Inclusive and Semi-Inclusive Spin Physics with
High Luminosity and Large Acceptance at 11 GeV
JLab, Dec.13-14, 2006

d/u ratio at large x with PVDIS

Wally Melnitchouk
Jefferson Lab

Outline

- how important is it to know d/u , anyway?

- review of d/u predictions

- how does PVDIS d/u extraction compare with other methods?

  $\longrightarrow$ *e.g.* BONUS , $^3He/^3H$, pp ($\rightarrow$ Christian Weiss)

- issues in PVDIS d/u extraction

  $\longrightarrow$ target mass corrections, higher twists ($\rightarrow$ Michael Ramsey-Musolf)

  $\longrightarrow$ charge symmetry violation ($\rightarrow$ Tim Londergan)

  $\longrightarrow$ heavy quarks

Why are PDFs at large x important?

- basic information on structure of bound states in QCD
  $\longrightarrow$ more direct connection with hadron structure models

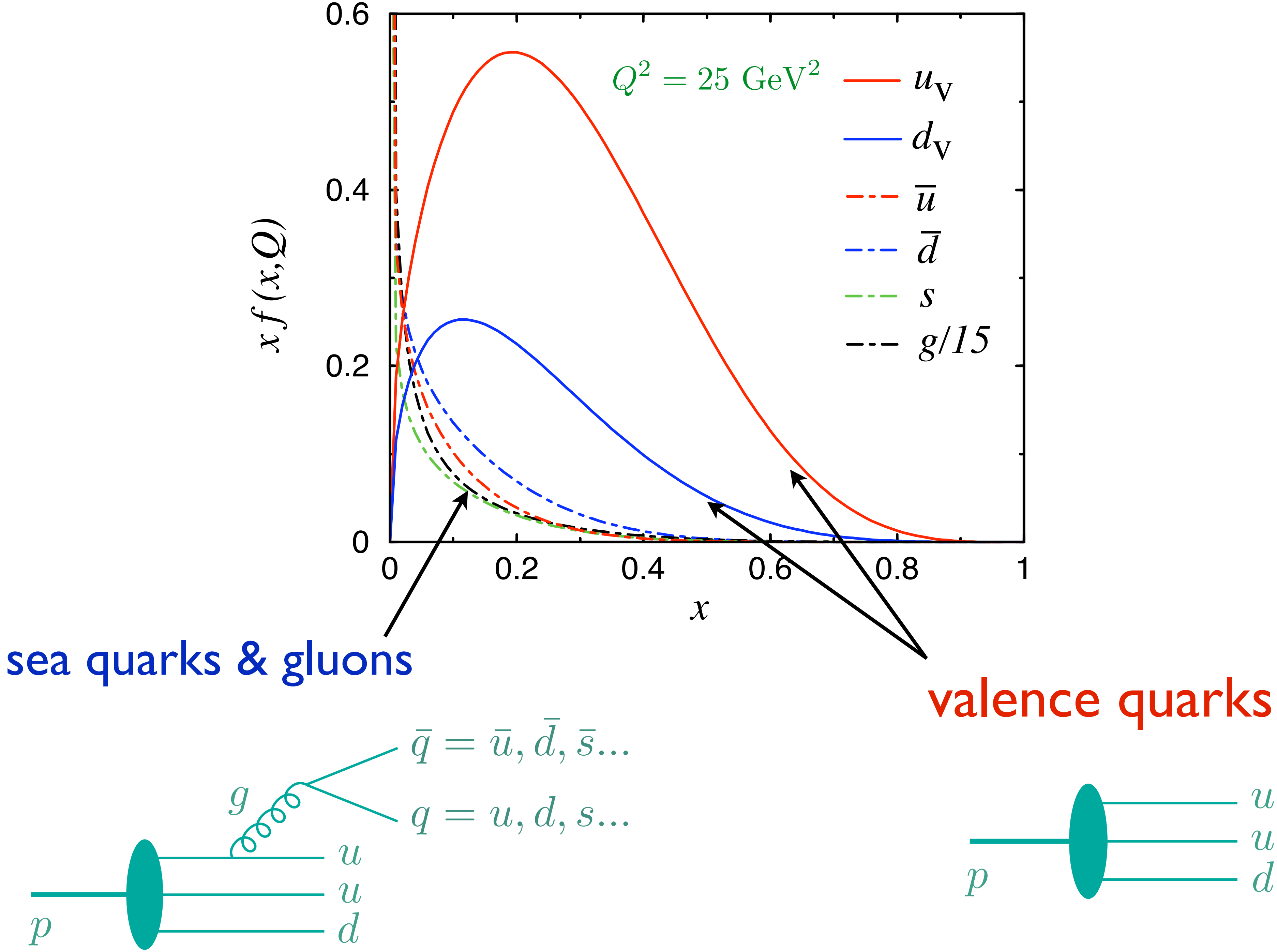
- clean connection with QCD, via lattice moments

- $x \sim 1$ region amenable to pQCD analysis

- backgrounds in high-energy collider searches for physics beyond the Standard Model
  $\longrightarrow$ evolution: high x at low Q^2 $\longleftrightarrow$ low x at high Q^2
  $\longrightarrow$ small uncertainties amplified
  $\longrightarrow$ HERA "anomaly" (1998), NuTeV "anomaly" (2002)
  $\longrightarrow$ neutrino oscillations

- input into nuclear physics & astrophysics calculations

d/u at large x



$Q^2 = 25\ \mathrm{GeV}^2$
u_V
d_V
$\overline{u}$
$\overline{d}$
s
$g/15$
$x\,f(x,Q)$
x
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
sea quarks & gluons
valence quarks
$\bar{q} = \bar{u}, \bar{d}, \bar{s}\ldots$
$q = u, d, s\ldots$
g
u
u
d
p
u
u
d
p

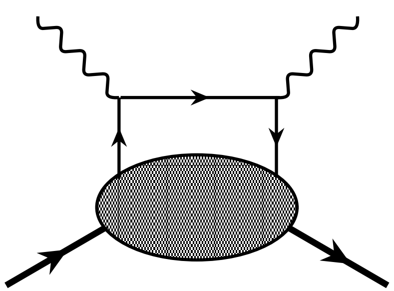
d/u predictions

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavour symmetry

proton wave function

$$p^{\uparrow} = -\frac{1}{3} d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6} u^{\uparrow}(ud)_1 - \frac{1}{3} u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0$$



interacting quark

spectator diquark

diquark spin

d/u predictions

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavour symmetry

proton wave function

$$p^\uparrow = -\frac{1}{3}d^\uparrow(uu)_1 - \frac{\sqrt{2}}{3}d^\downarrow(uu)_1 + \frac{\sqrt{2}}{6}u^\uparrow(ud)_1 - \frac{1}{3}u^\downarrow(ud)_1 + \frac{1}{\sqrt{2}}u^\uparrow(ud)_0$$

$\longrightarrow$ $u(x) = 2\ d(x)$ for all x

$\longrightarrow$ $\frac{F_2^n}{F_2^p} = \frac{2}{3}$

d/u predictions

- scalar diquark dominance

$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1$ has larger energy than $(qq)_0$

$\Longrightarrow$ scalar diquark dominant in $x \to 1$ limit

since only u quarks couple to scalar diquarks

$$\longrightarrow \quad \frac{d}{u} \to 0$$

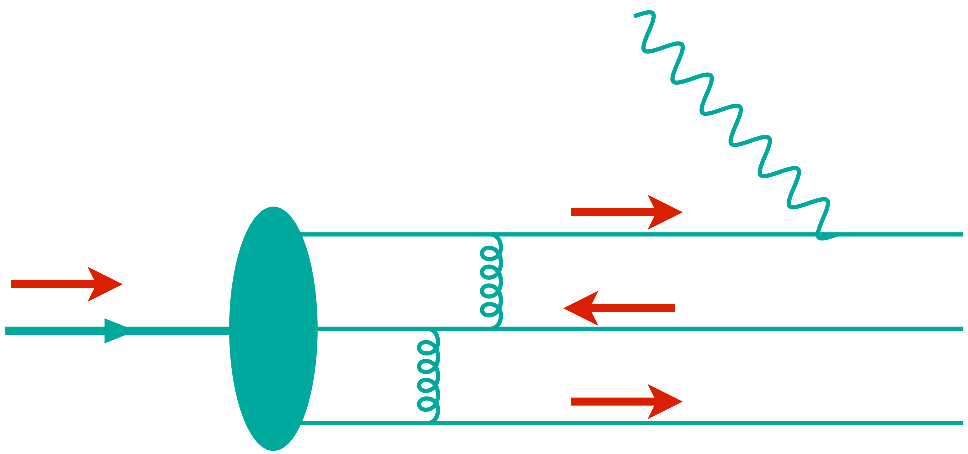
$$\longrightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

Feynman 1972, Close 1973, Close/Thomas 1988

d/u predictions

- hard gluon exchange

at large x, helicity of struck quark = helicity of hadron



$q^{\uparrow} \gg q^{\downarrow}$

$\Longrightarrow$ helicity-zero diquark dominant in $x \to 1$ limit

$\longrightarrow$ $\frac{d}{u} \to \frac{1}{5}$

$\longrightarrow$ $\frac{F_2^n}{F_2^p} \to \frac{3}{7}$

Farrar, Jackson 1975

d/u extraction

- At large x, valence u and d distributions extracted from p and n structure functions

$$F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v$$

$$F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v$$

- u quark distribution well determined from p

- d quark distribution requires n structure function

$$\Longrightarrow \quad \frac{d}{u} \approx \frac{4 - F_2^n/F_2^p}{4F_2^n/F_2^p - 1}$$

d/u extraction

- BUT no free neutron targets!
  (neutron half-life ~ 12 mins)

