Neutrino-Nucleus Scattering

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Introduction/Motivation

Neutrino properties: What we know in 2022

- very weakly interacting, electrically neutral, spin 1/2, tiny mass
- long lived (or stable), tiny or vanishing magnetic moment
- 3 light 'SM families' (ν_e , ν_μ , ν_τ)
- neutrinos oscillate $\Longleftrightarrow$ $m_\nu \neq 0$

Neutrino Properties

See the note on "Neutrino properties listings" in the Particle Listings.

Mass $m <$ 1.1 eV, CL = 90% (tritium decay)
Mean life/mass, $\tau/m >$ 300 s/eV, CL = 90% (reactor)
Mean life/mass, $\tau/m >$ 7×10^9 s/eV (solar)
Mean life/mass, $\tau/m >$ 15.4 s/eV, CL = 90% (accelerator)
Magnetic moment μ < 0.28×10^{-10} μ_B, CL = 90% (solar + radiochemical)

Number of Neutrino Types

Number $N = 2.996 \pm 0.007$ (Standard Model fits to LEP-SLC data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)

Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$
$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23}) = 0.539 \pm 0.022$ (S = 1.1) (Inverted order)
$\sin^2(\theta_{23}) = 0.546 \pm 0.021$ (Normal order)
$\Delta m^2_{32} = (-2.536 \pm 0.034) \times 10^{-3}$ eV^2 (Inverted order)
$\Delta m^2_{32} = (2.453 \pm 0.033) \times 10^{-3}$ eV^2 (Normal order)
$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$
δ, CP violating phase $= 1.36^{+0.20}_{-0.16}\ \pi$ rad

Neutrino properties: What we want to know

- **nature of neutrinos**:
  - Majorana or Dirac fermions?
  - are there sterile neutrinos?
- **neutrino masses**:
  - what are the absolute neutrino masses?
  - normal ($m_2 \ll m_3$) or inverted ($m_2 \gg m_3$) mass hierarchy? [we know $m_2 > m_1$ from MSW effect]
- **mixing matrix** (PMNS-matrix):
  - more precise measurement of mixing angles
  - is the PMNS matrix unitary?
  - amount of leptonic CP violation

Neutrino-Nucleus Scattering

A tool too:

- **detect neutrinos**
  - ➡ neutrino properties, neutrino oscillations, neutrino fluxes
  - ➡ Small νN cross sections $\rightarrow$ heavy targets $\rightarrow$ νN scattering $\oplus$ nuclear corrections
- **probe hadron structure**
  - ➡ structure functions, parton densities (flavor separation)
- **test electroweak physics**
  - ➡ weak interactions

From Atmospheric to UHE neutrinos

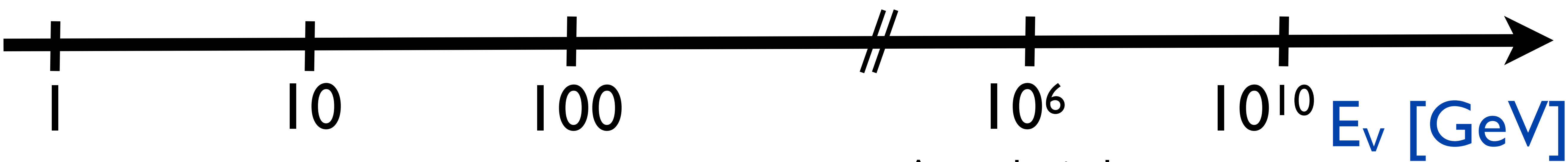
Atmospheric neutrinos

CCFR, NuTEV, CHORUS, CDHSW, NOMAD, SHIP, …

UHE neutrinos AUGER

LBL experiments

ICECUBE



Neutrino oscillations; precise knowledge of νA interactions needed

Astrophysical neutrinos observed!

Flavor separation of PDFs, nPDFs;
Proton PDFs: nuclear corrections;
dimuon production: main source of information on strange sea;
Non-singlet evolution of F_3: α_s;
Paschos-Wolfenstein relation, …

Neutrino interactions in the atmosphere;
CC DIS dominant;
small-x ($x \sim 10^{-7} \ldots 10^{-5}$);
Test of QCD evolution,
Access to BSM physics?

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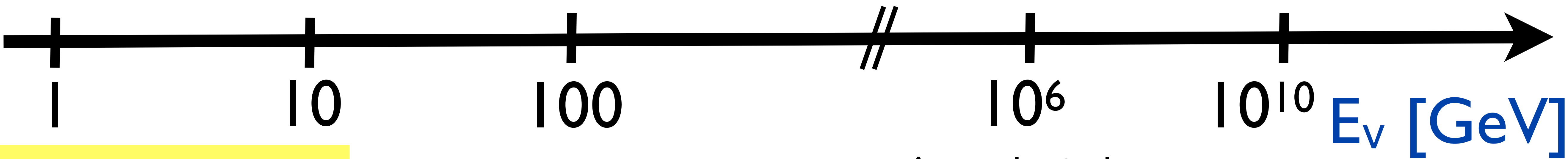
ICECUBE

UHE neutrinos
AUGER



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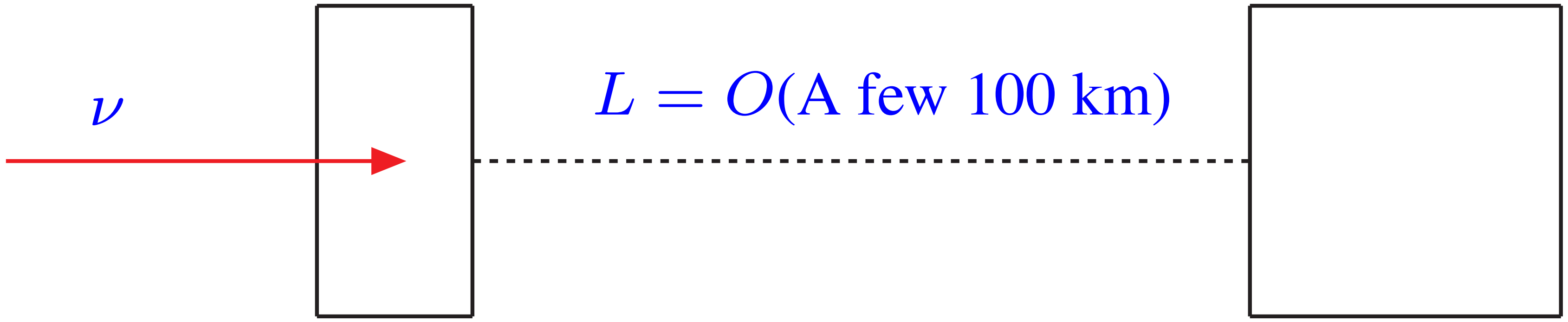
Long Baseline experiments



Near detector:

- neutrino flux
- neutrino beam energy spectrum
- cross sections before oscillation

Far detector:

- observation of charged and neutral current reactions

Detection requires good understanding of neutrino interactions

Nuclear effects distort measured kinematics of the neutrinos

Two (similar) detectors will not fully solve the problem:
Nuclear effects modify near and far spectra differently

Nuclear effects not always well understood.

General strategy has been to adapt nuclear effects from lA DIS in nuA DIS

Dedicated experiments to measure neutrino cross-sections!

Accelerator based neutrino experiments

G. P. Zeller, Particle Data Review 2020

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 –
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	$\nu, \overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

Inclusive, QE (pion less), Pion production processes
In the few GeV energy region

Measurements in the low GeV region

G. P. Zeller, Particle Data Review 2020

CC inclusive

experiment	measurement	target
ArgoNeuT	ν_μ [5,6], $\overline{\nu}_\mu$ [6]	Ar
MicroBooNE	ν_μ [7]	Ar
MINERνA	ν_μ [8,14,15,19], $\overline{\nu}_\mu$ [19], $\overline{\nu}_\mu/\nu_\mu$ [20]	CH, C/CH, Fe/CH, Pb/CH
MINOS	ν_μ [21], $\overline{\nu}_\mu$ [21]	Fe
NOMAD	ν_μ [22]	C
SciBooNE	ν_μ [23]	CH
T2K	ν_μ [9,10,12,24,25], ν_e [26,27], $\overline{\nu}_\mu/\nu_\mu$ [13]	CH, H_2O, Fe

CC/NC pionless

experiment	measurement	target
ArgoNeuT	2p [38]	Ar
K2K	M_A [39]	H_2O
MINERνA	$\frac{d\sigma}{dQ^2}$ [40–42], 1p [43], ν_e [44], $\frac{d^2\sigma}{dp_T dp_{\|\|}}$ [28,29], $\frac{d\sigma}{dp_n}\frac{d\sigma}{d\delta\alpha_T}$ [30], $\frac{d^2\sigma}{dE_{avail}dq_3}$ [45]	CH, Fe, Pb
MiniBooNE	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$ [31,32], M_A [46], NC [47,48]	CH_2
MINOS	M_A [49]	Fe
NOMAD	M_A, $\sigma(E_\nu)$ [50]	C
Super-K	NC [51]	H_2O
T2K	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$ [33–35], $\sigma(E_\nu)$ [52], M_A [53], NC [54], $\frac{d\sigma}{d\delta p_T}\frac{d\sigma}{d\delta\alpha_T}$ [36]	CH, H_2O

CC(≧1π), NC(≧1π)

experiment	$\pi^\pm$ measurement	π^0 measurement	target
ArgoNeuT	CC [66]	NC [67]	Ar
K2K	CC [68,69]	CC [70], NC [71]	CH, H_2O
MicroBooNE	–	CC [72]	Ar
MINERνA	CC [73–77]	CC [74,78,79], NC [80]	CH
MiniBooNE	CC [81,82]	CC [83], NC [84,85]	CH_2
MINOS	–	NC [86]	Fe
NOMAD	–	NC [87]	C
NOvA	–	NC [88]	C
SciBooNE	CC [89]	NC [90,91]	CH
T2K	CC [92,93]	–	CH, H_2O

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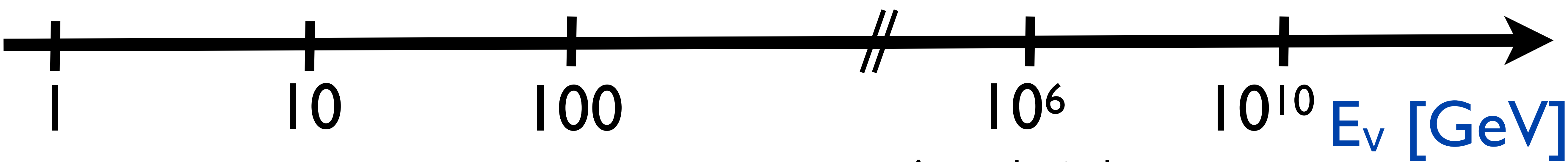

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Flavor separation of PDFs

NC charged lepton DIS: 2 structure functions (γ-exchange)

$$F_2^\gamma(x) \sim \frac{1}{9}[4(u+\bar{u}+c+\bar{c})+d+\bar{d}+s+\bar{s}](x)$$

$$F_2^\gamma(x) = 2xF_1^\gamma(x)$$

CC Neutrino DIS: 6 additional structure functions $F_{1,2,3}^{W+}$, $F_{1,2,3}^{W-}$

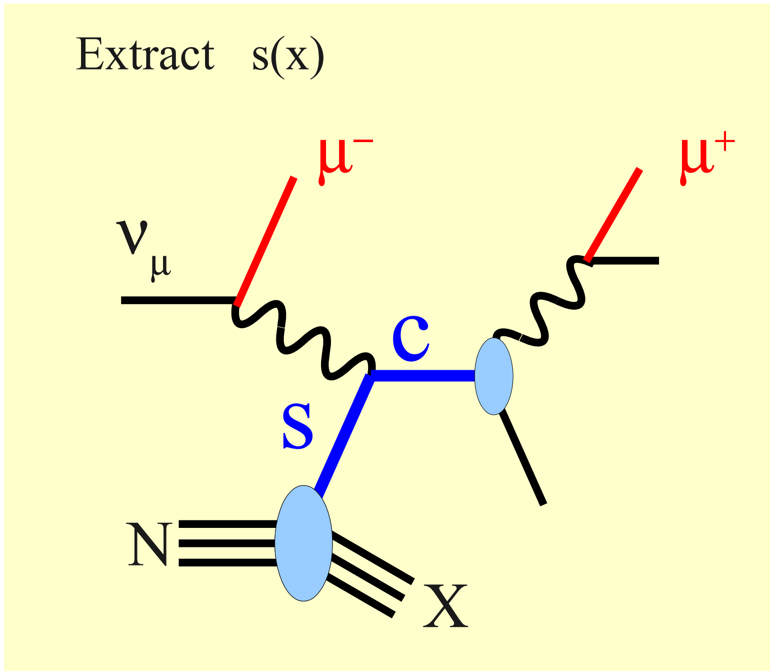
$$F_2^{W^+} \sim [d+s+\bar{u}+\bar{c}] \qquad F_3^{W^+} \sim 2[d+s-\bar{u}-\bar{c}]$$

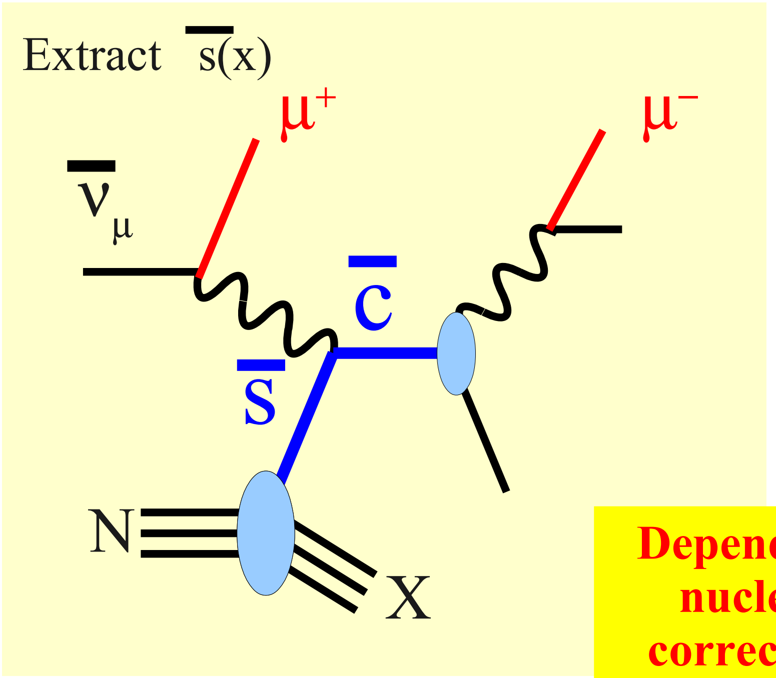
$$F_2^{W^-} \sim [\bar{d}+\bar{s}+u+c] \qquad F_3^{W^-} \sim 2[u+c-\bar{d}-\bar{s}]$$

Useful/needed to disentangle different quark parton flavors in a **global analysis** of proton or nuclear PDFs

Dimuon production and the strange PDF

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





Depends on nuclear corrections

- High-statistics data from CCFR and NuTeV: **Main source** of information!
- x~[0.01,0.4]
- νFe DIS: need nuclear corrections! Problem: Final State Interactions (FSI)
- CHORUS (νPb): compatible with NuTeV, could be included
- NOMAD (νFe): data now available

xF_3 and Isospin Violation

- xF_3 uniquely determined by neutrino-DIS

$$\frac{1}{2}F_3^{\nu A}(x) = d_A + s_A - \bar{u}_A - \bar{c}_A + \ldots,$$
$$\frac{1}{2}F_3^{\bar{\nu} A}(x) = u_A + c_A - \bar{d}_A - \bar{s}_A + \ldots$$

NuSOnG, 0803.0354
0906.3563

- The sum is sensitive to the valence quarks

→ Nonsinglet QCD evolution, determination of $\alpha_s(Q)$

- The difference can be used to constrain isospin violation

$$\Delta x F_3 = xF_3^{\nu A} - xF_3^{\bar{\nu} A} = 2xs_A^+ - 2xc_A^+ + x\,\delta I^A + \mathcal{O}(\alpha_S)$$
$$\delta I^A = \left(d_{p/A} - u_{n/A}\right) + \left(d_{n/A} - u_{p/A}\right) + \left(\bar{d}_{p/A} - \bar{u}_{n/A}\right)\left(\bar{d}_{n/A} - \bar{u}_{p/A}\right)$$

Electroweak precision tests

Hadronic Precision Observables

$$R^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}} \simeq g_L^2 + r g_R^2$$

$$R^{\bar\nu} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^{\bar\nu}_{\rm CC}} \simeq g_L^2 + r g_R^2$$

$$r = \frac{\sigma^{\bar\nu}_{\rm CC}}{\sigma^\nu_{\rm CC}}$$

g_L and g_R are effective L and R νq couplings

$$g_L^2 = \rho^2\left(\frac{1}{2} - s_w^2 + \frac{5}{9}s_w^4\right)$$

$$g_R^2 = \rho^2\left(\frac{5}{9}s_w^4\right)$$

Paschos-Wolfenstein (PW):

$$R^- = \frac{\sigma^\nu_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^\nu_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} \simeq g_L^2 - g_R^2 = \rho^2\left(\frac{1}{2} - s_w^2\right)$$

NuSOnG, 0803.0354 0906.3563

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Can new gauge bosons be observed in UHE cosmic neutrino events?

Consider CC and NC DIS in presence of heavy W', Z' bosons

arXiv:1401.6012

LHC: $\sqrt{S} = 13$ **TeV**

UHEνCR: $E_\nu = 10^{19}$ **eV** $\rightarrow \sqrt{S} \simeq 140$ **TeV**

	Process	σ [pb] (SM)	σ [pb] (SSM)
1.) CC DIS	$\nu_\mu N \to \mu^- + X$	$2.84 \cdot 10^4$	$2.84 \cdot 10^4$
2.) NC DIS	$\nu_\mu N \to \nu_\mu + X$	$1.20 \cdot 10^4$	$1.20 \cdot 10^4$
3.) GR$^{(\prime)}$ to had.	$\bar\nu_e e^- \to$ hadrons	$6.6 \cdot 10^{-2}$	41.16
4.) GR$^{(\prime)}$ to e^-	$\bar\nu_e e^- \to \bar\nu_e e^-$	$1.1 \cdot 10^{-2}$	6.86
5.) GR$^{(\prime)}$ to μ^-	$\bar\nu_e e^- \to \bar\nu_\mu \mu^-$	$1.1 \cdot 10^{-2}$	6.86
6.) ES into e^-	$\nu_e e^- \to \nu_e e^-, \ldots$	154.50	—
7.) ES into μ^-	$\nu_\mu e^- \to \mu^- \nu_e$	102.17	—

Table I. Cross sections at $E_\nu = 1.56 \cdot 10^{10}$ GeV in the SM and the SSM assuming $M_{W'} = M_{Z'} = 4$ TeV. The numbers in the 6th and 7th lines have been taken from figure 8 in [26]. The elastic neutrino scattering off electrons into an electron (line 6) receives contributions from the following processes: $\nu_e e^- \to \nu_e e^-, \bar\nu_e e^- \to \bar\nu_e e^-, \nu_\mu e^- \to \nu_\mu e^-$, and $\bar\nu_\mu e^- \to \bar\nu_\mu e^-$. The non-resonant production of a muon (line 7) is due to the process $\nu_\mu e^- \to \mu^- \nu_e$.

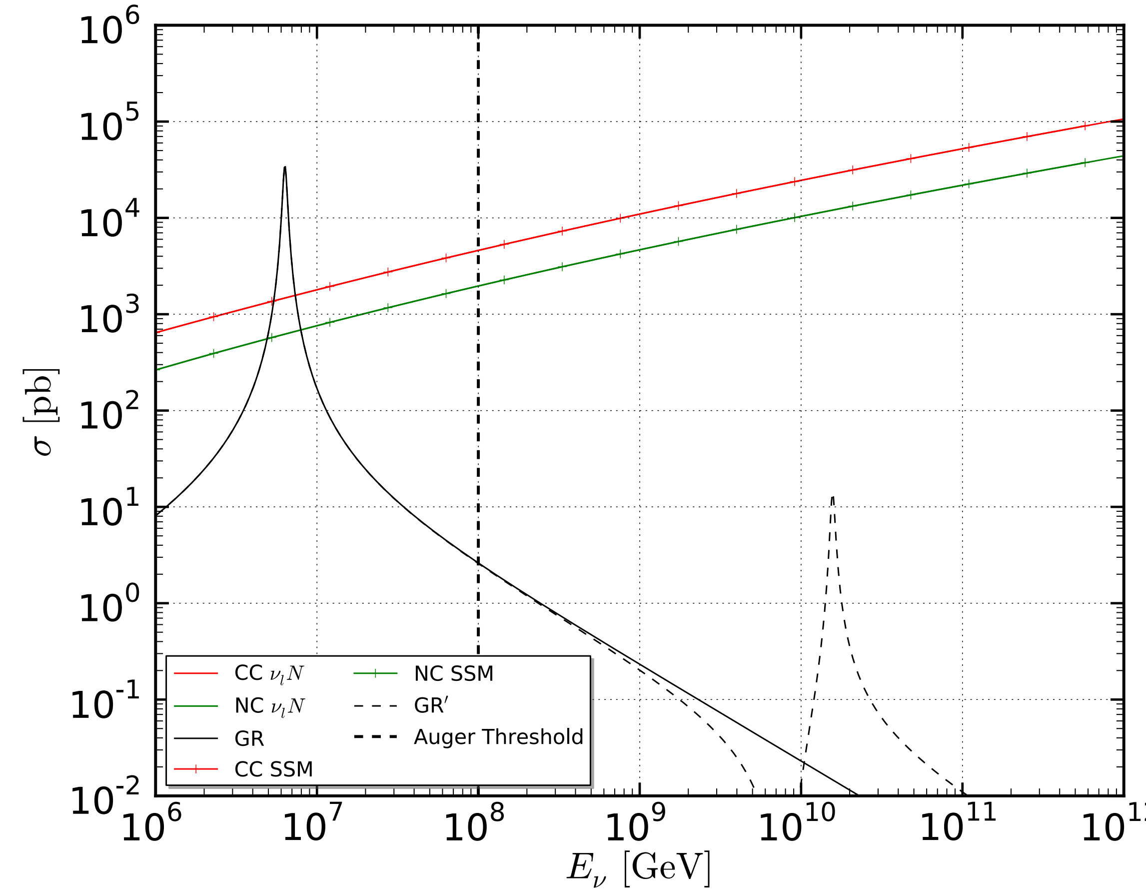


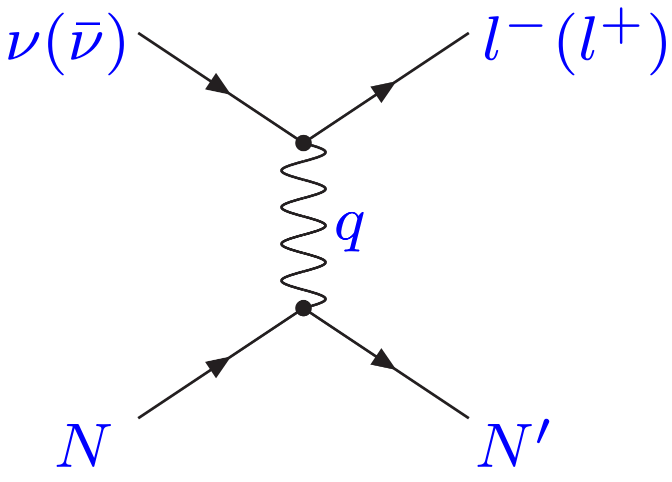
Figure 1. Total cross sections for CC $\nu_\mu N$ DIS (red line), NC $\nu_\mu N$ DIS (green line) and the Glashow resonance (solid black line) in dependence of the incoming neutrino energy. The vertical line at $E_\nu = 10^8$ GeV indicates the lower energy threshold of the Auger Observatory. The red and green crosses show the CC DIS and NC DIS cross sections, respectively, in the SSM with $M_{W'} = M_{Z'} = 4$ TeV. The resonant $\bar\nu_e e^-$ scattering including the contribution from the W' resonance is represented by the dashed, black line.

