QCD uncertainties at NuTeV

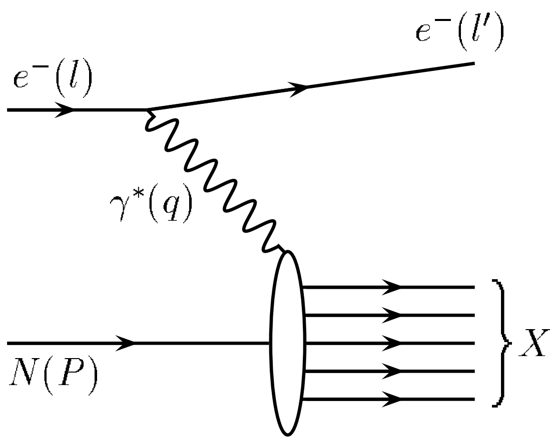
Sven-Olaf Moch

DESY Theorie
Zeuthen

1. **Deep-inelastic lepton-nucleon scattering**
   – **status of theory**
2. **The Paschos-Wolfenstein relation**
   – **parton distribution**
   – **charged current charm production**
   – **nuclear effects**
3. **Summary**

Introduction

Deep-inelastic lepton-hadron scattering



$Q^2 = -q^2$ negative 4-momentum transfer squared

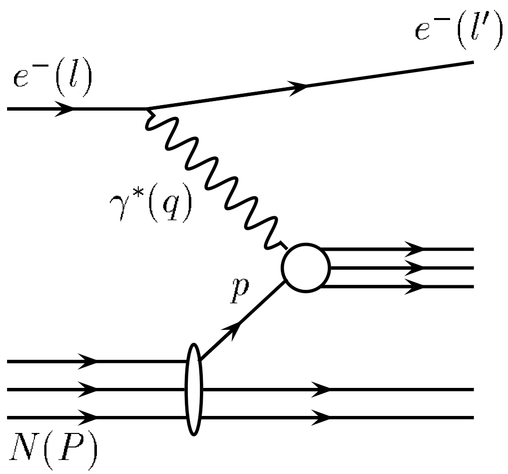
$x = \frac{Q^2}{2P\cdot q}$ parton momentum in Breit frame

$y = \frac{P\cdot q}{P\cdot l}$ $\frac{E_\gamma}{E_l}$ in proton rest frame (inelasticity)

– Neutral current scattering

$$\frac{d^2\sigma^\pm}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+(1-y)^2\right)F_2 - y^2 F_L \mp \left(1-(1-y)^2\right)xF_3\right]$$

The quark parton model



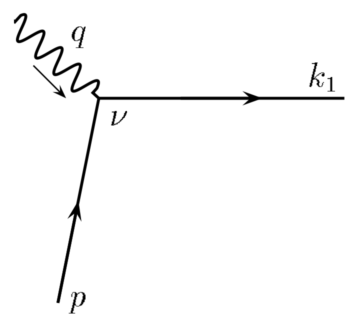
$$F_2 = \sum_q A_q x (q + \bar{q}) \qquad \text{with} \qquad A_q = e_q^2 + O\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

$$F_3 = \sum_q B_q x (q - \bar{q}) \qquad \text{with} \qquad B_q = O\left(\frac{Q^2}{Q^2 + M_Z^2}\right)$$

$$F_L = 0$$

– Pure electromagnetic interactions for $Q^2 \ll M_Z^2$

– Leading order hard scattering process



– Charged current scattering

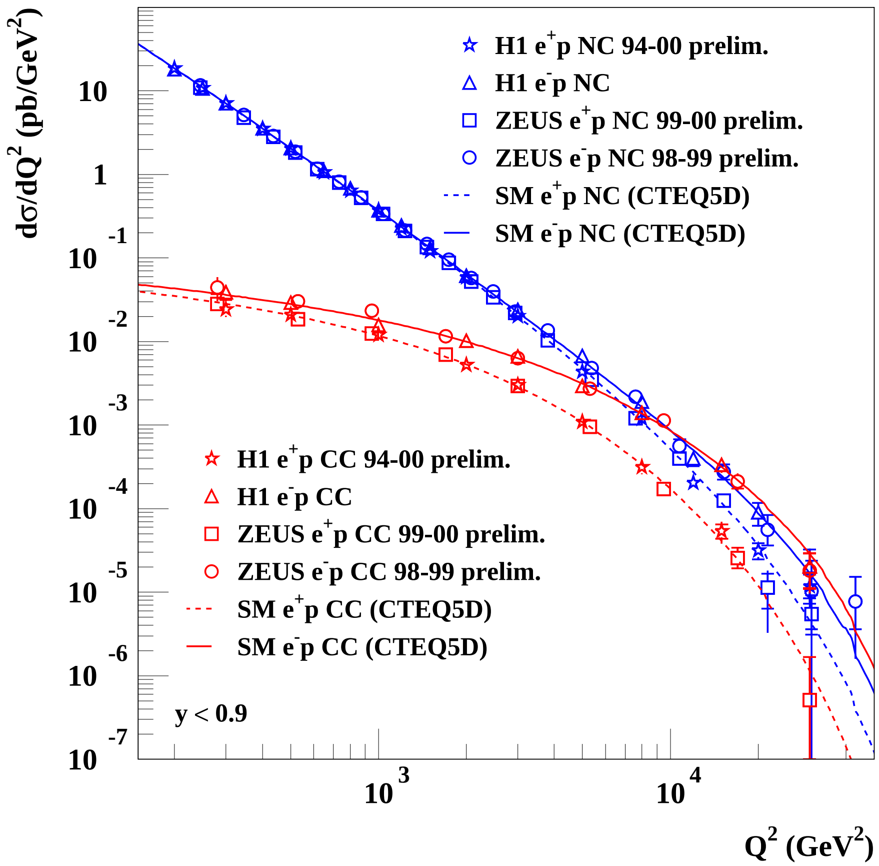
$$\frac{d^2\sigma^{\pm}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\frac{1}{(1+Q^2/M_W^2)^2}\left[\left(1+(1-y)^2\right)F_2 - y^2 F_L \mp \left(1-(1-y)^2\right)xF_3\right]$$

