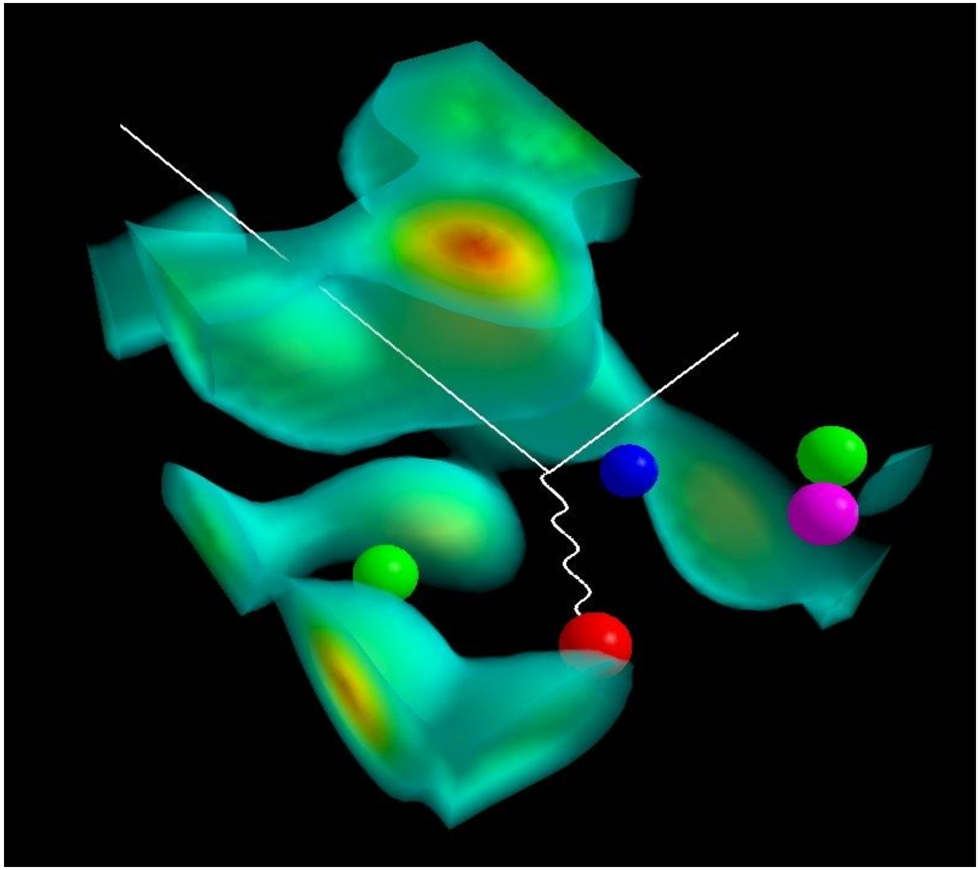
CSV in Parton Distribution Functions



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ARC Centre of Excellence for Particle Physics at the Terascale

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Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

HiX 2014

INFN Frascati – November 20th 2014

Outline

- **What is Charge Symmetry Violation**

- **Origins**
  - **$m_u \neq m_d$**
  - **electromagnetism**

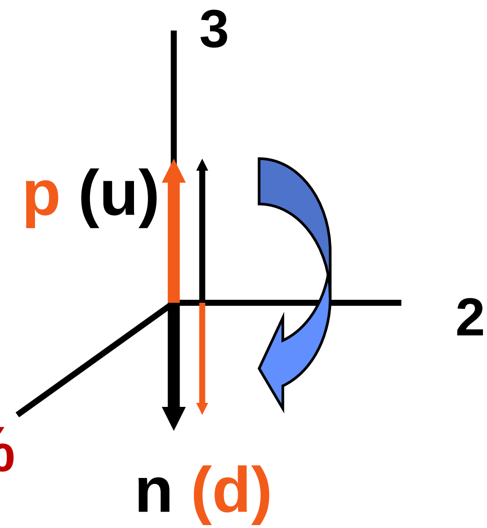
- **Who cares?**

Violation of Charge Symmetry

Charge Symmetry ~Universally Assumed for PDFs

Traditionally there is NO label "p" on PDF's !

Its assumed that charge symmetry: $\boxed{e^{i \pi I_2}}$ is exact.



Good at < 1% : e.g. $(m_n - m_p) / m_p \sim 0.1\%$

That is: $u \equiv u^p = d^n$

$d \equiv d^p = u^n$ **etc.**

Hence:

$$F_2^{\,n} = 4/9 \times (\, d(x) + \bar{d}(x) \,) + 1/9 \,(\, u(x) + \bar{u}(x) \,)$$

up-quark in n **down-quark in n**

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Charge Symmetry is almost universally *assumed* in the analysis of PDFs

- **it is vital to establish how accurately it is satisfied**

Define:

$$\delta u \equiv u^p - d^n$$
$$\delta d \equiv d^p - u^n$$

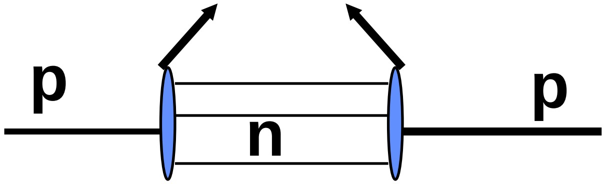
Role of Di-quark Correlations

On general grounds (conservation of energy & momentum) :

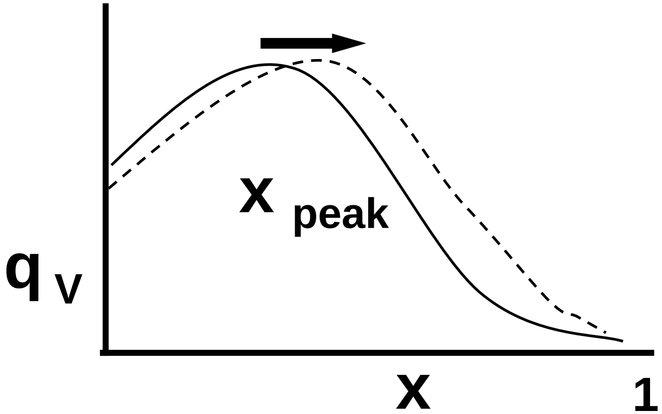
in the *ground state* of a baryon the peak of the valence PDF

Is determined by:

$\boxed{x_{peak} = (M - m_2) / M}$ **where m_2 is the mass of the di-quark spectator to the struck quark**



$m_2 / M = 2/3$ (CQM);
$= 3/4$ MIT bag ➡ $x_{peak} \sim 1/4$ to $1/3$



If $m_2 \downarrow$: x_{peak} moves to right
***enhancing large-x* distribution**

Close & Thomas, Phys Lett B212 (1988) 227

Effect of "Hyperfine" Interaction

Δ – N mass splitting: S=1 "di-quark" mass is 0.2 GeV greater than S=0

SU(6) wave function for proton :

hit d-quark : ONLY S=1 left

c.f. hit u-quark : 50% S=0 and 50% S=1

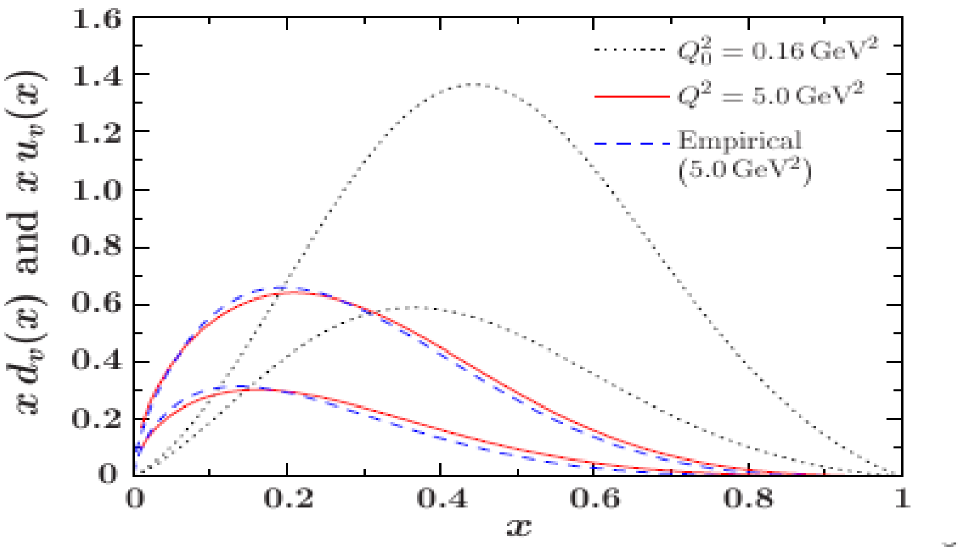
Hence*:

