Power Corrections to Structure Functions

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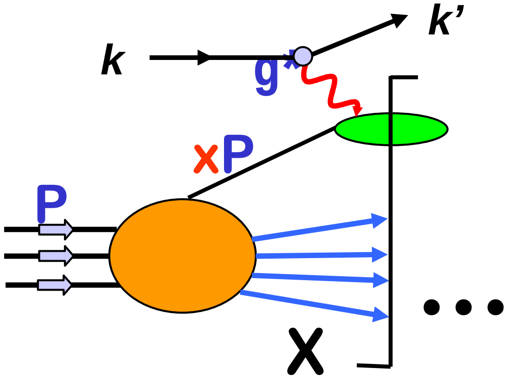
University of Wisconsin at Madison, Madison, WI

Outline of the Talk

- **Structure functions and parton distributions:**
  - Relations to lowest order and leading twist
- **Electromagnetic current and DIS:**
  - Resumming coherent QCD power corrections
  - Modifications to F_2 and F_L
- **Weak current and DIS:**
  - Valence and sea quark "shadowing" in $\nu + \mathrm{A}$
  - F_3 and QCD sum rules
- **p+A reactions at RHIC:**
  - Dynamical gluon "shadowing" - particle yields and correlations
- **Summary:**

Inclusive Deeply Inelastic Lepton-Hadron Scattering



Variables: $q = k - k', \; v = E - E',$

$$y = (E - E')/E, \;\; Q^2 = -q^2, \;\; x = Q^2/(2p \cdot q)$$

$$\frac{d\sigma_{lh}}{dxdy} = \frac{4\pi\alpha_{em}}{Q^2}\frac{1}{xy}\left[\frac{y^2}{2}2xF_1(x,Q^2) + \left(1 - y - \frac{m_N xy}{2E}\right)F_2(x,Q^2)\right]$$

$F_1(x,Q^2), \; F_2(x,Q^2)$ **- the DIS structure functions**

Convenient to calculate in a basis of polarization states of g*

QCD kicks in with the parton model / factorization

$$F_T(x,Q^2) = \frac{1}{2}\sum_f Q_f^2 \int d\lambda_0 e^{ix\lambda} \left\langle p \left| \overline{\Psi}(0)\frac{\gamma^+}{2p^+}\Psi(\lambda_0) \right| p \right\rangle$$

$$= \frac{1}{2}\sum_f Q_f^2 \, \phi_f(x,Q^2) + \mathcal{O}(\alpha_s)$$

$$F_L(x,Q^2) = 0 + \mathcal{O}(\alpha_s)$$

Lowest Order and Leading Twist relation

$$F_T(x,Q^2) = F_1(x,Q^2),$$

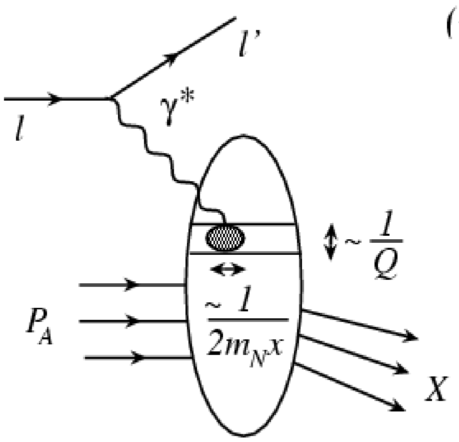
$$F_L(x,Q^2) = \frac{F_2(x,Q^2)}{2x} - F_1(x,Q^2),$$

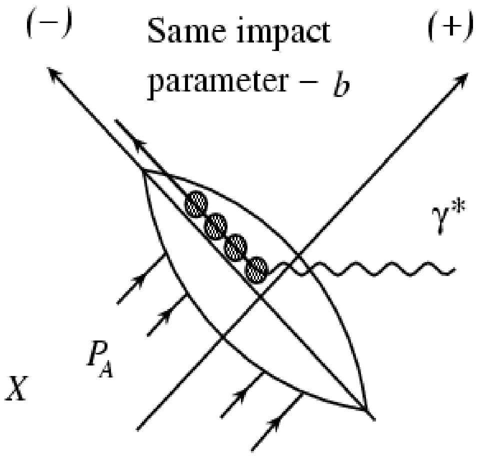
$$\text{if } \frac{4x^2 m_N^2}{Q^2} \ll 1$$

Used to determine the parton distribution functions (PDFs)