– The parton model in charged current scattering

$$\begin{aligned} F_1^{W^+} &= \bar{u}+d+s+\bar{c} \\ F_2^{W^+} &= 2x(\bar{u}+d+s+\bar{c}) \\ xF_3^{W^+} &= 2x(-\bar{u}+d+s-\bar{c}) \end{aligned}$$

$$\begin{aligned} F_1^{W^-} &= u+\bar{d}+\bar{s}+c \\ F_2^{W^-} &= 2x(u+\bar{d}+\bar{s}+c) \\ xF_3^{W^-} &= 2x(u-\bar{d}-\bar{s}+c) \end{aligned}$$

Electroweak measurements at HERA



- neutral/charged current cross sections become equal at high Q^2
- space-like electroweak precision test
  - M_W measurement
  - parton substructure
  - . . .

DIS in the QCD-improved parton model

– Structure function $F_2(x,Q)$ given as convolution

$$F_2(x,Q) \quad = \quad \sum_{\mathrm{p=partons}} \int_x^1 \frac{dz}{z}\, f_{\mathrm{p/N}}\left(\frac{x}{z},\mu\right) C_{2\mathrm{p}}\left(z,\frac{Q}{\mu};\alpha_s\right)$$

  – parton distributions $f_{\mathrm{p/N}}(z,\mu)$
  – coefficient functions $C_{2\mathrm{p}}(z,Q/\mu;\alpha_s)$ calculable in QCD

What are the parameters ?

– QCD input parameters
  – strong coupling $\alpha_s(M_Z) = 0.1183 \pm 0.0027$ Bethke `hep-ex/0211012`

  – charm quark mass :
    – $m_c(m_c) = 1.0 - 1.4\,\mathrm{GeV}$ Hagiwara et al. PDG 2002
    – $m_c(m_c) = 1.304(27)\,\mathrm{GeV}$ Kühn, Steinhauser `hep-ph/0109084`

  – parton distributions in the nucleon $u(x)$,$\bar{u}(x)$, $d(x)$,$\bar{d}(x)$, $s(x)$, . . ., $G(x)$

What has been done ?

- QCD corrections for DIS structure functions with massless quarks

- LO :
  - anomalous dimensions/splitting functions Gross, Wilczek ’73 ; Altarelli, Parisi ’77

- NLO :
  - complete one loop F_2 and F_L Bardeen, Buras, Duke, Muta ‘78
  - two loop anomalous dimensions/splitting functions Floratos, Ross, Sachrajda ‘79 ; Gonzalez-Arroyo, Lopez, Ynduráin ‘79 ; Curci, Furmanski, Petronzio ‘80 ; Furmanski, Petronzio ‘80
  - two loop F_L Duke, Kimel, Sowell ‘82 ; Devoto, Duke, Kimel, Sowell ‘85 ; Kazakov, Kotikov ‘88 ; Kazakov, Kotikov, Parente, Sampayo, Sanchez Guillen ‘90

- NNLO :
  - complete two loop F_2, F_3 and F_L Zijlstra, van Neerven ‘92 ; S.M., Vermaseren ‘99
  - fixed Mellin moments of F_2, F_3 and F_L at three loops Larin, Nogueira, van Ritbergen, Vermaseren ‘97 ; Retey, Vermaseren ‘00
  - approximate three loop splitting functions van Neerven, Vogt ’00
  - fermionic contribution to three loop non-singlet anomalous dimensions/splitting functions S.M, Vermaseren, Vogt ’02

What has been done ? (cont'd)

- QCD corrections for DIS structure functions with massive quarks

- Neutral current $\mathcal{O}(\alpha_s)$:
  - complete structure functions F_2 and F_L Witten '76 ; Glück, Reya '79
- Neutral current $\mathcal{O}(\alpha_s^2)$:
  - complete $\mathcal{O}(\alpha_s^2)$ F_2 and F_L Laenen, Riemersma, van Neerven, Smith '92
  - Monte-Carlo HVQDIS Harris, Smith '92

- Charged current $\mathcal{O}(\alpha_s)$:
  - complete corrections to νN DIS Gottschalk '81 ; van der Bij, Oldenborgh '91 ; Kramer, Lampe '92
  - Monte Carlo Kretzer, Mason, Olness '01
- Charged current $\mathcal{O}(\alpha_s^2)$:
  - $\mathcal{O}(\alpha_s^2 \ln^n(Q^2/m^2))$ contributions Buza, van Neerven '97

