The Strange-Antistrange Asymmetry

The NuTeV Measurement & a Peek at Future Prospects...

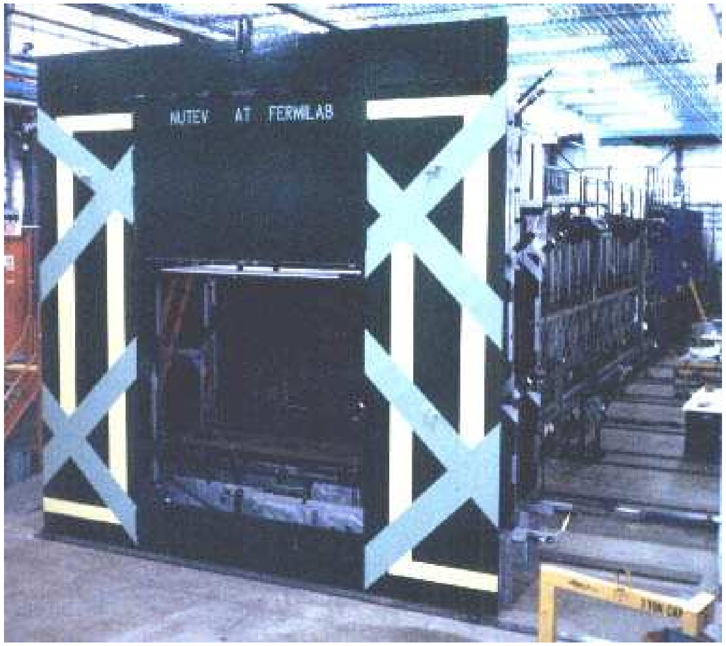
David A. Mason

Fermilab

Talking about a slightly different energy regime...

NuTeV

- ν-N DIS $(\langle E_\nu \rangle \sim 120GeV)$
- FNAL '96-'97 fixed target run
- 3.15×10^{18} protons on target
  - 886,004 ν, 255,045 $\overline{\nu}$ CC events
  - 5163 ν and 1380 $\overline{\nu}$ Dimuons
- Detector calibration beam throughout run
  - hadron, e, and muon beams
- High purity, selectable ν and $\overline{\nu}$ beams



The NuTeV Collaboration:

T. Adams[4], A. Alton[4], S. Avvakumov[8], L. de Barbaro[5], P. de Barbaro[8], R. H. Bernstein[3], A. Bodek[8], T. Bolton[4], J. Brau[6], D. Buchholz[5], H. Budd[8], L. Bugel[3], J. Conrad[2], R. B. Drucker[6], B. T. Fleming[2], R. Frey[6], J. A. Formaggio[2], J. Goldman[4], M. Goncharov[4], D. A. Harris[8], R. A. Johnson[1], J. H. Kim[2], S. Koutsoliotas[2], M. J. Lamm[3], W. Marsh[3], D. Mason[6], J. McDonald[7], K. S. McFarland[8,3], C. McNulty[2], D. Naples[7], P. Nienaber[3], V. Radescu[7], A. Romosan[2], W. K. Sakumoto[8], H. Schellmann[5], M. H. Shaevitz[2], P. Spentzouris[2], E. G. Stern[2], N. Suwonjandee[1], M. Tzanov[7], M. Vakili[1], A. Vaitaitis[2], U. K. Yang[8], J. Yu[3], G. P. Zeller[5], and E. D. Zimmerman[2]

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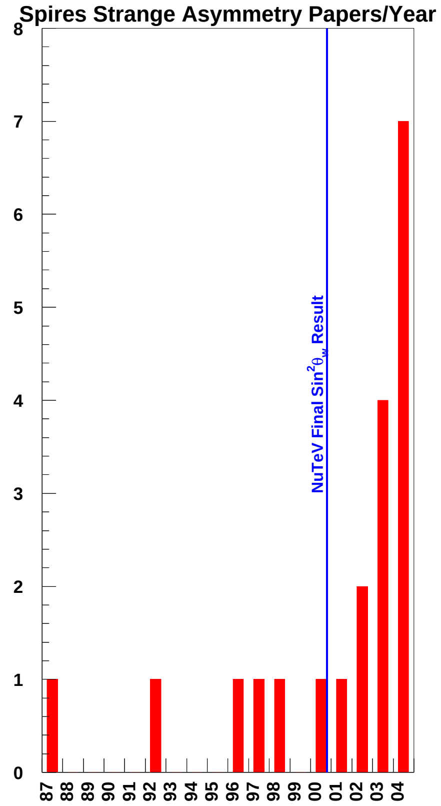
$\sin^2\theta_W$ and the Strange Asymmetry

- NuTeV measured $R^- = \frac{\sigma^{\nu}_{NC} - \sigma^{\overline{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\overline{\nu}}_{CC}}$
- From that $\sin^2\theta_W$ was extracted
  - Insensitive to sea quark uncertanties
  - But assumed $s(x) = \overline{s}(x)$
- 0.22773 ± 0.00135 (stat) ± 0.00093 (syst)

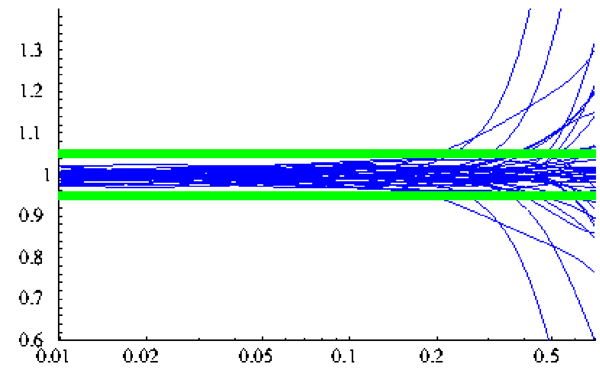
  (Zeller et al: PRL 88 (2002) 091802)
- 3 σ above world average
- R^- correction from asymmetric strange sea is proportional to $S^- \equiv \int x[s(x) - \overline{s}(x)]dx$
- Led to much theoretical speculation $\Longrightarrow$
- $S^- \sim 0.0068$ required to bring to world ave.



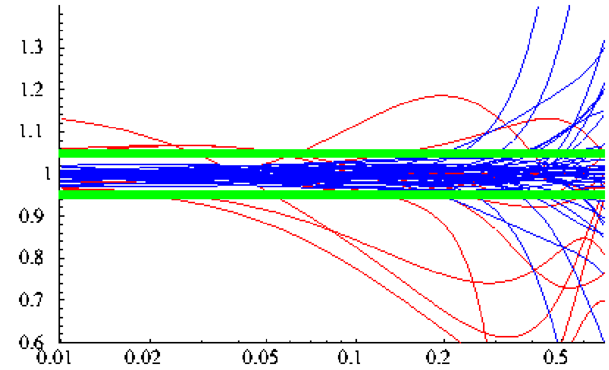
The Strange Uncertainty

- Not well constrained in global fits (through structure function differences)
- Parameterizations (e.g. CTEQ, MRST...) typically assume $s = \overline{s} = 0.2(\overline{u} + \overline{d})$
- Uncert. in pdf sets represent $\overline{u} + \overline{d}$ error, not error on strange
- Freeing strange in CTEQ6 fit $\Longrightarrow$
- Constraint from data is needed!
- (But must be in useful form for fits)

Standard CTEQ6 40 pdfs:

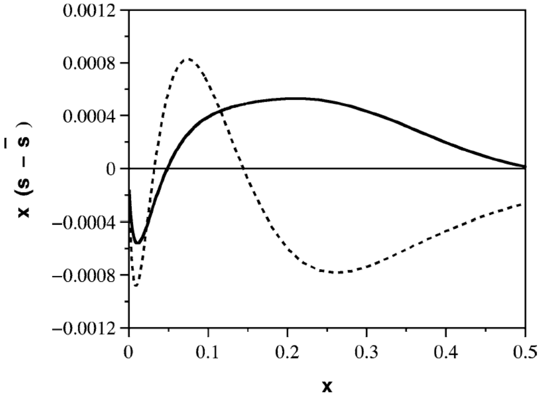


Freeing strange param:

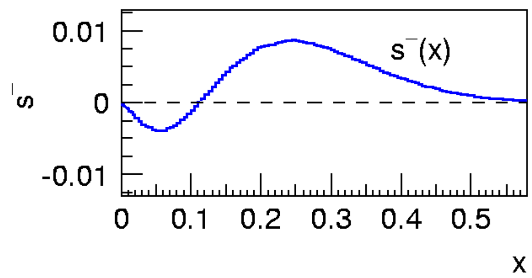


(F. Olness talk DIS 2005)