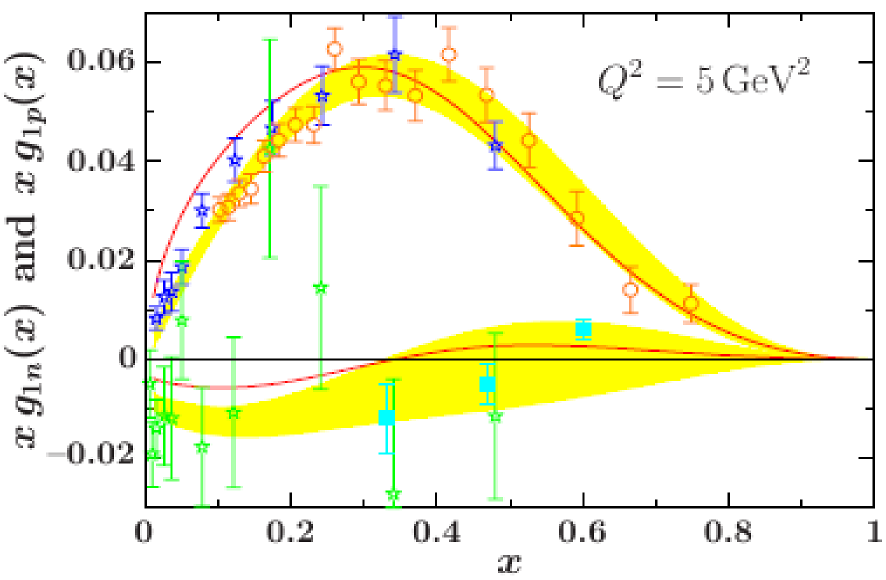
- u(x) dominates over d(x) for x > 0.3
- $u^{\uparrow}$ dominates over $u^{\downarrow}$ at large x
  and hence: $g^p_1(x) > 0$ at large x
- Similarly $g^n_1(x) > 0$ at large x

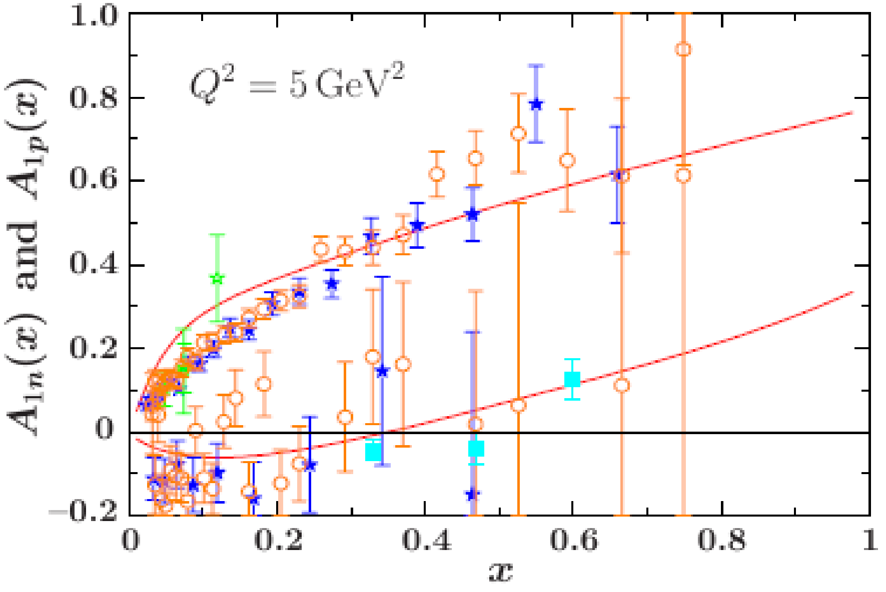
*Close & Thomas: 1988

More Modern (Confining) NJL Calculations

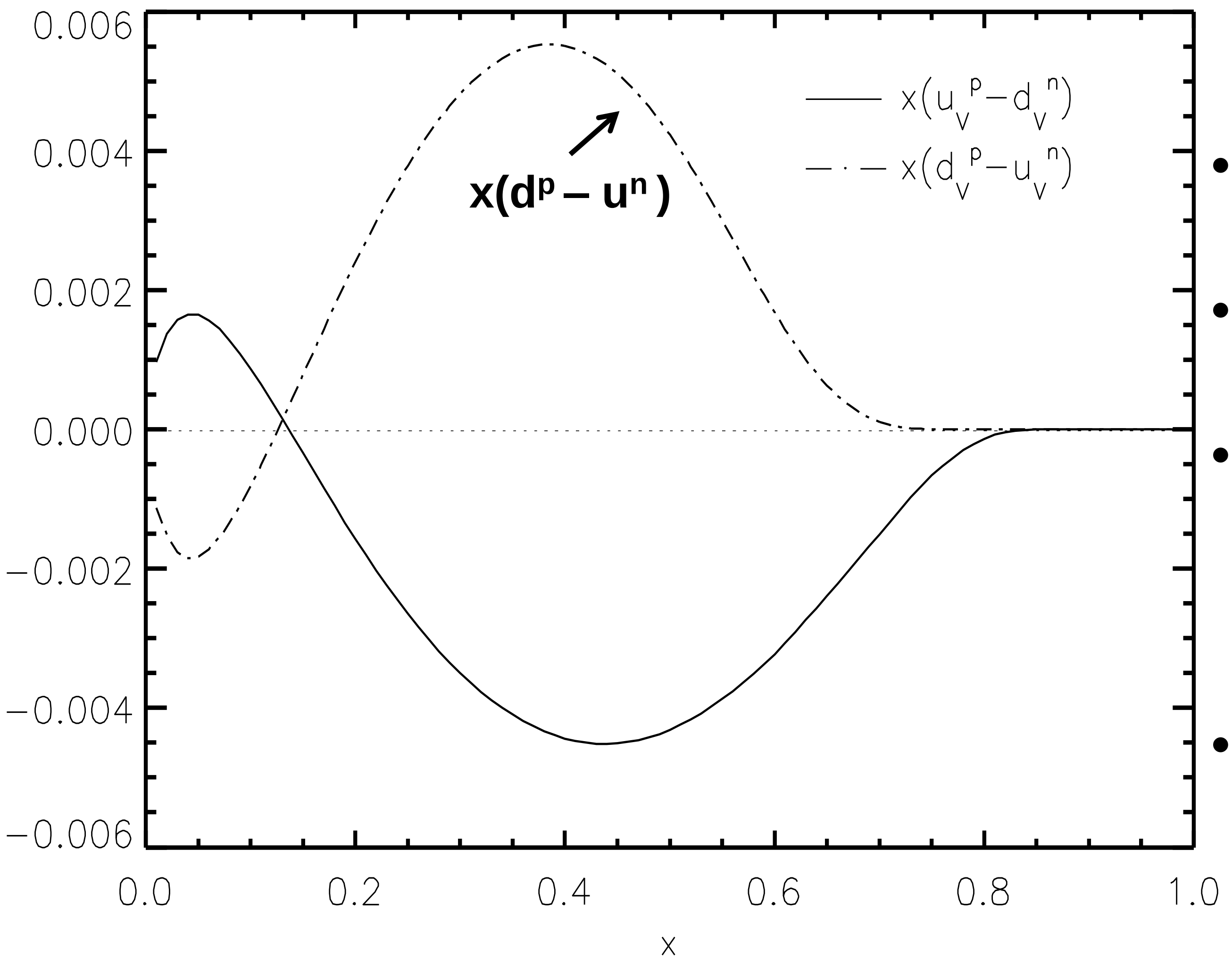
Cloët et al.,
Phys. Lett. B621, 246 (2005)
(μ = 0.4 GeV)







Application to Charge Symmetry Violation



- d in p : uu left
- u in n : dd left
- Hence m_2 lower by about 4 MeV for d in p than u in n
- Hence $d^p > u^p$ at large x.