Conclusion: Effects of W', Z' resonances in DIS too small to be observed at AUGER or any possible upgrade.
In addition: uncertainties due to small-x evolution. Bgd to possible signal in neutrino-electron scattering

Neutrino scattering: Kinematics

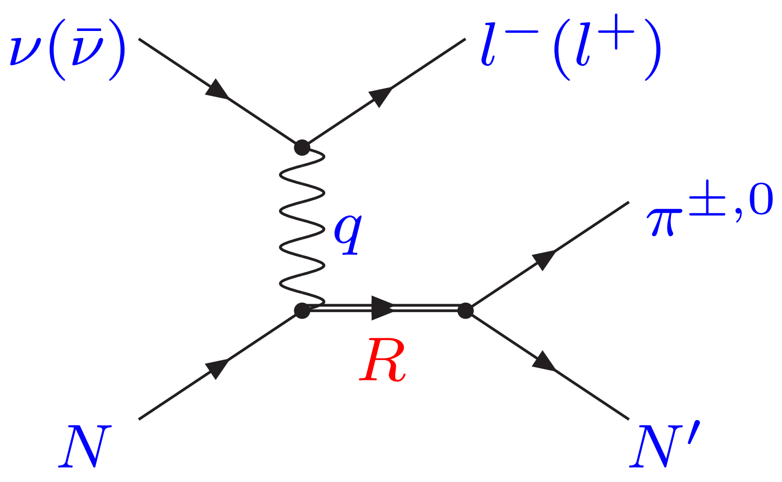
Main processes

- **Quasi-Elastic (QE) scattering**
  - CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N'$
  - NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N$



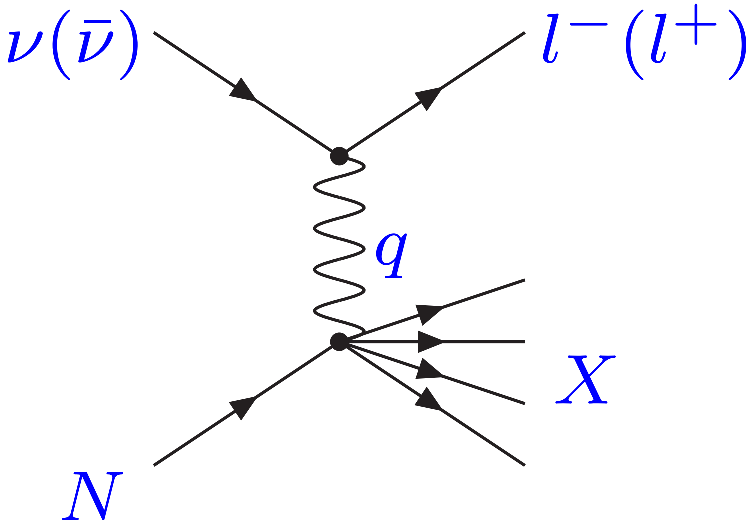
QE

- **Resonant (RES) (single) pion production**
  - CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + N' + \pi^{\pm,0}$
  - NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + N' + \pi^{\pm,0}$



RES

- **Deep Inelastic Scattering (DIS)**
  - CC: $\nu(\bar{\nu}) + N \rightarrow l^-(l^+) + X$
  - NC: $\nu(\bar{\nu}) + N \rightarrow \nu(\bar{\nu}) + X$



DIS

Kinematic variables

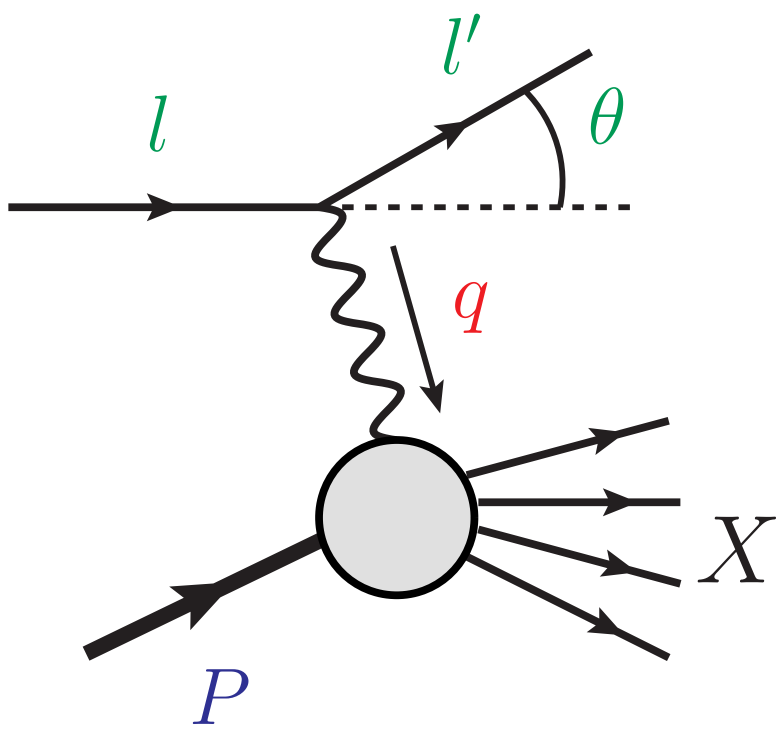
- Let's consider **inclusive DIS** where a sum over all **hadronic final states X** is performed:

  $e^-(l)+N(p) \rightarrow e^-(l')+X(p_X)$

- On-shell conditions: **$p^2=M^2$, $l^2=l'^2=m^2$**

- Measure energy and polar angle of scattered electron (**E',θ**)

- Other invariants of the reaction:



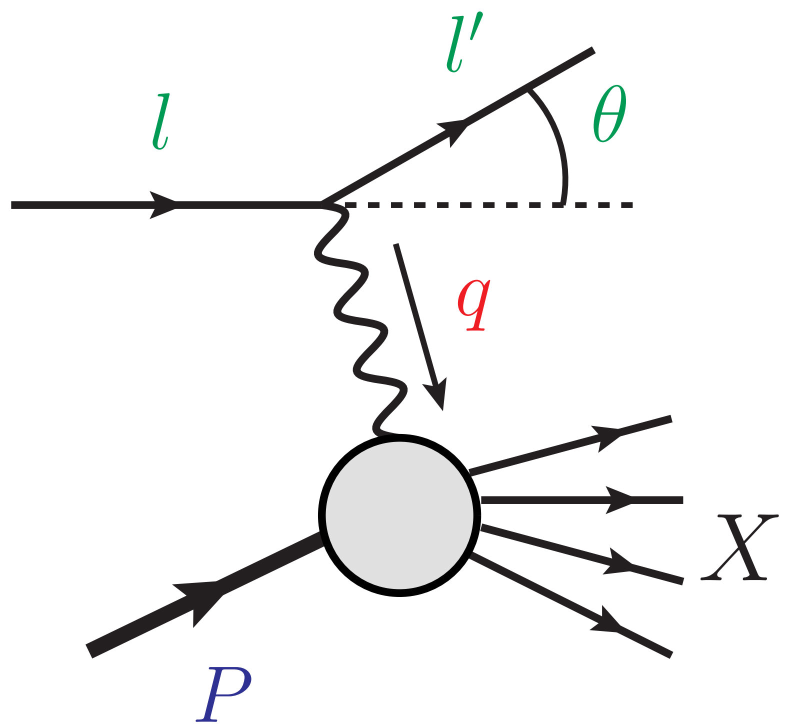
- $Q^2 = -q^2 = -(l-l')^2 > 0$, the square of the momentum transfer,
- $\nu = p \cdot q/M \overset{\text{lab}}{=} E_l - E_{l'}$,
- $0 \leq x = Q^2/(2p \cdot q) = Q^2/(2M\nu) \leq 1$, the (dimensionless) Bjorken scaling variable,
- $0 \leq y = p \cdot q/p \cdot l \overset{\text{lab}}{=} (E_l - E_{l'})/E_l \leq 1$, the inelasticity parameter,

* Here 'lab' designates the proton rest frame p=(M,0,0,0) which coincides with the lab frame for fixed target experiments

Kinematic variables

- There are two independent variables to describe the kinematics of inclusive DIS (up to trivial **φ** dependence):

  (E',,θ) or **(x,Q²)** or **(x,y)** or ...



- Relation between **Q²**, **x**, and **y**:

$$Q^2 = (2p\cdot l)\left(\frac{Q^2}{2p\cdot q}\right)\left(\frac{p\cdot q}{p\cdot l}\right) = Sxy = 2MExy$$

$$S = 2p\cdot l = (p+l)^2 - p^2 - l^2$$

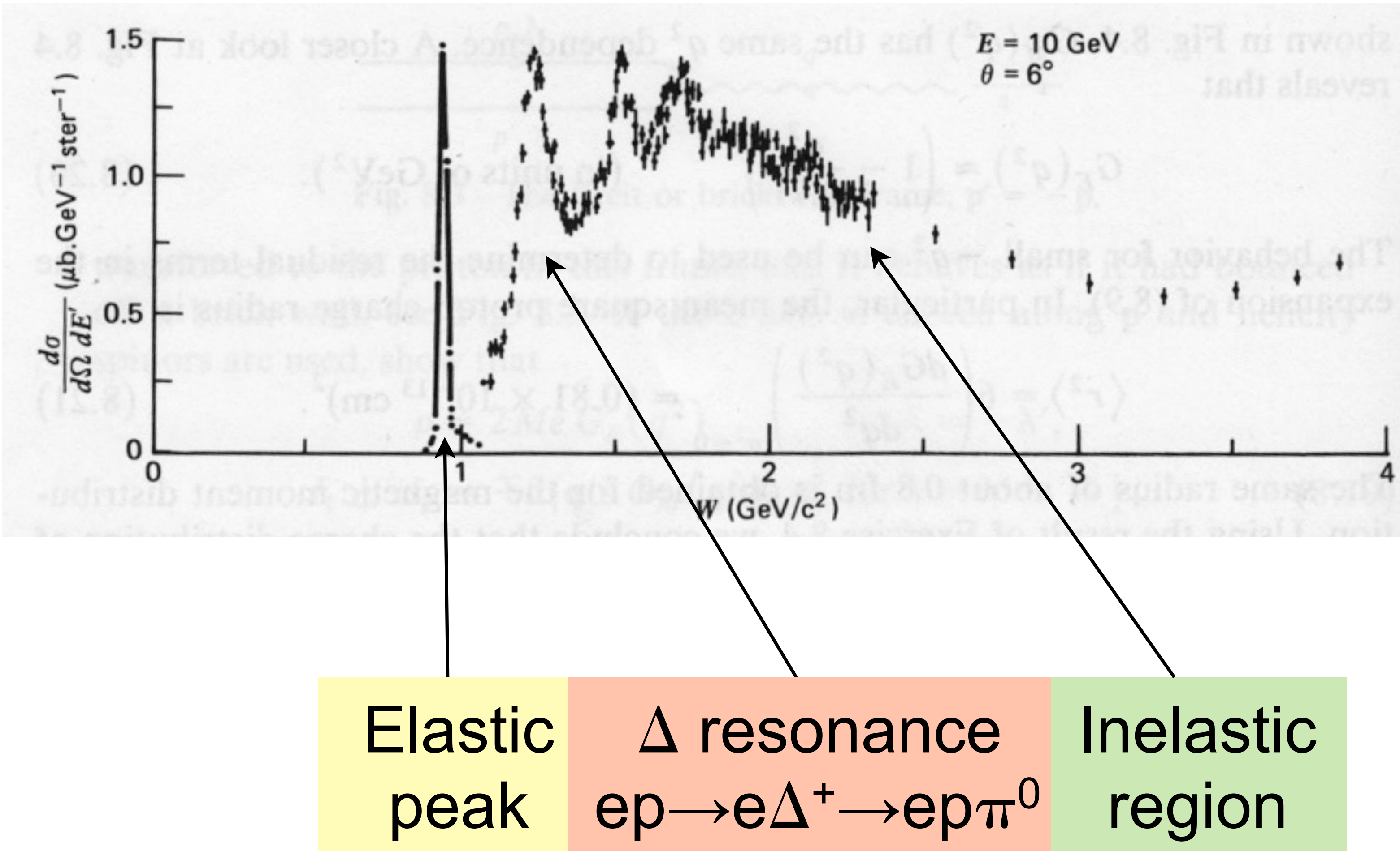
- Invariant mass **W** of the hadronic final state **X**:
  (also called missing mass since only outgoing electron measured)

$$W^2 \equiv M_X^2 = (p+q)^2 = M_N^2 + 2p\cdot q + q^2 = M_N^2 + \frac{Q^2}{x} - Q^2 = M_N^2 + \frac{Q^2}{x}(1-x)$$

elastic scattering: **W =M$_N$, x=1**

inelastic: **W ≥ M$_N$ + m$_\pi$, x<1**

The ep→eX cross section as function of W



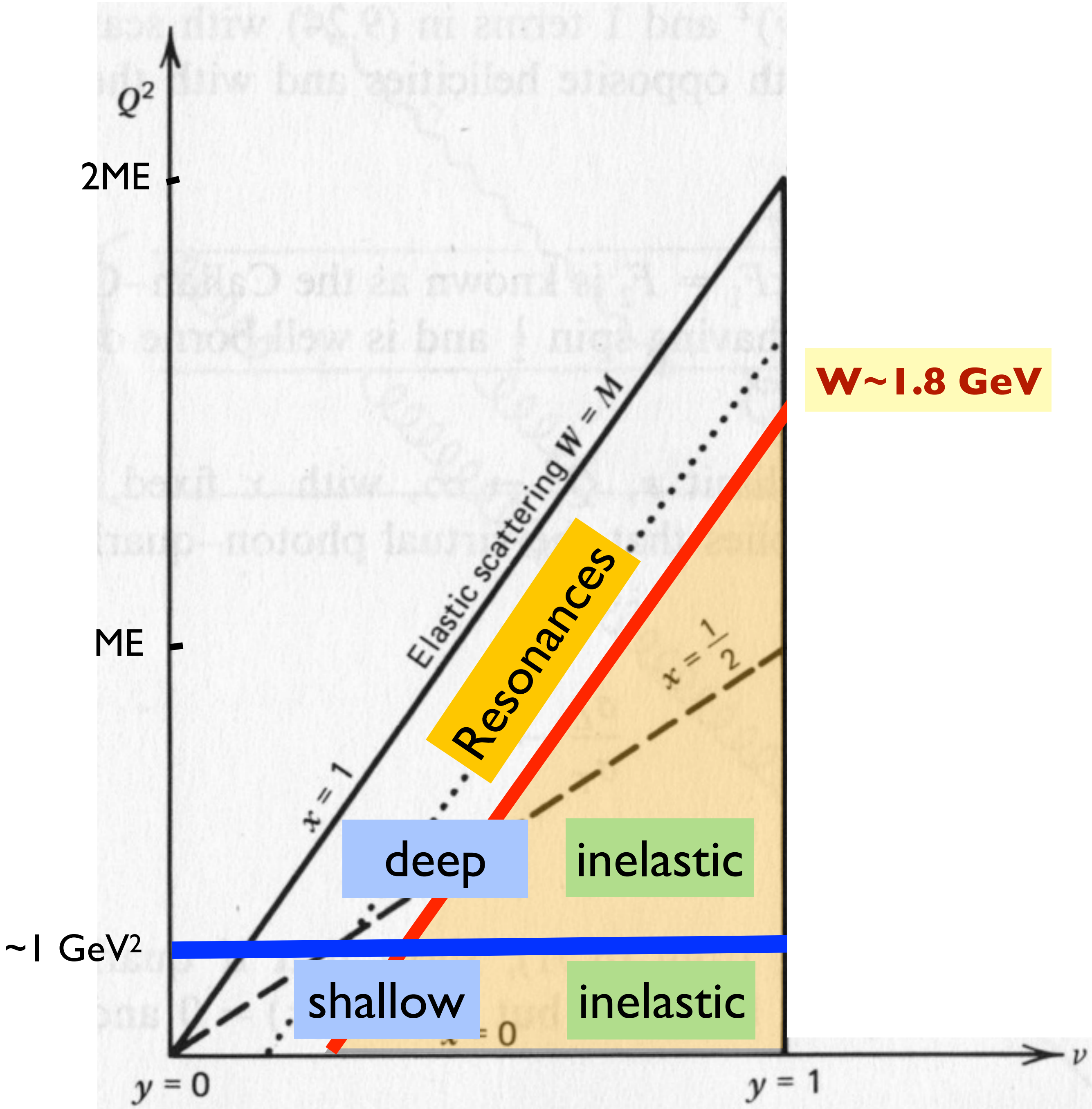
Halzen&Martin, Quarks&Leptons, Fig. 8.6

Data from SLAC;
The elastic peak at **W=M** has been reduced by a factor 8.5

- Elastic peak: **W=M**, **x=1** (proton doesn't break up: **ep→ep**)
- Resonances: **$W=M_R$, $\omega=1/x=1+(M_R^2-M^2)/Q^2$**
  (Note that there is also a non-resonant background in the resonance region!)
- 'Continuum' or 'inelastic region': **W>~1.8 GeV**
  complicated multiparticle final states resulting in a smooth distribution in **W**
  (Note there are also charmonium and bottonium resonances at W~3 and 9 GeV)

Phase Space in (ν,Q^2) plane

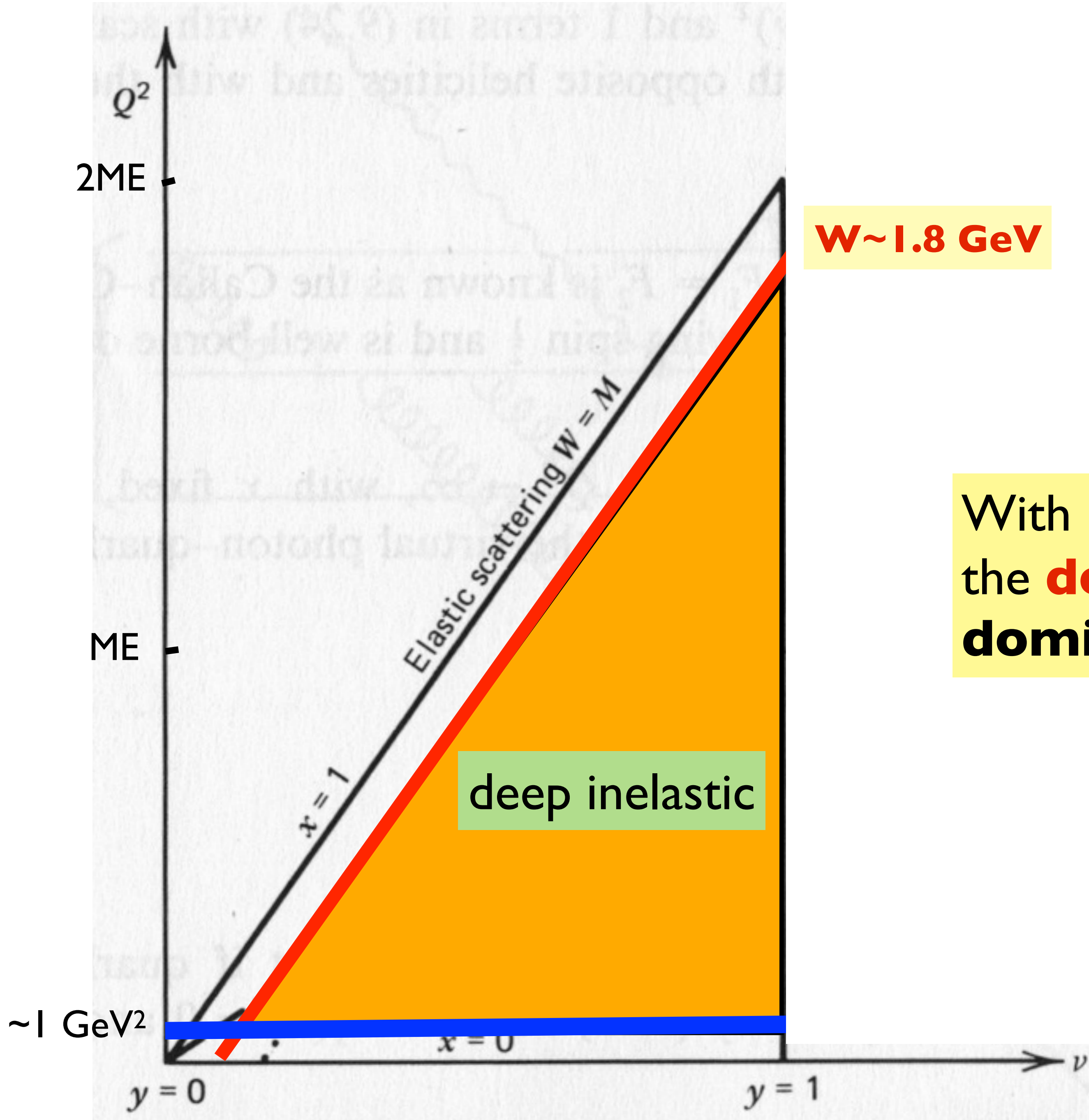
$Q^2=(2MEx)y$



- The phase space is separated into a resonance region (RES) and the inelastic region at **W~1.6 ... 1.8 GeV** (red line)
- The phase space is separated into a deep and a shallow region at **Q^2 ~1 GeV^2** (blue horizontal line)
- In global analyses of DIS data often the DIS cuts **Q^2>4 GeV^2, W>3.5 GeV** are employed
- The W-cut removes the large x region: **$W^2= M^2 + Q^2/x\ (1-x) > 3.5$ GeV**
- The Q-cut removes the smallest x: **$Q^2 = S\ x\ y > 4\ GeV^2$**

Phase Space in (ν,Q²) plane

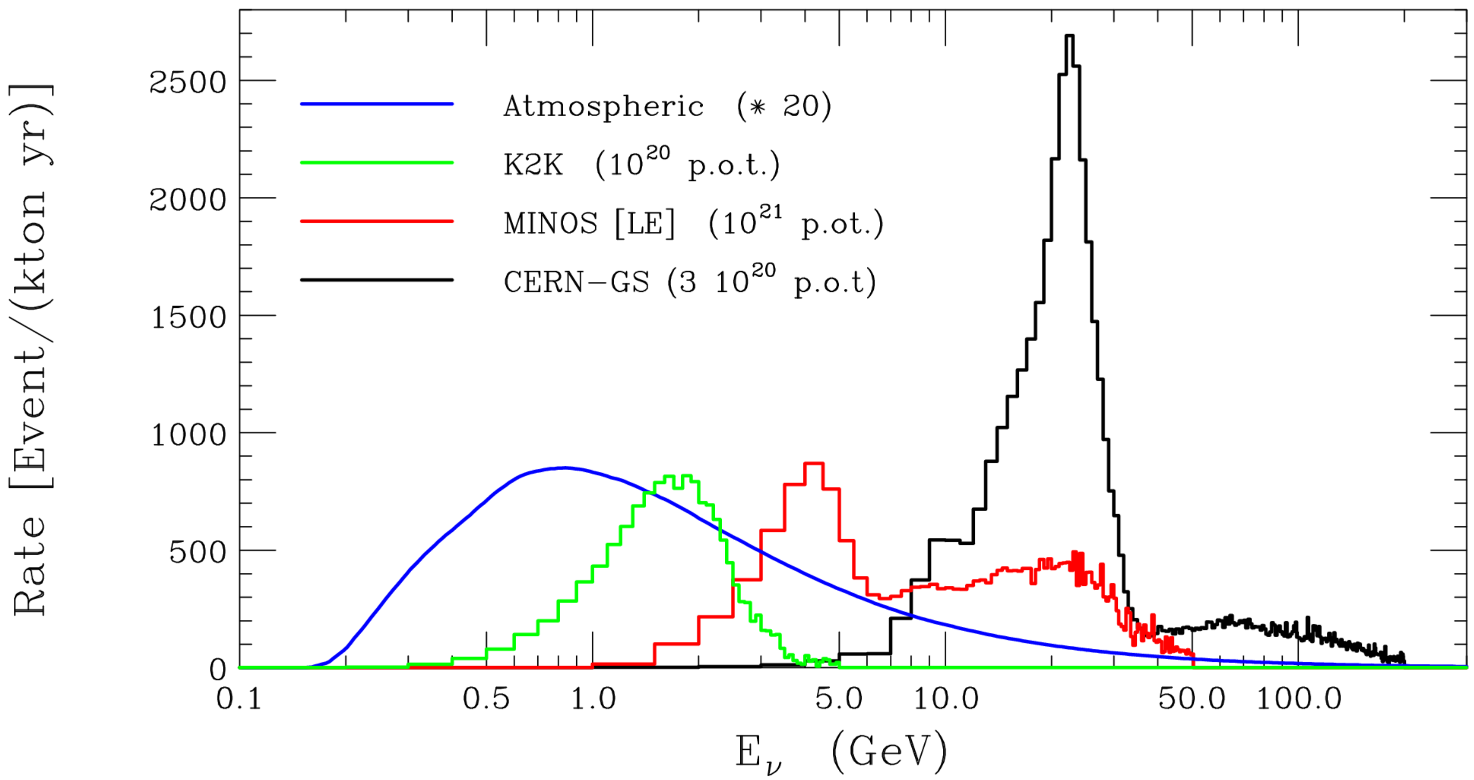
$Q^2=(2MEx)y$



With increasing energy **E** the **deep inelastic** region **dominates** the phase space!