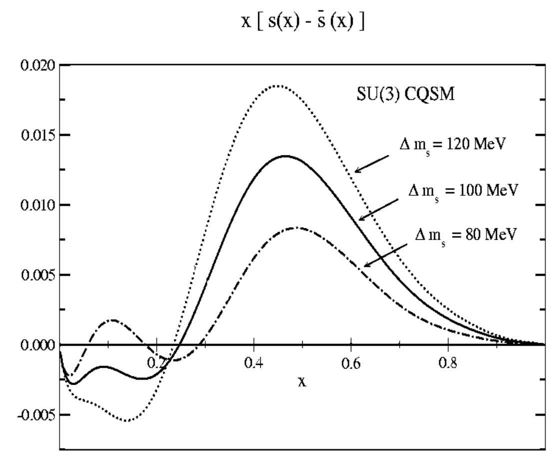
A Pantheon of Asymmetry Predictions



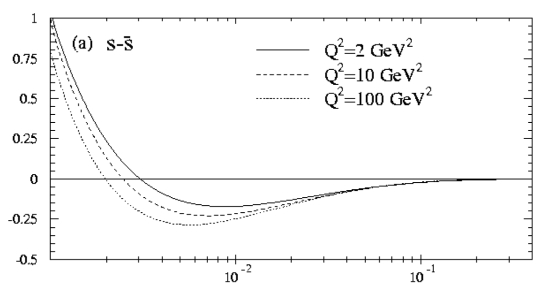
Cao & Signal ($xs - x\bar{s}$)



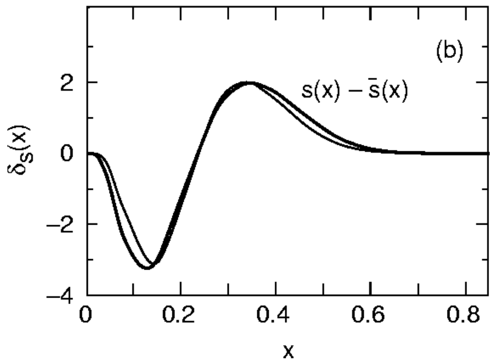
Alwal et al ($xs - x\bar{s}$)



Wakamatsu ($xs - x\bar{s}$)



Catani et al ($s - \bar{s}$)

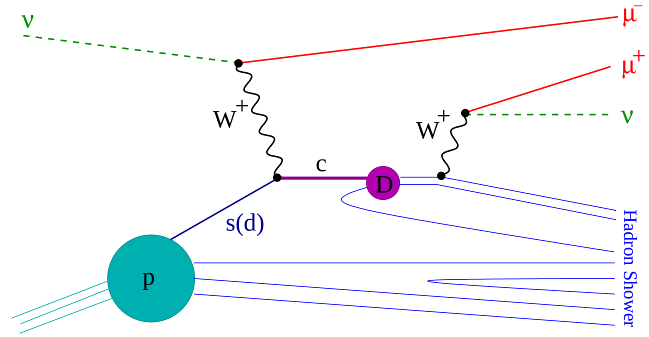


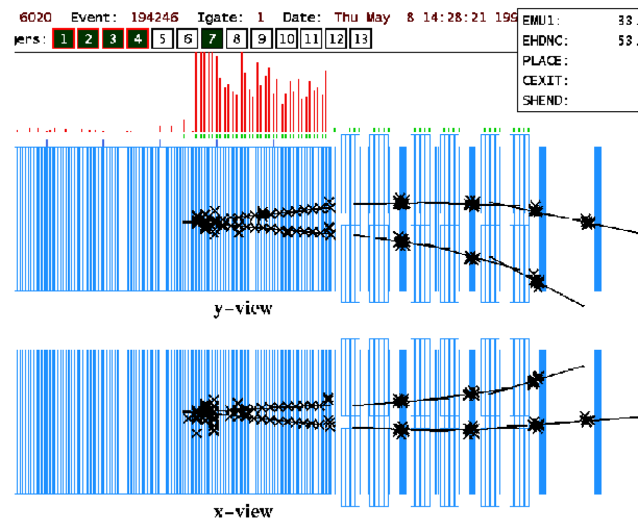
Brodsky & Ma ($s - \bar{s}$)

NuTeV can directly measure this!

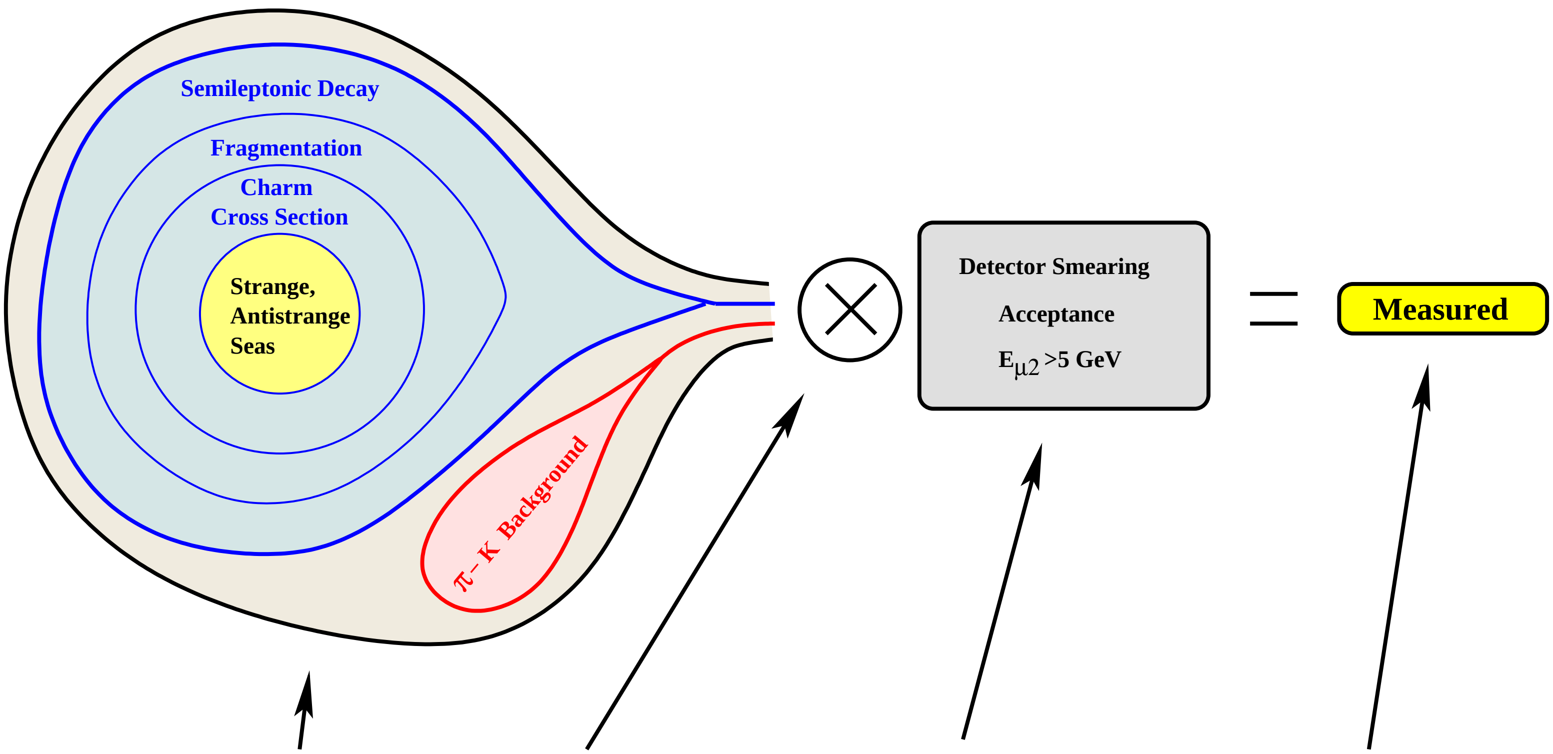
Charm Production ⇒ Dimuons

- CC νN makes charm
  $\longrightarrow$ fragmentation
  $\longrightarrow$ semileptonic decay to μ
- Very clear signature
- Direct look at strange sea
- With sign selected beam NuTeV can look at $s(x)$, $\overline{s}(x)$ independently
- Can also measure charm mass



