Parton Distribution Functions: strange, charm & bottom

I. Schienbein
LPSC Grenoble/Univ. Grenoble

collaborators F. Olness, O. Kusina, K. Kovarik, T. Stavreva, J.-Y. Yu, ...

Laboratoire de Physique
Subatomique et de Cosmologie

CEA Saclay, 28/06/2013

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Laboratoire de Physique
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CNRS IN2P3 Les deux infinis

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LPSC

- Unité Mixte de Recherche
  - CNRS: IN2P3 + INSU et INSIS
  - Universités: Université Joseph Fourier et Grenoble INP
- Personnels
  - Total de 225 personnes + environ 50 stagiaires/an
  - 66 physiciens permanents (38 CNRS et 28 EC: 19 UJF + 9 INPG)
  - 84 ITA et 7 IATOS
  - Environ 35 Doctorants et 20-25 Postdoc/CDD/CCD
- Projets scientifiques
  - Quarks et leptons [ATLAS & ILC, (D0), UCN]
  - Théorie et phénoménologie
  - Astroparticules et cosmologie [AUGER, DARK, Planck & MIMAC]
  - Physique hadronique et nucléaire [ALICE, (JLAB), Structure nucléaire]
  - Physique des Réacteurs
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Theory and Phenomenology

- **4 Staff members**
  - S. Kraml (CNRS)
  - M. Mangin-Brinet (CNRS)
  - I. Schienbein (UJF)
  - C. Smith (CNRS)
- **3 Post-Docs**
  - S. Kulkarni (-9/2014)
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  - A. Wingerter (-9/2013)
- **5 Doctoral students**
- voir: http://lpsc.in2p3.fr/index.php/activites-scientifiques/physique-theorique/presentation-generale

- **Collider phenomenology**
  - Heavy quark production (D and B)
  - Gamma+Q in pp, pA and AA
- **Parton Distribution Functions (PDFs)**
- **Physics beyond the SM (BSM)**
  - SUSY, BSM-Higgs
  - DM
  - GUTs, W', Z'
  - Flavour physics, Family symmetries
- **Other**
  - Hadronic physics, neutrino interactions
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PDFs

- **Global analyses of nuclear PDFs**
  - Nuclear PDFs from neutrino DIS: arXiv:0710.4897
  - Global analysis of nCTEQ PDFs: arXiv:0907.2357
  - Nuclear correction factors: arXiv:1012.0286
  - nCTEQ PDFs with uncertainties: in preparation

nCTEQ PDFs available at: projects.hepforge.org/ncteq

- **PDF-related work**
  - Review of Target Mass Corrections: arXiv:0709.1775
  - Gluon and charm PDFs from gamma+Q production in pA: arXiv:1012.1178
  - Heavy flavor schemes
    - DIS structure functions up to N3LO in the ACOT scheme: arXiv: 1203.0282
    - A generalization of the ACOT scheme (denoted H-VFNS): arXiv:1306.xxxx
  - Strange quark PDFs: arXiv:1203.1290
  - Intrinsic charm/bottom:
    - Probing IC with inclusive D meson production: arXiv:1202.0439 (LHC), arXiv:0901.4130 (RHIC,Tevatron)
    - Probing IC with gamma+Q production: arXiv:1305.3548
    - On intrinsic bottom: in preparation

Outline

- Parton Distribution Functions (PDFs)
- nCTEQ nuclear PDFs
- The strange content of the nucleon
- Charm in the nucleon
- Intrinsic Bottom?

Parton Distribution Functions (PDFs)

PDFs

- Information on hadronic structure
- Initial state for hard processes in collisions involving hadrons
  - Deep inelastic scattering (DIS): ℓA, νA
  - Drell-Yan (DY): $A + B \to \ell^+ + \ell^-$
  - Jets, Photons, Hadrons at large p_T; Heavy Quarks; . . .
    in pA, AA, (γA, eA) collisions
- Provide nuclear corrections for global analyses of **proton PDFs** in a flexible way

Theoretical Basis: Factorization

- Factorization theorems
  - provide (field theoretical) definitions of universal PDFs
  - make the formalism predictive
  - make a statement about the error

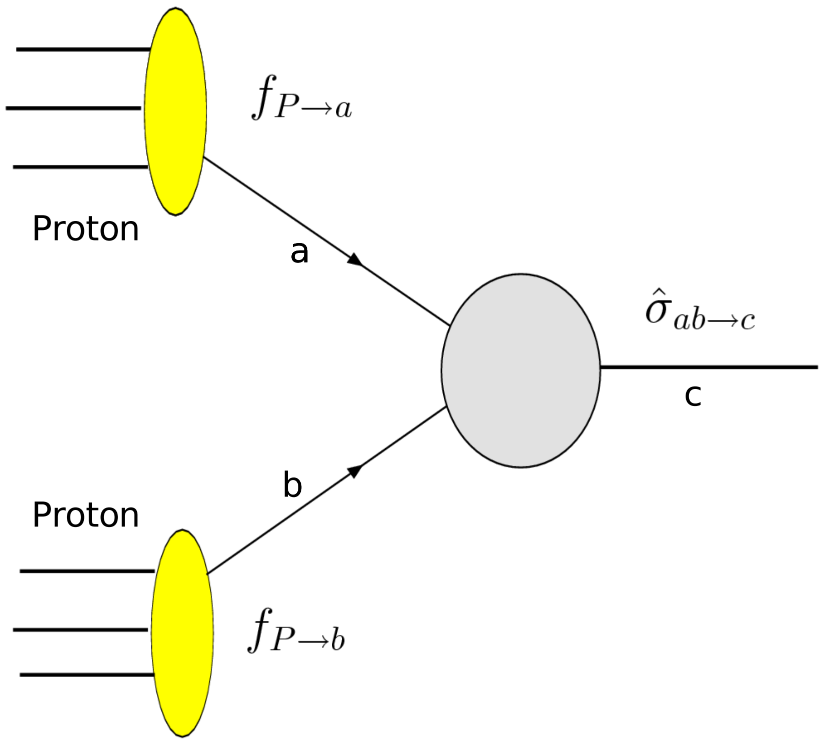
- PDFs and predicitions for observables+uncertainities **refer to this standard pQCD framework**

- There might be breaking of QCD factorization, deviations from DGLAP evolution — in particular in a nuclear environment

  Still need solid understanding of standard framework to establish deviations!

In the nuclear case, consider factorization as a working assumption to be tested phenomenologically

Factorisation



$$\sigma = f_{P\to a} \otimes f_{P\to b} \otimes \hat{\sigma}_{ab\to c}$$

From experiment

Calculable from theoretical model

Parton Distribution Functions (PDFs)

$f_{P\to a,b}(x, \mu^2)$

- Universal
- Describe the structure of hadrons
- Obey DGLAP evolution equations

The hard part $\hat{\sigma}_{ab\to c}(\mu^2)$

- Free of short distance scales
- Calculable in perturbation theory
- Depends on the process

Predictive Power

Universality: same PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$
- DY: $$\sigma_{A+B\to\ell^+ +\ell^- +X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ +\ell^- +X}$$
- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$
- Predictions for unexplored kinematic regions and for your favorite new physics process

The different partons

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 <-> QED radiation

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

Data

Data:

- Deep inelastic scattering data
  - H1 ,ZEUS (ep)
  - BCDMS,NMC (μp,μd)
  - CCFR (υ-Fe)
- p+pbar -> jet +X : D0, CDF
- DY pp: E605
- DY pd/pp: NA51, E866 (updated)
- W-lepton asymmetry: CDF
- υ-DIS dimuon data: Nutev

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

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

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

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

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

$s , \bar{s}$

Data sets fitted in MSTW 2008 NLO analysis [arXiv:0901.0002]

Data set	χ^2 / $N_{\rm pts.}$
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 $e^{\pm}p$ $F_2^{\rm charm}$	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
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BCDMS μp F_2	182 / 163
BCDMS μd F_2	190 / 151
NMC μp F_2	121 / 123
NMC μd F_2	102 / 123
NMC $\mu n/\mu p$	130 / 148
E665 μp F_2	57 / 53
E665 μd 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 νN F_2	49 / 53
CHORUS νN F_2	26 / 42
NuTeV νN xF_3	40 / 45
CHORUS νN 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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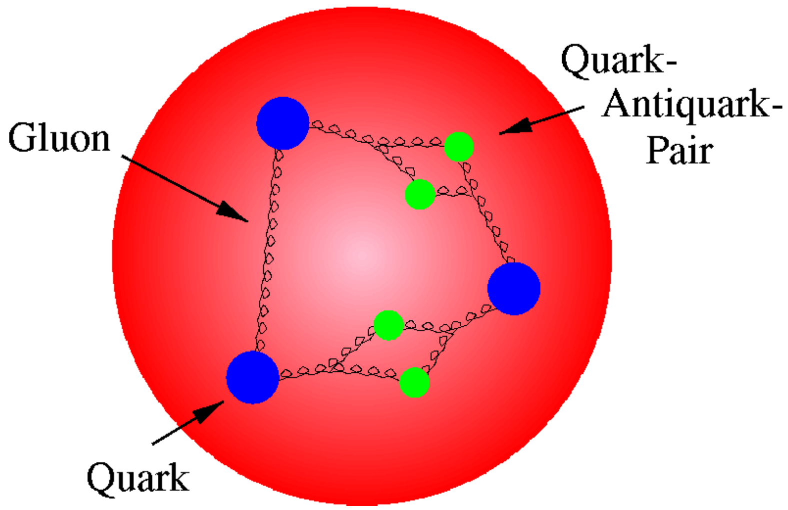

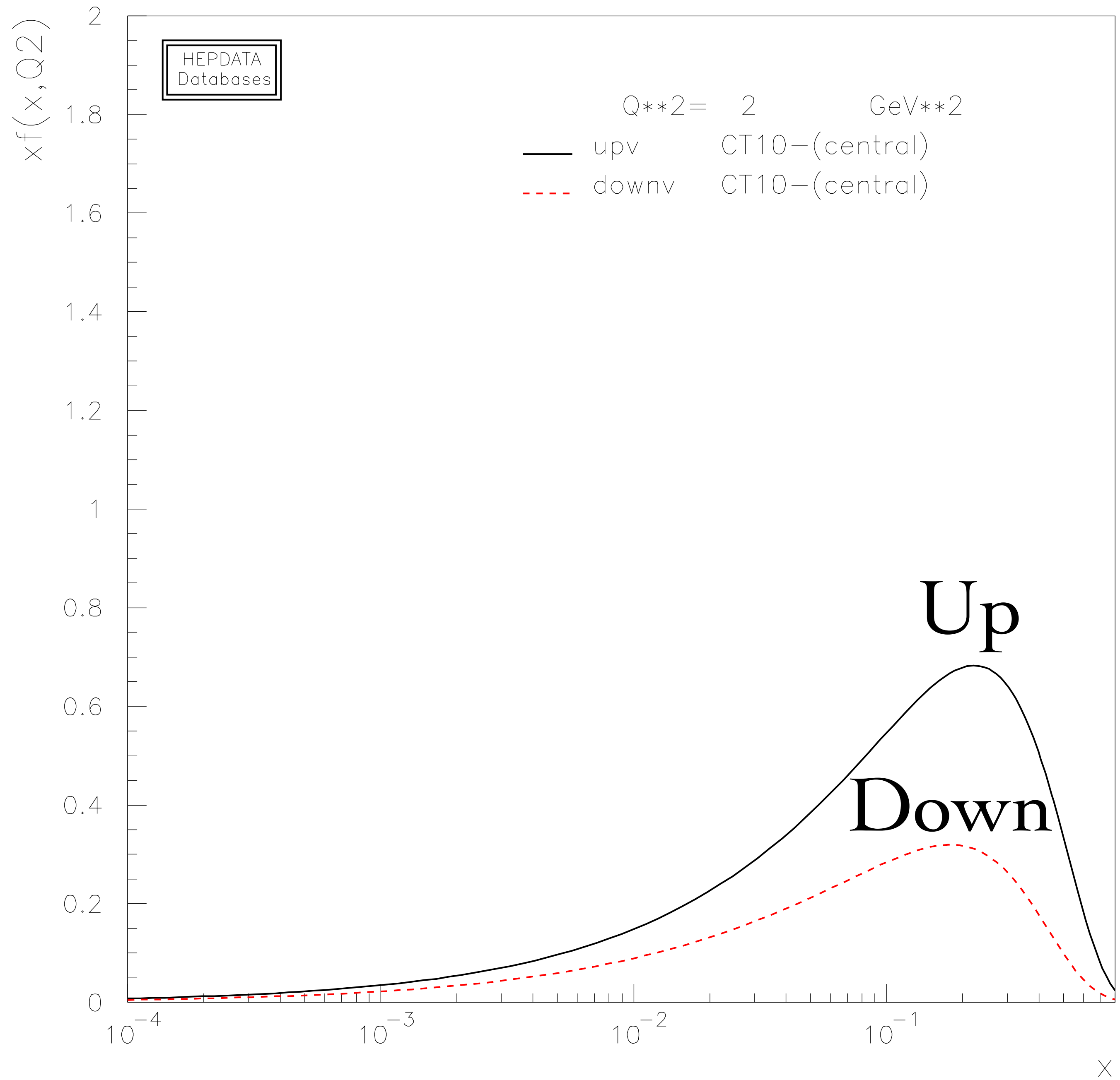

- Valence quarks p=|uud⟩

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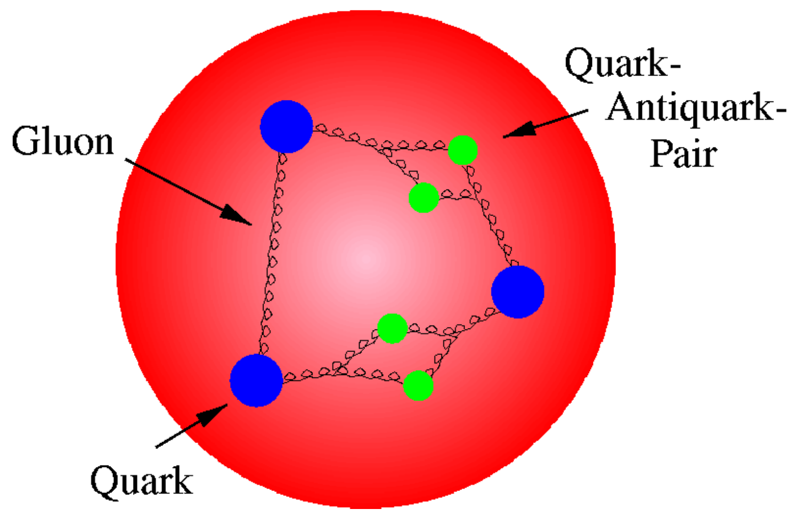
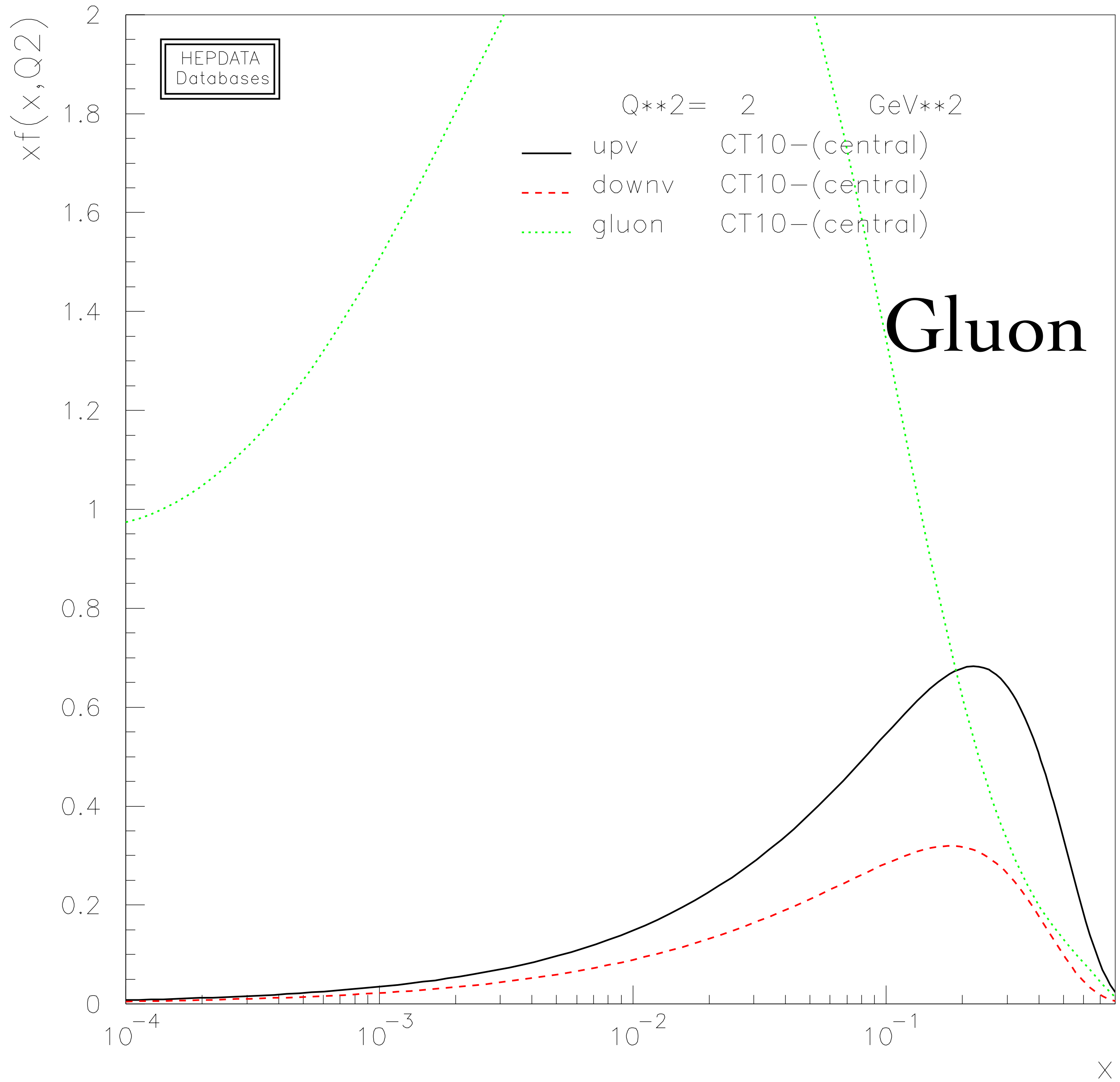


- Valence quarks
  p=|uud⟩

- Gluons

  carry about 40% of momentum



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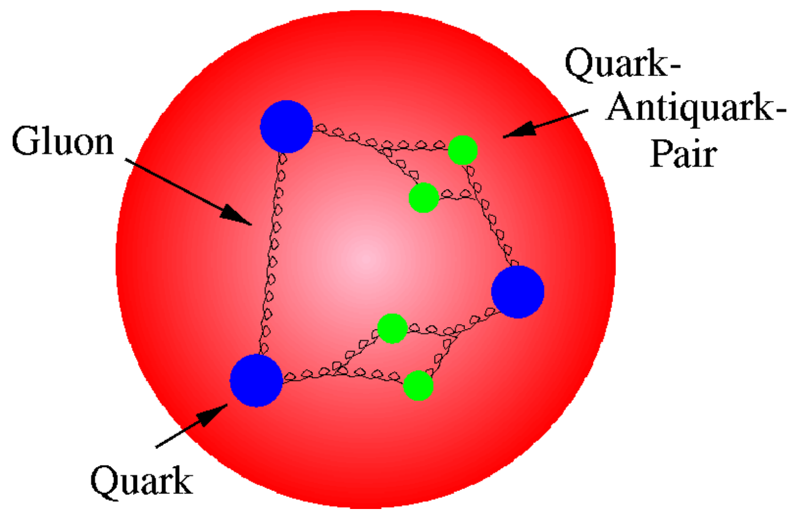

- Valence quarks
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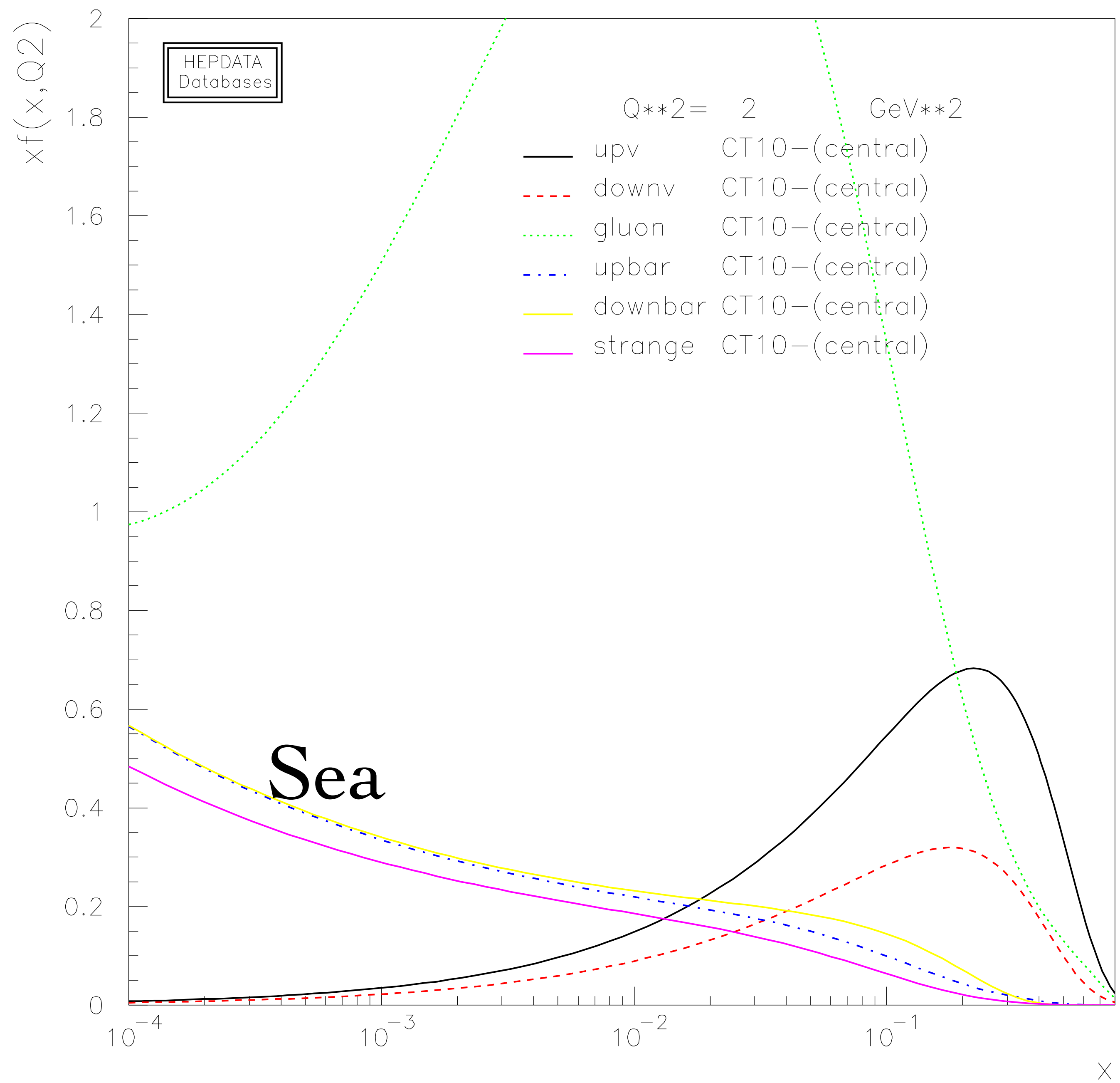
- Sea quarks
  light quark sea, strange sea



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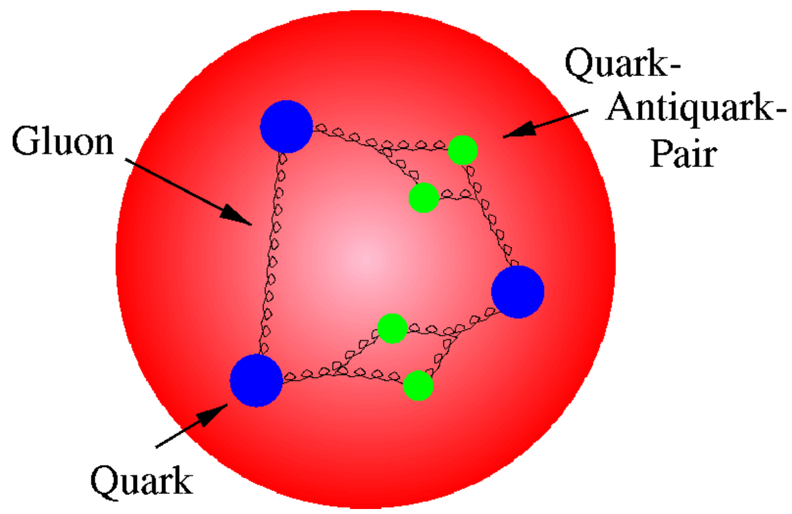

RGE's (DGLAP) known to NNLO

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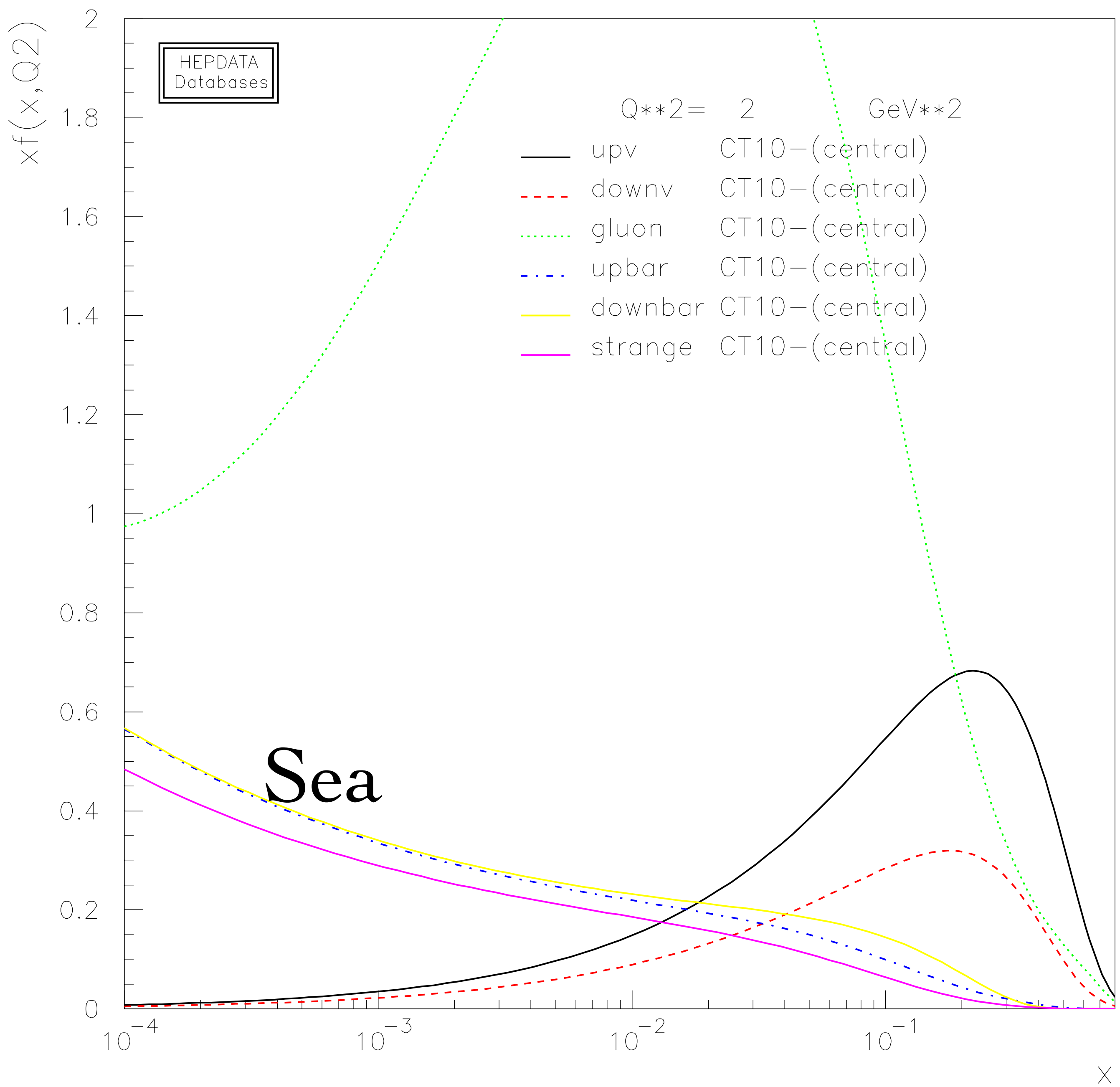

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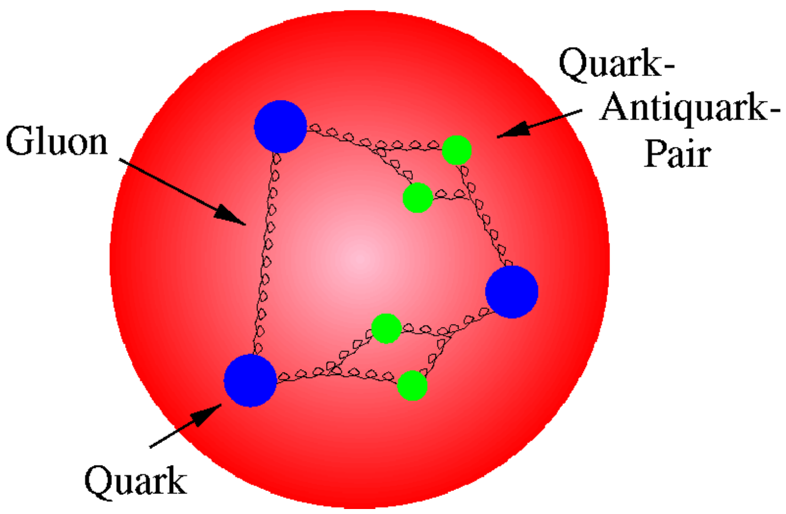

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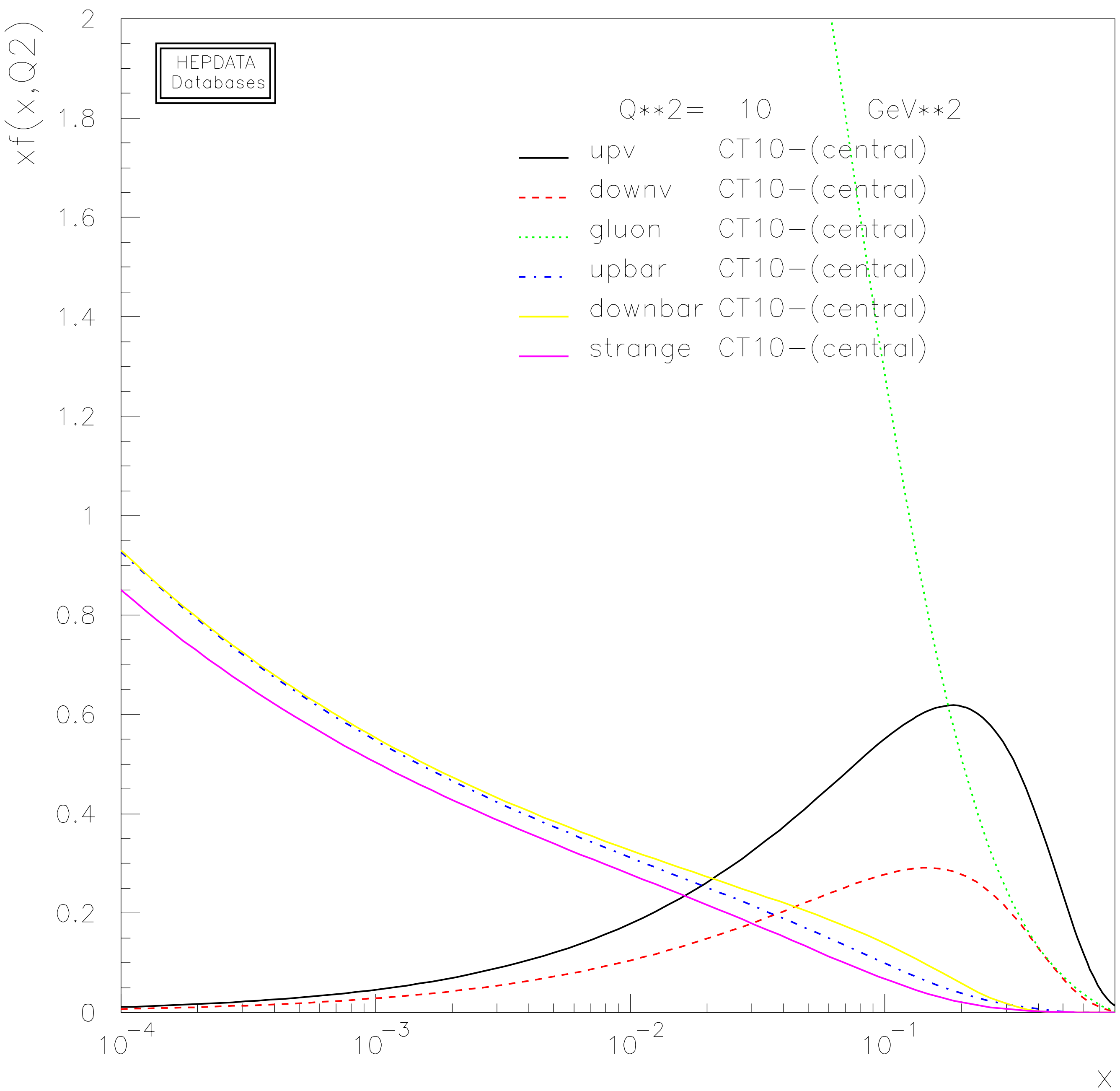

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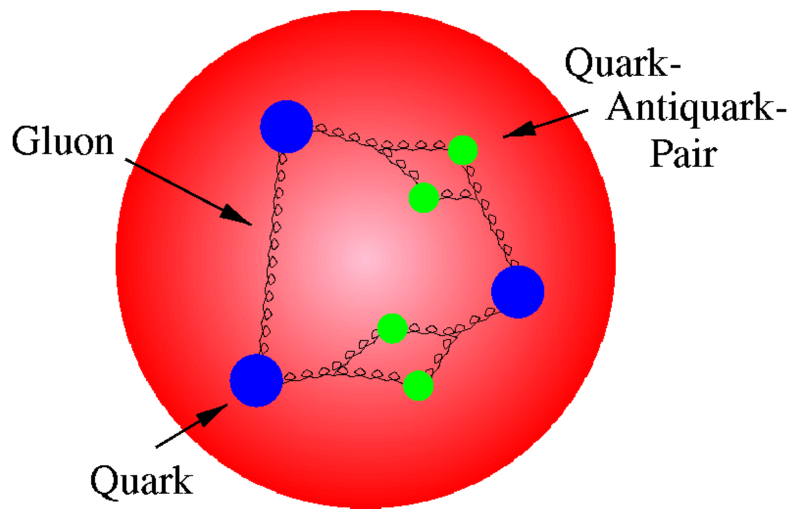

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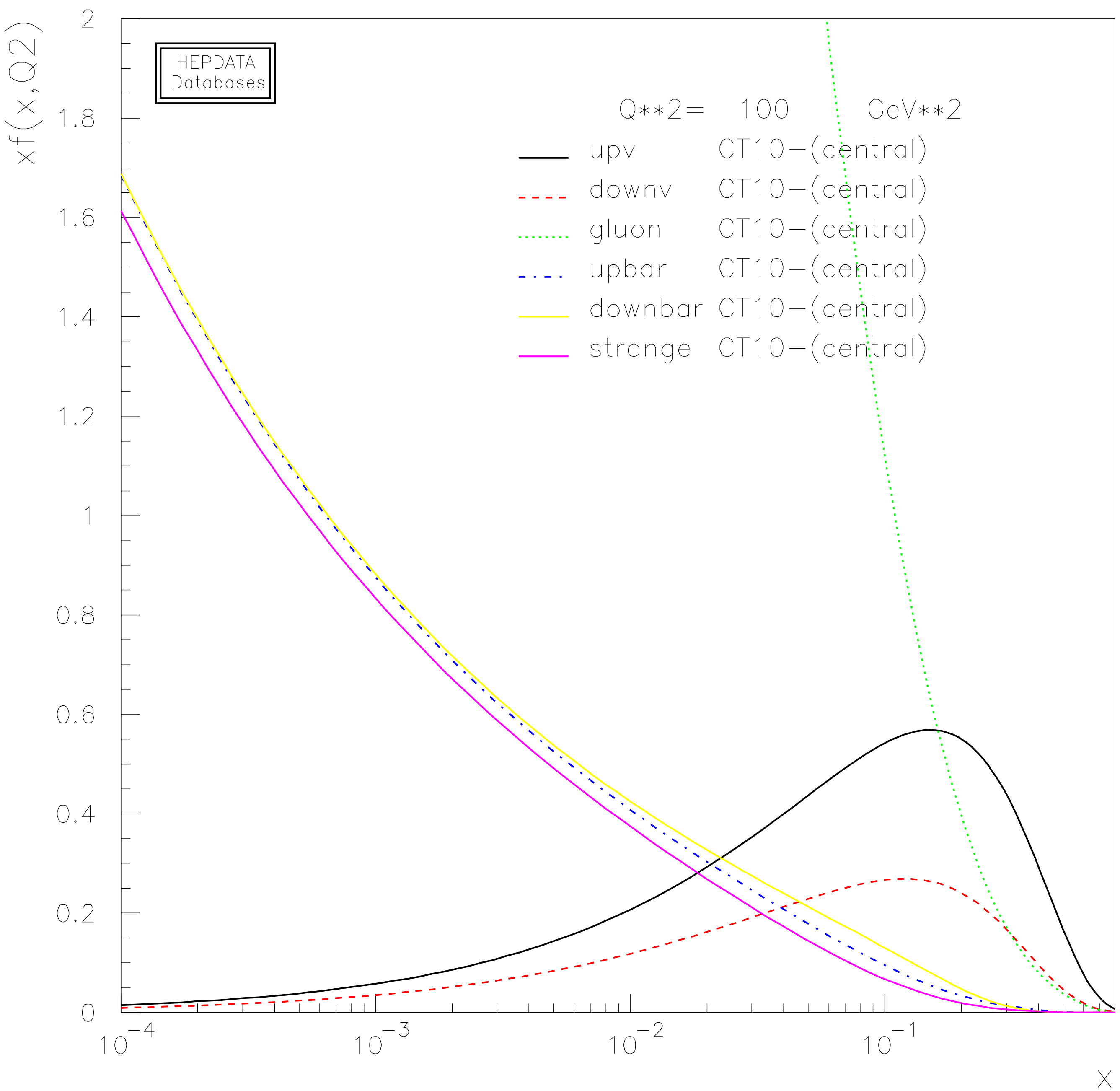

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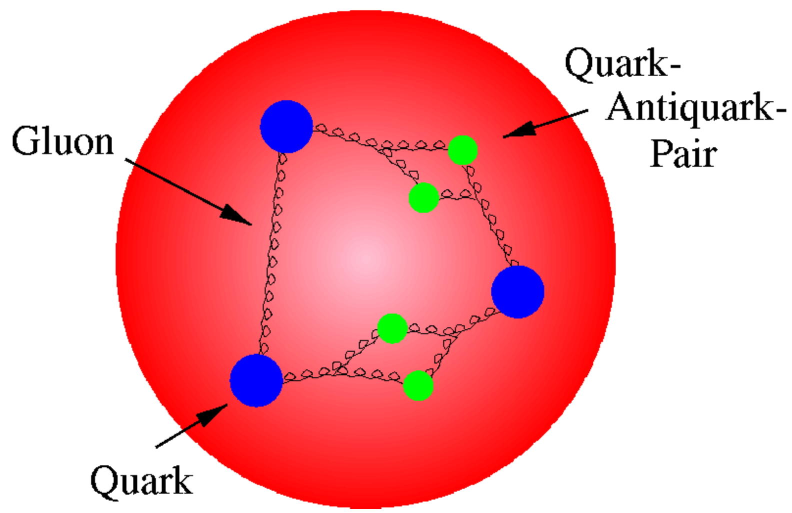

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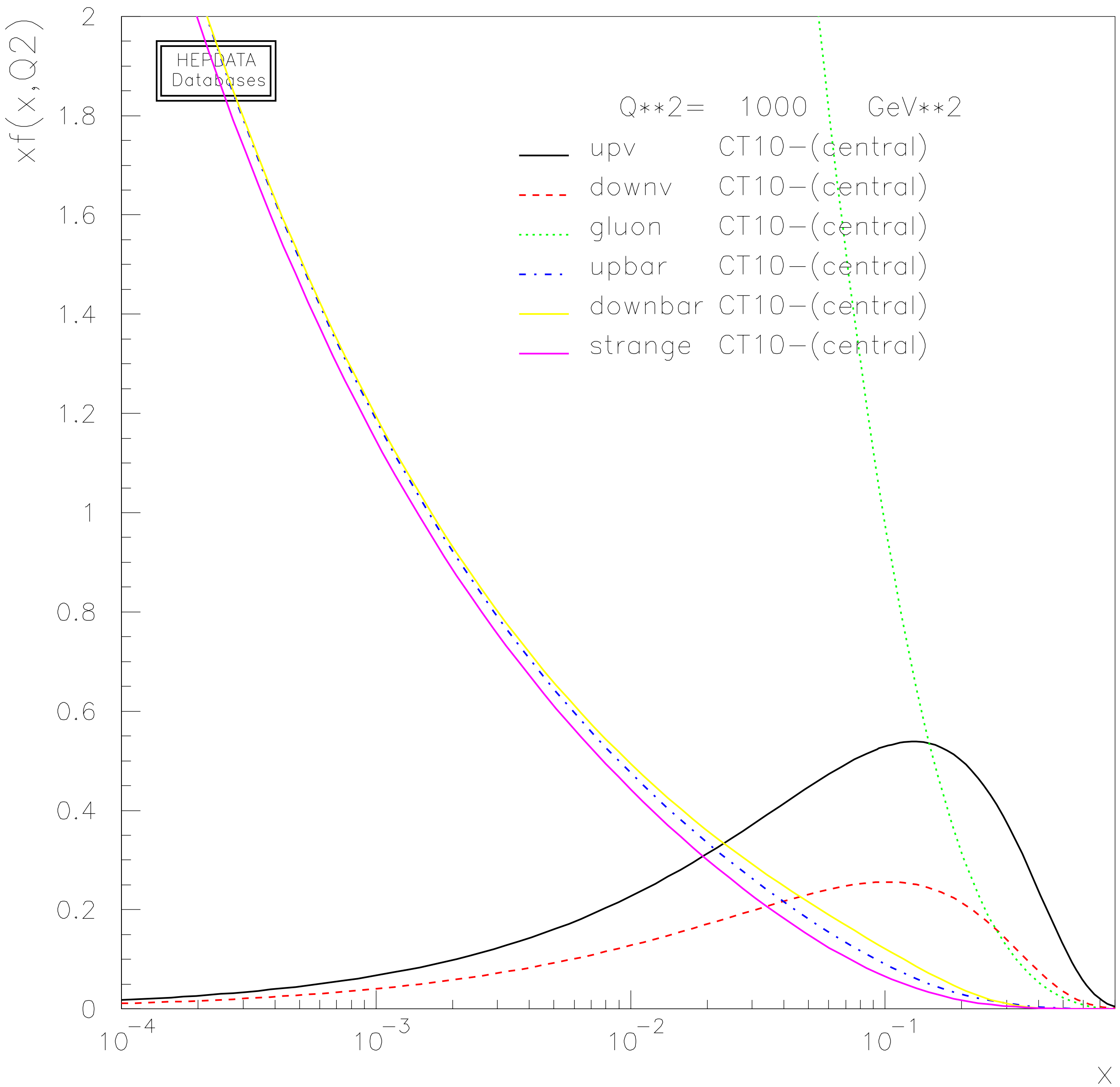

