Neutrino Interactions from GeV to TeV Scale

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CPNR Workshop, October 24-27, 2025
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My experience with neutrinos

The first Lecture

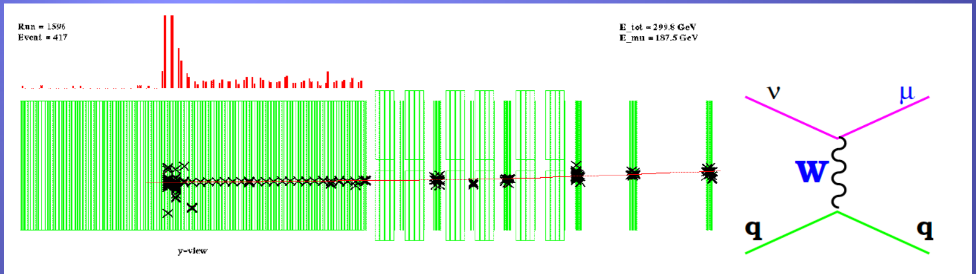
- PhD experiment with CCFR/NuTeV at Fermilab (1993-2000)
  - Differential Cross Sections and Structure Function Analyses (PRL 87, 251802 (2001), PRL 87, 251802 (2001))
  - Global Structure Functions analyses (PRL 82, 2467 (1999))
  - Phenomenology studies (NNLO, non-pQCD effect etc): (Eur Phys J C13, 241 (2000))
- Postdoc with CDF at Fermilab (2000~2005)
  - Modelling Neutrino Cross Section: J. Phys. G 29 (2003) 1899, while performing main job, CDF top quark physics

The Second Lecture

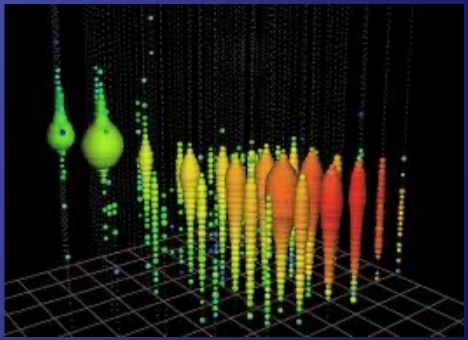
- ATLAS / CMS at Manchester (2006~2012) / Seoul National Univ. (2013~)
  - Search for heavy neutrinos

Neutrino Interactions

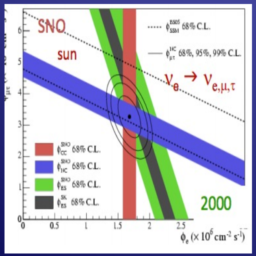
- Neutrino interactions at high Energy (10~500 GeV) have been used to probe parton dynamics inside nucleons for precision QCD studies, and electroweak physics in 1980~2000 (CDHSW, CHARM,CHORUS, CCFR, NuTeV)

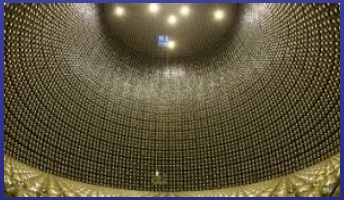


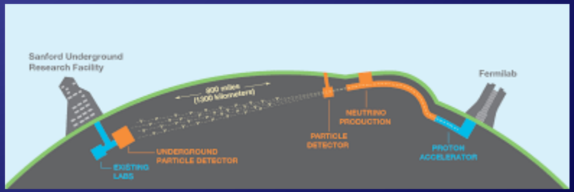
- Ultra high energy neutrino interactions
(>TeV scale) for astrophysics (IceCube, Antares)



- Neutrino Oscillations brings a precision QCD studies back,
but in Eν = few GeV region (T2K, Nova, Hyper-K, DUNE etc) since 2000







Precision QCD in neutrino

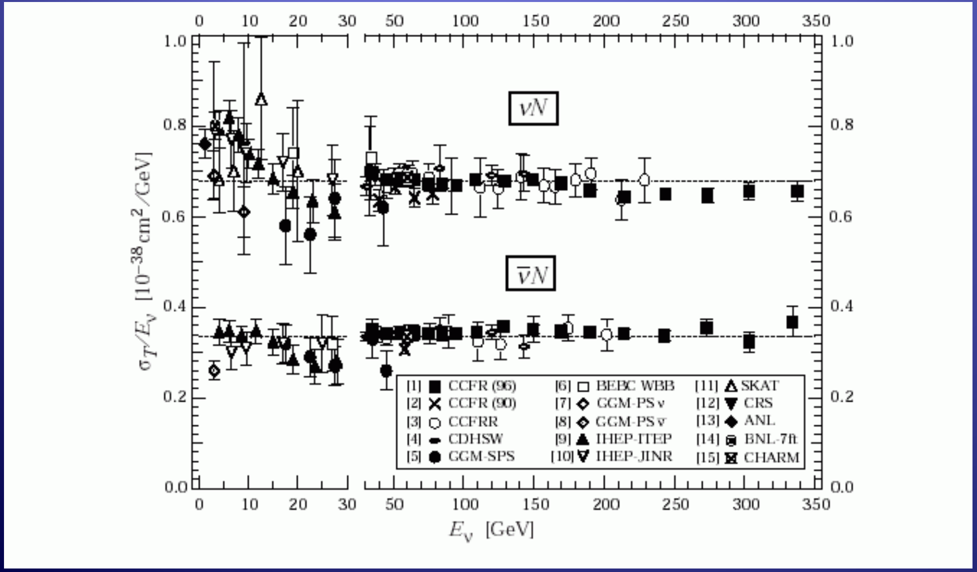
- High energy neutrino beam (10 ~ 300 GeV)

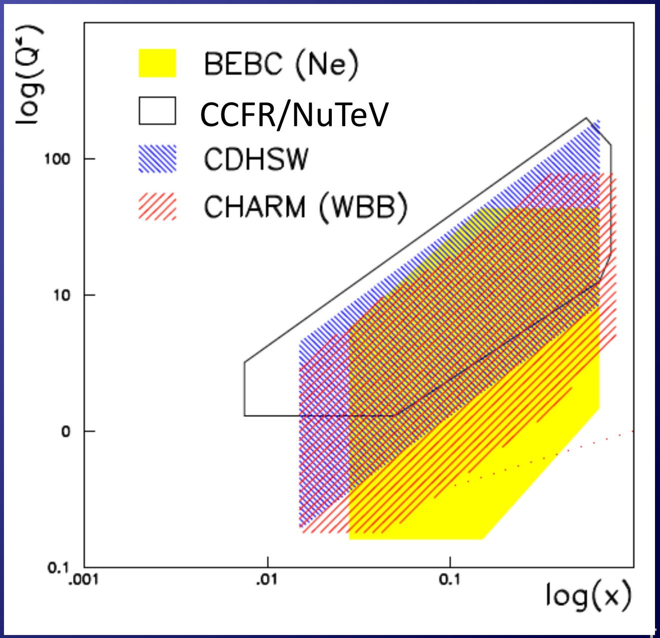
$$\frac{d^2\sigma}{dxdy}^{\nu(\overline{\nu})} = \frac{G^2ME}{\pi}\left[(1-y-\frac{Mxy}{2E})F_2 + \frac{y^2}{2}2xF_1 \pm y(1-\frac{y}{2})xF_3\right]$$

$$F_{2,LO} = \sum_{i=u,d.} xq_i(x,Q^2) + x\overline{q_i}(x,Q^2)$$

$$xF_{3,LO} = \sum_{i=u,d..} xq_i(x,Q^2) - x\overline{q_i}(x,Q^2)$$

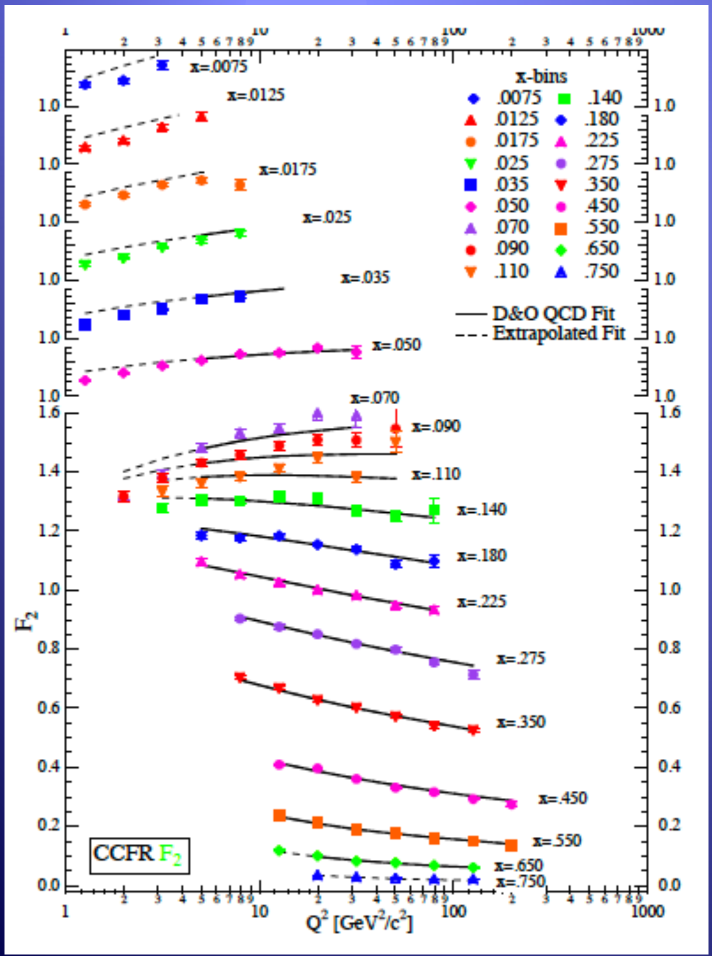
$$R = \frac{F_L}{2xF_1} = \frac{F_2}{2xF_1}(1+Q^2/\nu^2) - 1.$$

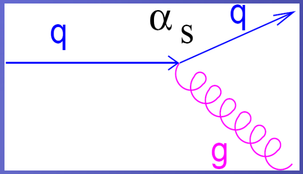


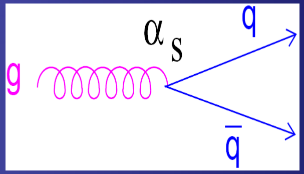


Precision QCD using Structure Functions (SFs)

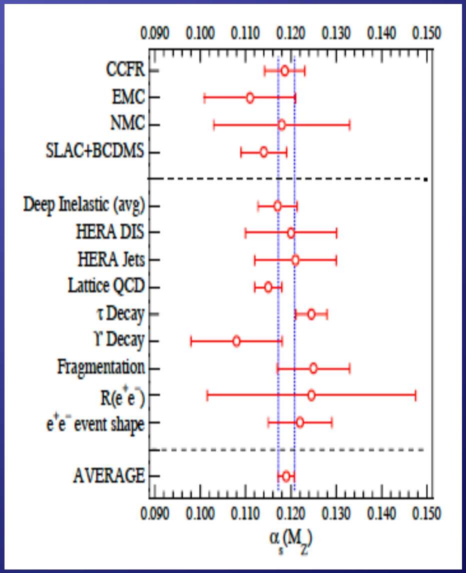
- DIS region: structure function QCD analysis (F_2, xF_3)
  With DGLAP evolution from high Q^2 to low Q^2 : extract Λ_{QCD} & PDFs