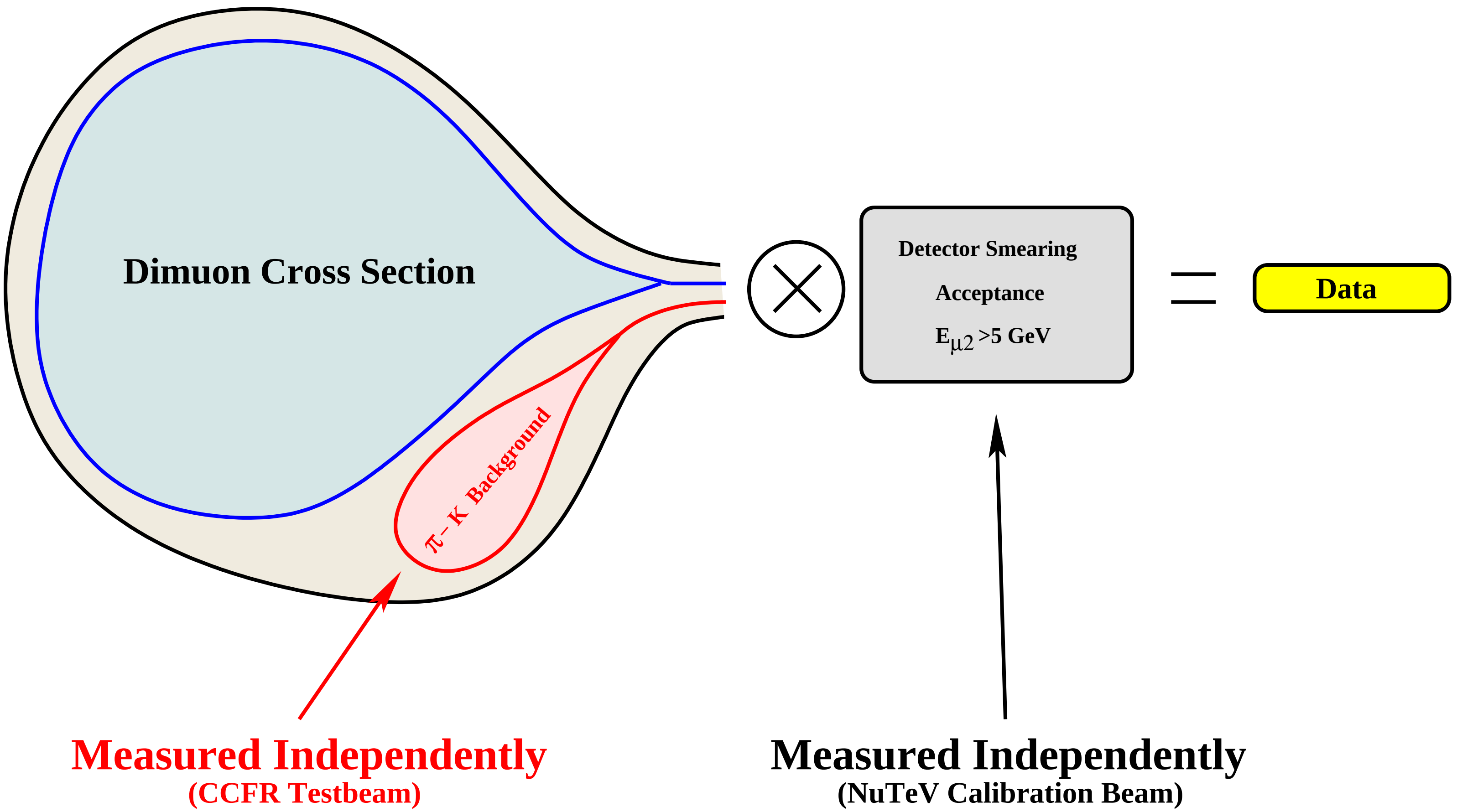


The Onion Representation of Dimuons



Physics convolved with experimental effects is what's measured

The Dimuon Cross Section



The Forward Dimuon Cross Section

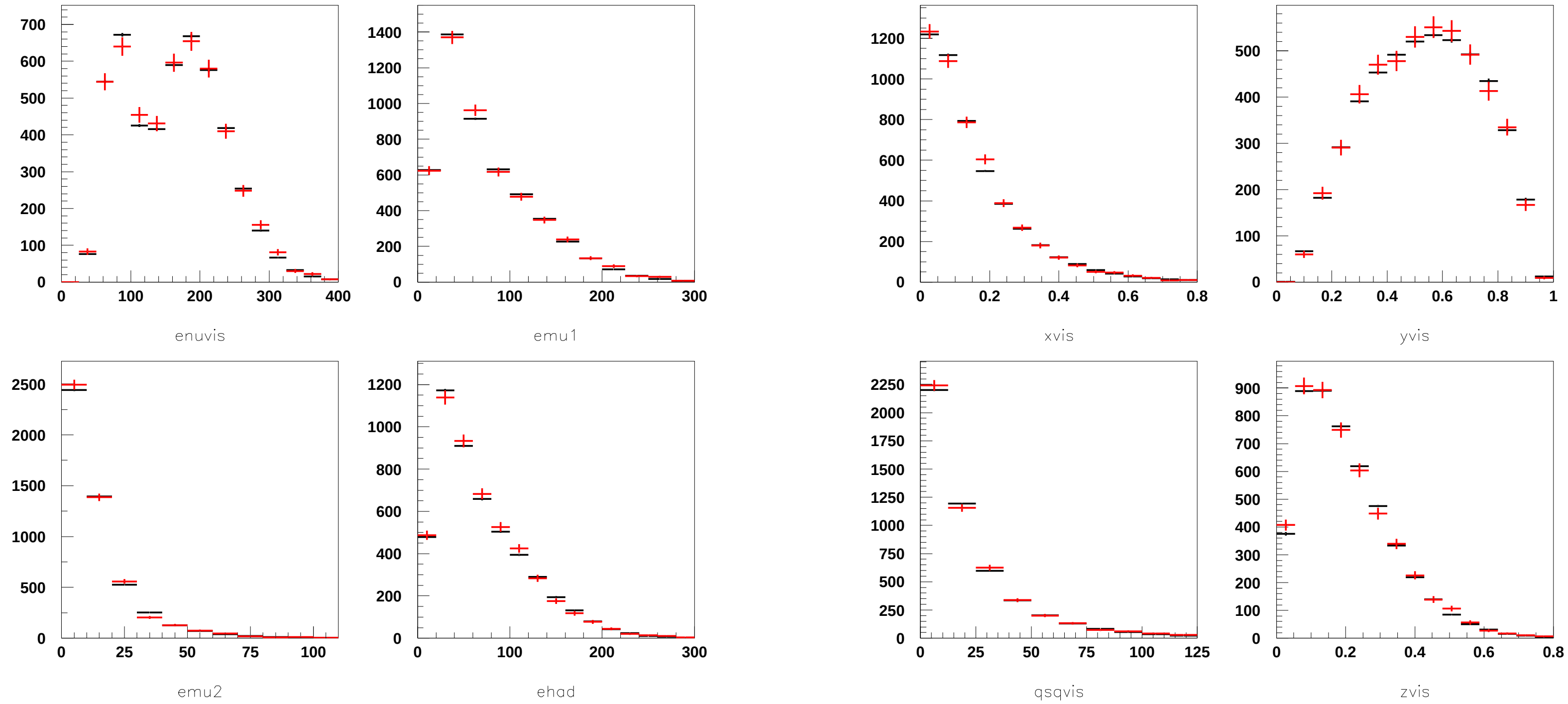
- Measure Dimuon rather than charm cross section
- Eliminates model dependence from:
  - Semileptonic Decay
  - Fragmentation
  - Order in α_s of Cross Section

- Model dependence only from effects which cross "$\otimes$" boundary
- Minimized in high acceptance events ($E_{\mu-charm} > 5$ GeV)
- With model dependence removed, can use simple (LO) model for extraction!

Forward Dimuon Cross Section: Cross section of dimuon events in iron such that the charm decay muon has energy > 5 GeV.

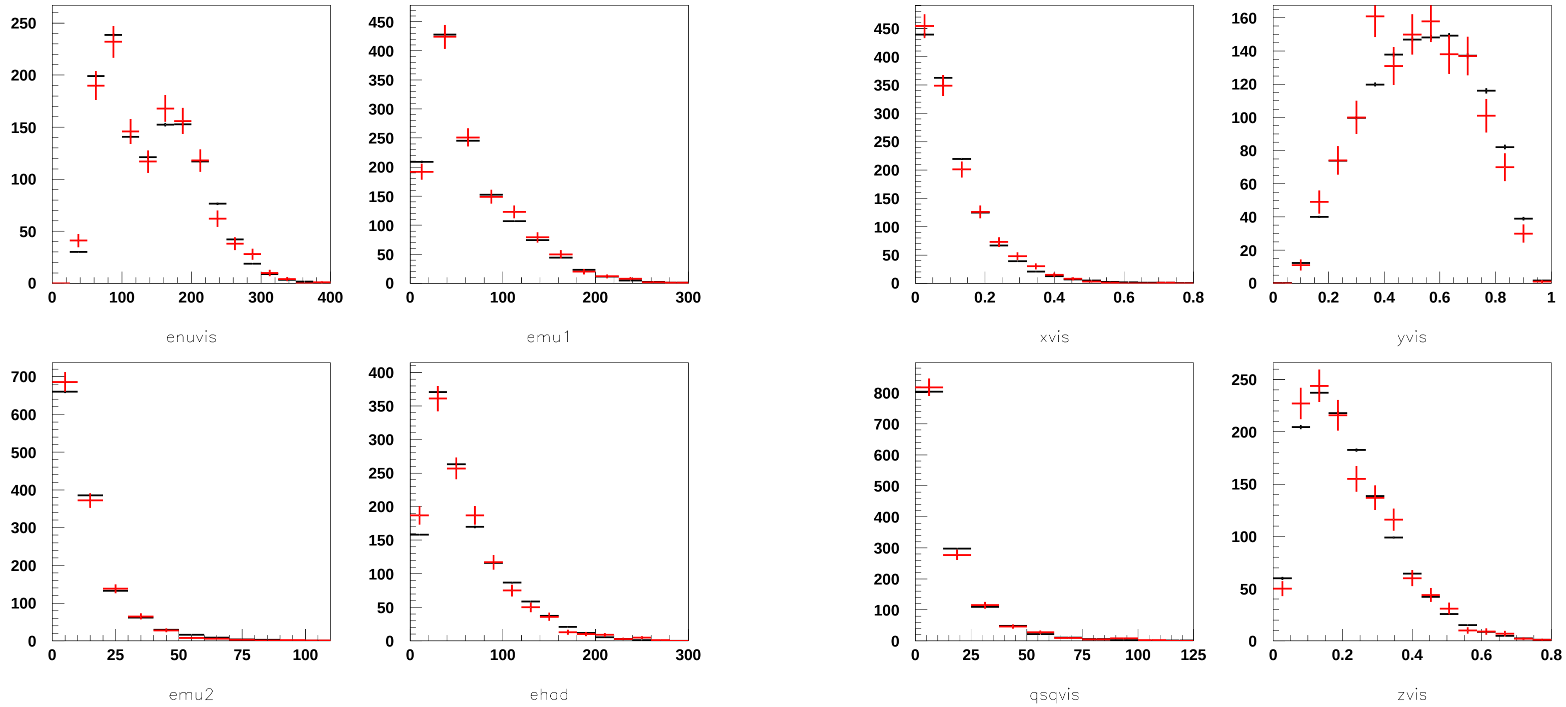
(Goncharov et al:PRD64 (2001) 112006)

