Nuclear PDFs (Parton Distribution Functions)

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30th Neutrino workshop "Neutrino Interaction Physics"
IPMU, Tokyo University, Kashiwa, Japan
https://www.icrr.u-tokyo.ac.jp/indico/event/91/

(with the project of Unification and Development of the Neutrino Science Frontier
http://www-he.scphys.kyoto-u.ac.jp/nufrontier/en/index.html

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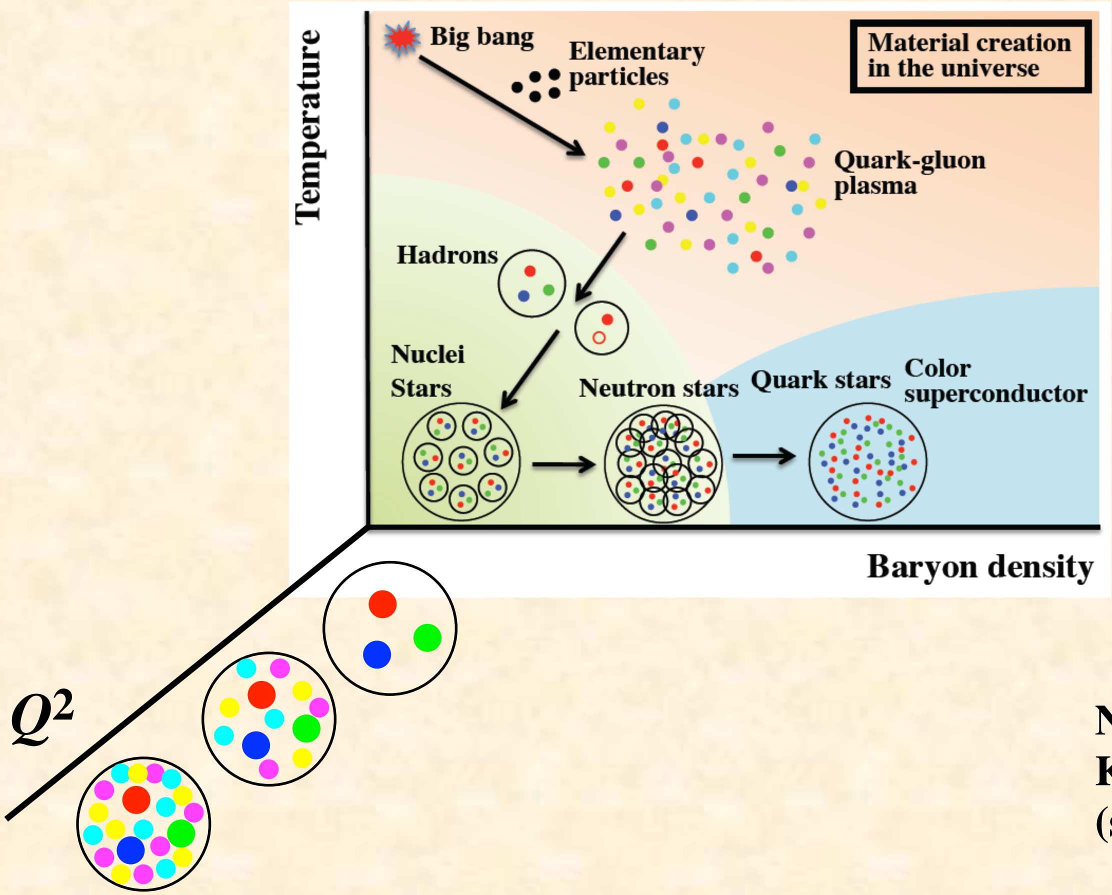
Contents

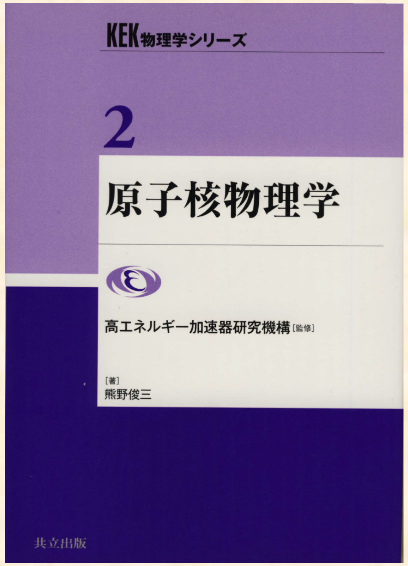
Motivation
& Introductory comments

Nuclear Physics: Ultimate high-density quantum many-body system bound by strong interactions

Nuclear physics is a field of investigating

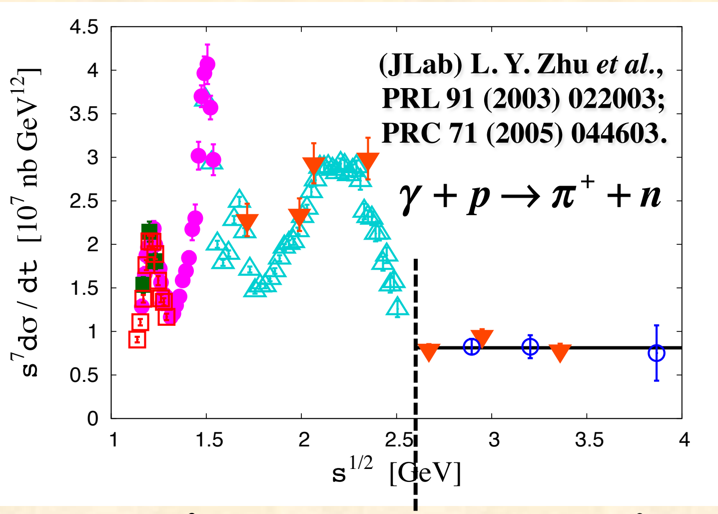
- **matter generation of universe,**
- **properties of quark-hadron many-body systems as ultimate materials.**





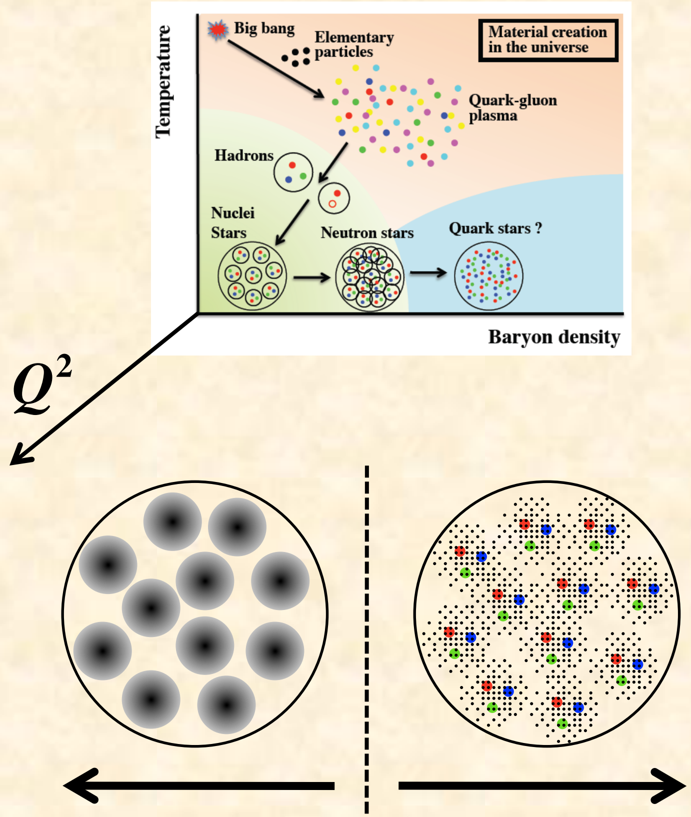
No official update after HKN2007, busy for KEK nuclear physics textbook in 2015 (someday, it would be traslated into English.)

Hadron degrees of freedom (d.o.f.) ⇔ Quark d.o.f.



Low energies:
Hadron degrees of freedom
(Resonances)

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

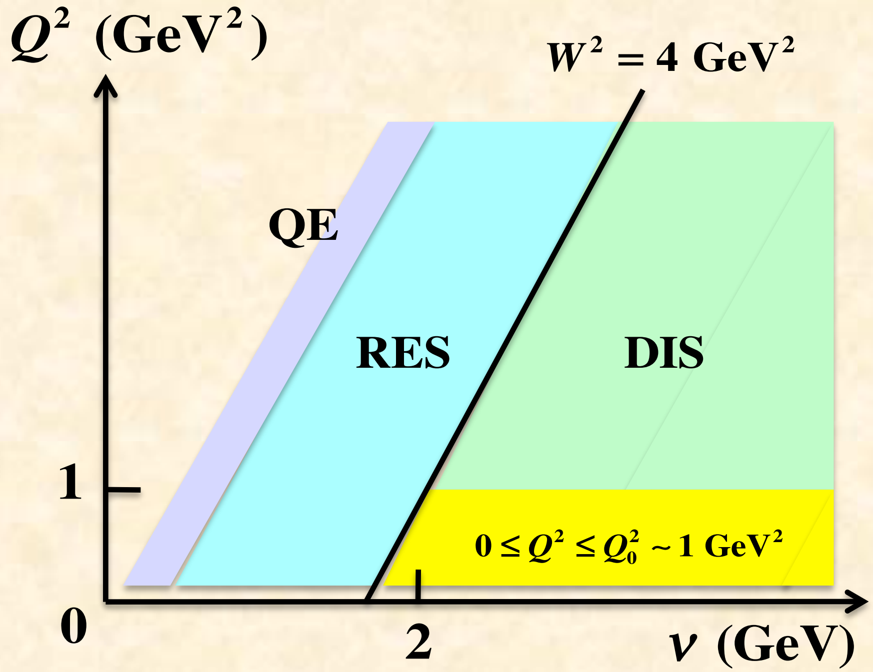


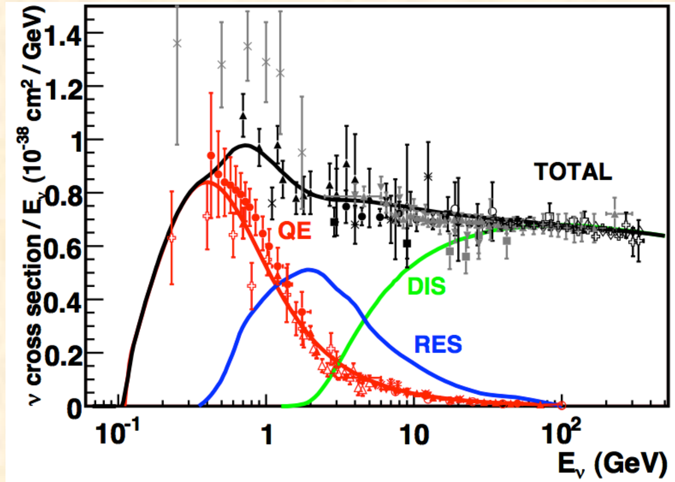
Low energies:
Hadron degrees of freedom

High energies:
Quark-gluon degrees of freedom

Nuclei should be described by quark and gluon degrees of freedom at high energies.

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)

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%

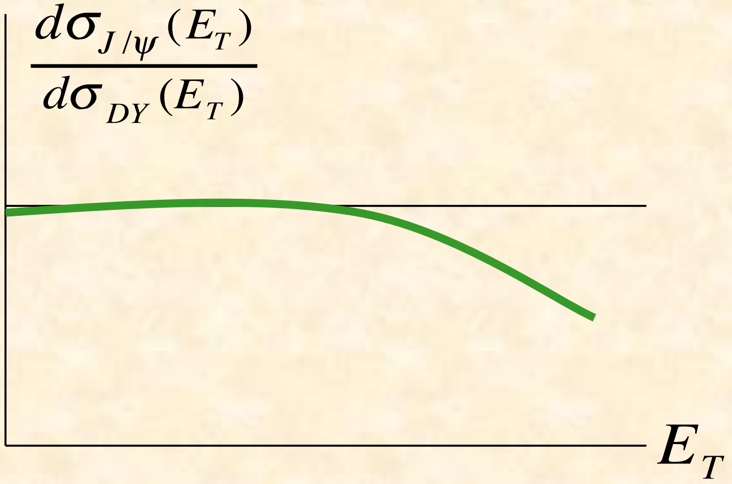
ν interactions

A.K.Ichikawa@KEK workshop 2015

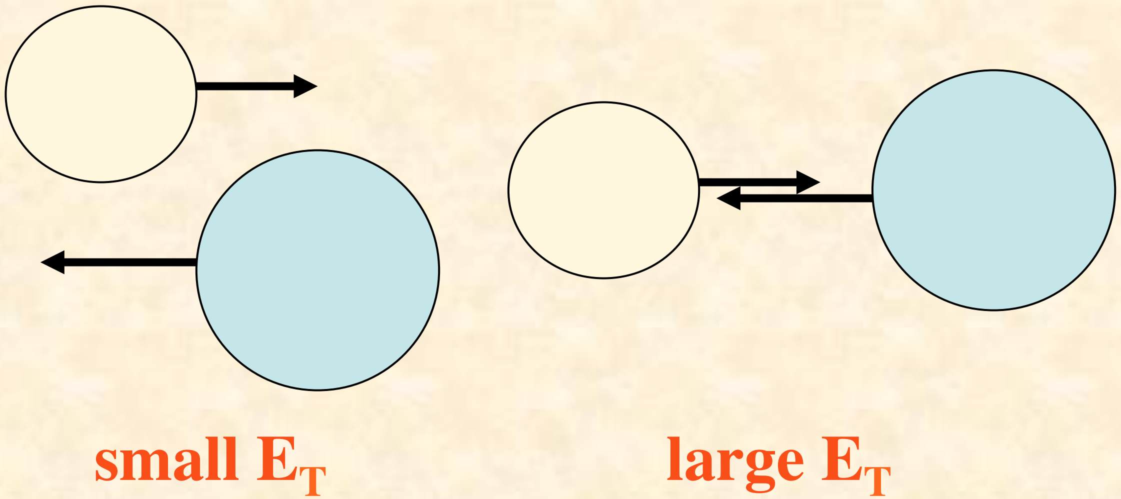
Activities at the J-PARC branch, KEK theory center
http://j-parc-th.kek.jp/html/English/e-index.html
Towards construction of a unified model for the neutrino-nucleus reactions,
S. X. Nakamura, H. Kamano, Y. Hayato, M. Hirai, W. Horiuchi,
S. Kumano, T. Murata, K. Saito, M. Sakura, T. Sato, Y. Suzuki
arXiv:1610.01464, Rep. Prog. Phys. in press.

Impact-parameter-dependent nuclear modifications I

J/ψ suppression



suppression of J/ψ cross section
at large E_T in comparison with DY



NPDF effects $\frac{J/\psi}{DY} \sim \frac{\text{gluon}}{\text{quark/antiquark}}$

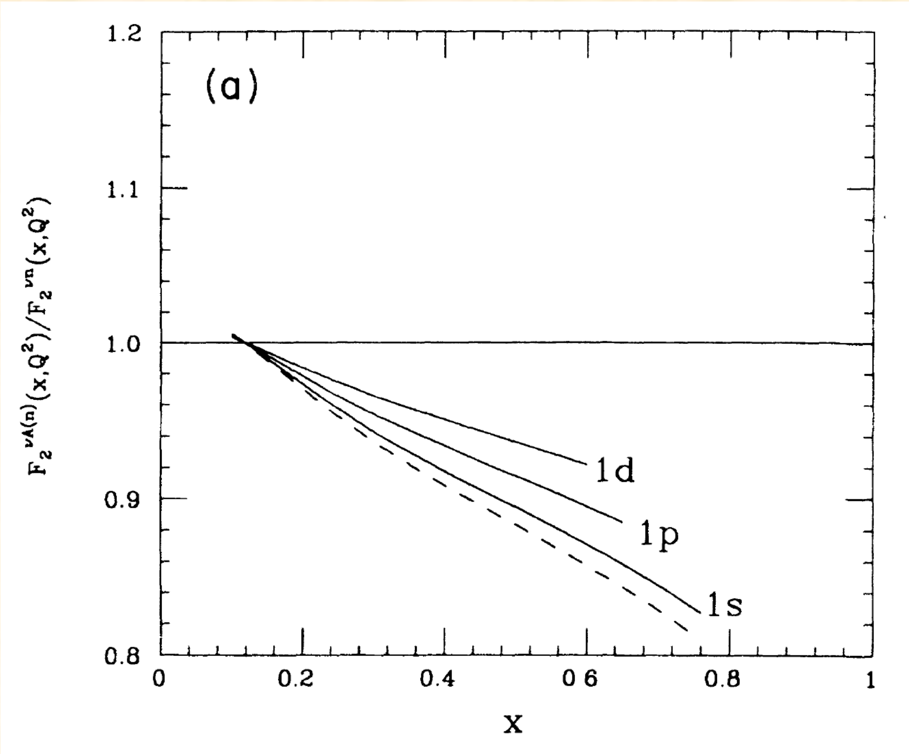
If the $g_A(x)$ modification is significantly different from the quark one, the suppression could be explained partially by the NPDF effect.

Local EMC effect,
SK and F.E. Close, PRC 41 (1990) 1855.