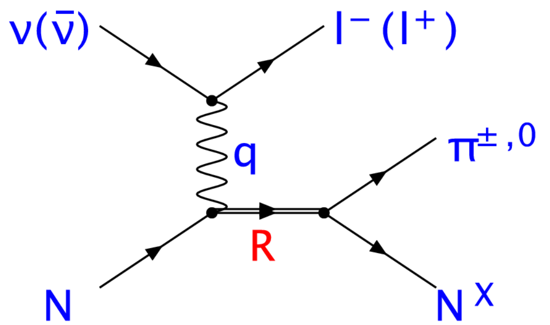
Neutrino cross sections at atmospheric ν energies

In the few GeV energy range QE, RES and DIS all important

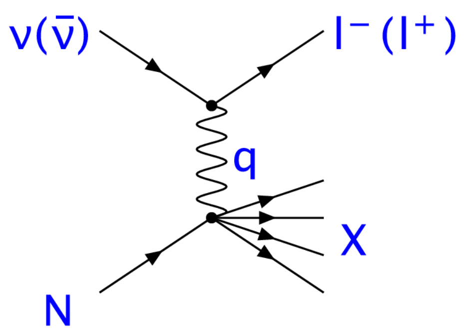


Paschos,JYY,PRD65(2002)033002

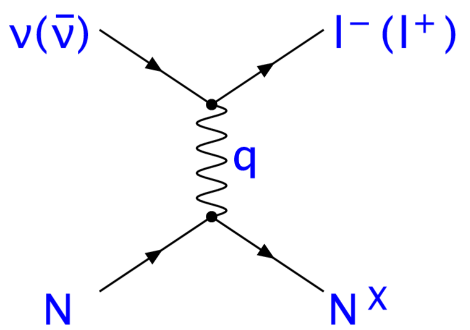
- Resonance production (RES)



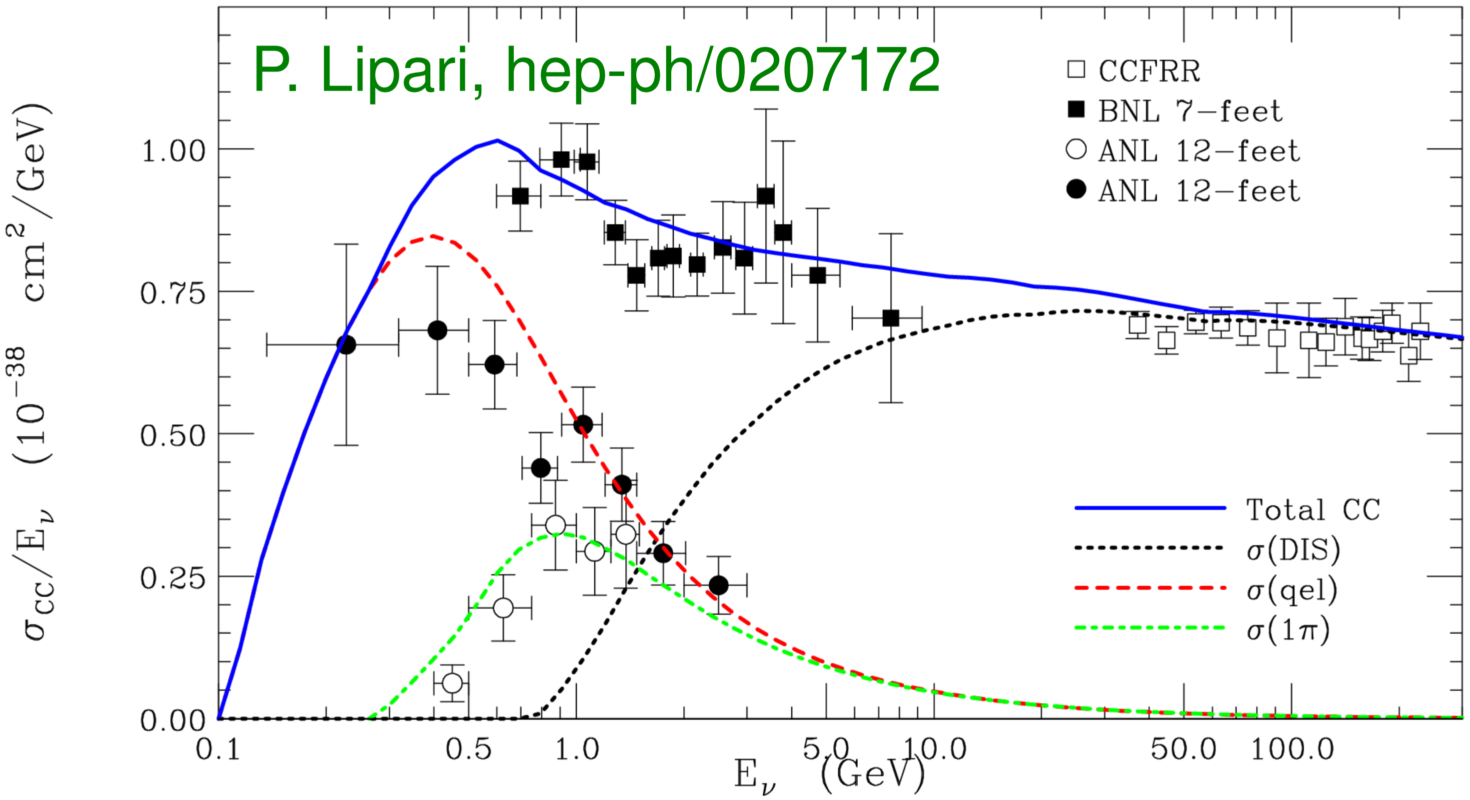
- Deep inelastic scattering (DIS)



- Quasi-elastic scattering (QE)

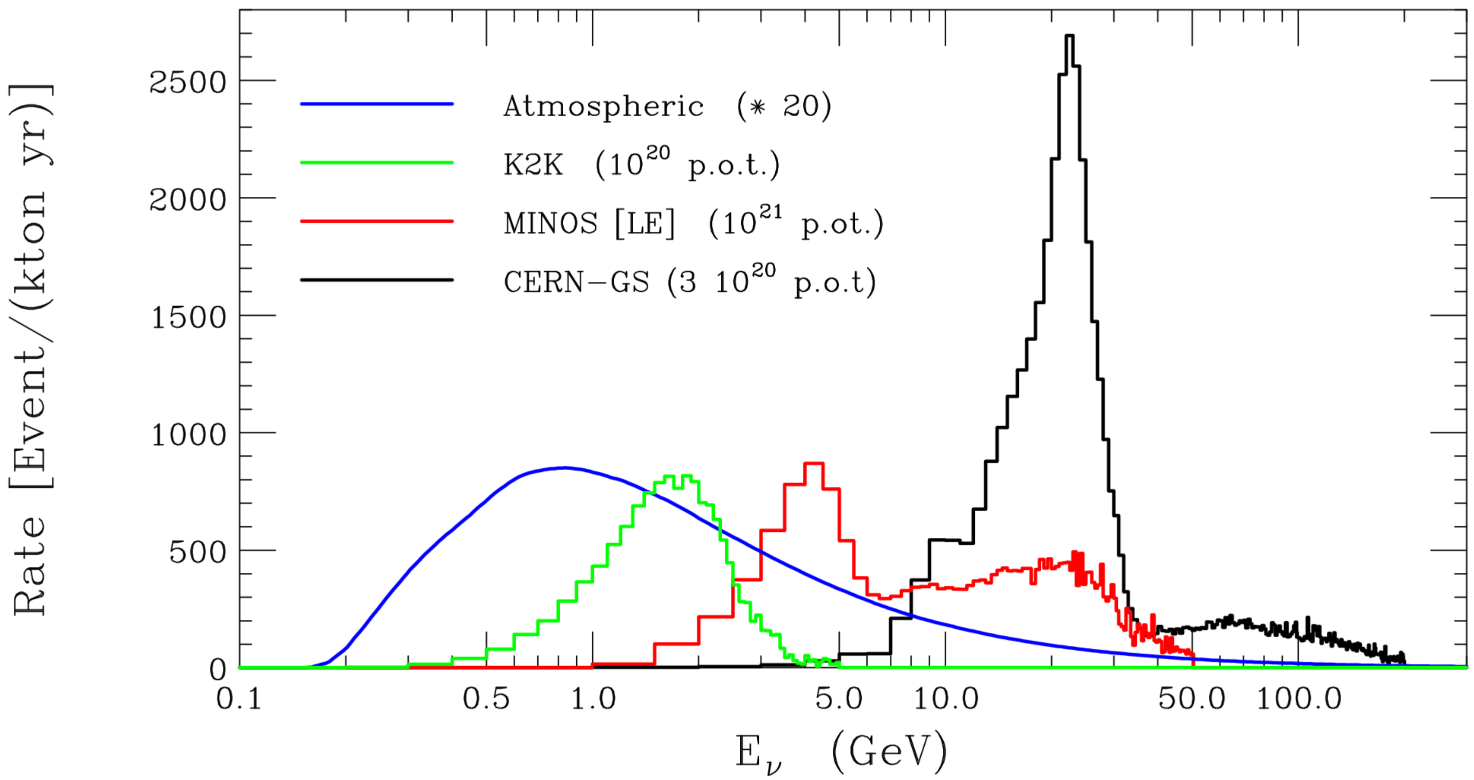


P. Lipari, hep-ph/0207172

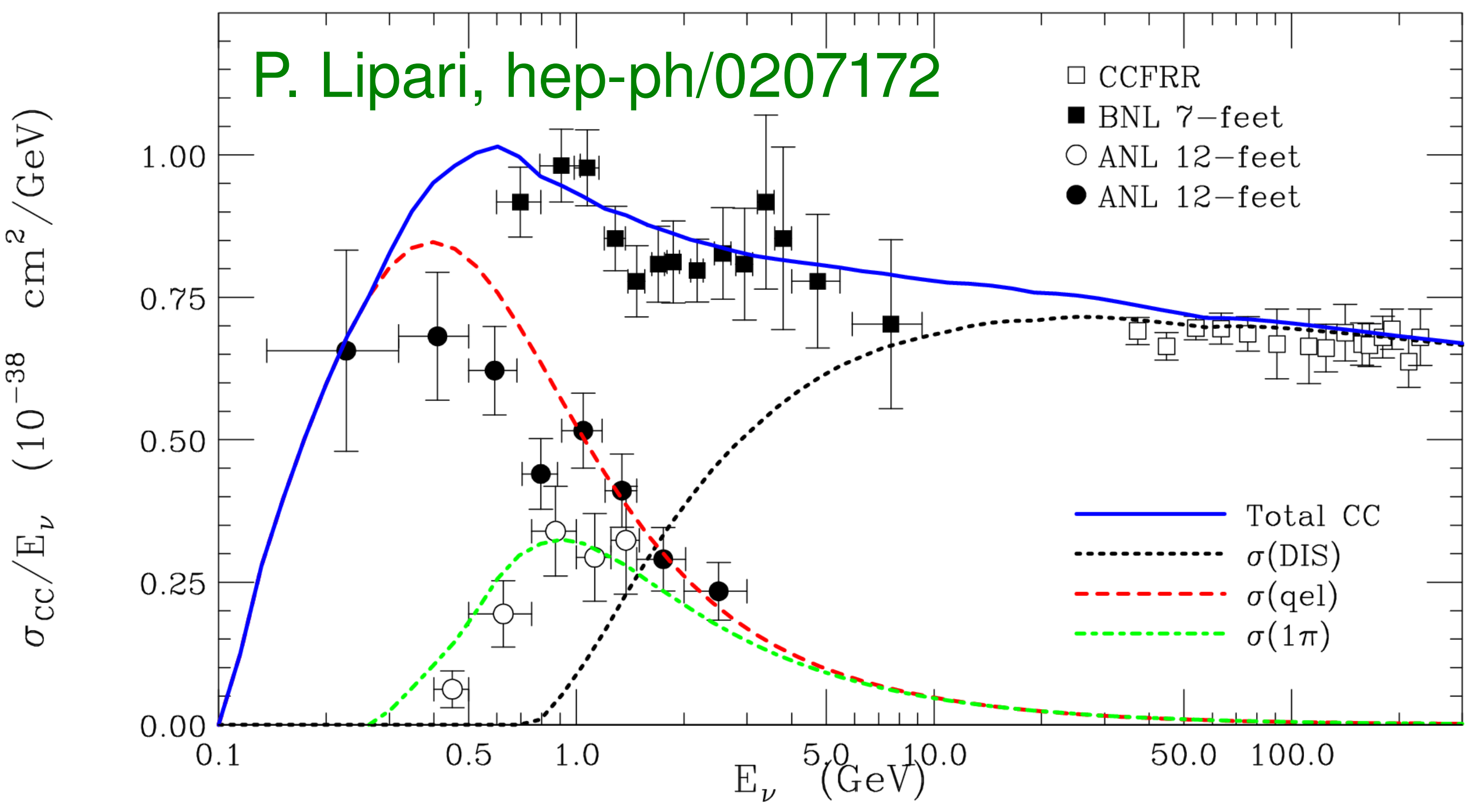


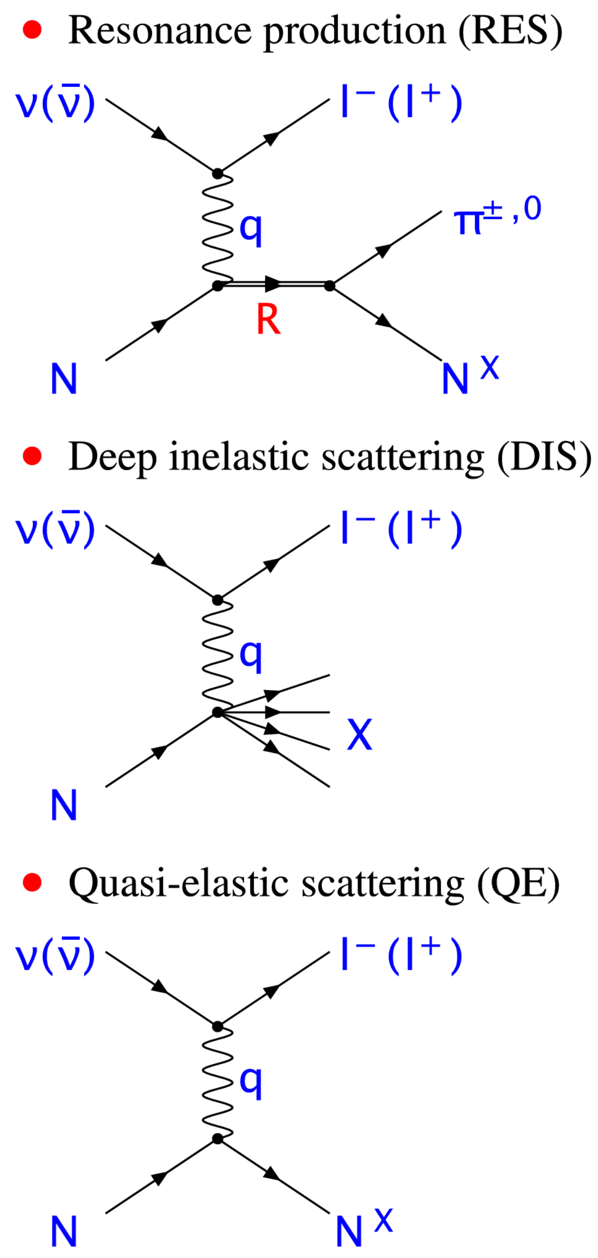
Neutrino cross sections at atmospheric ν energies

With increasing energy E the DIS region begins to dominate the phase space



Paschos,JYY,PRD65(2002)033002





Challenges

- **Take into account target mass effects in DIS**
- **Matching of DIS with RES**
  - ➡ Depends on W-cut
  - ➡ Resonances on top of continuous background: how to separate?
  - ➡ Quark-hadron duality: Partonic picture averages resonance contributions
- **Transition from the deep to the shallow region**
  - ➡ Bodek-Yang model. Quite old. Uses leading order GRV98 PDFs

Target Mass Corrections (TMC)

$$F_1^{\rm TMC}(x,Q^2) = \frac{x}{\eta r} F_1^{(0)}(\eta,Q^2) + \frac{M^2x^2}{Q^2r^2} h_2(\eta,Q^2) + \frac{2M^4x^3}{Q^4r^3} g_2(\eta,Q^2) \ ,$$

$$F_2^{\rm TMC}(x,Q^2) = \frac{x^2}{\eta^2 r^3} F_2^{(0)}(\eta,Q^2) + \frac{6M^2x^3}{Q^2r^4} h_2(\eta,Q^2) + \frac{12M^4x^4}{Q^4r^5} g_2(\eta,Q^2) \ ,$$

$$F_3^{\rm TMC}(x,Q^2) = \frac{x}{\eta r^2} F_3^{(0)}(\eta,Q^2) + \frac{2M^2x^2}{Q^2r^3} h_3(\eta,Q^2) + 0 \ ,$$

Nachtmann variable $\eta = \frac{2x}{1+r}$, $r = \sqrt{1 + 4x^2M^2/Q^2}$

- Master formula modular, easy to use!
- Resums leading twist TMC to all orders in $(M^2/Q^2)^n$
- Includes quark masses
- Valid at any order in α_s

Review: 0709.1775

New review almost ready (Nov/Dec2022) with special emphasis on nuclear case!

NuTEV data

TMC important at large x and small Q^2

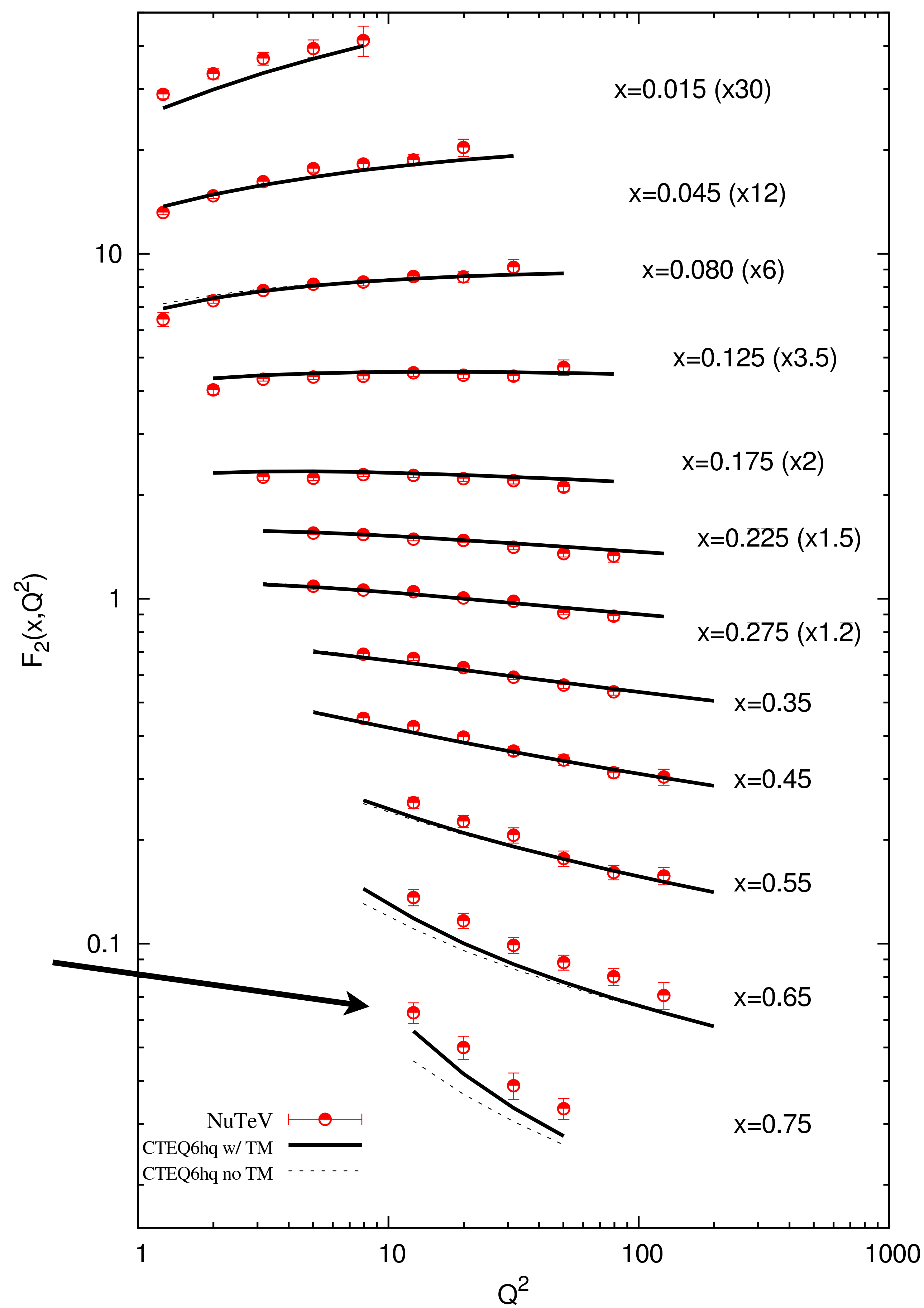


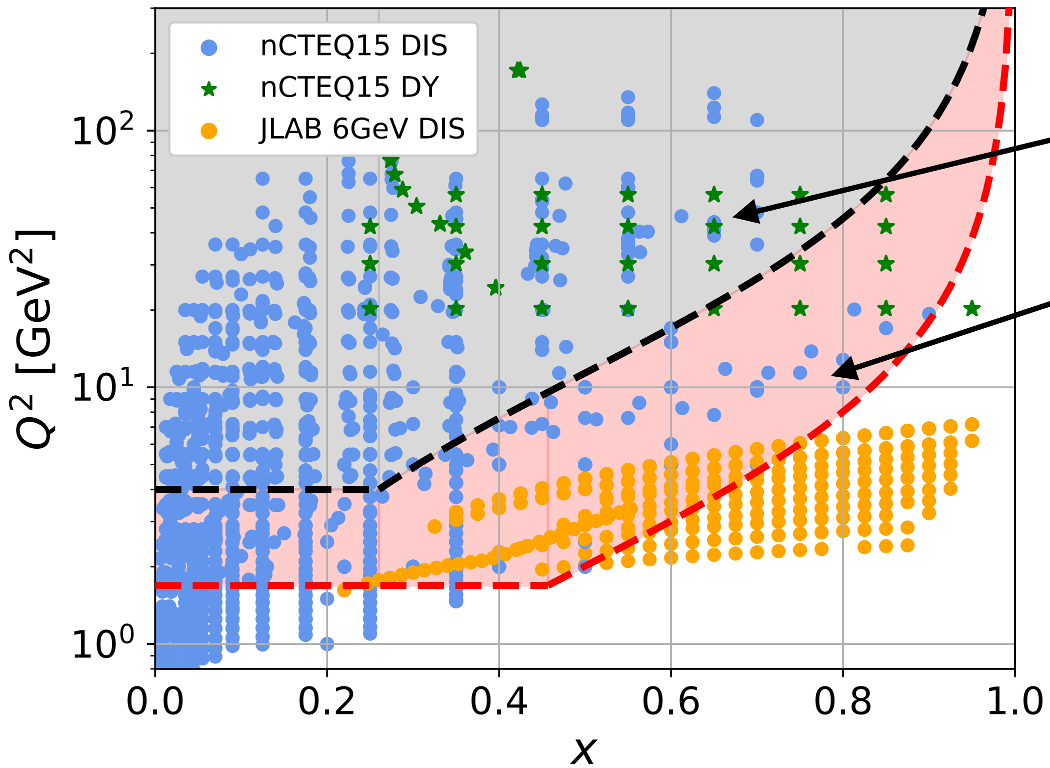
Figure 9. Comparison of the F_2 structure function, with and without target mass corrections, and NuTeV data [64]. The base PDF set is CTEQ6HQ [7].

