QCD for Precision Neutrino Physics

DIS2024

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XXXI International Workshop on Deep Inelastic Scattering

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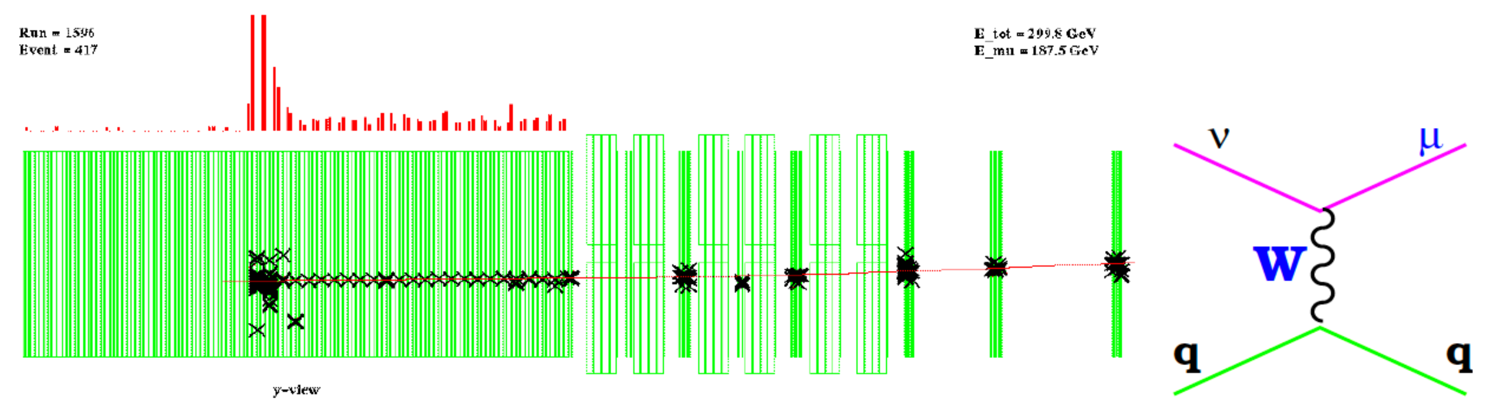
Precision QCD in neutrino

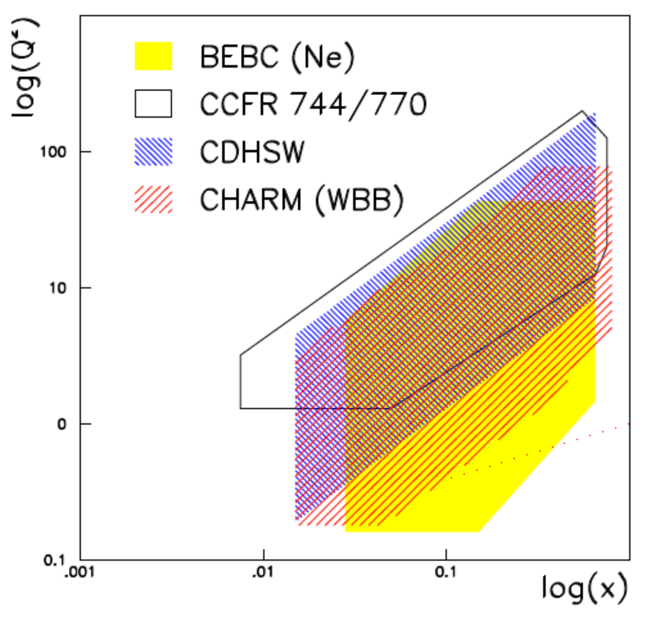
- High Energy Neutrino beam allows precision QCD studies in 1980~2000: CDHSW, BEPC, CHARM,CHORUS, CCFR, NuTeV