This amount of CSV would reduce NuTeV anomaly by ~1σ

From: Rodionov *et al.*, Mod Phys Lett A9 (1994) 1799; and E. Sather similar in approximate treatment

Remarkably Similar to MRST Fit a Decade Later

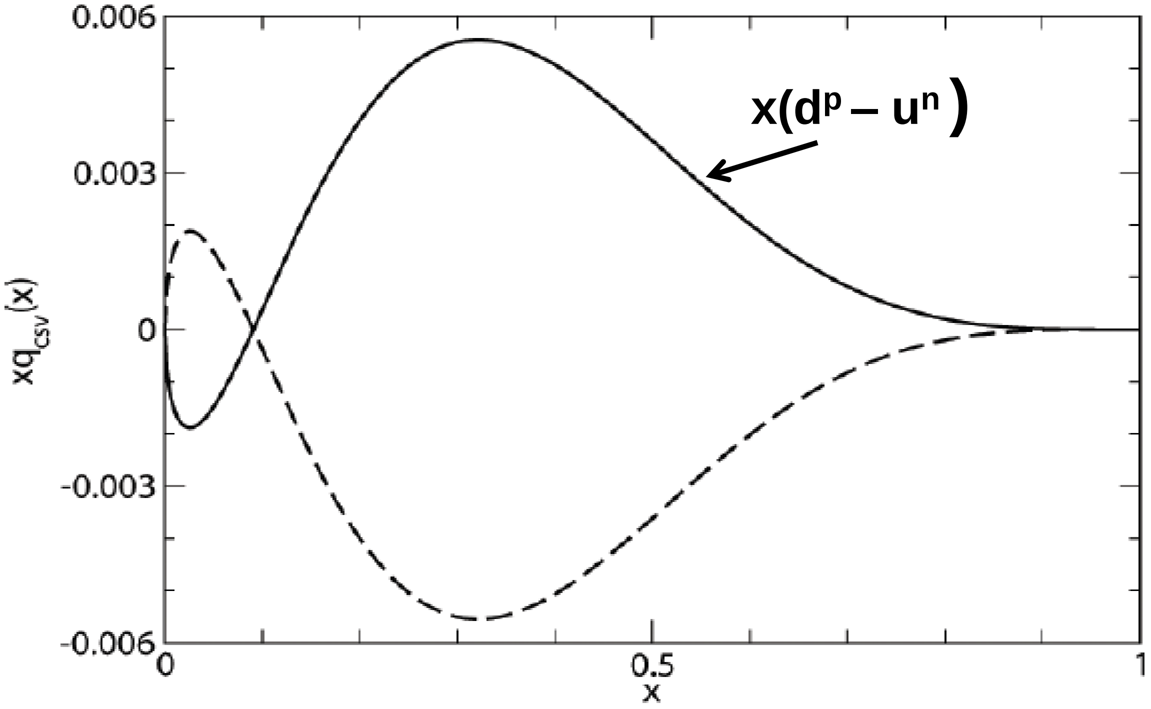
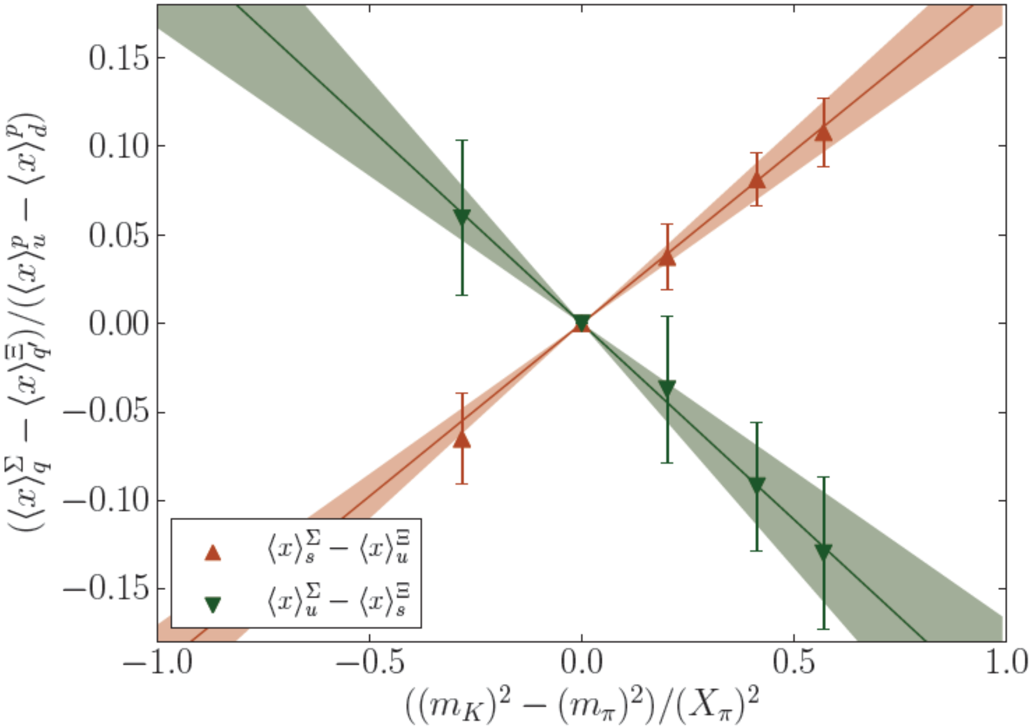


FIG. 5: The phenomenological valence quark CSV function from Ref. [23], corresponding to best fit value $\kappa = -0.2$ defined in Eq. (35). Solid curve: $x\delta d_{\rm v}$; dashed curve: $x\delta u_{\rm v}$.

Eur. Phys. J. C39 (2005) 155-161

Strong support from 2011 lattice QCD calculation

Study moments of octet baryon PDFs



$$\frac{\delta u}{\langle x\rangle^p_{u-d}} = \frac{m_\delta}{\overline{m}_q}\frac{(\langle x\rangle_u^{\Sigma^+} - \langle x\rangle_s^{\Xi^0})/\langle x\rangle^p_{u-d}}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

$$\frac{\delta d}{\langle x\rangle^p_{u-d}} = \frac{m_\delta}{\overline{m}_q}\frac{(\langle x\rangle_s^{\Sigma^+} - \langle x\rangle_u^{\Xi^0})/\langle x\rangle^p_{u-d}}{(m_K^2 - m_\pi^2)/X_\pi^2}$$

Deduce: $\delta u^+ = -0.0023(7)$ $\quad \delta d^+ = 0.0017(4)$

- **in excellent agreement with phenomenological estimates of Rodionov *et al*.** $\delta u^- = -0.0014$ **and** $\delta d^- = 0.0015$

Horsley et al., Phys. Rev. D83 (2011) 051501
and update by: Shanahan *et al*., arXiv:1303.4806

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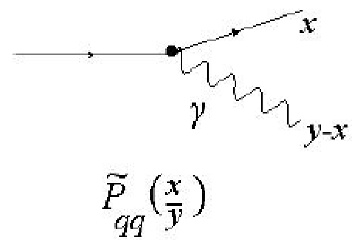
An additional source of CSV

- **In addition to the u-d mass difference, MRST (Eur Phys J C39 (2005) 155) and Glück et al (PRL 95 (2005) 022002) suggested that "QED splitting":**



- **which is obviously larger for u than d quarks, would be an additional source of CSV. Assume zero at some low scale and then evolve − so CSV from this source grows with Q^2**

- **Effect on NuTeV is exactly as for regular CSV and magnitude but grows logarithmically with Q^2**

