

nPDF extraction with hadron beams

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Outline

- I. Overview on data used in global analyses
 - proton PDF
 - nuclear PDF
- II. More detailed view
 - Drell-Yan lepton pair production
 - Ratio of DY cross sections
 - W-rapidity asymmetry
- III. Other interesting processes

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 - Drell-Yan ratio
 - W-asymmetry
- III. Other interesting processes

The different Parton Distributions:

$$u_v(x, Q^2), d_v(x, Q^2)$$

quark model, carry 50% of proton mom.

$$\bar{u}(x, Q^2), \bar{d}(x, Q^2)$$

light sea, E866: $\bar{u} \neq \bar{d}$

$$g(x, Q^2)$$

gluon, carries 40% of momentum

$$s(x, Q^2), \bar{s}(x, Q^2)$$

strange sea, NuTeV: $s \neq \bar{s}$

$$c(x, Q^2), b(x, Q^2)$$

heavy quark PDFs, perturbatively generated
possible intrinsic contribution at large-x

$$\gamma(x, Q^2)$$

Photon PDF in proton \leftrightarrow QED radiation

Small isospin violation: $u^p(x, Q^2) \neq d^n(x, Q^2)$
(already due to QED radiation)

I. Overview on data used in global analyses of PDFs

proton PDFs

Data:

- Deep inelastic scattering data
 - H1 ,ZEUS (ep)
 - BCDMS,NMC ($\mu p, \mu d$)
 - CCFR (ν -Fe)
- $p+pbar \rightarrow jet + X$: D0, CDF
- DY pp: E605
- DY pd/pp: NA51, E866 (updated)
- W-lepton asymmetry: CDF
- ν -DIS dimuon data: Nutev

Backbone: $10^{-5} < x < 0.1$
up > down, evolution of F2 \rightarrow gluon
 $F_L \rightarrow$ gluon

large-x gluon: $0.01 < x < 0.5$
dominated by systematics

$q\bar{q} \rightarrow \mu^+ \mu^-$ info on sea

Asymmetry: info on \bar{d}/\bar{u}

d/u at large-x ($u\bar{d} \rightarrow W^+$, $d\bar{u} \rightarrow W^-$)

s, \bar{s}

Data sets fitted in MSTW 2008 NLO analysis [[arXiv:0901.0002](https://arxiv.org/abs/0901.0002)]

Data set	$\chi^2 / N_{\text{pts.}}$
H1 MB 99 $e^+ p$ NC	9 / 8
H1 MB 97 $e^+ p$ NC	42 / 64
H1 low Q^2 96–97 $e^+ p$ NC	44 / 80
H1 high Q^2 98–99 $e^- p$ NC	122 / 126
H1 high Q^2 99–00 $e^+ p$ NC	131 / 147
ZEUS SVX 95 $e^+ p$ NC	35 / 30
ZEUS 96–97 $e^+ p$ NC	86 / 144
ZEUS 98–99 $e^- p$ NC	54 / 92
ZEUS 99–00 $e^+ p$ NC	63 / 90
H1 99–00 $e^+ p$ CC	29 / 28
ZEUS 99–00 $e^+ p$ CC	38 / 30
H1/ZEUS $e^\pm p F_2^{\text{charm}}$	107 / 83
H1 99–00 $e^+ p$ incl. jets	19 / 24
ZEUS 96–97 $e^+ p$ incl. jets	30 / 30
ZEUS 98–00 $e^\pm p$ incl. jets	17 / 30
DØ II $p\bar{p}$ incl. jets	114 / 110
CDF II $p\bar{p}$ incl. jets	56 / 76
CDF II $W \rightarrow l\nu$ asym.	29 / 22
DØ II $W \rightarrow l\nu$ asym.	25 / 10
DØ II Z rap.	19 / 28
CDF II Z rap.	49 / 29

Data set	$\chi^2 / N_{\text{pts.}}$
BCDMS $\mu p F_2$	182 / 163
BCDMS $\mu d F_2$	190 / 151
NMC $\mu p F_2$	121 / 123
NMC $\mu d F_2$	102 / 123
NMC $\mu n / \mu p$	130 / 148
E665 $\mu p F_2$	57 / 53
E665 $\mu d F_2$	53 / 53
SLAC $ep F_2$	30 / 37
SLAC $ed F_2$	30 / 38
NMC/BCDMS/SLAC F_L	38 / 31
E866/NuSea pp DY	228 / 184
E866/NuSea pd/pp DY	14 / 15
NuTeV $\nu N F_2$	49 / 53
CHORUS $\nu N F_2$	26 / 42
NuTeV $\nu N xF_3$	40 / 45
CHORUS $\nu N xF_3$	31 / 33
CCFR $\nu N \rightarrow \mu\mu X$	66 / 86
NuTeV $\nu N \rightarrow \mu\mu X$	39 / 40
All data sets	2543 / 2699

- **Red** = New w.r.t. MRST 2006 fit.

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nuclear PDFs

NPDFS FROM ℓA DIS AND DY DATA

Global analyses of NPDF by four groups:

- **HKN'07** [[PRC76\(2007\)065207](#)]
LO, NLO, error PDFs, $\chi^2/dof = 1.2$
- **EPS'09** [[JHEP0904\(2009\)065](#)]
LO, NLO, error PDFs, $\chi^2/dof = 0.8$
Use also inclusive π^0 data at midrap. from $d + Au$ and $p + p$ coll. at RHIC \rightarrow gluon
- **DS'04** [[PRD69\(2004\)074028](#)]
first NLO analysis, 'semi-global', no error PDFs, $\chi^2/dof = 0.76$
- **nCTEQ** [[PRD80\(2009\)094004](#)]
NLO, same data as HKN'07 (up to cuts), no error PDFs (so far), $\chi^2/dof = 0.95$, official release soon

Table from [Hirai et al., arXiv:0909.2329](#)

	R	Nucleus	Experiment	EPS09	HKN07	DS04	
DIS	A/D	D/p	NMC		0		
		4He	SLAC E139	0	0	0	
			NMC95	0 (5)	0	0	
		Li	NMC95	0	0		
		Be	SLAC E139	0	0	0	
		C	EMC-88, 90			0	
			NMC 95	0	0	0	
			SLAC E139	0	0	0	
			FNAL-E665			0	
		N	BCDMS 85			0	
			HERMES 03			0	
		Al	SLAC E49			0	
			SLAC E139	0	0	0	0
		Ca	EMC 90			0	
			NMC 95	0	0	0	0
			SLAC E139	0	0	0	0
			FNAL-E665			0	
		Fe	SLAC E87			0	
			SLAC E139	0 (15)	0	0	0
			SLAC E140			0	
			BCDMS 87			0	
		Cu	EMC 93	0	0		
		Kr	HERMES 03			0	
Ag	SLAC E139	0	0	0	0		
Sn	EMC 88			0			
Au	SLAC E139	0	0	0	0		
	SLAC E140			0			
Pb	FNAL-E665			0			
A/C	Be	NMC 96	0	0	0		
	Al	NMC 96	0	0	0		
	Ca	NMC 95			0		
		NMC 96	0	0	0	0	
	Fe	NMC 96	0	0	0		
	Sn	NMC 96	0 (10)	0	0	0	
	Pb	NMC 96	0	0	0	0	
A/Li	C	NMC 95	0	0			
	Ca	NMC 95	0	0			
DY	A/D	C	FNAL-E772	0	0	0	
		Ca		0 (15)	0	0	
		Fe		0 (15)	0	0	
		W		0 (10)	0	0	
A/Be	Fe	FNAL E866	0	0			
	W		0	0			
π pro	dA/pp	Au	RHIC-PHENIX	0 (20)			

EXPERIMENTAL INPUT



Use same data as HKN'07 (up to cuts)

- DIS F_2^A / F_2^D data sets: 862 points (before cuts)
- DIS $F_2^A / F_2^{A'}$ data sets: 297 points (before cuts)
- DY data sets $\sigma_{DY}^{pA} / \sigma_{DY}^{pA'}$: 92 points (before cuts)

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			NMC 95	0	0	0	
			SLAC E139	0	0	0	
		N	FNAL-E665			0	
			BCDMS 85			0	
		Al	HERMES 03			0	
			SLAC E49			0	
		Ca	SLAC E139	0	0	0	0
			EMC 90			0	
			NMC 95	0	0	0	0
			SLAC E139	0	0	0	0
		Fe	FNAL-E665			0	
			SLAC E87			0	
			SLAC E139	0 (15)	0	0	0
			SLAC E140			0	
		Cu	BCDMS 87			0	
		Kr	EMC 93	0	0		
		Ag	HERMES 03			0	
		Sn	SLAC E139	0	0	0	0
		Au	EMC 88			0	
			SLAC E139	0	0	0	0
		A/C	SLAC E140			0	
Pb	FNAL-E665			0			
Be	NMC 96		0	0	0		
Al	NMC 96		0	0	0		
Ca	NMC 95				0		
	NMC 96		0	0	0	0	
Fe	NMC 96		0	0	0	0	
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		Fe		0 (15)	0	0	
		W		0 (10)	0	0	
A/Be	Fe	FNAL E866	0	0			
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		Ag	SLAC E139	0	0	0	0
		Sn	EMC 88			0	
		Au	SLAC E139	0	0	0	0
			SLAC E140			0	
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		NMC 96	0	0	0	0	
	Fe	NMC 96	0	0	0		
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		Fe		0 (15)	0	0	
		W		0 (10)	0	0	
A/Be	Fe	FNAL E866	0	0			
	W		0	0			
π pro	dA/pp	Au	RHIC-PHENIX	0 (20)			

NUCLEAR CTEQ

Framework as in CTEQ6M proton fit:

- **Same functional form** for **bound proton PDFs** inside a nucleus A as for free proton PDFs (restrict x to $0 < x < 1$):

$$x f_k^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}, \quad k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s},$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

(bound neutron PDFs $f_k^{n/A}$ by isospin symmetry)

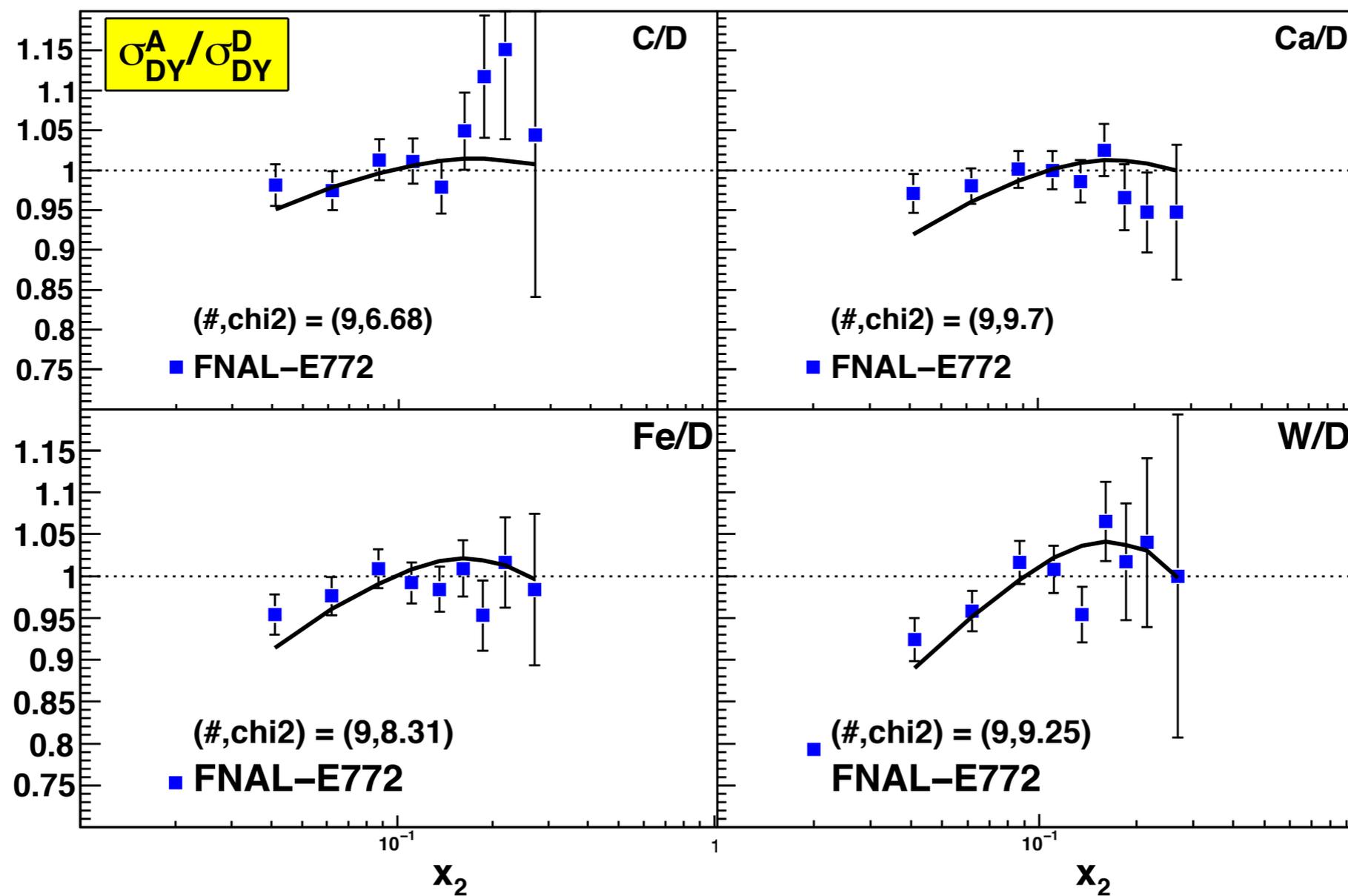
- **A -dependent fit parameters:** (reduces to free proton parameters $c_{k,0}$ for $A = 1$)

$$c_k \rightarrow c_k(A) \equiv c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}}), \quad k = 1, \dots, 5$$

- **PDFs for a nucleus (A, Z) :** $f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$
- **Input parameters:** $Q_0 = m_c = 1.3 \text{ GeV}$, $m_b = 4.5 \text{ GeV}$, $\alpha_s^{NLO, \overline{\text{MS}}}(M_Z) = 0.118$
- **Heavy quark treatment:** ACOT scheme
- **Standard DIS-cuts:** $Q > 2 \text{ GeV}$, $W > 3.5 \text{ GeV}$

