MEXT KAKENHI (#2504)

Japanese | English

Home | Outline | Link | Contact | Members only

Unification and Development of the Neutrino Science Frontier

Introduction

- Outline

Organization

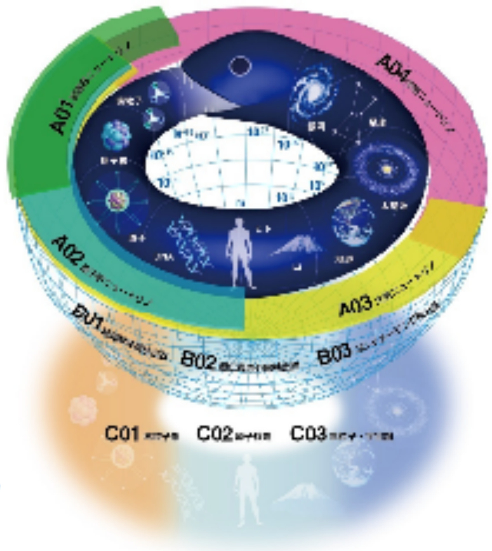
- Management group
- Research projects
- Publicly solicited

Others

- Award
- Link
- Contact
- Members only
- Sitemap

The main purposes of this project are:

- to investigate unknown properties of "neutrinos";
- to establish a new picture of nature through neutrino research;
- to approach the origin of elementary particles, the universe and the space-time.



We aim to reveal the nature of neutrinos by experimental studies, observation of nature using neutrinos, and theoretical studies.

Theory activities at J-PARC (KEK)

J-PARC Branch, KEK Theory Center

Institute of Particle and Nuclear Studies, KEK

203-1, Shirakata, Tokai, Ibaraki, 319-1106, Japan

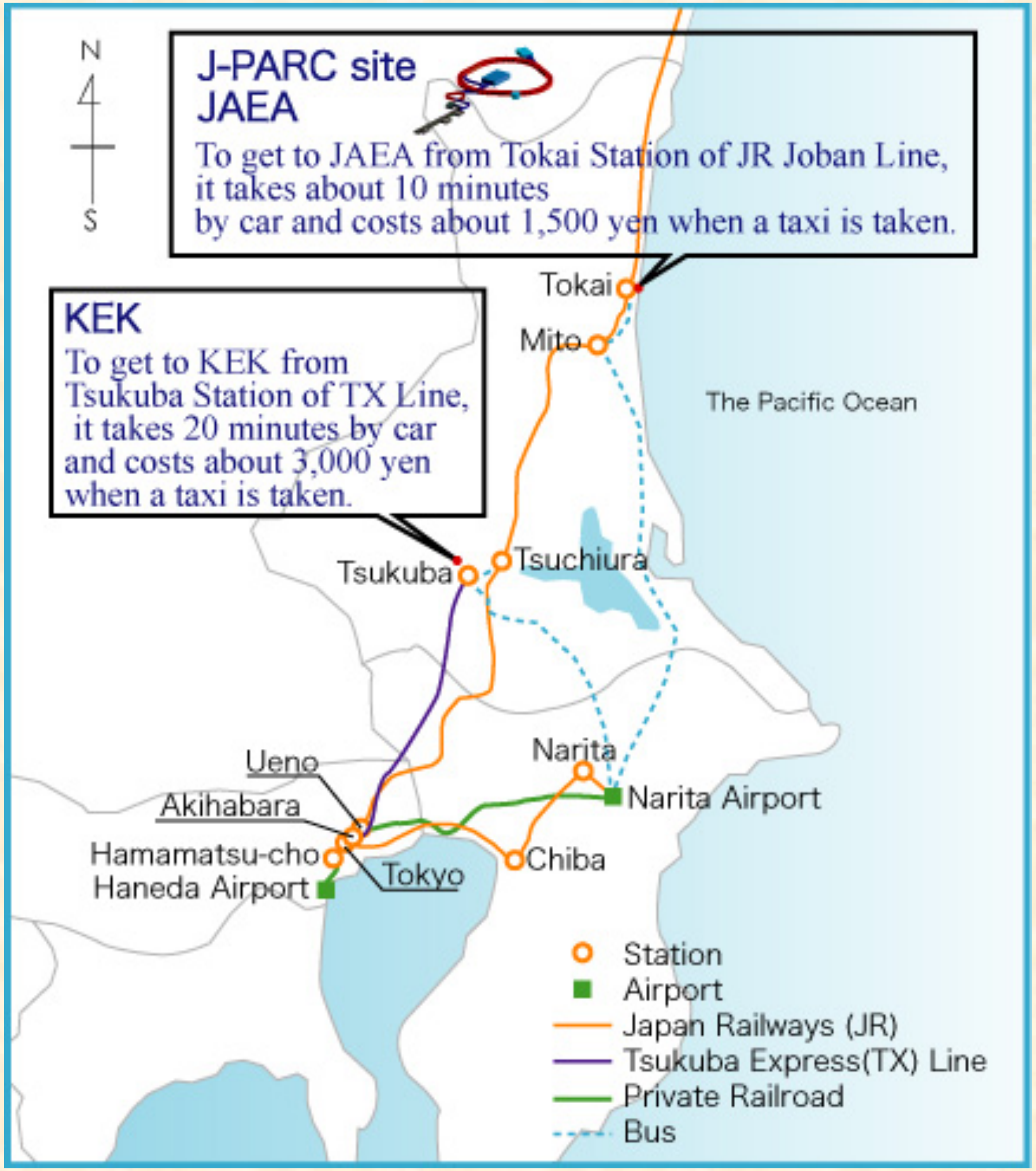
http://j-parc-th.kek.jp

Started in 2011

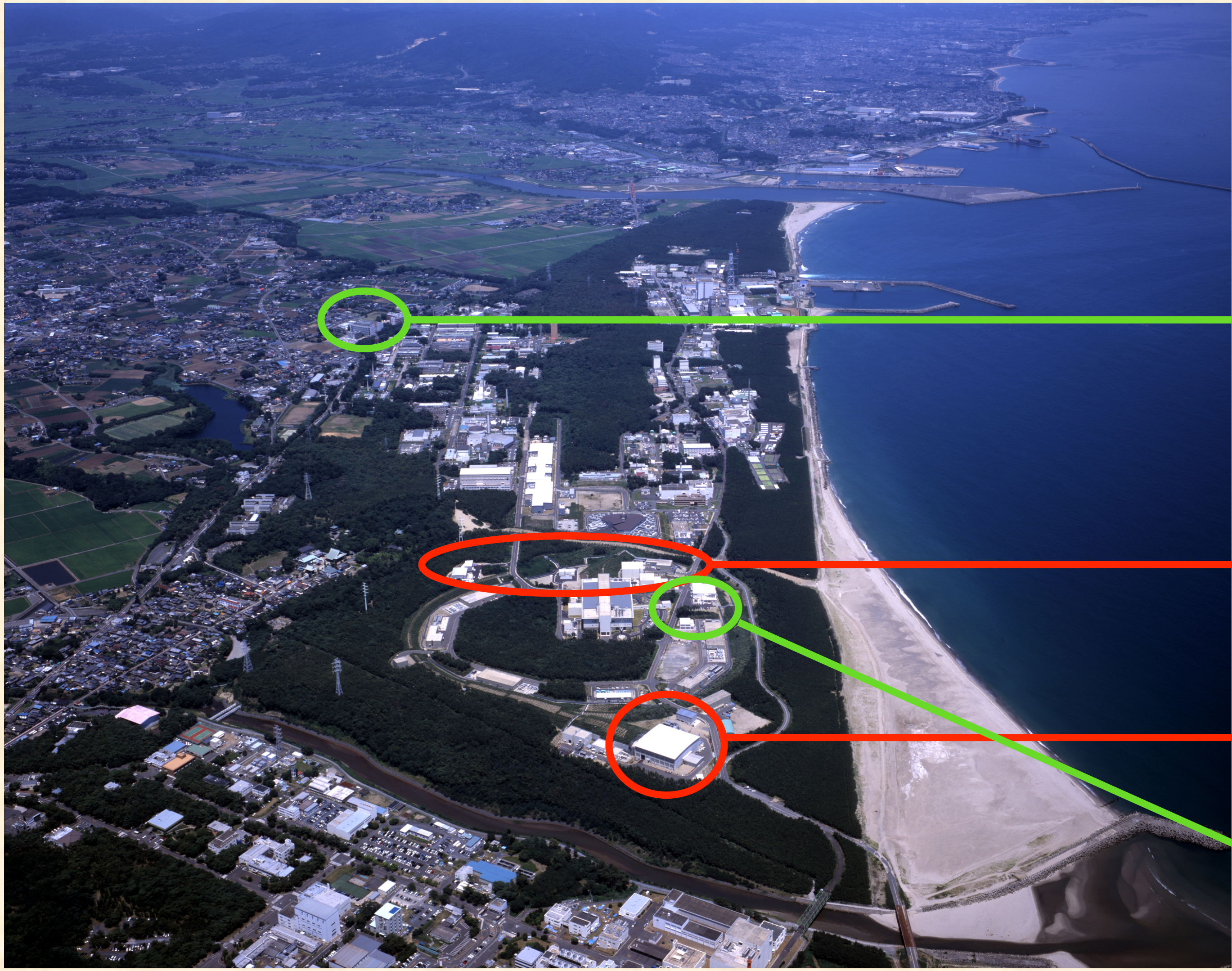
J-PARC location

J-PARC
(Japan Proton Accelerator Research Complex)

http://j-parc.jp/index-e.html



Aerial photograph



KEK Tokai campus,
J-PARC branch
KEK theory center

Neutrino
facility

Hadron
facility

Research
building

Theory activities at J-PARC (KEK)

J-PARC Branch, KEK Theory Center

Institute of Particle and Nuclear Studies, KEK

http://j-parc-th.kek.jp

4 permanent KEK staffs (A.Dote, K.Itakura, S.Kumano, O.Morimatsu)
+ 5 visiting staffs

T. Harada, M. Kitazawa, M. Takizawa, K. Tanaka, T. Sato

Hyper-nuclear physics

Heavy-ion physics

Charm physics

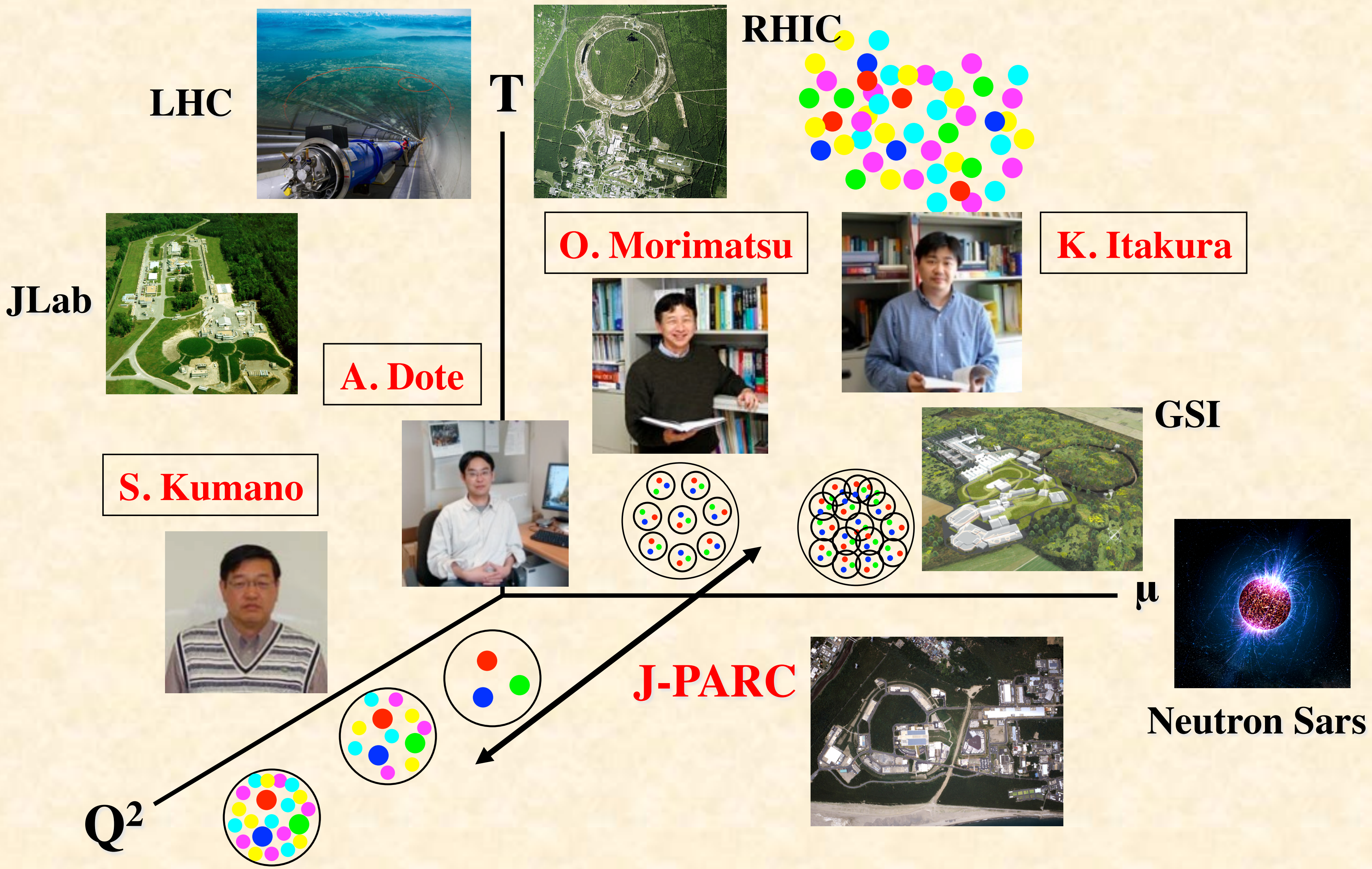
Structure functions

Neutrino-nuclear interactions





Hadron-physics staffs at KEK theory center



The End

The End

Lepton-nucleus deep inelastic scattering

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (SOKENDAI)
http://research.kek.jp/people/kumanos/