- **For NuTeV it gives:** $\Delta R^{\mathrm{QED}} = -0.0011$ **to which we assign 100% error**

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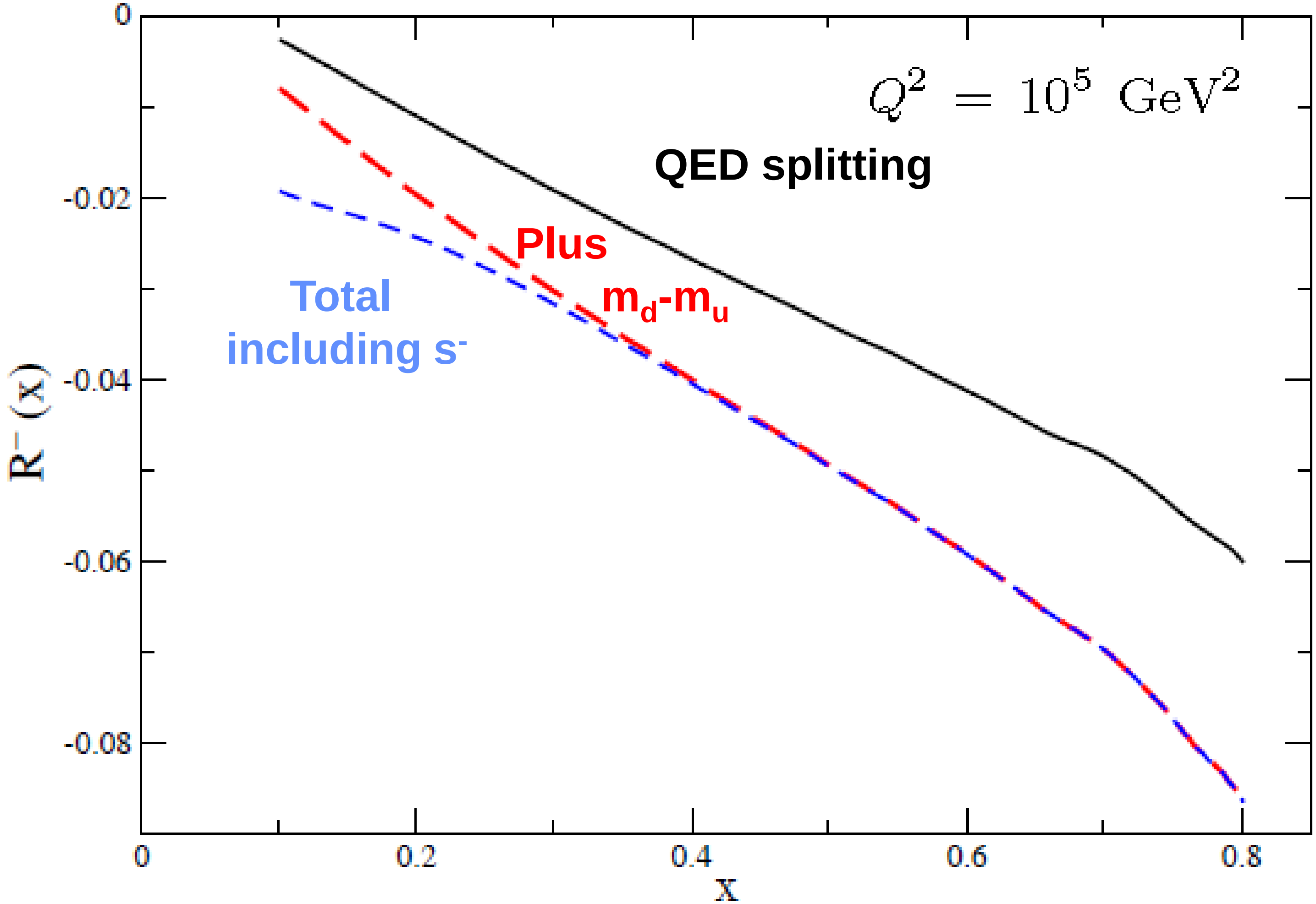
Test at Future EIC or LHeC – σ_{CC}

$$R^-(x) \equiv \frac{2(F_2^{W^-D}(x) - F_2^{W^+D}(x))}{F_2^{W^-p}(x) + F_2^{W^+p}(x)}$$



Hobbs et al., arXiv 1101.3923 [hep-ph]

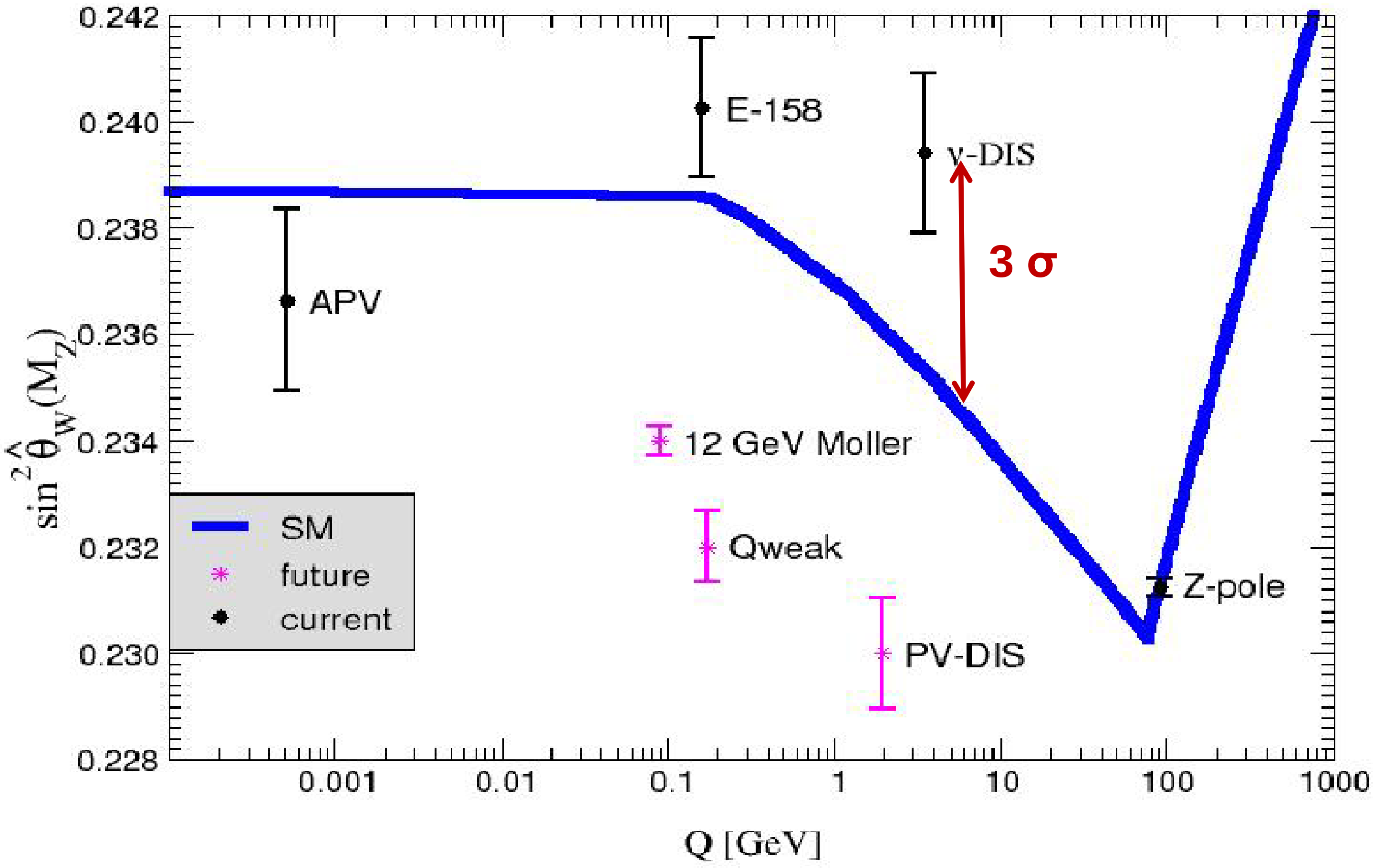
Why does it matter?

