Hadron structure at large x

Alberto Accardi
Hampton U. & Jefferson Lab

ECT*, Trento
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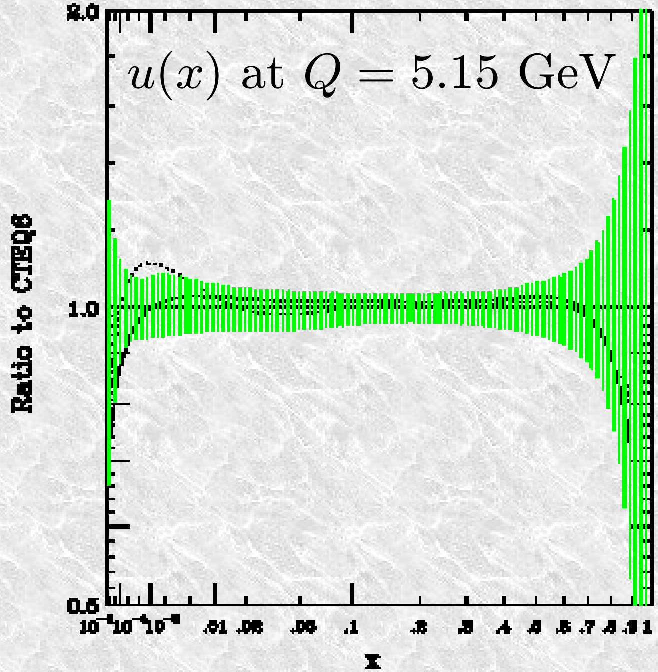
Outline

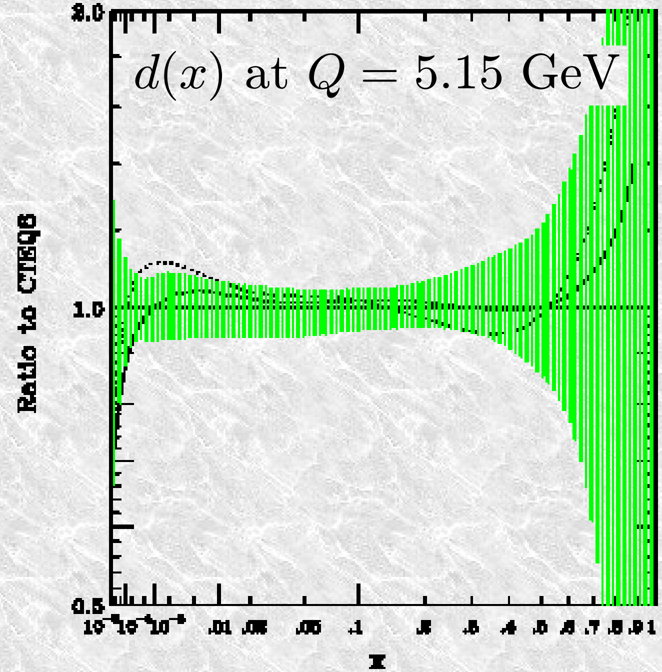
- **Why large x (and low-Q^2)**
- **Target Mass Corrections in collinear factorization**
  - F_2, F_L, g_1 DIS structure functions
  - SIDIS - preliminary
- **Jet mass corrections**
- **Global PDF fits at large x**
  - TMC, Higher Twist, Nuclear Corrections
  - unpolarized PDFs
- **What can break the Wandzura-Wilczek relation?**
  - g_2 and twist-3 quark-gluon correlations
- **Summary and outlook**

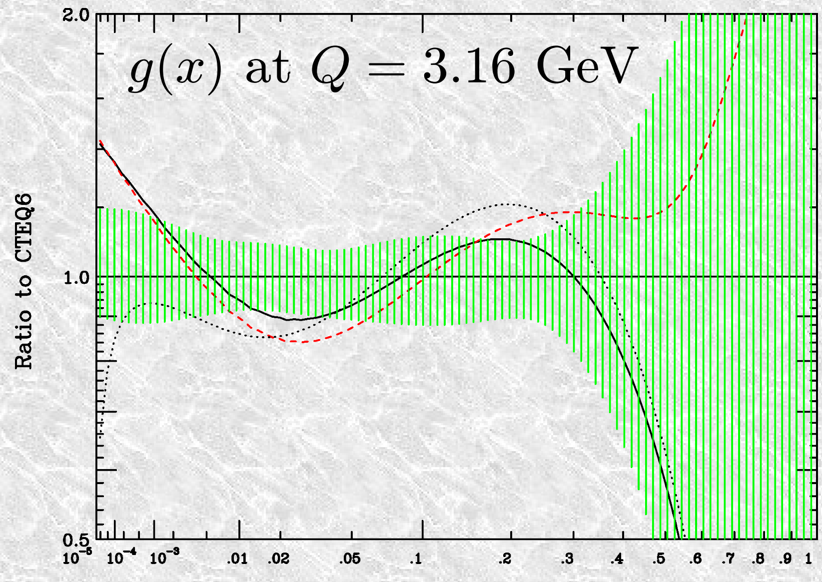
Why large-x, low-Q^2?

Why large x_B and low Q^2 ?

- Large uncertainties in quark and gluon PDF at $x > 0.5$ – e.g., CTEQ6





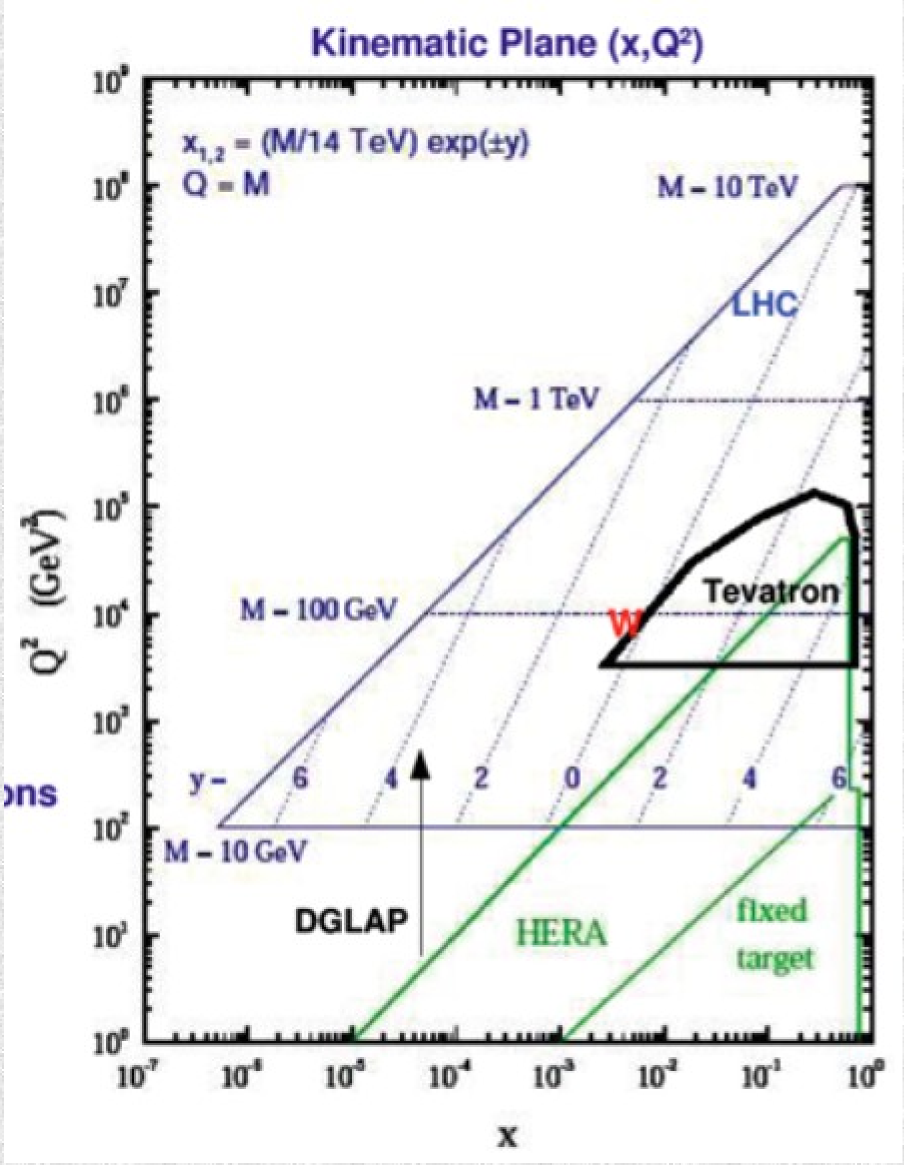


Why large x_B and low Q^2 ?

- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess in large-p_T spectra ⇔ large x PDF
  - Example: Z' production

$$M_{Z'} \gtrsim 200 \text{ GeV} \qquad x = \frac{m_T}{\sqrt{s}} e^y$$

$$x \geq 0.02 \text{ (LHC)}, \; 0.1 \text{ (Tevatron)}$$



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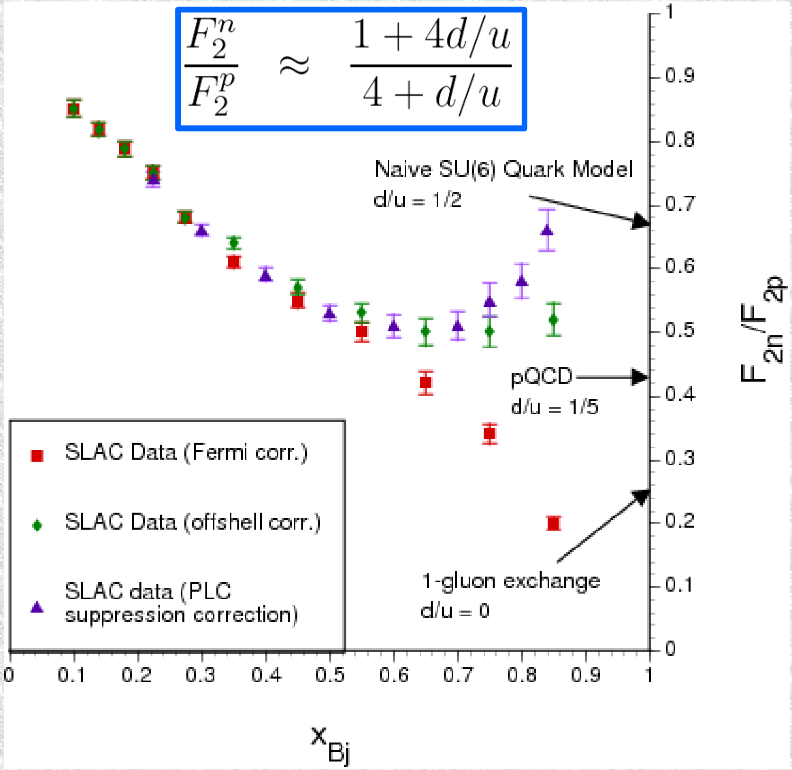
  - d/u ratio at x=1 ⇔ non-perturbative structure of the nucleon



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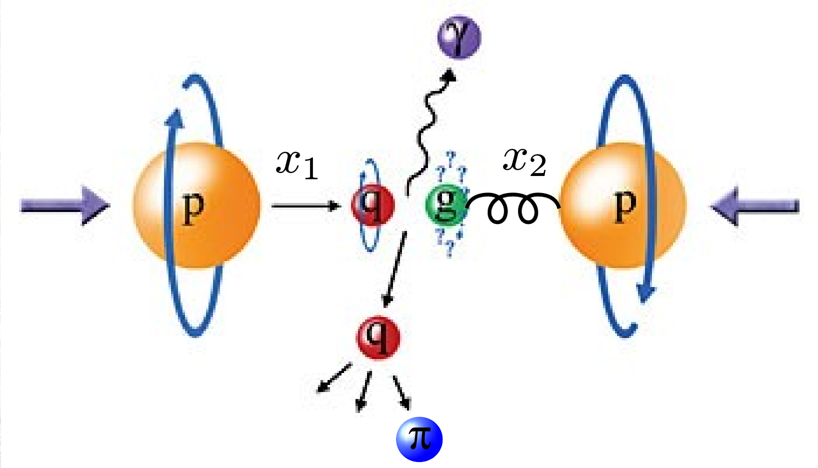
  - d/u ratio at $x=1$ $\Leftrightarrow$ non-perturbative structure of the nucleon
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

$$\sigma(p\vec{p} \to \pi^0 X) \propto \Delta q(x_1)\Delta g(x_2)\hat{\sigma}^{qg\to qg} \otimes D_q^{\pi^0}(z)$$



$$x_1 \sim \frac{p_T}{\sqrt{s}} e^{y}$$

$$x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$$

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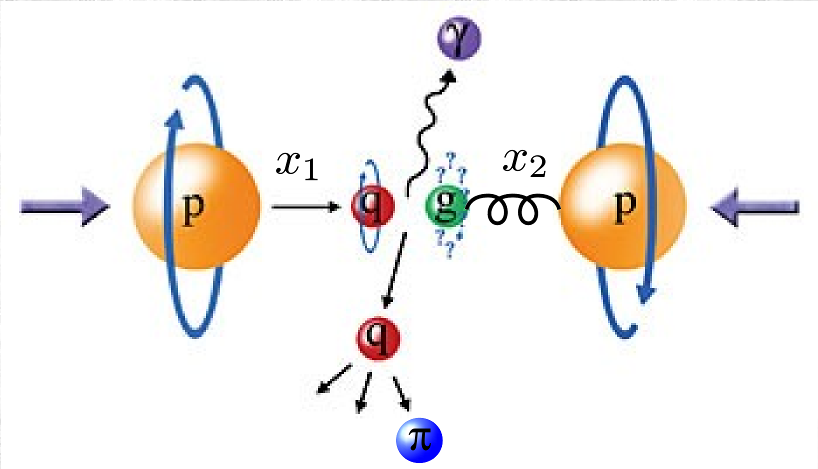

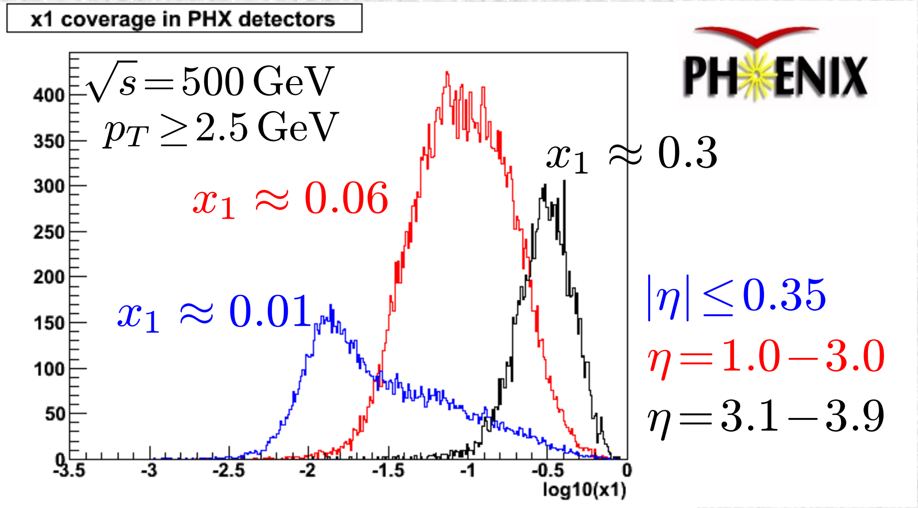

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- JLab has precision DIS data at large x_B , BUT low Q^2
  - need of theoretical control over
    1) higher twist $\propto \Lambda^2/Q^2$
    2) target mass corrections (TMC) $\propto x_B^2\, m_N^2/Q^2$
    3) jet mass corrections (JMC) $\propto m_j^2/Q^2$
    4) nuclear corrections
    5) large-x resummation, quark hadron duality, ...