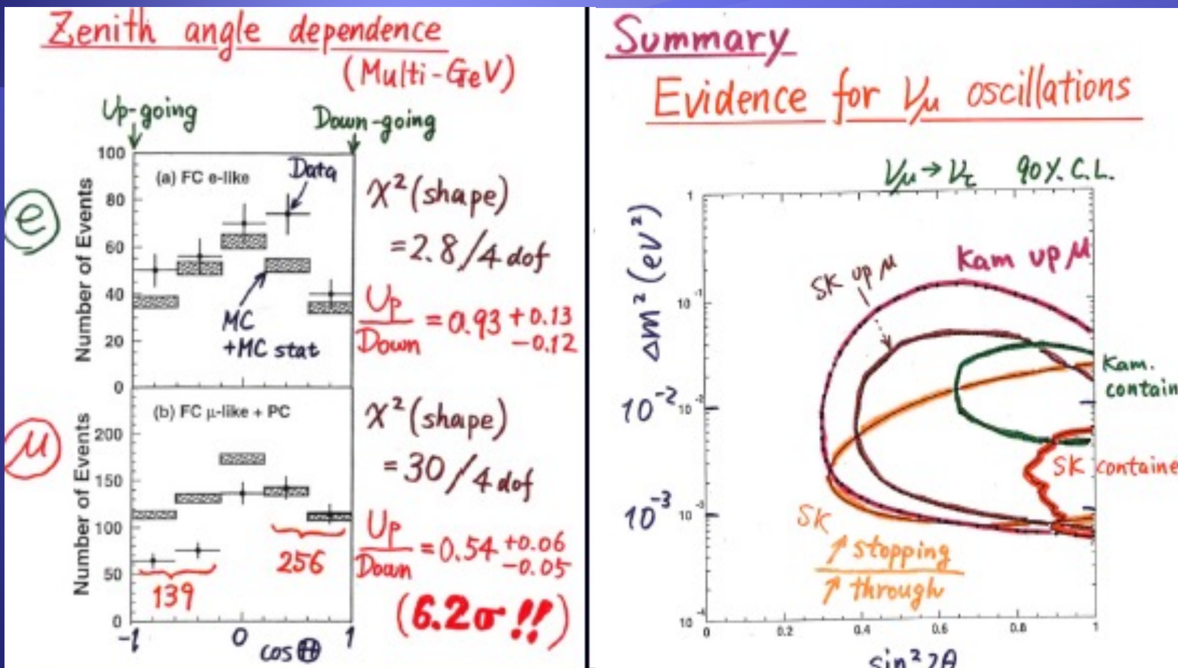




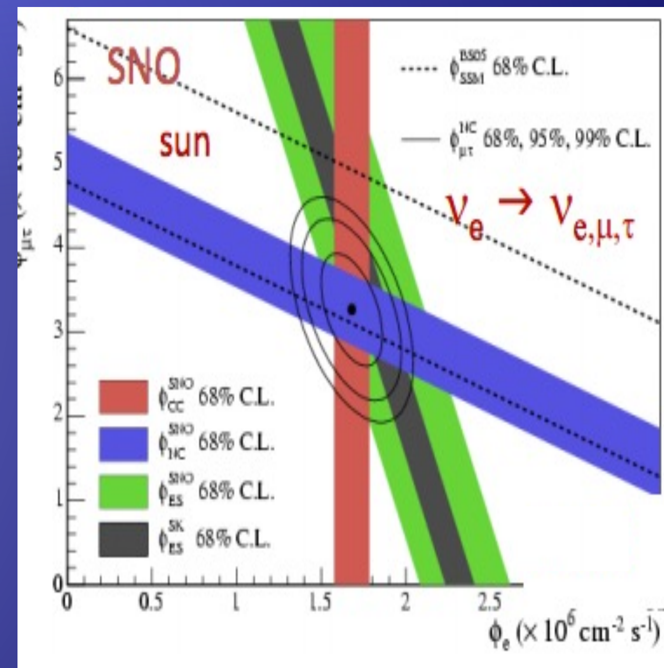
$$\frac{\partial q(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left(q(y,Q^2)P_{q\to qg}\left(\frac{x}{y}\right) + g(y,Q^2)P_{g\to q\bar{q}}\left(\frac{x}{y}\right)\right)$$



Neutrino Oscillations discovered



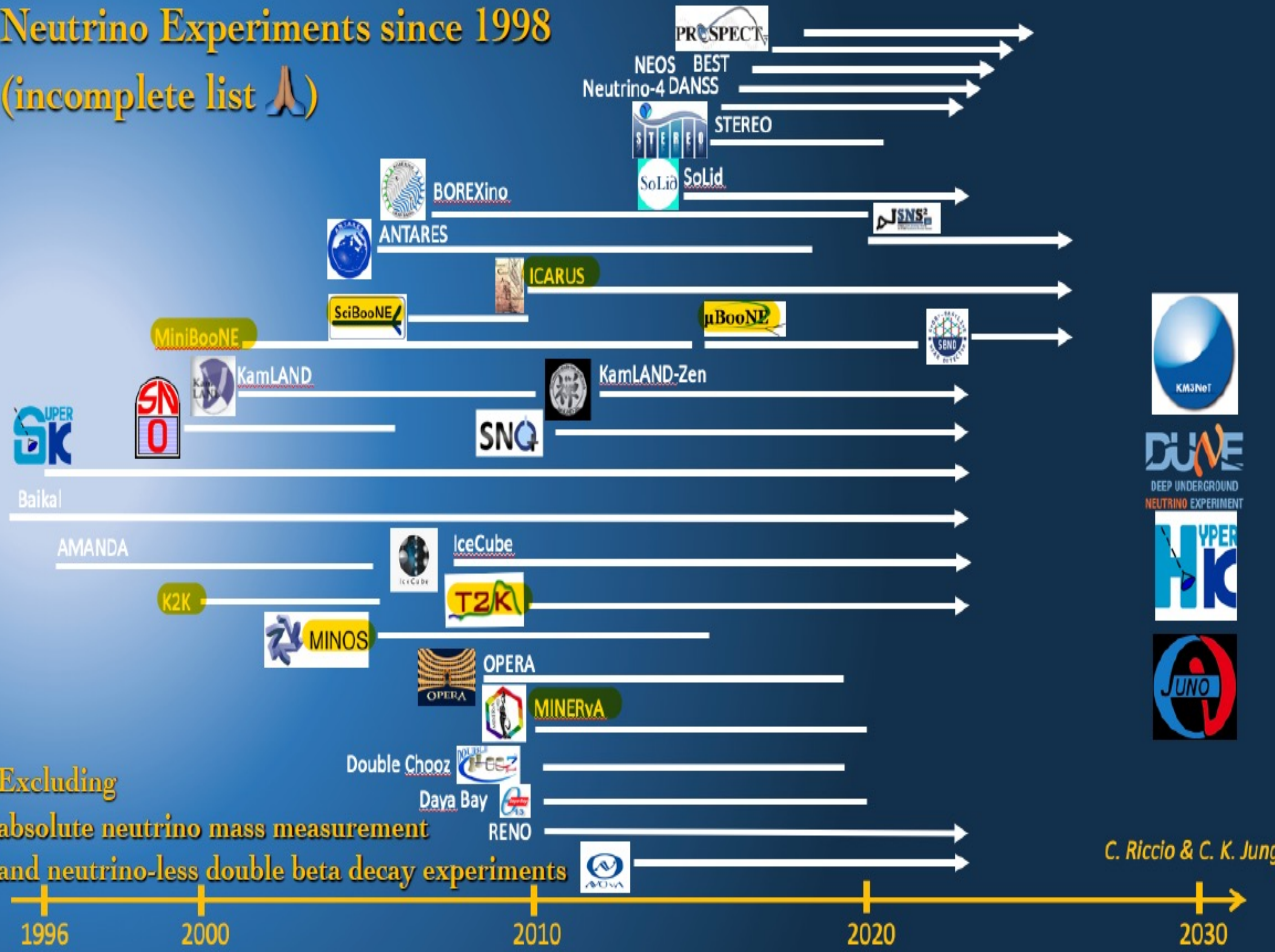
Neutrino 1998 by Kajita



2002 by SNO

- Discovery of Neutrino Oscillations in 1998 brings precision neutrino physics in QCD, but in Eν = few GeV region

Neutrino Experiments since 1998
(incomplete list 🙏)

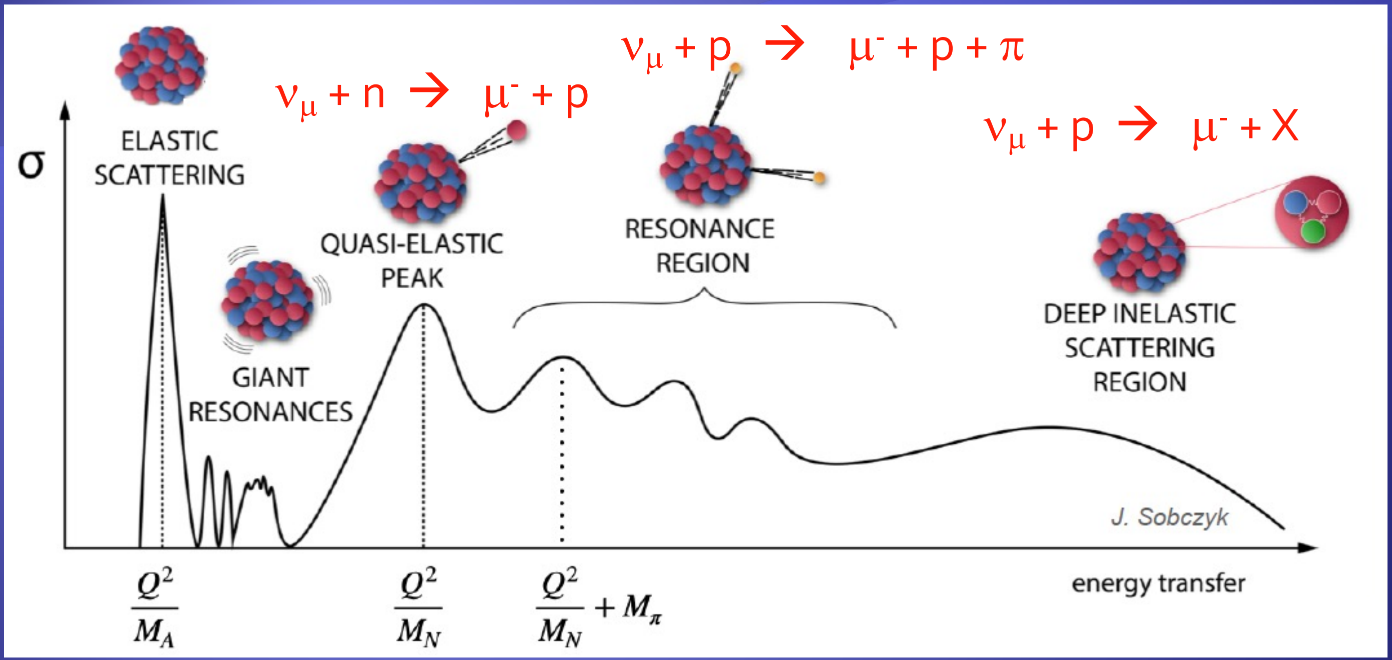


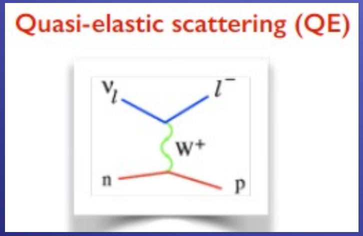
Excluding
absolute neutrino mass measurement
and neutrino-less double beta decay experiments

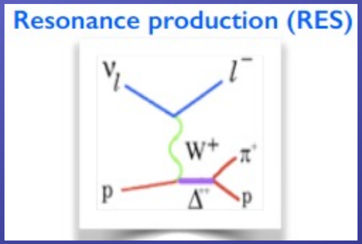
Physics Goals with Neutrinos

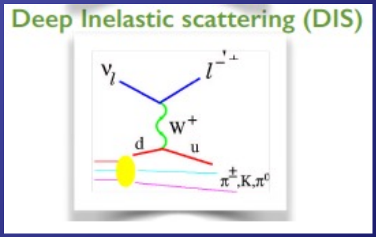
- Understanding of the matter-antimatter asymmetry in the Universe
  - CP violation
  - Leptogenis
- Source of non-zero neutrino mass
  - Seesaw mechanism
  - BSM model for Grand Unification
  - Dirac vs Majorana
- Absolute scale of neutrino mass
- Study of astrophysical high E neutrinos
- Precision measurements for new physics
  - Precision measurements of neutrino oscillation parameters (PMNS matrix]
  - Non-standard interactions