arXiv: 0709.1775

nCTEQ nPDFs with lower W-cut and JLAB data

arXiv:2012.11566

DIS and DY data entering the analysis



Standard cuts: Q>2 GeV, W>3.5 GeV

This analysis: Q>1.3 GeV, W> 1.7 GeV

Good fit $\chi^2/dof \sim 0.84$
Extension to even smaller W possible

Number of data depending on cuts

Q^2_{cut}	Q_{cut}	W_{cut} No Cut	W_{cut} 1.3	W_{cut} 1.7	W_{cut} 2.2	W_{cut} 3.5
1.3	$\sqrt{1.3}$	1906	1839	1697	1430	1109
1.69	1.3	1773	1706	1564	1307	1024
2	$\sqrt{2}$	1606	1539	1402	1161	943
4	2	1088	1042	952	817	708

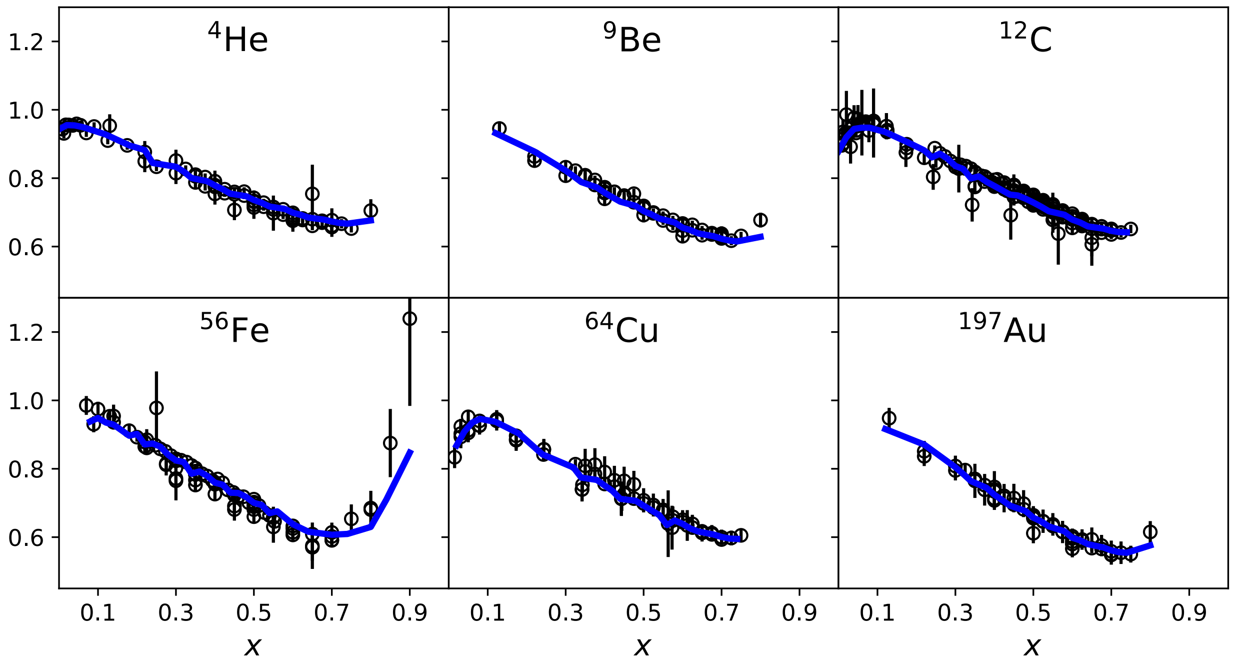
Several effects included

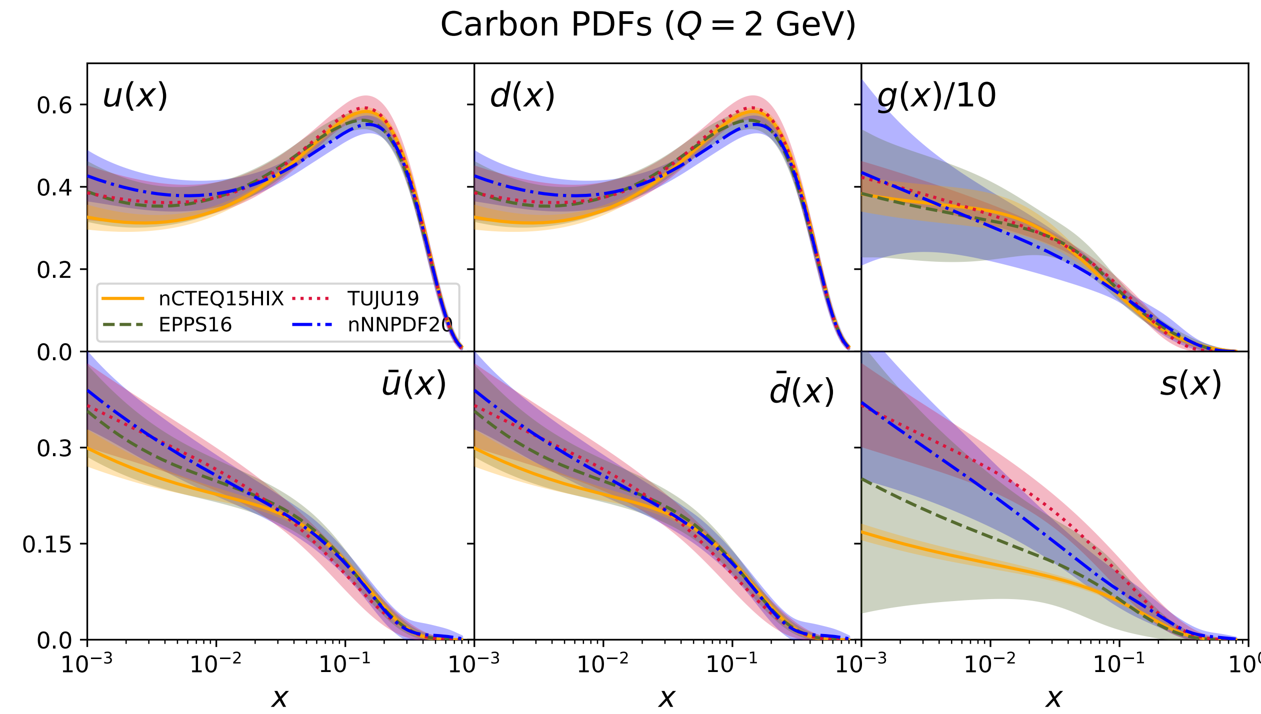
- **Higher Twist**
- **TMC**
- **Deuteron corrections**

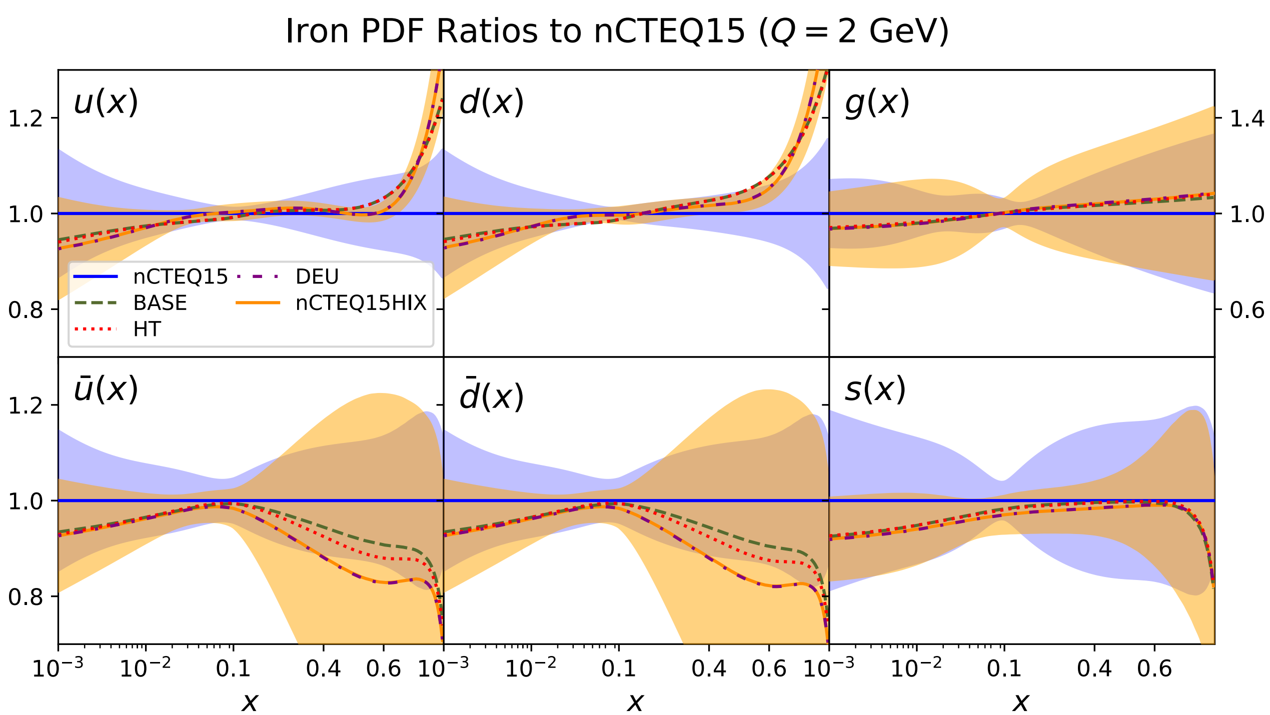
nCTEQ nPDFs with lower W-cut and JLAB data

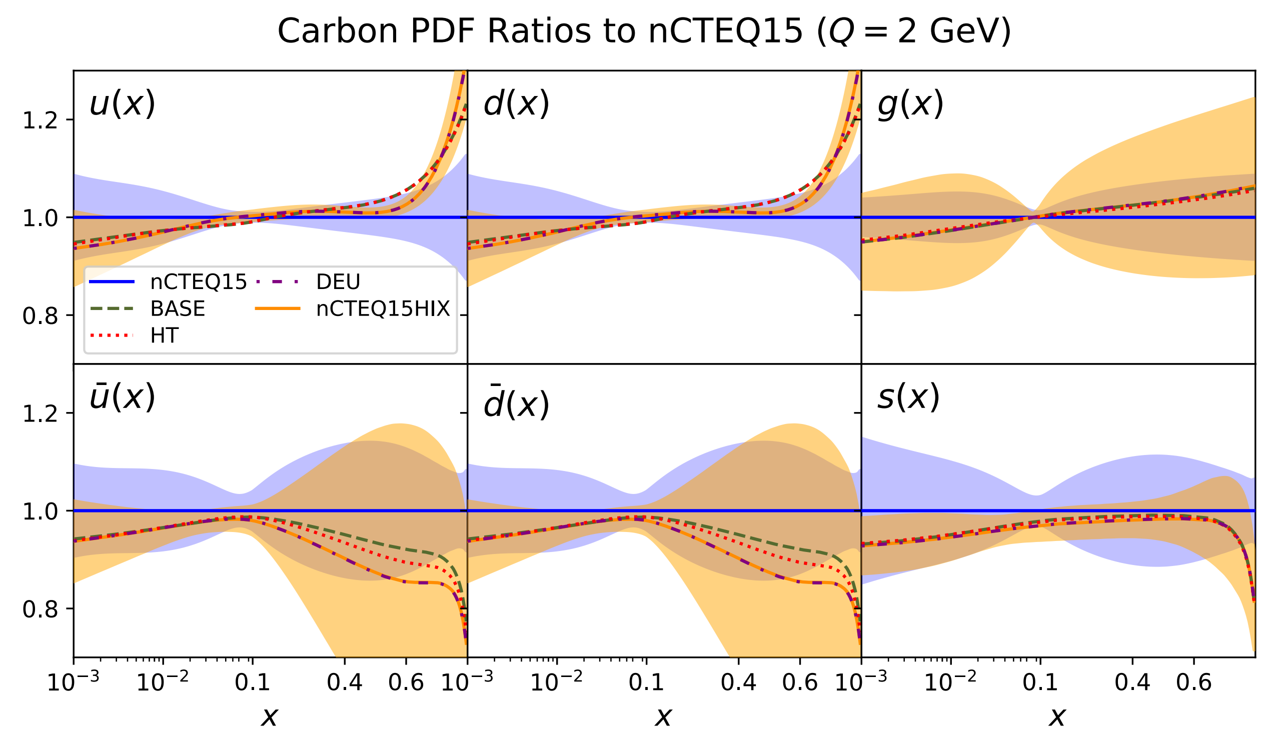
arXiv:2012.11566

$(F_2^A/F_2^D) \times (F_2^D/F_2^p)_{CJ}$ **vs data**





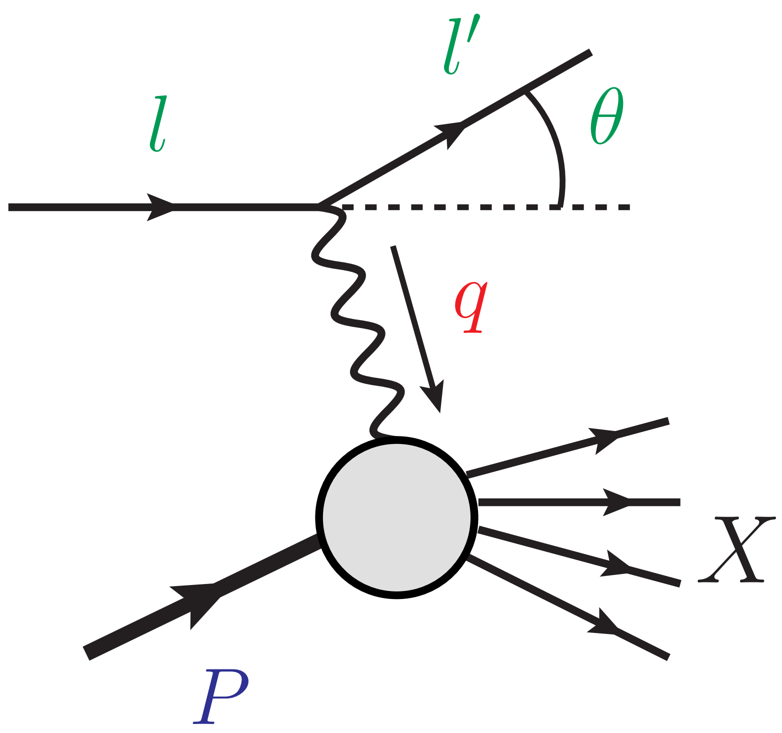




DIS

The cross section for inclusive ep→eX

- Let's consider **inclusive DIS** where a sum over all **hadronic final states X** is performed:



e⁻(l)+N(p) → e⁻(l')+X(p$_X$)

- The amplitude (**A**) is proportional to the interaction of a **leptonic current** (**j**) with a **hadronic current** (**J**):

$$A \sim \frac{1}{q^2} j^\mu J_\mu$$

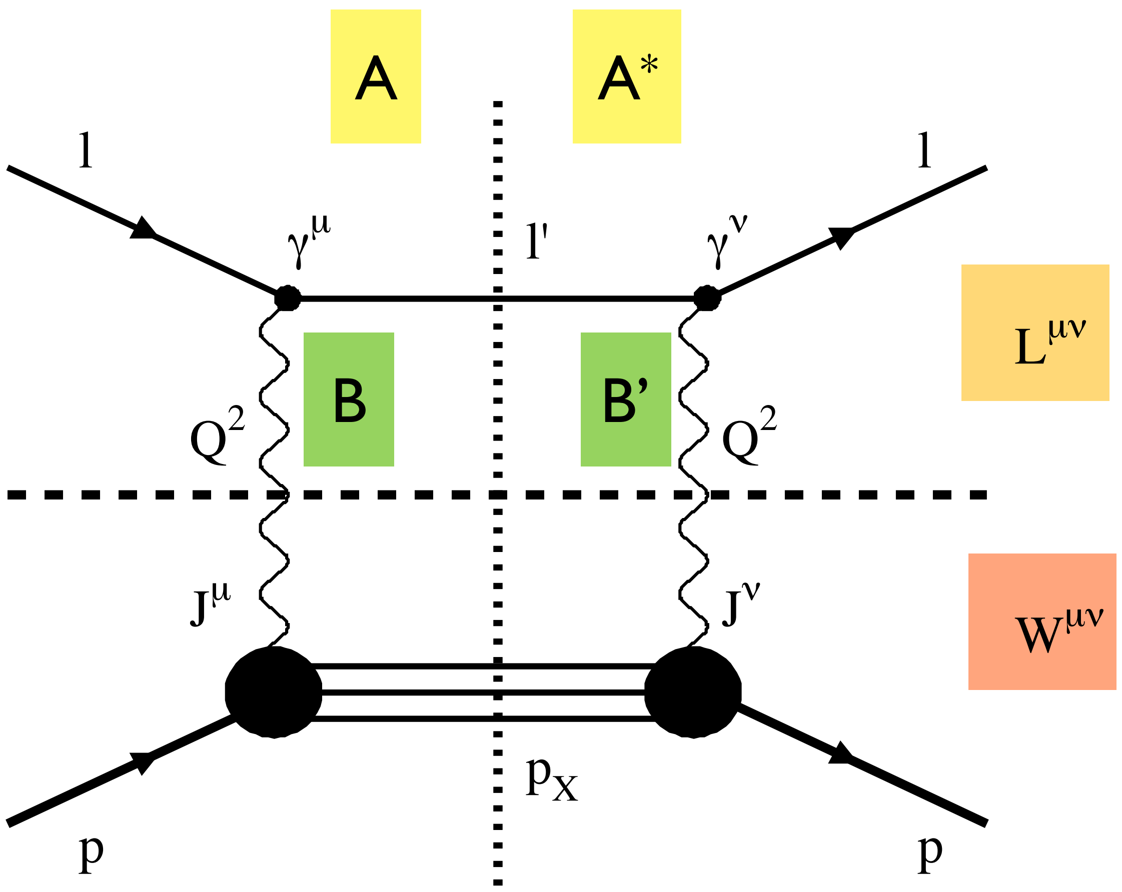
- The leptonic current is well-known perturbatively in QED:

$$j^\mu = \langle l', s_{l'} | \hat{j}^\mu | l, s_l \rangle = \bar{u}(l', s_{l'}) \gamma^\mu u(l, s_l)$$

- The hadronic current is non-pert. and depends on the multi-particle final state over which we sum:

$$J^\mu = \langle X, \text{spins} | \hat{J}^\mu | p, s_p \rangle$$

Cross section for CC and NC DIS



The differential cross section for DIS mediated by interfering gauge bosons **B**,**B'** can be written as:

$$\frac{d^2\sigma}{dxdy} = \sum_{B.B'} \frac{d^2\sigma^{BB'}}{dxdy}$$

- $B, B' \in \{\gamma, Z\}$ in the case of NC DIS
- $B = B' = W$ in the case of CC DIS

$$d\sigma^{BB'} \sim L^{BB'}_{\mu\nu} W^{\mu\nu}_{BB'}$$

Each of the terms **dσ^BB'** can be calculated from the general expression: PDG'17, Eq. (19.2)

$$\frac{d^2\sigma^{BB'}}{dxdy} = \frac{2S^2 y}{(4\pi)^2 F^2}\left[\frac{e^4}{Q^4}\chi_B\chi_{B'} L^{BB'}_{\mu\nu} W^{\mu\nu}_{BB'} 4\pi\right]$$
$$= \frac{4S^2}{F^2}\frac{2\pi\alpha^2}{Q^4} y\chi_B\chi_{B'} L^{BB'}_{\mu\nu} W^{\mu\nu}_{BB'}$$

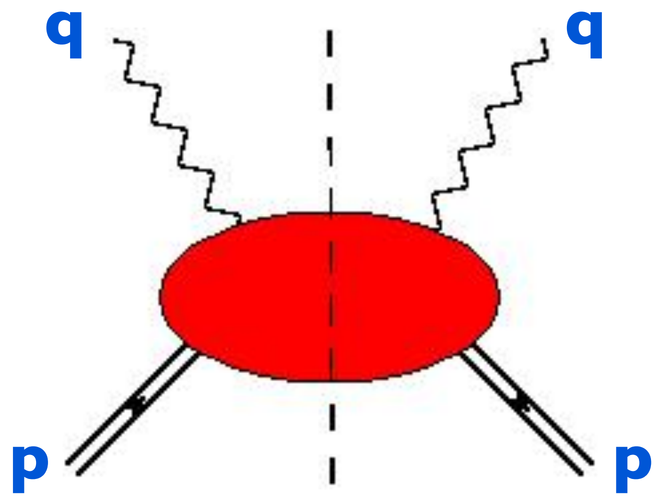
$$\chi_\gamma(Q^2) = 1$$
$$\chi_Z(Q^2) = \frac{g^2}{(2\cos\theta_w)^2 e^2}\frac{Q^2}{Q^2+M_Z^2} = \frac{G_F}{\sqrt{2}}\frac{M_Z^2}{2\pi\alpha}\frac{Q^2}{Q^2+M_Z^2}$$
$$\chi_W(Q^2) = \frac{g^2}{(2\sqrt{2})^2 e^2}\frac{Q^2}{Q^2+M_W^2} = \frac{G_F}{\sqrt{2}}\frac{M_W^2}{4\pi\alpha}\frac{Q^2}{Q^2+M_W^2}$$

The hadronic tensor and structure functions

- $W_{\mu\nu}(p,q)$ <u>cannot</u> be calculated in perturbation theory.
  It parameterizes our ignorance of the nucleon.

- Goal: write down most general covariant expression for $W_{\mu\nu}(p,q)$

- Other symmetries (current conservation, parity, time-reversal inv.) have to be respected as well, depending on the interaction



- All possible tensors using the independent momenta **p, q** and the metric **g** are:

$$g_{\mu\nu}, \quad p_\mu p_\nu, \quad q_\mu q_\nu, \quad p_\mu q_\nu + p_\nu q_\mu,$$
$$\epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma, \quad p_\mu q_\nu - p_\nu q_\mu$$

- For a (spin-averaged) nucleon, the most general covariant expression for $W_{\mu\nu}(p,q)$ is:

$$W^{\mu\nu}(p,q) = -g^{\mu\nu} W_1 + \frac{p^\mu p^\nu}{M^2} W_2 - i\epsilon^{\mu\nu\rho\sigma} \frac{p_\rho q_\sigma}{M^2} W_3 + \frac{q^\mu q^\nu}{M^2} W_4 + \frac{p^\mu q^\nu + p^\nu q^\mu}{M^2} W_5 + \frac{p^\mu q^\nu - p^\nu q^\mu}{M^2} W_6$$

- The structure functions W_i can depend only on the Lorentz-invariants $p^2=M^2$, q^2, and $p.q$

The hadronic tensor and structure functions

$$W^{\mu\nu}(p,q) = -g^{\mu\nu}W_1 + \frac{p^\mu p^\nu}{M^2}W_2 - i\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho q_\sigma}{M^2}W_3 + \frac{q^\mu q^\nu}{M^2}W_4 + \frac{p^\mu q^\nu + p^\nu q^\mu}{M^2}W_5 + \frac{p^\mu q^\nu - p^\nu q^\mu}{M^2}W_6$$

$d\sigma_{|W_4} \sim m_l^2$ $\quad d\sigma_{|W_5} \sim m_l^2$ $\quad d\sigma_{|W_6} = 0$

- Instead of **p.q** use **ν** or **x** as argument: **$W_i = W_i(\nu,q^2)$ or $W_i=W_i(x,Q^2)$**

- **W_6** doesn't contribute to the cross section! No (**$l_\mu q_\nu - l_\nu q_\mu$**) in the leptonic tensor

- **W_4** and **W_5** terms are proportional to the lepton masses squared in the cross section since **$q^\mu L_{\mu\nu} \sim m_l^2$**. Only place where they are relevant is charged current **ν_τ**-DIS.