- Treatment of heavy quarks (c-threshold) Aivazis, Collins, Olness, Tung '94 ; Thorne, Roberts '98 ; Chuvakin, Smith, van Neerven '00

The Paschos-Wolfenstein relation

– exact relation for massless quarks and isospin zero target

Paschos, Wolfenstein ’73 ; Llewellyn Smith ’83

$$R^- \quad = \quad \frac{\sigma^{\nu}_{\mathrm{NC}} - \sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}} - \sigma^{\bar{\nu}}_{\mathrm{CC}}} = \frac{1}{2} - \sin^2\theta_W$$

QCD corrections to the Paschos-Wolfenstein relation

– Second moments of PDFs $q^- = \int \mathrm{d}x\, x(q - \bar{q})$, expand in isoscalar combination $u^- + d^-$

Davidson, Forte, Gambino, Rius, Strumia `hep-ph/0112302`

$$R^- \quad = \quad \frac{1}{2} - \sin^2\theta_W + \left[1 - \frac{7}{3}\sin^2\theta_W + \frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)\right]\left(\frac{u^- - d^-}{u^- + d^-} - \frac{s^-}{u^- + d^-} + \frac{c^-}{u^- + d^-}\right)$$

– R^- is ideal observable

$\longrightarrow$ NLO QCD corrections multiply isovector combination $u^- - d^-$ and asymmetries s^-, c^-

– Situation is different for separate ratios $\frac{\sigma^{\nu}_{\mathrm{NC}}}{\sigma^{\nu}_{\mathrm{CC}}}$ and $\frac{\sigma^{\bar{\nu}}_{\mathrm{NC}}}{\sigma^{\bar{\nu}}_{\mathrm{CC}}}$

$\longrightarrow$ QCD corrections proportional to dominant isoscalar combination $u^- + d^-$

Parton distributions

- Unpolarized PDF's well known from small to relatively large x

  Glück, Reya, Vogt '98 ; Martin, Roberts, Stirling, Thorne '02 ; Lai et al. (CTEQ) '02
- Less information on polarized PDF's

  Blümlein, Böttcher '02
- Recent dedicated analyses of lepton-nucleon DIS (including neutrino data)

  Barone, Pascaud, Zomer `hep-ph/9907512` ; Botje `hep-ph/9912439` ; Alekhin `hep-ph/0011002`

- Scheme dependence
  - $\overline{\text{MS}}$-scheme vs. DIS-scheme $\longrightarrow$ affects radiative corrections in coefficient functions
  - e.g. $c_{2,q}^{(1)} = c_{2,g}^{(1)} = 0$ for coefficient functions, but different splitting functions, large logarithms for $x \longrightarrow 1$ in PDFs
- Scheme independent evolution $\longrightarrow$ fit F_2 and dF_2/dQ^2