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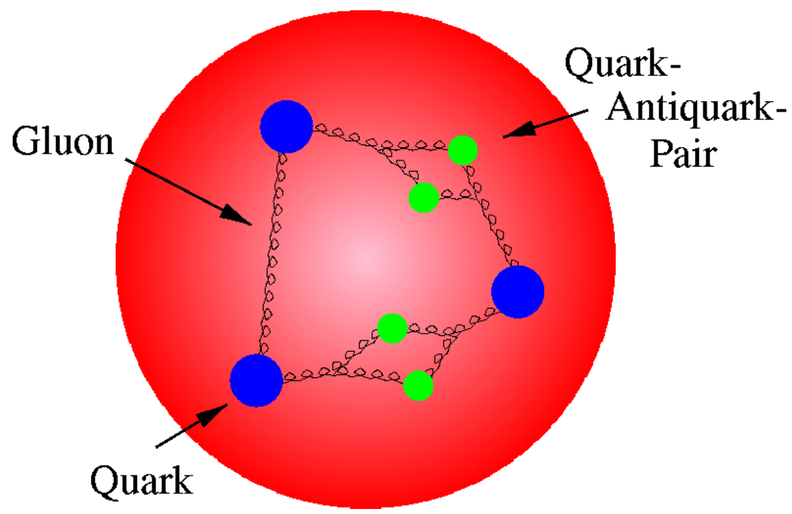

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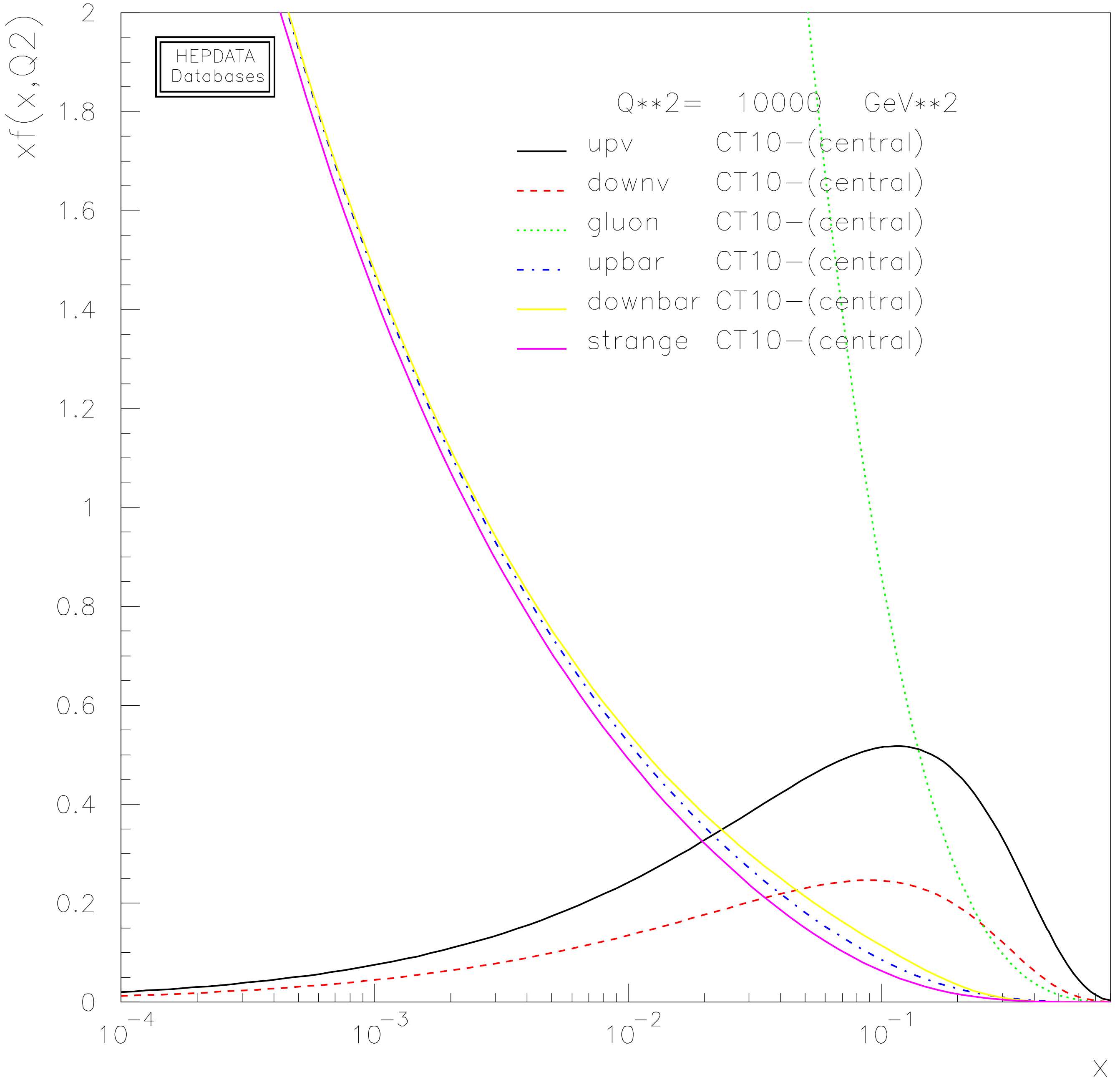

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  $p=|uud\rangle$
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Global Analysis: General Procedure

1.) Parameterize x-dependence of PDFs at input scale Q_0:

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2}P(x;A_3,\ldots);\, f=u_v, d_v, g, \bar{u}, \bar{d}, s, \bar{s}$$

2.) Evolve from Q_0 --> Q by solving the DGLAP evolution equations

--> f(x,Q)

3.) Define suitable Chi^2 function and minimize w.r.t. fit parameters

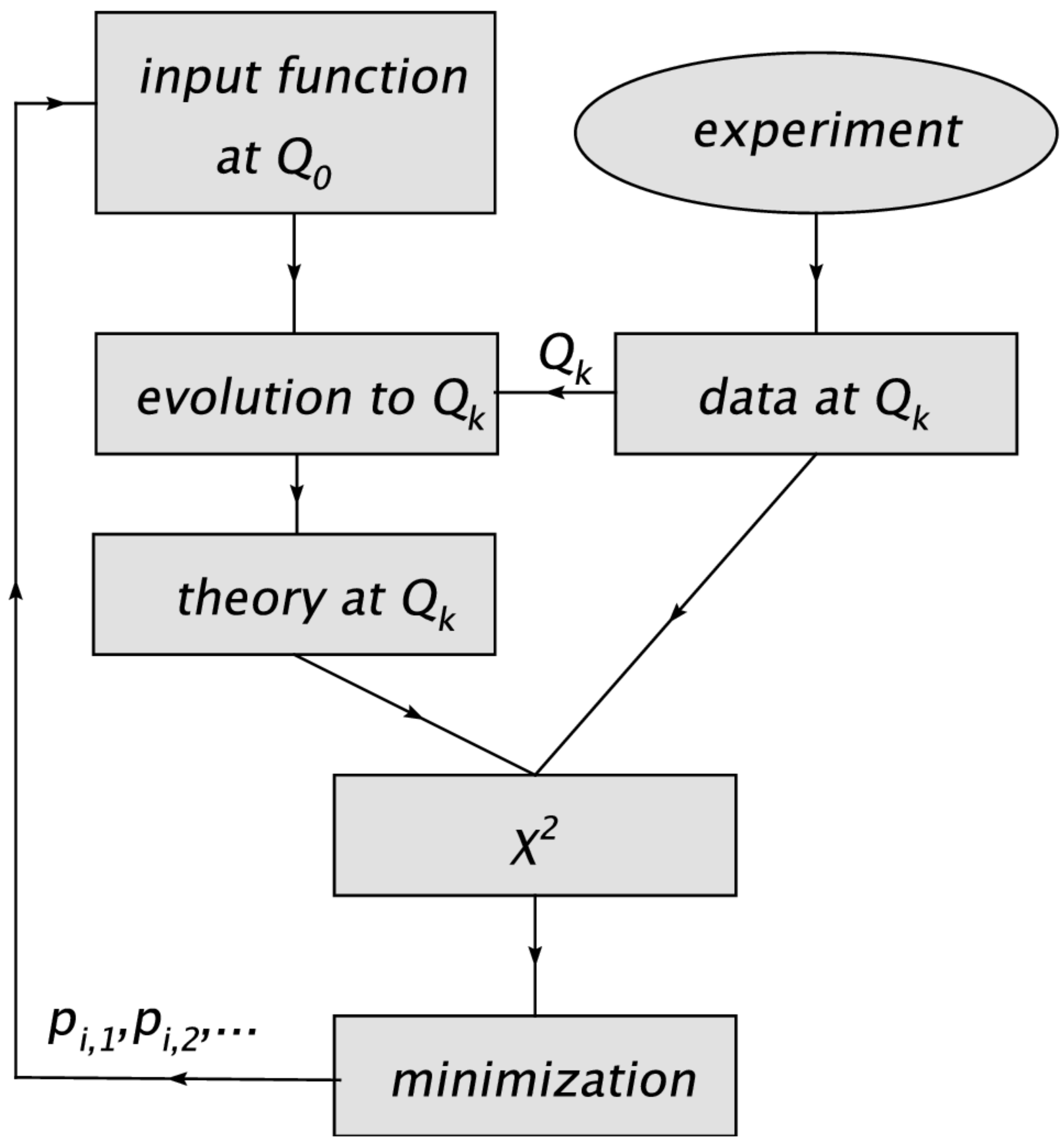
$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\, \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets

Flowchart



input function at Q_0
experiment
Q_k
evolution to Q_k
data at Q_k
theory at Q_k
χ^2
$p_{i,1}, p_{i,2}, \ldots$
minimization

nCTEQ nuclear PDF

Nuclear CTEQ parton distribution functions - Mozilla Firefox

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http://projects.hepforge.org/ncteq/

The CTEQ Meta-Page | Nuclear CTEQ parton distri...

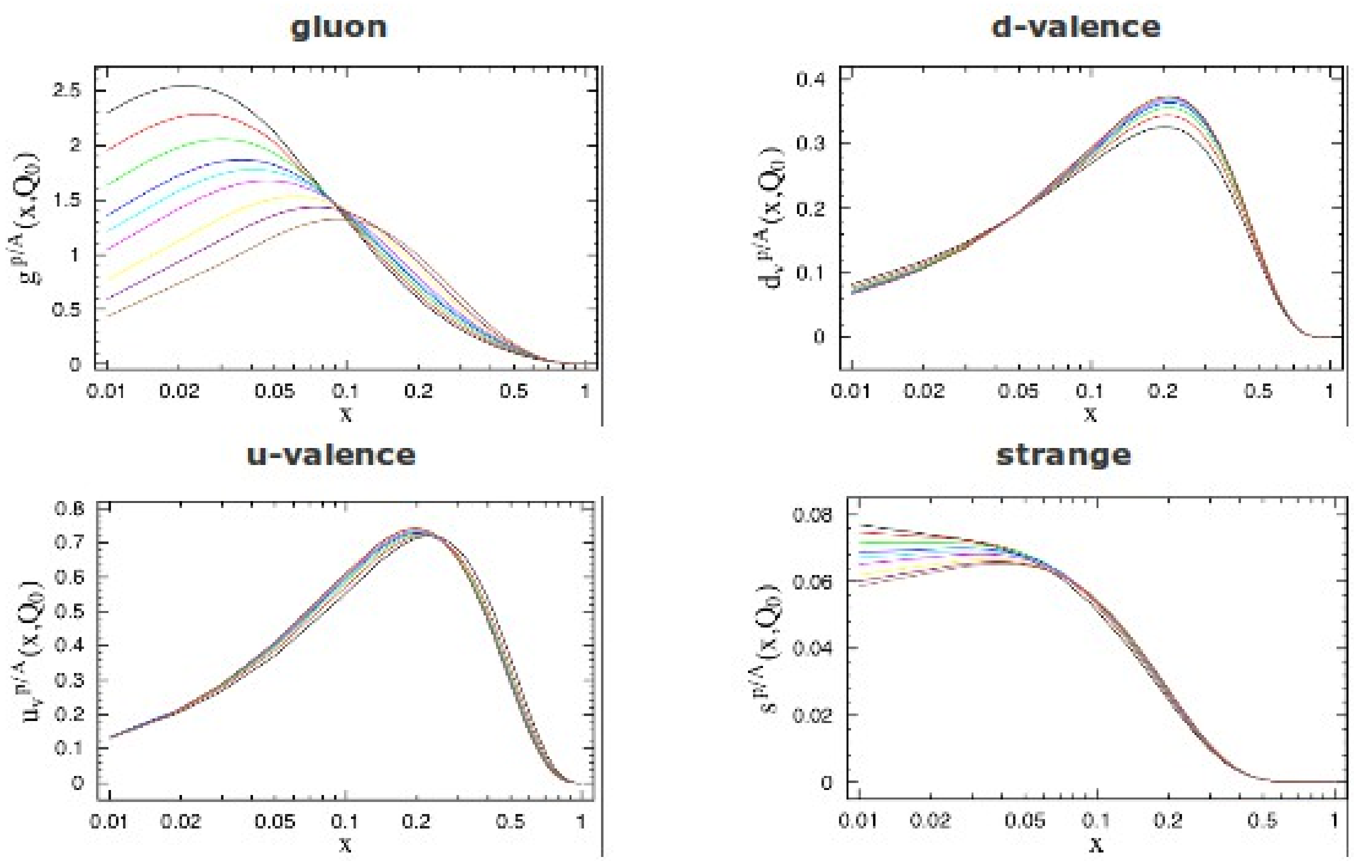
nCTEQ Go! hosted by CEDAR HepForge

nCTEQ

nuclear parton distribution functions

- Home
- PDF grids & code
- Papers & Talks
- Subversion
- Tracker
- Wiki

nCTEQ project is an extension of the CTEQ collaborative effort to determine parton distribution functions inside of a free proton. It generalizes the free-proton PDF framework to determine densities of partons in bound protons (hence nCTEQ which stands for nuclear CTEQ). More details on the framework and the first results can be found in arXiv:09072357 [hep-ph].
The effects of the nuclear environement on the parton densities can be shown as modified parton densities



where all black curves stand for free proton PDF and red, green, blue, cyan, pink, yellow, magenta and brown curves show PDF in protons bound in nuclei - from deuterium (red) to lead (brown).

K Kovarik,
I. Schienbein,
J.Y. Yu,
T. Stavreva,
T Jezo,
C. Keppel,
J.G. Morfin,
F. Olness,
J.F. Owens.

Done

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 paramters $c_{k,0}$ for $A = 1$)

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

- **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:** $Q > 2\ \text{GeV}$, $W > 3.5\ \text{GeV}$

EXPERIMENTAL INPUT

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

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 $\sigma_{\rm DY}^{pA}/\sigma_{\rm DY}^{pA'}$: 92 points (before cuts)

Table from Hirai et al.,arXiv:0909.2329

RESULTS: DECUT3 FIT

- 708 (1233) data points after (before) cuts
- 32 free paramters; 675 d.o.f.
- Overall $\chi^2/\mathrm{d.o.f.} = 0.95$
- individually:
  - for F_2^A/F_2^D: $\chi^2/\mathrm{pt} = 0.92$
  - for $F_2^A/F_2^{A'}$: $\chi^2/\mathrm{pt} = 0.69$
  - for DY: $\chi^2/\mathrm{pt} = 1.08$

nCTEQ Nuclear PDF's

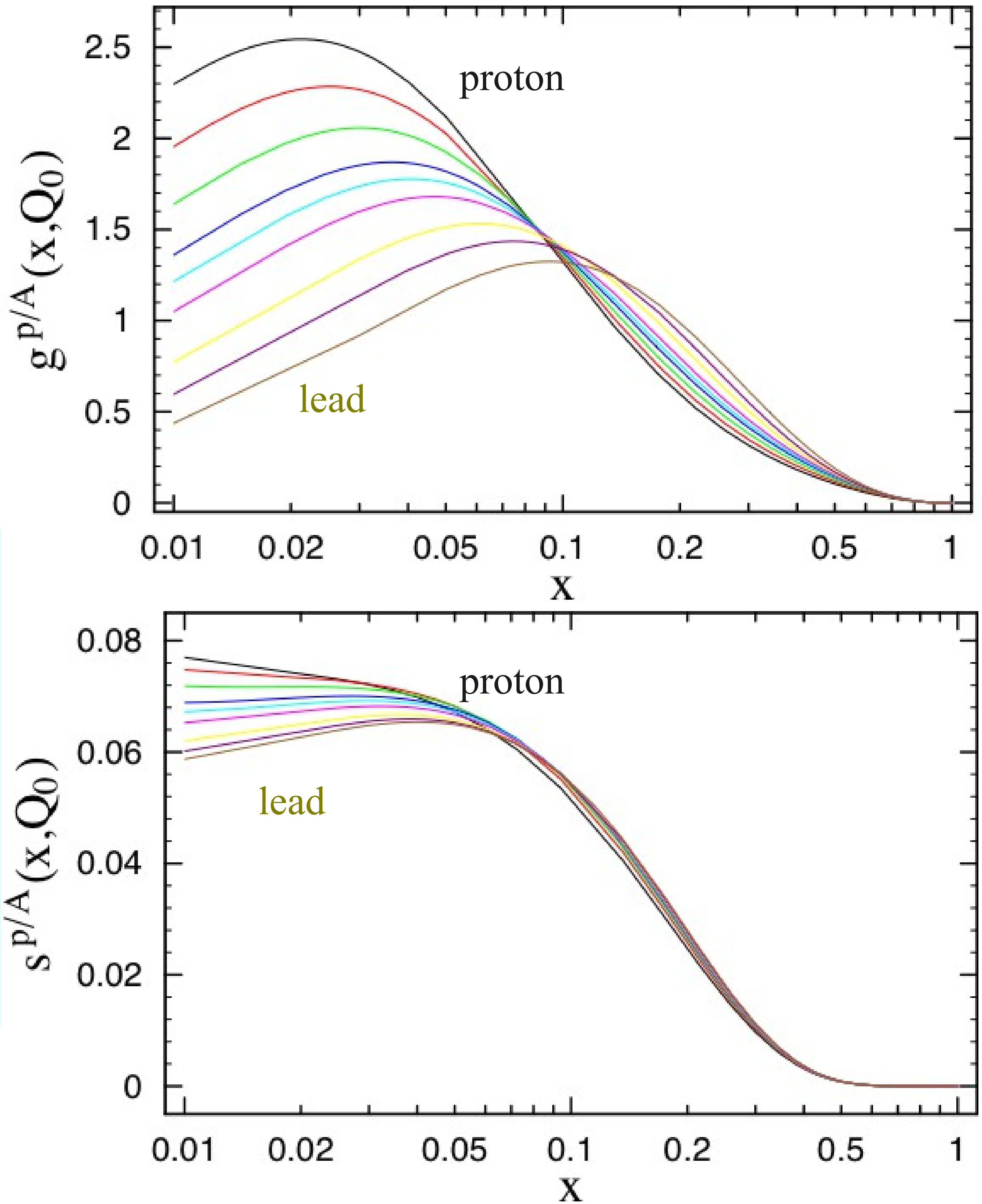
- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

A-Dependent PDFs

$$xf(x) = x^{a_1}(1-x)^{a_2}e^{a_3 x}(1+e^{a_4}x)^{a_5}$$

$$a_i \rightarrow a_i(A)$$

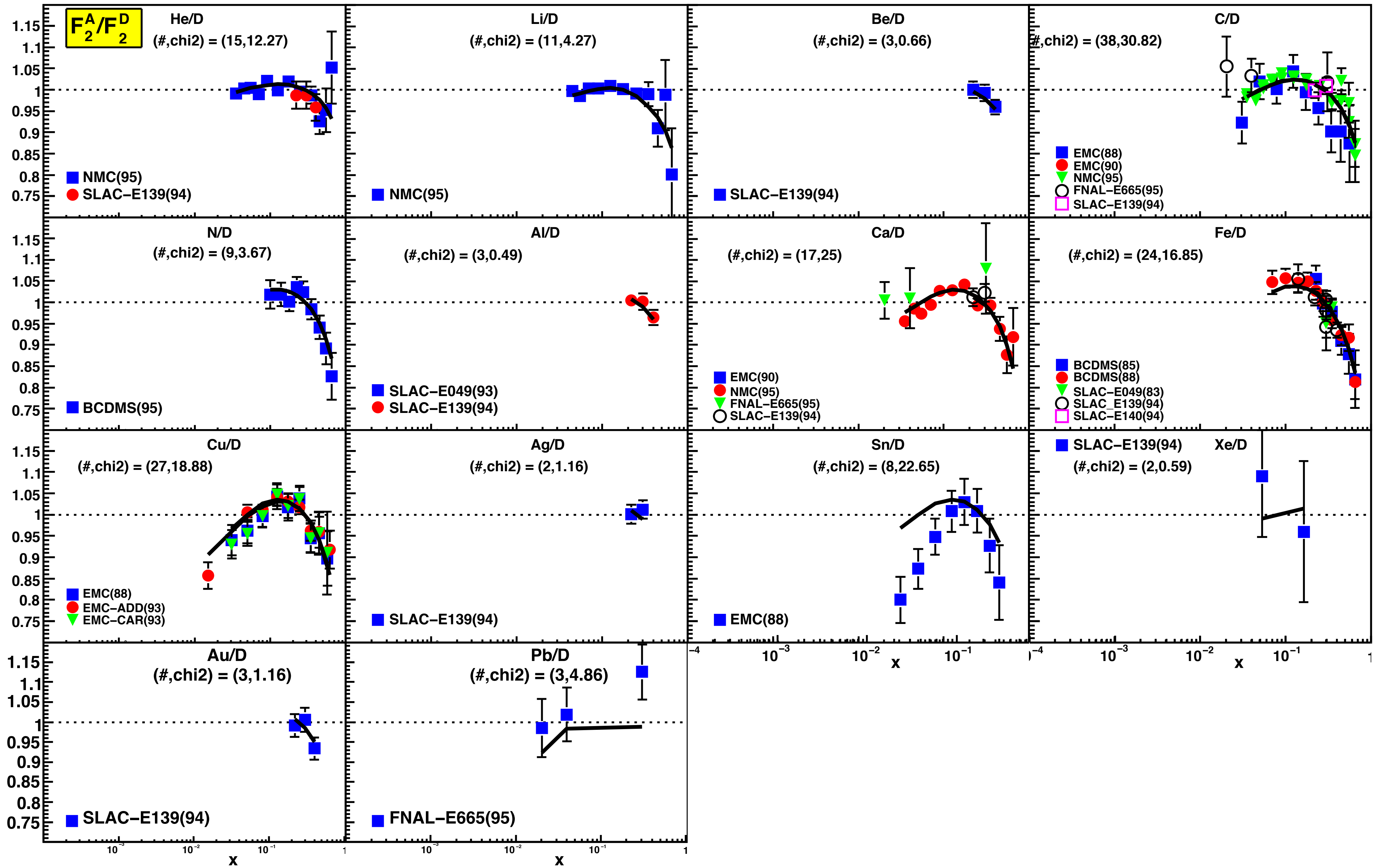
$$a_k = a_{k,0} + a_{k,1}\left(1 - A^{-a_{k,2}}\right)$$



Nuclear PDFs from neutrino deep inelastic scattering.
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin,
F. Olness, J.F. Owens. Phys.Rev.D77:054013,2008.