Workshop on "Neutrino-nucleus interaction in a few GeV region"
KEK Tokai Campus, Tokai, Japan, November 18-19, 2017
http://nuint.kek.jp/workshop/2017/nnint/

November 19, 2017

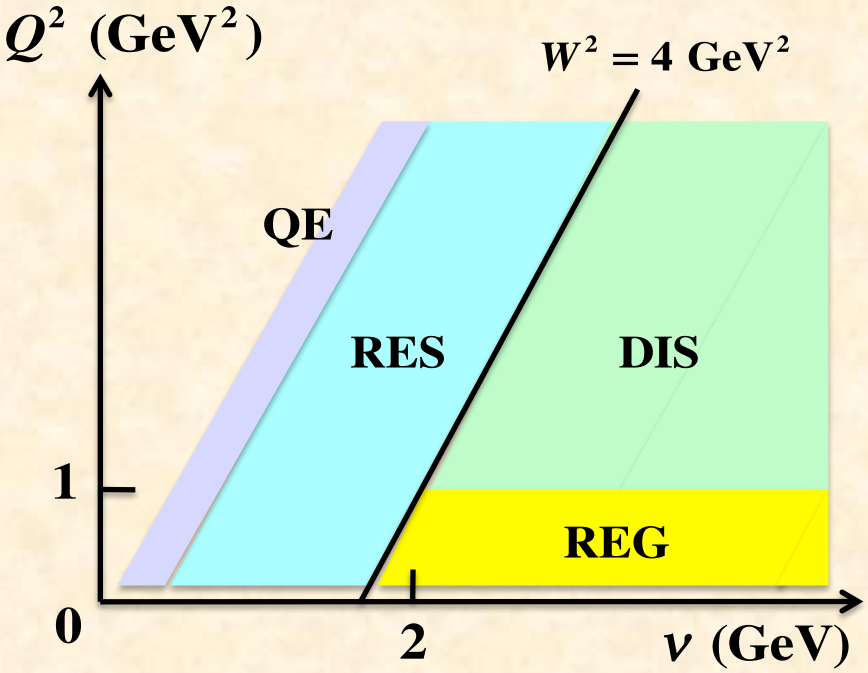
Contents

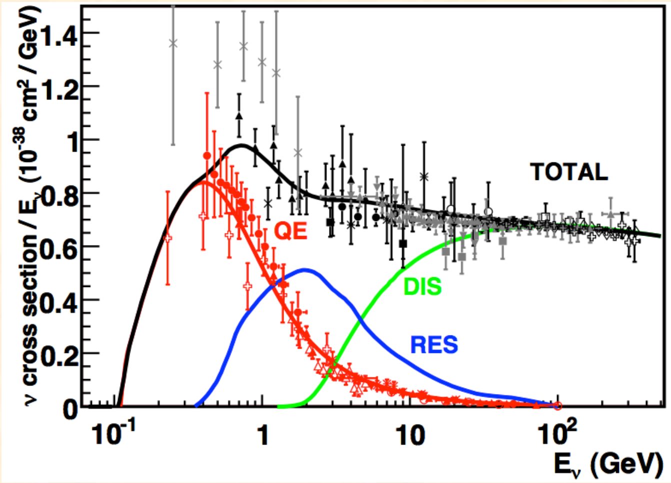
1. Motivation
2. Parton distributions functions (PDFs) for
   nucleons and nuclei
3. 3 dimensional view of nucleons and nuclei
   Hadron tomography, Gravitational physics
   Comments: Neutrino-induced pion production
   for gravitational form factors.

Motivation

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.

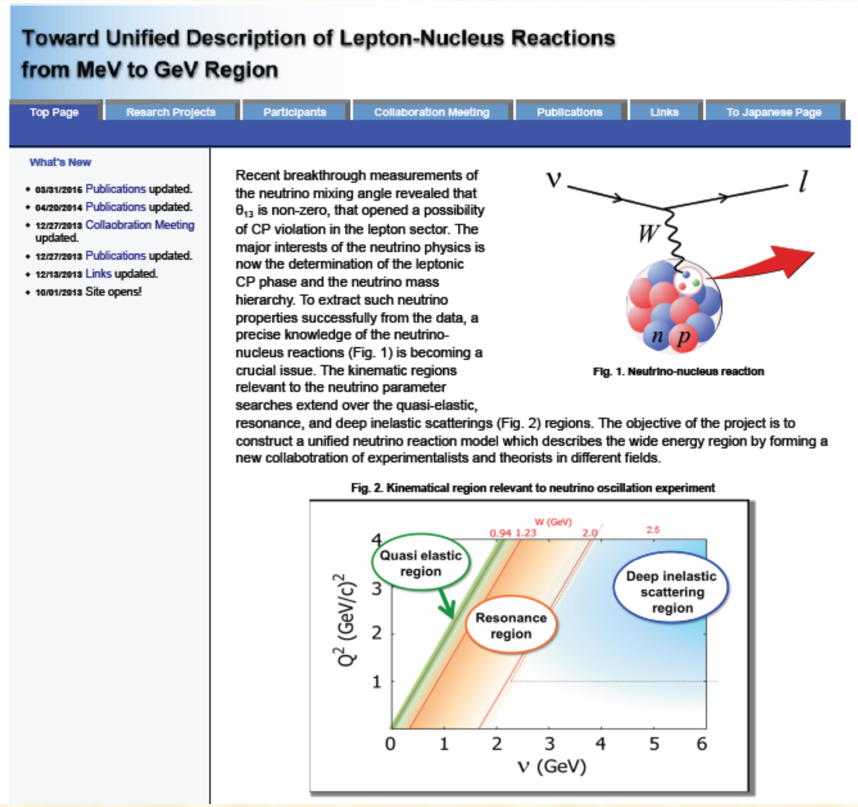
- QE (Quasi elastic)
- RES (Resonance)
- DIS (Deep inelastic scattering)
- REG (Regge)

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 | Rearch Projects | Participants | Collaboration Meeting | Publications | Links | To Japanese Page

What's New

- 03/31/2015 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!

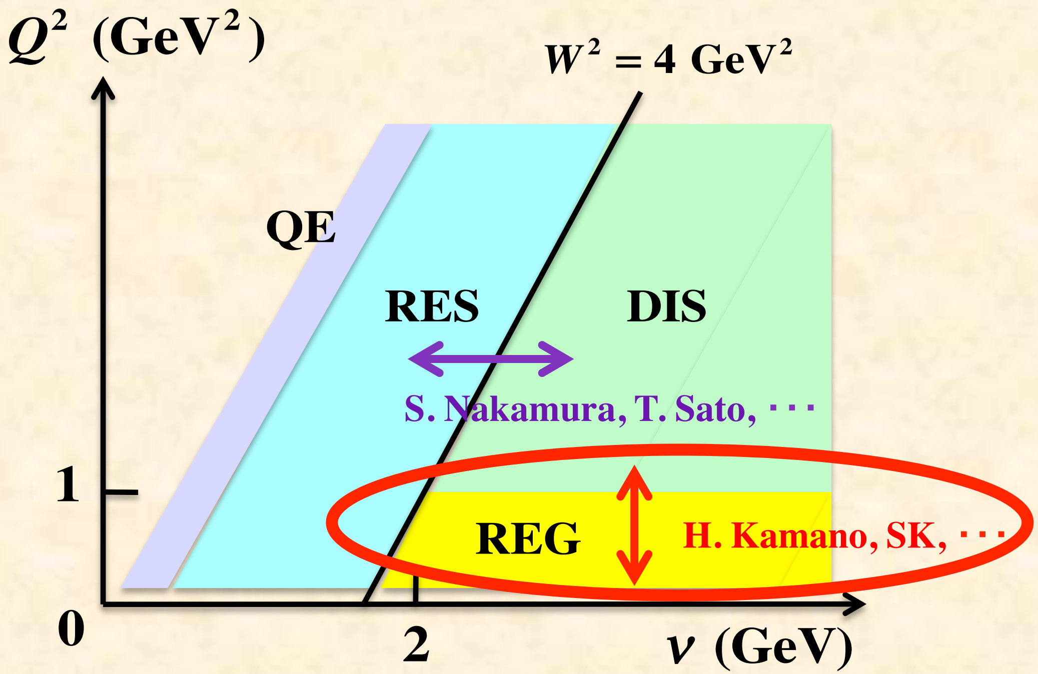
Recent breakthrough measurements of the neutrino mixing angle revealed that θ_{13} is non-zero, that opened a possibility of CP violation in the lepton sector. The major interests of the neutrino physics is now the determination of the leptonic CP phase and the neutrino mass hierarchy. To extract such 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

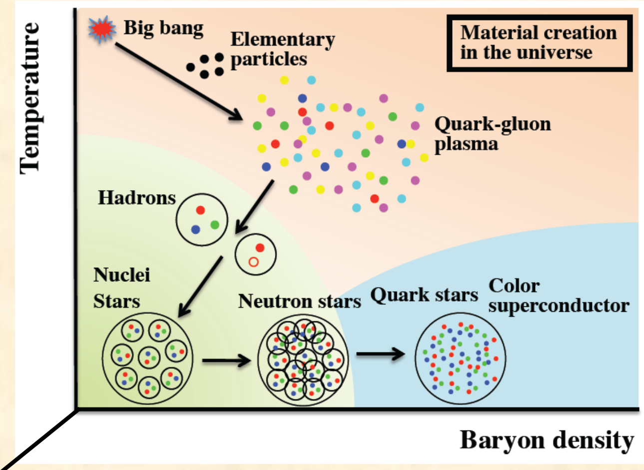


For the details, see

Towards a unified model of neutrino-nucleus reactions for neutrino oscillation experiments, S. X. Nakamura, H. Kamano, Y. Hayato, M. Hirai, W. Horiuchi, S. Kumano, T. Murata, K. Saito, M. Sakuda, T. Sato, and Y. Suzuki, Rep. Prog. Phys. 80 (2017) 056301.

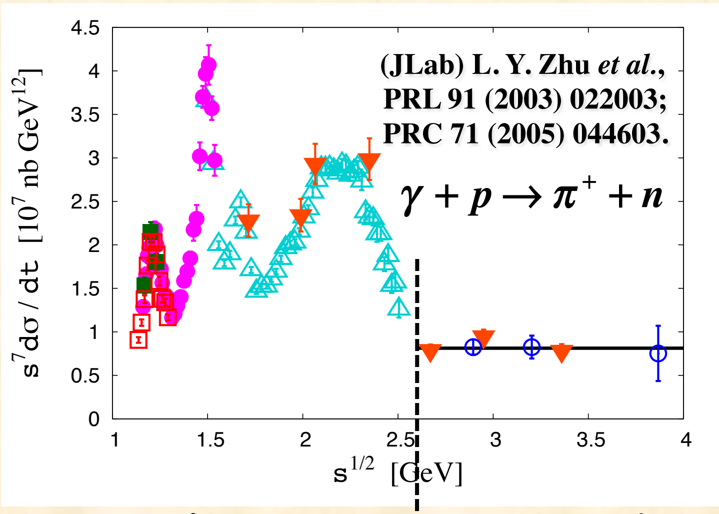
General motivation

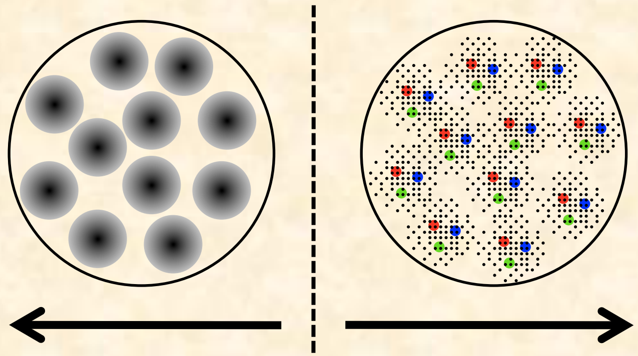
Ultimate purpose of Theoretical nuclear physics
= Describe hadronic many-body systems
in the whole phase diagram
from low to high energies.



Q^2

Transition from hadron to quark-gluon d.o.f.:
H. Kawamura, S. Kumano, T. Sekihara,
Phys. Rev. D 88 (2013) 034010.