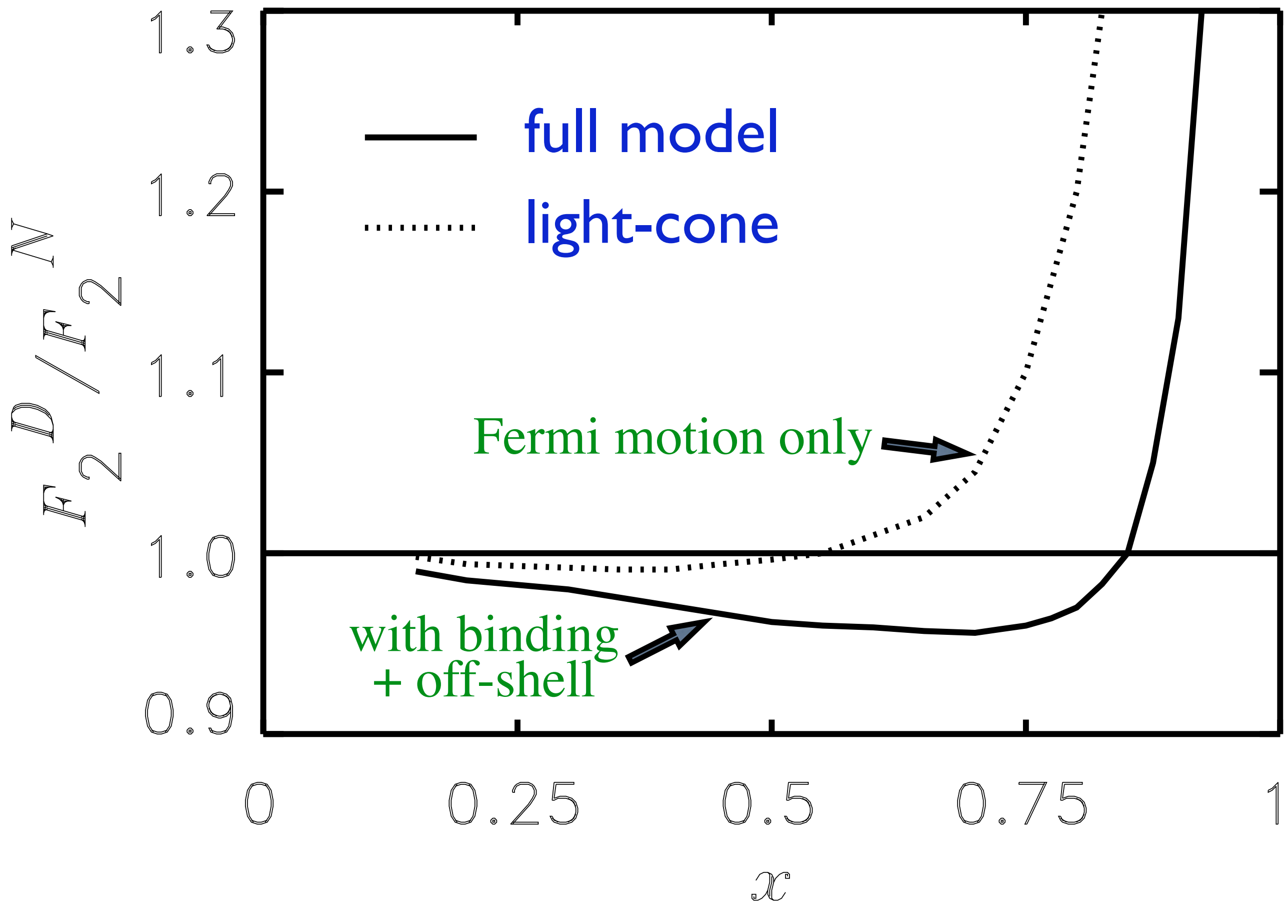
  → use deuteron as "effective neutron target"

- However: deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

  → nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  → "nuclear EMC effect"

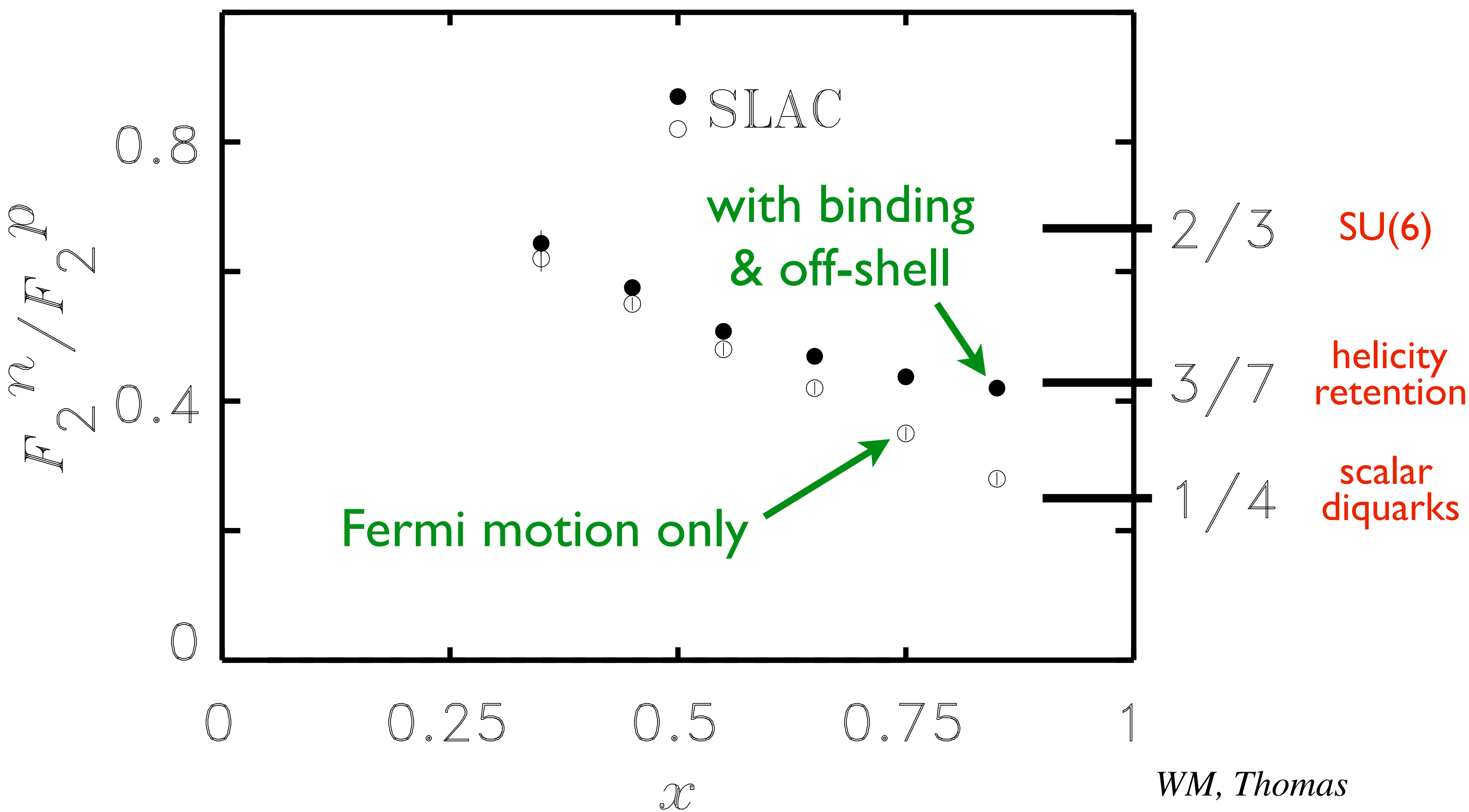
d/u extraction



Larger EMC effect (smaller d/N ratio)

→ F_2^n <u>underestimated</u> at large x

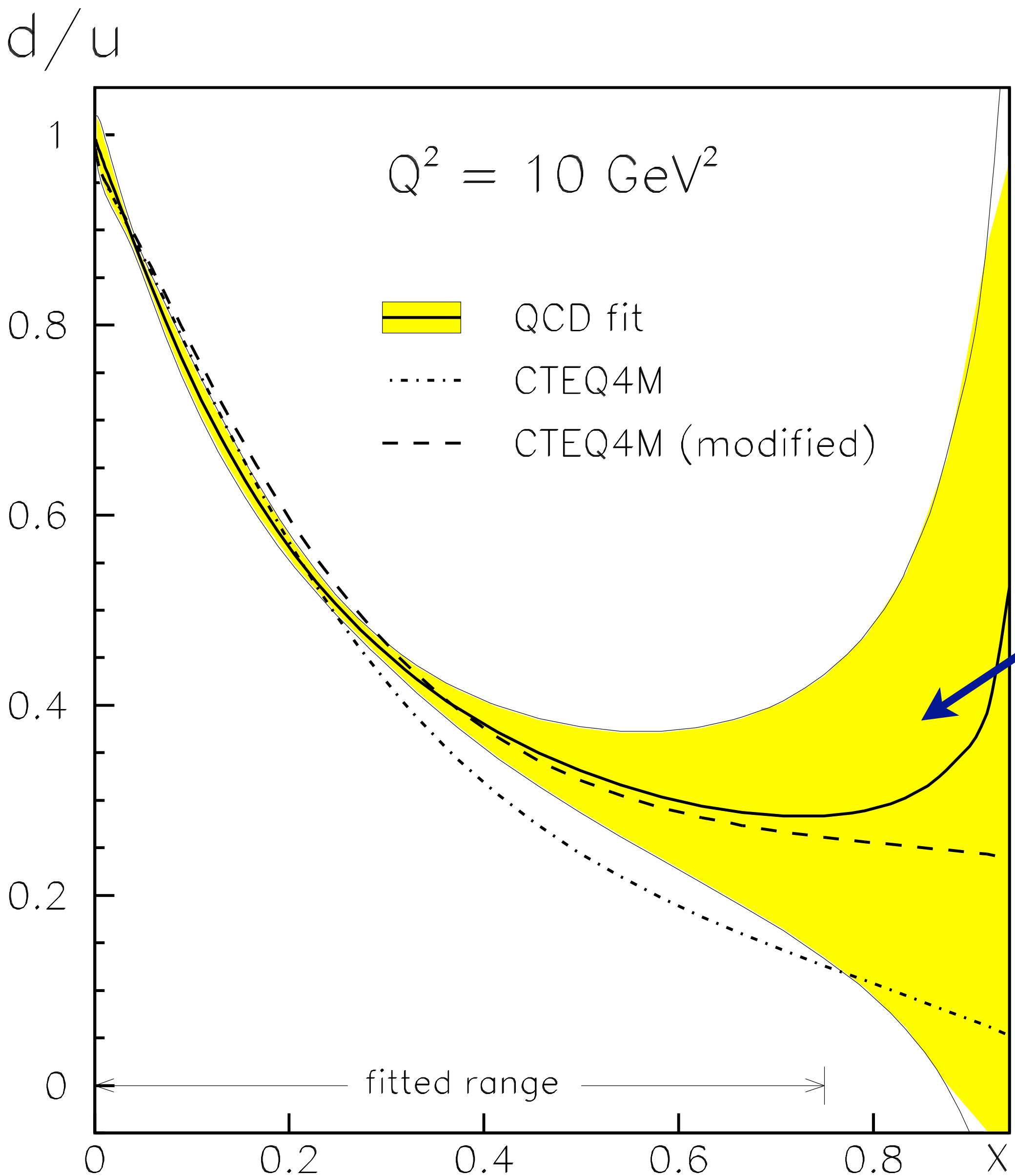
d/u extraction



WM, Thomas
Phys. Lett. B 377 (1996) 11

→ without EMC effect in d, F_2^n underestimated at large x

d/u extraction



uncertainty due to nuclear effects in neutron
(full range of nuclear models)