Good LO Data/MC Agreement: Neutrinos



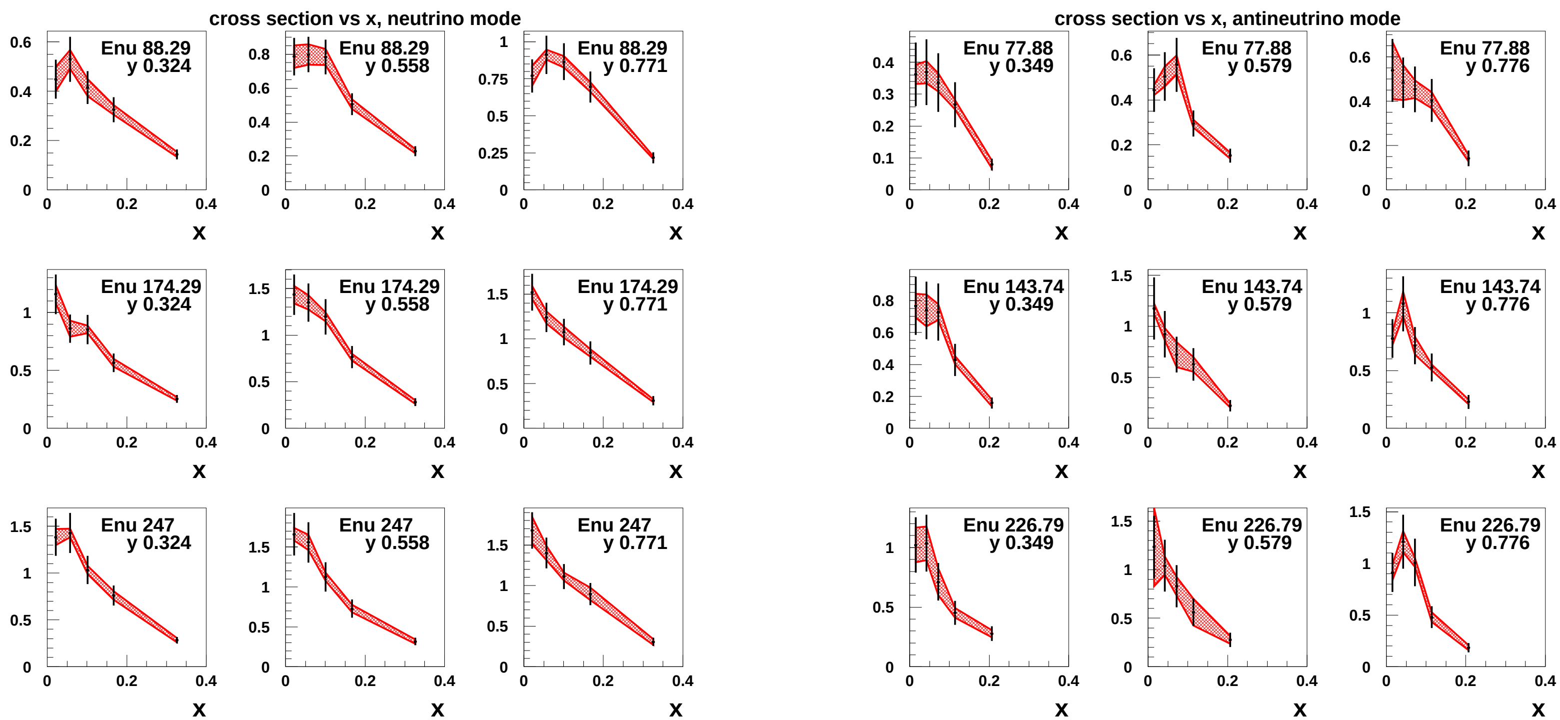
- Red points are data, black is MC, energies in GeV

Good LO Data/MC Agreement: Antineutrinos



- Red points are data, black is MC, energies in GeV

Forward Dimu Cross Section Table



- Plotting xsec vs x, normalized so $\frac{G_F^2 ME}{\pi} = 1$
- Table is available in electronic form for global fits!

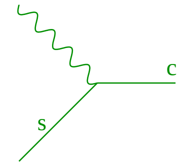
With the LO model having served its purpose

We now move to NLO:

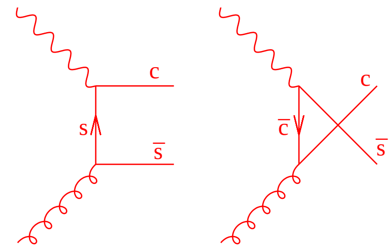
NLO charm production

- 1st order in QCD
- NLO of global interest
- Substantial gluon pdf
- But fragmentation requires convolution integral
- Dimuon acceptance depends on z, charm $p_\perp$

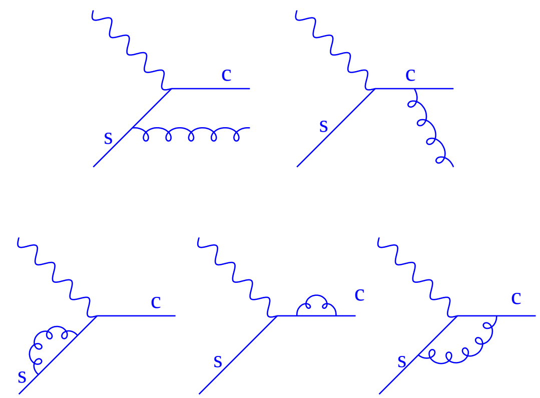
Leading Order
(Born)

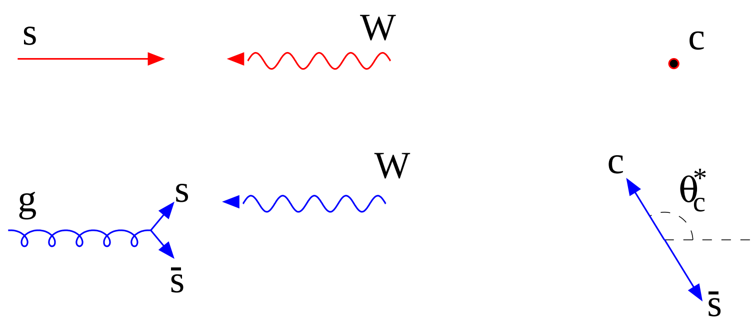


Next To Leading
Order
(gluon initiated)



Next To Leading
Order
(quark initiated)