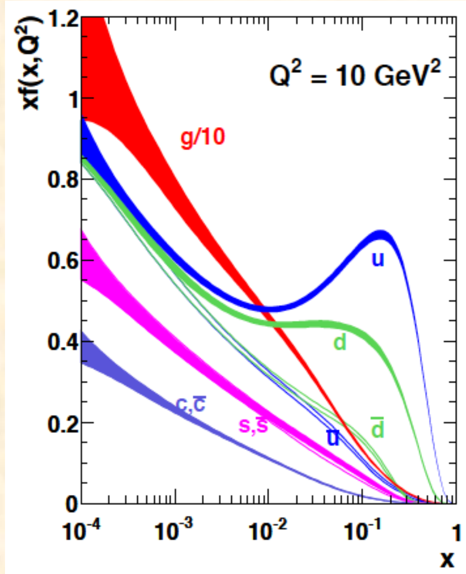
Low energies: Hadron degrees of freedom	High energies: Quark-gluon degrees of freedom

Low energies:
Hadron degrees
of freedom
(Resonances)

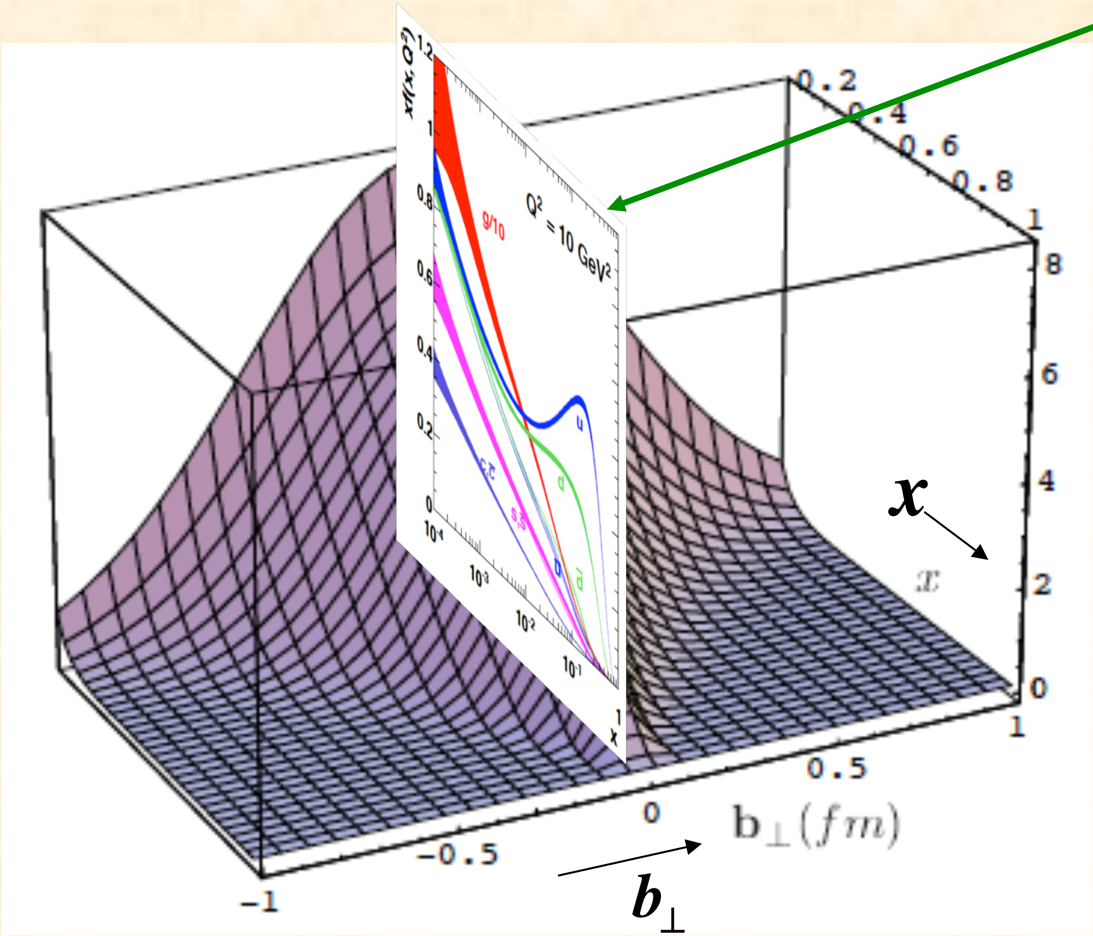
High energies:
Quark-gluon
degrees of freedom
(Perturbative QCD:
Constituent-counting rule)

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

3D view of hadrons and nuclei



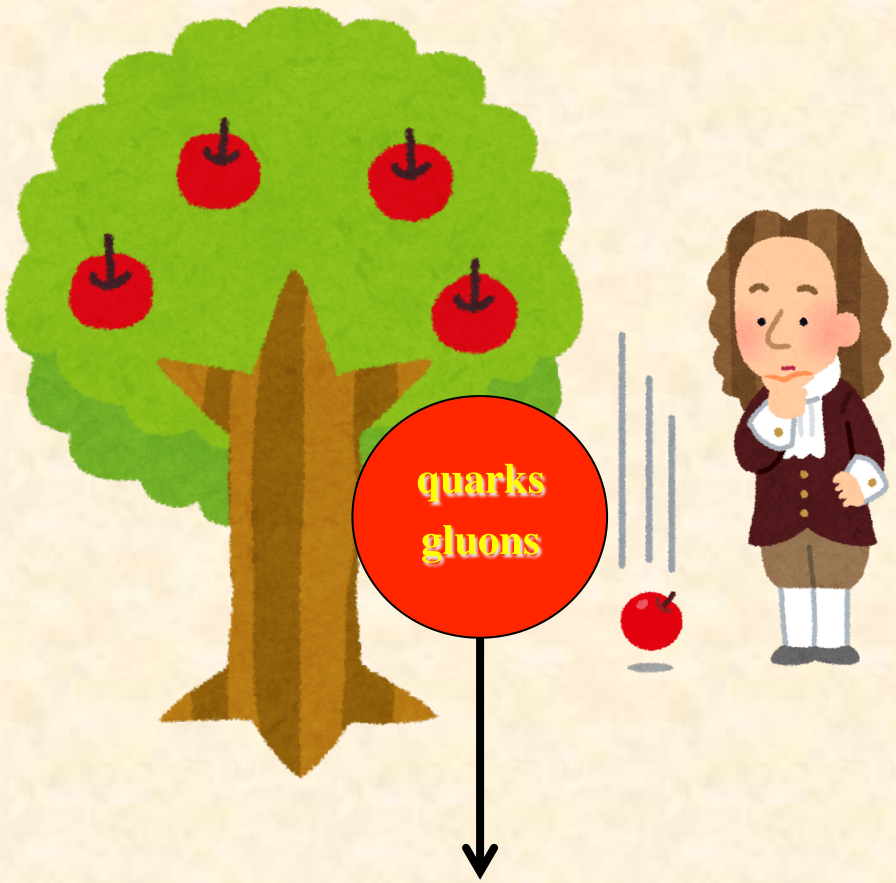
One-dimensional (Bjorken *x*) view of hadrons and nuclei

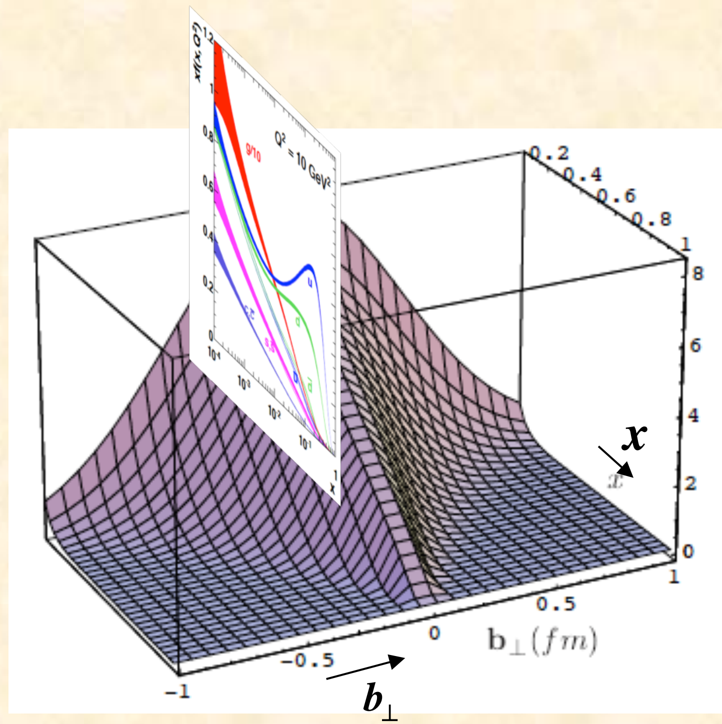


Three-dimensional (Bjorken $x + b_\perp$) view of hadrons and nuclei

Pion-production:

Using $\nu + N \rightarrow \mu + \pi + N'$, we can probe gravitational mass distributions in the nucleon and nuclei





Origin of gravity in terms of quarks and gluons…

Workshop on Gravitational physics with particle accelerators 2017

Nov.30, 2017, KEK Tokai, Japan

* hadron tomography topics

http://j-parc-th.kek.jp/workshops/2017/11-30/

----- Theory -----

Hadron tomography and quark-gluon energy-momentum tensor as a source of gravity

Shunzo Kumano (KEK/J-PARC)

Introduction to theory of gravity for novices, Shunya Mizoguchi (KEK)

Gravitational radius for pion by analysis of KEKB measurements, Qin-Tao Song (SOKENDAI/KEK)

Energy momentum tensor on lattice, Hiroshi Suzuki (Kyushu University)

Generalized parton distribution function studies at J-PARC, Kazuhiro Tanaka (Juntendo Univ/KEK)

----- Experiment -----

Ultracold neutron project at TRIUMF, Shinsuke Kawasaki (KEK)

Meson-pair production in two-photon processes at KEKB, Masataka Masuda (Tokyo University)

Probing strong gravity using geodetic precession in nuclear scale, Jiro Murata (Rikkyo University)

gamma-gamma collisions at ILC, Tomoyuki Sanuki (Tokhoku University)

Ultracold neutron project at J-PARC, Hirohiko Shimizu (Nagoya University)

Gravitational effects in muon experiments, Tamaki Yoshioka (Kyushu University)

Structure functions of nucleons and nuclei

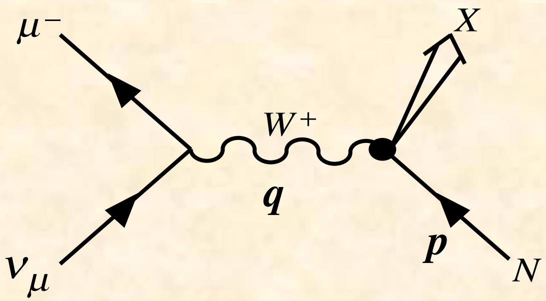
Deep inelastic scattering (DIS)