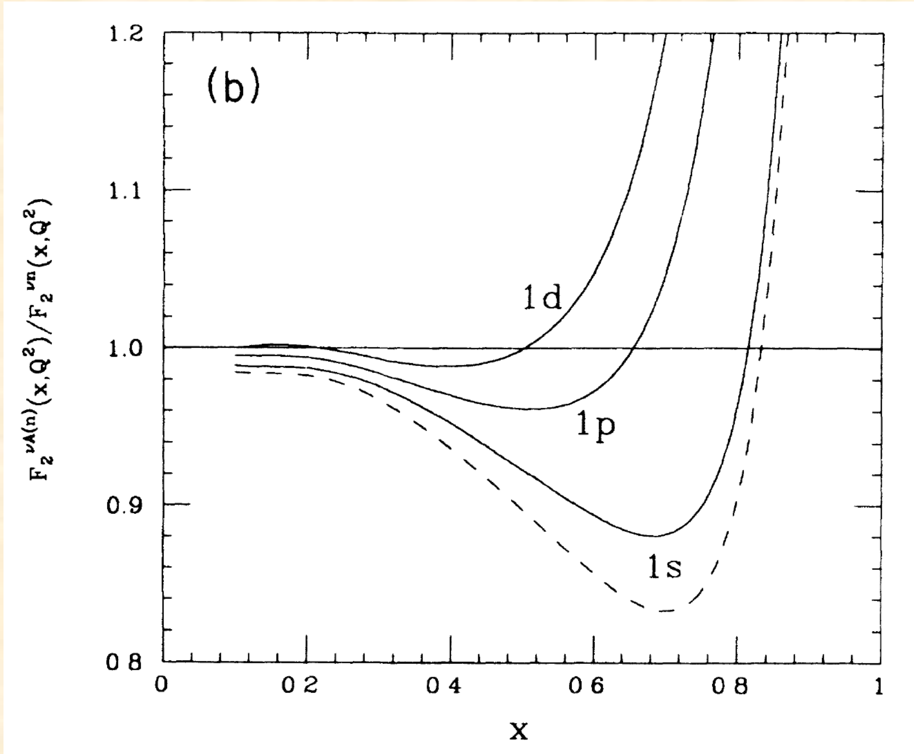
Impact-parameter-dependent nuclear modifications II

⇔ Local EMC effect [S. Kumano and F. E. Close, Phys. Rev. C 41 (1990) 1855]

Rescaling model ^{19}F



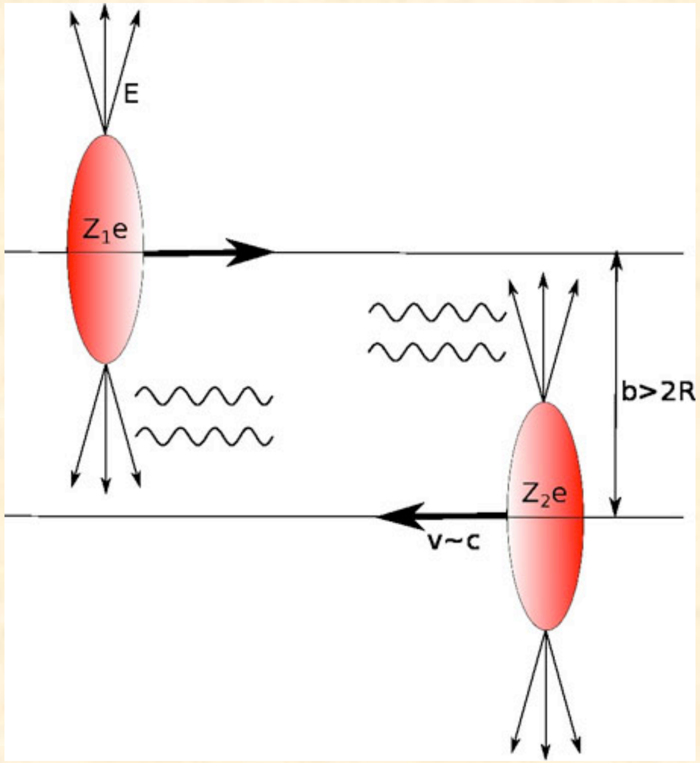
Binding model ^{19}F

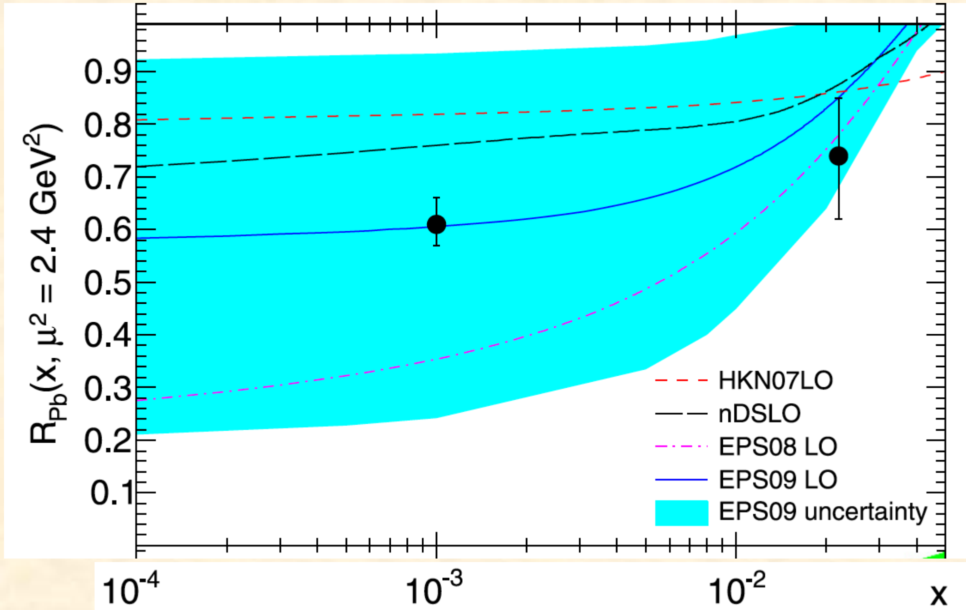


This workshop: Gluon shadowing

⇔ LHC/RHIC (esp. UltraPeripheral Collisions)

V. Guzey, E. Kryshen, M. Strikman, M. Zhalov, PLB 726 (2013) 290;
L. Frankfurt, V. Guzey, M. Strikman, M. Zhalov, PLB 752 (2016) 51.





Comments on Parton distribution functions in the nucleon

Recent works on unpolarized PDFs

ABKM (Alekhin, Blümlein, Klein, Moch)

ABKM-2010, 2011, S. Alekhin *et al*., Phys. Rev. D 81 (2010) 014032; Phys. Rev. D86（2012）054009;

ABM-2014, S. Alekhin *et al*., Phys. Rev. D89（2014）054028 [D91 (2015) 094002, D94 (2016) 114038]

ABMP-2016: S. Alekhin *et al*., arXiv:1609.03327.

CTEQ (Coordinated Theoretical-Experimental Project on QCD)

CTEQ6.6, P. M. Nadolsky *et al*., Phys. Rev. D 78 (2008) 013004.

CT10, H.-L. Lau *et al*., Phys. Rev. D 82 (2010) 074024.

CT12, J. F. Owens *et al*., Phys. Rev. D 87 (2013) 094012. CT14, S. Dulat *et al*., Phys. Rev. D 93 (2016) 033006.

GJR (Glück, Jimenez-Delgado, Reya)

GJR-2008, M. Gluck *et al*., Eur. Phys. J. C 53 (2008) 355; PRD79 (2009) 074023;

JR-2014, Phys. Rev. D89 (2014) 074049.

HERA (H1 and ZEUS collaborations)

HERAPDF, F. D. Aaron *et al*., JHEP 01 (2010) 109: Eur. Phys. J. C73（2013）2311;

H Abramowicz *et al*., Phys. Rev. D 93 (2016) 092002; I. Abt *et al*., Phys. Rev. D 94 (2016) 052007.

MSTW (Martin, Stirling, Thorne, Watt, L. A. Harland-Lang, P. Motylinski)

MSTW2008, A. D. Martin *et al*., Eur. Phys. J. C 63 (2009) 189;

MMHT2014, A. Harland-Lang *et al*., Eur. Phys. J. C (2015) 75.

Neural Network (Ball, Bertone, Carrazza, Del Debbio, Forte, Guffanti, Hartland, Latorre, Rojo, Ubiali, ...)

NNPDF, R. D. Ball *et al*., Nucl. Phys. B 838 (2010) 136; B855（2012）153;

B867（2013）244; B874（2013）36; B877（2013）290;

JHEP 04 (2015) 040; JHEP 1509 (2015) 191; arXiv:1605.06515.

CTEQ14

CT14, S. Dulat *et al*., PRD93 (2016) 033006

Functional form: $Q_0^2 = (1.3)^2\ \text{GeV}^2$

$$xf(x,Q_0^2) = x^{a_1}(1-x)^{a_2}P(x)$$

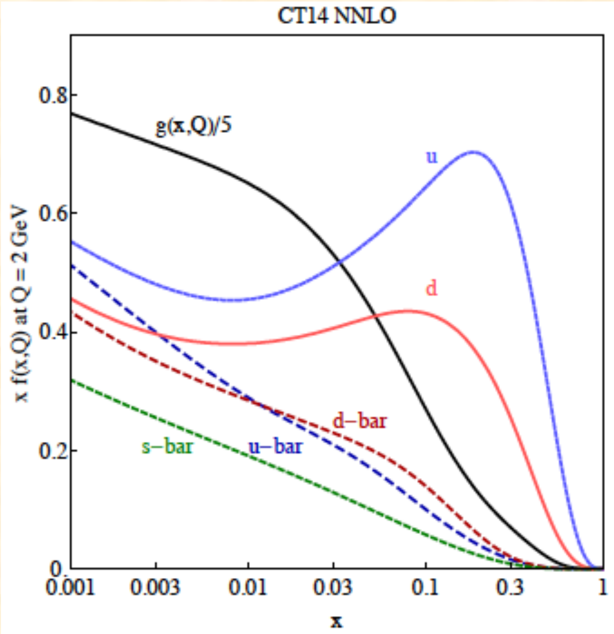
used to be $P(x) = \exp\left(a_0 + a_3\sqrt{x} + a_4 x + a_5 x^2\right)$

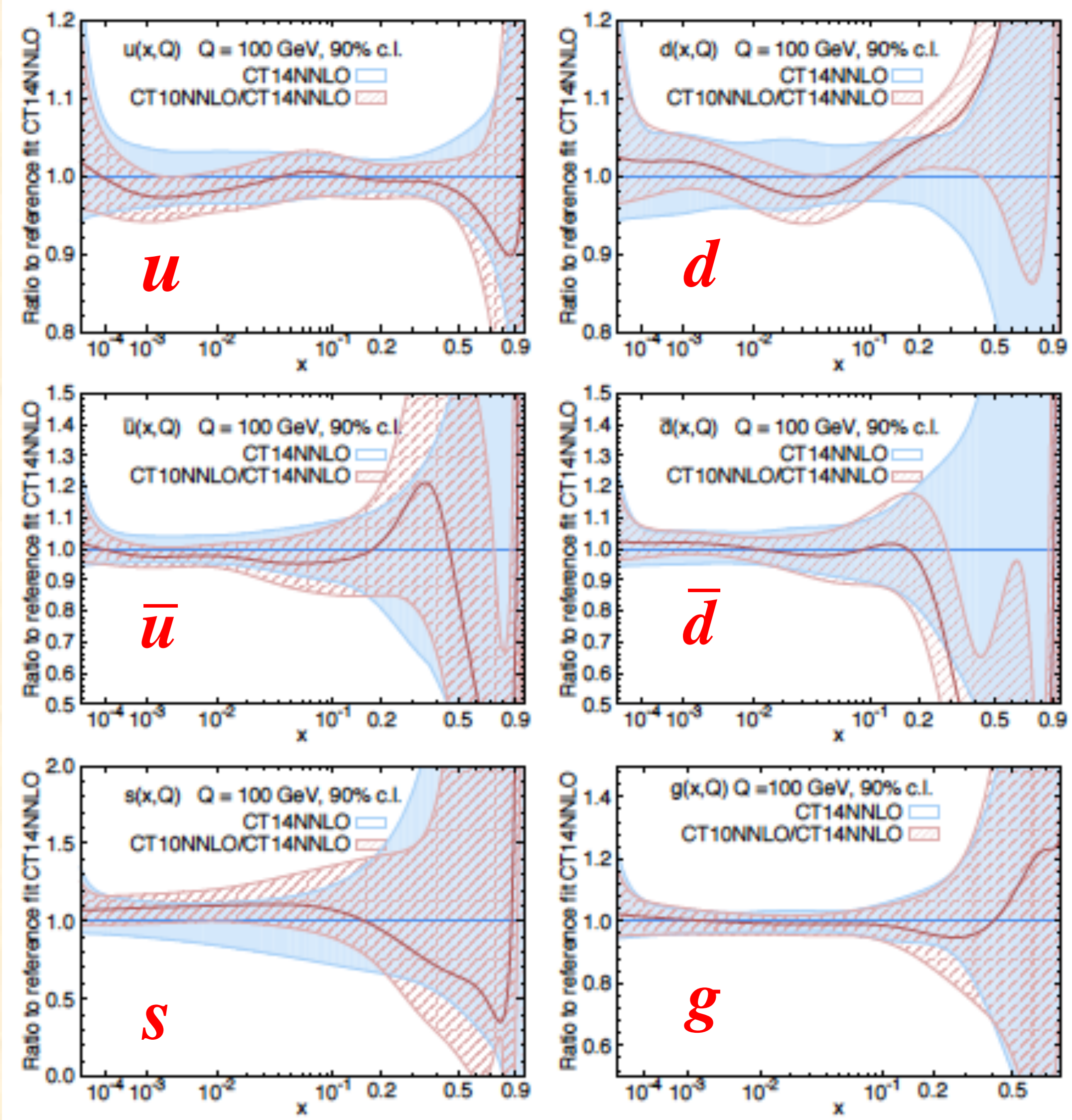
Expansion by Bernstein polynomials:

$$P(x) = \sum_{i=0}^{n} d_i p_i(y=\sqrt{x}),\ \ p_0(y) = (1-y)^4,$$

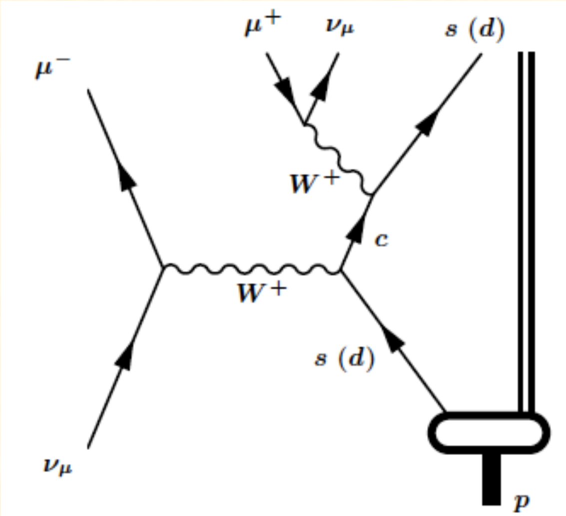
$$p_1(y) = 4y(1-y)^3,\ \ p_2(y) = 6y^2(1-y)^2,$$

$$p_3(y) = 4y^3(1-y),\ \ p_4(y) = y^4$$





$s(x)$ from neutrino-induced opposite-sign dimuon events



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

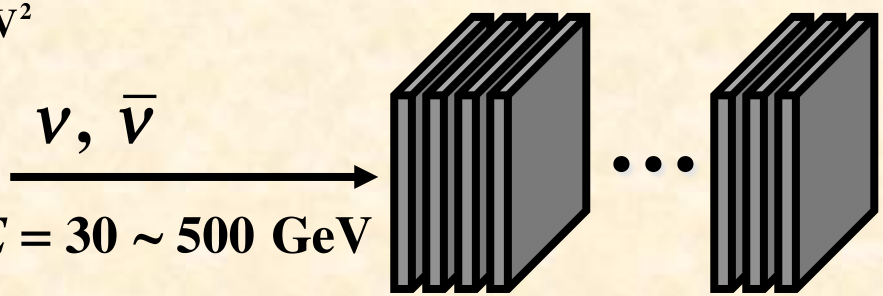
$$\kappa = \frac{\int dx\, x\,[s(x,Q^2)+\bar{s}(x,Q^2)]}{\int dx\, x\,[\bar{u}(x,Q^2)+\bar{d}(x,Q^2)]}$$

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

CCFR, NuTeV

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

$\nu,\ \bar{\nu}$

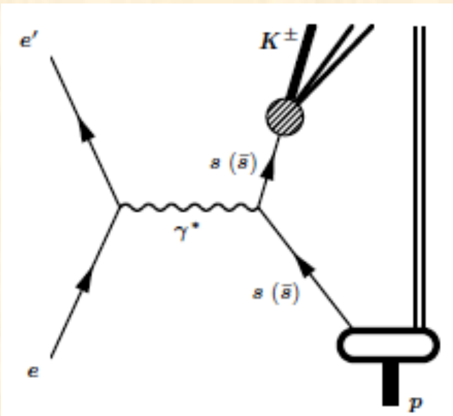


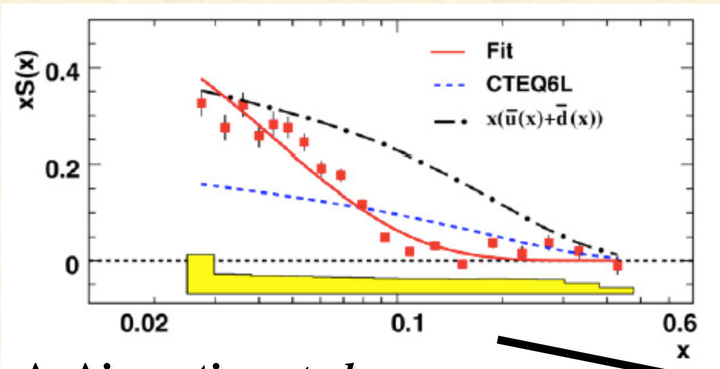
$E = 30 \sim 500$ GeV

Huge Fe target (690 ton)