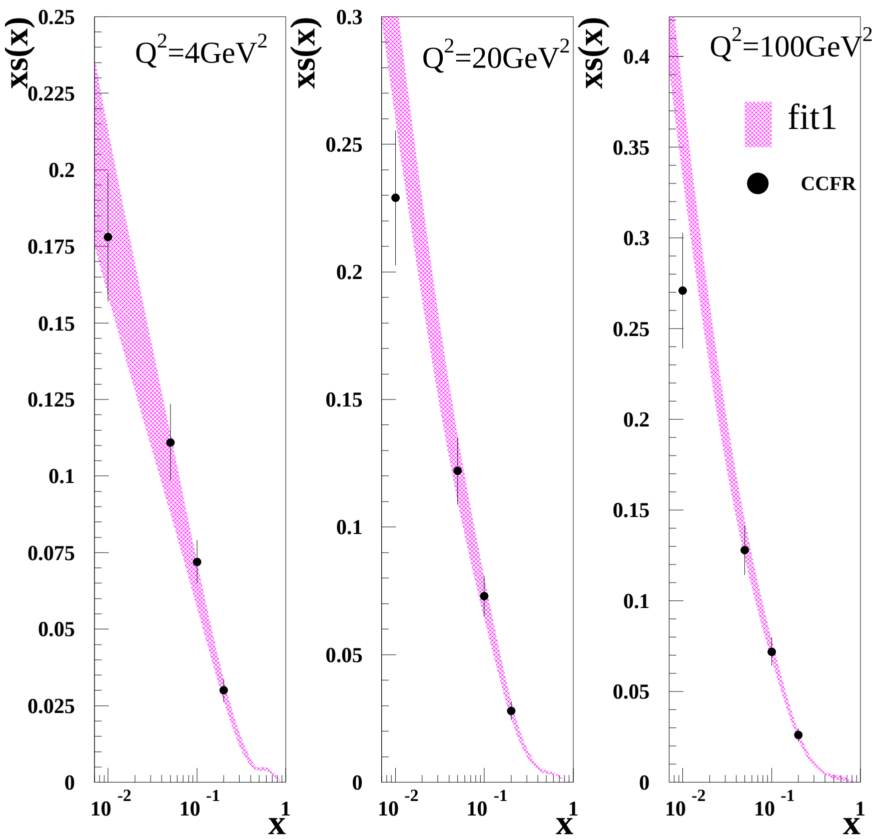
  Blümlein, Vogt '98

- PDF uncertainties
  - account for correlated errors in PDFs

    Botje `hep-ph/9912439` ; Giele, Keller, Kosower `hep-ph/0104052`

Total strange distribution

– The BPZ fit compared to CCFR data   Barone, Pascaud, Zomer hep-ph/9907512



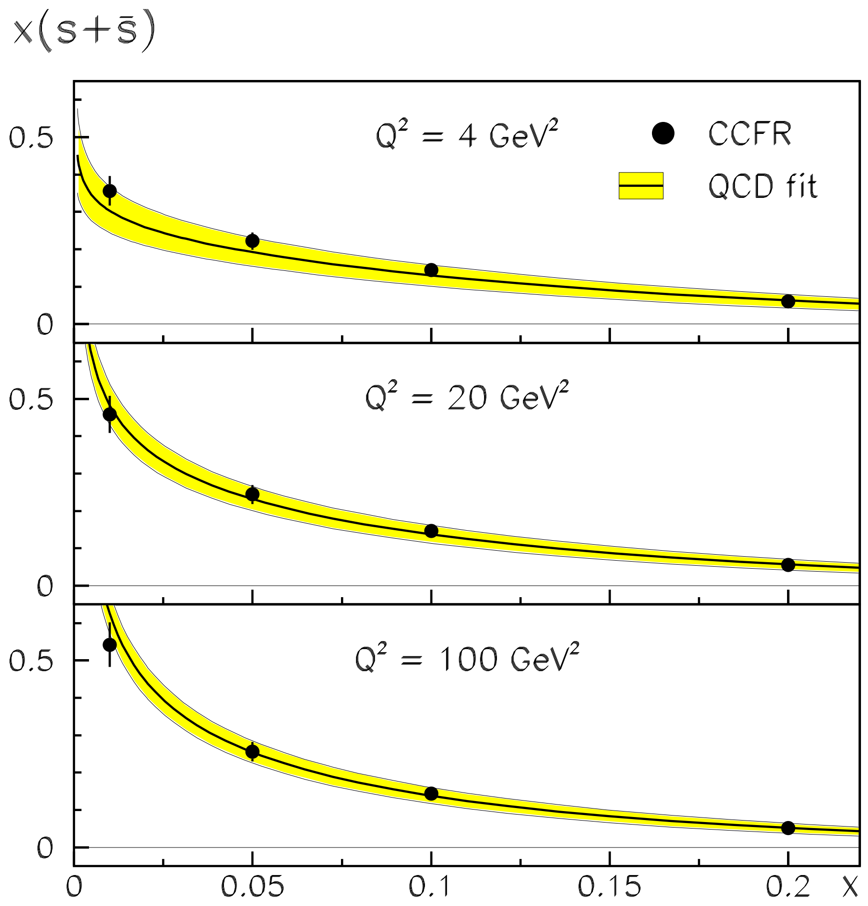
– standard assumptions in global fits

  – no strangeness in the proton
    $\longrightarrow s(x) = \bar{s}(x)$

  – isospin symmetry $\longrightarrow u_P(x) = d_N(x)$

Total strange distribution (cont'd)

– Error on total strange distribution in the QCD fit   Botje hep-ph/9912439



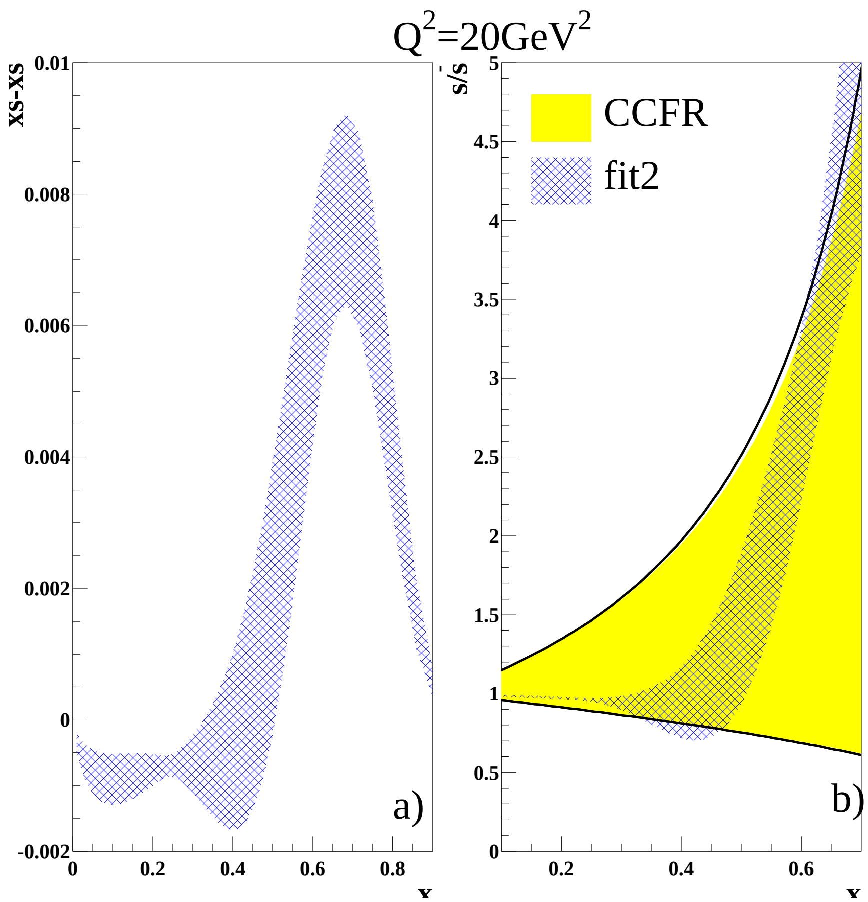
Typical uncertainities in PDF analysis :

- Input errors in PDFs
  - error on α_s
  - deuterium/iron nuclear corrections
  - strange quark content of the proton
  - charm threshold

- Theoretical error
  - variation of scales :
    renormalization/factorization scales
    $\mu^2_{r,f}, \quad Q^2/2 < \mu^2_{r,f} < 2Q^2$

Indications for a strangeness asymmetry ?