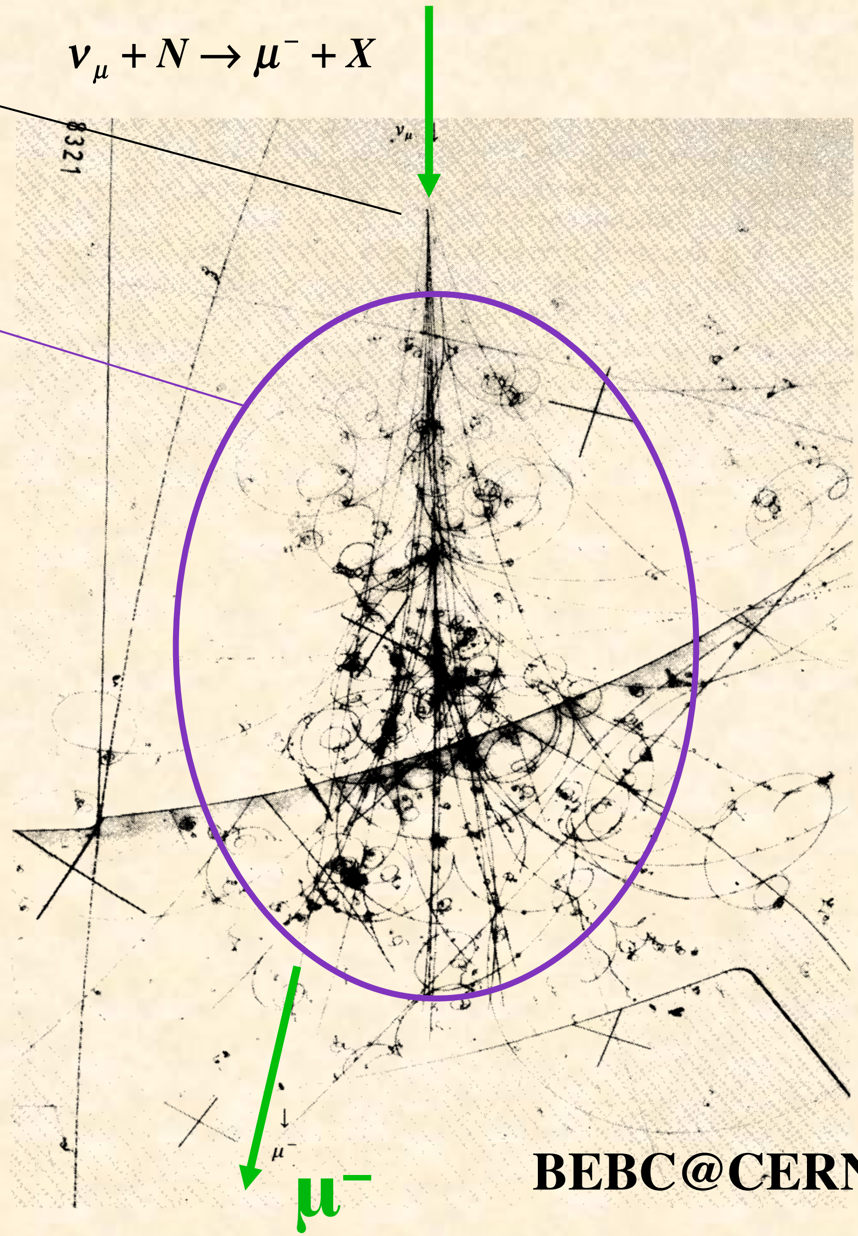
ν_μ ~200 GeV

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

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

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





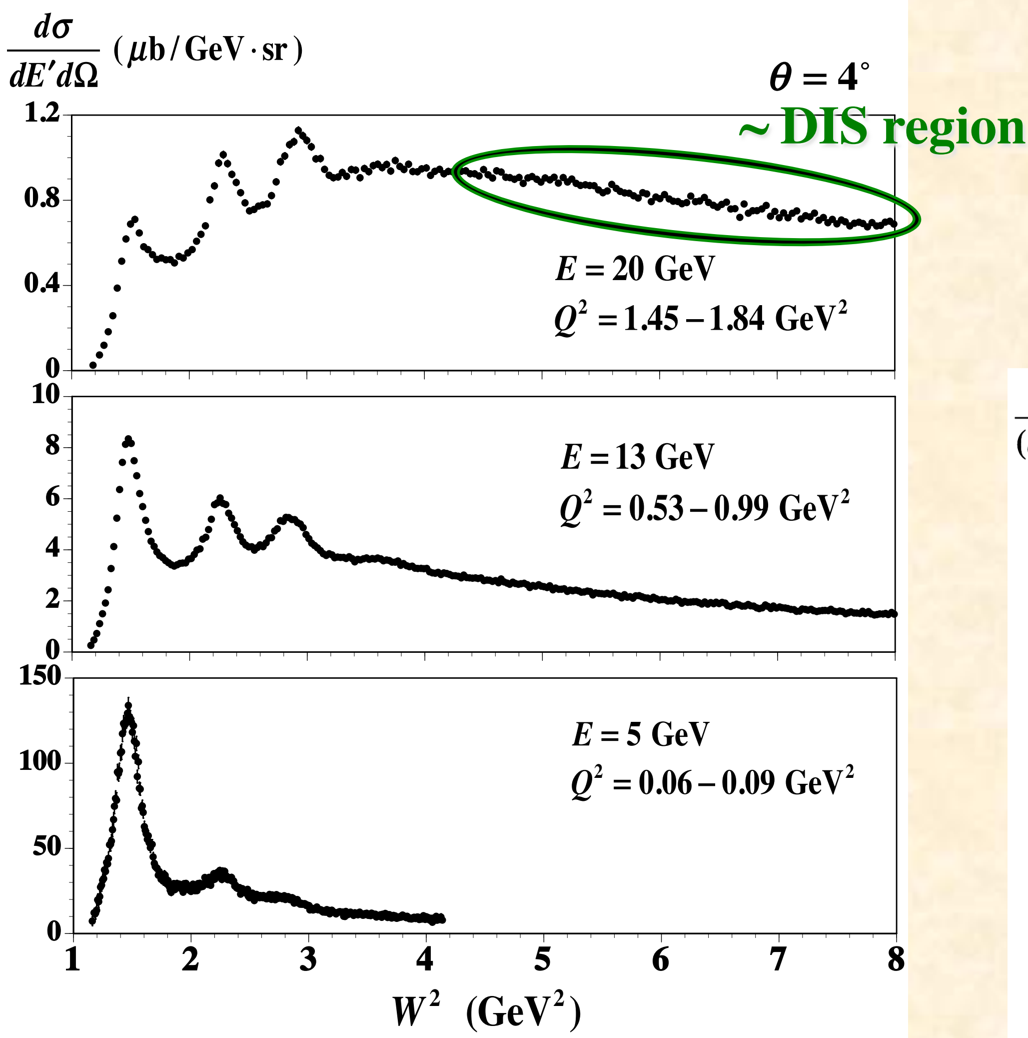
BEBC@CERN

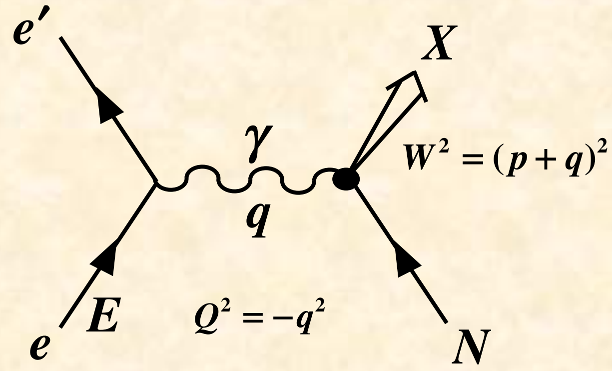
Momentum transfer: $q^2 = (k - k')^2 = -Q^2$

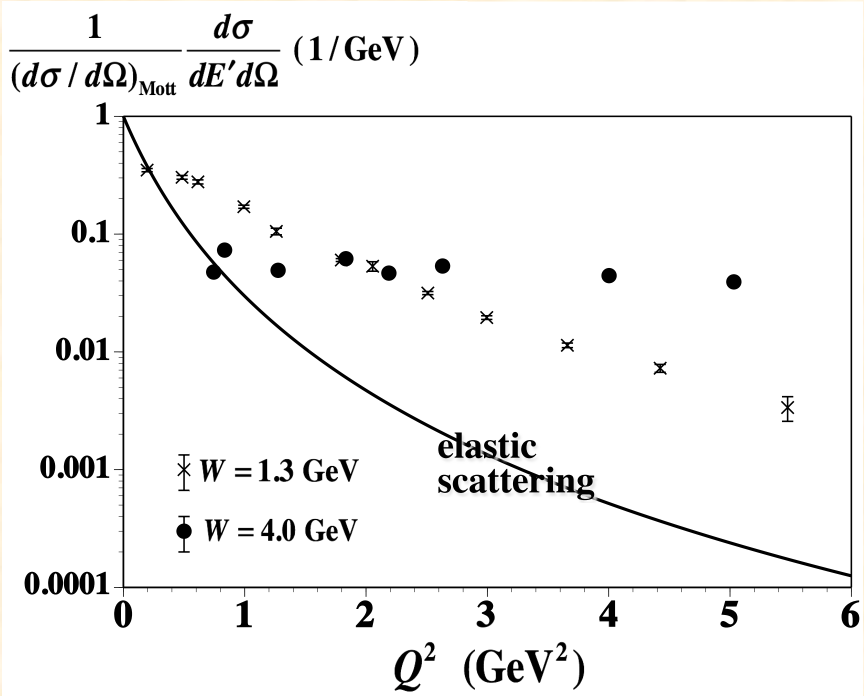
Bjorken scaling variable: $x = \dfrac{Q^2}{2p \cdot q}$

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

Lepton scattering

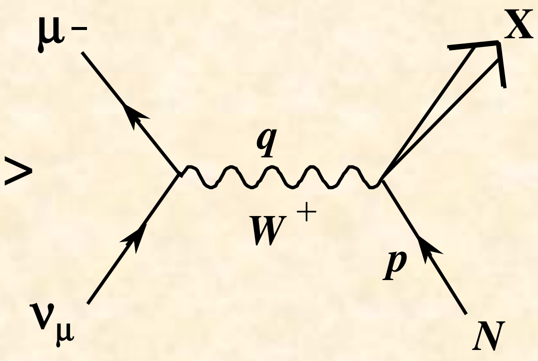






Neutrino deep inelastic scattering (CC: Charged Current)

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



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

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

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

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

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

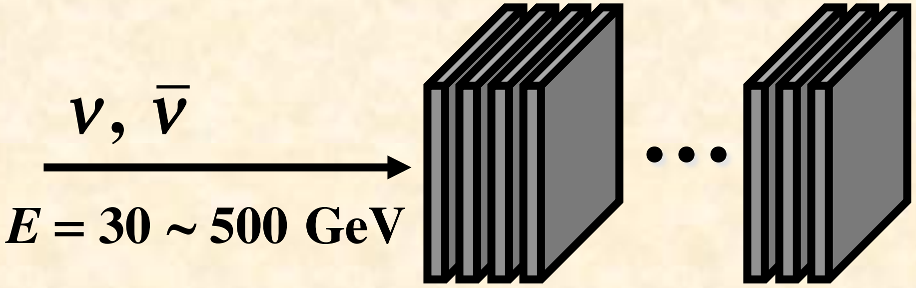
$$\frac{d\sigma^{CC}_{\nu,\bar{\nu}}}{dx\,dy} = \frac{G_F^2\,(s-M^2)}{2\pi\,(1+Q^2/M_W^2)^2}\left[x\,y^2F_1^{CC} + \left(1-y-\frac{M\,x\,y}{2E}\right)F_2^{CC} \underline{\pm x\,y\left(1-\frac{y}{2}\right)F_3^{CC}}\right]$$

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

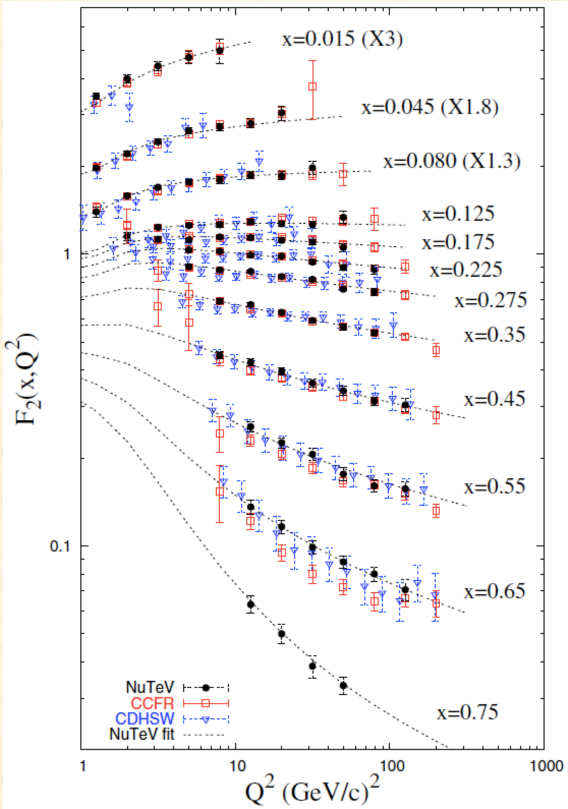
Experiment	Target	ν energy (GeV)
CCFR	Fe	30-360
CDHSW	Fe	20-212
CHORUS	Pb	10-200
NuTeV	Fe	30-500

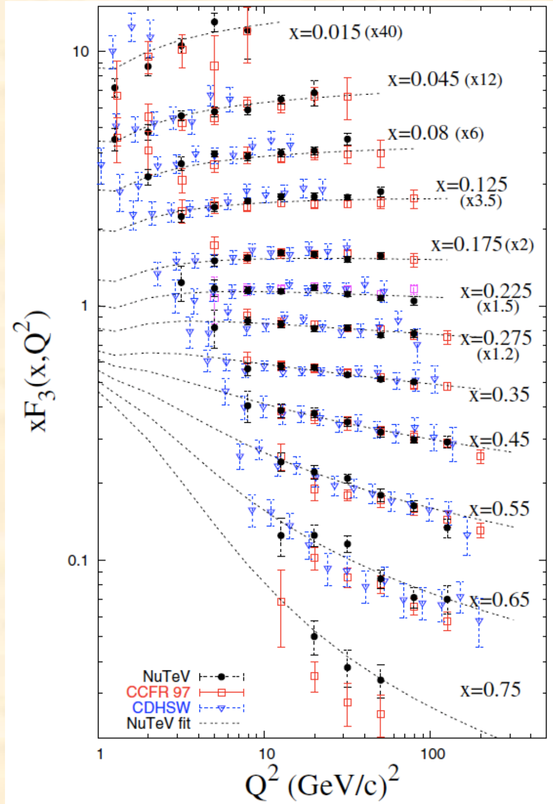


Huge Fe target (690 ton)

MINERνA (He, C, Fe, Pb), …

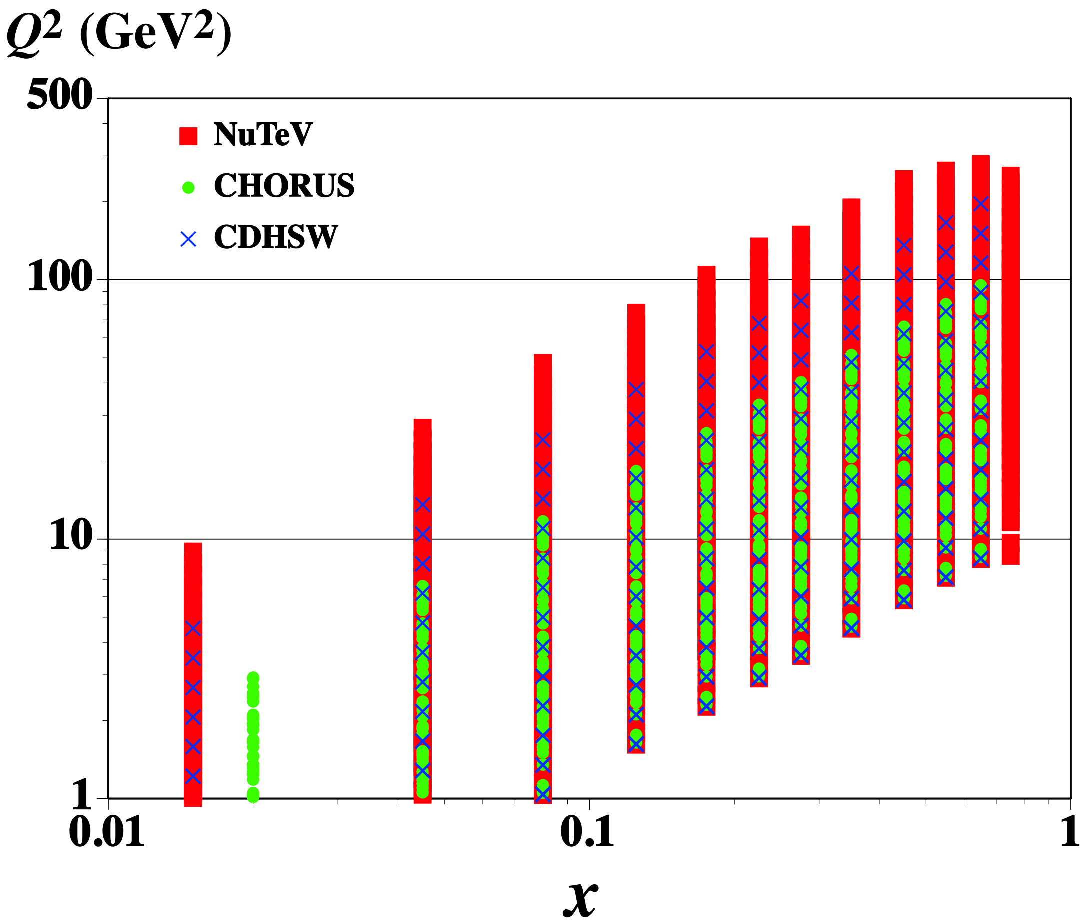
M. Tzanov *et al.* (NuTeV), PRD74 (2006) 012008.



