\Delta q - \Delta \bar{q})$$

$$g_1^{Z} = \frac{1}{2} \sum_q (g_V^2 + g_A^2)_q (\Delta q + \Delta \bar{q})$$

$$g_5^{Z} = \sum_q (g_V g_A)_q (\Delta q - \Delta \bar{q})$$

- NLO corrections known Stratmann WV

- huge potential, but needs detailed study

## Conclusions:

~ 25 years after discovery of weak bosons, they have become mature precision probes of the nucleon.

~ much potential for EIC, but needs careful study, in the light of what has been achieved

**Use weakly coupled probes to explore nucleon** ⟷ **Use nucleon to test electroweak interactions**