→ d distribution poorly known beyond $x \sim 0.5$

Diquarks as Inspiration and as Objects

Frank Wilczek*

September 17, 2004

hep-ph/0409168

One of the oldest observations in deep inelastic scattering is that the ratio of neutron to proton structure functions approaches $\frac{1}{4}$ in the limit $x \to 1$

$$\lim_{x\to 1} \frac{F_2^n(x)}{F_2^p(x)} \to \frac{1}{4} \tag{1.1}$$

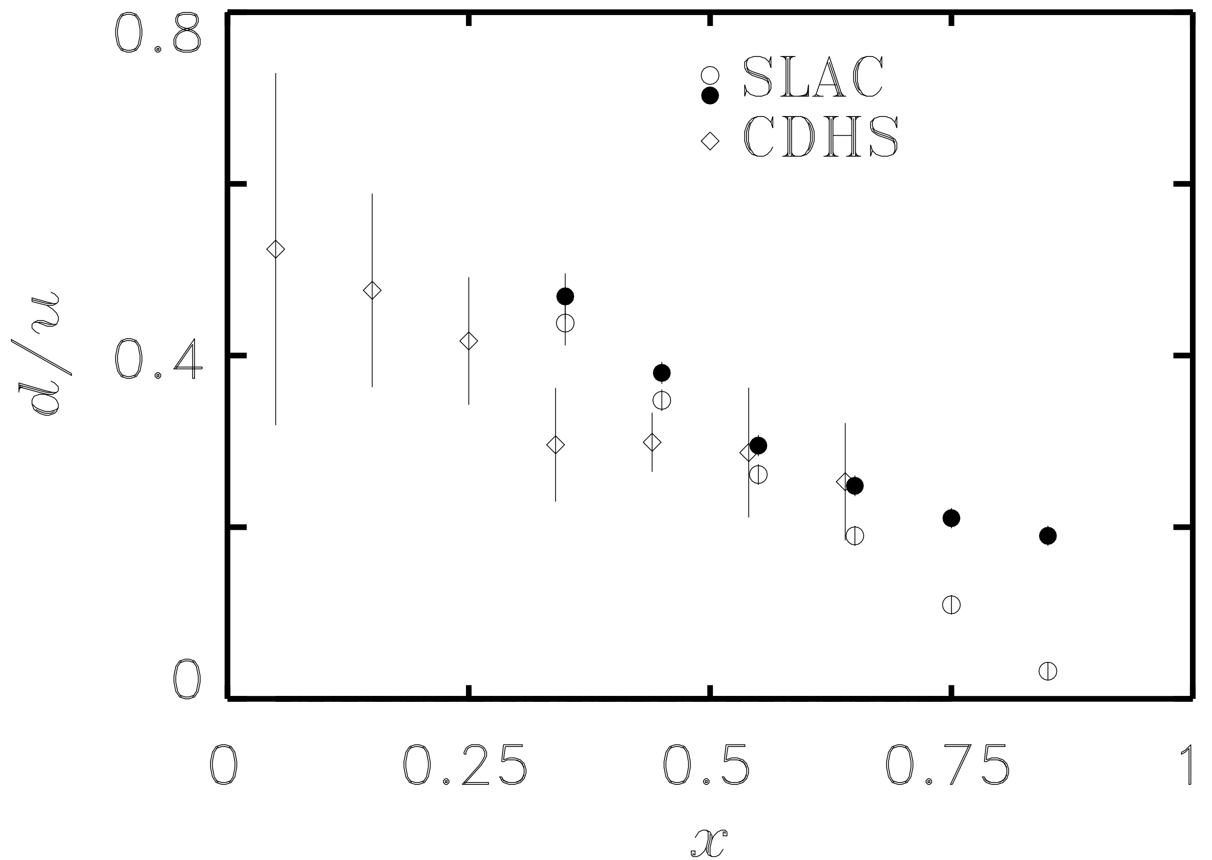
Folklore that experiment gives 1/4 limiting ratio...

Alternative extraction methods

Survey of methods to determine d/u

$e^{\mp}\ p \rightarrow \nu(\bar{\nu})X$ low event rates

$\nu(\bar{\nu})\ p \rightarrow l^{\mp}\ X$ low statistics at large x



$$F_2^{\nu p} = 2x\ (d + \bar{u}) \qquad xF_3^{\nu p} = x\ (d - \bar{u})$$

$$F_2^{\bar{\nu} p} = 2x\ (u + \bar{d}) \qquad xF_3^{\bar{\nu} p} = x\ (u - \bar{d})$$

Survey of methods to determine d/u

$e^{\mp}\ p \to \nu(\bar{\nu})X$ low event rates

$\nu(\bar{\nu})\ p \to l^{\mp}\ X$ low statistics at large x

$p\ p(\bar{p}) \to W^{\pm}X$ large lepton rapidity

$e\ p \to e\ \pi^{\pm}\ X$ $z \sim 1$, factorization

At large x $(x > 0.4 - 0.5)$, $\bar{q}(x) \approx 0$

$$\rightarrow \quad \sigma_p^{\pi^+} \sim 4\, u(x)\, D(z) \; + \; d(x)\, \bar{D}(z)$$

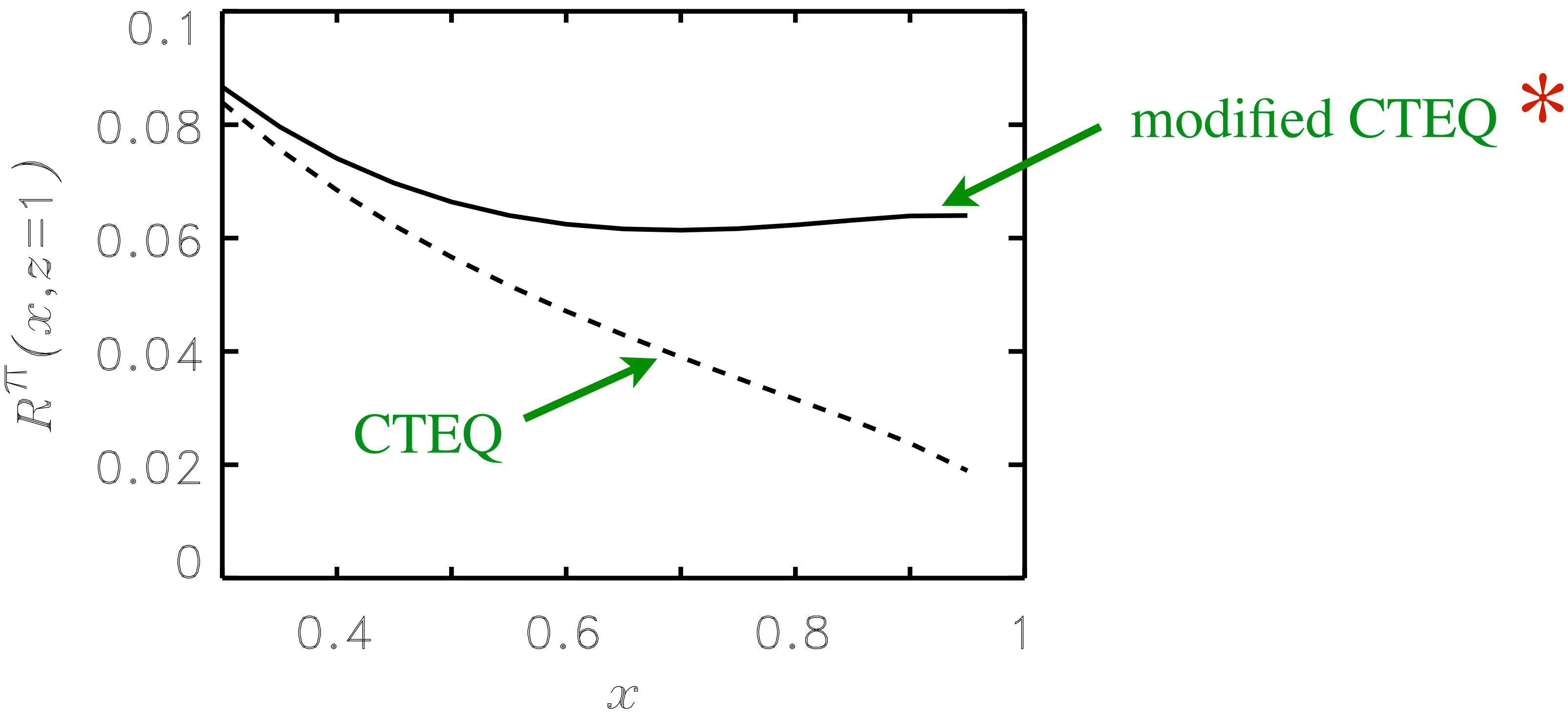
$$\sigma_p^{\pi^-} \sim 4\, u(x)\, \bar{D}(z) \; + \; d(x)\, D(z)$$

Ratio

$$R^\pi(x,z) = \frac{\sigma_p^{\pi^-}}{\sigma_p^{\pi^+}} = \frac{4\bar{D}(z)/D(z) + d(x)/u(x)}{4 + d(x)/u(x) \cdot \bar{D}(z)/D(z)}$$

$$\rightarrow \frac{1}{4}\frac{d(x)}{u(x)} \quad \text{in } z \rightarrow 1 \text{ limit}$$

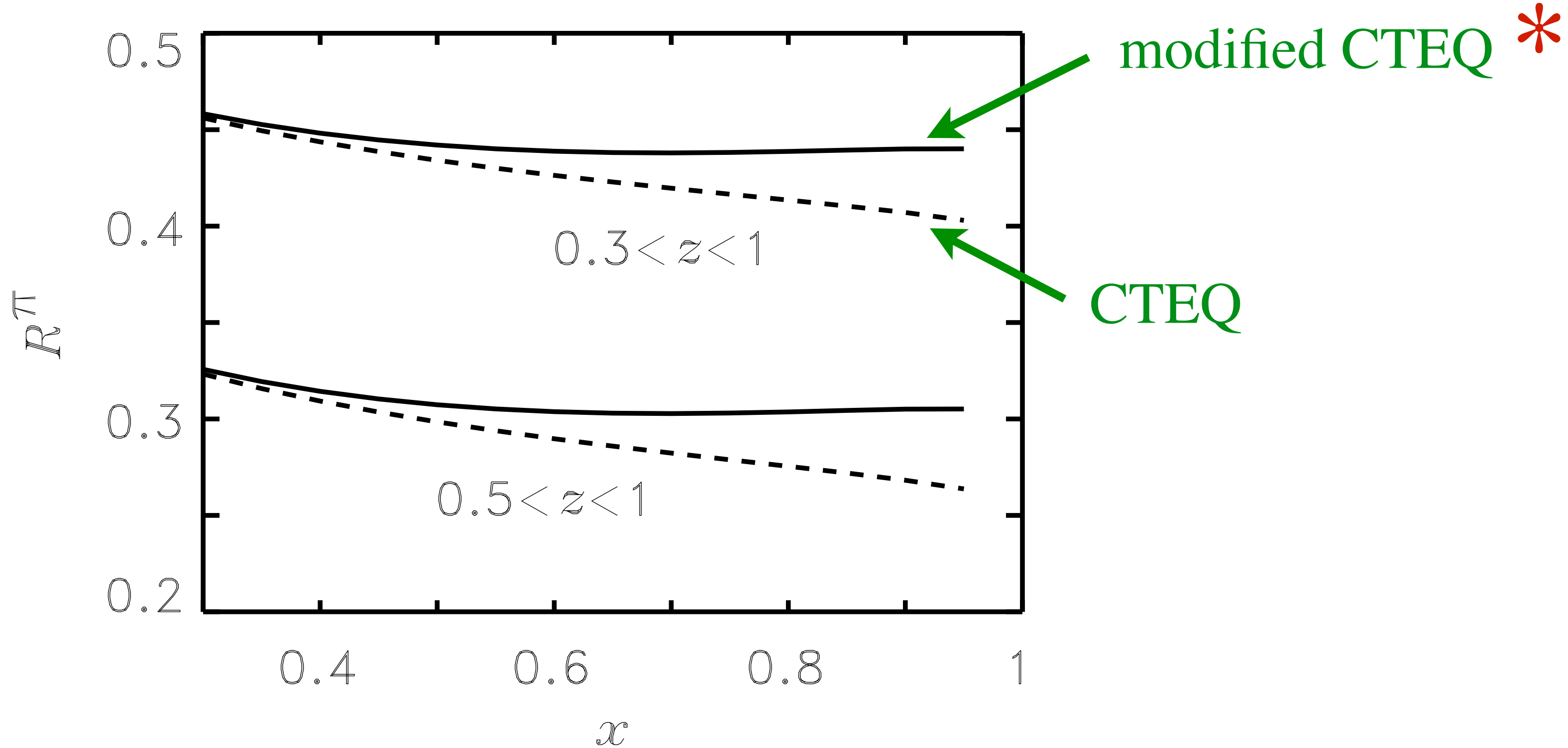
Semi-inclusive ratio at $z = 1$



$$* \quad \frac{d}{u} \rightarrow \frac{d}{u} + \Delta$$

$$\Delta = 0.2\ x^2 e^{-(1-x)^2}$$

Semi-inclusive ratio at $z < 1$



* $$\frac{d}{u} \to \frac{d}{u} + \Delta$$

$$\Delta = 0.2\ x^2 e^{-(1-x)^2}$$

Combine with "neutron" (deuteron) target

$\longrightarrow$ eliminate dependence on fragmentation function

$$\sigma_{\tilde{n}}^{\pi^+} \sim 4\ (\tilde{d}(x) + \epsilon_u(x))\ D(z)\ +\ (\tilde{u}(x) + \epsilon_d(x))\ \bar{D}(z)$$

