Strangeness Asymmetry of the Nucleon and the NuTeV Anomaly

- Background:
  - NuTeV measurement of the Weinberg angle, using the Paschos-Wolfenstein ratio – the *Anomaly* (2002)
  - CCFR-NuTeV measurements of dimuon production in ν, $\bar{\nu}$ scattering (2001)
  - CTEQ Global QCD Analysis of Parton Distributions
- Recent development:
  - "CTEQ" global analysis of the strangeness sector of nucleon structure, using the CCFR-NuTeV dimuon data; and its impact on the NuTeV anomaly (Aug, 03 —)
  - Constructive interaction between CTEQ-NuTeV
- Prospect:

Special Acknowledgements

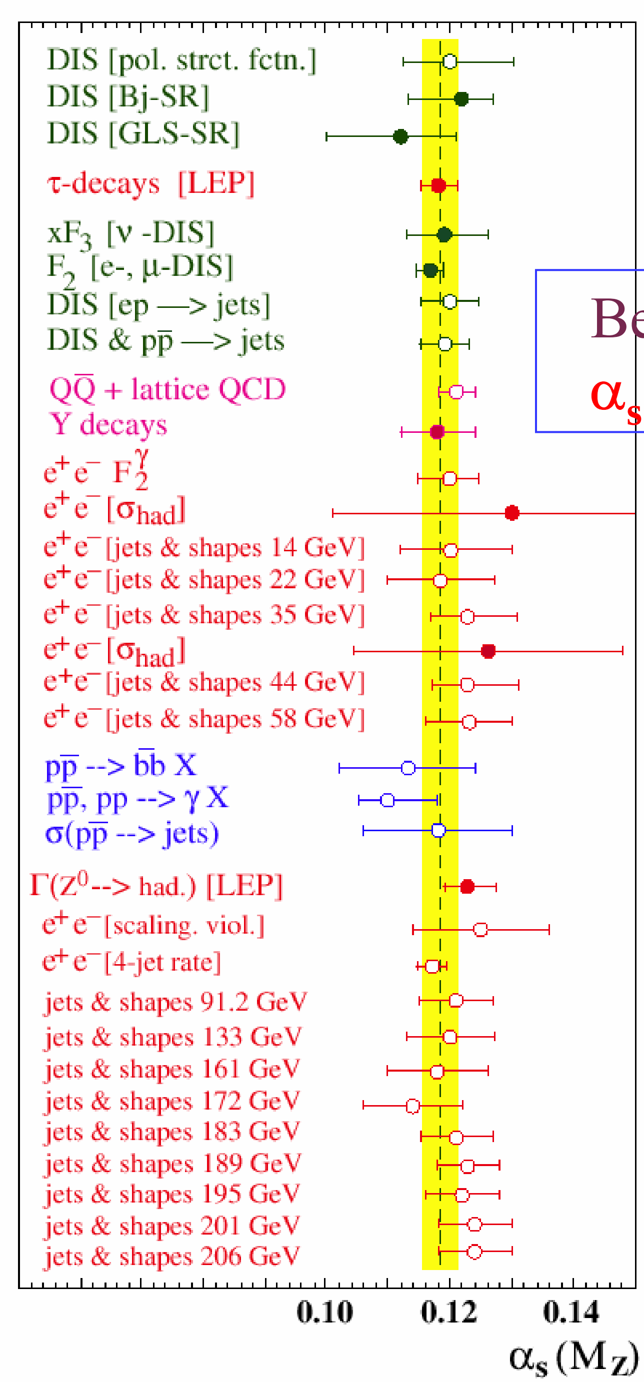
Fred Olness (SMU)
(with the help of T. Bolton and M. Goncherov of CCFR):
preparation of the dimuon data for global QCD analysis.

Jon Pumplin and Dan Stump (MSU)
development of the global analysis tools, and participation in the analysis.

Stefan Kretzer (BNL)
development of the programs for NLO calculation of the ν, $\bar{\nu}$ cross sections for the P-W ratio calculation.

Kevin McFarland (Rochester)
stimulating discussions about the differences of the methods of global analysis and experimental analysis.

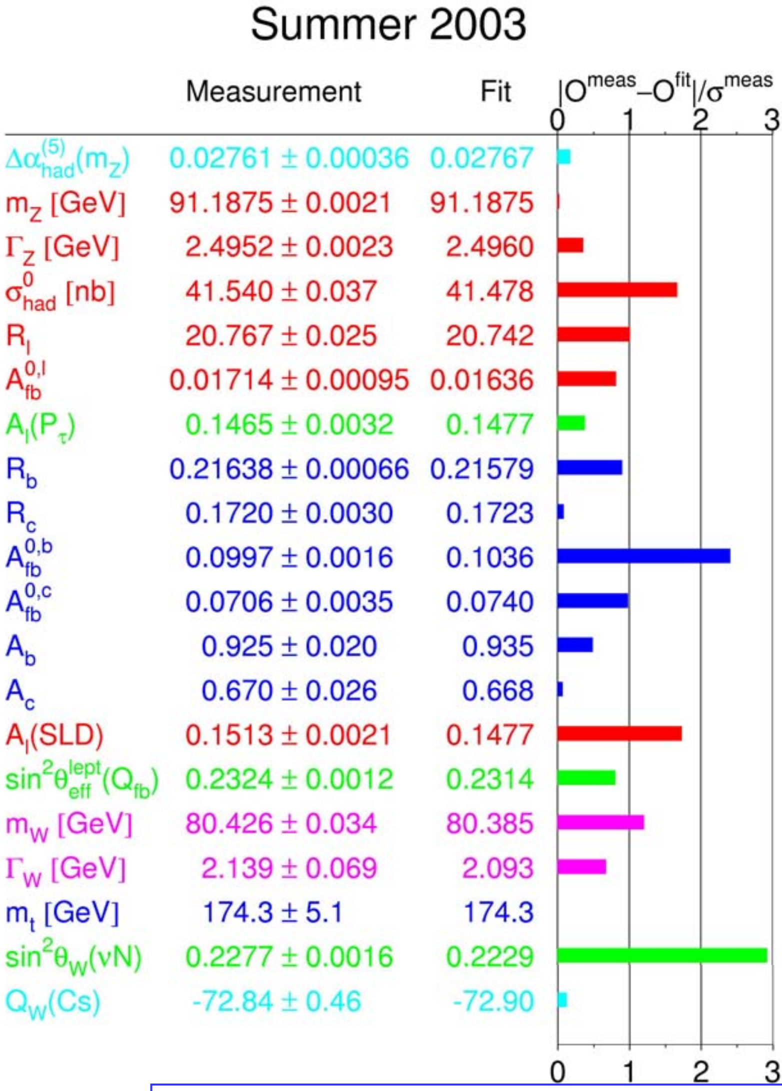
The SM Works Amazingly Well, …. except ….



