Neutrino physics and EIC

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Pre-DIS EIC workshop
Kobe, Japan, April 15, 2018
https://indico2.riken.jp/event/2720/

April 15, 2018

Contents

Possible connections of neutrino-interaction physics and EIC

No talk on neutrino at the 8th International Conference on Physics Opportunities at an ElecTron-Ion-Collider
March 19-23, 2018, Regensburg, Germany
https://indico.cern.ch/event/663878/

(1) Indirect: Relations to the current neutrino oscillation experiments.
Measurements of γA cross sections
including at small x ($= 10^{-4} \sim 10^{-2}$)

Weak = Vector − Axial-vector

We try to get accurate interaction information on the vector part as much as possible from EIC experiments, and then we apply it to neutrino-interaction physics with theoretical constraints on the axial-vector part.

(2) Direct: Charged-current measurements at EIC,
Neutral-current (γZ interference) measurements.

These measurements were studied at HERA for the proton.
The EIC may study them for not only the proton but also nuclei.

Motivation:
Introduction to
Neutrino-Nucleus Scattering

Strong physics overlap with neutrino physicists

Every year, we have an international workshop on

Neutrino-Nucleus Scattering in the Few-GeV Region (NuInt)

2015, Nov. 16-21, Osaka, https://indico.ipmu.jp/indico/event/46/

2017, June 25-30, Toronto, https://nuint2017.physics.utoronto.ca/

2018, Oct. 15-19, L'Aqila, https://indico.cern.ch/event/703880/

There is a satellite SIS/DIS workshop at L'Aqila on Oct.11-13, 2018.

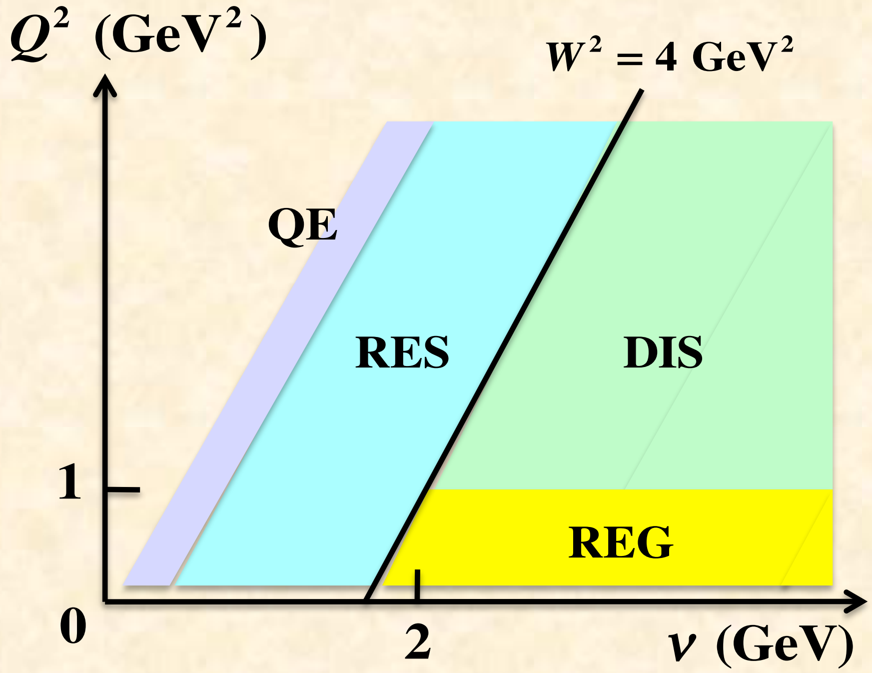
→ Strong physics overlap with EIC physicists.

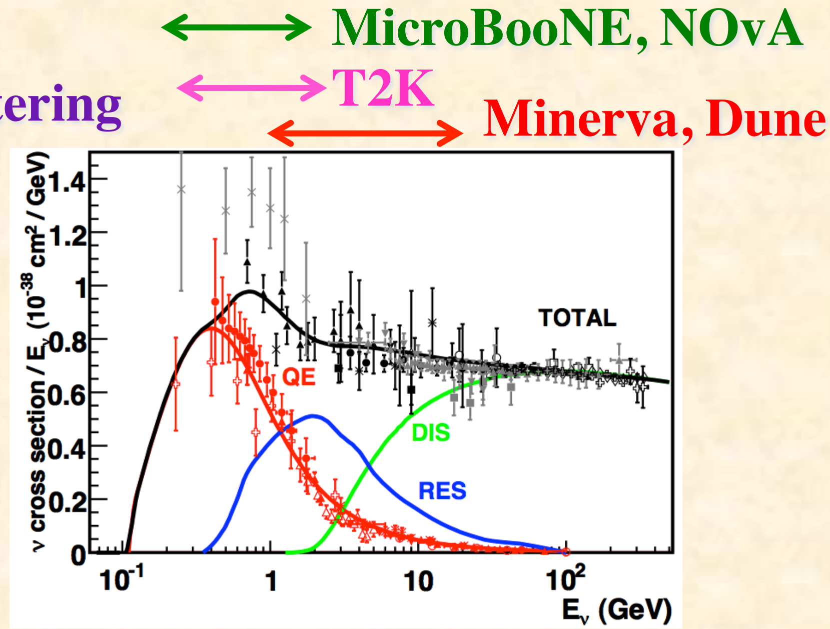
You are welcome to join!

Organizers: J. G. Morfin (Fermilab), C. Bonner (IPMU), H. Gallagher (Tufts), Y. Hayato (Tokyo), S. Kumano (KEK), U. Mosel (Giessen), J. Owens (Florida State), J. Paley (Fermilab), R. Petti (South Carolina), J. Sobczyk (Wroclaw)

Motivation

Kinematical regions of neutrino-nucleus scattering





J.L. Hewett *et al.*, arXiv:1205.2671,
Proceedings of the 2011 workshop
on Fundamental Physics at the Intensity Frontier

Depending on the neutrino beam energy, different physics mechanisms contribute to the cross section.

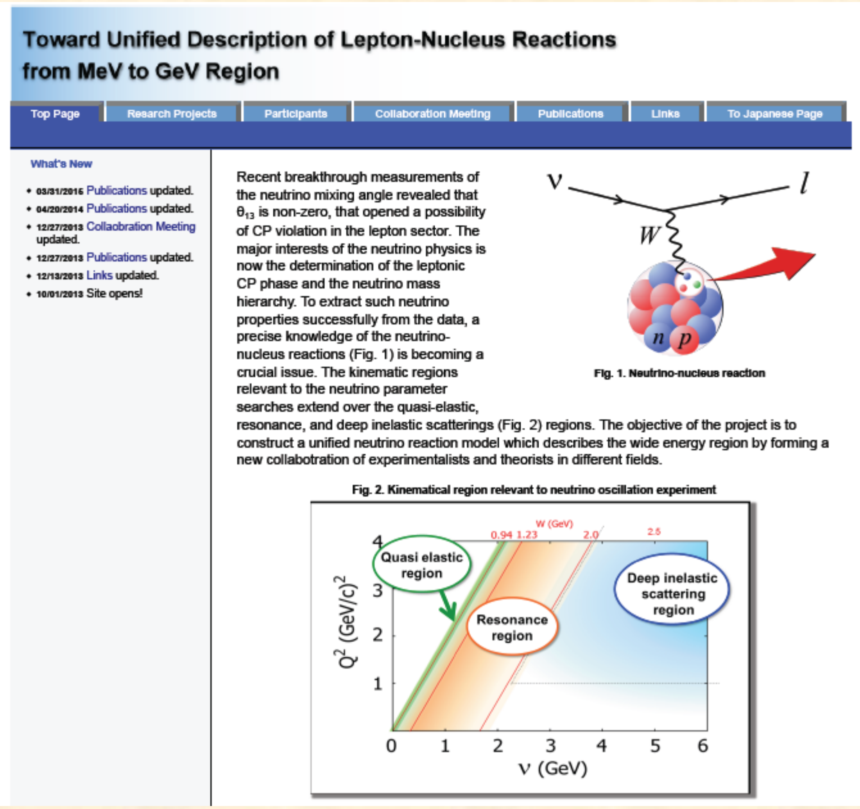
- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic scattering)
- REG (Regge)

ν flux		16%
ν flux and cross section	w/o ND measurement	21.8%
	w/ ND measurement	2.7%
ν cross section due to difference of nuclear target btw. near and far		5.0%
Final or Secondary Hadronic Interaction		3.0%
Super-K detector		4.0%
total	w/o ND measurement	23.5%
	w/ ND measurement	7.7%

ν interactions

A.K.Ichikawa@KEK workshop 2015

ν-interaction collaboration at J-PARC


Toward Unified Description of Lepton-Nucleus Reactions from MeV to GeV Region

Top Page | Resarch Projects | Participants | Collaboration Meeting | Publications | Links | To Japanese Page

What's New

- 03/31/2016 Publications updated.
- 04/20/2014 Publications updated.
- 12/27/2013 Collaobration Meeting updated.
- 12/27/2013 Publications updated.
- 12/13/2013 Links updated.
- 10/01/2013 Site opens!

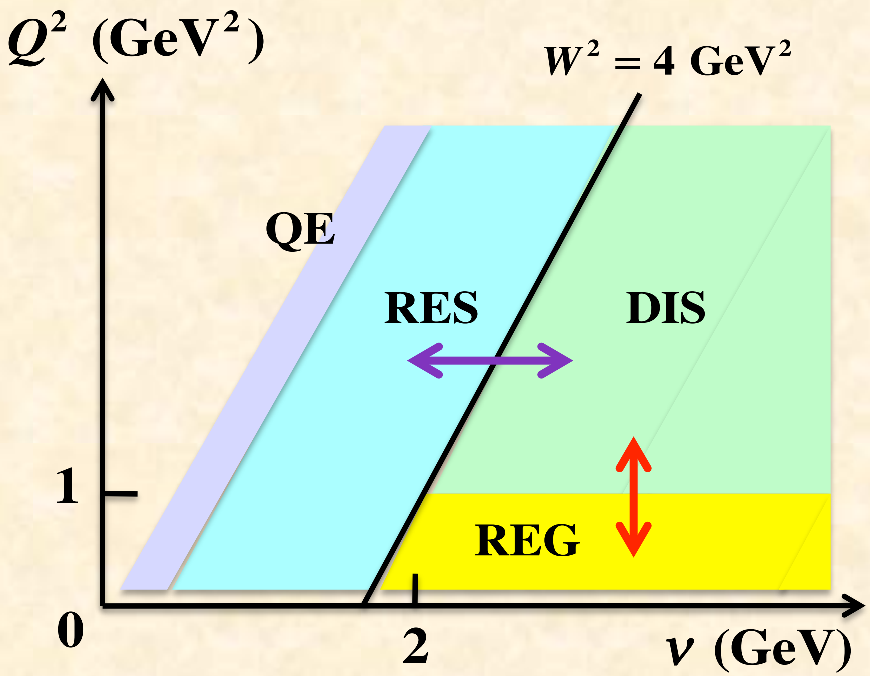
Recent breakthrough measurements of the neutrino mixing angle revealed that θ_{13} is non-zero, that opened a possibility of CP violation in the lepton sector. The major interests of the neutrino physics is now the determination of the leptonic CP phase and the neutrino mass hierarchy. To extract such neutrino properties successfully from the data, a precise knowledge of the neutrino-nucleus reactions (Fig. 1) is becoming a crucial issue. The kinematic regions relevant to the neutrino parameter searches extend over the quasi-elastic, resonance, and deep inelastic scatterings (Fig. 2) regions. The objective of the project is to construct a unified neutrino reaction model which describes the wide energy region by forming a new collabotration of experimentalists and theorists in different fields.

Fig. 1. Neutrino-nucleus reaction

Fig. 2. Kinematical region relevant to neutrino oscillation experiment

Activities at the J-PARC branch, KEK theory center
http://j-parc-th.kek.jp/html/English/e-index.html

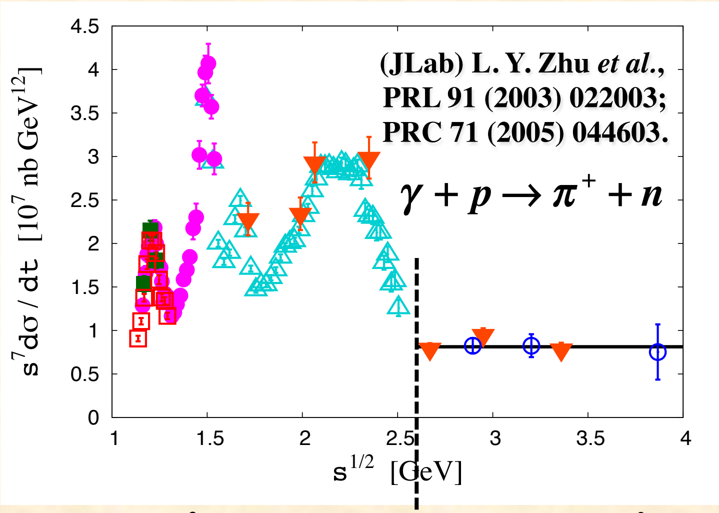
Y. Hayato, M. Hirai, W. Horiuchi, H. Kamano, S. Kumano, T. Murata, S. Nakamura, K. Saito, M. Sakuda, T. Sato
http://nuint.kek.jp/index_e.html



For the details, see

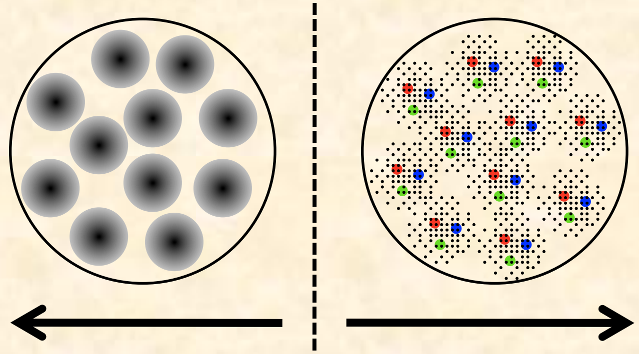
Towards a unified model of neutrino-nucleus reactions for neutrino oscillation experiments, S. X. Nakamura *et al*., Rep. Prog. Phys. 80 (2017) 056301.

Hadron and quark-gluon degrees of freedom



Low energies:
Hadron degrees of freedom (Resonances)

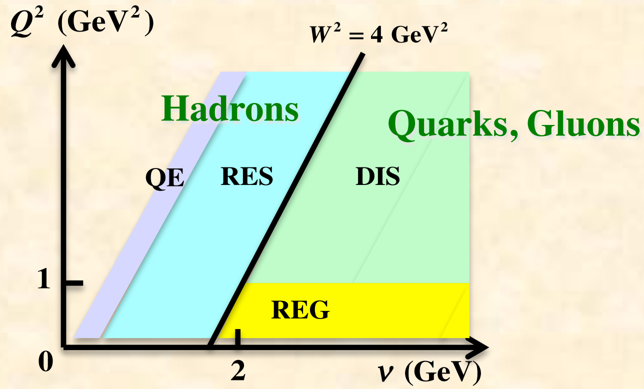
High energies:
Quark-gluon degrees of freedom (Perturbative QCD: Constituent-counting rule)



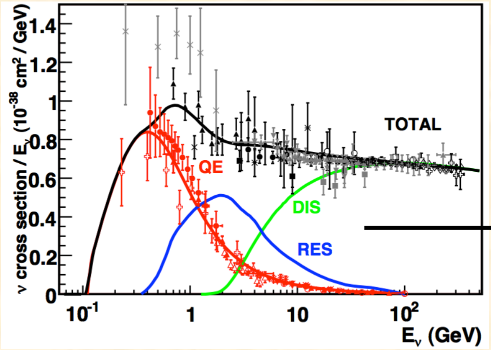
Low energies:
Hadron degrees of freedom

High energies:
Quark-gluon degrees of freedom

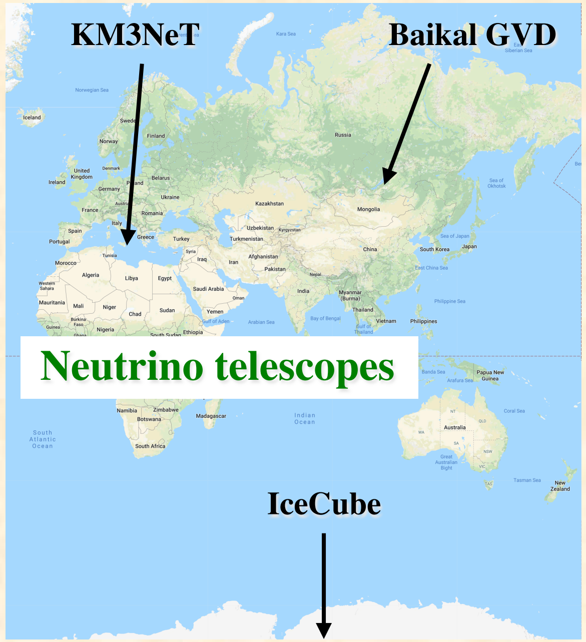
Nucleons and nuclei should be described by quark and gluon degrees of freedom at high energies, whereas they are described by hadron d.o.f. at low energies.

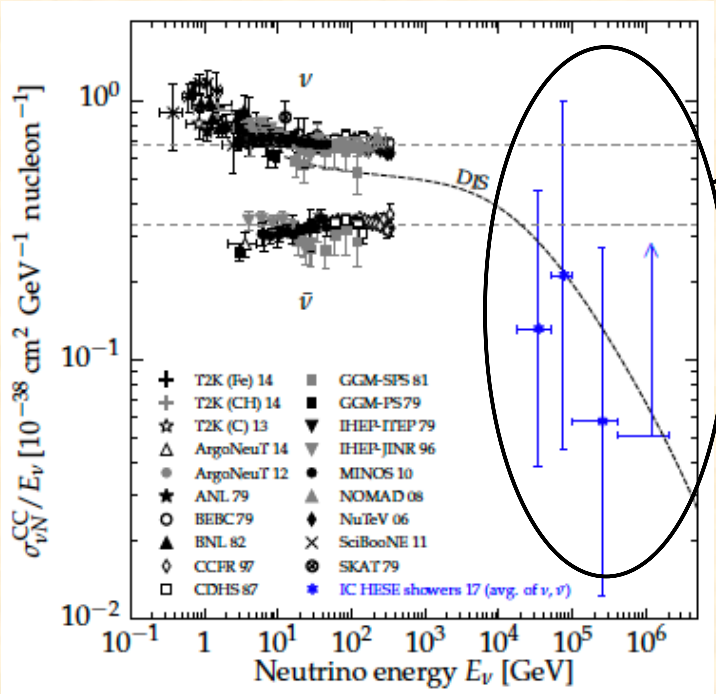


Ultrahigh-energy neutrino interactions



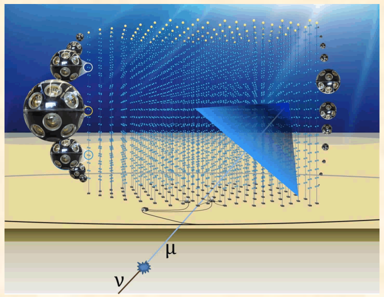
In the current neutrino oscillation experiments such as T2K, the DIS region is not important. However, ultrahigh-energy cross sections are dominated by DIS.