An example:

The NuTeV "Anomaly"

Radiative Corrections: Test of Weak Neutral Current

Not so long ago….



SM line: Erler et al., Phys.Rev.D72:073003,2005

NuTeV Anomaly

Phys. Rev. Lett. 88 (2002) 091802 : 400+ citations since….

Fermilab press conference, Nov. 7, 2001:

"We looked at $\sin^2 \theta_W$," said Sam Zeller. The predicted value was 0.2227. The value we found was 0.2277…. might not sound like much, but the room full of physicists fell silent when we first revealed the result."

"3 σ discrepancy : 99.75% probability ν are not like other particles…. only 1 in 400 chance that our measurement is consistent with prediction ," MacFarland said.

Paschos-Wolfenstein Ratio: Isoscalar Target

NuTeV measured (approximately) P-W ratio:

$$R^{PW} = \frac{\sigma(\nu\,\mathrm{Fe} \to \nu\,X) - \sigma(\bar{\nu}\,\mathrm{Fe} \to \bar{\nu}\,X)}{\sigma(\nu\,\mathrm{Fe} \to \mu^-\,X) - \sigma(\bar{\nu}\,\mathrm{Fe} \to \mu^+\,X)} = \frac{\mathrm{NC}}{\mathrm{CC}}\ \text{ratio}$$

$$= \tfrac{1}{2} - \sin^2\theta_W$$

NuTeV

$\sin^2\theta_W = 1 - M_W^2/M_Z^2 \quad = \quad 0.2277 \pm 0.0013 \pm 0.0009$

other methods

c.f. Standard Model $\quad = \quad 0.2227 \pm 0.0004$

(c.f. 1978: 0.230 ± 0.015)

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Correction to Paschos-Wolfenstein from CSV

- **General form of the correction is:**

$$\Delta R_{\rm PW} \simeq \left(1 - \frac{7}{3} s_W^2\right) \frac{\langle x_A\, u_A^- - x_A\, d_A^- - x_A\, s_A^- \rangle}{\langle x_A\, u_A^- + x_A\, d_A^- \rangle}$$

- **$u_A = u^p + u^n$; $d_A = d^p + d^n$ and hence**

  $u_A - d_A = (u^p - d^n) - (d^p - u^n) \equiv \delta u - \delta d$

- **N.B. In general the corrections are C-odd and so involve only valence distributions: $q^- = q - \bar{q}$**

- **Also the $x_A\, s_A^-$ term means that the asymmetry between strange and anti-strange quarks may add a correction**

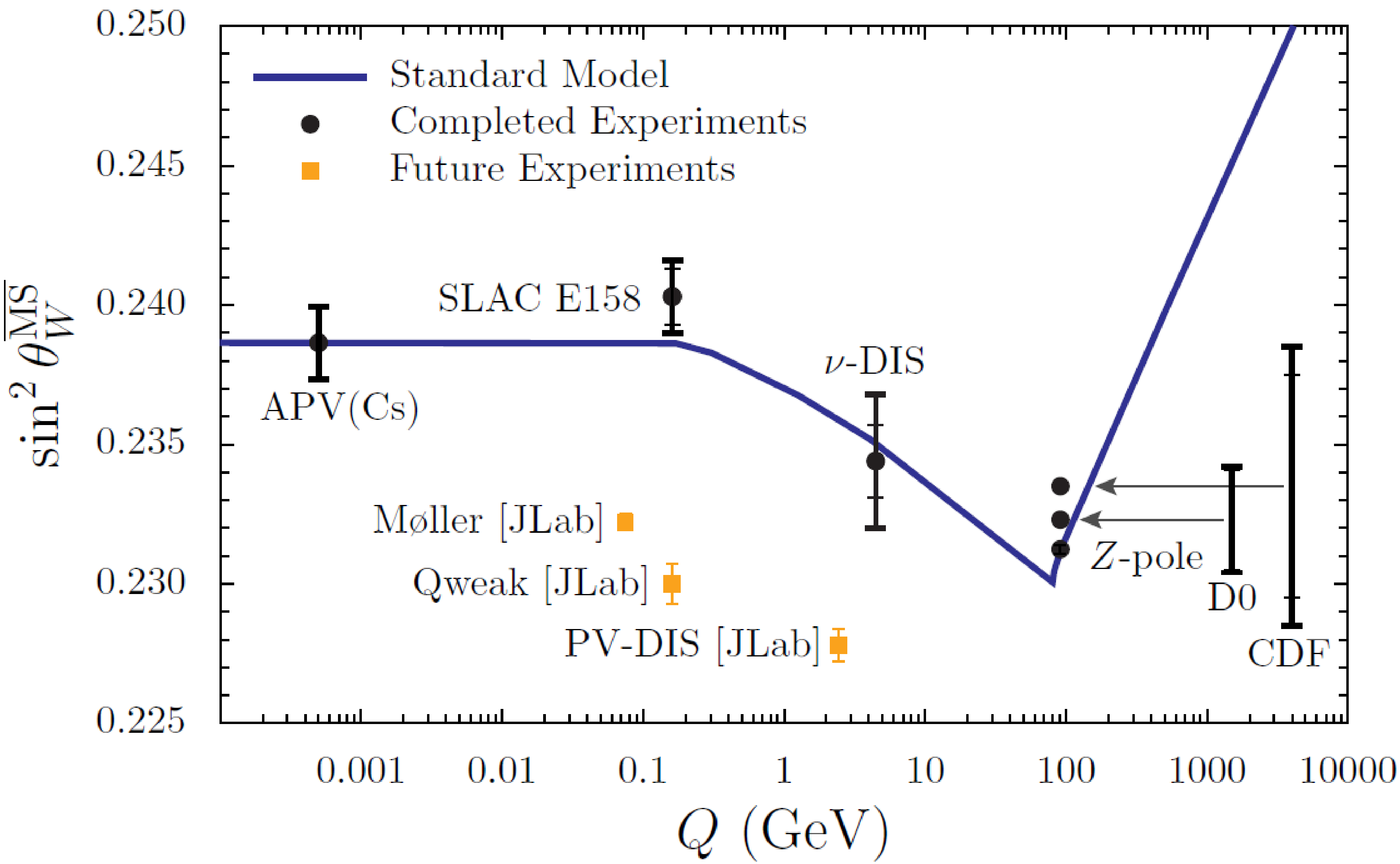
Davidson *et al*., hep-ph/0112302

Summary of Corrections to NuTeV Analysis

- **Isovector EMC effect:** $\Delta R^{\rho^0} = -0.0019 \pm 0.0006$
  - **using NuTeV functional**
- **CSV:** $\Delta R^{\rm CSV} = -0.0026 \pm 0.0011$
  - **again using NuTeV functional**
- **Strangeness:** $\Delta R^{s} = - 0.0011 \pm 0.0014$
  - **this is largest uncertainty (systematic error) ; desperate need for an accurate determination of $s^-(x)$, e.g. semi-inclusive DIS?**
- **Final result:** $\sin^2\theta_W = 0.2221 \pm 0.0013(\rm stat) \pm 0.0020(\rm syst)$
  - **c.f. Standard Model:** $\sin^2\theta_W = 0.2227 \pm 0.0004$

Bentz et al., Phys Lett B693 (2010) 462 (arXiv: 0908.3198)

