Forward Physics
Power Corrections and Correlations

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Outline of the Talk

- **Understanding shadowing:**
  - Resumming coherent QCD power corrections
  - Modifications to F_L and F_T (F_1, F_2 and F_3)
  - Relations to lowest order and leading twist
- **p+A reactions at RHIC:**
  - Understanding initial and final state multiple scattering
  - Dynamical gluon "shadowing" - yields and correlations
  - E-loss in cold nuclear matter
- **Open charm production and correlations:**
  - Partonic subprocesses and cross sections
  - Dynamical gluon "shadowing" - particle yields and correlations
- **Partial Summaries:**

Theoretical Approach

Collinear factorization approach: can be systematically expanded to include nuclear corrections

Other phenomenologies: data = model, not proven, anyone heard of NLO correction to a dipole or k_T model ...

NLO correction at LT

$$\sigma_{\rm hadron} = \sigma_0^{(2)} \left(1 + C_1^{(2)}\alpha_s + C_2^{(2)}\alpha_s^2 + C_3^{(2)}\alpha_s^3 + \cdots\right) T^{(2)} + \frac{\sigma_0^{(4)}}{Q^2}\left(1 + C_1^{(4)}\alpha_s + C_2^{(4)}\alpha_s^2 + C_3^{(4)}\alpha_s^3 + \cdots\right) T^{(4)} + \frac{\sigma_0^{(6)}}{Q^4}\left(1 + C_1^{(6)}\alpha_s + C_2^{(6)}\alpha_s^2 + C_3^{(6)}\alpha_s^3 + \cdots\right) T^{(6)} + \cdots$$

Non-perturbative matrix elements: Twist 2, 4, 6, ...

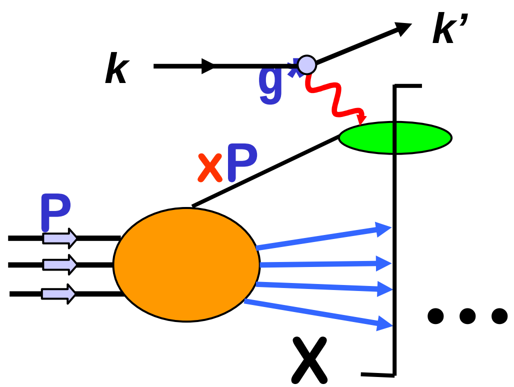
Twist: from Opertaor Product Expansion (OPE)

T = Dimension - Spin

Energy loss - enhanced by the nuclear size

Higher twist (elastic) corrections: dynamical shadowing

Inclusive Deeply Inelastic Lepton-Hadron Scattering



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

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

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

$F_1(x,Q^2), \; F_2(x,Q^2)$ - **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

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

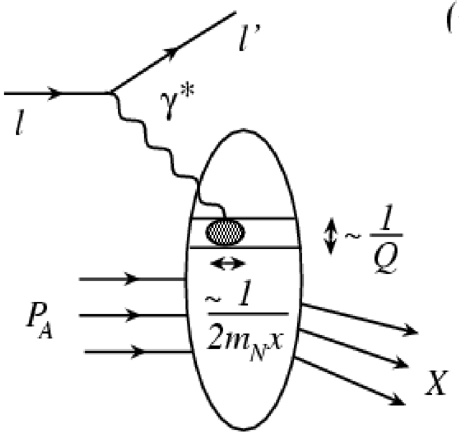
$$F_L(x,Q^2) = \frac{F_2(x,Q^2)}{2x} - F_1(x,Q^2),$$

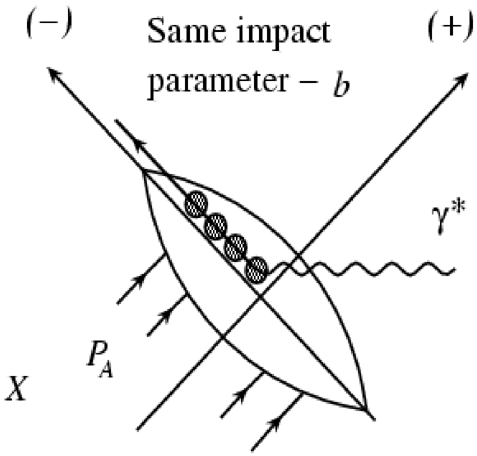
$$\text{if } \frac{4x^2 m_N^2}{Q^2} \ll 1$$

Used to determine the parton distribution functions (PDFs)

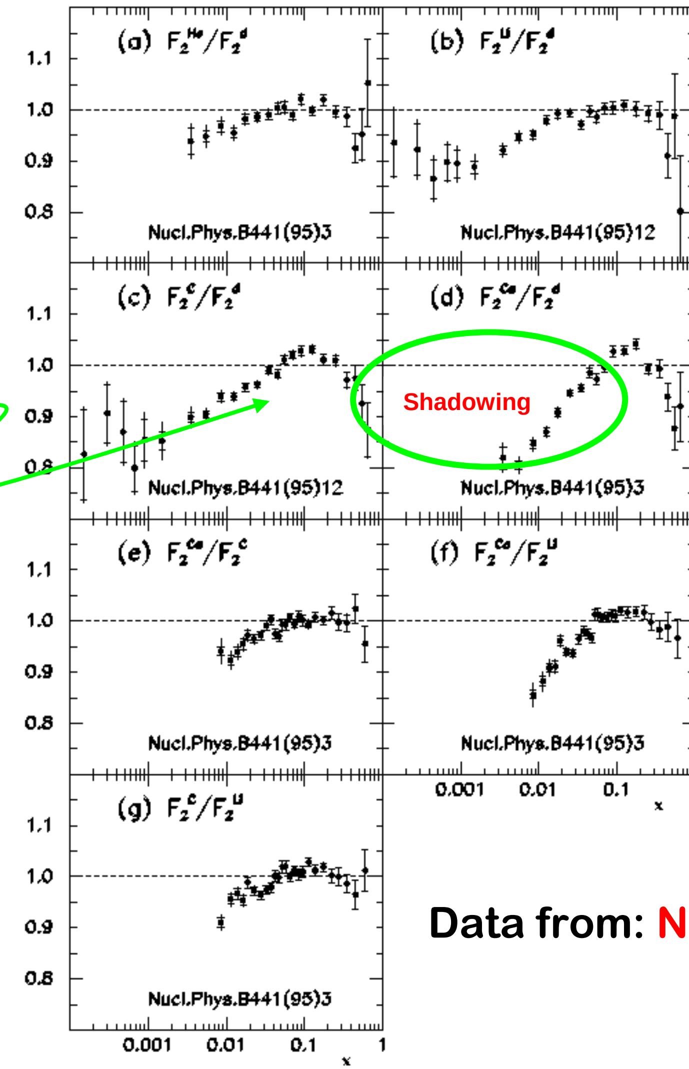
Both simple and dangerous

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**

Data from: NMC

What remains for theory:
power corrections in DIS - suppression

Ivan Vitev, LANL

The Idea Behind the Calculation

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

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

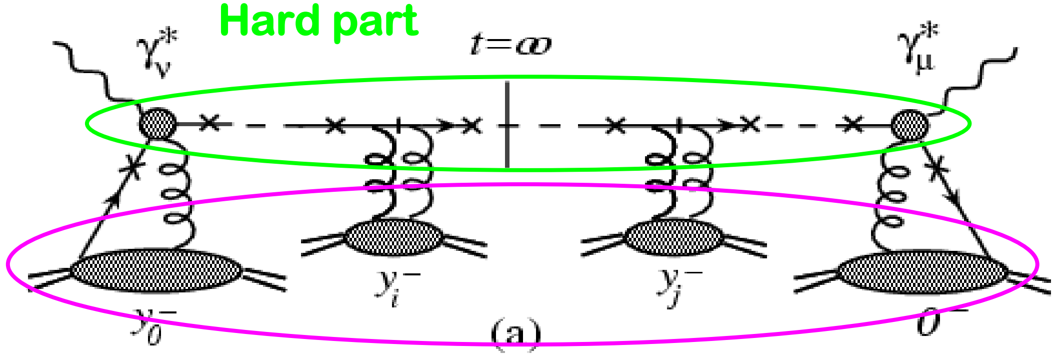
$$Cut = (2\pi) \frac{\gamma^+}{2p^+} \delta(x_i - x_B)$$

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

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: $\sim \xi^2 / Q^2$

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

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

Numerical A- and x_B-Dependence

Purely quantum effect

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

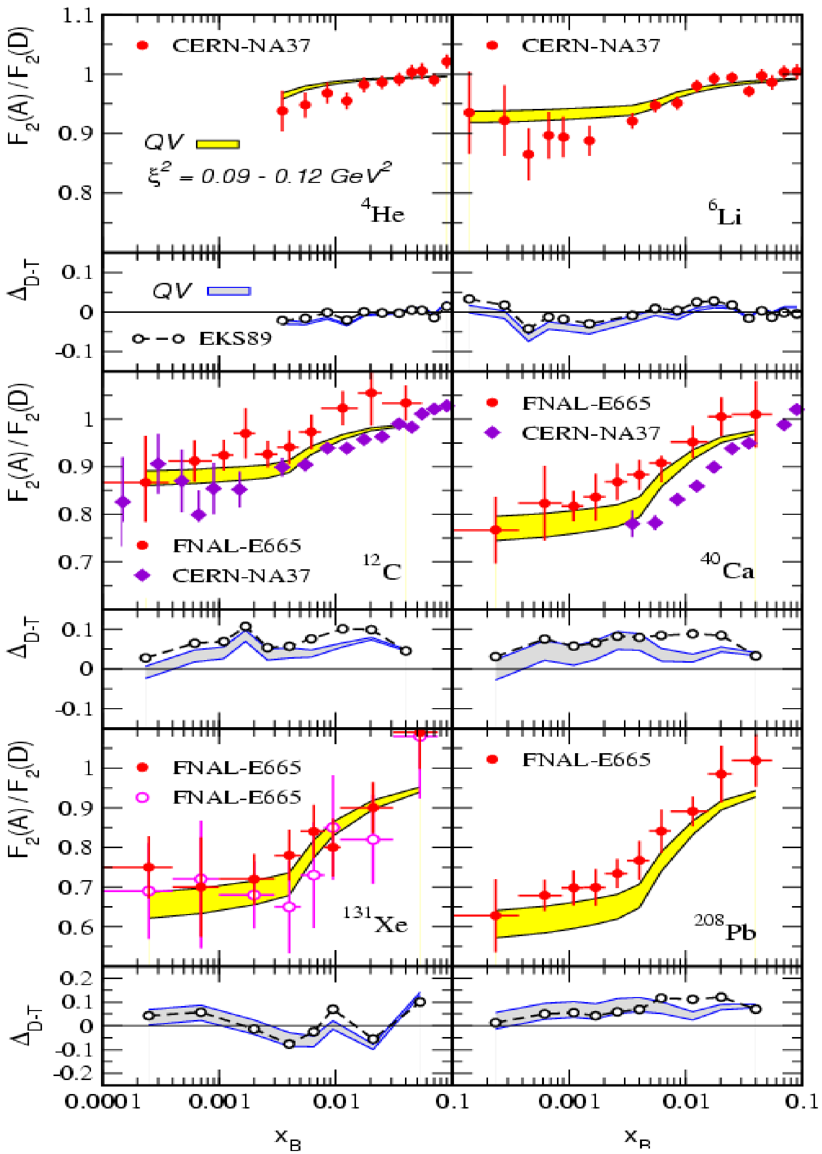
$$F_T^A(x,Q^2) \approx A\, F_T^{(LT)}\left(x + \frac{x\xi^2(A^{1/3}-1)}{Q^2}, Q^2 \right)$$