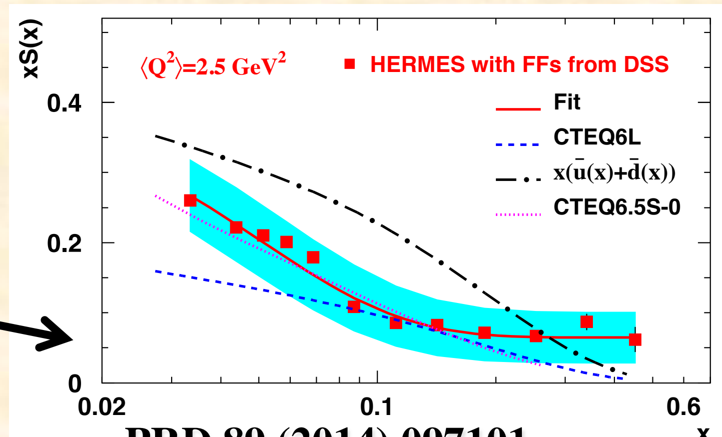
Issue: nuclear corrections

HERMES semi-inclusive measurement





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



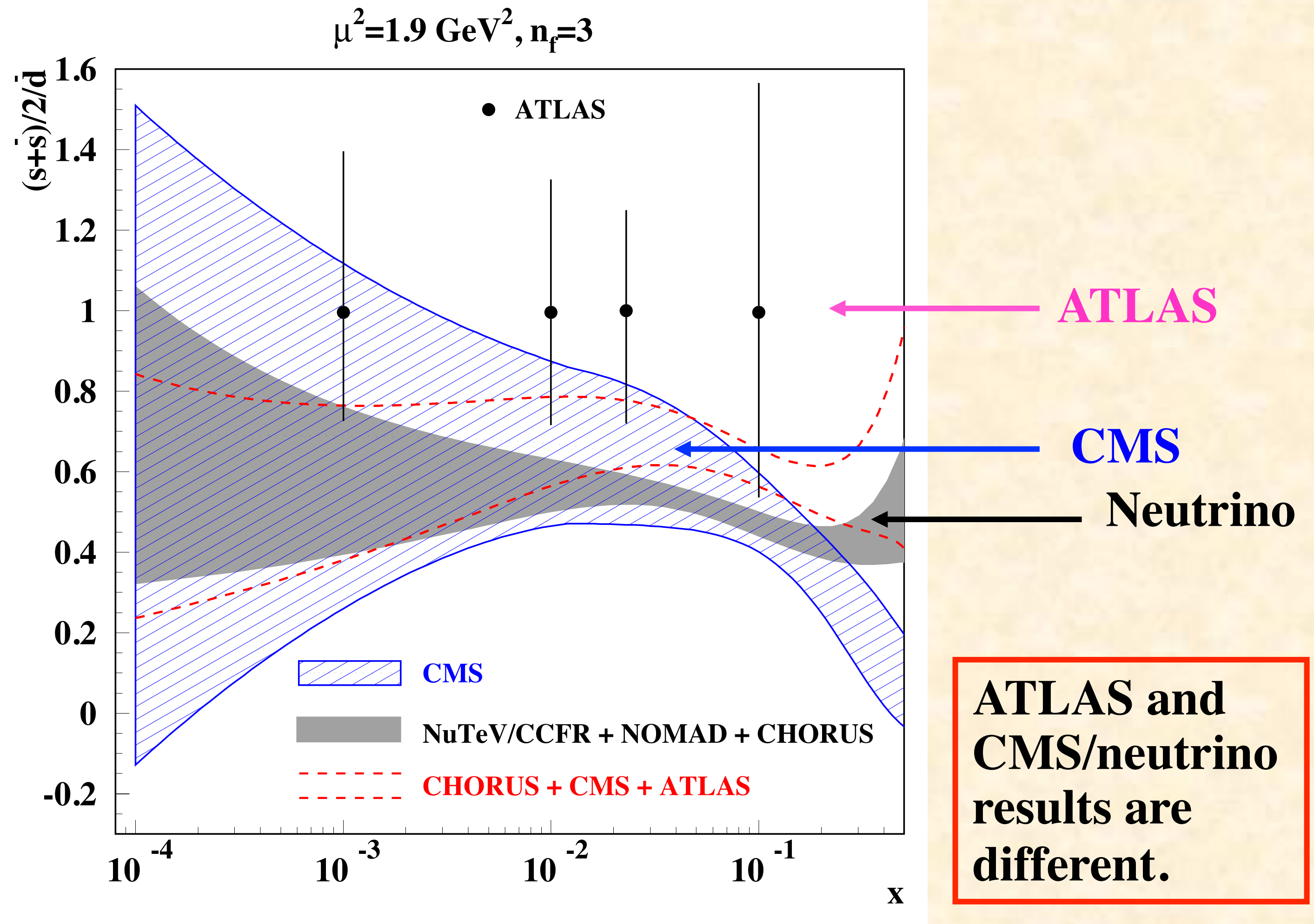
PRD 89 (2014) 097101.

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 and CMS/neutrino results are different.

Nuclear
Parton Distribution Functions

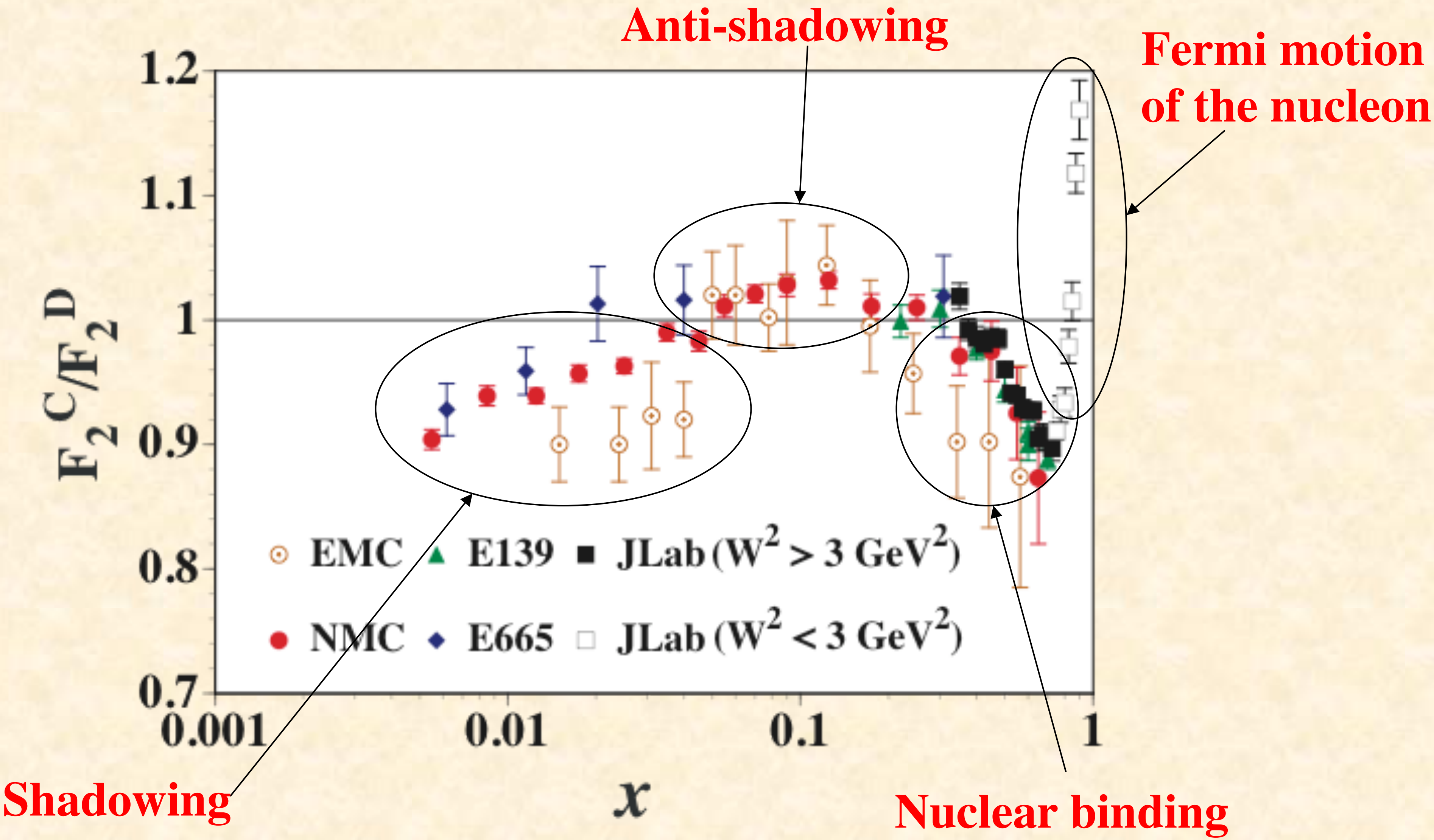
Our studies:

M. Hirai, S. Kumano, M. Miyama, Phys. Rev. D64 (2001) 034003.
First chi2 analysis on nuclear PDFs

M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C70 (2004) 044905.
First error analysis on nuclear PDFs

M. Hirai, S. Kumano, and T. -H. Nagai, Phys. Rev. C 76 (2007) 065207.
NLO with F2 and Drell-Yan

Nuclear modifications of structure function F_2



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

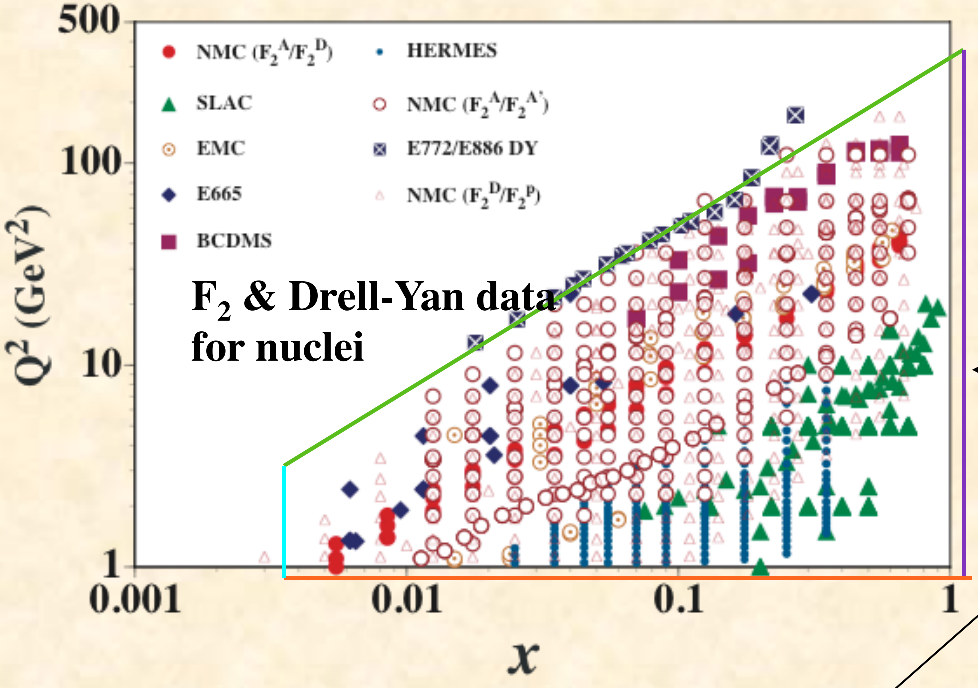
Current nuclear data are kinematically limited.

$$x = \frac{Q^2}{2p\cdot q} \simeq \frac{Q^2}{ys}$$

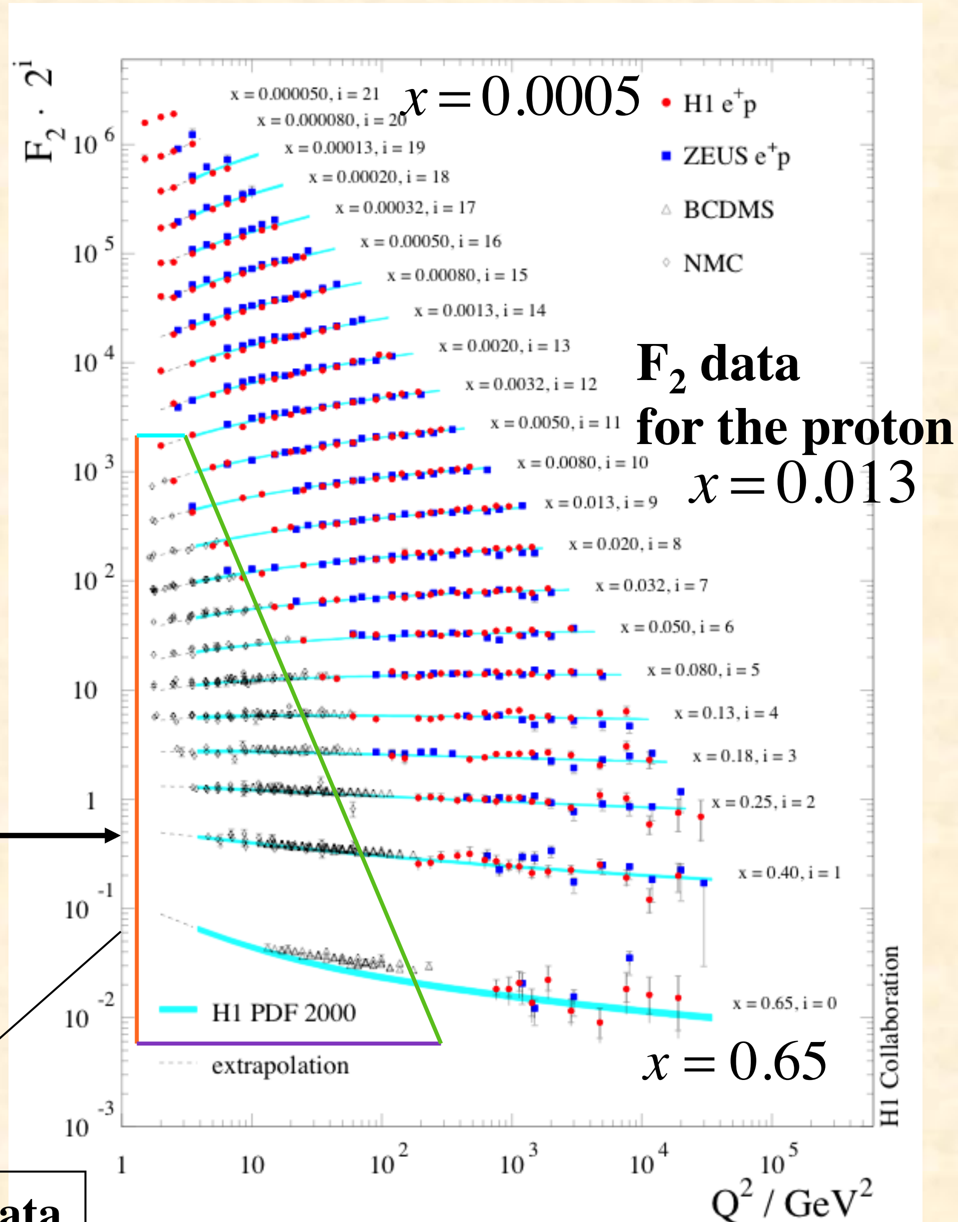
fixed target: $\min(x) = \frac{Q^2}{2M_N E_{lepton}} \le \frac{1}{2E_{lepton}(\text{GeV})}$

if $Q^2 \ge 1\ \text{GeV}^2$

for $E_{lepton}(\text{NMC}) = 200$ GeV, $\min(x) = \frac{1}{2\cdot 200} = 0.003$



(from H1 and ZEUS, hep-ex/0502008)



region of nuclear data

Functional form

Nuclear PDFs "per nucleon"

If there were no nuclear modification

$$Au^A(x) = Zu^p(x) + Nu^n(x), \quad Ad^A(x) = Zd^p(x) + Nd^n(x) \qquad p = \text{proton}, \quad n = \text{neutron}$$

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

$$\rightarrow \quad u^A(x) = \frac{Zu(x) + Nd(x)}{A}, \qquad d^A(x) = \frac{Zd(x) + Nu(x)}{A}$$

Take account of nuclear effects by $w_i(x, A)$

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

$$\bar{u}^A(x) = w_{\bar{q}}(x, A)\frac{Z\bar{u}(x) + N\bar{d}(x)}{A}, \qquad \bar{d}^A(x) = w_{\bar{q}}(x, A)\frac{Z\bar{d}(x) + N\bar{u}(x)}{A}$$

$$\bar{s}^A(x) = w_{\bar{q}}(x, A)\bar{s}(x)$$

$$g^A(x) = w_g(x, A)g(x)$$

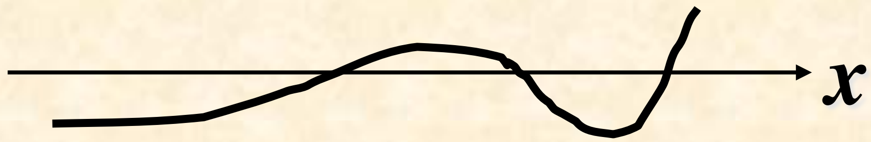
at Q^2=1 GeV^2 ($\equiv Q_0^2$)

Nuclear modifications and constraints

$$f_i^A(x,Q_0^2) = w_i(x,A) f_i(x,Q_0^2) \qquad i = u_v,\ d_v,\ \bar{u},\ \bar{d},\ \bar{s},\ g$$

$$w_i(x,A) = 1 + \left(1 - \frac{1}{A^\alpha}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^\beta}$$

Note: The region $x > 1$ cannot be described by this parametrization.



A simple function = cubic polynomial

Three constraints

Nuclear charge: $Z = A\int dx\left[\frac{2}{3}\left(u^A - \bar{u}^A\right) - \frac{1}{3}\left(d^A - \bar{d}^A\right) - \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{2}{3}u_v^A - \frac{1}{3}d_v^A\right]$

Baryon number: $A = A\int dx\left[\frac{1}{3}\left(u^A - \bar{u}^A\right) + \frac{1}{3}\left(d^A - \bar{d}^A\right) + \frac{1}{3}\left(s^A - \bar{s}^A\right)\right] = A\int dx\left[\frac{1}{3}u_v^A + \frac{1}{3}d_v^A\right]$

Momentum: $A = A\int dx\left[u^A + \bar{u}^A + d^A + \bar{d}^A + s^A + \bar{s}^A + g\right]$

$$= A\int dx\left[u_v^A + d_v^A + 2\left(\bar{u}^A + \bar{d}^A + \bar{s}^A\right) + g\right]$$

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; arXiv:1612.05741.
- 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. [⇦ Relevant for this workshop.]

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.