Barone, Pascaud, Zomer `hep-ph/9907512`



– Relax constraint $s(x) = \bar{s}(x)$
$\longrightarrow$ improved χ^2 in BPZ fit to CCFR data

– Ansatz for NLO QCD parametrization

$$xs(x, Q_0^2) = A_s x^{B_s} (1-x)^{C_s} (1 + D_s x^{E_s})$$
$$x\bar{s}(x, Q_0^2) = A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}} (1 + D_{\bar{s}} x^{E_{\bar{s}}})$$

– put $A_s = A_{\bar{s}}$ and $B_s = B_{\bar{s}}$
– impose no net strangeness

$$\int_0^1 dx\,(s(x) - \bar{s}(x)) = 0$$

The NuTeV analysis of dimuon production cross section

Goncharov et al. `hep-ex/0102049`

- Measurement of $\nu N, \overline{\nu} N \longrightarrow \mu^+ \mu^- + X$
  - uncertainities in fragmentation

    Peterson, Schlatter, Schmitt, Zerwas '83 ; Collins, Spiller '85
  - NLO fragmentation of heavy quarks

    Cacciari, Greco '97

- Parametrization of the strange distribtution at LO in QCD

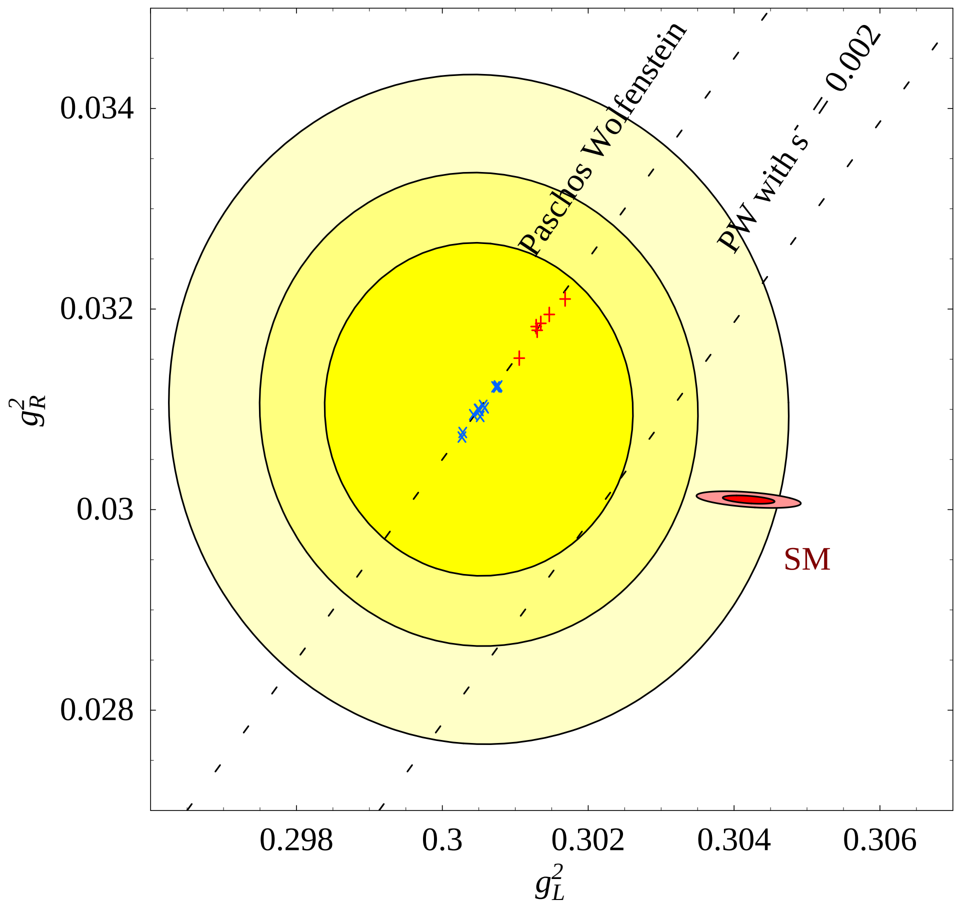
$$
\begin{aligned}
s(x,Q^2) &= \kappa_\nu \frac{\overline{u}(x,Q^2) + \overline{d}(x,Q^2)}{2} (1-x)^{\alpha_\nu} \\
\overline{s}(x,Q^2) &= \kappa_{\overline{\nu}} \frac{\overline{u}(x,Q^2) + \overline{d}(x,Q^2)}{2} (1-x)^{\alpha_{\overline{\nu}}}
\end{aligned}
$$

The current status

The issue of $s(x) \neq \overline{s}(x)$ is still not settled.