$$\sigma_{\tilde{n}}^{\pi^-} \sim 4\ (\tilde{d}(x) + \epsilon_u(x))\ \bar{D}(z)\ +\ (\tilde{u}(x) + \epsilon_d(x))\ D(z)$$

smeared quark distribution in nucleon bound in d

$$\tilde{q}(x) = \int \frac{dy}{y}\ f_{N/d}(y)\ q(x/y)$$

$$\epsilon_q(x) = \tilde{q}(x) - q(x)$$

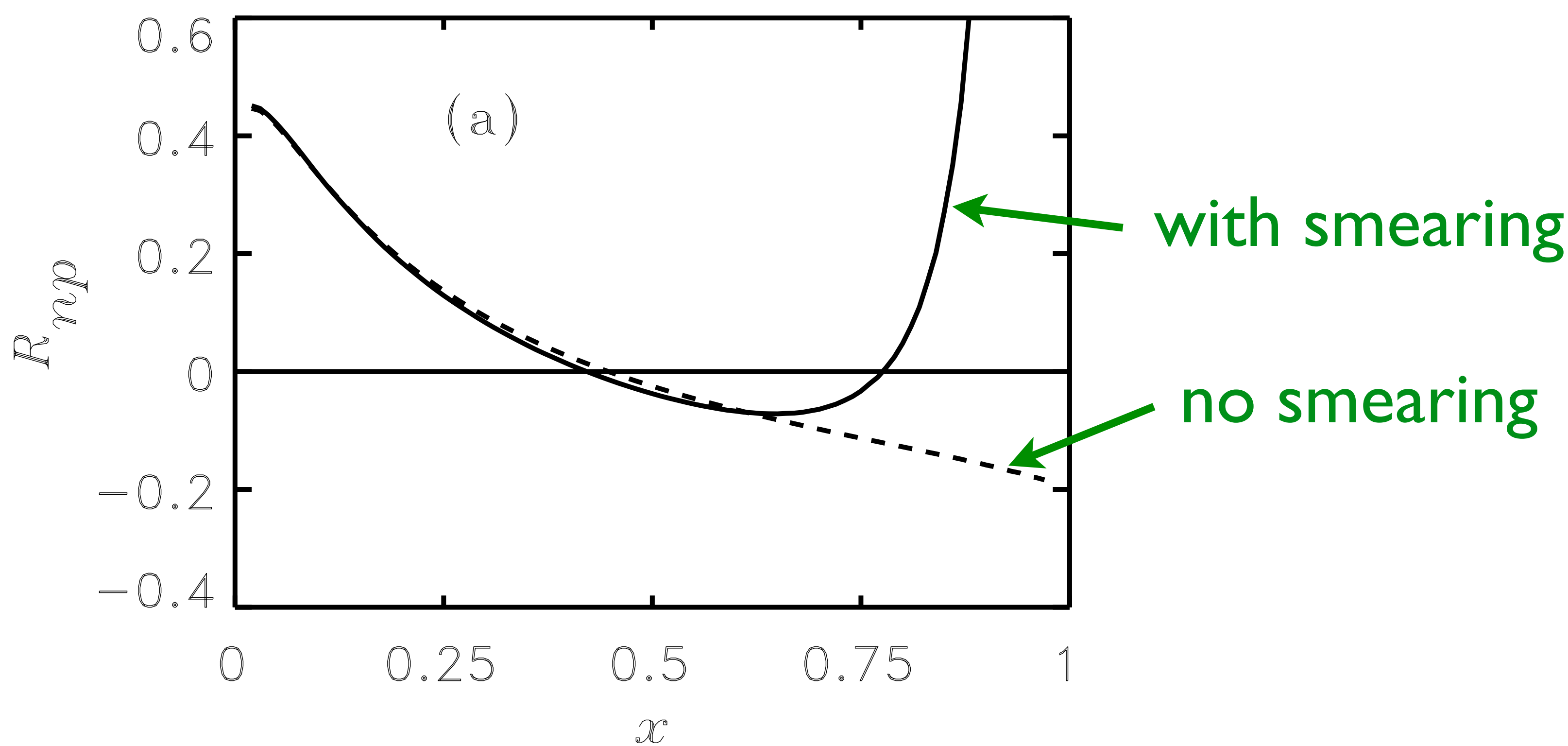
Ratio independent of fragmentation function

$$\rightarrow \quad R_{np} = \frac{\sigma_{\tilde{n}}^{\pi^+} - \sigma_{\tilde{n}}^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} = \frac{4\tilde{d}(x) - \tilde{u}(x) + 4\epsilon_u(x) - \epsilon_d(x)}{4u(x) - d(x)}$$

If no nuclear corrections

$$\tilde{q}(x) = q(x)$$

$$\rightarrow \quad R_{np} = \frac{4d(x)/u(x) - 1}{4 - d(x)/d(x)}$$



Survey of methods to determine d/u

$e^{\mp}\ p \to \nu(\bar{\nu})X$	low event rates
$\nu(\bar{\nu})\ p \to l^{\mp}\ X$	low statistics at large x
$p\ p(\bar{p}) \to W^{\pm}X$	large lepton rapidity
$e\ p \to e\ \pi^{\pm}\ X$	$z \sim 1$, factorization
$e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$	tritium target

A=3 mirror nuclei

EMC ratios in ^{3}He and ^{3}H:

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

Ratio of EMC ratios:

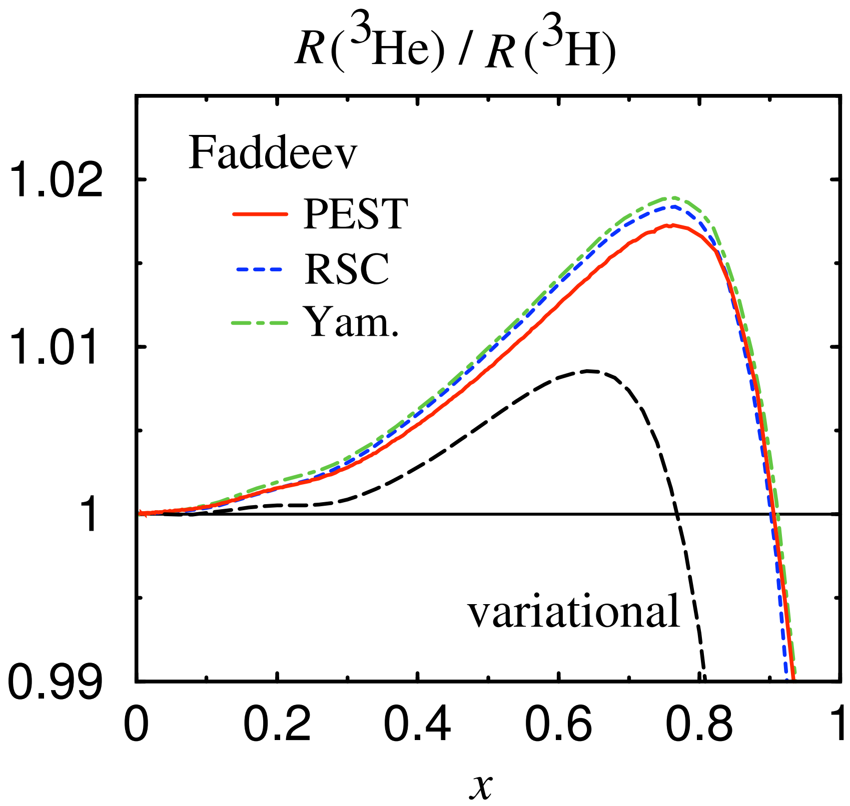
$$\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$$

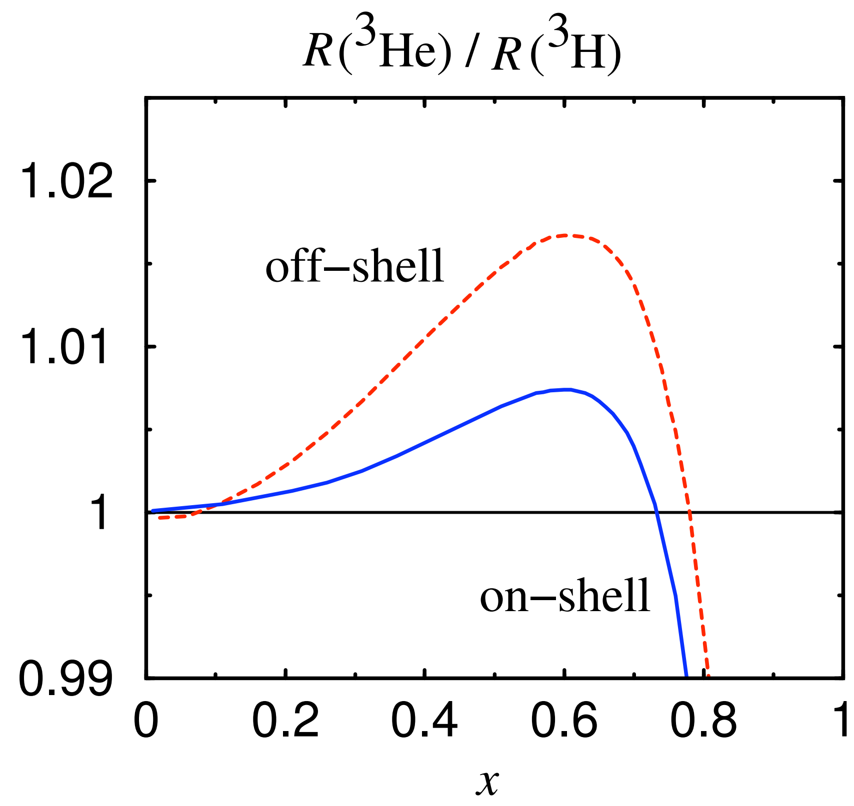
Neutron/proton ratio:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