- Parity and Time reversal symmetry implies **$W_{\mu\nu}=W_{\nu\mu}$**

- **$W_3=0$ and $W_6=0$** for parity conserving currents (like the e.m. current)

CC ν_τ-DIS

Albright, Jarlskog'75
Paschos, Yu'98
Kretzer, Reno'02

$$\frac{d^2\sigma^{\nu(\bar\nu)}}{dx\,dy} = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}\Big\{(y^2 x + \frac{m_\tau^2 y}{2E_\nu M_N})F_1^{W^\pm} + \Big[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{M_N x}{2E_\nu})y\Big]F_2^{W^\pm} \pm \Big[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M_N}\Big]F_3^{W^\pm} + \frac{\mathbf{m_\tau^2(m_\tau^2+Q^2)}}{\mathbf{4E_\nu^2 M_N^2 x}}\mathbf{F}_4^{W^\pm} - \frac{\mathbf{m_\tau^2}}{\mathbf{E_\nu M_N}}\mathbf{F}_5^{W^\pm}\Big\}$$

Albright-Jarlskog relations:

(derived at LO, extended by Kretzer, Reno)

$$F_4 = 0$$

valid at LO $[\mathcal{O}(\alpha_s^0)]$, $M_N = 0$
(even for $m_c \neq 0$)

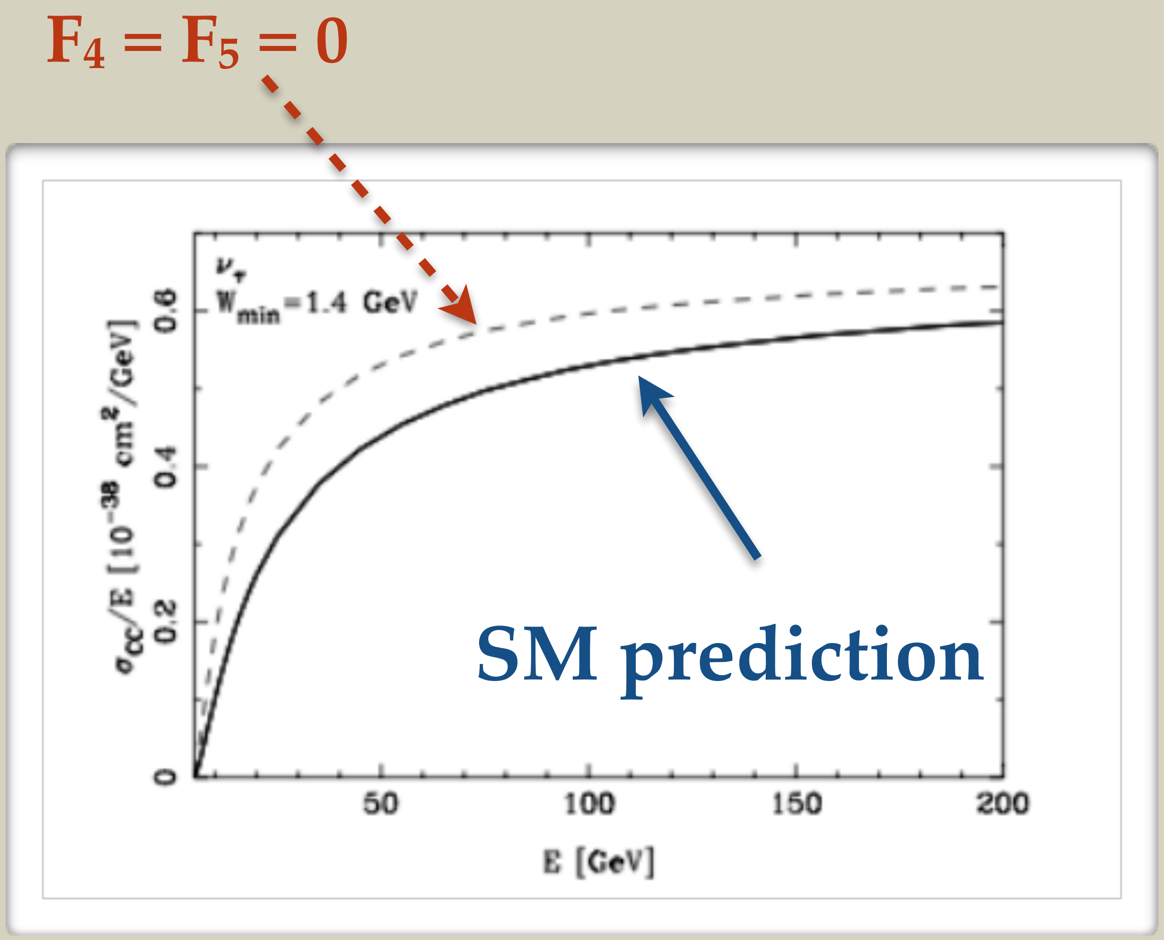
$$F_2 = 2xF_5$$

valid at **all orders** in α_s,
for $M_N = 0$, $m_q = 0$

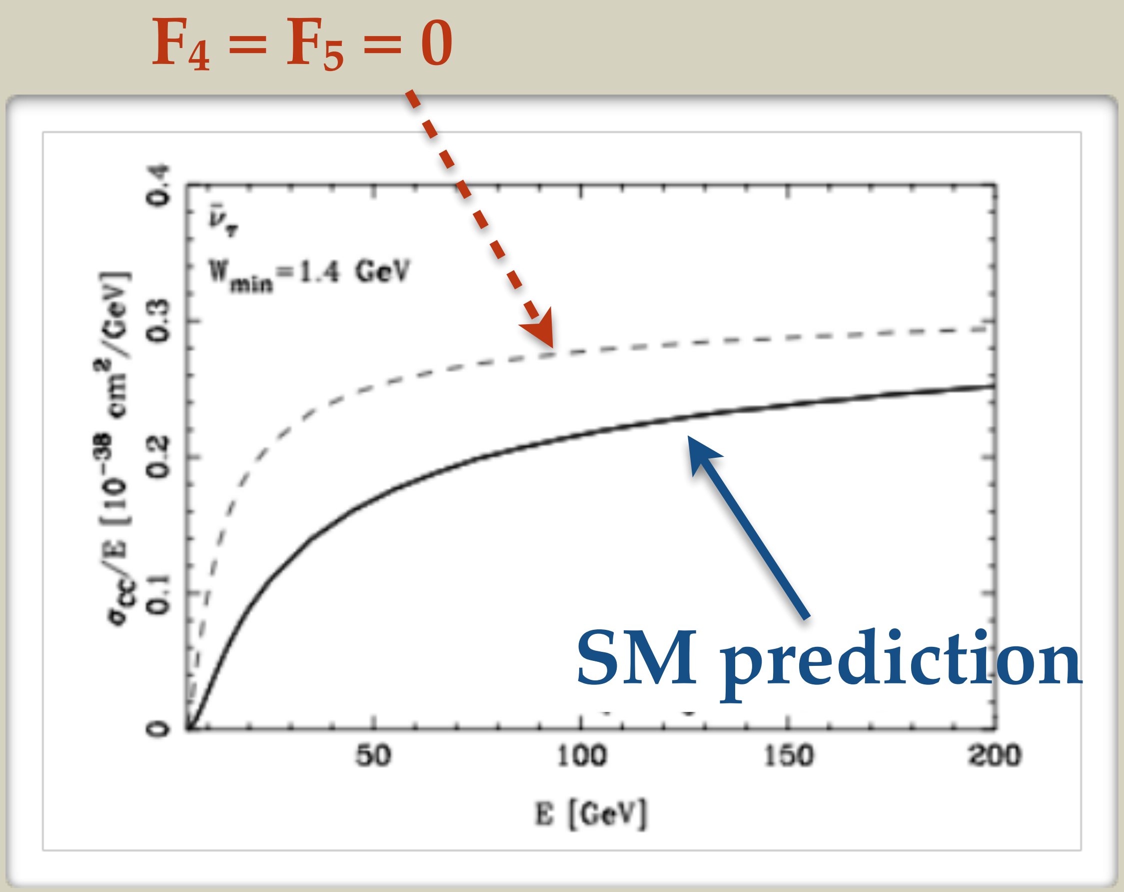
Full NLO expressions $(M_N \neq 0, m_c \neq 0)$: Kretzer, Reno'02

Sensitivity to F_4 and F_5

SHIP proposal, 1504.04855



ν_τ CC DIS cross-section

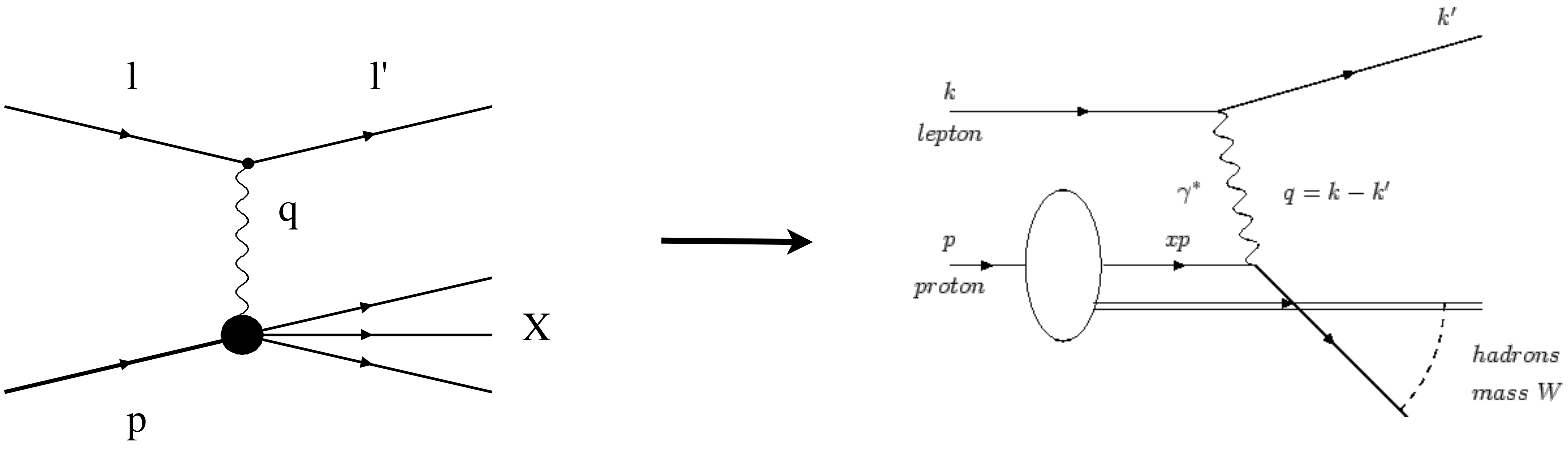


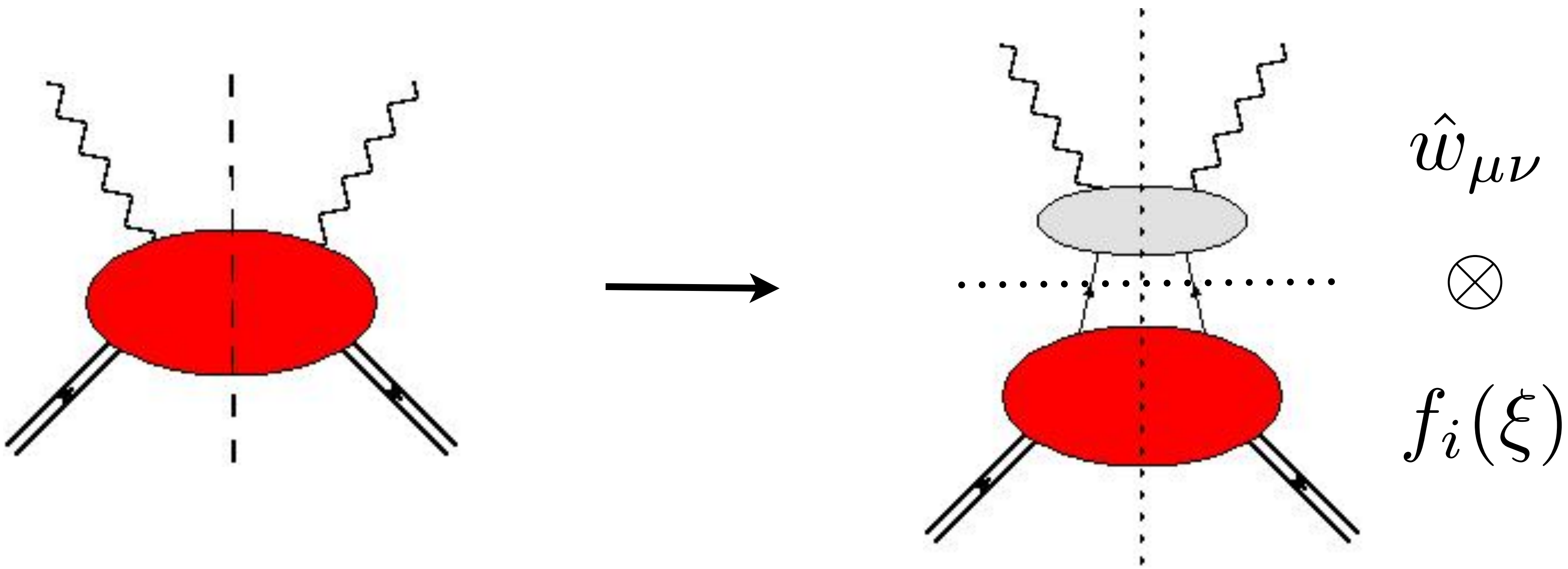
$\bar{\nu}_\tau$ CC DIS cross-section

Hadronic tensor

Two approaches (both factorize short and long distances):

1. Parton Model:

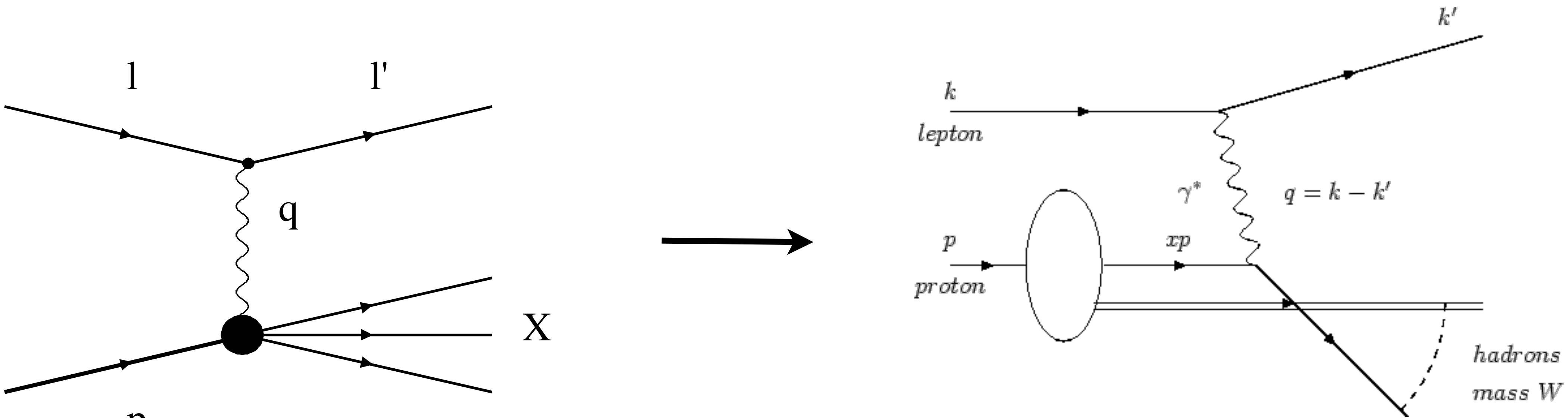


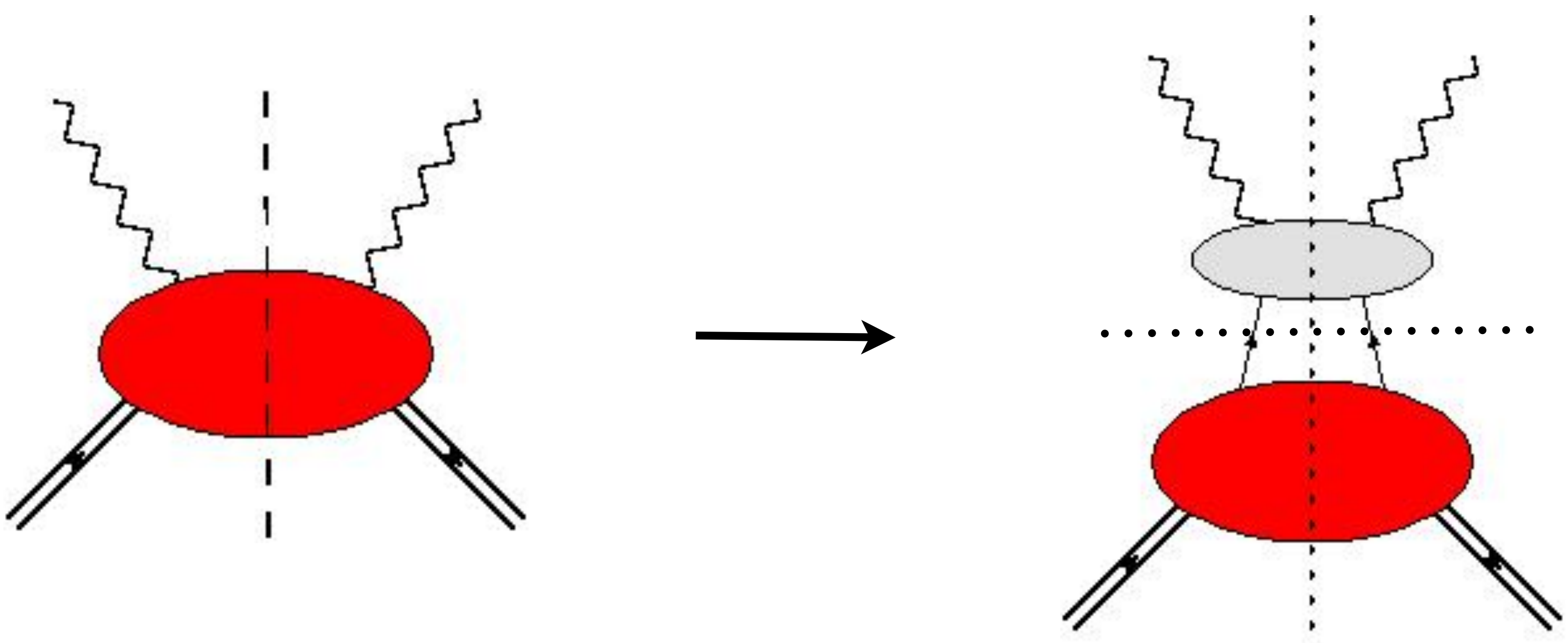


Hadronic tensor

Two approaches (both factorize short and long distances):

1. Parton Model:





$\hat{w}_{\mu\nu}$

$\otimes$

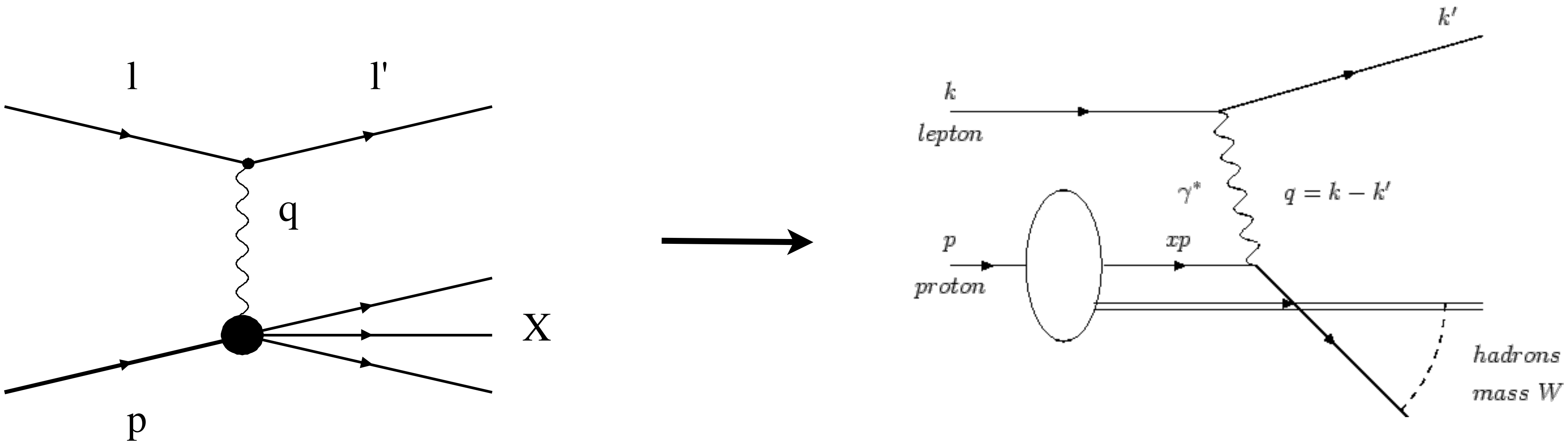
$f_i(\xi)$

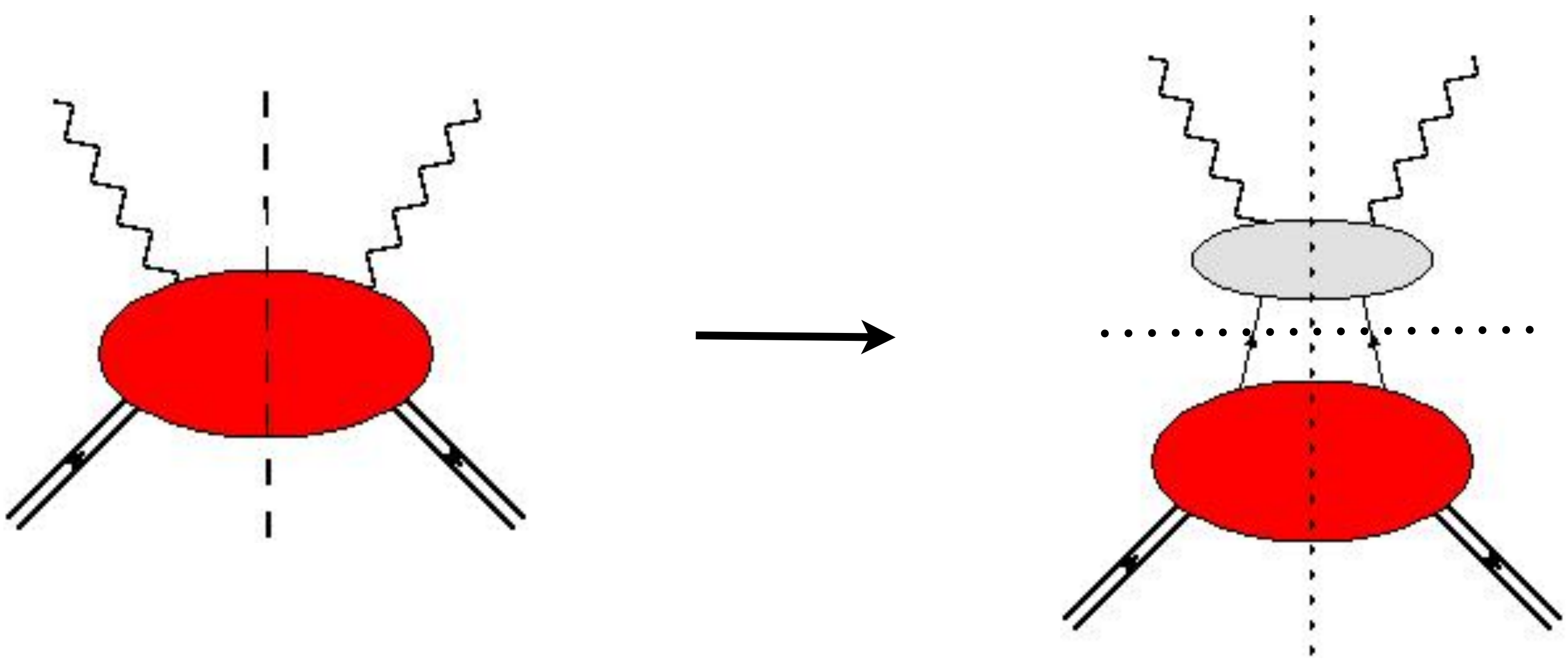
Partonic tensor:
calculable, not IR safe