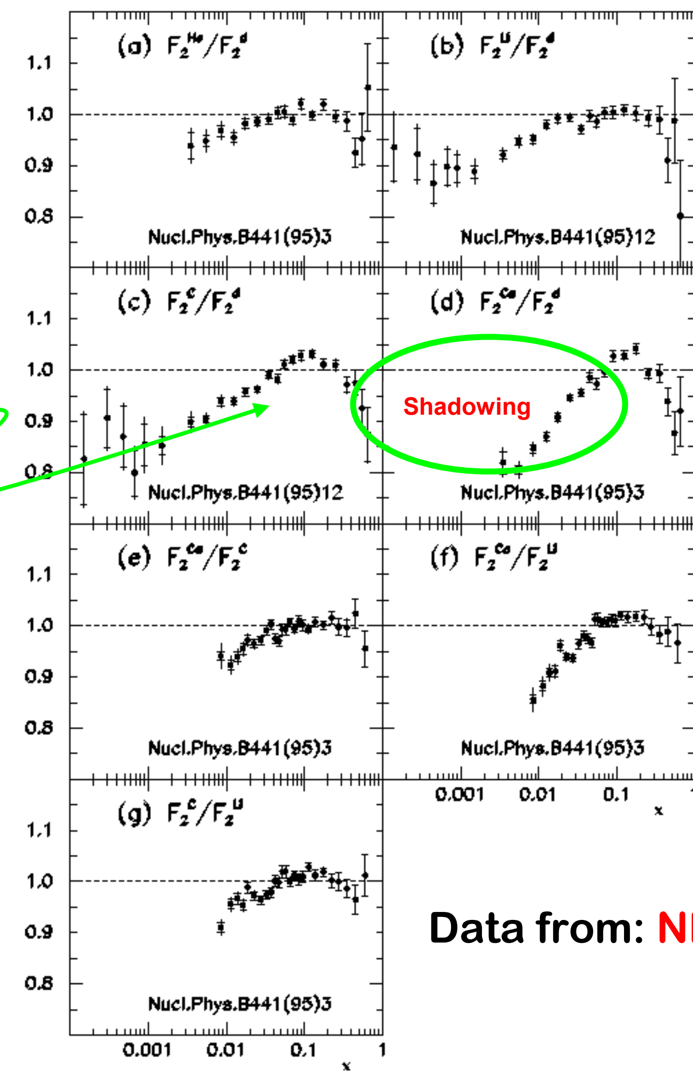
Both simple and dangerous

Lepton+Nucleus from Theory





Deviation from A-scaling: $\sigma_A \neq A \times \sigma$



Longitudinal size: $\sim 1/2m_N x$

If $x < 0.1$ then $\Delta z > r_0$

Transverse size: $\sim 1/Q$

If $Q < m_N$ then exceed the parton size

What remains for theory:
power corrections in DIS - suppression

Data from: **NMC**

FSI are always present:

S.Brodsky et al., Phys.Rev.D (2002)

Ivan Vitev, LANL

The Idea Behind the Calculation

- **Lightcone gauge:** $A \cdot n = A^+ = 0$
- **Breit frame:** $\bar{n} = [1,0,0_\perp],\ n = [0,1,0_\perp]$

$$q = -xp^+\bar{n} + \frac{Q^2}{2xp^+} n,\ \ p = \bar{n} p^+,\ \ xp + q = \frac{Q^2}{2xp^+} n$$

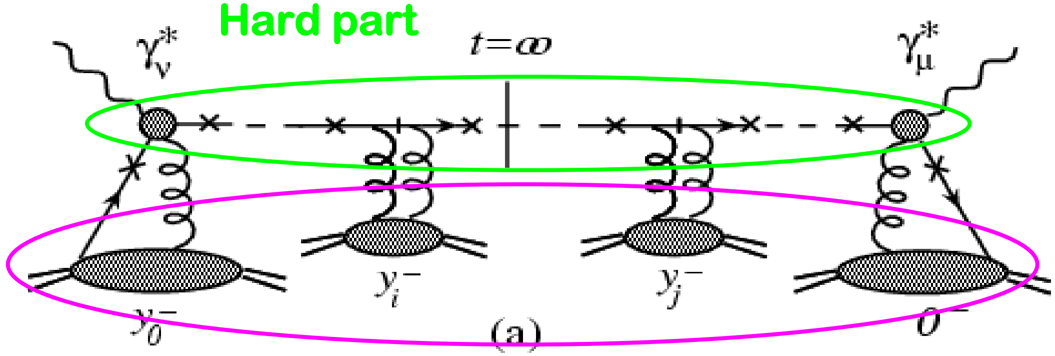
$$Cut = (2\pi)\frac{\gamma^+}{2p^+}\delta(x_i - x_B)$$

$$\Delta(x_i p + q) = \pm i \frac{\gamma^+}{2p^+}\frac{1}{x_i - x \pm i\varepsilon} \pm i \frac{xp^+\gamma^-}{Q^2}$$

Long distance **Short distance**

Perturbative

Hard part



Non-perturbative

Matrix element

$$\langle P|\hat{O}^{T=2+2n}|P\rangle = A\langle P/A|\hat{O}_q^{T=2}|P/A\rangle$$

Decompose $\prod_{i=1}^{n}\langle P/A|\hat{O}_g^{T=2}|P/A\rangle$

Contribution of single scatter: $\sim \xi^2 / Q^2$

$$\xi^2 = \left(\frac{3\pi\alpha_s(Q^2)}{8r_{0\perp}^2}\right)\langle p|\hat{F}^2(\lambda_i)|p\rangle$$

$$\hat{F}^2(\lambda_i) = \int \frac{d\tilde{\lambda}_i}{2\pi}\frac{F^{+\alpha}(\lambda_i)F_\alpha^{\ +}(\tilde{\lambda}_i)}{(p^+)^2}\theta(\lambda_i - \tilde{\lambda}_i) \Rightarrow \lim_{x\to 0}\frac{1}{2}xG(x,Q^2)$$