(items 1–4: } this talk)

Target mass corrections

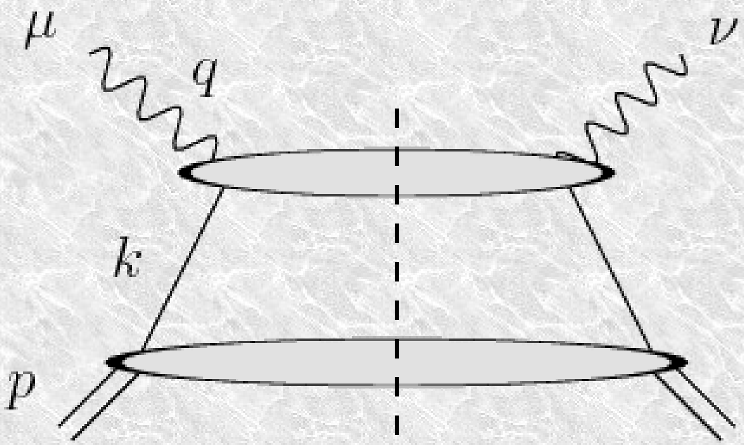
Accardi, Qiu, JHEP '08
Accardi, Melnitchouk, PLB '08

OPE and Target Mass Corrections

[Georgi, Politzer 1976; see review of Schienbein et al. 2007]

$$\int d^4z\, e^{-iq\cdot z} \langle N|T[j^{\dagger\mu}(z) j^\nu(0)]|N\rangle = \sum_k f^{\mu_1\ldots\mu_{2k}} A_{2k} \langle N| \underbrace{\mathcal{O}_{\mu_1\ldots\mu_{2k}}(0)}_{\text{symmetric, traceless}} |N\rangle$$

$$A_{2k} = \int_0^1 dy\, y^{2k} F(y) \qquad F(y) \sim \frac{1}{y^2} \sum_q e_q^2 q(y) \text{ (at LO)} \;\; = \text{“quark function”}$$



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$$A_{2k} = \int_0^1 dy\, y^{2k} F(y) \qquad F(y) \sim y^2 \sum_q e_q^2 q(y) \text{ (at LO)} = \text{"quark function"}$$

- Mellin transform, sum, transform back:

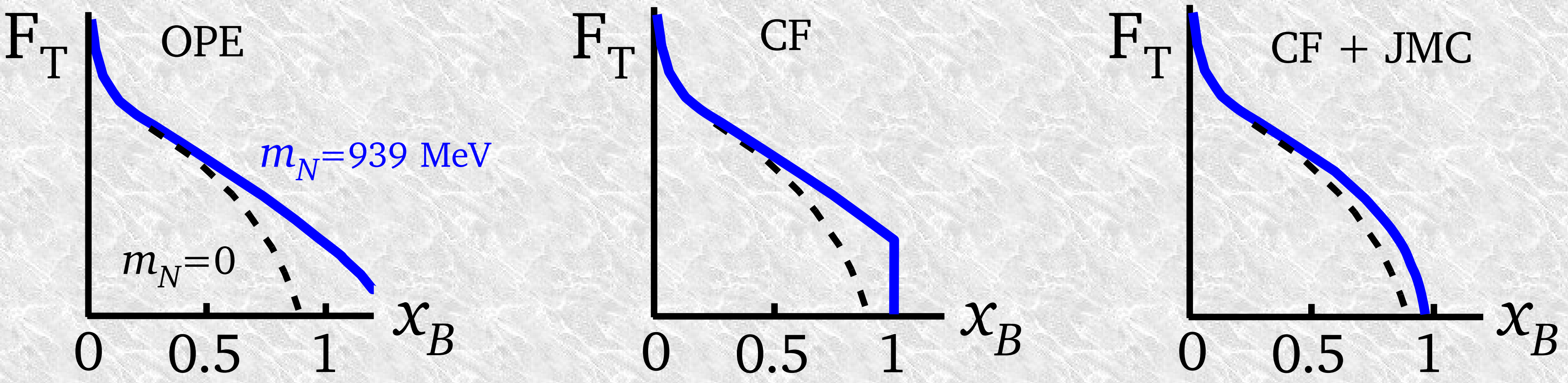
$$F_2^{GP}(x_B, Q^2) = \frac{x_B^2}{\rho_B^3} F(\xi) + 6\frac{m_N^2}{Q^2}\frac{x_B^3}{\rho_B^4}\int_\xi^1 d\xi' F(\xi') + 12\frac{m_N^4}{Q^4}\frac{x^4}{\rho_B^5}\int_\xi^1 d\xi' \int_{\xi'}^1 d\xi'' F(\xi'')$$

$$\xi = \frac{2x_B}{1+\sqrt{1+4x_B^2 m_N^2/Q^2}} \qquad \text{Nachtmann variable}$$

- Threshold problem: $x_B \le 1$ implies $0 \le \xi \le \xi_{th} \stackrel{\text{def}}{=} \xi(x_B{=}1)$
  - Inverse Mellin transform does not give back F(y) !! [Johnson, Tung 1979]
- Unphysical region: $F(y) \sim F_2(y)$ has support over $0<y<1$
  - $F_2^{GP}(x_B) > 0$ also for $x_B>1$!!

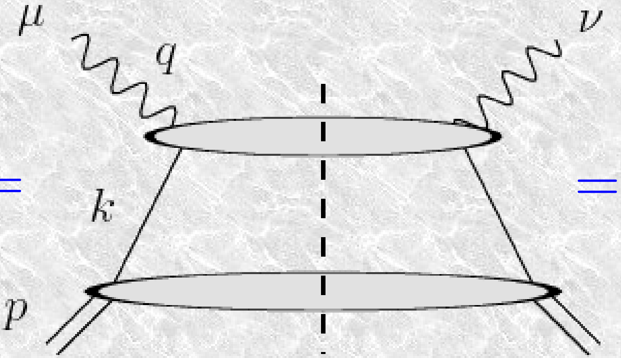
Collinear factorization - outline

- **Target Mass Corrections – $O(x_B^2\, m_N^2/Q^2)$**
  - momentum space, <u>no need of Mellin transf.</u>
  - kinematics of handbag diagram
    $\Rightarrow$ <u>no “unphysical region”</u> at $x_B > 1$ (!!)
  - any order in α_s at leading twist
- **Jet Mass Corrections – $O(m_j^2/Q^2)$**
  - The current jet is not a massless parton...



Kinematics with $m_N \neq 0$

$$W^{\mu\nu}(p,q) =$$



$$= \frac{1}{8\pi}\int d^4z\, e^{-iq\cdot z}\langle p|j^{\dagger\mu}(z)j^{\nu}(0)|p\rangle$$

- Lorentz invariants:

$$x_B = \frac{-q^2}{2p\cdot q} \qquad Q^2 = -q^2 \qquad x_f = \frac{-q^2}{2k\cdot q}$$

hadron level (observable) — parton level (theoretical)

- Light-cone fractional momenta, $p^{\pm} = (p_0 \pm p_3)/\sqrt{2}$

parton: $x = \dfrac{k^+}{p^+}$ (theoretical)

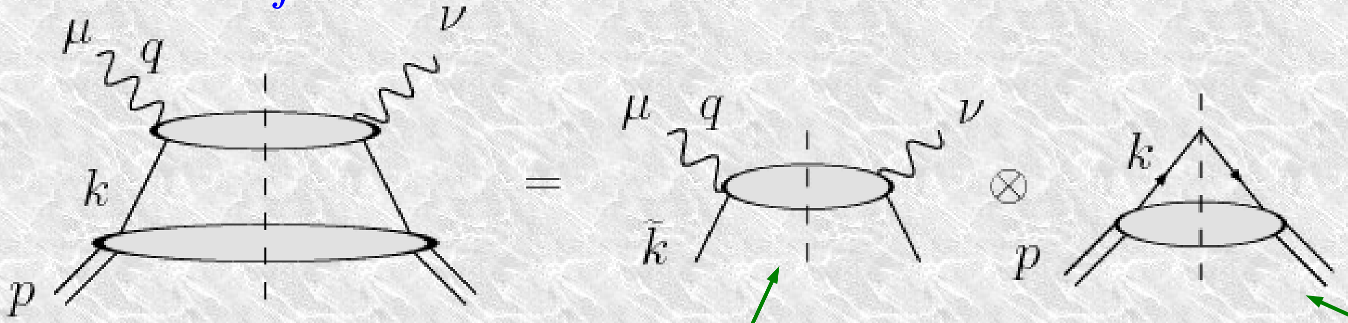
photon: $\xi = -\dfrac{q^+}{p^+} = \dfrac{2x_B}{1+\sqrt{1+4x_B^2 m_N^2/Q^2}}$ (observable)

- Bjorken limit: $\xi \to x_B$ recovers the massless ($m_N^2=0$) kinematics

Factorization theorem with $m_N \neq 0$

- Expand around $\tilde{k}^\mu = x p^+ \overline{n}^\mu \qquad \tilde{k}^2 = 0 \qquad \tilde{x}_f = \frac{-q^2}{2\tilde{k}\cdot q} = \frac{\xi}{x}$

$$W_N^{\mu\nu}(p,q) = \sum_f \int \frac{dx}{x} \mathcal{H}_f^{\mu\nu}(\tilde{k},q)\, \varphi_{f/N}(x,Q^2) + O(\Lambda^2/Q^2)$$



perturbative: doesn't know about the target's mass

dynamical TMC only from nucleon w.f.

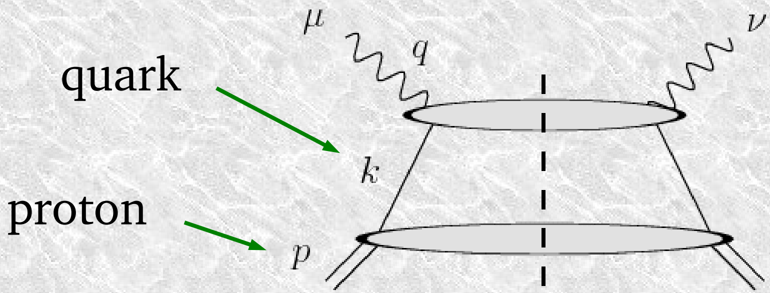
- Helicity structure functions F_T , F_L projected out of $W^{\mu\nu}$: *e.g.*,

$$F_T(x_B,Q^2) = \sum_f \int \frac{dx}{x} h_{fT}(\underbrace{\tilde{x}_f}_{=\,\xi/x},Q^2)\, \varphi_{f/N}(x,Q^2) + O(\Lambda^2/Q^2)$$

no kinematic prefactors [Aivazis, Olness, Tung 1994]

Kinematic constraints

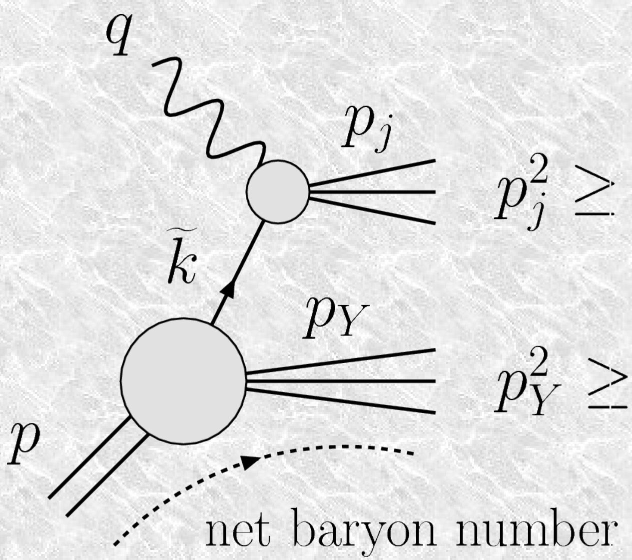
- General handbag diagram – on shell gluons and light quarks ($\widetilde{k}^2 = 0$):



$$x_B \le \widetilde{x}_f \le 1$$

i.e., $\xi \le x \le \xi / x_B$

- Proof (can be generalized to heavy and off-shell quarks – and nuclei)



$$p_j^2 \ge 0 \implies \widetilde{x}_f \le 1 \quad \longleftrightarrow \quad x \ge \xi$$

$$p_Y^2 \ge m_N^2 \implies \widetilde{x}_f \le x_B \quad \longleftrightarrow \quad x \le \xi / x_B$$

- If net baryon number appears in the upper blob (not for pQCD quarks)

$$\frac{x_B}{1 + x_B m_N^2 / Q^2} \le \widetilde{x}_f \le \frac{1}{1 + m_N^2 / Q^2}$$

No unphysical region!

- **TMC in collinear factorization:**

$$F_T(x_B,Q^2) = \sum_f \int_\xi^{\frac{\xi}{x_B}} \frac{dx}{x}\, h_{fT}\Big(\frac{\xi}{x},Q^2\Big)\, \varphi_f(x,Q^2)$$

$$\boxed{F_T(x_B,Q^2) = 0 \quad \text{at } x_B > 1}$$

- Bjorken limit $m_N^2/Q^2 \to 0$ recovers "**massless**" structure functions ($m_N=0$)

$$F_T(x_B,Q^2) \longrightarrow F_T^{(0)}(x_B,Q^2) \equiv \sum_f \int_{x_B}^1 \frac{dx}{x}\, h_{fT}\Big(\frac{x_B}{x},Q^2\Big)\, \varphi_f(x,Q^2)$$

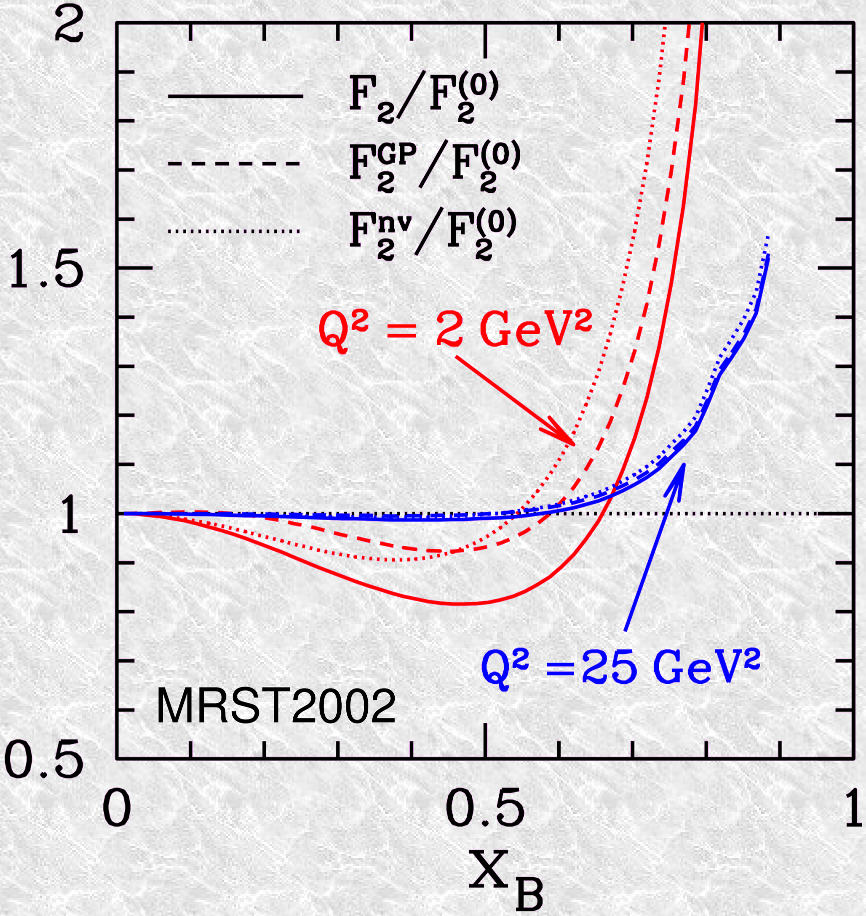
- Different from the "**naive**" collinear factorization TMC [Aivazis et al '94 Kretzer,Reno '02]