Stirling @ NuFact'02 Workshop

The NuTeV $\sin^2\theta_W$ result and global PDFs



– Error estimates from parton distributions for $\sin^2\theta_W$ at NuTeV

Davidson, Forte, Gambino, Rius, Strumia

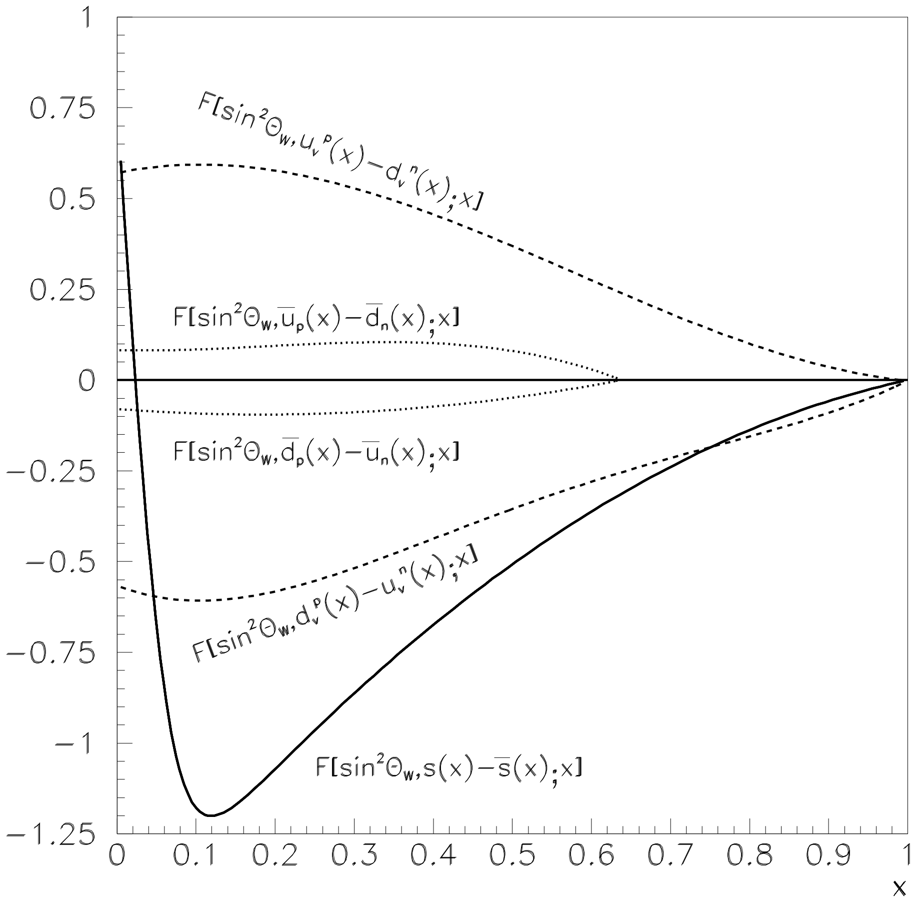
`hep-ph/0112302`

The explanation of the NuTeV result through an asymmetric strange sea [...] is only supported by an after-the-fact analysis of statistically poor data applied [...] in the wrong kinematic region.