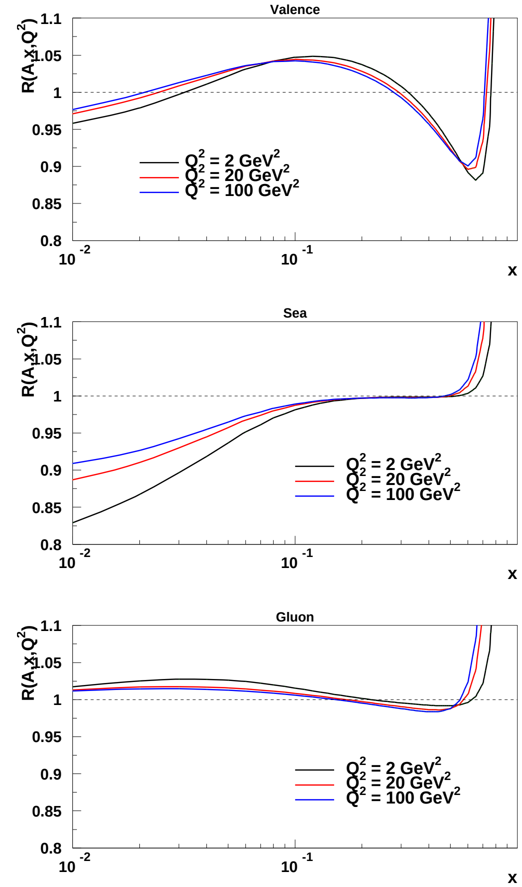
Elements in Dimuon Cross Section Table Fit

$$\frac{d\sigma_{charm}(E_\nu, x, y; m_c, s, \overline{s})}{dxdy} \otimes \mathcal{N}(A, x, Q^2) \cdot B_c \cdot \mathcal{A}_{\mu 2}(E_\nu, x, y; \epsilon, m_c) \; \Longrightarrow\!\boxed{\text{fit}}\!\Longrightarrow \; \frac{d\sigma_{2\mu}(E_\nu, x, y)}{dxdy}$$

$\frac{d\sigma_{2\mu}(E_\nu,x,y)}{dxdy}$	Measured NuTeV dimuon cross section
$\frac{d\sigma_{charm}(E_\nu,x,y;m_c,s,\overline{s})}{dxdy}$	Calculated inclusive charm cross section. depends on m_c, strange and antistrange seas.
$\mathcal{N}(A, x, Q^2)$	Nuclear corrections (iron target, proton pdfs) dependent on nucleus A, x, and Q^2, is convolved with pdf
B_c	Semileptonic branching ratio.
$\mathcal{A}_{\mu 2}(E_\nu, x, y; \epsilon, m_c)$	Acceptance function due to the 5 GeV cut on the muon from semileptonic charm decay $\left(\frac{\mathcal{N}(E_{\mu 2g} > 5 GeV)}{\mathcal{N}(all)}\right)$.

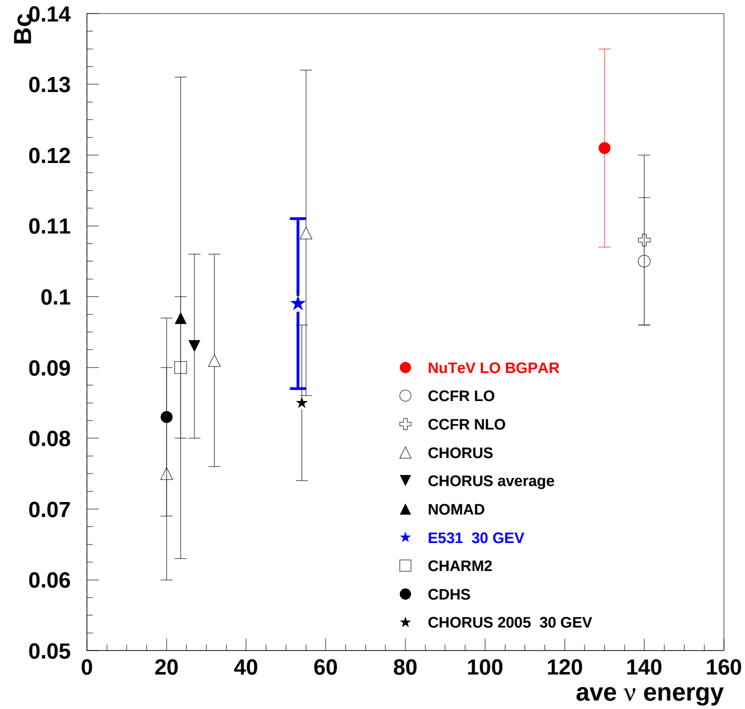
Nuclear Corrections: $\mathcal{N}(A, x, Q^2)$

- Proton based global fit pdf's require nuclear corrections (iron target)
- $\mathcal{N}$ depends on nucleus type, x, and Q^2
  - And whether valence, sea quarks or gluons involved
- Past analyses have used simple Q^2 independent parameterization
- First time $\mathcal{N}$ from global fits have been used
- de Florian et al, NLO corrections $\Longrightarrow$



Semi-muonic Branching Ratio: B_c

- B_c is an average semi-μ branching ratio over all charm states
- Fitting to cross section table requires taking from external measurements
- 2004 PDG value of 0.099 ± 0.012 used
- B_c uncertainty $\Rightarrow$ half of uncertainty in this strange asymmetry measurement



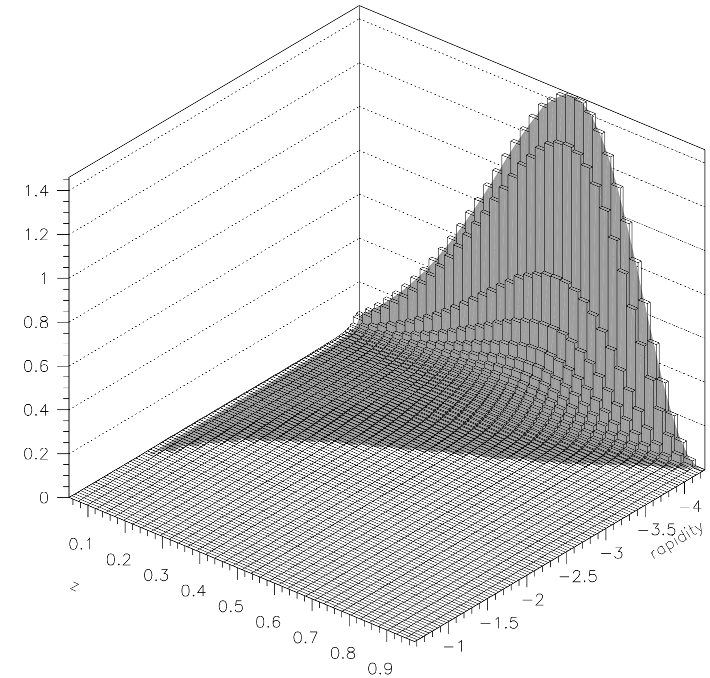
$E_{\mu-charm} > 5$ GeV Acceptance $\mathcal{A}_{\mu 2}$ –DISCO!

- Fitting table requires $E_{\mu 2} > 5$ GeV acceptance correction
- 2μ acceptance depends on fragmentation
- Also depends on charm $p_{\perp}$ at NLO
- $\Rightarrow$ need cross section differential in both
- I.e. need:

$$\frac{d\sigma_{charm}}{d\xi\ dy\ dz\ d\eta_c}$$

where $\eta_c = \frac{1}{2} \log \frac{E_c + p_{c||}}{E_c - p_{c||}}$

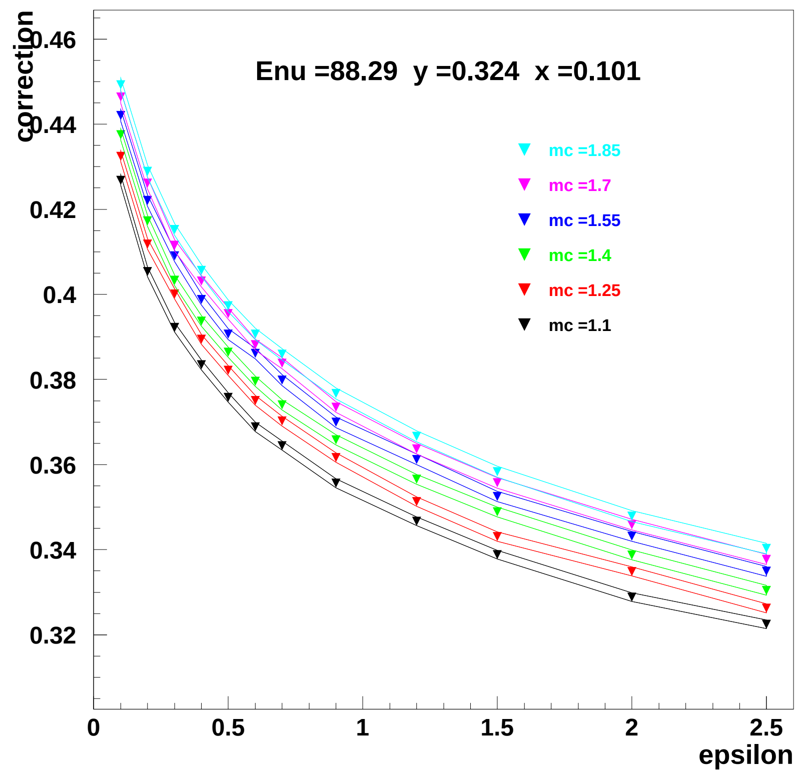
(i.e. a true rapidity, not pseudorapidity)