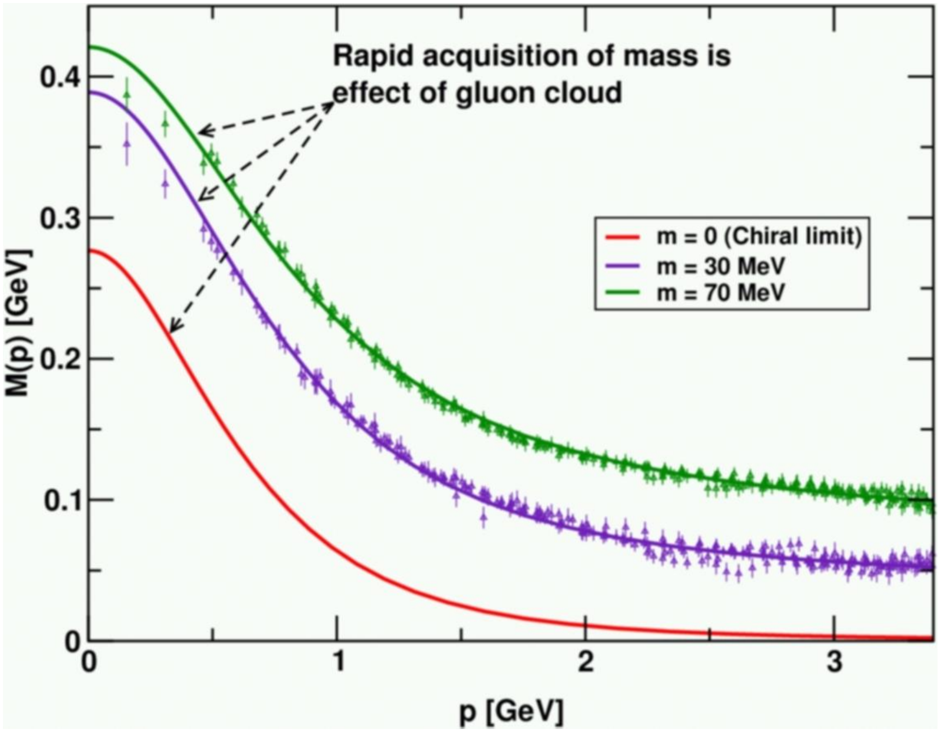
The Standard Model works… again



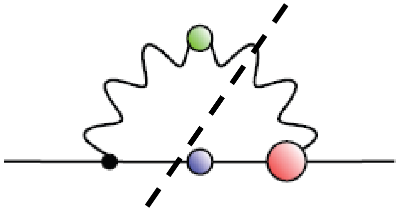
Bentz et al., Phys Lett B693 (2010) 462
(arXiv: 0908.3198)

Can we do better theoretically?

- **Apart from small symmetry breaking effects nothing in hadronic physics depends on current masses**



- **Rather we expect constituent-scale mass function M(0) ~ 400 MeV to be what enters – reduces initial photon distribution**



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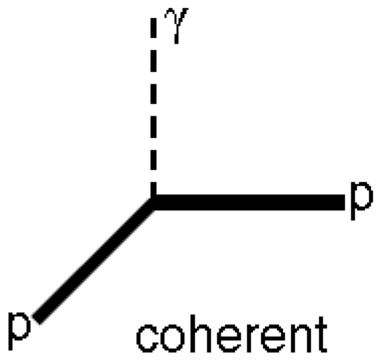
New approach

- **Martin and Ryskin (Eur. Phys. J. C (2014) 74, 3040)**

- **At low scale - of order M(0) – primary source of photon distribution is the coherent radiation from the proton and neutron as a whole**



$$\gamma^{p}_{\mathrm{coh}}\left(x, Q_0^2\right) = \frac{\alpha^{\mathrm{QED}}}{2\pi}\,\frac{[1+(1-x)^2]}{x} \times \int_0^{|t|<Q_0^2} \mathrm{d}q_t^2 \frac{q_t^2}{\left(q_t^2 + x^2 m_p^2\right)^2} F_1^2(t)$$

- **Natural choice for Q_0 is ~M(0), which is the typical model scale in quark model calculations of PDFs**

Include initial photon distribution in NJL model

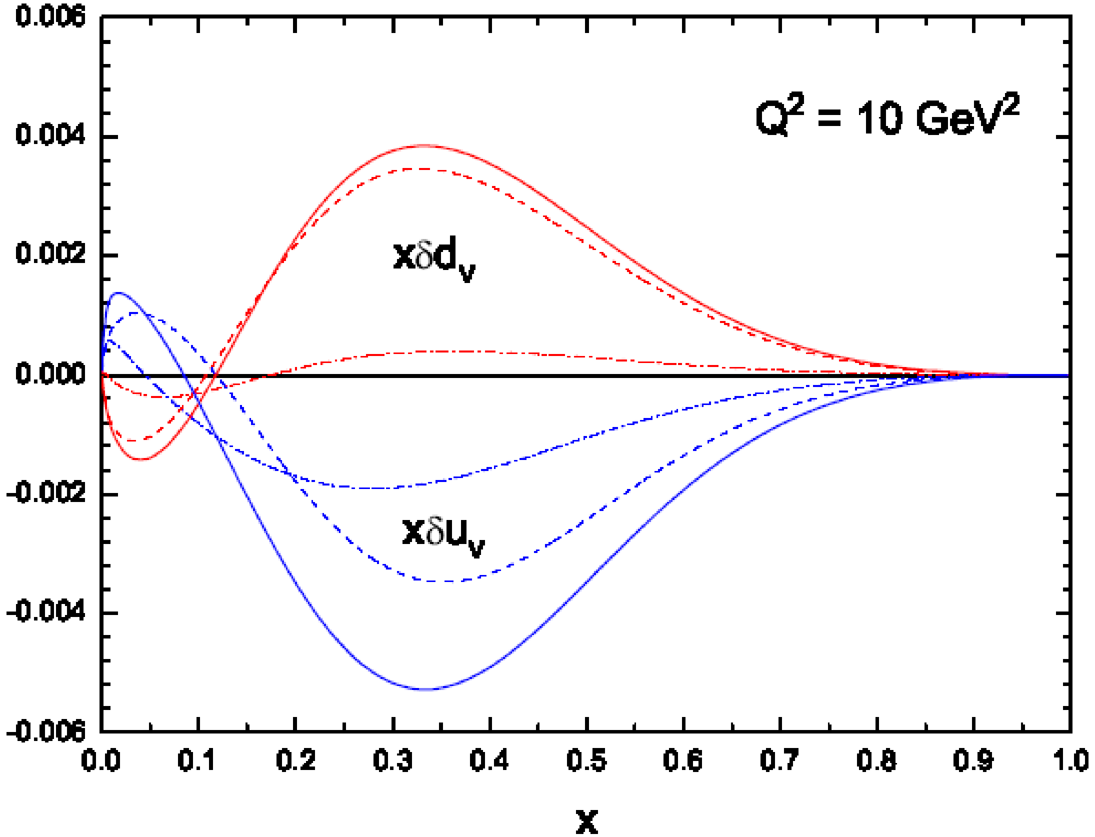


Figure 2: (colour online). The isospin-violating majority $x\delta u_v$ and minority $x\delta d_v$ valence parton distributions at $Q^2 = 4\ \mathrm{GeV}^2$ and $Q^2 = 10\ \mathrm{GeV}^2$. Dash-dotted, dashed and solid curves represent pure QED, pure QCD and total contributions, respectively.

Cloet, Thomas, Wang & Young – to appear

Mass differences plus e-m correction

	$Q^2 = 4\ \mathrm{GeV}^2$			$Q^2 = 10\ \mathrm{GeV}^2$		
	QED	QCD	QED+QCD	QED	QCD	QED+QCD
δU_v	-0.00072	-0.00132	-0.00204	-0.00078	-0.00121	-0.00199
δD_v	0.00005	0.00132	0.00137	0.00011	0.00121	0.00132

A little smaller e-m correction than earlier estimates BUT agrees within quoted errors......

Major open question is <x (s – sbar)>

- **Recent advances (to be published) mean:**

  This is definitely positive (also reduces NuTeV anomaly – more bad luck!) but theoretically almost certainly less than 0.0006

- **BUT experimental determination would be very valuable!**

Summary

- Charge symmetry violation is theoretically unavoidable
  For $m_u \neq m_d$ lattice QCD strongly supports phenomenology

- Confirmation of CSV prediction through lattice QCD reinforces insights into large-x behaviour of PDFs

- Experimental confirmation of CSV, including photon radiation?
  − ***ideal experiment for an EIC***

- Establishing iso-vector EMC effect (d_A / d much larger (~25%) than u_A /u in a nucleus like Pb or Au) would also drive a dramatic new picture of nuclear structure - c.f. Ian Cloet talk
  − ***ideal experiment for an EIC***

- These effects naturally resolve the NuTeV anomaly (within sizeable systematic errors)

We really need to pin down <x(s – sbar)> !