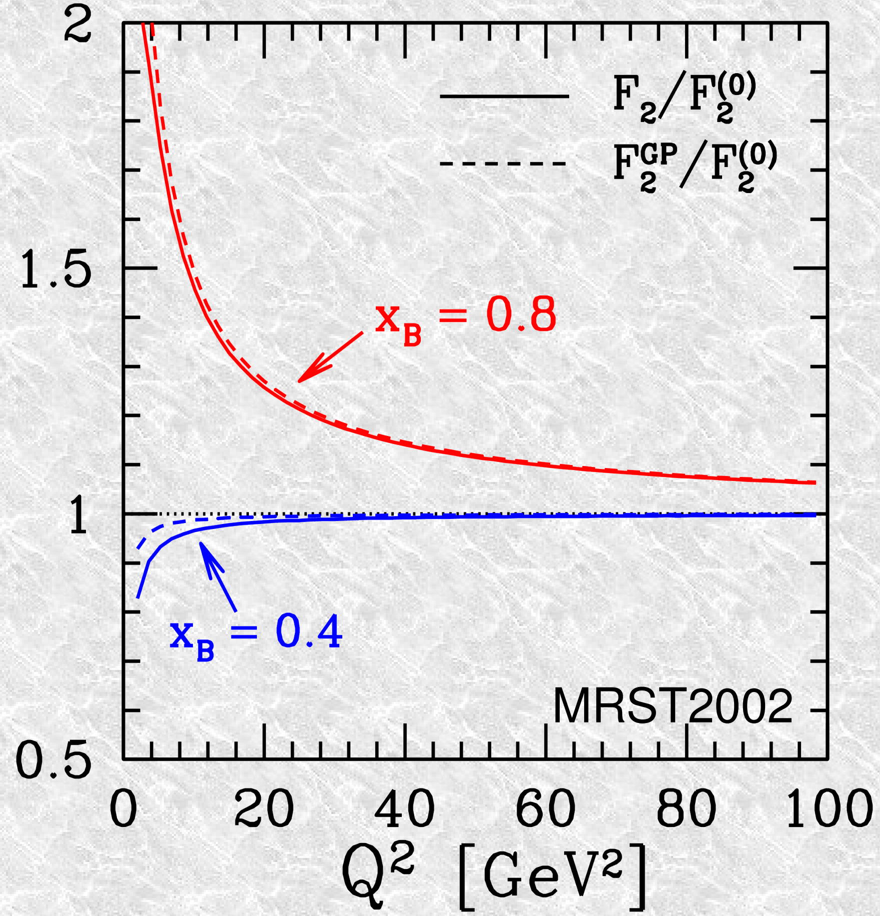
$$F_T^{nv}(x_B,Q^2) \equiv F_T^{(0)}(\xi,Q^2) = \sum_f \int_\xi^1 \frac{dx}{x}\, h_{fT}\Big(\frac{\xi}{x},Q^2\Big)\, \varphi_{f/N}(x,Q^2)$$

which does not vanish at $x_B > 1$

Target mass corrections – F_2 at NLO

Accardi, Qiu, JHEP 0807

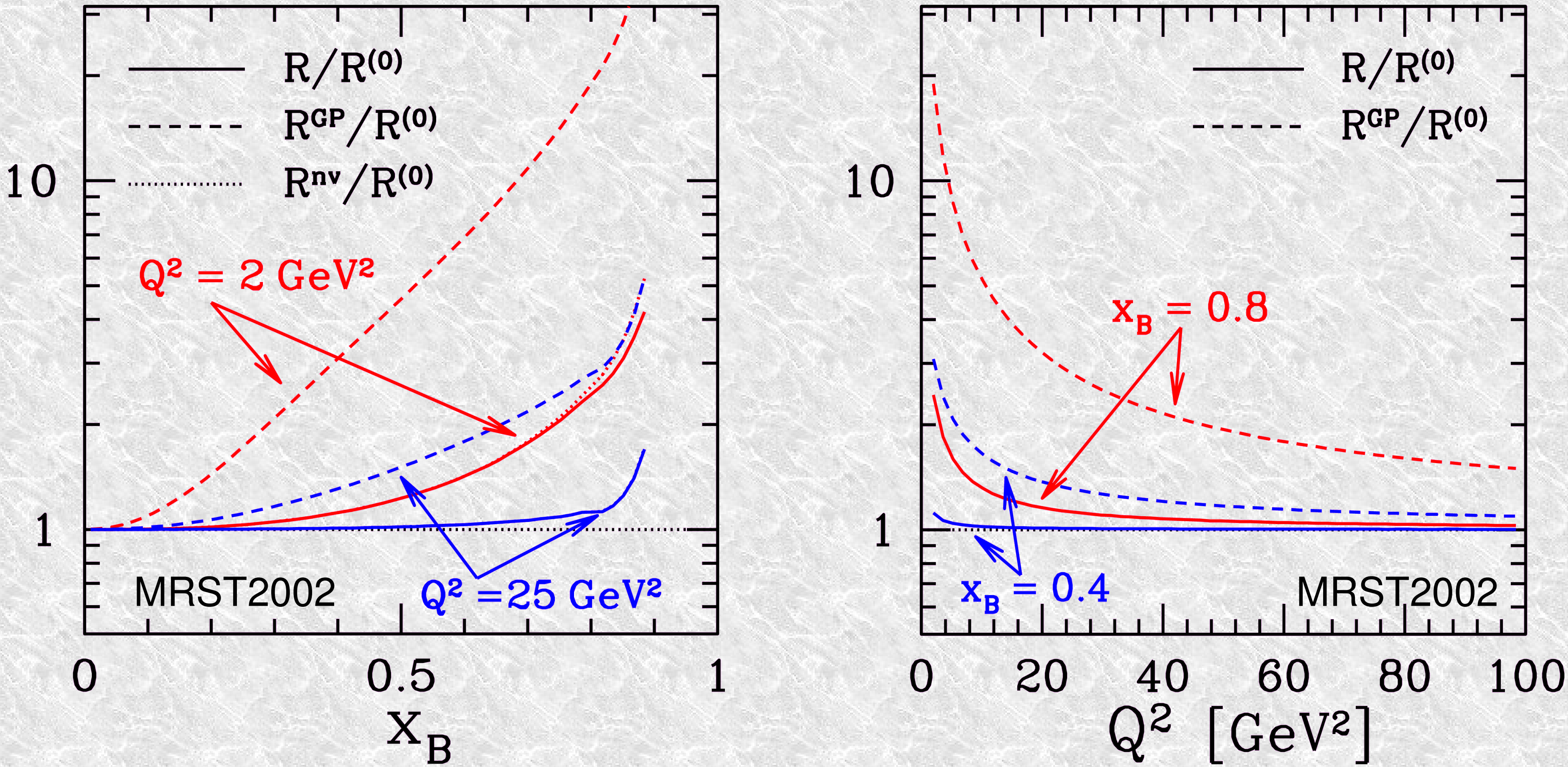




$$F_2^{nv}(x_B) = \frac{1}{1 + 4x_B^2 \frac{m_N^2}{Q^2}} \frac{x_B}{\xi} F_2^{(0)}(\xi)$$

Target mass corrections – σ_L/σ_T at NLO

Accardi, Qiu, JHEP 0807



$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{F_1}$$

$$F_{1,L}^{nv}(x_B) = F_{1,L}^{(0)}(\xi)$$

Polarized DIS

Accardi, Melnitchouk, PLB 670 (08) 114

- **TMC for virtual photon asymmetries (leading twist):**

$$g_1(x_B) = \frac{1}{1+\gamma^2} \sum_f \int_{\xi}^{\frac{\xi}{x_B}} \frac{dx}{x}\, g_{1,f}^{(0)}\Big(\frac{\xi}{x}, Q^2\Big)\, \Delta\varphi_f(x, Q^2)$$

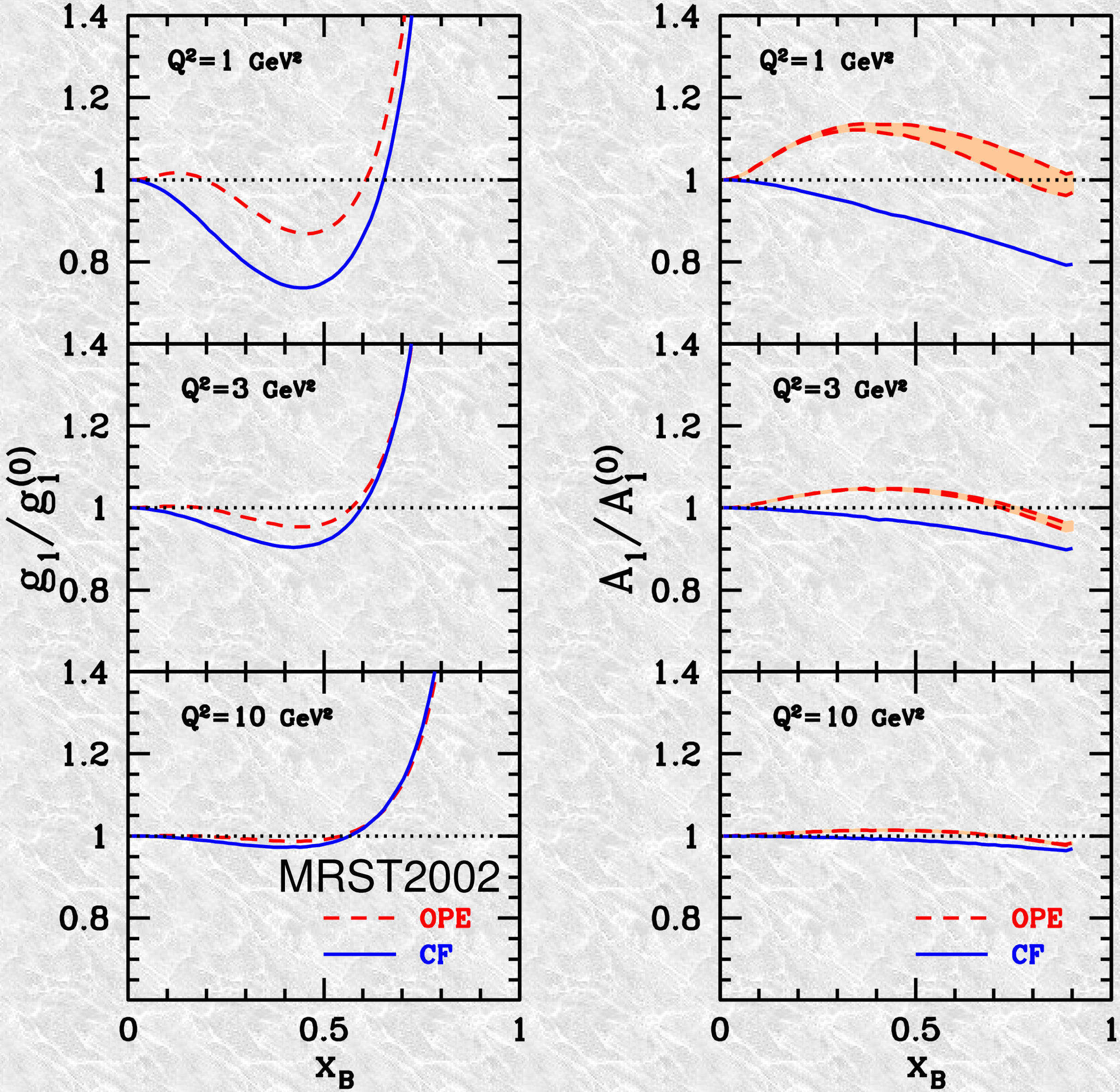
polarized PDF

$$A_1(x_B) = \frac{1+\gamma^2}{F_1(x_B)} g_1(x_B)$$

with $\gamma^2 = 4x_B^2 \frac{m_N^2}{Q^2}$

Polarized DIS at LO

Accardi, Melnitchouk, PLB 670 (08) 114



- g1 similar to F2
- A1 has smaller corrections
- The approximation

$$A_1 = (1+\gamma^2)\frac{g_1}{F_1} \approx \frac{A_\parallel}{D}$$

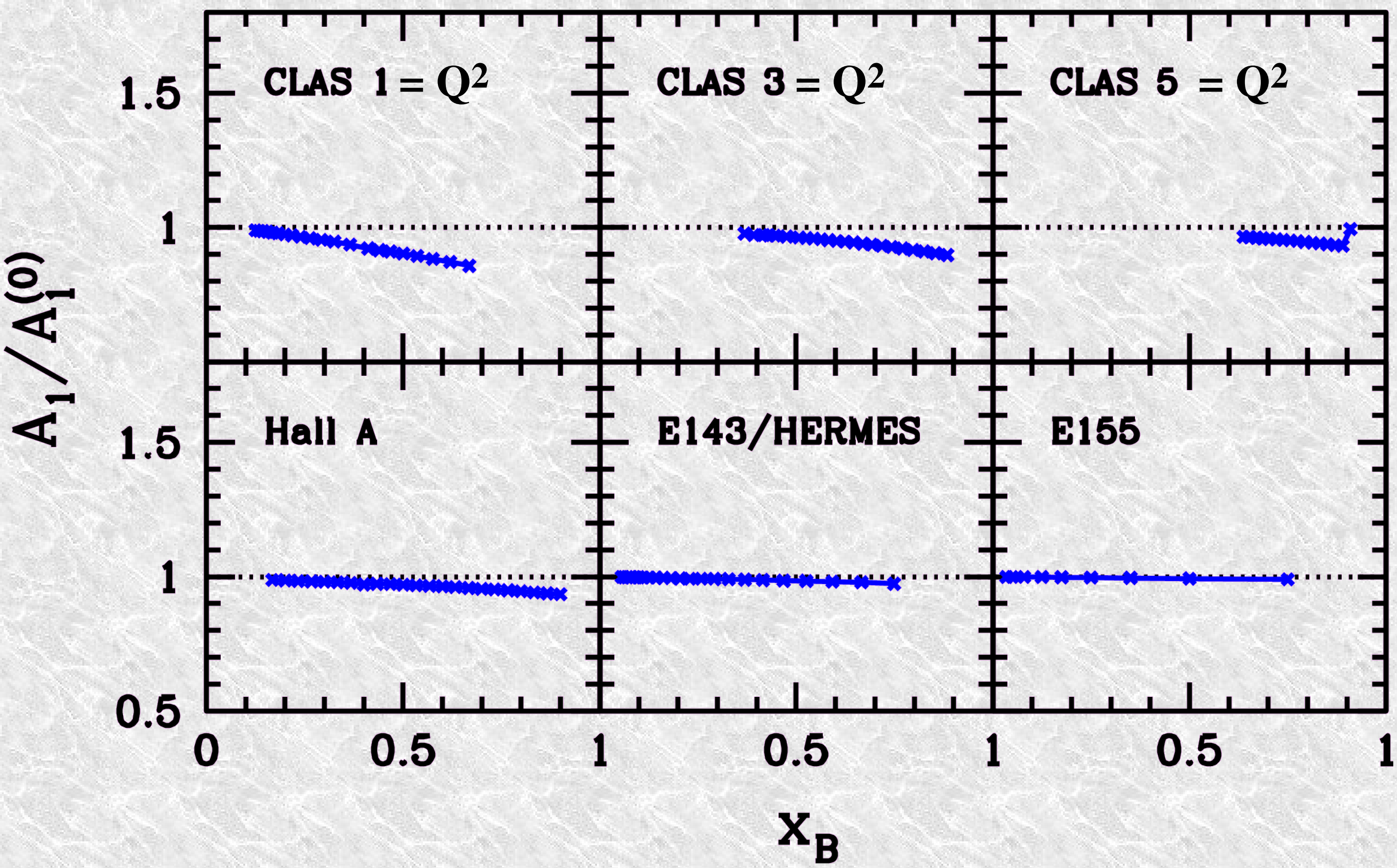
which is equivalent to

$$A_1 \approx A_1^{(0)}$$

is **NOT** suitable for precision measurements at Jlab: needs both $A_\parallel$ and $A_\perp$