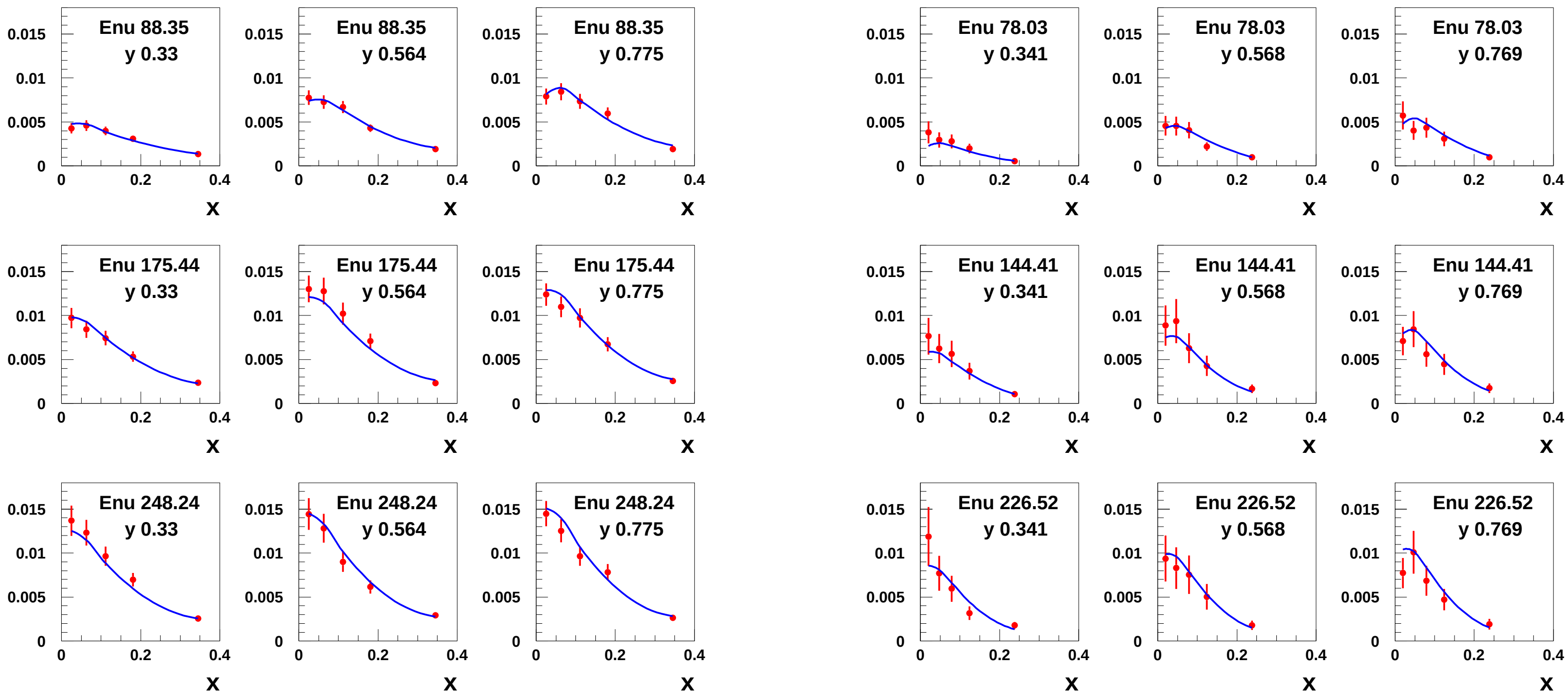
(Kretzer, Olness & Mason: Phys.Rev.D65:074010,2002)

Acceptance Tables

- Ratio of dimuons which pass $E_{\mu-charm} > 5$ GeV cut
- Acceptances calculated for each of 90 table points (1 shown) $\Longrightarrow$
- In grid of 12 ϵ, 6 m_c points
  - m_c dependence is NLO effect from rapidity
- In each table bin, 20 $z \times 40$ η_c bins
- Decay 20,000 dimuons in each



NLO fits table well!



- Plotting xsec vs x, normalized so $\frac{G_F^2 ME}{\pi} = 1$

A Progression of Fits...

- Performed several fits, taking charm mass, nonstrange pdfs, branching ratio from external measurements:
  1. Treating strange/antistrange seas as modification of pre-evolved pdfs
  2. Defining s, $\overline{s}$ pdfs at Q_0, evolving properly
  3. Using CTEQ parameterization, evolving properly, satisfying sum rules
- Also studied dependence of strange asymmetry on shape

Traditional fit first...

$$s(x,Q^2) = \kappa(1-x)^{\alpha}\left[\frac{\overline{u}(x,Q^2)+\overline{d}(x,Q^2)}{2}\right]$$

$$\overline{s}(x,Q^2) = \overline{\kappa}(1-x)^{\overline{\alpha}}\left[\frac{\overline{u}(x,Q^2)+\overline{d}(x,Q^2)}{2}\right]$$

- Factors applied to already evolved pdfs
- $S^- = 0.0023 \pm 0.0006$ (stat)

  $\left(S^- \equiv \int x\,[s(x)-\overline{s}(x)]\,dx\right)$
- But do we get this answer because of the approximate QCD evolution?

Parameter	Value
m_c	1.20 GeV (fixed)
ϵ	0.60 (fixed)
κ	0.596 ± 0.028
$\overline{\kappa}$	0.521 ± 0.026
α	1.34 ± 0.49
$\overline{\alpha}$	1.54 ± 0.46
B_c	0.099 (fixed)

To evolve properly...

$$\mu^2 \frac{d}{d\mu^2}\phi_{i,h}(x,\mu^2) = \sum_{j=q,\overline{q},G} \int_x^1 \frac{d\xi}{\xi} P_{ij}\left(\frac{x}{\xi}, \alpha_s(\mu^2)\right) \phi_{j,h}(\xi,\mu^2)$$

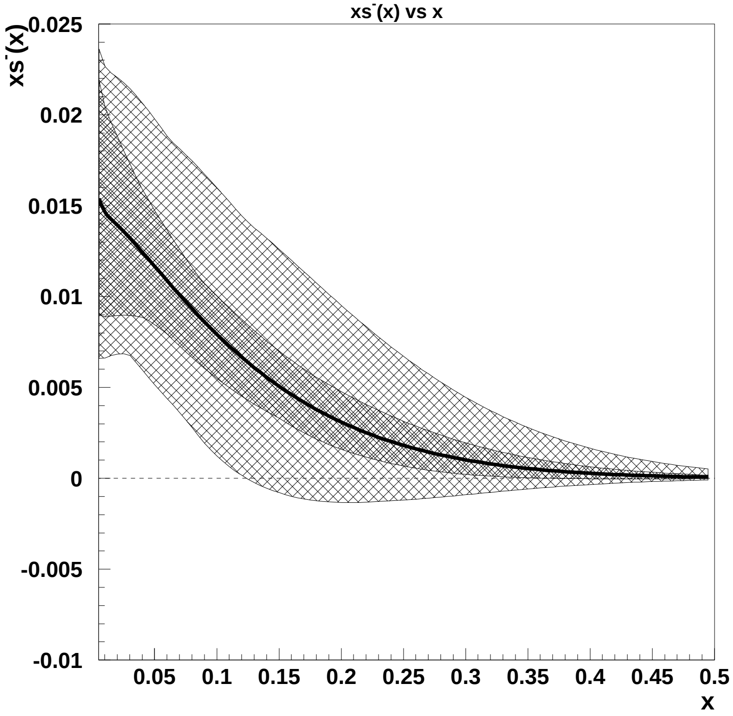
- pdf must be solution of DGLAP equation (above)
- Define at an initial scale ($\mu_0 = Q_0$) then numerically solve to find pdf ,$\phi_{j,h}(\xi,\mu^2)$, at arbitrary scale, μ.
- Some freedom in pdf definitions is required ($s \neq \overline{s}$)
- Use modified version of EVLCTEQ evolution code which allows $s \neq \overline{s}$ (thanks to Wu-Ki Tung)
- Use LHApdf v1.2 package as a wrapper
- CTEQ6M pdfs, defining $s, \overline{s}$ at $Q_0 = 1.3$ GeV

Redo $\kappa - \alpha$ fit, evolving properly:

Description	κ	$\overline{\kappa}$	α	$\overline{\alpha}$	S^-
Central value	0.415	0.332	0.87	1.09	0.00195
Statistical error	0.031	0.030	0.68	0.71	0.00055
ν π-K (15%)	0.012	0.009	0.38	0.08	0.00041
$\overline{\nu}$ π-K (21%)	0.006	0.018	0.05	0.14	0.00031
Emuff scale (1%)	0.007	0.016	0.19	0.01	0.00002
Had energy scale (0.5%)	0.008	0.009	0.15	0.04	0.00010
R_L (20%)	0.011	0.018	0.06	0.02	0.00005
MC statistics	0.014	0.021	0.16	0.06	0.00000
Emu2 rangeout	0.013	0.021	0.31	0.06	0.00012
Flux norm	0.002	0.006	0.07	0.00	0.00000
Total Table Systematics	0.028	0.044	0.58	0.18	0.00054
Charm mass	0.015	0.011	0.07	0.14	0.00006
Fragmentation ϵ	0.009	0.009	0.25	0.06	0.00023
B_C	0.053	0.055	1.32	0.19	0.00125
Total External Measurement	0.056	0.057	1.35	0.24	0.00127
Total Systematics	0.063	0.072	1.47	0.30	0.00138

$\kappa - \alpha\ xs^{-}(x)$ vs x

- $\chi^2 = 36.9$ out of 39.8 DoF
- $xs^{-}(x)$ vs x, inner band stat. error, outer band total $\Longrightarrow$
- Asymmetry agrees well with approximate evolution fit
- But $\int_0^1 [s(x) - \overline{s}(x)]dx$ isn't zero.
- Technically should also satisfy sum rules.