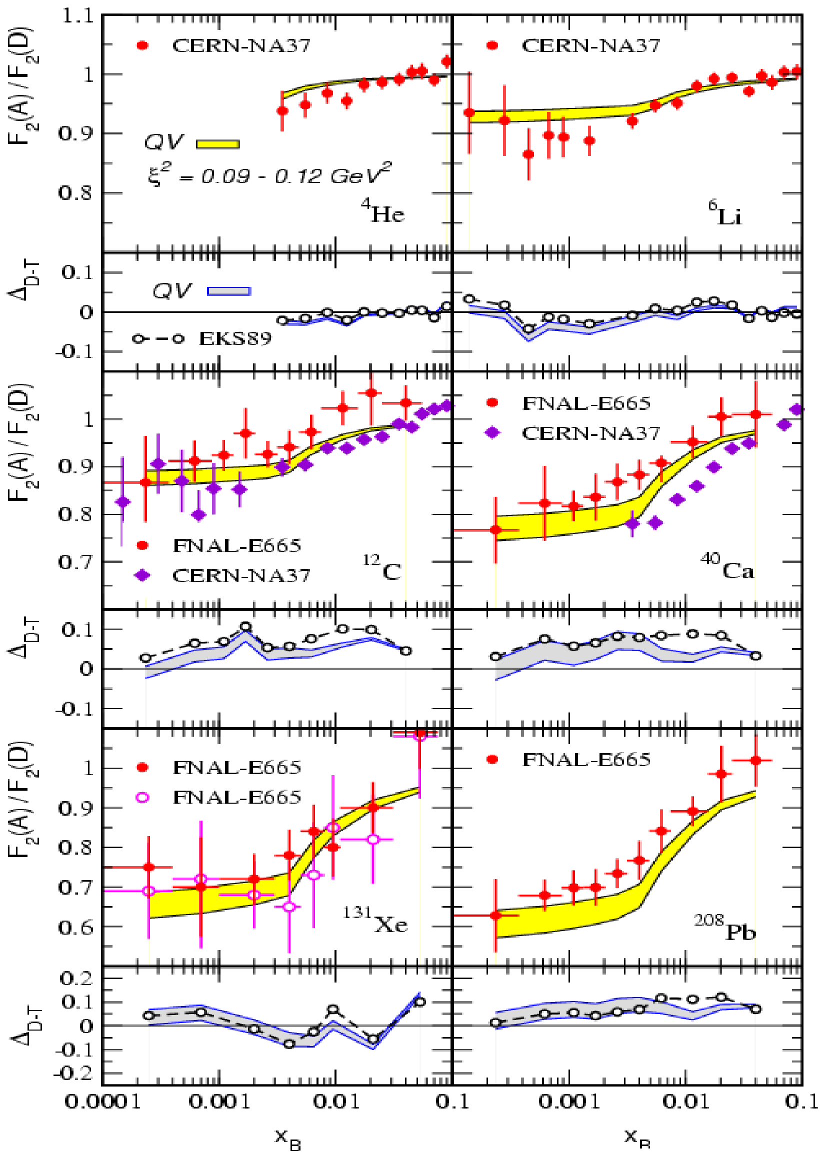
Numerical A- and x_B-Dependence

Purely quantum effect

$$\exp\left[+ \frac{\xi^2 (A^{1/3}-1)}{Q^2} x \frac{d}{dx} \right] F_2(x)$$

$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2 (A^{1/3}-1)}{Q^2}, Q^2 \right)$$

The scale of higher twist per nucleon is <u>small</u> $\xi^2 \simeq 0.1\ GeV^2$

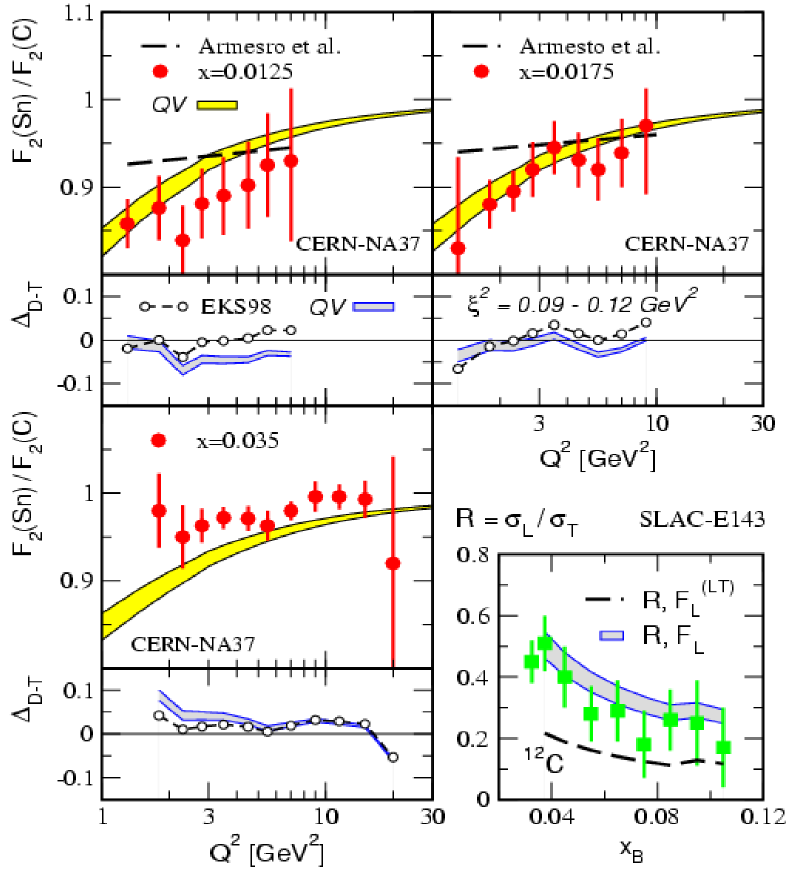


- Favorable comparison for the x- and A-dependence NA37 (NMC) and E665 data

- For $Q^2 \to 0$ we impose $Q^2 = m_N^2$.
  (discussion of $\mathcal{O}(\alpha_s^n)$ and parton size)

J.W.Qiu, I.V., Phys.Rev.Lett. 93 (2004)

Q^2-dependence and $F_L(x,Q^2)$ from Power Corrections



J.W.Qiu, I.V.,Phys.Rev.Lett.93 (2004)

Two more tests:

NMC data shows evidence for a power law in $1/Q^2$ behavior in $F_2(Sn)/F_2(C)$

$$R(x,Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_L(x,Q^2)}{F_1(x,Q^2)}$$

$$F_L^A(x,Q^2) \approx A\, F_L^{(LT)}(x,Q^2) + \frac{4\xi^2}{Q^2} F_T^A(x,Q^2)$$

- The Leading Twist (LT) $R(x,Q^2)$ is not sensitive to modifications of the nPDFs