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

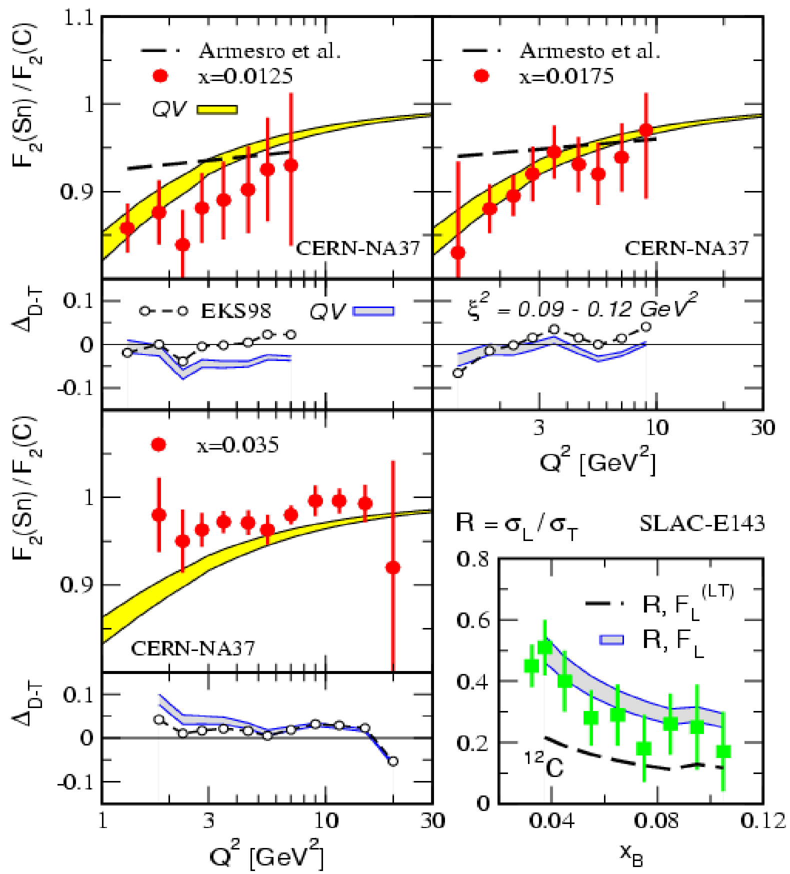
- Favorable comparison for the x- and A-dependence NA37 (NMC) and E665 data
- For $Q^2 \to 0$ we impose $Q^2 = m_N^2$.

Finite resolution: same for all models (r_{max})

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 $F_2(Sn)/F_2(C)$

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

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

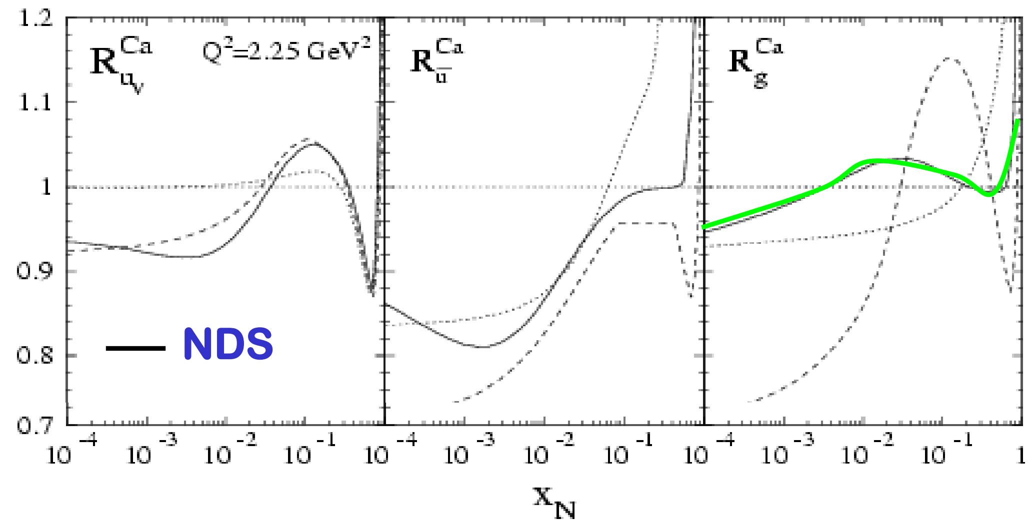
- The Leading Twist (LT) $R(x,Q^2)$ is not sensitive to modifications of the nPDFs

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



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

Very small (negligible) gluon shadowing

- Paradox: for initial state shadowing models $C_A/C_F = 2.25$

- Natural: for final state resummed power corrections

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

Modifications to $\nu + A$ Scattering

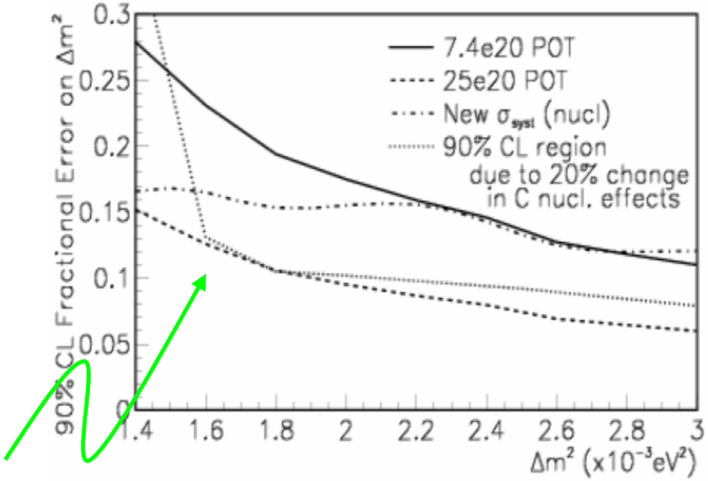
- **No theory** for the shadowing in $\nu + A$ (exchange $W^{\pm}, Z^{0}$)
- 3σ **deviation** from the Standard Model (Now $1.8\ \sigma$)

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

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

NuTeV experiment

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



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

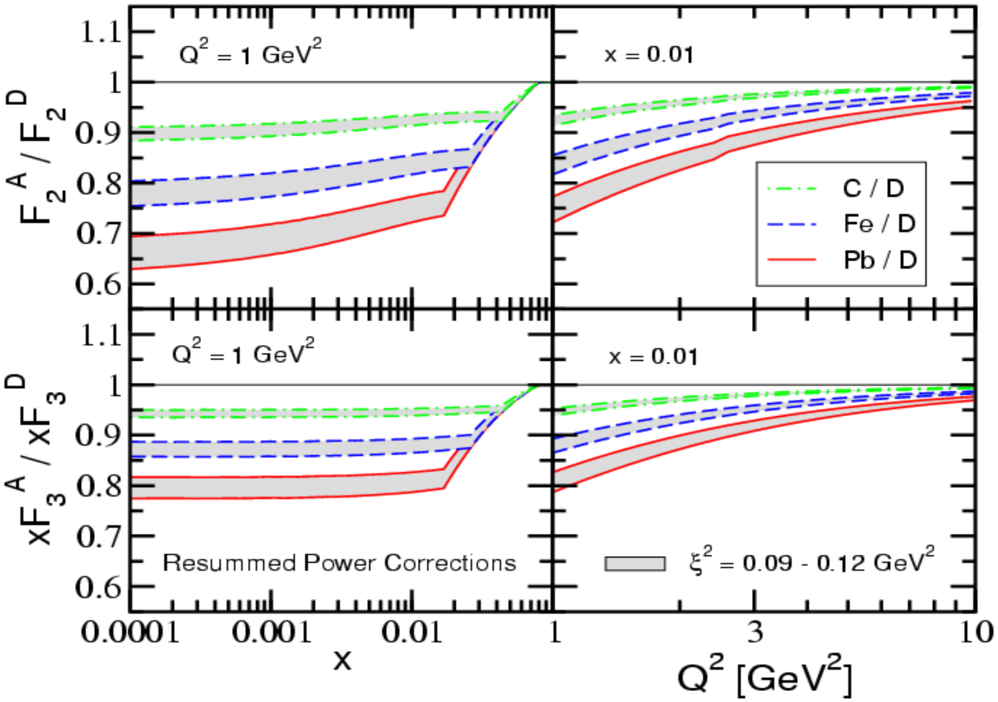
Cross sections matter

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

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 $xF_3(x)$

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

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

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

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

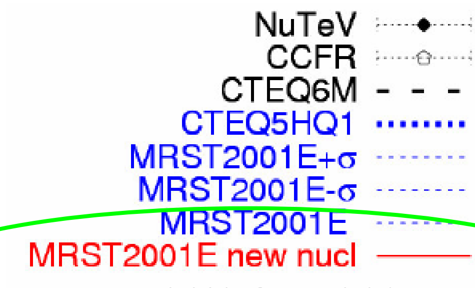
$$F_{1,3}^{(\nu W^+)}(x_B,Q^2) = \{2\} A \left(\sum_{D,U} |V_{DU}|^2 \phi_D(x_B + x_{\xi^2} + x_{M_U}) \pm \sum_{\bar{U},\bar{D}} |V_{\bar{U}\bar{D}}|^2 \phi_{\bar{U}}(x_B + x_{\xi^2} + x_{M_{\bar{D}}}) \right)$$