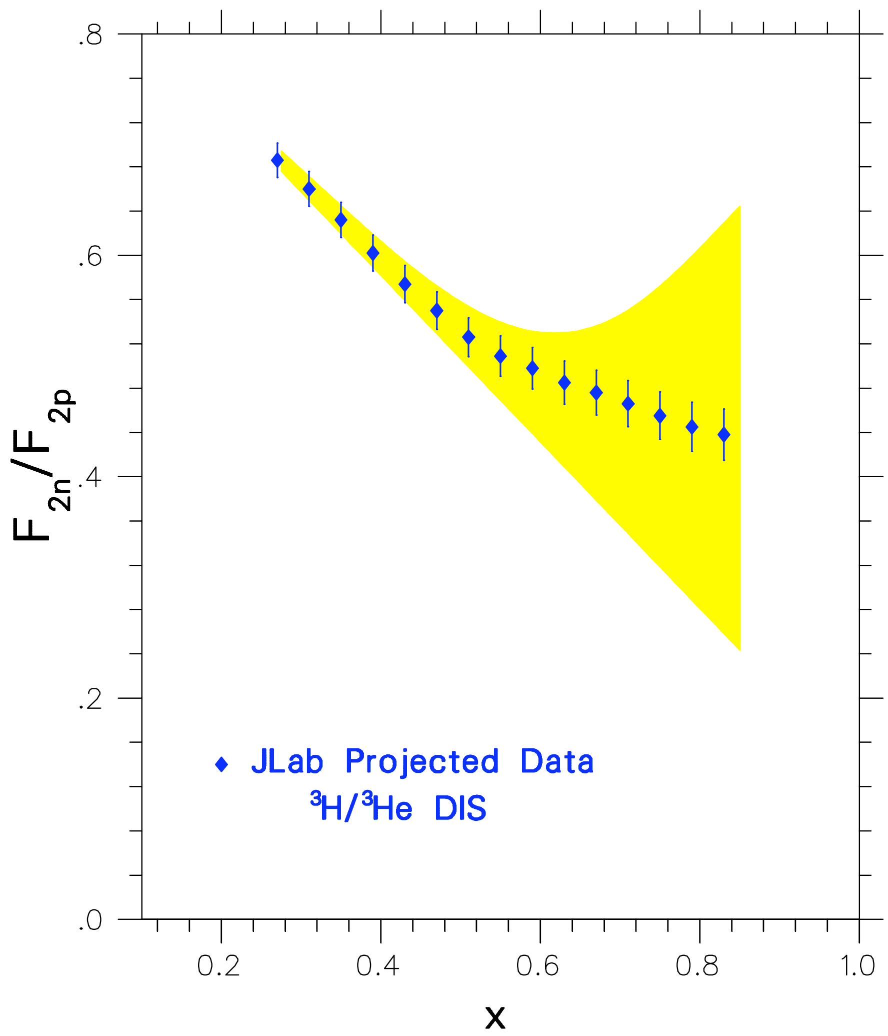
A=3 mirror nuclei

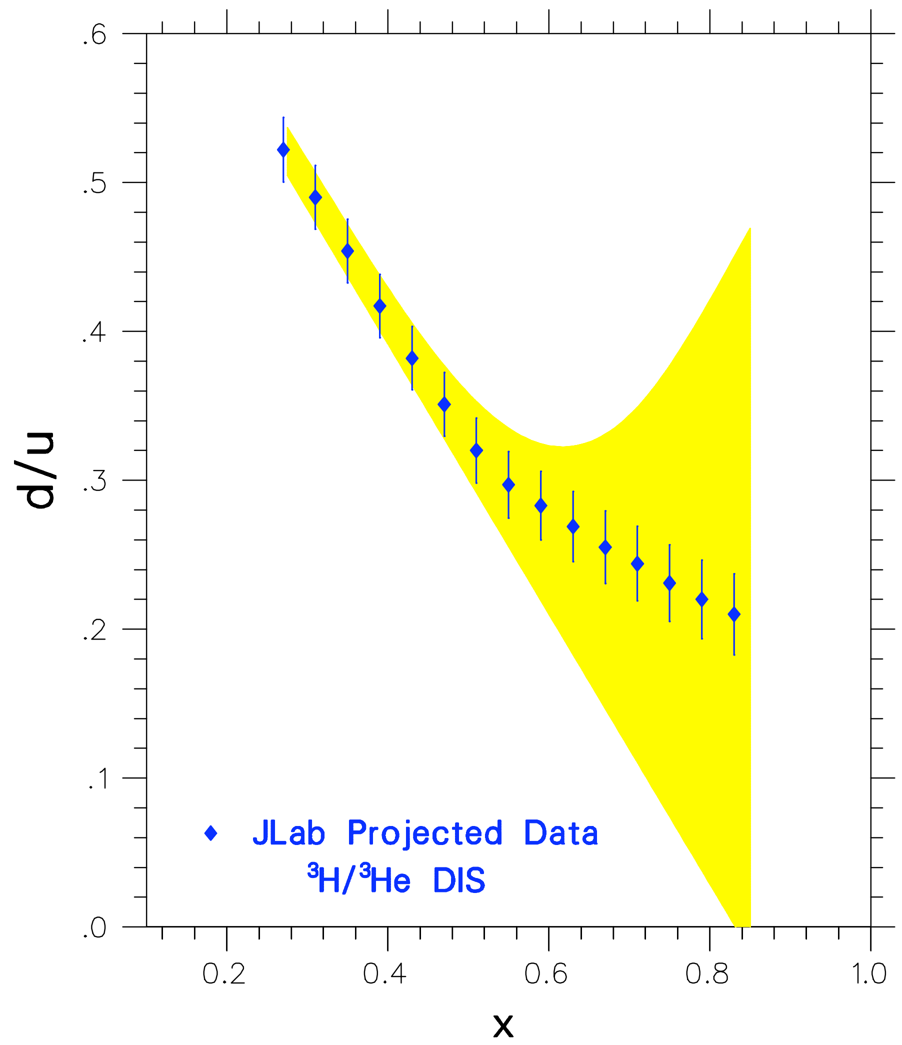
Nuclear effects mostly cancel in ratio of ratios





A=3 mirror nuclei





Proposal: PR12-06-118

Title: Measurement of F_2^n/F_2^p, d/u Ratios and A=3 EMC Effect in Deep Inelastic Scattering off the Tritium and Helium Mirror Nuclei

Spokesperson: G. Petratos

Motivation: The experiment addresses important physics issues. The EMC effect, F_2^n/F_2^p, and d/u will be studied with 1% accuracy up to x=.83 in the mass-3 system where the nuclear wave functions are well known. At high x, the d/u will be determined for valence quarks. Model calculations using different nucleon-nucleon interactions and different nucleon structure functions demonstrate that F_2^n/F_2^p can be extracted with a systematic uncertainty of .02. Because the two targets are measured in one set up, many experimental uncertainties cancel out.

Measurement and Feasibility: Based on the wealth of experience with this kind of experiments in Hall A, the experiment appears feasible**.**

Issues: The PAC is aware that Tritium safety is a major issue for Lab. Management. However, given the experience with a tritium target in experiments with electron beams at Saclay and MIT/Bates the safety issue might be solved. A special JLab. Management review of the safety aspects of the Tritium target is the condition for approval.
At this point it is important to stress that the PAC considers the physics goals of this experiment as highlights of the 12GeV physics program. Part of the program – the u/d ratio- will probably be investigated by PR12-06-113 that has been conditionally approved. Given the importance of the physics issues and the unique position of JLab. to address those questions the PAC would like to see both experiments to be done. The methods are completely different and, thus, provide the necessary cross check of the results. This PAC is convinced that this proposal alone justifies the effort to implement the Tritium target.

Recommendation: Conditional approval

Survey of methods to determine d/u

$e^{\mp}\ p \to \nu(\bar{\nu}) X$ — low event rates

$\nu(\bar{\nu})\ p \to l^{\mp}\ X$ — low statistics at large x

$p\ p(\bar{p}) \to W^{\pm} X$ — large lepton rapidity

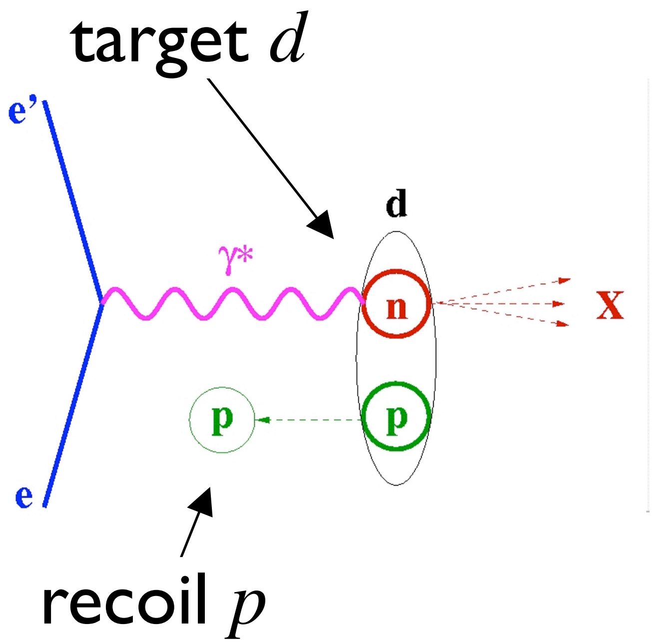
$e\ p \to e\ \pi^{\pm}\ X$ — $z \sim 1$, factorization

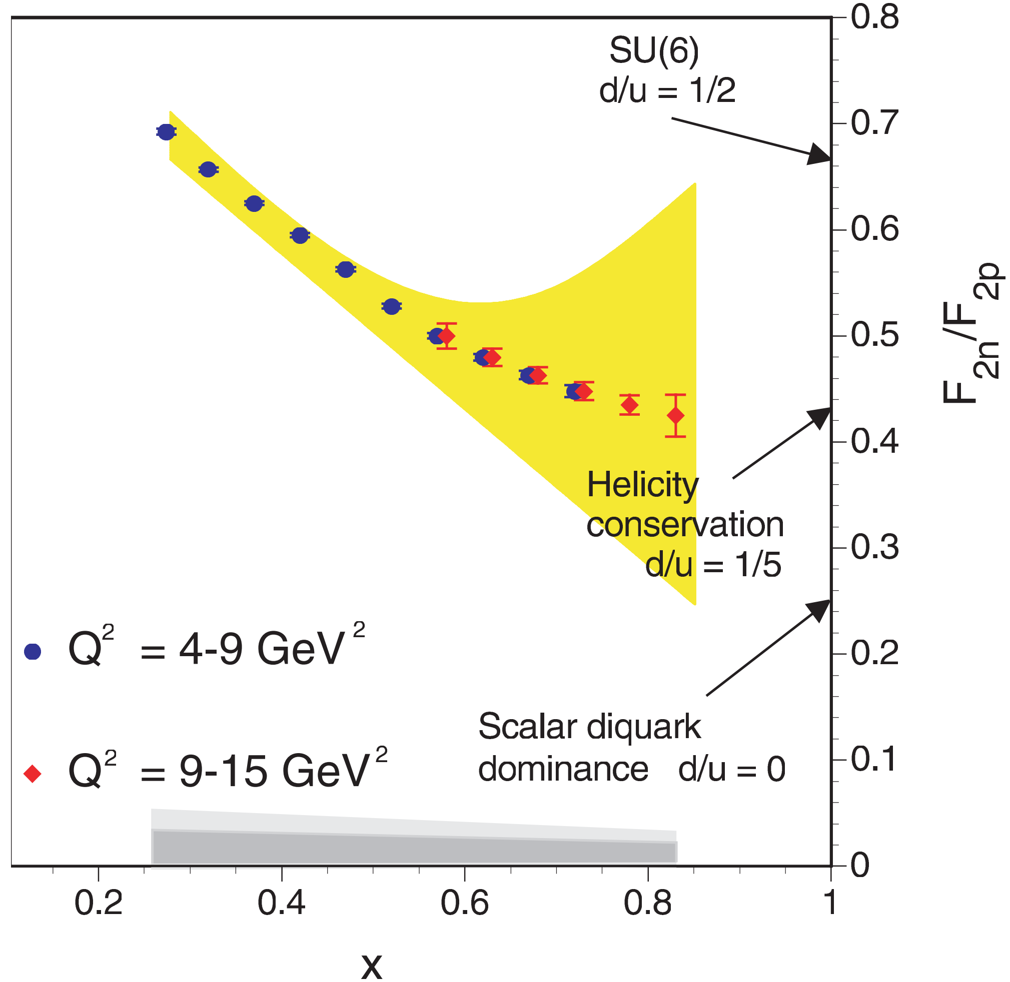
$e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$ — tritium target