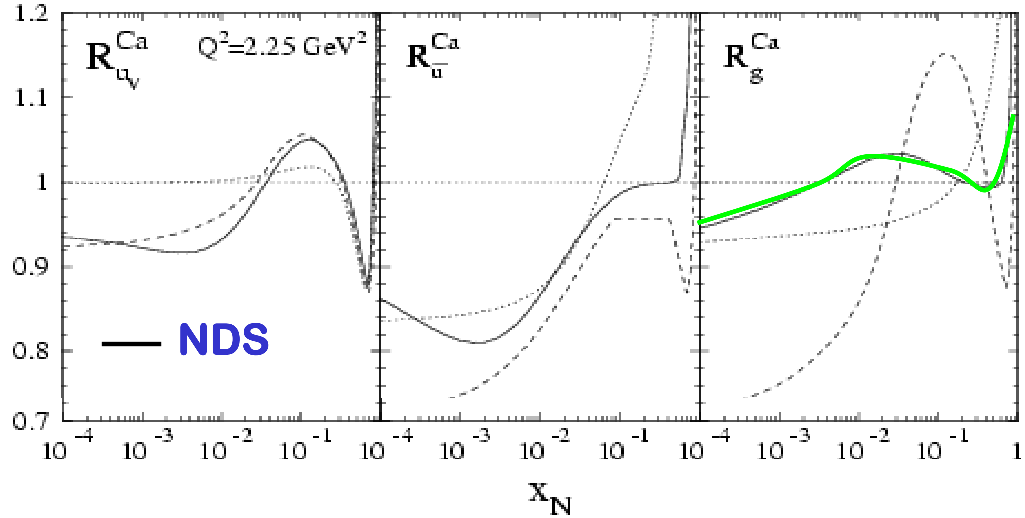
How to Check the Origin of Shadowing

Experimental data

TABLE I: Nuclear data included in the fit.

Measurement	Collaboration	Refs.	# data
F_2^{He}/F_2^D	NMC	[13]	18
	SLAC-E139	[14]	18
F_2^{Be}/F_2^D	SLAC-E139	[14]	17
F_2^C/F_2^D	NMC	[13]	18
	SLAC-E139	[14]	7
F_2^{Al}/F_2^D	SLAC-E139	[14]	17
F_2^{Ca}/F_2^D	NMC	[13]	18
	SLAC-E139	[14]	7
F_2^{Fe}/F_2^D	SLAC-E139	[14]	23
F_2^{Ag}/F_2^D	SLAC-E139	[14]	7
F_2^{Au}/F_2^D	SLAC-E139	[14]	18
F_2^{Be}/F_2^C	NMC	[15]	15
F_2^{Al}/F_2^C	NMC	[15]	15
F_2^{Ca}/F_2^C	NMC	[15]	15
F_2^{Fe}/F_2^C	NMC	[15]	15
F_2^{Pb}/F_2^C	NMC	[15]	15
F_2^{Sn}/F_2^C	NMC	[16]	145
$\sigma_{DY}^C/\sigma_{DY}^D$	E772	[17]	9
$\sigma_{DY}^{Ca}/\sigma_{DY}^D$	E772	[17]	9
$\sigma_{DY}^{Fe}/\sigma_{DY}^D$	E772	[17]	9
$\sigma_{DY}^W/\sigma_{DY}^D$	E772	[17]	9
Total			420

- Only NLO analysis is directly sensitive to gluon distributions in the nucleus
- So far only one such analysis with extremely interesting results



D. de Florian, R. Sassot, Phys.Rev.D69 (2004)

Very small (negligible) gluon shadowing

- **Problematic:** for initial state shadowing models $C_A/C_F = 2.25$
- **Natural:** for final state resummed power corrections

Modifications to $\nu + A$ Scattering

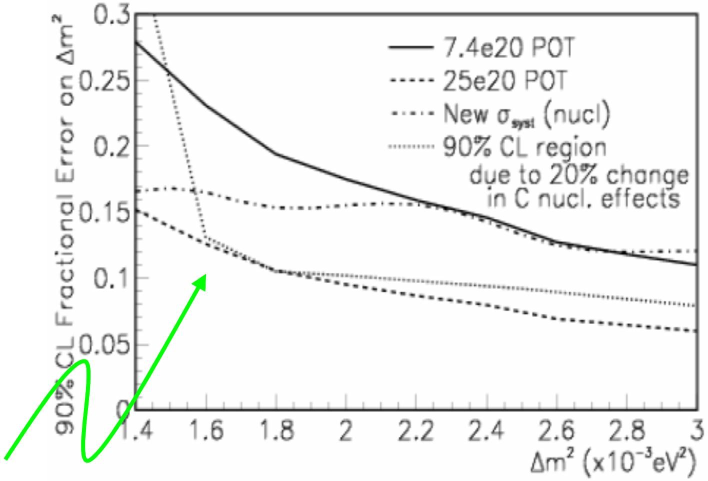
- **No theory** for the shadowing in $\nu + A$ (exchange $W^{\pm}, Z^{0}$)
- 3σ **deviation** from the Standard Model (Now $1.8\ \sigma$)

$$\sin^2\theta_W(SM) = 0.2227 \pm 0.0004$$

$$\sin^2\theta_W(NuTeV) = 0.2277 \pm 0.0013 \pm 0.0009 \pm \ldots$$

NuTeV experiment

G.P.Zeller *et al.*, Phys.Rev.Lett 88 (2002)