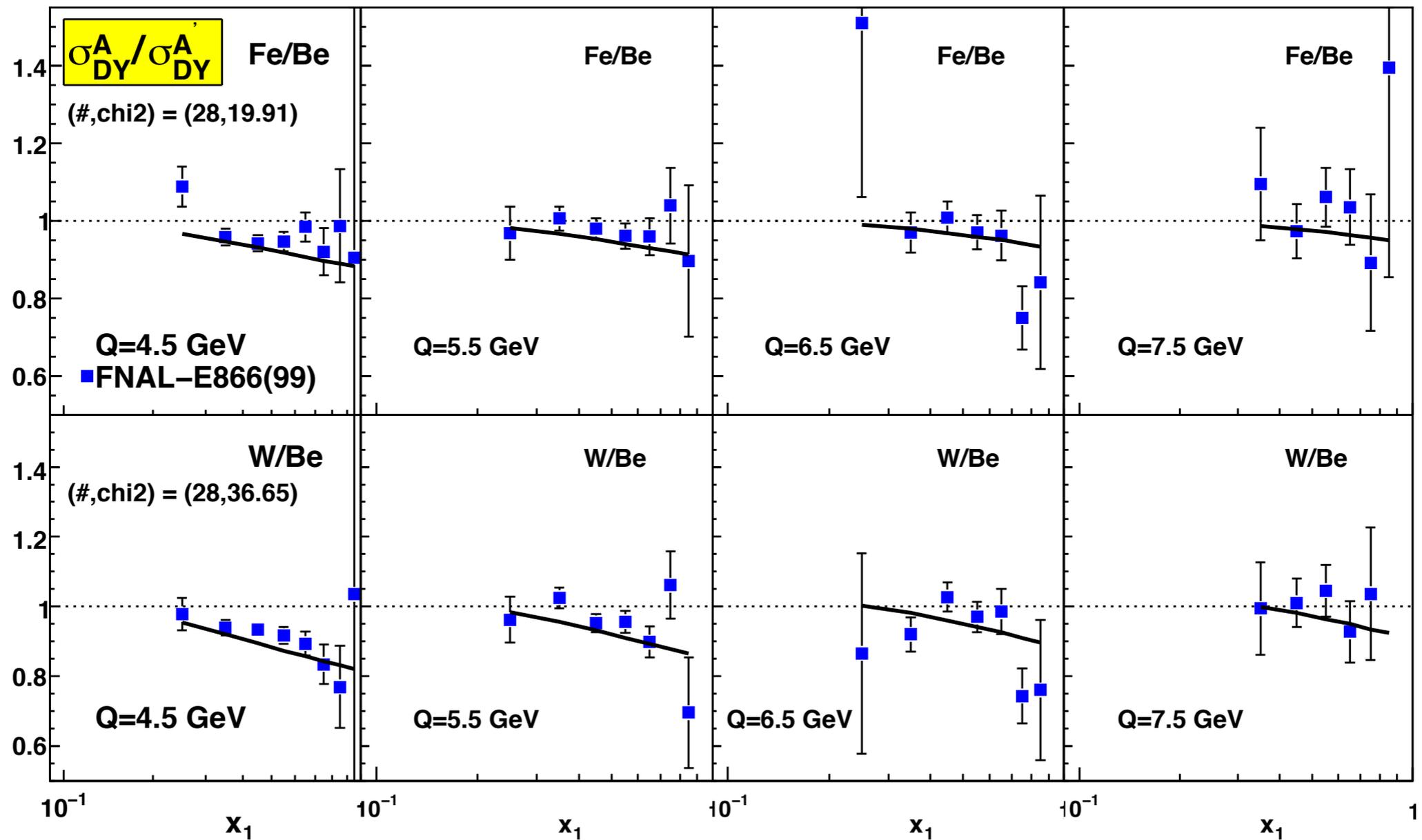
RESULTS: DEECUT3 FIT

DRELL-YAN DATA



RESULTS: DECUT3 FIT

DRELL-YAN DATA



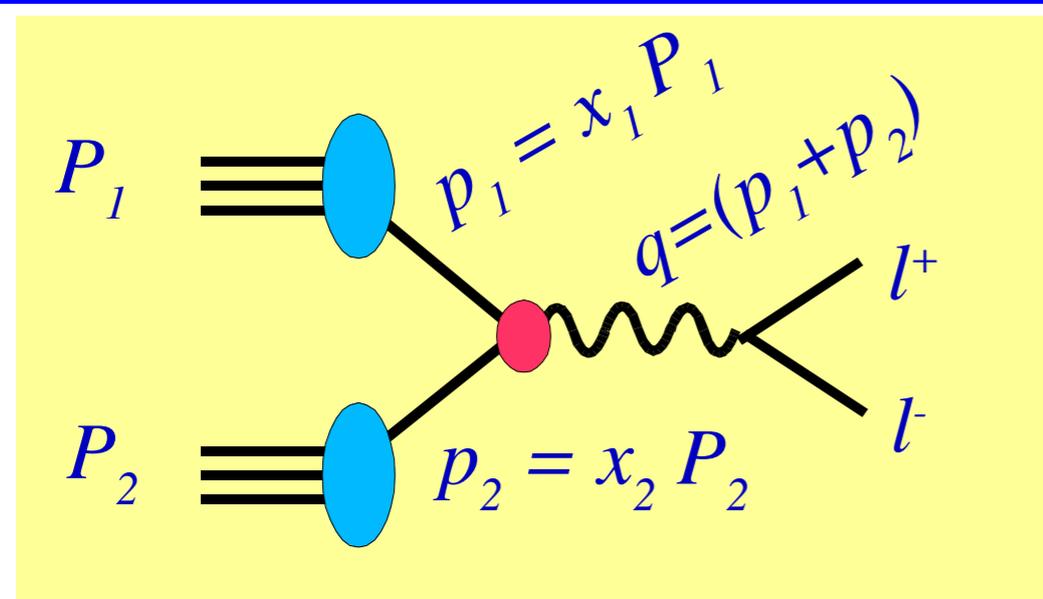
Summary: used hadronic processes

- **Proton case:**
 - **DY:** FNAL E605 (pCu) → info on quark sea
 - **DY:** FNAL E866=NuSea (pd/pp) → info on $d\bar{u}(x)/u\bar{d}(x)$
 - **W-asymmetry** (D0 II, CDF II) → info on $d(x)/u(x)$ at large x
 - **Z-rapidity** (CDF II)
 - **Inclusive jet production** (D0 II, CDF II) → info on gluon at large x
- **Nuclear case:**
 - **DY:** FNAL E772 (C/D, Ca/D, Fe/D, W/D) → info on quark sea
 - **DY:** FNAL E866 (Fe/Be, W/Be) → info on quark sea
 - **Inclusive pion production:** RHIC PHENIX (dAu/pp) → info on gluon
 - Note: NO inclusive jet production data available so far;
AFTER could measure this with $p_T = 20 \dots 40$ GeV → large- x gluon nPDF

II. More detailed view

Drell-Yan lepton pair production and anti-quark PDFs

Kinematics in the Hadronic Frame



$$P_1 = \frac{\sqrt{s}}{2} (1, 0, 0, +1) \quad P_1^2 = 0$$

$$P_2 = \frac{\sqrt{s}}{2} (1, 0, 0, -1) \quad P_2^2 = 0$$

$$s = (P_1 + P_2)^2 = \frac{\hat{s}}{x_1 x_2} = \frac{\hat{s}}{\tau}$$

Therefore

$$\tau = x_1 x_2 = \frac{\hat{s}}{s} \equiv \frac{Q^2}{s}$$

Fractional energy² between partonic and hadronic system

$$\frac{d\sigma}{dQ^2} = \sum_{q, \bar{q}} \int dx_1 \int dx_2 \{ q(x_1) \bar{q}(x_2) + \bar{q}(x_1) q(x_2) \} \hat{\sigma}_0 \delta(Q^2 - \hat{s})$$

Hadronic cross section

Parton distribution functions

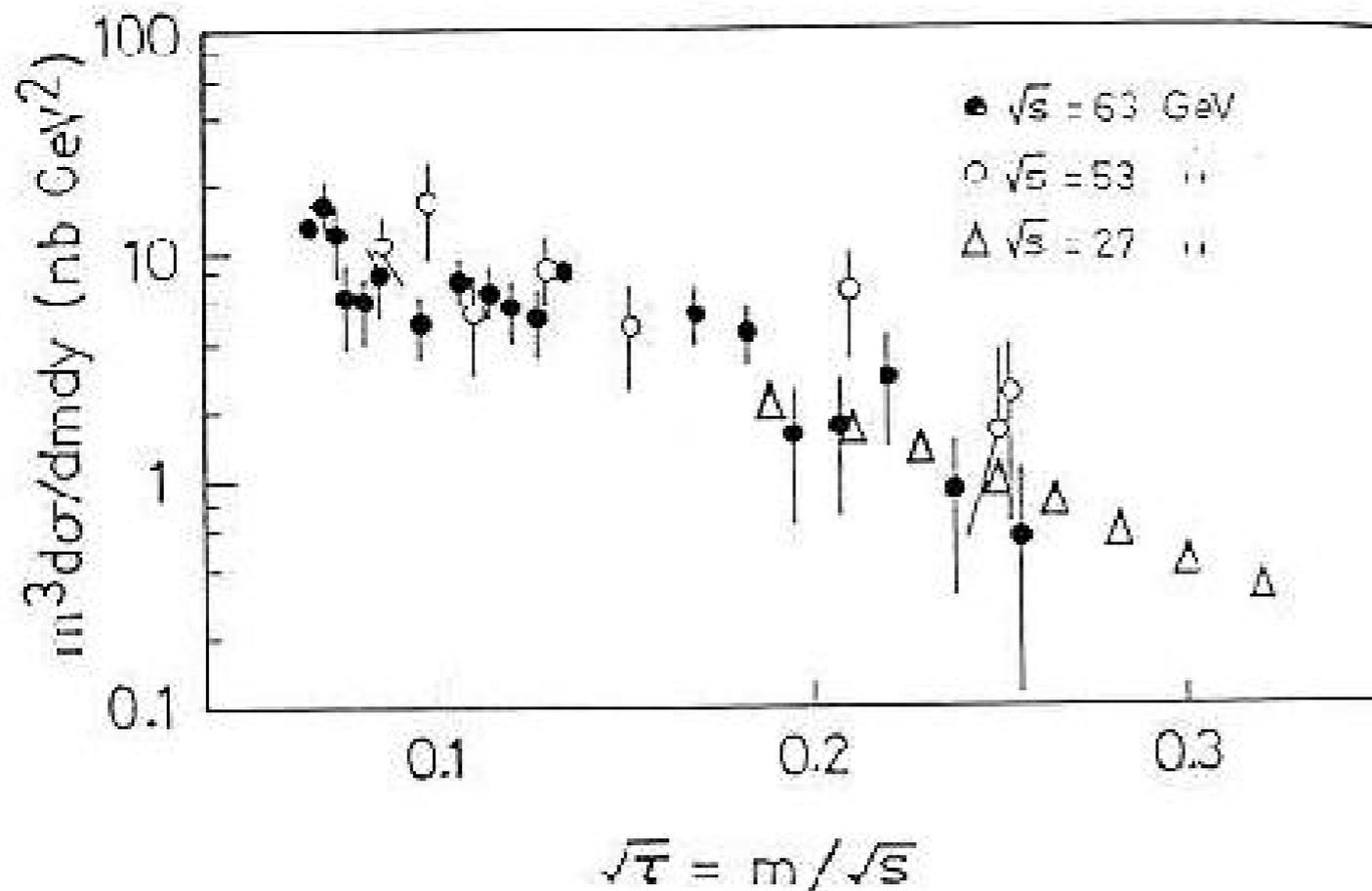
Partonic cross section

Scaling form of the Drell-Yan Cross Section

Using: $\hat{\sigma}_0 = \frac{4\pi\alpha^2}{9\hat{s}} Q_i^2$ and $\delta(Q^2 - \hat{s}) = \frac{1}{sx_1} \delta(x_2 - \frac{\tau}{x_1})$

we can write the cross section in the scaling form:

$$Q^4 \frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9} \sum_{q,\bar{q}} Q_i^2 \int_{\tau}^1 \frac{dx_1}{x_1} \tau \left\{ q(x_1) \bar{q}(\tau/x_1) + \bar{q}(x_1) q(\tau/x_1) \right\}$$



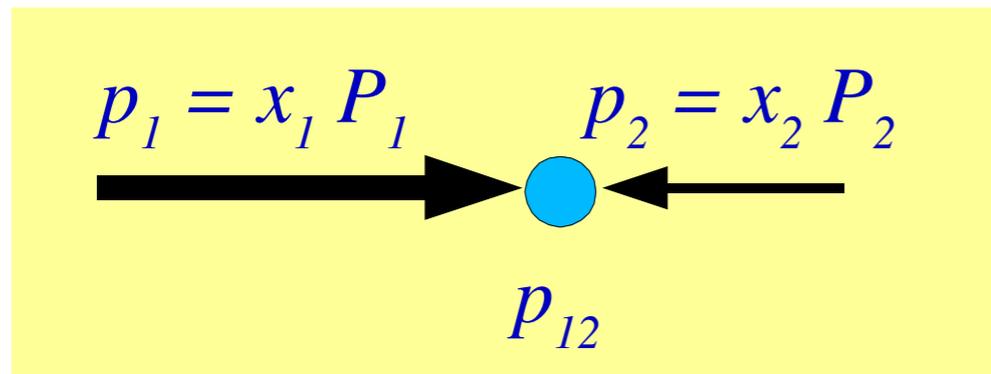
Notice the RHS is a function of only τ , not Q .

This quantity should lie on a universal scaling curve.

Cf., DIS case, & scattering of point-like constituents

Longitudinal Momentum Distributions

Partonic CMS has longitudinal momentum w.r.t. the hadron frame



$$p_{12} = (p_1 + p_2) = (E_{12}, 0, 0, p_L)$$

$$E_{12} = \frac{\sqrt{s}}{2} (x_1 + x_2)$$

$$p_L = \frac{\sqrt{s}}{2} (x_1 - x_2) \equiv \frac{\sqrt{s}}{2} x_F$$

x_F is a measure of the longitudinal momentum

The rapidity is defined as:

$$x_{1,2} = \sqrt{\tau} e^{\pm y}$$

$$y = \frac{1}{2} \ln \left\{ \frac{E_{12} + p_L}{E_{12} - p_L} \right\} = \frac{1}{2} \ln \left\{ \frac{x_1}{x_2} \right\}$$

$$dx_1 dx_2 = d\tau dy$$

$$dQ^2 dx_F = dy d\tau s \sqrt{x_F^2 + 4\tau}$$

$$\frac{d\sigma}{dQ^2 dx_F} = \frac{4\pi\alpha^2}{9Q^4} \frac{1}{\sqrt{x_F^2 + 4\tau}} \tau \sum_{q, \bar{q}} Q_i^2 \{ q(x_1) \bar{q}(\tau/x_1) + \bar{q}(x_1) q(\tau/x_1) \}$$

Let's compare data and theory

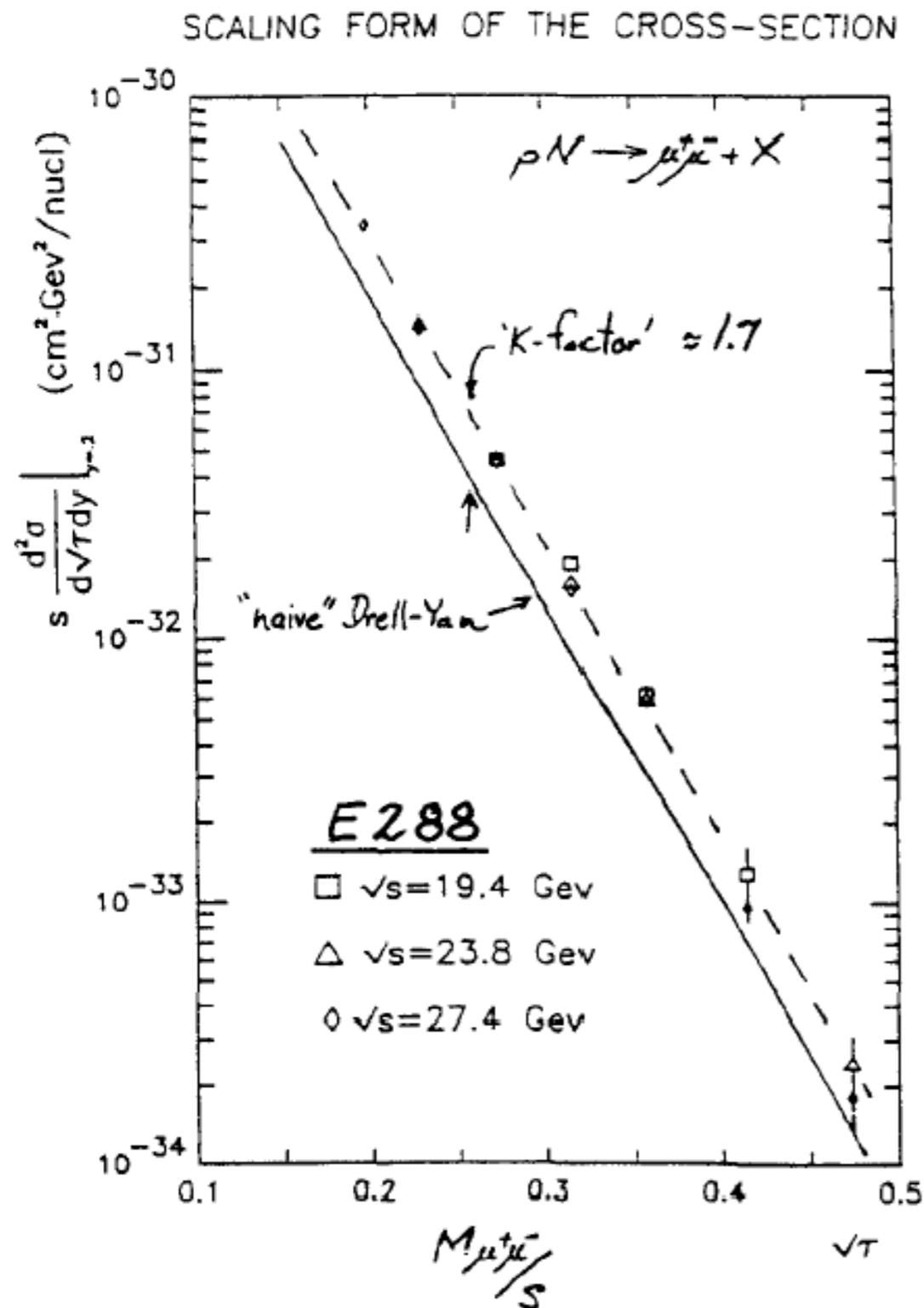


Table 1.2: Experimental K -factors.