Neutrino-Nuclei Interactions









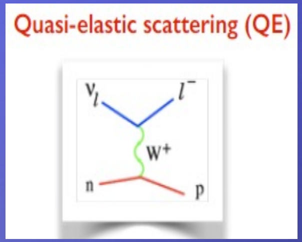
- Neutrino oscillation experiments: beam energies from 0.1 to 10 GeV
- Resonance region overlapped with DIS region

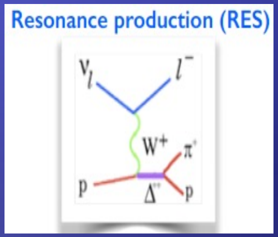
Neutrino-Nuclei Interactions

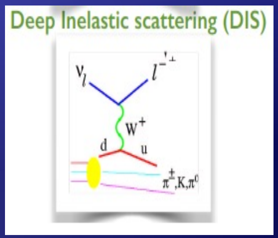
- ❑ Quasi-Elastic / Elastic (W=Mn):
  $\nu_\mu + n \rightarrow \mu^- + p$
  - ➢ well measured and described by form factors

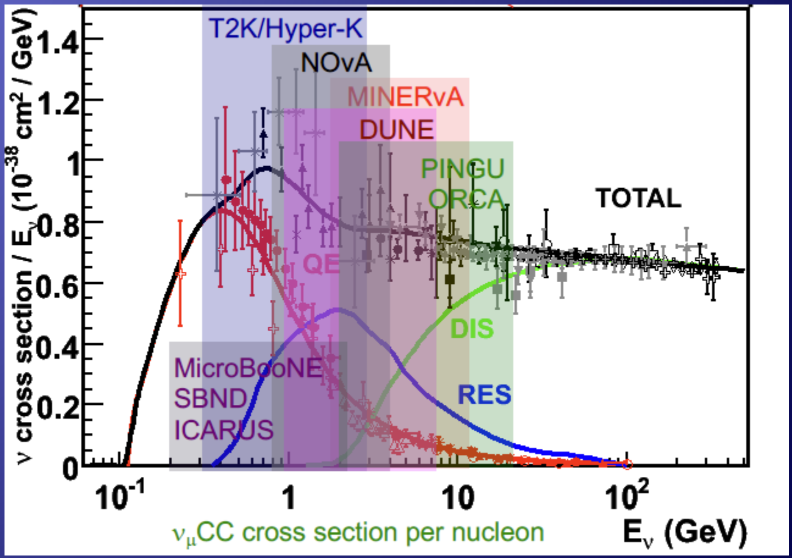
- ❑ Resonance (low Q^2, W< 2 GeV):
  $\nu_\mu + p \rightarrow \mu^- + p + \pi$
  - ➢ poorly measured, only 1st resonance described by Regin and Seghal model

- ❑ Deep Inelastic (high Q2)
  $\nu_\mu + p \rightarrow \mu^- + X$
  - ➢ well measured by high energy experiments and well described by quark-parton model, but not at low Q^2 region
  - ➢ Large overlap with resonance region



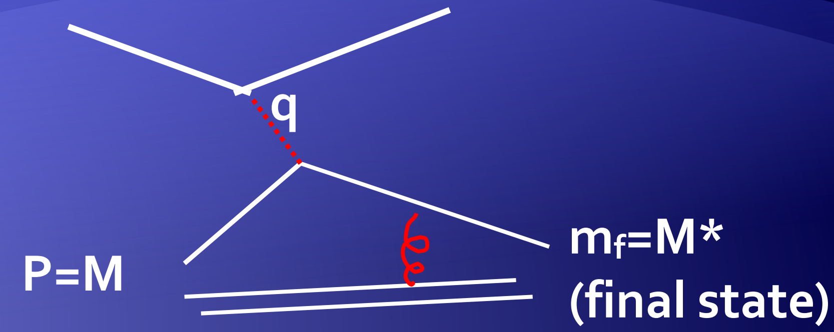




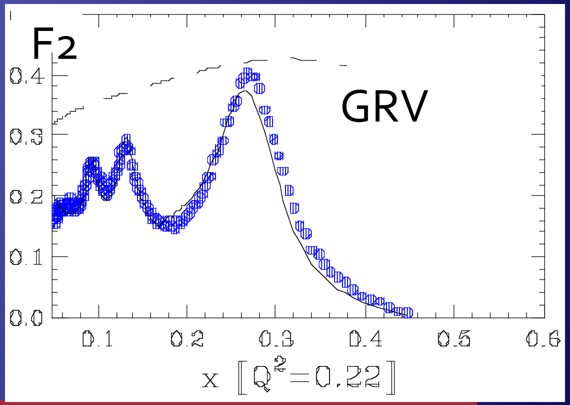


Neutrino-Nuclei Cross Sections

- Can we build up a model to describe all Q^2 region from high down to very low energies ?
  [DIS, resonance, even down to Q^2=0 limit]



- Describe them in terms of quark-parton model including resonance scattering
- With PDFS, it is straightforward to convert charged-lepton scattering cross sections into neutrino cross section.
  (just matter of different couplings)

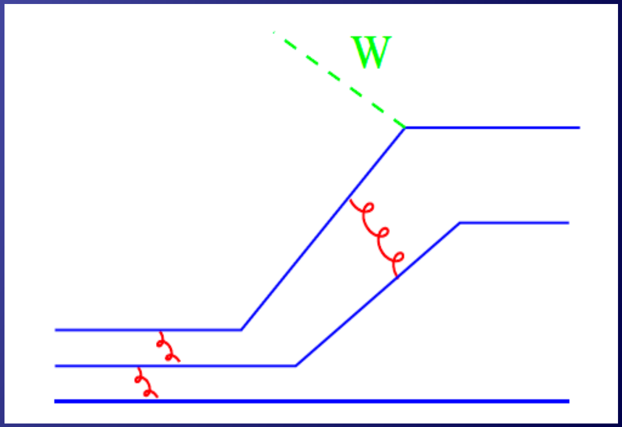


- Major Challenges
  - non-perturbative QCD effects (not resolving a single quark)
  - Large uncertainty on PDFs at high x & low Q^2
  - Overlapped with a DIS contribution
  - Additional axial-vector contribution in neutrino scattering

Non-pQCD effect at low Q^2

- Higher twist effect (dynamic): at low Q^{2}, not able to resolve a single parton, but scattering with multi-partons
- The contributions from higher twist diagrams are suppressed by powers of $1/Q^2$

- Empirical model: use data to fit the higher twist effect using an empirical formular.
  $F_2(LT)\ (1+h2(x)/Q^2 + h4(x)/Q^4)$
- Renormalon model: predict Q^2, and x dependence on SFs: get the overall size
  from the data
- Enough SLAC/Jefferson Lab e-N DIS data
  in low Q^2 region not used by PDF groups



$$F_2(x,Q^2) = F_2^{pQCD+TM}\left[1+\frac{D_2(x,Q^2)}{Q^2}+\frac{D_4(x,Q^2)}{Q^4}\right]$$

$$D_2(x,Q^2) = \frac{a_2}{q(x,Q^2)}\int_x^1 \frac{dz}{z} c_2(z) q(x/z,Q^2).$$

M. Dasgupta and B.R. Webber, Phys. Lett. **B382**, 273 (1996).

Non-pQCD effect at low Q²

- Kinematic higher twist (target mass effect)
  - Nucleon target mass effect is not negligible

    → use Nachtmann variable

$$\xi = \frac{2x}{1+\sqrt{1+4x^2M^2/Q^2}} .$$

--> Full calculations

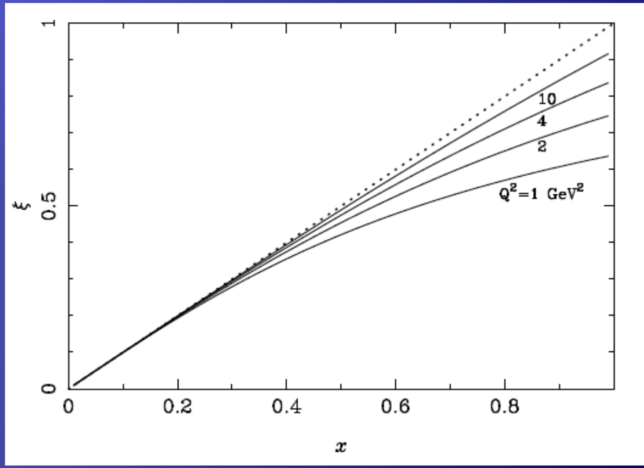
$$F_2^{\mathrm{TMC}}(x,Q^2) = \frac{x^2}{\xi^2 r^3} F_2^{(0)}(\xi) + \frac{6M^2x^3}{Q^2 r^4} h_2(\xi) + \frac{12M^4x^4}{Q^4 r^5} g_2(\xi)$$

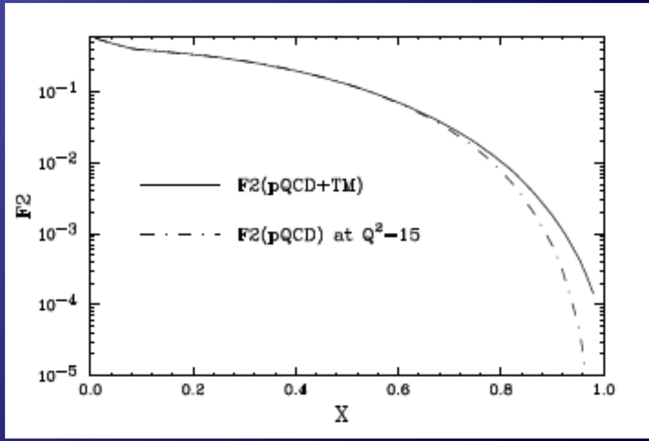
$$h_2(\xi,Q^2) = \int_\xi^1 du\, \frac{F_2^{(0)}(u,Q^2)}{u^2}$$

$$g_2(\xi,Q^2) = \int_\xi^1 du\, h_2(u,Q^2) = \int_\xi^1 du \int_u^1 dv\, \frac{F_2^{(0)}(v,Q^2)}{v^2}$$

$$r = \sqrt{1+\frac{4x^2M^2}{Q^2}}$$

- A dominant player:
  using Nachtman variable





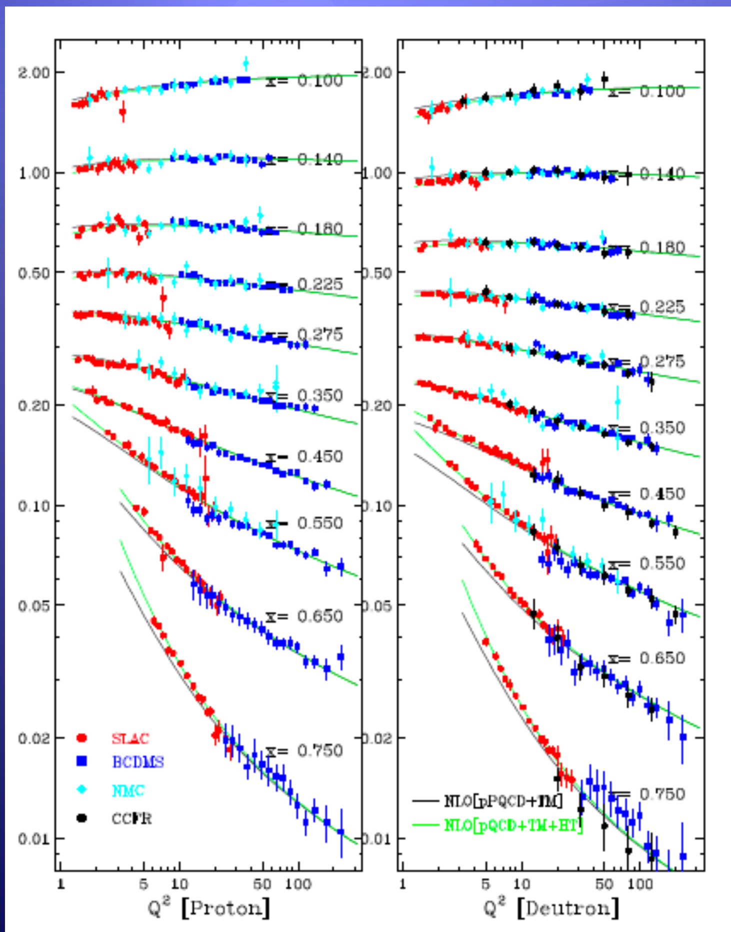
Higher Twist Effects 1

Studies of higher twist and higher order effects in NLO and NNLO QCD analysis of lepton-nucleon scattering data on F_2 and $R = \sigma_L/\sigma_T$