Polarized DIS at LO

Accardi, Melnitchouk, PLB 670 (08) 114



- Precision measurements of A_1 at JLAB requires both $A_{\parallel}$ and $A_{\perp}$

Unpolarized SIDIS at LO

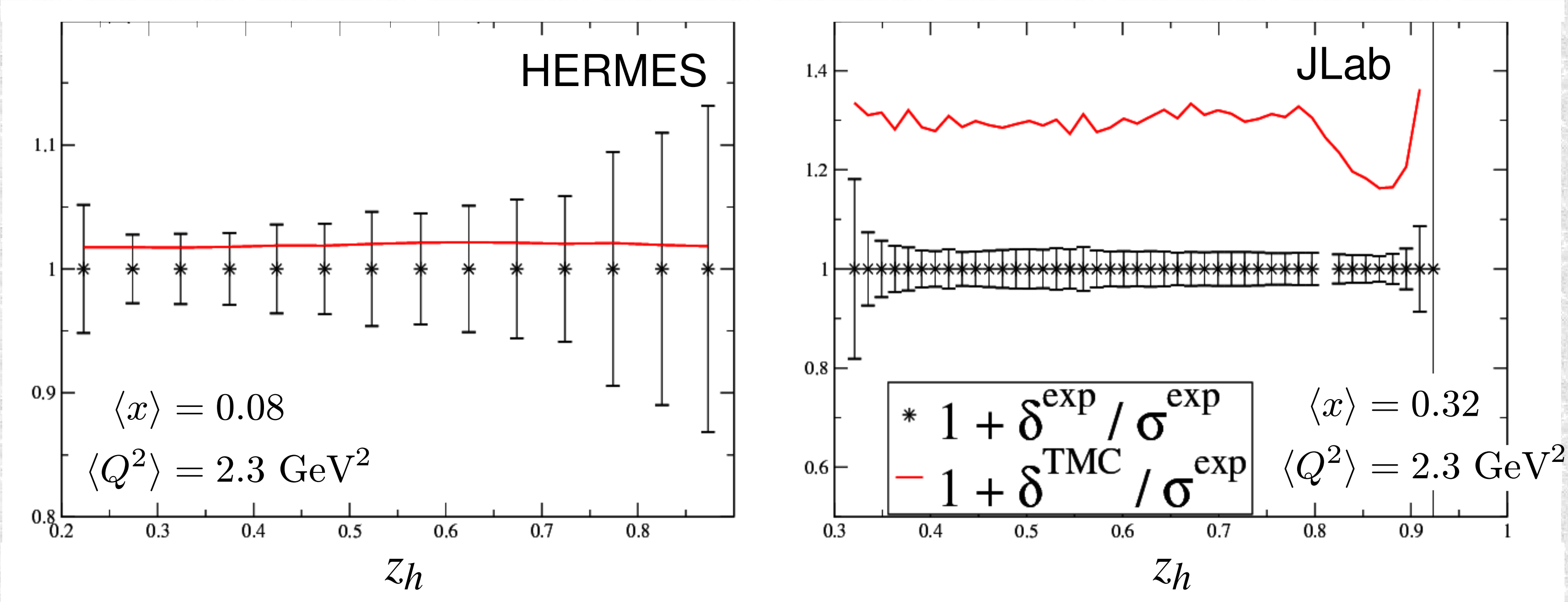
Accardi, Hobbs, Melnitchouk, in progress

TMC also for hadron fragmentation

$$\frac{d\sigma^h}{dz_h} \sim \sum_q e_q^2 \varphi_q(\xi) D_q^h(\zeta_h)$$

$$\zeta_h = \frac{1}{2} z_h \frac{\xi}{x_B}\left[1 + \sqrt{1 - 4\frac{x_B^2}{z_h^2}\frac{m_N^2 m_h^2}{Q^4}}\right]$$

hadron mass correction



- **Large corrections at Jefferson Lab!** (because of large-x, mostly)

Jet mass corrections

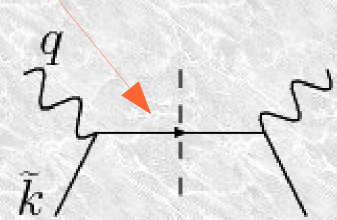
Accardi, Qiu, JHEP '08

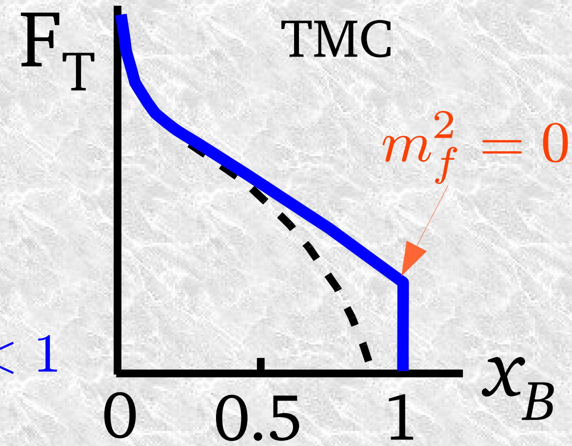
Jet smearing at LO

- At leading order for F_T,

$m_f^2 = 0$

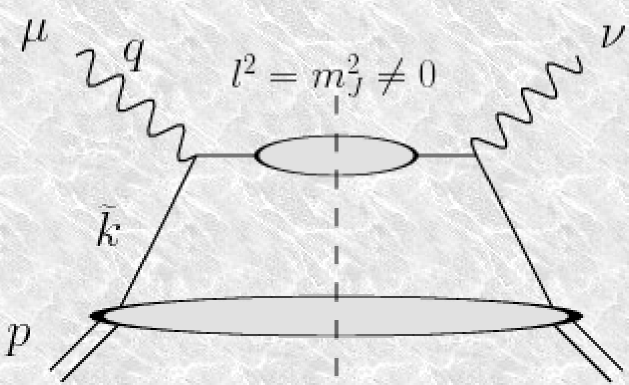
$$h_{fT}\left(\frac{\xi}{x}, Q^2\right) = \frac{1}{2} e_f^2 \delta\left(\frac{\xi}{x} - 1\right) \quad =$$





$$F_T(x_B, Q^2) = \frac{1}{2} \sum_f e_f^2 \varphi_f(\xi, Q^2) = F_T^{(0)}(\xi, Q^2) \quad \text{at } x_B < 1$$

- Ansatz: jet with a non zero mass, smoohtly distributed in m_j^2



$$(k+q)^2 = m_j^2 \longrightarrow \delta\left[x - \xi\left(1 + \frac{m_j^2}{Q^2}\right)\right]$$

jet mass distribution = "Jet Function"

$$F_T(x_B, Q^2) = \int_0^\infty dm_j^2 \, J_m(m_j^2) \int_\xi^{\frac{\xi}{x_B}} dx \, \frac{1}{2} e_q^2 \delta\left[x - \xi\left(1 + \frac{m_j^2}{Q^2}\right)\right] \varphi_f(x, Q^2)$$

note the limits

$$= \int_0^{\frac{1-x_B}{x_B} Q^2} dm_j^2 \, J_m(m_j^2) \, F_T^{(0)}\left(\xi\left(1 + \frac{m_j^2}{Q^2}\right), Q^2\right)$$

Jet smearing at LO

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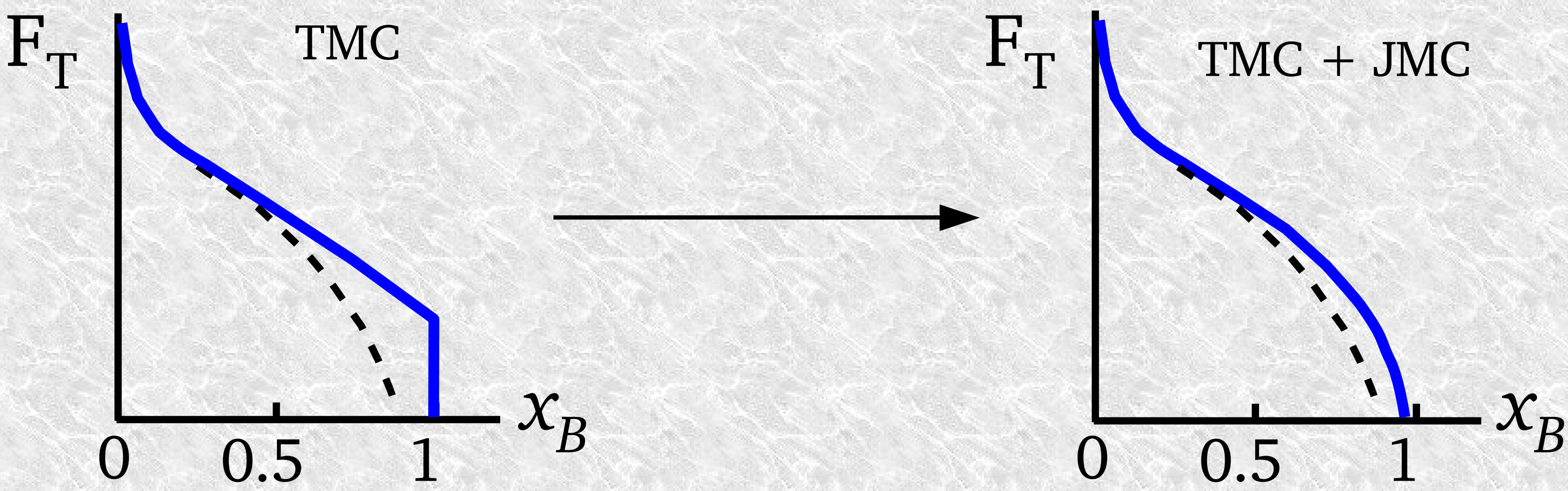
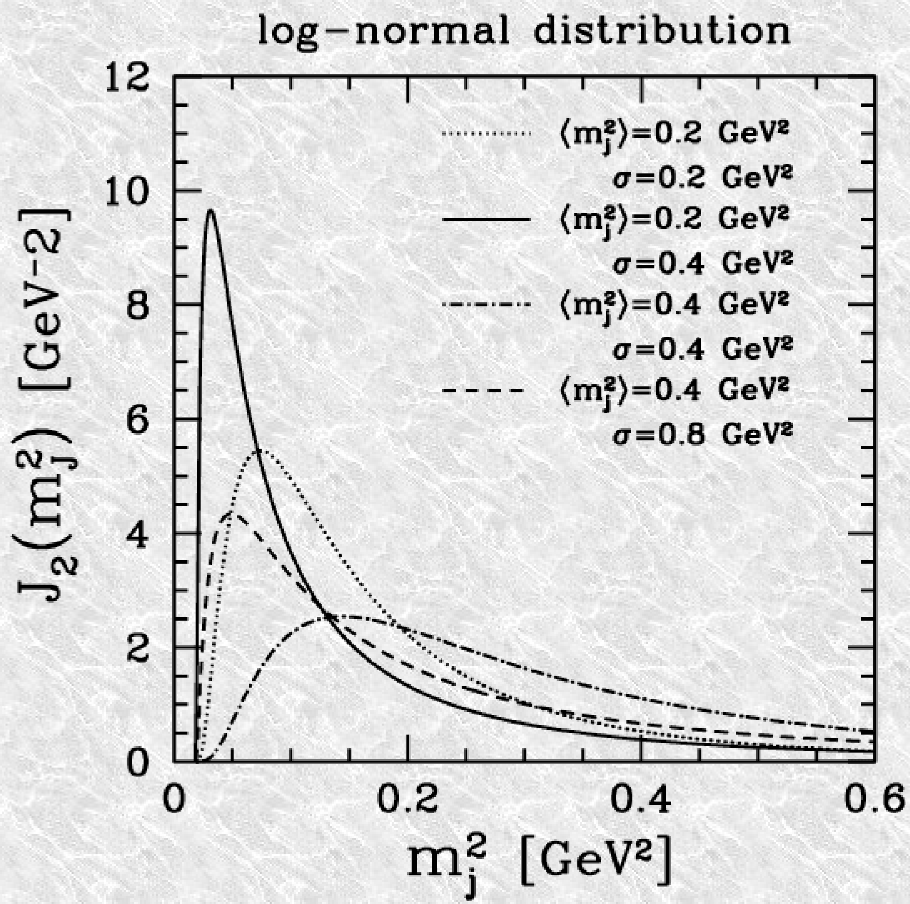


connection with lattice QCD ?