$e\ d \to e\ p\ X$ — BONUS: spectator proton tagging

"BONUS" experiment

$e\ d \rightarrow e\ p\ X$





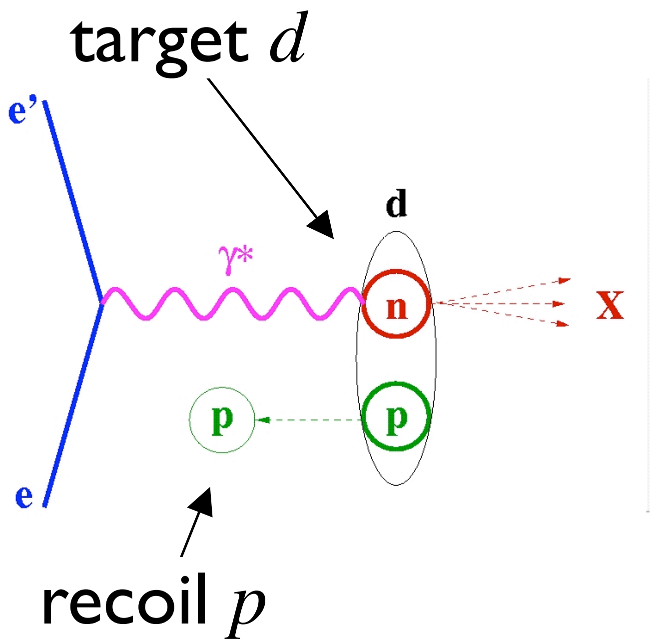
slow backward p

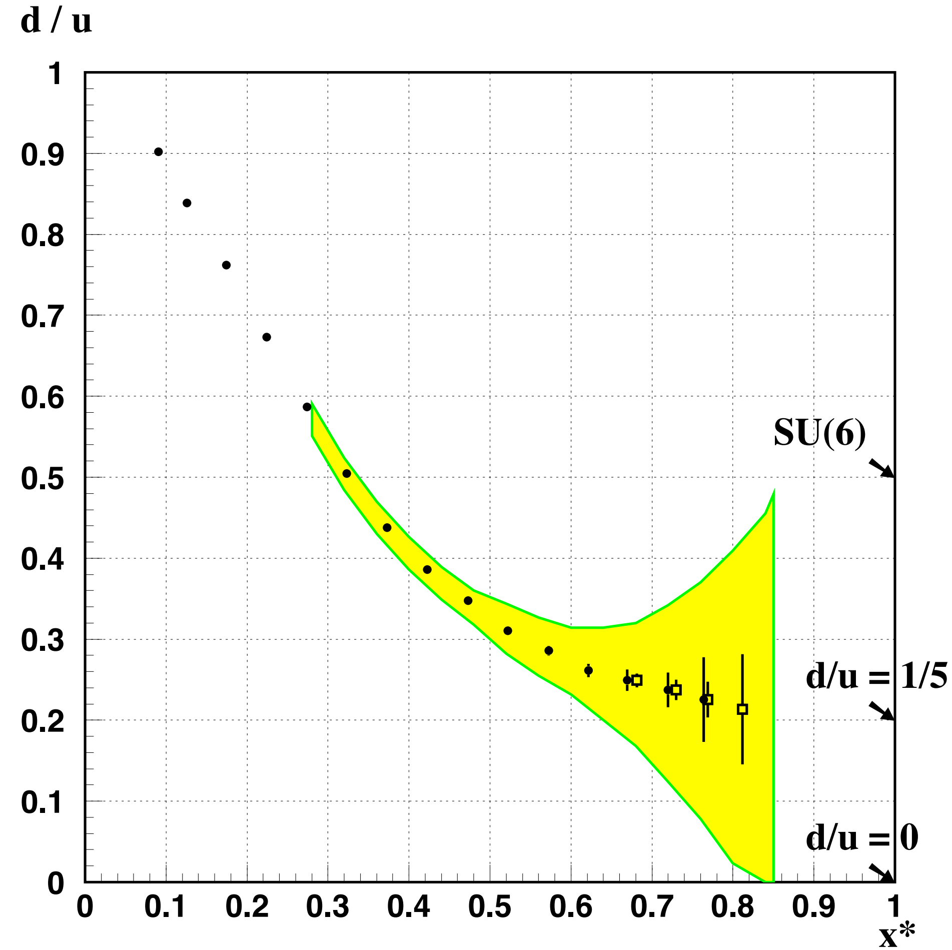
- neutron nearly on-shell
- minimize rescattering

JLab Hall B experiment ("BoNuS")
completed run Dec. 2005

"BONUS" experiment

$$e\ d \rightarrow e\ p\ X$$





slow backward p

- neutron nearly on-shell
- minimize rescattering

PAC30

Proposal: PR12-06-113

Title: The Structure of the Free Neutron at Large $x_{Bjorken}$

Spokespersons: S. Bueltmann, S. Kuhn, H. Fenker, W. Melnitchouk, M.E. Christy, C.E. Keppel, V. Tvaskis, K. Griffioen

Motivation: The ratio of proton to neutron spin-independent nucleon structure functions F_{2n}/F_{2p} in deep-inelastic scattering is poorly known at large x due to the remaining large nuclear theoretical uncertainty in the determination of the free neutron structure function. To clarify once and for all the behavior of this important ratio as x tends to unity, it is proposed to minimize the effect of the nuclear corrections by insuring that the deep inelastic scattering (DIS) occurs on an almost on-shell neutron. This is achieved by tagging the slow recoiling proton (of about 70 MeV/c) momentum in the backward hemisphere of CLAS12 from the electro-disintegration of the deuteron. The d/u parton distributions ratio will then be determined at large x within the quark parton model with a precision capable of discriminating between constituent quarks models and pQCD predictions using current quarks.

Measurement and Feasibility: It is proposed to measure the $^2H(e,ep)X$ reaction in the DIS region for $Q^2 > 1$ $(GeV/c)^2$ using the CLAS 12 detector in combination with an RTPC to detect recoiling protons with slow momenta $p_s < 200$ MeV/c and large recoil angles $\theta_{pq} < 110^0$. This measurement is a natural extension of the BONUS experiment (E03-02) which ran successfully in the fall of 2005 demonstrating the feasibility of this elegant experimental technique. The proposed measurement will reach a value of $x = 0.75$ with a stringent $W = 2$ GeV cut, but would have data to extend this study to values of x in the resonance region.

Issues: While the PAC is encouraged to note the successful running of the BONUS experiment, it would benefit by knowing the results which are not yet available. The PAC is optimistic that the BONUS technique will provide a good understanding of the nuclear effects, but would like to see it established once the first BONUS experiment analysis is complete and experience with at least one other experiment has been gained . The upgrade of the RTPC and associated electronics, as well as the increase of the present RTPC length and diameter, are crucial to achieving the statistical uncertainty and to reaching the physics goals at the largest possible x.

Recommendation: Conditional approval

Survey of methods to determine *d/u*

$e^{\mp}\ p \to \nu(\bar{\nu}) X$	low event rates
$\nu(\bar{\nu})\ p \to l^{\mp}\ X$	low statistics at large x
$p\ p(\bar{p}) \to W^{\pm} X$	large lepton rapidity
$e\ p \to e\ \pi^{\pm}\ X$	$z \sim 1$, factorization
$e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$	tritium target
$e\ d \to e\ p\ X$	BONUS: spectator proton tagging
$\vec{e}_L(\vec{e}_R)\ p \to e\ X$	PVDIS *no nuclear effects!*

PVDIS

- Left-right parity-violating asymmetry

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$= \frac{G_F}{2\sqrt{2}\pi\alpha} \frac{1}{\mathcal{F}^\gamma} \Big(g_A \left[2xy^2 F_1^{\gamma Z} + 2(1-y) F_2^{\gamma Z} \right] + g_V \; xy(2-y) \; F_3^{\gamma Z} \Big)$$

(unpolarized) electromagnetic cross section

$$\mathcal{F}^\gamma = 2xy^2 F_1 + 2(1-y) F_2$$

PVDIS

- Left-right parity-violating asymmetry at large Q^2

$$A_{LR} = \frac{Q^2 G_F}{2\sqrt{2}\pi\alpha}\left(a(x) + \frac{y(2-y)}{2-2y+y^2}b(x)\right)$$

$$a(x) = \frac{1}{\mathcal{Q}(x)}\sum_q e_q C_{1q}\ q(x) \qquad b(x) = \frac{1}{\mathcal{Q}(x)}\sum_q e_q C_{2q}\ q(x)$$

$$\mathcal{Q}(x) = \sum_q e_q^2\ q(x)$$

- for p target

$$a(x) \propto \frac{1 + 0.912\ d/u}{1 + 0.25\ d/u}$$

PVDIS issues

Issues at large x

- **Target mass corrections**
  - ➡ finite M^2/Q^2 effects (but leading twist!)