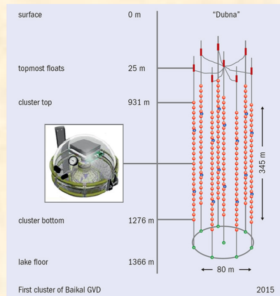


IceCube

M. Bustamante and A. Connolly, arXiv:1711043



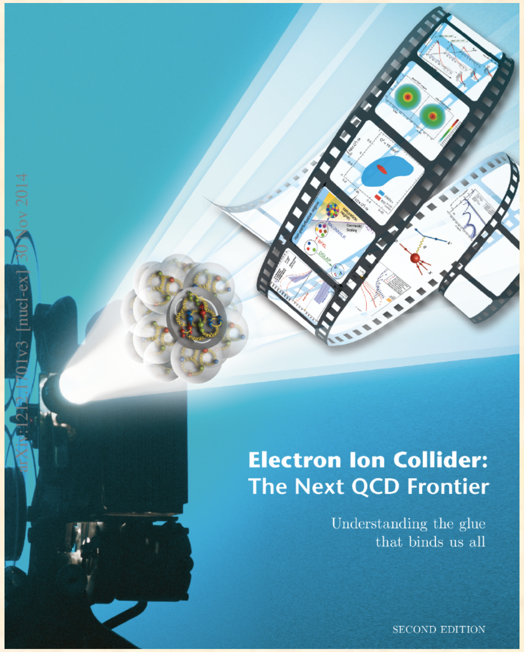
KM3NeT
(Cubic Kilometre Neutrino Telescope)

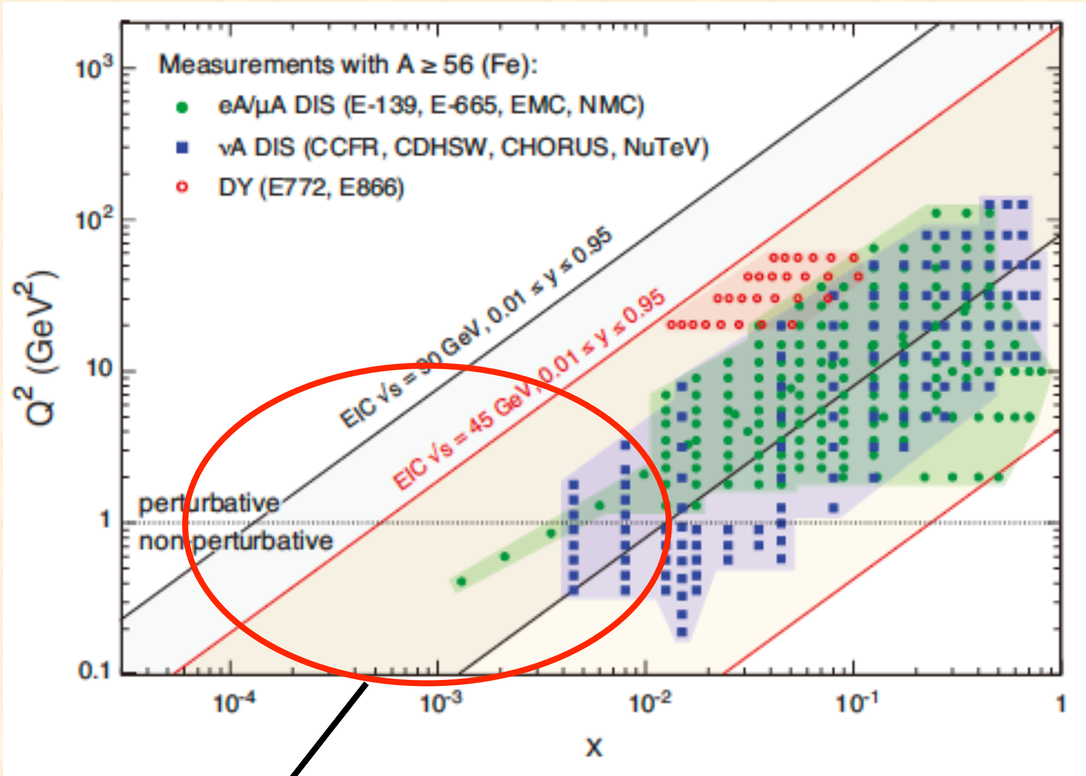


Baikal GVD
(Gigaton Volume Detector)

Kinematical region of EIC

arXiv:1212.1701





EIC: Measurements at $x = 10^{-4} \sim 10^{-2}$ with reasonably-large Q^2

Structure functions of nucleon and nuclei

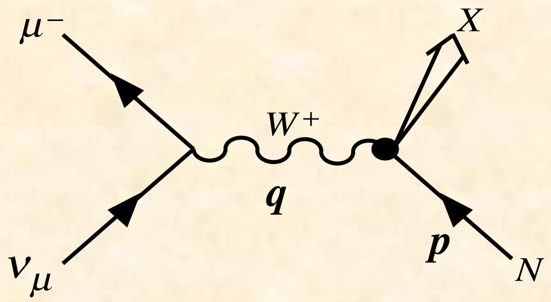
Deep inelastic scattering (DIS)

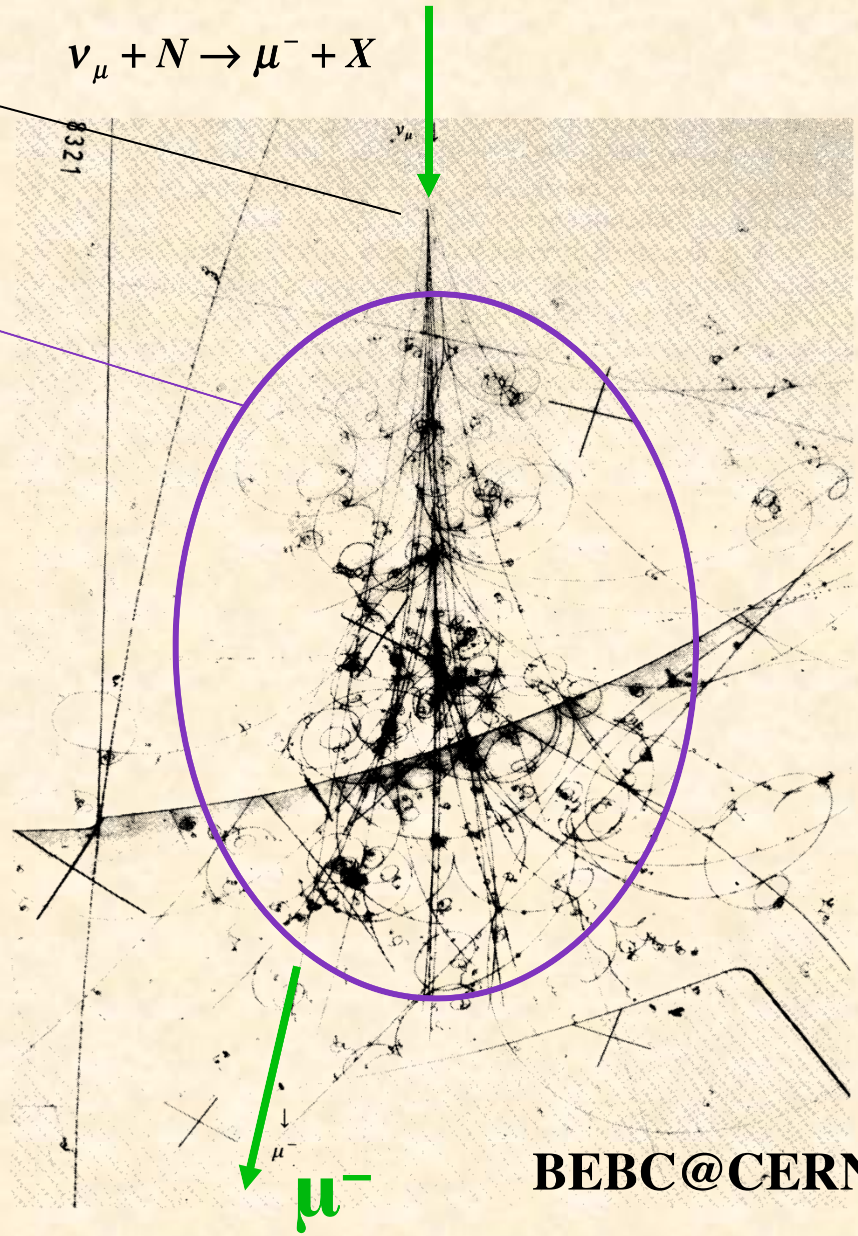
ν_μ ~ 200 GeV

$\nu_\mu + N \rightarrow \mu^- + X$

A nucleon is broken up by a high-energy neutrino.

Hadrons are produced; however, these are not usually measured. (inclusive reaction)





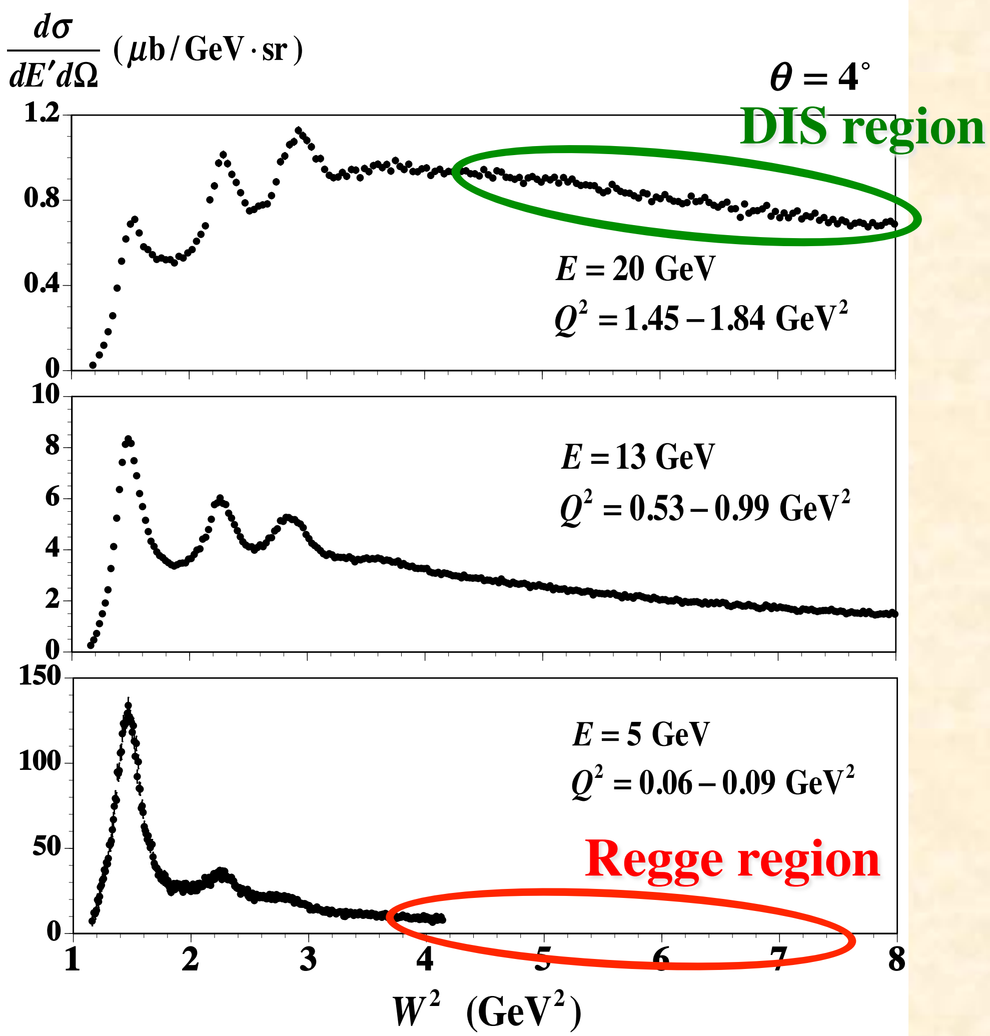
Momentum transfer: $q^2 = (k - k')^2 = -Q^2$

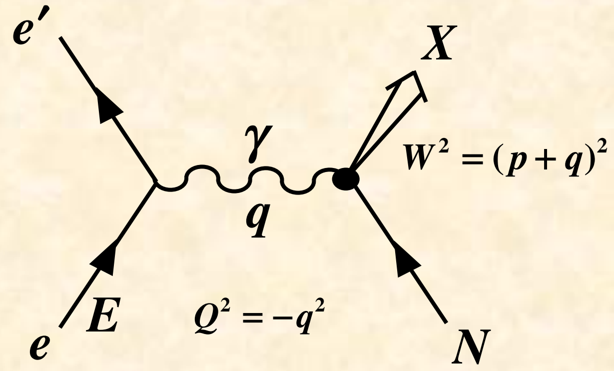
Bjorken scaling variable: $x = \dfrac{Q^2}{2p \cdot q}$

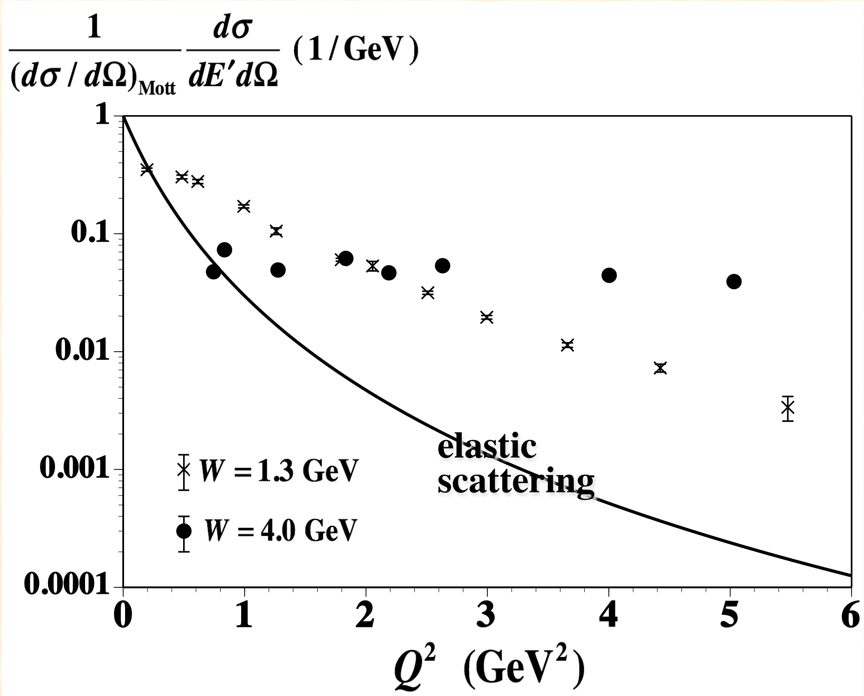
Invariant mass: $W^2 = p_X^2 = (p+q)^2$

BEBC@CERN

Lepton scattering



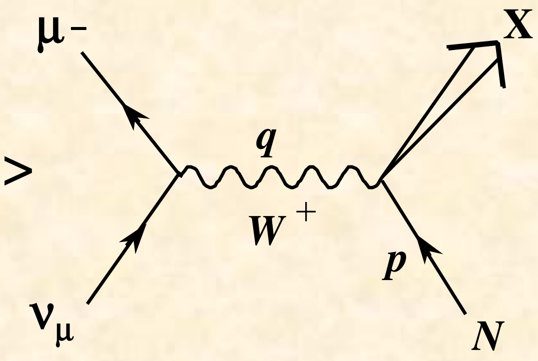




Neutrino deep inelastic scattering (CC: Charged Current)

$$d\sigma = \frac{1}{4k\cdot p}\,\frac{1}{2}\sum_{spins}\sum_{X}(2\pi)^4\,\delta^4(k+p-k'-p_X)\,|M|^2\,\frac{d^3k'}{(2\pi)^3\,2E'}$$

$$M = \frac{1}{1+Q^2/M_W^2}\,\frac{G_F}{\sqrt{2}}\,\bar{u}(k',\lambda')\,\gamma^{\mu}\,(1-\gamma_5)\,u(k,\lambda)\,<X|J_{\mu}^{CC}|p,\lambda_p>$$



$$\frac{d\sigma}{dE'd\Omega} = \frac{G_F^2}{(1+Q^2/M_W^2)^2}\,\frac{k'}{32\pi^2 E}\,L^{\mu\nu}\,W_{\mu\nu}$$

$$L^{\mu\nu} = 8\left[k^{\mu}k'^{\nu} + k'^{\mu}k^{\nu} - k\cdot k'\,g^{\mu\nu} + \underline{i\varepsilon^{\mu\nu\rho\sigma}k_{\rho}k'_{\sigma}}\right], \quad \varepsilon_{0123} = +1$$

$$W_{\mu\nu} = -W_1\left(g_{\mu\nu} - \frac{q_{\mu}q_{\nu}}{q^2}\right) + W_2\,\frac{1}{M^2}\left(p_{\mu} - \frac{p\cdot q}{q^2}q_{\mu}\right)\left(p_{\nu} - \frac{p\cdot q}{q^2}q_{\nu}\right) + \frac{i}{2M^2}\,\underline{W_3\varepsilon_{\mu\nu\rho\sigma}p^{\rho}q^{\sigma}}$$

$$MW_1 = F_1\,,\ \ \nu W_2 = F_2\,,\ \ \nu W_3 = F_3\,,\ \ x = \frac{Q^2}{2p\cdot q}\,,\ \ y = \frac{p\cdot q}{p\cdot k}$$

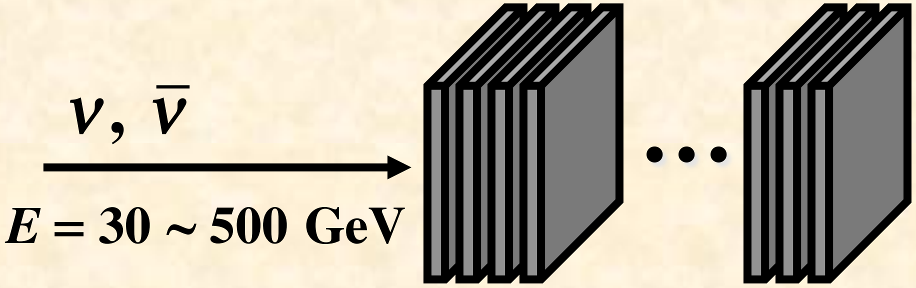
$$\frac{d\sigma^{CC}_{\nu,\bar{\nu}}}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi\,(1+Q^2/M_W^2)^2}\left[x\,y^2 F_1^{CC} + \left(1 - y - \frac{M\,x\,y}{2E}\right)F_2^{CC} \underline{\pm\,x\,y\left(1-\frac{y}{2}\right)F_3^{CC}}\right]$$