Bethke:

α_s **2002**

P. Gambino, LepPho2003: **global EWWG fit**



Summer 2003

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90

except for NuTeV, perhaps …

(Gambino)

Global EWWG fit

with NuTeV

M_H^{fit}=96 GeV, M_H<219 GeV at 95%CL

χ^2/dof=25.4/15 4.5% prob

without NuTeV

M_H^{fit}=91 GeV, M_H<202 GeV at 95%CL

χ^2/dof=16.8/14 26.5% prob

NuTeV
Anomaly

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The “NuTeV Anomaly”

The NuTeV $\sin^2\theta_W$ measurement:

It was inspired by, and is related (but not identical) to, the Paschos-Wolfenstein Ratio:

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} - \sin^2\theta_W$$

(isoscalar target, ...)

NuTeV $\sin^2\theta_W = 0.2277 \pm 0.0016$

LEP EWWG $\sin^2\theta_W = 0.2227 \pm 0.00037$

a 3.1 σ discrepancy

Must be corrected for a target with a fractional neutron excess, δN, $s \neq \bar{s}$, ...

SM explanation(s) or Signal for New Physics?

SM: Corrections to the P-W Relation Due to Strangeness Asymmetry, Isospin Violation, … etc.

$$
\begin{aligned}
R^- \approx\ & \Delta_u^2 + \Delta_d^2 \\
& - \delta N \left(\frac{U_v - D_v}{V_p} \right) (3\Delta_u^2 + \Delta_d^2) \\
& + \frac{\delta U_v - \delta D_v}{2V_p} (3\Delta_u^2 + \Delta_d^2) \\
& + \frac{\boxed{\delta S}}{V_p} (2\Delta_d^2 - 3(\Delta_d^2 + \Delta_u^2)\epsilon_c),
\end{aligned}
$$

$$\Delta_{u,d}^2 = (\epsilon_L^{u,d})^2 - (\epsilon_R^{u,d})^2$$ (Weinberg Angle)

where

$$
\begin{aligned}
\delta N &\equiv (A - 2Z)/A \\
V_p &= U_p - \overline{U}_p + D_p - \overline{D}_p \\
\delta D_v &\equiv D_p - \overline{D}_p - U_n + \overline{U}_n \\
\delta U_v &\equiv U_p - \overline{U}_p - D_n + \overline{D}_n \\
\delta \overline{D} &\equiv \overline{D}_p - \overline{U}_n \\
\delta \overline{U} &\equiv \overline{U}_p - \overline{D}_n \\
\delta S &\equiv \langle S \rangle - \langle \overline{S} \rangle
\end{aligned}
$$

ϵ_c : charm-mass kinematic correction factor

CCFR-NuTeV: PR D65, 111103 (2002)

Emphasis of this talk

CCFR-NuTeV Analysis of Strange Quarks and the Weinberg Angle Measurement

- Ingredients to the CCFR-NuTeV dimuon analysis:
  - Data on $\nu N, \bar{\nu} N \longrightarrow \mu^+ \mu^- + X$
  - Fragmentation functions

    Peterson, Schlatter, Schmitt, Zerwas '83 ; Collins, Spiller '85

    heavy quark fragmentation: Cacciari, Greco '97
  - Buras-Gaemer Para./CTEQ/GRV non-strange partons
  - Strange distributions given by

$$s(x,Q^2) = \kappa_\nu \frac{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}{2}(1-x)^{\alpha_\nu}$$

$$\bar{s}(x,Q^2) = \kappa_{\bar{\nu}} \frac{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}{2}(1-x)^{\alpha_{\bar{\nu}}}$$

Will come back to this ansatz later!

- ⇒ Gave parameters κ and α; but no actual plots of $s(x,Q)$, …

For discussing implications of the strange quark on NuTeV anomaly, the key is the Strangeness Asymmetry.

Define:

$$[s^{\pm}] \equiv \int_0^1 s^{\pm}(x)\,dx \equiv \int_0^1 [s(x) \pm \bar{s}(x)]\,dx$$

and the corresponding momentum fractions:

$$[S^{\pm}] \equiv \int_0^1 S^{\pm}(x)\,dx \equiv \int_0^1 x[s(x) \pm \bar{s}(x)]\,dx$$

In particular, it is **$[S^-]$** that is proportional to X-sec. differences, hence it is the relevant quantity directly appearing in the P-W ratio correction term.

CCFR-NuTeV (PR D65, 111103) claimed **$[S^-]$** ~ **0.0027** ± 0.0013 --in the **opposite direction** of accounting for the anomaly.

Previous work on SM corrections to R^-:

Davidson etal, Barone etal,
Miller/Thomas, Kulagin, … etc.

$$\underbrace{R^- = \frac{1}{2} - s_W^2 - \left(\underbrace{\delta N \frac{\int x(u_v - d_v)dx}{\int x(u_v + d_v)dx}}_{\text{neutron excess}} + \underbrace{\frac{\int x(s - \bar{s})dx}{\int x(u_v + d_v)dx}}_{\text{strange asymmetry}} \right) \left[1 - \frac{7}{3} s_W^2 + \underbrace{\frac{4\alpha_s}{9\pi}\left(\frac{1}{2} - s_W^2 \right)}_{\substack{\text{NLO correction} \\ \text{(NuTeV : LO)}}} \right] + \dots}$$

These corrections have been under close scrutiny by many authors, in particular BPZ (Barone et.al) and Davidson et.al. (including new physic senarios).

Conclusion? Inclusive! ; "only a comprehensive global QCD analysis can clarify the relevant issues involved … "

“CTEQ” Global Analysis of the Strangeness Asymmetry

- Same ingredients as “CTEQ6” analysis (almost)
- Add CCFR-NuTeV dimuon data (and a few more updates)
- Allow a non-symmetric strangeness sector:

Parametrization of the Strangeness sector (at some $Q=Q_0$)

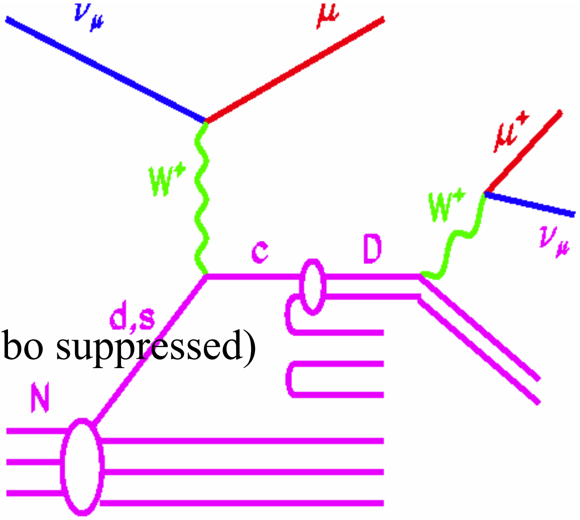
$$\begin{aligned} s^{+}(x,Q_0) &= A_0\, x^{A_1}(1-x)^{A_2} P_{+}(x;A_3,A_4,\ldots) \\ s^{-}(x,Q_0) &= s^{+} \tanh[a\, x^{b}(1-x)^{c} P_{-}(x;x_0,d,e,\ldots)] \end{aligned}$$

$$P_{-}(x) = (1 - \frac{x}{x_0} + dx^2 + ex^3 + \ldots)$$

Where x_0 is to be determined by the strangeness number sum rule condition $[s^-] = 0$.