Recall: CSV confirmed reinforces insight into HiX Behaviour of PDFs

Δ – N mass splitting: S=1 "di-quark" mass is 0.2 GeV greater than S=0

SU(6) wave function for proton :

hit d-quark : ONLY S=1 left

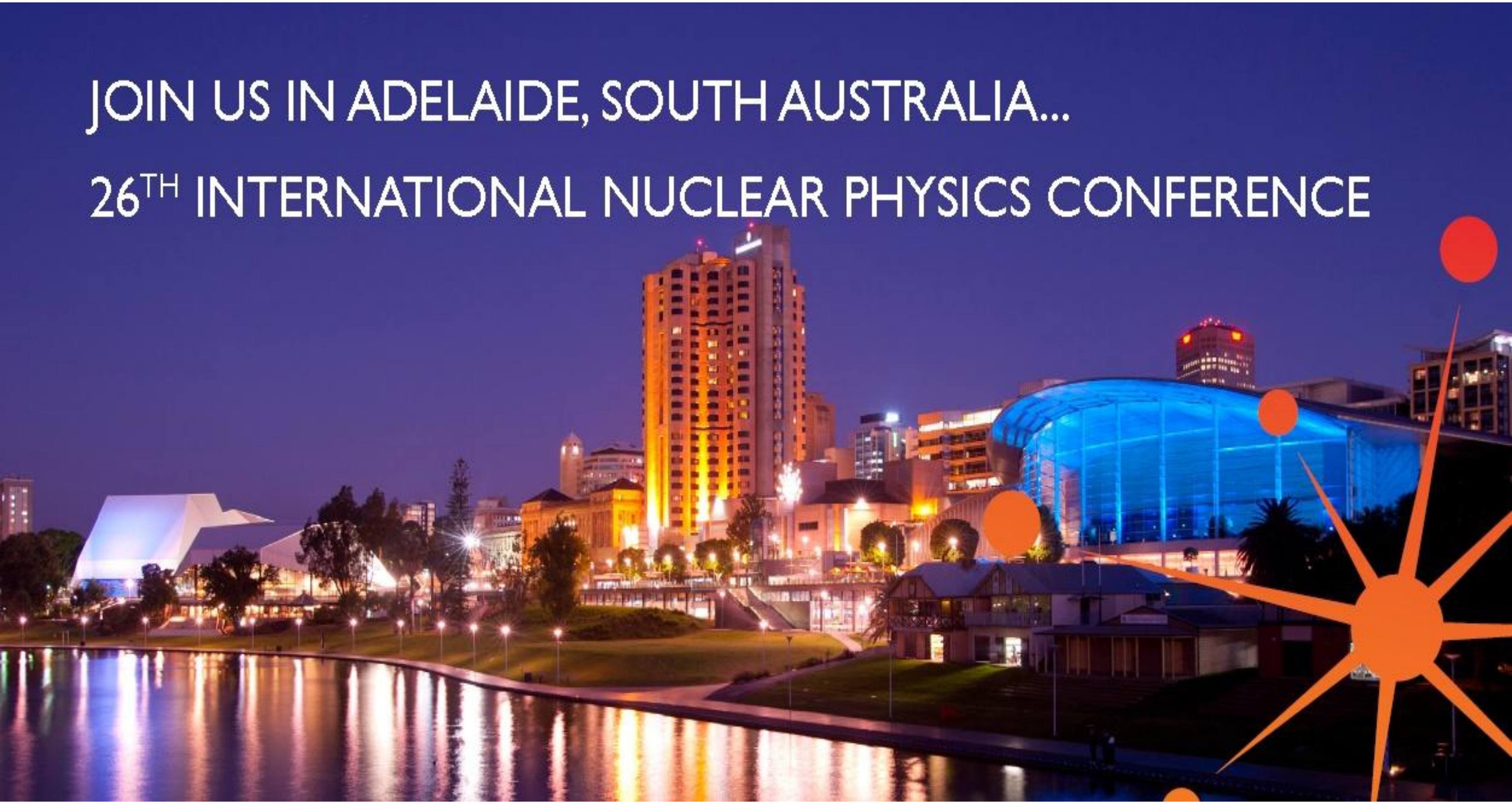
c.f. hit u-quark : 50% S=0 and 50% S=1

Hence*:

- $u(x)$ dominates over $d(x)$ for $x > 0.3$
- $u^{\uparrow}$ dominates over $u^{\downarrow}$ at large x
  and hence: $g^p_1(x) > 0$ at large x
- Similarly $g^n_1(x) > 0$ at large x

*Close & Thomas: 1988

INPC2016: Adelaide September 11-16, 2016



http://www.physics.adelaide.edu.au/cssm/workshops/inpc2016/

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Separate Neutrino and Anti-Neutrino Ratios

- **Biggest criticism of this explanation was that NuTeV actually measured R^{ν} and $R^{\bar{\nu}}$, separately:**
  Claim we should compare directly with these.

- **Have done this:**

$$\delta R^{\nu} = \frac{2\left(3\, g_{Lu}^2 + g_{Ru}^2\right)\langle x_A\, u_A^- - x_A\, d_A^-\rangle}{\langle 3\, x_A\, u_A + 3\, x_A\, d_A + x_A\, \bar{u}_A + x_A\, \bar{d}_A + 6\, x_A\, s_A\rangle}$$

$$\delta R^{\bar{\nu}} = \frac{-2\left(3\, g_{Rd}^2 + g_{Ld}^2\right)\langle x_A\, u_A^- - x_A\, d_A^-\rangle}{\langle x_A\, u_A + x_A\, d_A + 3\, x_A\, \bar{u}_A + 3\, x_A\, \bar{d}_A + 6\, x_A\, \bar{s}_A\rangle}$$

- **Then R^{ν} moves from 0.3916 ± 0.0013 c.f. 0.3950 in the Standard Model to 0.3933 ± 0.0015;**

  $R^{\bar{\nu}}$ **moves from 0.4050 ± 0.0027 to 0.4034 ± 0.0028, c.f. 0.4066 in SM**

- **This is tremendous improvement :**
  χ^2 changes from 7.2 to 2.6 for the two ratios!

Bentz et al., Phys Lett B693 (2010) 462
(arXiv: 0908.3198)

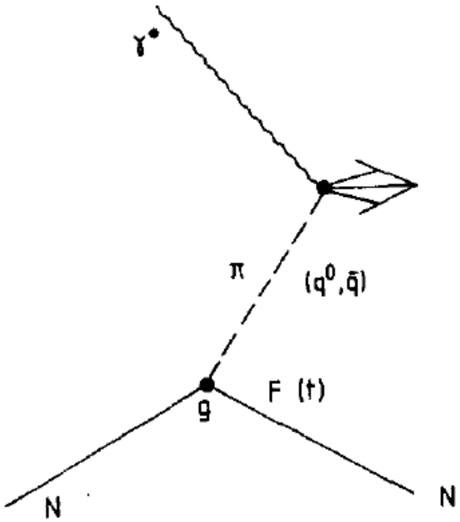
Asymmetries in the Sea:

– from Chiral Symmetry

Symmetry Breaking in the Nucleon Sea

- **Role of pion cloud in DIS first investigated by (Feynman) and Sullivan**
- **Generally ignored until:**

Volume 126B, number 1,2 (1983) PHYSICS LETTERS



A LIMIT ON THE PIONIC COMPONENT OF THE NUCLEON THROUGH SU(3) FLAVOUR BREAKING IN THE SEA

A.W. THOMAS
CERN, Geneva, Switzerland

Dominant role of π^+ for proton predicts violation of Gottfried sum-rule

"Clearly the pion exchange process of fig. 1 does predict that the excess of $\bar{D}$ to $\bar{U}$ should be in the ratio 5 to 1 in the proton."