Neutrino DIS experiments

• **CDHS,**	**H. Abramowics *et al*.,**	**Z. Phys. C 25 (1984) 29**
• **WA25,**	**D. Allasia *et al*.,**	**Z. Phys. C 28 (1985) 321**
• **WA59,**	**K. Varvell *et al*.,**	**Z. Phys. C 36 (1987) 1**
• **CDHSW,**	**P. Berge *et al*.,**	**Z. Phys. C 49 (1991) 187**
• **Serpukhov,**	**A. V. Sidorov *et al*.,**	**Eur. Phys. J. C 10 (1999) 405**
• **CCFR,**	**U.-K. Yang *et al*.,**	**PRL 86 (2001) 2742**
• **NuTeV/CCFR $\mu^+\mu^-$,**	**M. Goncharov *et al*.,**	**PRD 64 (2001) 112006**
• **CHORUS,**	**G. Onengut *et al*.,**	**PLB 632 (2006) 65**
• **NuTeV,**	**M. Tzanov *et al*.,**	**PRD 74 (2006) 012008**
• **Minverva,**	**J. Mousseau *et al*.,**	**PRD 93 (2016) 071101, in progress**

Neutrino DIS experiments

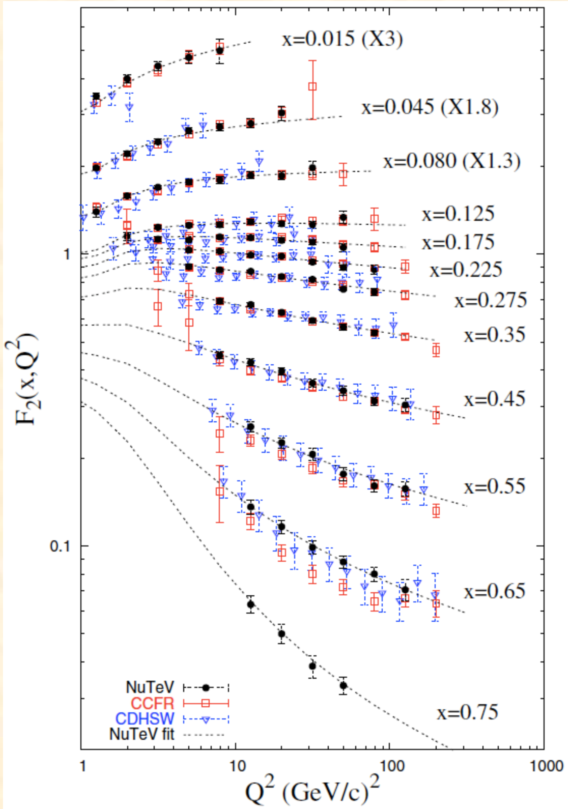
Experiment	Target	ν energy (GeV)
CCFR	Fe	30-360
CDHSW	Fe	20-212
CHORUS	Pb	10-200
NuTeV	Fe	30-500

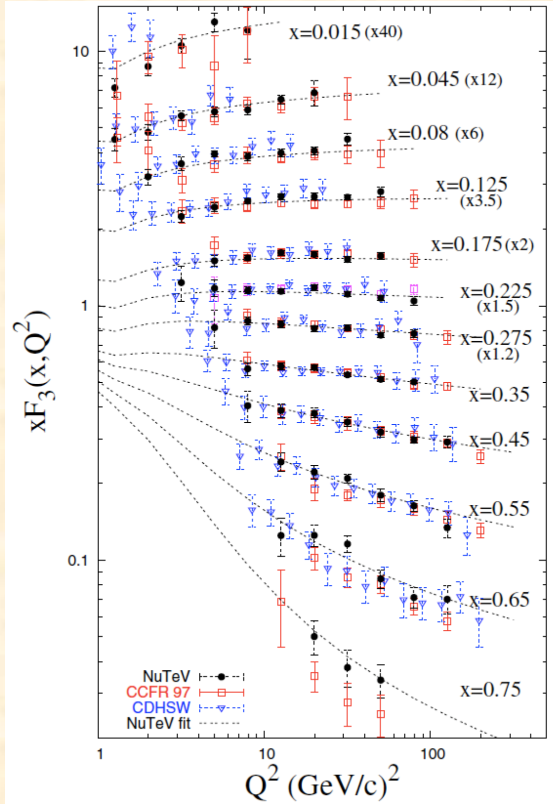


Huge Fe target (690 ton)

MINERνA (He, C, Fe, Pb), …

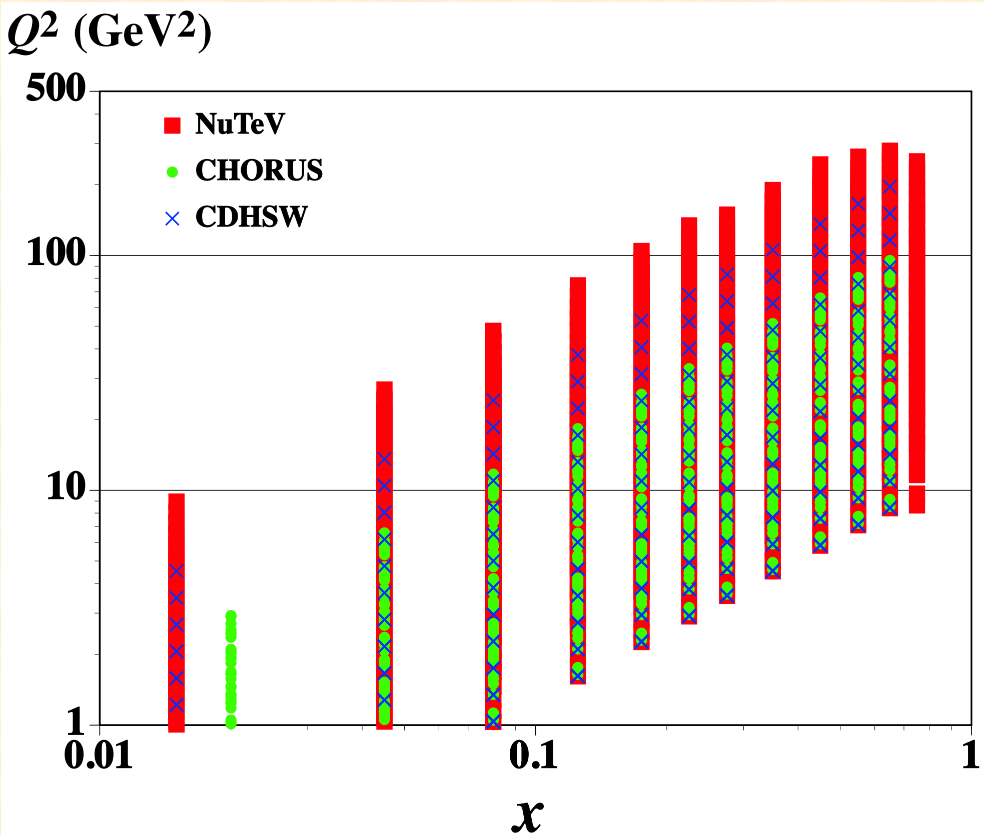
M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.



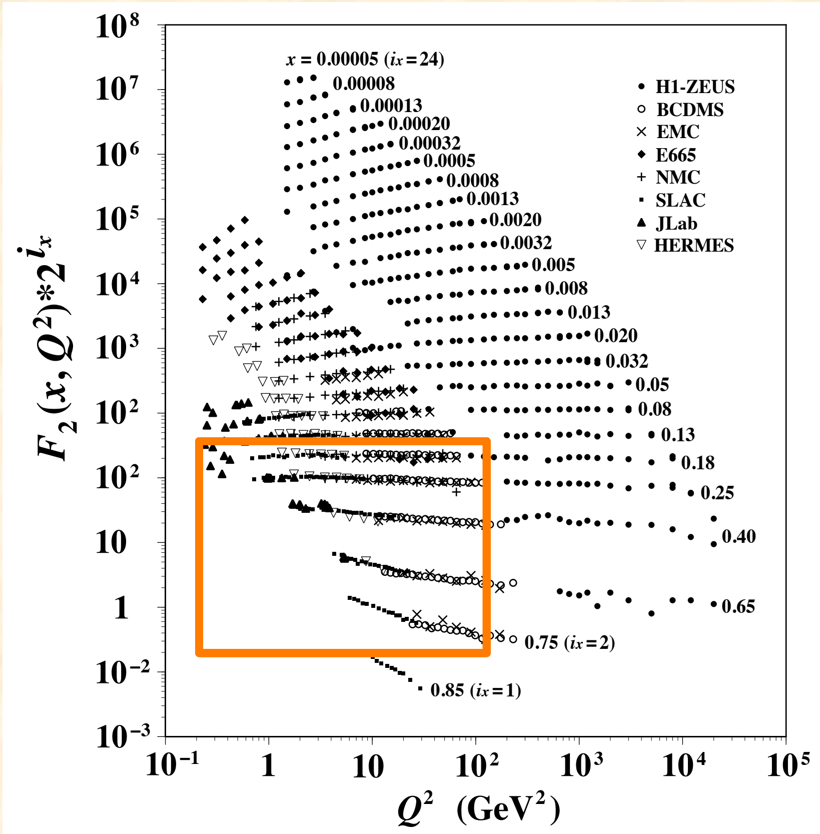


Neutrino DIS experiments: kinematical range

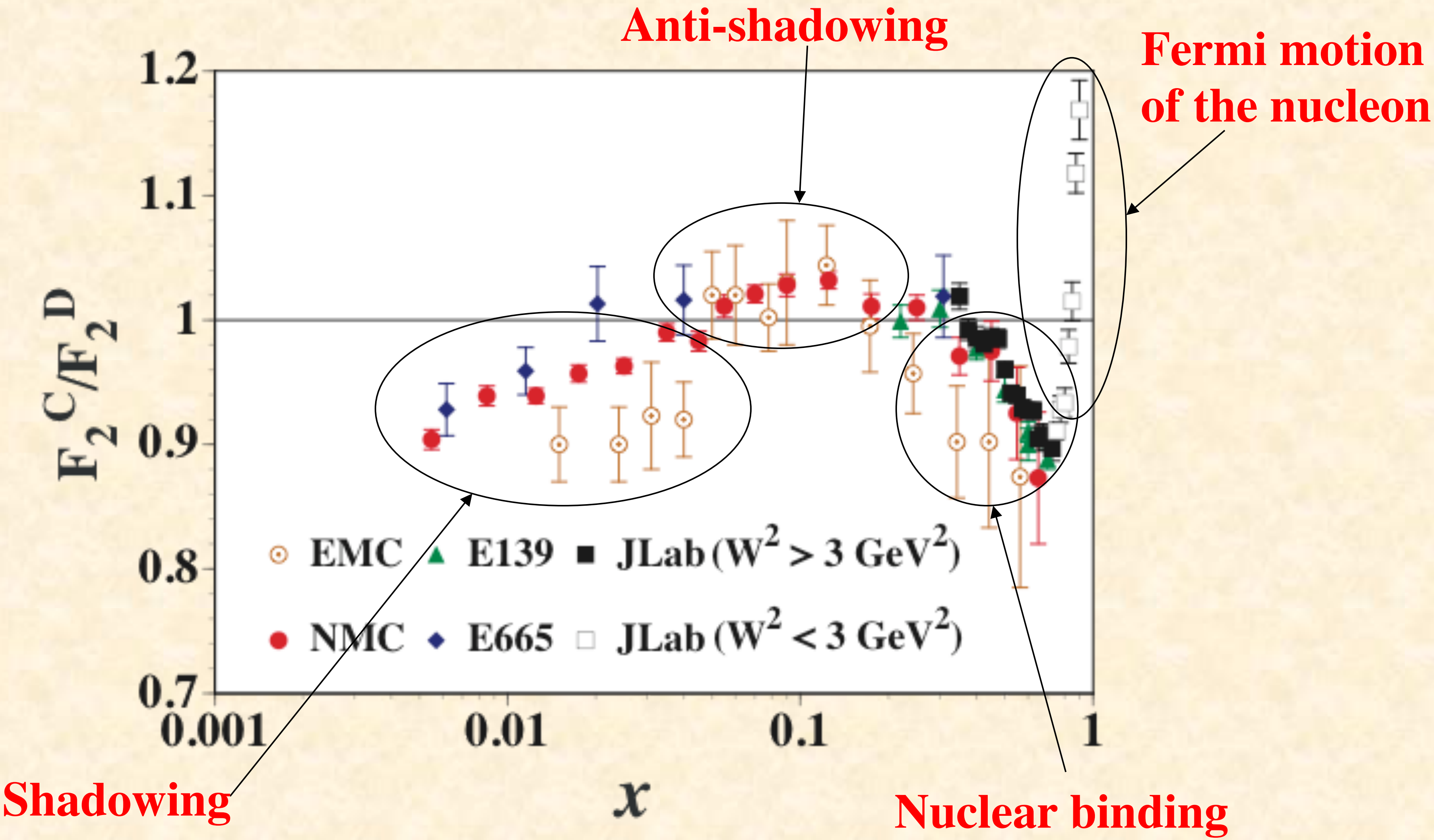
Neutrino DIS



Charged-lepton DIS



Nuclear modifications of structure function F_2



D. F. Geesaman, K. Saito, A. W. Thomas,
Ann. Rev. Nucl. Part. Sci. 45 (1995) 337

Global analyses on nuclear PDFs

I may miss some papers.

HKN M. Hirai, S. Kumano, and T. -H. Nagai, Phys. Rev. C 76 (2007) 065207.
Charged-lepton DIS, DY

EPS K. J. Eskola, H. Paukkunen, and C. A. Salgado, JHEP 04 (2009) 065;
Eur. Phys. J. C77 (2017) 163.
Charged-lepton DIS, DY, π^0 production in dAu, Neutrino

nCTEQ I. Schienbein, J. Y. Yu, C. Keppel, J. G. Morfin, F. I. Olness, J. F. Owens,
Phys. Rev. D 77 (2008) 054013; D80 (2009) 094004;
K. Kovarik *et al.*, PRL 106 (2011) 122301; PoS DIS2013 (2013) 274;
PoS DIS2014 (2014) 047; Phys. Rev. D 93 (2016) 085037.
Neutrino DIS, Charged-lepton DIS, DY

DSZS D. de Florian, R. Sassot, P. Zurita, M. Stratmann,
Phys. Rev. D85 (2012) 074028.
Charged-lepton DIS, DY, RHIC-π

See also L. Frankfurt, V. Guzey, and M. Strikman, Phys. Rev. D 71 (2005) 054001;
Phys. Lett. B687 (2010) 167; Phys. Rept. 512 (2012) 255;
Phys. Lett. B726 (2013) 290; B752 (2016) 51.
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023; C 82 (2010) 054614;
C 90 (2014) 045204; D 94 (2016) 113013.
A. Bodek and U.-K. Yang, arXiv:1011.6592.

Global nuclear PDF analysis

Q^2 evolution by the DGLAP equation

- Supply the initial nuclear PDFs $f_i(x)$ at the initial scale Q_0^2.
- No unique functional form.

The nuclear PDFs should satisfy the following conservations.

- Baryon number: $A\int\left[\frac{1}{3}u_v^A(x)+\frac{1}{3}d_v^A(x)\right]dx = A$
- Charge: $A\int\left[\frac{2}{3}u_v^A(x)-\frac{1}{3}d_v^A(x)\right]dx = Z$
- Momentum: $A\sum_{i=q,\bar{q},g}\int xf_i^A(x)\,dx = A$ (Note: NPDFs are defined the ones per nucleon.)

Three parameters are fixed by these conditions.

The distributions are neglected in the region $1 < x < A$.

- No DIS data.
- Structure functions are very small in this region.