Hadronic tensor

Two approaches (both factorize short and long distances):

1. Parton Model:





$$\hat{w}_{\mu\nu}$$

$$\otimes$$

$$f_i(\xi)$$

Partonic tensor:
calculable, not IR safe

Parton distribution:
still not calculable,
but **universal**

Hadronic tensor

Two approaches (both factorize short and long distances):

2. Operator Product Expansion (OPE):

a) short distance expansion

$$A(x)B(0) \underbrace{\simeq}_{x_\mu \to 0} \sum_i C_i(x) O_i(x/2)$$

b) light cone expansion

$$A(x/2)B(-x/2) \underbrace{\simeq}_{x^2 \to 0} \sum_{j,i} C_i^{(j)}(x) x^{\mu_1} \cdots x^{\mu_j} O^{(j,i)}_{\mu_1 \cdots \mu_j}(0)$$

Light cone dominance of DIS hadronic tensor

Wilson coefficients

local ops. of definite spin j (symmetric traceless tensors of rank j)

$$C_i^{(j)} \underbrace{\propto}_{x^2 \to 0} (\sqrt{x^2})^{d_{j,i} - j - d_A - d_B}$$

Light cone ops. with lowest twist dominate!

twist = dimension - spin

OPE

Operator product expansion

$$\int d^4x \; e^{iq\cdot x} \langle N|T(J^\mu(x)J^\nu(0))|N\rangle$$

$$= \sum_k \left(-g^{\mu\nu}q^{\mu_1}q^{\mu_2} + g^{\mu\mu_1}q^\nu q^{\mu_2} + q^\mu q^{\mu_1} g^{\nu\mu_2} + g^{\mu\mu_1}g^{\nu\mu_2}Q^2\right)$$

$$\times q^{\mu_3}\cdots q^{\mu_{2k}} \frac{2^{2k}}{Q^{4k}} A_{2k}\Pi_{\mu_1\cdots\mu_{2k}}$$

$$\langle N|\mathcal{O}_{\mu_1\cdots\mu_{2k}}|N\rangle$$

local operators

Georgi, Politzer (1976)

$$\Pi_{\mu_1\cdots\mu_{2k}} = p_{\mu_1}\cdots p_{\mu_{2k}} - (g_{\mu_i\mu_j} \text{ terms})$$

$$= \sum_{j=0}^{k}(-1)^j \frac{(2k-j)!}{2^j(2k)^j} g\cdots g \; p\cdots p$$

traceless, symmetric
rank-$2k$ tensor

From nucleons to nuclei

The following discussion will be part of
A new review of Target Mass Corrections
With particular focus on nuclear targets
(to appear in Nov/Dec 2022)

Nuclear modifications

- Neutrino experiments use heavy nuclear targets:
  Pb, Fe, Ar, H_2O, C

- As discovered more than 30 years ago by the European Muon Collaboration, nucleon structure functions are modified by the nuclear medium (EMC effect)

- Studies of nucleon structure: need to correct for nuclear effects

- Nuclear effects interesting in its own right!

  - Many models exist.

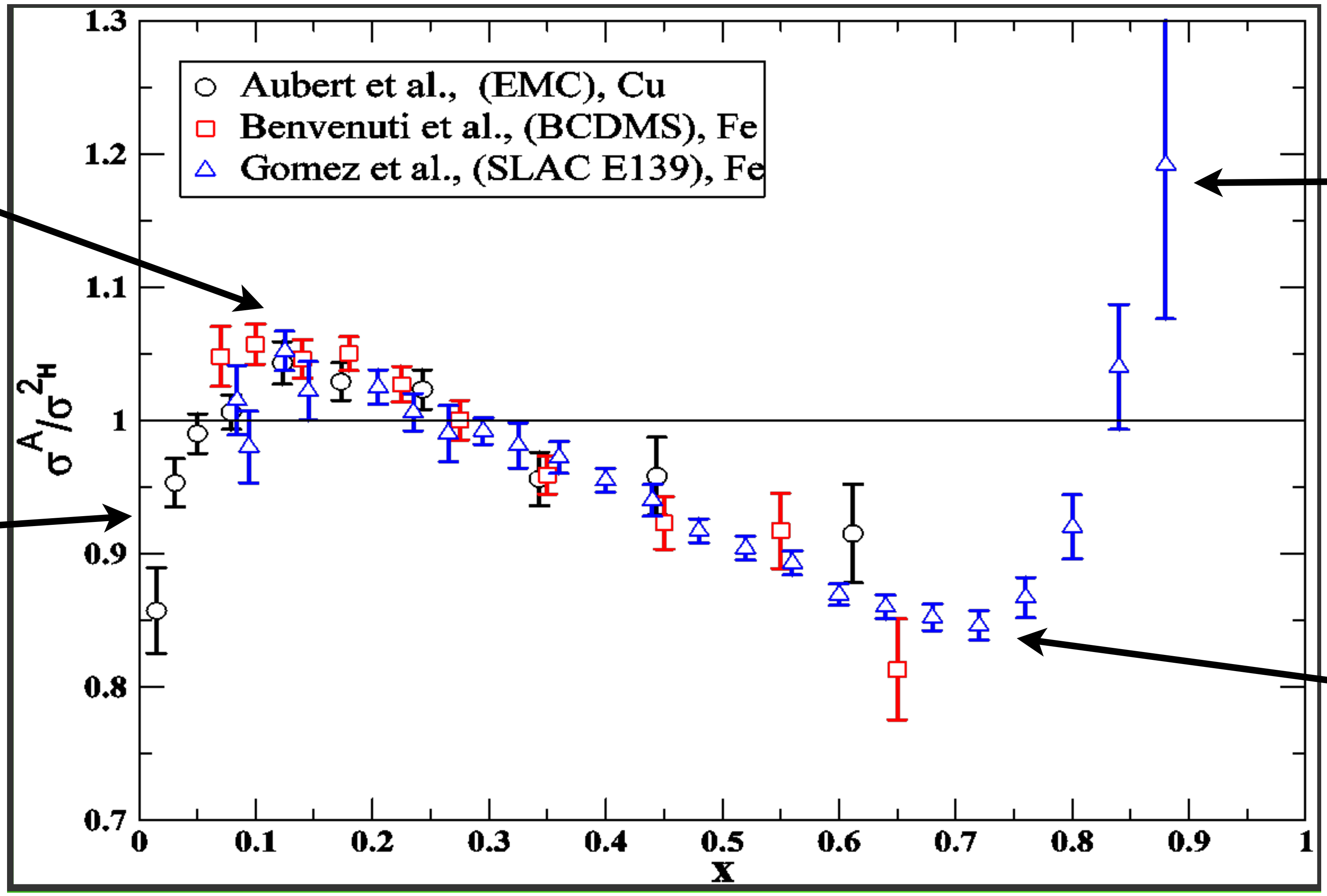
  - However, charged lepton nuclear effects still not fully explained, in particular the EMC effect ($0.3 < x < 0.7$)

The EMC effect

$$F_2^A(x) \neq ZF_2^p(x) + NF_2^n(x)$$

Anti-shadowing enhancement

Shadowing suppression at small x



Rise due to Fermi motion

EMC effect

DIS on a nuclear target

Consider deep inelastic lepton–nucleon collisions: $l(k) + A(p_A) \to l'(k') + X$

Introduce the usual DIS variables: $q \equiv k - k'$, $\quad Q^2 \equiv -q^2$, $\quad x_A \equiv \frac{Q^2}{2p_A \cdot q}$

Hadronic tensor: $W^A_{\mu\nu} \propto \langle A(p_A)|\ J_\mu J^\dagger_\nu\ |A(p_A)\rangle = \sum_i\ a^{(i)}_{\mu\nu}\ \tilde{F}^A_i(x_A, Q^2)$,
where $a^{(i)}_{\mu\nu}$ are Lorentz-tensors composed out of the 4-vectors q and p_A and the metric $g_{\mu\nu}$

Express structure functions in the QCD improved parton model in terms of NPDFs

$$\tilde{\mathcal{F}}^A_k(x_A, Q^2) = \int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A}\ \tilde{f}^A_i(y_A, Q^2) C_{k,i}(x_A/y_A) + \tilde{\mathcal{F}}^{A,\tau\geq 4}_k(x_A, Q^2)$$

NPDFs: Fourier transforms of matrix elements of twist-two operators composed out of the quark and gluon fields:

$$\tilde{f}^A_i(x_A, Q^2) \propto \langle A(p_A)|\ O_i\ |A(p_A)\rangle$$

Definitions of $\tilde{F}^A_i(x_A, Q^2)$, $\tilde{f}^A_i(x_A, Q^2)$, and the varibale $0 < x_A < 1$ carry over one-to-one from the well-known free nucleon case

Evolution Equations and Sum Rules

DGLAP as usual:

$$\frac{\mathrm{d}\tilde{f}_i^A(x_A,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A} P_{ij}(y_A)\, \tilde{f}_j^A(x_A/y_A,Q^2)\ ,$$
$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A} P_{ij}(x_A/y_A)\, \tilde{f}_j^A(y_A,Q^2)\ ,$$

Sum rules:

$$\int_0^1 \mathrm{d}x_A\, \tilde{u}_v^A(x_A,Q^2) = 2Z+N\ ,$$
$$\int_0^1 \mathrm{d}x_A\, \tilde{d}_v^A(x_A,Q^2) = Z+2N\ ,$$

B cons.: 1/3 <u_v> + <d_v> = A

C cons.: 2/3 <u_v> - 1/3 <d_v> = Z

and the momentum sum rule

$$\int_0^1 \mathrm{d}x_A\, x_A\, \left[\tilde{\Sigma}^A(x_A,Q^2)+\tilde{g}^A(x_A,Q^2)\right] = 1\ ,$$

where $N = A - Z$ and $\tilde{\Sigma}^A(x_A) = \sum_i(\tilde{q}_i^A(x_A)+\tilde{\bar{q}}_i^A(x_A))$ is the quark singlet combination

Rescaled definitions!

Problem: average momentum fraction carried by a parton $\propto A^{-1}$
since there are 'A-times more partons' which have to share the momentum

- Different nuclei (A, Z) not directly comparable
- Functional form for x-shape would change drastically with A
- Need to rescale!

PDFs are number densities: $\tilde{f}_i^A(x_A)\,\mathrm{d}x_A$ is the number of partons carrying a momentum fraction in the interval $[x_A, x_A + \mathrm{d}x_A]$

Defi ne rescaled NPDFs $f_i^A(x_N)$ with $0 < x_N := Ax_A < A$:

$$\boxed{f_i^A(x_N)\,\mathrm{d}x_N := \tilde{f}_i^A(x_A)\,\mathrm{d}x_A}$$

The variable x_N can be interpreted as parton momentum fraction w.r.t. the **average** nucleon momentum $\bar{p}_N := p_A/A$

Rescaled evolution equations and sum rules

Evolution:

$$\frac{\mathrm{d}f_i^A(x_N, Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N/A}^{1}\frac{\mathrm{d}y_A}{y_A}\,P(y_A)\,f_i^A(x_N/y_A, Q^2)\,,$$
$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{A}\frac{\mathrm{d}y_N}{y_N}\,P(x_N/y_N)\,f_i^A(y_N, Q^2)\,.$$

Assume that $f_i^A(x_N) = 0$ for $x_N > 1$, then **original, symmetrical** form recovered:

$$\frac{\mathrm{d}f_i^A(x_N, Q^2)}{\mathrm{d}\ln Q^2} = \begin{cases} \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{1}\frac{\mathrm{d}y_N}{y_N}\,P(y_N)\,f_i^A(x_N/y_N, Q^2) & : 0 < x_N \leq 1 \\ 0 & : 1 < x_N < A, \end{cases}$$

Sum rules for the rescaled PDFs:

$$\int_0^A \mathrm{d}x_N\, u_v^A(x_N) = 2Z + N\,,$$
$$\int_0^A \mathrm{d}x_N\, d_v^A(x_N) = Z + 2N\,,$$

and

$$\int_0^A \mathrm{d}x_N\, x_N\left[\Sigma^A(x_N) + g^A(x_N)\right] = A\,,$$

Rescaled structure functions

The rescaled structure functions can be defi ned as

$$x_N \mathcal{F}_i^A(x_N) := x_A \tilde{\mathcal{F}}_i^A(x_A) \ ,$$

with $\mathcal{F}_{1,2,3}(x) = \{F_1(x), F_2(x)/x, F_3(x)\}$.

More explicitly:

$$\begin{aligned} F_2^A(x_N) &:= \tilde{F}_2^A(x_A) \ , \\ x_N F_1^A(x_N) &:= x_A \tilde{F}_1^A(x_A) \ , \\ x_N F_3^A(x_N) &:= x_A \tilde{F}_3^A(x_A) \ . \end{aligned}$$

This leads to consistent results in the parton model using the rescaled PDFs.

Consistent also for the target mass corrected structure functions!

Effective PDFs of bound nucleons

Further decompose the NPDFs $f_i^A(x_N)$ in terms of effective parton densities for **bound** protons, $f_i^{p/A}(x_N)$, and neutrons, $f_i^{n/A}(x_N)$, inside a nucleus A:

$$f_i^A(x_N, Q^2) = Z\, f_i^{p/A}(x_N, Q^2) + N\, f_i^{n/A}(x_N, Q^2)$$

- The bound proton PDFs have the **same** evolution equations and sum rules as the free proton PDFs **provided** we neglect any contributions from the region $x_N > 1$
- Neglecting the region $x_N > 1$, is consistent with the DGLAP evolution
- The region $x_N > 1$ is expected to have a minor influence on the sum rules of less than one or two percent (see also [PRC73(2006)045206])
- Isospin symmetry: $u^{n/A}(x_N) = d^{p/A}(x_N)$, $d^{n/A}(x_N) = u^{p/A}(x_N)$

An observable $\mathcal{O}^A$ is then given by:

$$\mathcal{O}^A = Z\, \mathcal{O}^{p/A} + N\, \mathcal{O}^{n/A}$$

In conclusion: the free proton framework can be used to analyse nuclear data

nCTEQ activities and neutrino DIS

nCTEQ collaboration

- **nCTEQ** is part of **CTEQ** (The Coordinated Theoretical-Experimental Project on QCD)
- Devoted to understanding **QCD** at the **interface between nuclear and particle physics**:
  - Understand **nuclei** in terms of **quark and gluon degrees of freedom**
  - Understand **nuclear corrections** needed to use nuclear data in **studies of nucleon structure**
- Webpage: https://ncteq.hepforge.org/

nCTEQ
nuclear parton distribution functions

nCTEQ collaboration

- **Initiated in 2006** by **Fred Olness**, **IS** and **Ji-Young Yu** (**SMU Dallas**) joined by the CTEQ members **C. Keppel** (**Hampton Univ./JLAB**), **J. G. Morfin** (**FNAL**), and **J. Owens** (**Florida State Univ.**)

- **Members in 2022** (* have left the field):

  - **SMU Dallas**: F. Olness (CTEQ), B. Clark*, E. Godat*, F. Lyonnet*

  - **FNAL**: J. G. Morfin (CTEQ), T. J. Hobbs

  - **FSU**: Jeff Owens (CTEQ)

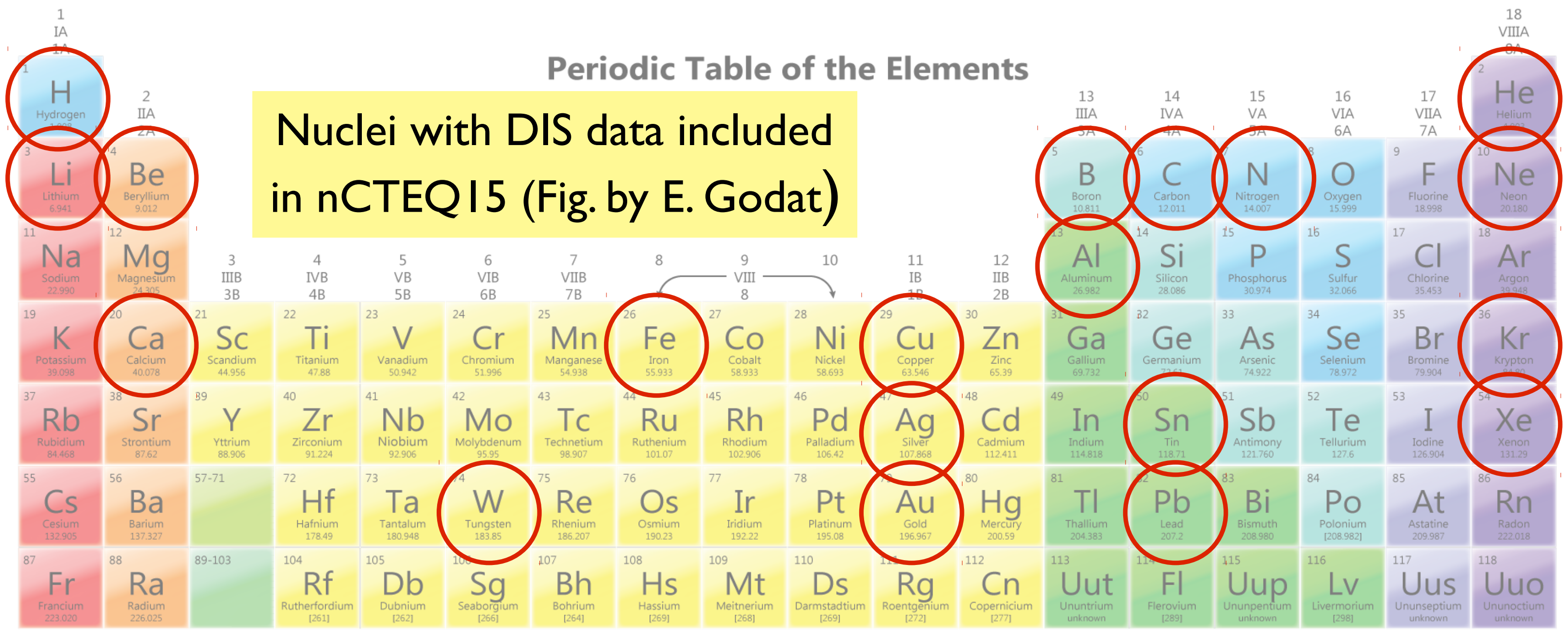
  - **LPSC Grenoble:** I. Schienbein (CTEQ), Ji-Young Yu, Chloé Léger

  - **JLAB**: C. Keppel (CTEQ)

  - **INP Krakow**: A. Kusina, Richard Ruiz

  - **Univ. Münster**: M. Klasen (CTEQ), K. Kovarik (CTEQ), T. Jezo, Pit Duwentáster, Khairol Faik Muzakka, Peter Risse

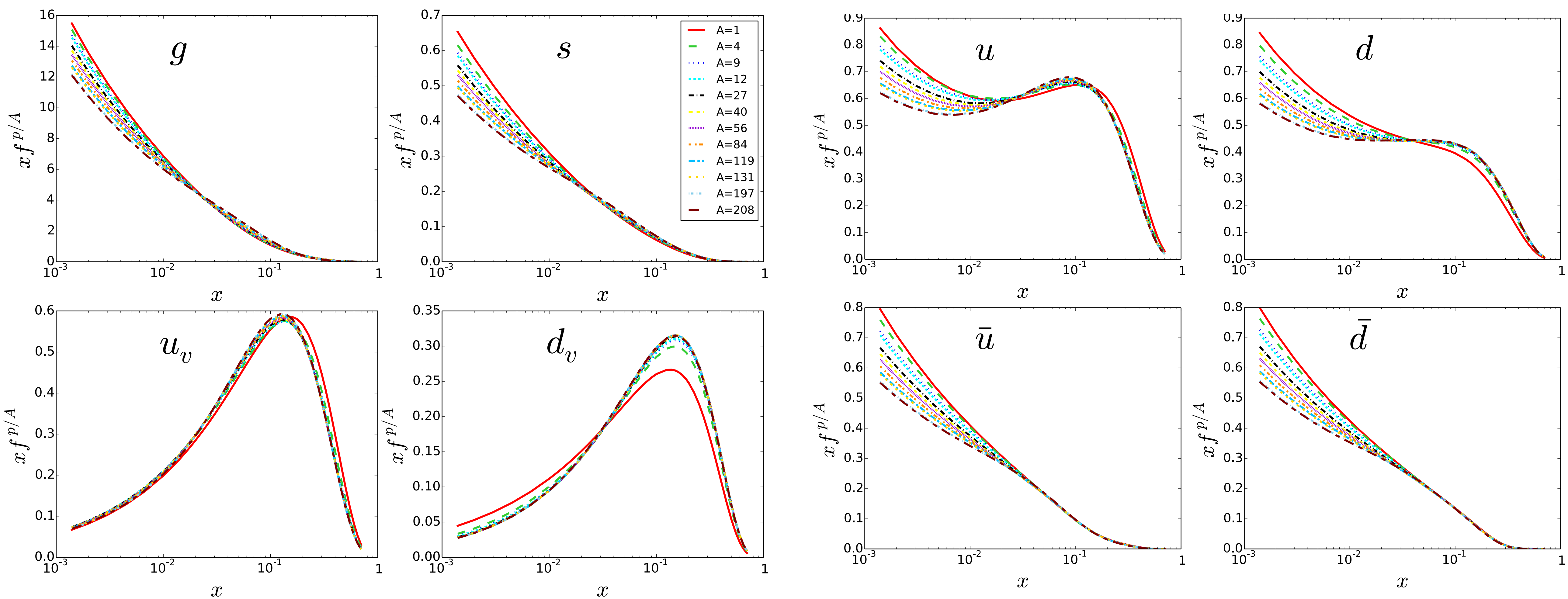
A- and x-dependence of the partonic structure



- Fundamental quest
- New data from LHC, EIC, AFTER@LHC, etc. will allow for a refined parametrization; zoom in on high-x region
- Ultimately, fits to lead only (or other targets); no need to combine different A in one analysis

nCTEQ15, arXiv:1509.00792

$$x f_i^{p/A}(x, Q_0) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$



Theoretical Framework (pQCD formalism)

Factorization Theorems:

- Provide (field theoretical) **definitions** of the **universal** PDFs
- Make the formalism **predictive**!
- Make a statement about the **error** of the factorization formula

PDFs and predictions for **observables+uncertainties** **refer to this standard pQCD framework**

Need a solid understanding of the standard framework!