- Rigorously – after some toil:
  - $J_m(m_j^2)$ is the spectral function of a vacuum quark propagator, smeared by soft momentum exchanges with the target jet

Estimate of Jet Mass Corrections

- **Toy jet function**
  - log-normal distribution
  - $<m_j^2> = 0.2 - 0.4$ GeV^2
  - $\sigma = 1\text{-}2 <m_j^2>$



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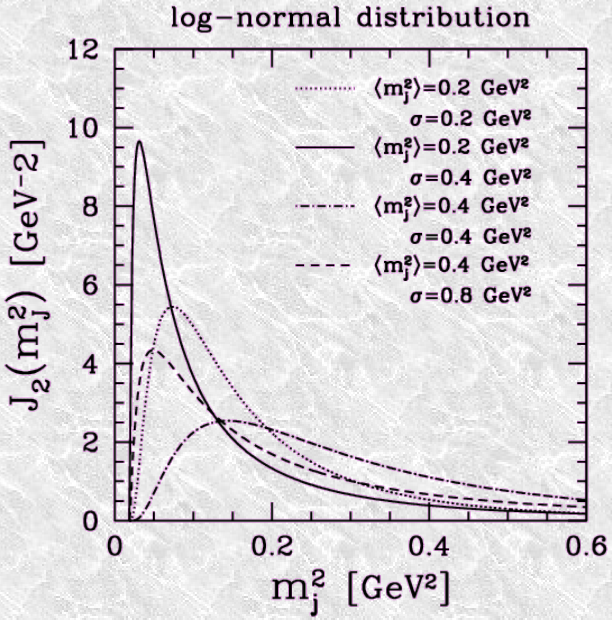
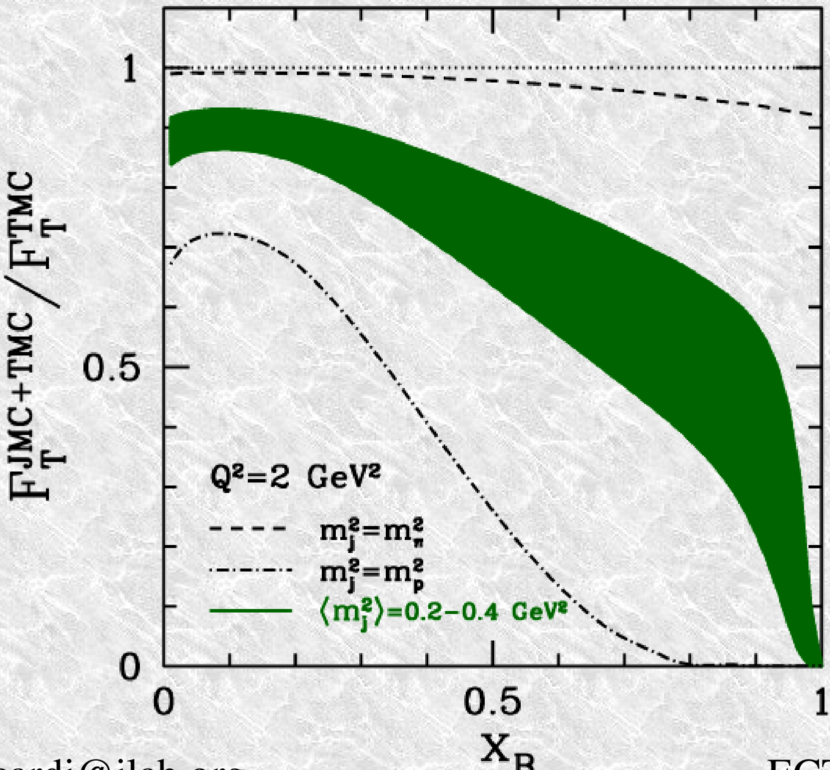
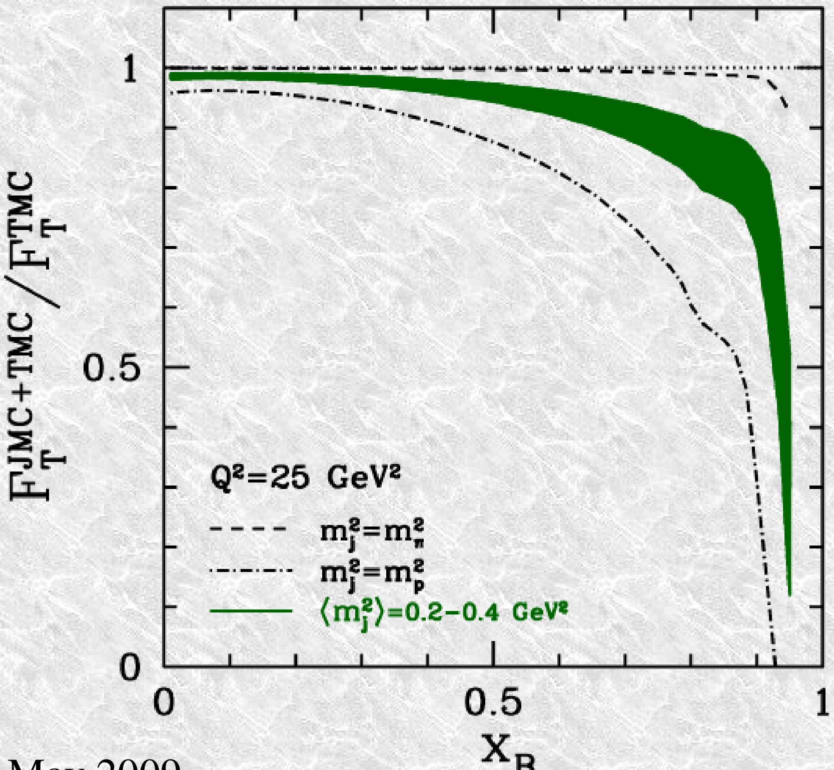




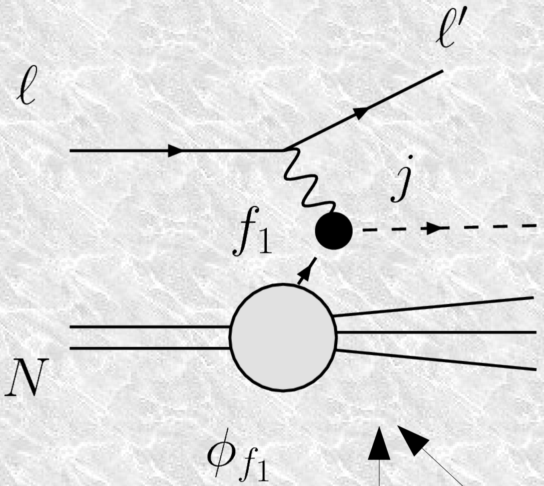


Global PDF fits

Work in progress with:

E.Christy, C.Keppel, W.Melnitchouk, P.Monaghan, J.Morfín, J.Owens

Factorization of hard scattering processes



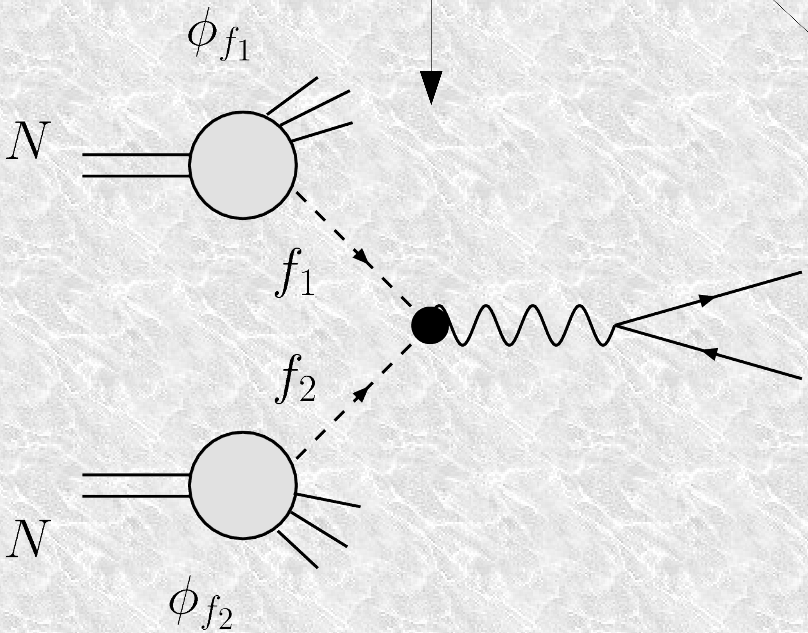
- **perturbative QCD factorization** of short and long distance physics

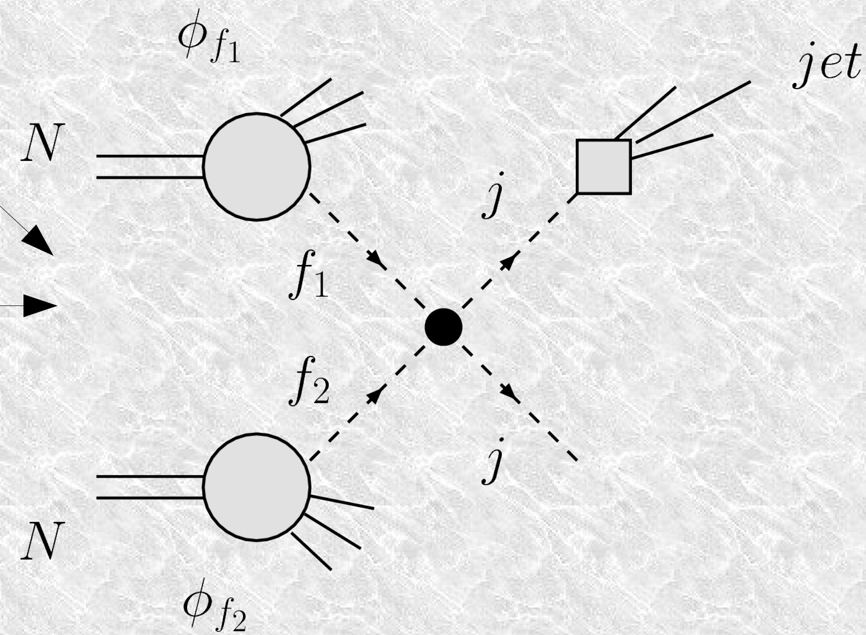
$$d\sigma_{\rm hadron} = \sum_{f_1,f_2,i,j} \phi_{f_1} \otimes \hat\sigma^{f_1 f_2 \to ij}_{\rm parton} \otimes \phi_{f_2}$$

Parton Distribution Fns (from inclusive DIS)

pQCD cross section

- **Universality**: PDF from DIS describe also DY, p+p→ jets+X, ...





Global PDF fits

- **Problem:** we need a set of PDFs in order to calculate a particular hard-scattering process

- **Solution:**
  - generate PDFs using a parametrized functional form at a given initial scale Q_0 and evolving it at any Q.
  - Choose a data set for a choice of different hard scattering processes
  - Repeatedly vary the parameters and evolve the PDFs again
  - Obtain an optimal fit to a set of data.

- Examples: CTEQ6.1, MRST2002 for unpolarized protons
  DSSV, LSS for polarized protons

- For details, see J. Owens' lectures at the 2007 CTEQ summer school

Collaboration and goals

- **JLab / CTEQ collaboration: cteqX**
  - A. Accardi, E. Christy, C. Keppel, W. Melnitchouk, P. Monaghan, J. Morfín, J. Owens

- Initial Goals:
  - Extend PDF global fits to larger values of x_B and lower values of Q
  - Wealth of data from older SLAC experiments and newer Jlab, DY
  - see if PDF errors can be reduced using new JLAB data

Global fit details

- We are using **Jeff Owens' NLO DGLAP fitting package**
  - use CTEQ6.1 parametrization of PDFs at Q_0=1.3 GeV
  - Can fit DIS, Drell-Yan, W asymmetry, jets, γ+jet
  - statistical and systematic errors added in quadrature
  - PDF errors computed by the Hessian method, $\Delta\chi^2=1$

- **New in this work:**
  - γ+jet
  - Multiple TMC and HT terms added
  - Higher-twist contributions by a multiplicative factor
  - Nuclear corrections for deuteron targets added
  - option for finite d/u at $x \to 1$ is being considered

Higher-Twists parametrization

- Parametrize the higher-twist contributions by a multiplicative factor:

$$F_2(data) = F_2(TMC) \times \left(1 + \frac{C(x_B)}{Q^2}\right)$$

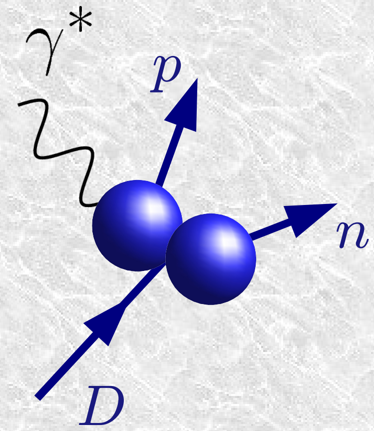
with

$$C(x_B) = a\, x^b\, (1 + c\, x)$$

- Comments
  - parametrization is sufficiently flexible to give good fits to data
  - c parameter allows negative HT at small x_B

Deuterium corrections

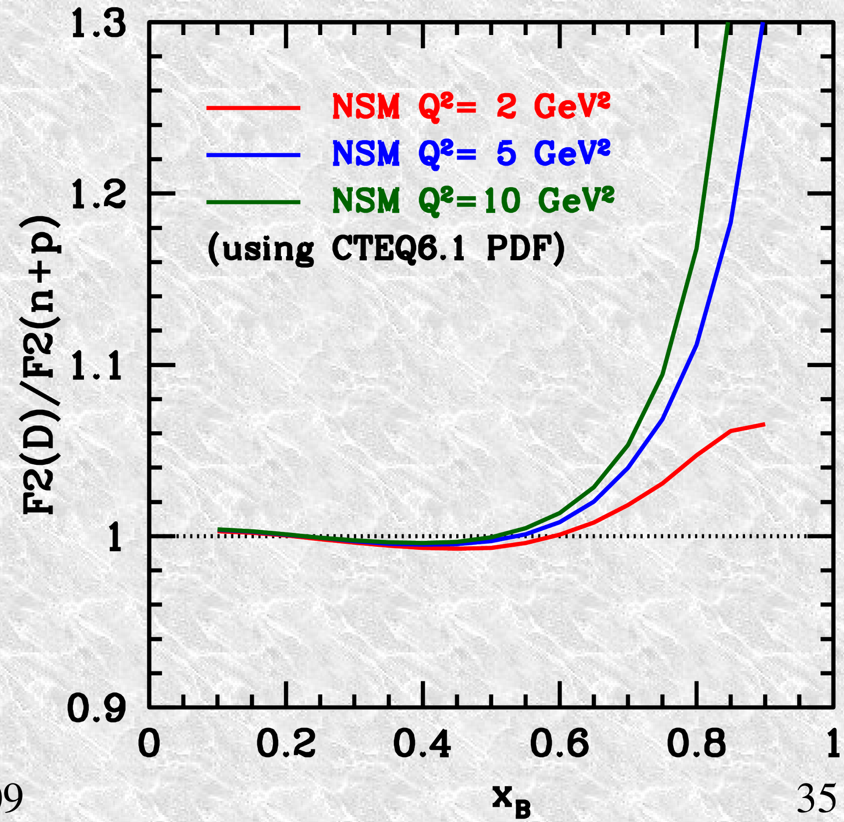
- Nuclear Smearing Model [Kahn et al., arXiv:0809.4308 Accardi et al., *in preparation*]
  - nucleon Fermi motion and binding energy
  - use non-relativistic deuteron wave-function
  - finite-Q^2 corrections (very important!)