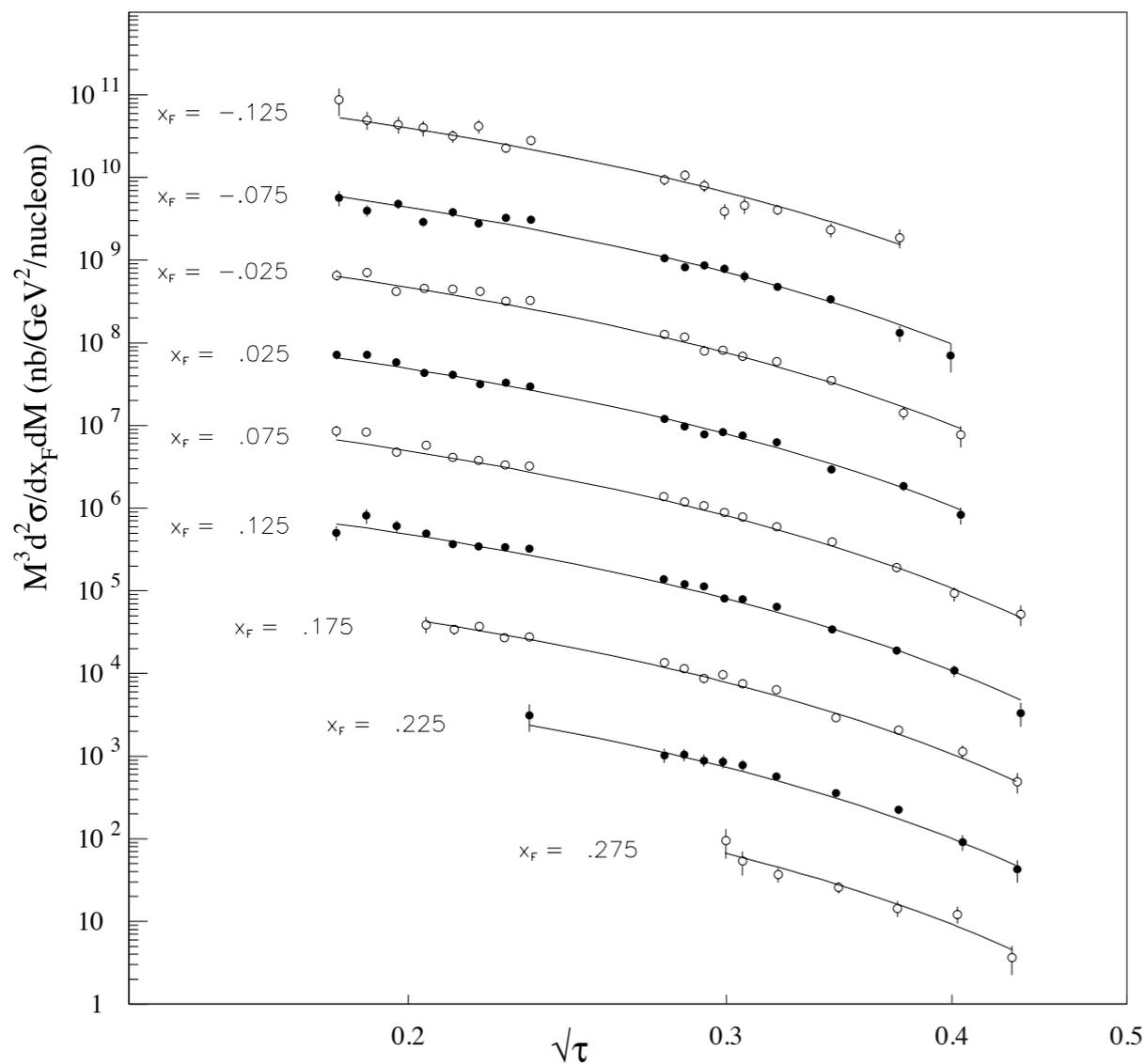
Experiment	Interaction	Beam Momentum	$K = \sigma_{\text{meas.}}/\sigma_{\text{DY}}$
E288 [Kap 78]	$p Pt$	300/400 GeV	~ 1.7
WA39 [Cor 80]	$\pi^\pm W$	39.5 GeV	~ 2.5
E439 [Smi 81]	$p W$	400 GeV	1.6 ± 0.3
NA3 [Bad 83]	$(\bar{p} - p)Pt$	150 GeV	2.3 ± 0.4
	$p Pt$	400 GeV	$3.1 \pm 0.5 \pm 0.3$
	$\pi^\pm Pt$	200 GeV	2.3 ± 0.5
	$\pi^- Pt$	150 GeV	2.49 ± 0.37
NA10 [Bet 85]	$\pi^- Pt$	280 GeV	2.22 ± 0.33
	$\pi^- W$	194 GeV	$\sim 2.77 \pm 0.12$
E326 [Gre 85]	$\pi^- W$	225 GeV	$2.70 \pm 0.08 \pm 0.40$
E537 [Ana 88]	$\bar{p} W$	125 GeV	$2.45 \pm 0.12 \pm 0.20$
E615 [Con 89]	$\pi^- W$	252 GeV	1.78 ± 0.06

J. C. Webb, Measurement of continuum dimuon production in 800-GeV/c proton nucleon collisions, arXiv:hep-ex/0301031.

Excellent agreement between data and theory

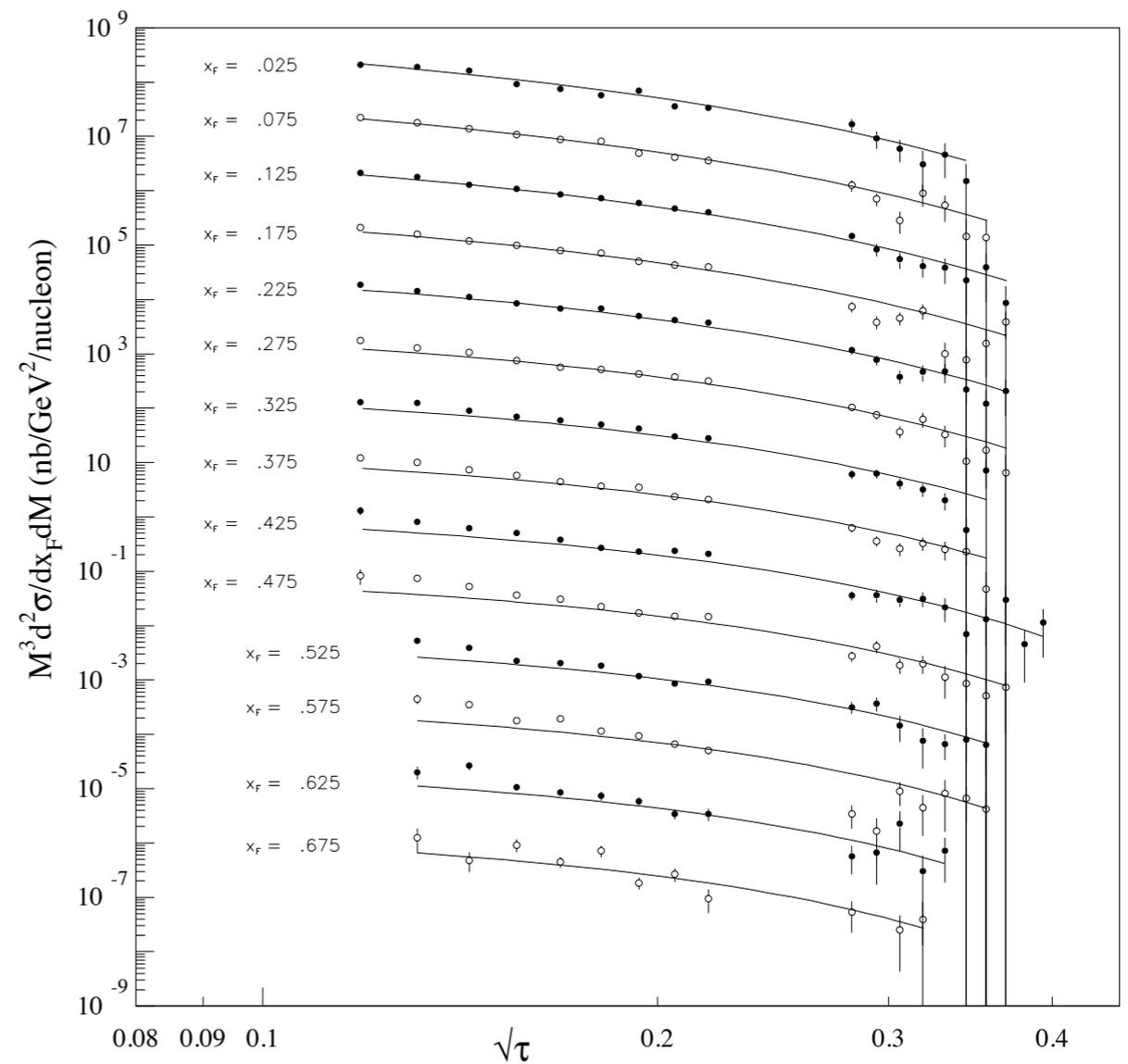
p + Cu at 800 GeV

E605 (p Cu $\rightarrow \mu^+ \mu^- X$) $p_{\text{LAB}} = 800$ GeV



p + d at 800 GeV

E772 (p d $\rightarrow \mu^+ \mu^- X$) $p_{\text{LAB}} = 800$ GeV



pp & pN processes sensitive to
anti-quark distributions

A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne,
Eur. Phys. J. C23, 73 (2002);
Eur. Phys. J. C14, 133 (2000);
Eur. Phys. J. C4, 463 (1998)

Discussion

- FNAL E605
 - fixed target pCu collisions
 - 800 GeV proton beam, $\sqrt{S} = 38.8$ GeV
 - di-muon invariant mass 7...17 GeV; $7./38.8 = 0.18$
 - sensitive to quark PDFs down to $x \sim 0.03$
 - **normalization uncertainty 15%**
- Modern measurement of DY with AFTER very interesting
 - NLO and NNLO calculations available
 - improved PDFs, modern statistical methods
 - different kinematic range due to higher cms-energy
 - Usually nuclear corrections assumed to be negligible:
→ AFTER can test with different nuclear targets
 - extraction of nPDFs with data for a single nucleus thinkable, **no modeling of A-dependence!**

Ratio of DY cross sections and the asymmetry of the light quark sea

Gottfried sum rule and the asymmetry in the light quark sea

$$I_G(Q^2) = \int \frac{dx}{x} [F_2^{lp}(x, Q^2) - F_2^{ln}(x, Q^2)]$$

Leading order parton model:

$$I_G(Q^2) = \frac{1}{3} - \frac{2}{3} \int_0^1 dx (\bar{d}(x, Q^2) - \bar{u}(x, Q^2))$$

Experimental result:

$$I_G^{NMC}(Q^2 = 4) = 0.235 \pm 0.026$$

Consequence: the light quark sea is asymmetric!
dbar > ubar (the integral)

$$\bar{d}(N = 1) > \bar{u}(N = 1)$$

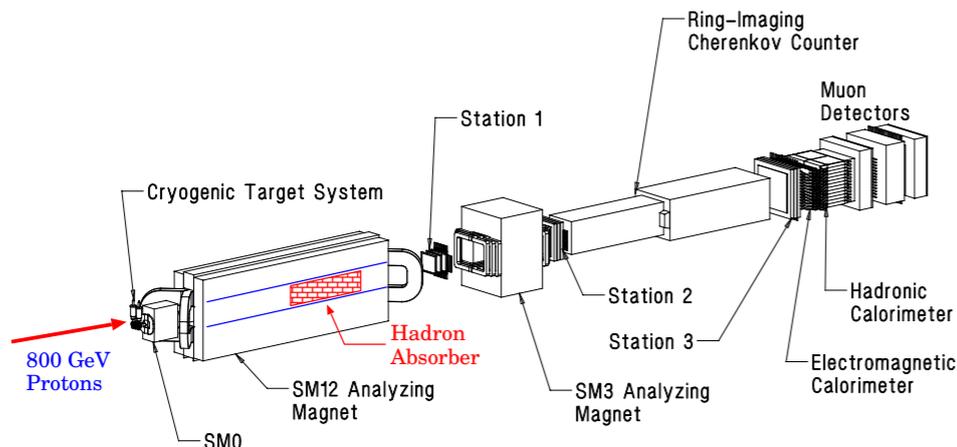
$$\text{Mellin moment: } f(N) = \int_0^1 dx x^{N-1} f(x)$$