- For pp and ep collisions there a **rigorous factorization proofs**
- For pA and AA factorization is a **working assumption** to be tested phenomenologically

  There might be breaking of QCD factorization, deviations from DGLAP evolution, other nuclear matter effects to be included

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Global analysis of nuclear PDFs

Same approach as for proton PDF determinations

1. Boundary conditions:
   Parameterize x-dependence of PDFs at initial scale Q_0

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

2. Evolve from Q_0 to Q solving the DGLAP evolution equations: $f(x,Q)$

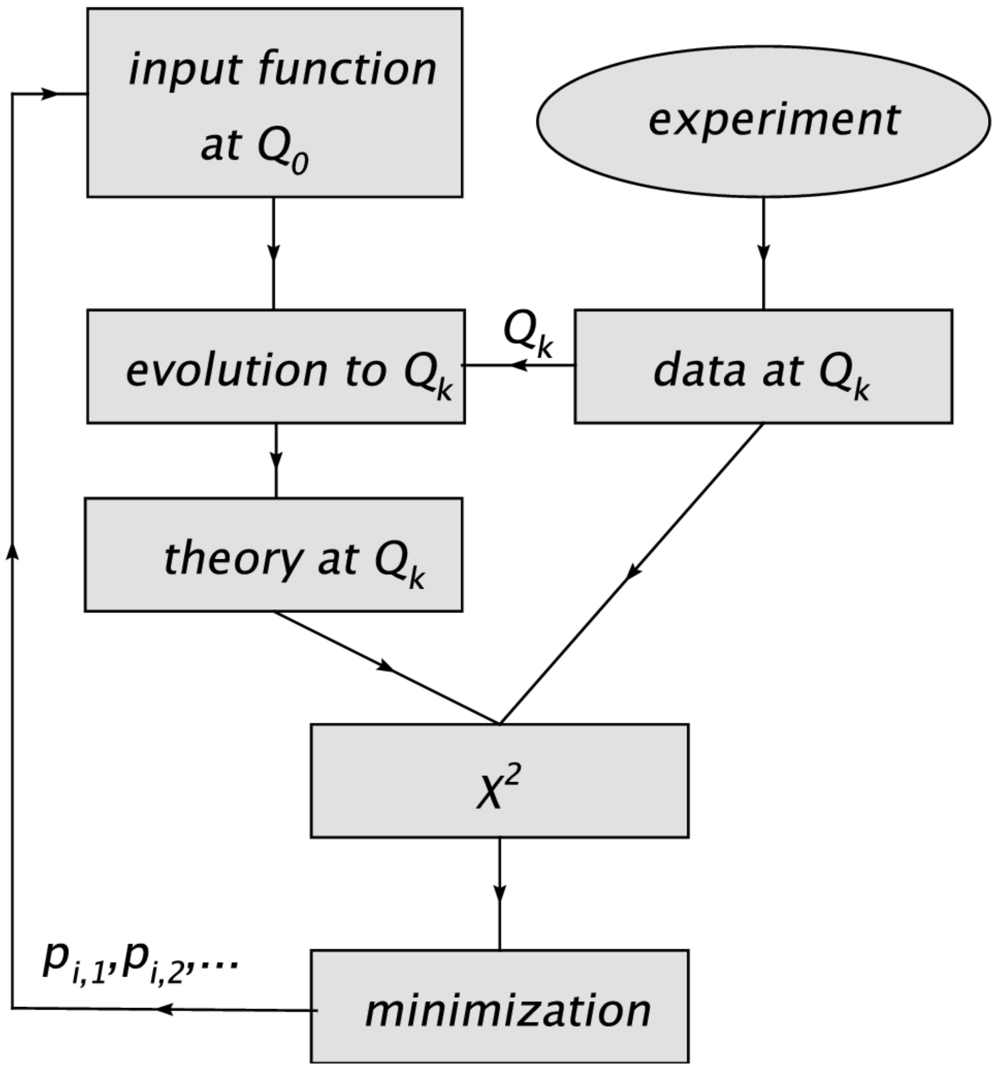
3. Define suitable χ^2 function and minimize w.r.t. fit parameters

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

Sum over experiments

Sum over data points

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



nCTEQ topics

nCTEQ nuclear PDFs:

- **Fundamental quest**: determine x- and A-dependence of quark and gluon PDFs in a variety of nuclei
- First global analysis of charged lepton DIS + DY data: PRD80(2009)094004
  - Combine data for many nuclear A: simple parameterisation of A-dependence
- Global analysis of nCTEQ15 nuclear PDFs: PRD93(2016)085037
  - Data: lA DIS, DY, RHIC pi^0 data
  - Hessian analysis of PDF uncertainties

nCTEQ topics

nCTEQ nuclear PDFs:

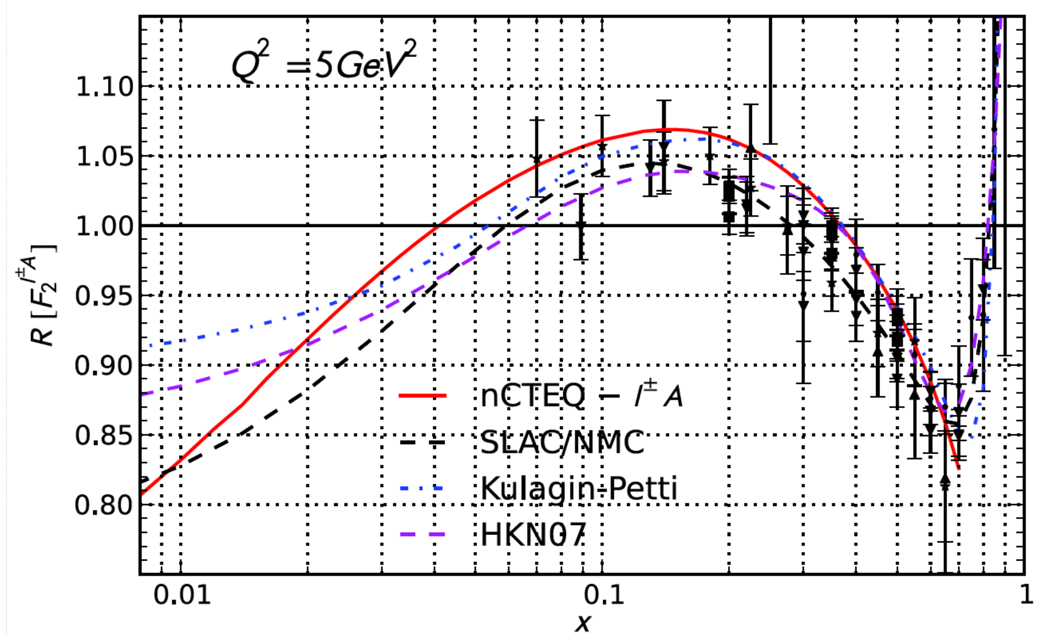
- **Preparation of next global release** (**nCTEQ2023**)
  - Performed detailed analysis of neutrino DIS data Next global analysis use (CHORUS+Dimuon data) **[2204.13157]**
  - LHC heavy quark data (gluon) **[2204.09982]**
  - Inclusion hadron production data (gluon) **[2105.09873]**
  - Explored lower W and Q-cuts using JLAB data **[2012.11566]**
  - LHC W/Z production data **[2007.09100]**
  - New review of Target Mass Corrections **[Nov/Dec 2022]**

nCTEQ topics

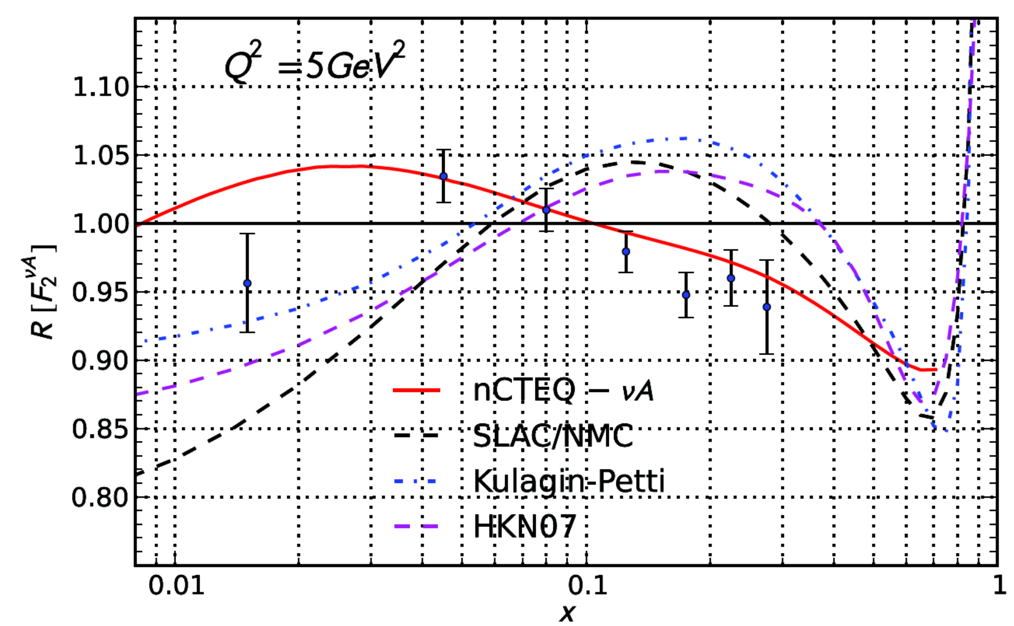
Neutrino deep inelastic scattering:

- Neutrino data important for many reasons: flavour separation of PDFs, ew precision physics, …
- Are nuclear corrections in neutrino DIS the same as in charged lepton DIS?
- Several studies have been performed:
  - “iron PDFs: PRD77(2008)054013
  - nCTEQ analysis of nuA+lA+DY data: PRL106(2011)122301
  - Differences independent of the proton baseline: Kalantarians, Keppel, PRC96(2017)032201

Fit to $l^{\pm}A$ DIS and DY data
$\chi^2/\mathrm{dof} = 0.89$



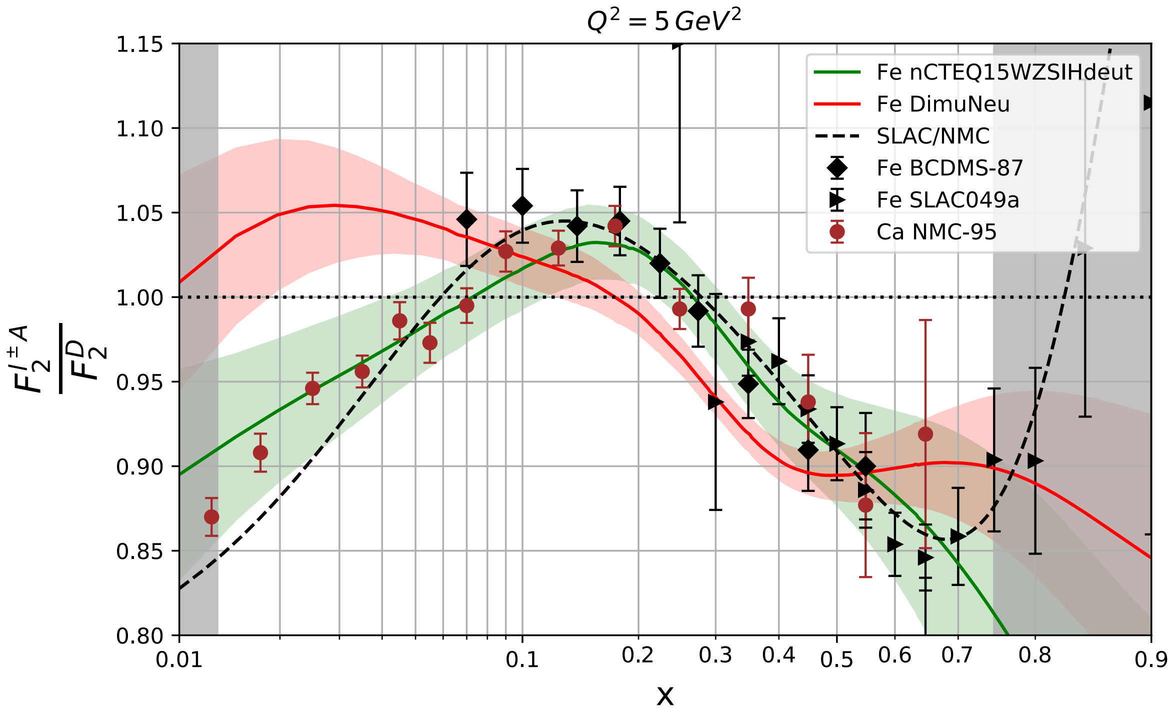
Fit to νA DIS data only
$\chi^2/\mathrm{dof} = 1.33$



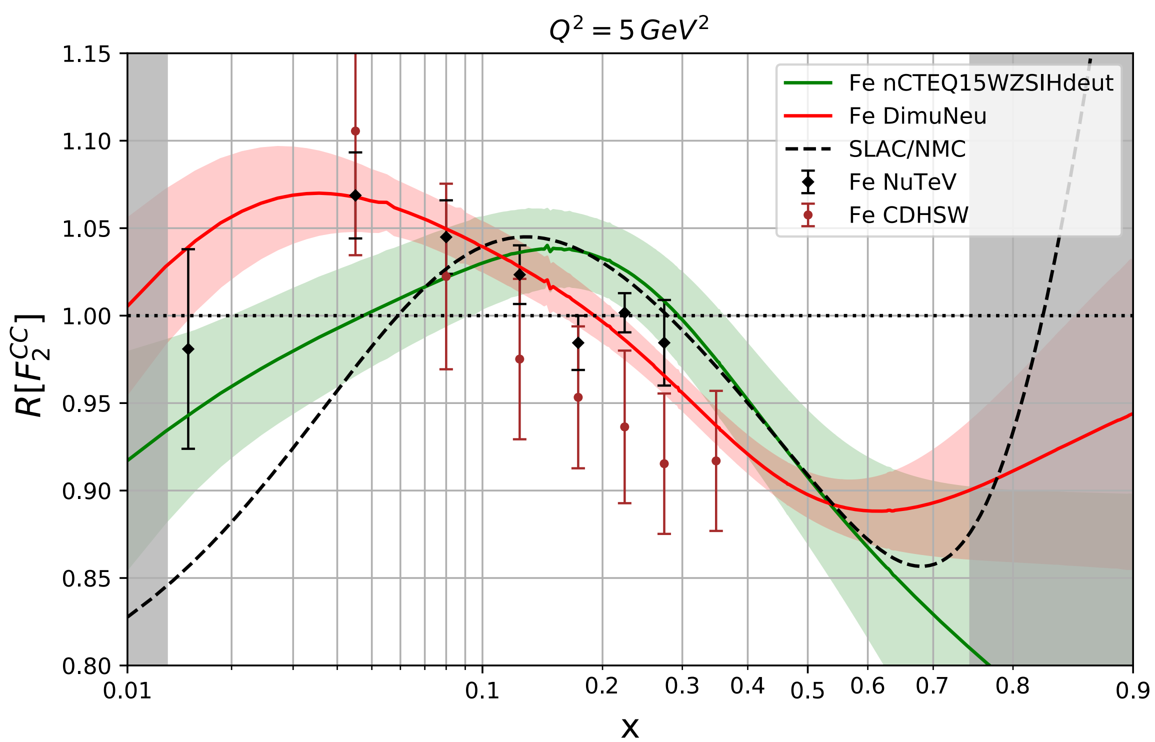
Neutrino DIS vs Charged lepton DIS

Ultimate analysis: " Compatibility of Neutrino DIS data and Its Impact on Nuclear Parton Distribution Functions", arXiv:2204.13157

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.	Ref.
CDHSW ν	Fe	23 - 188	465	No	[48]
CDHSW $\bar{\nu}$			464		
CCFR ν	Fe	35 - 340	1109	No	[50]
CCFR $\bar{\nu}$			1098		
NuTeV ν	Fe	35 - 340	1170	Yes	[23]
NuTeV $\bar{\nu}$			966		
Chorus ν	Pb	25 - 170	412	Yes	[27]
Chorus $\bar{\nu}$			412		
CCFR dimuon ν	Fe	110 - 333	40	No	[19]
CCFR dimuon $\bar{\nu}$		87 - 266	38		
NuTeV dimuon ν	Fe	90 - 245	38	No	[19]
NuTeV dimuon $\bar{\nu}$		79 - 222	34		



- Most thorough analysis so far (thesis K. F. Muzak, U Münster): different tools to analyse compatibility of data
- Neutrino data creates significant tensions between key data sets: neutrino vs charged lepton+DY+LHC
- Tensions among different neutrino data sets: iron (CDHSW, NuTeV, CCFR) vs lead (CHORUS)?
- Next global analysis will include CHORUS and Di-muon data but not NuTeV, CCFR, CDHSW data



nCTEQ topics

Paper in collaboration with Or Hen and students soon to appear

- Work on SRC in the context of a global analysis (new SRC based parameterisation of the nPDFs)
- More work on Neutrinos planned in view of DUNE
  - Revisit our calculations for QE and RES
  - Extend nPDF analyses in the resonance region
  - Matching between RES and DIS
  - Matching between shallow inelastic and deep inelastic region
  - Comparison with low energy cross section data
- Collaborations with nuclear theorists on neutrino interactions for DUNE very welcome

Backup

Electroweak precision tests

QCD for PW-style analysis

$$R^- = \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} \simeq \frac{1}{2} - s_w^2 + \delta R^-_A + \delta R^-_{QCD} + \delta R^-_{EW}$$

- δR^-_A: non-isoscalarity of the target
- δR^-_{QCD}: QCD effects
- δR^-_{EW}: higher order ew effects

$$\delta R^-_{QCD} = \delta R^-_s + \delta R^-_I + \delta R^-_{NLO}$$

- δR^-_s: due to strangeness asymmetry: $s^- \equiv s - \bar{s} \neq 0$
- δR^-_I: due to isospin violation: $u^p(x) \neq d^n(x)$
- δR^-_{NLO}: higher order QCD effects

see, e.g., hep-ph/0405221

Quasi-Elastic Scattering

Charged Current (CC) in a nutshell

Matrix element [1]

$$\mathcal{M} = \frac{ig^2\cos\theta_c}{4}\frac{g_{\mu\nu}}{q^2-M_W^2}\underbrace{\bar{u}(k_2)\gamma^\mu(1-\gamma_5)u(k_1)}_{leptonic\,part}\underbrace{\bar{u}(p_2)\Gamma^\nu u(p_1)}_{hadronic\,part}$$

- Hadronic vertex

$$\Gamma^\nu = \gamma^\nu F_1^V(q^2) + i\sigma^{\nu\alpha}\frac{q_\alpha\xi F_2^V(q^2)}{2M_N} + \frac{q^\nu F_3^V(q^2)}{M_N} + \gamma^\nu\gamma_5 F_A(q^2) + \frac{q^\nu\gamma_5 F_p(q^2)}{M_N} + \frac{\gamma_5(p_1+p_2)^\nu}{M_N}F_3^A(q^2)$$

The weak form factors of the nucleon:

(a) $F_{1,2,3}^V,\ F_A,\ F_p,\ F_3^A$ real because of time reversal invariance

(b) $F_1^V,\ F_2^V,\ F_A,\ F_p$ real and $F_3^{V,A}$ imaginary because of charge symmetry

(a), (b) $\Rightarrow F_3^A = F_3^V = 0, \quad F_{1,2}^V,\ F_A,\ F_p$ real

Cross section ['Rosenbluth formula']

$$\frac{d\sigma^{\nu,\bar\nu}}{dQ^2} = \frac{M_N^2G^2\cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2)\mp B(q^2)\frac{s-u}{M_N^2}+C(q^2)\frac{(s-u)^2}{M_N^4}\right]$$

[1] See for example: Llewellyn Smith, Phys. Rep. 3 (1972) 261

- Weak Vector form factors $F_{1,2}^V$ related to e.m. form factors $F_{1,2}^{p,n}$:

$$F_1^V(q^2) = F_1^p - F_1^n\,, \quad (\kappa^p-\kappa^n)F_2^V(q^2) = \kappa^pF_2^p - \kappa^nF_2^n$$

with $\kappa^p \simeq 1.79, \kappa^n \simeq -1.91$ (anomalous magn. moments)

- E.m. form factors: $F_{1,2} \leftrightarrow G_{E,M}$ (Sachs):

$$G_E = F_1 - \tau\kappa F_2\,, \qquad F_1 = (1+\tau)^{-1}(G_E+\tau G_M)$$
$$G_M = F_1 + \kappa F_2\,, \qquad \kappa F_2 = (1+\tau)^{-1}(G_M - G_E)$$

with $\tau \equiv Q^2/4M^2$; $\quad F_1^p(0)=1, F_1^n(0)=0, F_2^{p,n}(0)=1$
$G_{E,M}^{p,n}$ precisely measured in electron scattering

- Axial vector form factor $F_A(q^2)$ to be measured in neutrino scattering

$$F_A(q^2) = \frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}$$

with $M_A \simeq 1.0$ GeV (to be extracted), $F_A(q^2=0) = -1.267$

- Pseudo-scalar form factor $F_p(q^2)$ least-well known;
However $\propto m_l^2/M^2$ in cross section $\rightarrow$ only important at lowest energies ($E_\nu \lesssim 0.2$ GeV)
Use approximation given in [2]:

$$F_p(q^2) = 2M_N^2\frac{F_A(q^2)}{(m_\pi^2-q^2)}$$

[1] See reviews: Budd, Bodek, talk at NuInt'02; Bernard et al, J. Phys. G:Nucl. Part. Phys. 28(2002)1
[2] Llewellyn Smith, Phys. Rep. 3 (1972) 261

Nuclear corrections

Pauli factor $g([W], Q^2)$

$$g = 1 - N^{-1} D$$

$$D = \begin{cases} Z & 2x < u - v \\ \frac{A}{2}\left(1 - \frac{3x(u^2+v^2)}{4} + \frac{x^3}{2} - \frac{3(u^2-v^2)^2}{32x}\right) & u - v < 2x < u + v \\ 0 & 2x > u + v \end{cases}$$

$$x = \frac{|\mathbf{q}|}{2k_F}, \quad u = \left(\frac{2N}{A}\right)^{\frac{1}{3}}, \quad v = \left(\frac{2Z}{A}\right)^{\frac{1}{3}}$$

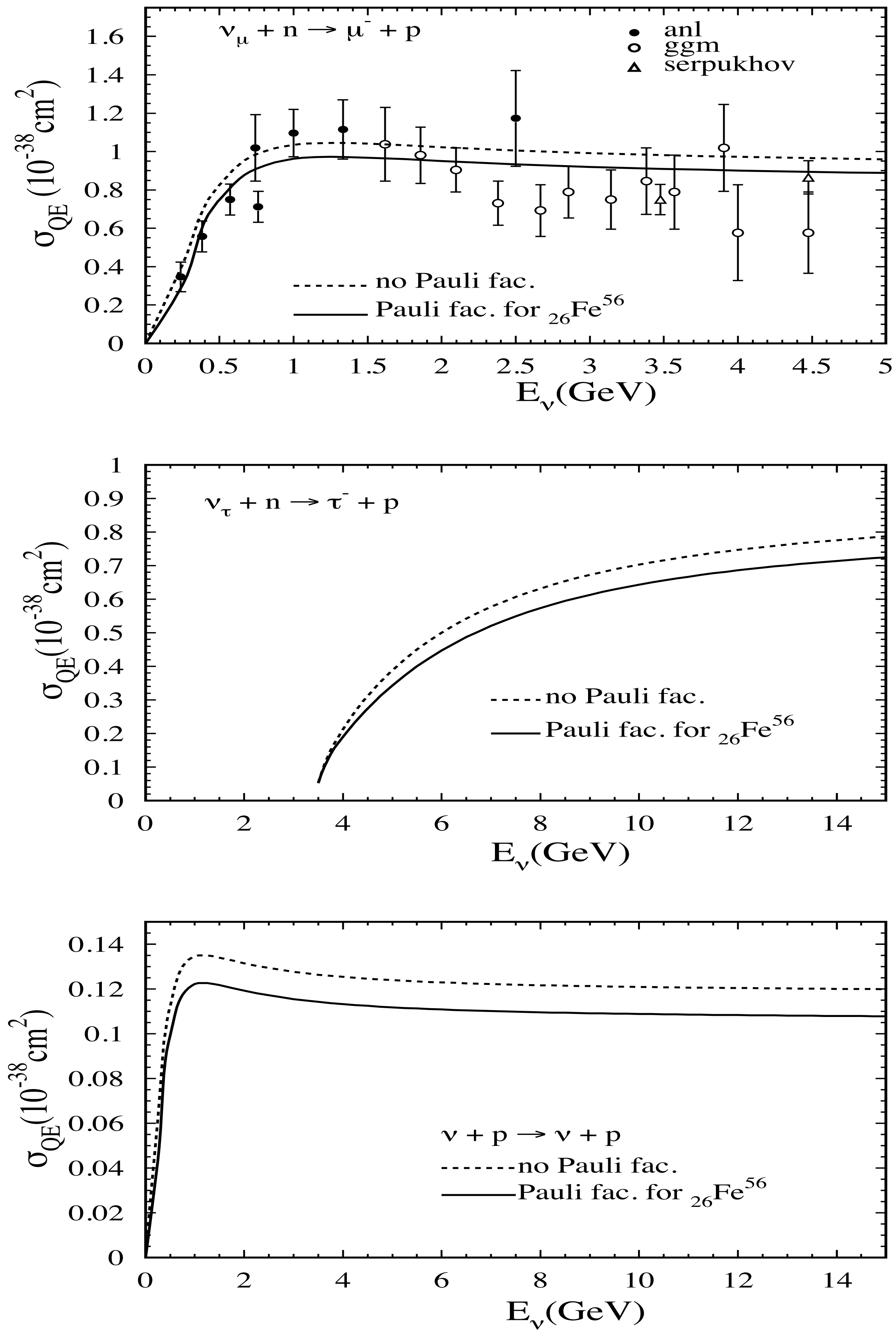
Fermi momentum: $k_F = 1.36\,\mathrm{fm}^{-1}$