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)

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

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

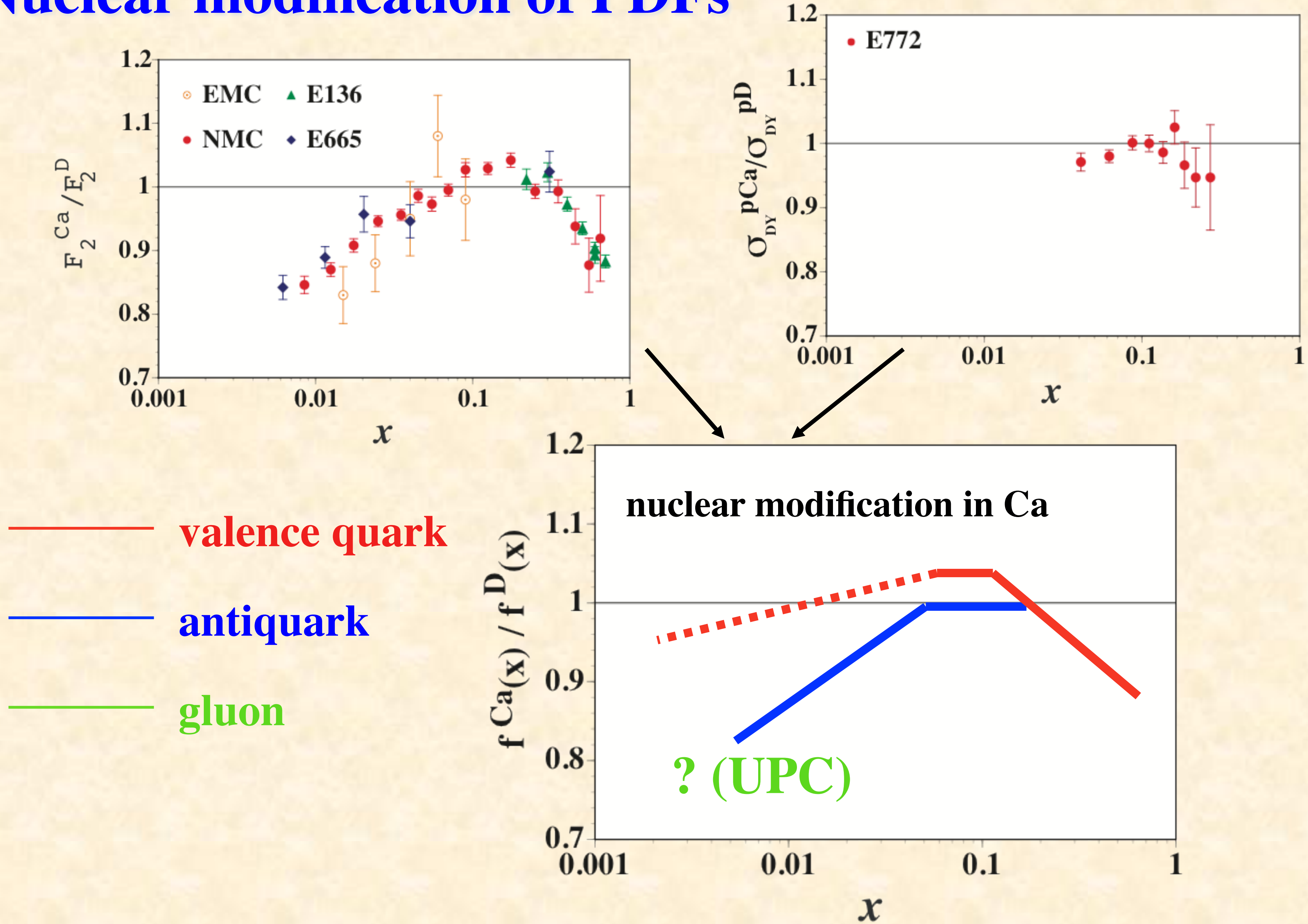
$$x f_i^{N/A}(x) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1 + e^{A_4} x)^{A_5} & : i = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s} \\ A_0 x^{A_1}(1-x)^{A_2} + (1 + A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u} \end{cases}$$

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

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

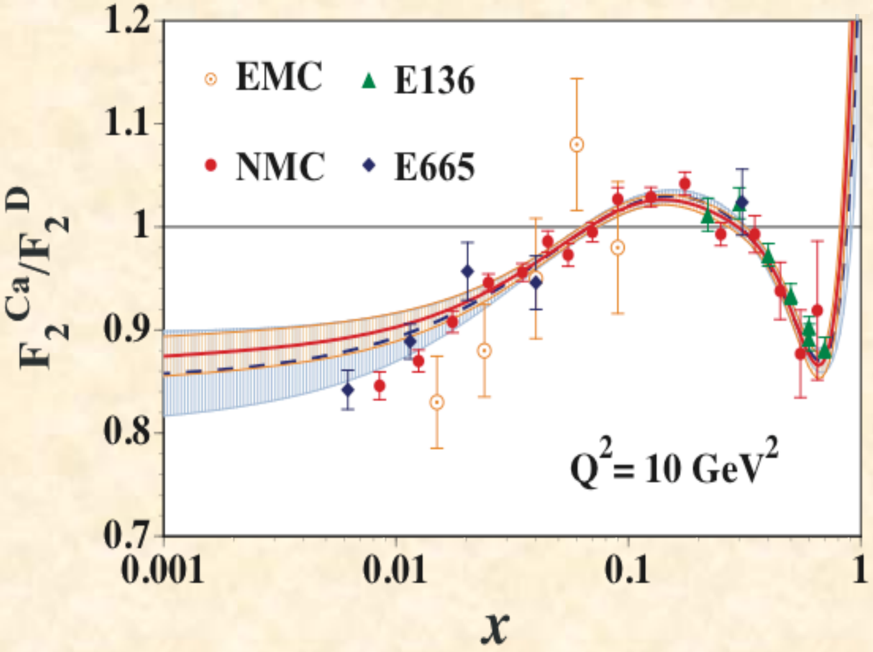
$$R_s^A(x) = R_v^A(x)\frac{\varepsilon_s}{\varepsilon_1}\frac{1 + a_s x^{\alpha_s}}{1 + a_s}, \quad R_g^A(x) = R_g^A(x)\frac{\varepsilon_g}{\varepsilon_1}\frac{1 + a_g x^{\alpha_g}}{1 + a_g}$$

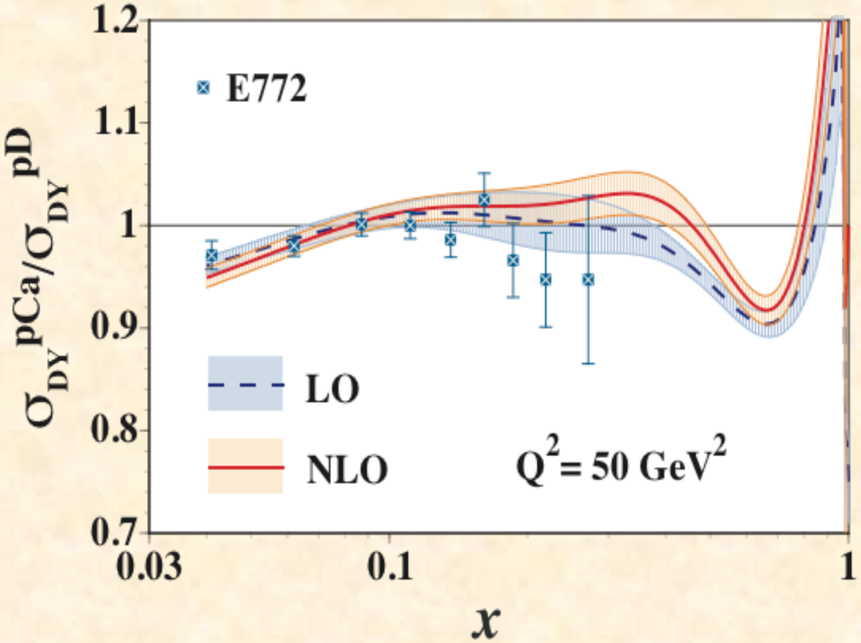
Nuclear modification of PDFs



Comparison with F_2^{Ca}/F_2^{D} & $\sigma_{DY}^{pCa}/\ \sigma_{DY}^{pD}$ data

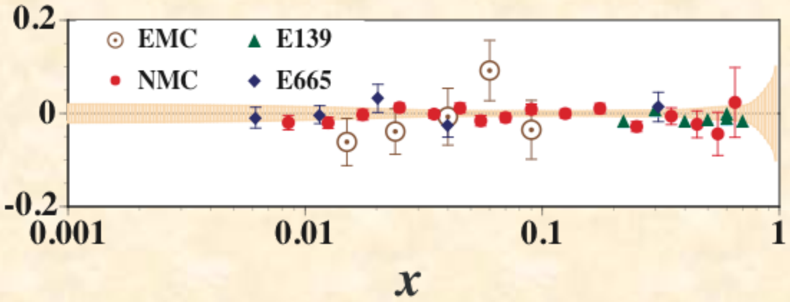
LO analysis **NLO analysis**

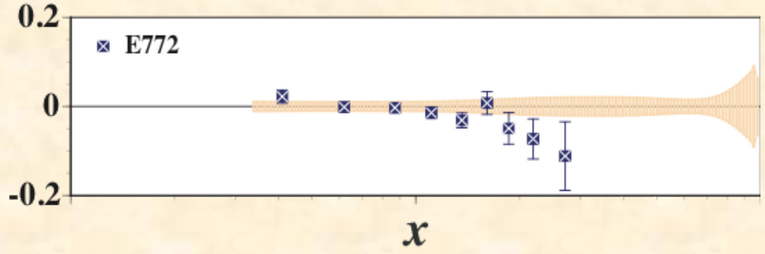




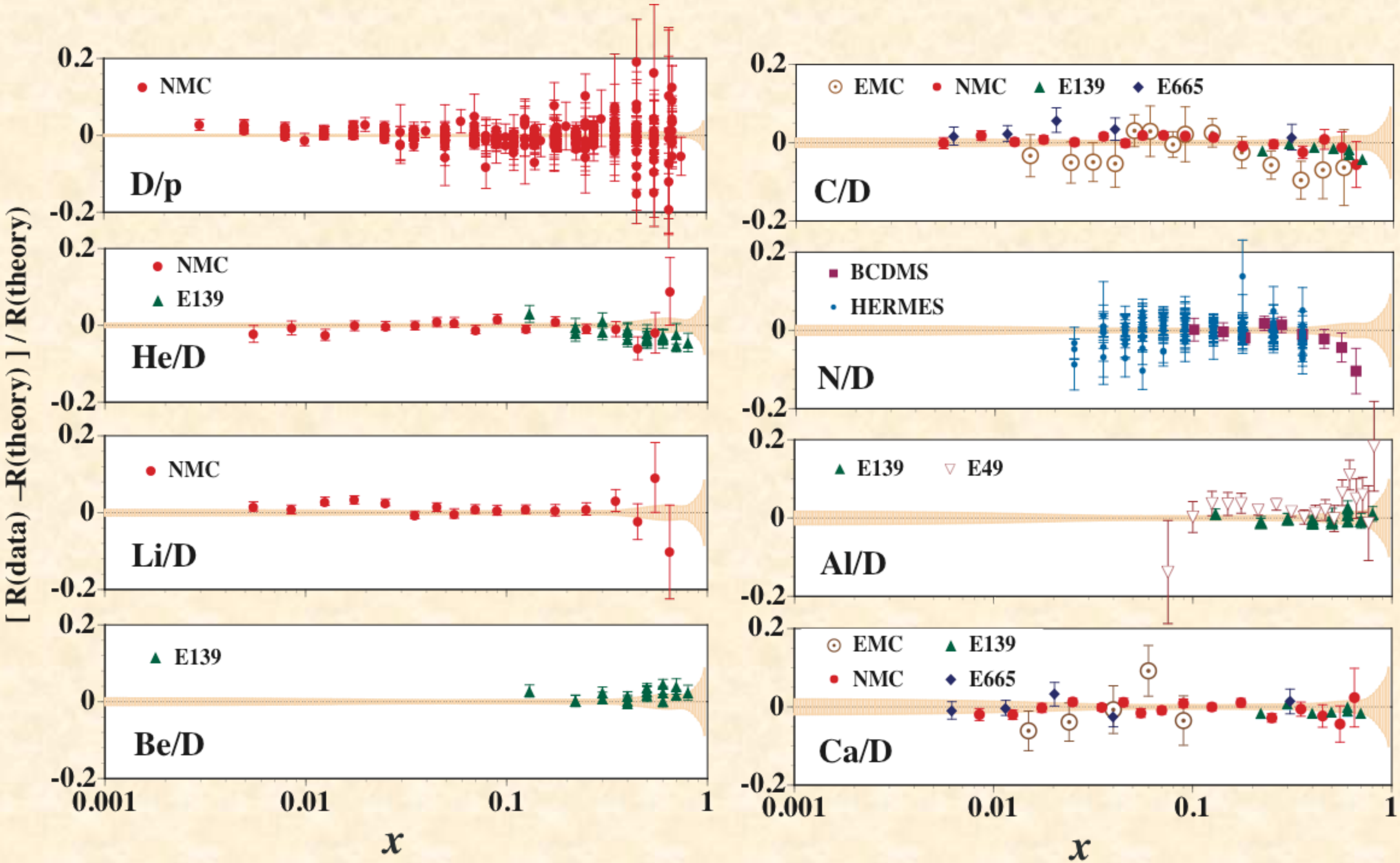
$(R^{exp}-R^{theo})/R^{theo}$ at the same Q^2 points

$R= F_2^{Ca}/F_2^{D},\ \sigma_{DY}^{pCa}/\ \sigma_{DY}^{pD}$





Comparison with F_2^A/F_2^D data: Light nuclei



Scaling Violation and Gluon Distributions

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

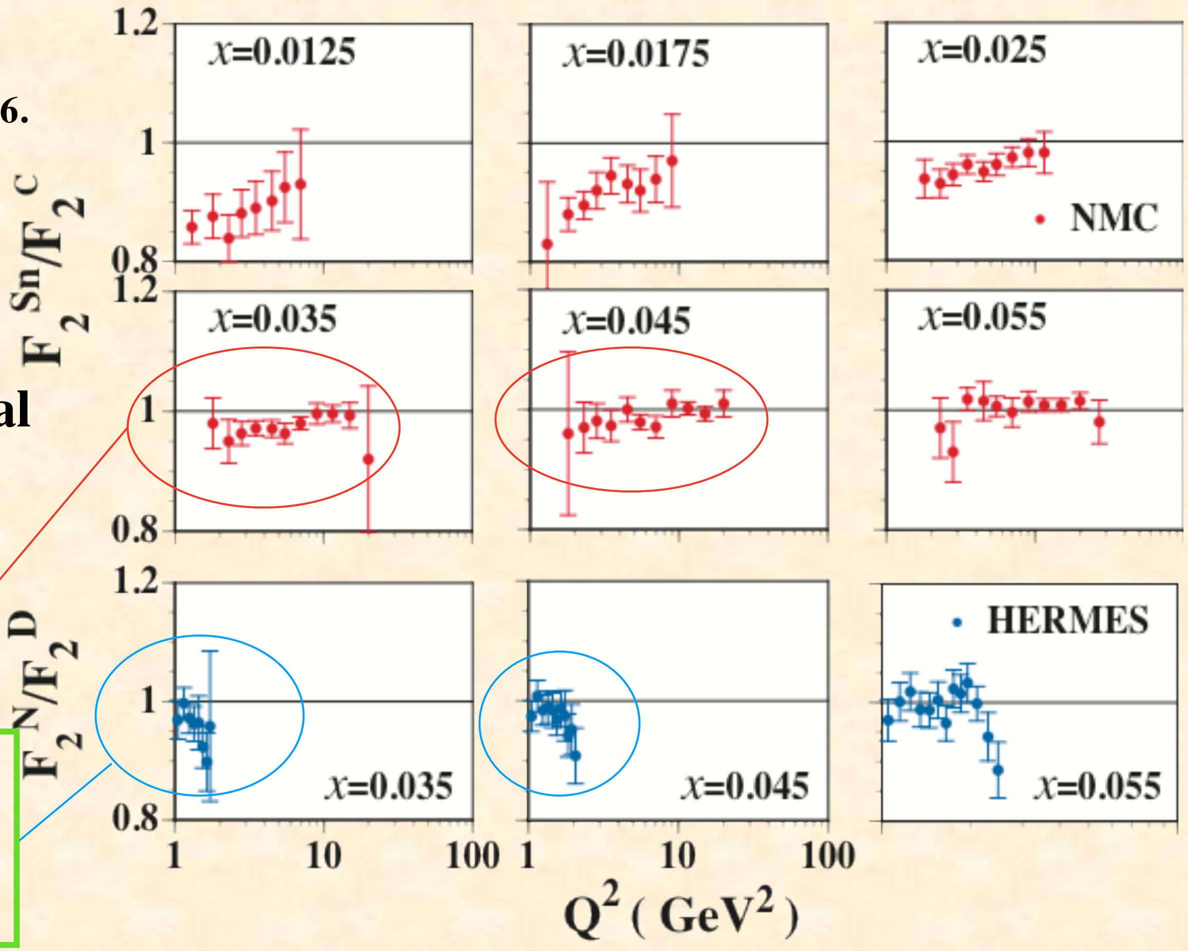
dominant term at small x

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

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

$$\frac{\partial F_2}{\partial\left(\ln Q^2\right)} \approx \frac{20\,\alpha_s}{27\pi} xg$$

Q² dependence of F_2 is proportional to the gluon distribution.

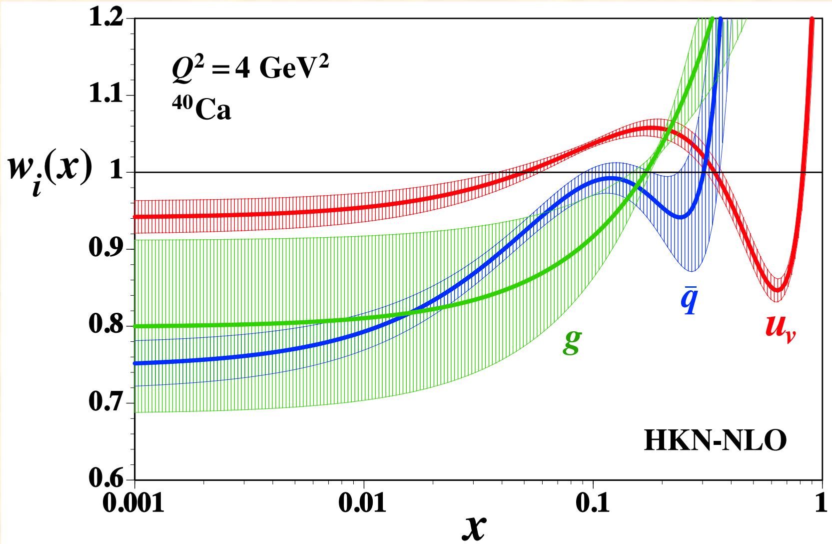


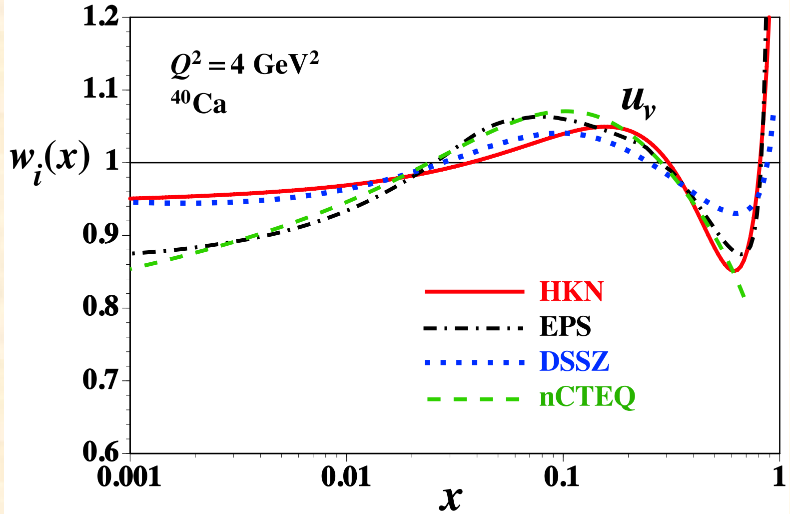
No experimental consensus of Q² dependence!
→ $G^A(x)$ determination is difficult.