Georgi, Politzer, PRD14 (1976) 1829
Kretzer, Reno, PRD69 (2004) 034002

- **Higher twists**
  - ➡ dynamical quark-quark correlations, $1/Q^2$ suppressed

- **Quark-hadron duality**
  - ➡ low-W resonances conspire to produce scaling function

WM, Ent, Keppel, Phys. Rept. 406 (2005) 127

- **Large-x resummation**
  - ➡ extend validity of pQCD by resumming large-x logs arising from soft & collinear gluons

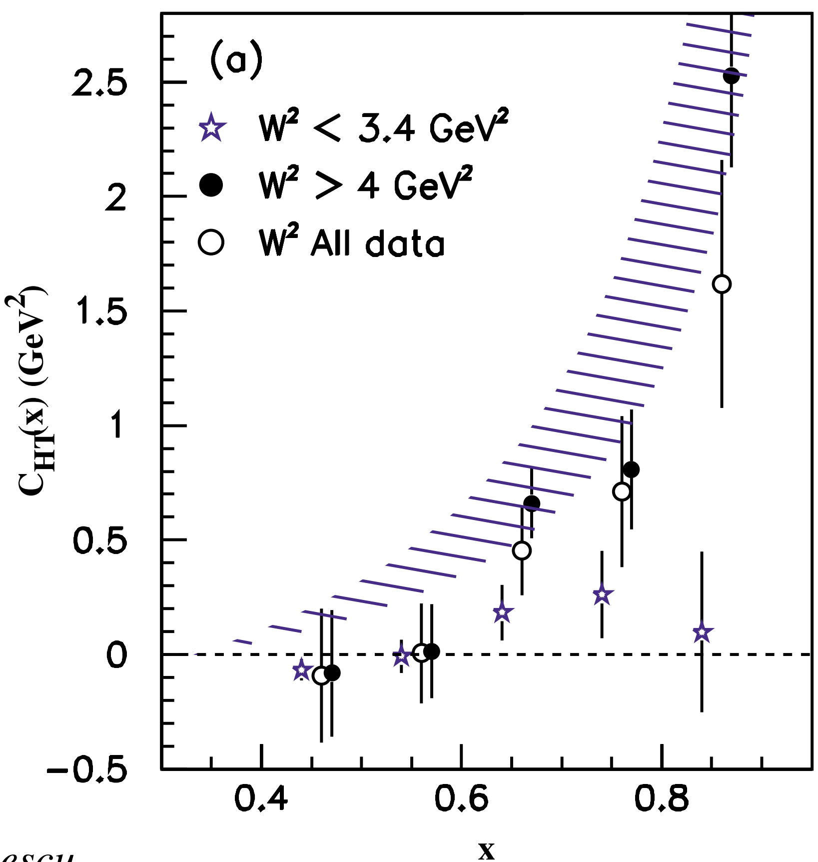
Sterman, NPB281 (1987) 310; Catani, Trentadue, NPB327 (1989) 323
Corcella, Magnea, hep-ph/050742; Vogelsang, AIP Conf. Proc. 747 (2005) 9

Phenomenological higher twists

- parameterized total structure function as

$$F_2(x,Q^2) = F_2^{LT}(x,Q^2)\left(1+\frac{C_{HT}(x)}{Q^2}+\Delta H(x,Q^2)\right)$$

+ TMC
+ large-x resummation



→ large-x resummation reduces C_{HT}

→ lower-W data require negative $1/Q^4$ term

Liuti, Ent, Keppel, Niculescu, Phys. Rev. Lett. 89 (2002) 162001
(see also Alekhin, Kulagin, Petti 2005)

Target mass corrections

- n-th moment of F_2 structure function (leading twist!)

$$M_2^n(Q^2) = \int dx\; x^{n-2}\; F_2(x,Q^2)$$

$$= \sum_{j=0}^{\infty} \left(\frac{M^2}{Q^2}\right)^j \frac{(n+j)!}{j!(n-2)!} \frac{A_{n+2j}}{(n+2j)(n+2j-1)}$$

"quark distribution function"

$$\Rightarrow \quad A_n = \int_0^1 dy\; y^n\; F(y) \qquad F(y) \equiv \frac{F_2(y)}{y^2}$$

Georgi, Politzer (1976)

Target mass corrections

- inverse Mellin transform (+ tedious manipulations)

$$F_2^{\rm GP}(x,Q^2) = \frac{x^2}{r^3} F(\xi) \; + \; 6 \frac{M^2}{Q^2} \frac{x^3}{r^4} \int_\xi^1 d\xi' \; F(\xi')$$

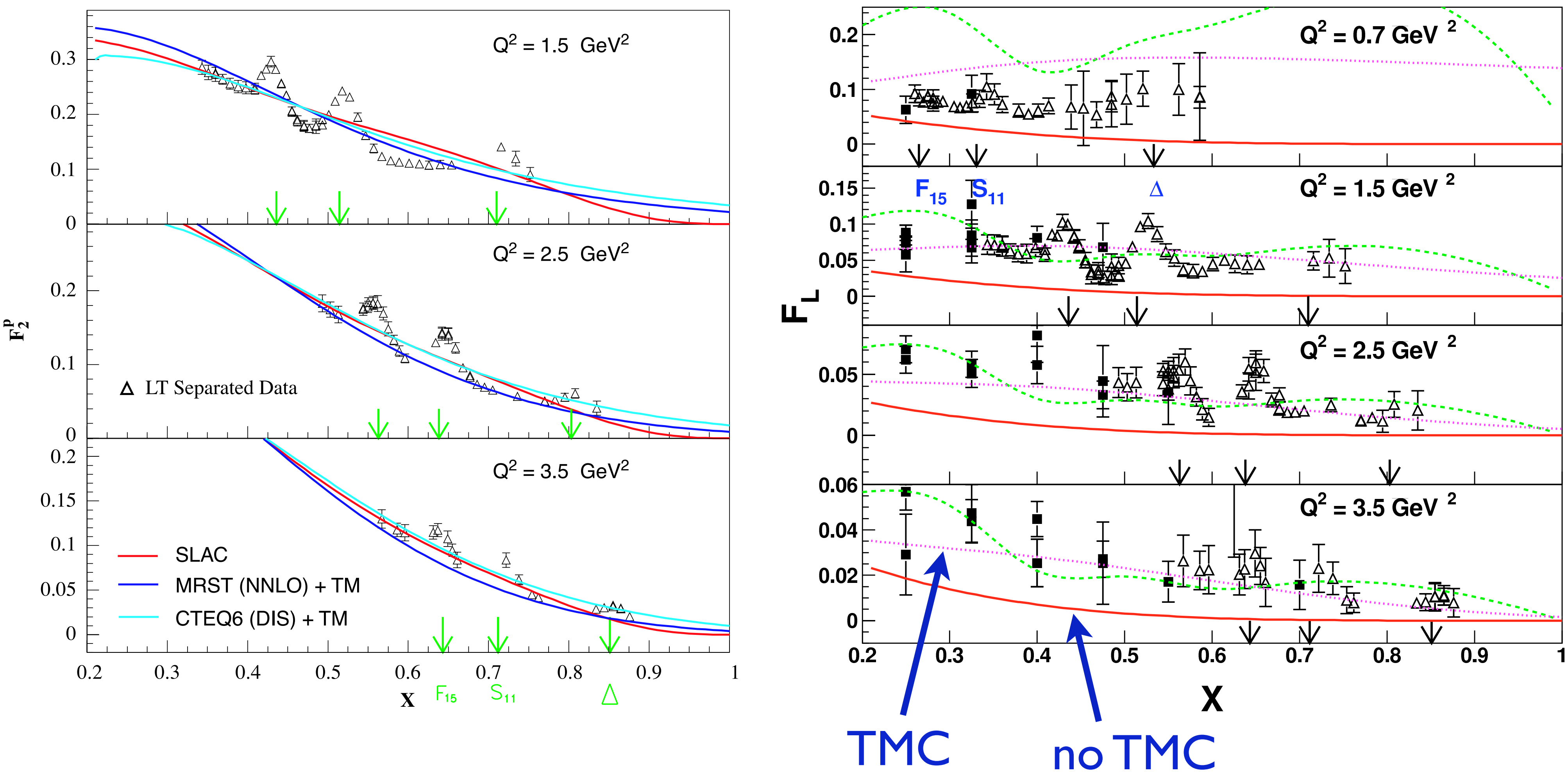
$$+ \; 12 \frac{M^4}{Q^4} \frac{x^4}{r^5} \int_\xi^1 d\xi' \; \int_{\xi'}^1 d\xi'' \; F(\xi'')$$

$$\xi = \frac{2x}{1+r} \qquad\qquad r = \sqrt{1 + 4x^2 M^2/Q^2}$$

... similarly for other structure functions F_1, F_L

Target mass corrections

Christy et al. (2005)



➡ TMCs significant at large x^2/Q^2, especially for F_L

Threshold problem

- if $F(y) \sim (1-y)^{\beta}$ at large y

  then since $\xi_0 \equiv \xi(x=1) < 1$

  ⇨ $F(\xi_0) > 0$

  ⇨ $F_i^{\rm TMC}(x=1, Q^2) > 0$

  is this physical?

  ⇨ problem with GP formulation?

Possible solution

- work with ξ_0 dependent PDFs

  → n-th moment A_n of distribution function

$$A_n = \int_0^{\xi_{\max}} d\xi \; \xi^n \; F(\xi)$$

  → what is $\xi_{\max}$?

  - GP use $\xi_{\max} = 1, \;\; \xi_0 < \xi < 1$ unphysical

  - strictly, should use $\xi_{\max} = \xi_0$

Steffens, WM
PRC 73 (2006) 055202

Possible solution

- what is effect on phenomenology?

  → try several "toy distributions"

standard TMC ("sTMC")

$$q(\xi) = \mathcal{N}\ \xi^{-1/2}\ (1-\xi)^3\ , \qquad \xi_{\max} = 1$$

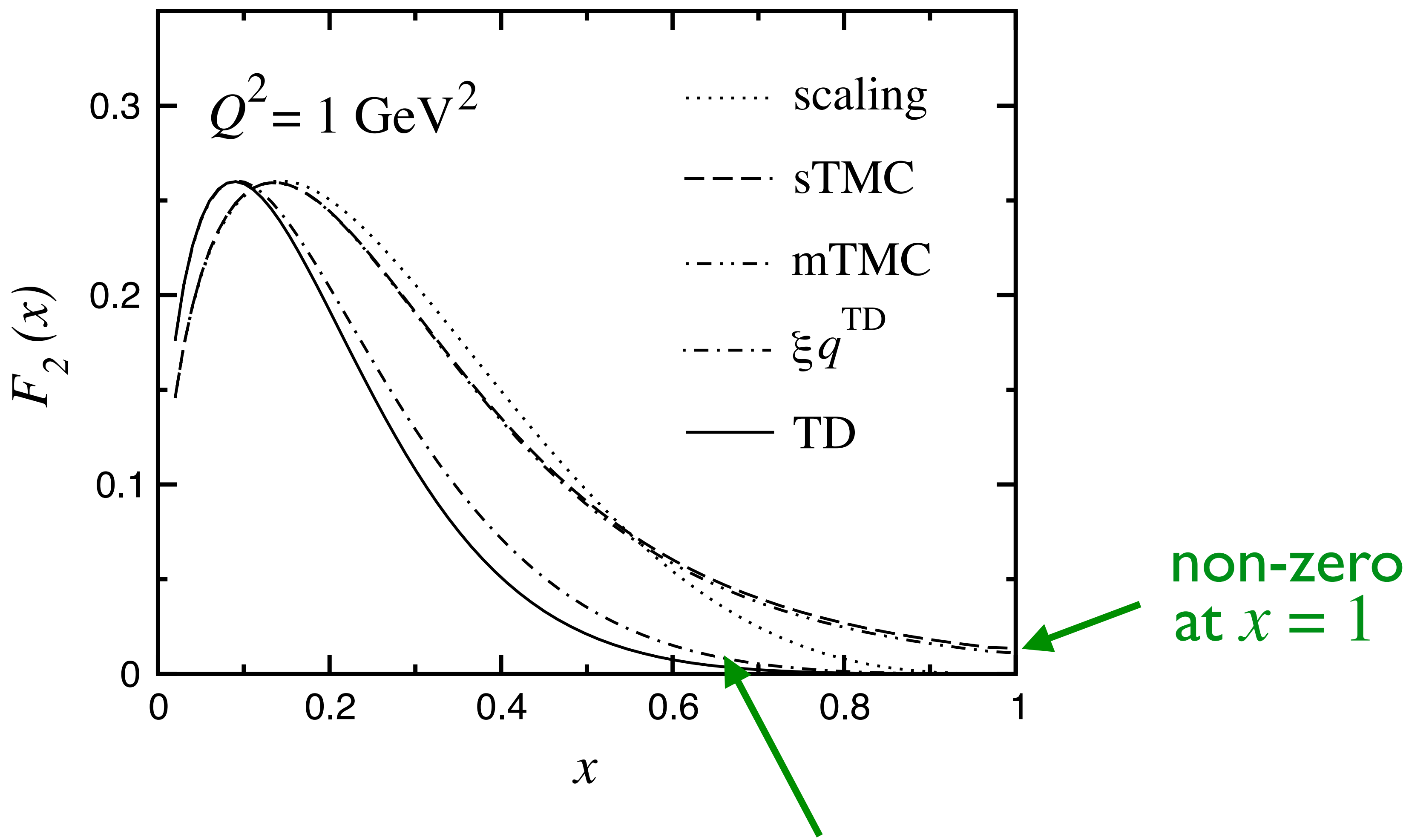
modified TMC ("mTMC")