RESULTS: DECUT3 FIT

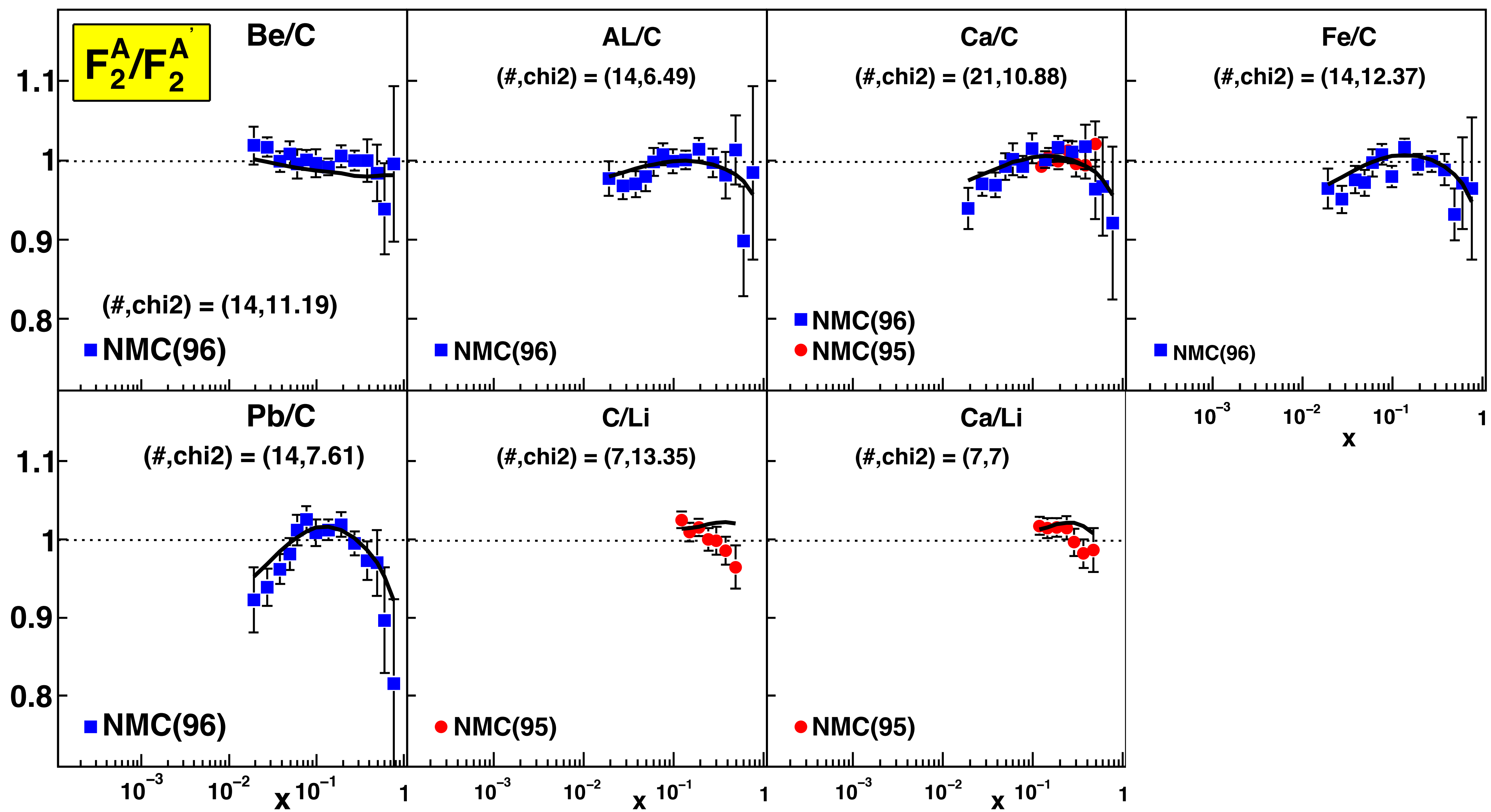
DIS DATA VS *x*



Friday, June 28, 13

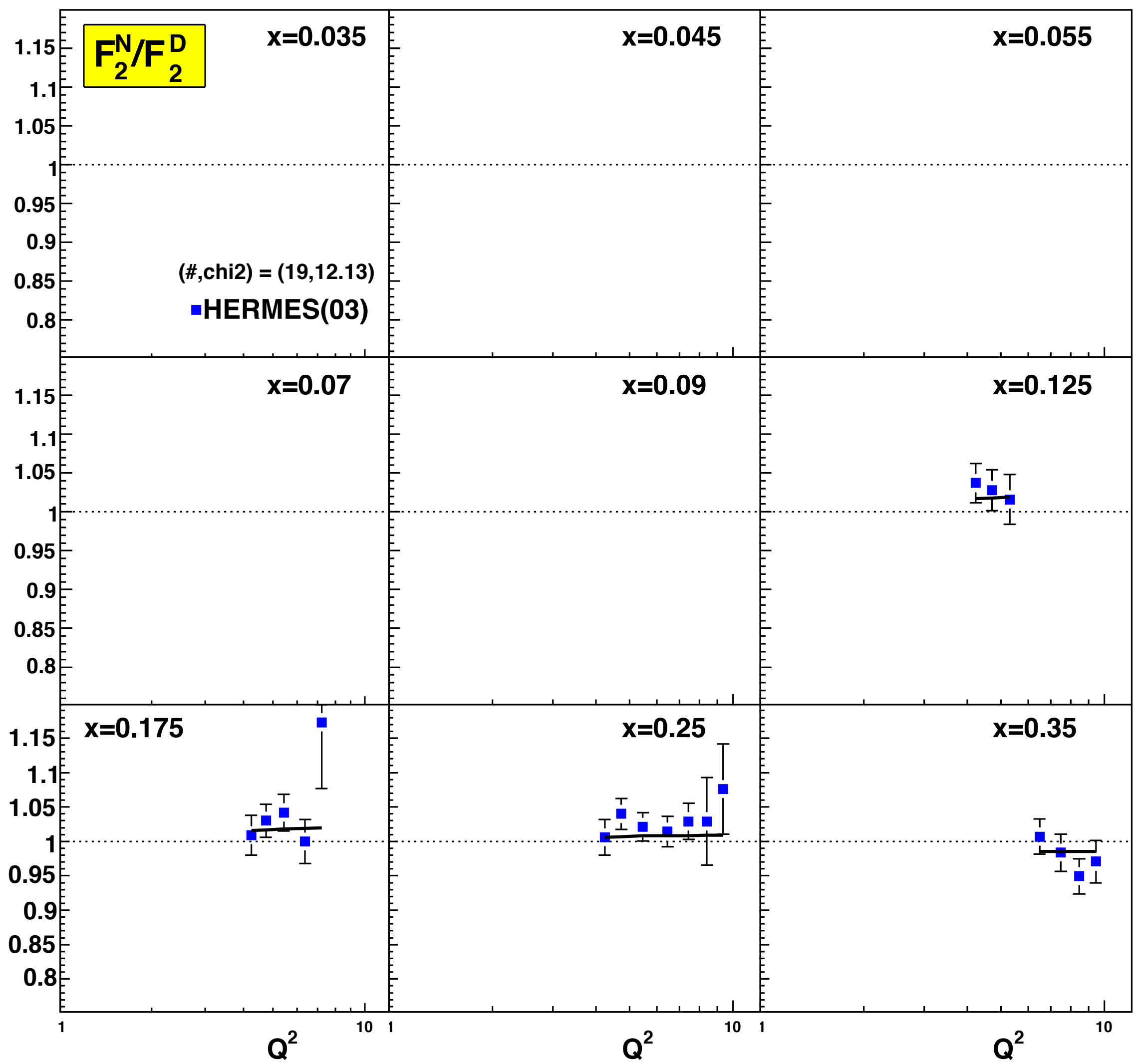
RESULTS: DECUT3 FIT

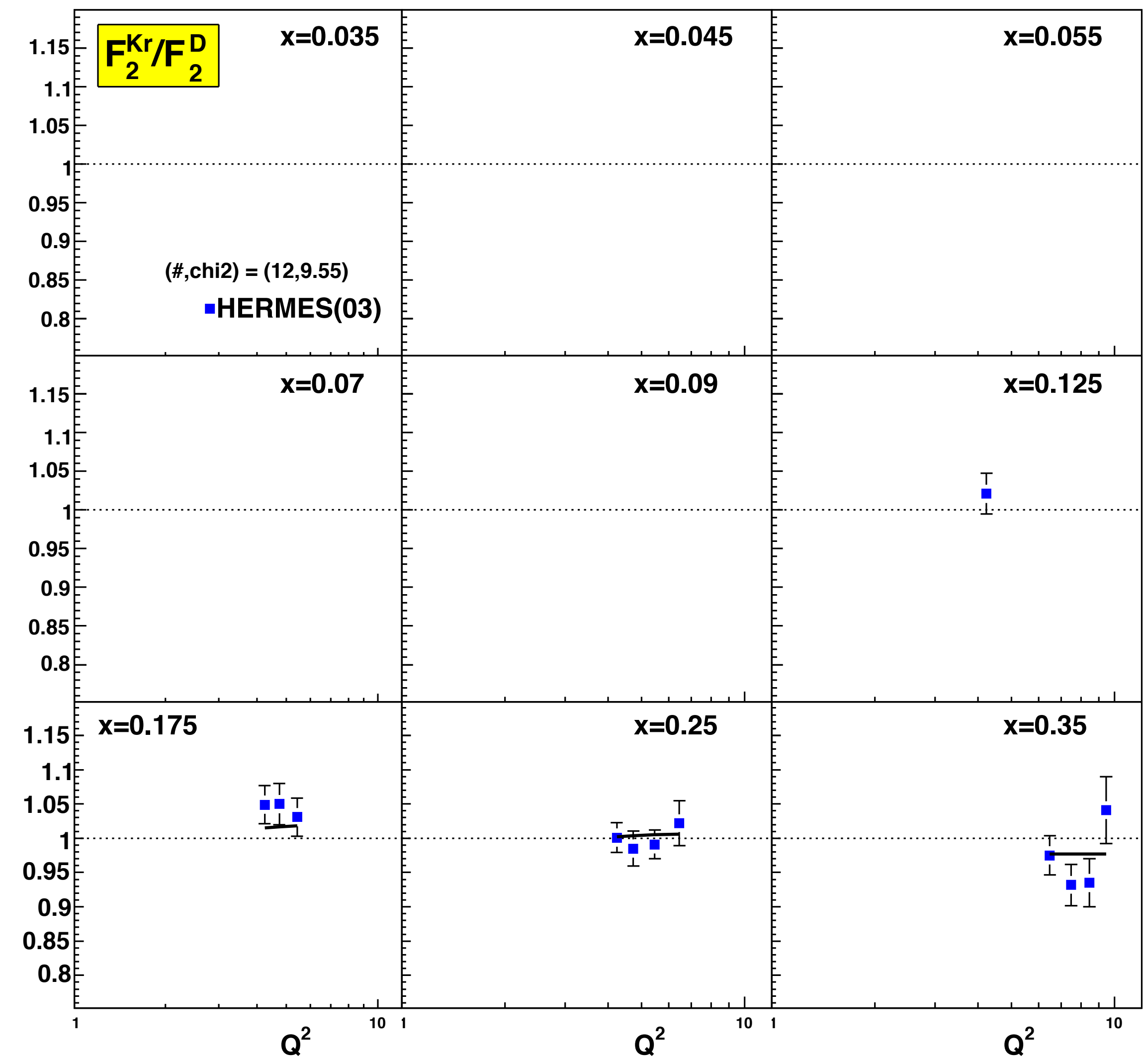
DIS DATA VS *x*



RESULTS: DECUT3 FIT

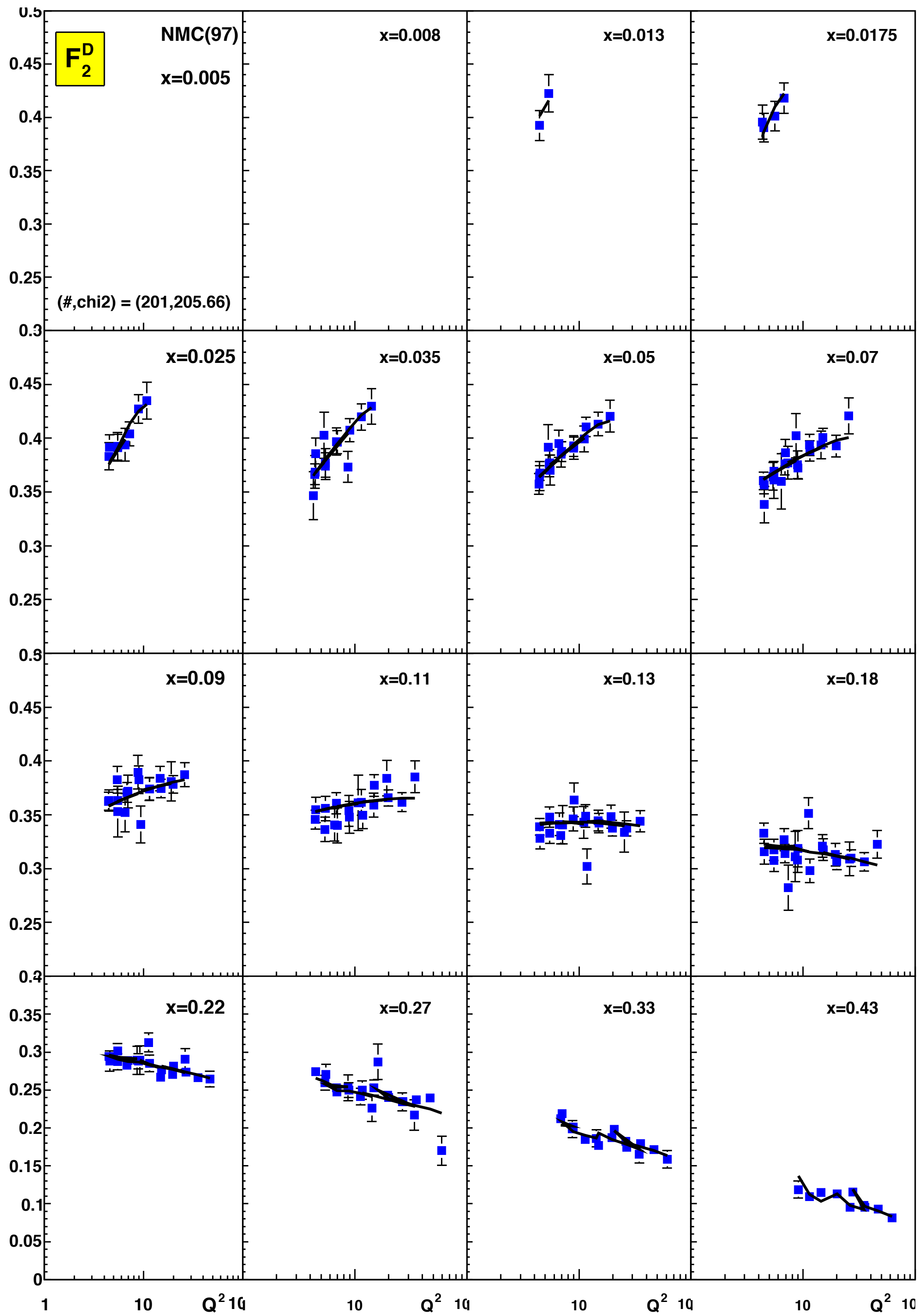
HERMES DATA VS Q^2

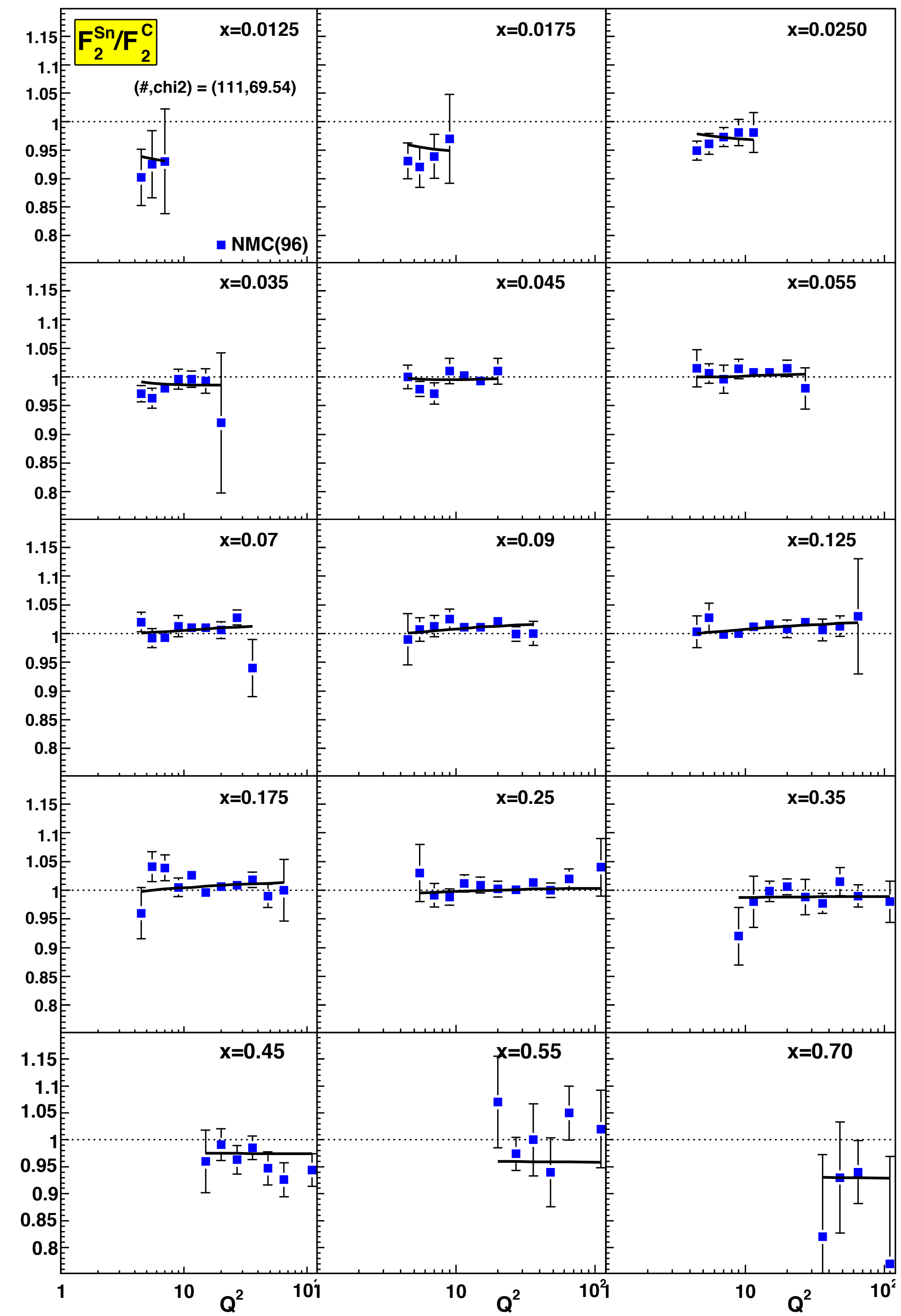


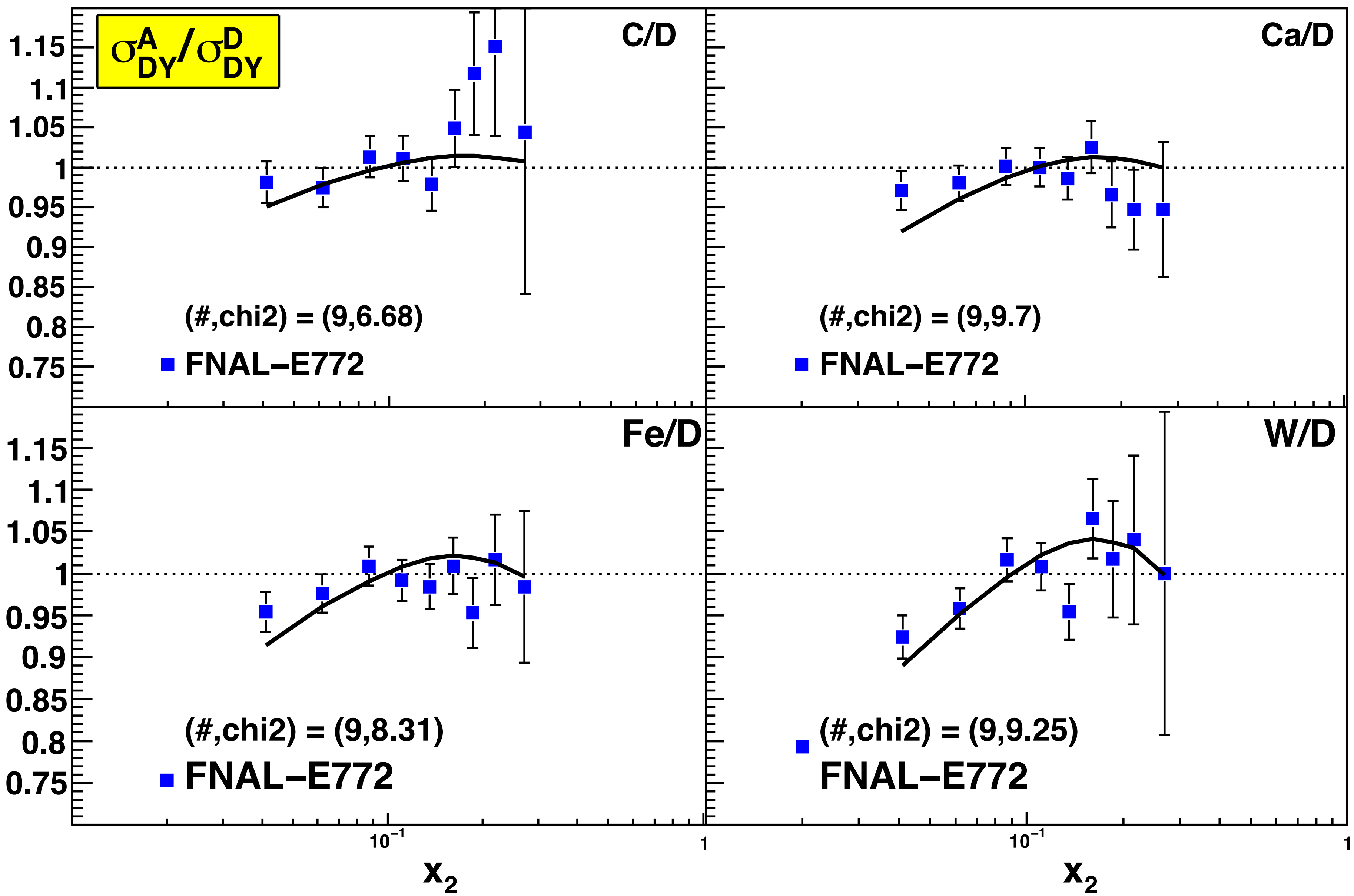


RESULTS: DECUT3 FIT

NMC DATA FOR D AND Sn/C VS Q^2



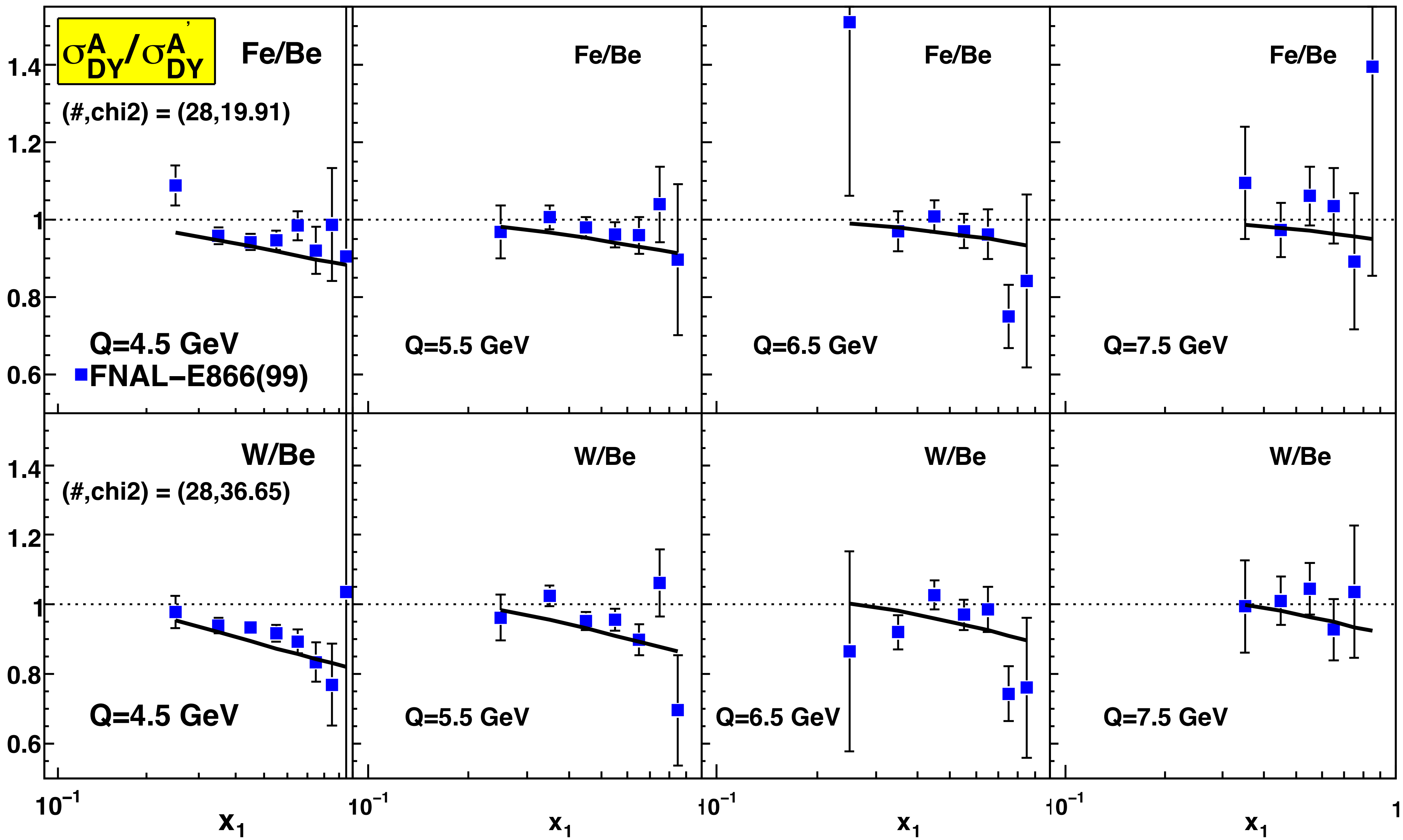




$\sigma^A_{DY}/\sigma^D_{DY}$
C/D
Ca/D
Fe/D
W/D
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
(#,chi2) = (9,6.68)
(#,chi2) = (9,9.7)
(#,chi2) = (9,8.31)
(#,chi2) = (9,9.25)
FNAL–E772
10^{-1}
1
x_2

RESULTS: DECUT3 FIT

DRELL–YAN DATA



The strange content of the nucleon

arXiv:1203.1290

Strange PDF

- Before dimuon data (~2001) essentially no experimental constraints on strange sea
- Theoretical assumptions necessary!
  - Early parametrisations (Duke-Owens): SU(3)-symmetric sea
  - Even SU(2)-symmetry is broken! (Gottfried sum rule, E866 experiment)
  - Later parametrisations (e.g. CTEQ6.1): SU(3) symmetry is broken; strange sea ~ 1/2 light sea
- CTEQ6.6 and later: dimuon data! strange PDF fitted with 2 free parameters

$$x\bar{u} = x\bar{d} = x\bar{s} = A_S(1-x)^{\eta_S} S/6$$

$$\bar{d}(x) > \bar{u}(x)$$

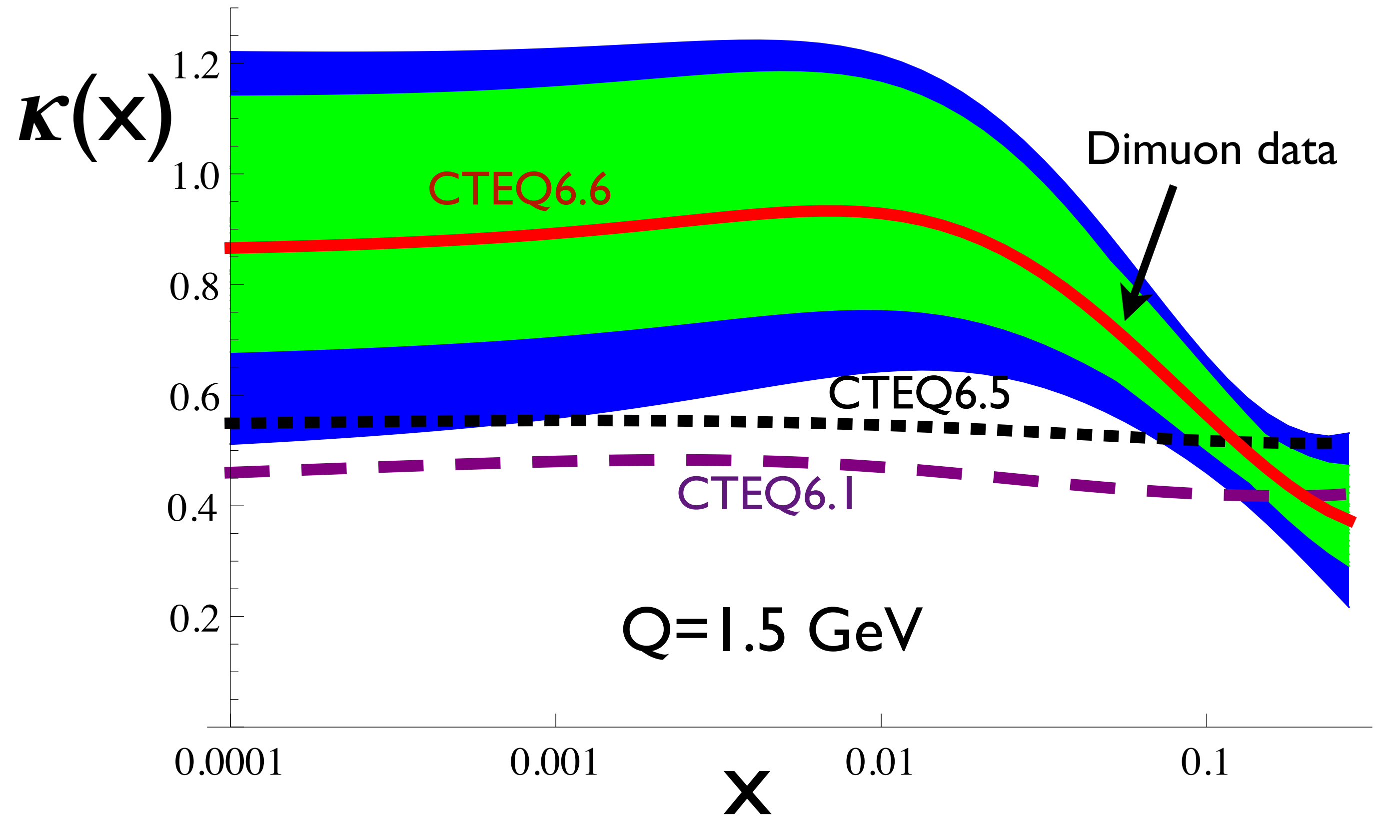
$$s = \bar{s}$$
$$(s+\bar{s})(x, Q_0) = \kappa(\bar{u}+\bar{d})(x, Q_0)$$
$$\kappa \simeq 0.5$$

Strange PDF: Uncertainty

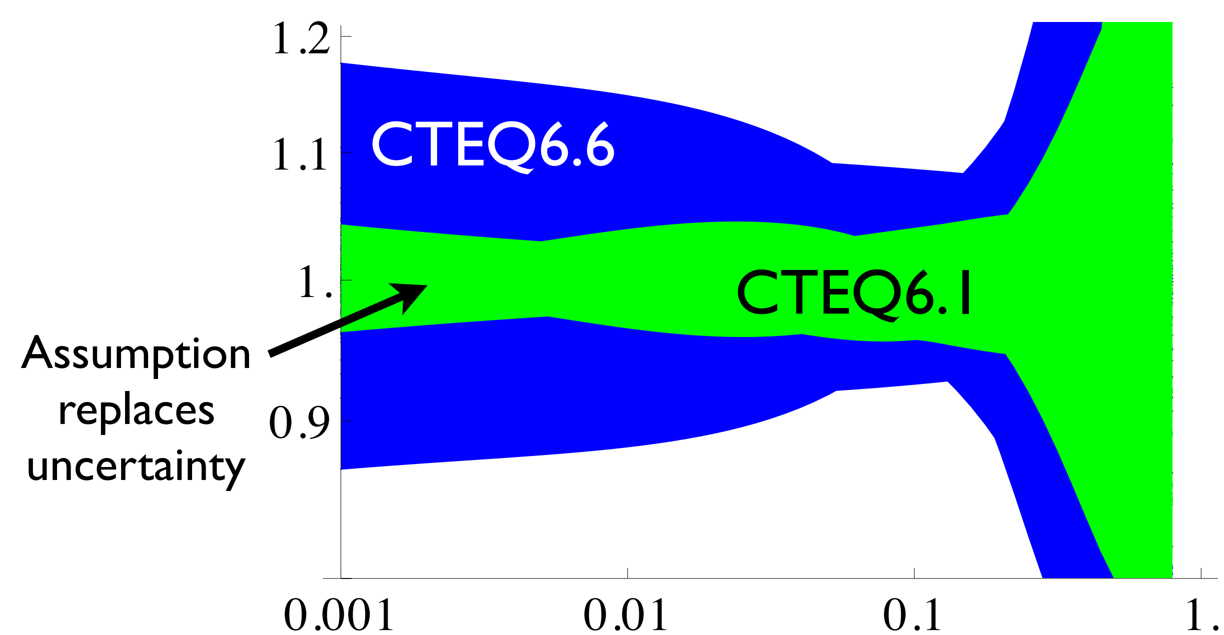
- Knowledge of strange PDF is limited (see figures)
- If exact SU(3) symmetry:
  ubar = dbar = sbar and κ=1
- $m_s >> m_u, m_d$:
  expect ubar = dbar > sbar and κ<1
- CTEQ6.1, CTEQ6.5: κ=0.5
  by design
- CTEQ6.6: κ=0.5 at x=0.1
  central PDF a factor 2 larger for small x
- Green error band: (upper figure)
  enveloppe of 44 CTEQ6.6 error PDFs
- Blue error band: (upper figure)

$$\Delta X = \frac{1}{2}\sqrt{\sum_{i=1}^{N_p}[X(S_i^+) - X(S_i^-)]^2}$$

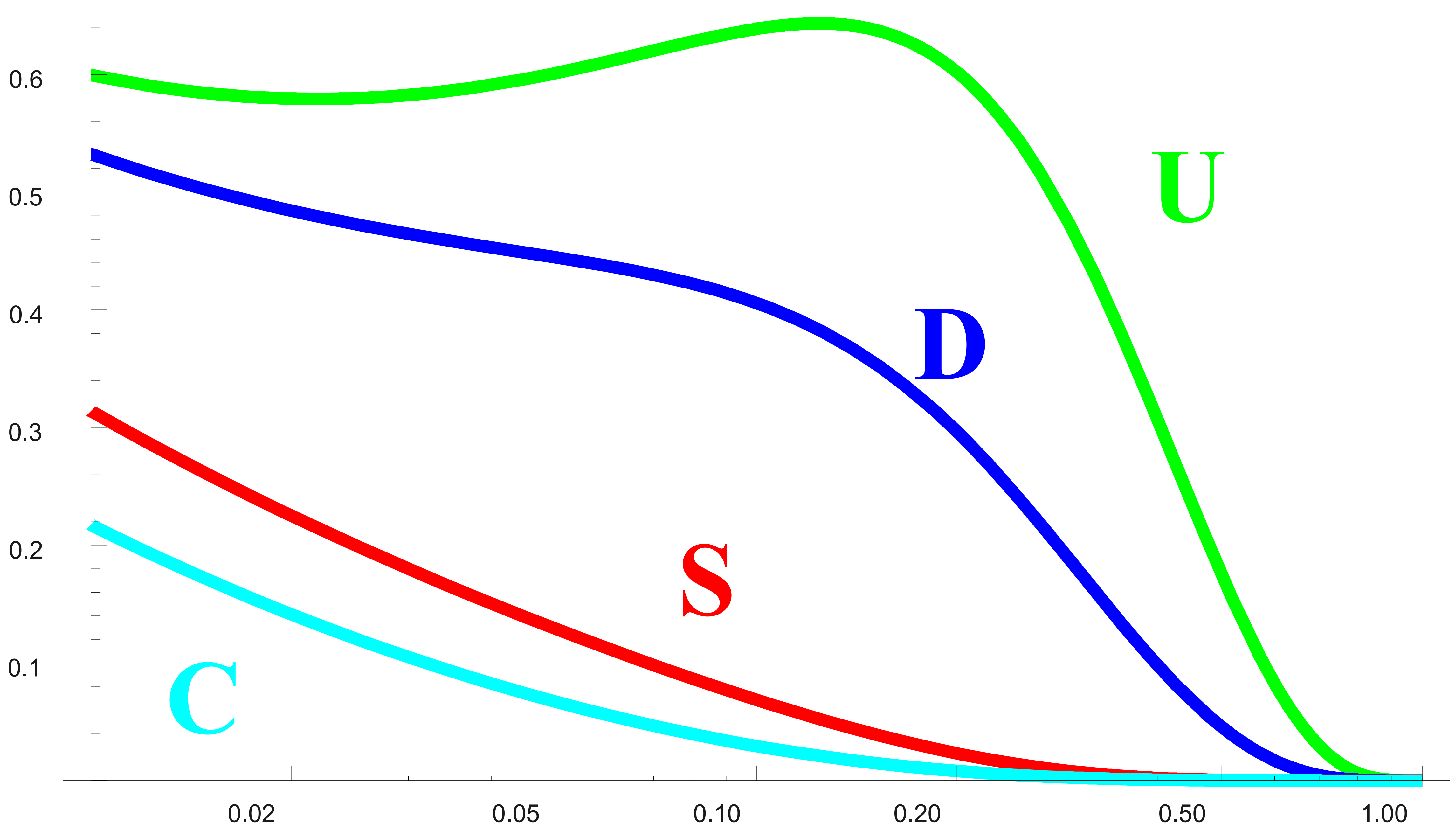
$$\kappa(x,Q) = \frac{s(x,Q)}{[\bar{u}(x,Q)+\bar{d}(x,Q)]/2}$$



Relative uncertainty of strange sea at Q=2 GeV



What constrains the Strange???



Strange PDF: experimental constraints

Difference of CC and NC DIS structure functions

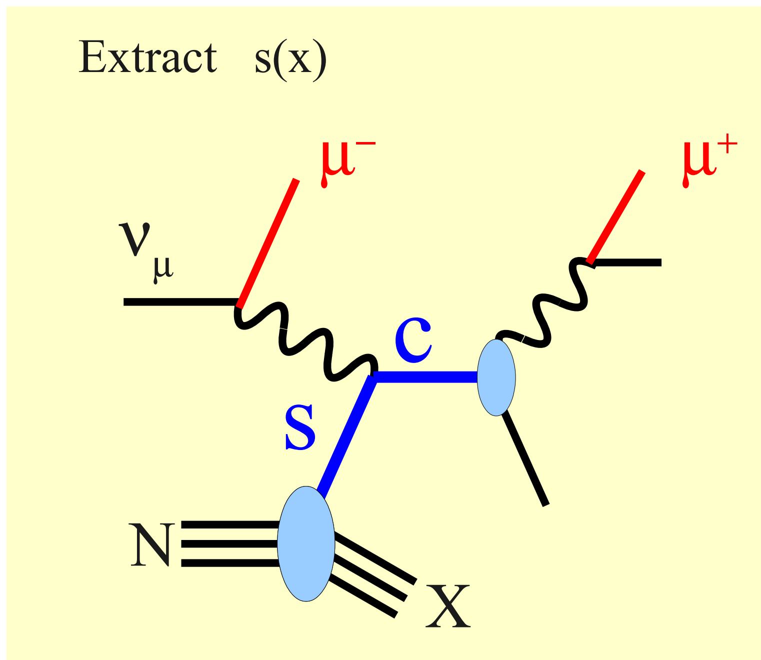
$$\Delta F_2 = \frac{5}{18} F_2^{CC} - F_2^{NC} \simeq \frac{x}{6}[s(x) + \bar{s}(x)]$$

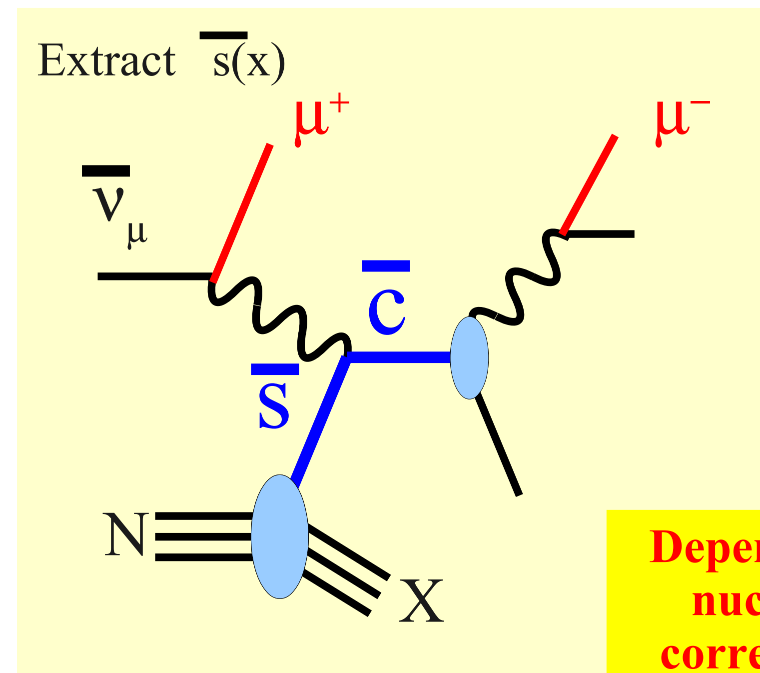
- valid at LO, neglecting charm and isospin violation
- difference of large structure functions giving small strange distribution: large uncertainties
- very weak constraints

see, T. Adams et al., arXiv:0906.3563

Strange PDF: experimental constraints

Opposite sign dimuon production in neutrino DIS: $\nu N \rightarrow \mu^+ \mu^- X$



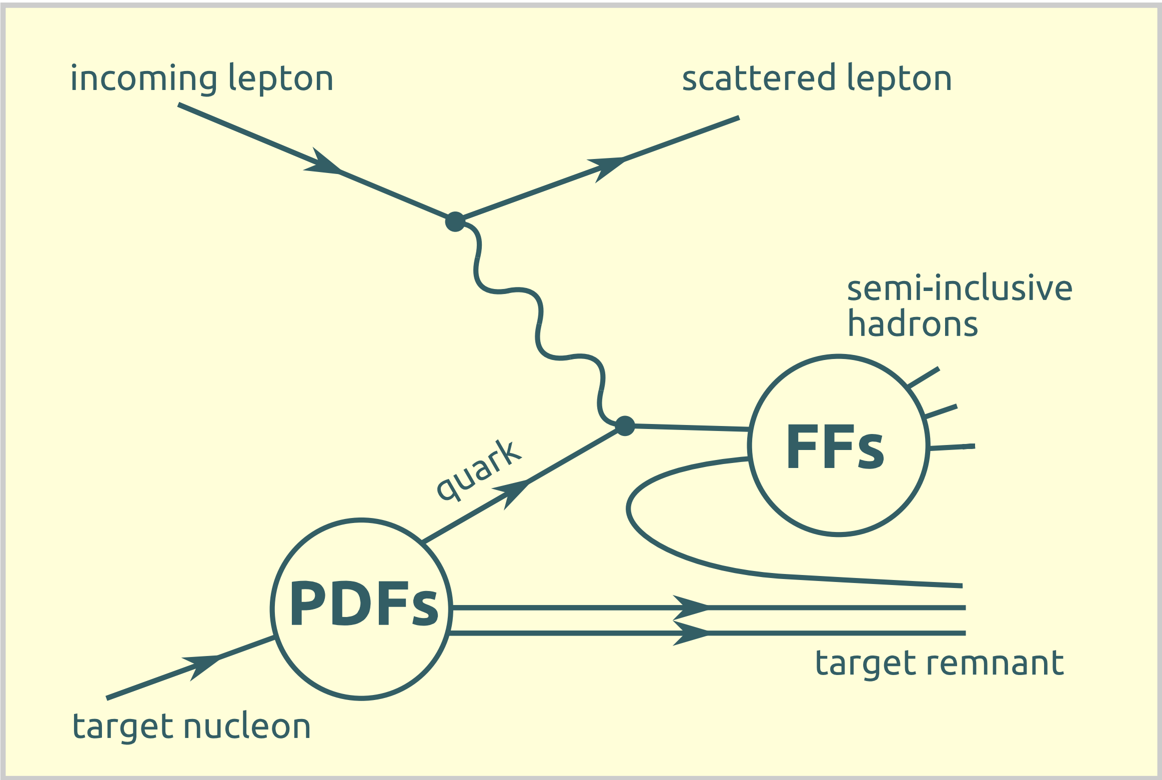


Depends on nuclear corrections

- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections!
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data not yet published, in principle very interesting

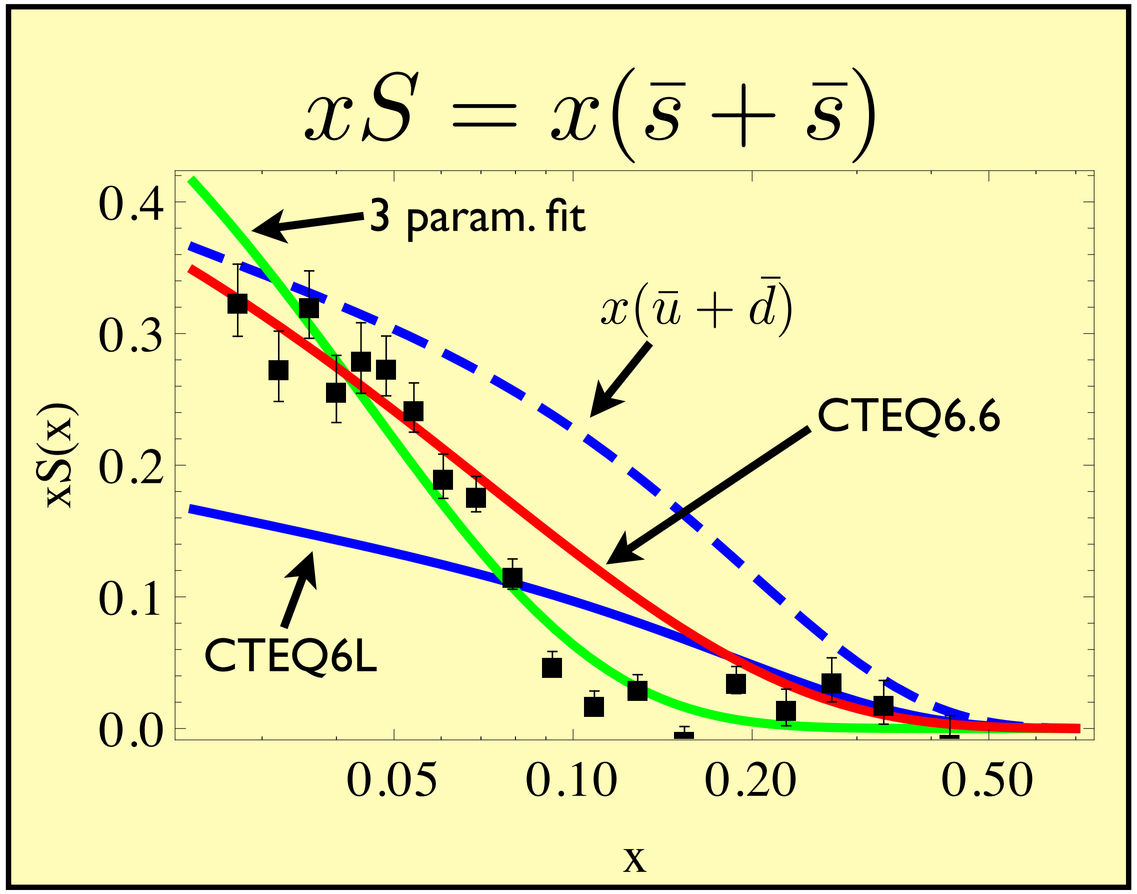
Strange PDF: experimental constraints

Semi-Inclusive DIS (SIDIS): e+N→K+X



$$\frac{d\sigma}{dx dQ^2 dz} \propto \sum_q e_q^2 f_q(x,Q^2) D_q^K(z,Q^2)$$
$$\sim \frac{1}{9} s(x,Q^2) D_s^K(z,Q^2)$$

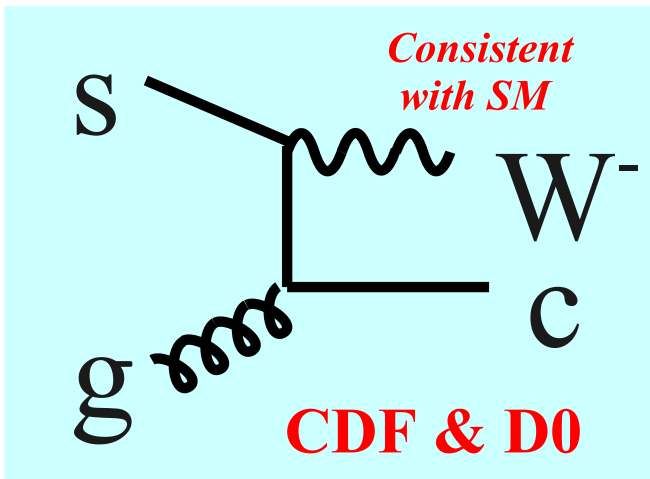
- SIDIS data from HERMES
- $e^+ + D \rightarrow K + X$
- depends on fragmentation functions (FF)
- not (yet) included in global analyses
- compatible with CTEQ6.6 (red curve)



Strange PDF: experimental constraints

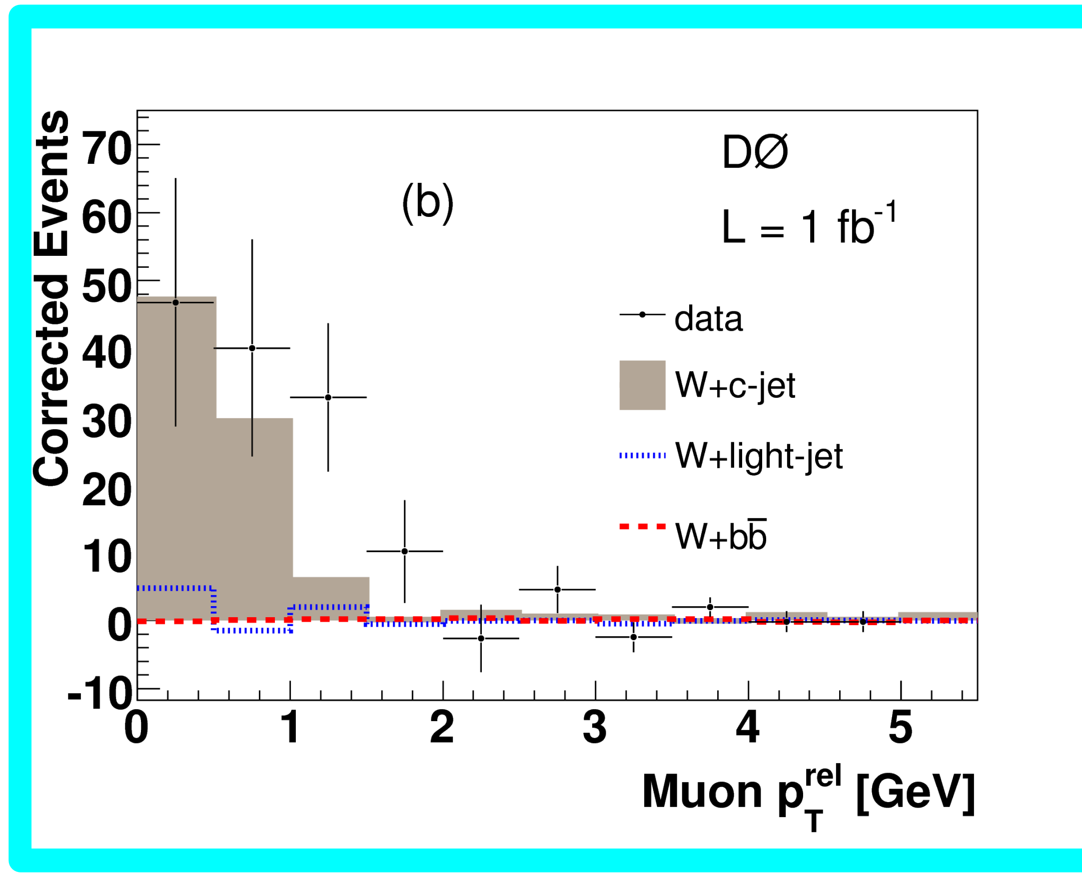
Production of a vector boson+heavy quark: s+g →W+c

s g→Wc at the Tevatron



CDF: PRL 100:091803,2008.
D0: PLB666:23,2008.

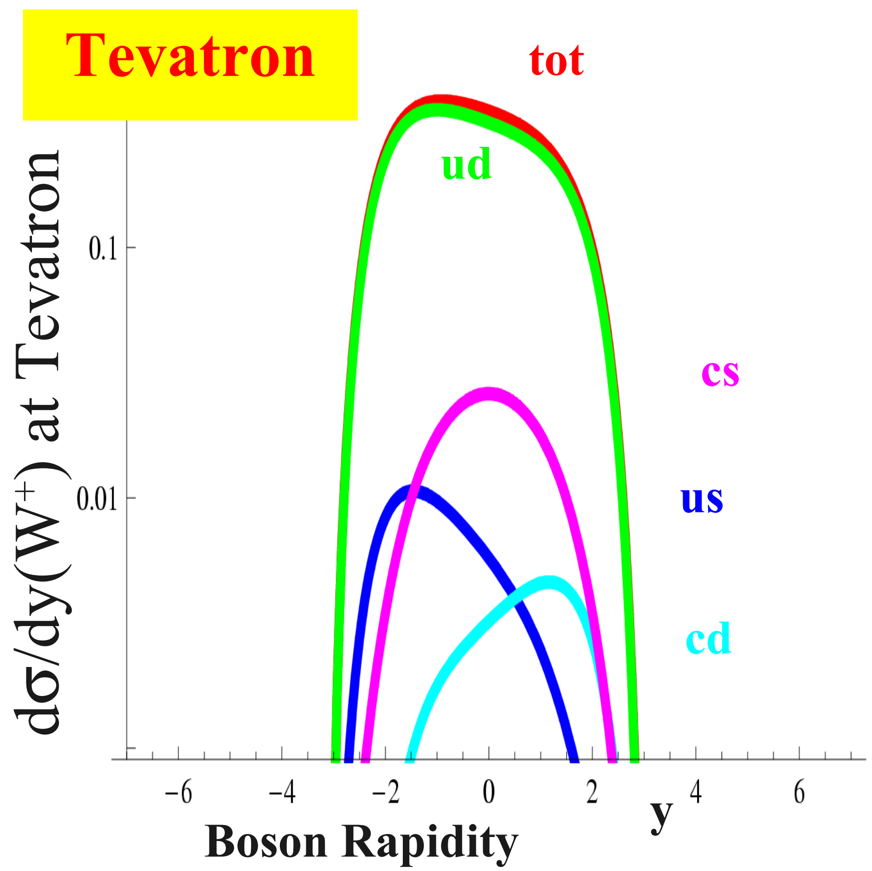
- Tevatron: analysis with ~1 fb^{-1} consistent with SM
- no nuclear corrections
- different kinematic region than neutrino DIS
- hadron-hadron initial state more challenging
- not yet competitive but updated analyses in progress

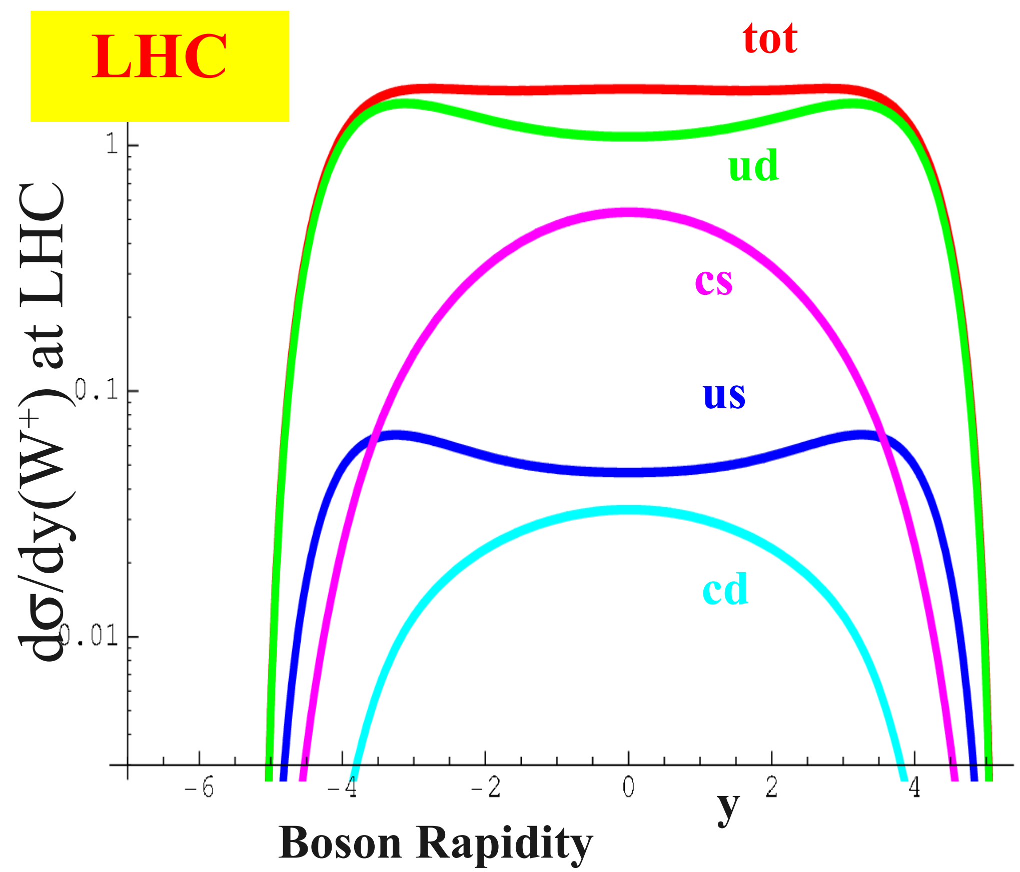


Also a challenge at LHC

Drell-Yan production of W/Z at the LHC

- Benchmark processes, essential to know impact of PDF uncertainties
- Conversely, W/Z production to constrain PDFs