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

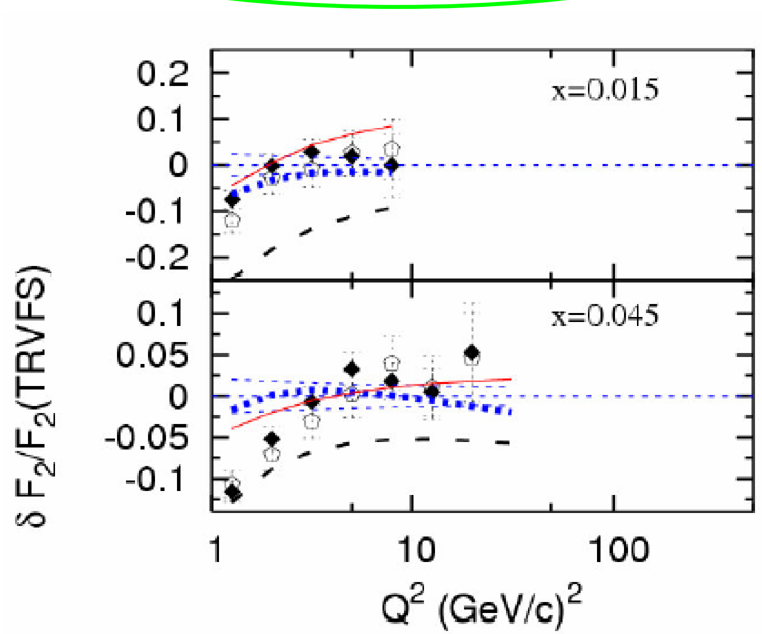
$$x_B \rightarrow x_B\left(1 + \frac{\xi^2(A^{1/3}-1)}{Q^2} + \frac{M^2}{Q^2}\right) = x_B\left(1 + \frac{m_{dyn}^2 + M^2}{Q^2}\right)$$

NuTeV / CCFR Structure Functions

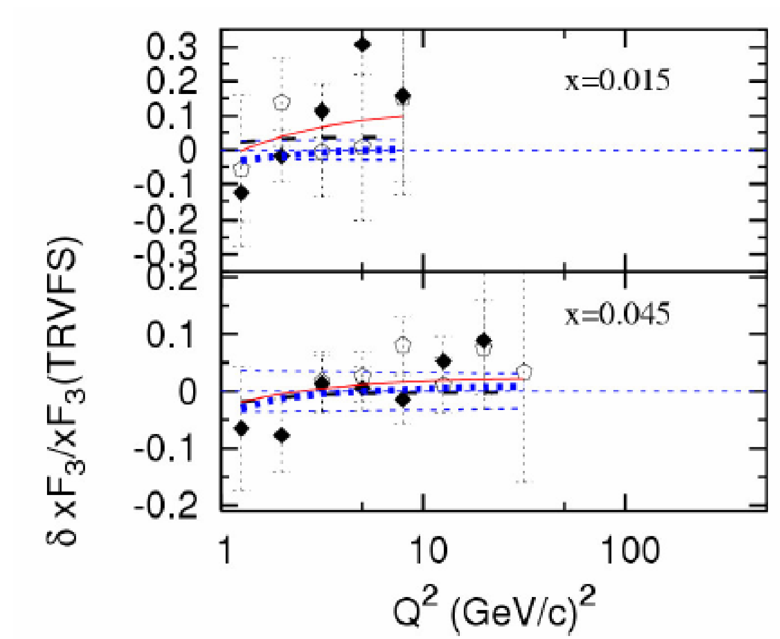
M.Tzanov, DPF 2004 fall meeting Riverside, CA, DIS 2005 Madison, WI



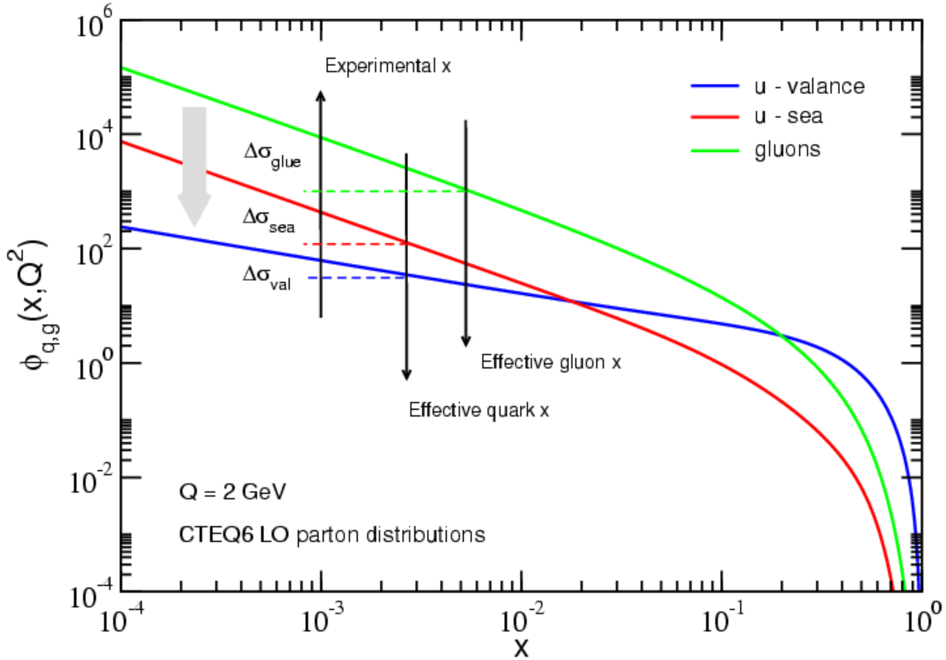
J.W.Qiu, I.V.



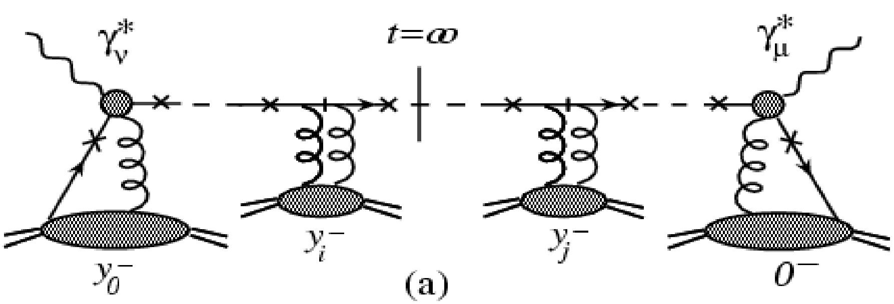
- **Focus on the small Q^2 and $x < 0.1$ region**
- **Look relative to MRST 2001 (CTEQ 5,6 have included the data in their analysis thus incorrectly including the nuclear effect in PDFs)**



Physics 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)

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

Summary of High Twist Shadowing

- "Shadowing" results from the coherent final state parton scattering with several nucleons

- The effect is purely quantum. It enters as a shift of the quantum phase and suppresses the SF. The PDFs are the same a in the nucleon

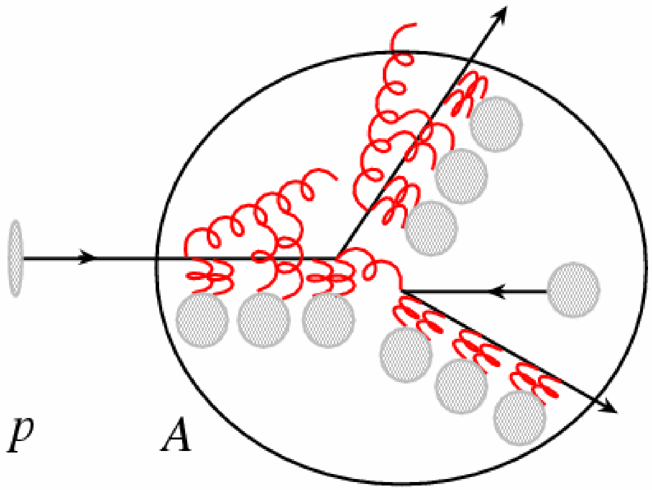
- The shadowing effect exhibits higher twist (power) behavior, i.e. strong Q^2 dependence

- Nuclear matter has refraction index for quarks and gluons

p+A Collisions are not DIS

Type of scattering	Transverse momentum dependence of the nuclear effect
Elastic (incoherent)	Cronin effect: small suppression at low p_T, enhancement at moderate p_T, disappears at high p_T. Dijet acoplanarity: p_T diffusions, broadening of away-side corelations
Inelastic (radiative)	Single inclusives: suppression at all p_T, weak p_T dependence, persists at high p_T (amplified near kinematic bounds). Double inclusive: suppression of high p_T correlations, reapearance of the energy at low p_T
Coherent (elastic $t-$channel)	Both single and double inclusive: suppression at low p_T, disappears at high p_T, pronounced p_T dependence

TABLE I: Effect of elastic, inelastic and coherent multiple scattering on the transverse momentum dependence of single and double inclusive hadron production in the perturbative regime.