Neutron, proton, nucleon number: $N,\ Z,\ A$

three-momentum transfer: $|\mathbf{q}| = \frac{q^2}{2M_N}\sqrt{1 - \frac{4M_N^2}{q^2}}$

- rescattering and absorption of recoiling hadrons and Fermi motion are neglected
- Note: typo in Eq. (3.33) in Llewellyn Smith, Phys. Rep. 3 (72) 261

Total CC and NC cross sections of QE



- Good agreement with data
- Pauli factor is small
- CC: ν_τ threshold effect
- NC: no threshold effect
- Other nuclear effects:
  Fermi motion,
  Binding energy

Kinematics of QE: $2 \to 2$ process

QE kinematics allows to reconstruct E_ν on an event by event basis:

$$E_\nu = E_\nu[E_\mu, \cos\theta_\mu] = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{k}_\mu|\cos\theta_\mu}$$

Problems:

- 0-pion events ≠ QE
  1π-events with absorbed or unidentified pions contribute significantly
  For 1π-events the formula above would underestimate the true E_ν

- The relation gets more complicated with binding energy and Fermi motion:

$$\begin{aligned} E_\nu &= E_\nu[E_\mu, \cos\theta_\mu, \vec{p}, \epsilon_B] \qquad (3) \\ &= \frac{(E_p + \epsilon_B)E_\mu - (2E_p\epsilon_B + \epsilon_B^2 + m_\mu^2)/2 - \vec{p}\cdot\vec{k}_\mu}{E_p + \epsilon_B - E_\mu + |\vec{k}_\mu|\cos\theta_\mu - |\vec{p}|\cos\theta_p}, \end{aligned}$$

see, e.g.,, hep-ph/0312123

Single pion resonance production (RES)

Single pion resonance production

- RES on free nucleons
  - $\exists$ several calculations in the literature [1-4]
  - Our calculation uses [4] $\oplus$ updated form factors [5] as input
  - calculations differ by about 20 %
- Nuclear corrections
  - Our approach (see talk) [6,7]
  - $\exists$ other approaches from 'nucl-th side' (not familiar with them)

---

[1] Adler, Ann. Phys. 50(1968)189;

[2] Fogli, Nardulli, NPB160(79)116; NPB165(80)162

[3] Rein, Sehgal, Ann. Phys. 133(81)79

[4] Zucker, PRD4(71)3350; Schreiner, von Hippel, NPB58(73)333

[5] Alvarez-Ruso, S.K. Singh, Vicente Vacas, PRC57(98)2693

[6] Paschos, Pasquali, Yu, NPB588(2000)263

[7] Paschos, I.S., Yu, work in progress; I.S., J.-Y. Yu, talk at NuInt'02

Delta-resonance production

The triple-differential cross section

$$\frac{d\sigma}{dQ^2 dW dE_\pi} = \frac{1}{\beta\gamma|p_\pi^{CMS}|}\frac{WG_F^2}{16\pi M_N^2}\times \sum_{i=1}^{3}\left[K_i\widetilde{W}_i - \frac{1}{2}K_i D_i(3\cos^2\theta_\pi - 1)\right]$$

- G_F: Fermi constant, $M_N (N = n, p)$: Nucleon mass
  $\beta\gamma$: Boost from LAB $\to \pi N$-CMS
- Kinematic factors:
  $K_1(Q^2, E_\nu),\ K_2(Q^2, E_\nu, W),\ K_3(Q^2, E_\nu, W)$
- Structure functions:
  - $\widetilde{W}_1,\ \widetilde{W}_2,\ \widetilde{W}_3,\ D_1,\ D_2,\ D_3$: can be expressed in terms of helicity amplitudes
- Helicity amplitudes:
  - $T_{3/2,1/2},\ T_C,\ U_{3/2,1/2},\ U_C,\ U_D$
  - depend on $f(W)$ and form factors (*) $(C_i^V, C_i^A,\ i = 1, ..., 5)$
- Breit – Wigner factor $f(W)$

$$f(W) = \frac{\sqrt{\frac{\Gamma_\Delta(W)}{2\pi}}}{(W - M_\Delta) - 1/2i\Gamma_\Delta(W)}$$

Schreiner von Hippel, Nucl. Phys. **B58**, 333 (1973)

(*) Alvarez-Ruso et al., Phys. Rev. **C57**, 2693 (1998)

- Form factors
  - The vector form factors

$$C_3^V(Q^2) = \frac{2.05}{(1 + \frac{Q^2}{0.54\,\mathrm{GeV}^2})^2}$$
$$C_4^V(Q^2) = -\frac{M_N}{M_\Delta}C_3^V$$
$$C_5^V(Q^2) = 0$$

  - The axial vector form factors

$$C_k^A(Q^2) = C_k(0)\left(1 + \frac{a_k Q^2}{b_k + Q^2}\right)\left(1 + \frac{Q^2}{m_a^2}\right)^{-2}$$
$$C_6^A(Q^2) = \frac{g_\Delta f_\pi}{2\sqrt{3}M_N}\frac{M^2}{m_\pi^2 + Q^2}$$

$$k = 3, 4, 5,\ C_3^A(0) = 0,\ C_4^A(0) = -0.3,\ C_5^A(0) = 1.2$$
$$a_4 = a_5 = -1.21,\ b_4 = b_5 = 2\,\mathrm{GeV}^2, m_a = 1.0\,\mathrm{GeV}$$
$$g_\Delta = 28.6,\ f_\pi = 0.97 m_\pi, m_\pi = 0.14\,\mathrm{GeV}$$

Note:
All the form factors need to be multiply $\sqrt{3}$ due to
$< \Delta^{++}|V_\alpha|p >= \sqrt{3} < \Delta^+|V_\alpha^{em}|p >$.

Alvarez-Ruso et al, Phys. Rev. C57, 2693 (1998)

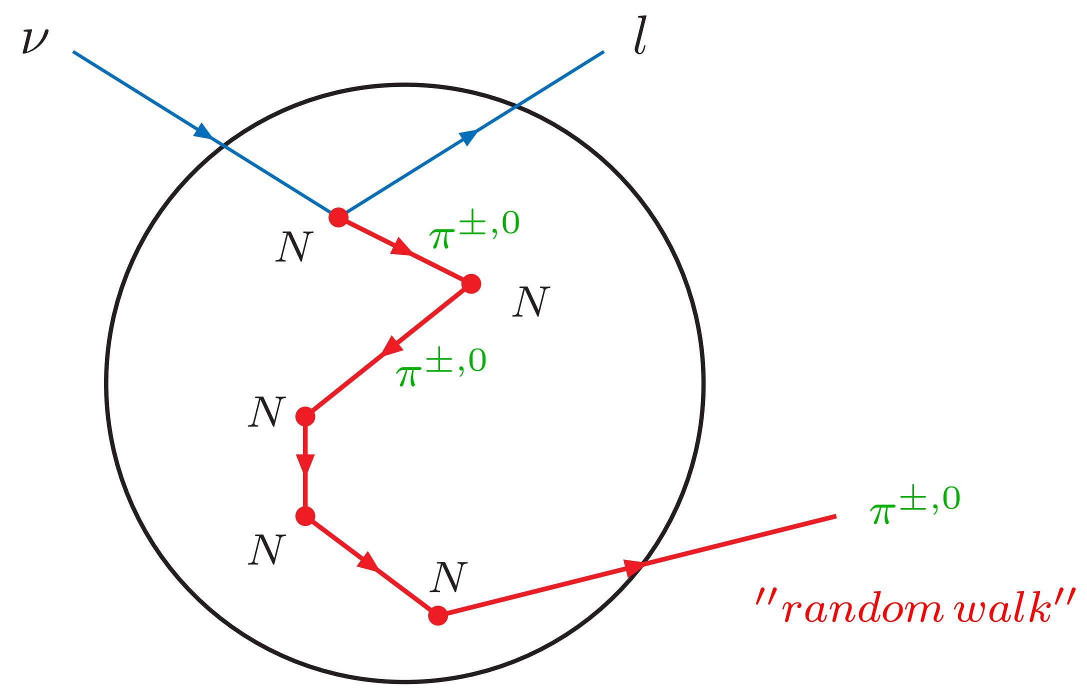
Nuclear effects

- Initial state:
  - Pauli Principle,
  - Fermi motion
- Final state:
  Pion multiple scattering
  - Pion charge exchange
  - Pion absorption

- Reactions

$$\nu + T \to l + T' + \pi^{\pm,0}$$

  - T: nuclear target ($_8O^{16}$, $_{18}Ar^{40}$, $_{26}Fe^{56}$)
  - T': final nuclear state
- Two step process



1. single pion production in νN scattering
   $\longrightarrow$ Pauli Principle, Fermi motion
2. multiple scattering of pions
   $\longrightarrow$ Charge exchange, absorption, Pauli Principle

- step 2 is described by the charge exchange matrix M
  - only depends on properties of the target
    $\longrightarrow$ charge density profile $\rho(r)$
- basic assumption: two steps independent $\longrightarrow$ predictive power

Comparison with MiniBooNE data

arXIV:1411.6637

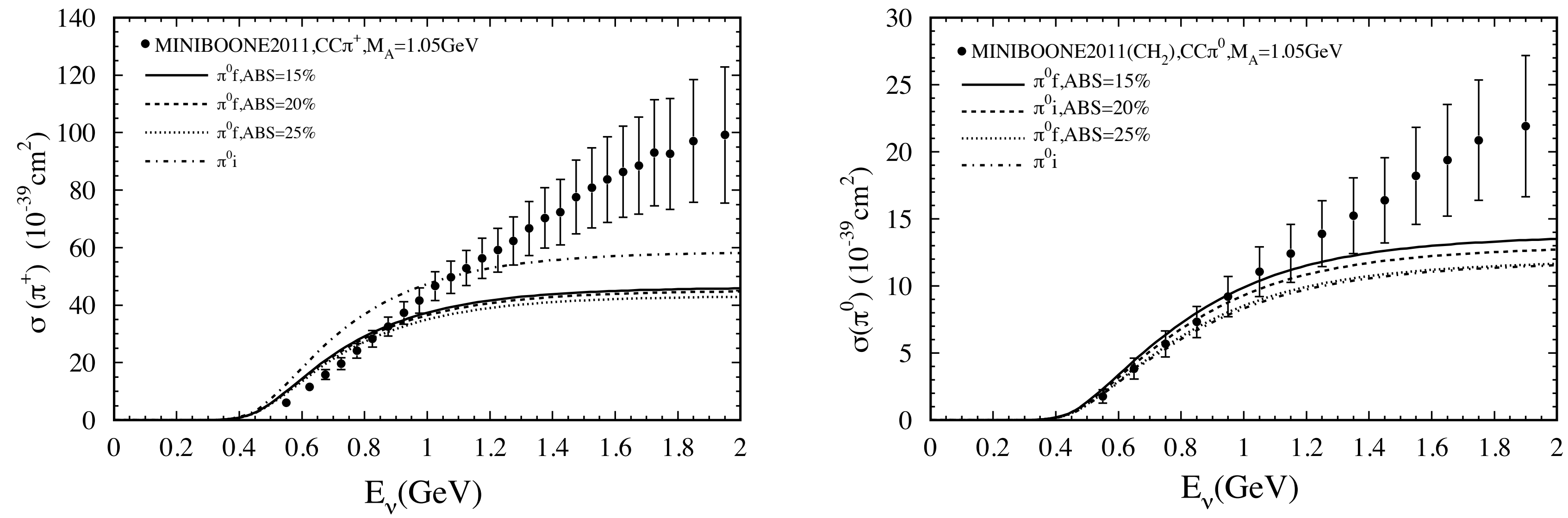


Figure 2: Total cross sections for CC1π^+ (left) and CC1π^0 (right) production in mineral oil (CH_2) in dependence of the neutrino energy E_ν. The CC1π^+ data are from Tab. V (Fig. 20) in [2] and the CC1π^0 data from Tab. VI (Fig. 8) in [3].

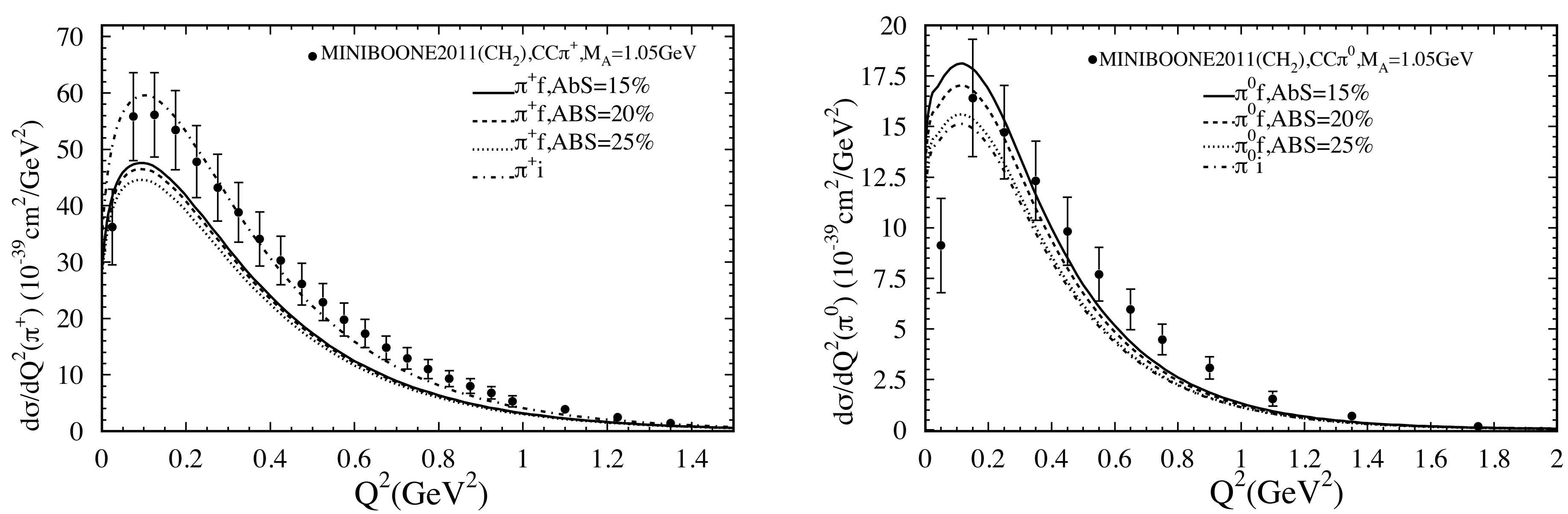


Figure 3: Q^2-differential cross sections for CC1π^+ (left) and CC1π^0 (right) production in mineral oil (CH_2) in dependence of Q^2. The CC1π^+ data are from Tab. VII (Fig. 21) in [2] and the CC1π^0 data from Tab. VII (Fig. 9) in [3].

Comparison with MiniBooNE data

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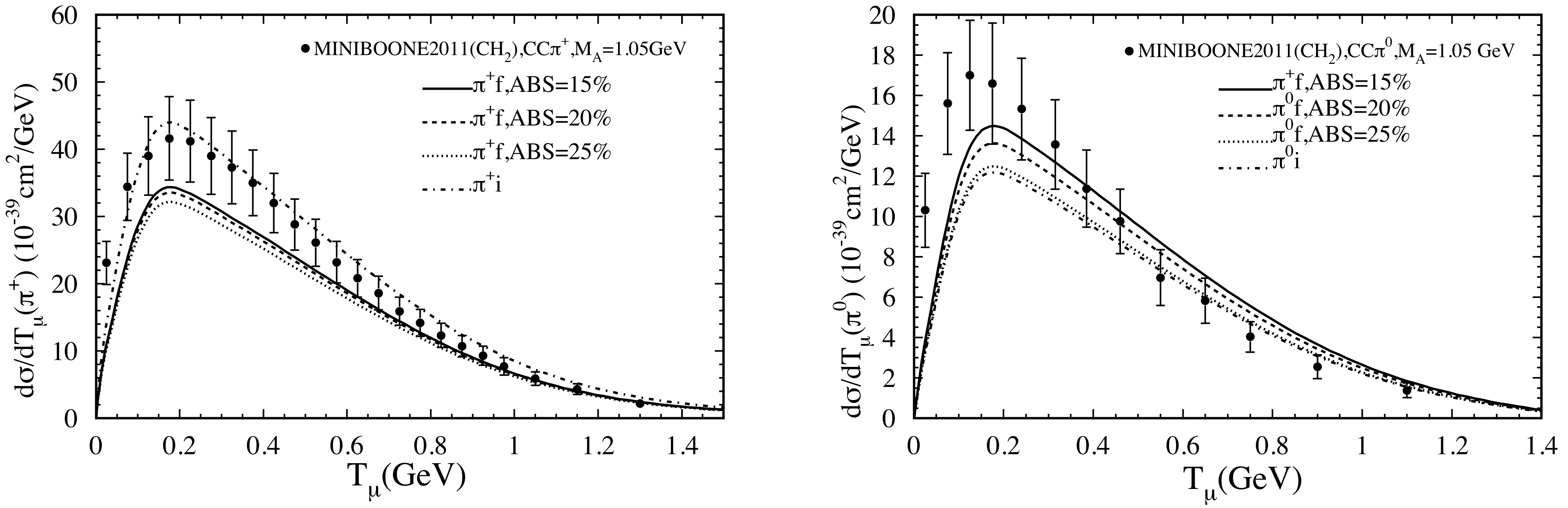

Figure 4: Same as in Fig. 3 for the differential cross sections in dependence of the kinetic energy of the muon T_μ. The $CC1\pi^+$ data are from Tab. VIII (Fig. 22) in [2] and the $CC1\pi^0$ data from Tab. VIII (Fig. 10) in [3].

Comparison with MiniBooNE data

arXIV:1411.6637

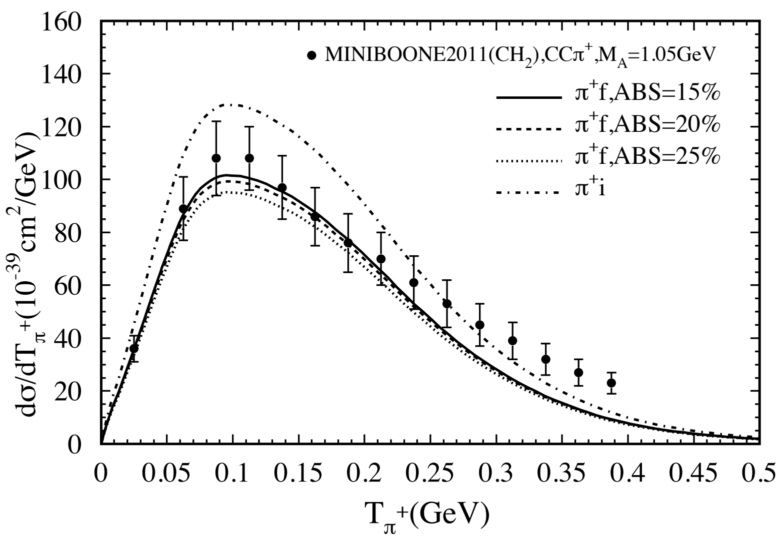

Figure 5: Differential cross sections for CC1π^+ production in mineral oil in dependence of the kinetic energy of the pion T_π^+ [cf. Tab. VI (Fig. 23) in [2]].

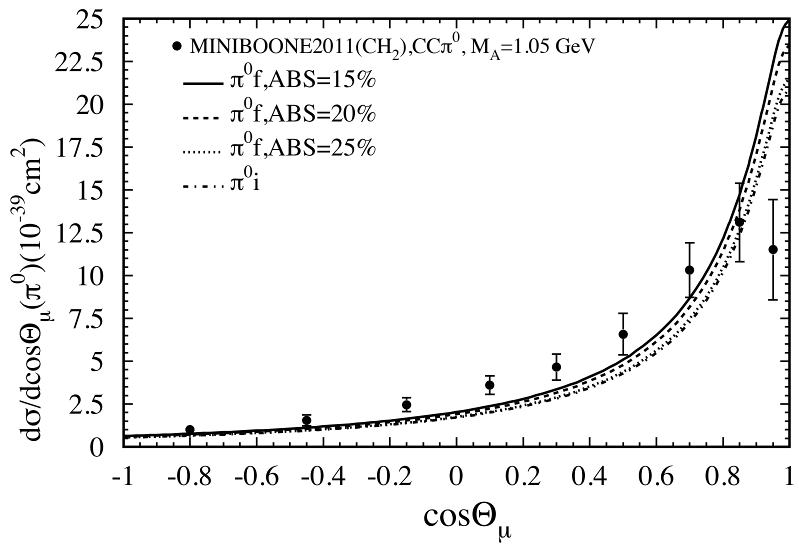

Figure 7: Differential cross sections for CC1π^0 production in mineral oil in dependence of the muon polar angle $\cos\theta_\mu$ [cf. Tab. IX (Fig. 11) in [3]].

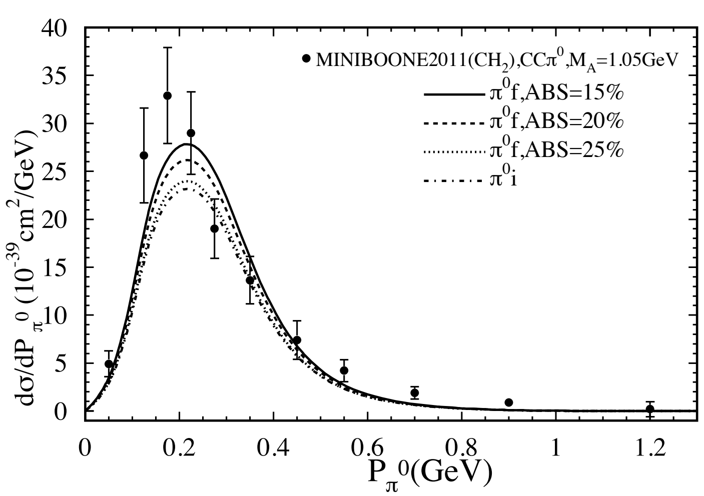

Figure 6: Differential cross sections for CC1π^0 production in mineral oil in dependence of the pion momentum P_π^0 [cf. Tab. X (Fig. 12) in [3]].

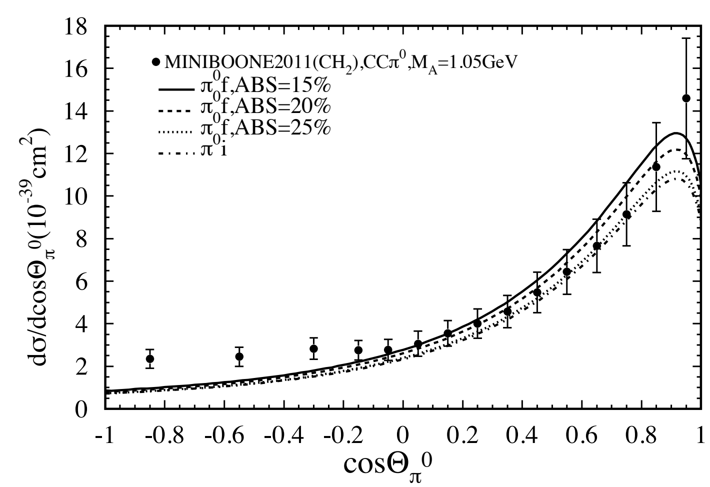

Figure 8: Same as in Fig. 7 for the pion polar angle $\cos\theta_{\pi^0}$ [cf. Tab. XI (Fig. 13) in [3]].