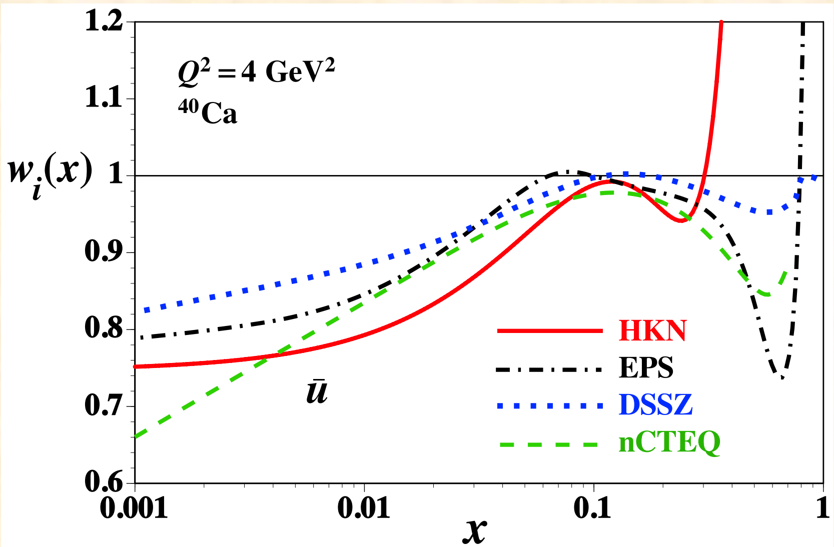
Review on neutrino interactions (arXiv: 1610.01464)

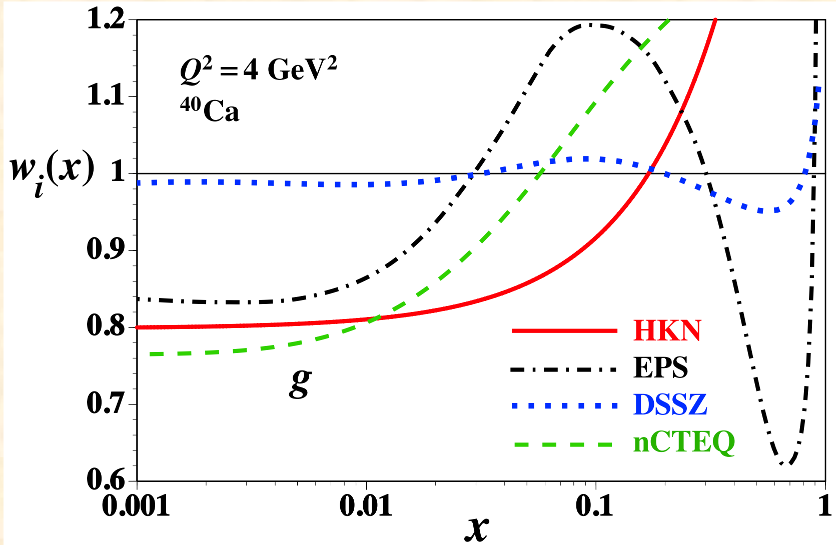
Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments

S.X. Nakamura[1], H. Kamano[2,3], Y. Hayato[4], M. Hirai[5], W. Horiuchi[6], S. Kumano[2,3], T. Murata[1], K. Saito[7,3], M. Sakuda[8], T. Sato[1,3], Y. Suzuki[9,10]









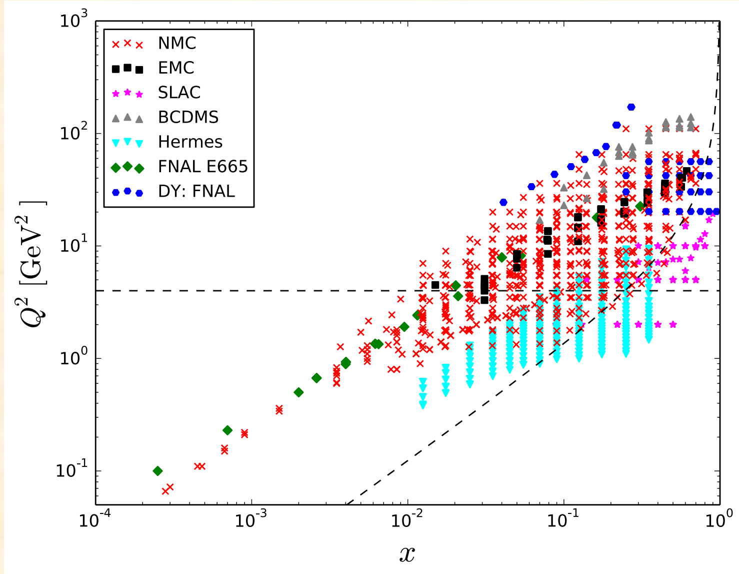
Recent analysis by nCTEQ15: data set

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

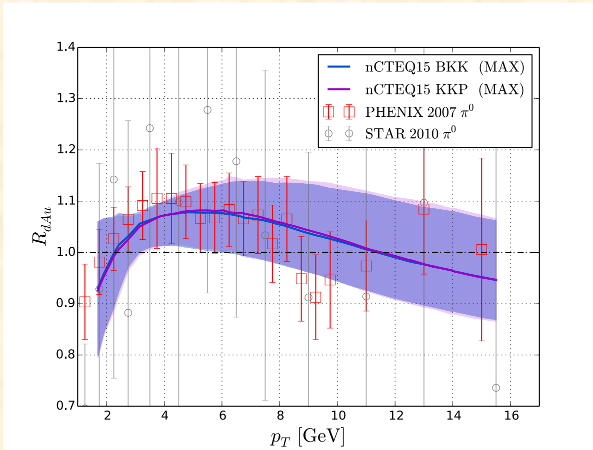


Drell-Yan

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: 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

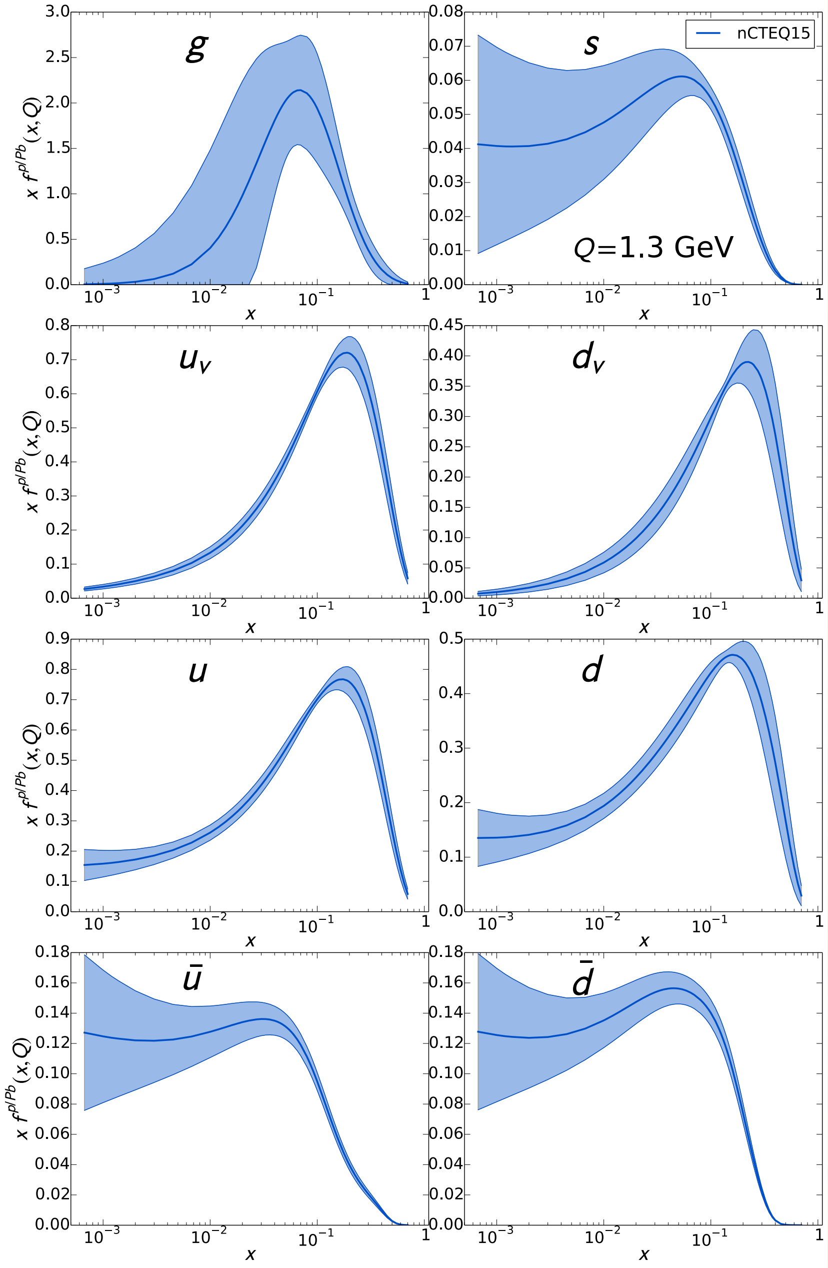
$R_{dAu}^{\pi}/R_{pp}^{\pi}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	[67]	21	20	6.63
	STAR-2010	STAR	[68]	13	12	1.41
Total:				34	32	8.04

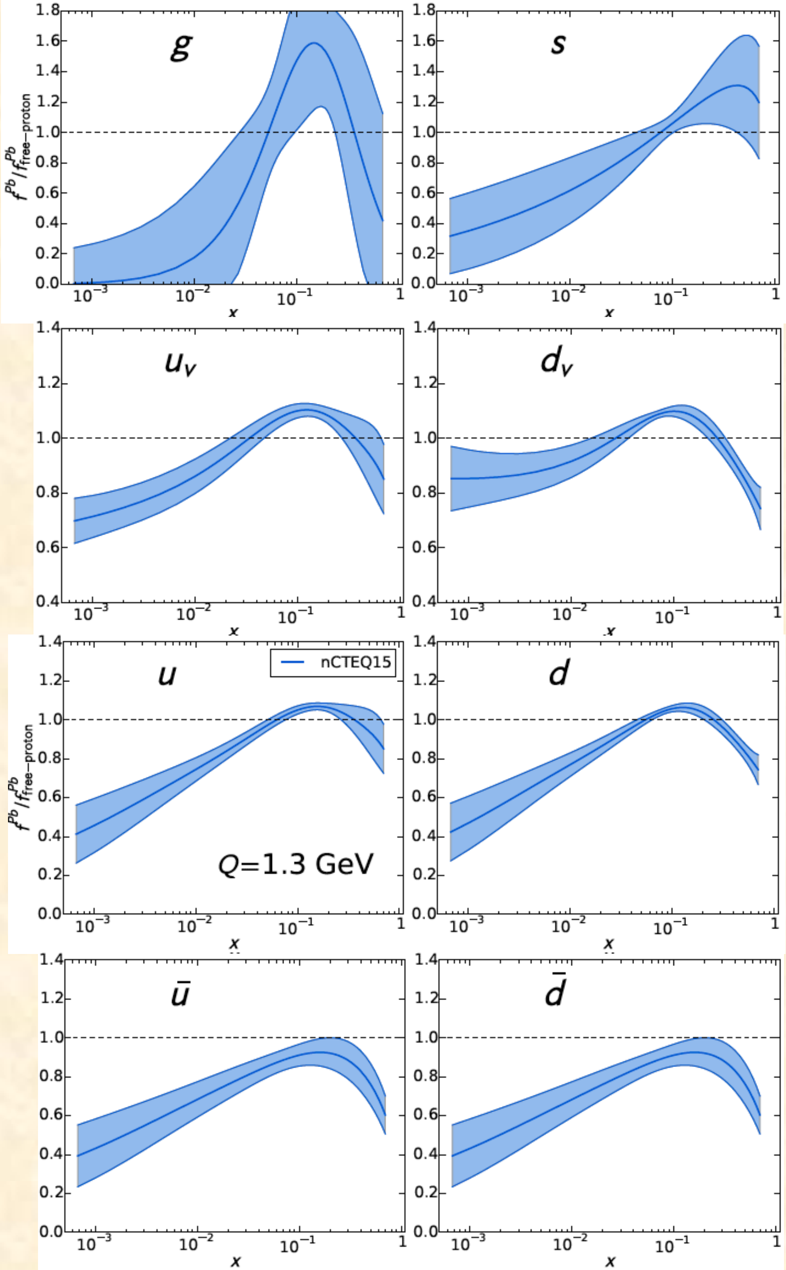


- DIS: $Q > 2$ GeV and $W > 3.5$ GeV
- DY: $2 < M < 300$ GeV
- π^0 production: $p_T > 1.7$ GeV