$0 \le x_A = \frac{Q^2}{2M_A\nu} \le 1.$

$x_A = \frac{Q^2}{2M_A\nu} = \frac{M_N}{M_A}\frac{Q^2}{2M_N\nu} \simeq \frac{1}{A}x \le 1$

$\Rightarrow$ $0 \le x \lesssim A$ for a nucleus

Functional form of initial distributions at Q_0^2

Initial nuclear PDFs at

$$f_i^A(x) = \frac{1}{A}\left[Z f_i^{p/A}(x) + (A-Z) f_i^{n/A}(x)\right]$$

$f_i^{N/A}(x)$: PDF of bound nucleon in the nucleus

Isospin symmetry is assumed: $u \equiv d^n = u^p,\ d \equiv u^n = d^p$

Functional forms

- HKN07 ($Q_0^2 = 1$ GeV^2)

$$f_i^A(x) = w_i(x,A,Z)\frac{1}{A}\left[Z f_a^p(x) + (A-Z) f_a^n(x)\right], \qquad w_i(x,A,Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{0.1}}$$

- EPS09 ($Q_0^2 = 1.69$ GeV^2)

$$f_i^{N/A}(x) \equiv R_i^A(x) f_i^{\text{CTEQ6.1M}}(x,Q_0^2),\ R_i^A(x) = \begin{cases} a_0 + (a_1 + a_2 x)[\exp(-x) - \exp(-x_a)] & (x \le x_a: \text{shadowing}) \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & (x_a \le x \le x_e: \text{antishadowing}) \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & (x_e \le x \le 1: \text{EMC\&Fermi}) \end{cases}$$

- CTEQ-08 ($Q_0^2 = 1.69$ GeV^2)

$$x f_i^{N/A}(x) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1 + e^{A_4} x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s} \\ A_0 x^{A_1}(1-x)^{A_2} + (1 + A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u} \end{cases}$$

- DSZS12 ($Q_0^2 = 1.0$ GeV^2)

$$f_i^{N/A}(x) \equiv R_i^A(x) f_i^{MSTW\,2009}(x,Q_0^2),\ R_v^A(x) = \varepsilon_1 x^{\alpha_v}(1-x)^{\beta_1}[1 + \varepsilon_2(1-x)^{\beta_2}][1 + a_v(1-x)^{\beta_3}]$$

$$R_s^A(x) = R_v^A(x)\frac{\varepsilon_s}{\varepsilon_1}\frac{1 + a_s x^{\alpha_s}}{1 + a_s}, \quad R_g^A(x) = R_g^A(x)\frac{\varepsilon_g}{\varepsilon_1}\frac{1 + a_g x^{\alpha_g}}{1 + a_g}$$

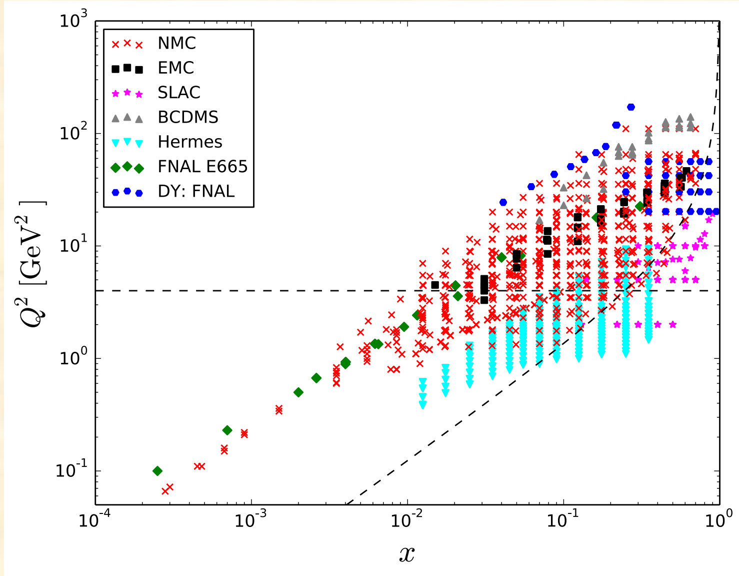
Recent analysis by nCTEQ15: data set

K. Kovarik *et al.*, PRD 93 (2016) 085037

Charged-lepton DIS

F_2^A/F_2^D Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
D	NMC-97	5160	[48]	292	201	247.73
He/D	Hermes	5156	[49]	182	17	13.45
	NMC-95,re	5124	[50]	18	12	9.78
	SLAC-E139	5141	[51]	18	3	1.42
Li/D	NMC-95	5115	[52]	24	11	6.10
Be/D	SLAC-E139	5138	[51]	17	3	1.37
C/D	FNAL-E665-95	5125	[53]	11	3	1.44
	SLAC-E139	5139	[51]	7	2	1.36
	EMC-88	5107	[54]	9	9	7.41
	EMC-90	5110	[55]	9	0	0.00
	NMC-95	5113	[52]	24	12	8.40
	NMC-95,re	5114	[50]	18	12	13.29
N/D	Hermes	5157	[49]	175	19	9.92
	BCDMS-85	5103	[56]	9	9	4.65
Al/D	SLAC-E049	5134	[57]	18	0	0.00
	SLAC-E139	5136	[51]	17	3	1.14
Ca/D	NMC-95,re	5121	[50]	18	12	11.54
	FNAL-E665-95	5126	[53]	11	3	0.94
	SLAC-E139	5140	[51]	7	2	1.63
	EMC-90	5109	[55]	9	0	0.00
Fe/D	SLAC-E049	5131	[58]	14	2	0.78
	SLAC-E139	5132	[51]	23	6	7.76
	SLAC-E140	5133	[59]	10	0	0.00
	BCDMS-87	5101	[60]	10	10	5.77
	BCDMS-85	5102	[56]	6	6	2.56
Cu/D	EMC-93	5104	[61]	10	9	4.71
	EMC-93(chariot)	5105	[61]	9	9	4.88
	EMC-88	5106	[54]	9	9	3.39
Kr/D	Hermes	5158	[49]	167	12	9.79
Ag/D	SLAC-E139	5135	[51]	7	2	1.60
Sn/D	EMC-88	5108	[54]	8	8	17.20
Xe/D	FNAL-E665-92	5127	[62]	10	2	0.72
Au/D	SLAC-E139	5137	[51]	18	3	1.74
Pb/D	FNAL-E665-95	5129	[53]	11	3	1.20
Total:				1205	414	403.70

$F_2^A/F_2^{A'}$ Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/Li	NMC-95,re	5123	[50]	25	7	5.56
Ca/Li	NMC-95,re	5122	[50]	25	7	1.11
Be/C	NMC-96	5112	[63]	15	14	4.08
Al/C	NMC-96	5111	[63]	15	14	5.39
Ca/C	NMC-95,re	5120	[50]	25	7	4.32
	NMC-96	5119	[63]	15	14	5.43
Fe/C	NMC-96	5143	[63]	15	14	9.78
Sn/C	NMC-96	5159	[64]	146	111	64.44
Pb/C	NMC-96	5116	[63]	15	14	7.74
Total:				296	202	107.85

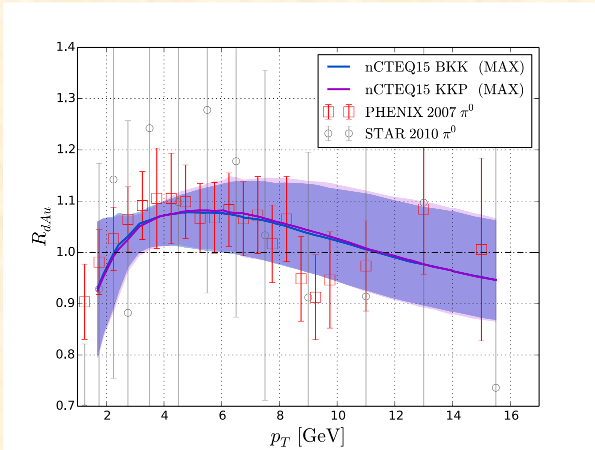


Drell-Yan

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	[65]	9	9	7.92
Ca/H2	FNAL-E772-90	5204	[65]	9	9	2.73
Fe/H2	FNAL-E772-90	5205	[65]	9	9	3.17
W/H2	FNAL-E772-90	5206	[65]	9	9	7.28
Fe/Be	FNAL-E886-99	5201	[66]	28	28	23.09
W/Be	FNAL-E886-99	5202	[66]	28	28	23.62
Total:				92	92	67.81

Pion-production in dA

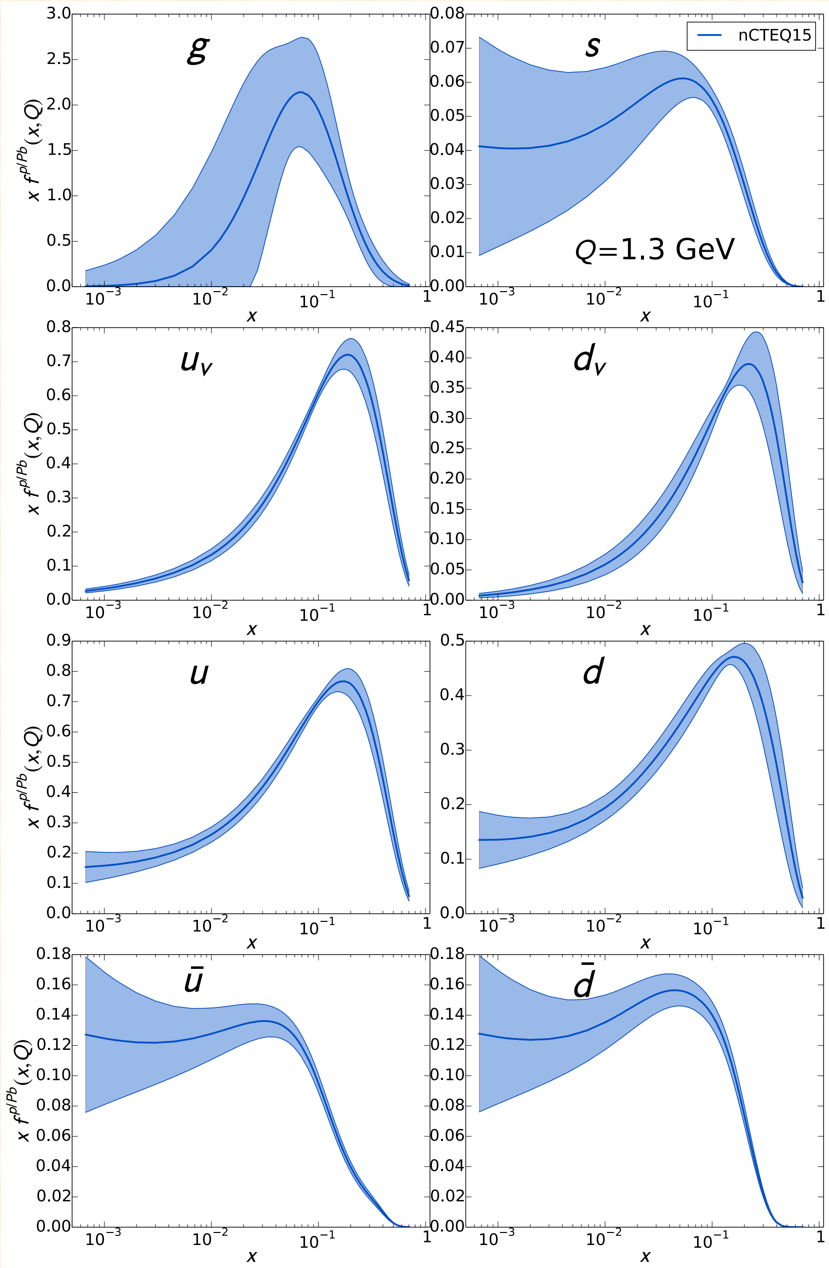
$R_{dAu}^{\pi}/R_{pp}^{\pi}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	[67]	21	20	6.63
	STAR-2010	STAR	[68]	13	12	1.41
Total:				34	32	8.04

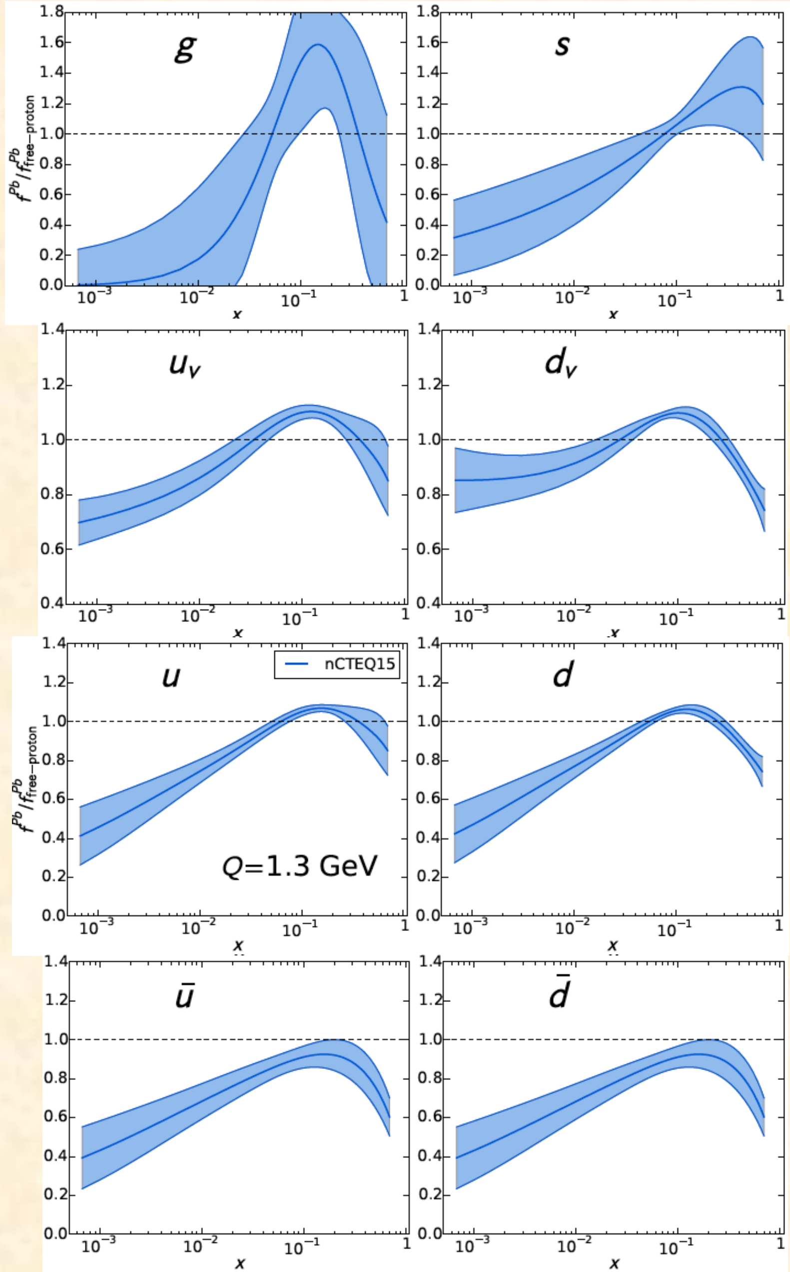


- DIS: $Q > 2$ GeV and $W > 3.5$ GeV
- DY: $2 < M < 300$ GeV
- π^0 production: $p_T > 1.7$ GeV

nCTEQ15

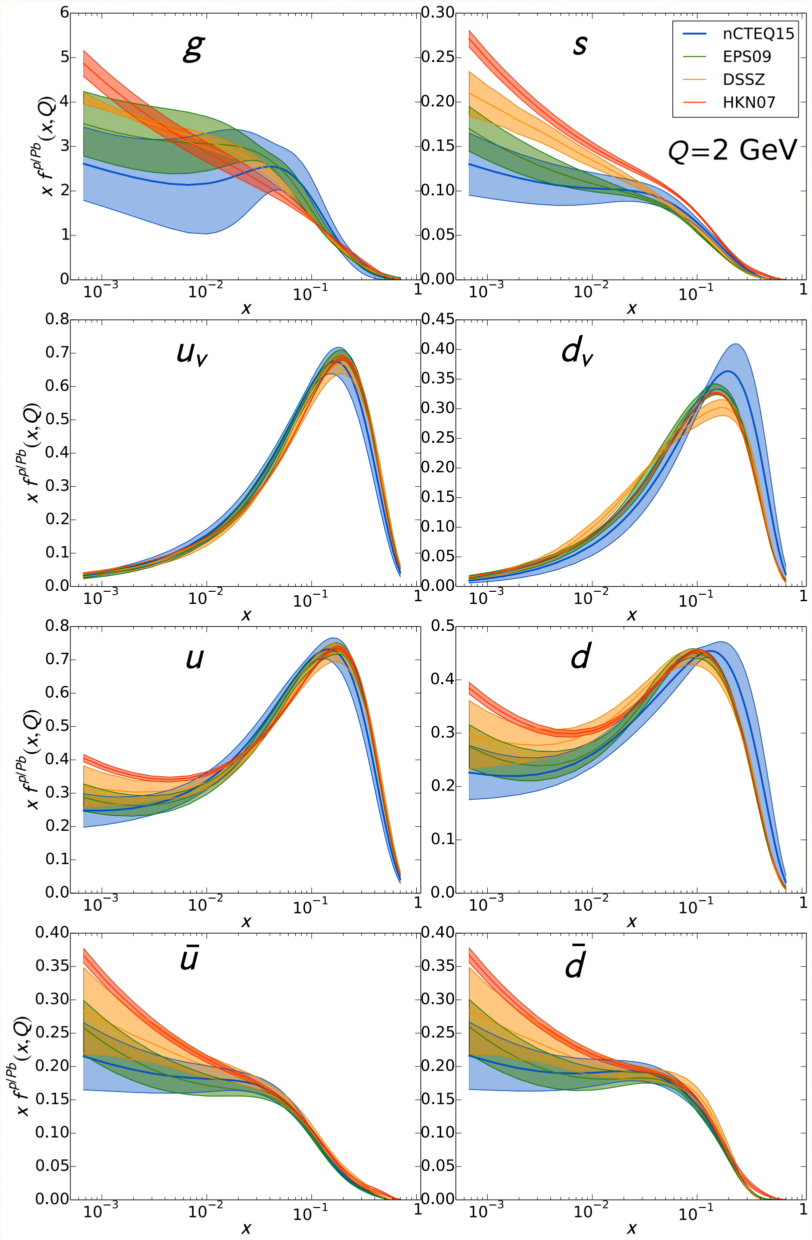
$Q^2 = (1.3)^2 \text{ GeV}^2$

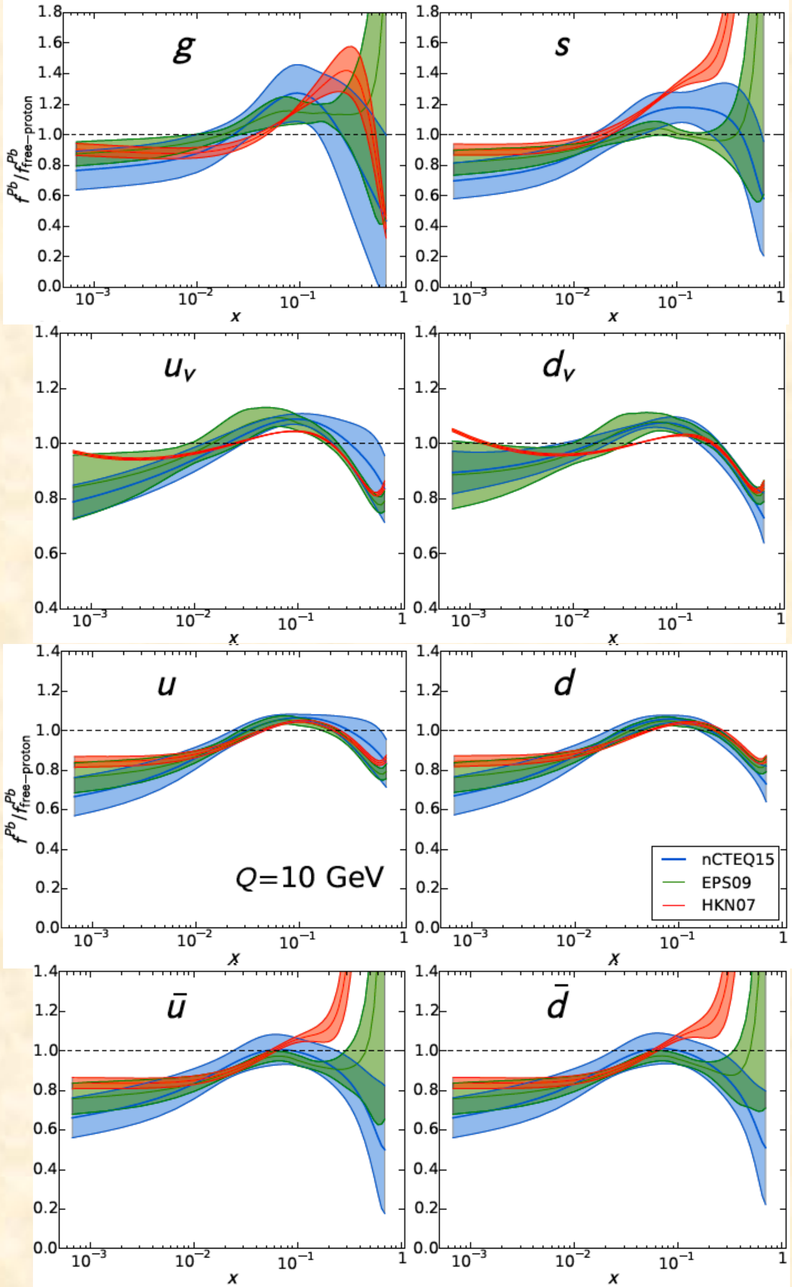




nCTEQ15: Comparison with others

$Q^2 = (2)^2\ \text{GeV}^2$





Scaling Violation and Gluon Distributions

EIC contribution

$$\frac{\partial}{\partial \log Q^2} q_i^+(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[\sum_j P_{q_i q_j}(x/y)\, q_j^+(y,Q^2) + P_{qg}(x/y)\, g(y,Q^2)\right]$$