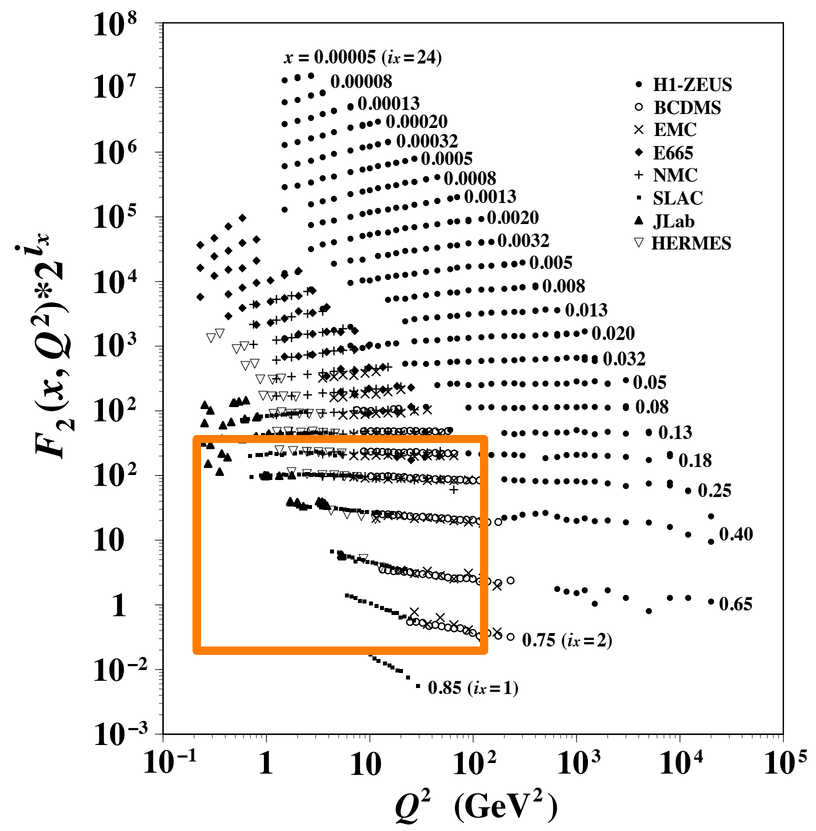


Neutrino DIS experiments: kinematical range

Neutrino DIS

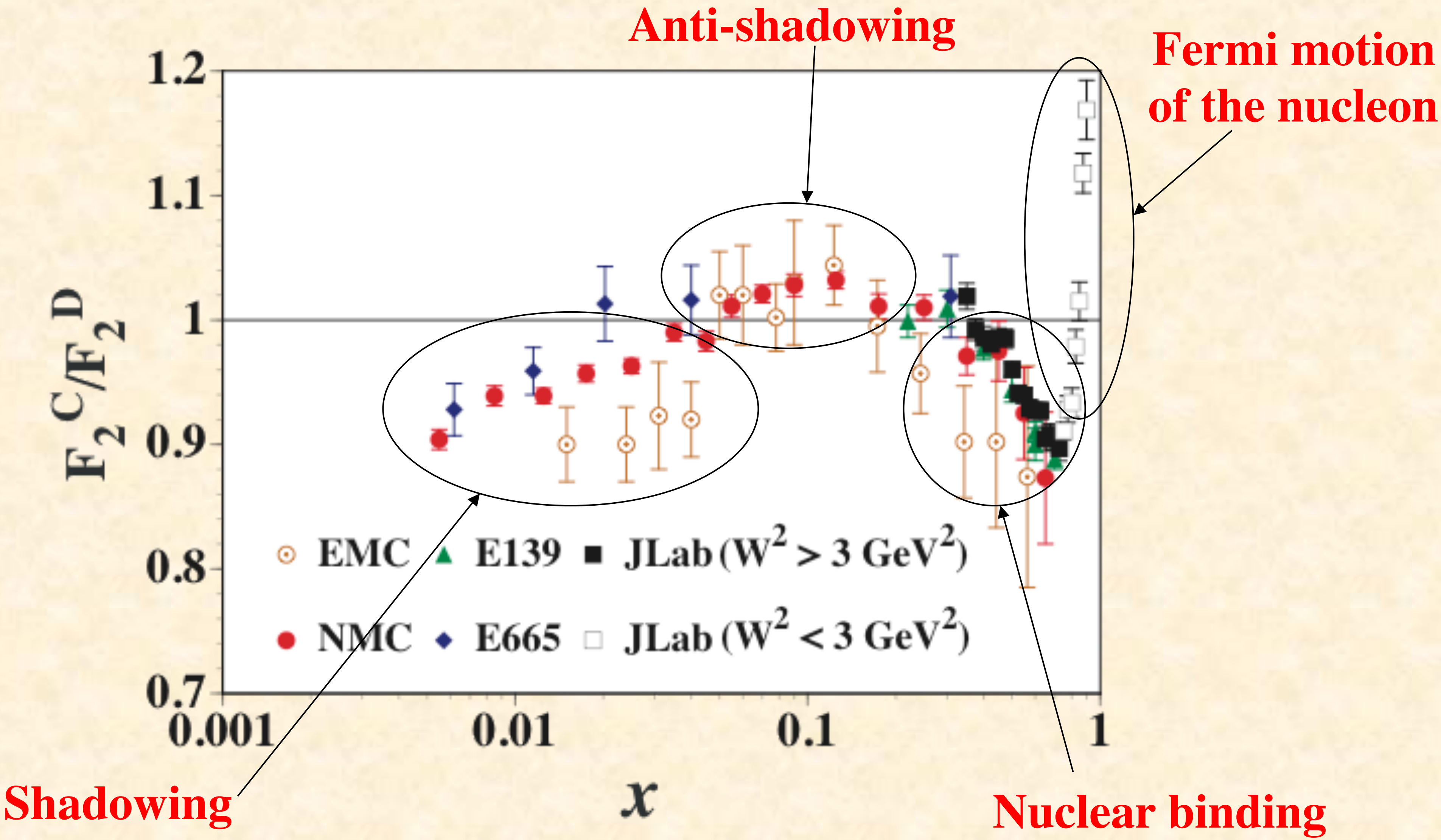


Charged-lepton DIS



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

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.
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)

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

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

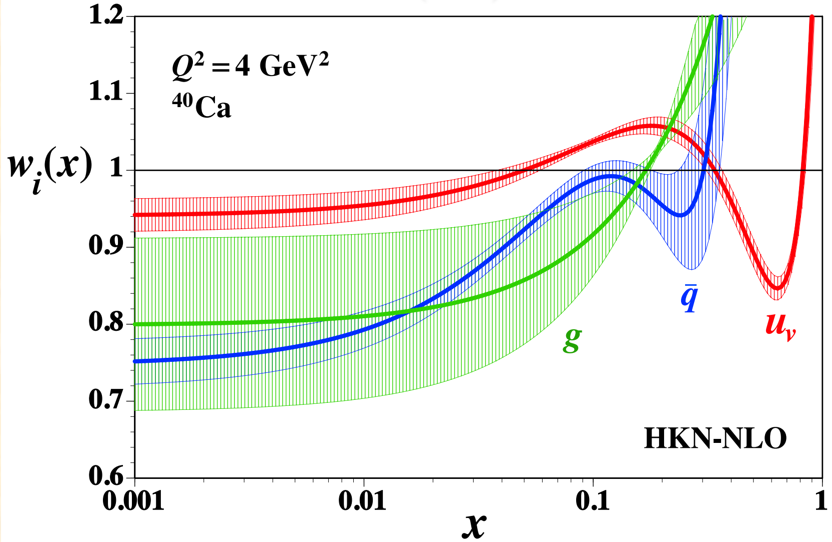
Review on neutrino interactions

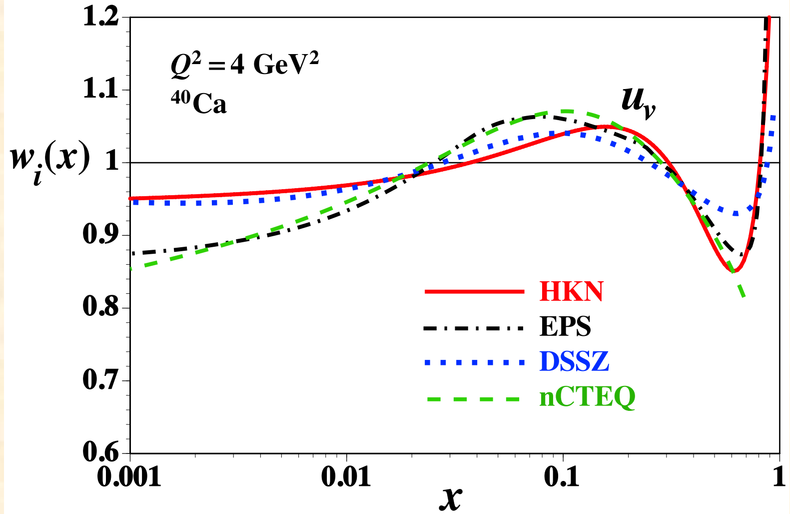
(Rep. Prog. Phys. 80 (2017) 056301.)

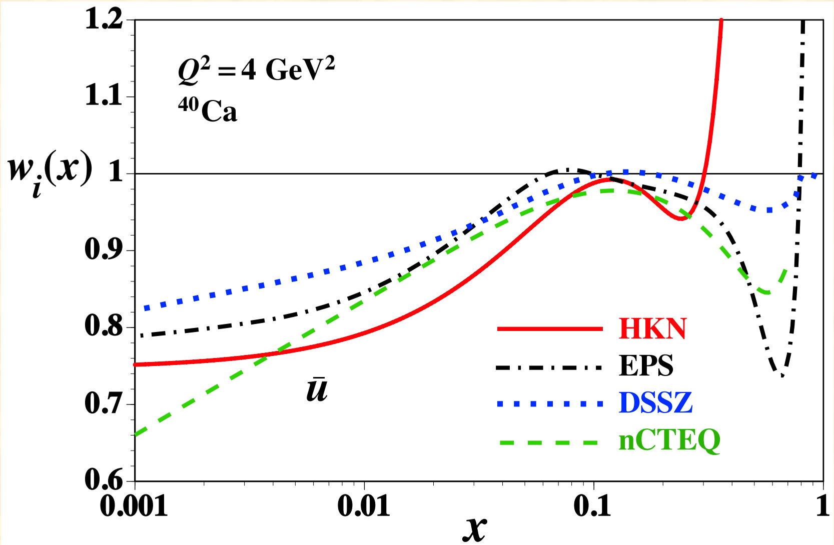
Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments

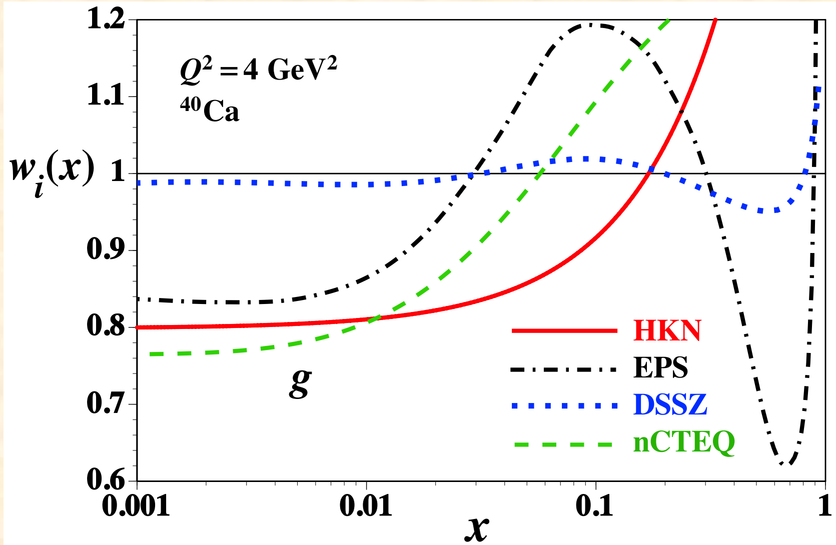
S.X. Nakamura[1], H. Kamano[2,3], Y. Hayato[4], M. Hirai[5], W. Horiuchi[6], S. Kumano[2,3], T. Murata[1], K. Saito[7,3], M. Sakuda[8], T. Sato[1,3], Y. Suzuki[9,10]