Strangeness Structure of the Nucleon: Dimuon Production in $\nu, \bar{\nu}$ Scattering

- This is the process that provides the most direct (LO) constraints on the strangeness sector of the parton structure of the nucleon.



(*d* is Cabibbo suppressed)

# of events:

di-muon	NuTeV	CCFR	Combined
Neutrino	5012	5030	10042
Anti-Nu	1458	1060	2518

* High stats & high precision data
* Best constraints on strange quark

$$\frac{d\sigma^{+}_{\mu^\pm\mu^\mp}}{dx\ dy} = \int d\Gamma\, d\Omega\ \frac{d\sigma_{\mu^\mp c}}{dx\ dy\ d\Gamma} \otimes D_c(\Gamma) \otimes \Delta_c(\Omega)\Big|_{E_{\mu^\pm} > 5\ GeV}$$

Di-muon cross-section

Charm Production cross-section

Fragmentation Function

Decay Distribution

Modeling needed for comparing theory with data.

M. Goncharov et al., NuTeV Collaboration PRD 64:110226 (2001)

Qualitative Expectations:

(really by hindsight)

Because of strangeness # SR:

$$\int s^-(x)\,dx = 0$$

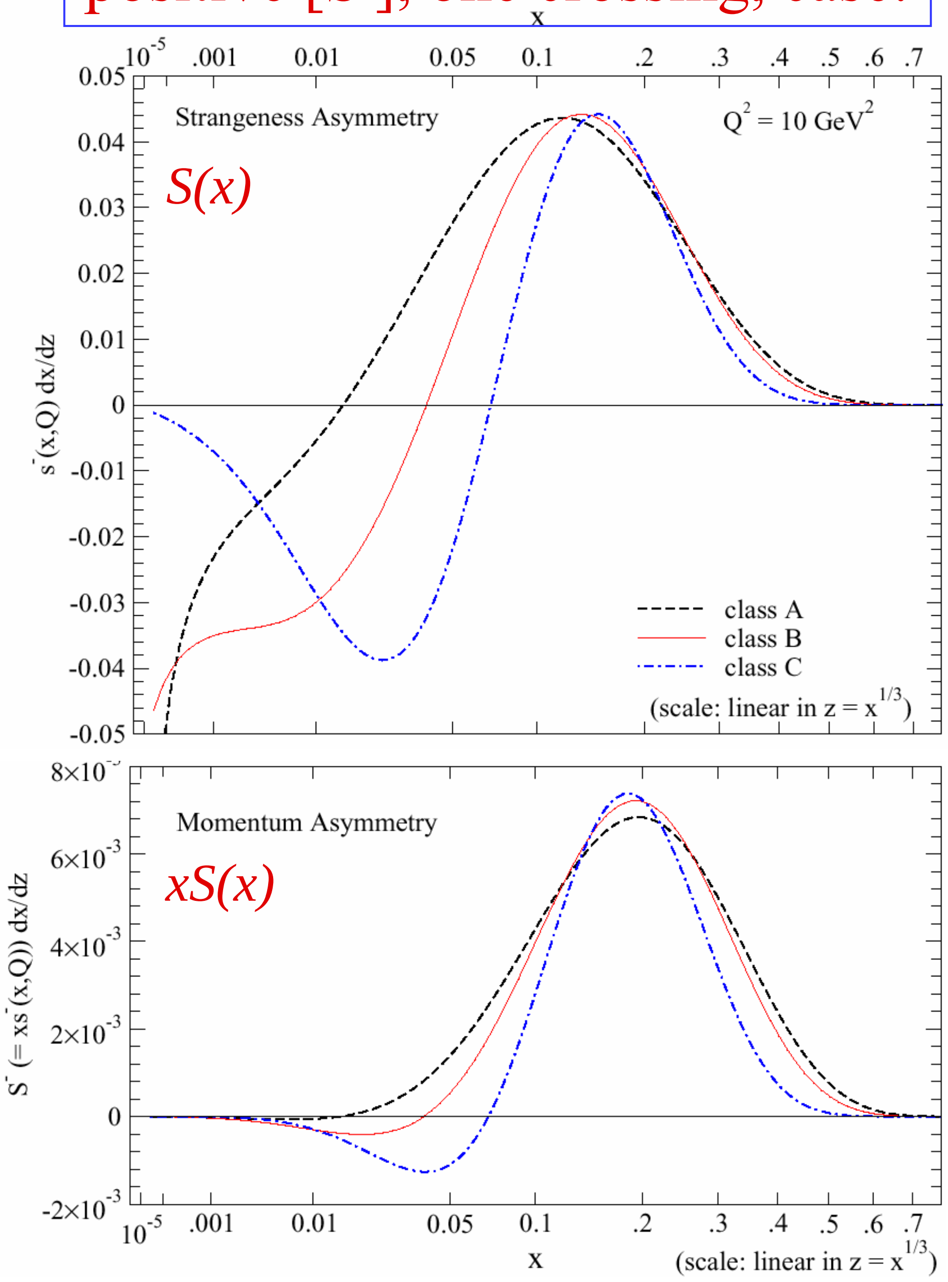
$s^-(x)$ function must look like:

Or, negative [S-] case:
just flip the curves.

Which way is it going to be?

Theory	$[S^-]$
(e.g. Λk fluctuation)	+
Expt.: CCFR-NuTeV dimuon: - $s^-(x)$ in $0.01 < x < 0.3$ BPZ: + $s^-(x)$ for $x > 0.5$	+

positive $[S^-]$, one crossing, case:



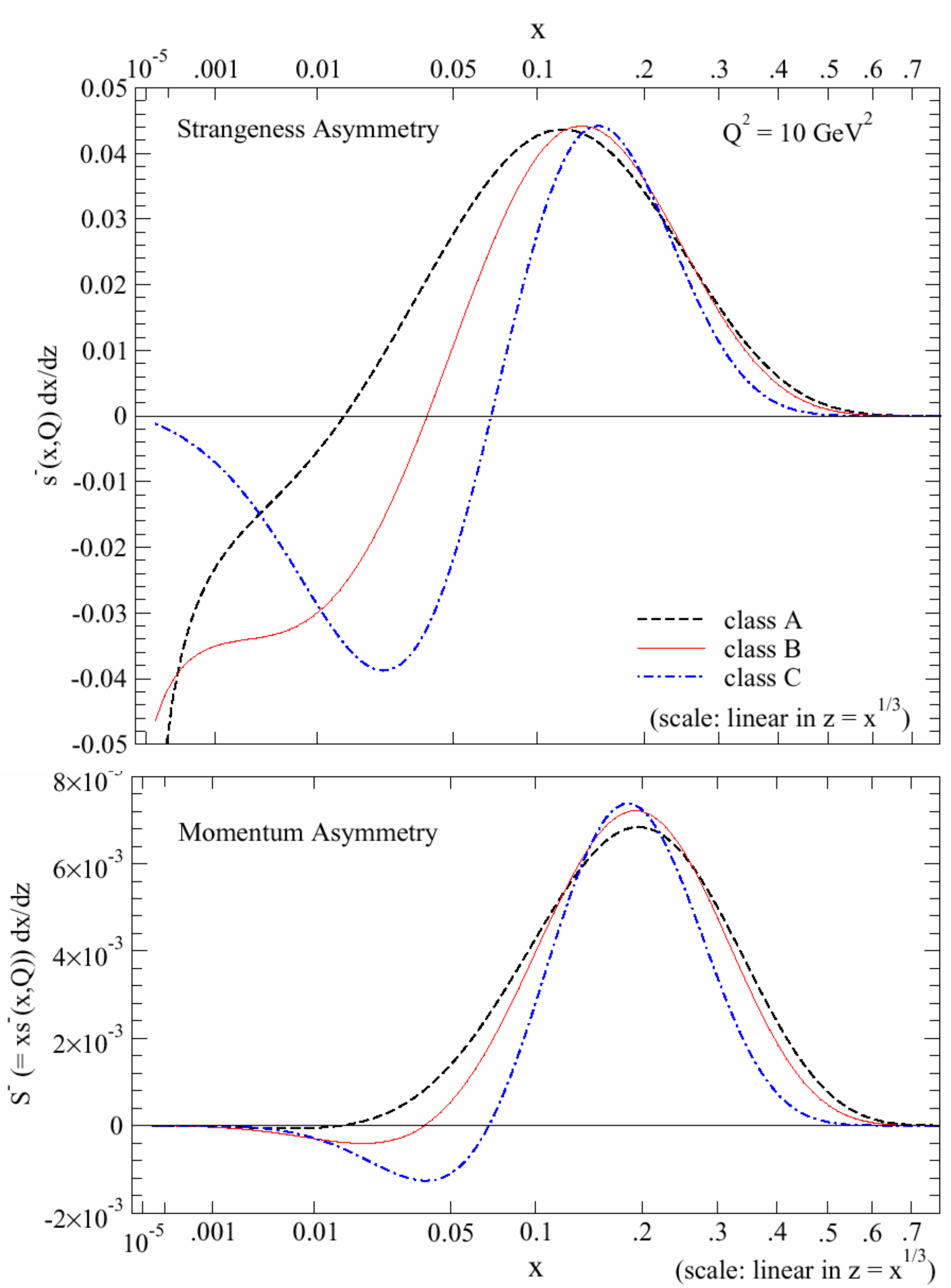
What did we find?

Three representative "best fits" with different small-x behavior:

Along with many other examples with similar characteristics. (Later)

$0.001 < [S^-] < 0.003$

Cf. CCFR-NuTeV:
$- 0.0027 \pm 0.0013$



Representative PDF sets obtained with this global QCD analysis:

5 representative fits obtained using LM method

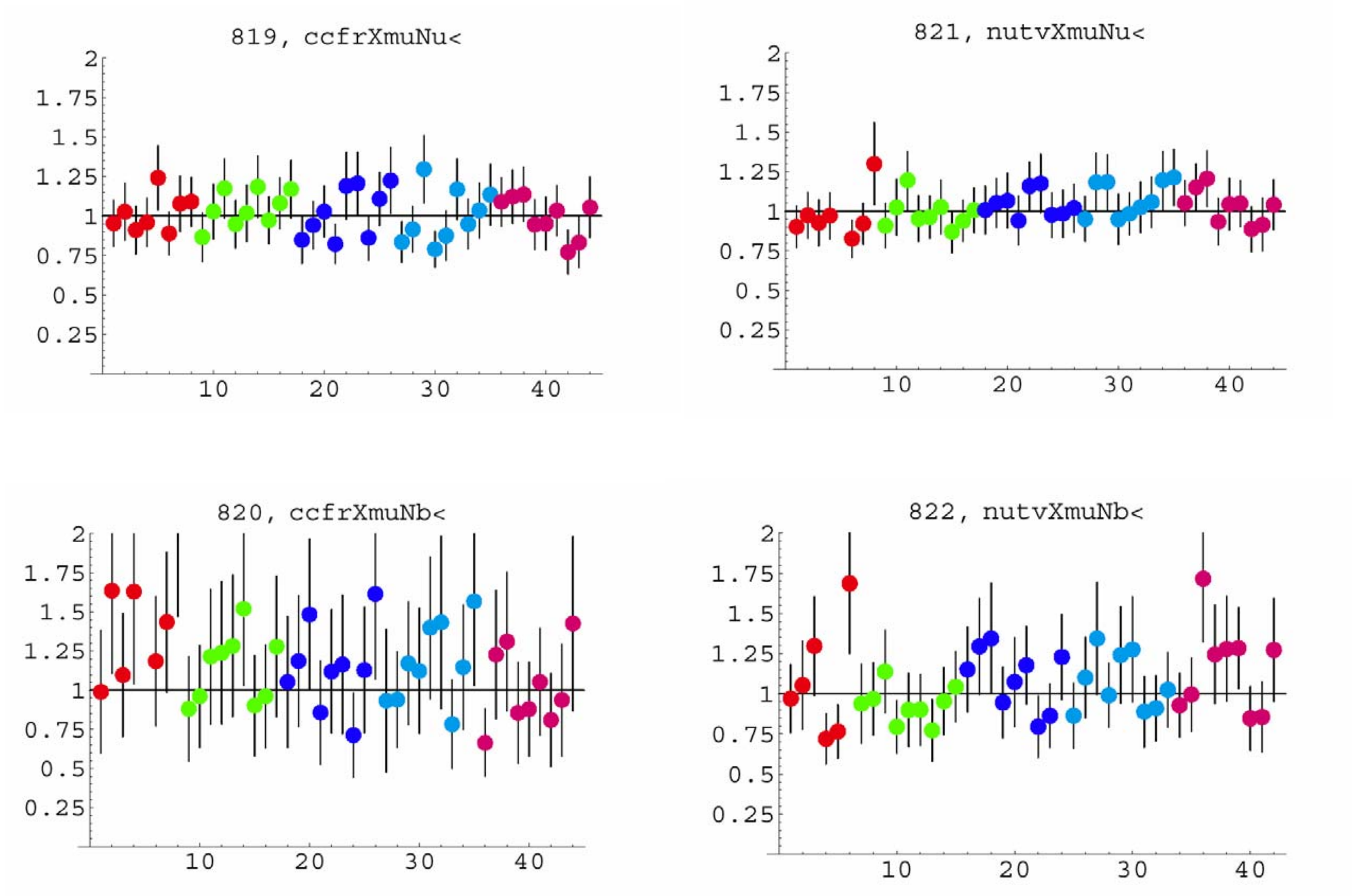
	# pts	B+	A	B	C	B-
$A_1 + b$	-	-0.78	-0.99	-0.78	0	-0.78
$[S^-] \times 100$	-	0.540	0.312	0.160	0.103	-0.177
Dimuon	174	**1.30**	1.02	*1.00* (126)	1.01	**1.26**
Inclusive I	194	0.98	0.97	*1.00* (141)	1.03	**1.09**
Inclusive II	2097	1.00	1.00	*1.00* (2349)	1.00	1.00