→ NuSea: measurement of x-dependence

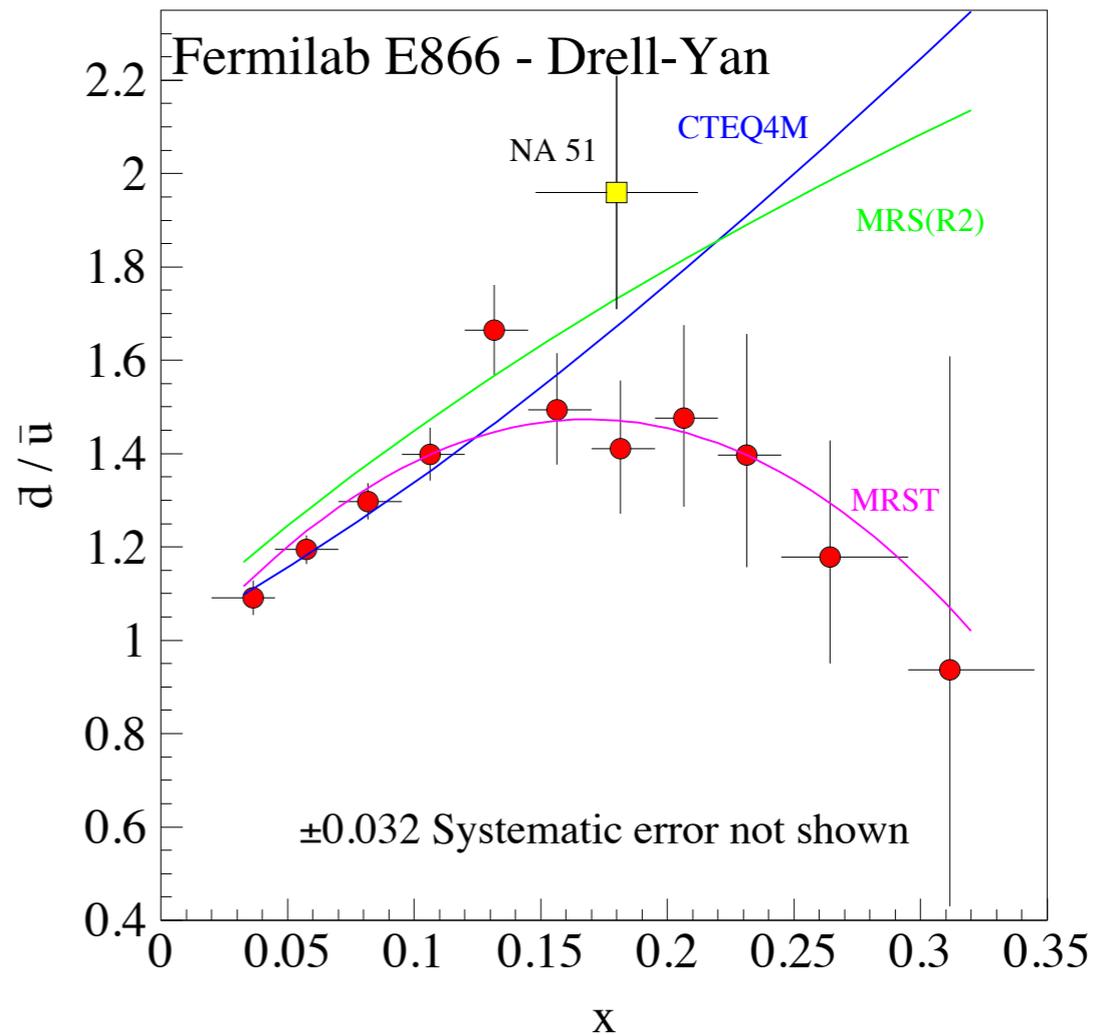
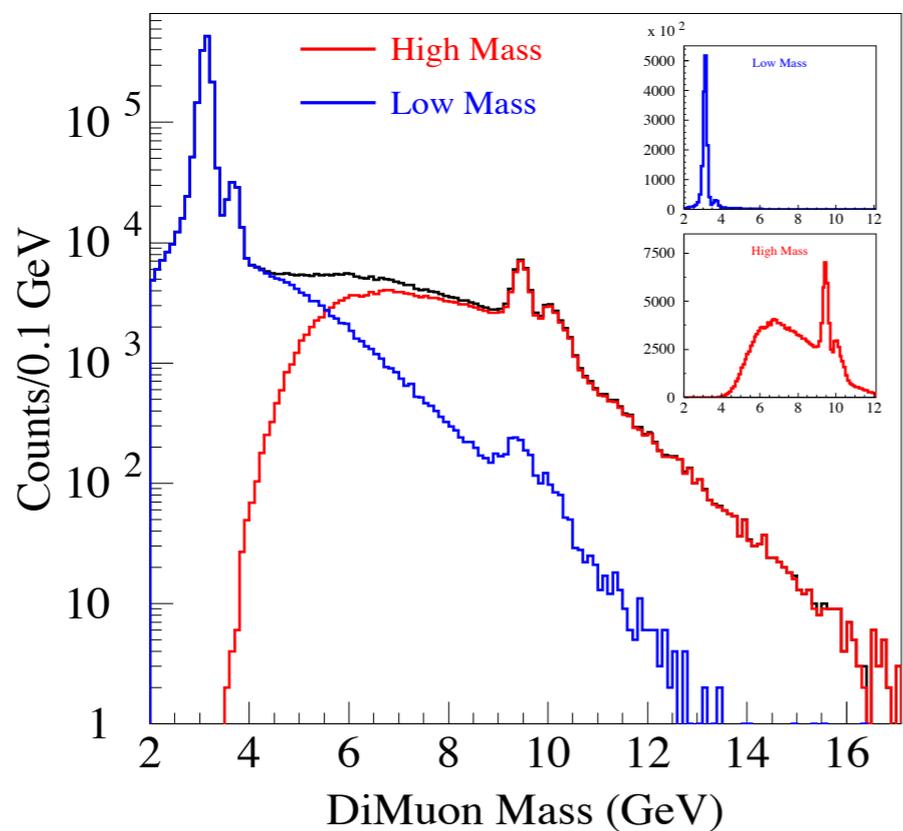
For a detailed discussion:
Kataev, hep-ph/0311091

A measurement of $\bar{d}(x)/\bar{u}(x)$ Antiquark asymmetry in the Nucleon Sea FNAL E866/NuSea

ACU, ANL, FNAL, GSU, IIT, LANL, LSU,
NMSU, UNM, ORNL, TAMU, Valpo.



800 GeV $p + p$ and $p + d \rightarrow \mu^+ \mu^- X$



Cross section ratio of pp vs. pd

Obtain the neutron PDF via isospin symmetry:

$$u \Leftrightarrow d$$

$$\bar{u} \Leftrightarrow \bar{d}$$

In the limit $x_1 \gg x_2$:

$$\sigma^{pp} \propto \frac{4}{9} u(x_1) \bar{u}(x_2) + \frac{1}{9} d(x_1) \bar{d}(x_2)$$

$$\sigma^{pn} \propto \frac{4}{9} u(x_1) \bar{d}(x_2) + \frac{1}{9} d(x_1) \bar{u}(x_2)$$

For the ratio we have:

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \frac{\left(1 + \frac{1}{4} \frac{d_1}{u_1}\right)}{\left(1 + \frac{1}{4} \frac{d_1}{u_1} \frac{\bar{d}_2}{\bar{u}_2}\right)} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right) \approx \frac{1}{2} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right)$$

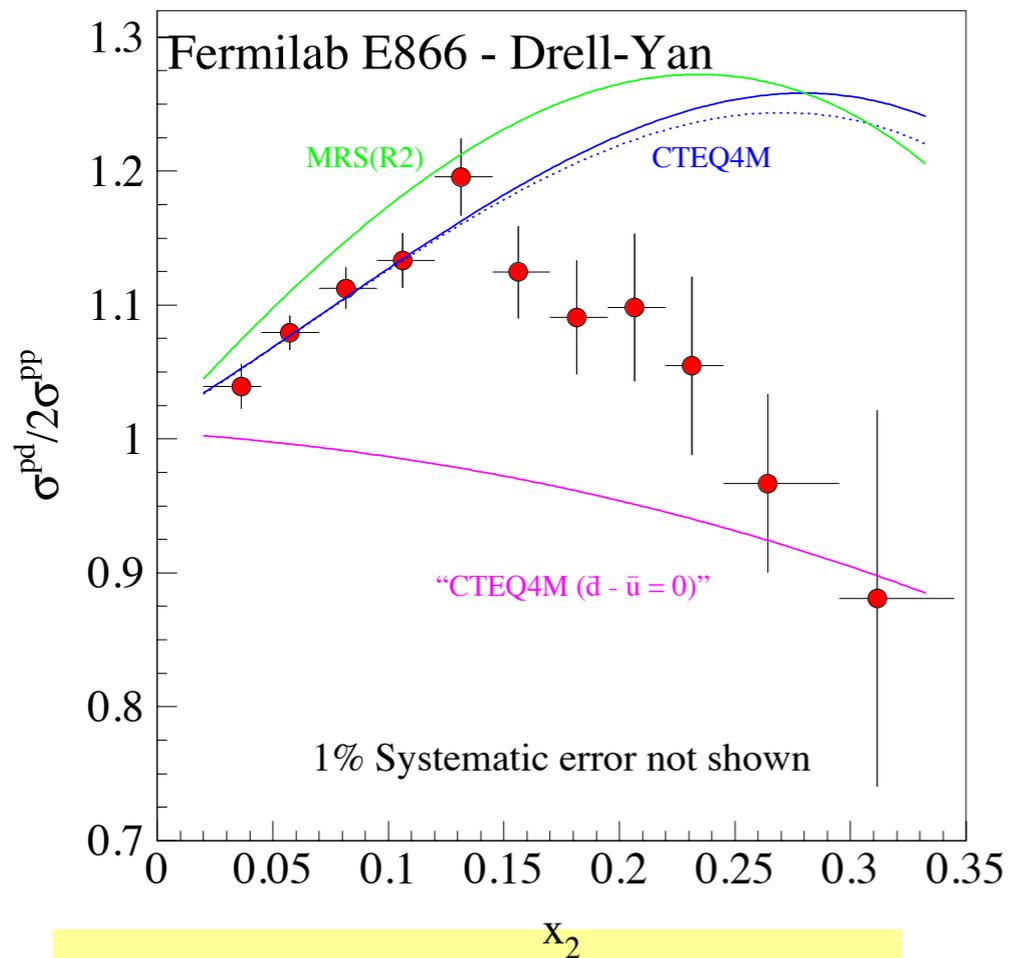
As promised, this provides information about the sea-quark distributions

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right)$$

EXERCISE: Verify the above.

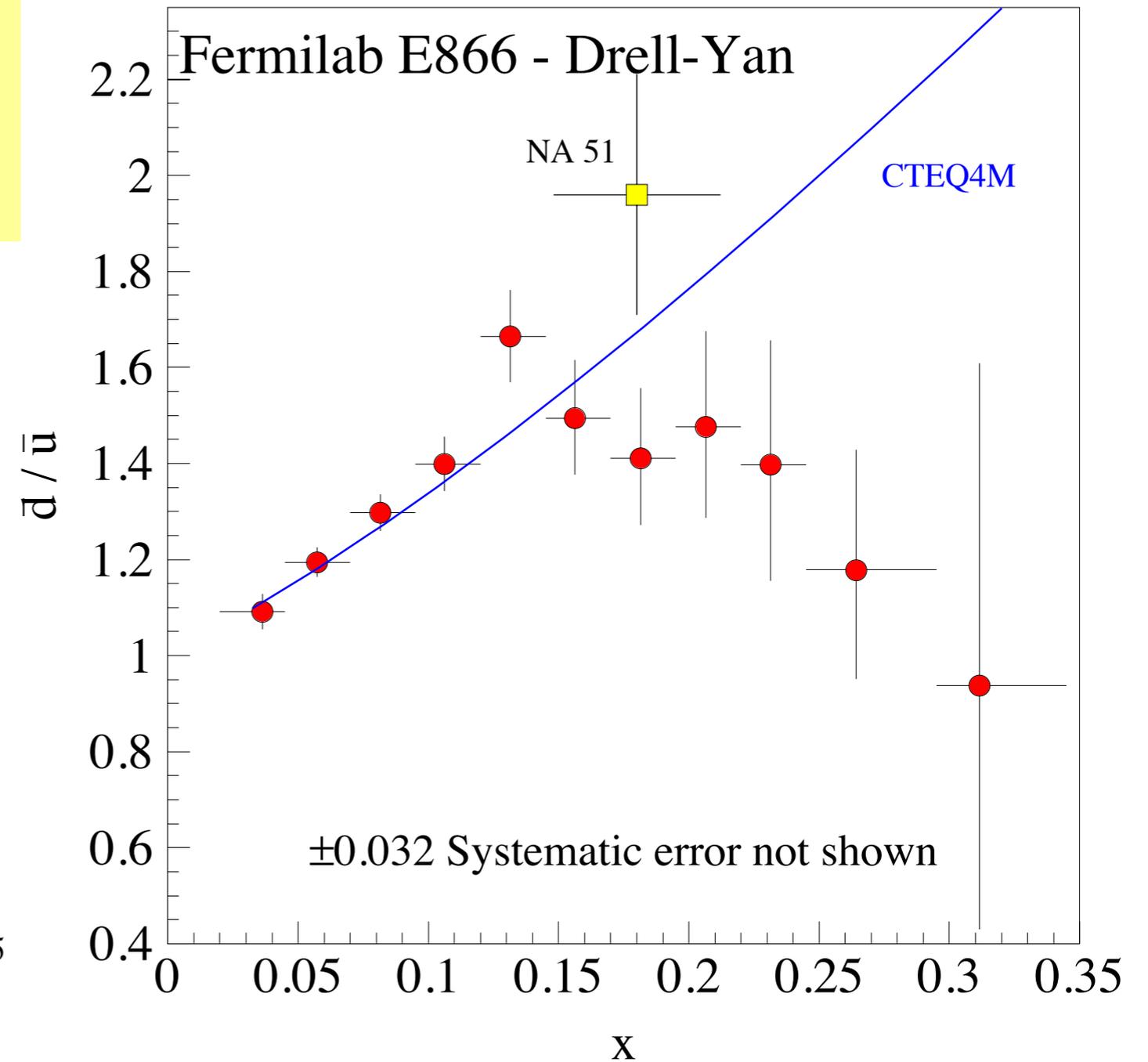
Does the theory match the data???

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \left(1 + \frac{\bar{d}_2}{\bar{u}_2} \right)$$