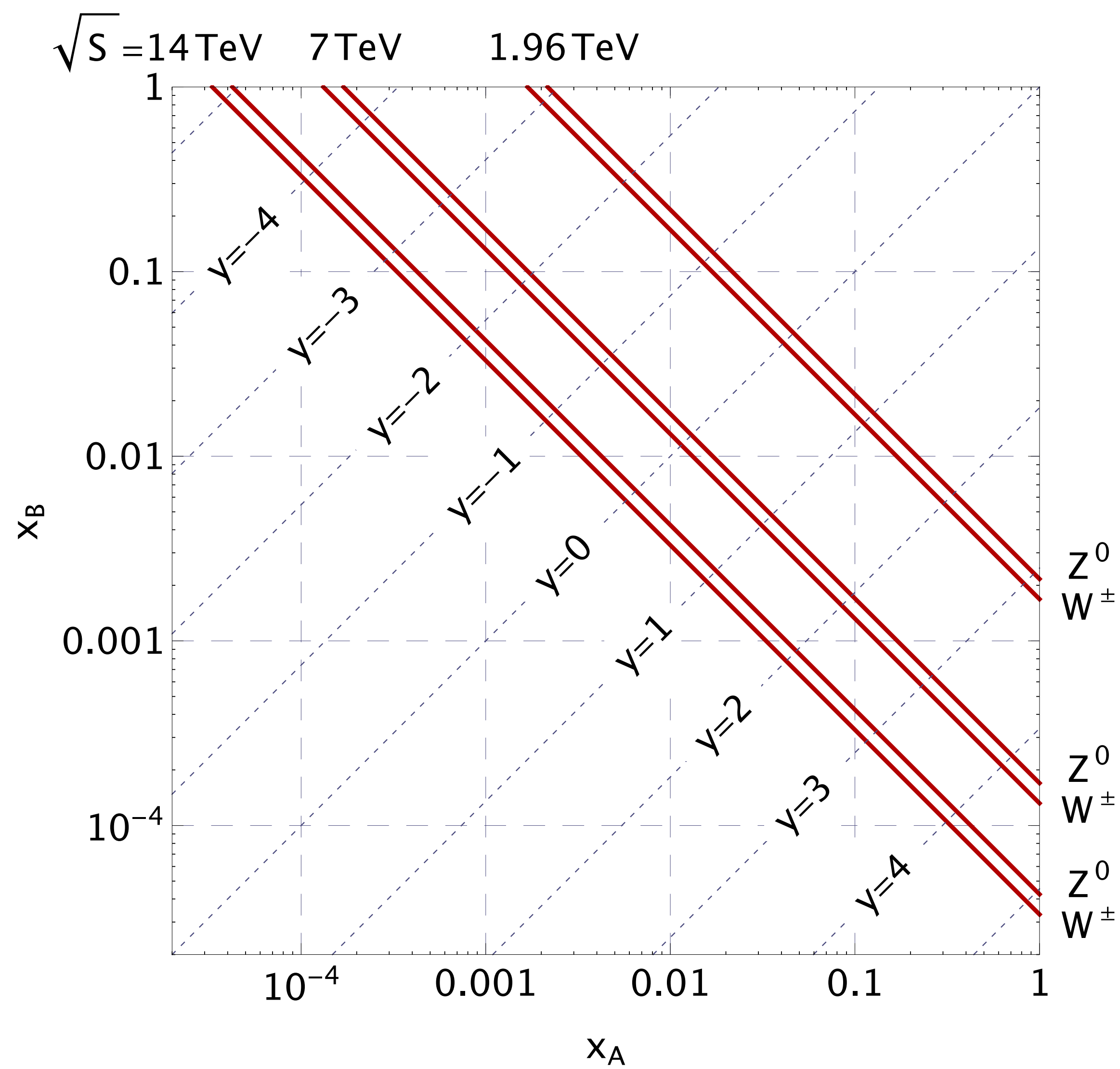




- Larger energy ⇒ probes PDFs to small momentum fractions x
- Larger rapidity (y) ⇒ access to **very** small x
- Larger contribution from the **sc-channel**

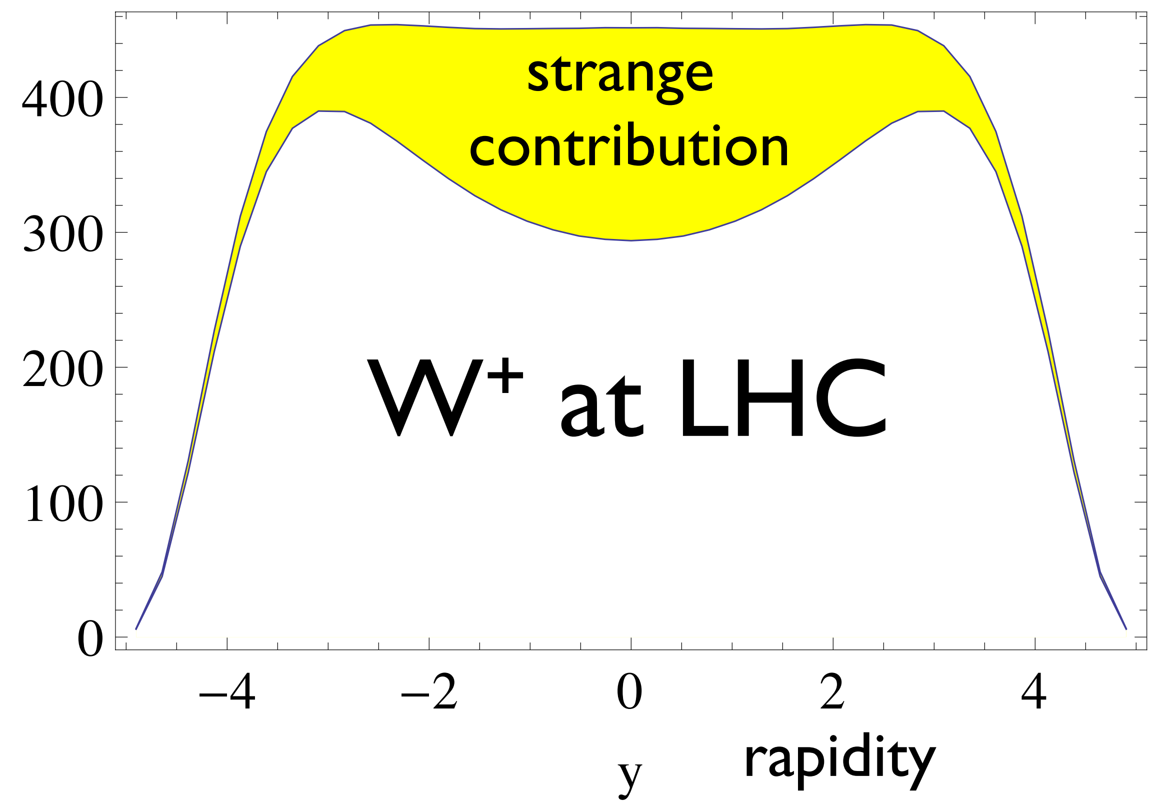
Drell-Yan production of W/Z at the LHC

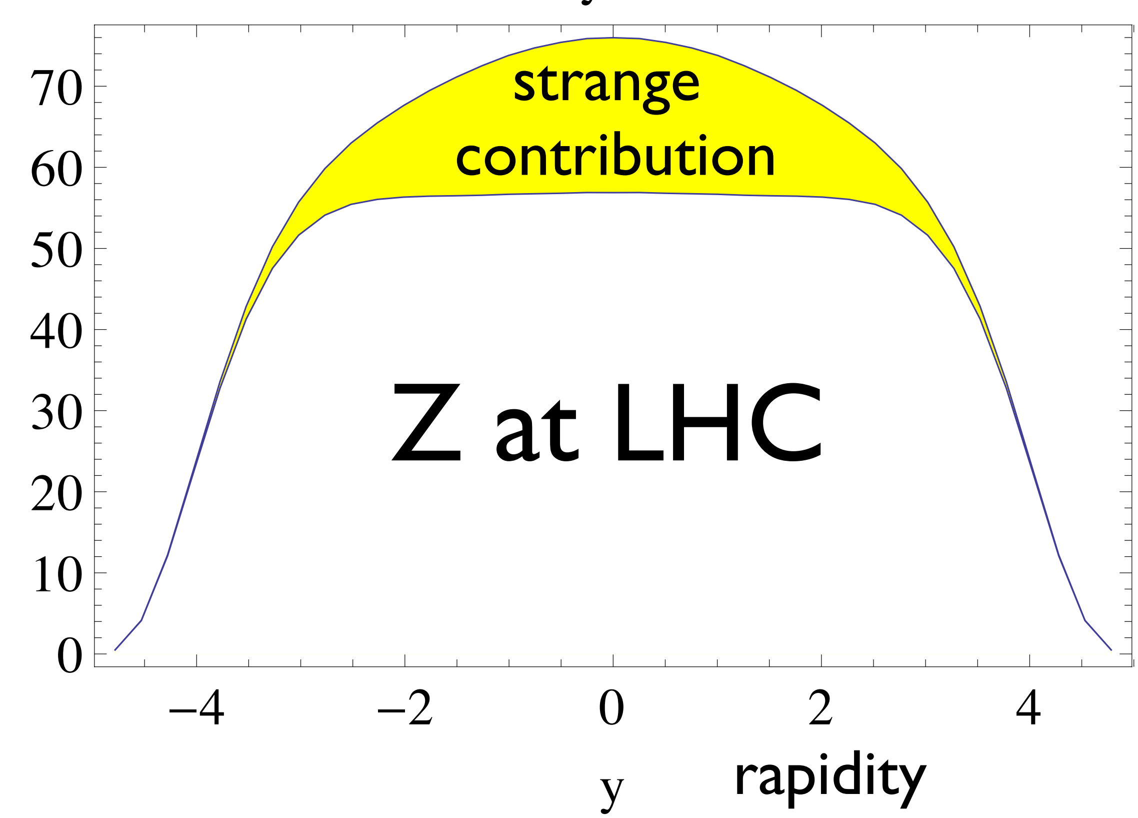
Kinematic plane



Uncertainty of strange-PDF will feed into benchmark process

$d^2\sigma/dM/dy$ [pb/GeV]



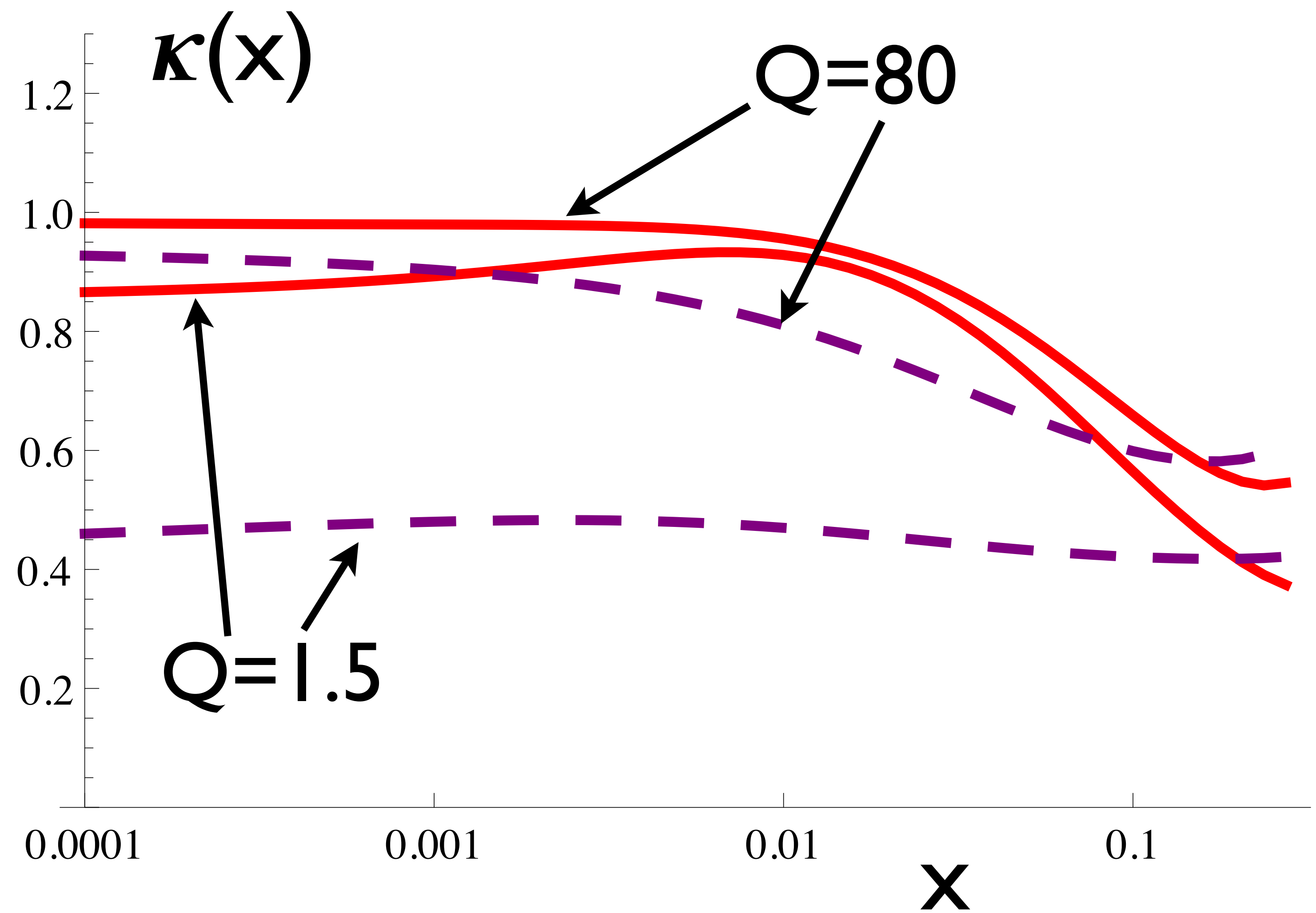


VRAP code: Anastasiou, Dixon, Melnikov, Petriello, PRD69(2004)094008

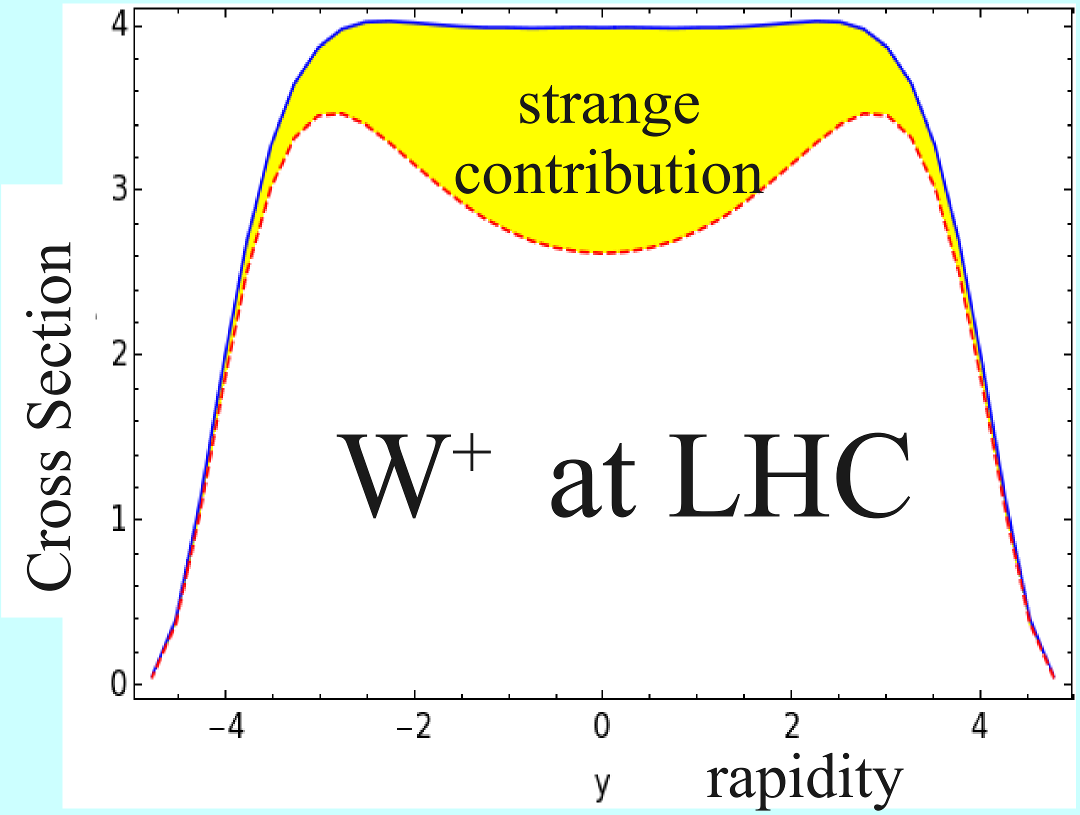
Evolution of Kappa

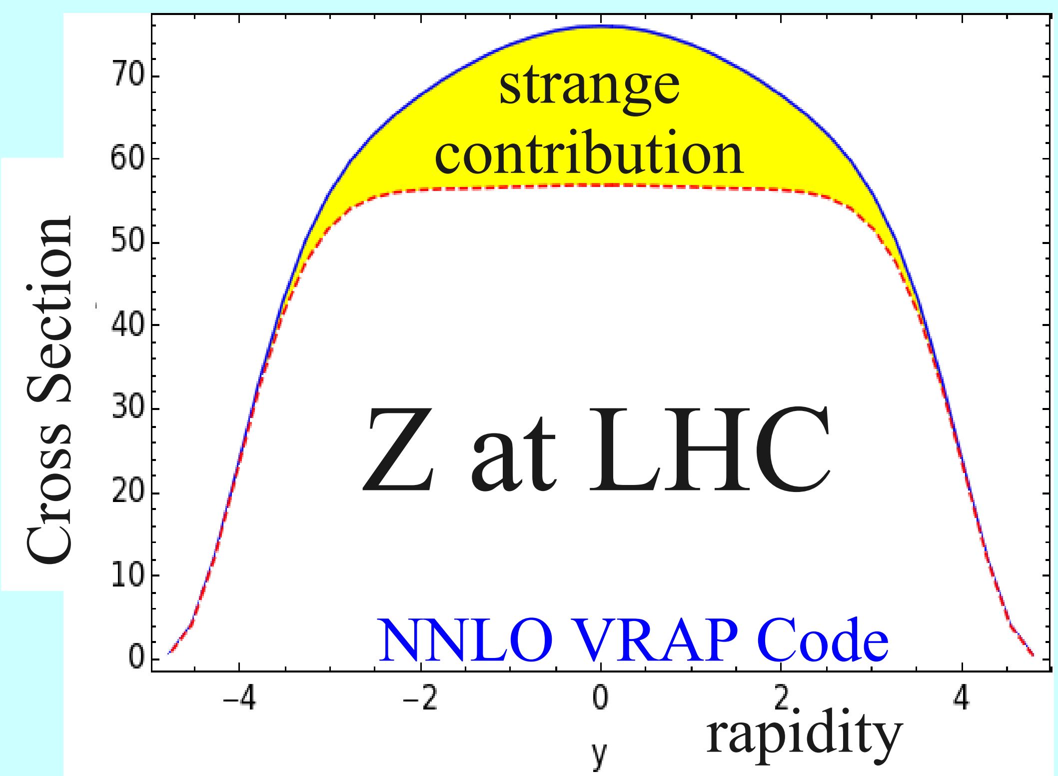
Can W/Z data constrain the strange PDF?

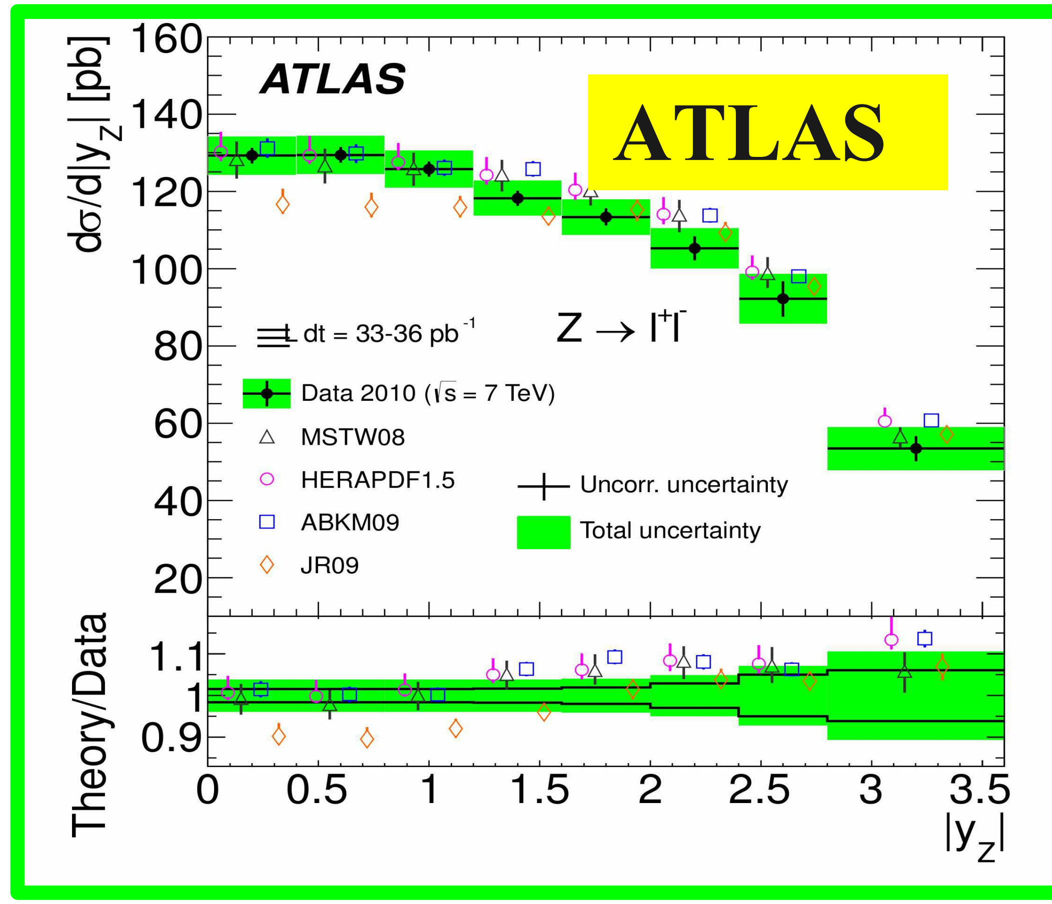
- Higher scales:
  production of s(x) via gluon splitting moves $\kappa(x)$ to the SU(3) symmetric limit!
- LHC7 sensitive to x~0.01
- LHC14 sensitive to x~0.005
- Need very precise measurement at Q=80 GeV to constrain strange PDF at Q=1.5 GeV!

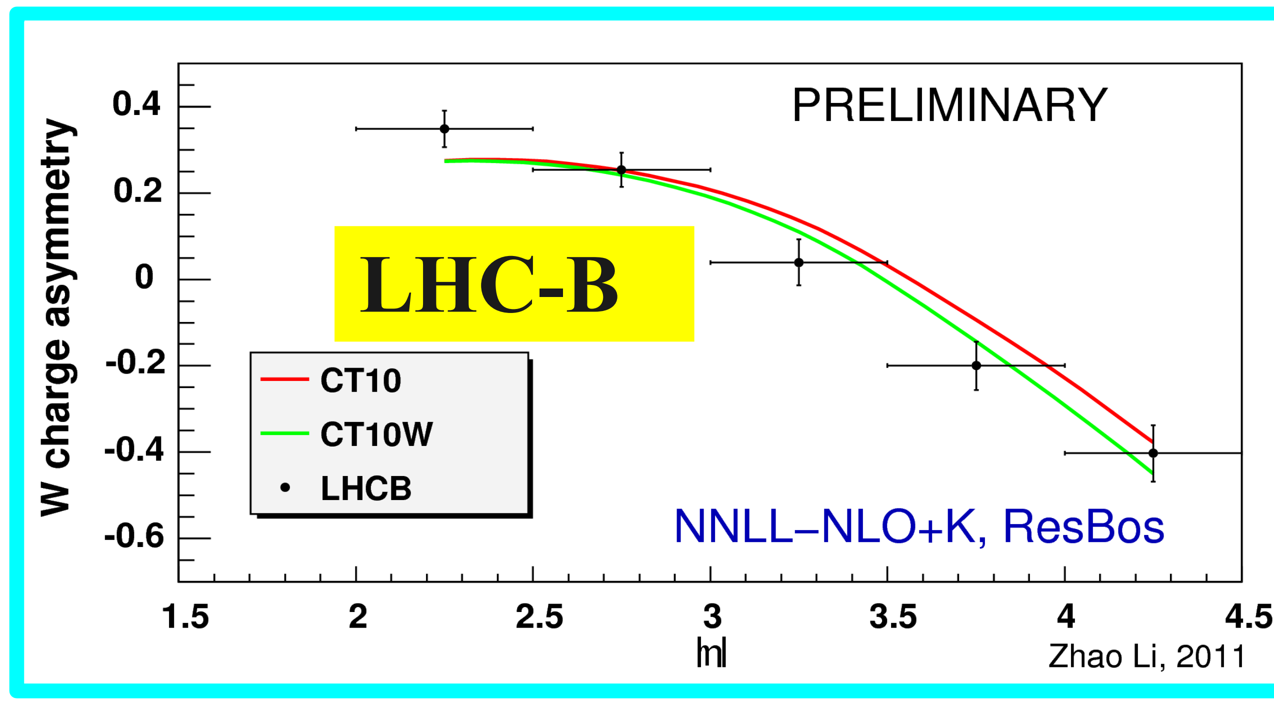


PDF Uncertainties ⇒ S(x) PDF ⇔ W/Z at LHC









NNLO VRAP Code
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

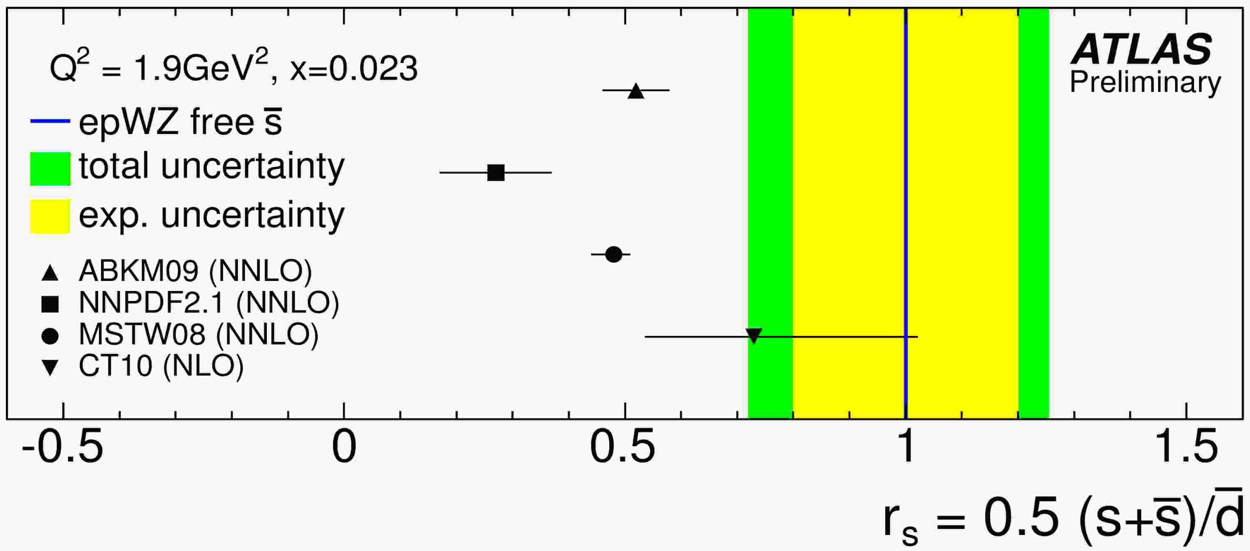
Kusina, Stavreva, Berge, Olness,
Schienbein, Kovarik, Jezo, Yu, Park
Phys.Rev. D85 (2012) 094028

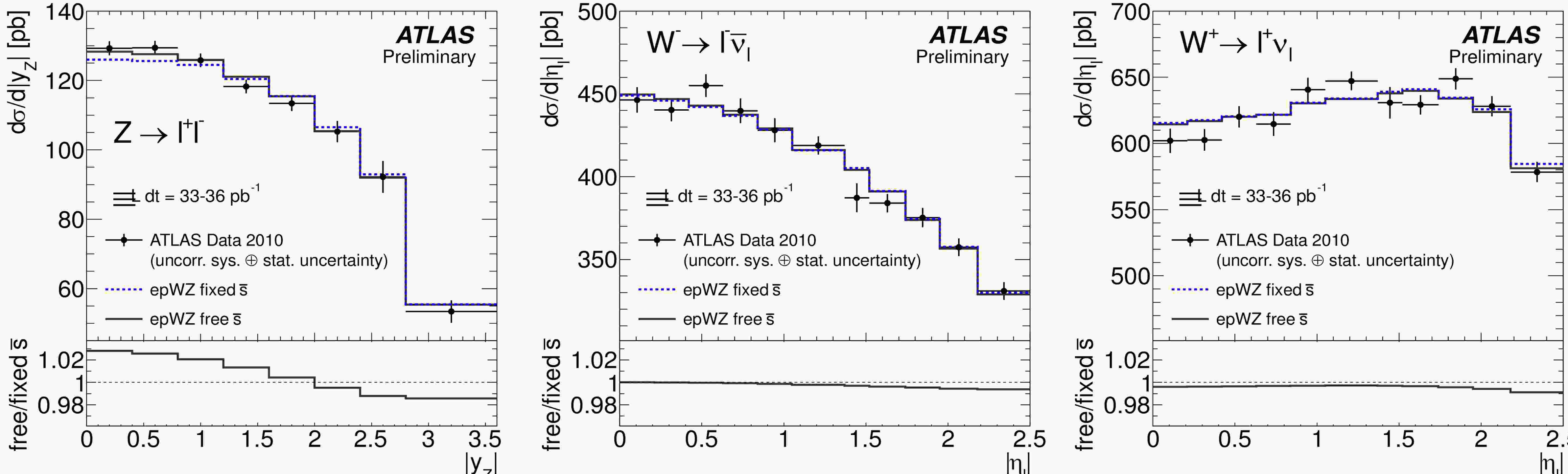
y distribution shape can constrain s(x) PDF

W, Z data sensitivity to strange sea

- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$
- Fit with free strange sea gives no supression

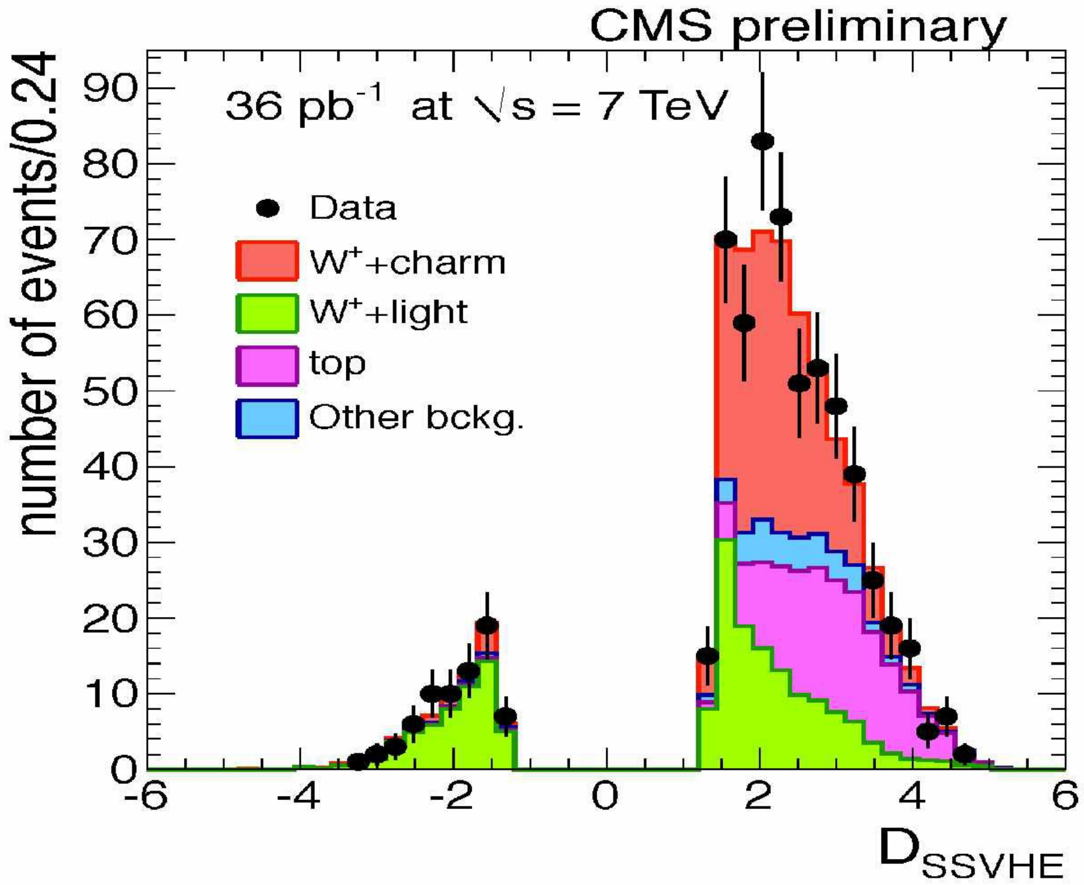
$$r_s = 1.00 \pm 0.20_{\mathrm{exp}}\ {}^{+0.16}_{-0.20}\ {}_{\mathrm{sys}}$$

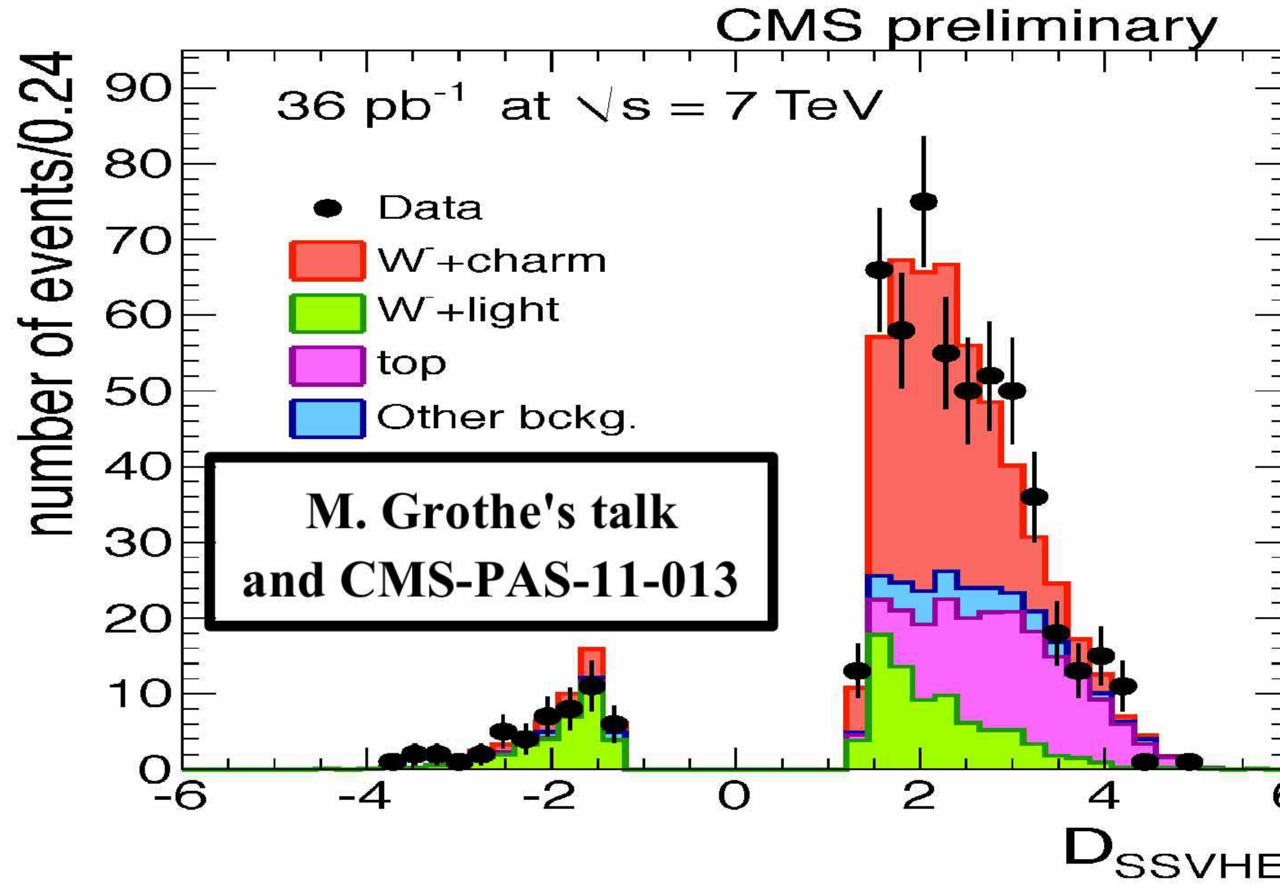




ATLAS-STDM-2011-43 → PRL

First LHC results on W+charm (CMS)





- Sensitive to strange quark PDFs (process dominated by s+g → W + charm):
  - PDF uncertainties from the second quark generation are a potential source of uncertainty for the W mass measurement at the LHC
  - Data-driven control of light-quark and top backgrounds
  - Enormous margin for improvement (only 2010 statistics used), new method (secondary vertex tagging), complementary to the one employed until now at Tevatron (semileptonic charm decay tagging):

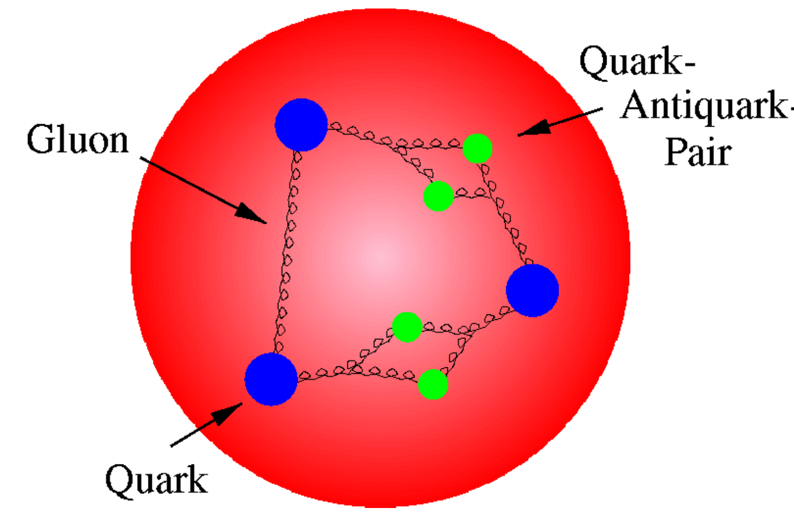
$$\underline{For\ \ p_T^{jet} > 20\ \ GeV, |\eta^{jet}| < 2.1:}$$

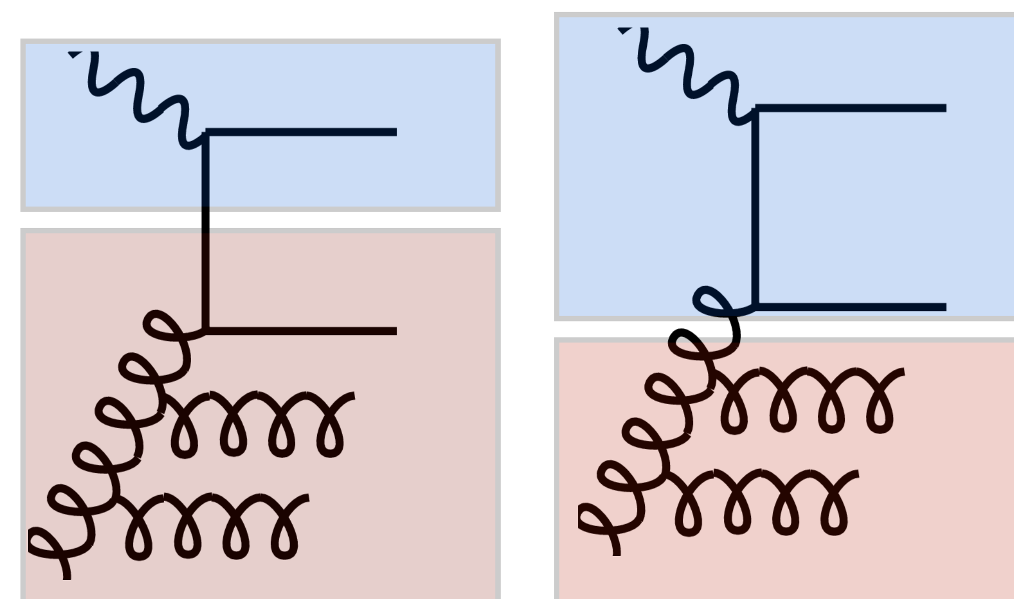
$$\frac{\sigma(W^+ + charm)}{\sigma(W^- + charm)} = 0.92 \pm 0.19(stat.) \pm 0.04(syst.); \quad \frac{\sigma(W + charm)}{\sigma(W + jets)} = 0.142 \pm 0.015(stat.) \pm 0.024(syst.)$$

Charm in the nucleon

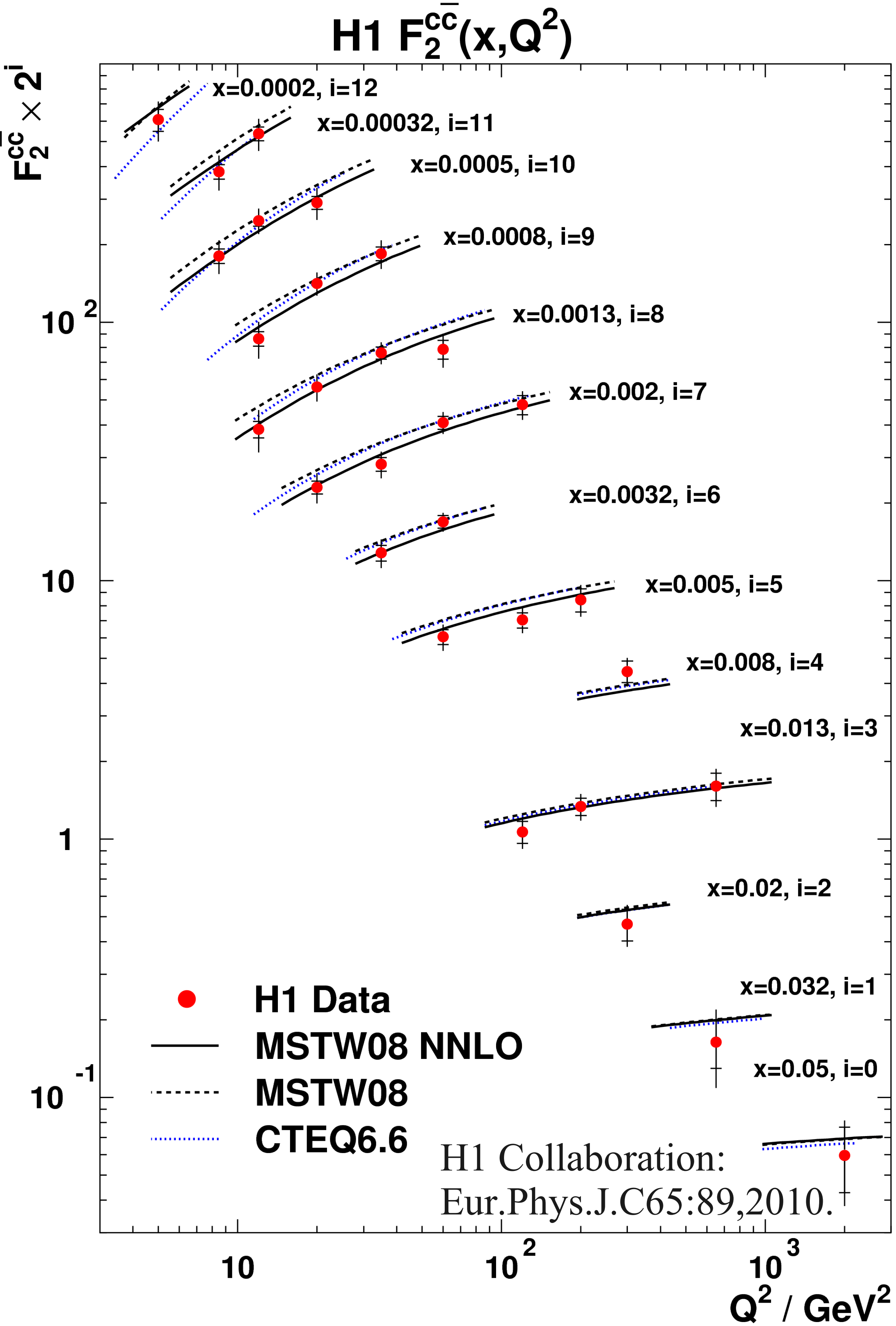
Is there charm in the nucleon?