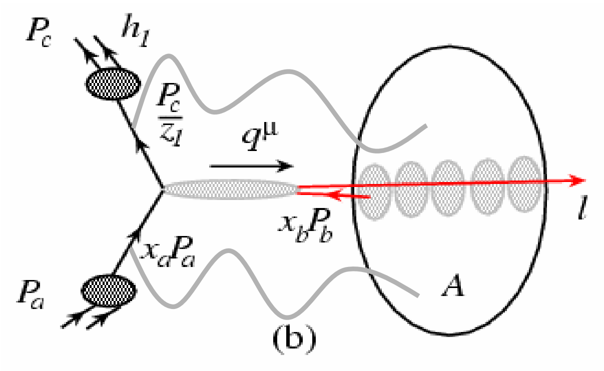
- **p+A collisions do not carry direct information about PDFs (unfortunately all effects)**
- **Forward (backward) physics not equal small x (large x)**

1) Initial state energy loss and broadening - DY

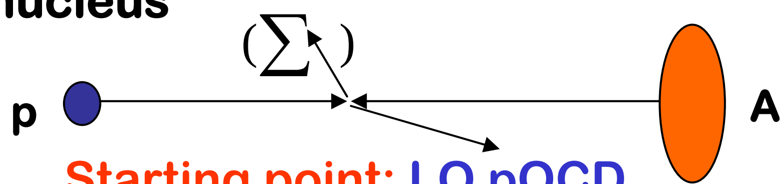
2) Shadowing - DIS

3) Final state e-loss is added in p+A

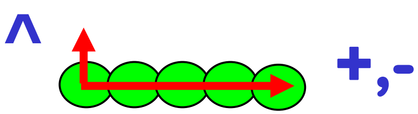
p+A Collisions



Resume the multiple final state scattering of the parton "d" with the remnants of the nucleus



Starting point: LO pQCD



- **Interested in the maximum coherent rescattering of the small x_b parton in the nucleus**
- **Other interactions are less coherent (elastic) and sppressed at forward rapidity by a large scale 1/u, 1/s**

$$\frac{d\sigma_{NN}^{h_1}}{dy_1 d^2 p_{T1}} = K \sum_{abcd} \int_{z_1\,\min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1^{\,2}} \int_{x_a\,\min}^{1} x_a \frac{\phi(x_a)}{x_a} \frac{1}{x_a S + U/z_1} \frac{\alpha_s^2}{S} \int_0^1 x_b \delta(x_b - \overline{x}_b)\, F(x_b)$$

$$\frac{d\sigma_{NN}^{h_1 h_2}}{dy_1 dy_2 d^2 p_{T1} d^2 p_{T2}} = \frac{\delta(\Delta\varphi - \pi)}{p_{T1} p_{T2}} \sum_{abcd} \int_{z_1\,\min}^{1} dz_1 \frac{D_{h_1/c}(z_1)}{z_1} D_{h_2/d}(z_2) \frac{\phi(\overline{x}_a)}{\overline{x}_a} \frac{\alpha_s^2}{S^2} \int_0^1 x_b \delta(x_b - \overline{x}_b)\, F(x_b)$$

$\phi(x_b)$ **- standard parton distribution functions**

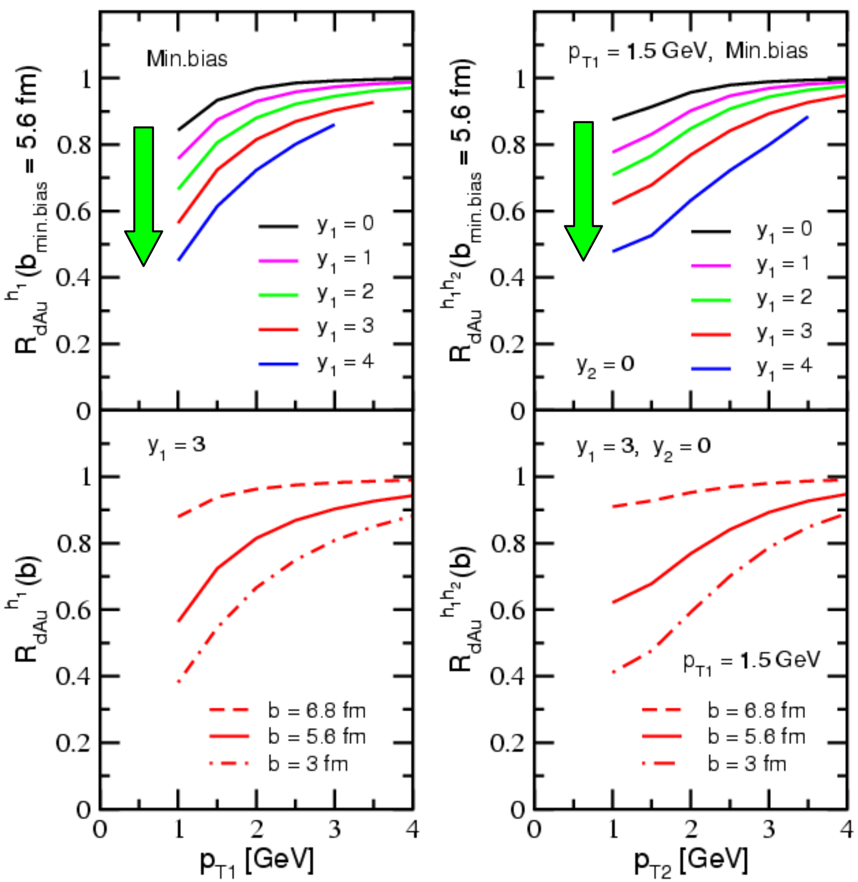
$D_{h_1/c}(z_1)$ **- standard parton distribution functions**

Isolate all the x_b dependence of the integrand: $F(x_b) = \frac{\phi(x_b)}{x_b} \left| \overline{M}^{\,2}_{ab\to cd} \right|$

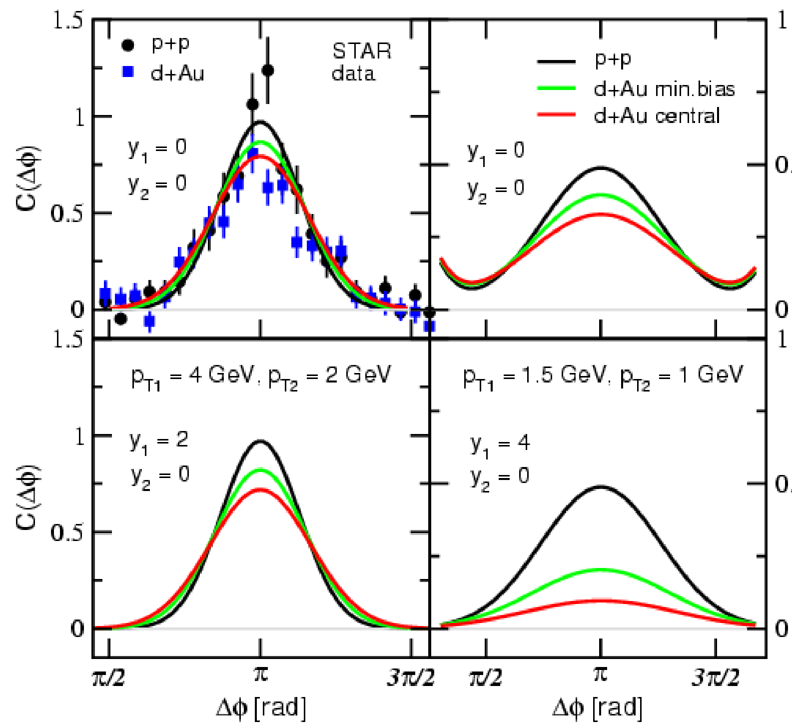
Numerical Results

$$\sum_{N=0,\infty} \int dx_b \delta(x_b - \bar{x}_b) F(x_b) \;\to$$

$$\int dx_b \delta(x_b - \bar{x}_b) F\left(x_b + x_b C_d \frac{\xi^2}{-t} (A^{1/3} - 1) \right)$$



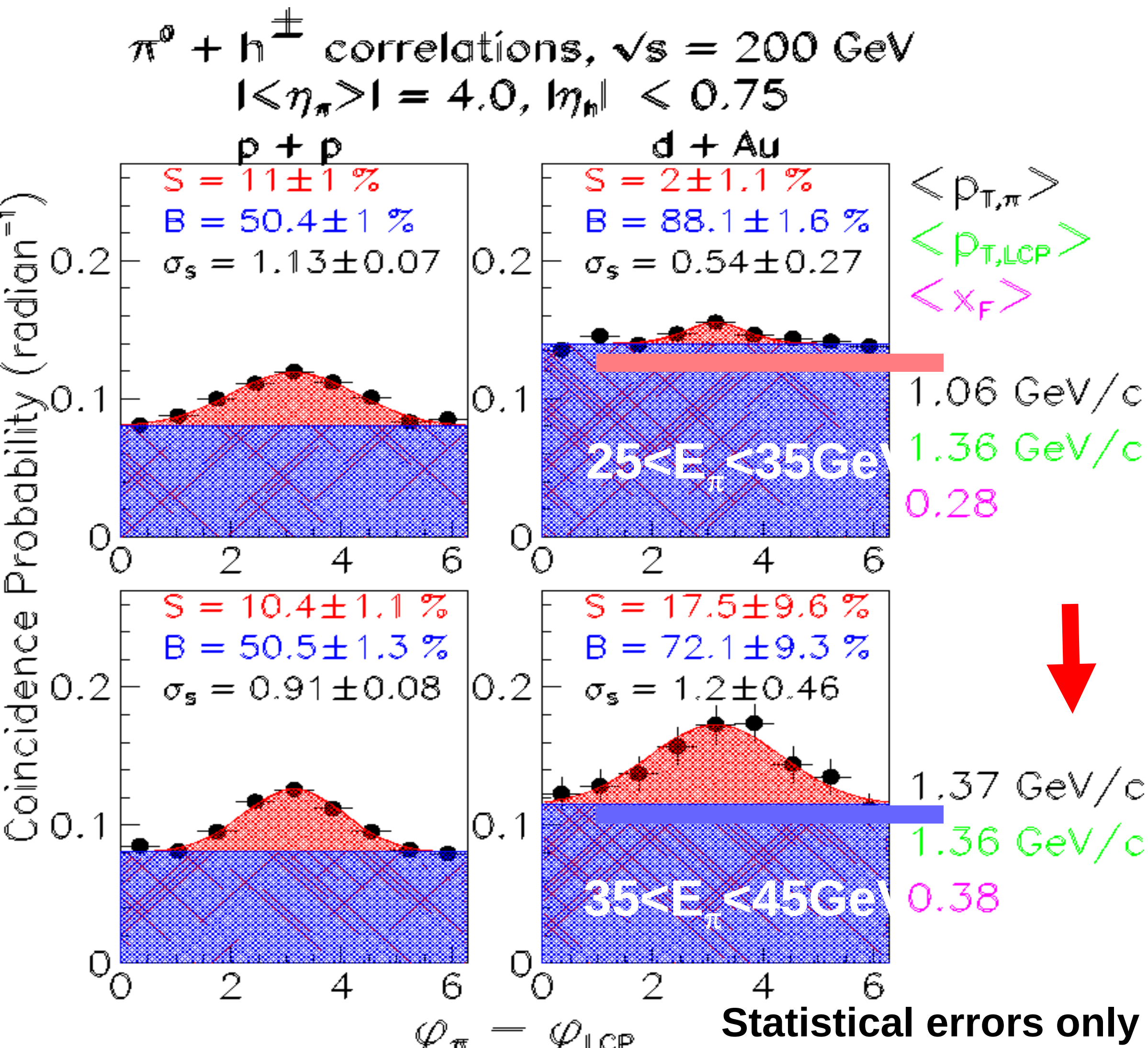
- **Similar** power corrections modification to **single and double inclusive hadron production**
  - **increases** with **rapidity and centrality**
  - **disappears** at **high p_T** in accord with the QCD factorization theorems