- **MINOS** up and running - a case for **MINERvA**

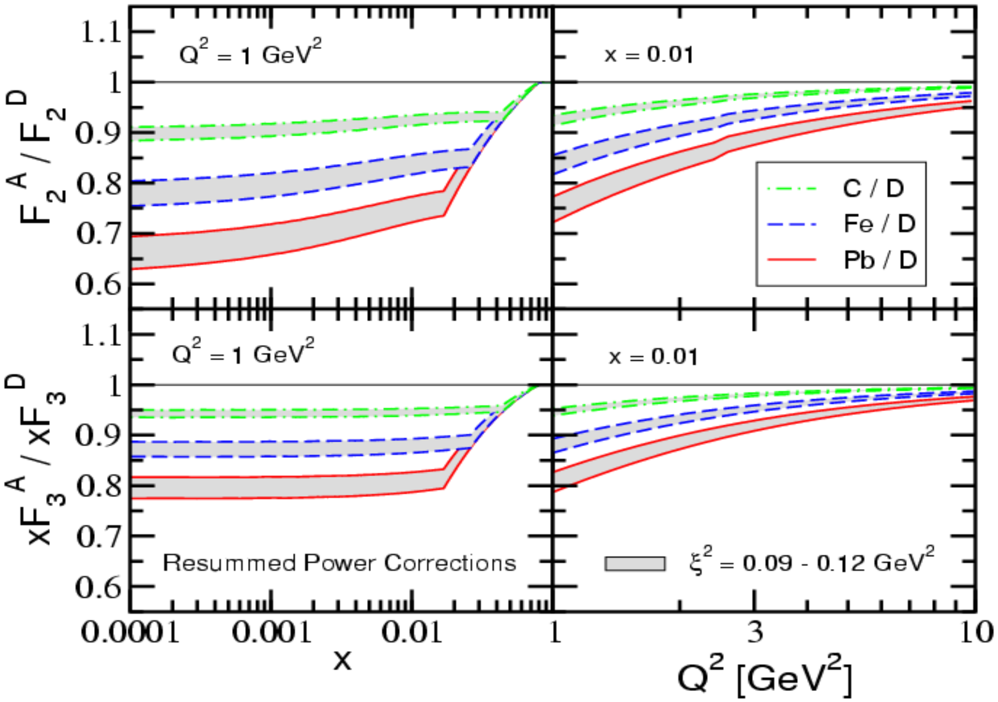
Cross sections matter

$$\frac{d\sigma^{\nu,\bar{\nu}}{}_{cc}}{dx\,dy} \propto \frac{1}{(\sin^2\theta_W)^2}\left[\frac{y^2}{2}2xF_1^{W^\pm}(x,Q^2) + \left(1 - y - \frac{m_N xy}{2E}\right)F_2^{W^\pm}(x,Q^2) \pm \left(y - \frac{y^2}{2}\right)xF_3^{W^\pm}(x,Q^2)\right]$$

Axial and **vector** part (weak current)

Similarly for the neutral current

Results: $F_2(x,Q^2)$ and $xF_3(x,Q^2)$



J.W.Qiu, I.V., Phys.Lett.B 587 (2004)

First theory of valance quark shadowing $xF_3(x)$

$$\phi_{sea}(x) \propto 1/x \qquad \phi_{val.}(x) \propto 1/\sqrt{x}$$

$$S_{sea} \propto \phi_{sea}(x+\Delta x)/\phi_{sea}(x) \approx 1 - \frac{\Delta x}{x}$$

$$S_{val} \propto \phi_{val}(x+\Delta x)/\phi_{val}(x) \approx 1 - \frac{1}{2}\frac{\Delta x}{x}$$

$$x_M = x_B \frac{M^2}{Q^2} \qquad x_{\xi^2} = x_B \frac{\xi^2(A_{1/3}-1)}{Q^2}$$

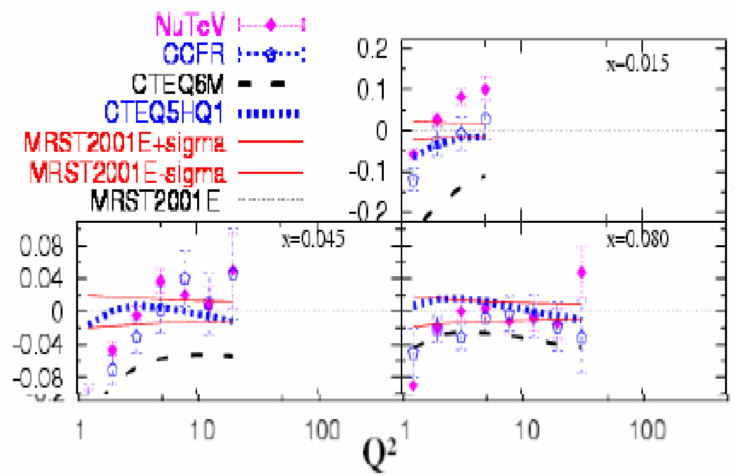
$$F_{1,3}^{(\nu W^+)}(x_B,Q^2) = \{2\} A \left(\sum_{D,U} |V_{DU}|^2 \phi_D(x_B + x_{\xi^2} + x_{M_U}) \pm \sum_{\bar{U},\bar{D}} |V_{\bar{U}\bar{D}}|^2 \phi_{\bar{U}}(x_B + x_{\xi^2} + x_{M_{\bar{D}}}) \right)$$

- **Physics: generation of a dynamical parton mass in the nuclear field**

$$x_B \to x_B\left(1+\frac{\xi^2(A^{1/3}-1)}{Q^2}+\frac{M^2}{Q^2}\right) = x_B\left(1+\frac{m_{dyn}^2+M^2}{Q^2}\right)$$