Further Satisfying QCD requirements

- Stepped up collaboration with phenomenologists

  (Amundson, Kretzer, Olness, Soper, Tung)

- Using a "CTEQ inspired" parameterization (hep-ph/0312323)

$$s^+(x,Q_0) = \kappa^+(1-x)^{\alpha^+}x^{\gamma^+}\left[\overline{u}(x,Q_0)+\overline{d}(x,Q_0)\right]$$

$$s^-(x,Q_0) = s^+(x)\tanh\left[\kappa^-(1-x)^{\alpha^-}x^{\gamma^-}\left(1-\frac{x}{x_0}\right)\right]$$

$$s = \frac{s^+ + s^-}{2} \qquad \overline{s} = \frac{s^+ - s^-}{2}$$

- Flavor sum rule satisfied by x_0 such that $\int s^-(x,Q_0)dx = 0$

- Total momentum sum rule satisfied by rescaling gluon to balance any change in $\int xs^+$ (thanks to Dave Soper)
  - Gluon sea is large, uncertainty is also large
  - Strange sea is small
  - $\Rightarrow$ gluon uncertainty can handle small perturbation ($< 1\%$)

s^+, s^- fit results:

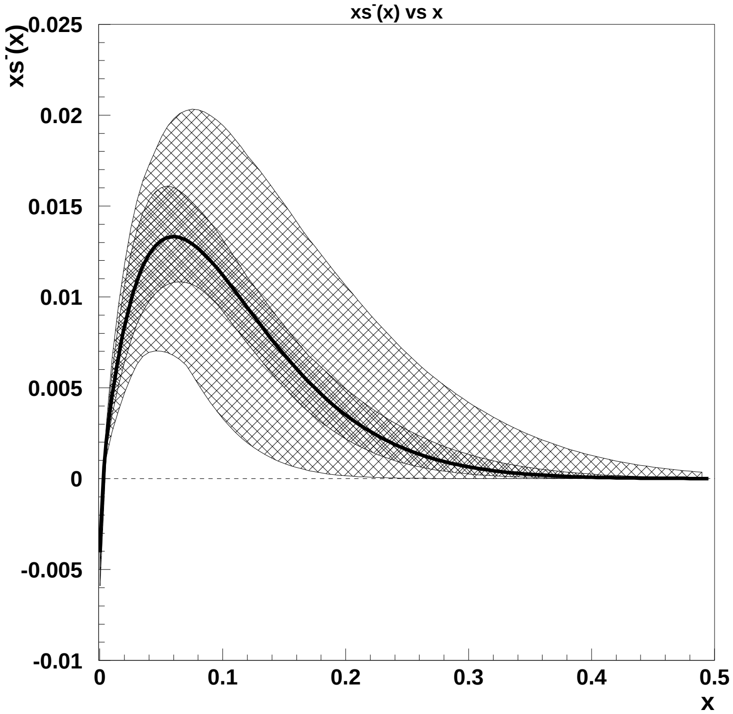
Parameter	Value
m_C	1.20 GeV (fixed)
ϵ	0.60 (fixed)
κ^+	0.551 ± 0.126
κ^-	$(-0.881 \pm 0.567) \times 10^{-2}$
α^+	1.11 ± 0.69
α^-	6.31 ± 4.06
γ^+	0.072 ± 0.064
γ^-	-0.102 ± 0.080
B_C	0.099 (fixed)

$$\eta_S = \frac{\int_0^1 xs^+(x)dx}{\int_0^1 [\overline{u}(x)+\overline{d}(x)]dx}$$

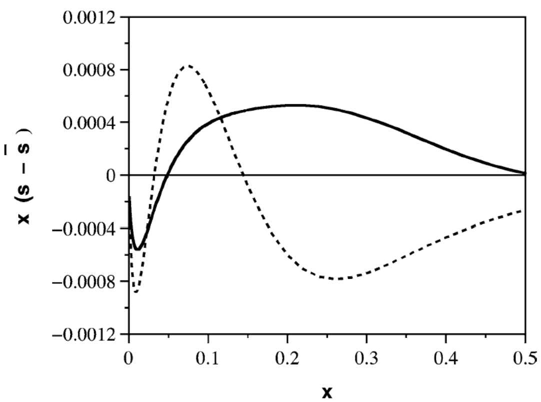
η_S	S^-	Systematic
0.0612	0.00196	central value
0.0011	0.00046	statistics
0.0026	0.00034	ν π-K model
0.0019	0.00025	$\overline{\nu}$ π-K model
0.0020	0.00004	μ spectrometer p scale (1%)
0.0014	0.00008	hadron energy scale (0.5%)
0.0018	0.00005	R_L in table model (20%)
0.0026	0.00001	table extraction MC statistics
0.0030	0.00012	μ2 range out energy (2.5%)
0.0006	0.00005	ν, $\overline{\nu}$ relative normalization
0.0060	0.00045	total systematics
0.0022	0.00002	$\Delta m_C = 0.10$
0.0020	0.00021	$\Delta\epsilon_{C-S} = 0.3$
0.0101	0.00111	$\Delta B_C = 0.012$
0.0068	0.00046	CTEQ6 PDF uncertainties
0.0007	0.00038	Nuclear corrections
0.0126	0.00128	total external measurement

s^+, s^- asymmetry

- $\chi^2 = 38.2$ out of 37.8 DoF
- s^- prefers to satisfy sum rule by spiking negative at low x
- Crossing point at x_0=0.004
- gluon sea only needs 0.07% change
- Asymmetry still consistent with previous two fits



A Reminder of the Pantheon of Asymmetries



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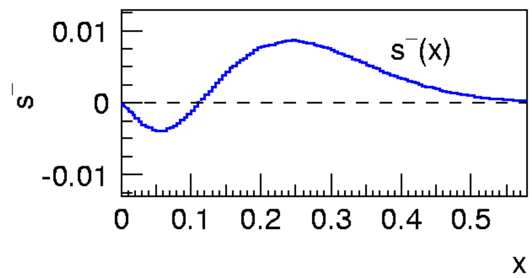
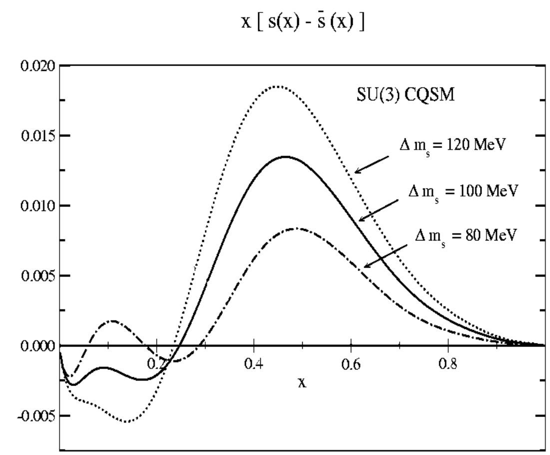
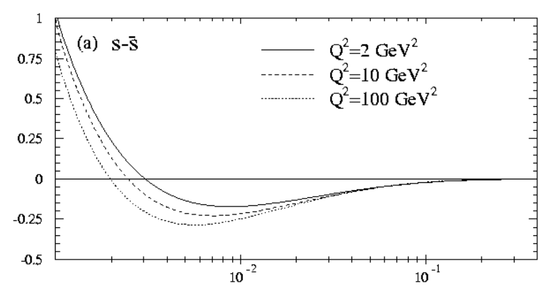


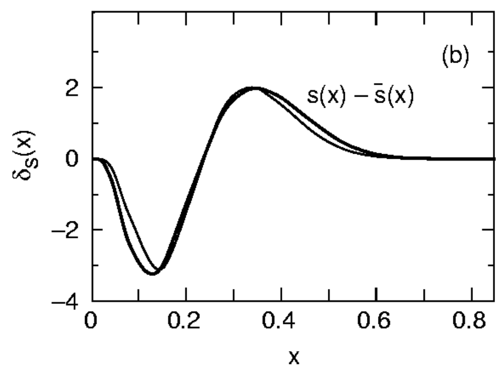
Alwal et al ($xs - x\bar{s}$)