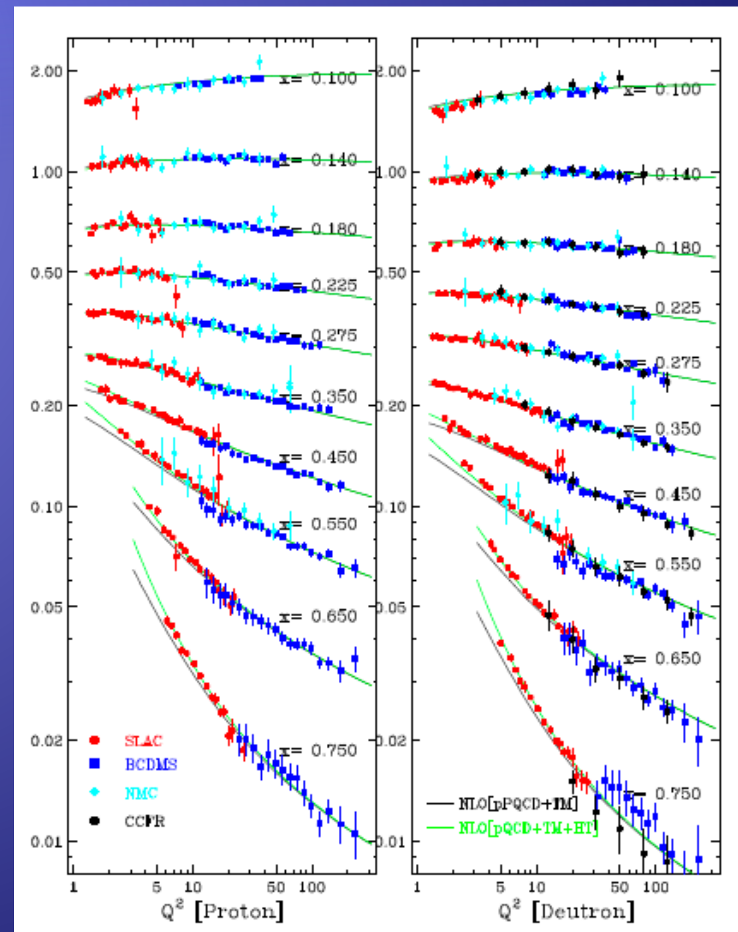
U.K. Yang & A. Bodek

The European Physical Journal C - Particles and Fields **13**, 241–245 (2000) | Cite this article

- Both higher twists models describe the SFs data (0.1<x0.75) (SLAC, BCDMS, NMC, and R): CCFR shown for comparison



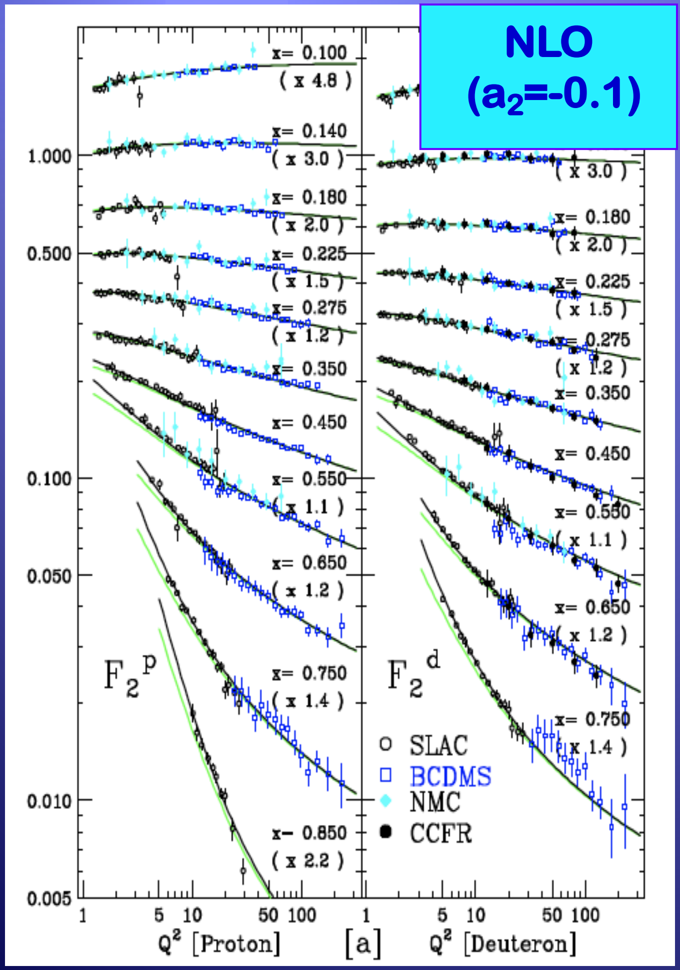
Empirical Model

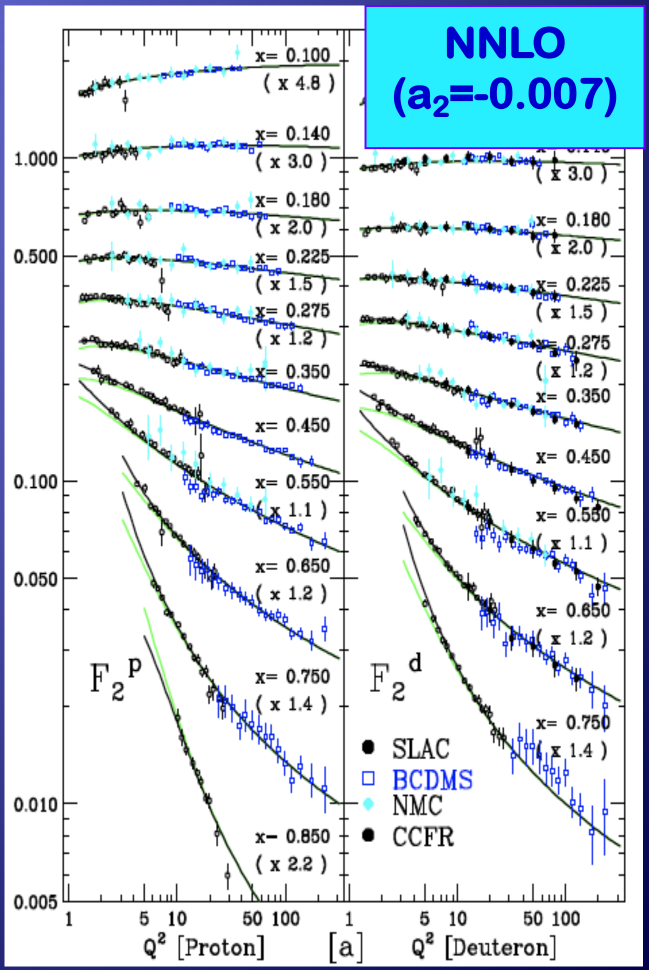


Renormalon Model: a2=-0.1

Higher Twist Effects 2

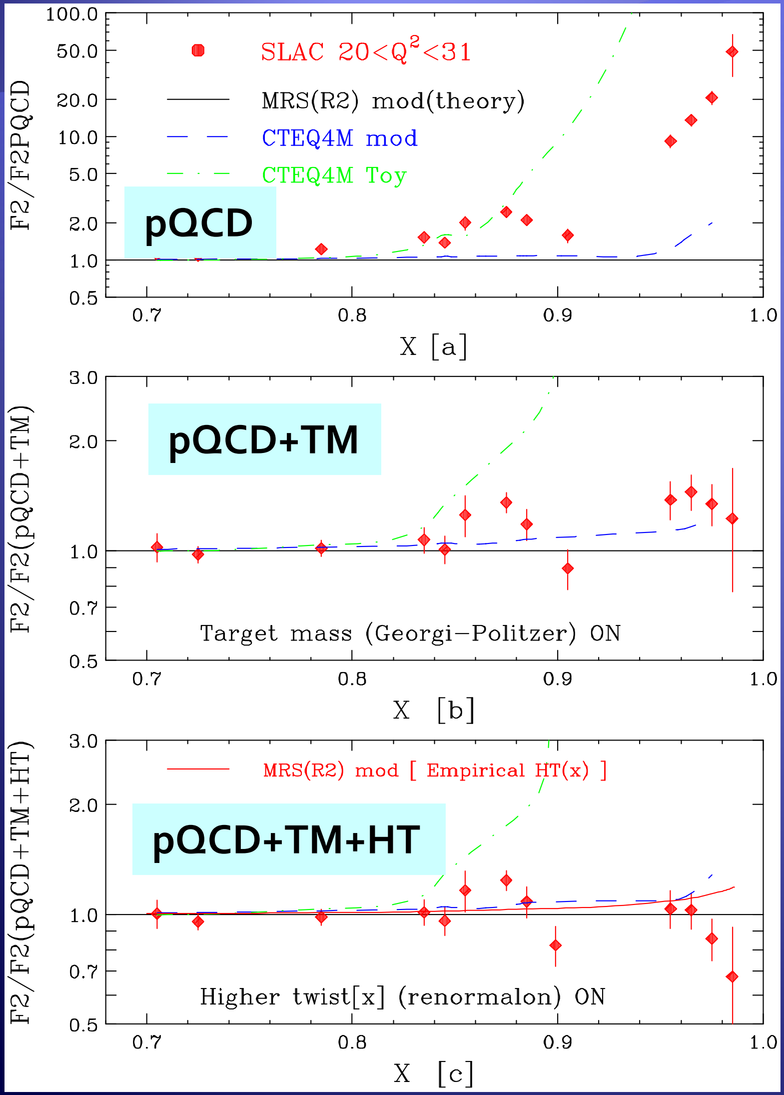
- Higher twist effects in NLO are similar to missing NNLO terms
- NNLO pQCD+TM can describe the non-perturbative QCD effects at low Q^2





Higher Twist Effects 3

- Very high x and low Q^2



Parton Distributions, d/u, and Higher Twist Effects at High x

U. K. Yang and A. Bodek
Phys. Rev. Lett. **82**, 2467 – Published 22 March 1999

- Very high x and low Q^2 data is well described by the pQCD+TM+HT
- Extraction of the high x PDF is promising (1999)
  - still a large uncertainty (2025) at high x

Lessons from QCD studies

- NLO & NNLO analyses with DIS data: PRL 82, 2467 (1999), Eur. Phys. J. **C13**, 241 (2000) by Bodek and Yang
  - Kinematic higher twist (target mass) effects are large
  - Resonance region can be well described (duality works)
  - Most of dynamic higher twist corrections (in NLO analysis) are similar to missing NNLO higher order terms
  - Valence quarks PDFs up to x=0.95 in good agreement with data
- NNLO pQCD+TM with NNLO PDFs can describe the non-perturbative QCD effects at low Q^2
- Thus, we reverse the approach to build the model:
  - Use effective LO PDFs with a news scaling variable, ξw to absorb target mass, higher twist, missing QCD higher order

$$x_{Bj} = \frac{Q^2}{2M\nu} \Rightarrow \xi_W = \frac{Q^2 + B}{\{M\nu[1+\sqrt{(1+Q^2/\nu^2)}] + A\}}$$

$$F_2(x,Q^2) \to \frac{Q^2}{Q^2+C} F_2(\xi_w, Q^2)$$

Modeling Cross Sections for all Q^2 regions

- For MC Generator, Bodek-Yang LO approach: (pseudo NNLO)
  - Use effective LO PDFs with a new scaling variable, ξ_w to absorb target mass, higher twist, missing QCD higher orders

$$x_{Bj} = \frac{Q^2}{2M\nu} \Longrightarrow \xi_W = \frac{Q^2 + B}{\{M\nu[1+\sqrt{(1+Q^2/\nu^2)}] + A\}}$$