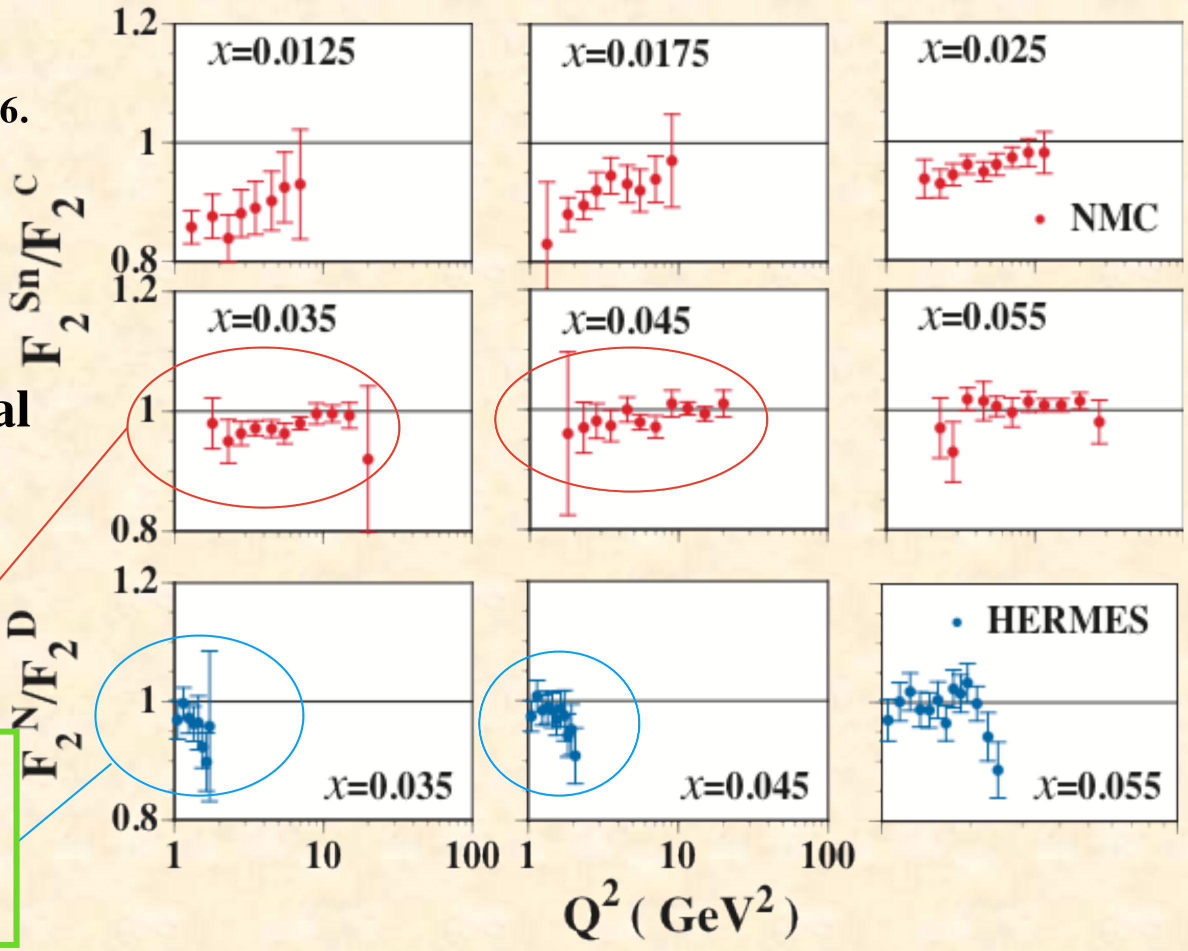
dominant term at small x

$$q_i^+ = q_i + \bar{q}_i$$

at small x K. Prytz, PLB 311 (1993) 286.

$$\frac{\partial F_2}{\partial(\ln Q^2)} \simeq \frac{20\alpha_s}{27\pi} xg$$

Q^2 dependence of F_2 is proportional to the gluon distribution.

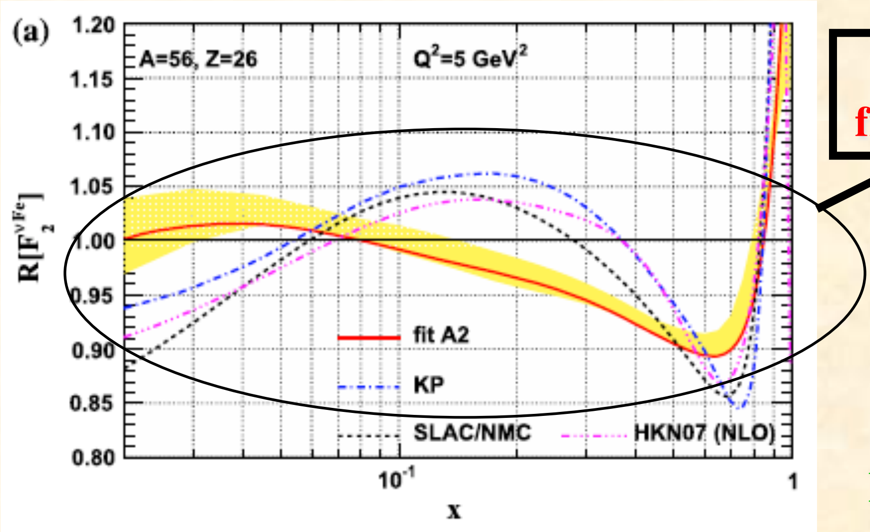


No experimental consensus of Q^2 dependence!

→ $G^A(x)$ determination is difficult.

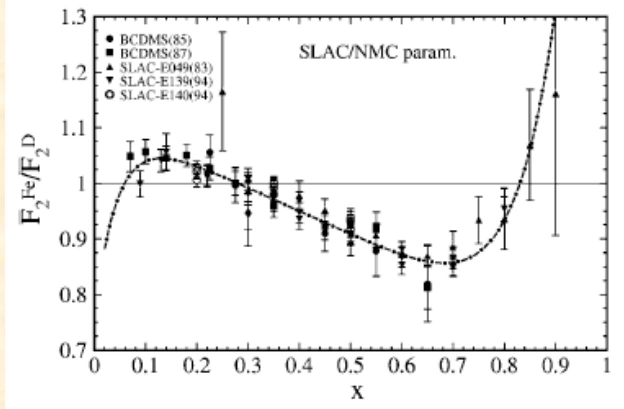
Analysis of CTEQ-2008 (Schienbein *et al.*)

I. Schienbein *et al.*,
PRD 77 (2008) 054013

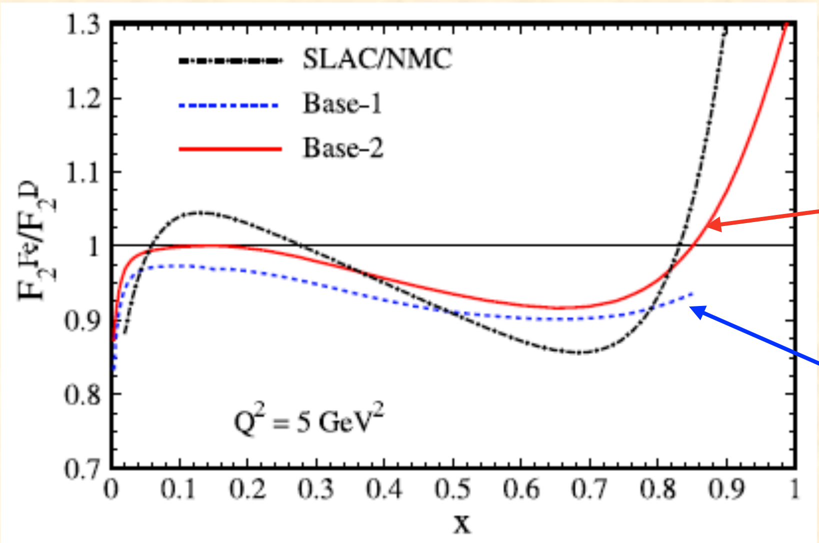


Differences from typical NPDFs.

Charged-lepton scattering



Neutrino scattering



Base-1
- remove CCFR data
- incorporate deuteron corrections

Base-2 corresponds to CTEQ6.1M with s≠sbar
- include CCFR data
  Charged-lepton correction factors are applied.
- s≠sbar

Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.

Base-1: However, it depends on the analysis method for determining "nucleonic" PDFs.

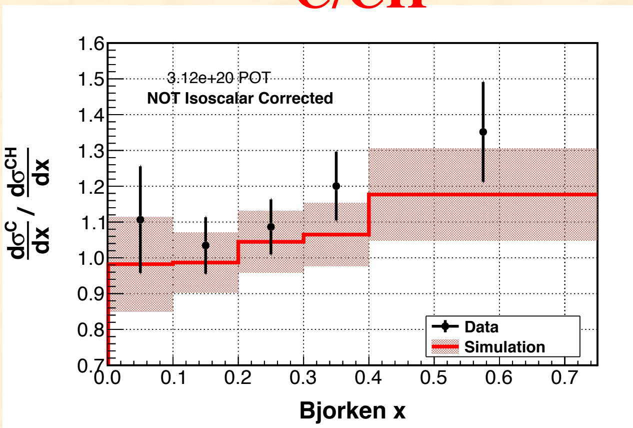
Recent progress on neutrino DIS ⇔ Charged DIS

Measurements by Minerνa

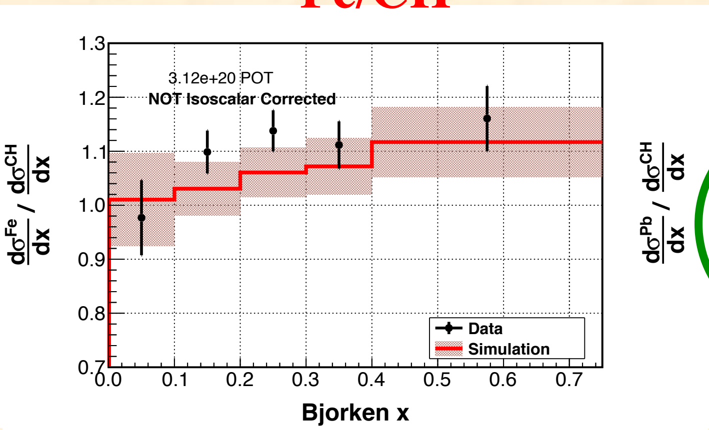
B. G. Tice *et al.*, PRL 112 (2014) 231801;
J. Mousseau *et al.*, PRD 93 (2016) 071101(R).

Different shadowing from charged-lepton case?!

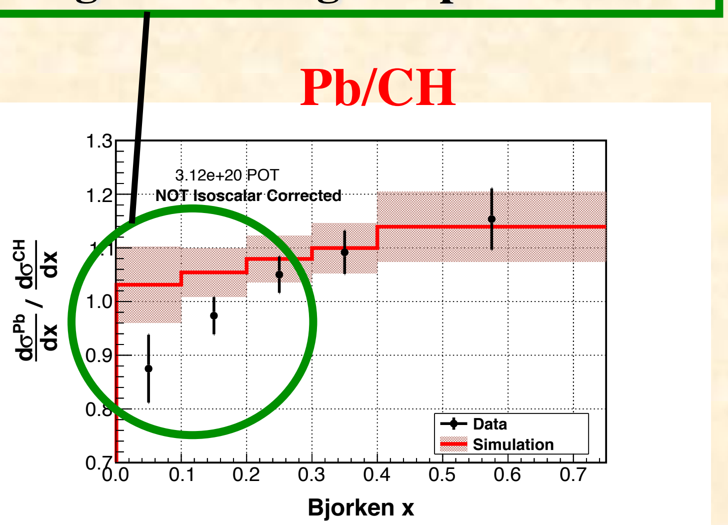
C/CH



Fe/CH

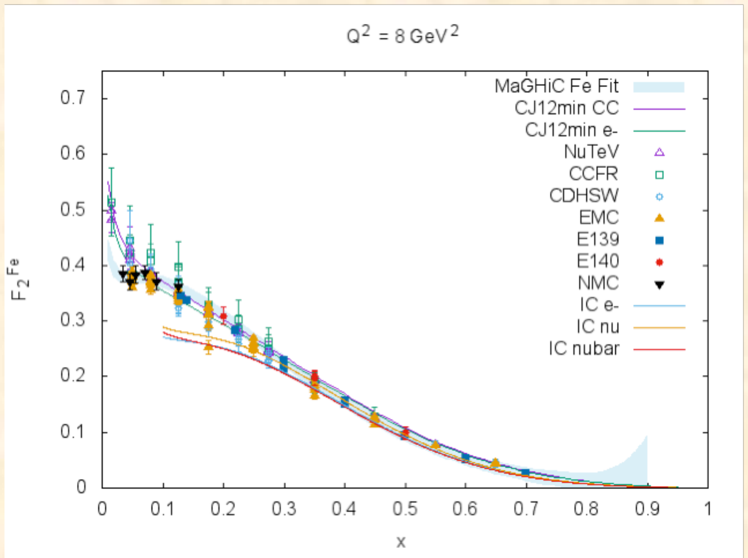


Pb/CH



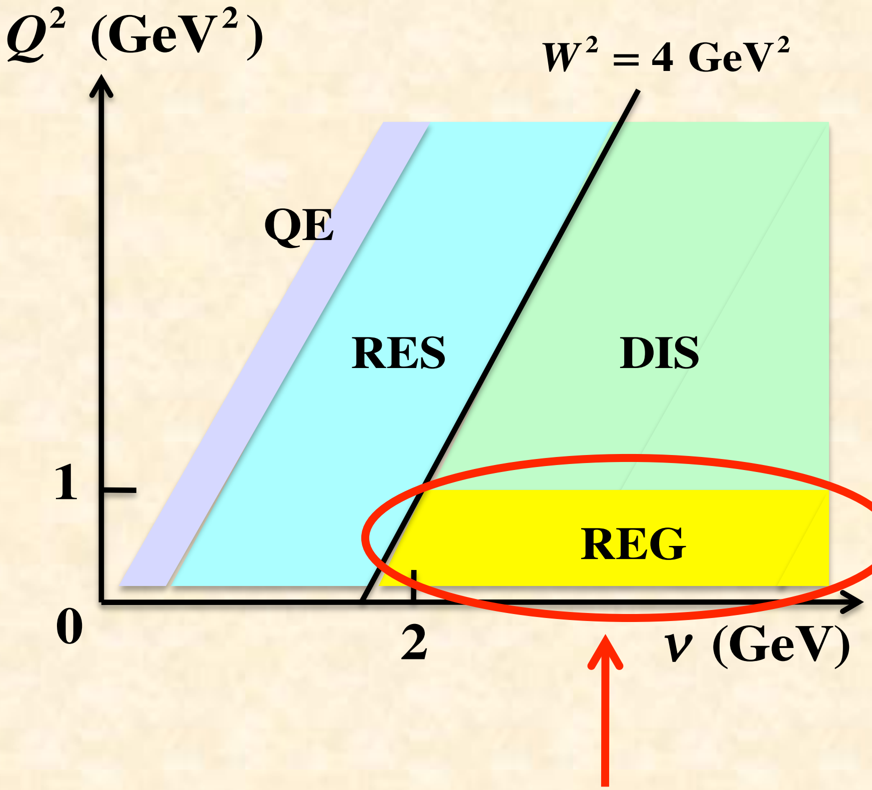
N. Kalantarians, E. Christy, and C. Keppel,
Phys. Rev. C 96, 032201 (2017)

According to this analysis, both structure functions are same except for the small-*x* region (x<0.05) .



Small Q^2 region

$Q^2 \to 0$ region: Theoretical background



$$F_{T,L} = \frac{\gamma}{\pi} Q^2 \sigma_{T,L}, \quad \gamma = \frac{|\vec{q}\,|}{q_0} = \sqrt{1 + \frac{Q^2}{\nu^2}}$$

$\sigma_{T,L}$ = Total ν cross section

$$\sim \sum_f (2\pi)^4 \delta(p + q - p_f) \left| \langle f | \varepsilon_{T,L} \cdot J(0) | p \rangle \right|^2$$

$F_{T,L}$ = transverse, longitudinal cross section

Vector current conservation: $q_\mu W^{\mu\nu} = 0$

$$\Rightarrow F_L^V \sim Q^2 F_T^V \text{ as } Q^2 \to 0$$

PCAC (Partially Conserved Axial-vector Current):

$\partial_\mu A^\mu(x) = f_\pi m_\pi^2 \pi(x)$, A^μ = Axial-vector current,

f_π = Pion-decay constant, π = Pion field

$$\Rightarrow F_L^A \sim \frac{f_\pi^2}{\pi} \sigma_\pi \text{ as } Q^2 \to 0,$$

Pion-scattering cross section: σ_π

References:
A. Donnachie and P. V. Landshoff, Z. Phys. C 61 (1994) 139
B. Z. Kopeliovich, Nucl. Phys. B 139 (2005) 219;
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023.

$Q^2 \to 0$ region: Practical descriptions in ν reactions

$F_{1,2,3}^{\nu A}(x, Q^2 \to 0)$

(1) FLUKA, G. Battistoni *et al*.,

Acta Phys. Pol. B 40 (2009) 2431

$$F_{2,3}(x,Q^2) = \frac{2Q^2}{Q_0^2 + Q^2} F_{2,3}(x,Q_0^2)$$

(2) A. Bodek and U.-K. Yang, arXiv:1011.6592

charged-lepton:

$$F_2^{e/\mu}(x,Q^2 < 0.8 \text{ GeV}^2) = K_{valence}^{vector}(Q^2) F_{2,LO}^{valance}(\xi_w, Q^2 = 0.8 \text{ GeV}^2) + K_{sea}^{vector}(Q^2) F_{2,LO}^{sea}(\xi_w, Q^2 = 0.8 \text{ GeV}^2)$$

$$K_{valence}^{vector}(Q^2) = \frac{Q^2}{Q^2 + C_s}, \quad K_{sea}^{vector}(Q^2) = \left[1 - G_D^2(Q^2)\right] \frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}$$

$$G_D(Q^2) = \frac{1}{(1 + Q^2/0.71)^2}, \quad \xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2\left[1 + \sqrt{1 + 4M^2x^2/Q^2}\right] + 2Ax}$$

neutrino:

Separate $F_i^\nu(x,Q^2)$ into vector and axial-vector parts.