Normalized χ^2 values

Processes having some sensitivity to s^-

Processes having no sensitivity to s^- (majority)

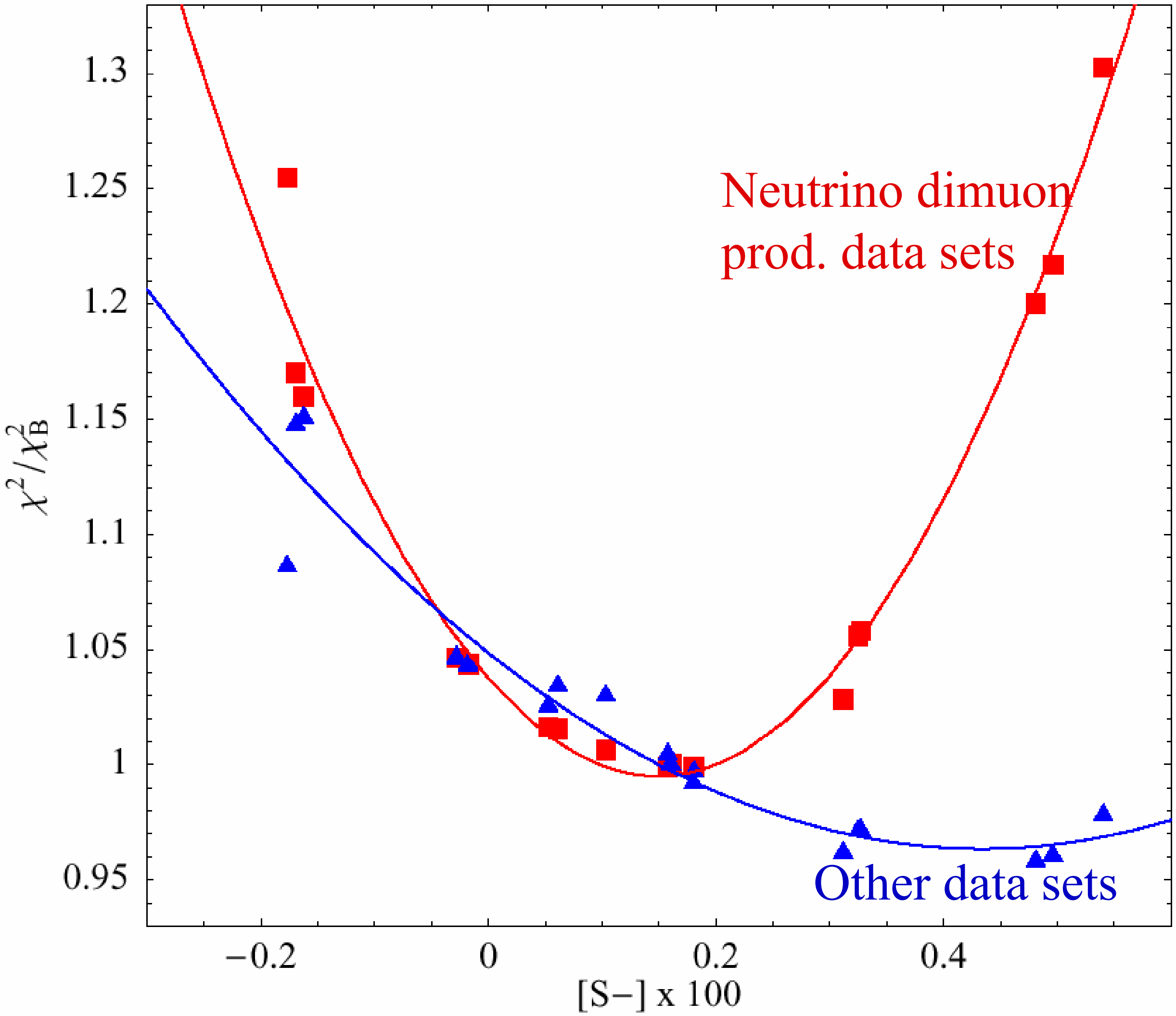
Quality of fit to the neutrino dimuon data



(Data points are color-coded according to x; for each x, they are ordered in y.)

What does this analysis say about the Strangeness Asymmetry?

Use the Lagrange
Multiplier Metho
in the CTEQ glob
analysis toolkit t
probe the full
range of [S-]
consistent with
theory and
experiment.

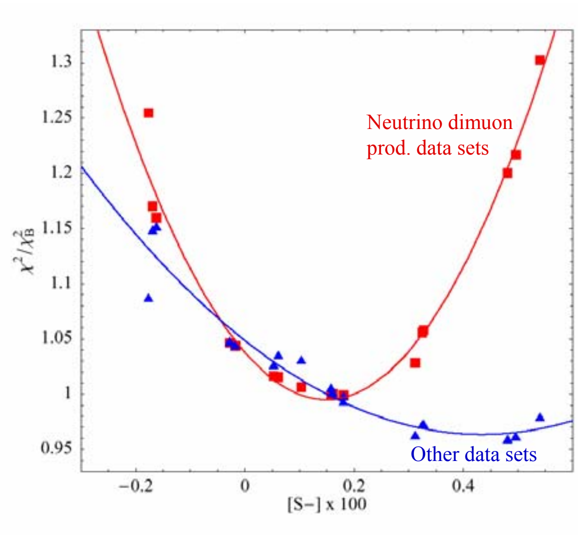


Rule of thumb:

The 3 σ anomaly corresponds to

$[S^-] \times 100 \simeq 0.5$

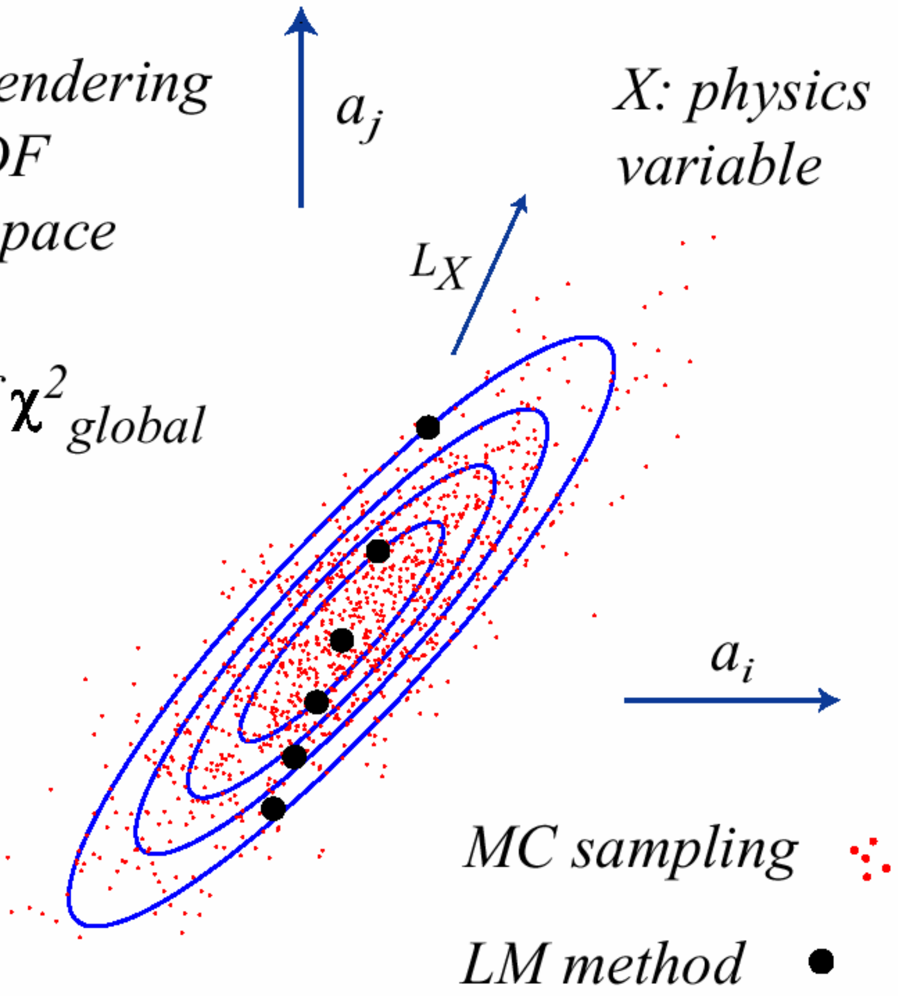
The Lagrange Multiplier Method in Global Analysis



2-dim (i,j) rendering of d-dim PDF parameter space

contours of $\boldsymbol{\chi}^2_{global}$

X: physics variable



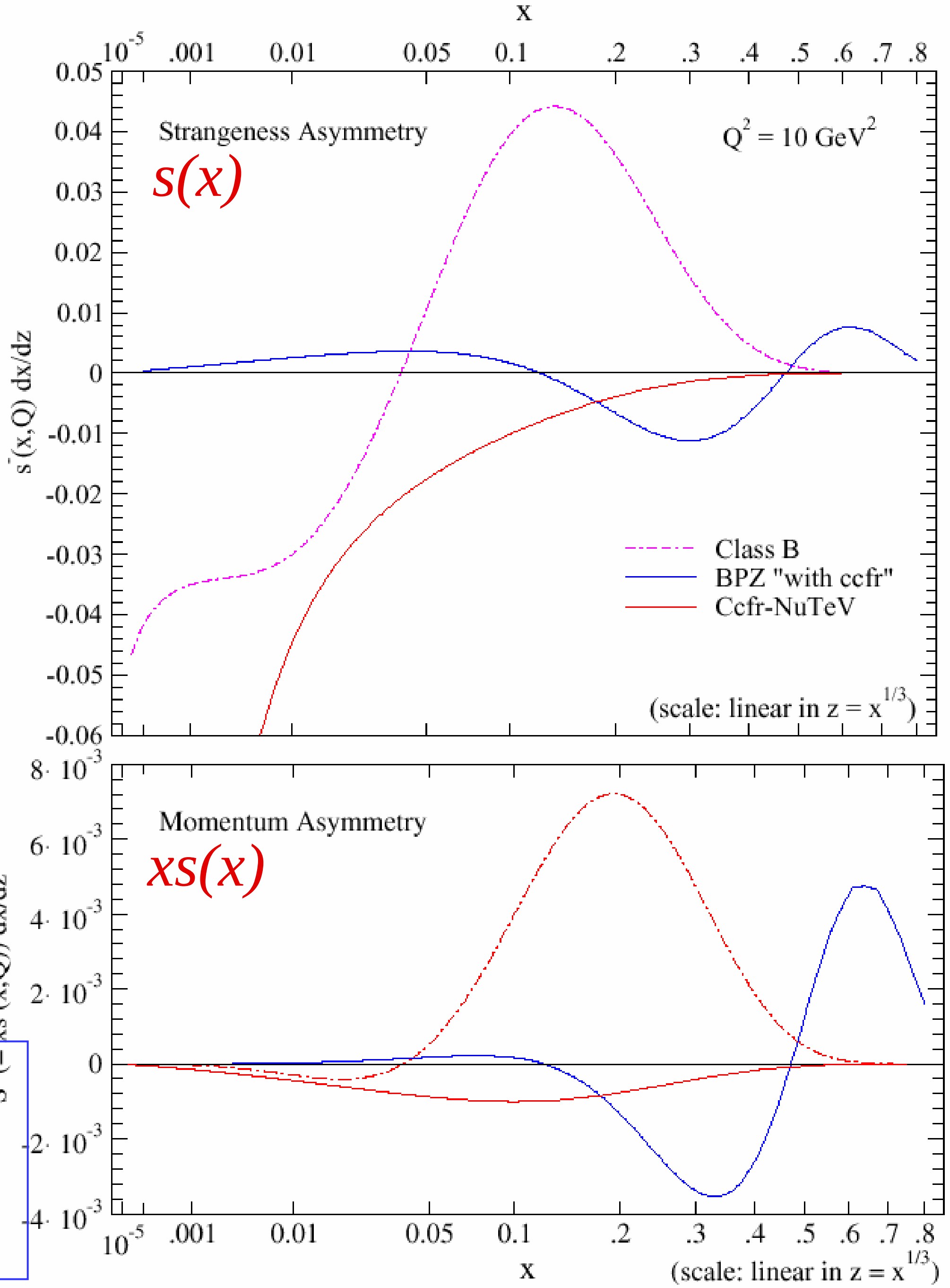
Constrained fits using modified χ^2 function:

$$\Psi(\lambda, a) = \chi^2_{\mathrm{global}}(a) + \lambda X(a)$$

and vary λ over an appropriate range.

What about the CCFR-NuTeV claim (to the contrary); and the BPZ analysis?

A picture is better than a
thousand words?



The CCFR ansatz:

$$s(x,Q^2) = \kappa_\nu \frac{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}{2}(1-x)^{\alpha_\nu}$$

$$\bar{s}(x,Q^2) = \kappa_{\bar{\nu}} \frac{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)}{2}(1-x)^{\alpha_{\bar{\nu}}}$$

violates Strangeness # SR and QCD evolution.

BPZ: (i) inclusive X-secs are not sensitive to $s^-(x)$; (ii) large-x behavior of $s^-(x)$ not natural.