nCTEQ15

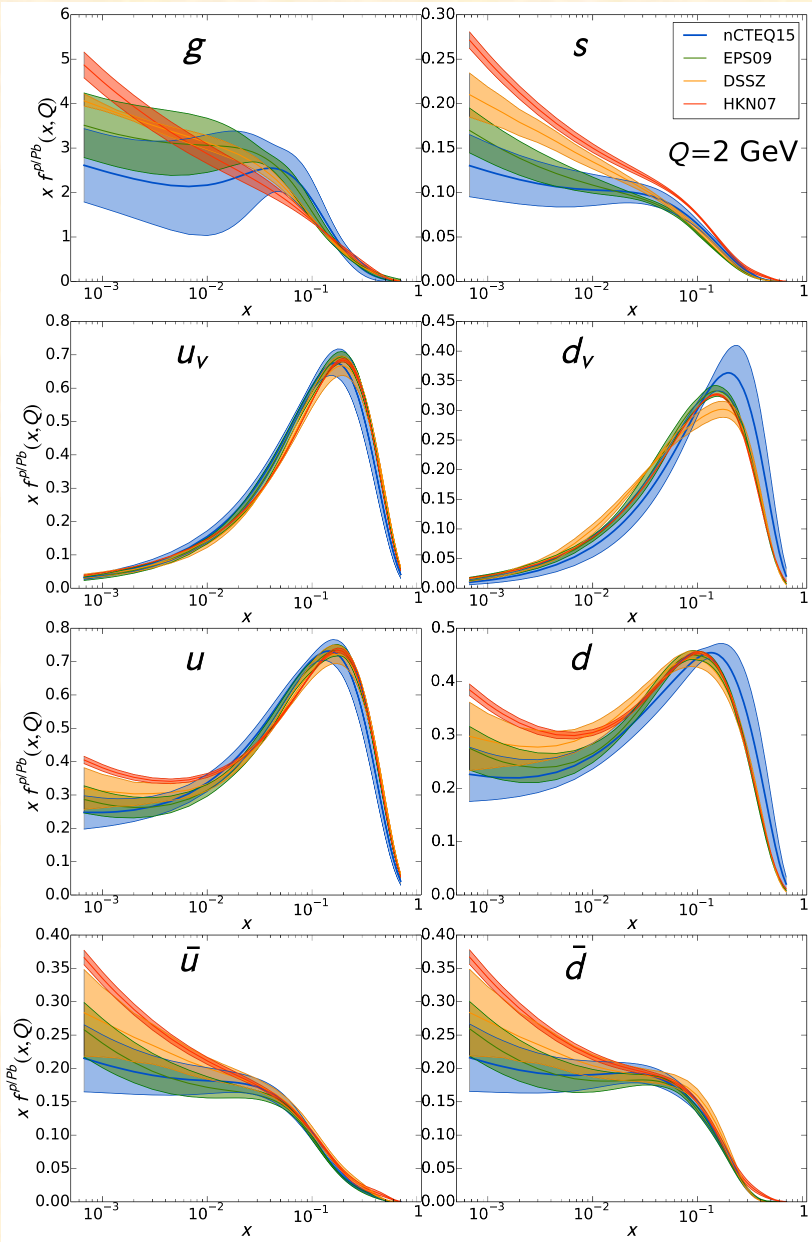
$Q^2 = (1.3)^2\ \text{GeV}^2$

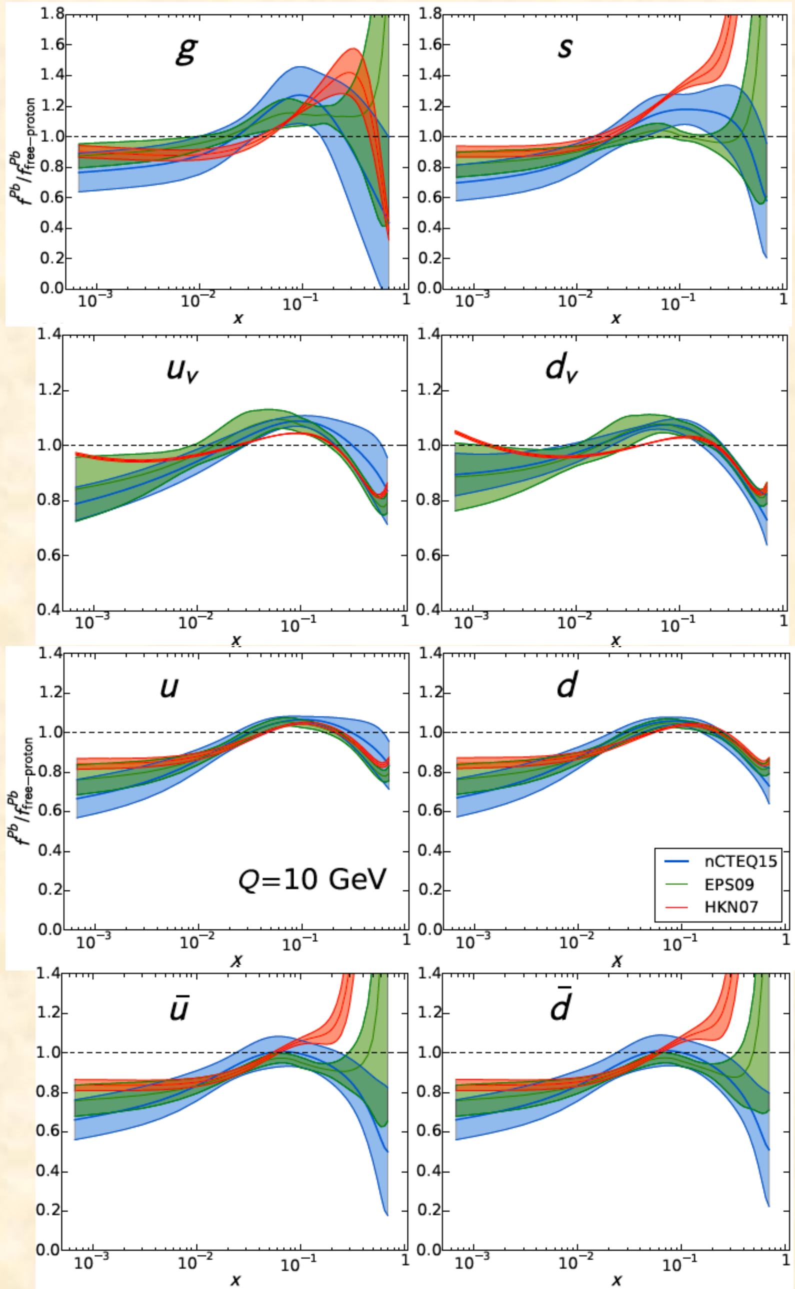




nCTEQ15: Comparison with others

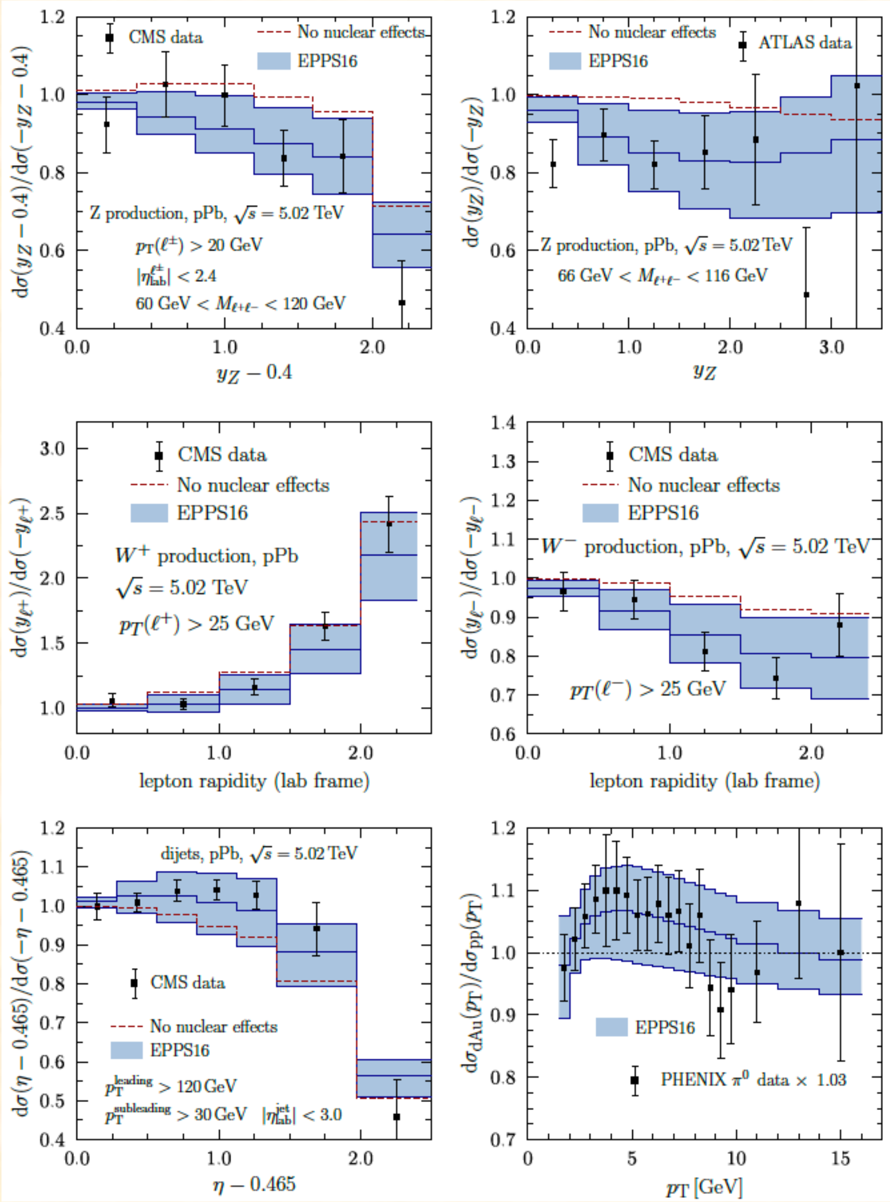
$Q^2 = (2)^2\ \mathrm{GeV}^2$





EPPS16: addition of LHC data

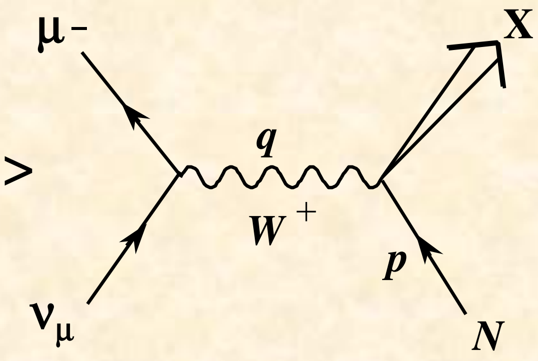
Experiment	Observable	Collisions	Data points	χ^2	Ref.
SLAC E139	DIS	e^-He(4), e^-D	21	12.2	[72]
CERN NMC 95, re.	DIS	μ^-He(4), μ^-D	16	18.0	[73]
CERN NMC 95	DIS	μ^-Li(6), μ^-D	15	18.4	[74]
CERN NMC 95, Q^2 dep.	DIS	μ^-Li(6), μ^-D	153	161.2	[74]
SLAC E139	DIS	e^-Be(9), e^-D	20	12.9	[72]
CERN NMC 96	DIS	μ^-Be(9), μ^-C	15	4.4	[75]
SLAC E139	DIS	e^-C(12), e^-D	7	6.4	[72]
CERN NMC 95	DIS	μ^-C(12), μ^-D	15	9.0	[74]
CERN NMC 95, Q^2 dep.	DIS	μ^-C(12), μ^-D	165	133.6	[74]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-D	16	16.7	[73]
CERN NMC 95, re.	DIS	μ^-C(12), μ^-Li(6)	20	27.9	[73]
FNAL E772	DY	pC(12), pD	9	11.3	[76]
SLAC E139	DIS	e^-Al(27), e^-D	20	13.7	[72]
CERN NMC 96	DIS	μ^-Al(27), μ^-C(12)	15	5.6	[75]
SLAC E139	DIS	e^-Ca(40), e^-D	7	4.8	[72]
FNAL E772	DY	pCa(40), pD	9	3.33	[76]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-D	15	27.6	[73]
CERN NMC 95, re.	DIS	μ^-Ca(40), μ^-Li(6)	20	19.5	[73]
CERN NMC 96	DIS	μ^-Ca(40), μ^-C(12)	15	6.4	[75]
SLAC E139	DIS	e^-Fe(56), e^-D	26	22.6	[72]
FNAL E772	DY	e^-Fe(56), e^-D	9	3.0	[76]
CERN NMC 96	DIS	μ^-Fe(56), μ^-C(12)	15	10.8	[75]
FNAL E866	DY	pFe(56), pBe(9)	28	20.1	[77]
CERN EMC	DIS	μ^-Cu(64), μ^-D	19	15.4	[78]
SLAC E139	DIS	e^-Ag(108), e^-D	7	8.0	[72]
CERN NMC 96	DIS	μ^-Sn(117), μ^-C(12)	15	12.5	[75]
CERN NMC 96, Q^2 dep.	DIS	μ^-Sn(117), μ^-C(12)	144	87.6	[79]
FNAL E772	DY	pW(184), pD	9	7.2	[76]
FNAL E866	DY	pW(184), pBe(9)	28	26.1	[77]
CERN NA10★	DY	π^-W(184), π^-D	10	11.6	[52]
FNAL E615★	DY	π^+W(184), π^-W(184)	11	10.2	[53]
CERN NA3★	DY	π^-Pt(195), π^-H	7	4.6	[51]
SLAC E139	DIS	e^-Au(197), e^-D	21	8.4	[72]
RHIC PHENIX	π^0	dAu(197), pp	20	6.9	[28]
CERN NMC 96	DIS	μ^-Pb(207), μ^-C(12)	15	4.1	[75]
CERN CMS★	$W^\pm$	pPb(208)	10	8.8	[43]
CERN CMS★	Z	pPb(208)	6	5.8	[45]
CERN ATLAS★	Z	pPb(208)	7	9.6	[46]
CERN CMS★	dijet	pPb(208)	7	5.5	[34]
CERN CHORUS★	DIS	νPb(208), $\bar{\nu}$Pb(208)	824	998.6	[50]
Total			1811	1789	



Comments on neutrino DIS

Neutrino deep inelastic scattering (CC: Charged Current)

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



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

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

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

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

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

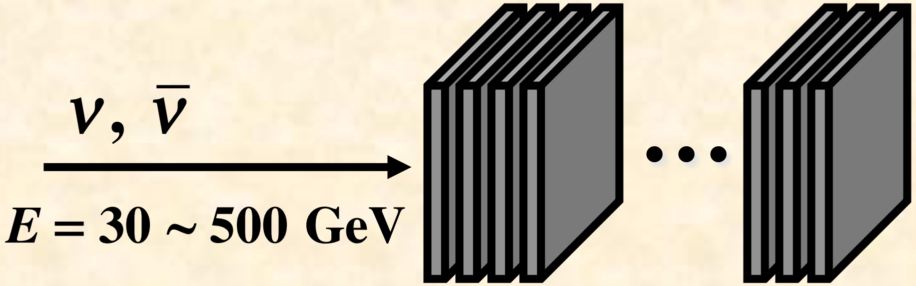
$$\frac{d\sigma_{\nu,\bar{\nu}}^{CC}}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi\,(1+Q^2/M_W^2)^2}\left[x\,y^2F_1^{CC} + \left(1-y-\frac{M\,x\,y}{2E}\right)F_2^{CC} \underline{\pm x\,y\left(1-\frac{y}{2}\right)F_3^{CC}}\right]$$

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

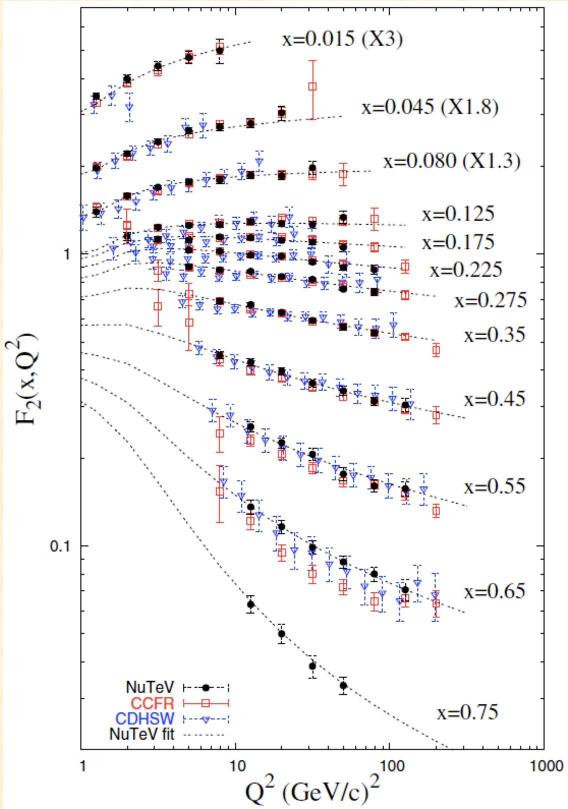
Experiment	Target	ν energy (GeV)
CCFR	Fe	30-360
CDHSW	Fe	20-212
CHORUS	Pb	10-200
NuTeV	Fe	30-500

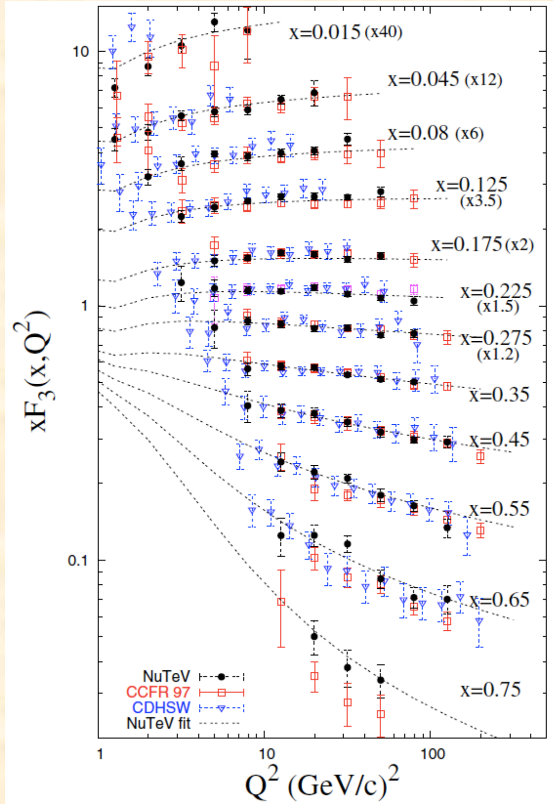


Huge Fe target (690 ton)

MINERνA (He, C, Fe, Pb), …

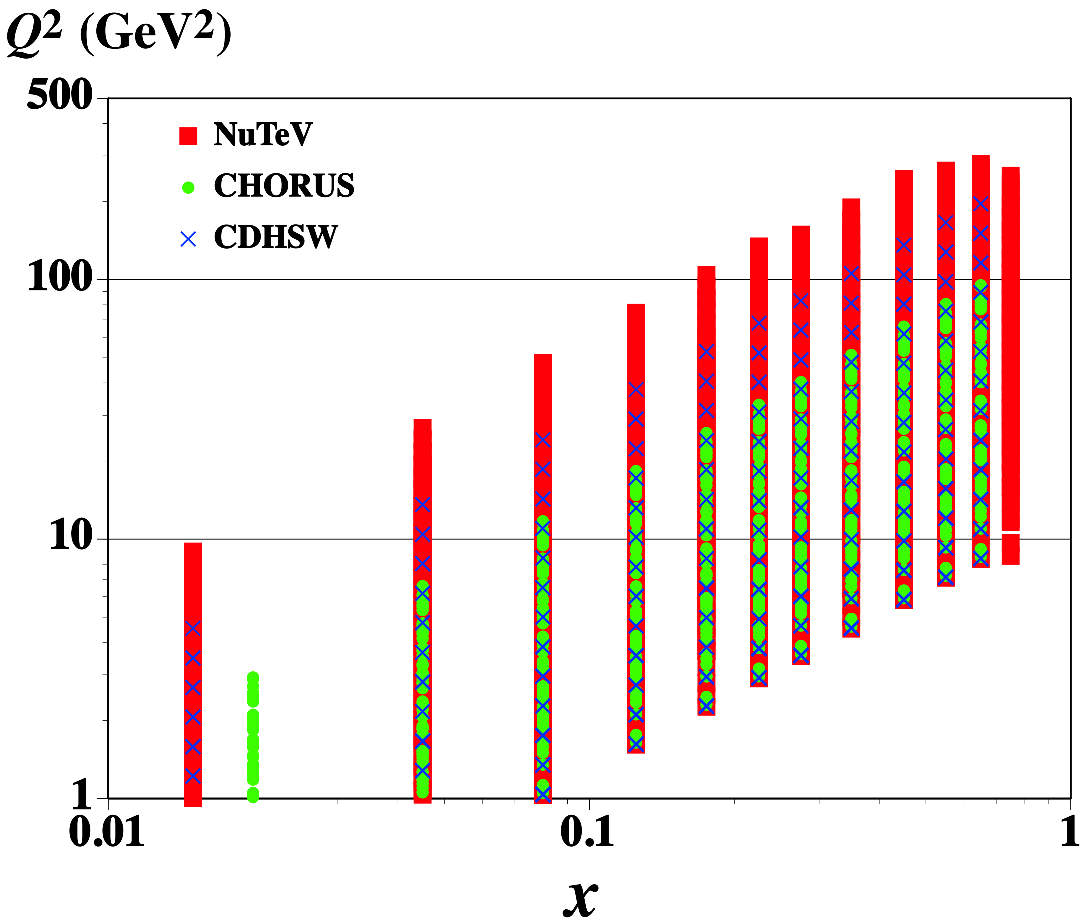
M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.