Pion Cloud (cont.)

- It only makes sense to consider this as a separate process *provided there is a significant rapidity gap*

- Often forgotten later when investigators added ρ and heavier mesons

- Probably πΔ Fock component makes sense but nothing much heavier

- Predicted violation of Gottfried sum-rule not confirmed for 10 years

Gottfried Sum Rule: NMC 1994: $S_G = 0.258 \pm 0.017 \; [Q^2 = 4\,\mathrm{GeV}^2]$

$$S_G = \int_0^1 \frac{dx}{x}\left[F_{2p}(x) - F_{2n}(x)\right] = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,\left[\bar{d}(x) - \bar{u}(x)\right]$$

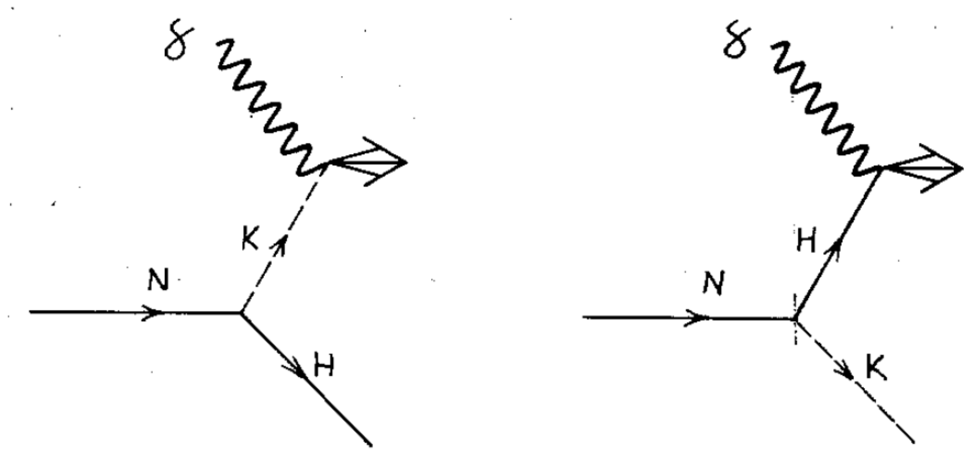
- Consistent with range predicted by the pion cloud....

$$\int_0^1 dx\,[\,\bar{d} - \bar{u}\,] = 2\,P_{N\pi}/3 - P_{\Delta\pi}/3$$

ε 0.11 – 0.15

Strange Sea of the Nucleon

Similar mechanism for kaons implies $s - \bar{s}$ goes through zero for x of order 0.10



- **Later, naive 5-quark additions often (implicitly) violate parity**

- **This predicted asymmetry in the strange sea has *STILL* not been measured experimentally....**

− but it *does* matter!

Signal and Thomas, Phys. Lett. 191B (1987) 205

Dependence of s- $\bar{s}$ on assumed cross-over

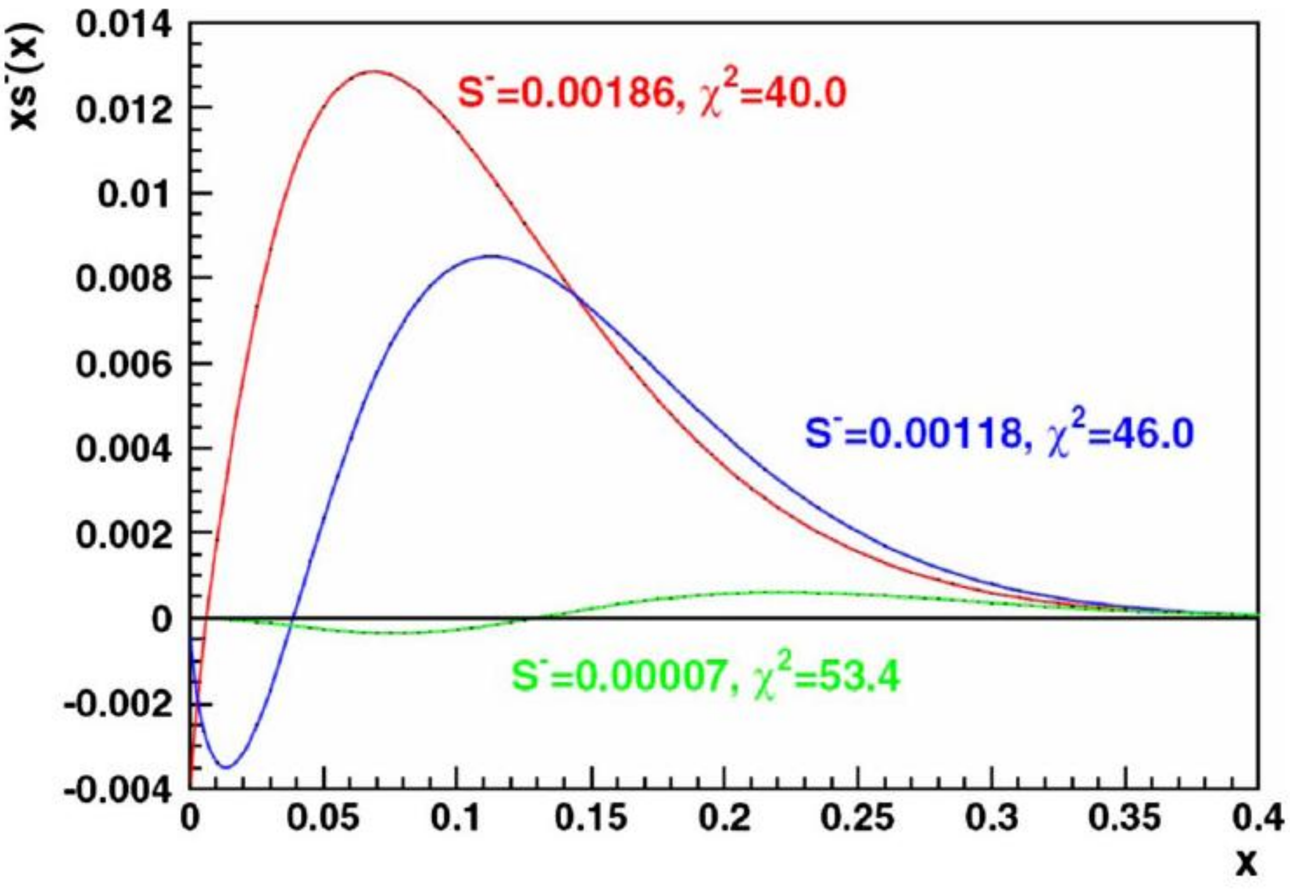


FIG. 16. (Color online) The quantity $xs^{-}(x) = x[s(x) - \bar{s}(x)]$ vs x, as extracted by the NuTeV Collaboration. Three different results are shown, corresponding to different values of the zero-crossing point. The χ^2 value is listed for each curve. From Mason *et al.*, 2007.

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VOLUME 85, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 2000

Dynamical Symmetry Breaking in the Sea of the Nucleon

A. W. Thomas,[1] W. Melnitchouk,[1,2] and F. M. Steffens[3]

$$(S - \bar{S})^{(n)} = \int_0^1 dx\, x^n [s(x) - \bar{s}(x)] = V_\Lambda^{(n)} \cdot f_{\Lambda K}^{(n)} - V_K^{(n)} \cdot f_{K\Lambda}^{(n)}$$

$$f_{K\Lambda}^{(n)}|_{\mathrm{LNA}} = \frac{27}{25} \frac{M^2 g_A^2}{(4\pi f_\pi)^2} (M_\Lambda - M)^2 (-1)^n \frac{m_K^{2n+2}}{\Delta M^{2n+4}} \log(m_K^2/\mu^2),$$

nth moment of $\bar{s}$ is of order $m_K^{2n+2} \log m_K^2$

LNA contribution to the nth moment of s is of order $m_K^2 \log m_K^2$

- **i.e. non-analytic behaviour of s and $\bar{\text{s}}$ are different and therefore s – $\bar{\text{s}}$ has to be non-zero *as a matter of principle*!**