M. Hirai, S. Kumano, T. -H. Nagai, PRC76 (2007) 065207.



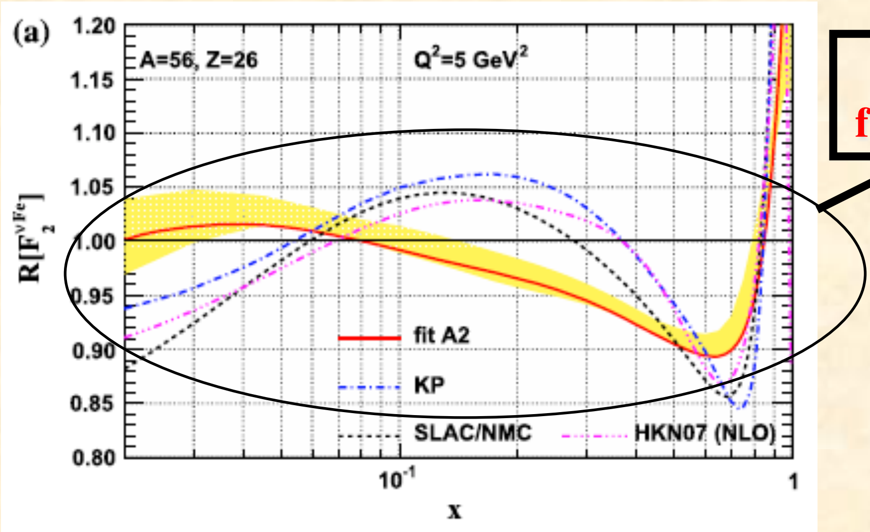






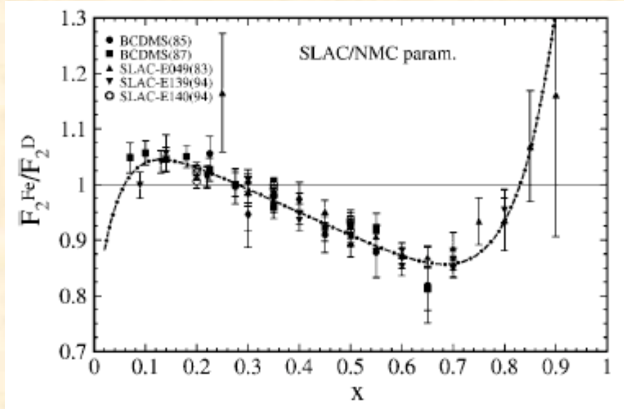
Analysis of CTEQ-2008 (Schienbein *et al.*)

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

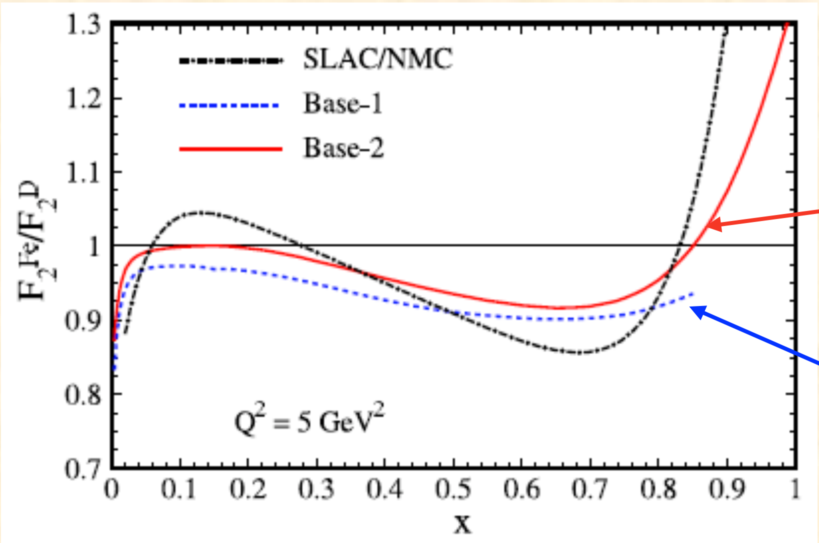


Differences from typical NPDFs.

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.

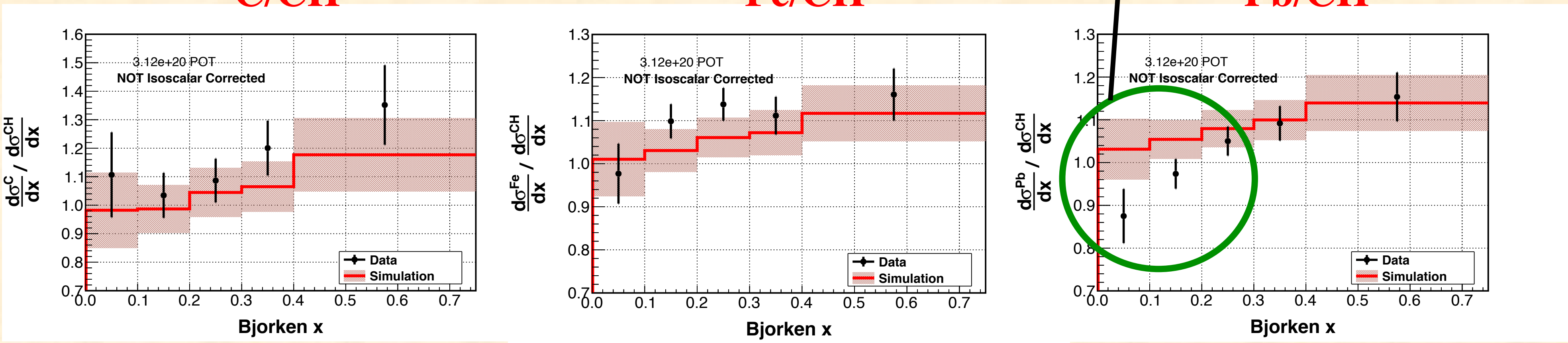
Base-1: However, it depends on the analysis method for determining "nucleonic" PDFs.

Recent progress on neutrino DIS ⇔ Charged DIS

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

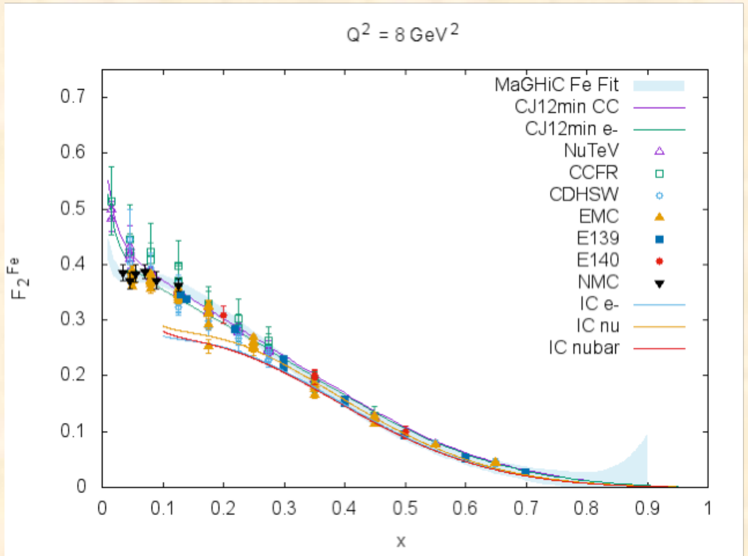
Different shadowing from charged-lepton case?!

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) .



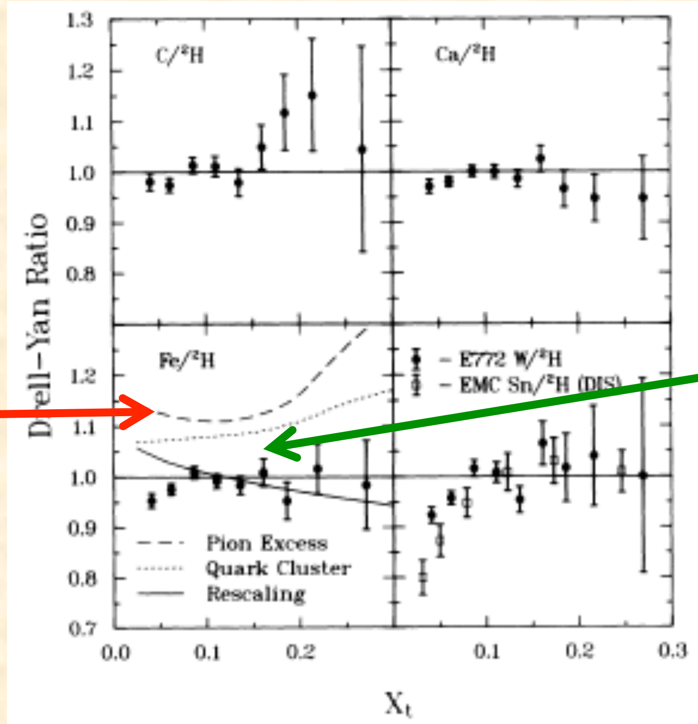
Nuclear antiquark distributions and Drell-Yan

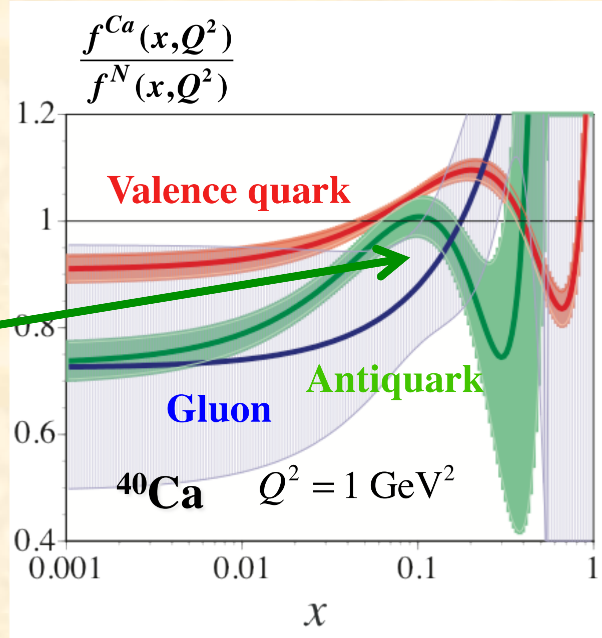
D. M. Alde *et al.*,
PRL. 64, 2479 (1990).

$$\frac{\sigma_{pA}}{\sigma_{pD}} \approx \frac{\bar{q}_A}{\bar{q}_D}$$

No nuclear effects
from pion contributions

E. L. Berger, F. Coester, R. B. Wiringa,
PRD 29, 398 (1984)



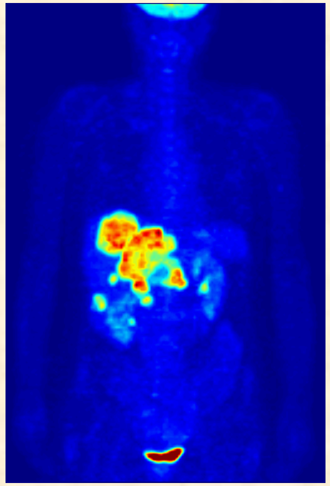


Fermilab-E906 in progress!

From lepton scattering to hadron tomography then to gravitational physics

Nucleon (hadron) tomography

PET (Positron Emission Tomography)



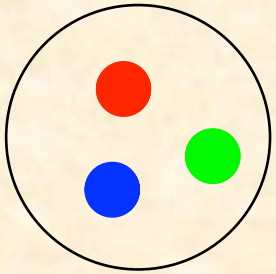
Classical density distribution

3D picture of nucleon

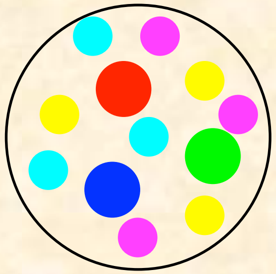
(Density distribution of quantum system: Quantum tomography)

1D(Bjorken-x) picutre@HERA

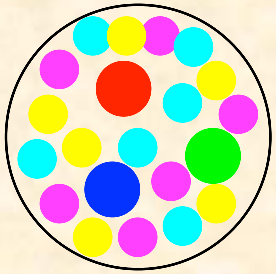
Low energy



Intermediate energy



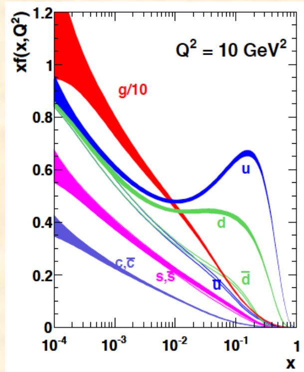
High energy



Wigner distribution and various structure functions

Form factor

PDF (Parton Distribution Function)



$\int dx\, d^2k_T$

$\int d^2k_T,\ \Delta \to 0$

GTMD $W(x, \vec{k}_T, \Delta) \xrightarrow[\Delta^+ \to 0]{}$ Wigner $W(x, \vec{k}_T, \vec{r}_T)$

3D world

$\Delta = p' - p$

$\int d^2k_T$

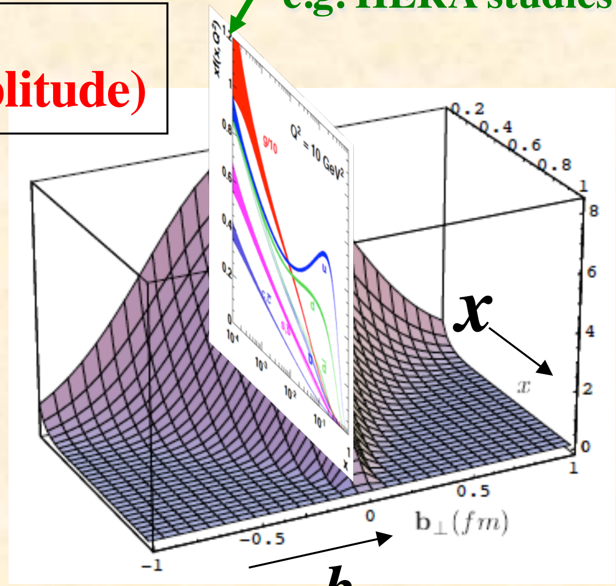
e.g. HERA studies

GPD (Generalized Parton Distribution)

$\xrightarrow[s \leftrightarrow t]{}$ GDA (Generalized Distribution Amplitude)

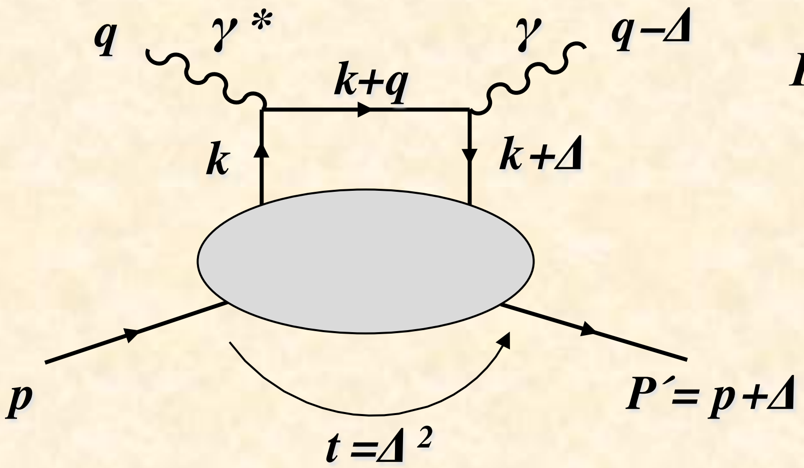
$\Delta \to 0$

TMD (Transverse Momentum Dependent) parton distribution



Our work by the two-photon process $\gamma\gamma \to h\bar{h}$.