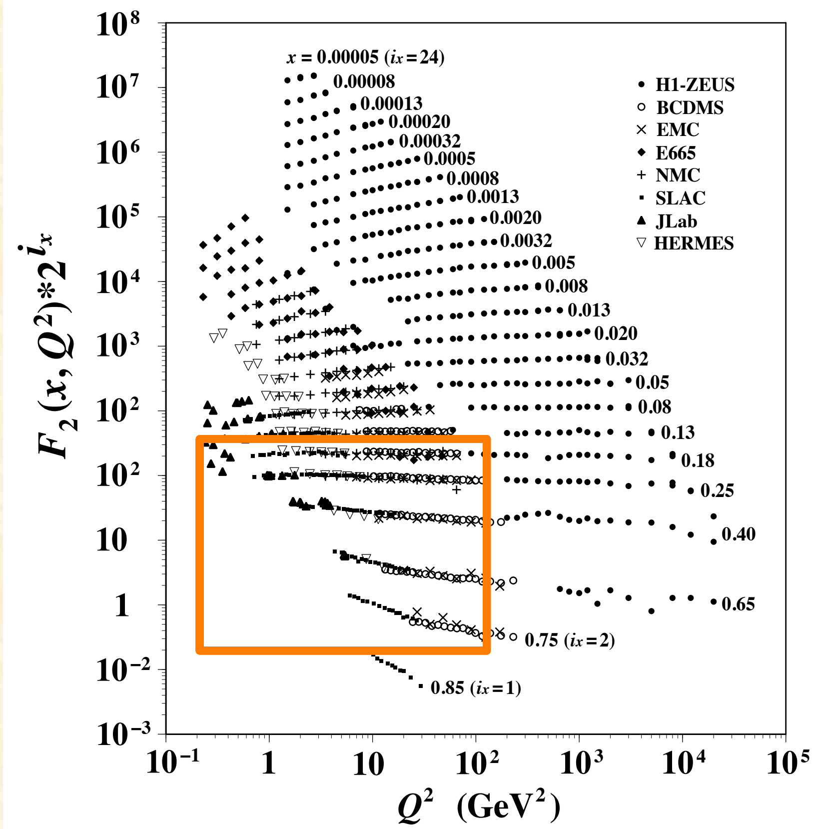


Neutrino DIS experiments: kinematical range

Neutrino DIS



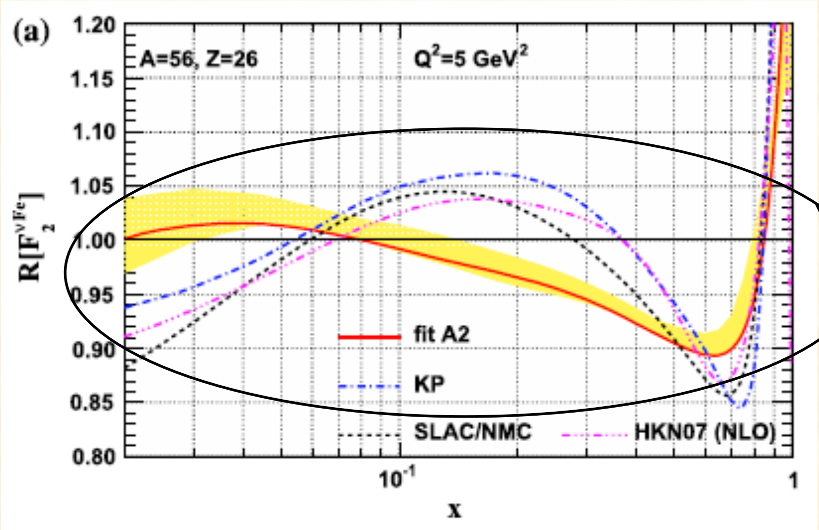
Charged-lepton DIS



S. Kumano, Nuclear Physics (in Japanese), KEK Physics Series, Volume 2, Kyoritsu Shuppan (2015)

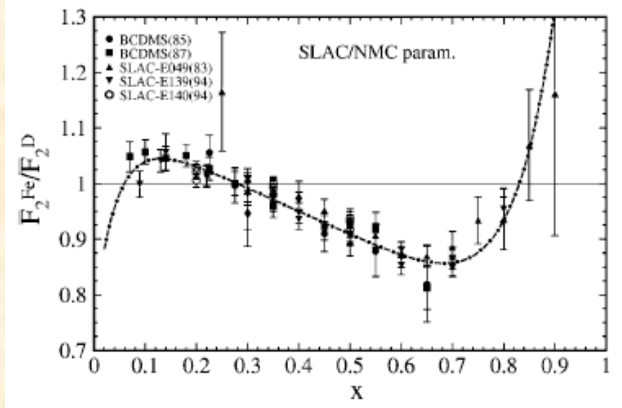
Analysis of CTEQ-2008 (Schienbein *et al.*)

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

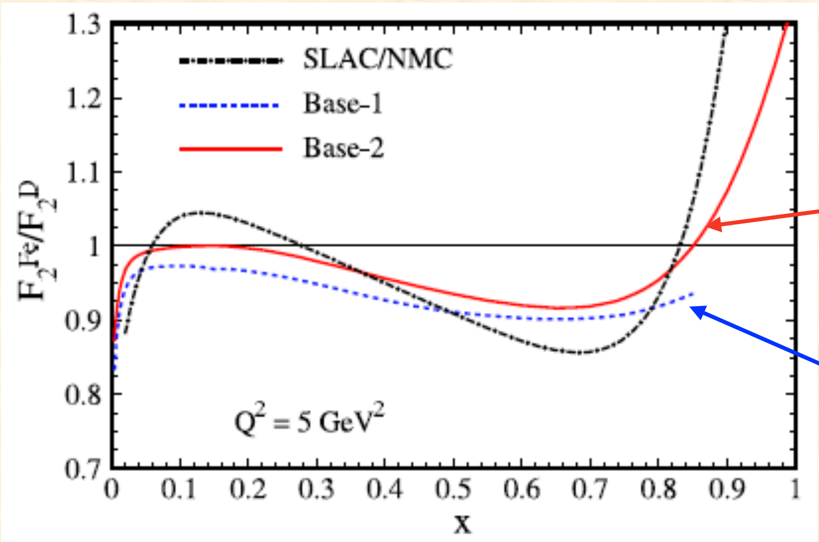


Differences from typical NPDFs.

Charged-lepton scattering



Neutrino scattering



Base-1
- **remove CCFR data**
- **incorporate deuteron corrections**

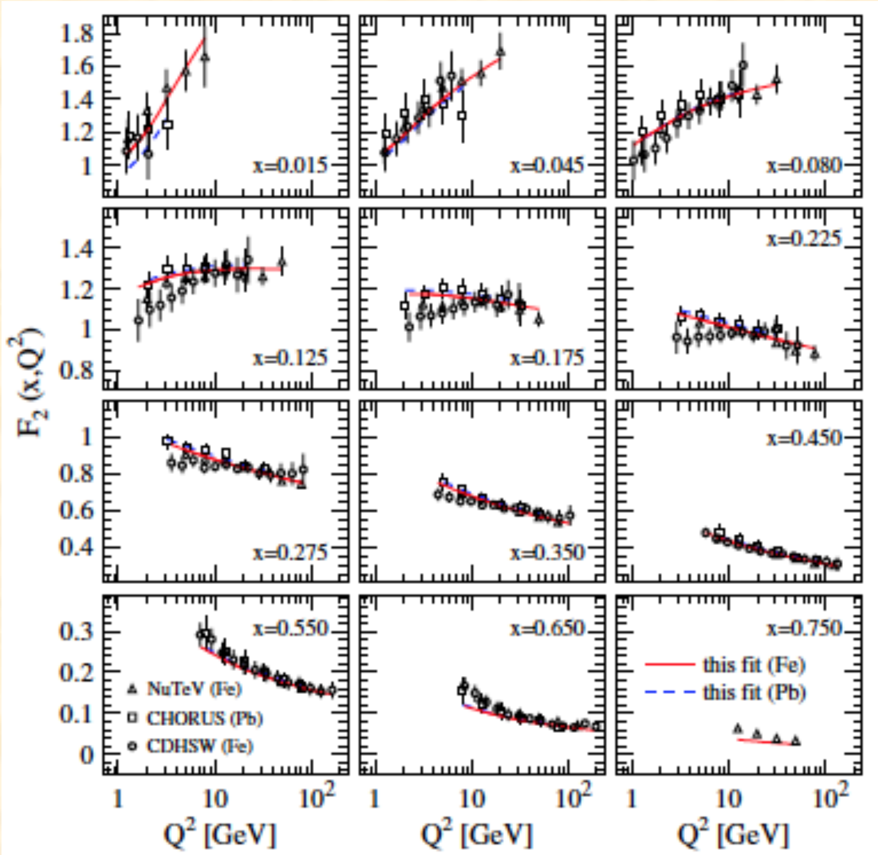
Base-2 **corresponds to CTEQ6.1M with s≠sbar**
- **include CCFR data**
  Charged-lepton correction factors are applied.
- **s≠sbar**

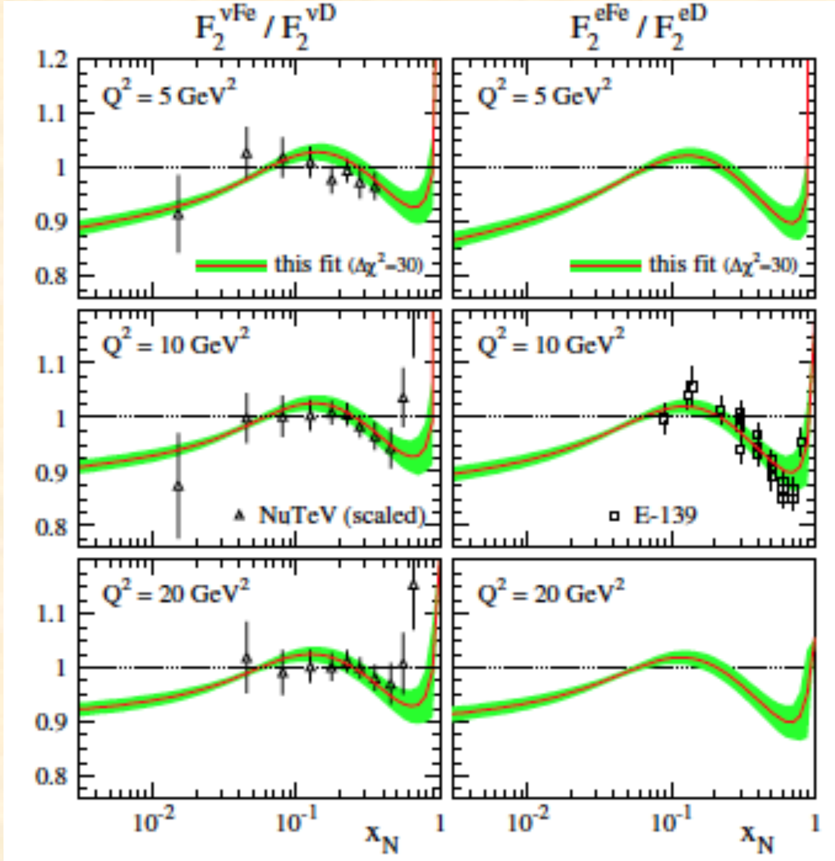
Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.

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

Neutrino DIS ⇔ Charged DIS issue

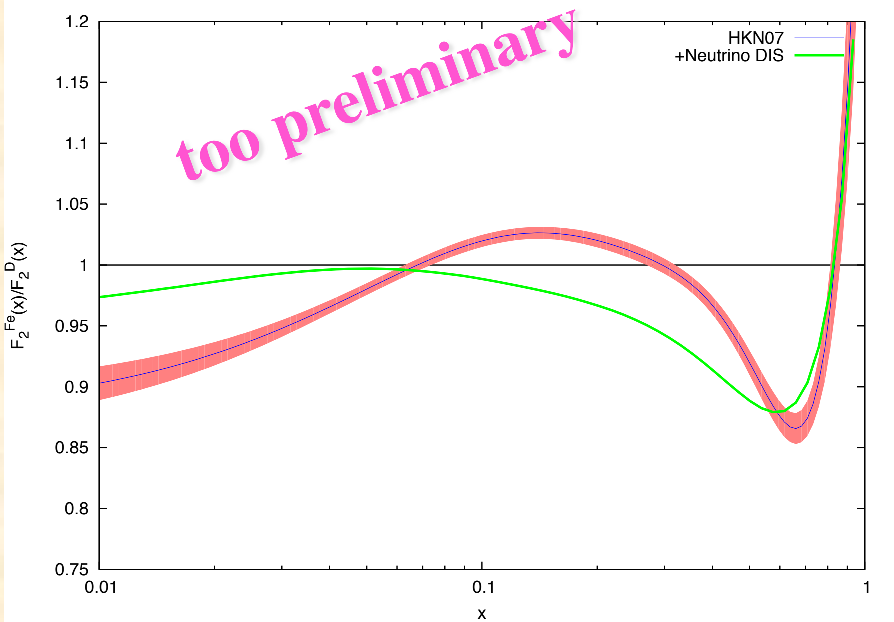
D. de Florian, R. Sassot, P. Zurita, and M. Stratmann,
Phys. Rev. D 85 (2012) 074028.

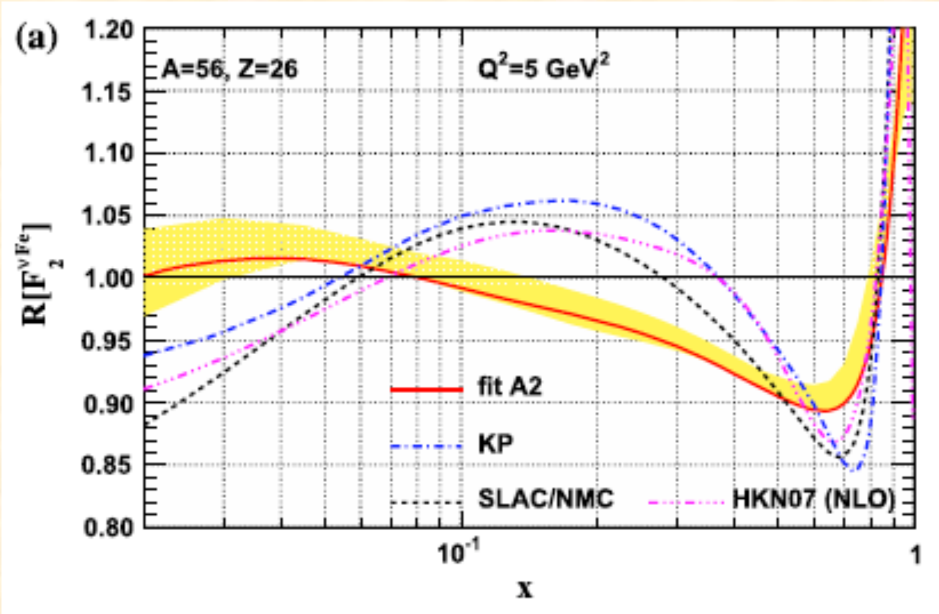




According to their analysis, the issue does not exist!?

Our research in progress (M. Hirai, SK, K. Saito)

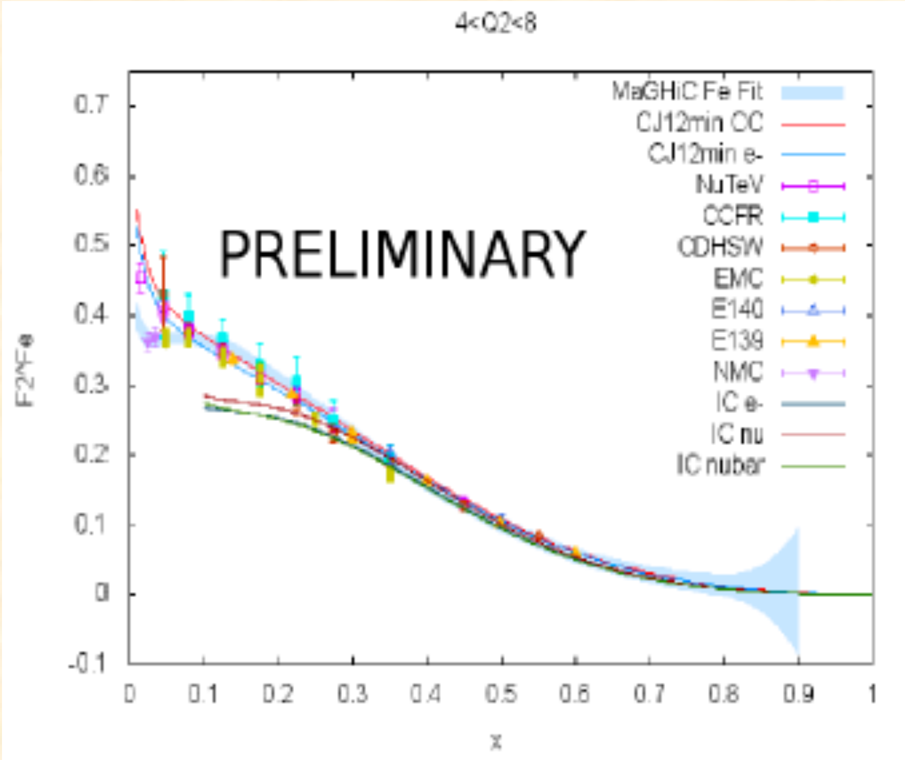




We are getting a similar modification to the nCTEQ one.

N. Kalantarians: Neutrino DIS ⇔ Charged DIS

N. Kalantarians at NuInt15
JPS Conf. Proc. 12 (2016) 010028.

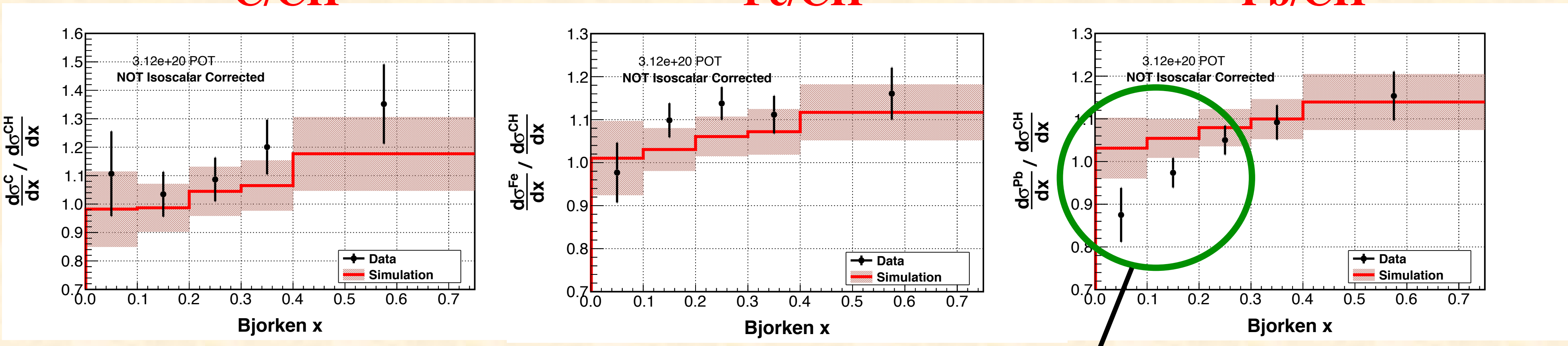


According to this analysis, both structure functions are same except for the small-*x* region (*x*<0.05) !?

Measurements by Miner*v*a

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

C/CH Fe/CH Pb/CH



Different shadowing from charged-lepton case?!

Summary on nuclear PDFs

Global analyses for the nuclear PDFs
by using data of charged-lepton, neutrino DIS, pA, AA collisions

Valence quark: reasonably good, in progress at JLab, Minerva for large x

Antiquark: good only at $x = 0.1$, in progress at Fermilab (E906) $x = 0.1 \sim 0.4$.