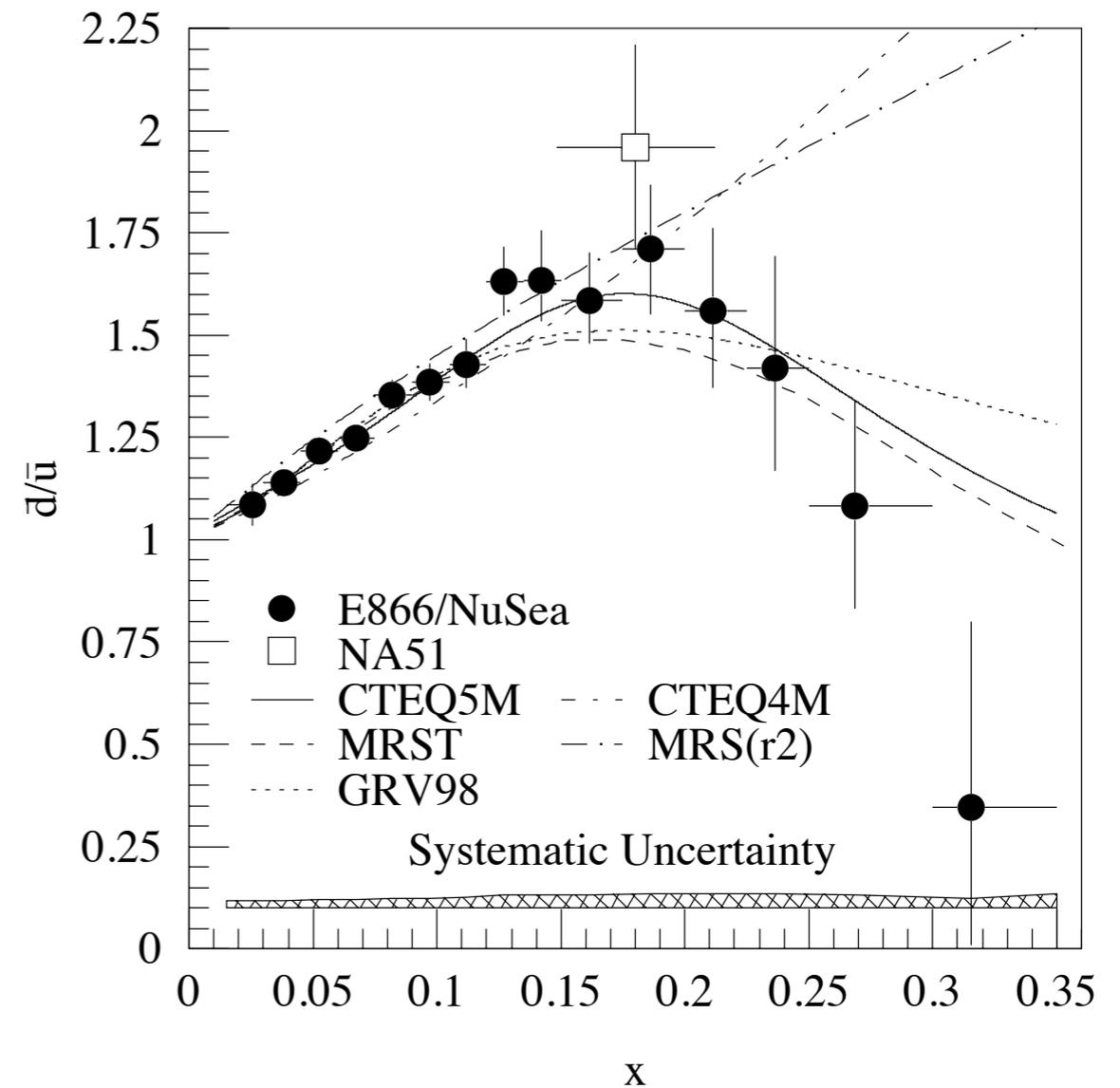
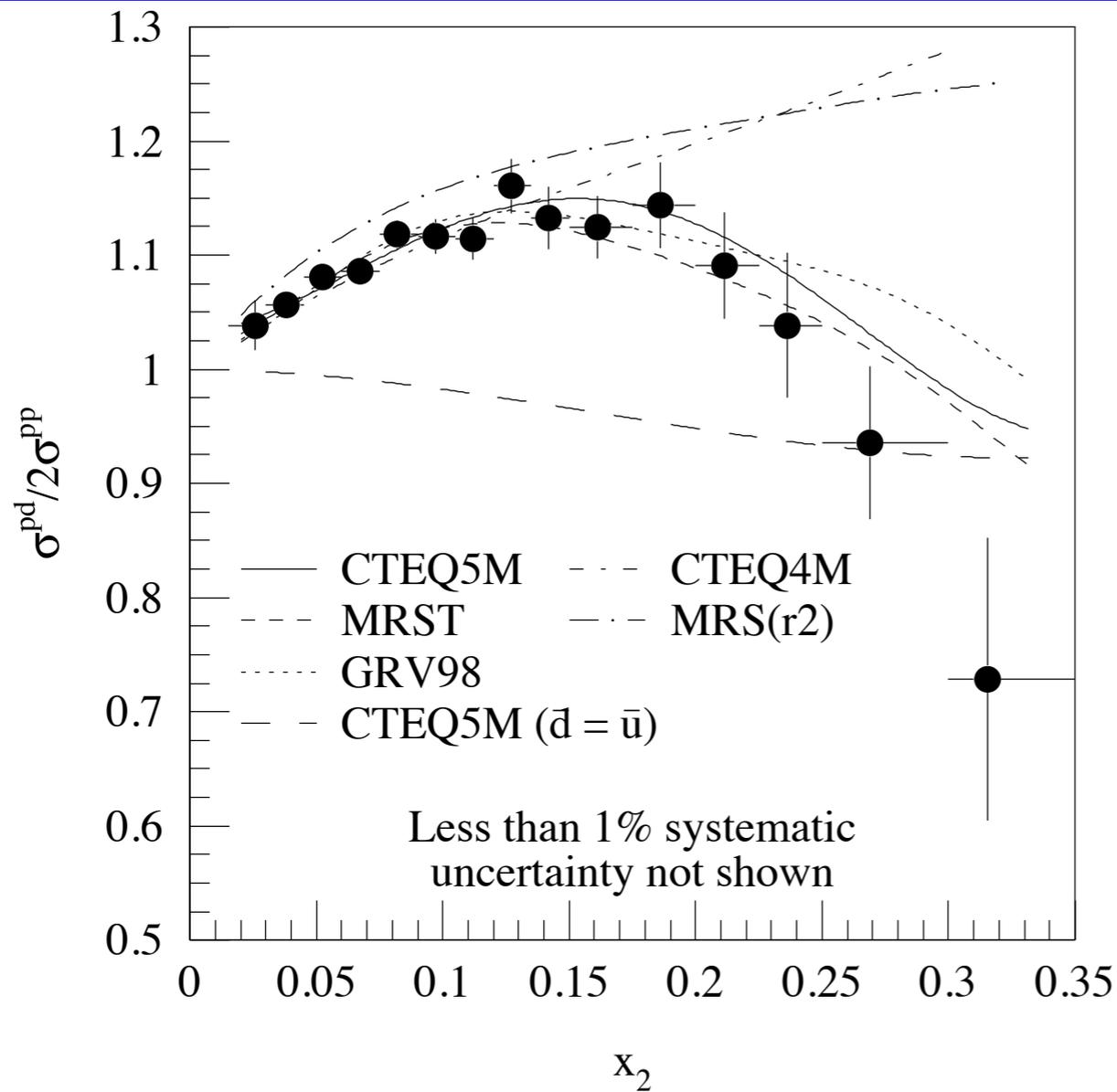
Implies $R < 1$ for large x :

$$\bar{d} \ll \bar{u}$$



E.A. Hawker, et al. [FNAL E866/NuSea Collaboration], Measurement of the light antiquark flavor asymmetry in the nucleon sea, PRL 80, 3715 (1998)

E866 required significant changes in the hi-x sea distributions



With increased flexibility in the parameterization of the sea-quark distributions, good fits are obtained

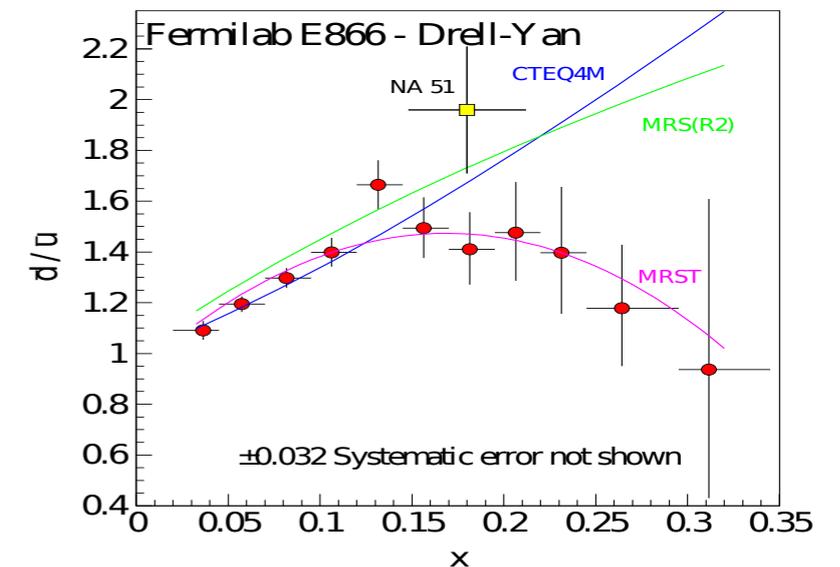
E.A. Hawker, et al. [FNAL E866/NuSea Collaboration], Measurement of the light antiquark flavor asymmetry in the nucleon sea, PRL 80, 3715 (1998)

H. L. Lai, et al. [CTEQ Collaboration], Global {QCD} analysis of parton structure of the nucleon: CTEQ5 parton distributions, EPJ C12, 375 (2000)

Discussion

- FNAL E866/NuSea ~1998
 - pp data (shifted upwards by 8.7% in MSTW08)
→ modern analysis might be useful!
 - ratio of pd over pp DY:
 - normalization uncertainty cancels
 - sensitive to $\bar{d}(x)/\bar{u}(x)$
 - Can **AFTER** improve precision of data?
Extend kinematic reach to larger $x > 0.3$?
 - Note, at small $x < 0.05$: $\bar{d} = \bar{u}$
SU(2)-symmetric sea (even more the higher the scale)
- Usually nuclear corrections assumed to be negligible:
→ **AFTER** can test with different nuclear targets

Isospin asymmetry in the nucleon light sea: $\bar{d}(x) \neq \bar{u}(x)$

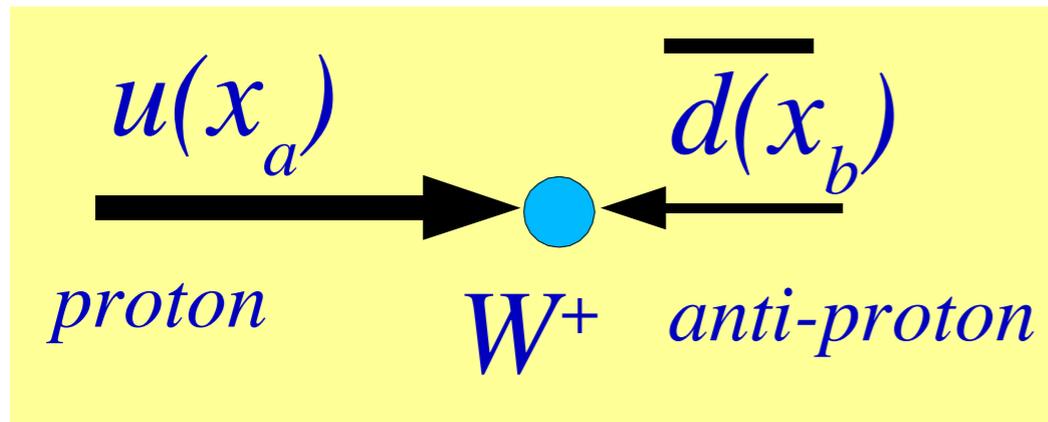


**W rapidity asymmetry in p-pbar:
probing d/u ratio**

Where do the W's and Z's come from ???

$$\frac{d\sigma}{dy}(W^\pm) = \frac{2\pi}{3} \frac{G_F}{\sqrt{2}} \sum_{q\bar{q}} |V_{q\bar{q}}|^2 \left[q(x_a) \bar{q}(x_b) + q(x_b) \bar{q}(x_a) \right]$$

flavour decomposition of W cross sections



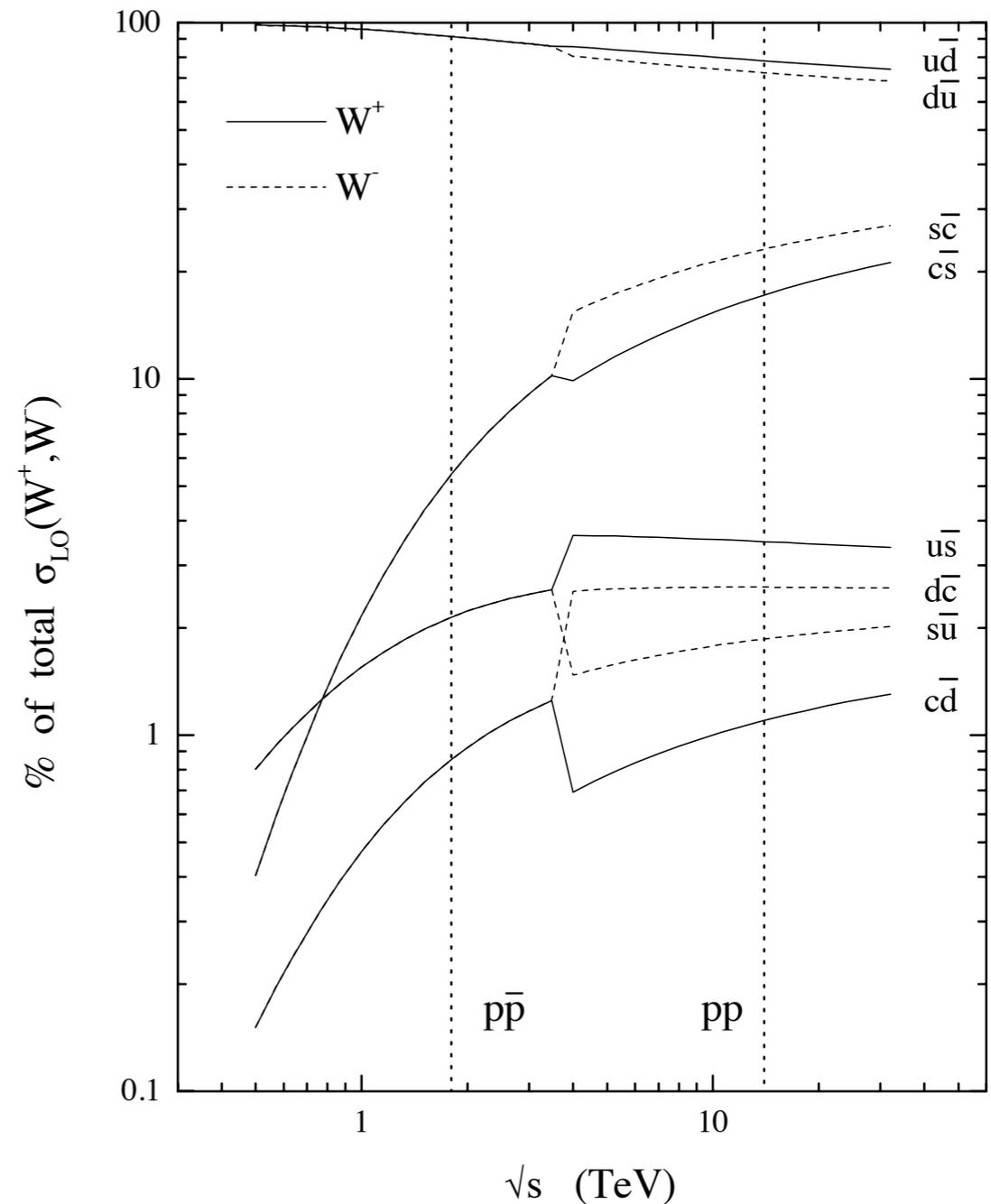
For anti-proton:

$$u(x) \Leftrightarrow \bar{u}(x) \qquad d(x) \Leftrightarrow \bar{d}(x)$$

Therefore

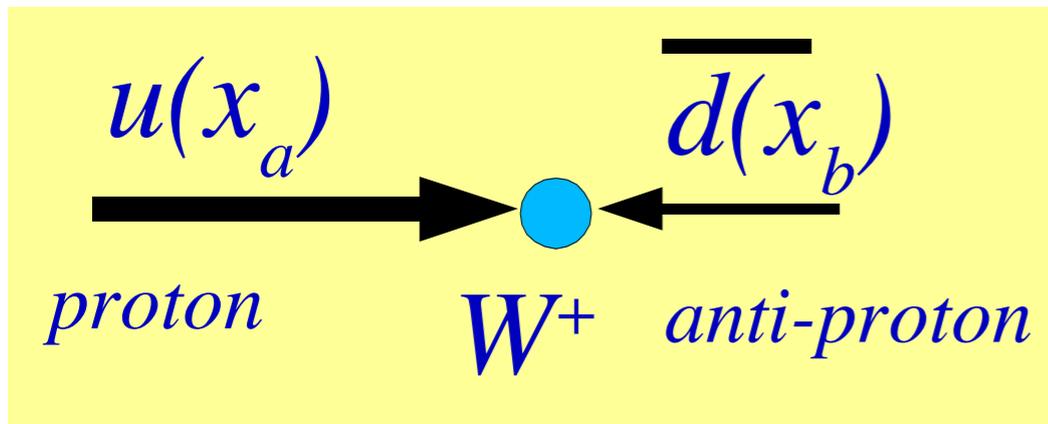
$$\frac{d\sigma}{dy}(W^+) \approx \frac{2\pi}{3} \frac{G_F}{\sqrt{2}} \left[u(x_a) d(x_b) \right]$$

$$\frac{d\sigma}{dy}(W^-) \approx \frac{2\pi}{3} \frac{G_F}{\sqrt{2}} \left[d(x_a) u(x_b) \right]$$



A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne,
Eur. Phys. J. C23, 73 (2002); Eur. Phys. J. C4, 463 (1998)

A bit of calculation



$$A(y) = \frac{\frac{d\sigma}{dy}(W^+) - \frac{d\sigma}{dy}(W^-)}{\frac{d\sigma}{dy}(W^+) + \frac{d\sigma}{dy}(W^-)}$$