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

Forward Correlations

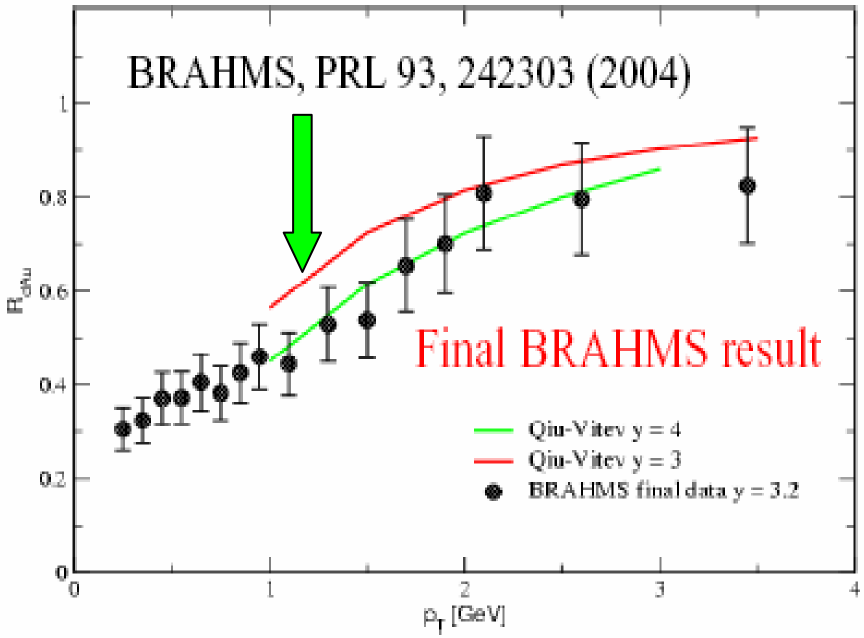
STAR **Preliminary:** L.Bland, [STAR Colaboration]



Statistical errors only

- There isn't mono jettiness or g-fusion
- I think that the p+A analysis has under and over estimated the away-side area
- There may be room for some suppression due to power corrections

p+A Yields



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

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

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

Suppression increases with rapidity and centrality

Suppression disappears at high p_T

Data supports this type of power behavior

Comparison to the data:

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

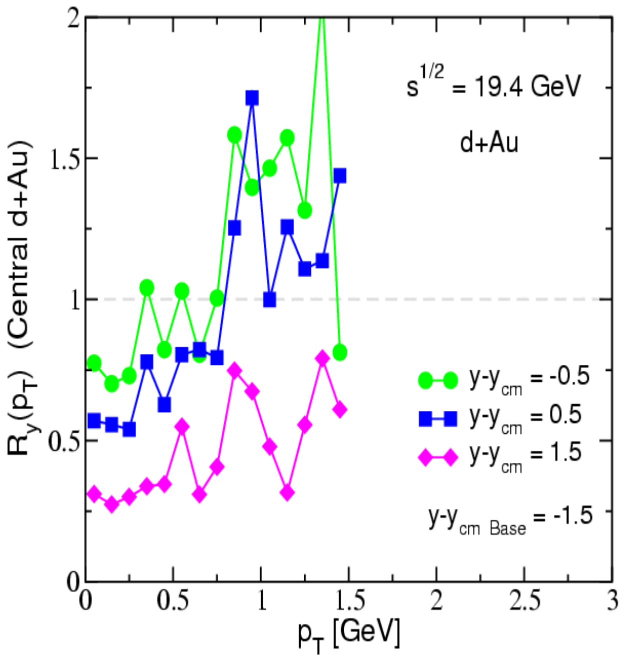
However, there may be room for additional suppression - may be 50 % more, may be a factor of 2

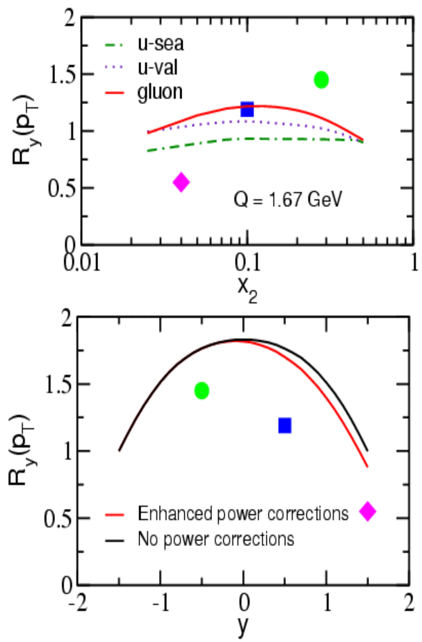
Energy Loss in Cold Nuclear Matter

- **Before jumping to conclusions investigate existing data**

NA35 collaboration: d+Au (interestingly enough) data - $\sqrt{s_{NN}} = 19.4\ GeV$

Same rapidity asymmetry as at $\sqrt{s_{NN}} = 200\ GeV$





T.Goldman *et al.*, in preparation

- **Leading twist shadowing: (phenomenology) clearly insufficient (in fact antishadowing)**
- **Power corrections (theory) : clearly insufficient (~13%)**

Leaves additional effects: enegy loss

One Implementation of Energy Loss

Bertsch-Gunion bremsstrahlung:

$$\frac{dn_G}{dy} = \frac{3\alpha_s}{\pi} \ln\left(\frac{m_\rho^2}{\Lambda_{QCD}^2}\right)$$

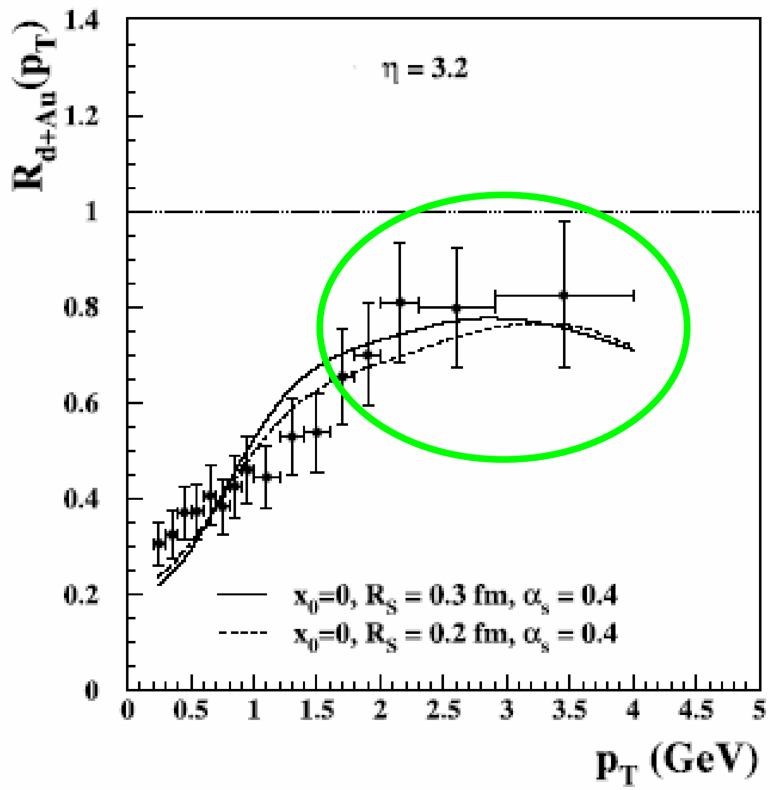
Implemented as "Sudakov Form Factors":

$$S(x_F) = (1 - x_F)^{dn_G/dy}$$

This is one way of implementing energy loss (large rapidity gap events, amplification near kinematic bounds)