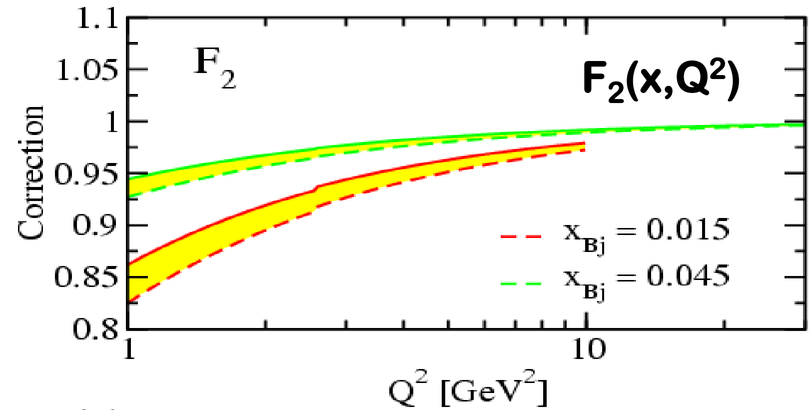
Comparison to NuTeV / CCFR

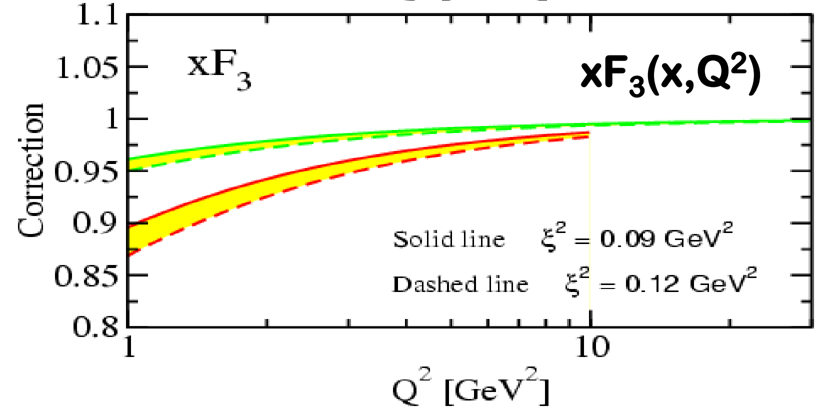
NuTeV / CCFR - DPF 2004 Riverside, CA



Power law deviation between data and the theory

- Focus on the **small Q^2 and $x < 0.1$ region**
- Look **relative to MRST 2001.** They do not including the nuclear effect in PDFs



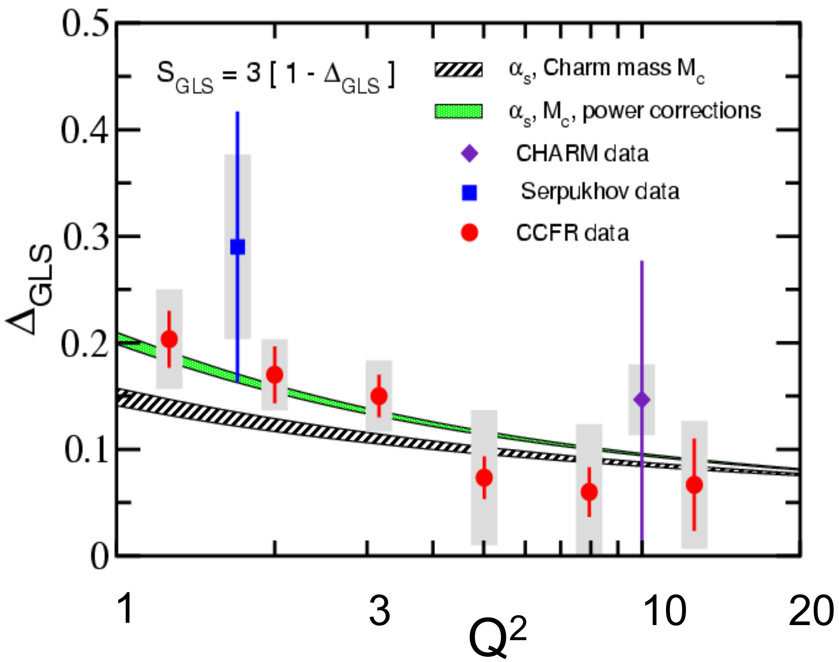


J.W.Qiu, I.V., Phys.Lett.B 587 (2004)

Suppression is 12% and 6% in the two lowest x bins at $Q^2 = 1.3$ GeV^2

QCD Sum Rules

J.W.Qiu, I.V., Phys.Lett.B 587 (2004)



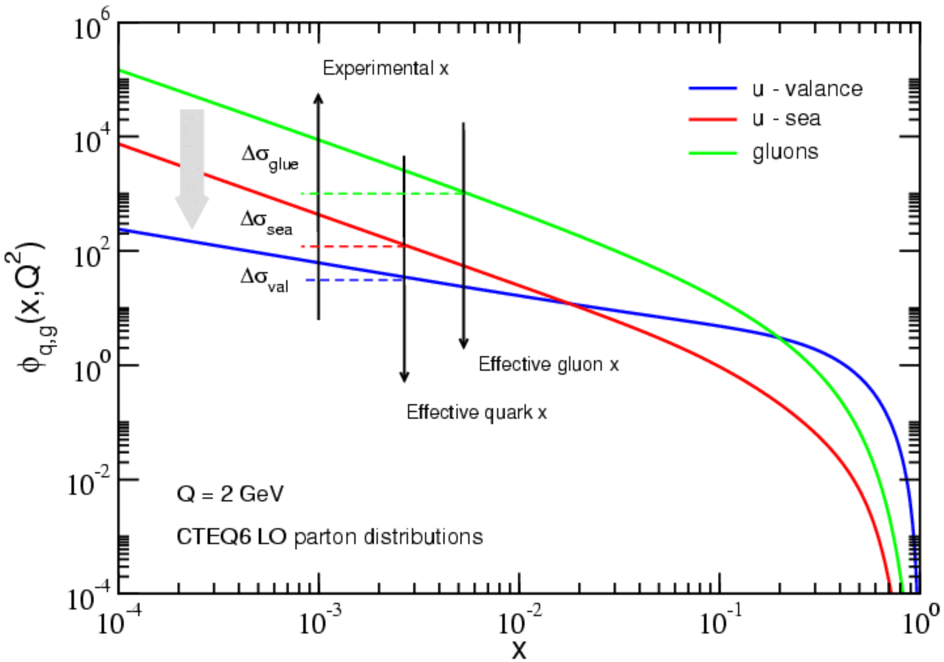
$$S_{GLS} = \int_0^1 dx \, \frac{1}{2x} \left(xF_3^{\nu N}(x,Q^2) + xF_3^{\bar{\nu} N}(x,Q^2) \right)$$
$$= 3(1 - \Delta_{GLS})$$