  - Multiply all PDFs by K factors for photo production limit and higher twist

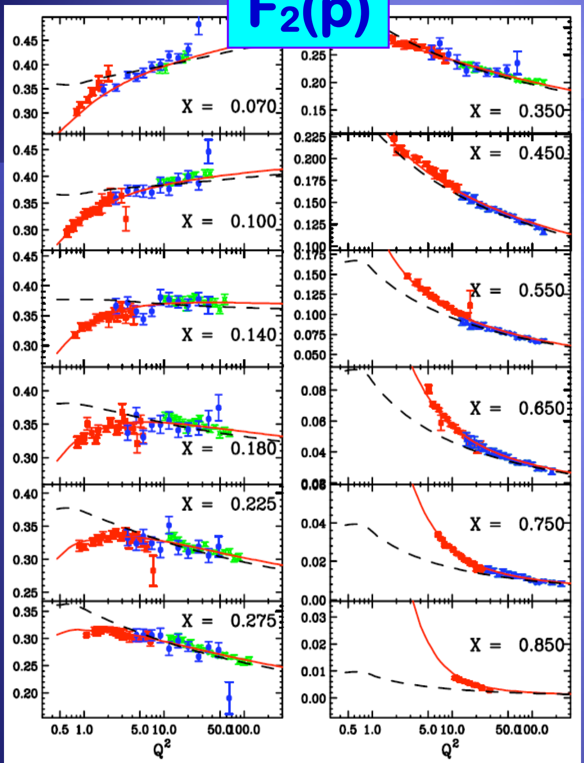
$$F_2(x,Q^2) \rightarrow \frac{Q^2}{Q^2+C} F_2(\xi_w, Q^2)$$

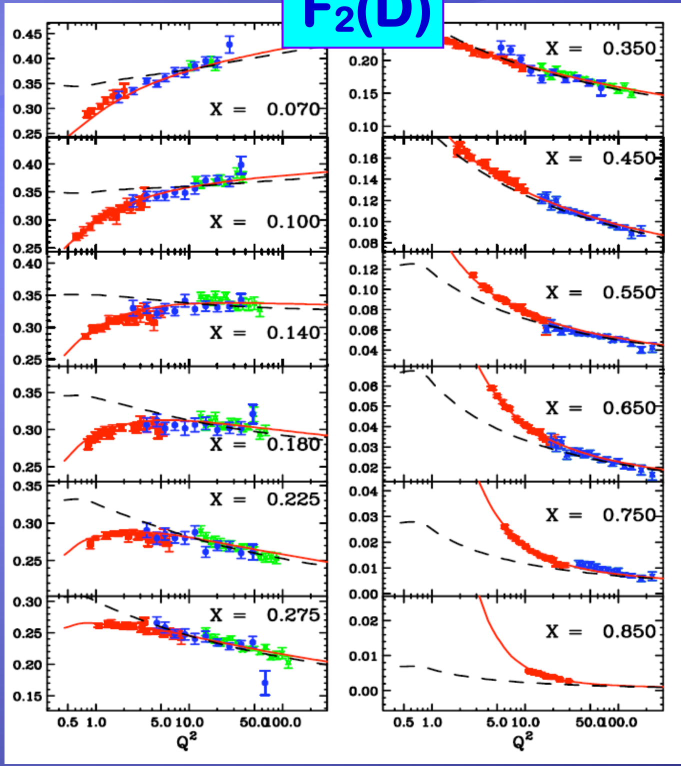
- Kval (u,d) = $[1- G_D{}^2 (Q^2)] * [Q^2+C_{2V}] / [Q^2+C_{1V}]$,

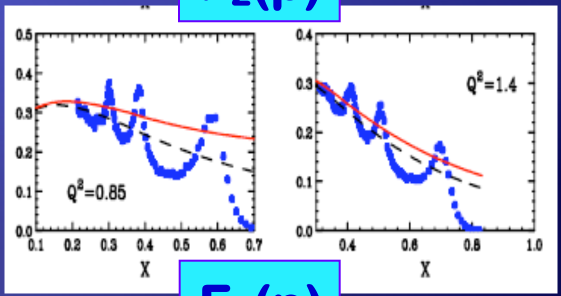
where $G_D{}^2 (Q^2) = 1/ [1+Q^2 / 0.71]^4$ (motivated by Adler Sum Rule)

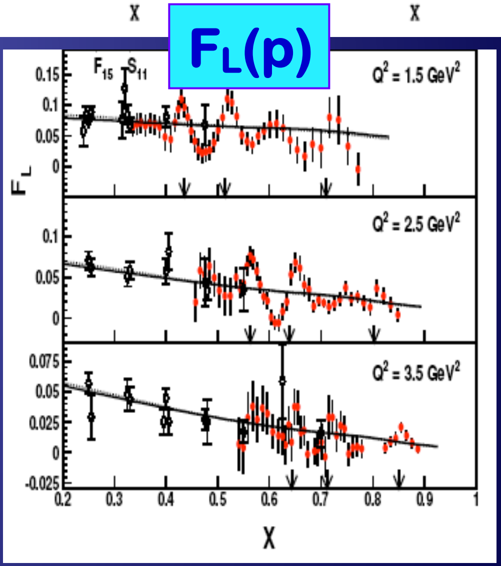
- Ksea (u,d,s) = $Q^2/[Q^2+Csea]$

Fit to F_2 data and Predictions









———	Effective LO
- - -	x_{bj}

- Excellent Fitting results on all DIS F_2, (χ^2/DOF=1235/1200)
- Predictions for resonance region F_2, F_L
- Quark-hadron duality works

J. Phys. G 29 (2003) 1899

Photo-production data

- In the BY model, freeze the DGLAP evolution at $Q^2 = Q^2_{min}$

$$F_2(x, Q^2 < 0.8) = K(Q^2) * F_2(\xi w, Q^2=0.8)$$

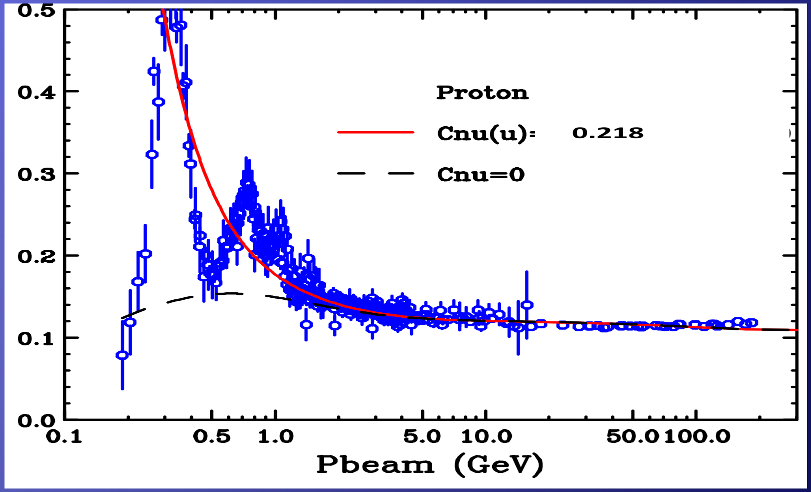
- Additional K^{LW} factor for valence quarks:

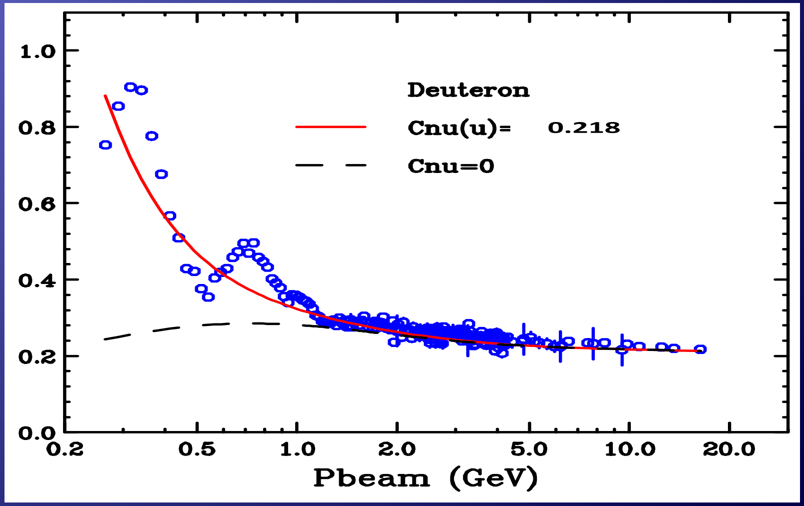
$$Kval = K^{LW} * [1 - G_D{}^2 (Q^2)] * [Q^2 + C_{2V}] / [Q^2 + C_{1V}]$$

$$K^{LW} = (\nu^2 + C^\nu)/\nu^2$$

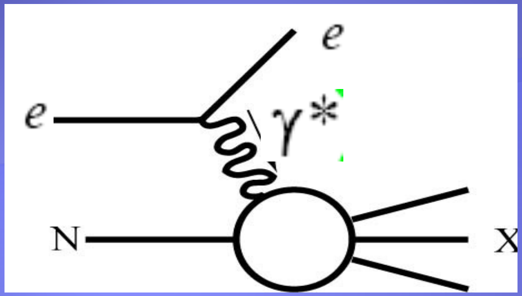
This makes a duality work all the way down to $Q^2=0$ (for charged leptons)

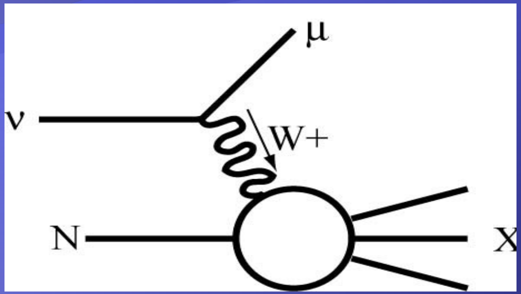
- Photo-production data with ν(Pbeam)>1 GeV included in the fitting





e-N vs ν-N scattering cross sections





e-N DIS scattering

$$\frac{d^2\sigma}{dxdy} = \frac{4\alpha^2 ME}{Q^4}\left[\frac{y^2}{2}2xF_1(x,Q^2) + (1-y)F_2(x,Q^2)\right]$$

ν-N DIS scattering

$$\frac{d^2\sigma^{\nu,\bar{\nu}}}{dxdy} = \frac{G_F^2 ME}{\pi}\left[\frac{y^2}{2}2xF_1(x,Q^2) + (1-y)F_2(x,Q^2) \pm (y - \frac{y^2}{2})xF_3(x,Q^2)\right]$$

- Charged-lepton (e, μ) scattering

  F2(p) = x[4/9(u+u) + 1/9(d+d) + 1/9(s+s)]

  F2(n) = x[4/9(d+d) + 1/9(u+u) + 1/9(s+s)]

  assuming $d_p = u_n$

- Neutrino scattering

  F2(ν) = x[(u+u) + (d+d) + (s+s)]

  xF3(ν) = x[(u-u) + (d-d)]

Neutrino cross sections

- Effective LO model using parton model with ξw describe all DIS and resonance F_2 data as well as photo-production data (Q^2=0 limit): vector contribution works well
- Neutrino Scattering:
  - Do we see an axial vector contribution at low Q^2?
  - Nuclear effect in neutrino? different from charged lepton scattering data?
  - Heavy charm mass effect ? ($W^*+s \rightarrow c$) different from charged lepton scattering ($g \rightarrow cc$, $\gamma^* + c \rightarrow c$)

    - use ξw slow rescaling algorithm for F_2, $2xF_1$, and xF_3
  - Effective LO model works for xF_3? Yes with NLO correction f(x)
  - Use $R=R_{1998}$ to get $2xF_1$