Gluon: large uncertainties in the whole-x region, LHC, RHIC

Issues

- Charged-lepton DIS ⇔ Neutrino DIS
- Matching with resonance model and $Q^2 \to 0$ region
- Gluon distributions (UPC)

New experimental information

- JLab, Fermilab-DY, Minerva, LHC, …, EIC, ILC, …

Comments on Two-photon physics (UPC?)

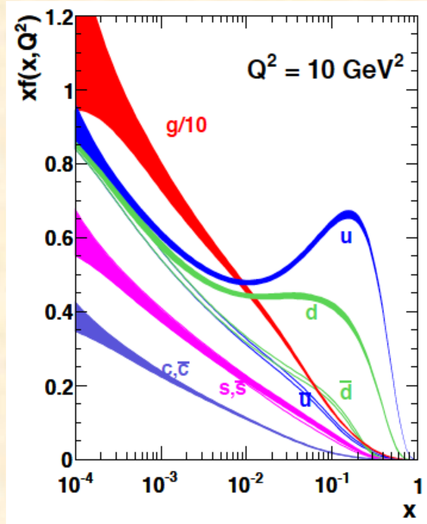
H. Kawamura and S. Kumano,
Phys. Rev. D 89 (2014) 054007;

S. Kumano, Q.-T. Song, and O. Teryaev,
Research in progress.

Wigner distribution and various structure functions

Wigner operator: $\hat{w}(k_+,\vec{k}_\perp,\vec{r}) \equiv \int d\xi_- d^2\xi_\perp e^{i(\xi_- k_+ - \vec{\xi}_\perp \cdot \vec{k}_\perp)} \bar{\psi}\left(\vec{r}-\vec{\xi}/2\right)\psi\left(\vec{r}+\vec{\xi}/2\right)$

Wigner distribution: $W(x,\vec{k}_\perp,\vec{r}) \equiv \int \frac{d^3q}{(2\pi)^3} \langle \vec{q}/2 | \hat{w}(\vec{r},k_+,\vec{k}_\perp) | -\vec{q}/2 \rangle, \quad x = k_+ / p_+$



Form factor ← $\int dx\, d^2k_\perp$

PDF (Parton Distribution Function) ← $\int d^2k_\perp d^3r$

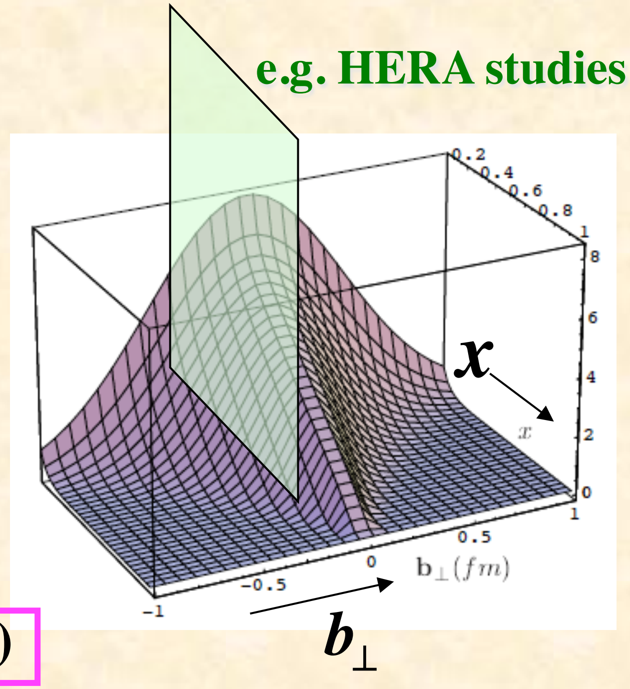
Wigner distribution $W(x,\vec{k}_\perp,\vec{r})$

3D world

$\int d^3r$ → **TMD (Transverse Momentum Dependent) parton distribution**

$\int d^2k_\perp dz$ → **GPD (Generalized Parton Distribution)**

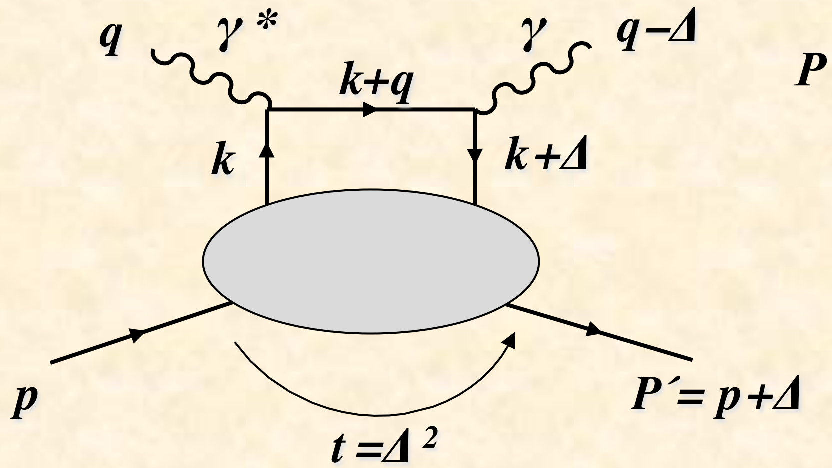
e.g. HERA studies



s-t crossing →

$\gamma\gamma \to h\bar{h}$ **GDA (Generalized Distribution Amplitude)**

Generalized Parton Distributions (GPDs)



$$P = \frac{p+p'}{2}, \quad \Delta = p' - p$$

Bjorken variable $x = \frac{Q^2}{2p\cdot q}$

Momentum transfer squared $t = \Delta^2$

Skewdness parameter $\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$

GPDs are defined as correlation of off-forward matrix:

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p'|\bar{\psi}(-z/2)\gamma^+\psi(z/2)|p\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[H(x,\xi,t)\bar{u}(p')\gamma^+u(p) + E(x,\xi,t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u(p)\right]$$

Forward limit: PDFs

$$H(x,\xi,t)\big|_{\xi=t=0} = f(x)$$

First moments: Form factors

Dirac and Pauli form factors F_1, F_2 $\int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

Second moments: Angular momenta

Sum rule: $J_q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H_q(x,\xi,t=0) + E_q(x,\xi,t=0)\right], \quad J_q = \frac{1}{2}\Delta q + L_q$

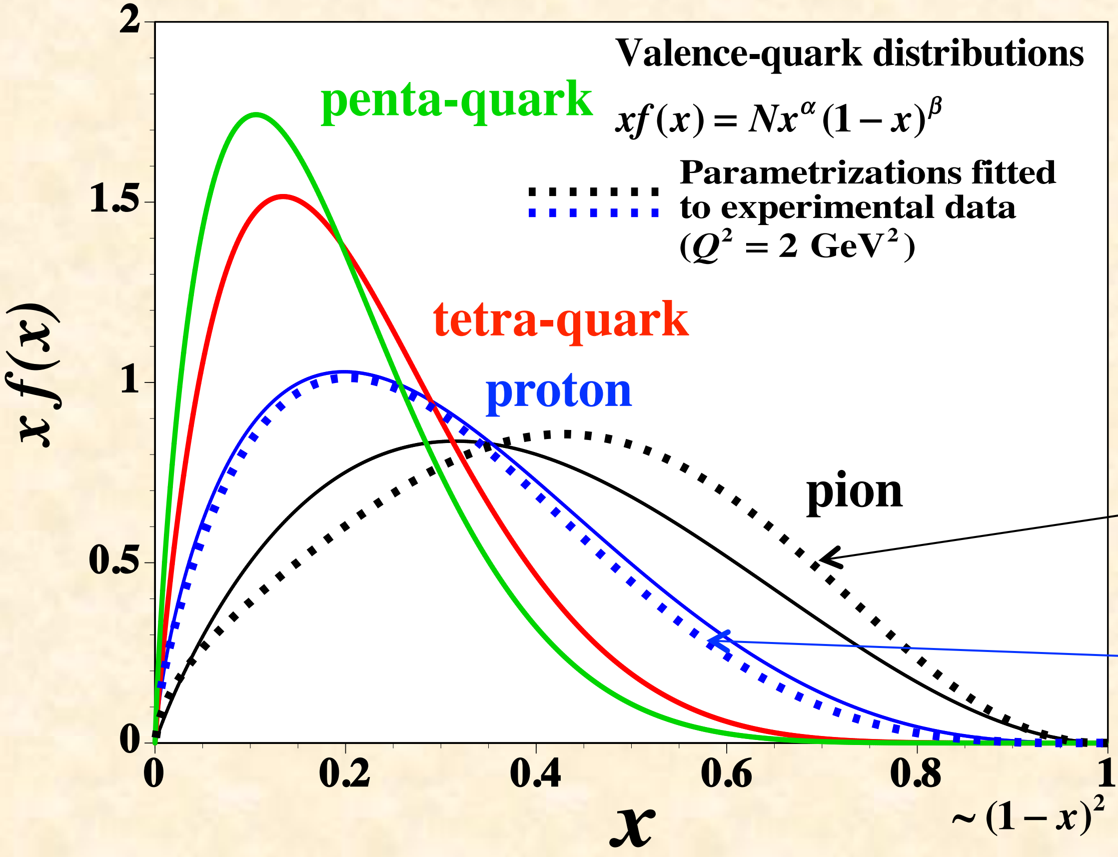
Simple function of GPDs

$H_q^h(x,t) = f(x)F(t,x)$

M. Guidal, M.V. Polyakov, A.V. Radyushkin, M. Vanderhaeghen, PRD 72, 054013 (2005).

Longitudinal-momentum distribution (PDF) for valence quarks: $f(x) = q_v(x) = c_n x^{\alpha_n}(1-x)^{\beta_n}$

- Valence-quark number sum rule (charge and baryon numbers): $\int_0^1 dx\, f(x) = n$
- Constituent conting rule at $x \to 1$: β_n (n = number of constituents)
- Momentum carried by quarks $\langle x \rangle_q \simeq \int_0^1 dx\, x f(x)$



$\sim (1-x)^2$ for π

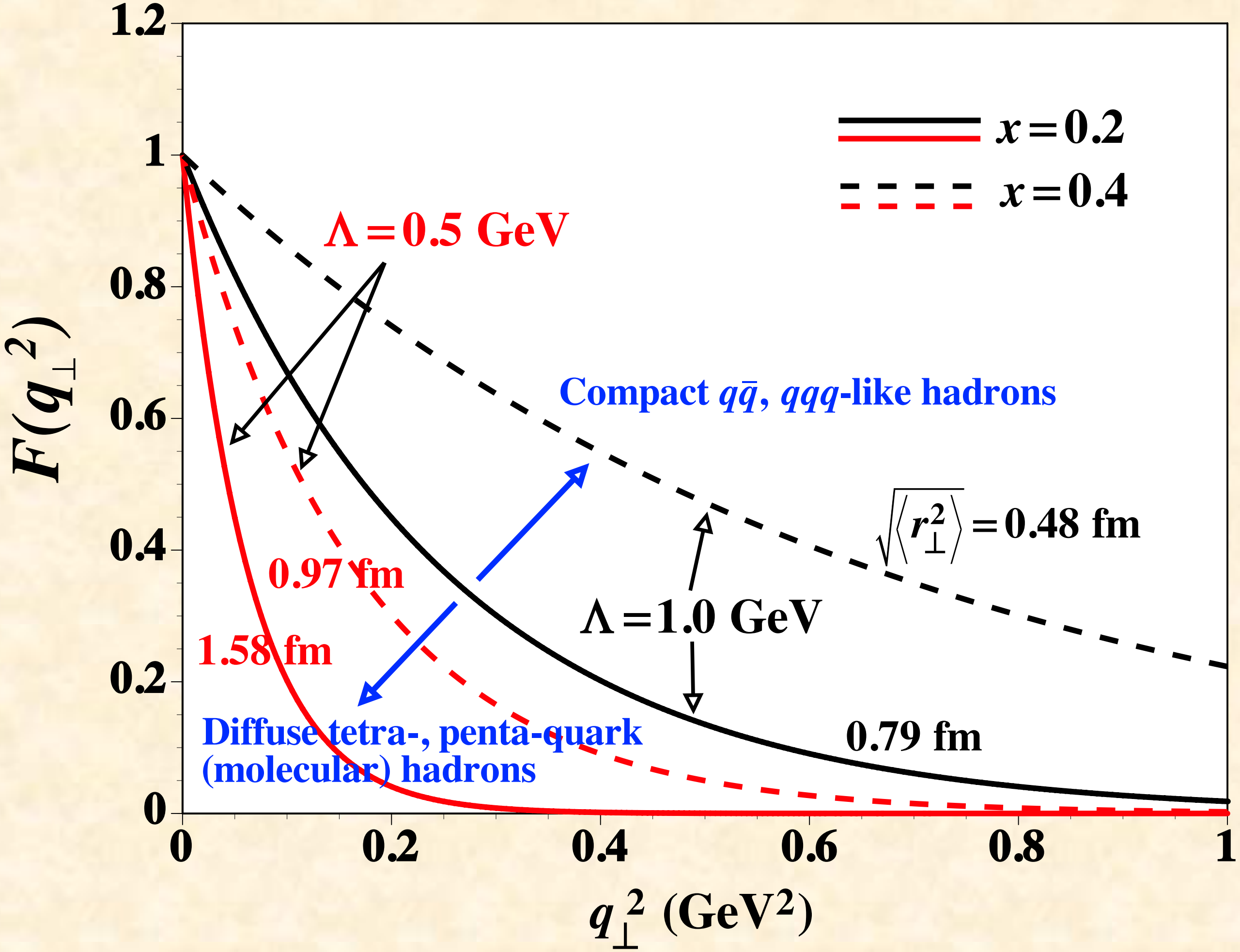
Gedankenexperiment, but … read our paper for studying exotics in high-energy processes at KEK-B, Linear Collider, ….

π: M. Aicher, A. Schafer, W. Vogelsang, PRL 105 (2010) 252003.

p: A. D. Martin, R. G. Roberts, W. J. Stirling, PLB 636, 259 (2006)

Two-dimensional form factor

$$H_q^h(x,t) = f(x)F(t,x), \quad F(t,x) = e^{(1-x)t/(x\Lambda^2)}, \quad \langle r_\perp^2 \rangle = \frac{4(1-x)}{x\Lambda^2}$$



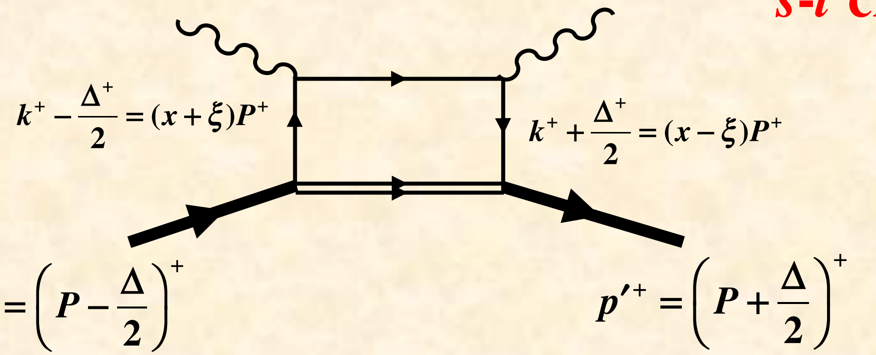
GPD $H_q^h(x,\xi,t)$ and GDA $\Phi_q^{h\bar{h}}(z,\zeta,W^2)$

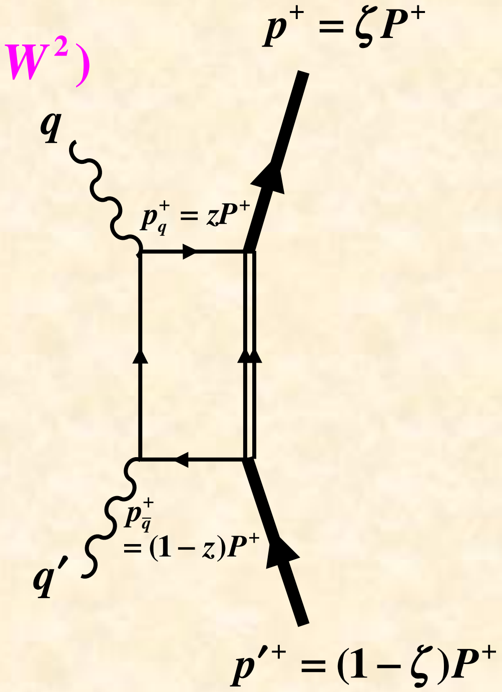
GPD: $H_q(x,\xi,t)=\int\frac{dy^-}{4\pi}\,e^{ixP^+y^-}\langle h(p')|\bar{\psi}(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+=\frac{(p+p')^+}{2}$

GDA: $\Phi_q(z,\zeta,s)=\int\frac{dy^-}{2\pi}\,e^{izP^+y^-}\langle h(p)\bar{h}(p')|\bar{\psi}(-y/2)\gamma^+\psi(y/2)|0\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$

DA: $\Phi_q^h(z,\zeta,s)=\int\frac{dy^-}{2\pi}\,e^{izP^+y^-}\langle h(p)|\bar{\psi}(-y/2)\gamma^+\gamma_5\psi(y/2)|0\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$

$H_q^h(x,\xi,t)$ ⟷ **s-t crossing** ⟷ $\Phi_q^{hh}(z,\zeta,W^2)$





$P=\frac{p+p'}{2}$, $\Delta=p'-p$

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

Momentum transfer squared: $t=\Delta^2$

Skewness parameter: $\xi=\frac{p^+-p'^+}{p^++p'^+}=-\frac{\Delta^+}{2P^+}$

Bjorken variable for $\gamma\gamma^*$: $z=\frac{Q^2}{2q\cdot q'}$

Light-cone momentum ratio for h in $h\bar{h}$: $\zeta=\frac{p^+}{P^+}=\frac{1+\beta\cos\theta}{2}$

Invariant mass of $h\bar{h}$: $W^2=(p+p')^2$

Summary on two-photon physics

Hadron tomography (3-dimensional structure) studies are in progress mainly by GPDs (Generalized Parton Distributions) and TMDs (Transverse-Momentum-Dependent parton distributions).

It is possible to investigate GDAs (Generalized Distribution Amplitudes)
= s-t crossed functions to GPDs
in principle by two-photon processes of UPCs.

It is especially interesting to study tomography for exotic-hadron candidates because they cannot be investigated in the GPDs (no fixed target for unstable hadrons).

The End

The End