With the previous approximation,

$$A \approx \frac{u(x_a)d(x_b) - d(x_a)u(x_b)}{u(x_a)d(x_b) + d(x_a)u(x_b)} = \frac{R_{du}(x_b) - R_{du}(x_a)}{R_{du}(x_b) + R_{du}(x_a)}$$

where $R_{du}(x) = \frac{d(x)}{u(x)}$

$$x_{1,2} = x_0 e^{\pm y} \simeq x_0 (1 \pm y)$$

We can make Taylor expansions:

$$R_{du}(x_{1,2}) \approx R_{du}(x_0) \pm y x_0 R'_{du}(\sqrt{\tau})$$

Thus, the asymmetry is:

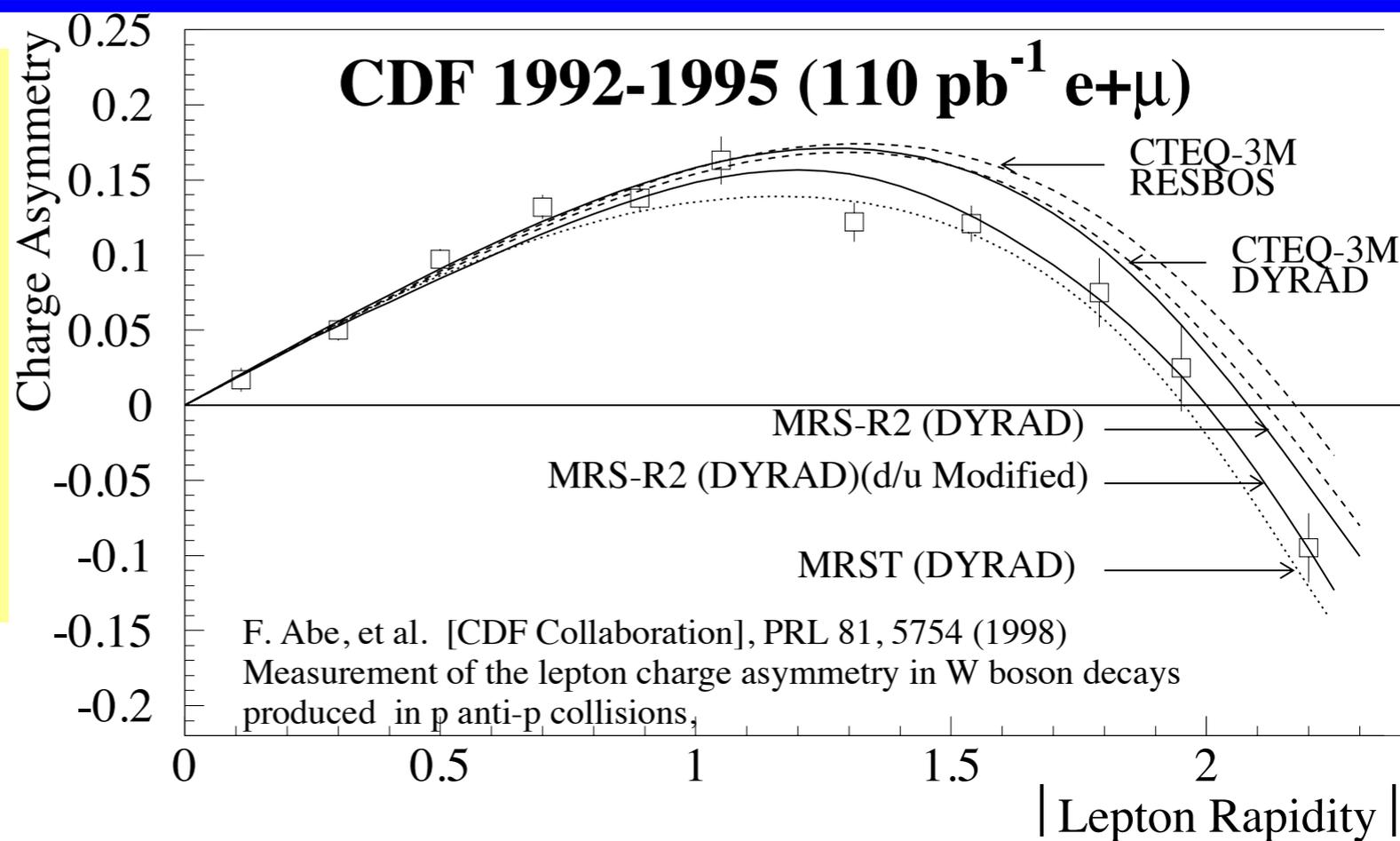
$$A(y) = -y x_0 \frac{R'_{du}(x_0)}{R_{du}(x_0)}$$

EXERCISE: Verify the above.

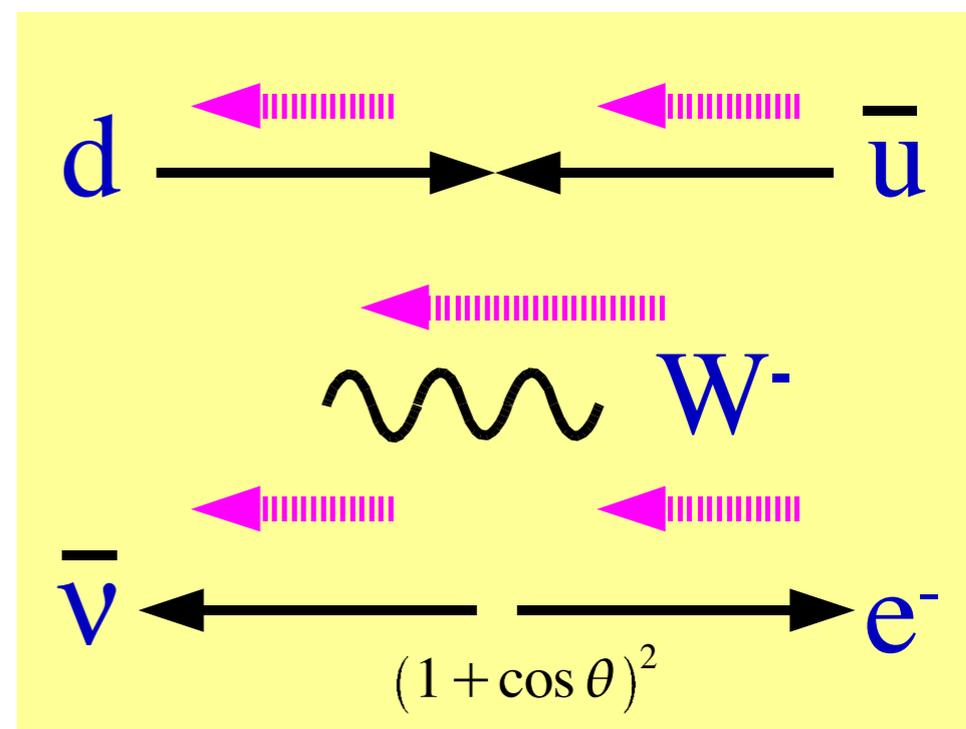
Charged Lepton Asymmetry

Unfortunately,
we don't measure the W
directly since $W \rightarrow e\nu$.

Still the lepton contains
important information



$$A(y) = \frac{\frac{d\sigma}{dy}(l^+) - \frac{d\sigma}{dy}(l^-)}{\frac{d\sigma}{dy}(l^+) + \frac{d\sigma}{dy}(l^-)}$$

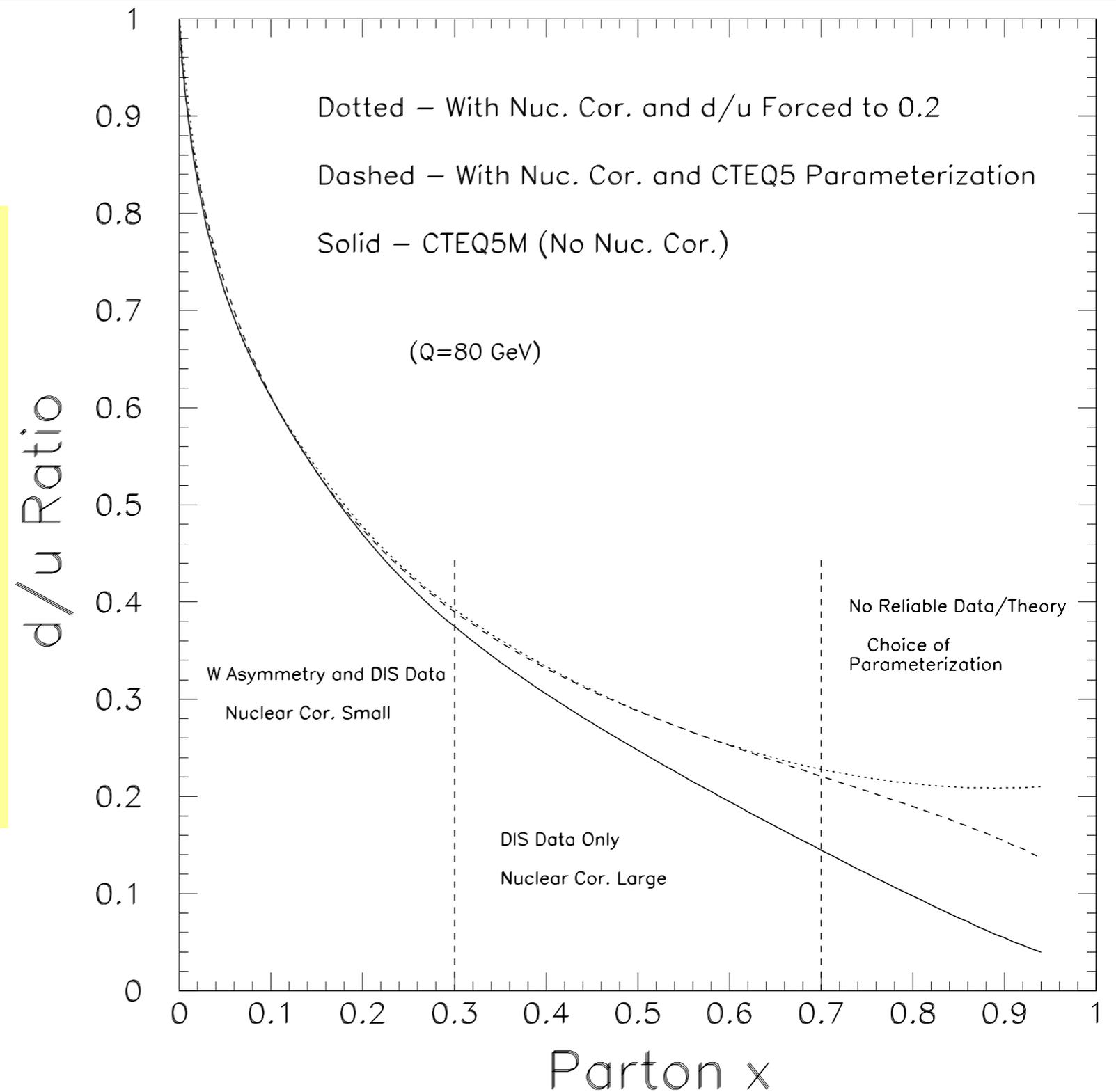


d/u Ratio at High-x

The form of the d/u ratio at large x as a function of

1) Parameterization

2) Nuclear Corrections



S. Kuhlmann, et al., Large-x parton distributions, PL B476, 291 (2000)

III. Other interesting processes

Other interesting processes

- Prompt photon production: gluon (Juan Rojo's talk)
- Heavy quark production:
 - inclusive D, B meson production: gluon PDF, HQ PDF
 - lower cms energy better to probe large-x intrinsic charm (IC); lower cms allows for more central rapidities
- photon + Q
 - pp collisions: intrinsic charm/bottom (IC, IB)
 - pA collisions: nuclear gluon
 - AA: probe heavy quark energy loss
- Vector boson production at LHC: strange PDF
At lower energies not useful for strange PDF, since dominated by light quarks
- W+c: strange PDF

A colleague: “If QCD is right, there has to be IC”
(which normalization?)

Intrinsic charm:

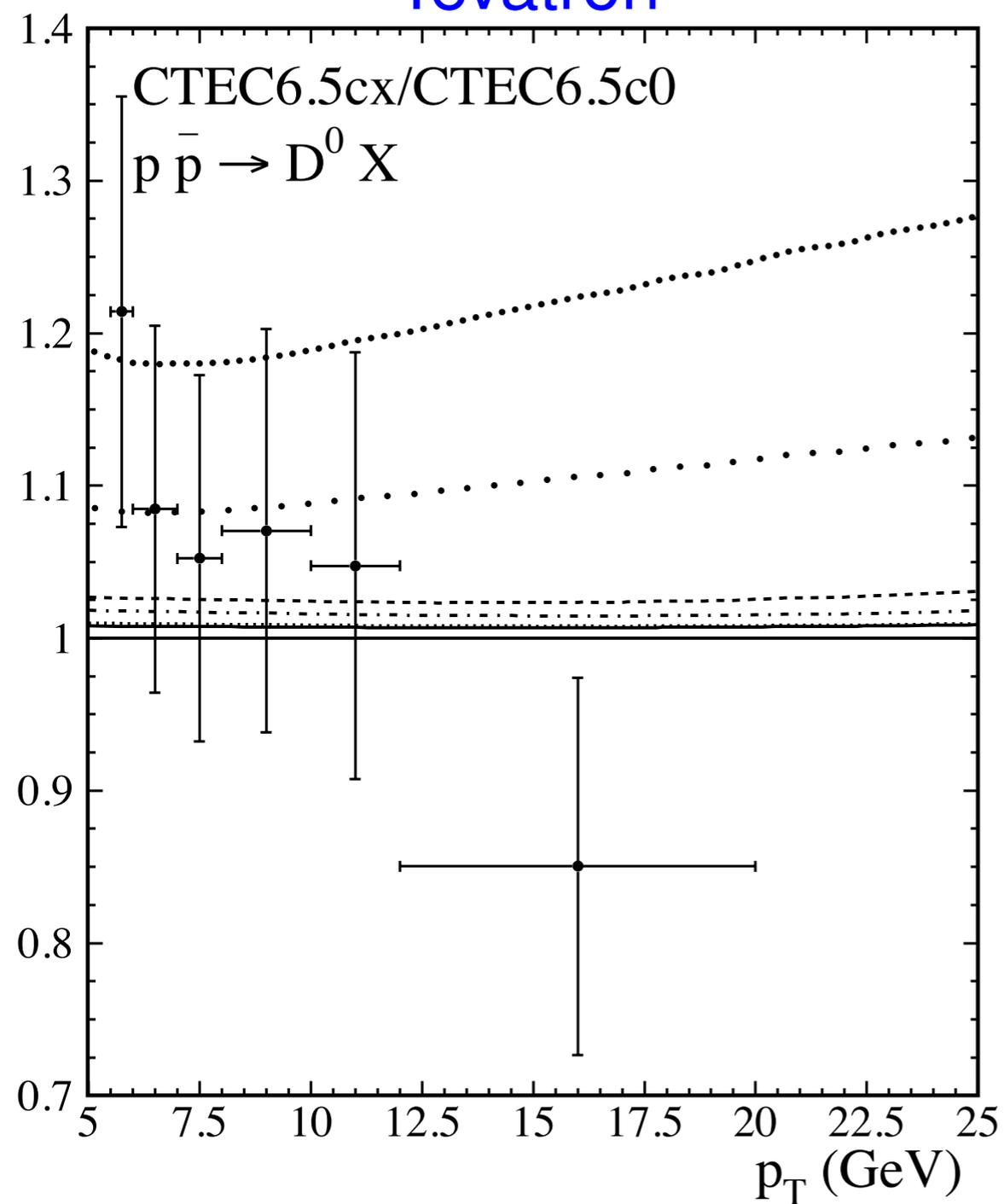
$c(x, \mu_0) \neq 0$ at initial scale $\mu_0 = m_c$

Models implemented in CTEQ 6.5C ([PRD75, 2007](#))