- Standard approach: Charm entirely perturbative
- Heavy Flavour Schemes
  - FFNS: charm not in the proton
    keep logs(Q/m) in fixed order
  - VFNS: charm PDF in the proton
    resum logs(Q/m)
- Different Heavy Flavour Schemes = different ways to organize the perturbation series
- What is structure? What is interaction?
  Freedom to choose the factorization scale
- However, charm not so much heavier than Lambda_QCD
- There could be a non-perturbative intrinsic charm component
- Important to test the charm PDF experimentally

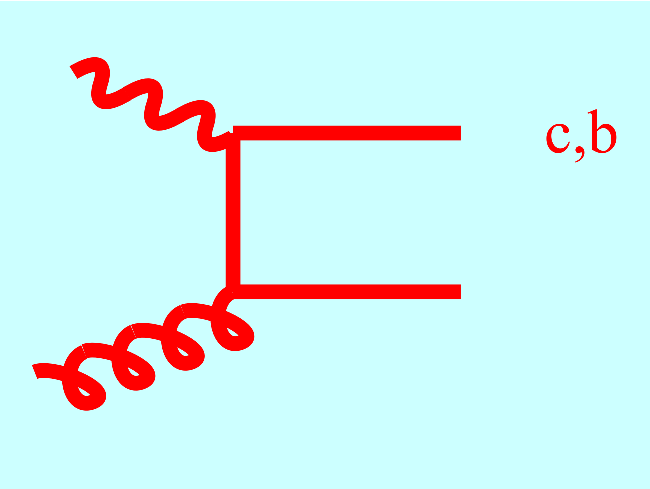


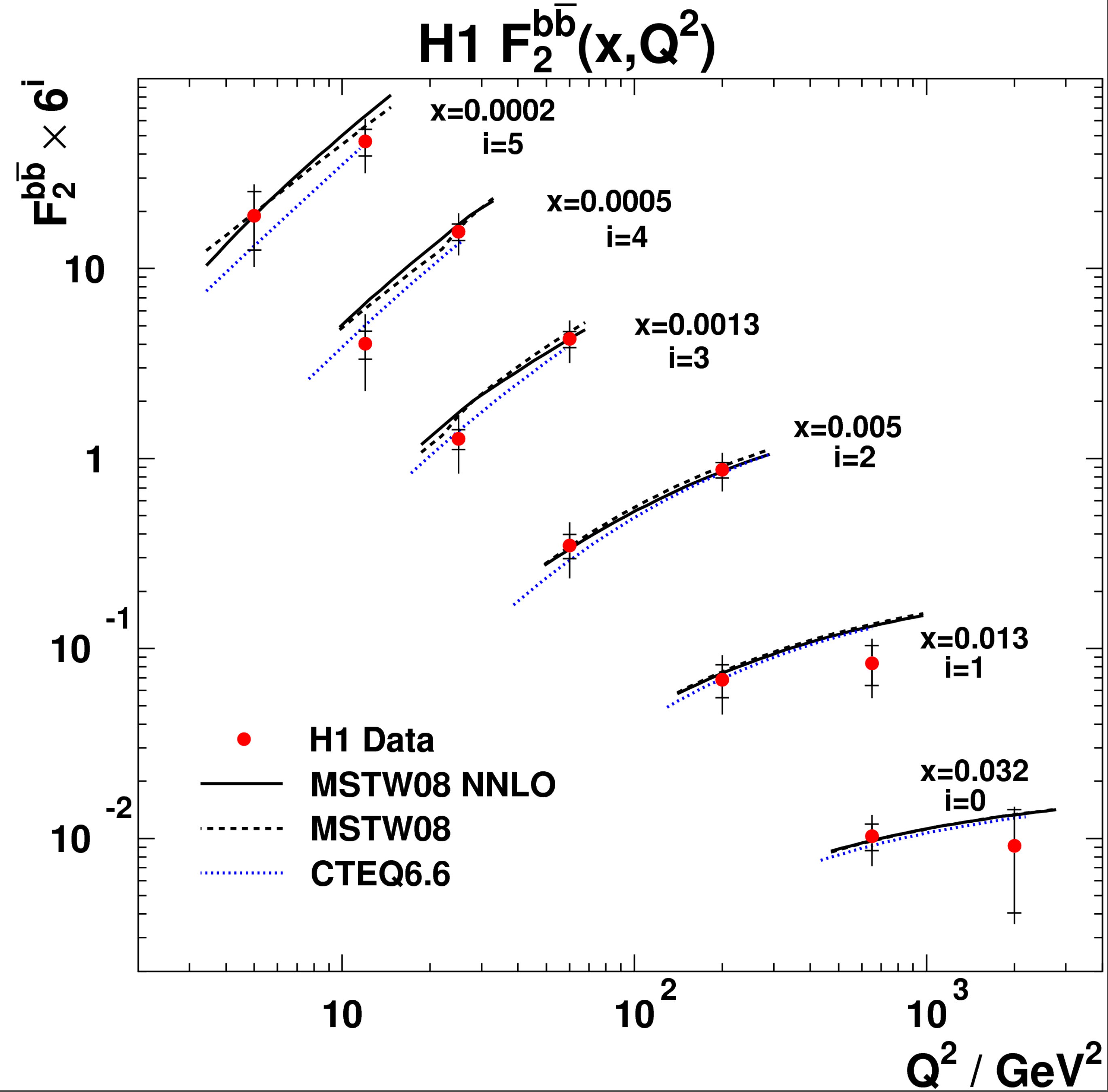


Heavy Flavor Components will play prominent role at LHC



c & b tied to gluon PDFs





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 %

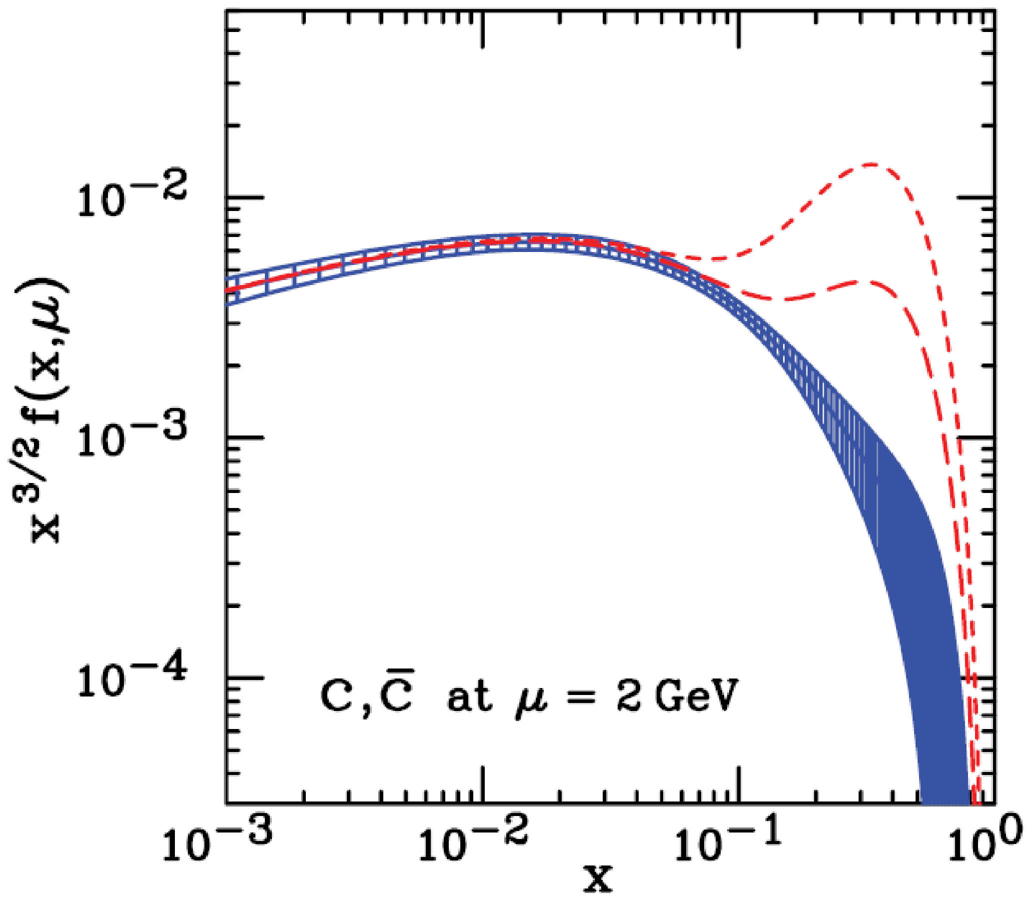
1. Light-cone Fock-space picture (Brodsky et al.), concentrated at large x
   $\langle x \rangle_{c+\bar{c}} = 0.57, 2.0\,\%$
2. Meson-cloud model (Navarra et al.)
   $\langle x \rangle_{c+\bar{c}} = 0.96, 1.8\,\%$
3. Phenomenological model: sea-like charm, broad in x
   $\langle x \rangle_{c+\bar{c}}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

A global fit by CTEQ to extract intrinsic-charm

PHYSICAL REVIEW D 75, 054029 (2007)

Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]

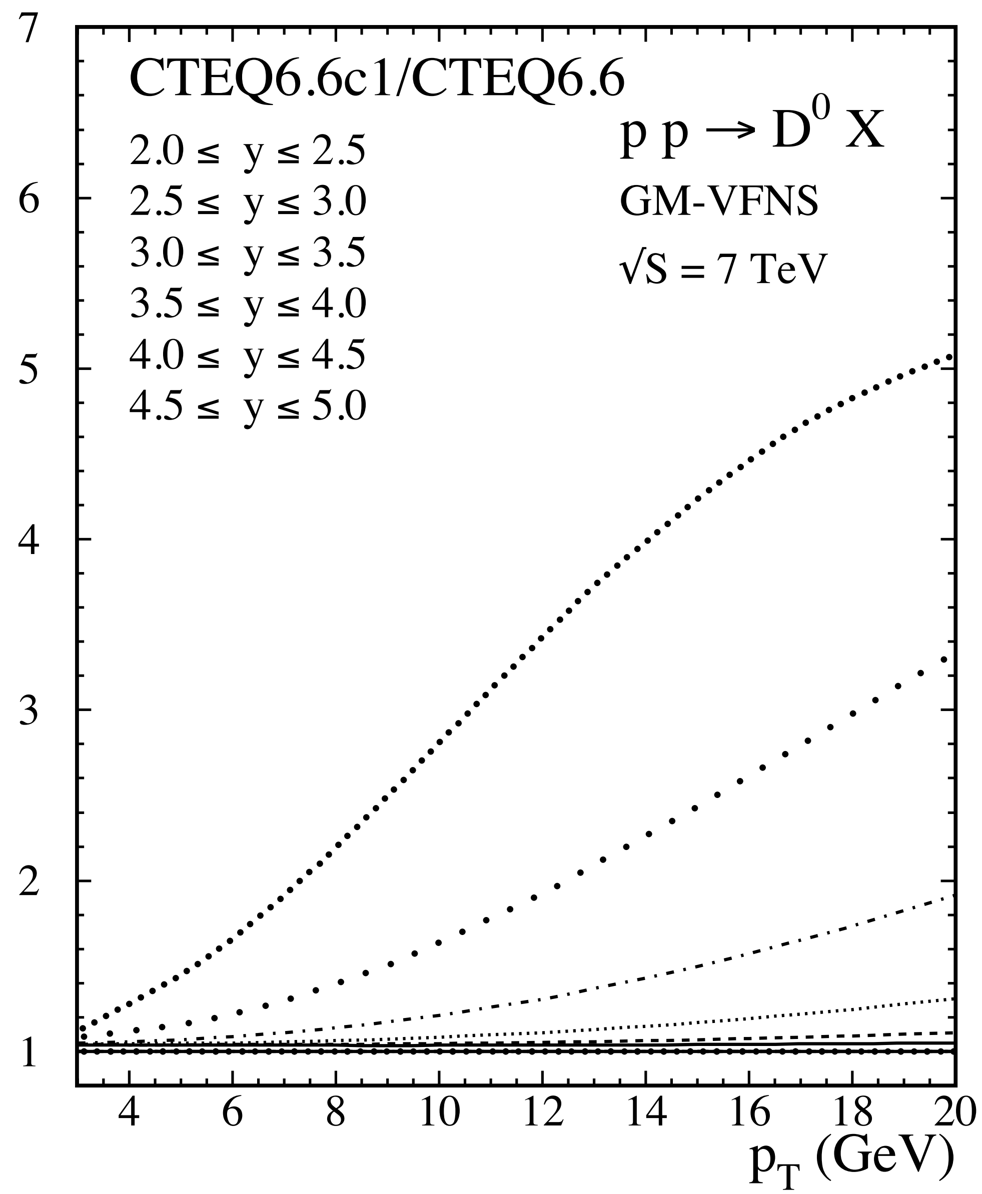


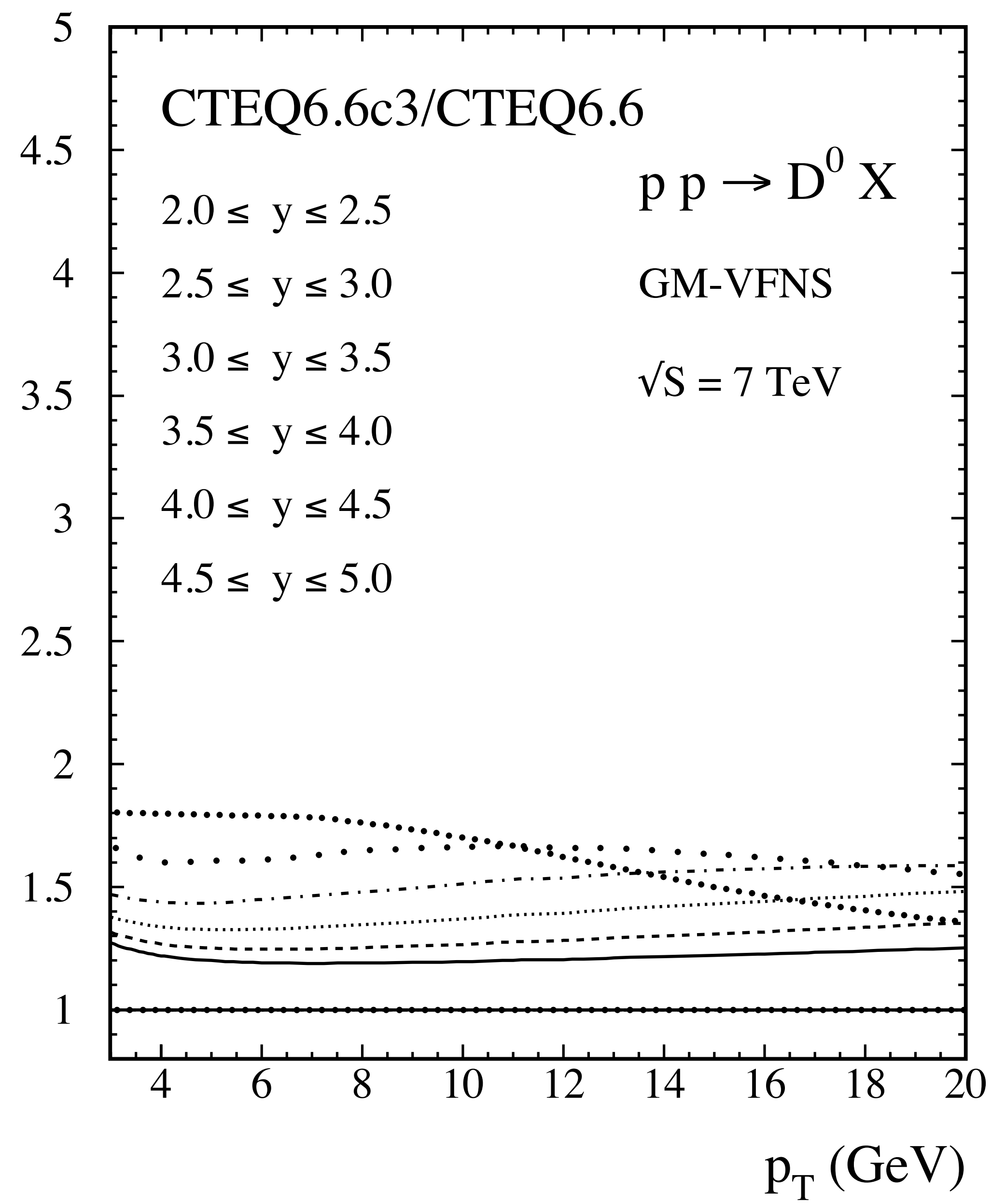
Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)

We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm





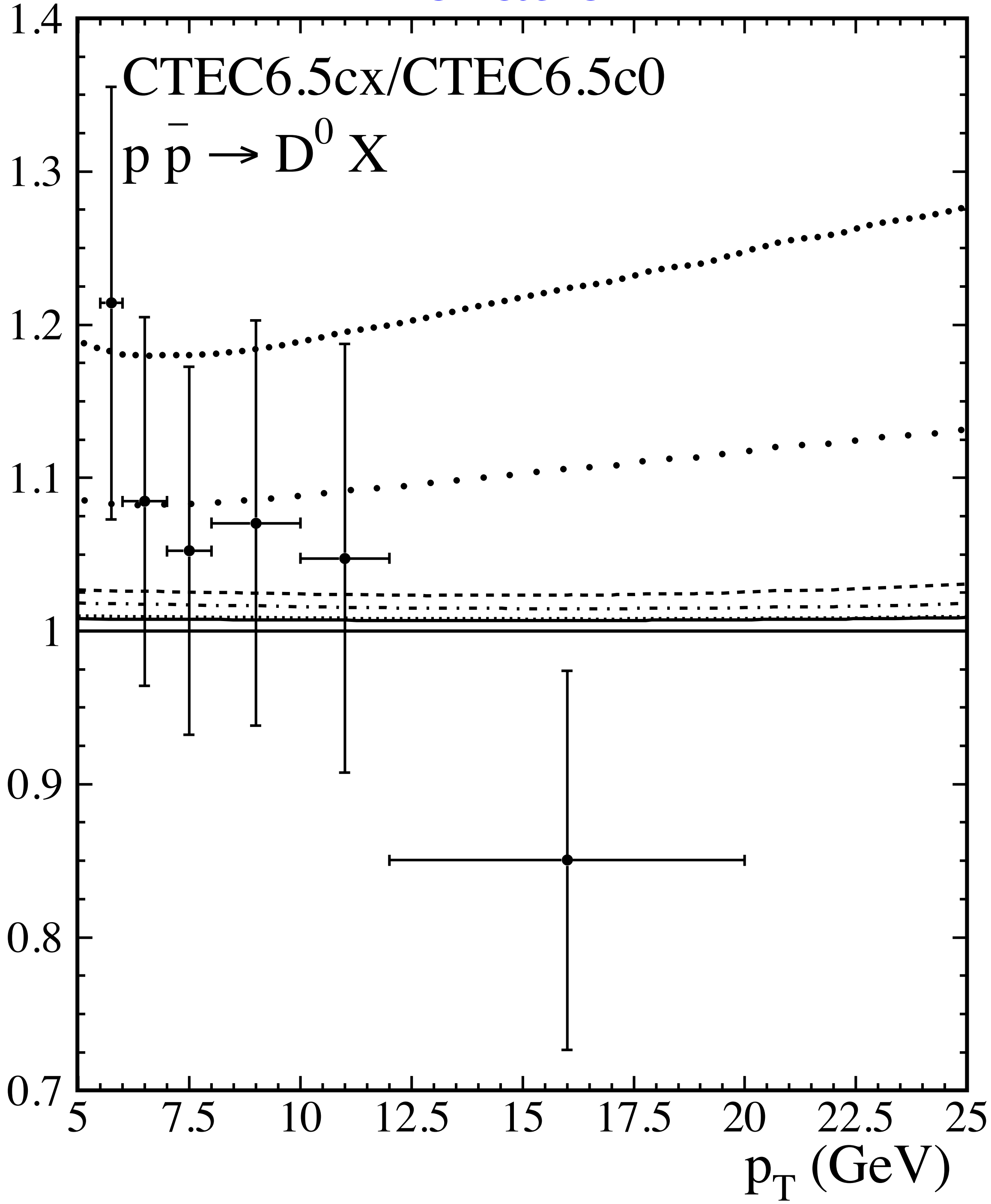
CTEQ6.6 updated:

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

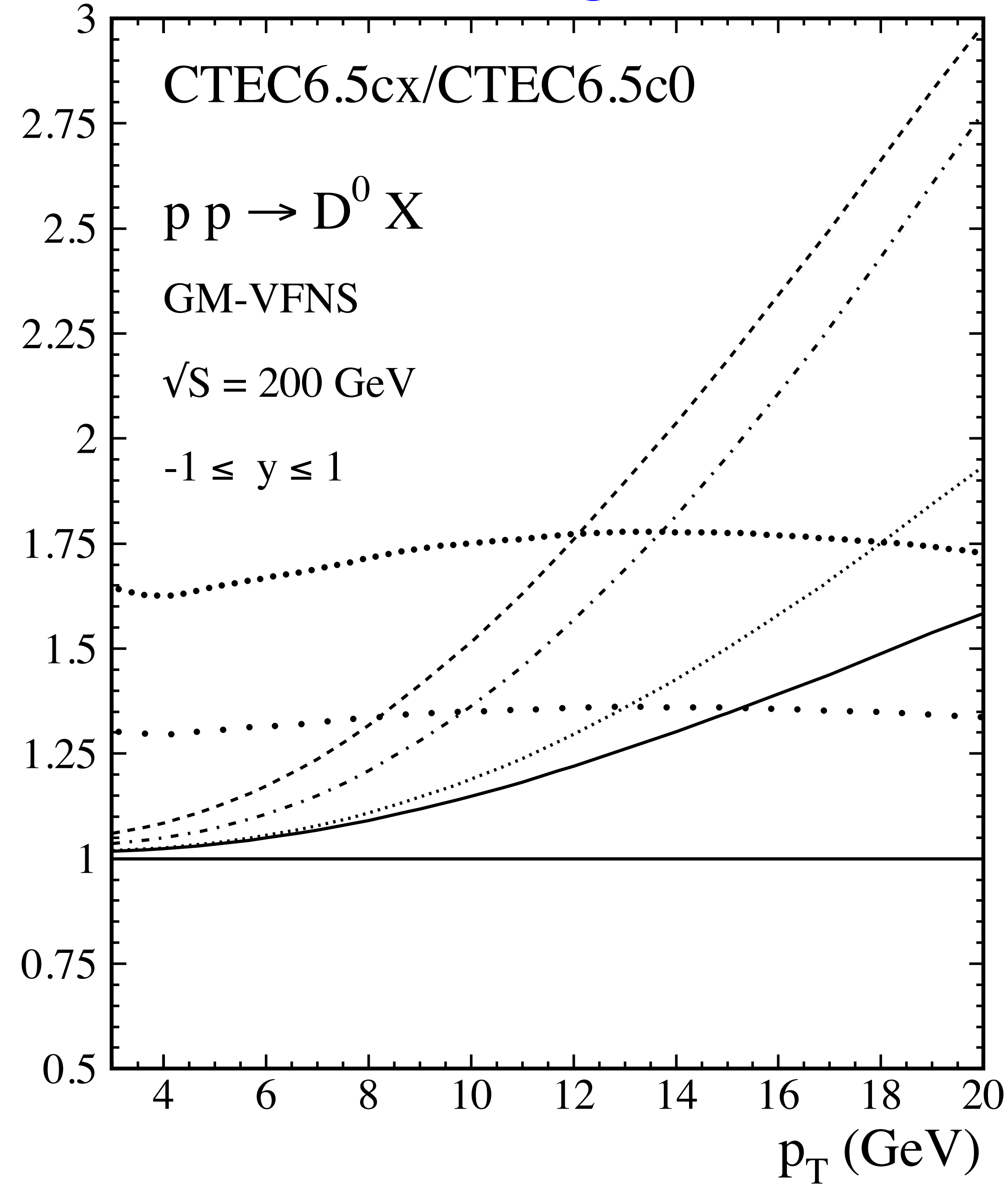
high-strength sea-like charm

➜ large effects expected at large rapidities

Tevatron

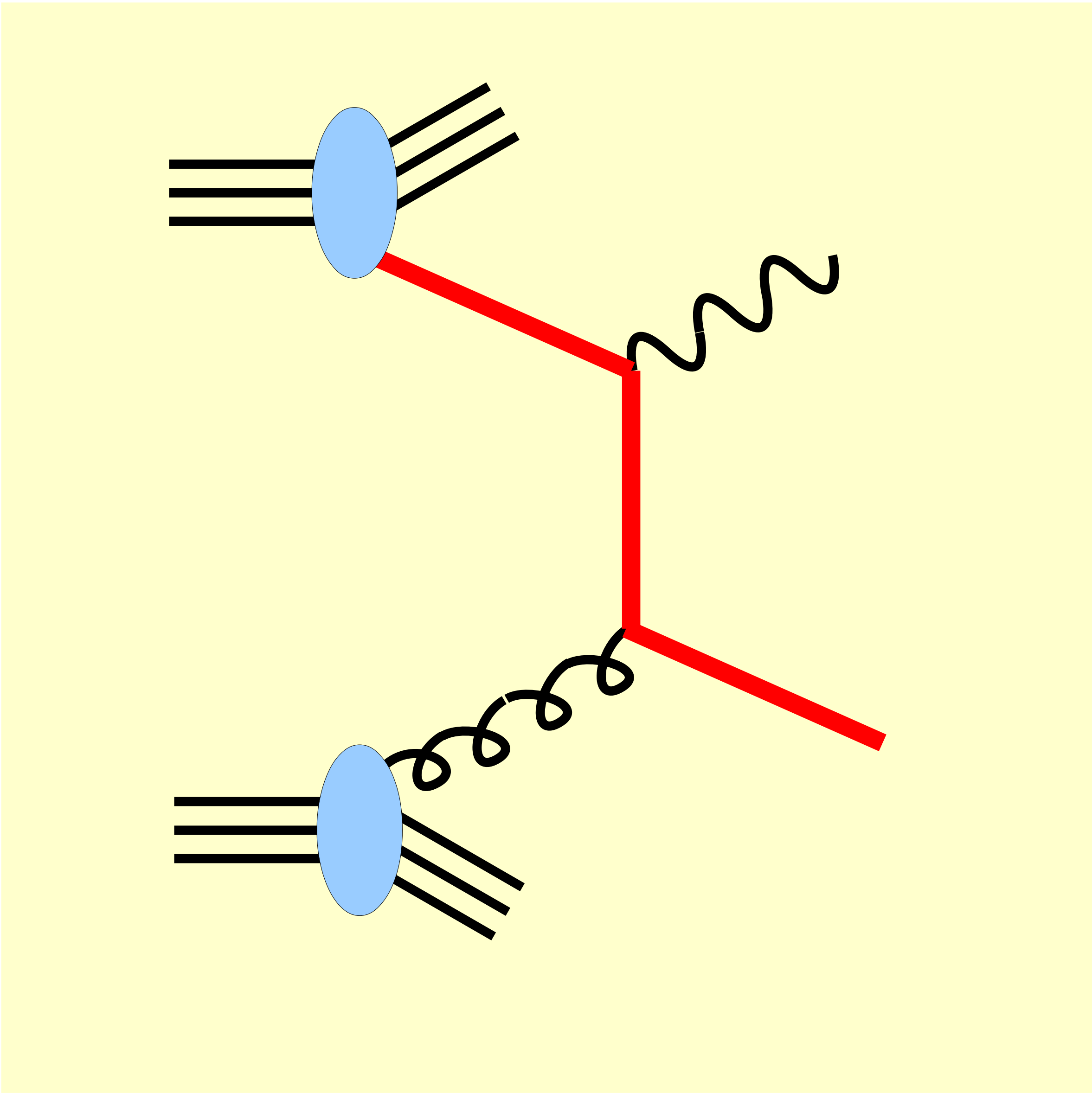


RHIC



PRD79, 2009

How to Access Heavy Flavor Components Directly???



$$c\,g \rightarrow c\,\gamma$$

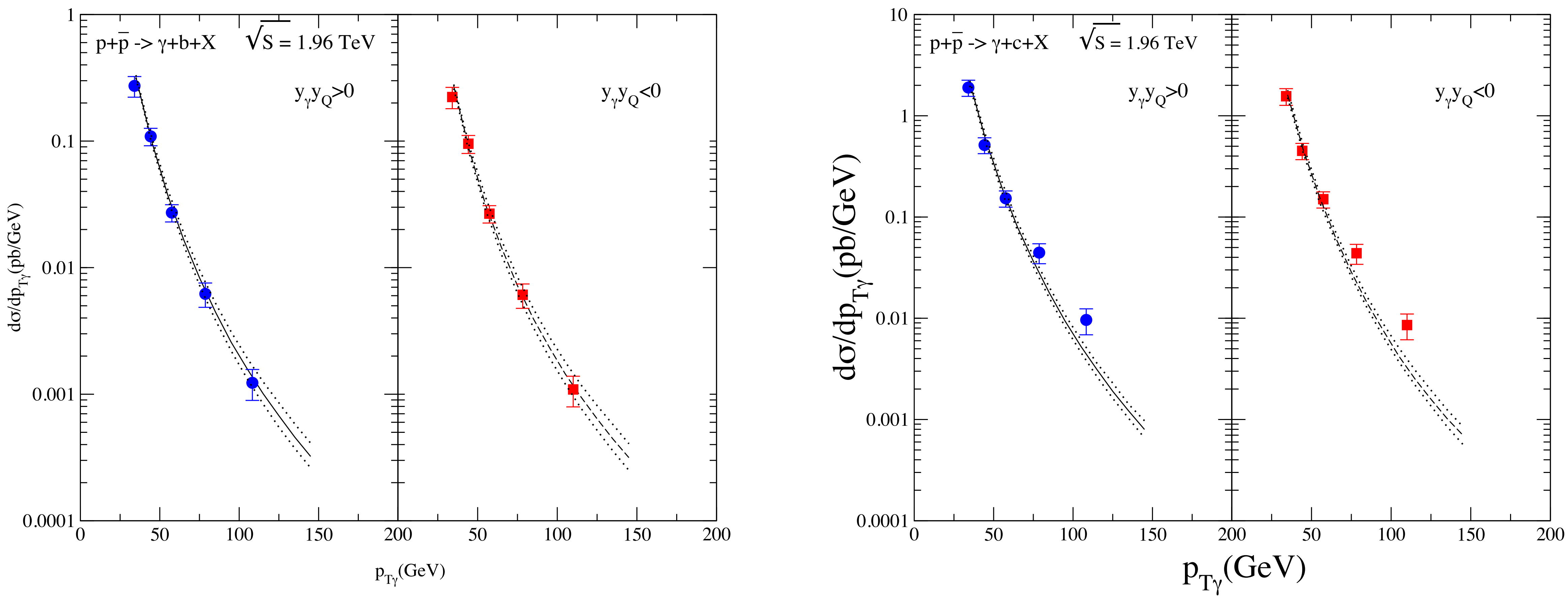
$$b\,g \rightarrow b\,\gamma$$

$$s\,g \rightarrow c\,W$$

$$c\,g \rightarrow b\,W$$

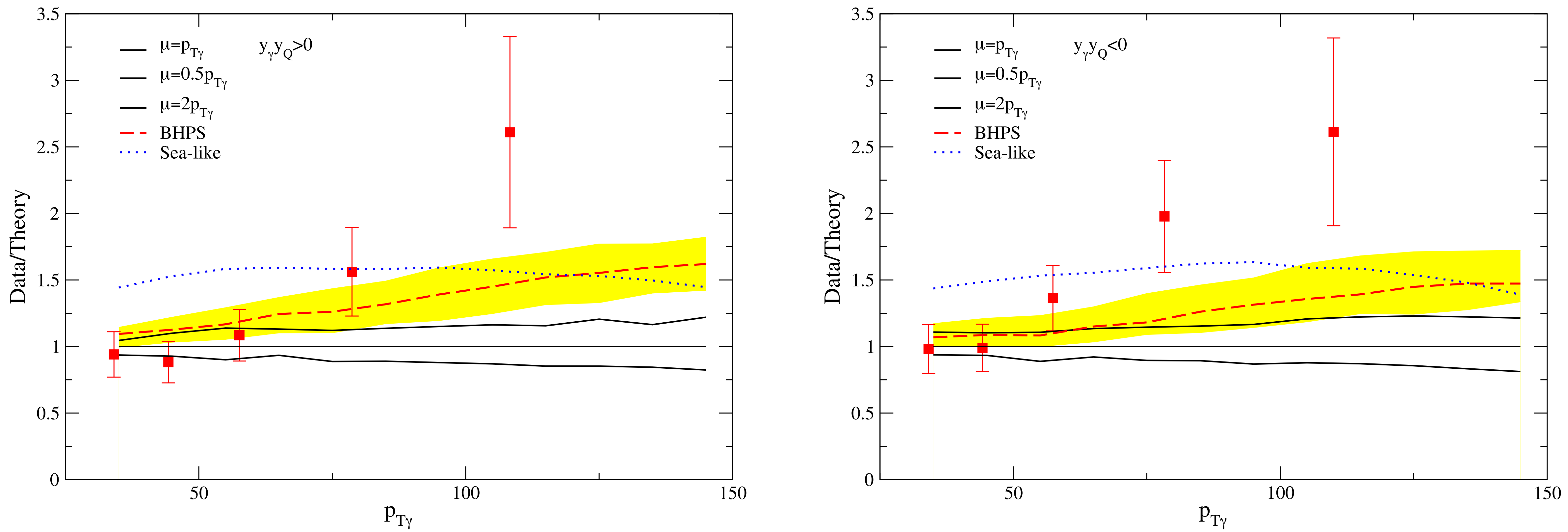
Comparison between theory & data

Measurements by DØ Collaboration [arXiv:0901.0739]



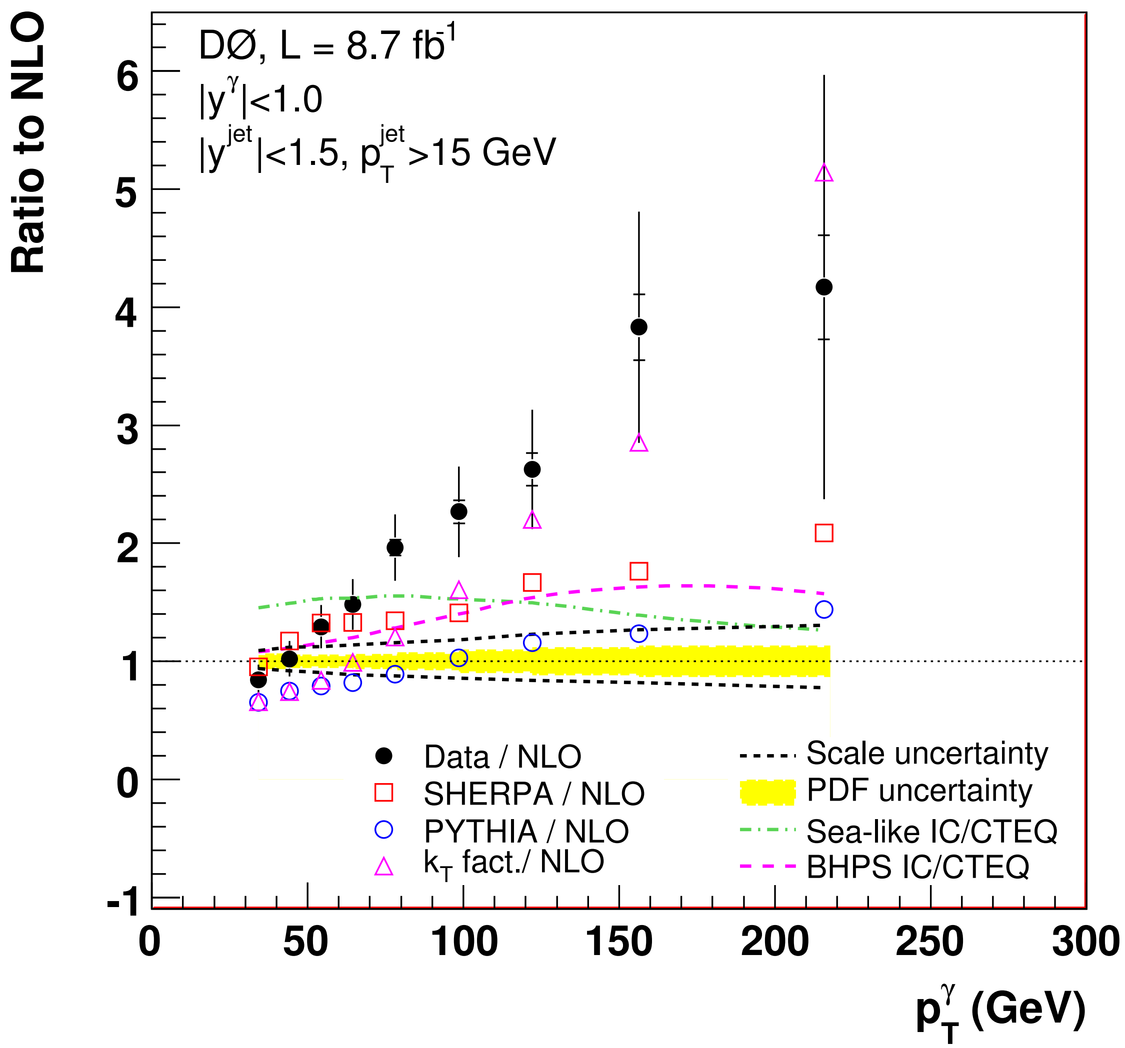
- Really good agreement for $\gamma + b$
- Not so for $\gamma + c$
- Given this: Possible explanation - existence of intrinsic charm rather than higher order corrections