$$q(\xi) = \mathcal{N}\ \xi^{-1/2}\ (1-\xi)^3\ \Theta(\xi - \xi_0), \qquad \xi_{\max} = \xi_0$$

threshold dependent ("TD")

$$q^{\mathrm{TD}}(\xi) = \mathcal{N}\ \xi^{-1/2}\ (\xi_0 - \xi)^3\ , \qquad \xi_{\max} = \xi_0$$

TMCs in F_2

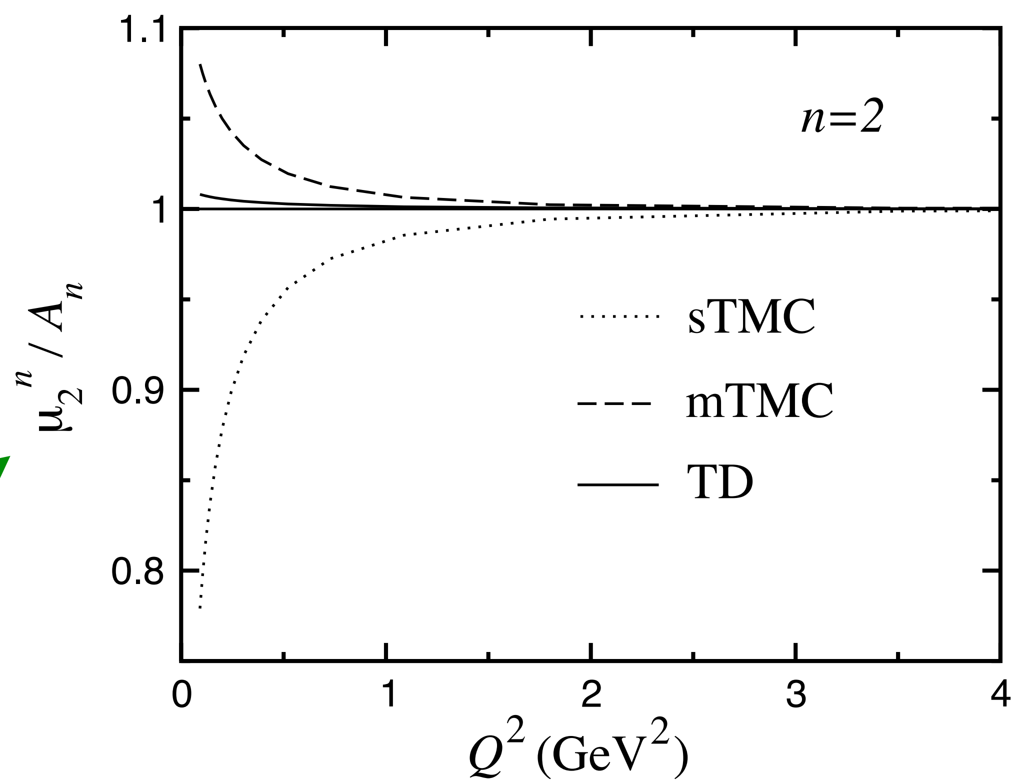


→ correct threshold behavior for "TD" correction

Nachtmann F_2 moments

- designed to remove target mass effects explicitly from structure function moment

Nachtmann moment



→ moment of structure function agrees with moment of PDF to 1% down to very low Q^2

Higher twists

- how important will HT be for PVDIS at 12 GeV?

  → ultimately, determine empirically

  → test importance of TMCs in relevant kinematics

  → need lever arm in Q^2 for fixed x

  → perform combined LT+HT fit to data, including higher order pQCD, TMC & phenomenological $1/Q^2$ effects

Intrinsic sea quarks

- Intrinsic (nonperturbative) sea quarks can exist at large x

  $\longrightarrow$ *cf.* perturbative sea at small x

- Intrinsic charm can arise through virtual fluctuations

$$p \to \bar{D}^0(u\bar{c}) + \Lambda_c(udc)$$

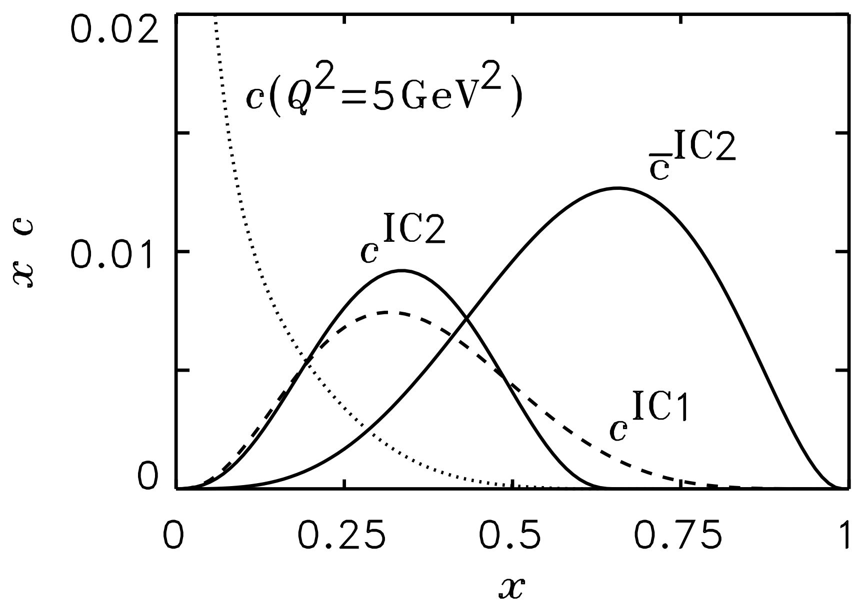
$$c(x) \approx \frac{3}{2} f_{\Lambda_c/N}(3x/2)$$

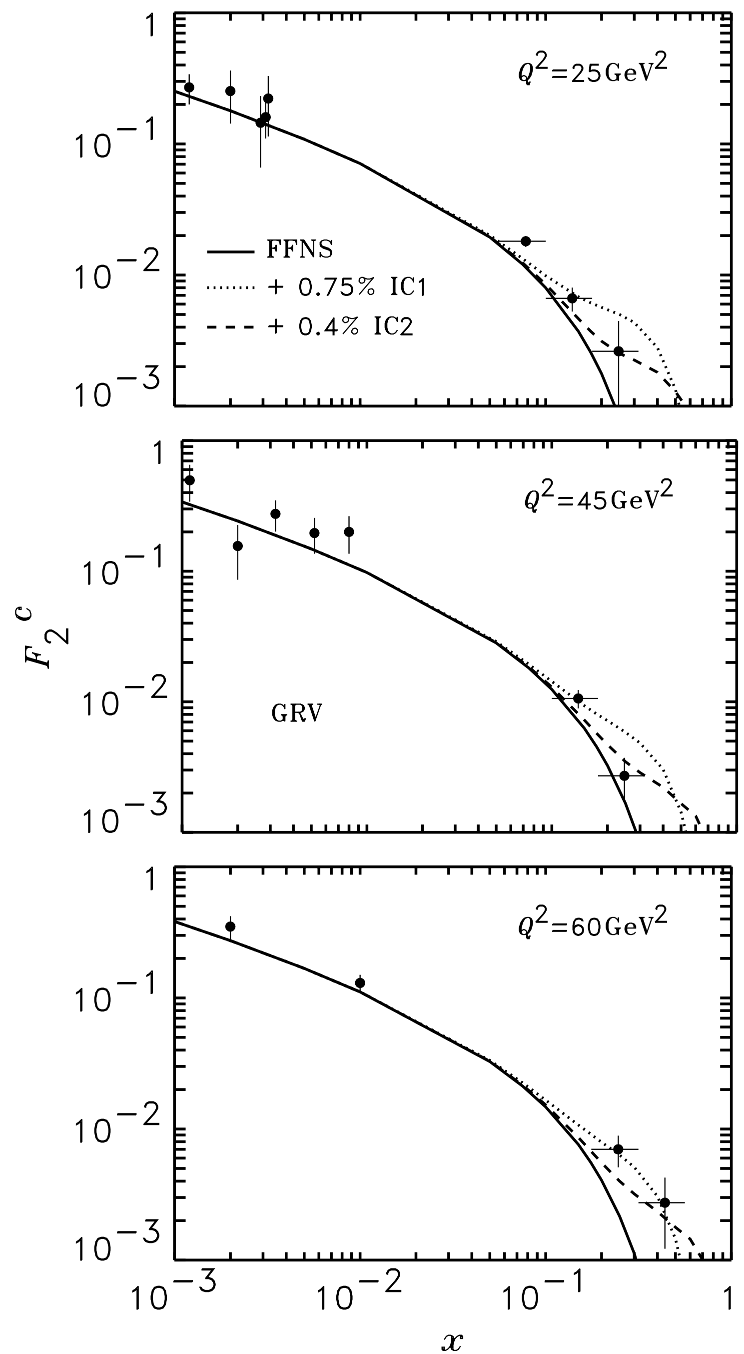
$$\bar{c}(x) \approx f_{D/N}(x)$$

different shapes for c and $\bar{c}$

$\longrightarrow$ hard x distribution because of large c mass

Intrinsic sea quarks





IC1: Brodsky et al.

IC2: meson cloud

(< 0.4% normalization)

WM, Thomas, PLB414 (1997) 134
Steffens, WM, Thomas, EPJC11 (1999) 673

Summary

- d quark distribution poorly known at large x

- PVDIS data will determine d/u ratio at large x,
  free of any nuclear effects issues

  $\longrightarrow$ complement e scattering data ($e.g.$ BONUS, A=3 DIS)

- need to take care of some background issues

  $\longrightarrow$ similar issues relevant for other d/u experiments