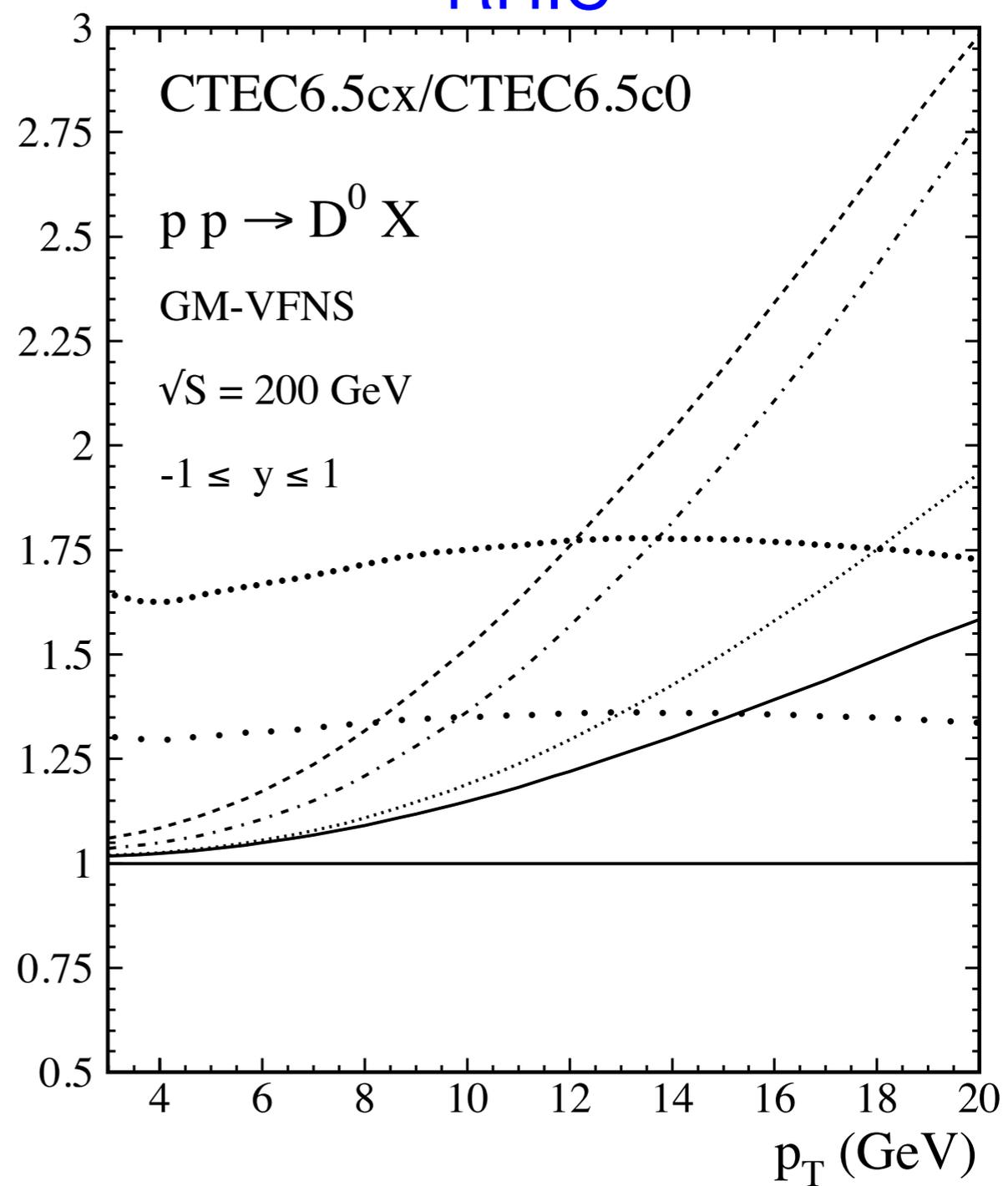
global fit allows average momentum $\langle x \rangle_{c+\bar{c}}$ or order 1 %

- 1 Light-cone Fock-space picture (Brodsky et al.), concentrated at large x
 $\langle x \rangle_{c+\bar{c}} = 0.57, 2.0 \%$
- 2 Meson-cloud model (Navarra et al.)
 $\langle x \rangle_{c+\bar{c}} = 0.96, 1.8 \%$
- 3 Phenomenological model: sea-like charm, broad in x
 $\langle x \rangle_{c+\bar{c}} = 1.1, 2.4 \%$

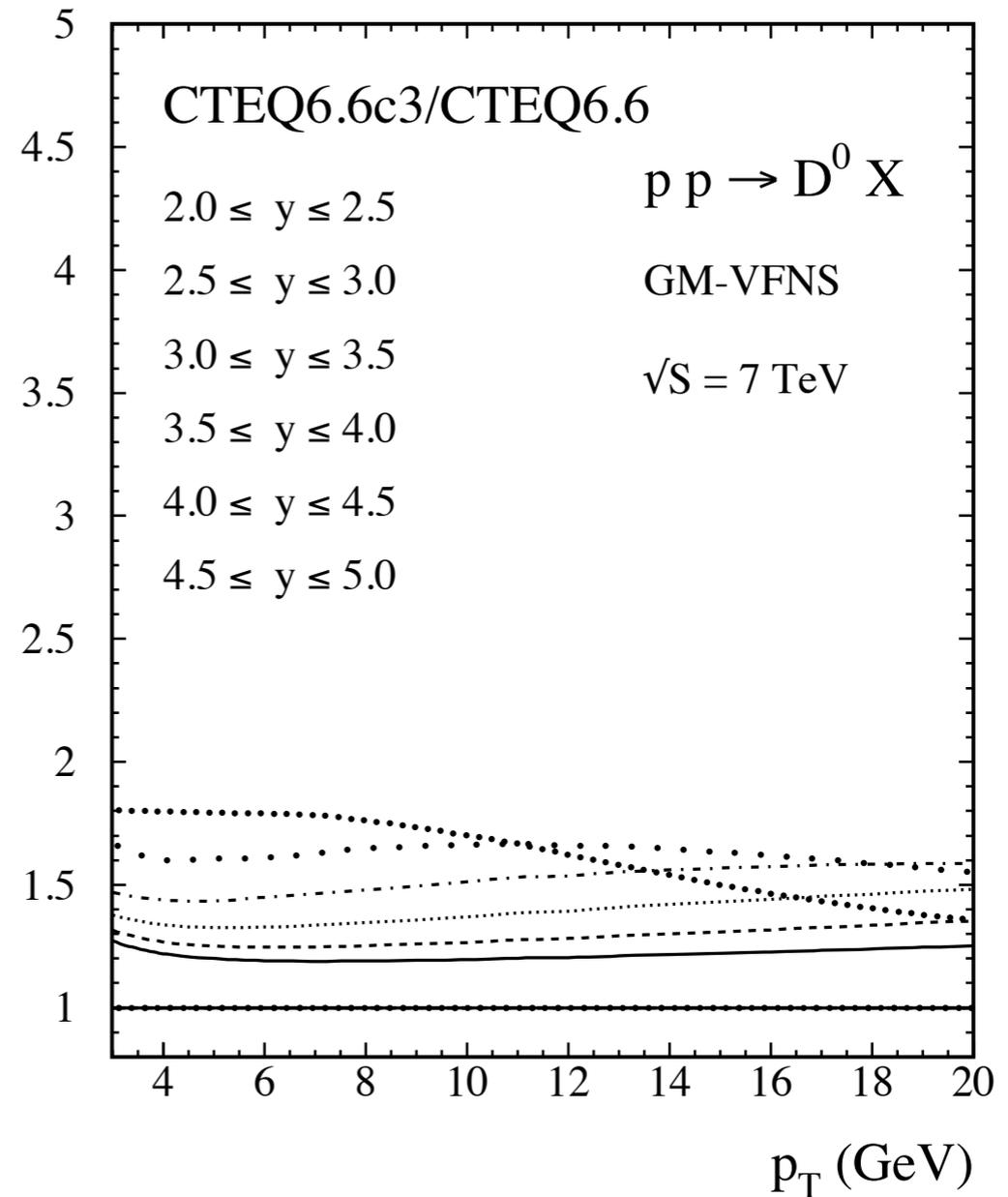
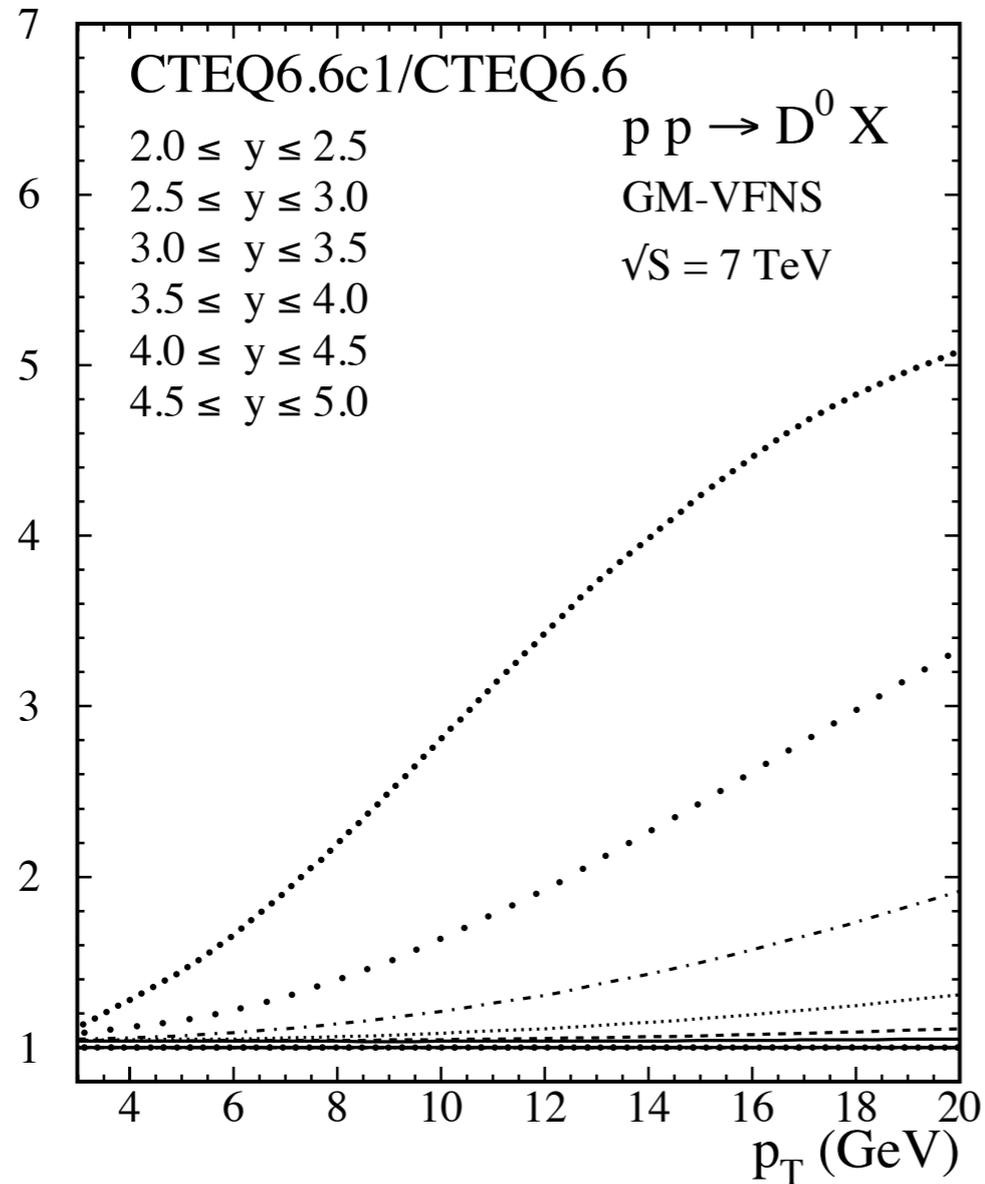
Tevatron



RHIC



PRD79, 2009



CTEQ6.6 updated:

BHPS, 3.5 % ($c + \bar{c}$) at $\mu = 1.3 \text{ GeV}$

high-strength sea-like charm

→ large effects expected at large rapidities

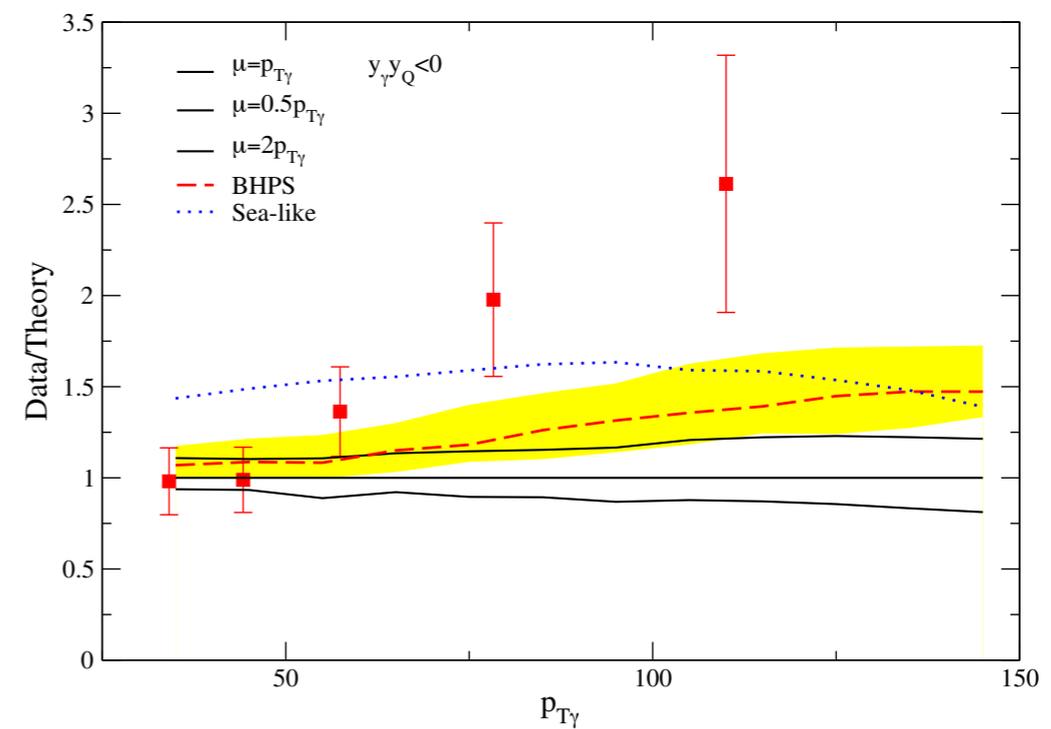
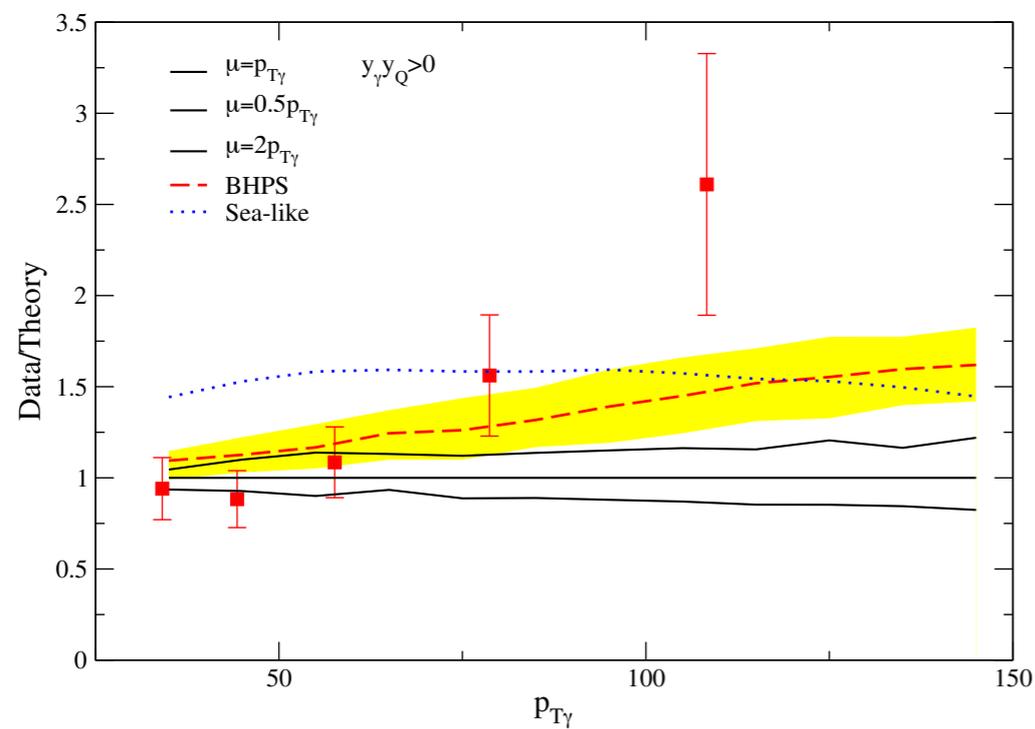
Intrinsic charm/bottom PDF via direct photon + heavy quark production