B. Kopeliovich *et al.*, hep-ph/0501260

Where energy loss arguably plays a role

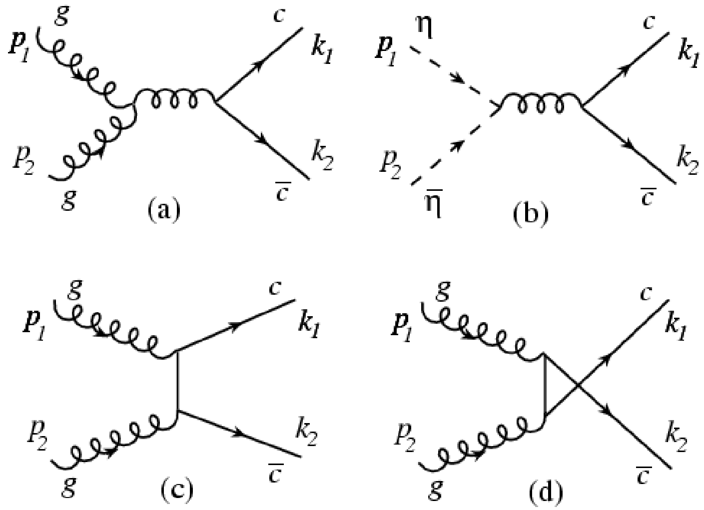


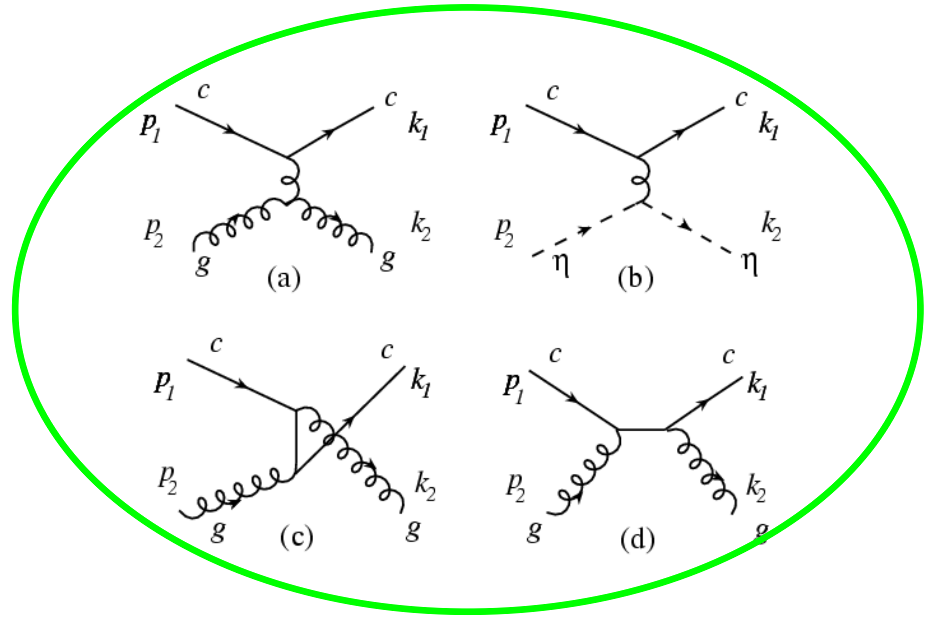
Summary of p+A (Light Hadrons)

- p+A is not substitute for DIS. Don't learn much about PDFs. Learn about multiple parton interactions
- Calculated the upper limit of the suppression in p+A reactions from shadowing.
- The results are compatible with the data but the current statistics and systematics are large
- At large x_F energy loss can play a significant role. There is low energy p+A to be analized. Low energy RHIC run.

Open Charm Production

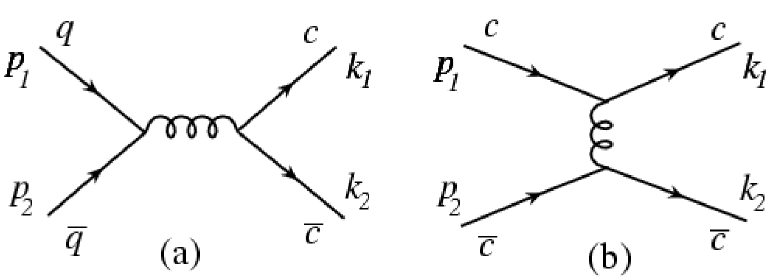
Time direction

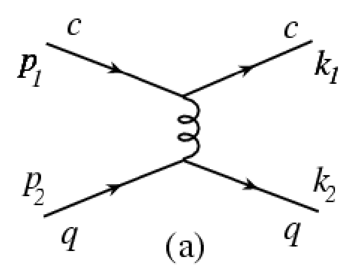




Popular belief

In practice to LO **(To be checked)**



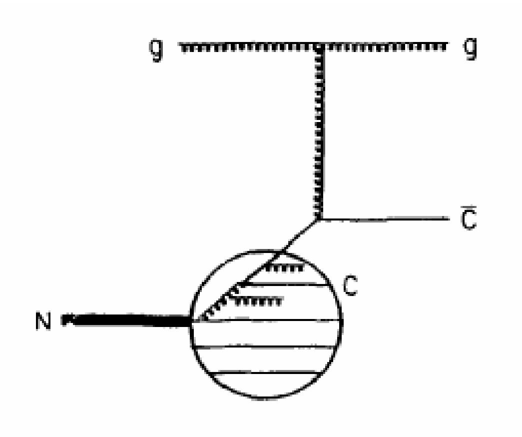


Many of the interesting features that follow are related to the $cg \rightarrow cg$ $cq(\overline{q}) \rightarrow cq(\overline{q})$ **scattering**

Research of Literature

L. Odoricio, Nucl.Phys.B 209 (1982)

Flavor excitation = charm quark pdfs



We present a calculation of the contribution of flavour excitation diagrams to the hadronic production of open charm. The main new ingredients in the calculation are: (i) a proper treatment of the QCD evolution of the input charm sea distribution, with constraints from the existing charm structure function data; (ii) use of the available charm transverse momentum data to fix the cutoff which regulates the divergence in the diagrams. We are then able to make a stable calculation of the resulting charm cross section. The flavour excitation contribution turns out to be an order of magnitude larger than for fusion. As a result the observed magnitudes of the charm cross section at accelerator and ISR energies are satisfactorily reproduced, thus eliminating a long standing difficulty of the perturbative QCD approach to open charm production. Furthermore, we calculate the longitudinal and transverse spectra of charmed hadrons using a simple recombination model. We show that the existing ISR data on the production of fast $_c$ are well, and naturally, reproduced by this approach. Qualitative predictions for bottom production are also discussed.

D^0 and D^+ at the Tevatron

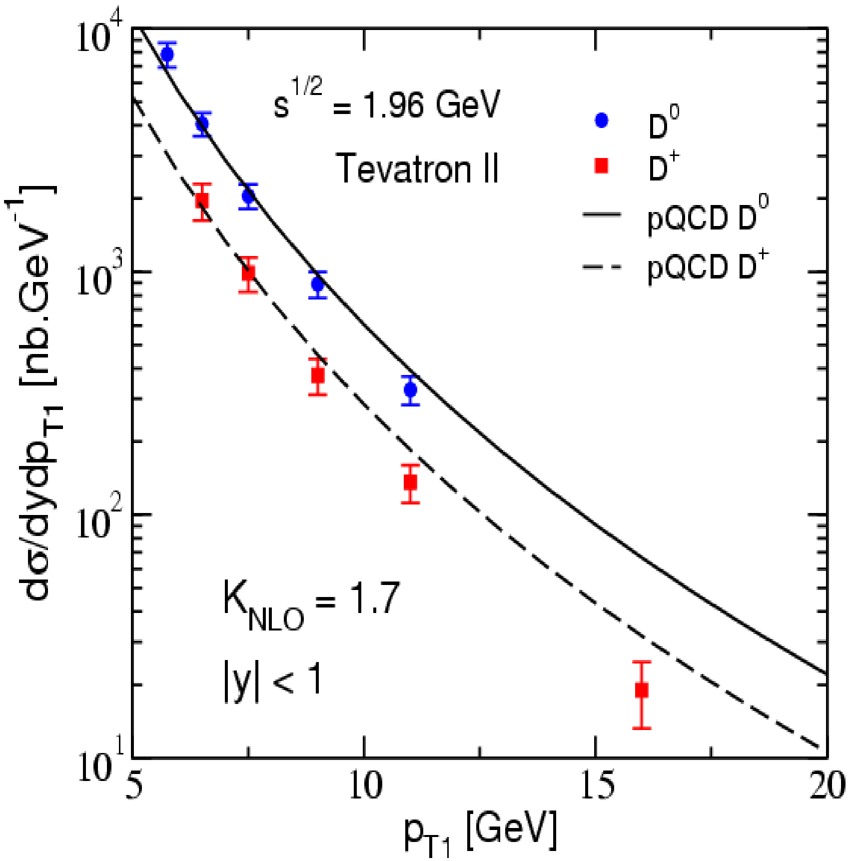
$$\frac{d\sigma_{NN}^{D_1}}{dy_1 d^2 p_{T_1}} = K_{NLO} \sum_{abcd} \int_{x_{1,2}\leq 1} dy_2 \int_{x_{1,2}\leq 1} dz_1$$
$$\times \frac{1}{z_1^2} D_{D_1/c}(z_1) \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2$$

- **Fragmentation functions: From heavy quark effective field theory (Vector and Pseudoscalar)**

E.Braaten *et al.*, Phys.Rev.D 51 (1995)