$F_i^\nu(x,Q^2)_{\text{vector}} \to Q^2 \to 0 \quad (Q^2 \to 0)$ as the charged-lepton case.

$F_i^\nu(x,Q^2)_{\text{axial-vector}} \neq 0 \quad (Q^2 \to 0)$ due to PCAC.

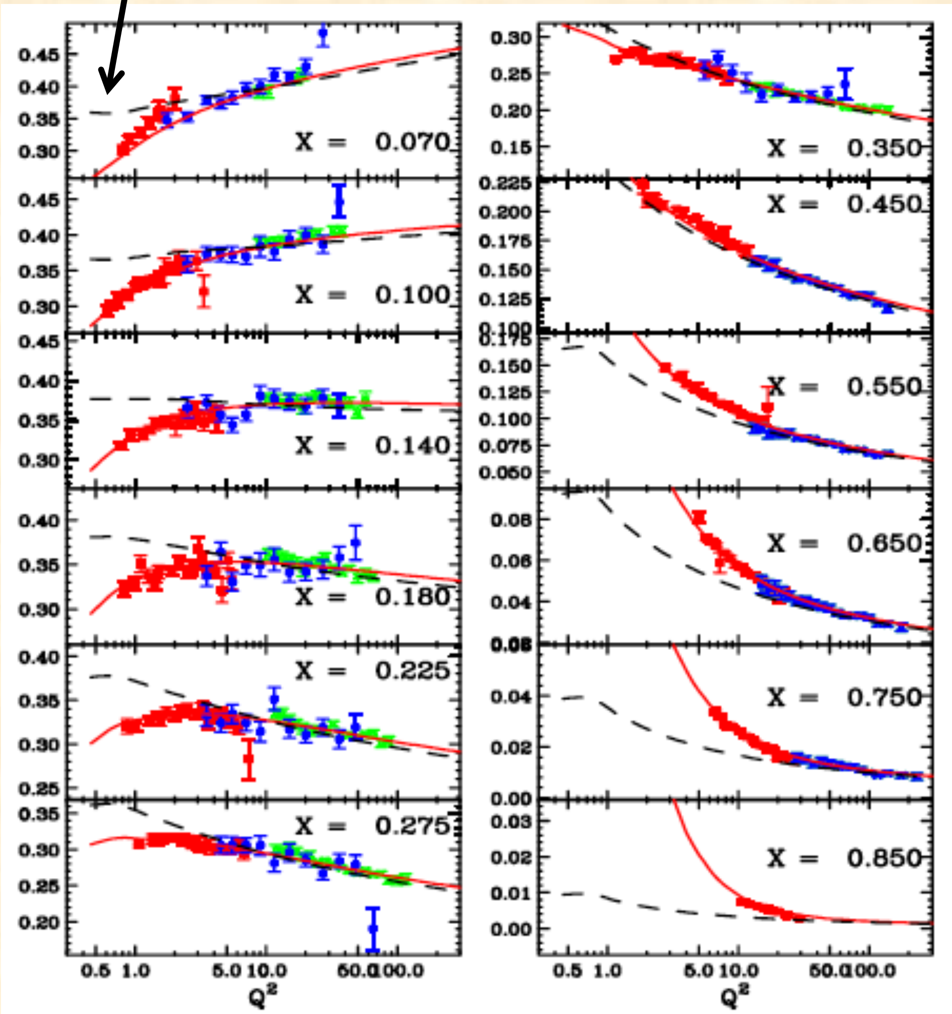
Actual expressions are slightly complicated (see the original paper).

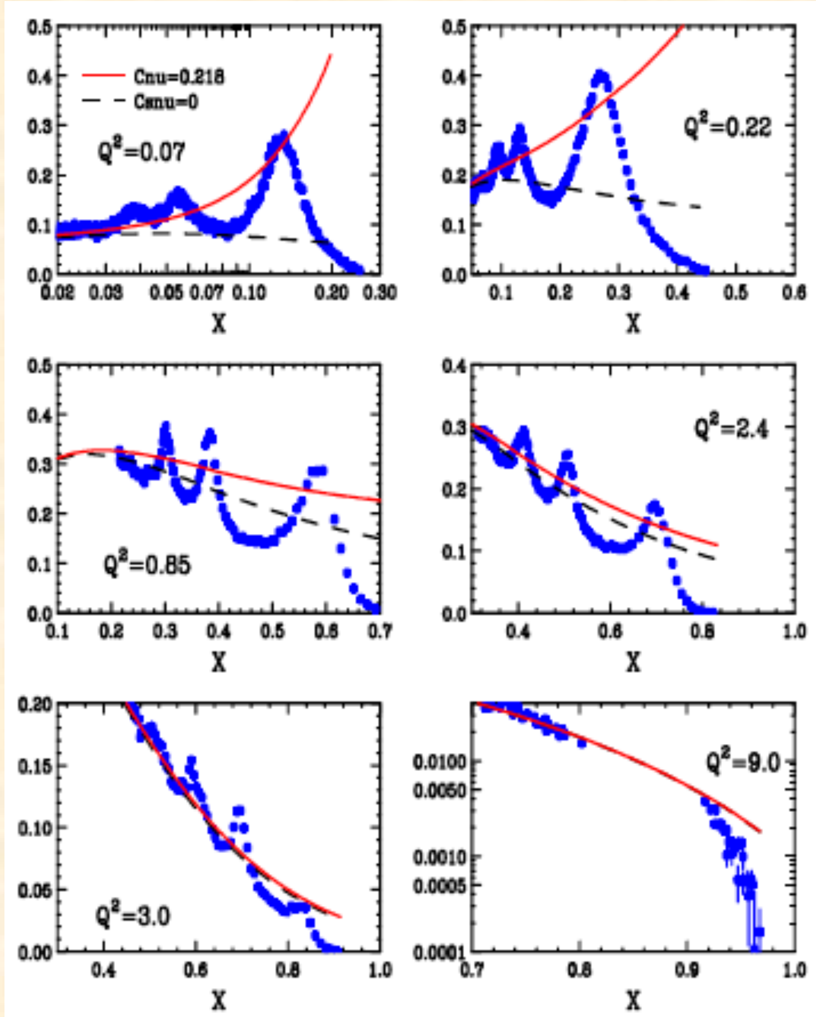
Comparison with charged-lepton data

A. Bodek and U.-K. Yang, arXiv:1011.6592

Summary on duality:
W. Melnitchouk, R. Ent, C. E. Keppel,
Phys. Rept. 406 (2005) 127.

– – – GRV98





Analysis in the Regge region

H. Kamano and SK

- There are accurate structure-function (or PDF) code in the DIS region for both nucleon and nuclei: $F_2(x,Q^2)$ at $Q^2 \geq Q_0^2 = 1 \sim 2$ GeV^2, $W^2 \geq W_0^2 \sim 4$ GeV^2.

- We use a DIS code and extrapolate it to the Regge region. So far, our analysis is on charged-lepton F_2.

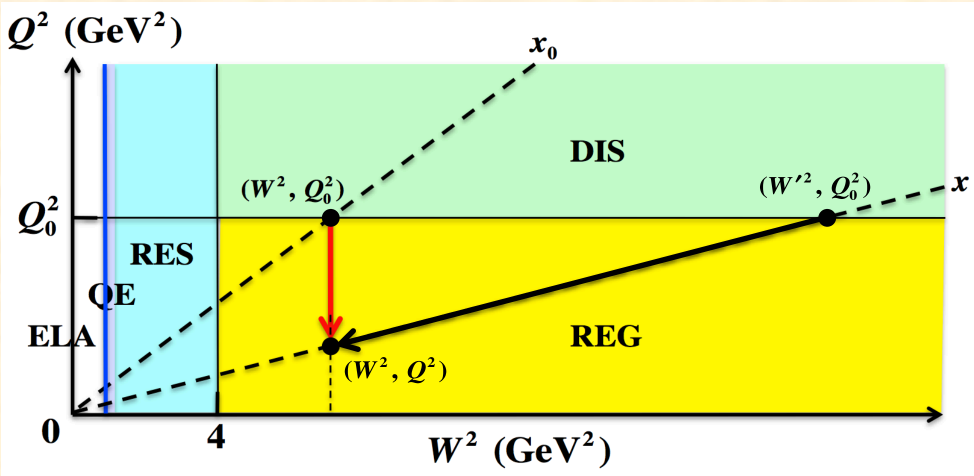
$$F_2(x,Q^2) = w(x,Q^2;x_0,Q_0^2)F_2(x_0,Q_0^2), \quad w(x,Q^2;x_0,Q_0^2) = \frac{F_2^{\text{REG}}(x,Q^2)}{F_2^{\text{REG}}(x_0,Q_0^2)}$$

$F_2^{\text{REG}}(x,Q^2) =$ structure function valid in the Regge region.

- We parametrize $F_2^{\text{REG}}(x,Q^2)$ based on the Regge + Pomeron picture.
  A. Donnachie and P. V. Landshoff, ZP C61 (1994) 139; PLB 518 (2001) 63;
  H. Abramowicz, E. Levin, A. Levy, U. Maor (ALLM), PLB 269 (1991) 465; hep-ph/9712415;
  I. Abt *et al*., M. Wing, PRD 94, 034032 (2016).

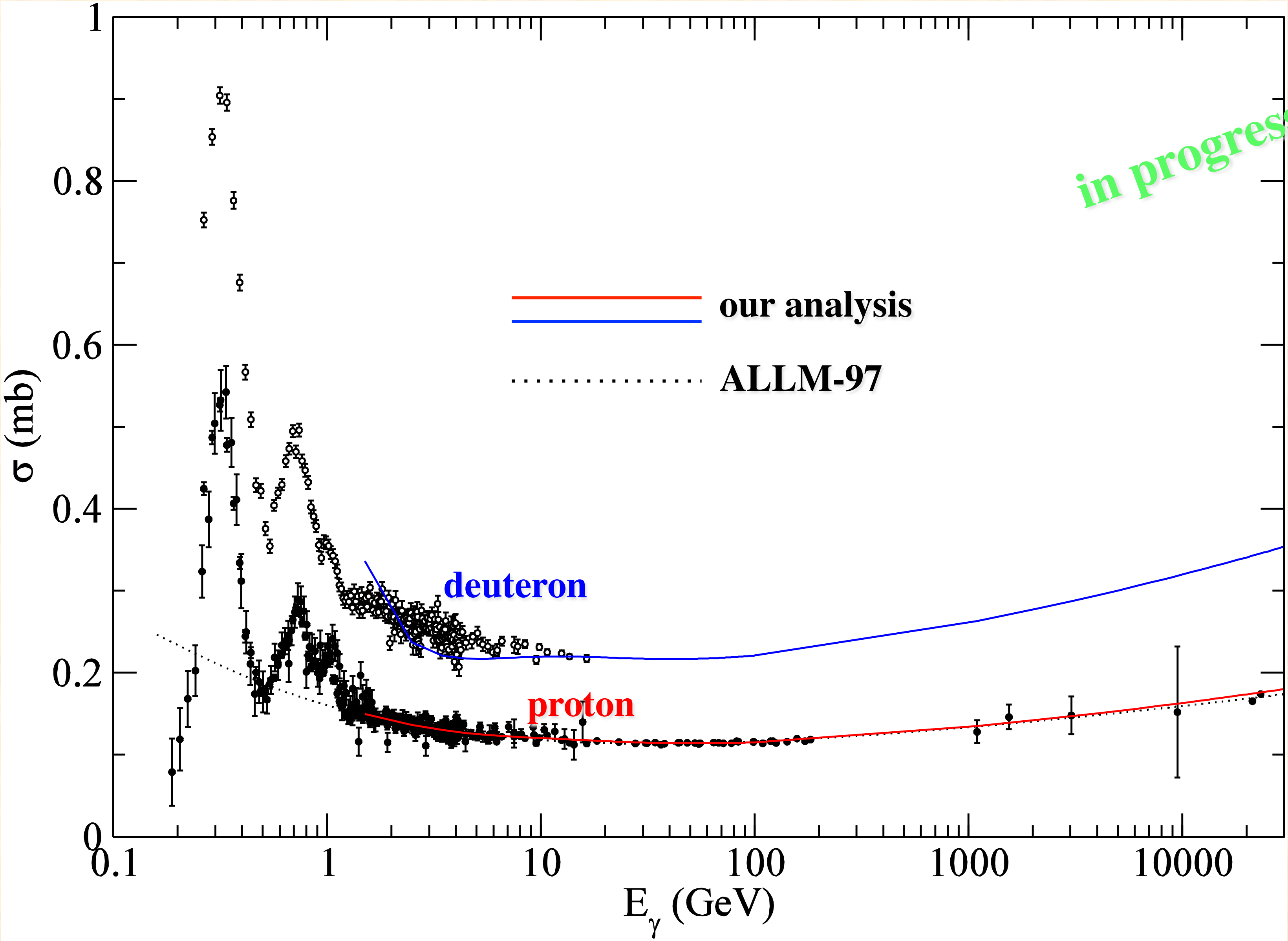
$$F_2^{\text{REG}}(x,Q^2) = \frac{Q^2}{m_0^2+Q^2}\left[F_2^P(x,Q^2)+F_2^R(x,Q^2)\right]$$

$$F_2^V(x,Q^2) = c_V x_V^{a_V(t)}(1-x)^{b_V(t)}, \quad V = P, R, \quad t = \ln\left[\frac{\ln\{(Q^2+\mu_0^2)/\Lambda^2\}}{\ln(\mu_0^2/\Lambda^2)}\right]$$



Experiment / Publication	Year
SLAC	1992
Fermilab-E665	1996
NMC	1997
H1-ZEUS	2010
HERMES	2011
JLab-C	2015
PDG2016-γp	2016

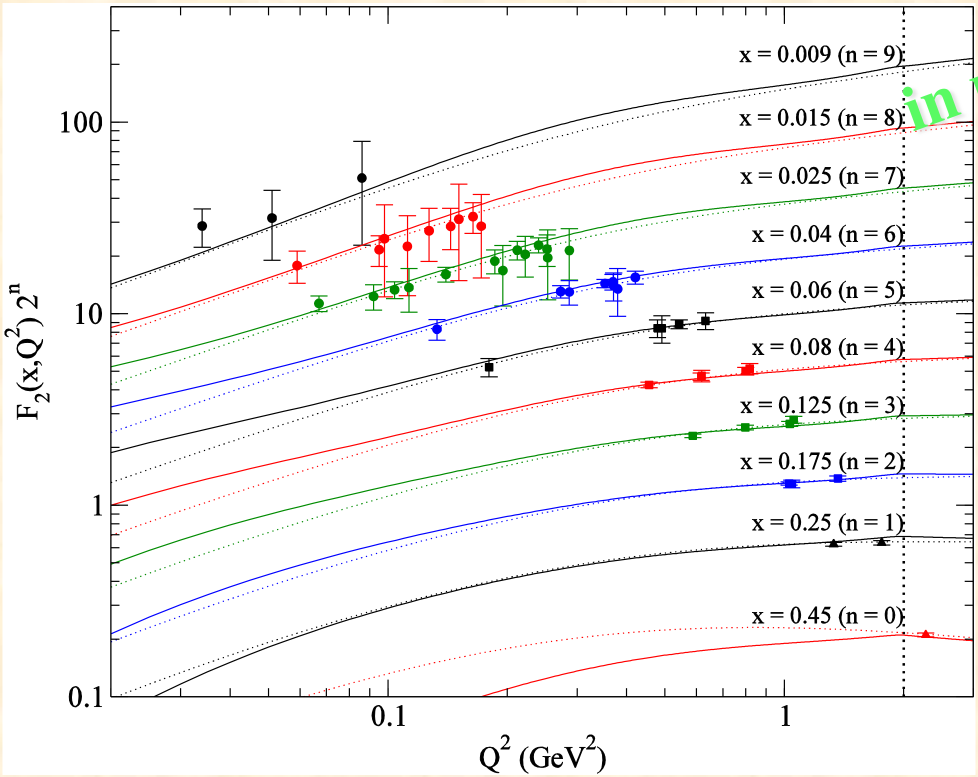
Photoproduction ($\gamma + p,d \rightarrow X$) cross sections



Comparison with JLab/SLAC data

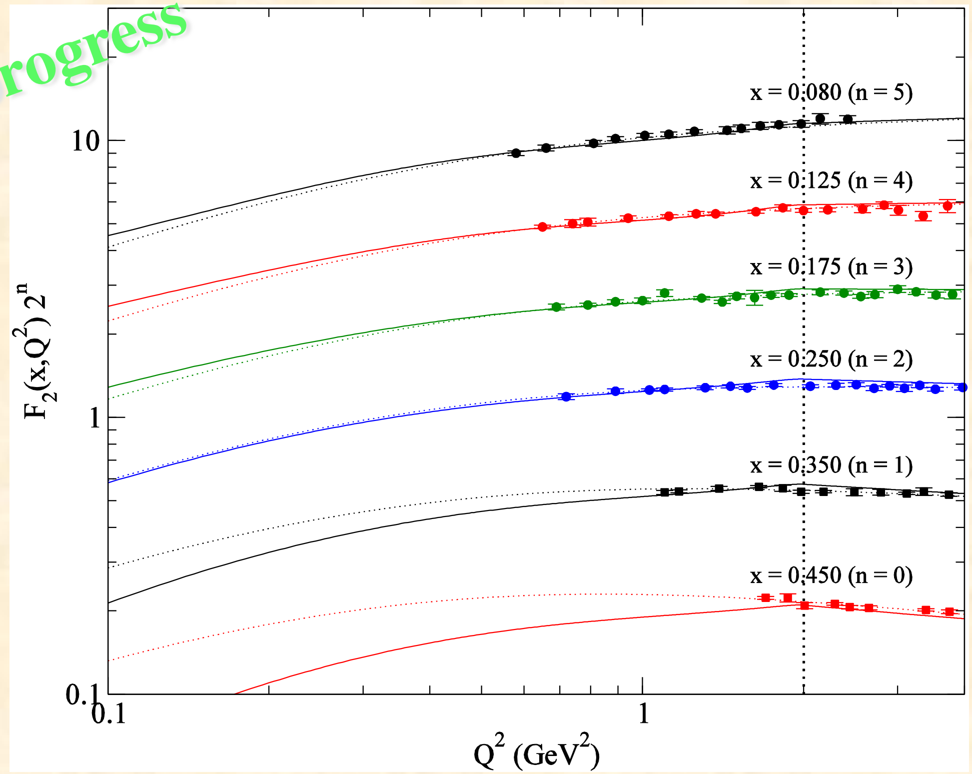
our analysis (solid line)
ALLM-97 (dotted line)