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:

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

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p'|\bar{\psi}(-z/2)\gamma^+\gamma_5\psi(z/2)|p\rangle\Big|_{z^+=0,\vec{z}_\perp=0} = \frac{1}{2P^+}\left[\tilde{H}(x,\xi,t)\bar{u}(p')\gamma^+\gamma_5u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\frac{\gamma_5\Delta^+}{2M}u(p)\right]$$

Forward limit: PDFs $H(x,\xi,t)\big|_{\xi=t=0} = f(x), \quad \tilde{H}(x,\xi,t)\big|_{\xi=t=0} = \Delta f(x),$

First moments: Form factors

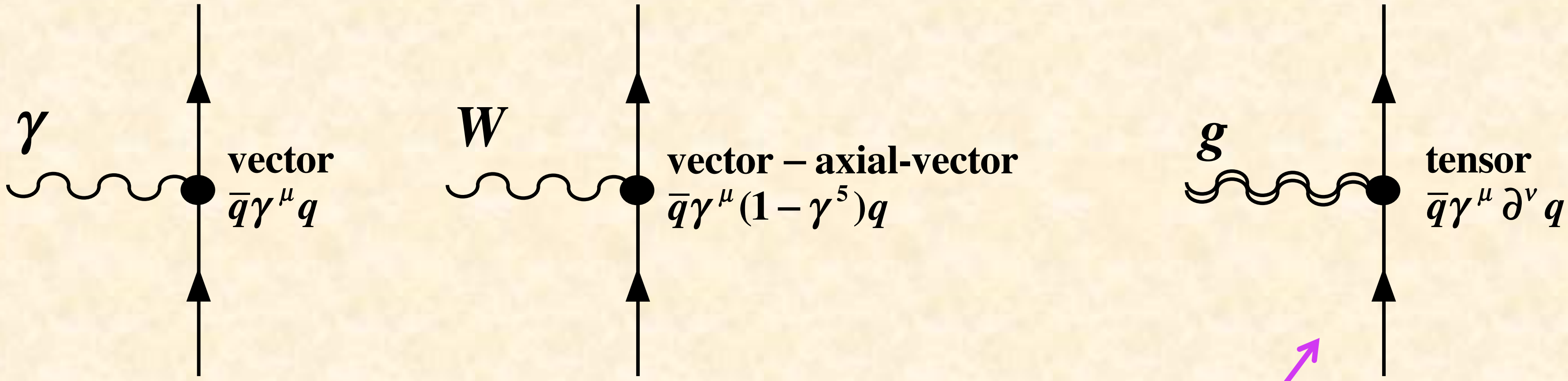
Dirac and Pauli form factors F_1, F_2 $\quad \int_{-1}^{1} dx\, H(x,\xi,t) = F_1(t), \quad \int_{-1}^{1} dx\, E(x,\xi,t) = F_2(t)$

Axial and Pseudoscalar form factors G_A, G_P $\quad \int_{-1}^{1} dx\, \tilde{H}(x,\xi,t) = g_A(t), \quad \int_{-1}^{1} dx\, \tilde{E}(x,\xi,t) = g_P(t)$

Second moments: Angular momenta

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

Why gravitational interactions with hadrons ?



Electron-proton elastic scattering cross section:

$$\frac{d\sigma}{d\Omega}=\frac{\alpha^2 E_f\cos^2\frac{\theta}{2}}{4E_i^3\sin^4(\theta/2)}\left[\frac{G_E^2+\tau G_M^2}{1+\tau}+2\tau G_M^2\tan^2\frac{\theta}{2}\right],\quad \tau=-\frac{q^2}{4M^2}$$

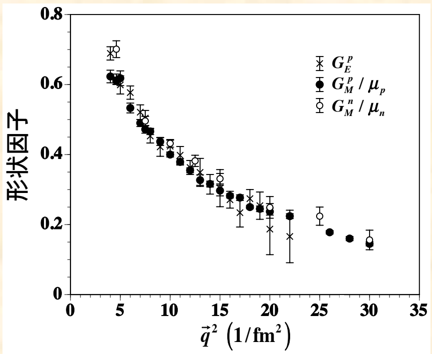
$$F(\vec{q})=\int d^3x\, e^{i\vec{q}\cdot\vec{x}}\rho(\vec{x})=\int d^3x\left[1-\frac{1}{2}(\vec{q}\cdot\vec{x})^2+\cdots\right]\rho(\vec{x})$$

$$\langle r^2\rangle=\int d^3x\, r^2\rho(\vec{x}),\quad r=|\vec{x}|$$

$$\sqrt{\langle r^2\rangle}=\text{root-mean-square (rms) radius}$$

$$F(\vec{q})=1-\frac{1}{6}\vec{q}^{\,2}\langle r^2\rangle+\cdots,\qquad \langle r^2\rangle=-6\left.\frac{dF(\vec{q})}{d\vec{q}^{\,2}}\right|_{\vec{q}^{\,2}\to 0}$$

$$\rho(r)=\frac{\Lambda^3}{8\pi}e^{-\Lambda r}\Leftrightarrow \text{Dipole form: } F(q)=\frac{1}{\left(1+|\vec{q}|^2/\Lambda^2\right)^2},\quad \Lambda^2\simeq 0.71\ \text{GeV}^2$$



How about gravitational radius?

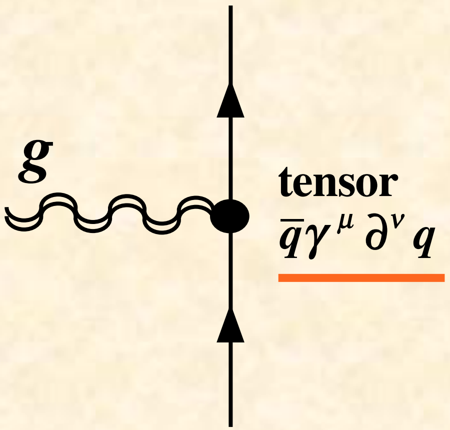
Proton-charge-radius puzzle:

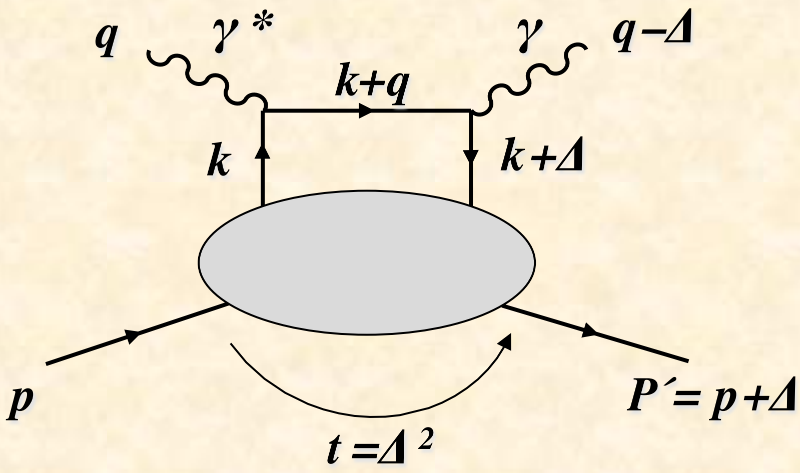
$R_{\text{electron scattering}}$ = 0.8775 fm

⇕

$R_{\text{muonic atom}}$ = 0.8418 fm

Gravitational interactions and 3D structure functions





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

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

Non-local operator of GPDs/GDAs:

$$\left(P^+\right)^n \int dx\, x^{n-1} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left[\bar{q}(-z/2)\gamma^+ q(z/2) \right]_{z^+=0, \vec{z}_\perp=0} = \left(i\frac{\partial}{\partial z^-} \right)^{n-1} \left[\bar{q}(-z/2)\gamma^+ q(z/2) \right]_{z=0}$$

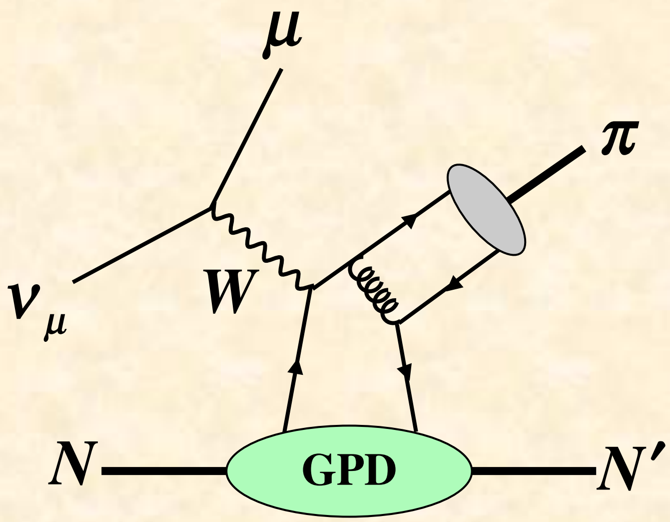
$$= \bar{q}(0)\gamma^+ \left(i\overleftrightarrow{\partial}^+ \right)^{n-1} q(0)$$

= energy-momentum tensor of a quark for $n = 2$ (electromagnetic for $n = 1$)

= source of gravitiy

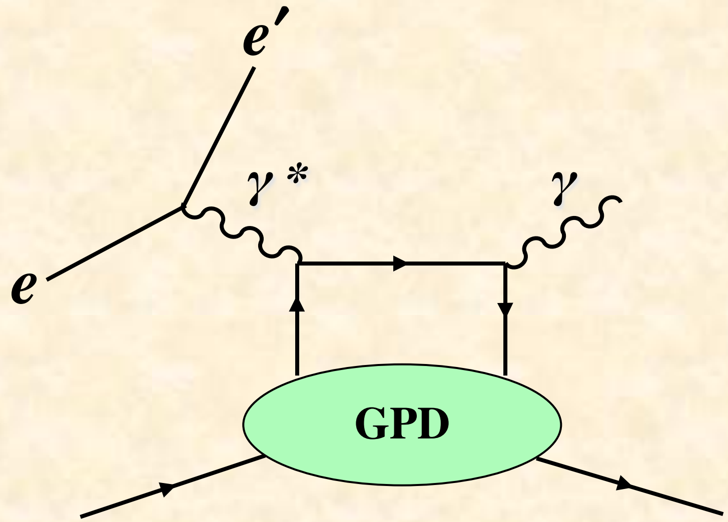
Neutrino-induced pion production for gravitational physics

$\nu_\mu + N \to \mu + N' + \pi$



$\nu_\mu + N \to \mu + N' + \pi$

$\longleftrightarrow$



DVCS (Deeply virtual Compton scattering)

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

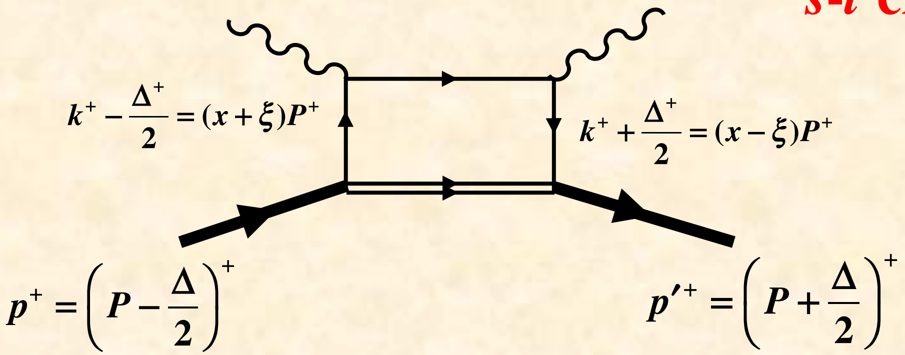
GPD: $H_q(x,\xi,t) = \int \frac{dy^-}{4\pi} e^{ixP^+y^-} \langle h(p')|\overline{\psi}(-y/2)\gamma^+\psi(y/2)|h(p)\rangle\Big|_{y^+=0,\vec{y}_\perp=0}$, $\quad P^+ = \frac{(p+p')^+}{2}$