Bernstein (NuTeV) hep-ex/0210061

The PDF error functional from NuTeV

Zeller, McFarland et al. (NuTeV) `hep-ex/0203004`

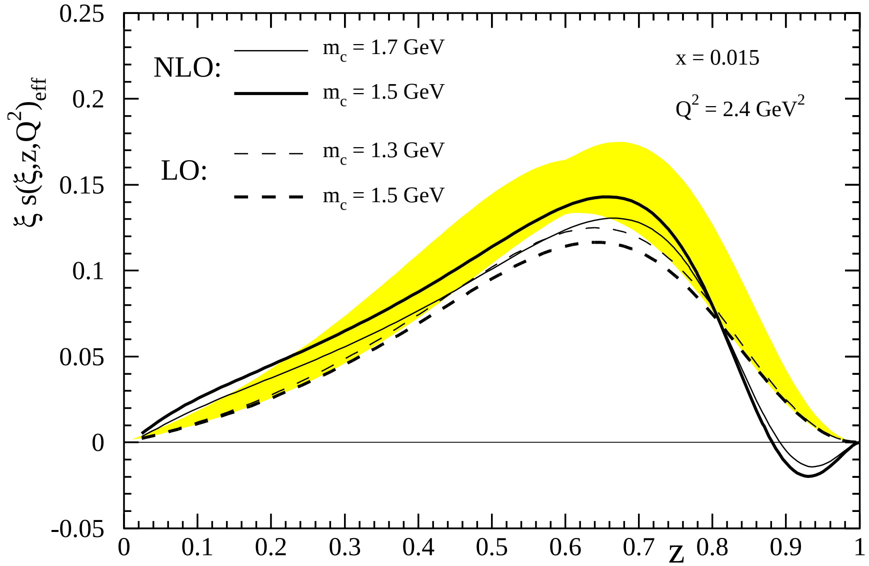


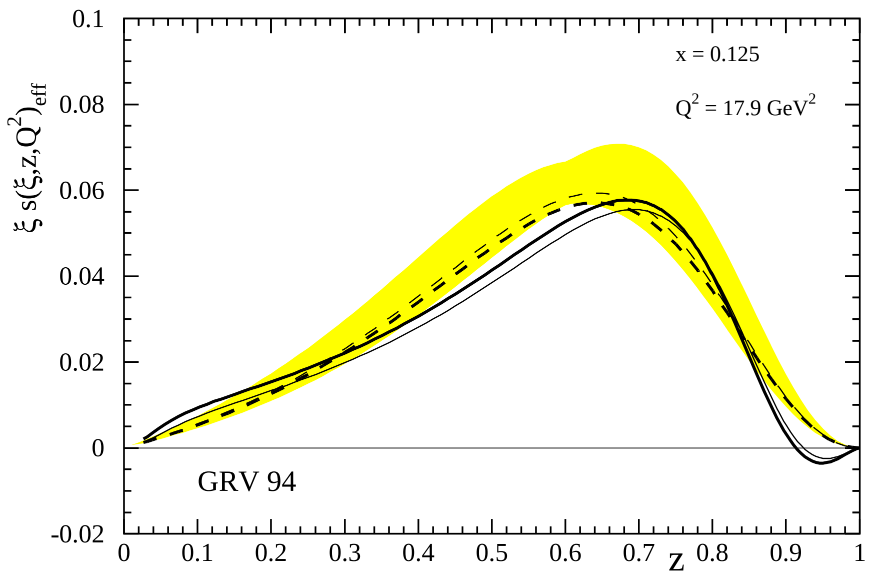
$$\Delta \sin^2\theta_W = \int_0^1 dx F_s(x)\,(s(x)-\bar{s}(x)) + \int_0^1 dx F_I(x)\,(u_P(x)-d_N(x)) + \dots$$

– in particular :
  $s > \bar{s} \quad \longrightarrow \quad \sin^2\theta_W$ decreases

– dimuon cross section puts further constraints on $s, \bar{s}$

Charged current charm production





– plot momentum distribution of D mesons

– momentum fraction z

– Peterson fragmentation function

Peterson, Schlatter, Schmitt, Zerwas '83

$$\xi s(z)_{eff} \simeq \text{const.} \frac{d^3\sigma^{(c\bar{s})}}{dxdydz}$$

– yellow band

$\longrightarrow$ "data" from CCFR

– dependence on charm mass

Glück, Kretzer, Reya '97

Nuclear effects

- nuclear shadowing at low Q^2 ; vector meson dominance and higher twist
- modified Paschos-Wolfenstein relation in nuclei ; isoscalar corrections for iron
- nuclear charge symmetry breaking ; MIT bag model, $m_u - m_d$ mass difference
- ...

Some references

Miller, Thomas `hep-ex/0204007`

Zeller, McFarland et al. (NuTeV) `hep-ex/0207052`

Kovalenko, Schmidt, Yang `hep-ph/0207158`

Melnithchouk, Thomas `hep-ex/0208016`

Kumano `hep-ph/0209200`

Bernstein (NuTeV) `hep-ex/0210061`

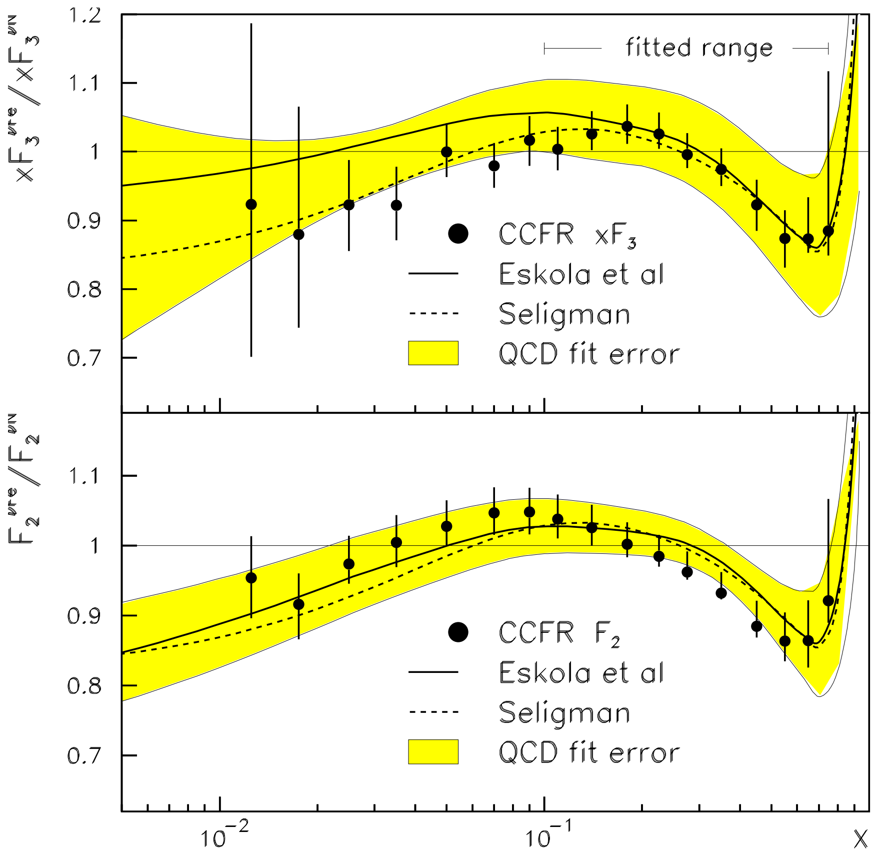
Londergan, Thomas `hep-ex/0301147`

Kulagin `hep-ph/0301045`

. . . to be continued . . .