- **Branching ratios taken into account**

$D^{0*} \to D^0 \; (BR\ 100\%) \quad \cdots$



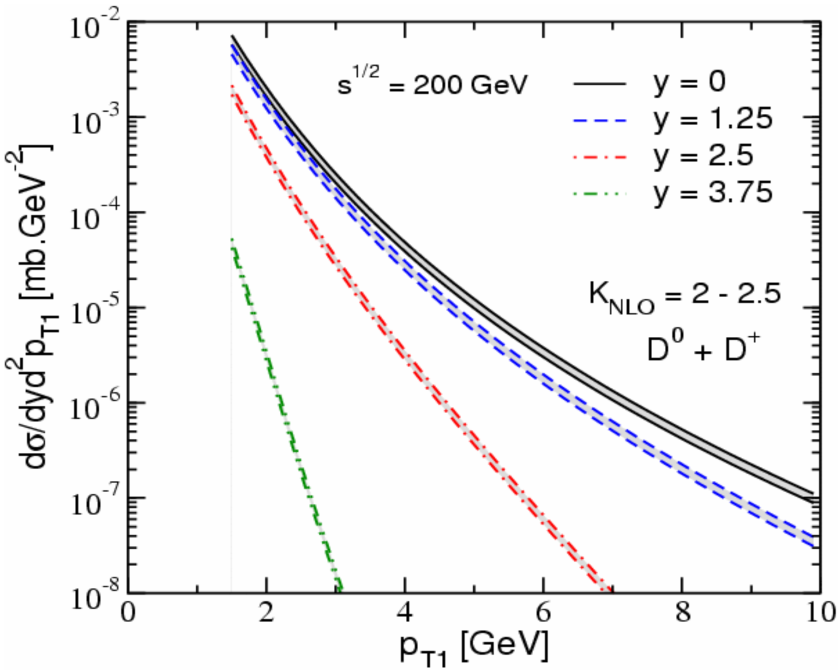
Very reasonable K-factor: K_{NLO} = 1.7

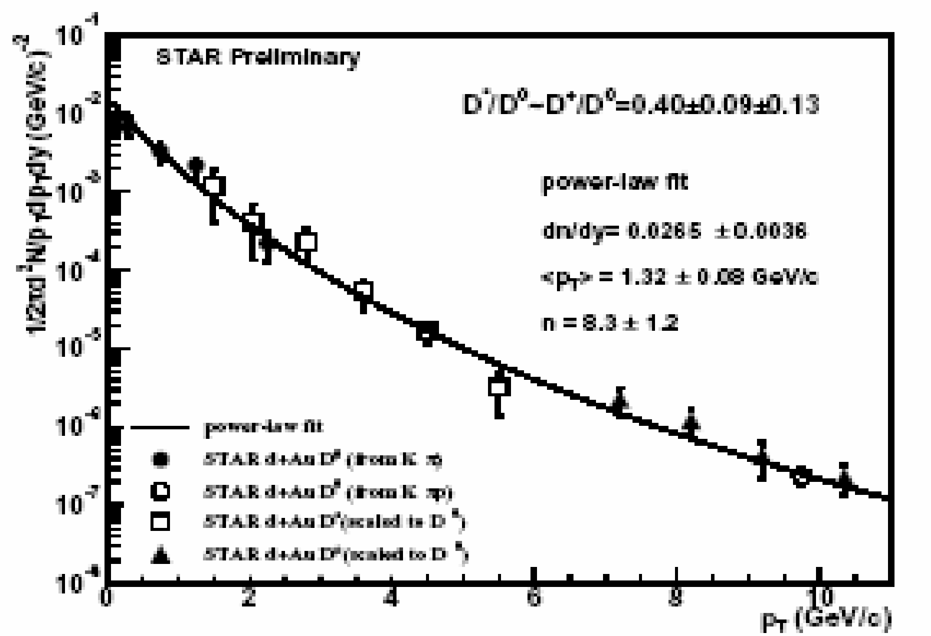
Slightly stiffer power law

Data from:

D.Acosta *et al.*, Phys.Rev.Lett. 91 (2003)

Predicted Cross Sections at RHIC





H. Zhang, nucl-ex/0410038

Comparable results to:

M.Cacciari, P.Nason and R.Vogt, hep-ph/0502203

Case for a new experimental capability to detect directly heavy quarks

Preliminary STAR: power law spectrum seems noticeably stiffer

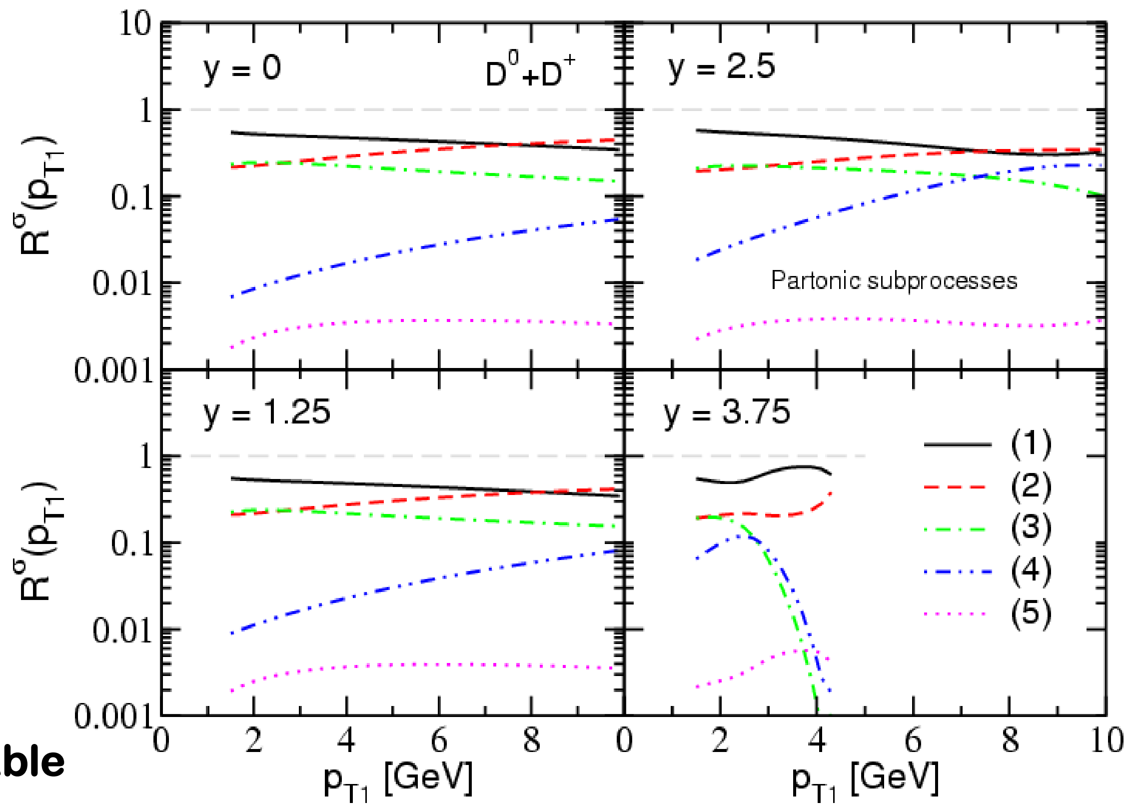
Remember - at the Tevatron the same calculation was slightly stiffer

Contribution of Partonic Subprocesses

Define partial cross sections

$$R^{\sigma}(p_{T_1}) = \frac{d\sigma^{D_1}_{ab\to cd}}{dy_1 d^2 p_{T_1}} \Big/ \frac{d\sigma^{D_1}_{tot}}{dy_1 d^2 p_{T_1}}$$

Gluon fussion is not the dominant mechanism for open charm production



Clearly one expects 2 things:

- **Dynamical shadowing comparable to light pions**
- **Trigger dependent hadrochemistry**

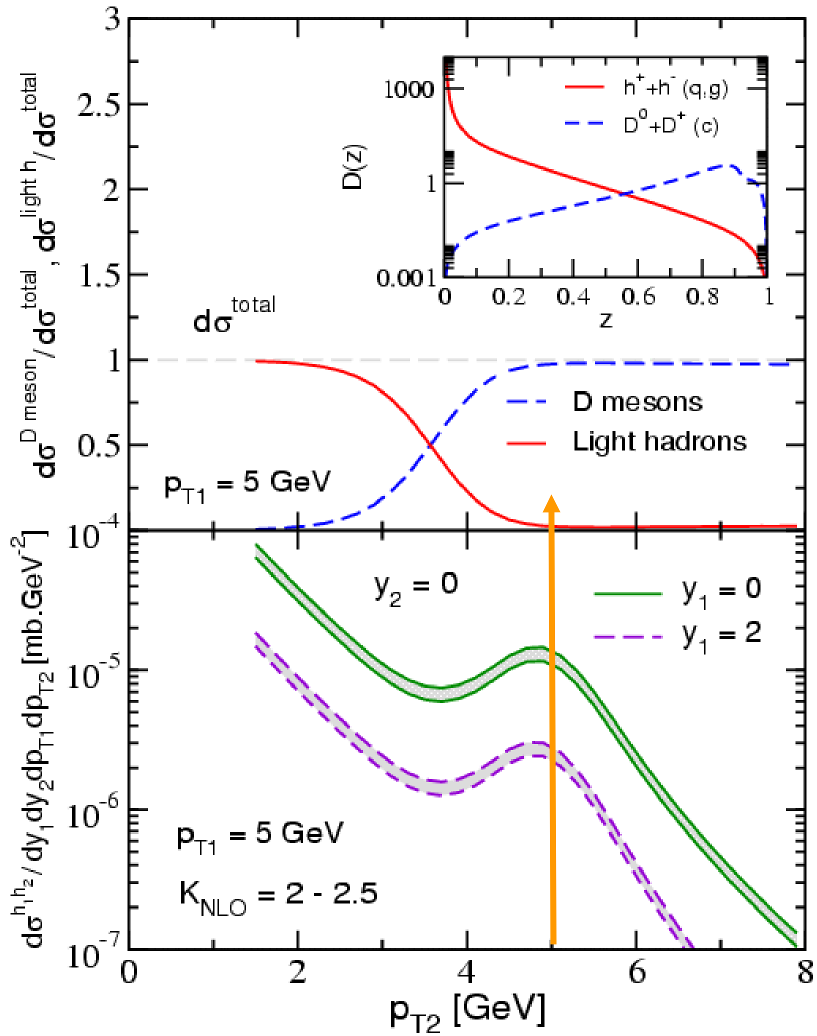
$$(1)\ cg \to cg,\ (2)\ cq(\bar{q}) \to cq(\bar{q})$$
$$(3)\ gg \to c\bar{c},\ (4)\ q\bar{q} \to c\bar{c}$$
$$(5)\ c\bar{c} \to c\bar{c}$$

How to test this? - di-hadron correlations

D Triggered Correlations

$$\frac{d\sigma^{D_1 h_2}_{NN}}{dy_1 dy_2 dp_{T_1} dp_{T_2}} = K_{NLO} \sum_{abcd} 2\pi \int_{x_1\le 1, x_2 \le 1, z_2 \le 1} dz_1 \times \frac{1}{z_1} D_{D_1/c}(z_1) D_{h_2/d}(z_2) \frac{\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \times \frac{\alpha_s^2}{S^2} |\overline{M}_{ab\to cd}|^2 \, .$$

- **Very strong dependence of particle species in the away side jet on p_{T2}**
- **Non-monotonic behavior on the away side yields: anti D at $p_{T2} = p_{T1}$**