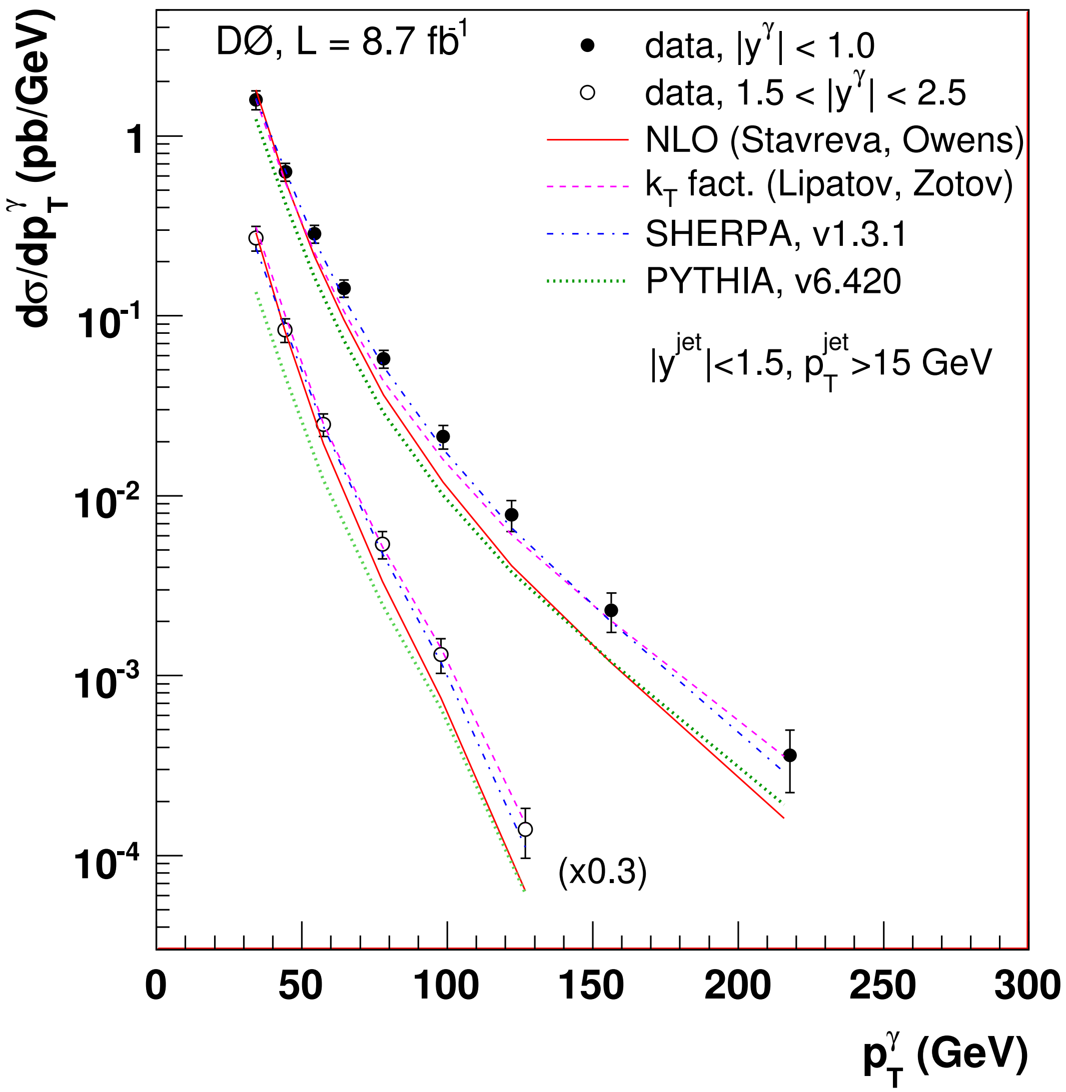
Intrinsic Charm effect on $\gamma + c$



- Sealike - overshoots data at low pT and undershoots at high pT
- BHPS - the cross section grows at large pT, but still below data
- Result inconclusive -
  - New Measurements - Tevatron - CDF & DØ
  - Test at pp Colliders - RHIC & LHC

new results DØ



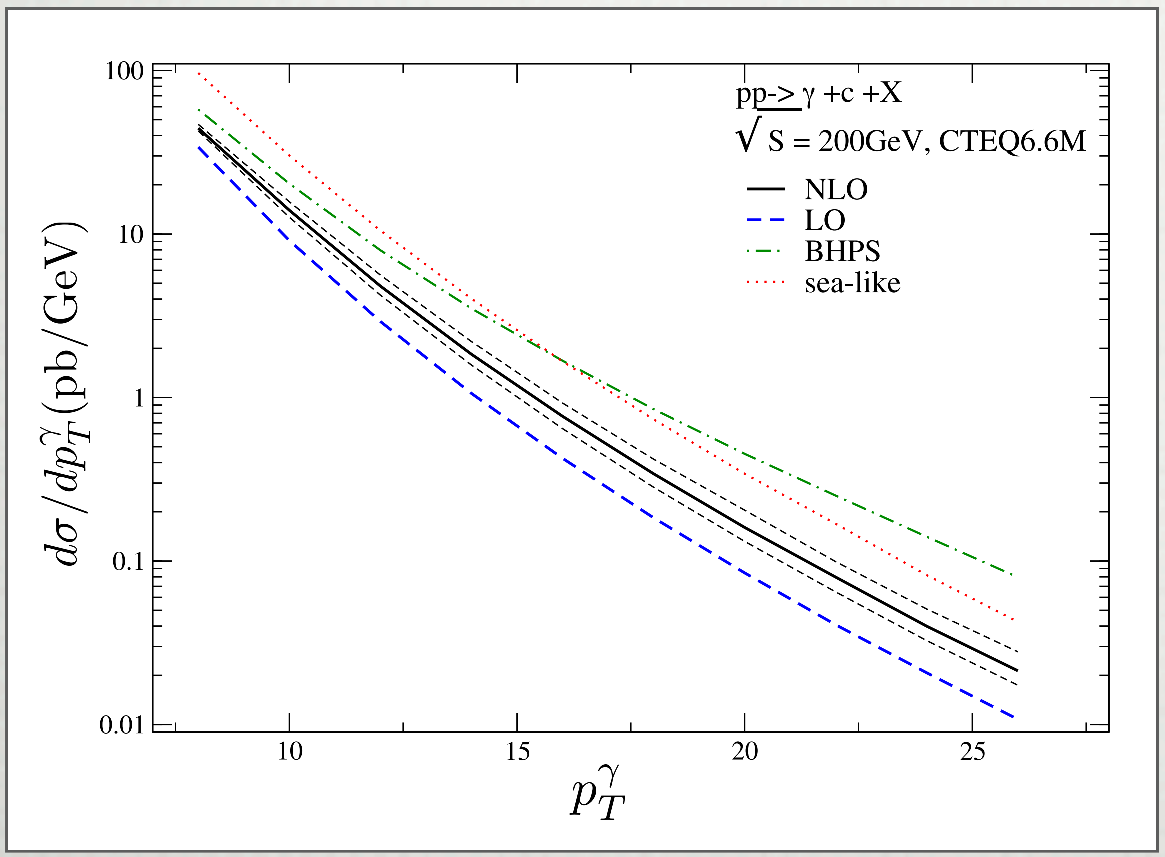


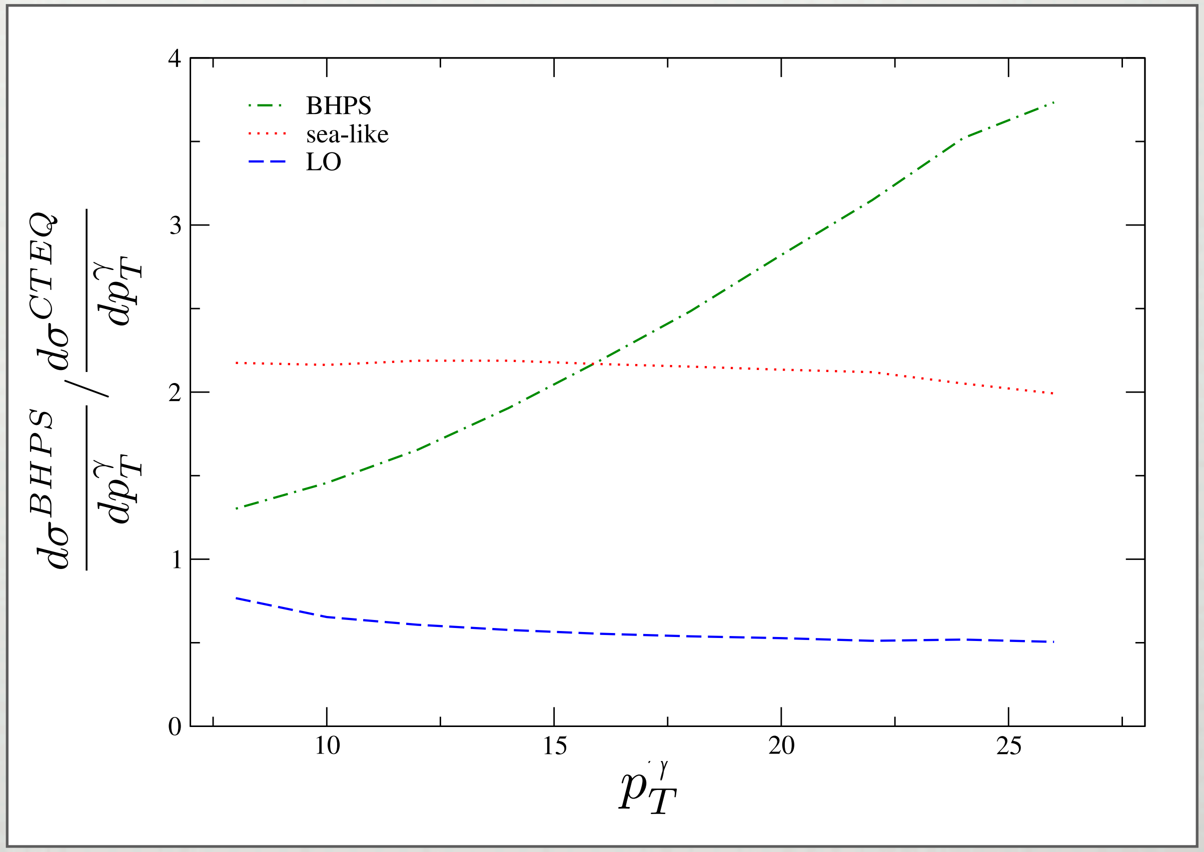
- $\gamma + c$ - left - arXiv:1210.5033
- $\gamma + b$ - right - arXiv:1203.5865
- Even higher discrepancy - now consider all leading jets

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

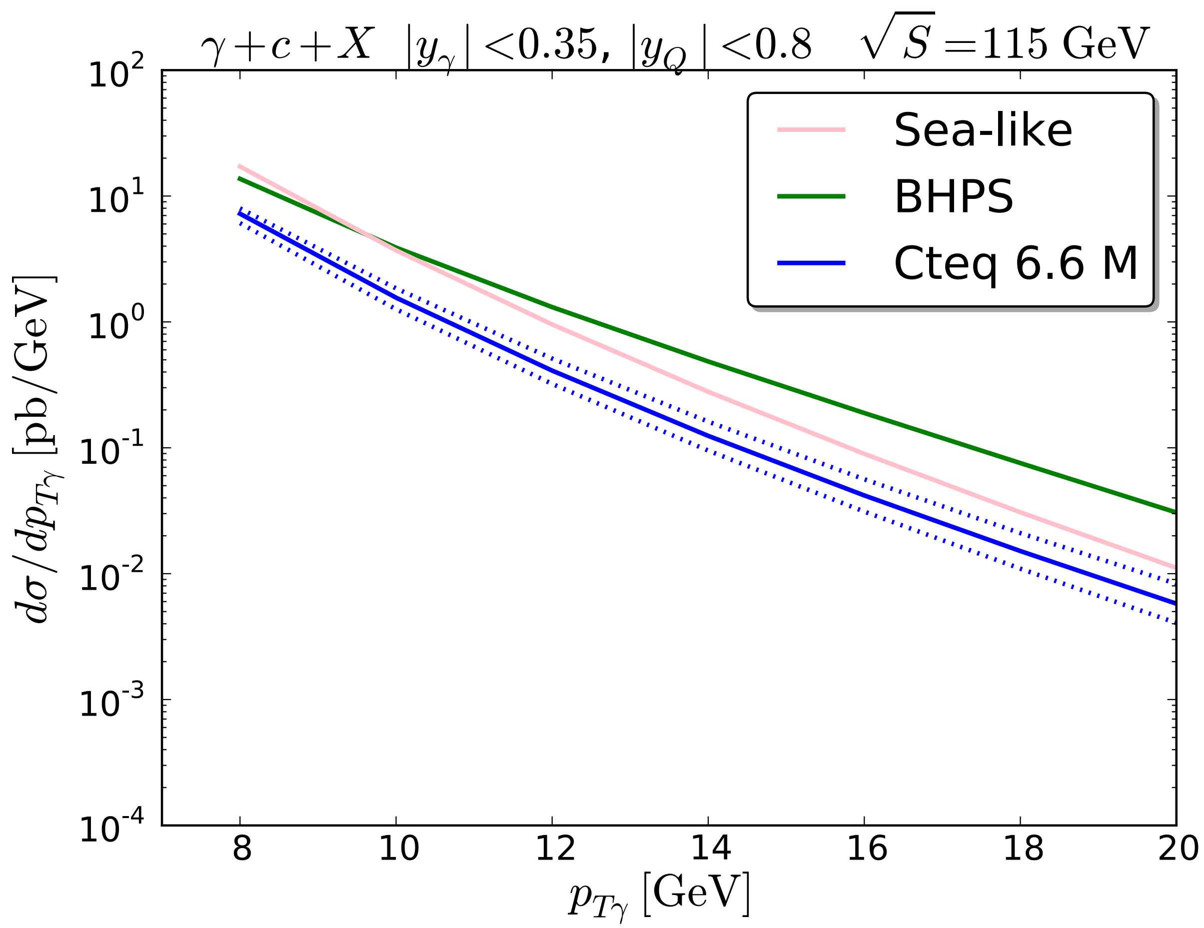
	p_T min	Rapidity	Isolation
Photon	7 GeV	$\|y_\gamma\|<0.35$	R=0.5, p_T = 0.7GeV
Heavy Jet	5 GeV	$\|y_Q\|<0.8$	---

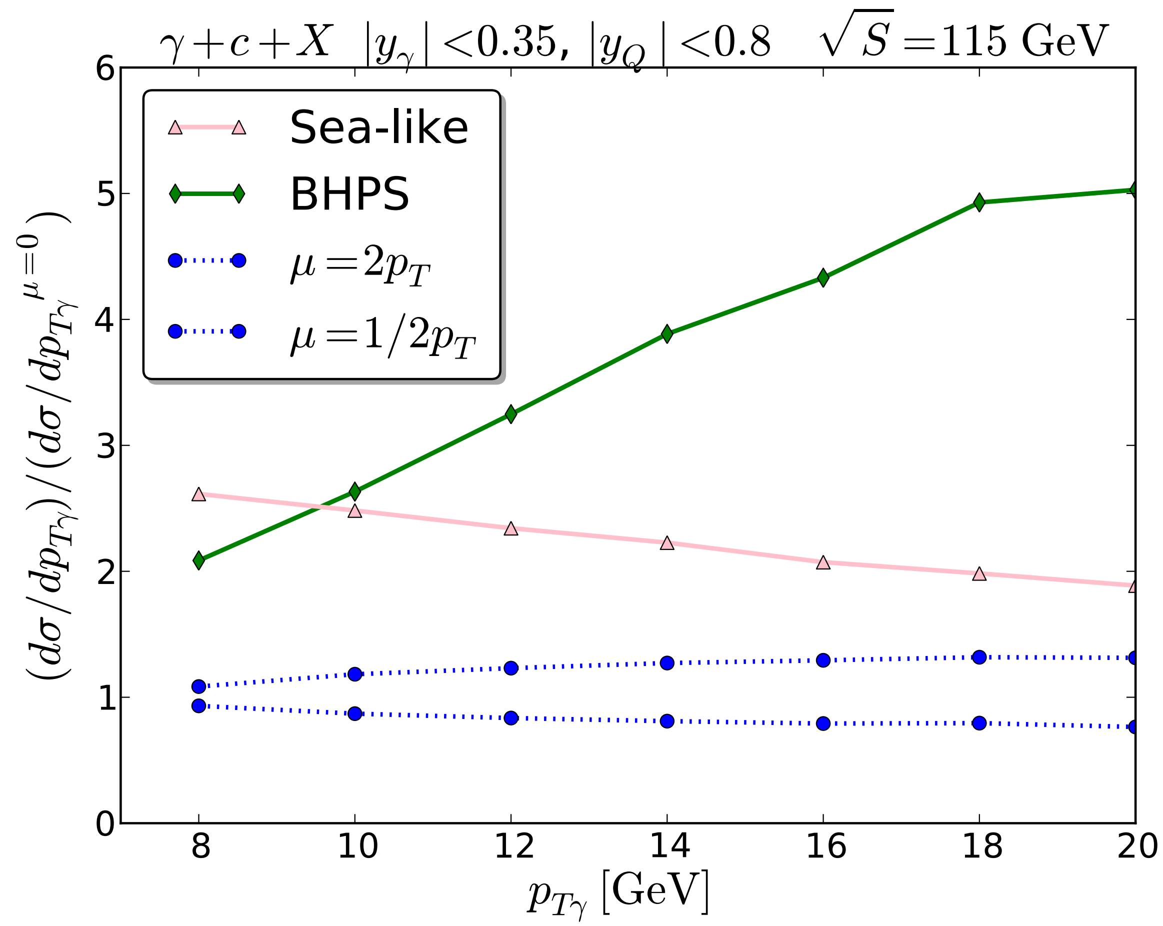




Probing IC with γ+Q at AFTER

See talk by T. Stavreva

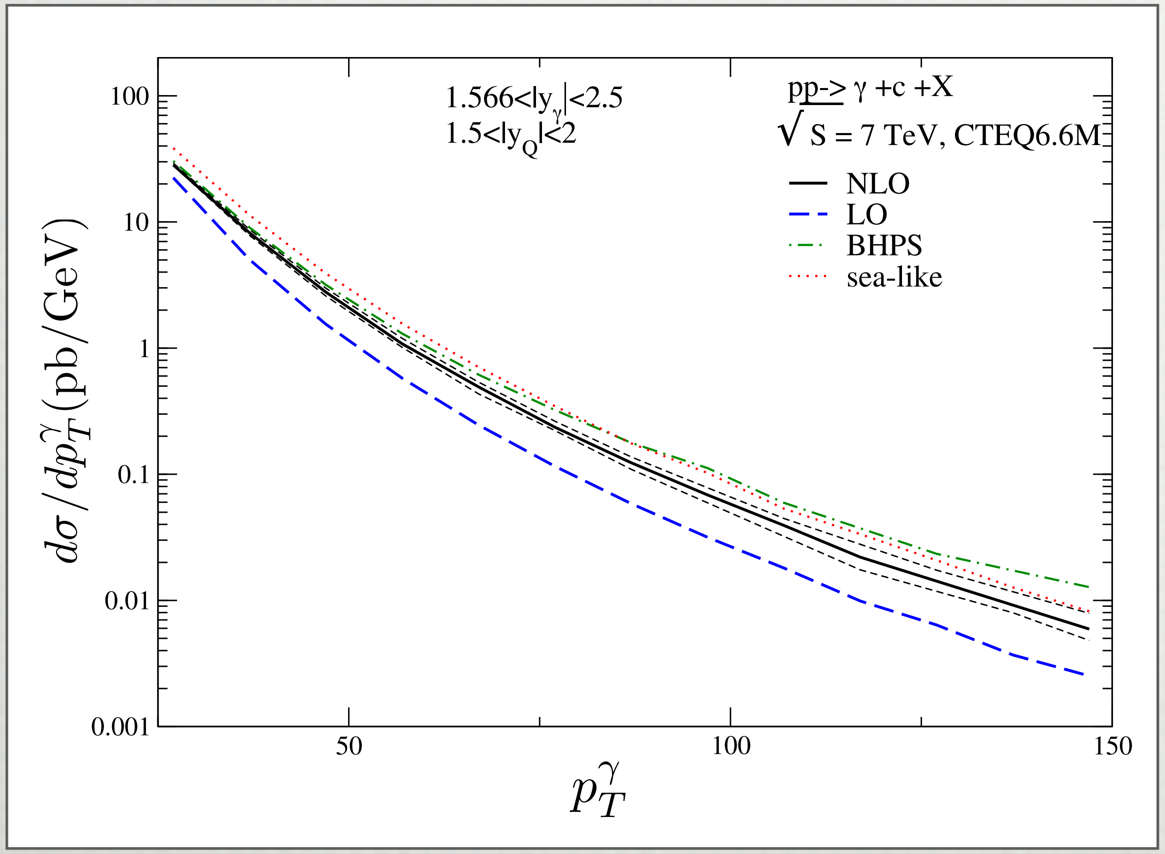


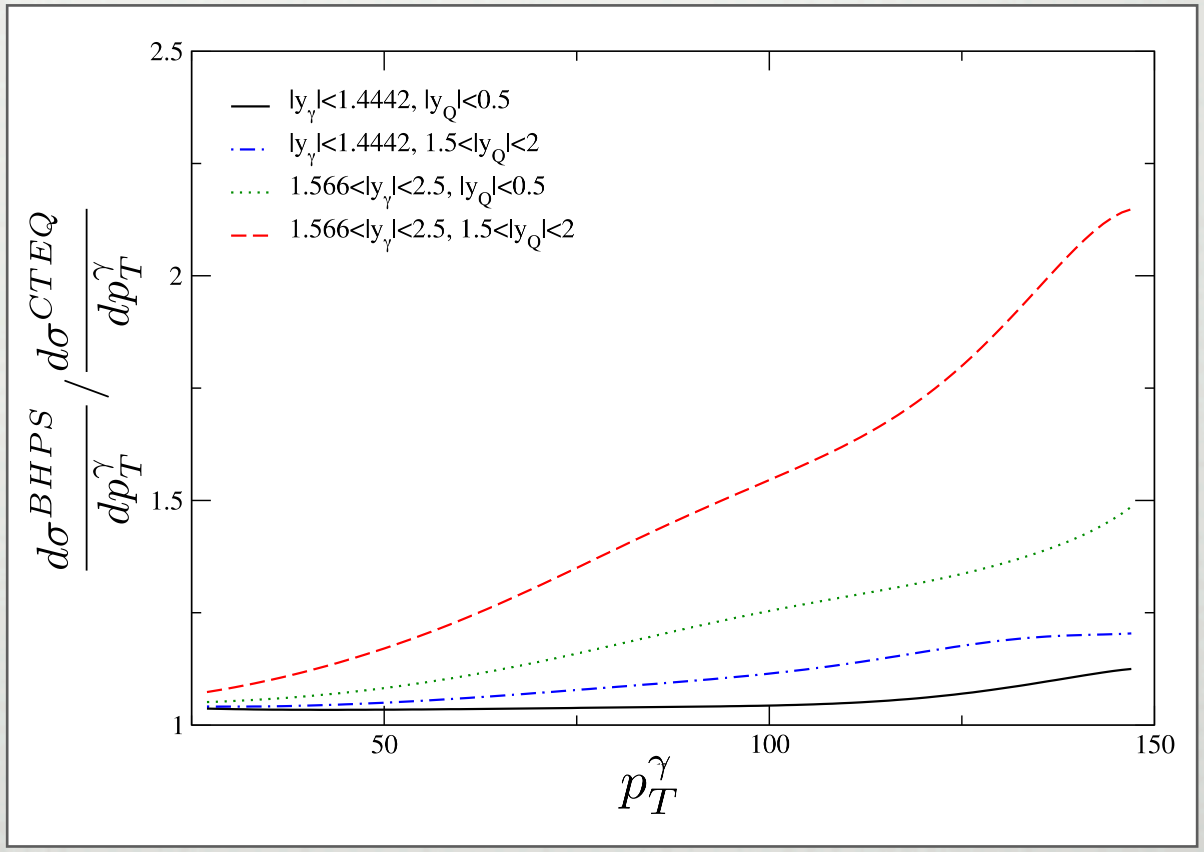


LHC-CMS

- 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 = 4.2GeV
		$1.56<\|y_\gamma\|<2.5$	
Heavy Jet	18 GeV	$\|y_Q\|<2.0$	---



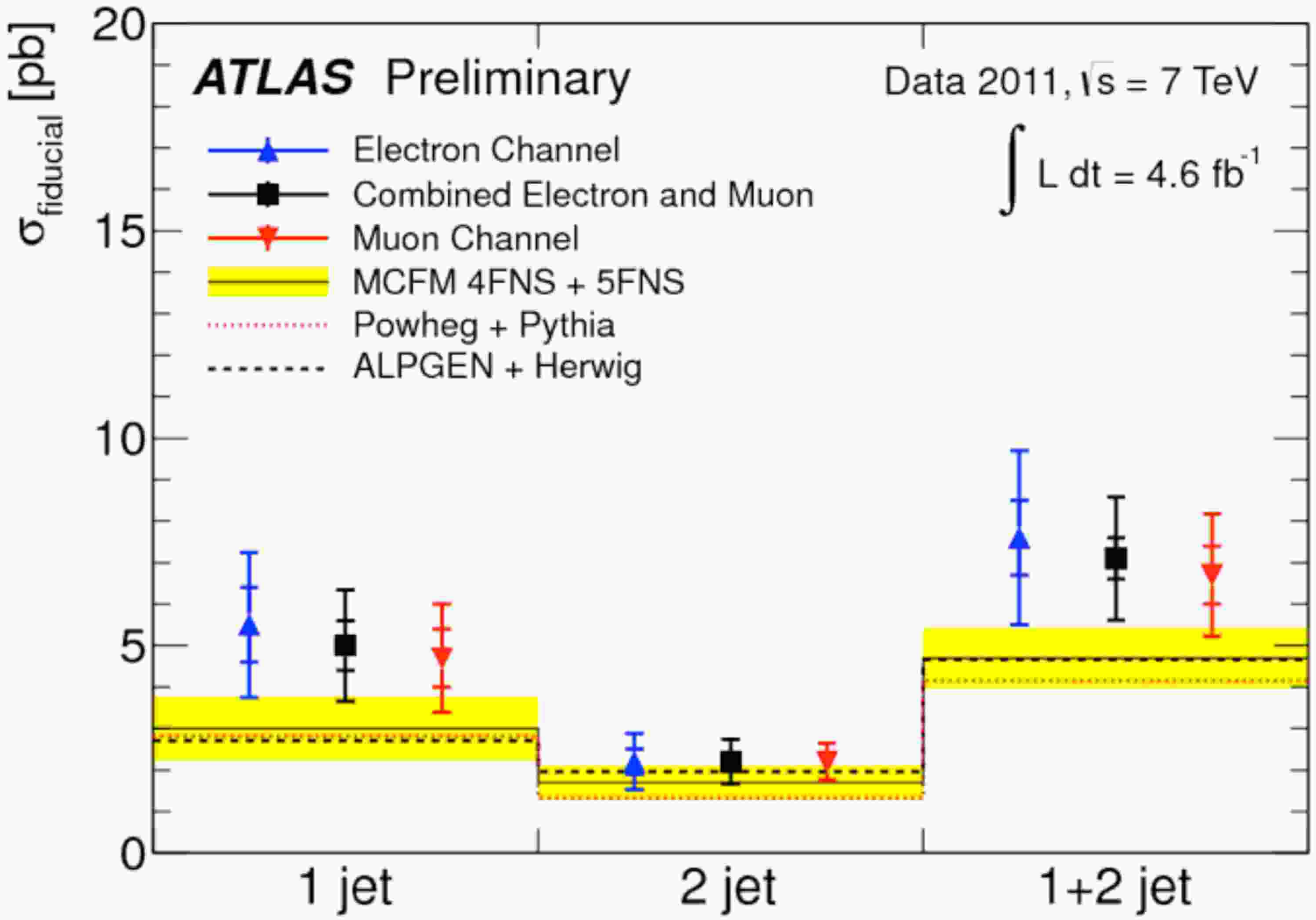


[CMS notes: CMS PAS EGM-10-005, CMS PAS BPH-10-009]

New D0 and ATLAS Wb results

- Measurements are dominated by jet energy scale uncertainties (not statistics)

ATLAS - 2011



D0

Measured (electron channel)
1.00 ± 0.04 (stat) ± 0.12 (sys) pb
NLO Calculation (MCFM)
1.28 +0.40-0.33 (theory) pb

From D0, NLO in agreement with measurement

From ATLAS, theory is consistent within 1.5 sigma

Monida Dunford
(Heidelberg U)
Kyoto, November 2012

http://cdsweb.cern.ch/record/1493495

http://arxiv.org/abs/1210.0627

Intrinsic Bottom?

Intrinsic bottom?

- No global analysis of intrinsic bottom exists due to lack of experimental constraints
- Important electro-weak and new physics processes couple to the b-quark PDF
- How can we estimate size of a potential intrinsic bottom component?
- **Observations:**
  - IB evolves with a (standalone) non-singlet evolution equation
  - Adding an IB-PDF does not spoil the other PDFs and sum rules much
  - Possible the IB component! (in preparation)

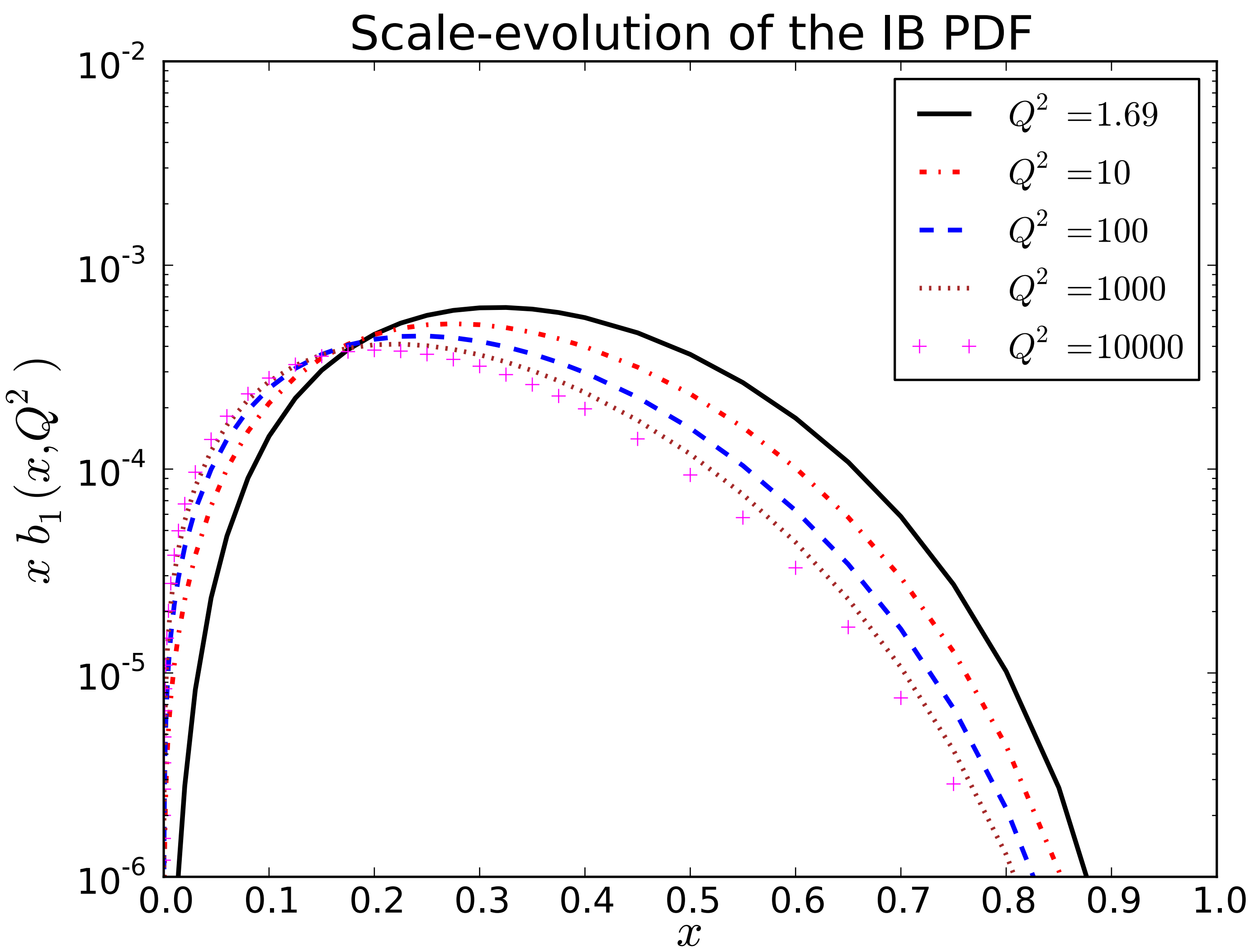
BHPS:

$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]\,.$$

Parametrically:

$$b_1(x, m_c) = \frac{m_c^2}{m_b^2} c_1(x, m_c)$$

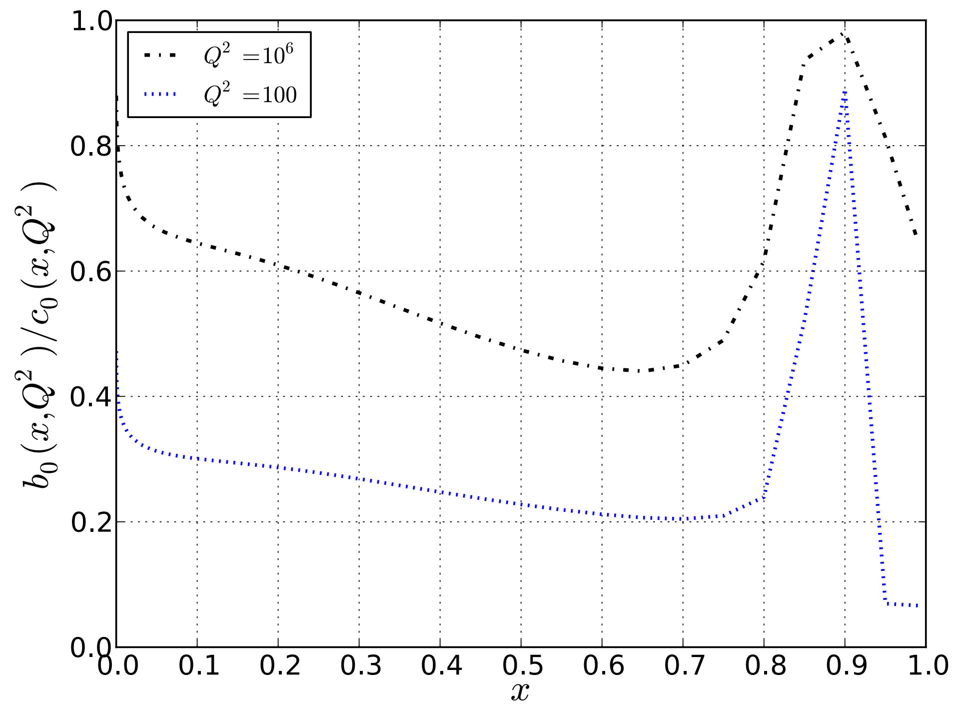
Scale evolution of IB

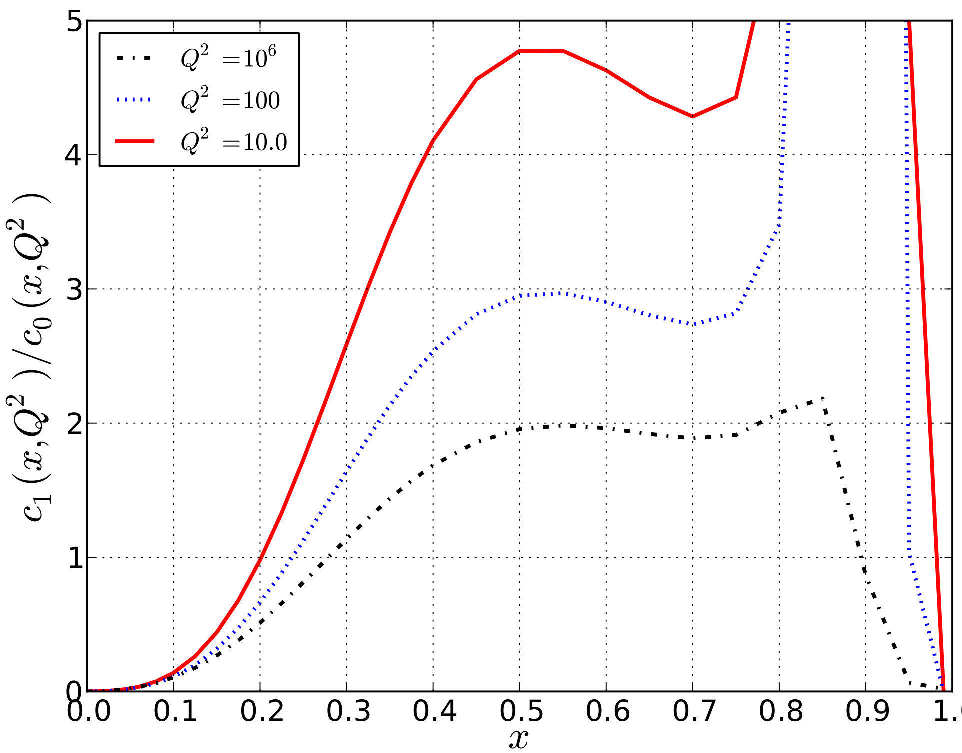


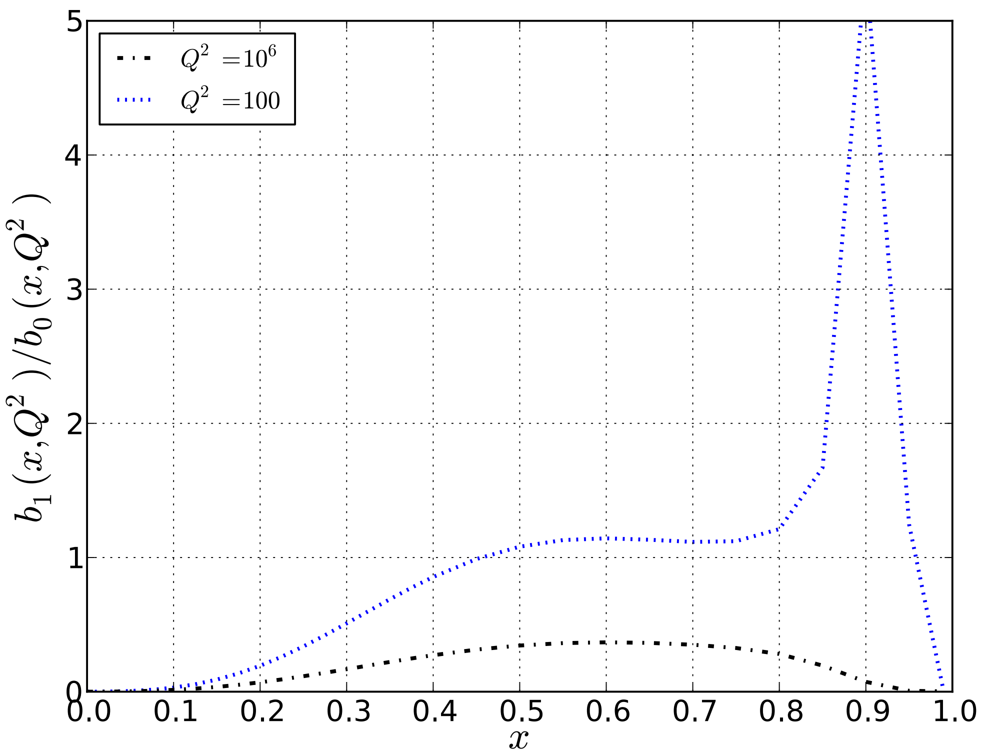
Can add the intrinsic b_1 PDF to the radiatively generated b_0 PDF:
$b(x) = b_0(x) + b_1(x)$

Allows to estimate the effect of IB

IB less important than IC







Conclusions

- nCTEQ nuclear PDFs [soon with uncertainties]
- At LHC, strange and heavy quark PDFs increasingly important
- Discussed experimental constraints on strange PDF, impact on W/Z production
- Discussed observables sensitive to charm PDF
- How to model intrinsic bottom

Merci!

Evolution Equations

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q\,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q\,,$$
$$\dot{Q} = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q\,.$$

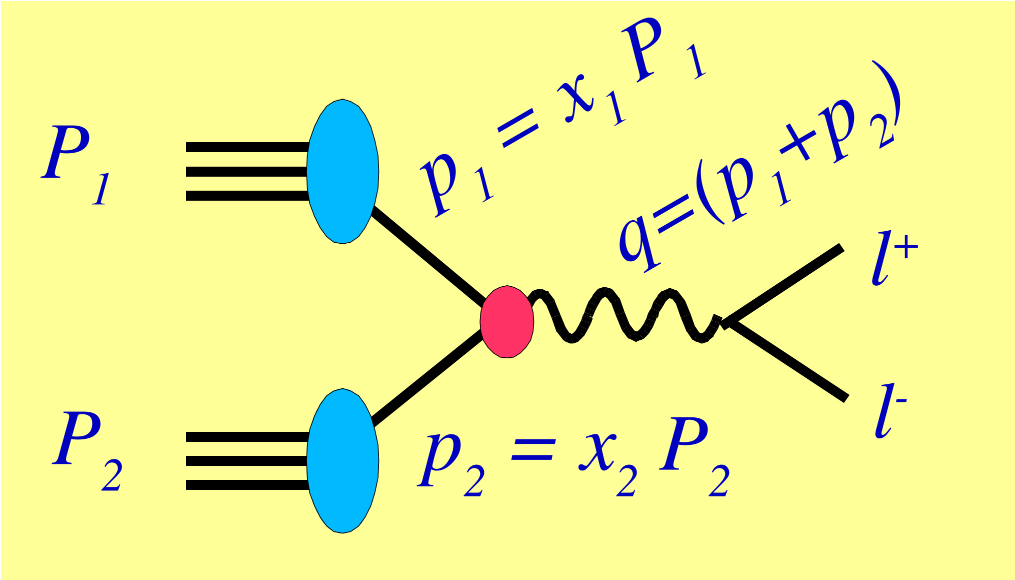
$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 + \cancel{P_{gQ} \otimes Q_1}\,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 + \cancel{P_{qQ} \otimes Q_1}\,,$$
$$\dot{Q}_0 + \dot{Q}_1 = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 + P_{QQ} \otimes Q_1\,.$$

Evolution Equations

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 \,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 \,,$$
$$\dot{Q}_0 = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 \,.$$

$$\dot{Q}_1 = P_{QQ} \otimes Q_1 \,.$$

Kinematics in the Hadronic Frame



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

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

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

Therefore

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

Fractional energy² between partonic and hadronic system

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

Hadronic cross section

Parton distribution functions

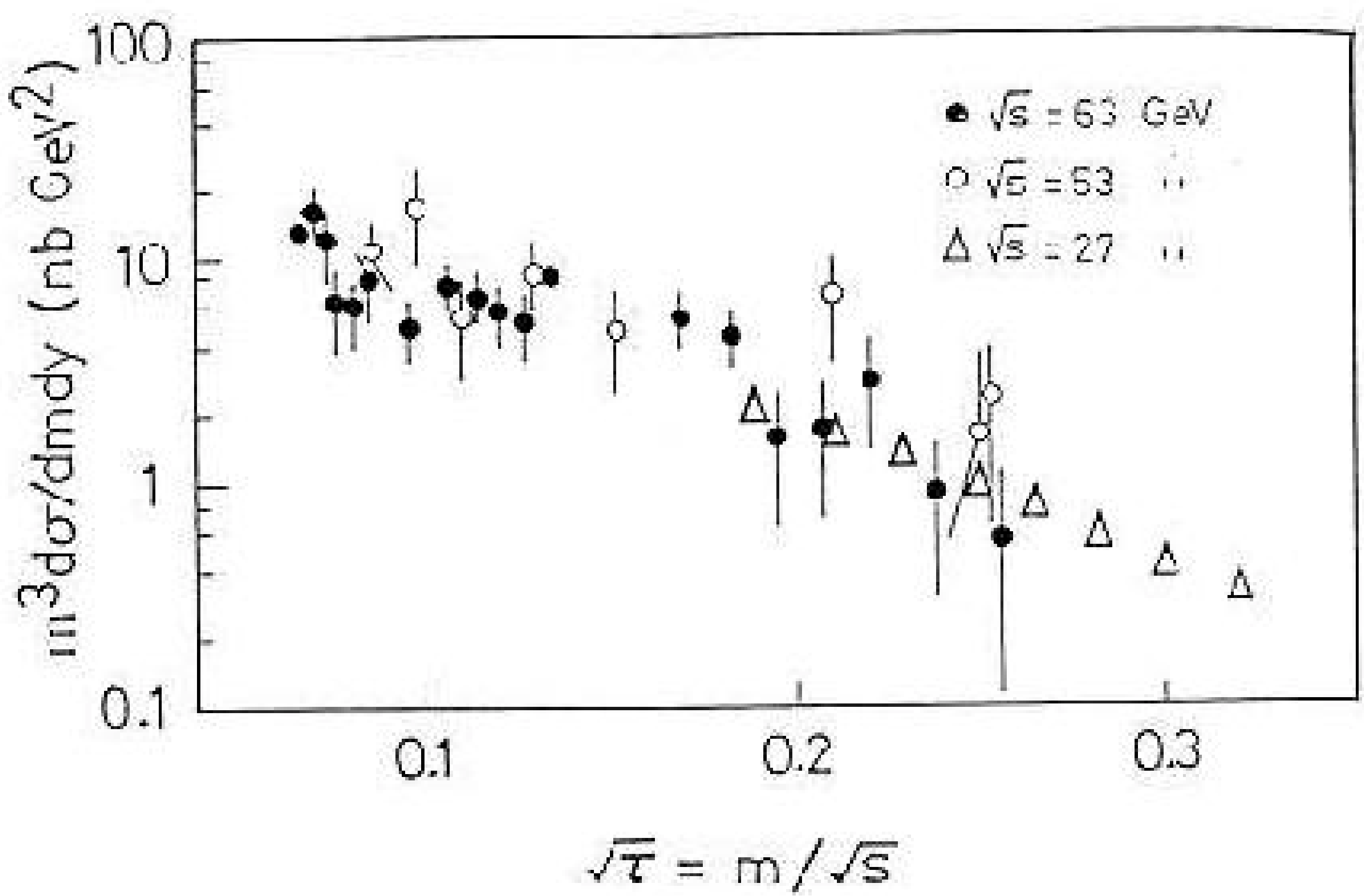
Partonic cross section

Scaling form of the Drell-Yan Cross Section

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

we can write the cross section in the scaling form:

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



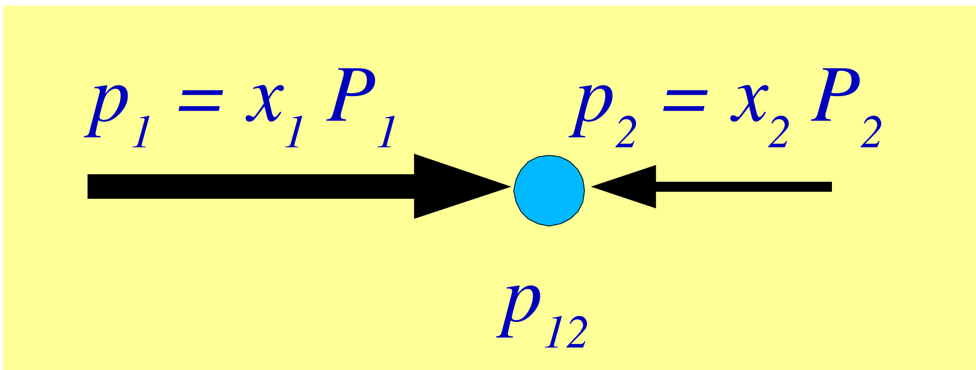
Notice the RHS is a function of only τ, not Q.