Wakamatsu ($xs - x\bar{s}$)

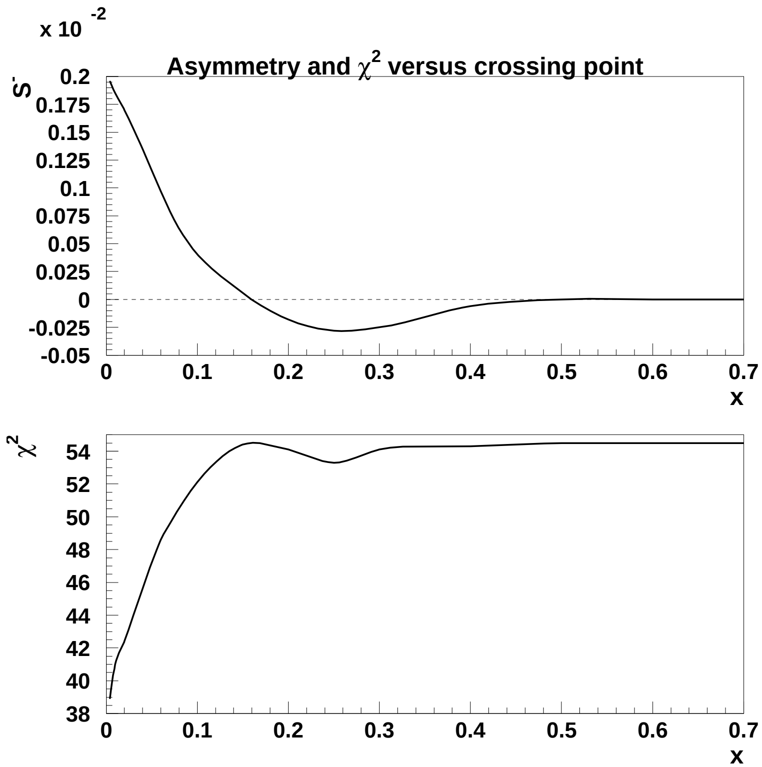


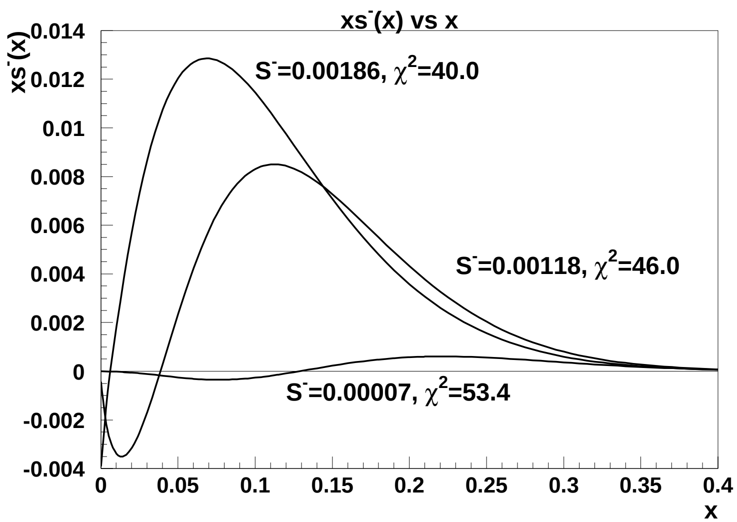
Catani et al ($s - \bar{s}$)



Brodsky & Ma ($s - \bar{s}$)

So we look at the asymmetry vs. crossing point...





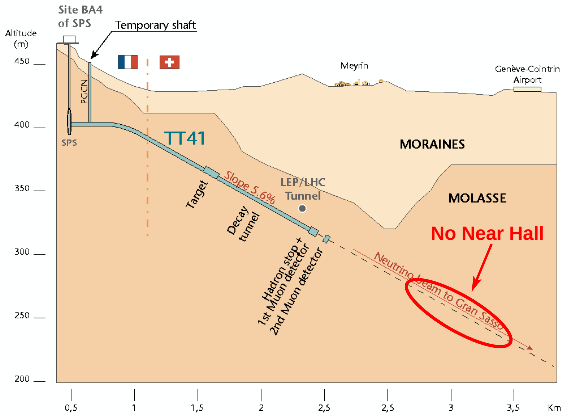
$$s^-(x,Q_0) = s^+(x)\tanh\left[\kappa^-(1-x)^{\alpha^-}x^{\gamma^-}\left(1-\frac{x}{x_0}\right)\right]$$

- We have measured the strange asymmetry to be positive
  - First complete NLO analysis for this process
  - Sign selected beam ensures pure ν, $\overline{\nu}$ samples
  - Multiple fits, including proper evolution, QCD sum rules satisfied
  - Modern nuclear corrections
- Found asymmetry difficult to accomodate with x_0 at high x
- What might we expect experimentally beyond this measurement?

Other ν $s - \bar{s}$ measurements?

From CERN?

- CHORUS & NOMAD:
  - Ran in CERN SPS horn focused beam, mostly ν, some $\overline{\nu}$
  - $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments $\Longrightarrow$ fine grained detectors.
  - Many charm measurements, dimuon results expected soon
- Future – CNGS? $\Longrightarrow$

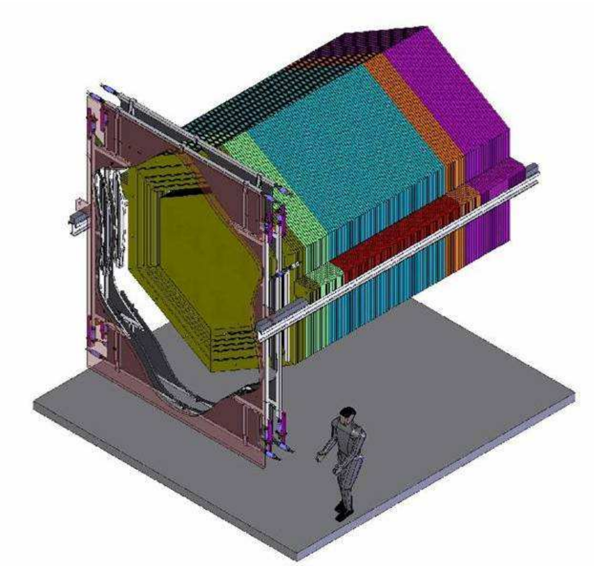


NuMI beam? MINOS?

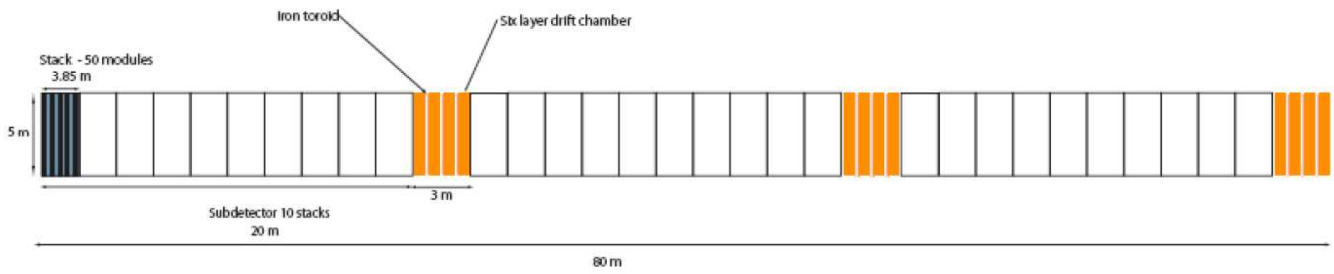
- MINOS near detector has unprecedented ν CC event sample on tape
- $\Longrightarrow$ large dimuon sample
- Low energy would make hard to separate from backgrounds
- Would need pure $\overline{\nu}$ sample as well to measure $s - \overline{s}$

MINERνA?

- Fine grained detector with good particle ID
  - Strange particle tagging will be possible
  - Can NC strange particle production provide additional insight into $s(x)$?
  - MINERνA's particle ID should allow charm production measurements beyond the "traditional" dimuon signature (ν energy permitting)
- To look at $s - \overline{s}$ would need ν and $\overline{\nu}$ data



Possibly further in the future: "CMF"



- An idea for the interim between Collider & ILC
- A ν DIS experiment to run in the "original" FNAL ν beamline
- 100x NuTeV statistics with a high energy sign selected beam
- Test beam calibrated CHARMII-like glass detector
- Primary goals include precision electoweak & SF measurements
- Statistics coupled with more precise B_c could really nail strange sea

In the meantime, here is what we know:

$$S^{-}_{NLO,CTEQ6} = +0.00196 \pm \underset{\text{(stat)}}{0.00046} \pm \underset{\text{(syst)}}{0.00045} \pm \underset{\text{(external)}}{0.00128}$$

$$m_c = 1.41 \pm \underset{\text{(stat)}}{0.10} \pm \underset{\text{(syst)}}{0.08} \pm \underset{\text{(external)}}{0.12}\ \text{GeV}/c^2$$