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

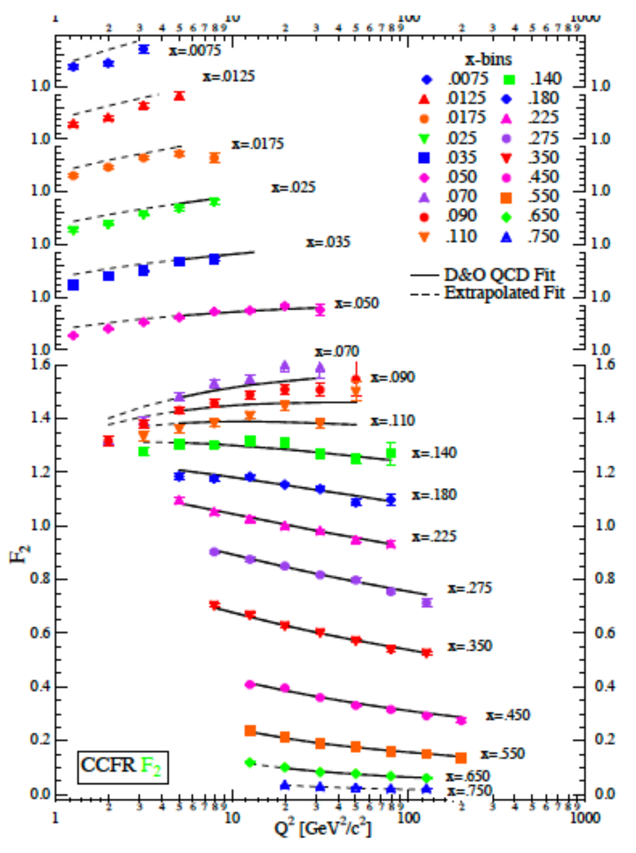
$$F_{2,LO} = \sum_{i=u,d.} xq_i(x,Q^2) + x\overline{q_i}(x,Q^2)$$

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



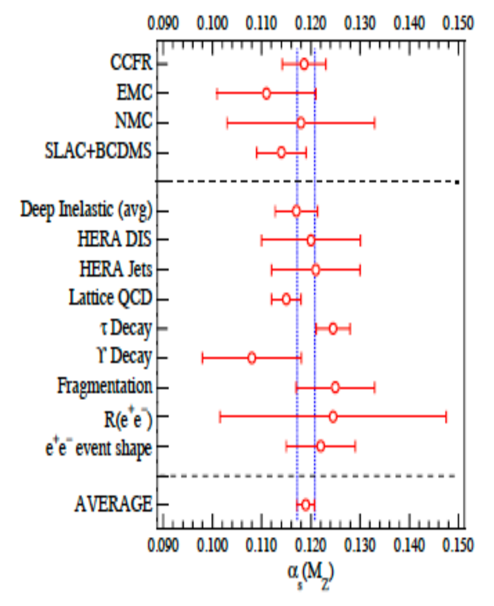
Precision QCD using neutinos

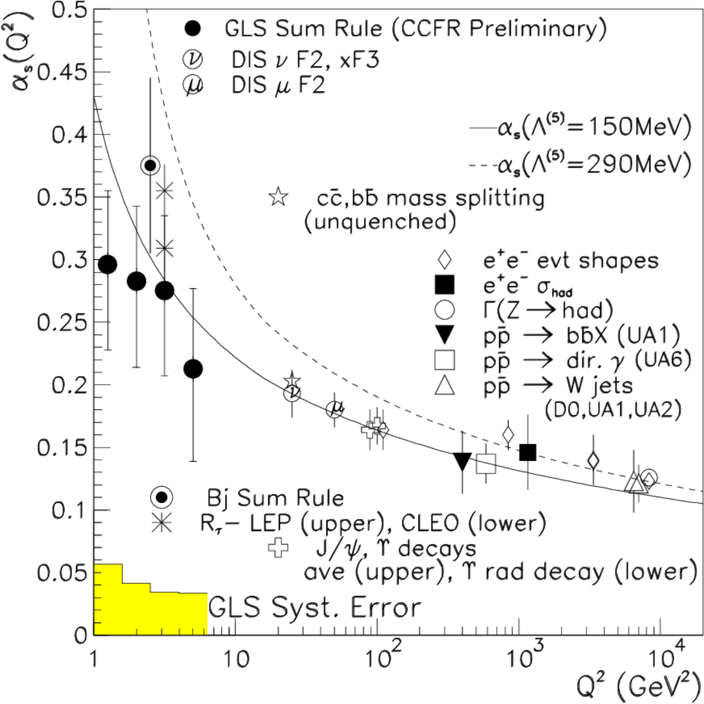
- High statistics high E neutrino data: CC and NC



$$\frac{dq^{NS}(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\, q^{NS}(y,Q^2)P_{qq}(x/y),$$