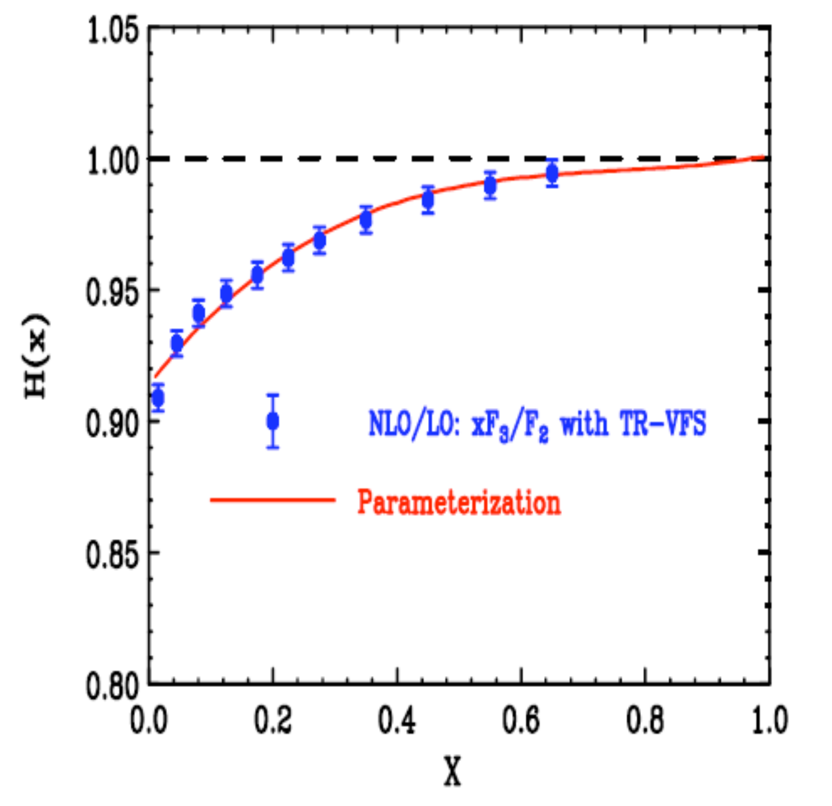
Effective LO model for xF_3?

- Scaling variable, ξw absorbs higher order effect for F_2, but the higher order effects for xF_3 can be different
- Use NLO QCD to get double ratio

$$H(x) = \frac{xF_3(\mathrm{NLO})}{xF_3(\mathrm{LO})} / \frac{F_2(\mathrm{NLO})}{F_2(\mathrm{LO})}$$

not 1 but almost indep. of Q^2

- Enhance anti-neutrino cross section by 3%



Axial Vector Structure Functions

- At high Q^2 , vector and axial vector contribution are same, but not at low Q^2
- K factors for axial contributions: type II

$$K_{sea}^{vector} = \frac{Q^2}{Q^2 + C} \Rightarrow K_{sea}^{axial} = \frac{Q^2 + 0.55 C_{sea}^{axial}}{Q^2 + C_{sea}^{axial}}$$

$$K_{val}^{axial} = \frac{Q^2 + 0.1 C_{val}^{axial}}{Q^2 + C_{val}^{axial}}$$

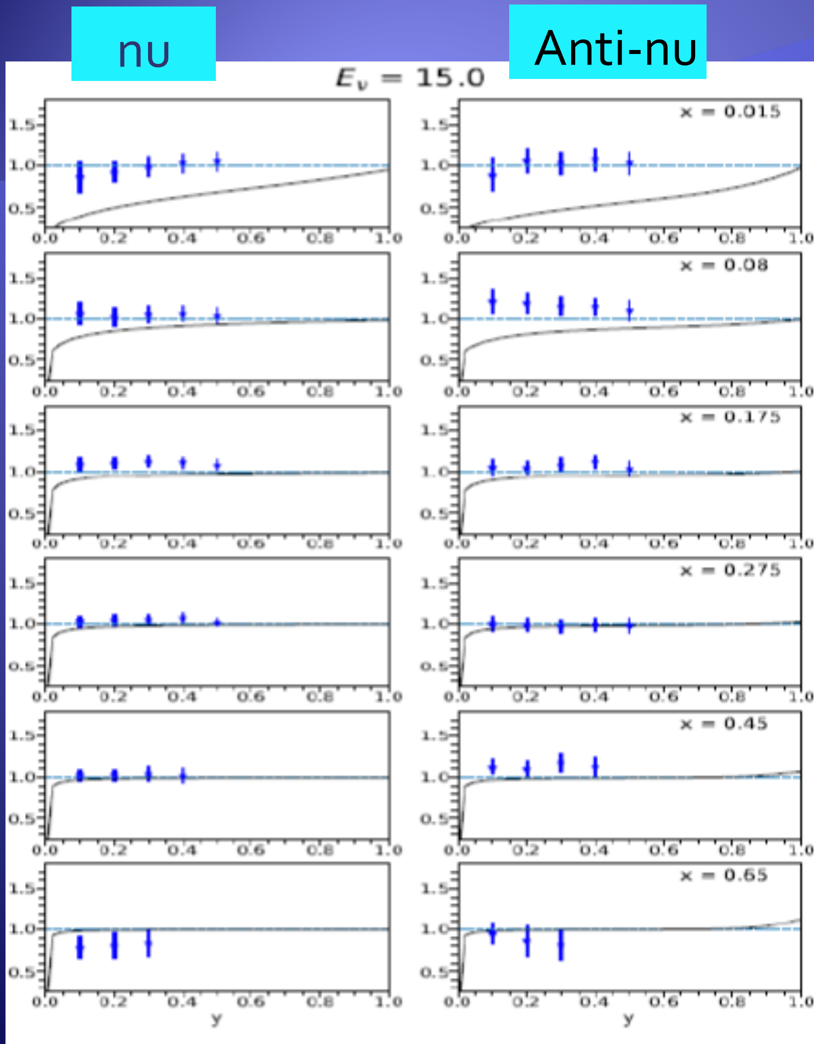
$$\text{where } C_{sea}^{axial} = 0.75, \;\; C_{val}^{axial} = 0.18$$

  - 0.55 was chosen to satisfy the prediction from PCAC by Kulagin, agrees with CCFR/CHROUS data for F_2 extrapolation to (Q^2=0)

- But, the non-zero PCAC component of F_2^{axial} at low Q^2: mostly longitudinal

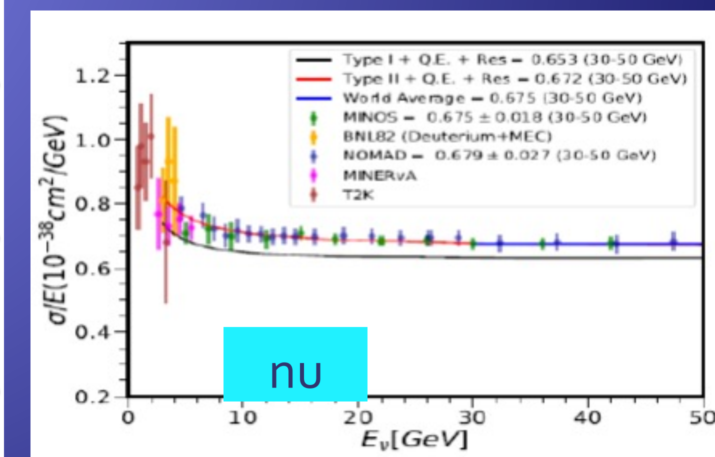
$$2xF_1^{axial} = 2xF_1^{vector}$$

Axial-vector contributions from neutrino data (CCFR (Fe), CHORUS (Pb))



- Blue point: CHORUS/theory (type II)
- Solid line:theory (type I)/(type II)

- Type I (Vector = Axial at low Q^2)
- Type II (Vector < Axial at low Q^2)



→Different axial vector contributions are clearly shown!

Bodek-Yang(BY) Model

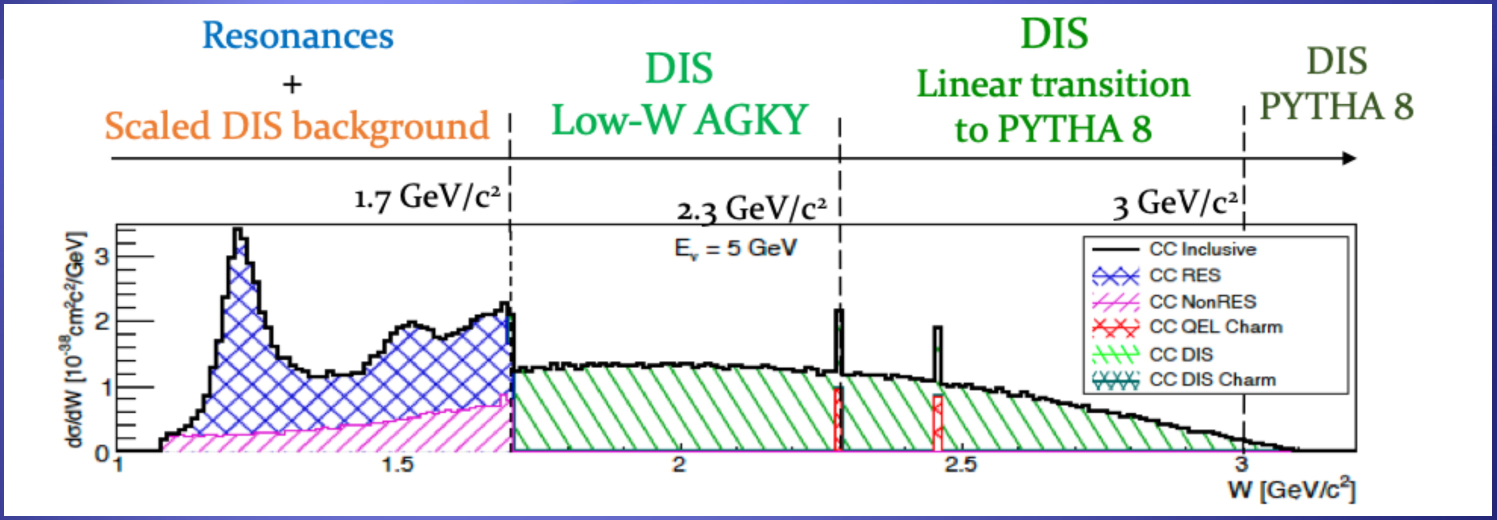
- BY Effective LO model with ξw describe all e/μ DIS and resonance data as well as photo-production data (down to Q^2=0): provide a good reference for neutrino cross section
- Model also works well down to W=1.4 GeV, thus providing overlap with resonance models
- Low energy neutrino experiments can normalize their data to our model to extract their flux

J. Phys. G 29 (2003) 1899, arXiv.2108.09240

TABLE III. Summary of the neutrino event generators and choice of models used by each to generate the inclusive cross-section predictions against which comparisons to this measurement are made. RFG = relativistic Fermi gas, LFG = local Fermi gas, LS = Llewellyn Smith, RPA = random phase approximation, RS = Rein-Sehgal, BS = Berger-Sehgal, BY = Bodek-Yang, PY = PYTHIA, BUU = Boltzmann-Uehling-Uhlenbeck.