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

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

$H_q^h(x,\xi,t)$ $\quad\longleftrightarrow\quad$ $\Phi_q^{hh}(z,\zeta,W^2)$

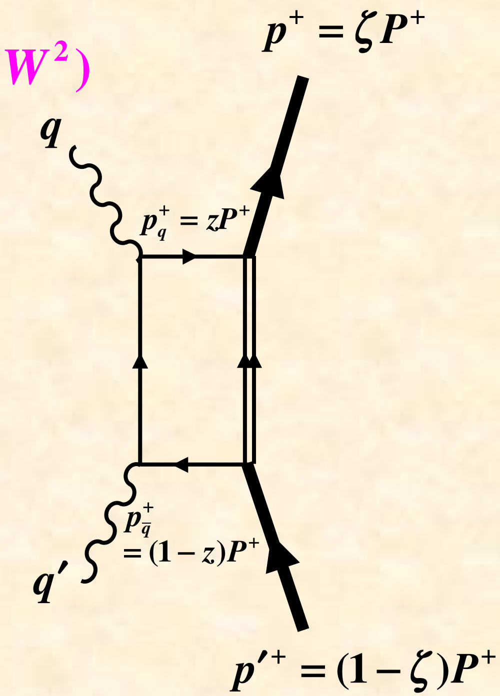
***s-t* crossing**



$z \Leftrightarrow \frac{1-x/\xi}{2}$

$\zeta \Leftrightarrow \frac{1-1/\xi}{2}$

$W^2 \Leftrightarrow t$



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

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

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

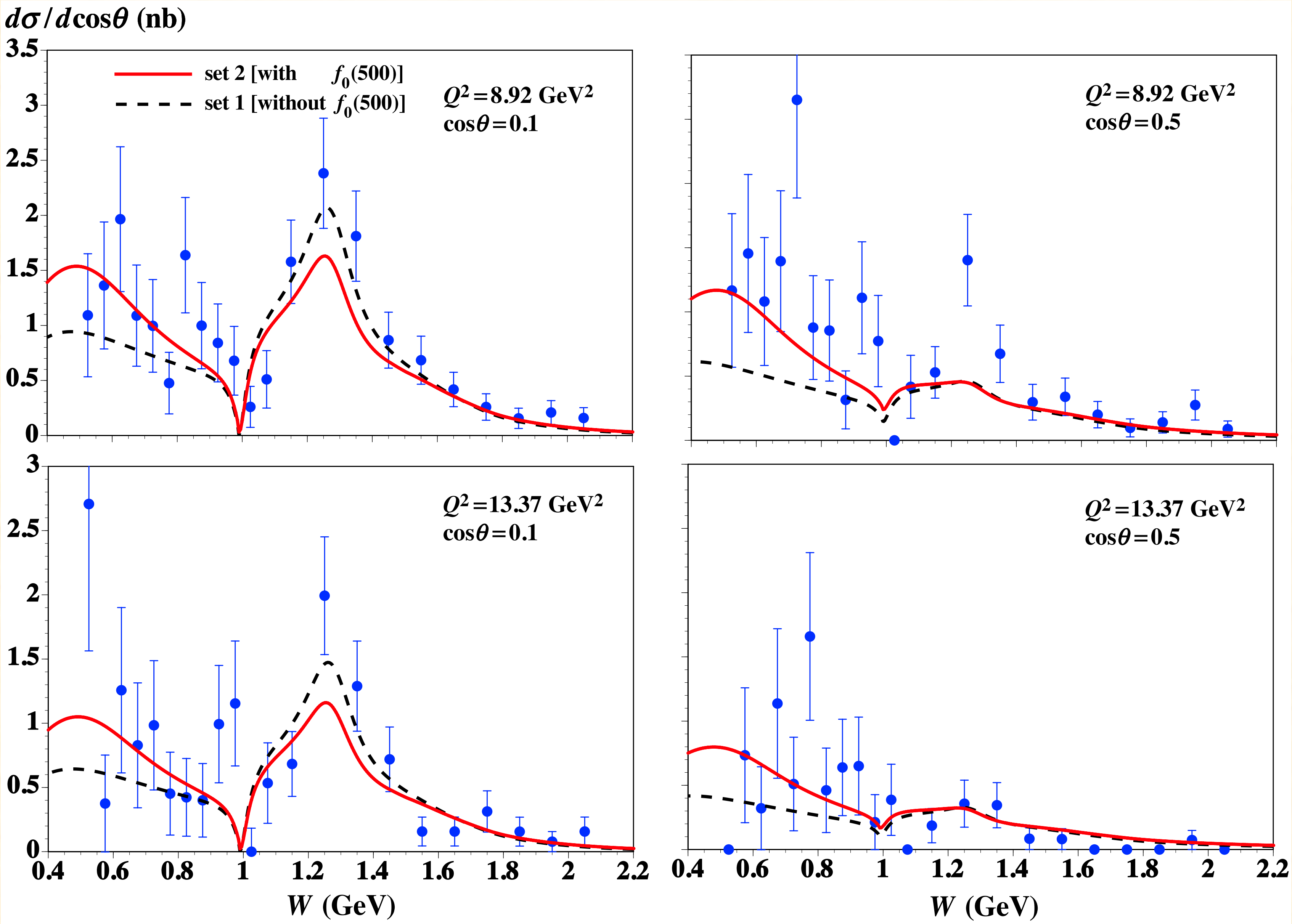
Skewdness parameter: $\xi = \frac{p^+ - p'^+}{p^+ + p'^+} = -\frac{\Delta^+}{2P^+}$

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

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

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

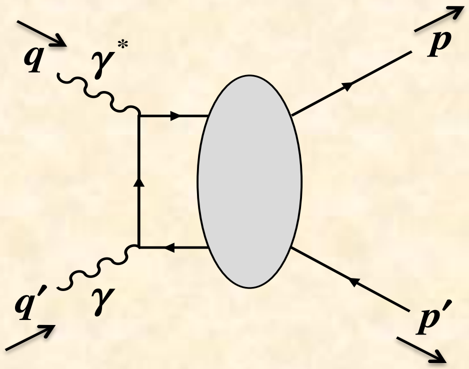
Analysis results: $Q^2 = 8.92,\ 13.37\ \mathrm{GeV}^2$, $\cos\theta$=0.1, 0.5



Gravitational form factors and radii for pion

$$\int_0^1 dz(2z-1)\Phi_q^{\pi^0\pi^0}(z,\zeta,s) = \frac{2}{(P^+)^2}\langle \pi^0(p)\pi^0(p')|T_q^{++}(0)|0\rangle$$

$$\langle \pi^0(p)\pi^0(p')|T_q^{\mu\nu}(0)|0\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu} - P^\mu P^\nu\right)\Theta_{1,q}(s) + \Delta^\mu\Delta^\nu\Theta_{2,q}(s)\right]$$



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

$T_q^{\mu\nu}$: energy-momentum tensor for quark

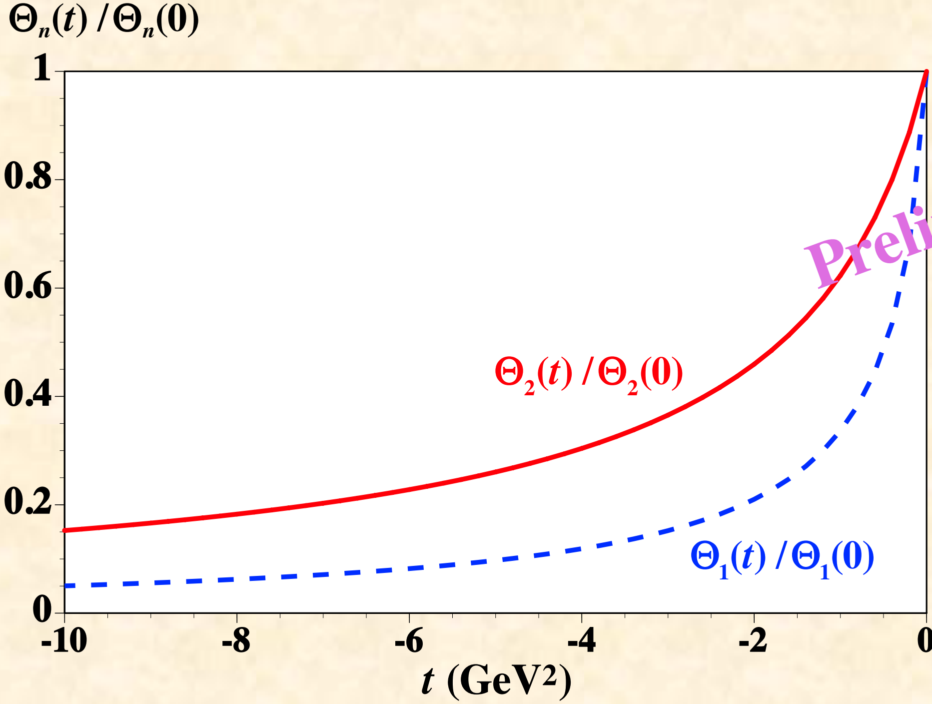
$\Theta_{1,q}$, $\Theta_{2,q}$: gravitational form factos for pion

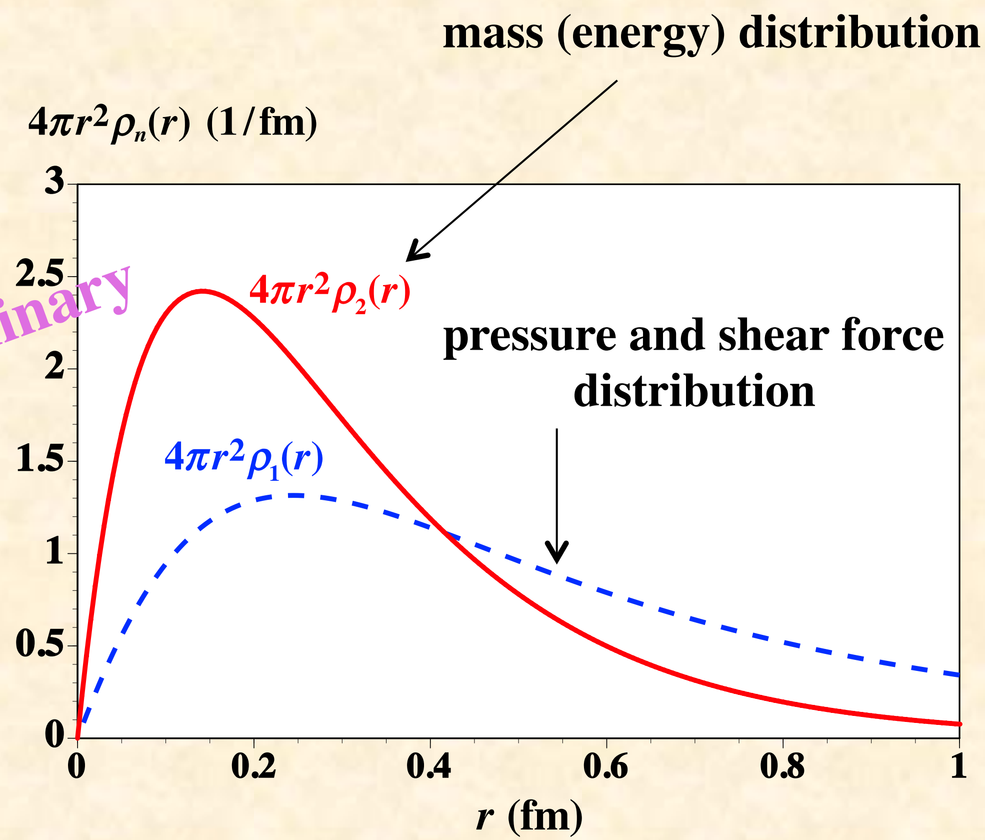
Analyiss of $\gamma^*\gamma \to \pi^0\pi^0$ cross section
$\Rightarrow$ Generalized distribution amplitudes $\Phi_q^{\pi^0\pi^0}(z,\zeta,s)$
$\Rightarrow$ Timelike gravitational form factors $\Theta_{1,q}(s)$, $\Theta_{2,q}(s)$
$\Rightarrow$ Spacelike gravitational form factors $\Theta_{1,q}(t)$, $\Theta_{2,q}(t)$
$\Rightarrow$ Gravitational radii of pion

Spacelike gravitational form factors and radii for pion

$$\langle \pi^0(p') | T_q^{\mu\nu}(0) | \pi^0(p) \rangle = \frac{1}{2}\left[\left(t g^{\mu\nu} - q^\mu q^\nu\right)\Theta_{1,q}(s) + P^\mu P^\nu \Theta_{2,q}(s)\right]$$

$$P = p + p', \quad q = p' - p$$





Generalized Distribution Amplitudes (GDAs) and gravitational radius for pion

S. Kumano, Q.-T. Song, O. Teryaev,

KEK-TH-1959, J-PARC-TH-0086,

to be submitted for publication.

8th International Conference on Quarks and Nuclear Physics

November 13-17, 2018, Tsukuba, Japan
http://www-conf.kek.jp/qnp2018/

Quark and gluon structure of hadrons:
- parton distribution functions, generalized parton distributions,
- transverse momentum distributions, high-energy hadron reactions, …

Hadron spectroscopy:
- heavy quark physics, exotics, N*, ...

Hadron interactions and nuclear structure:
- hypernuclear physics, kaonic nuclei, baryon interactions, ...

Hot and cold dense matter:
- quark-gluon plasma, color glass condensate, dense stars,
- strong magnetic field, mesons in nuclear medium, hadronization, ...

Summary

- **Lepton-nucleus cross sections should be understood in the wide kinematical regions for neutrino experiments.**
  Especially, the order of 5% accuracy is needed for future oscillation measurements.

- **There are significant studies in the quasi-elastic, resonace, and DIS regions *separatedly*.**
  $\rightarrow$ It is desirable to have a unified code for calculating the cross sections.

- **The Regge region ($W^2 \geq 4$ GeV^2, $Q^2 < 1$ GeV^2) is not well investigated.**

  $\rightarrow$ Kamano's talk

- **Hadron tomography can be investigated by neuetrino-induced pion production.**

- **Hadron tomography $\rightarrow$ Gravitational form factros can be obtained.**

The End

The End