$$F_{2A}(x_B) = \int_{x_B}^{\infty} dy \mathcal{S}_A(y, \gamma, x_B) F_2^{TMC}(x_B/y, Q^2)$$

$$\gamma = \sqrt{1 + 4x_B^2 m_N^2 / Q^2}$$

$$\frac{x_B}{y} = \frac{p_N \cdot q}{p_D \cdot q}$$



cteqX vs. CTEQ

- **CTEQ**

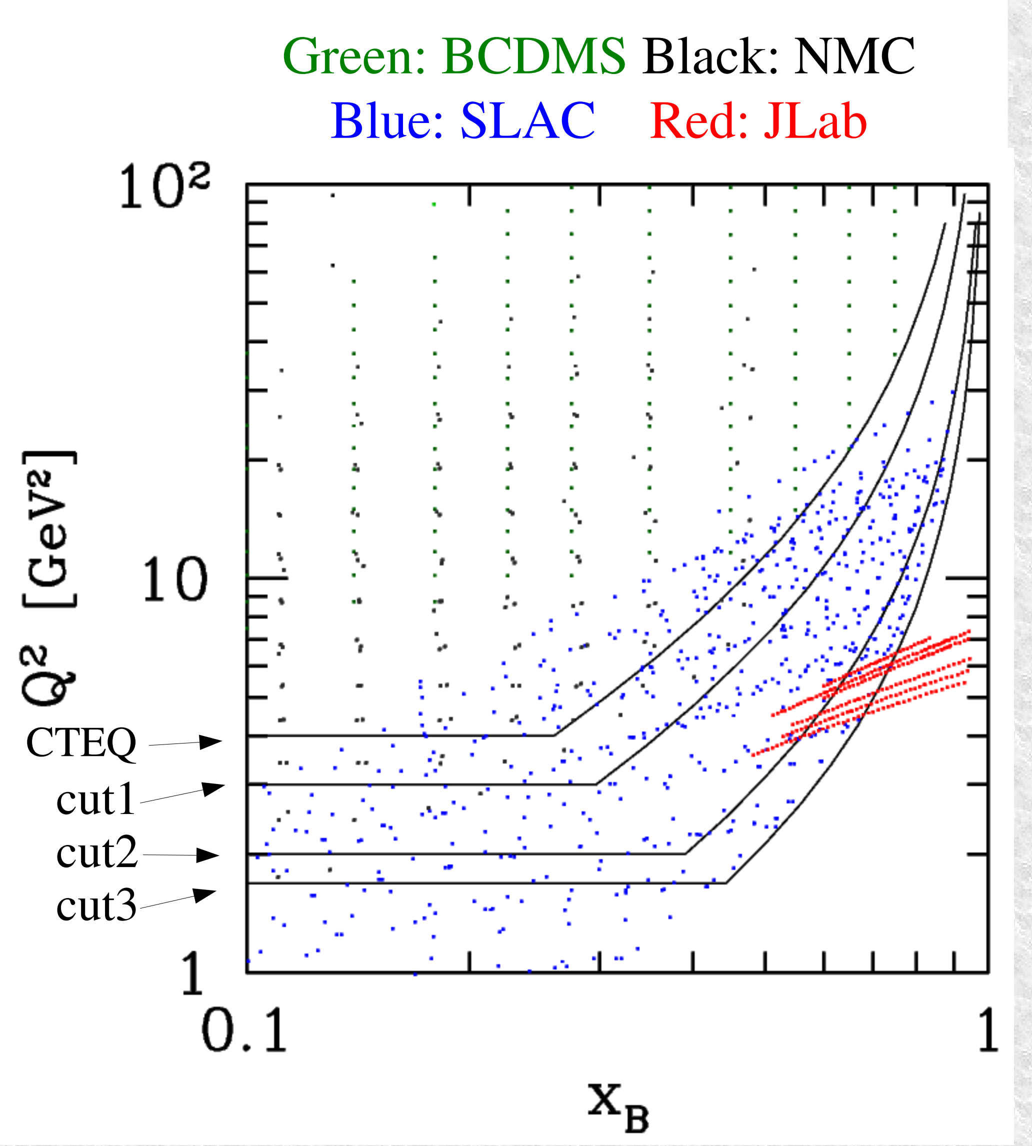
$$Q^2 \geq 4\ \text{GeV}^2 \quad W^2 \geq 12.25\ \text{GeV}^2$$

  - not so large x, not so low Q^2
  - hope $1/Q^2$ corrections not large

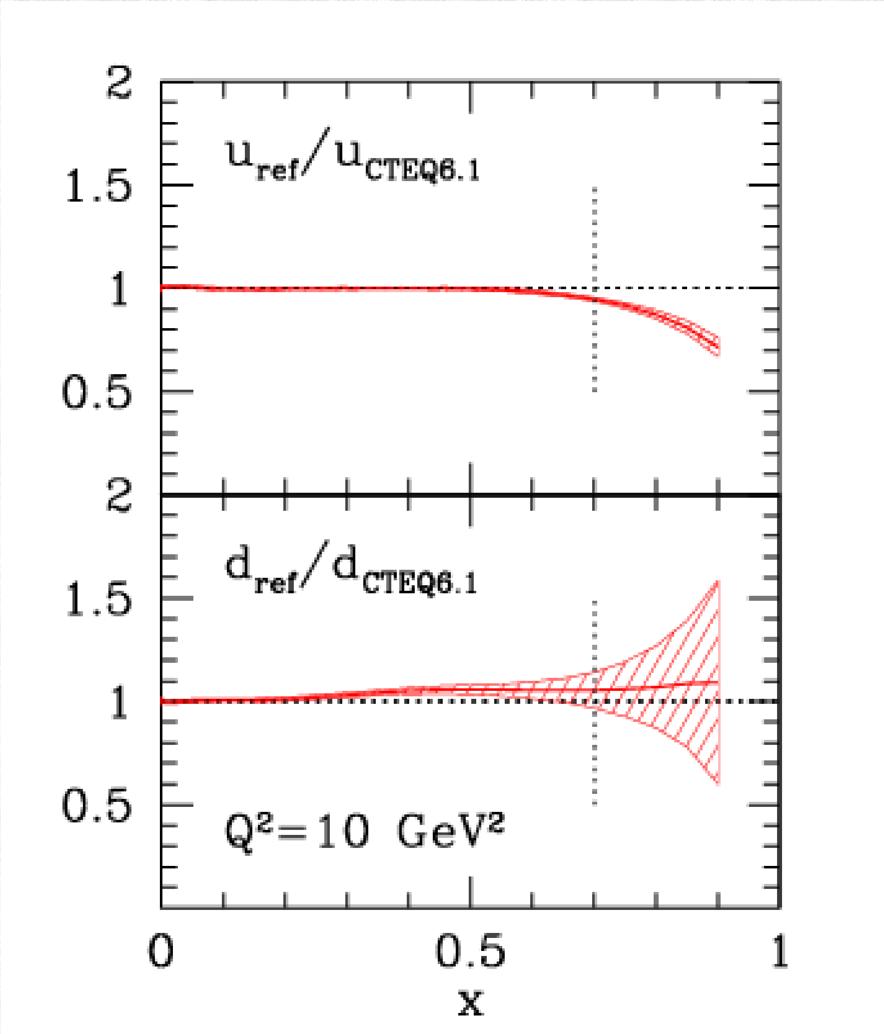
- **cteqX**
  - **TMC, HT, deuteron corrections**
  - Progressively lower the cuts:

	Q^2 [GeV^2]	W^2 [GeV^2]
CTEQ ≡ cut0	4	12.25
cut1	3	8
cut2	2	4
cut3	1.69	3

  - Better large-x, low-Q^2 coverage



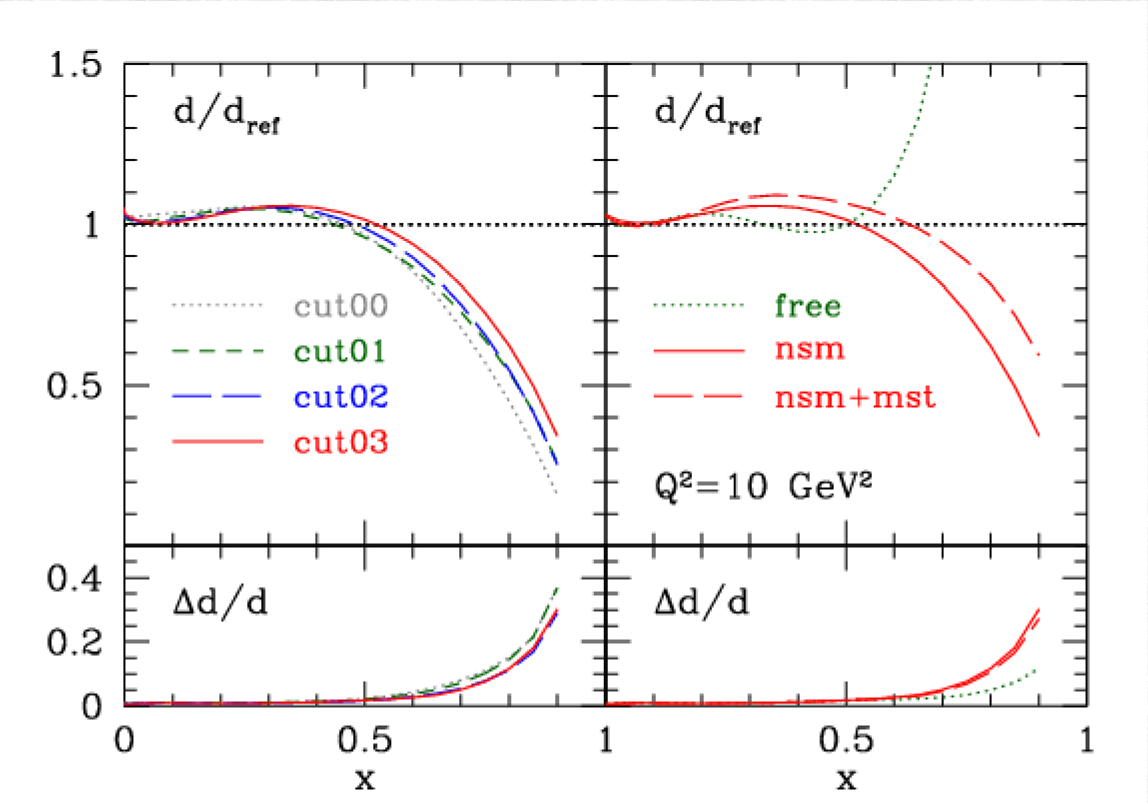
Reference fit vs. CTEQ6.1



- **Reference fit:** cut0, no corrections

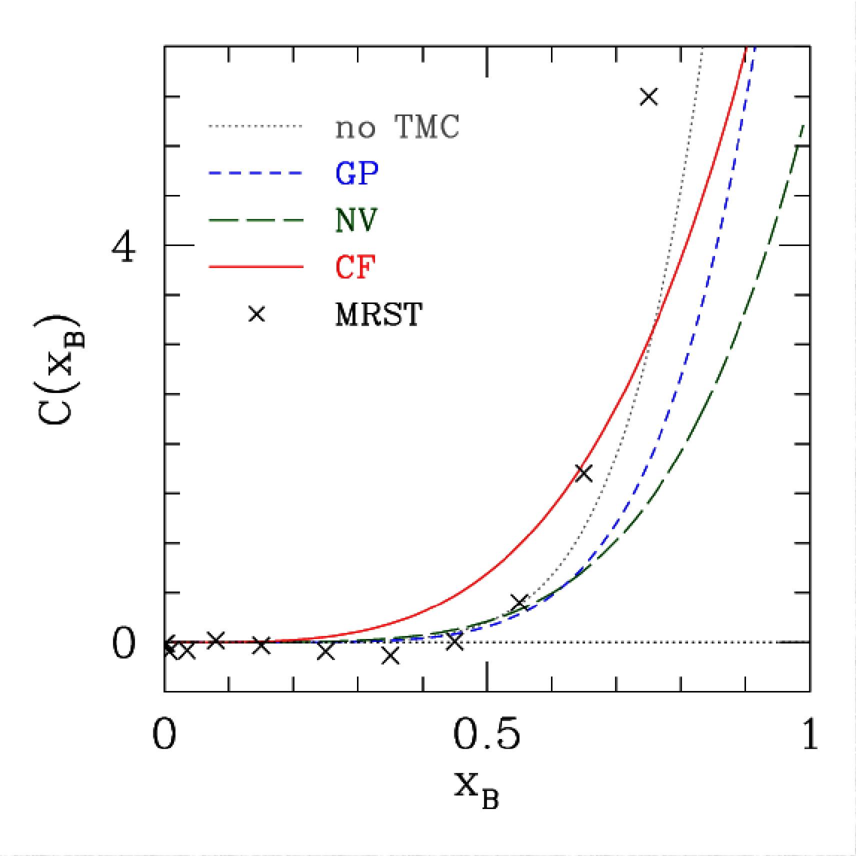
	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	√
	NMC	√
	BCDMS	√
	H1	√
	ZEUS	√
DY	E605	√
	E866	NO
W	CDF '98 (ℓ)	√
	CDF '05 (ℓ)	NO
	D0 '08 (ℓ)	NO
	D0 '08 (e)	NO
	CDF '09 (W)	NO
jet	CDF	√
	D0	√
γ+jet	D0	NO

d-quark suppression



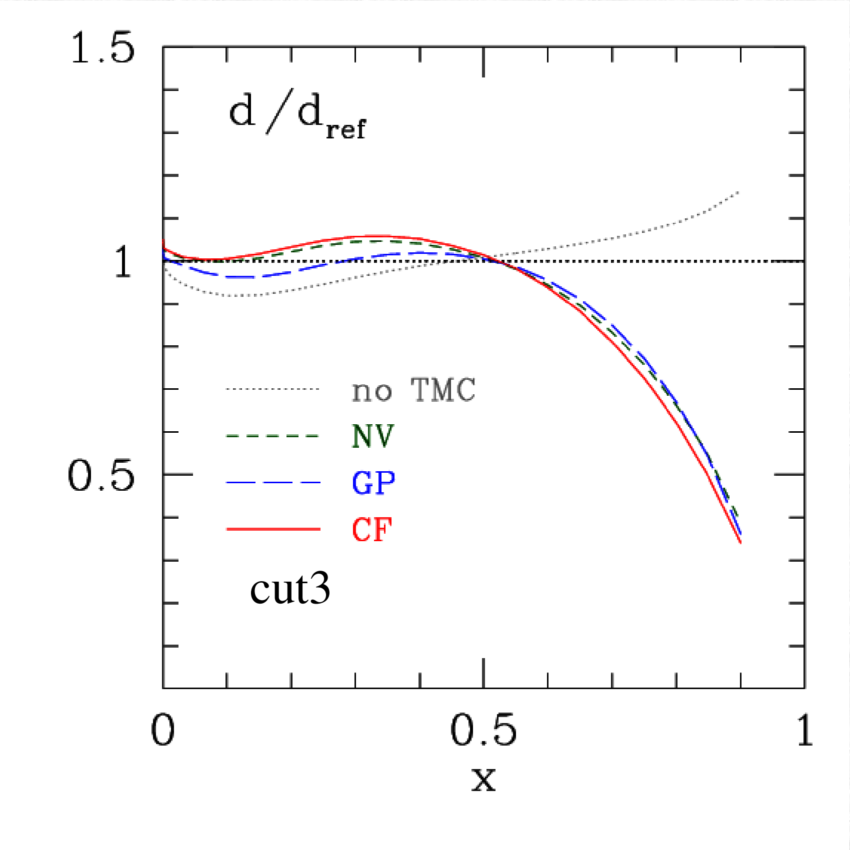
- **Suppression of *d*-quark**
  - *u*-quark almost doesn't change (not shown)
- **Relatively stable against kinematic cuts**
- **Deuterium corrections have large effect on *d*-quark**
  - sensitivity to off-shell corrections [MST = Melnitchouk et al., '94]
  - use WA21 data on ν(νbar)-p to cross-check *d* without Deuterium? [w/ L.Y.Zhu]