Generator	QE/MEC initial state	QE	MEC	Res	DIS	FSI
GENIE v2.12.2	RFG	L-S	Empirical	RS	BY + PY 6	hA (data-driven empirical cascade)
GENIE v3.00.06	LFG	València	València	BS	BY + PY 6	hN (Oset (pions) + GENIE (nucleons))
NEUT v5.4.0	LFG	València	València	RS	BY + PY 5	Oset + external data
NuWro 2019	LFG	L-S + RPA	València	BS	BY + PY 6	Oset (pions) + NuWro (nucleons)
GiBUU 2019	LFG	GiBUU Model			BY + PY 6	BUU Equations

Tuning resonance, inelastic scatting cross sections into MC generators



PRD 104 (2021) 072009

GENIE's Shallow-Inelastic Scattering model

RES

- Rein-Sehgal or Bergher-Sehgal are the starting point
- Added additional resonances
- Dipole Parameterization

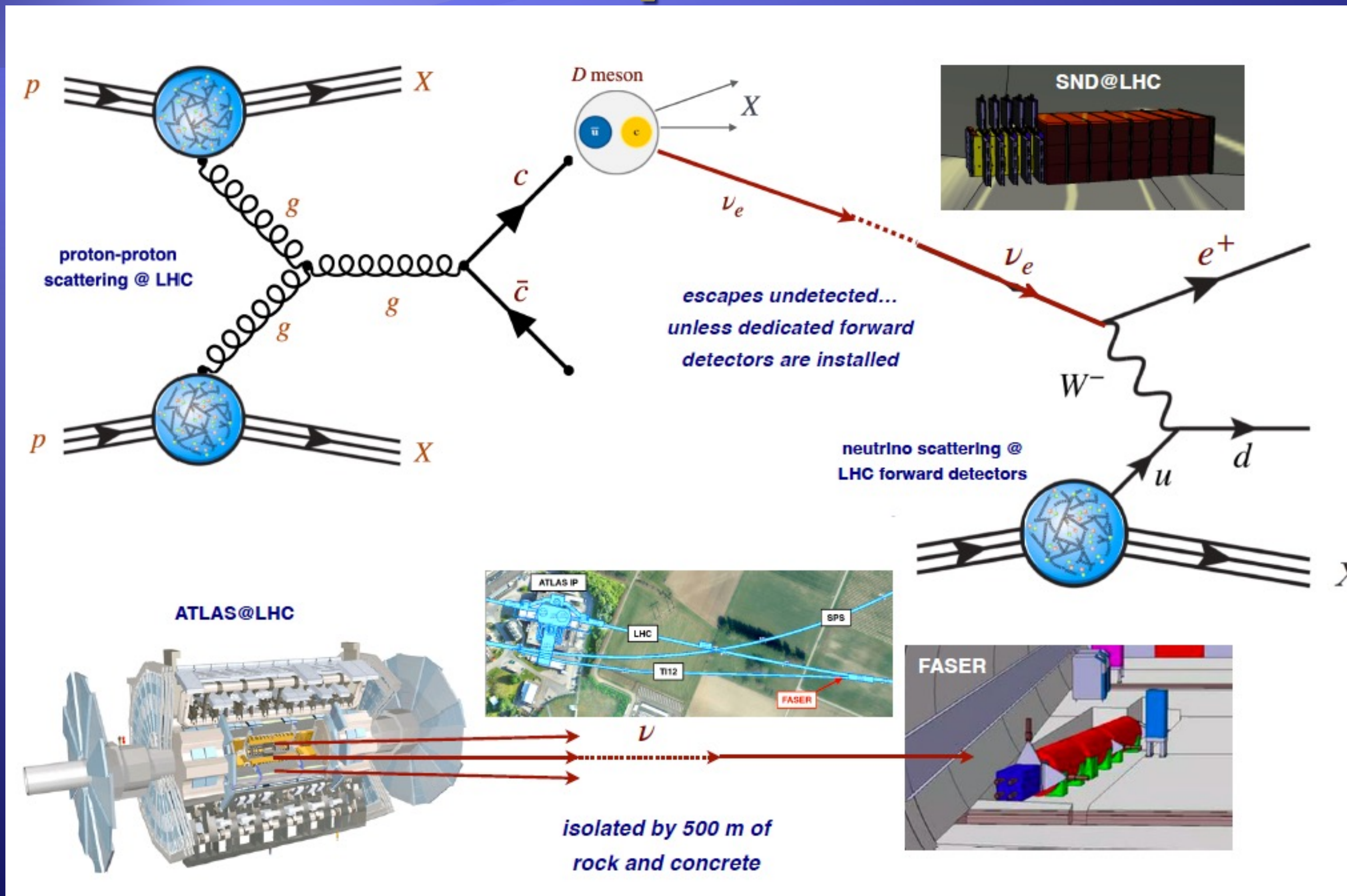
Non-resonant bkg

- Duality-based approach
- Scaled Bodek-Yang model
- Scaling factors depend on initial state and hadron multiplicity
- Coupled to low-W AGKY model

DIS

- Bodek-Yang model
- Cross-section calculation at partonic level
- AGKY hadronization model

TeV neutrinos at the LHC: Faser experiment



Faser at the LHC:

Presented in ICHEP 2024

PHYSICAL REVIEW LETTERS 133, 021802 (2024)

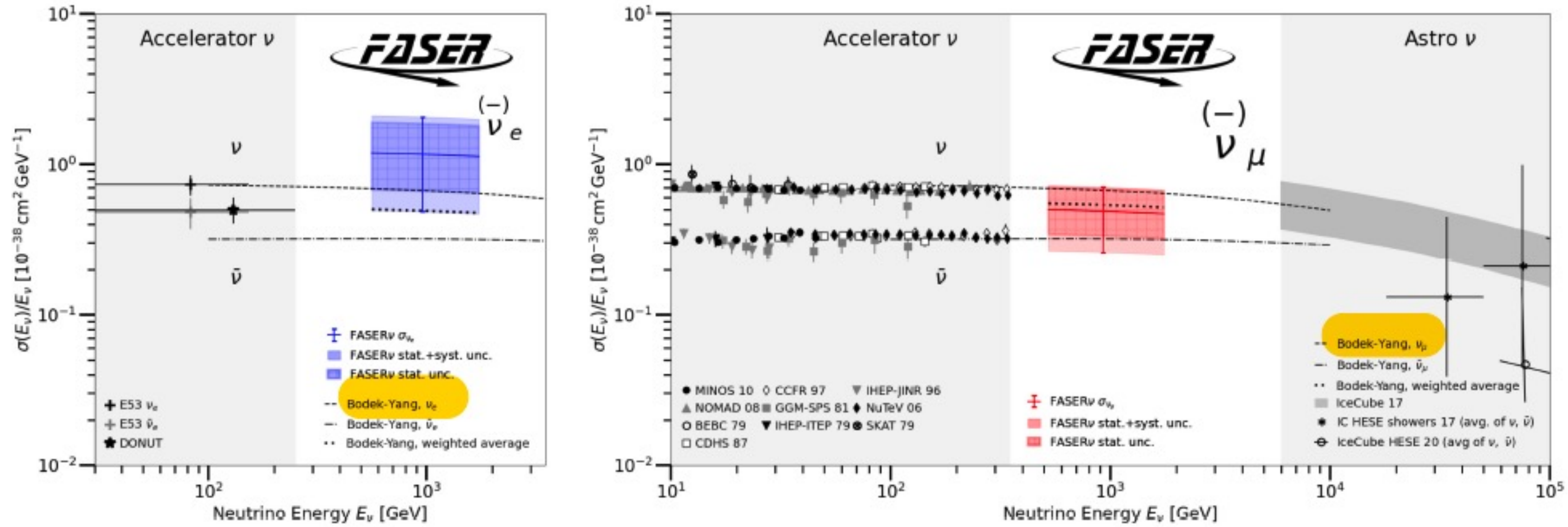
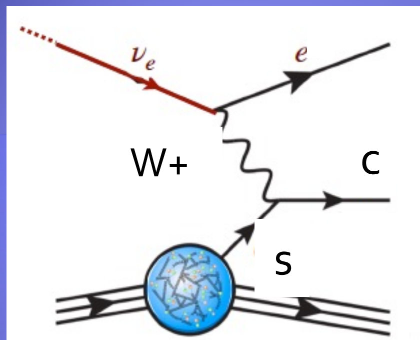
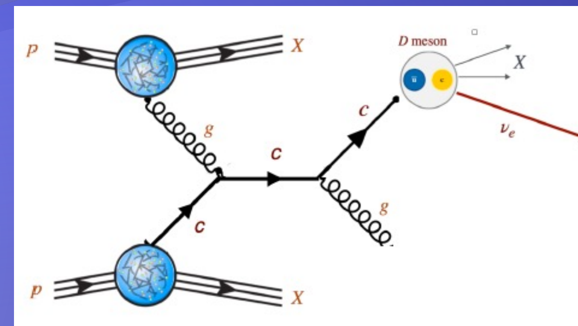
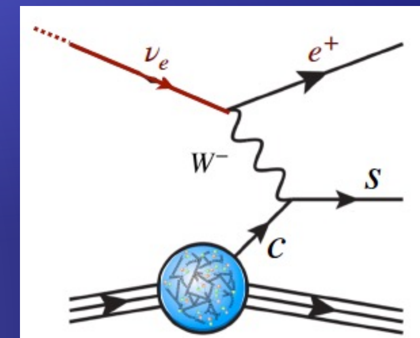


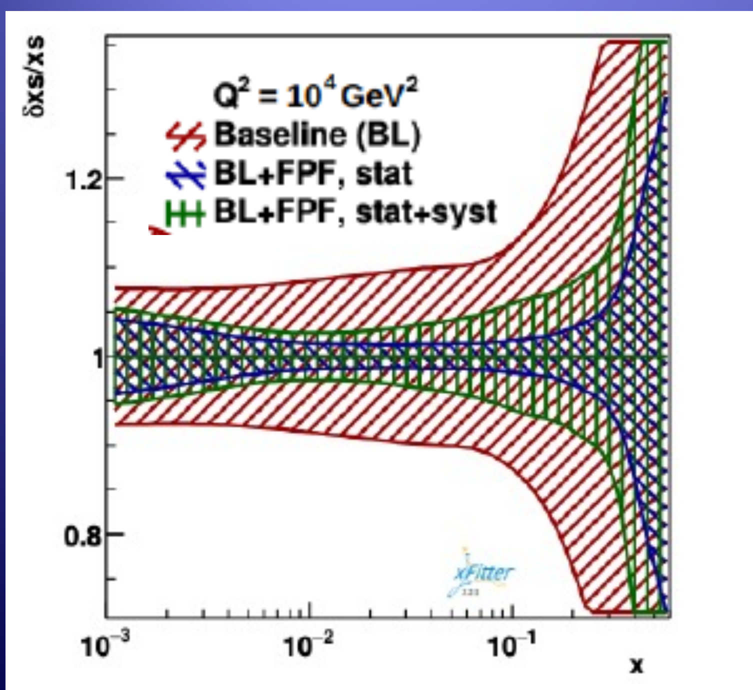
FIG. 4. The measured cross section per nucleon for ν_e (left) and ν_μ (right). The dashed contours labeled "Bodek-Yang" are cross sections predicted by the Bodek-Yang model, as implemented in GENIE. Note that the displayed experiments do not all use the same targets.