D.Gross and C.Llewellyn Smith , Nucl.Phys. B 14 (1969)

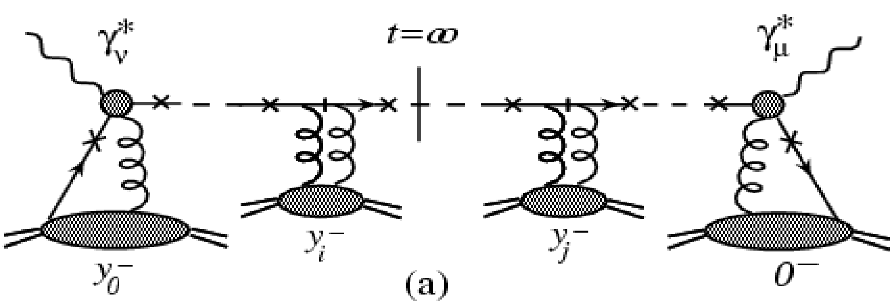
- To Lowest Order (LO) $S_{GLS} = 3, \ \Delta_{GLS} = 0$
- At Next-to-Leading Order $\Delta_{GLS} = \alpha_s / \pi$

- Leading twist shadowing does not change the sum rules (only redistributes momentum)
- Neutrino data is clearly indicative of the high twist nature of nuclear shadowing

Summary of the Dynamical Power Corrections



T.Goldman *et al.*, in preparation



- Shadowing in the perturbative regime is calculable based on the uncertainty principle and energy conservation
- Soft final state interactions generate dynamical parton mass $m^2_{dyn} = \xi^2 A^{1/3}$
- If dictated by the uncertainty principle $x_B < 0.1$ the energy of the struck parton should be larger

$$x_B \to x_B\left(1+\frac{m^2_{dyn}}{Q^2}\right)$$

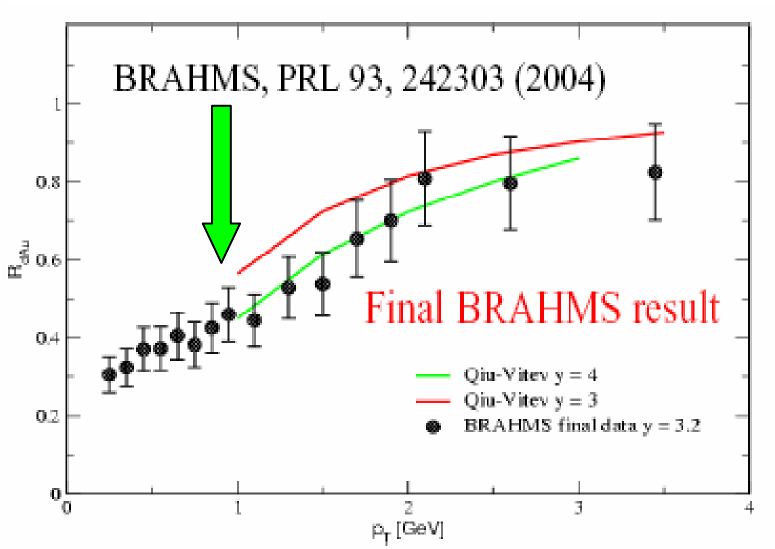
- Clearly a high twist and process dependent effect (final state)

$$S_g > S_{u-sea} > S_{u-val}$$

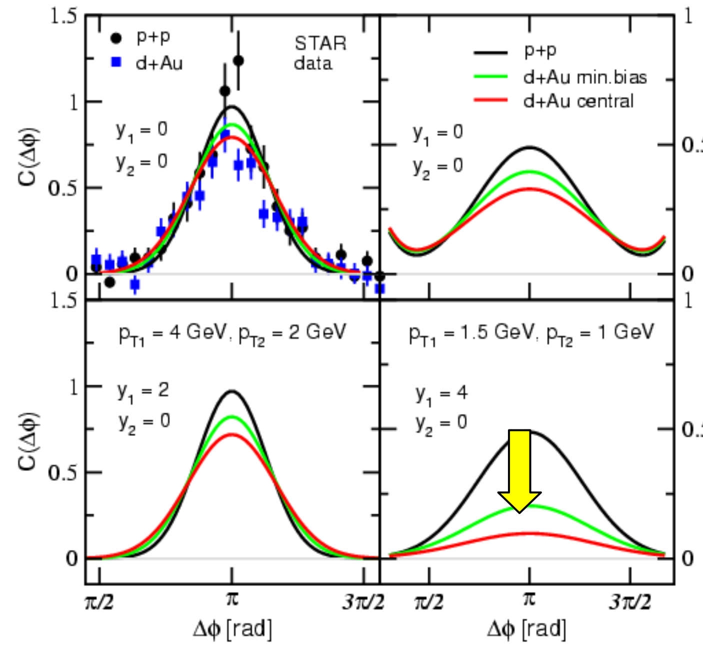
p+A Yields and Correlations

$$F(x_b) \;\rightarrow\; F\left(x_b + x_b C_d \frac{\xi^2}{-t} (A^{1/3} - 1) \right)$$

$$F(x_b) = \frac{\phi(x_b)}{x_b} \left| \overline{M}^{\,2}_{ab \to cd} \right|$$



J.W.Qiu, I.V., hep-ph/0405068



Comparison to the data:

I.Arsene *et al.*, Phys.Rev.Lett. 93 (2004)

Suppression increases with rapidity and centrality

Suppression disappears at high p_T

Data supports this type of power behavior

Conclusions

- "Shadowing" results from the coherent final state parton scattering with several nucleons (dynamical parton mass, refraction index of nuclear matter for q, g)
- The effect is purely quantum. It enters as a shift of the quantum phase and suppresses the SF exhibits power behavior, i.e. strong Q^2 dependence
- Predicts new high twist contribution to FL. Predicts the difference in sea and valence quark shadowing in neutrino-A reactions and the modification of the QCD sum rules
- For p+A reactions results can be generalized to dynamical gluon shadowing. Suppression of the hadron yields and correlations

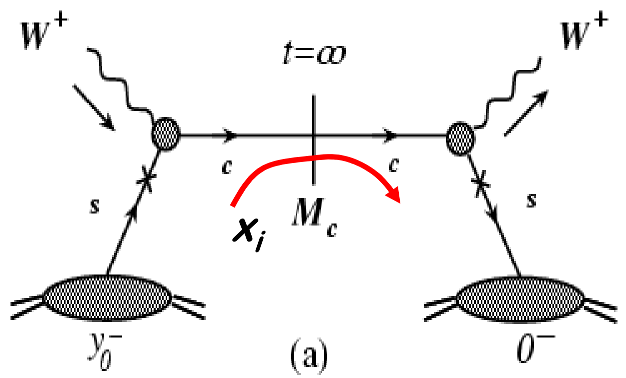
New Contribution to $F_L(x,Q^2)$

On-shell paricle (M)

$$Cut = (2\pi)\frac{x_B}{Q^2}\overbrace{\left(x_M p^+ \gamma^- + (Q^2/2x_B p^+)\gamma^+ \pm M\right)}^{\text{On-shell paricle (M)}}$$

$$\times\, \delta(x_i - x_B - x_M) \qquad \text{(Cuts fix kinematics)}$$

$$x_M = x_B \frac{M^2}{Q^2}$$



J.W.Qiu, I.V., Phys.Lett.B 587 (2004)

- **Even if one neglects** $\phi_c(x,Q^2)$, $\phi_{\bar{c}}(x,Q^2)$ **mass effects show up due to the charge exchange**

- **Along the way we will develop techniques that may be useful in the discussion of charm production at RHIC**

|V| - the CKM matrix elements

$U = (u,c,t)$, $D = (d,s,b)$

$$F_L^{(\nu W^+)}(x_B,Q^2) = \sum_{D,U} |V_{DU}|^2 \frac{M_U^2}{Q^2}\phi_D(x_B + x_{M_U}) + \sum_{\bar{U},\bar{D}} |V_{\bar{U}\bar{D}}|^2 \frac{M_{\bar{D}}^2}{Q^2}\phi_{\bar{U}}(x_B + x_{M_{\bar{D}}})$$

$$F_L^{(\bar{\nu} W^-)}(x_B,Q^2) = \sum_{U,D} |V_{UD}|^2 \frac{M_D^2}{Q^2}\phi_U(x_B + x_{M_D}) + \sum_{\bar{D},\bar{U}} |V_{\bar{D}\bar{U}}|^2 \frac{M_{\bar{U}}^2}{Q^2}\phi_{\bar{D}}(x_B + x_{M_{\bar{U}}})$$

Mass and Nuclear Enhanced Power Corrections

$$\Delta(xp+q) = \pm i \frac{x_B}{Q^2} p^+\gamma^-$$

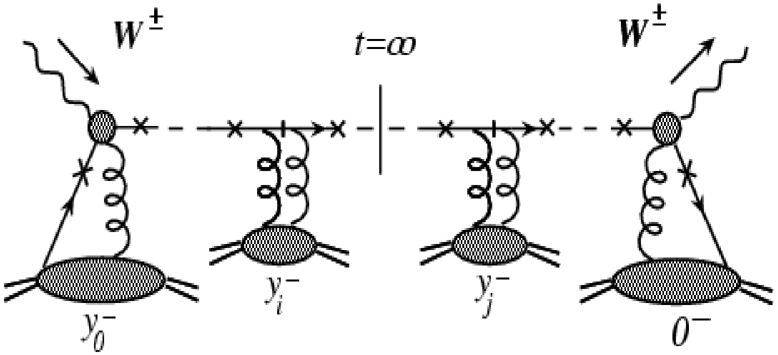
$$\pm i \frac{x_B}{Q^2} \frac{\overbrace{x_M p^+\gamma^- + (Q^2/2x_B p^+)\gamma^+}^{\gamma\cdot\tilde{p}} \pm M}{x-(x_B+x_M)\pm i\varepsilon}$$

Special propagator structure:

$$\left(\gamma\cdot\tilde{p}+M\right)\gamma_\perp\left(\gamma\cdot\tilde{p}+M\right)=0$$

$$\left(\gamma\cdot p\right)\gamma_\perp\left(\gamma\cdot p\right)=0$$

- **Equations of motion - nuclear enhanced power corrections and mass corrections commute**



- **Demonstrated that the corrections can be resummed**

- **Physics interpretation – generation of a dynamical parton mass in the nuclear chromomagnetic field**

$$x_B \rightarrow x_B\left(1+\frac{\xi^2(A^{1/3}-1)}{Q^2}+\frac{M^2}{Q^2}\right) = x_B\left(1+\frac{m_{dyn}^2+M^2}{Q^2}\right)$$