JLab



in progress

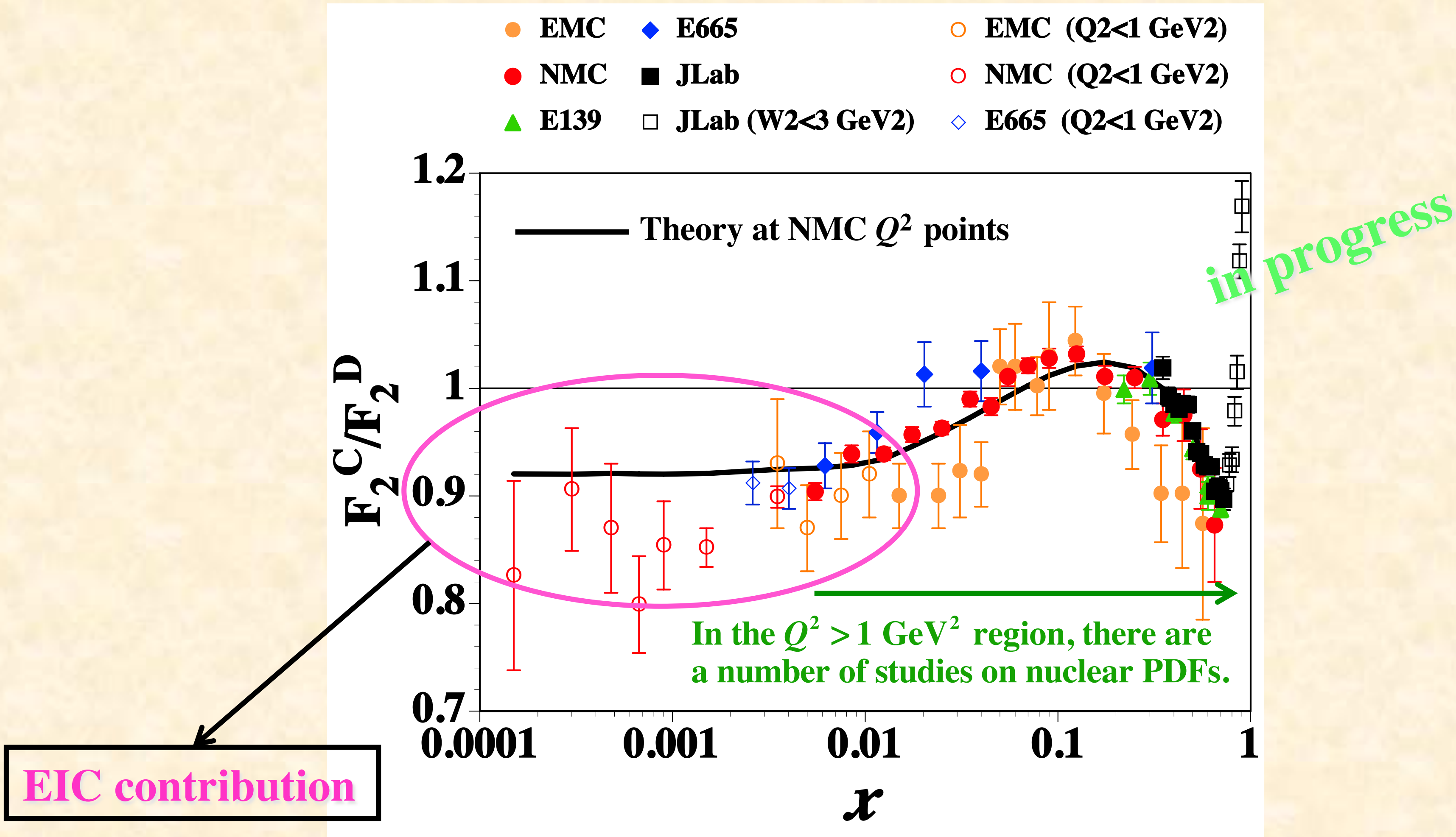
SLAC



Comparison with nuclear data on F_2^A / F_2^D

$$F_2^A(x,Q^2) = w(x,Q^2;x_0,Q_0^2)F_2^A(x_0,Q_0^2)$$

At this stage, we use $w(x,Q^2;x_0,Q_0^2)$ obtained for the nucleon, so that nuclear modifications are constained only in $F_2^A(x_0,Q_0^2)$.



“Direct” relation of EIC to Neutrino-interaction physics

(from HERA to EIC)

Neutral- and charged-current measurements at HERA

H. Abramowicz *et al.*, Eur. Phys. J. C 75 (2015) 580.

$$\sigma^{\pm}_{r,NC} = \frac{x\,Q^4}{2\pi\,\alpha^2 Y_+}\frac{d\sigma^{e^\pm p}_{NC}}{dx\,dQ^2} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L, \qquad Y_\pm = 1 \pm (1-y)^2$$

$$\tilde{F}_2 = F_2^\gamma - \kappa_Z v_e F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_2^Z, \qquad \kappa_Z(Q^2) = \frac{Q^2}{4\sin^2\theta_W \cos^2\theta_W (M_W^2 + Q^2)}$$

$$\tilde{F}_L = F_L^\gamma - \kappa_Z v_e F_L^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_L^Z, \qquad v_e = -\frac{1}{2} + 2\sin^2\theta_W, \qquad a_e = -\frac{1}{2}$$

$$\tilde{F}_3 = \quad -\kappa_Z a_e F_2^{\gamma Z} + \kappa_Z^2 2 v_e a_e F_2^Z$$

In parton model, $\tilde{F}_L = 0$, $\qquad v_q = \pm\frac{1}{2} - 2e_q \sin^2\theta_W, \quad a_q = \pm\frac{1}{2}, \qquad \pm = +(u,c), \;\; = -(d,s)$

$$(F_2^\gamma,\, F_2^{\gamma Z},\, F_2^Z) = (e_u^2,\; 2e_u v_u,\; v_u^2 + a_u^2)\,x(u + \bar{u} + c + \bar{c}) + (e_d^2,\; 2e_d v_d,\; v_d^2 + a_d^2)\,x(d + \bar{d} + s + \bar{s})$$

$$(0,\quad F_3^{\gamma Z},\, F_3^Z) = (0,\quad 2e_u a_u,\, 2v_u a_u)(u - \bar{u} + c - \bar{c}) \quad + (0,\quad 2e_d a_d,\, 2v_d a_d)(d - \bar{d} + s - \bar{s})$$

$$\sigma^{\pm}_{r,CC} = \frac{2\pi\,x}{G_F^2}\left(\frac{M_W^2 + Q^2}{M_W^2}\right)^2 \frac{d\sigma^{e^\pm p}_{CC}}{dx\,dQ^2} = \frac{1}{2}\left[Y_+ F_2^{\pm CC} \mp Y_- x F_3^{\pm CC} - y^2 F_L^{\pm CC}\right]$$

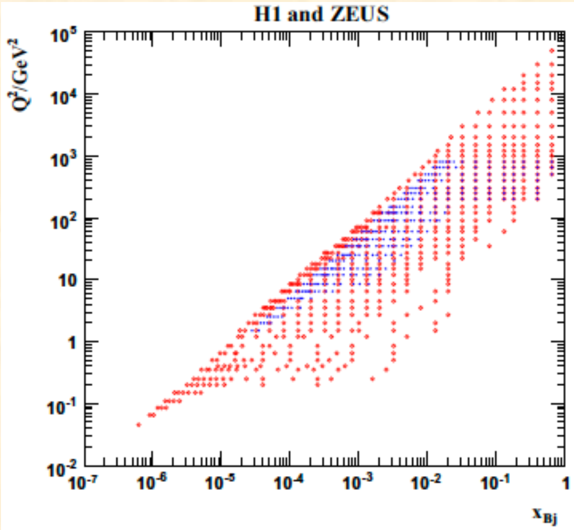
In parton model, $F_L^{\pm CC} = 0$

$$F_2^{+CC} = x(d + s + \bar{u} + \bar{c}), \qquad F_3^{+CC} = d + s - \bar{u} - \bar{c}$$

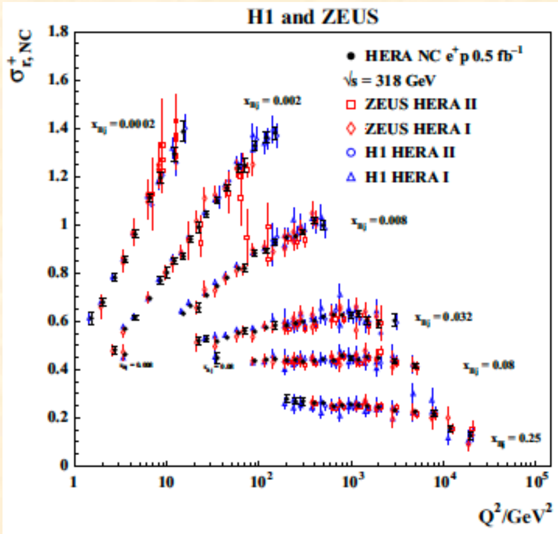
$$F_2^{-CC} = x(\bar{d} + \bar{s} + u + c), \qquad F_3^{-CC} = -\bar{d} - \bar{s} + u + c$$

Neutral- and charged-current cross sections at HERA

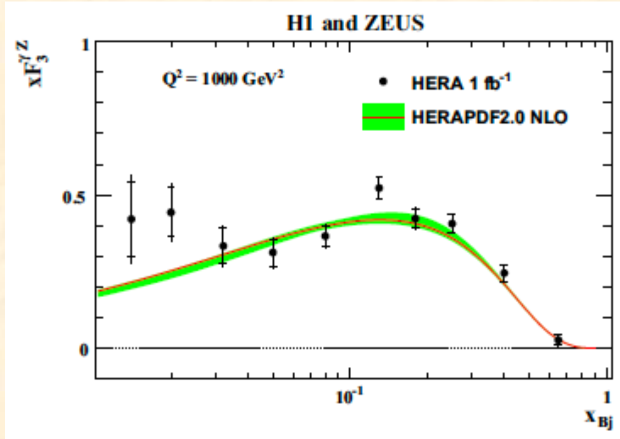
kinematical range



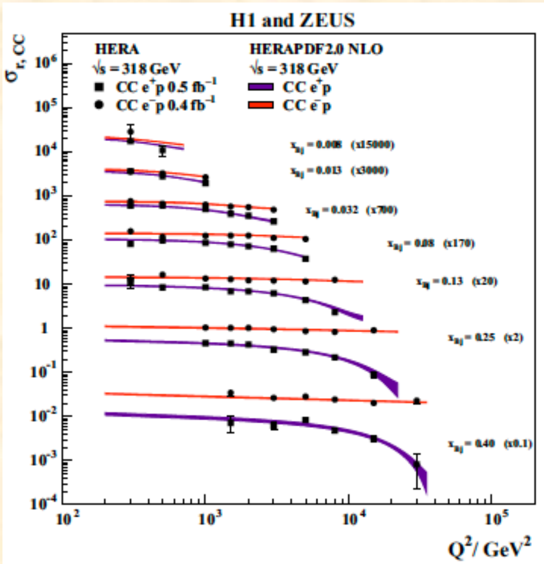
NC measurements



γZ interference



CC measurements



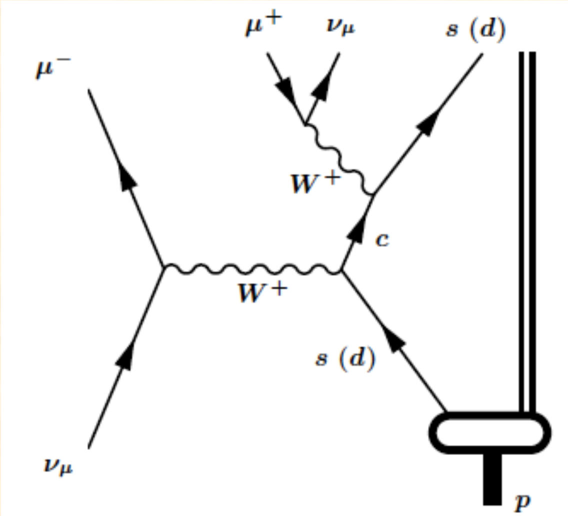
CC measurements

- limited number of data at $0.008 \le x \le 0.4$
- only for proton

$\rightarrow$ room for improvements by EIC

Strangeness in the nucleon

Neutrino-induced opposite-sign dimuon events



A. Kayis-Topaksu *et al.*, NPB7 98 (2008) 1.
U. Dore, arXiv: 1103.4572 [hep-ex].

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

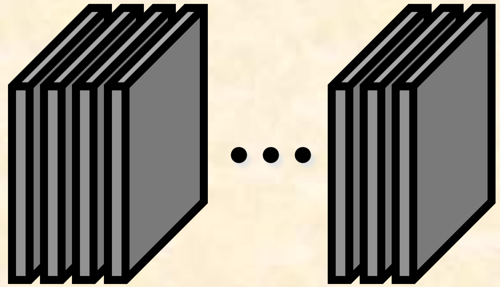
$$Q^2 = 20\ \mathrm{GeV}^2$$

Experiment	κ
This analysis	0.33 ± 0.07
CDHS [1]	0.47 ± 0.09
CCFR [2]	0.44 ± 0.09
CHARM II [3]	0.39 ± 0.09
NOMAD [4]	0.48 ± 0.17
NuTeV [5]	0.38 ± 0.08

CCFR, NuTeV

ν, $\bar{\nu}$

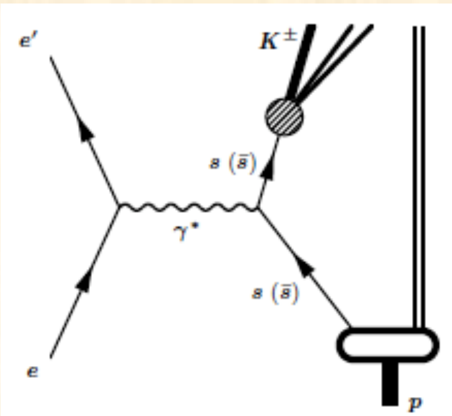
$E = 30 \sim 500$ GeV

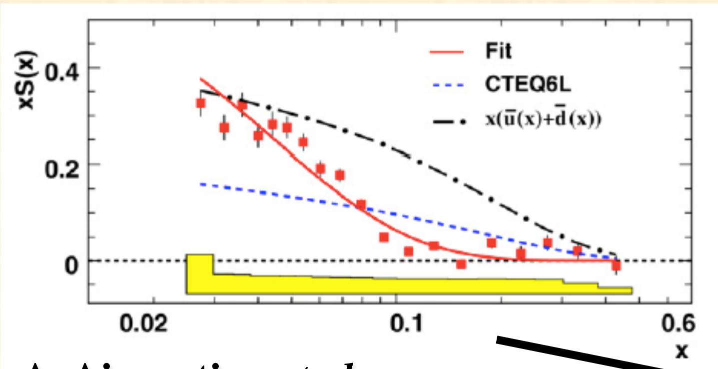


Huge Fe target (690 ton)

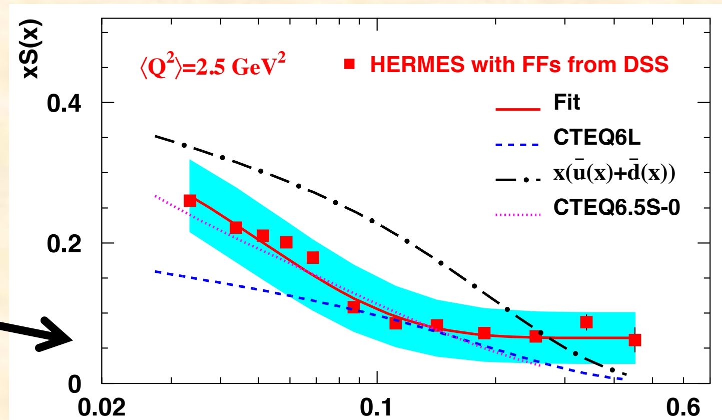
Issue: nuclear corrections

HERMES semi-inclusive measurement





A. Airapetian *et al.*,
PLB 666 (2008) 446.



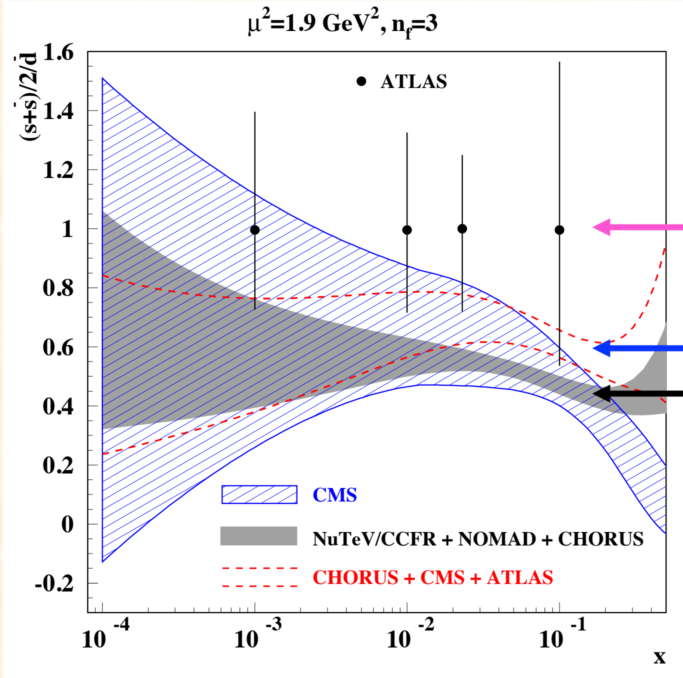
PRD 89 (2014) 097101.

Strange-quark distribution with LHC measurements

S. Alekhin *et al.*,
PRD 91 (2015) 094002.

Neutrino: $s + W \rightarrow c$

LHC: $g + s \rightarrow W + c$



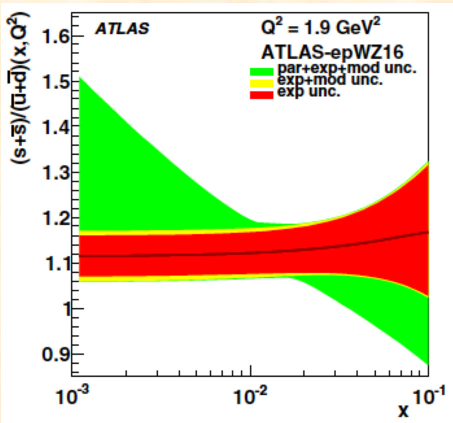
ATLAS

CMS

Neutrino

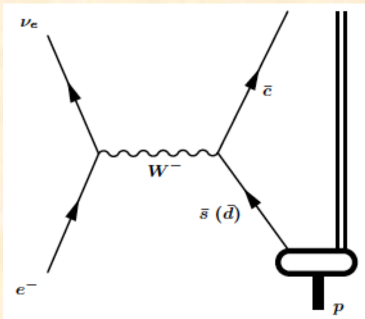
ATLAS and CMS/neutrino results are different.