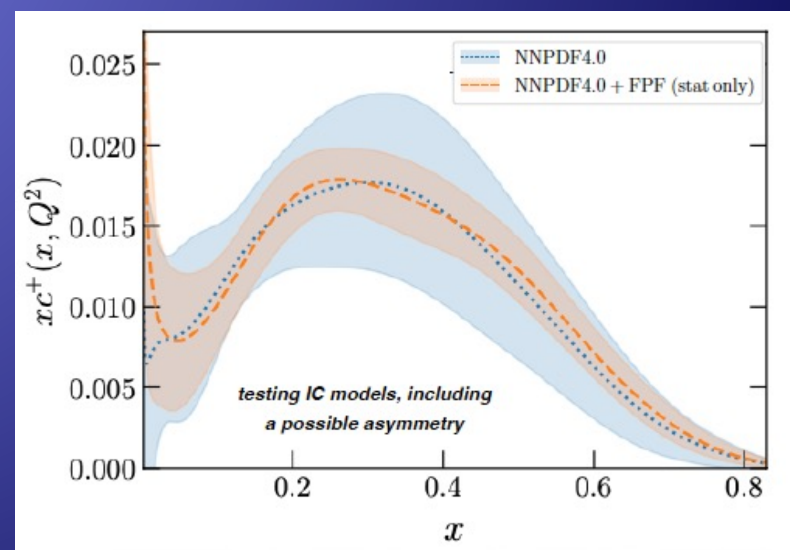
Impact of the LHC Neutrinos











Summary and Outlook

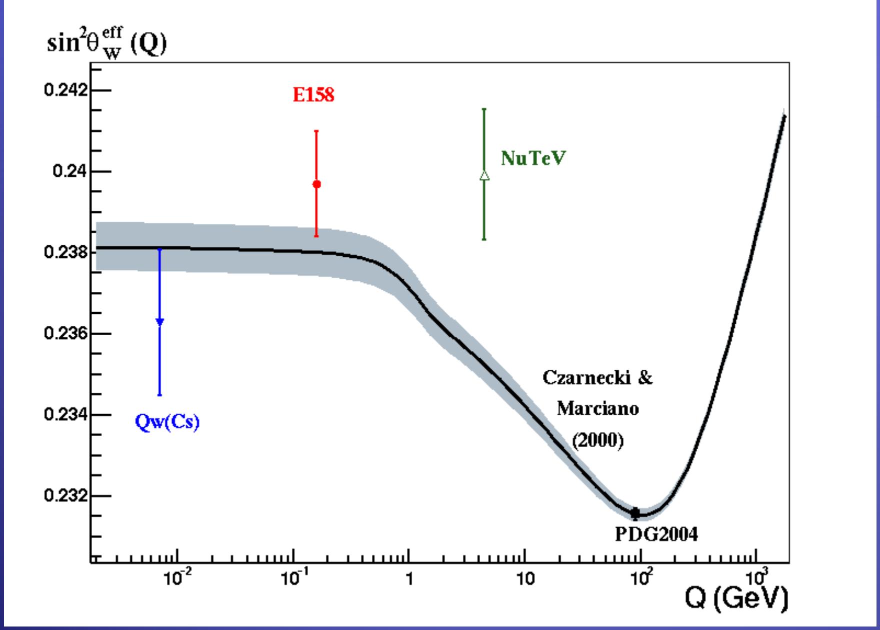
- Neutrino experiments have provided precision QCD studies using high energy and high intensity neutrino beams.
- Neutrino oscillation experiments brought new challenges in understanding neutrino interactions in low neutrino energy region
- Many improvements and important measurements have been made for last two decades in building models: resonance, SIS, DIS regions
- Bodek-Yang model have been used for DIS and DIS regions.
- For future neutrino oscillation experiments for DUNE, HyperK, it is important to understand following effects
    - Different nuclear effect in neutrino

      (LHC collider experiments, Drell-Yan, W, Z)
    - Axial vector contribution
    - Proper systematic treatments in old dataset is important
    - Inputs from LHC Forward Physics Programs will be useful

Thank You
Bodek-Yang

Backup slides

Precision Neutrino data: electroweak mixing angle (CC / NC ratio)



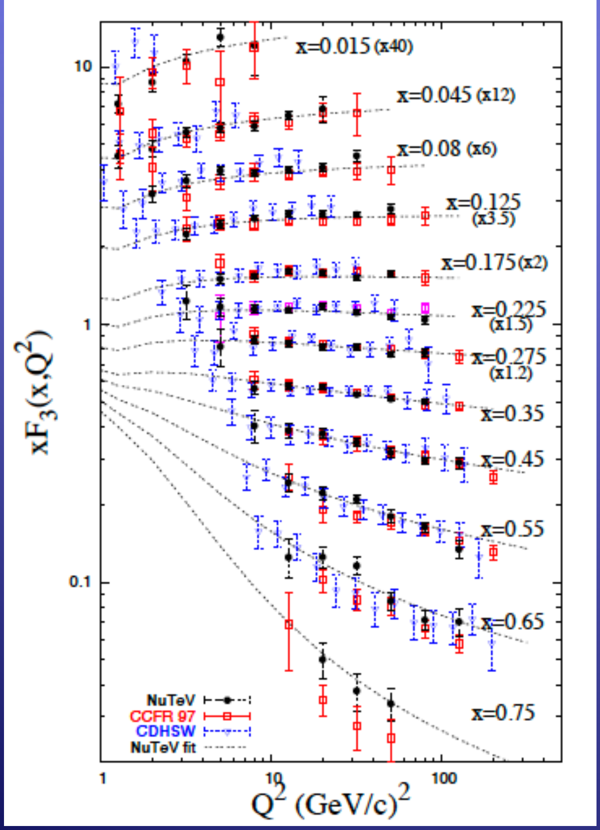
PRL 88 (2002) 091802

3σ effects bring many issues!

- Missing higher order QCD effect
- Different nuclear shadowing effect between NC and CC
- Charge symmetry violation
  (d quark pdf inside neutron
  vs u quark density inside proton)
- Asymmetry in strange sea
  (strange vs anti-strange quark)
- Possible to make an agreement within 1σ : PLB 693 (2010) 462 by Bentz et al.

Nuclear effect in neutrino?

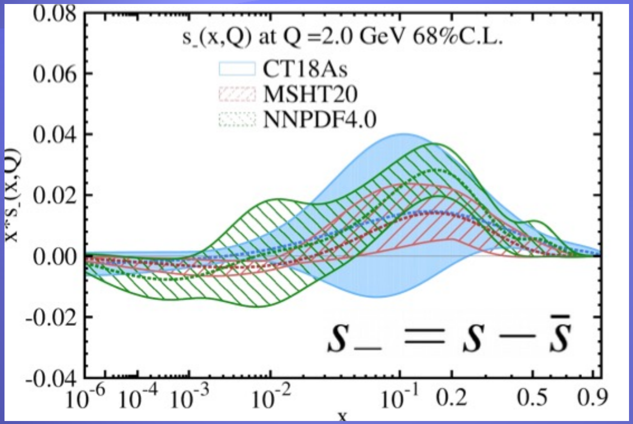
- Charged lepton scattering data (p,D) show good agreement with precision neutrino data in $0.01<x<0.6$ and $1<Q^2<100$ GeV^2
- But discrepancy shown in high x (>0.5) between CCFR and NuTeV data

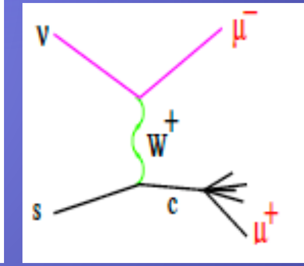


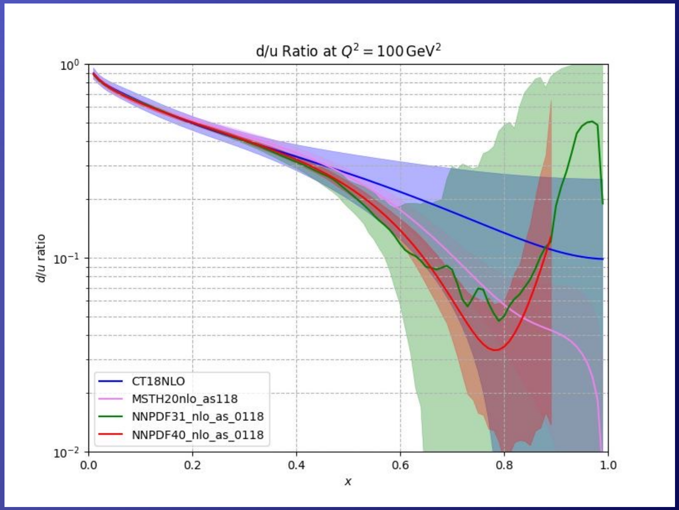
- NuTeV: refurbished CCFR detector, Better and precise calibration than CCFR calibrations
- Different neutrino effect at high x region?
- Future test will be necessary

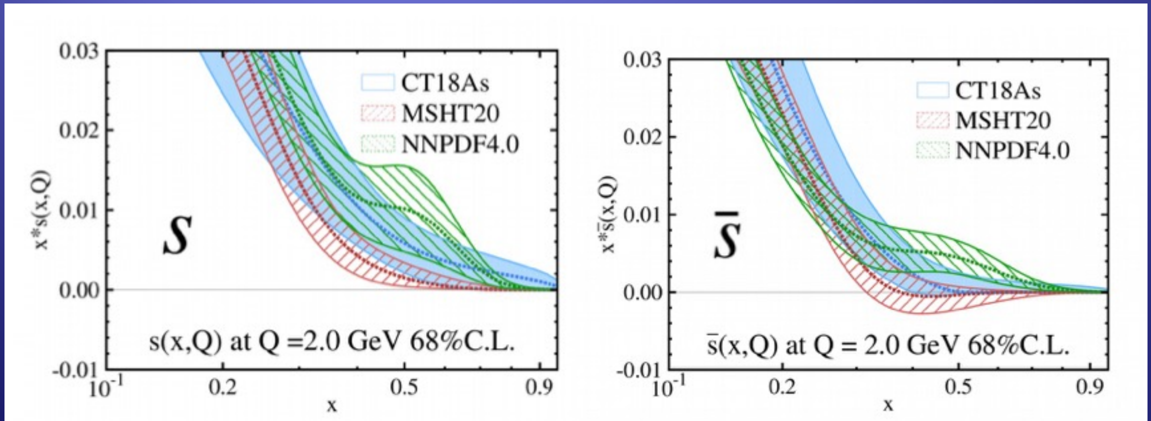
Asymmetry in strange quark

➢ Tension from ATLAS W/Z data and neutrino dimuon data









Hou, Huey-Wen Lin, Mengshi Yan, C.-P. Yuan, 2211.11064]

DUNE Cross Section Modeling

Cross Section Modeling

DUNE TDR Cross Section Model (Eur. Phys. J. C 80, 978 (2020))

- Example: DUNE TDR LBL Analysis
- All of the uncertainty in ν-Ar modeling is captured in these ~30 parameters
  - The LBL analysis implicitly assumes that every other part of the xsec model is correct
  - e.g. the shapes of the distributions modified by these parameters are assumed to be correct; they need only be scaled by a correct parameter value
- The ND fit can strongly constrain these parameters
  - DUNE ND will collect nearly 1M events per week
- It turns out to be very easy to constrain xsec errors beyond the level at which we trust our models (see next slides)
  - In the DUNE TDR analysis, non-zero xsec errors were achieved by choosing minimum-allowed values for detector errors

GENIE Xsec Parameters

Description	1σ
Quasielastic	
M_A^{QE}, Axial mass for CCQE	$^{+0.25}_{-0.15}$ GeV
QE FF, CCQE vector form factor shape	N/A
p_F Fermi surface momentum for Pauli blocking	±30%
Low W	
M_A^{RES}, Axial mass for CC resonance	±0.05 GeV
M_V^{RES} Vector mass for CC resonance	±10%
Δ-decay ang., θ_π from Δ decay (isotropic → R-S)	N/A
High W (BY model)	
A_{HT}, higher-twist in scaling variable ξ_w	±25%
B_{HT}, higher-twist in scaling variable ξ_w	±25%
C_{V1u}, valence GRV98 PDF correction	±30%
C_{V2u}, valence GRV98 PDF correction	±40%
Other neutral current	
M_A^{NCRES}, Axial mass for NC resonance	±10%
M_V^{NCRES}, Vector mass for NC resonance	±5%

GENIE FSI Parameters

Description	1σ
N. CEX, Nucleon charge exchange probability	±50%
N. EL, Nucleon elastic reaction probability	±30%
N. INEL, Nucleon inelastic reaction probability	±40%
N. ABS, Nucleon absorption probability	±20%
N. PROD, Nucleon π-production probability	±20%
π CEX, π charge exchange probability	±50%
π EL, π elastic reaction probability	±10%
π INEL, π inelastic reaction probability	±40%
π ABS, π absorption probability	±20%
π PROD, π π-production probability	±20%

Additional Xsec Parameters

Uncertainty	Mode
BeRPA [A,B,D]	$1p1h$/QE
ArC2$p2h$ [ν,$\bar{\nu}$]	$2p2h$
E_{2p2h} [A,B] [ν,$\bar{\nu}$]	$2p2h$
NR [ν,$\bar{\nu}$] [CC,NC] [n,p] [1π,2π,3π]	Non-res. pion
ν_e PS	ν_e,$\overline{\nu}_e$ inclusive
$\nu_e/\overline{\nu}_e$ norm	ν_e,$\overline{\nu}_e$ inclusive
NC norm.	NC