Main Conclusions of the CTEQ Study

- By including dimuon data (which is sensitive to $s(x)$ and $\bar{s}(x)$ at LO), and by fully exploring the allowed parameter space in a global QCD analysis, we now have a good general picture of the status of the strangeness sector of nucleon structure. (More than just some specific fits to data.)

- Experimental constraints on $s(x)$ and $\bar{s}(x)$ are still relatively weak. There are still large uncertainties in any specific region of x, as seen from the wide range spanned by even the good fits A,B, C. Because of other sources of uncertainties, the band of possible $s^-(x)$ values will be considerably wider.

- However, the strong <u>interplay</u> between the existing <u>experimental</u> constraints and the global <u>theoretical</u> constraints, particularly sum rules, places quite robust limits on acceptable values of the strangeness asymmetry momentum integral $[S^-]$.

- We estimate that $-0.001 < [S^-] < 0.004$. A sizable negative $[S^-]$ is disfavored by both dimuon and other inclusive data. (Non-perturbative theoretical models also disfavor this possibility.)

Implication on the NuTeV anomaly

We have done a NLO calculation of the P-W ratio, based on a recent work of Kretzer and Reno, using the new CTEQ PDFs.

According to this calculation, a value of $[S^-] < 0.0017$ (central value) can reduce the NuTeV anomaly from a 3 σ effect to 1.5 σ; a value of $[S^-] \sim 0.003 - 0.004$ would then reduce it to within 1 σ. The actual effect on the NuTeV measurement must await re-analysis by the experimental group, correcting current flaws, extending to NLO, as well as taking into account global constraints.

Other Corrections to P-W Relation and NuTeV Analysis
(Londergon, WIN03)

⋆ $N \neq Z$ **Corrections to NuTeV Measurement**

- “Isoscalar” correction: significant, but should be under control

Isospin Violation in PDF

⋆ **CSV Contributions to NuTeV Measurement**

- model calc’n: reduce NuTeV anomaly from $3\sigma \Rightarrow 2\sigma$.

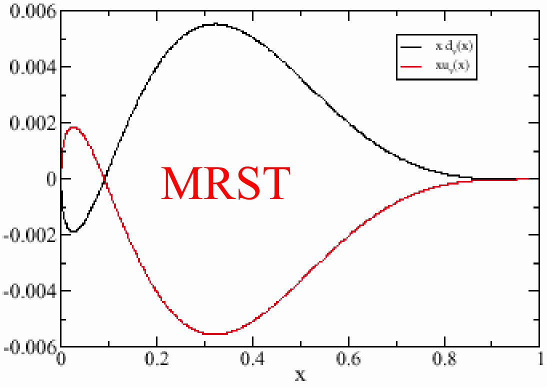
Sather
[PL **B274**, 433 (92)]

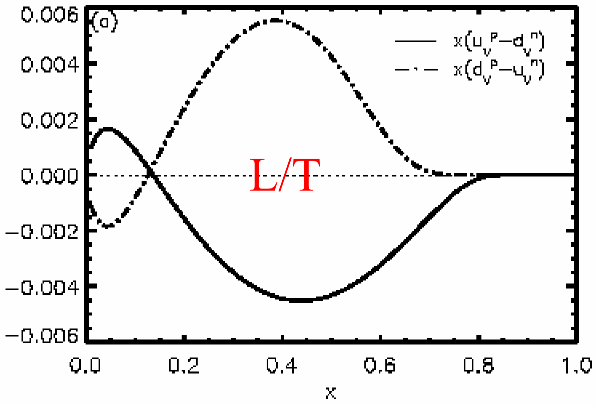
- Theoretical arguments for sign, magnitude of CSV contribution.

[JTL/AWT PL **B558**, 132 (03); PR **D67**, 111901 (03)]

- First phenomenological fits of parton CSV PDFs

MRST [hep-ph/0308087]





What’s happening?

Some very lively discussions and interaction have taken place between various members of CCFR-NuTeV collaboration and our group. (both in public and in private setting).

What do we agree on? The two analyses are quite different!

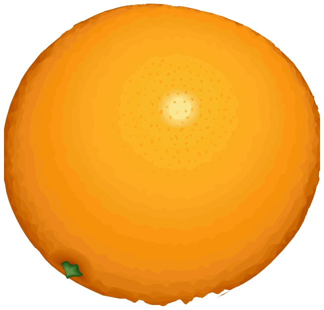
The CCFR-NuTeV analysis is a dedicated one, focusing on the dimuon process, particularly the experimental aspects. The theoretical model used has a number of rather serious flaws.

The CTEQ analysis is a global analysis, using all available experimental constraints and the full implementation of PQCD. However, in this first try, the dimuon data sets are only included in an approximate way.

What’s Next? ….

(MacFarland, WIN03, 10.08)

What Needs to Be Resolved?



NuTeV

- Functional form does not evolve correctly
  - from Q_0 of 12.6 GeV^2 to range of 4-100 GeV^2
- Strangeness number Sum-rule violated
- Not global fit -- with outside PDFs, d-quark distributions not adjusted for changes in s(x)

CTEQ

- NLO global fit to Inclusive processes; LO cross-section for dimuons;
- Dimuon acceptance corrections to data model-dependent;
- m_c used isn't CCFR-NuTeV best fit to dimuon data

These concerns have been studied recently by us. The results contributed to the updated uncertainties quoted.

- Nuclear corrections for proton PDFs handled consistently in two analyses?

What to Expect?

- Full NLO analyses are under active development by both groups—with help from each other. If done properly by both, the apple and the orange must converge to a universal fruit—the strange quark distribution of nature.

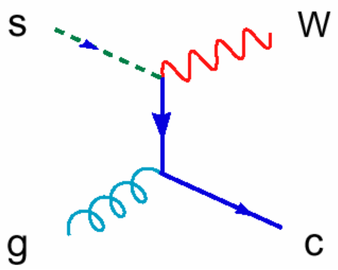
CTEQ group:

- A full analysis of the newly opened up strangeness sector—$s^+(x)$ and $s^-(x)$.
- This is just one aspect of the continued effort to refine our understanding of the parton structure of the nucleon in general.

Probing the Sea Quark PDFs: s, c, b using tagged final states $W/Z/\gamma + c/b$?