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:

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

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

$$dx_1\, dx_2 = d\tau\, dy$$

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

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

Let's compare data and theory

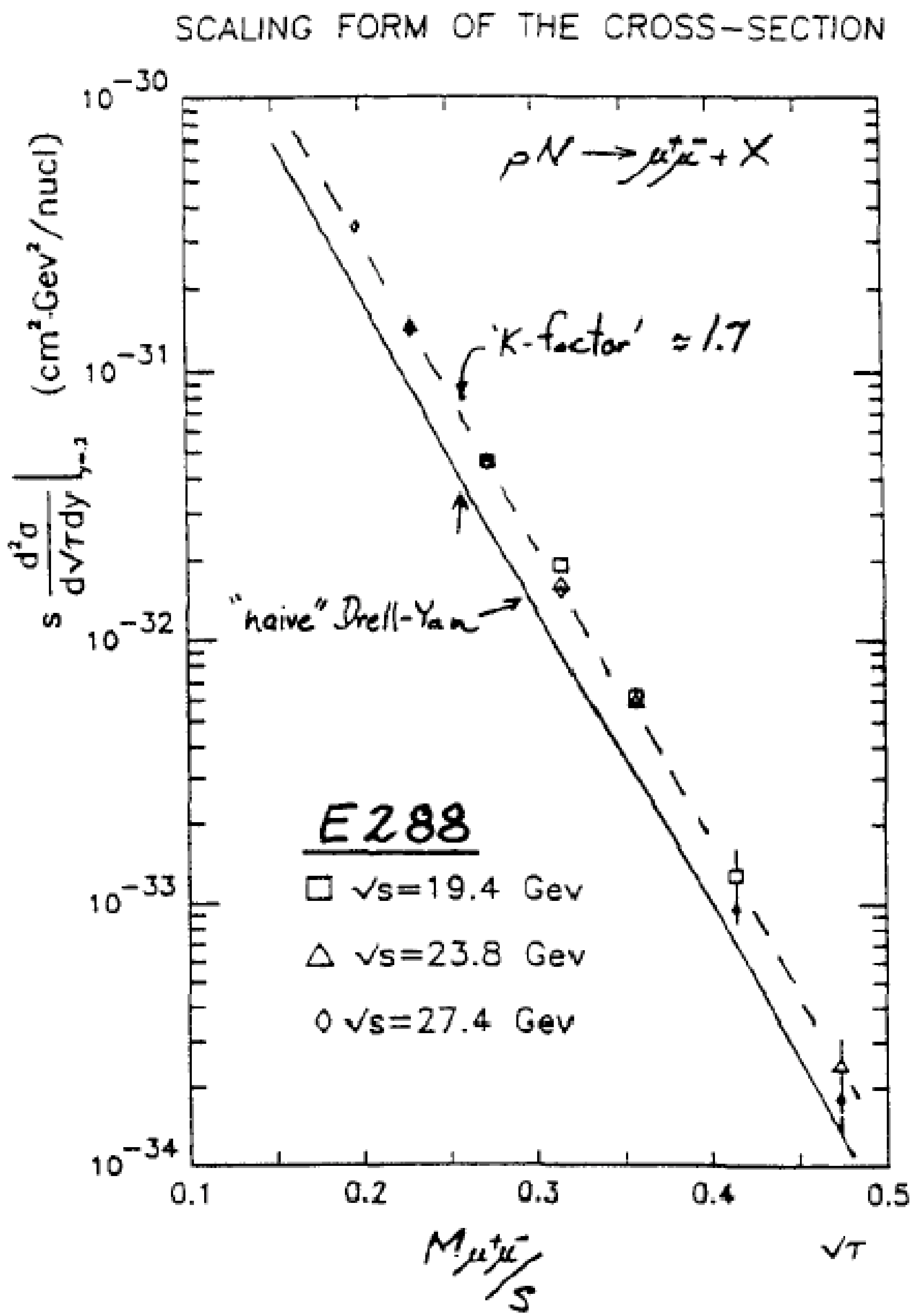


Table 1.2: Experimental K-factors.

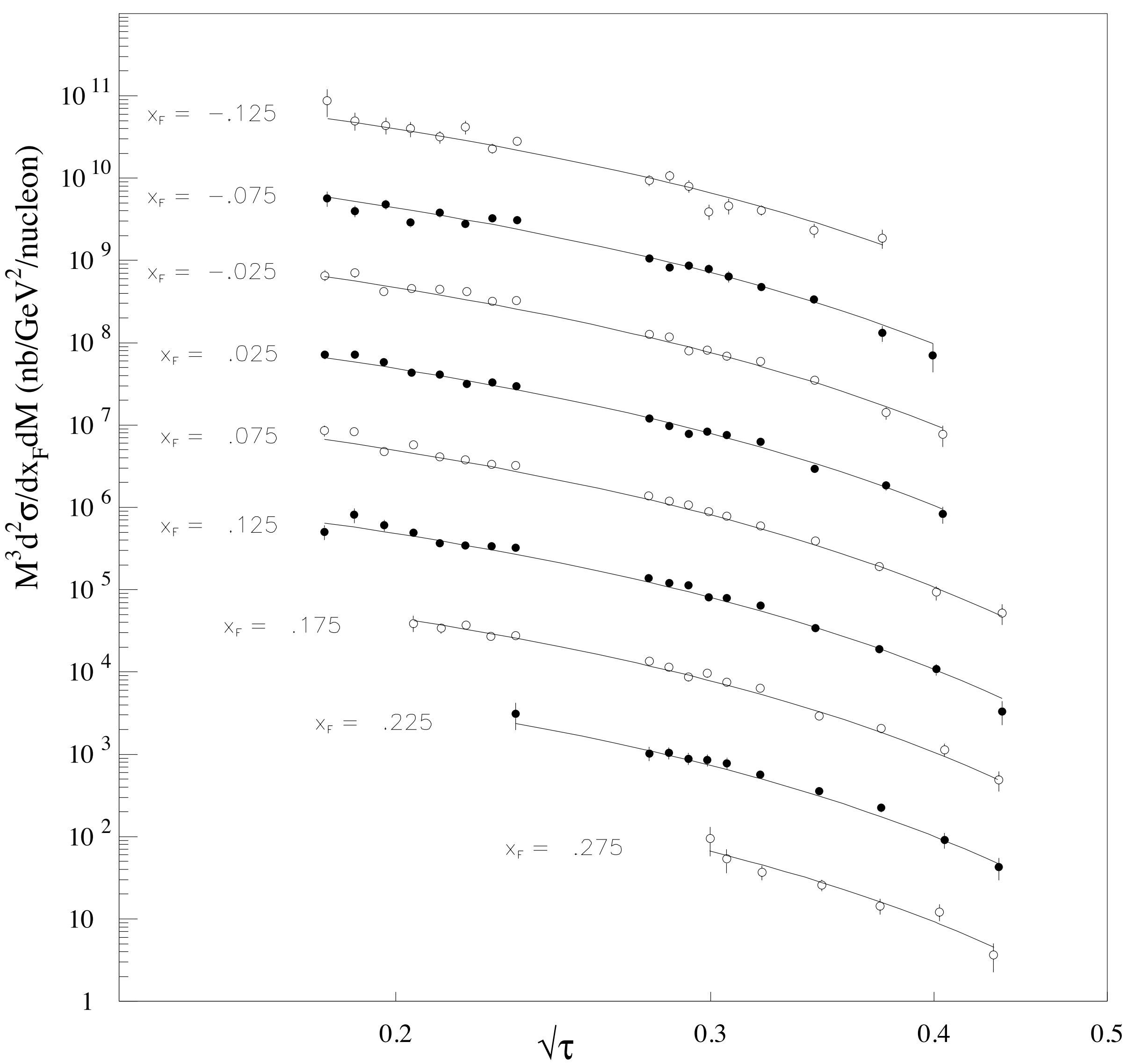
Experiment	Interaction	Beam Momentum	$K = \sigma_{\text{meas.}}/\sigma_{\text{DY}}$
E288 [Kap 78]	$p\ Pt$	300/400 GeV	~ 1.7
WA39 [Cor 80]	$\pi^{\pm}\ W$	39.5 GeV	~ 2.5
E439 [Smi 81]	$p\ W$	400 GeV	1.6 ± 0.3
NA3 [Bad 83]	$(\bar{p}$ - $p)Pt$	150 GeV	2.3 ± 0.4
	$p\ Pt$	400 GeV	$3.1 \pm 0.5 \pm 0.3$
	$\pi^{\pm}\ Pt$	200 GeV	2.3 ± 0.5
	$\pi^{-}\ Pt$	150 GeV	2.49 ± 0.37
	$\pi^{-}\ Pt$	280 GeV	2.22 ± 0.33
NA10 [Bet 85]	$\pi^{-}\ W$	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

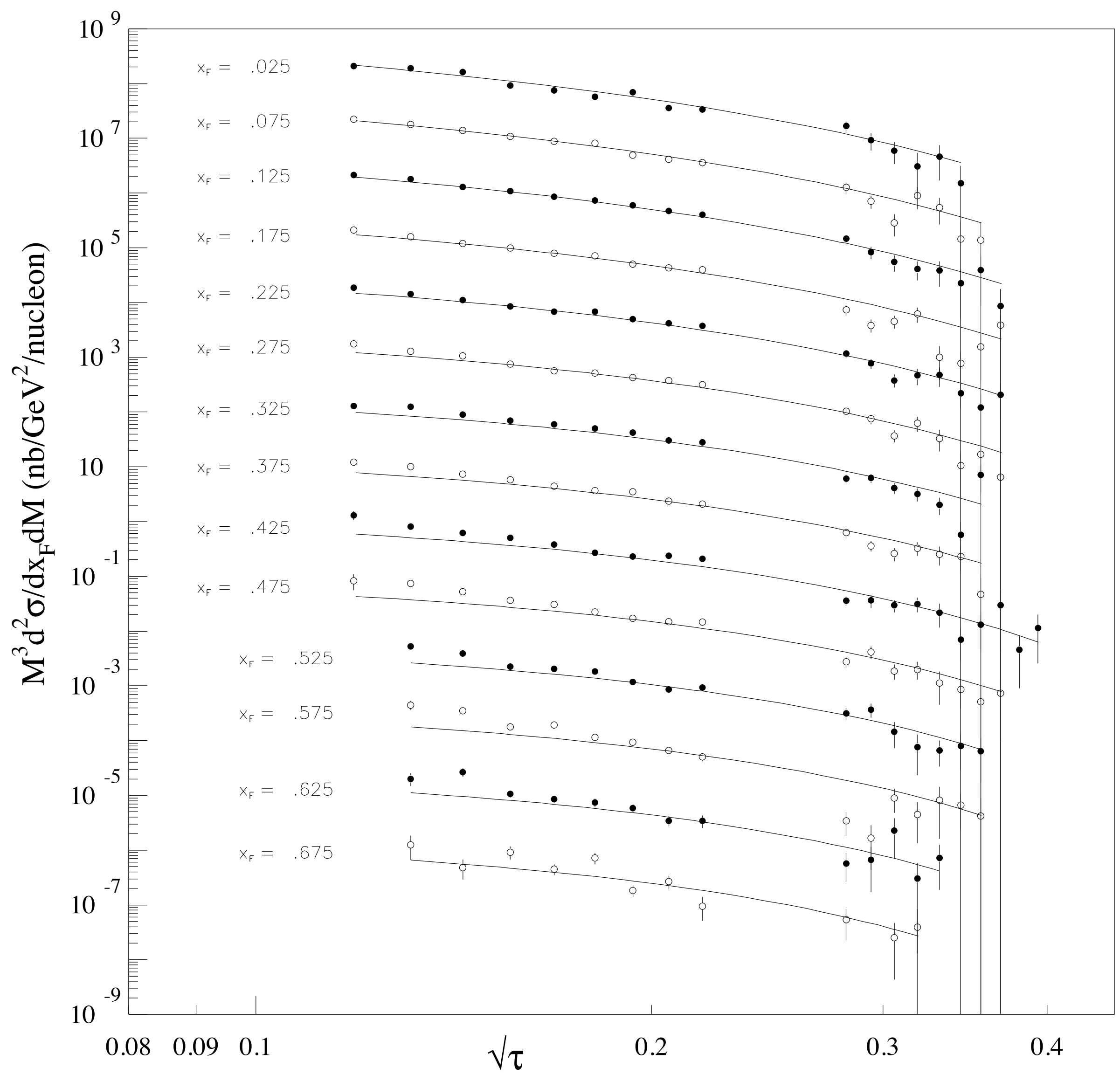
p + Cu at 800 GeV

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



p + d at 800 GeV

E772 (p d $\rightarrow \mu^+\mu^-$ X) p_{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~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)

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

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

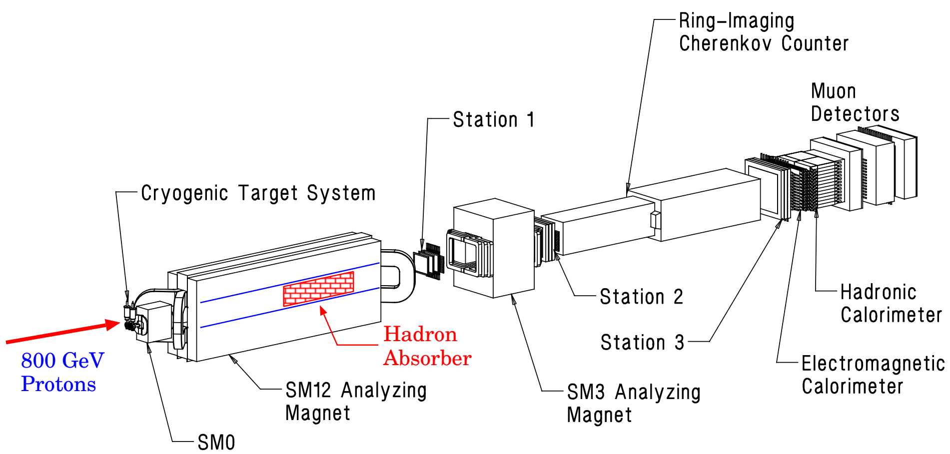
→ NuSea: measurement of x-dependence

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

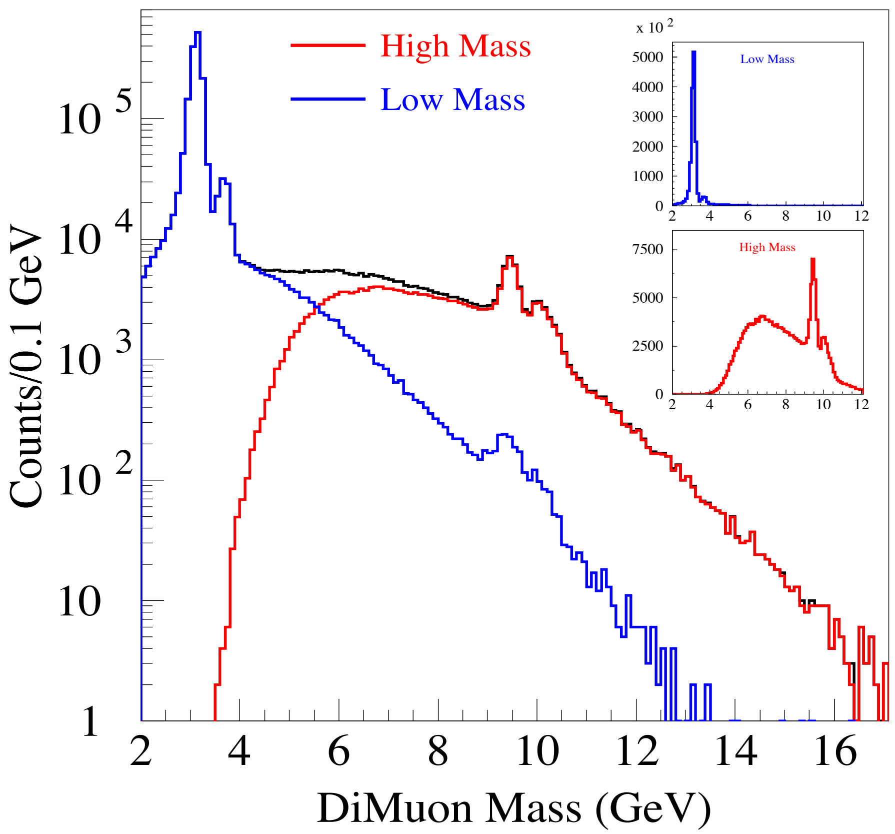
Slide from E866 website

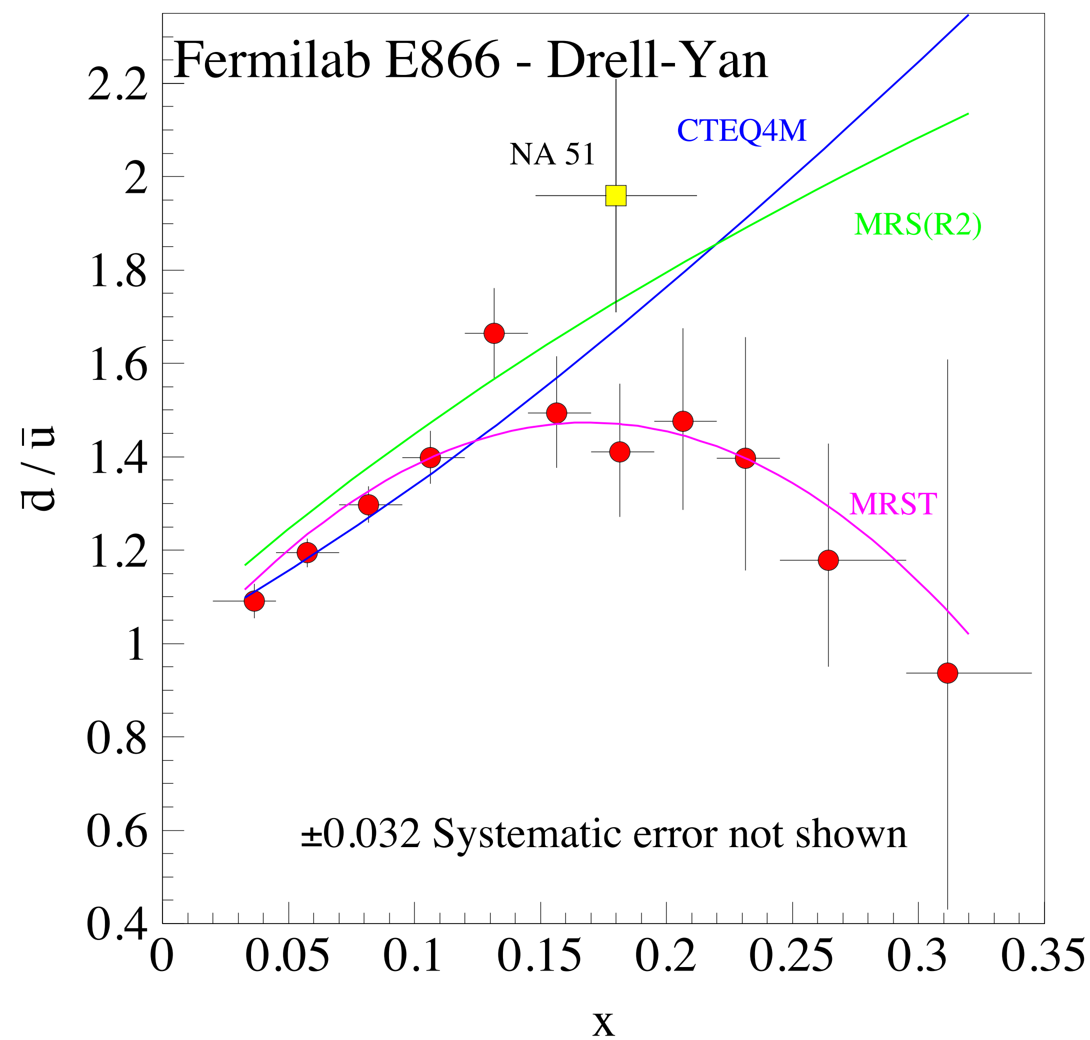
A measurement of $\bar{d}(x)/\bar{u}(x)$
Antiquark asymmetry in the Nucleon Sea
FNAL E866/NuSea

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



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





Fred Olness
CTEQ summer school

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 $x_1 >> x_2$:

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

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

For the ratio we have:

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

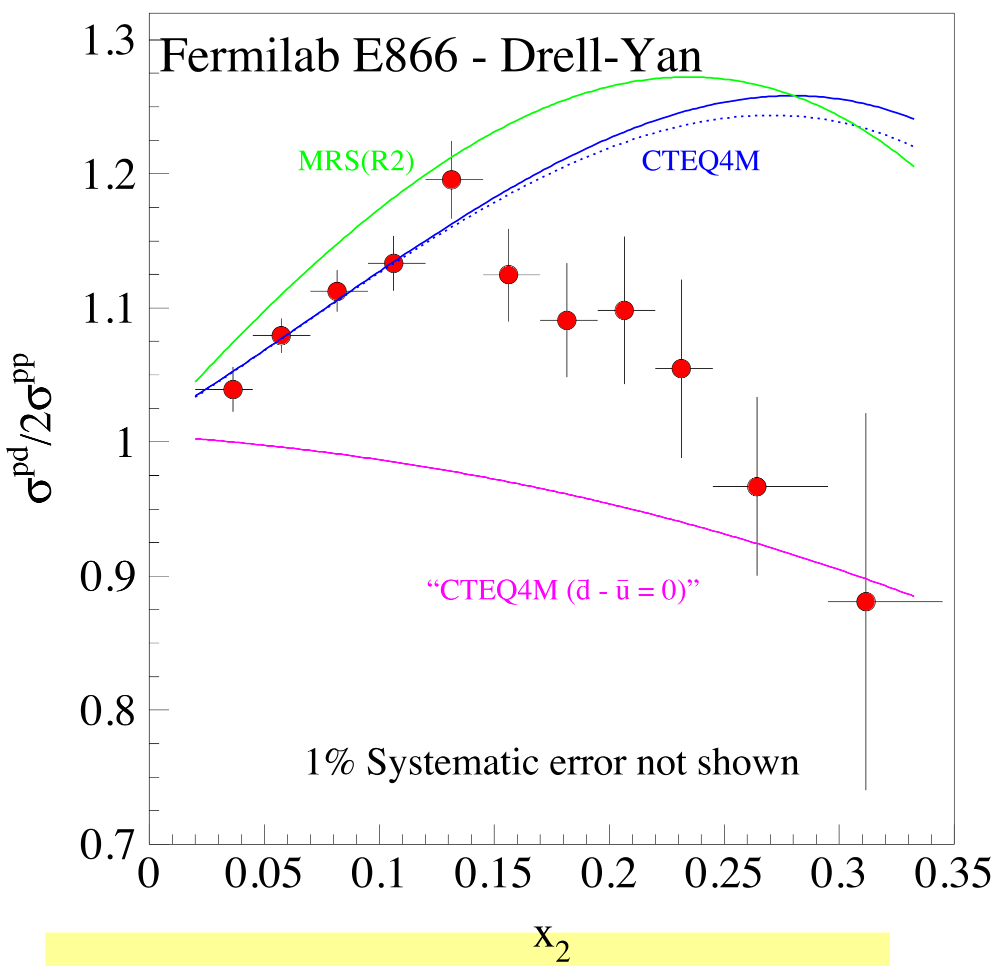
As promised, this provides information about the sea-quark distributions

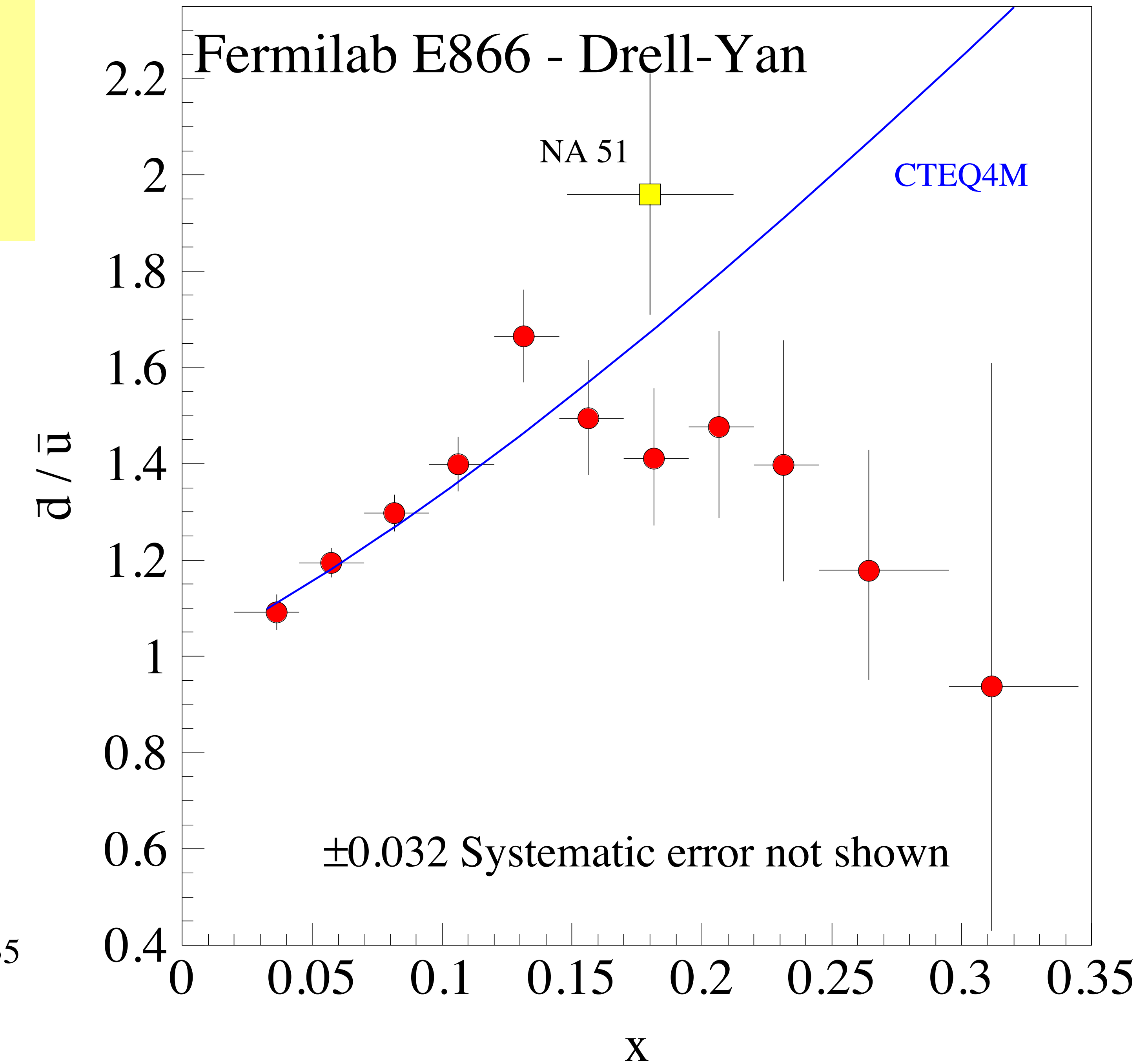
$$\frac{\sigma^{pd}}{2\,\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}_2}{\bar{u}_2}\right)$$

EXERCISE: Verify the above.

Does the theory match the data???

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



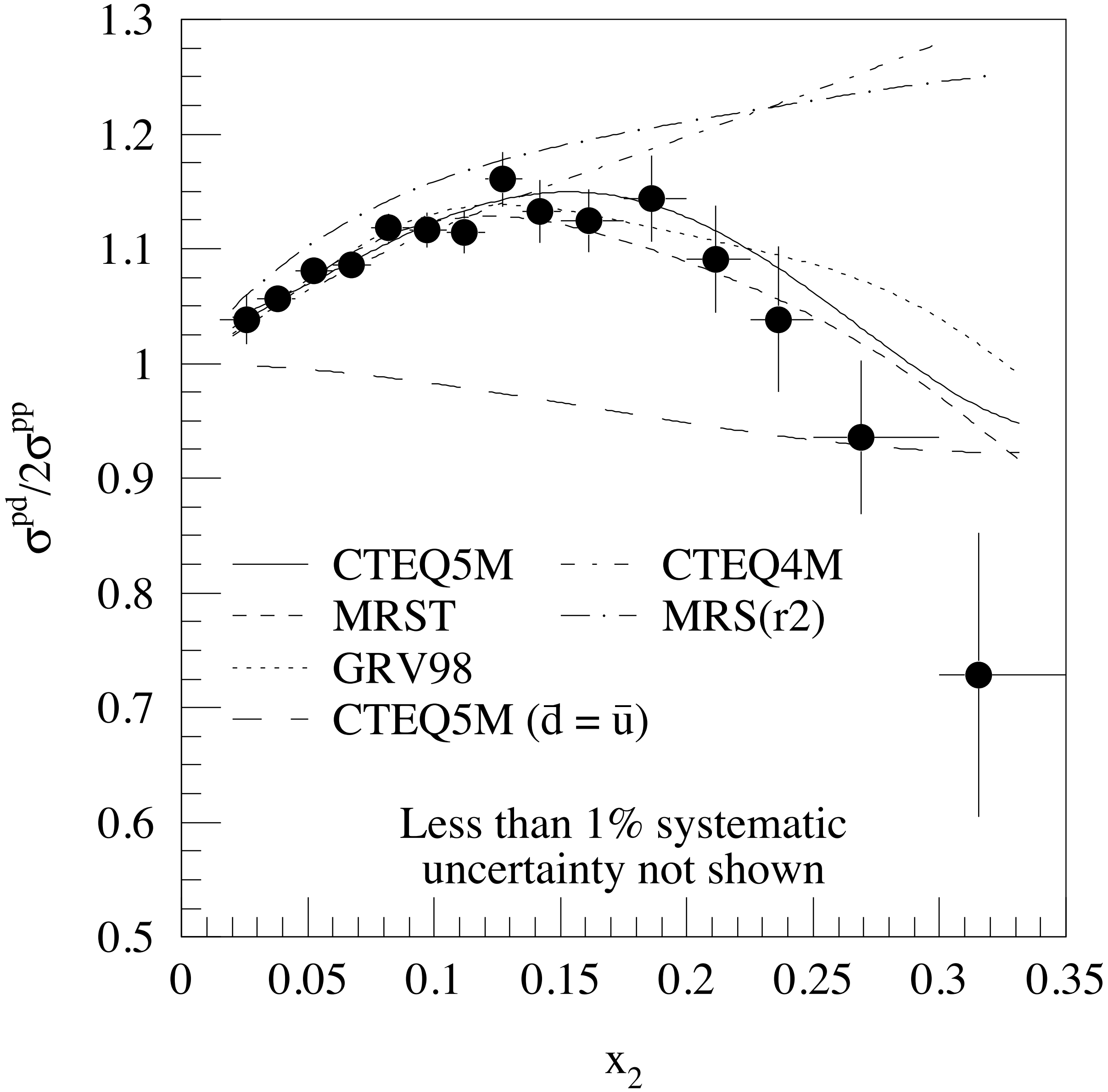


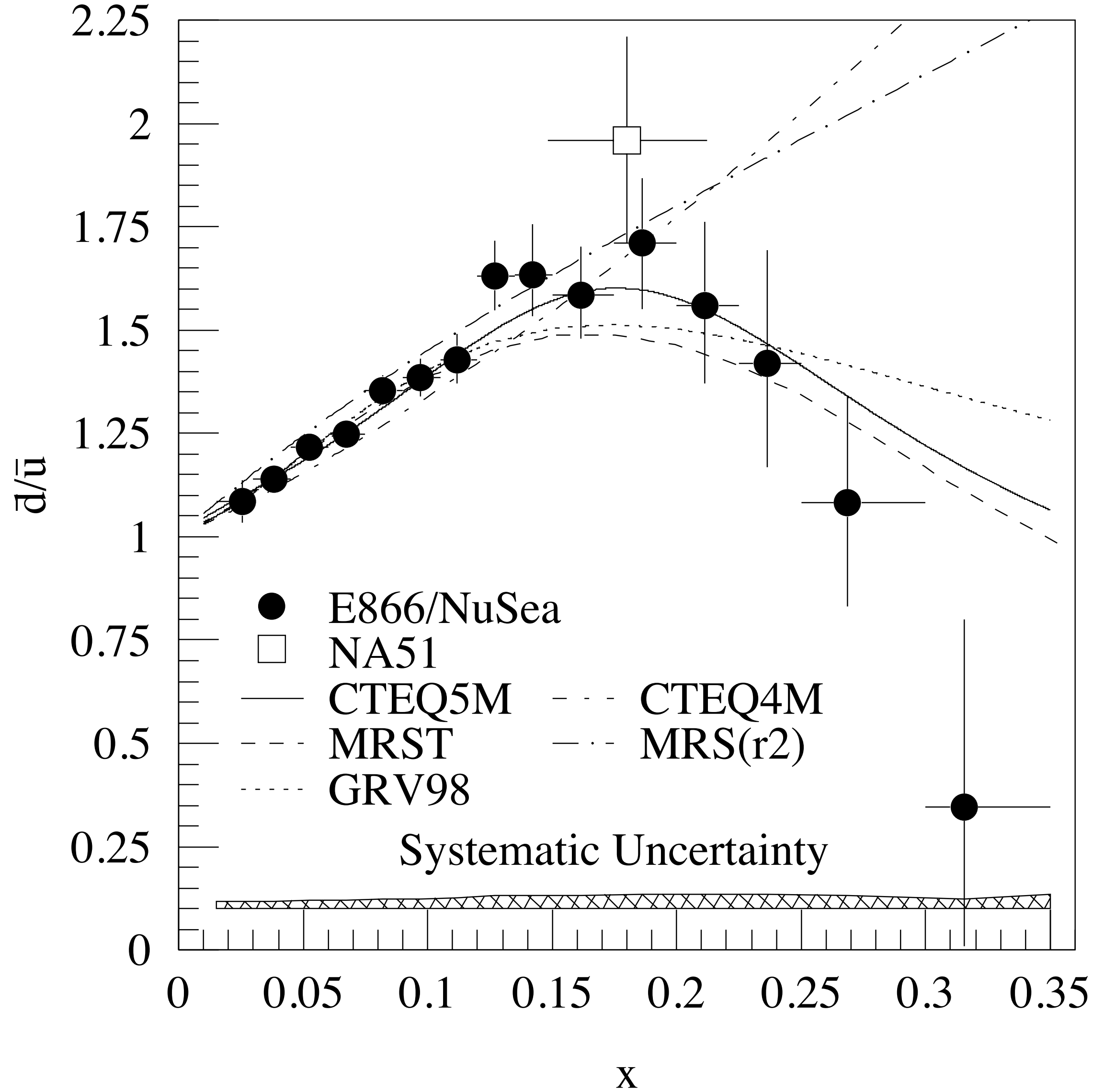
Implies R<1 for large x:

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

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

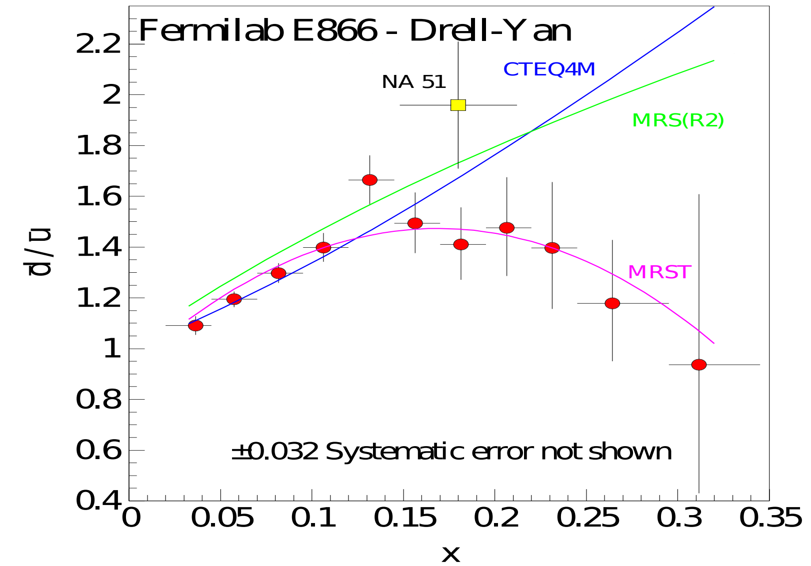
E.A. Hawker, et al. [FNAL E866/NuSea Collaboration], Measurement of the light antiquark flavor asymmetry in the nucleon sea, PRL 80, 3715 (1998)

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 dbar(x)/ubar(x)
  - Can AFTER improve precision of data?
    Extend kinematic reach to larger x>0.3?
  - Note, at small x<0.05: dbar = ubar
    SU(2)-symmetric sea (even more the higher the scale)
- Usually nuclear corrections assumed to be negligible:
  →AFTER can test with different nuclear targets

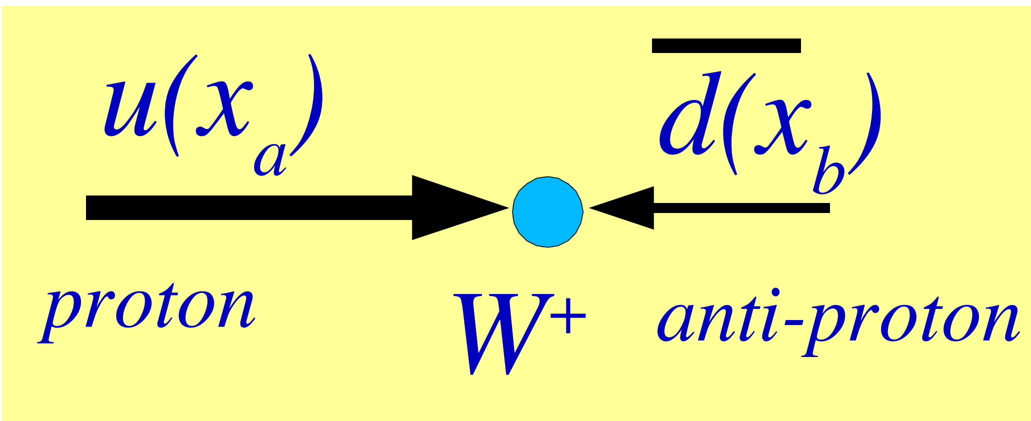
Isospin asymmetry in the nucleon light sea: $\bar{d}(x) \neq \bar{u}(x)$



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

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

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



For anti-proton:

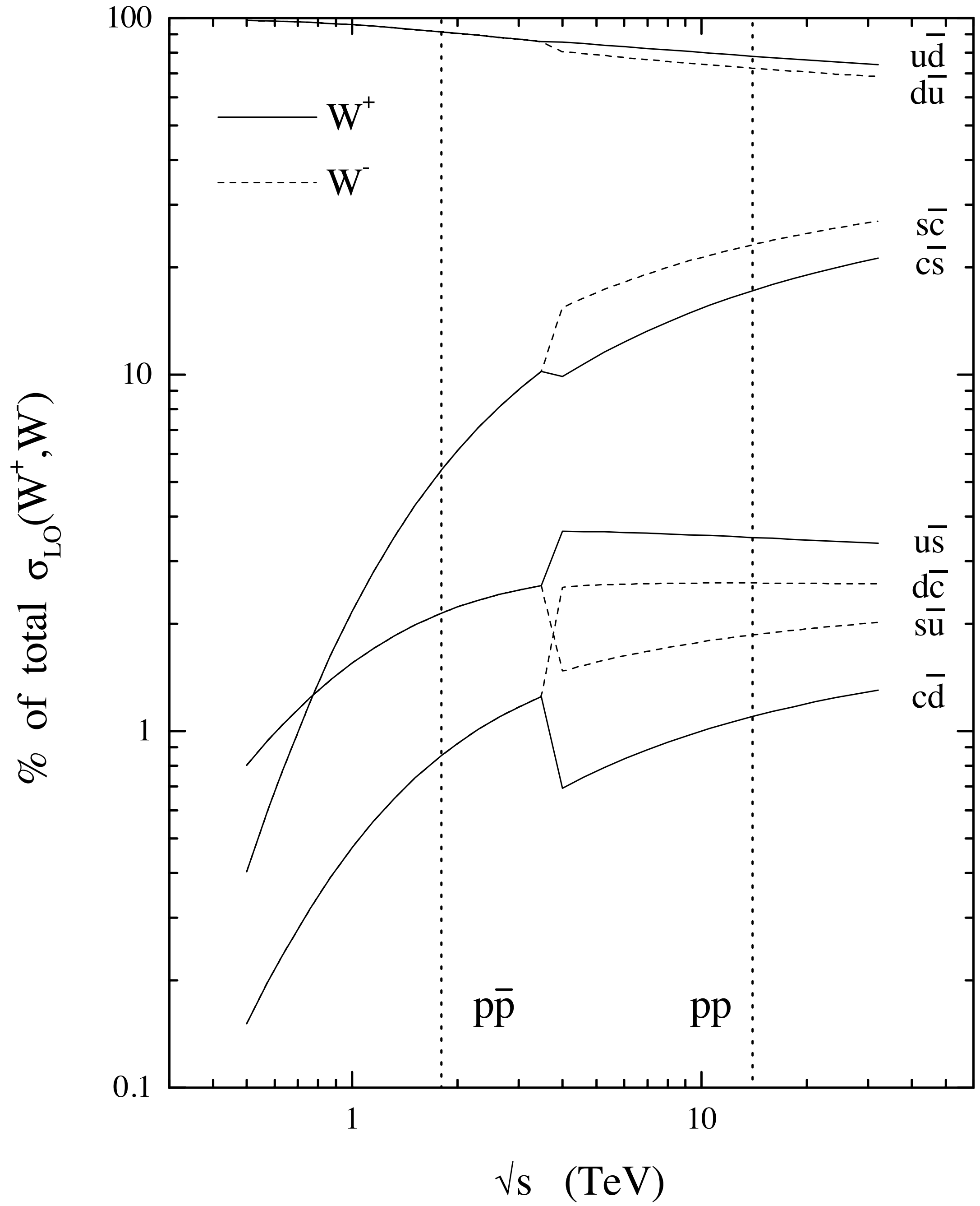
$$u(x) \Leftrightarrow \bar{u}(x) \qquad d(x) \Leftrightarrow \bar{d}(x)$$