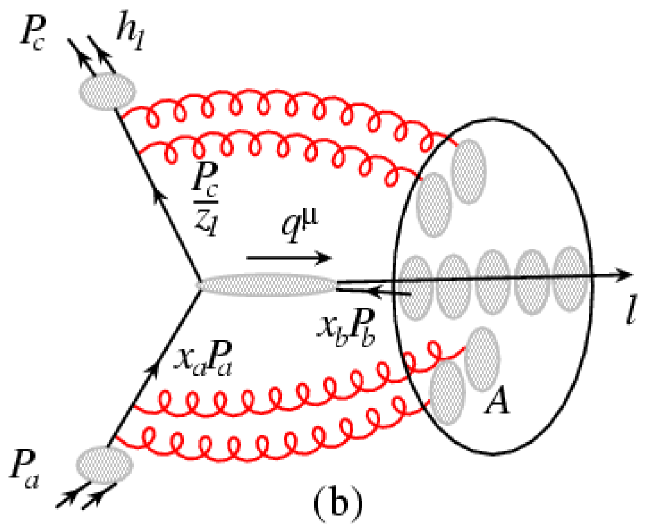
T.Goldman *et al.*, in preparation

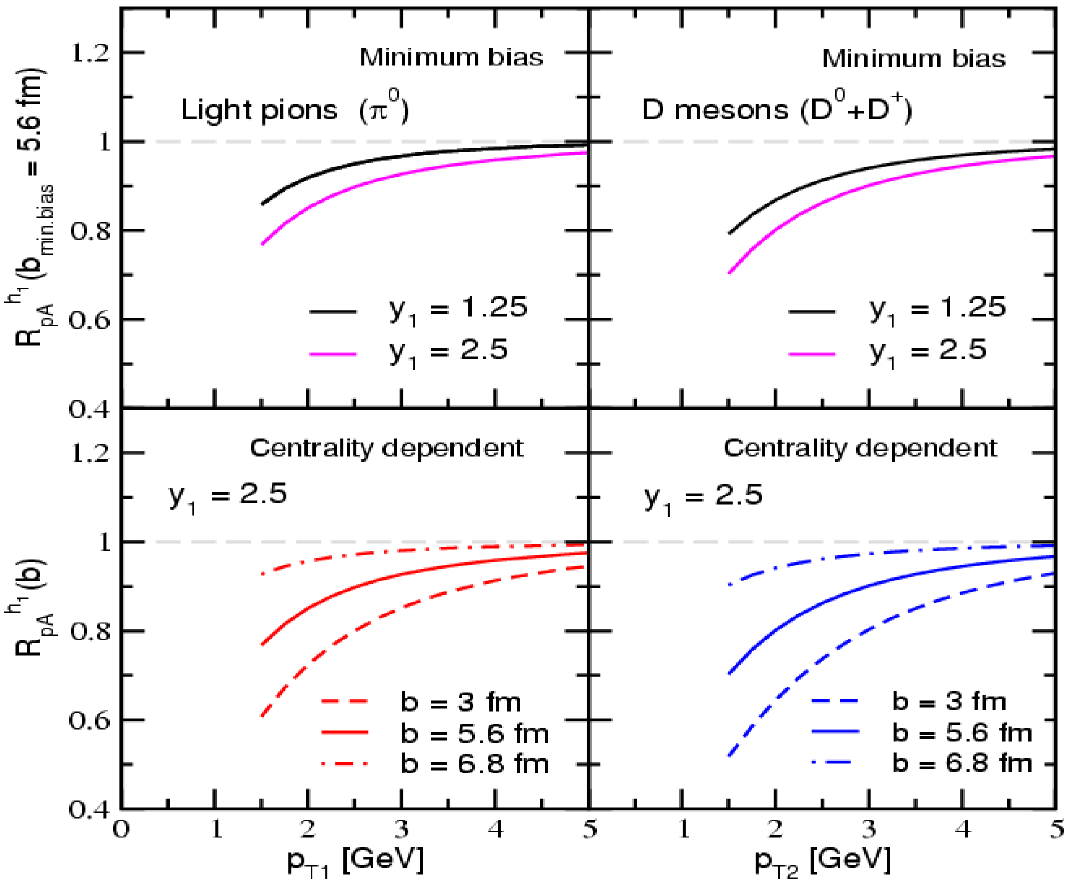
Never measured before:

Real possibility for RHIC experiments to discover D meson triggered correlations

Constrain D meson production, c quark fragmentation

Dynamical Shadowing to Inclusive D^0+D^+





Increases with centrality:

(dynamical shadowing has little to do with A but with the local path length through nuclear matter)

Increases with rapidity:

(slightly)

Disappears at high p_T:

(power correction type, coherent elastic)

Quite similar to light pions (even slightly larger)

(D^0+D^+) - (D^0+D^-) Triggered Correlations

Similar results for the D meson triggered correlations

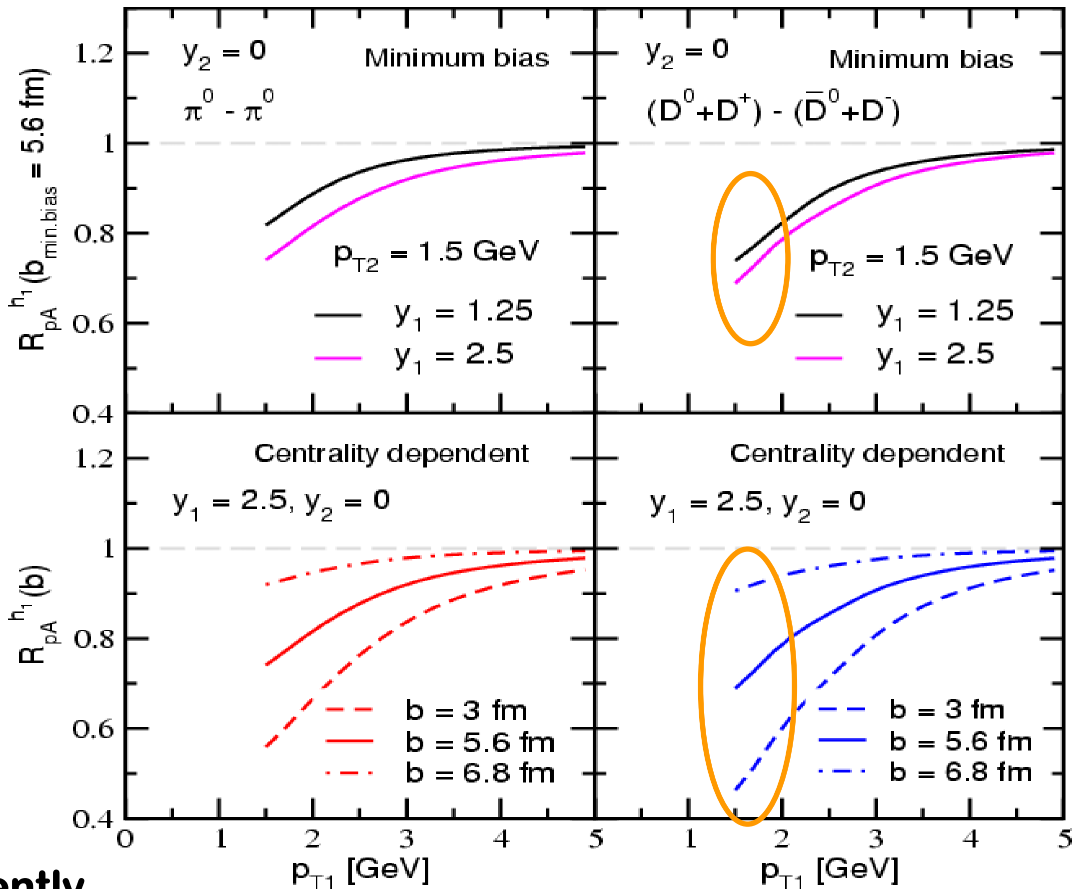
$$\hat{t} = (x_a P_a - p_c / z_1)^2$$

- **We know for a fact that the c quark rescatters (as in DIS)**

$$\xi^2 (A^{1/3} - 1) / (-\hat{t})$$

- **In light hadrons**

$$C_A / C_F \xi^2 (A^{1/3} - 1) / (-\hat{t})$$



Naively expected that the partonic composition will matter but apparently what dominates is:

$$z_{light\ hadons} < z_{charm\ mesons}$$

Experimentally probably biased to $p_{T1} = p_{T2}$

Summary of Open Charm and Open Charm Correlations

- A large contribution to the open cham (single) hard cross section comes from scattering on quarks and gluons
- Non-trivial hadron composition of D triggered correlations should be experimentally tested
- The power corrections a similar to the light hadrons but the reason is different - the large z_1, z_2 even if it is q rather than g rescattering
- We have calculated the upper high twist shadowing limit - a baseline for the energy loss

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

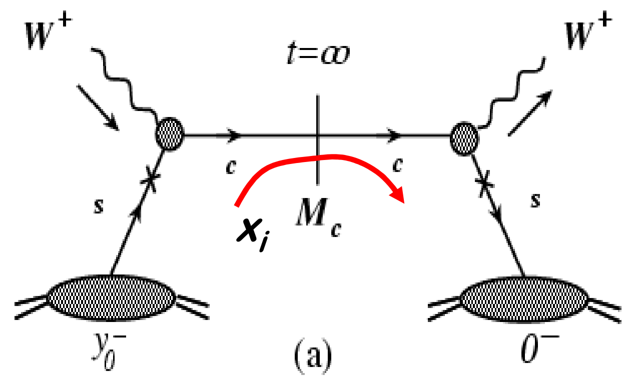
On-shell paricle (M)

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

$$\times\,\delta(x_i - x_B - x_M)$$

(Cuts fix kinematics)

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



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

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

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

|V| - the CKM matrix elements

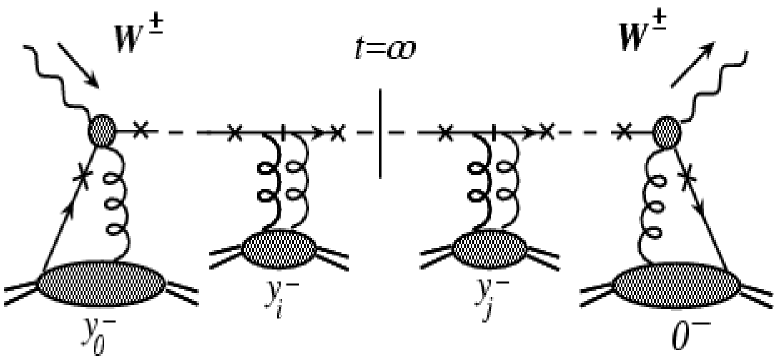
$U = (u,c,t)$, $D = (d,s,b)$

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

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

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:

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

- **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**

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

Summary of Neutrino-Nucleus Scattering

- Resummed power corrections are the first consistent way to address valence/sea quark shadowing
- Neutrino-nucleus reactions help discover the physical meaning of higher twist - generation of dynamical parton mass
- For light quarks we have dynamical chiral symmetry breaking (similar to electrons in B field)
- Goes in the direction of reducing the discrepancy between the NuTeV experiment and the SM
- The qualitative power law behavior at small x is seen by NuTeV / CCFR. Expect comparison