- LO: Compton hard scattering process $g + Q \rightarrow \gamma + Q$
direct access to the gluon PDF and the heavy quark PDF
- Full NLO calculation including photon fragmentation contribution
(photon isolation suppresses photon fragmentation)
[Owens, Stavreva, PRD79]
- In pA collisions useful to constrain nuclear gluon PDF [arXiv:1012.1178]
- In AA collisions probe of heavy quark energy loss
- In pp collisions probe of IC and IB

TEVATRON-DO

- Direct photon in association with charm / bottom quark jets @ D0
 - comparison of NLO theory predictions with D0 measurements [[arXiv:0901.3791](#), [arXiv:0901.0739](#)]
 - bottom quark agrees well but charm quark theory is off
 - discrepancy in photon+charm description allows for testing models of intrinsic charm

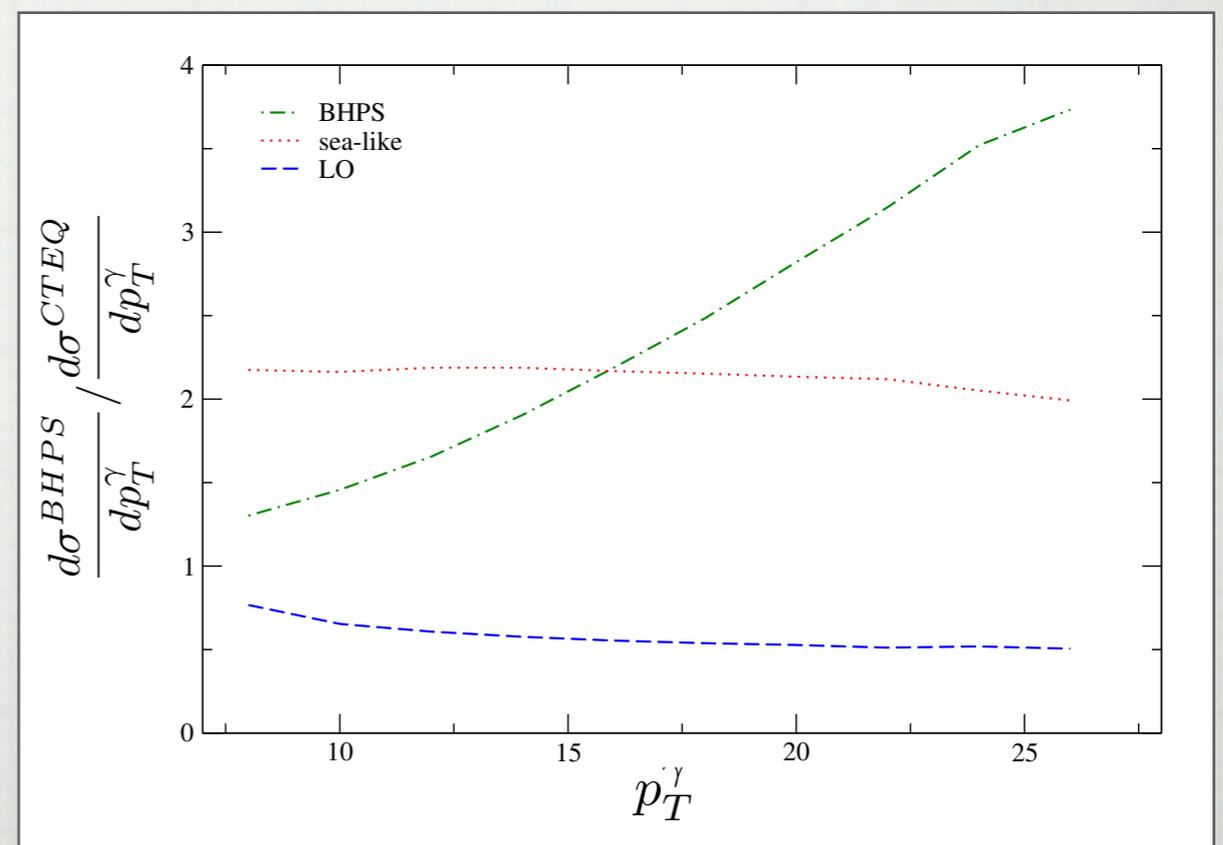
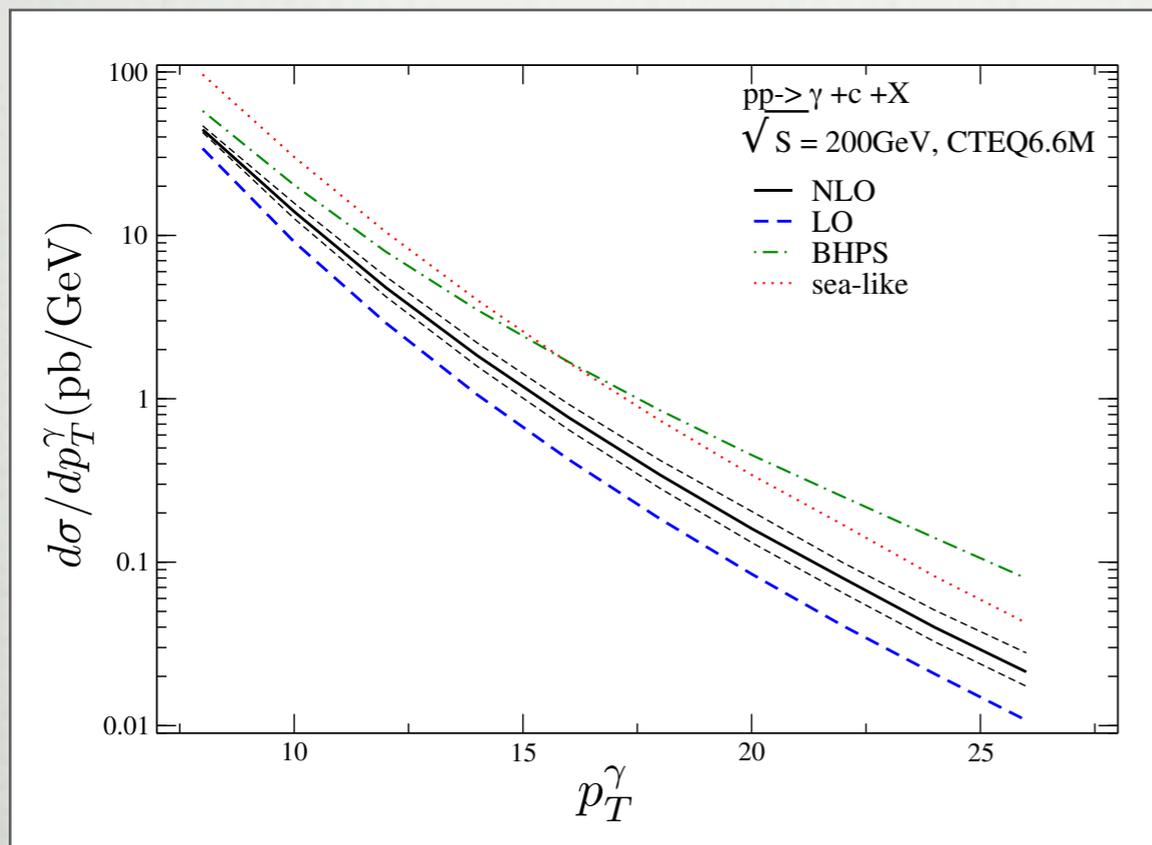
photon + charm



RHIC-PHENIX

- Direct photon in association with charm / bottom quark jets @ RHIC
 - smaller c.m.s energy @ RHIC probes higher x - very sensitive to intrinsic charm

	p_T min	Rapidity	Isolation
Photon	7 GeV	$ y_\gamma < 0.35$	$R=0.5, p_T = 0.7\text{GeV}$
Heavy Jet	5 GeV	$ y_Q < 0.8$	---

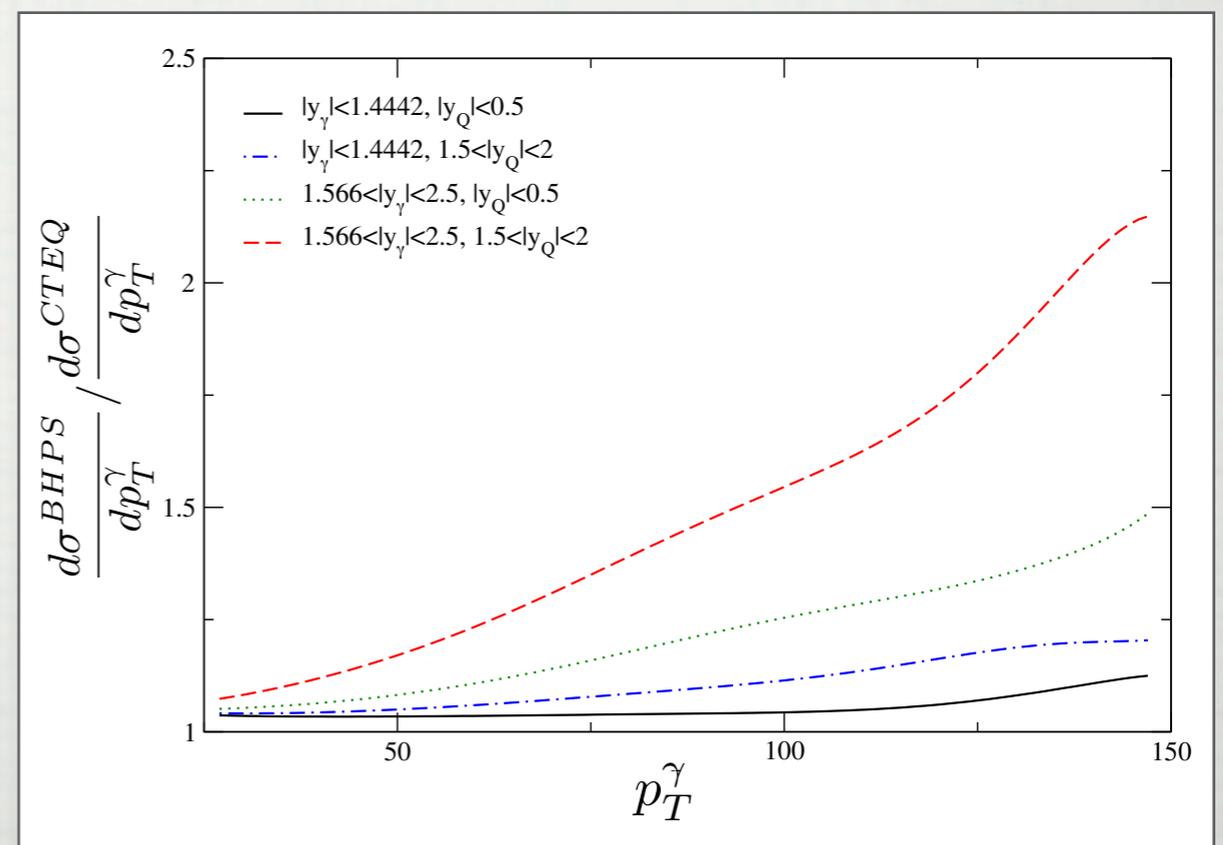
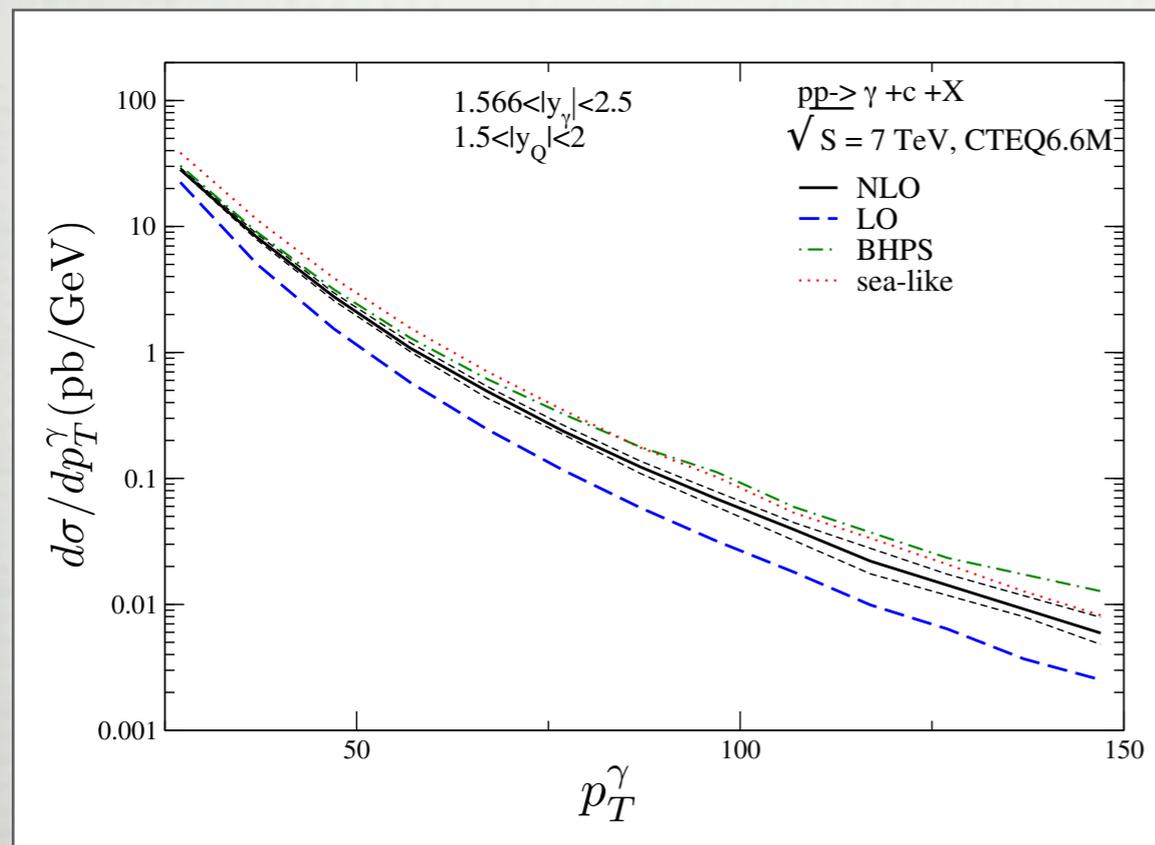


LHC-CMS

Direct photon in association with charm / bottom quark jets @ CMS

- CMS cuts on photon & HQ transverse momentum, rapidity & isolation cuts

	p_T min	Rapidity	Isolation
Photon	20 GeV	$ y_\gamma < 1.4442$	$R=0.4, p_T = 4.2\text{GeV}$
		$1.56 < y_\gamma < 2.5$	
Heavy Jet	18 GeV	$ y_Q < 2.0$	---



[CMS notes: CMS PAS EGM-10-005, CMS PAS BPH-10-009]