TMC vs HT



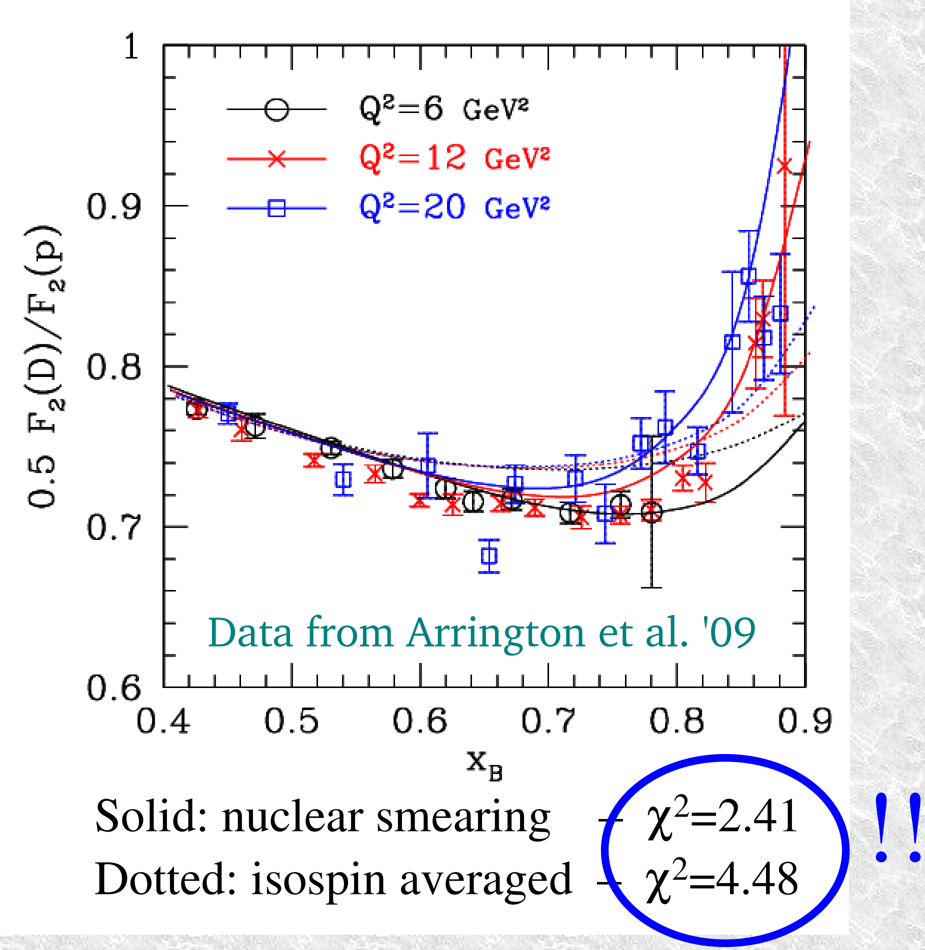
- **Extracted higher-twist term depends on the type of TMC used**
  - $Q^2 > 1.69$ GeV^2 and $W^2 > 3$ GeV^2 (referred to as "cut03")
  - lower cuts $\Rightarrow x_B < 0.85$ compared to $x_B < 0.7$ in CTEQ/MRST
  - No evidence for negative HT

Preliminary results – TMC vs HT



- **Extracted twist-2 PDF much less sensitive to choice of TMC**
  - fitted HT function compensates the TMC
  - except when no TMC is included

Preliminary results – D/p ratios

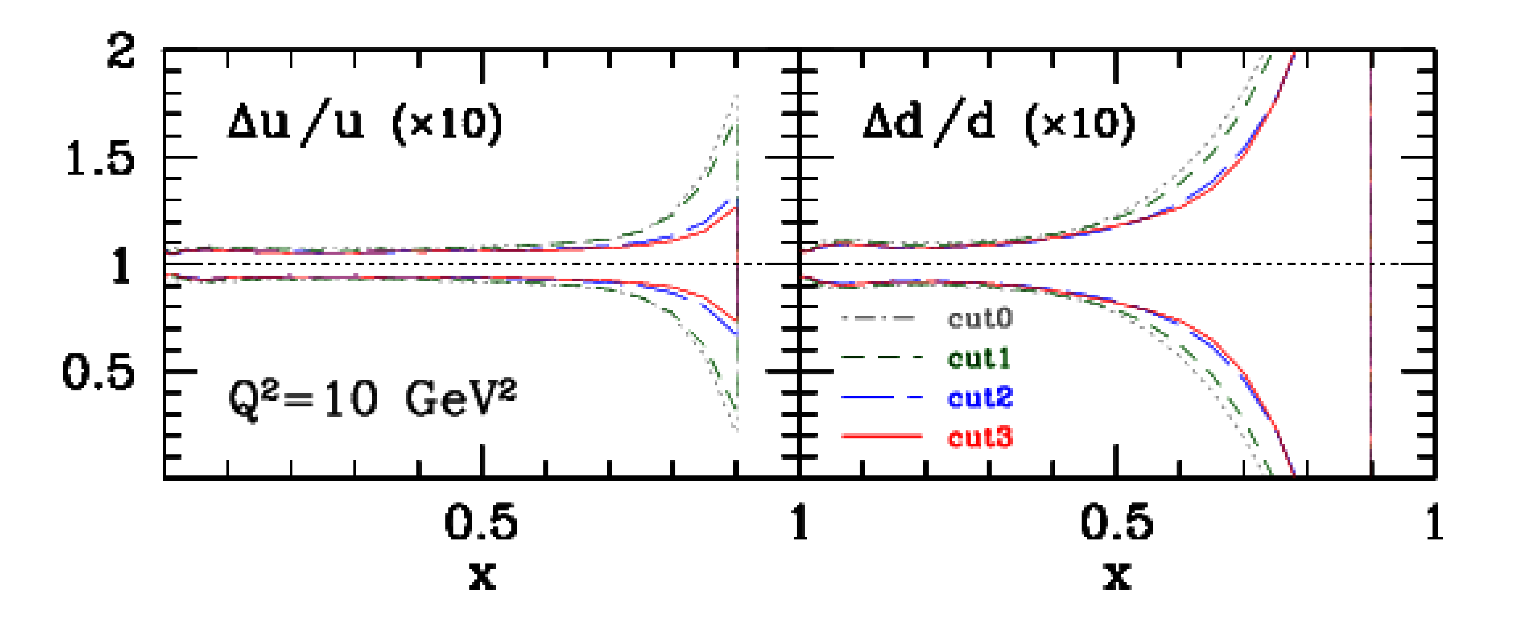


- **Nuclear smearing essential for D/p ratio at x_B>0.6**
  - It is essential to go beyond Bjorken limit: finite-Q^2 corrections
  - off-shell corrections don't sensibly change the result

Preliminary results – PDF errors

- PDF errors at large *x* are reduced by lowering the cuts

	Q^2 [GeV^2]	W^2 [GeV^2]
cut00	4	12.25
cut01	3	8
cut02	2	4
cut03	1.69	3



- **Note:** errors multiplied by 10 for rough comparison to CTEQ6 errors

Summary of cteqX fits

- **New global PDF fits are underway**,
  - with expanded kinematic range and data set
- **Suppressed *d/u* ratio at large *x*** compared to CTEQ6.1
  - TMC, HT essential for good fits, stability of PDF
  - Large effect of deuterium corrections, also for standard CTEQ cuts
  - need ν(νbar)-*p* data to further constrain *d*-quark
- **PDF errors reduced**
  - by expanded large-*x* data set
  - SLAC+JLab + recent DY
- **Tension with DY data sets**
  - E-866 lepton pair data, and DØ W→*leptons* asymmetry data prefer an enhanced *d/u* ratio at large *x*
  - But... directly measured *W* asymmetry likes *d* suppression

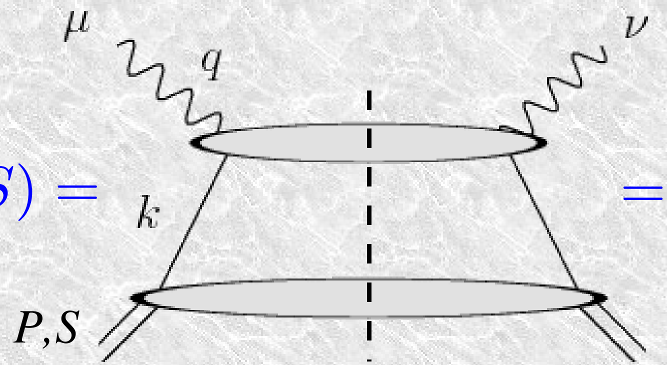
Higher-twist terms also are interesting

Accardi, Bacchetta, Melnitchouk, Schlegel:
arXiv:0905.3118, full paper in preparation

The g_2 structure function

- DIS cross section determined by the hadronic tensor

$$W^{\mu\nu}(q,P,S) =$$



$$= \frac{1}{8\pi}\int d^4z\, e^{-iq\cdot z}\langle P,S|j^{\dagger\mu}(z)j^{\nu}(0)|P,S\rangle$$

- Inclusive DIS structure functions:

$$\begin{aligned} W^{\mu\nu}(p,q,S) = & \Big(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\Big)F_1(x_B,Q^2) \\ & + \Big(p^\mu - q^\mu\frac{p\cdot q}{q^2}\Big)\Big(p^\nu - q^\nu\frac{p\cdot q}{q^2}\Big)\frac{F_2(x_B,Q^2)}{p\cdot q} \\ & + \frac{1}{p\cdot q}\varepsilon^{\mu\nu\rho\sigma}q_\rho\Big[S_\sigma g_1(x_B,Q^2) + \Big(S_\sigma - \frac{S\cdot q}{p\cdot q}p_\sigma\Big)g_2(x_B,Q^2)\Big] \end{aligned}$$

The g_2 structure function

- g_2 is a special structure function:
  - it is the only one with twist-3 contributions that can be measured in inclusive DIS
  - in the OPE analysis, its twist-3 term can be isolated:

$$g_2(x) = \underbrace{g_2^{WW}(x)}_{\text{"Wandzura-Wilczek relation"}} + \underbrace{\Delta(x)}_{\text{"pure twist-3 term" (quark-gluon correlations)}}$$

$$g_2^{WW}(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$$

moments are matrix elements of twist-3 operators

The Wandzura-Wilczek relation

- Lorentz Invariance Relations (LIR) and Equations Of Motion (EOM) imply

$$g_2(x) = g_2^{WW}(x) + \tilde{\delta}(x) + \hat{\delta}(x) + \frac{m_q}{\Lambda}\delta_m(x)$$

negligible
for light quarks

where

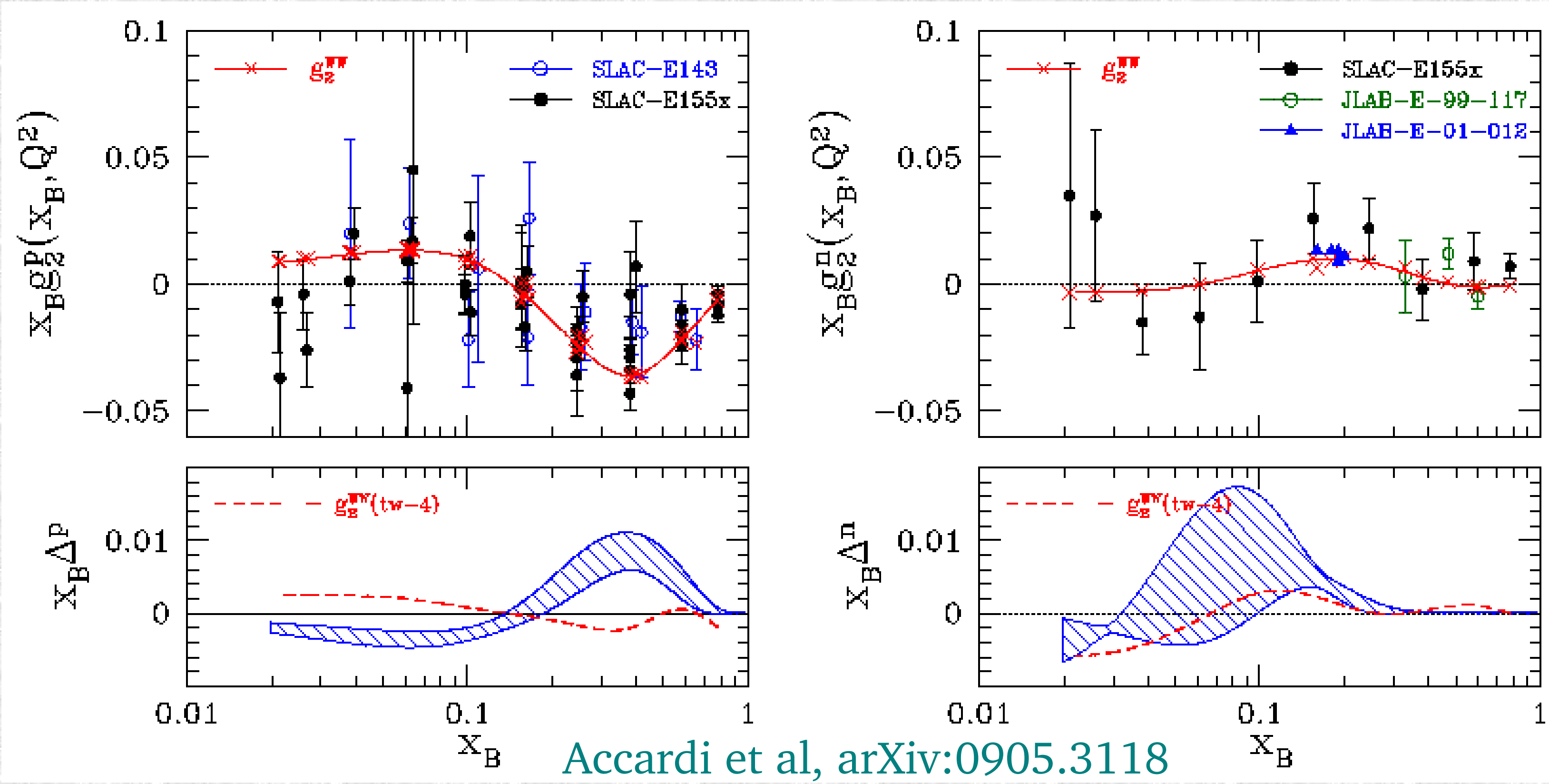
$$\tilde{\delta}(x) = \frac{1}{2}\sum_a e_a^2 \int_x^1 \frac{dy}{y}\frac{d}{dy}\left[y\tilde{g}_T^a(y)\right]$$

$$\hat{\delta}(x) = \frac{1}{2}\sum_a e_a^2 \int_x^1 \frac{dy}{y}\hat{g}_T^a(y)$$

pure twist-3
(quark-glue correlations)

- **The WW relation is broken by 2 "pure twist-3" terms**
  - can in principle be large and canceling: **need to measure separately**
  - it is a first principles, model independent decomposition (Lorentz invariance, Dirac equations of motion)

Experimental WW breaking



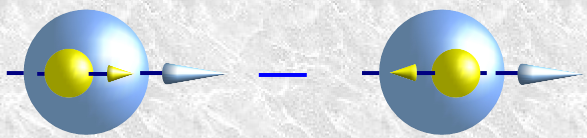
Accardi et al, arXiv:0905.3118

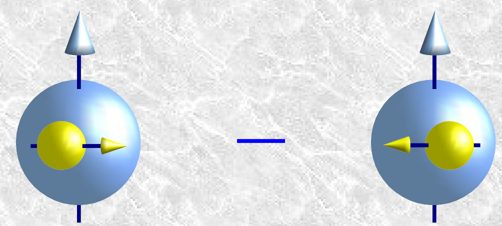
	proton		χ^2/d.o.f.	r_{tot}	r_{low}	r_{hi}
(I)	Δ_{th}	$= 0$	1.22			
(II)	Δ_{th}	$= \alpha(1-x)^\beta\left((\beta+2)x-1\right)$				
	α	$= 0.13 \pm 0.05$				
	β	$= 4.4 \pm 1.0$	1.05	15-32%	18-36%	14-31%
	neutron					
(I)	Δ_{th}	$= 0$	1.66			
(II)	Δ_{th}	$= \alpha(1-x)^\beta\left((\beta+2)x-1\right)$				
	α	$= 0.64 \pm 0.92$				
	β	$= 24 \pm 10$	1.11			18-40%

15-40%
not small, contrary to standard claims!