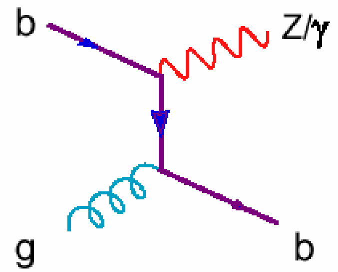
$s(x, Q)$:

$g + s \to W + c$



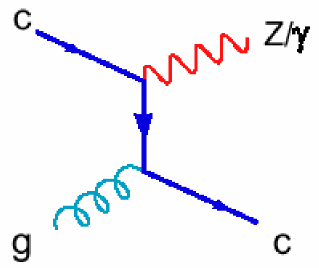
$b(x, Q)$:

$g + b \to Z/\gamma +$

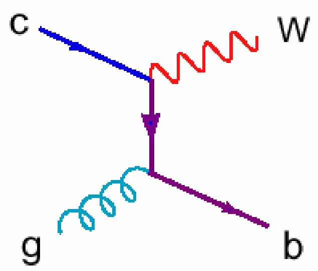


$c(x, Q)$:

$g + c \to Z/\gamma +$



$g + c \to W + b$



Neutrino X-sec. Ratios, NuTeV measurement & P.W. Ratio

$$R_\nu \equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)}{\sigma(\nu\mathcal{N}\to\mu X)} = \frac{(3g_L^2+g_R^2)q+(3g_R^2+g_L^2)\bar{q}}{3q+\bar{q}} = g_L^2 + r g_R^2$$

$$R_{\bar\nu} \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)} = \frac{(3g_R^2+g_L^2)q+(3g_L^2+g_R^2)\bar{q}}{q+3\bar{q}} = g_L^2 + \frac{1}{r} g_R^2,$$

$$r \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)}{\sigma(\nu\mathcal{N}\to\mu X)} = \frac{3\bar{q}+q}{3q+\bar{q}}$$

$$R_{\mathrm{PW}} \equiv \frac{R_\nu - rR_{\bar\nu}}{1-r} = \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_{\mathrm{W}}$$

$$g_L^2 \equiv g_{Lu}^2 + g_{Ld}^2 = \frac{1}{2} - \sin^2\theta_{\mathrm{W}} + \frac{5}{9}\sin^4\theta_{\mathrm{W}}, \qquad g_R^2 \equiv g_{Ru}^2 + g_{Rd}^2 = \frac{5}{9}\sin^4\theta_{\mathrm{W}}.$$

$$g_L^2 = \rho^2\left(\frac{1}{2} - s_{\mathrm{W}}^2 k + \frac{5}{9}s_{\mathrm{W}}^4 k^2\right), \qquad g_R^2 = \frac{5}{9}\rho^2 s_{\mathrm{W}}^4 k^2 \qquad q = (u+d)/2$$

$$\begin{aligned} \rho &\approx 1.0087 + 0.0001(M_t/\,\mathrm{GeV} - 175) - 0.0006\ln(m_h/100\,\mathrm{GeV}), \\ k &\approx 1.0350 + 0.0004(M_t/\,\mathrm{GeV} - 175) - 0.0029\ln(m_h/100\,\mathrm{GeV}) \end{aligned}$$

NLO QCD Corrections to the P-W Relation

$$R_{\rm PW} = g_L^2 - g_R^2 + \frac{(u^- - d^-) + (c^- - s^-)}{\mathcal{Q}^-}$$

$$\left\{ \left[\frac{3}{2}(g_{Lu}^2 - g_{Ru}^2) + \frac{1}{2}(g_{Ld}^2 - g_{Rd}^2)\right] \right.$$

$$\left. + \frac{\alpha_s}{2\pi}(g_L^2 - g_R^2)(\frac{1}{4}\delta C^1 - \delta C^3) \right\}$$

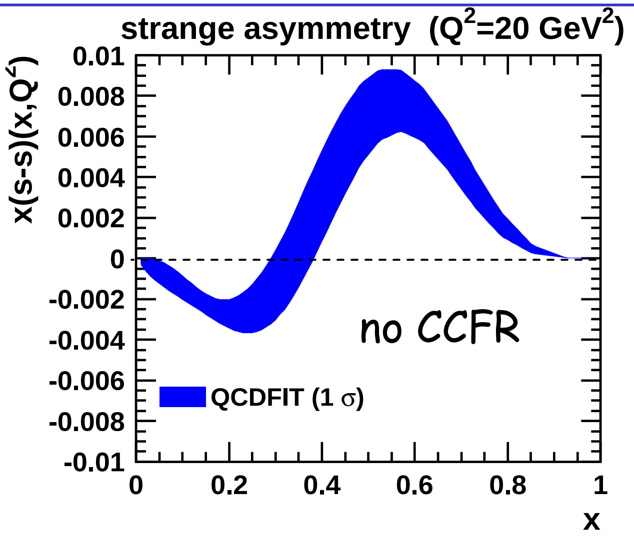
Wilson Coefficients: $\delta C^1 \equiv C^1 - C^2,\ \delta C^3 \equiv C^3 - C^2;$

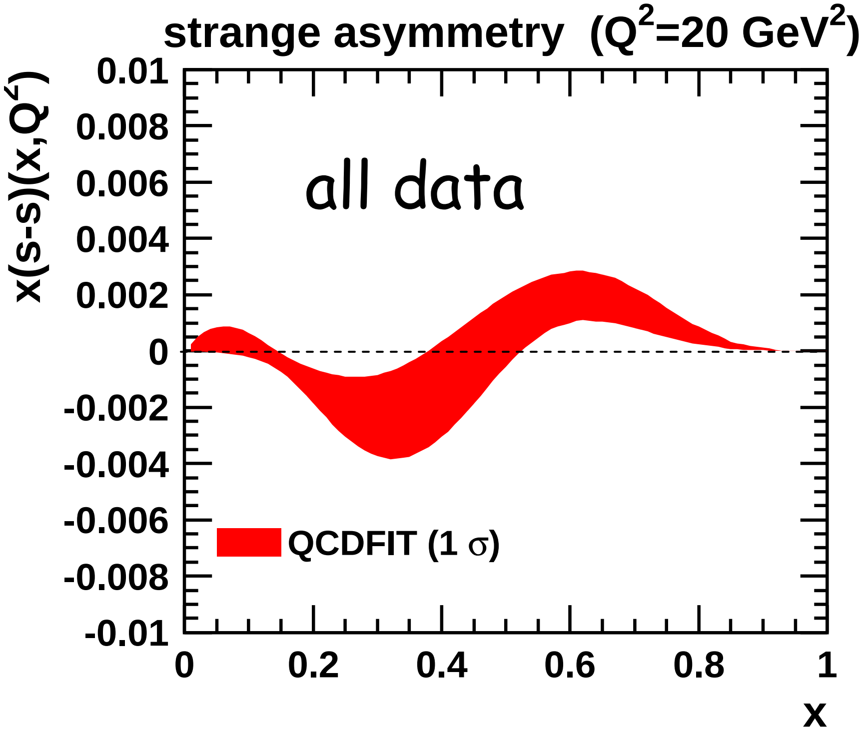
C^i is the the second moment of the quark W.C. to F^i.

Results on the strange sea asymmetry from BPZ

without CCFR, same asymmetry
as in previous studies

$$\int_0^1 (xs - x\bar{s})\ \mathrm{d}x = 1.8 \pm 0.5 \times 10^{-3}$$





using all data sets, the asymmetry
is strongly reduced

$$\int_0^1 (xs - x\bar{s})\ \mathrm{d}x = 1.8 \pm 3.8 \times 10^{-4}$$

momentum asymmetry is
compatible with zero