Therefore

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

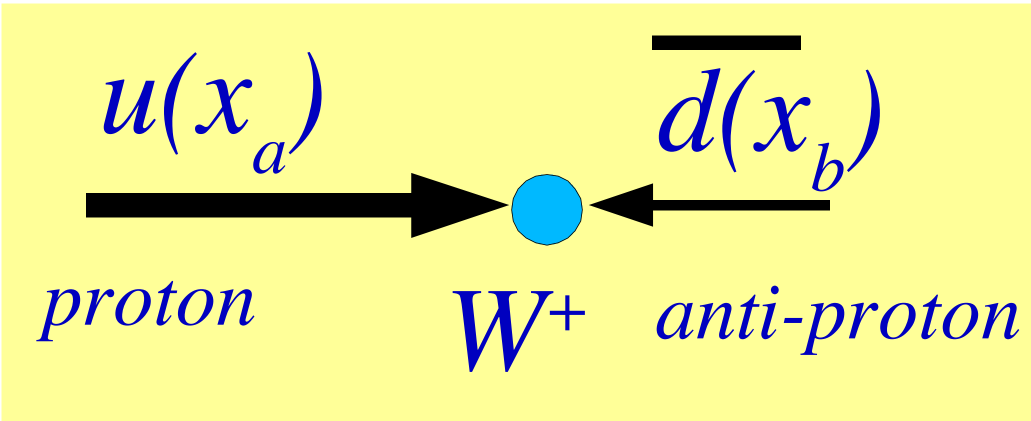
$$\frac{d\sigma}{dy}(W^{-}) \approx \frac{2\pi}{3}\frac{G_F}{\sqrt{2}}\left[d(x_a)\,u(x_b)\right]$$

flavour decomposition of W cross sections



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

We can make Taylor expansions:

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

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

Thus, the asymmetry is:

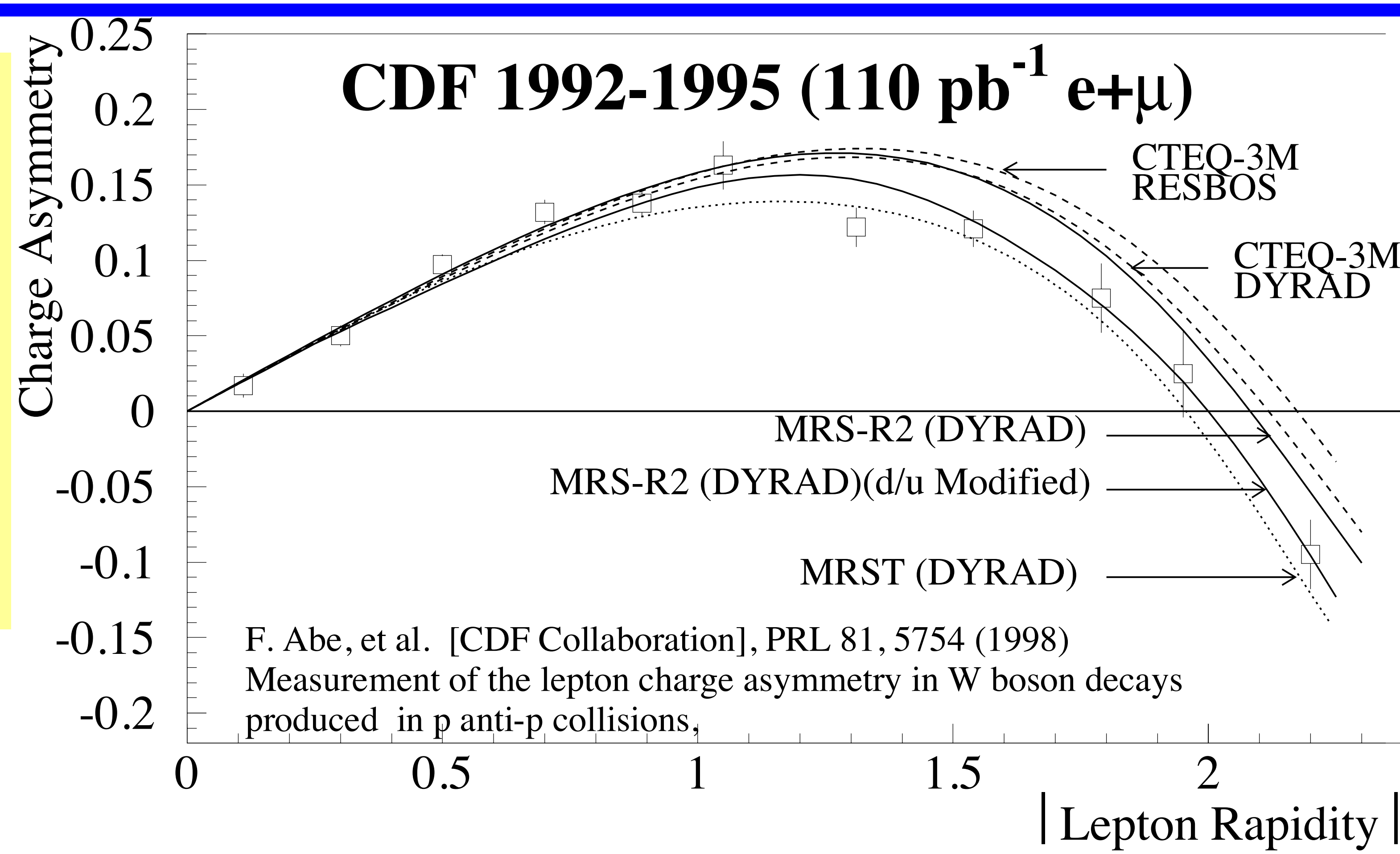
$$A(y) = -y\, x_0 \frac{R'_{du}(x_0)}{R_{du}(x_0)}$$

EXERCISE: Verify the above.

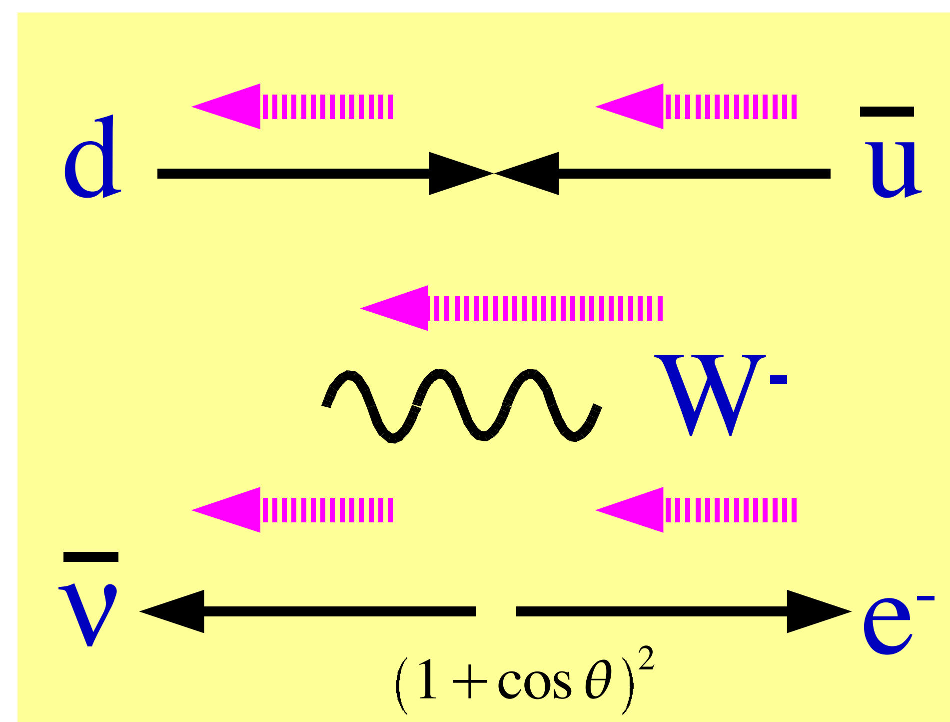
Charged Lepton Asymmetry

Unfortunately,
we don't measure the W directly since W→eν.

Still the lepton contains important information



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

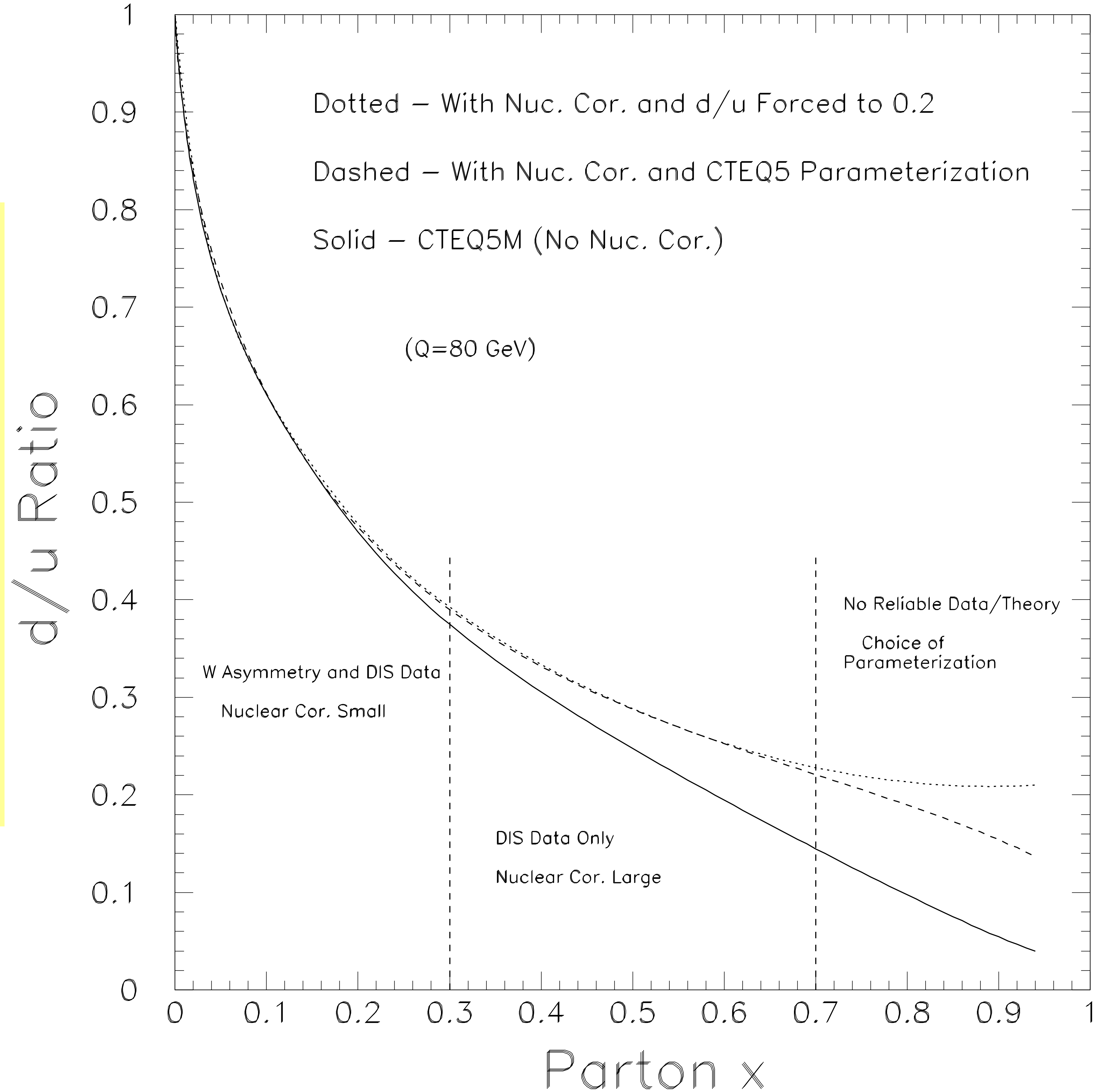


d/u Ratio at High-x

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

1) Parameterization

2) Nuclear Corrections

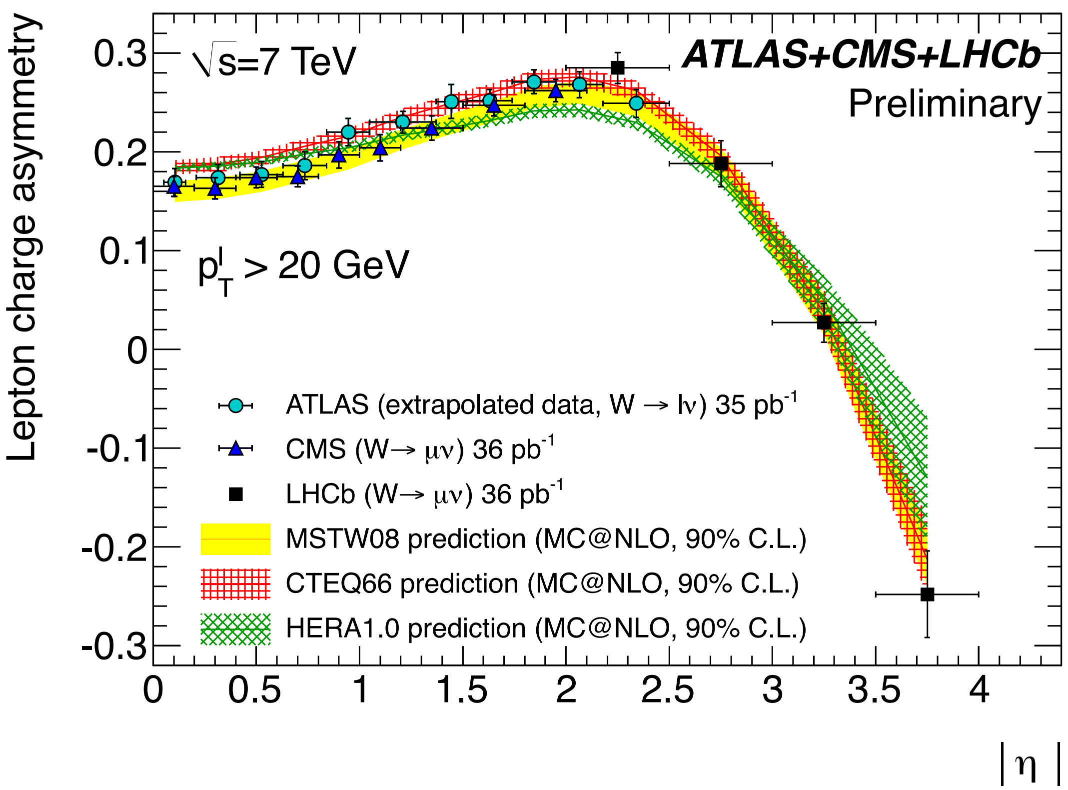


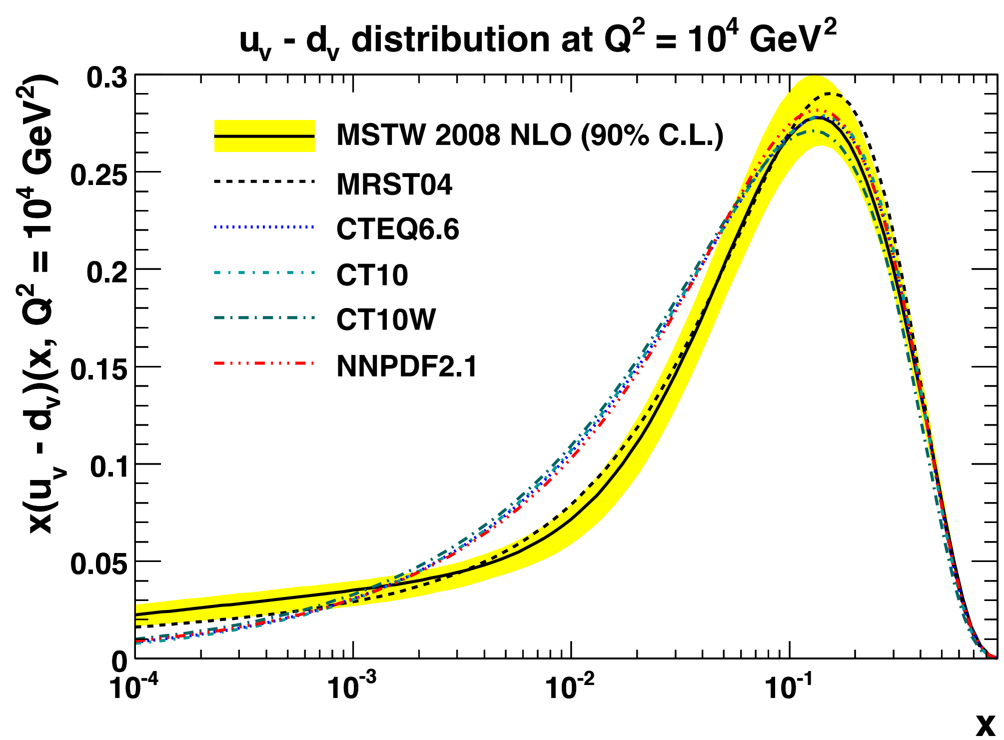
S. Kuhlmann, et al., Large-x parton distributions, PL B476, 291 (2000)

$W^\pm \to \ell^\pm \nu$ charge asymmetry at the LHC

$$A_W(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W} \approx \frac{u_v(x_1) - d_v(x_1)}{u(x_1) + d(x_1)}$$

$$A_\ell(\eta_\ell) = \frac{d\sigma(\ell^+)/d\eta_\ell - d\sigma(\ell^-)/d\eta_\ell}{d\sigma(\ell^+)/d\eta_\ell + d\sigma(\ell^-)/d\eta_\ell} \equiv A_W(y_W) \otimes (W^\pm \to \ell^\pm \nu)$$





- First PDF constraint from LHC data (→ NNPDF2.2).
- **MSTW08** has input $xu_v \propto x^{0.29\pm0.02}$ and $xd_v \propto x^{0.97\pm0.11}$. Many other groups **assume** equal powers ⇒ potential bias.

PDF Uncertainties

<u>Sources:</u>

- Experimental Errors to be propagated to the PDFs
- Theoretical Uncertainties
- Details of the Global Fits
- Inconsistencies in the use of the PDFs/application of the theoretical framework

There are known Unknowns ...

Errors of experimental data

Methods: to propagate exp. errors to PDFs

- **Hesse Matrix**
  - Eigenvector PDFs
  - Quadratic approximation
  - Simple computation of correlations
- **Lagrange Multipliers**
  - No quadratic approximation
  - Time consuming
- **Monte Carlo Methods**
  - generate N data samples by varying data within errors
  - N fits to the N samples -> Estimate uncertainty

Hessian method:

Assume only one fit parameter a --> Expand $\chi^2(a)$ around Minimum a_0

$$\chi^2(a)=\chi^2(a_0)+\frac{1}{2}\chi^{2''}(a_0)(a-a_0)^2+\ldots$$

Eigenvalue of Hessian 'matrix'

Determine Tolerance T <--> 1-sigma uncertainty: $T=\Delta\chi^2$

--> 1-σ uncertainty range for parameter a such that:

$$\chi^2(a)=\chi^2(a_0)+\Delta\chi^2 \Rightarrow \Delta a=T\sqrt{2/\chi^{2''}(a_0)}$$

--> best fit PDF: a_0 , two 'Eigenvector' PDFs: $a_0+\Delta a, a_0-\Delta a$

1-σ uncertainty for Observable X:

$$\Delta X=\frac{X(PDF[a_0+\Delta a])-X(PDF[a_0-\Delta a])}{2}\propto\Delta a\propto T$$

Generalization to n parameters: add in quadrature

Neutrino data

- Correlated errors
- Radiative correct.
- with and w/o iso-scalar corrections

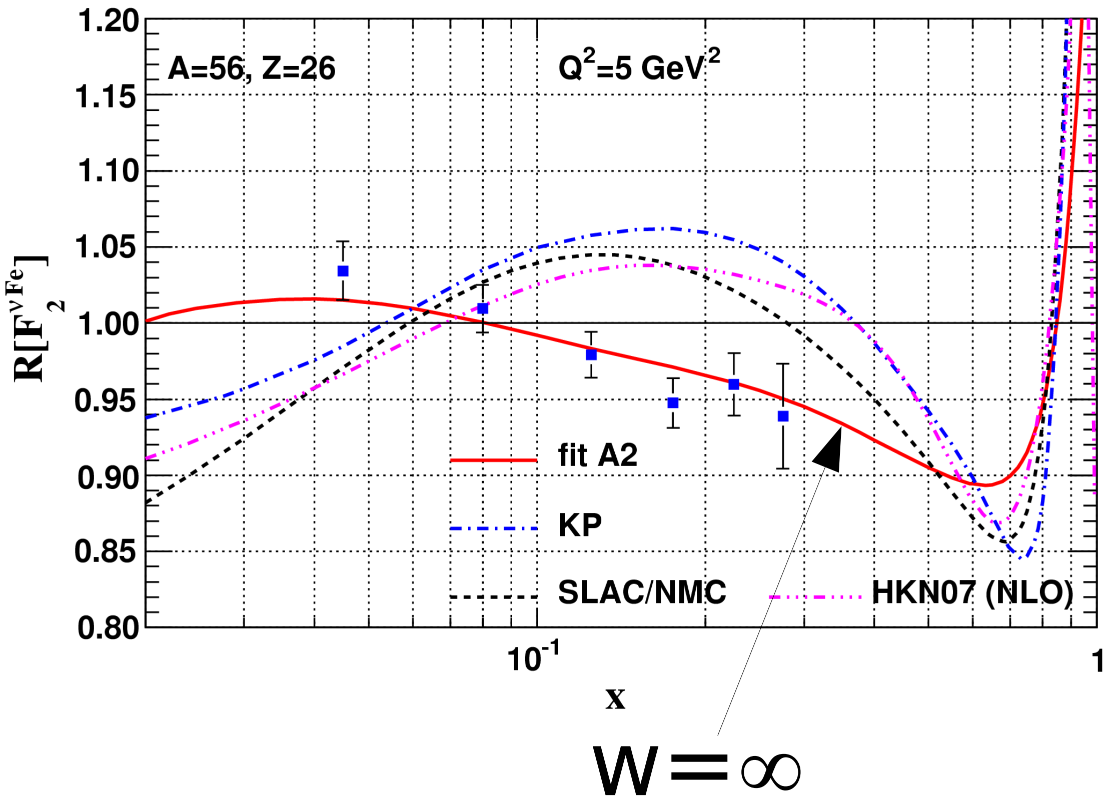
ID	$\mathbf{d\sigma^{\nu A}/dxdy}$: Observable	Experiment	# data
33	Pb	CHORUS ν	607 (412)
34	Pb	CHORUS $\bar{\nu}$	607 (412)
35	Fe	NuTeV ν	1423 (1170)
36	Fe	NuTeV $\bar{\nu}$	1195 (966)
37	Fe	CCFR ν di-muon	44 (44)
38	Fe	NuTeV ν di-muon	44 (44)
39	Fe	CCFR $\bar{\nu}$ di-muon	44 (44)
40	Fe	NuTeV $\bar{\nu}$ di-muon	42 (42)
	Total:		4006 (3134)

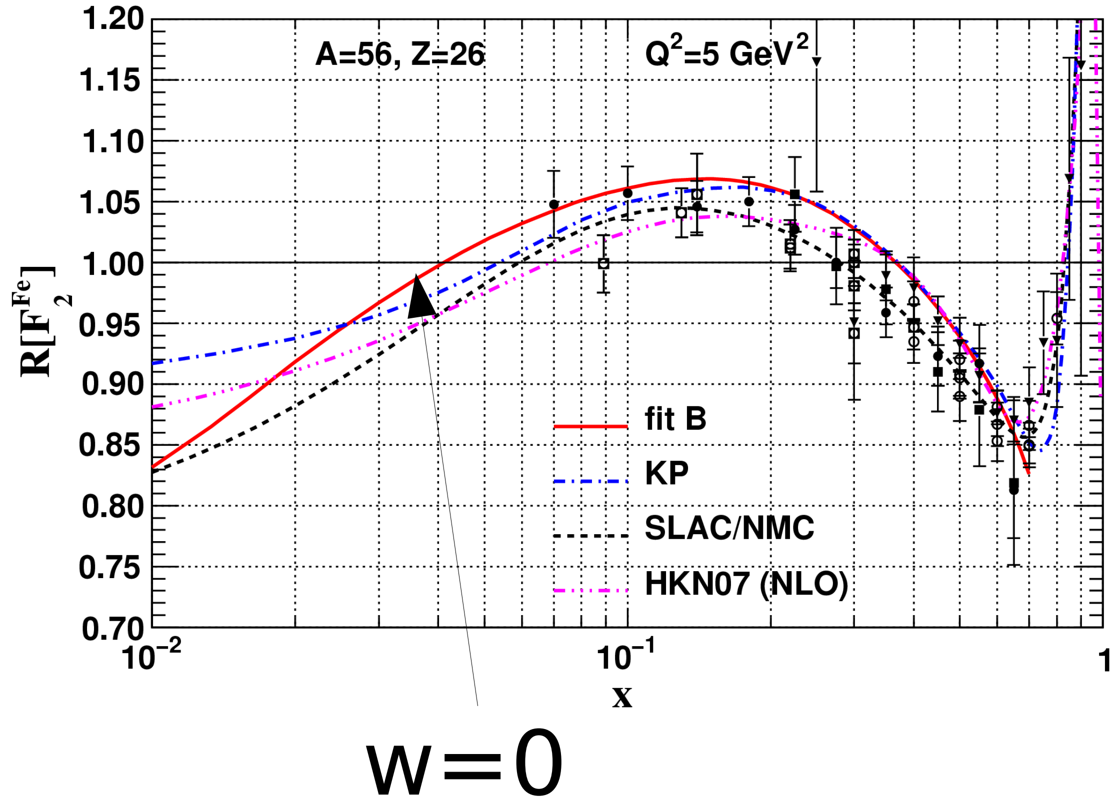
Fits to lA, DY and νA data

- Many neutrino data points
- Use a weight parameter w to combine data sets
- w=0: only lA+DY data
- w=∞: only νA data

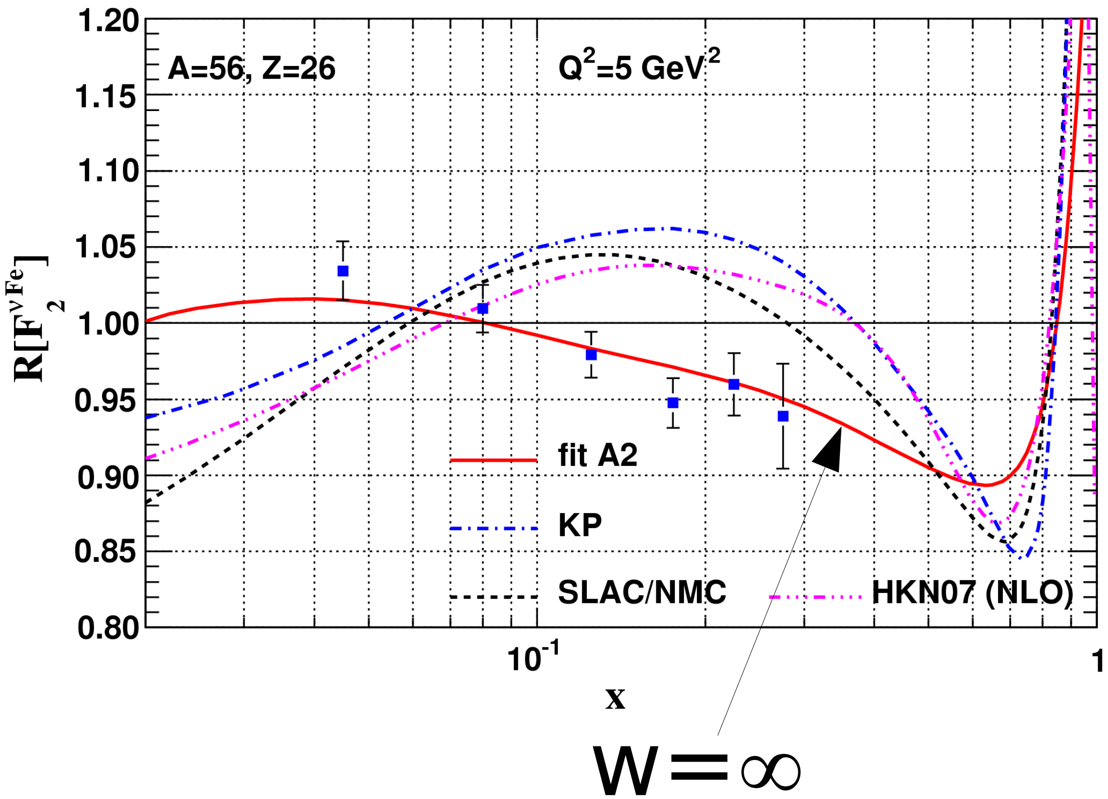
Weight	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	708	639 (0.90)	-	-	639 (0.90)
$w = 1/7$	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	-	-	3134	4192 (1.33)	4192 (1.33)

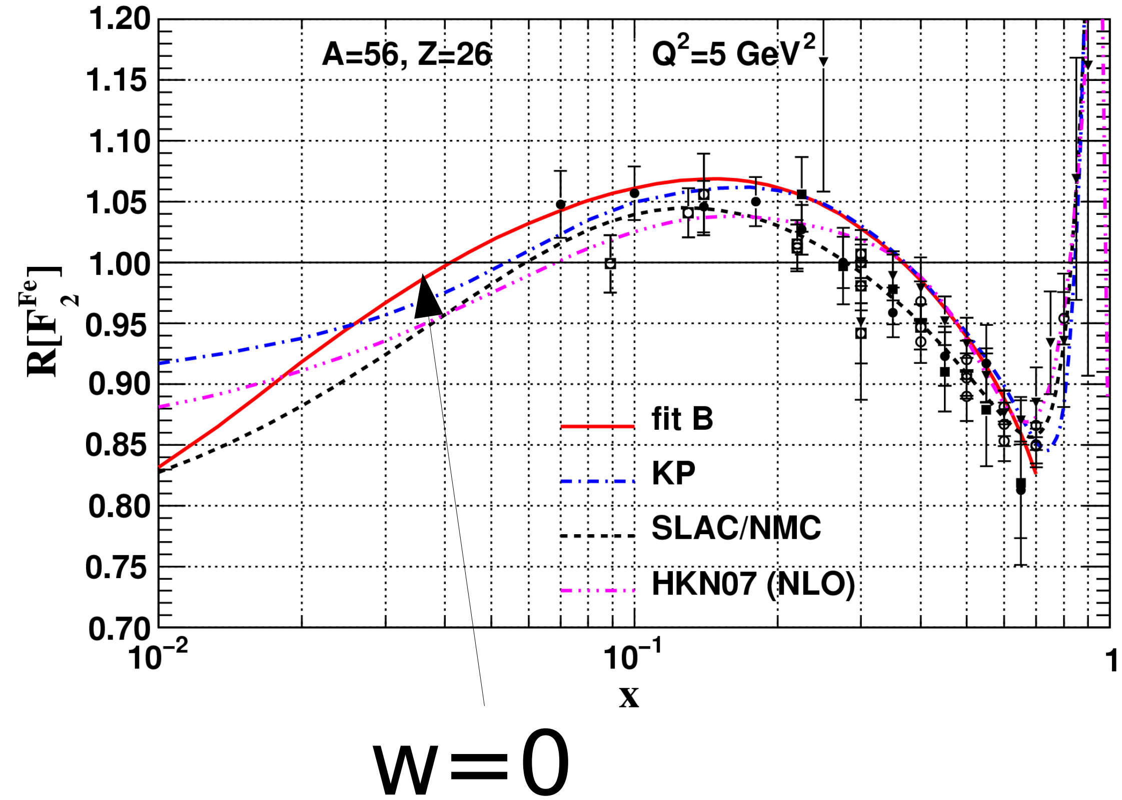
Nuclear correction factors



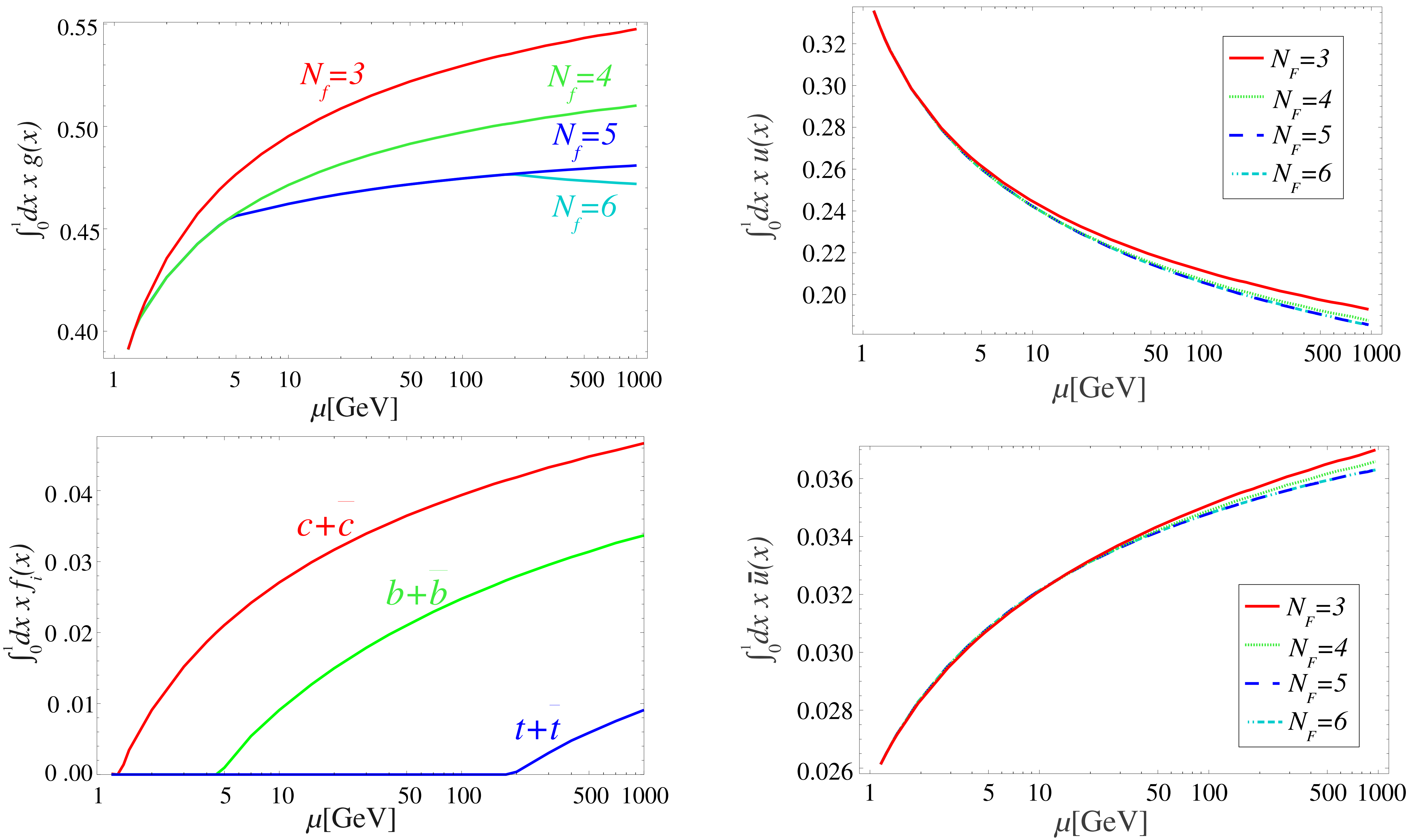


Nuclear correction factors

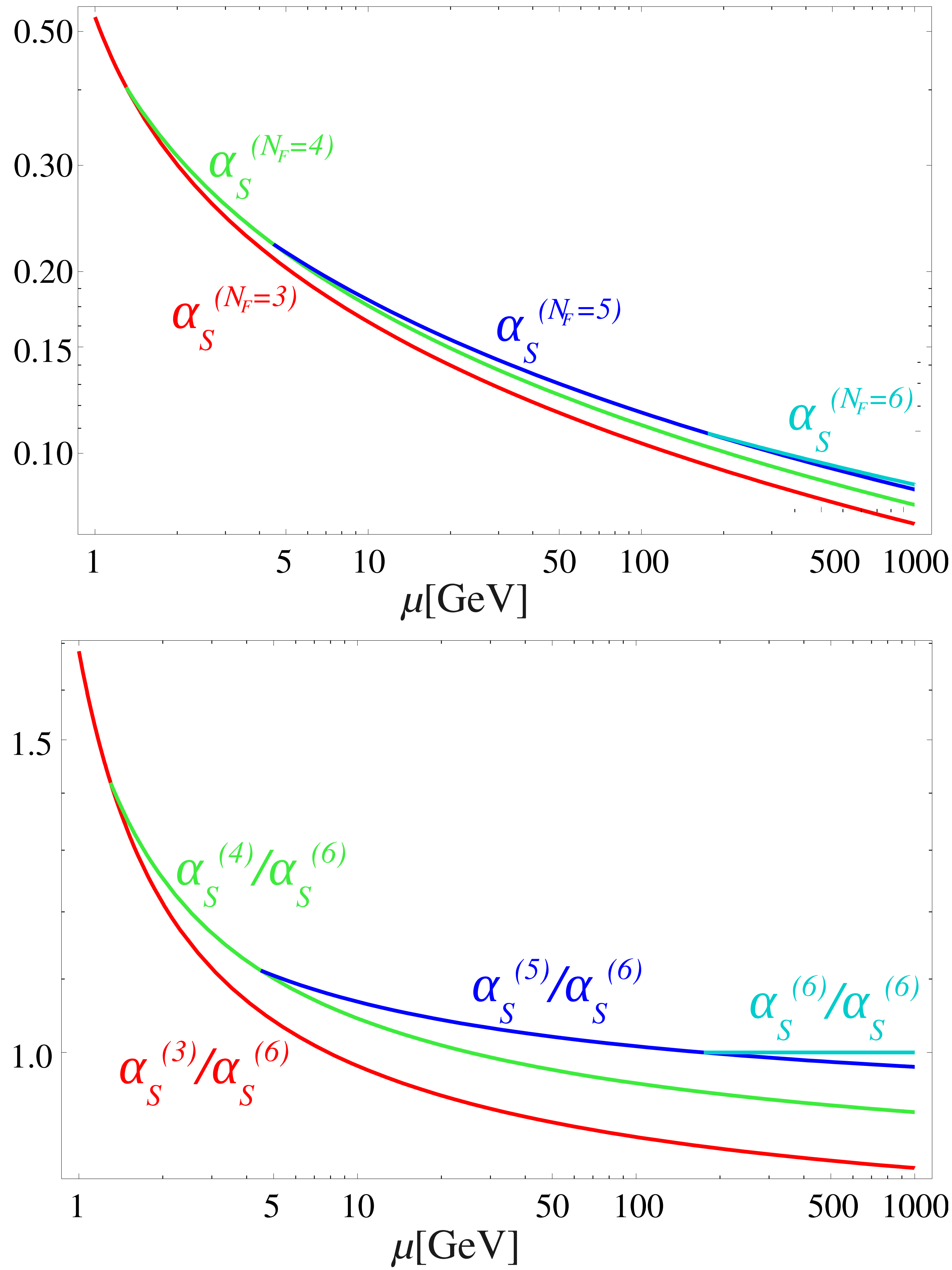




- Nuclear effects in lA DIS and νA DIS are different!
- Important for global analyses of (nuclear) PDF
- Important for neutrino precision observables



0.55
0.50
0.45
0.40
$\int_0^1 dx\, x\, g(x)$
N_f=3
N_f=4
N_f=5
N_f=6
1
5
10
50
100
500
1000
μ[GeV]
0.32
0.30
0.28
0.26
0.24
0.22
0.20
$\int_0^1 dx\, x\, u(x)$
N_F=3
N_F=4
N_F=5
N_F=6
1
5
10
50
100
500
1000
μ[GeV]
0 .04
0 .03
0 .02
0 .01
0 .00
$\int_0^1 dx\, x\, f_i(x)$
$c+\bar{c}$
$b+\bar{b}$
$t+\bar{t}$
1
5
10
50
100
500
1000
μ[GeV]
0.036
0.034
0.032
0.030
0.028
0.026
$\int_0^1 dx\, x\, \bar{u}(x)$
N_F=3
N_F=4
N_F=5
N_F=6
1
5
10
50
100
500
1000
μ[GeV]


0.50
0.30
0.20
0.15
0.10
$\alpha_S^{(N_F=4)}$
$\alpha_S^{(N_F=3)}$
$\alpha_S^{(N_F=5)}$
$\alpha_S^{(N_F=6)}$
1
5
10
50
100
500
1000
μ[GeV]
1.5
1.0
$\alpha_S^{(4)}/\alpha_S^{(6)}$
$\alpha_S^{(5)}/\alpha_S^{(6)}$
$\alpha_S^{(6)}/\alpha_S^{(6)}$
$\alpha_S^{(3)}/\alpha_S^{(6)}$
1
5
10
50
100
500
1000
μ[GeV]