Error in nuclear effects for ν-Fe scattering

– ratios of $\frac{F_2^{\nu\mathrm{Fe}}}{F_2^{\nu N}}$ and $\frac{xF_3^{\nu\mathrm{Fe}}}{xF_3^{\nu N}}$ with errors   Botje `hep-ph/9912439`



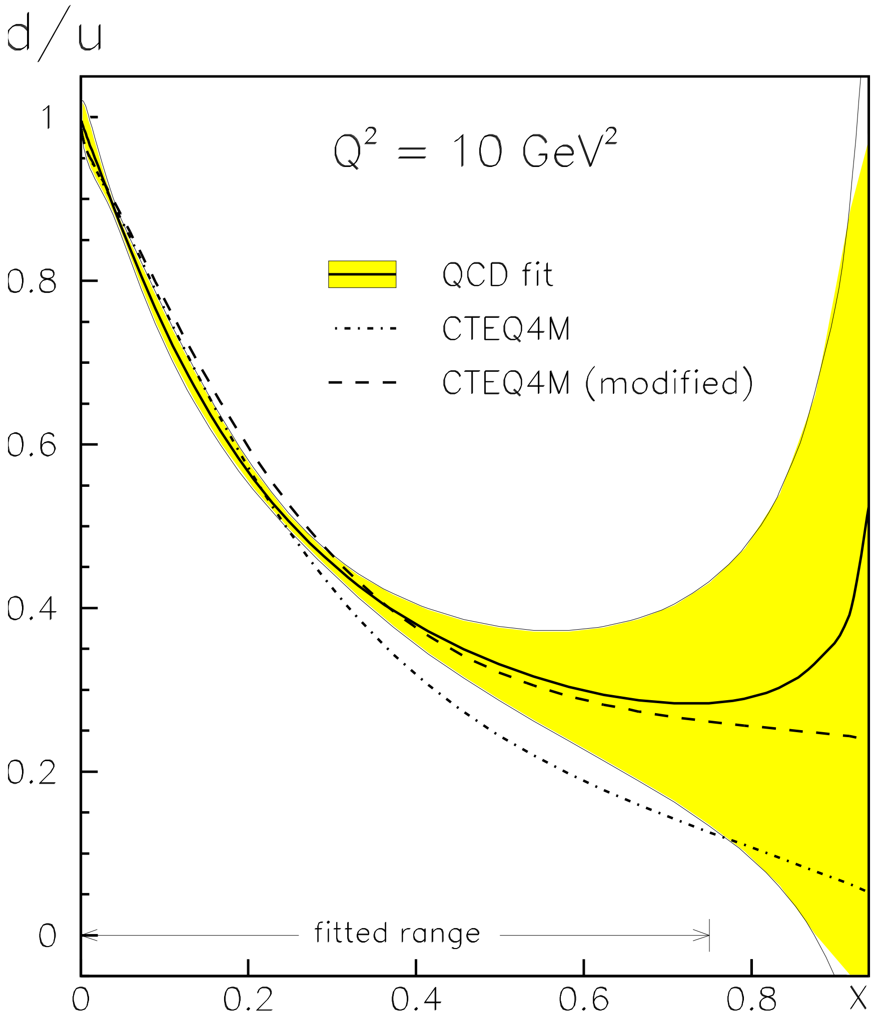
– $xF_3^{\nu\mathrm{Fe}} = xF_3^{\nu N}\,[1 + K_{\mathrm{Fe}}(R_{\mathrm{Fe}} - 1)]$

– R_{Fe} = parametrization of $\frac{xF_3^{\nu\mathrm{Fe}}}{xF_3^{\nu N}}$

– Assume 50% error ($K_{\mathrm{Fe}} = 1 \pm 0.5$)

The d/u ratio

– Error band for ratio of d/u Botje hep-ph/9912439



– ratio $\frac{F_2^P}{F_2^N}$ is sensitive to d/u at large x

$$\frac{F_2^P}{F_2^N} \simeq \frac{1+4d/u}{4+d/u} \text{ as } x \to 1$$

– d/u badly constrained at large x

– $d/u \longrightarrow \infty$ from QCD fit Botje '99

– $d/u \longrightarrow 0.2$ Bodek, Yang '98

– $d/u \longrightarrow 0$ from CTEQLai et al. '96

Summary

Summary

– NuTeV has thoroughly investigated QCD effects, both in the nucleon and in nuclear matter

– PDF uncertainites should be addressed in global analyses
– NLO QCD predictions should be incorporated in future analyses

`In this situation, it is worthwhile relying on [...] NuTeV data for cross-sections and SFs [...] to clarify the situation with the help of independent analyses [...], which should include all types of QCD effects, including those related to NLO perturbative QCD corrections.`

Kataev, Kumano `hep-ph/0211052`; WG 3 summary NuFact'02 Workshop

Chances and opportunities

– νN DIS at NuTeV can
  – help in understanding the quark flavor content of the nucleon
  – provide important input for the issue of $s(x) \neq \bar{s}(x)$