How interesting are $\tilde{g}_T$ and $\hat{g}_T$?

- **Transverse momentum dependent (TMD) quark distributions**

$g_1^a(x, \vec{k}_T^2) =$  long. polarized quarks in a long. polarized nucleon

$g_{1T}^a(x, \vec{k}_T^2) =$  long. polarized quarks in a transv. polarized nucleon

$$g_T^a(x, \vec{k}_T^2) = g_1^a(x, \vec{k}_T^2) + g_2^a(x, \vec{k}_T^2)$$

twist-3
no parton model interpretation

- **Collinear PDFs**, are defined by transverse momentum integration

$$g_{1\,(1T)}(x) = \int d^2k_T\, g_{1\,(1T)}(x, \vec{k}_T)$$

$$g_{1T}^{(1)}(x) = \int d^2k_T\, \frac{\vec{k}_T^2}{2M} g_{1T}(x, \vec{k}_T)$$

How interesting are $\tilde{g}_T$ and $\hat{g}_T$?

Lorentz Invariance: $$g_T^a(x) = g_1^a(x) + \frac{d}{dx}\, g_{1T}^{a(1)}(x) + \hat{g}_T^a(x)$$

Eqs. of motion: $$g_{1T}^{a(1)}(x) = x g_T^a(x) - x\tilde{g}_T^a(x) - \frac{m}{M}\, h_1^a(x)$$

WW relation: $$g_2(x) = g_2^{WW}(x) + \tilde{\delta}(x) + \hat{\delta}(x)$$

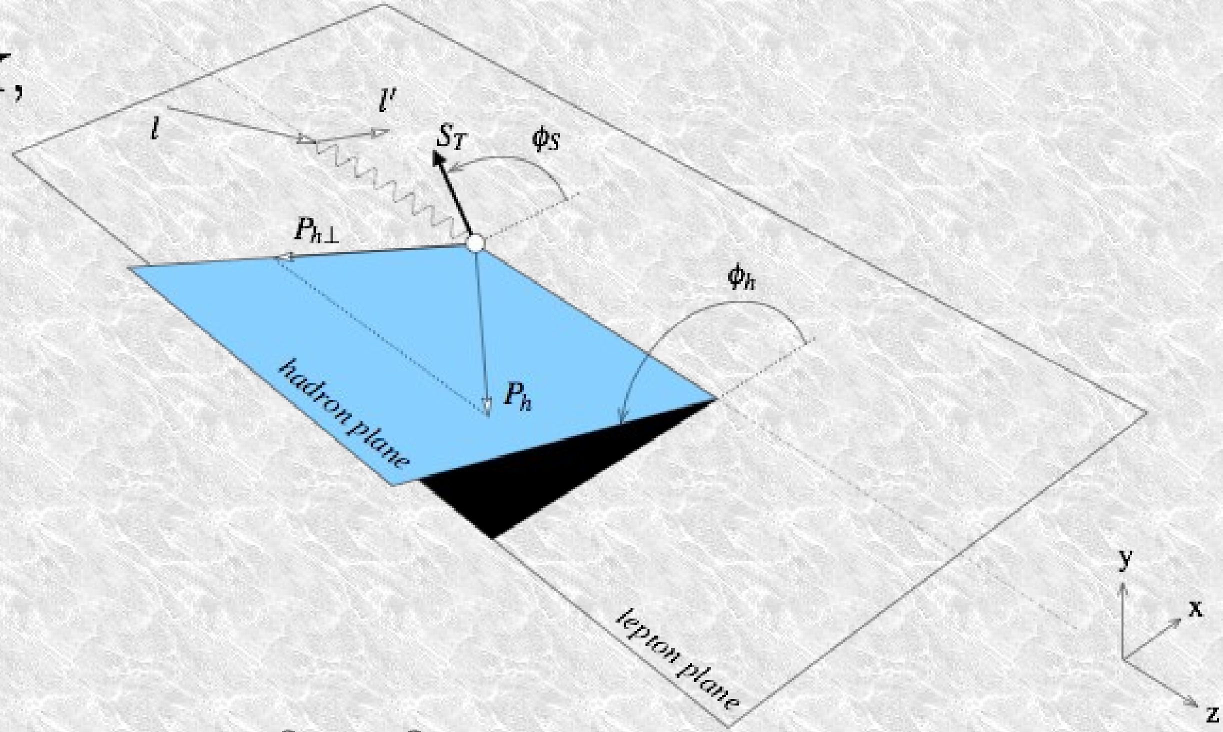
- $\hat{g}_T, \tilde{g}_T$ access different "projections" of $D(x,x')$ – important for
  - QCD evolution of g_2
  - computation of high-k_T spin asymmetries / tails of TMDs
- 3 independent measurements (g_T, g_1, $g_{1T}^{(1)}$) for 2 independent relations:
  - test of TMD factorization
  - connection to collinear factorization

$$g_{1T}^{(1)}(x) \overset{TMD}{=} \int d^2k_T\, \frac{\vec{k}_T^2}{2M}\, g_{1T}(x,\vec{k}_T) \overset{CF}{=} \int \frac{d\lambda e^{i\lambda x}}{4\pi S_T} \langle P,S|\bar{\psi}(0)\gamma^+\partial_\alpha\gamma_5\psi(\lambda n)|P,S\rangle$$

How can we measure $\tilde{g}_T$ and $\hat{g}_T$?

- Need to measure $g_{1T}^{(1)}$: **double L-T spin asymmetry in SIDIS**

$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X,$$



$$x_B = \frac{Q^2}{2\,P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot l}$$

$$\gamma = \frac{2Mx_B}{Q} \qquad z_h = \frac{P\cdot P_h}{P\cdot q}$$

Long. pol. beam
Trans. pol. target

$$d\sigma_{LT} \propto y\sqrt{1-y}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}(x_B, z_h, P_{h\perp}^2, Q^2)$$
$$+\,y(1-y/2)\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}(x_B, z_h, P_{h\perp}^2, Q^2)$$
$$+\,y\sqrt{1-y}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}(x_B, z_h, P_{h\perp}^2, Q^2)$$

$$\int \frac{|P_{h\perp}|}{z_h M}\,F_{LT}^{\cos(\phi_h-\phi_S)}(x_B, z_h, P_{h\perp}^2, Q^2) = \sum_q e_q^2\,x_B\,g_{1T}^{(1)q}(x_B)\,D_1^q(z_h)$$

Summary

- **Hadrons at large x / low Q^2 including:**
  - TMC – in coll.fact. free from threshold problem
  - JMC – new! at LO only, so far
  - HT, nuclear corrections

- **New PDFs at large x**
  - HT+TMC:
    - ✓ stable twist-2
    - ✓ economical higher-twist parametrization
  - nuclear smearing – essential for deuterium at $x_B > 0.5$
  - Extended data set – reduced PDF errors

- **Twist-3 quark-gluon correlations in polarized DIS**
  - test of TMD factorization
  - TMD / connection
  - evolution of g_2

Outlook

1) Unpolarized hadrons

- Nuclear smearing & nuclear PDF
  [w/ Qiu, Vary]

- JMC: phenomemology, NLO
- quark-hadron duality [w/ Qiu]
- large-x resummation
  [w/ Jlab group]

- TMC for DY, p+p at large x_F
  [w/ Schlegel, Metz ??]

cteqX fits $(\varphi \equiv f_1)$

- F_L : gluons, small and large x
- nuclear PDFs [w/ SMU group ??]
- ... for the future ...

Outlook

2) Polarized hadrons

- TMC for TMDs
  - SIDIS @ NLO in coll.fact.
  - for TMDs [w/ Prokhudin, Melis ?]
- polarized JMC [w/ Bacchetta, Schlegel]
  - new observables ?
  - transversity in inclusive DIS ??
- Twist-3, g_2 evolution & C.
  [w/ Bacchetta, Schlegel ?]

Polarized cteqX ? $(\Delta\varphi \equiv g_1)$

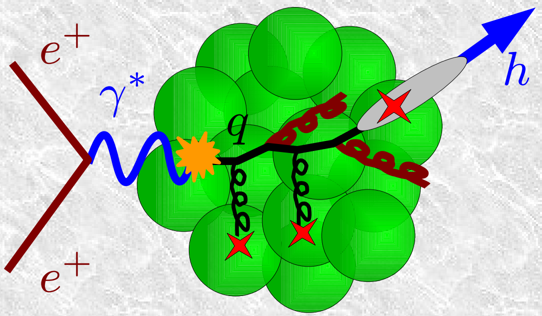
- TMC+HT+nuclear corrections
  [w/ Vogelsang, Strattman, Sassot ?]
- ... for the future ...

Transversity fits ?? $(\delta\varphi \equiv h_1)$

[w/ Torino group ??]

Outlook

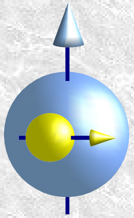
3) Preparing for the future



Electron Ion Collider

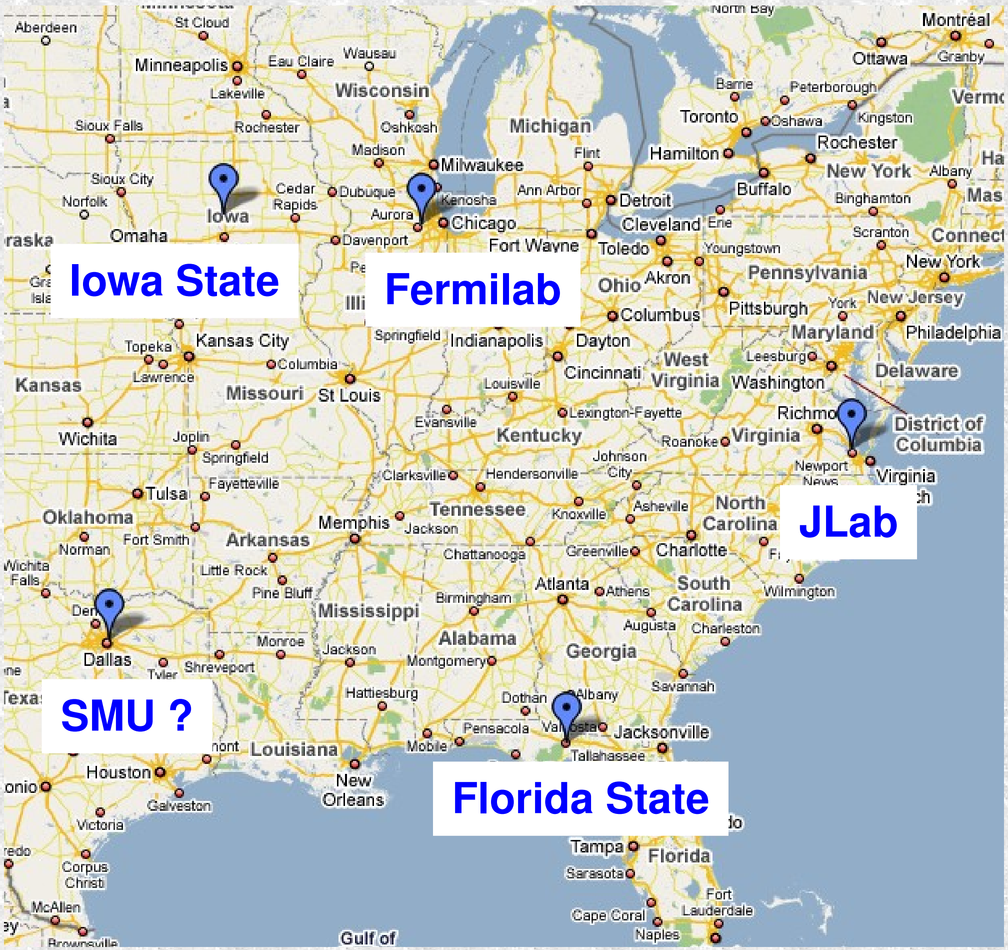
Hadronization in cold nuclear matter
(study group coordinator)

Spin physics



PAX, PANDA (?) @ FAIR

Outlook



Thank you!

Appendix

Lorentz Invariance Relation

- Lorentz invariance relates $g_1(x)$, $g_{1T}(x)$ and $g_T(x)$:

$$g_T^a(x) = g_1^a(x) + \frac{d}{dx}\, g_{1T}^{a(1)}(x) + \hat{g}_T^a(x)$$

pure twist-3
(quark-glue correlations)

where

$$\hat{g}_T(x) = \int dx' \, \frac{\overline{D}(x,x') + \overline{D}(x',x)}{x'-x}$$

$$\overline{D}(x,x') = \tfrac{1}{2}\Big[\overline{D}_1(x,x') + \overline{D}_2(x',x)\Big]$$

Bukhvostov,Kuraev,Lipatov '83
Belitsky, hep-ph/9703432

and in light-cone gauge

$$\frac{M}{P^+} S_T^i \overline{D}_1(x,x') = -\frac{g_s}{8} \int \frac{d\xi^-}{2\pi}\frac{d\eta^-}{2\pi}\, e^{ik\cdot\xi - ik'\cdot\eta} \langle P,S|\bar\psi(\eta)\gamma^+ \not{A}_T(0)\gamma^i\gamma_5\psi(\xi)|P,S\rangle$$

$$\frac{M}{P^+} S_T^i \overline{D}_2(x',x) = -\frac{g_s}{8} \int \frac{d\xi^-}{2\pi}\frac{d\eta^-}{2\pi}\, e^{ik'\cdot\eta - ik\cdot\xi} \langle P,S|\bar\psi(\xi)\gamma^+ \gamma^i \not{A}_T(0)\gamma_5\psi(\eta)|P,S\rangle$$

Equations Of Motion relation

- The Dirac equation of motion $\not{D}\psi - m\psi = 0$ implies

$$g_{1T}^{a(1)}(x) = x g_T^a(x) - x\tilde{g}_T^a(x) - \frac{m}{M} h_1^a(x)$$

negligible
for light quarks

pure twist-3
(quark-glue correlations)

where in light-cone gauge,

$$\tilde{g}_T^a(x) = \frac{1}{x}\int dx' \overline{D}(x,x')$$

$$= \frac{g_s}{2x}\frac{P^+}{M S_T^i}\int\frac{d\xi^-}{2\pi}\langle P,S|\bar{\psi}^a(0)\gamma^+\Big(\not{A}_T(0) - \not{A}_T(\xi)\Big)\gamma_5\,\psi^a(\xi)|P,S\rangle$$

- **Note:** $\hat{g}_T, \tilde{g}_T$ are different projection of the $\overline{\mathrm{D}}$(x,x') quark-gluon correlator

Jet function – outlook

- We need to develop a "phenomenology" of the jet function:
  - from Dyson-Schwinger equations?
  - from $e^+e^- \to$ jets?
  - from Monte Carlo simulations?
  - ...
- Can we compare the fitted $J_m \approx J_2$ to lattice QCD computations ??

$$\int_0^\infty dm_j^2\, J_2(m_j^2)\, 2\pi\delta(l^2 - m_j^2)\,\theta(l^0) = \frac{1}{4l^-}\int d^4z e^{iz\cdot l}\mathrm{Tr}\big[\gamma^- \langle 0|\overline{\psi}(z)\psi(0)|0\rangle\big]$$

  - Landau gauge vs. light-cone gauge
  - Euclidean vs. Minkowski space
- Should we ultimately regard it only as a phenomenological tool?
  - fit it to DIS data, in the spirit of "global QCD fits"
- Need extension to NLO, polarized DIS