M. Aaboud et al. (ATLAS),
Eur. Phys. J. C 77 (2017) 367.



Strangeness at EIC

Charm production in CC DIS



Inclusive CC DIS

$$\sigma^-_{r,CC} = x\left[u + c + (1-y)^2(\bar{d} + \bar{s})\right]$$

Longstanding NuTeV $\sin^2\theta_W$ anomaly

G. P. Zeller *et al.*, PRL 88 (2002) 091802;
90 (2003) 239902 (E).

Others: $\sin^2\theta_W = 1 - m_W^2/m_Z^2 = 0.2227 \pm 0.0004$

NuTeV: $\sin^2\theta_W = 0.2277 \pm 0.0013\ (\text{stat}) \pm 0.0009\ (\text{syst})$

Paschos-Wolfenstein relation

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_W$$

for isoscalar nucleon

NuTeV target: ^{56}Fe ($Z = 26$, $N = 30$)
not isoscalar nucleon
→ Nuclear effects should be carefully taken into account.

Charged-current (CC) cross sections for νA and $\bar{\nu}$A

$$\frac{d\sigma_{CC}^{\nu A}}{dxdy} = \sigma_0 x\left[d^A + s^A + (1-y)(\bar{u}^A + \bar{c}^A)\right], \quad \frac{d\sigma_{CC}^{\bar{\nu} A}}{dxdy} = \frac{d\sigma_{CC}^{\nu A}}{dxdy}(q \leftrightarrow \bar{q}), \quad \sigma_0 = \frac{G_F^2 s}{\pi}$$

Neutral-current (CC) cross sections

$$\frac{d\sigma_{CC}^{\nu A}}{dxdy} = \sigma_0 x \left[\left\{u_L^2 + u_R^2(1-y)\right\}(u^A + c^A) + \left\{u_R^2 + u_L^2(1-y)\right\}(\bar{u}^A + \bar{c}^A)\right.$$
$$\left. + \left\{d_L^2 + d_R^2(1-y)\right\}(d^A + s^A) + \left\{d_R^2 + d_L^2(1-y)\right\}(\bar{d}^A + \bar{s}^A)\right]$$

$$\frac{d\sigma_{CC}^{\bar{\nu} A}}{dxdy} = \frac{d\sigma_{CC}^{\nu A}}{dxdy}(L \leftrightarrow R), \quad u_L = +\frac{1}{2} - \frac{2}{3}\sin^2\theta_W, \ u_R = -\frac{2}{3}\sin^2\theta_W$$

$$d_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W, \ u_R = +\frac{1}{3}\sin^2\theta_W$$

$$R_A^- = \frac{\sigma_{NC}^{\nu A}/dxdy - \sigma_{NC}^{\bar{\nu} A}/dxdy}{\sigma_{CC}^{\nu A}/dxdy - \sigma_{CC}^{\bar{\nu} A}/dxdy} = \frac{\{1-(1-y)^2\}\left[(u_L^2 - u_R^2)\{u_v^A(x) + c_v^A(x)\} + (d_L^2 - d_R^2)\{d_v^A(x) + s_v^A(x)\}\right]}{d_v^A(x) + s_v^A(x) - (1-y)^2\{u_v^A(x) + c_v^A(x)\}}, \quad q_v^A \equiv q^A - \bar{q}^A$$

$$= \frac{\left(\frac{1}{2} - \sin^2\theta_W\right)\{1 + \varepsilon_v(x)\varepsilon_n(x)\} + \frac{1}{3}\sin^2\theta_W\{\varepsilon_v(x) + \varepsilon_n(x)\} + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)\varepsilon_s(x) + \left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right)\varepsilon_c(x)}{1 + \varepsilon_v(x)\varepsilon_n(x) + \frac{1+(1-y)^2}{1-(1-y)^2}\{\varepsilon_v(x) + \varepsilon_n(x)\} + \frac{2\{\varepsilon_s(x) - (1-y)^2\varepsilon_c(x)\}}{1-(1-y)^2}}$$

$$= \frac{1}{2} - \sin^2\theta_W + O(\varepsilon_v) + O(\varepsilon_n) + O(\varepsilon_s) + O(\varepsilon_c) + \cdots$$

PRD 66 (2002) 111301

(1) Differnce between nuclear modifications of u_v and d_v (including isospin violation)

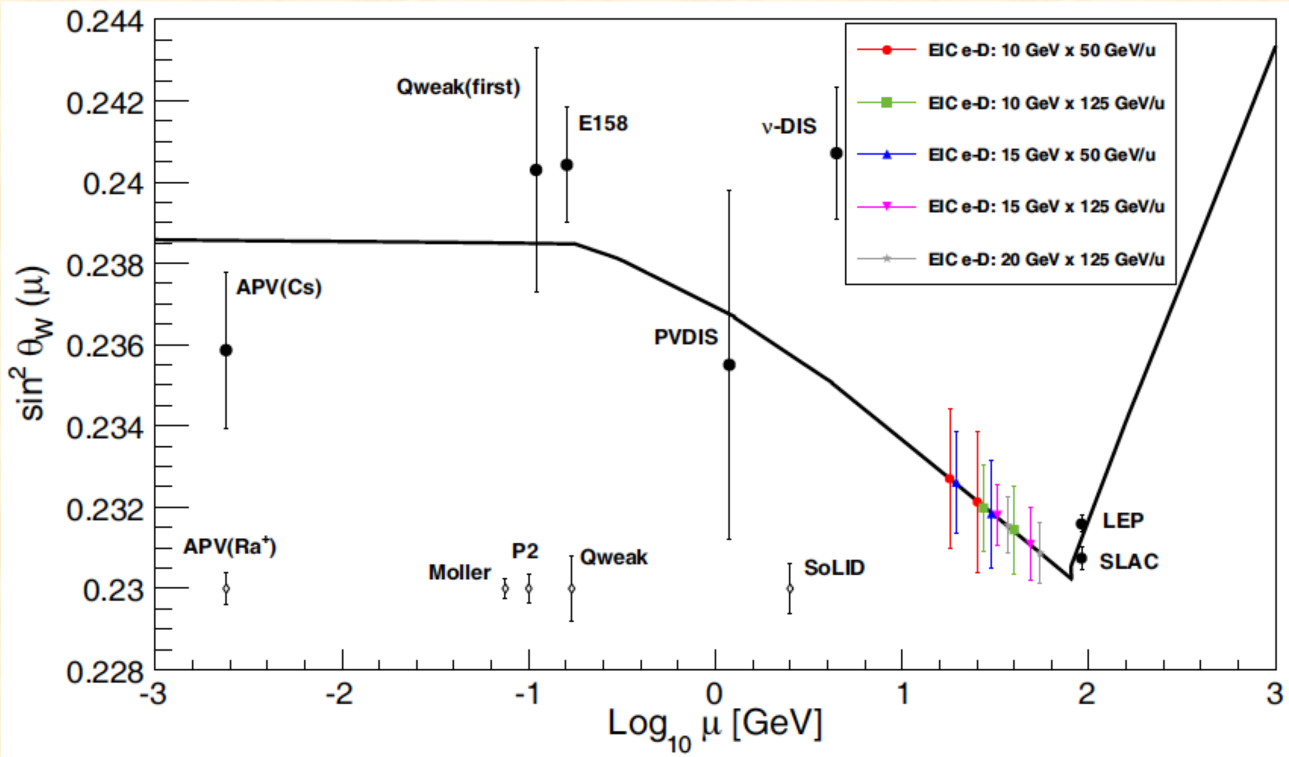
$$\varepsilon_v(x) = \frac{w_{d_v}(x) - w_{u_v}(x)}{w_{d_v}(x) + w_{u_v}(x)}, \quad u_v^A(x) = w_{u_v}(x)\frac{Zu_v(x) + Nd_v(x)}{A}, \quad d_v^A(x) = w_{d_v}(x)\frac{Zd_v(x) + Nu_v(x)}{A}$$

(2) Neutron excess: $\varepsilon_n(x) = \frac{N-Z}{A}\frac{u_v(x) - d_v(x)}{u_v(x) + d_v(x)}$ **(This effect is taken into account in the NuTeV analysis.)**

(3) Valence srange, charm: $\varepsilon_s(x),\ \varepsilon_c(x) = \frac{2s_v^A(x) \text{ or } 2c_v^A(x)}{\left[w_{u_v}(x) + w_{d_v}(x)\right]\left[u_v(x) + d_v(x)\right]}, \quad q_v^A \equiv q^A - \bar{q}^A$

Because different tiny factors (flavor dependent nuclear modifications, isospin violation in PDFs, strange valence, charm valence, ⋯) contribute to the deviation from the Paschos-Wolfenstein relation, it is not easy to solve the NuTeV anomaly.

Weaking-mixing-angle measurements at EIC



S. Mantry, BSM/EW physics at EIC (2017)

Physics of beyond the standard model at EIC,

see BSM/EW physics at EIC mini ad-hoc workshop,
Dec. 19 2017, JLab
https://www.jlab.org/indico/event/248/
International workshop on physics with positrons at Jefferson Lab, Sept. 12-15, 2017, JLab,
Proceedings of Y. Furletova and S. Mantry

Ultrahigh-energy neutrino interactions

A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP 08 (2011) 042.

$$\frac{d\sigma_{CC}^{\nu/\bar{\nu}\,N}}{dx\,dQ^2} = \frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \sigma_{r,CC}^{\pm}, \quad \sigma_{r,CC}^{\nu/\bar{\nu}} = Y_+ F_2^{\nu/\bar{\nu},CC} \pm Y_- x F_3^{\nu/\bar{\nu},CC} - y^2 F_L^{\nu/\bar{\nu},CC}, \quad \pm = \nu(+),\ \bar{\nu}(-), \quad Y_\pm = 1 \pm (1-y)^2, \quad F_L^{\nu/\bar{\nu},CC} = 0$$

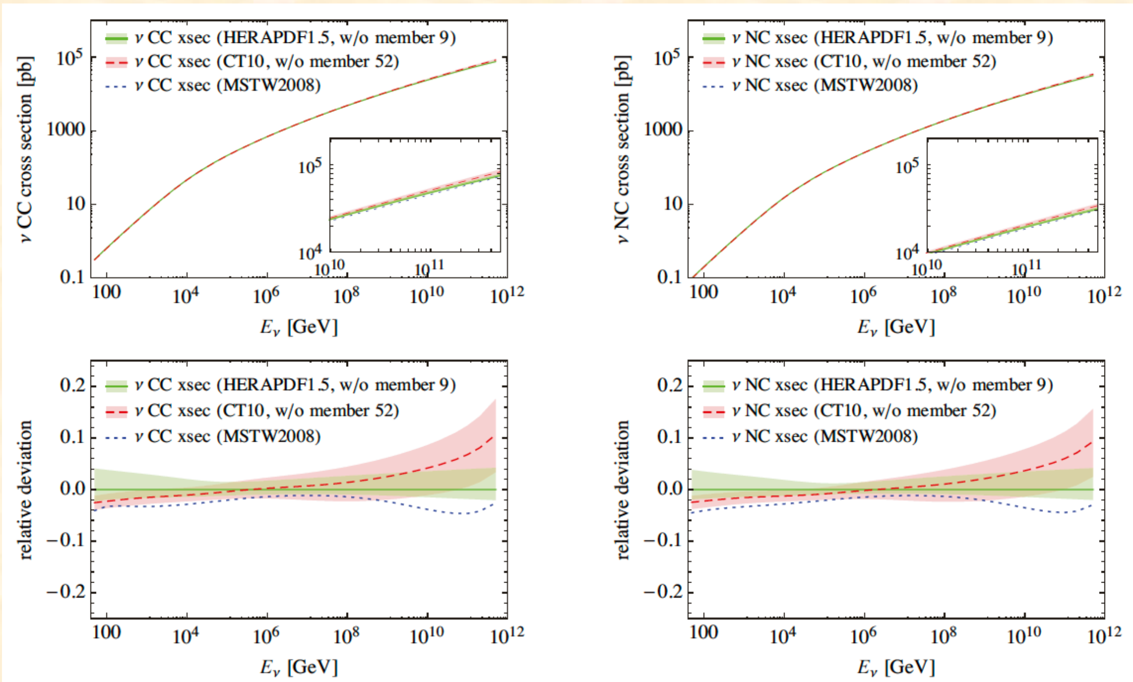
$$F_2^{\nu,CC} = x(u+d+2s+2b+\bar{u}+\bar{d}+2\bar{c}), \quad F_3^{\nu,CC} = u+d+2s+2b-\bar{u}-\bar{d}-2\bar{c}$$

$$F_2^{\bar{\nu},CC} = x(u+d+2c+\bar{u}+\bar{d}+2\bar{s}+2\bar{b}), \quad F_3^{\bar{\nu},CC} = u+d+2c-\bar{u}-\bar{d}-2\bar{s}-2\bar{b}$$

NC cross section is given in the similar way with the structure functions: $F_L^{\nu/\bar{\nu},NC} = 0$

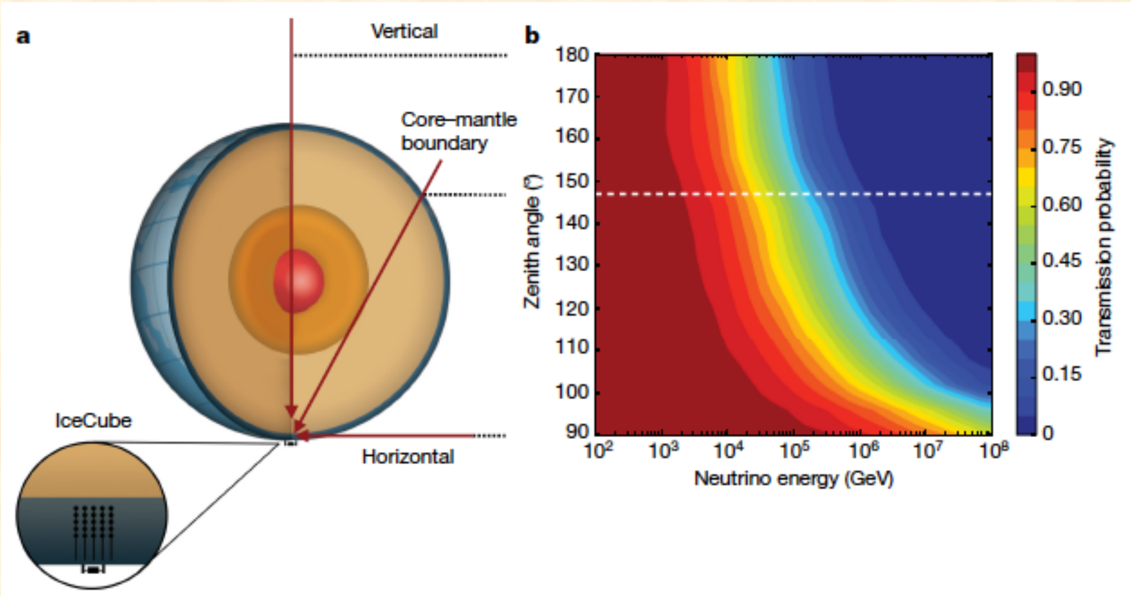
$$F_2^{\nu,NC} = x\left[\frac{1}{2}(a_u^2+v_u^2+a_d^2+v_d^2)(u+\bar{u}+d+\bar{d}) + (a_d^2+v_d^2)(s+\bar{s}+b+\bar{b}) + (a_u^2+v_u^2)(c+\bar{c})\right]$$

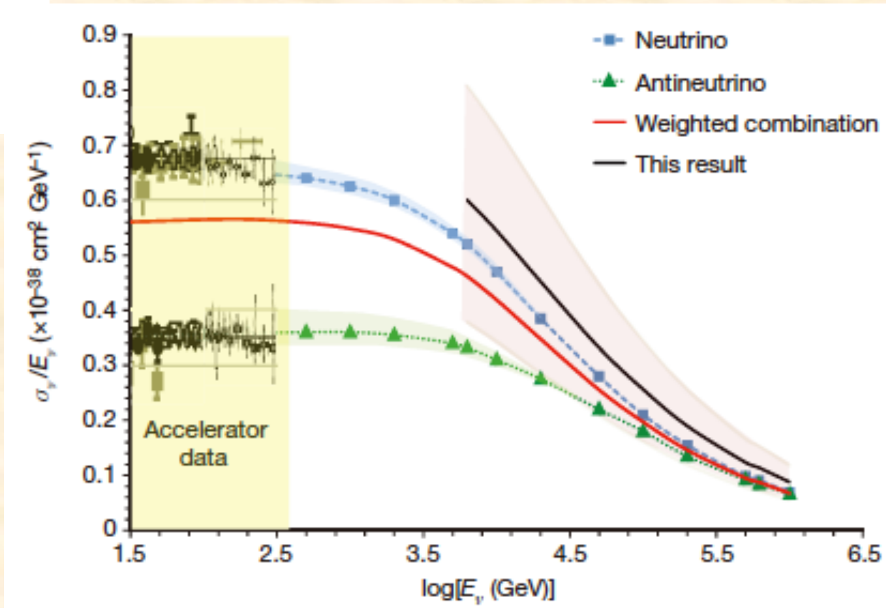
$$F_3^{\nu,CC} = x\left[(v_u a_u + v_d a_d)(u-\bar{u}+d-\bar{d})\right]$$



Ultrahigh-energy neutrino interactions at IceCube

M.G. Aartsen et al. (IceCube Collaboration), Nature 551 (2017) 596; Erratum 554 (2018) 554.
M. Bustamante and A. Connolly, arXiv:1711043.





So far, the IceCube cross sections are consistent with the standard-model ones by considering experimental errors.

Summary

EIC can contribute to neutrino physics, although their relaions may not be well studied.
(e.g. There was no talk on POETIC-2018 on a relation to neutrino physics.)

- **There is a strong overlap among EIC physicists and neutrio community, especially with people on neutrino-interaction simulation codes.**
- **The order of 5% accuracy is needed for future oscillation measurements.**
- **Knowlege of ultra-high-energy lepton interactions is neeeded for neutrino telescopes such as IceCube.**
- **There are significant studies in the quasi-elastic, resonace, and DIS regions separatedly.**
  → It is desirable to have a unified code for calculating the cross sections.
  (Physics: quark-hadron duality)
- **The Regge region ($W^2 \geq 4$ GeV^2, $Q^2 < 1$ GeV^2) is not well investigated.**
  → EIC could singificantly improve the situation.
- **Charged-current interactions:**
  improvments of HERA data, new measurements for nuclei
- **Strange-quark distribution, NuTeV weak-mixing anomaly, ⋯, new physics**

The End

The End