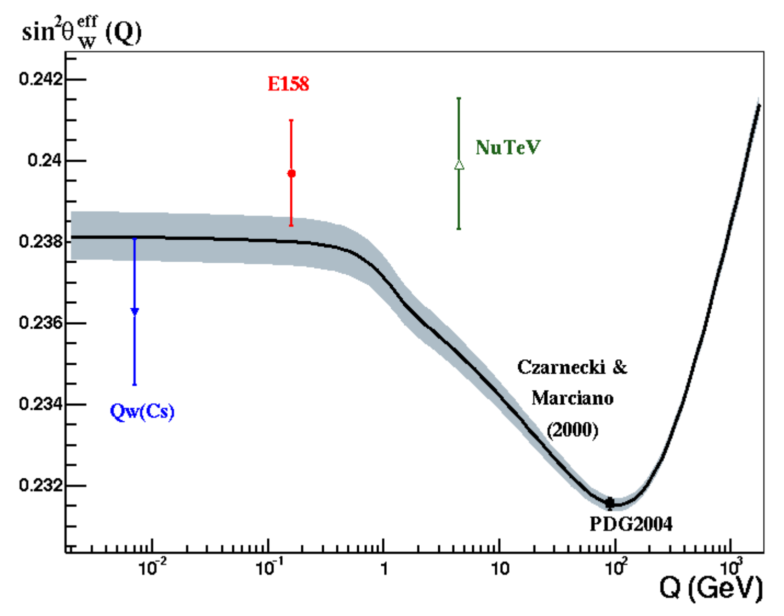
$$\frac{dq^{S}(x,Q^2)}{d\ln Q^2} = \frac{\alpha_S(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\, \left[q^{S}(y,Q^2)P^{S}_{qq}(x/y) + G(y,Q^2)P_{qG}(x/y)\right],$$





$$\int_0^1 xF_3(x,Q^2)\frac{dx}{x} = 3\left(1-\frac{\alpha_s}{\pi} - a(n_f)\left(\frac{\alpha_s}{\pi}\right)^2 - b(n_f)\left(\frac{\alpha_s}{\pi}\right)^3\right)$$

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



PRL 88 (2002) 091802

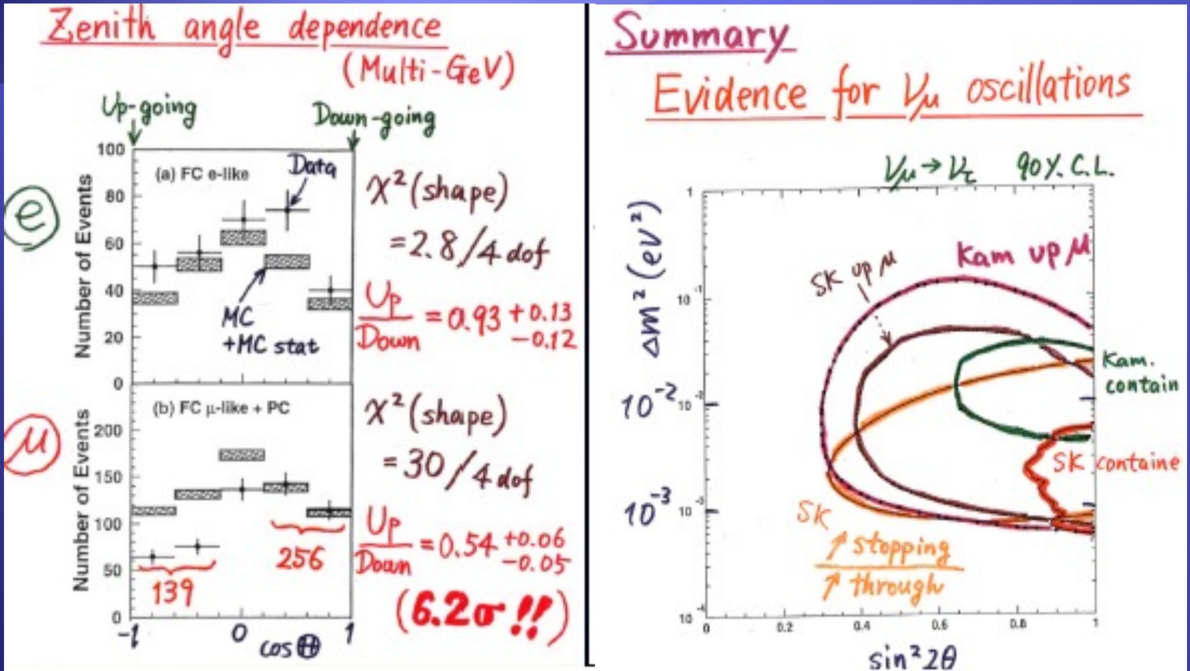
3σ effects bring many issues!

- Missing higher order QCD effect
- Different nuclear shadowing effect between NC and CC
- Charge symmetry violation

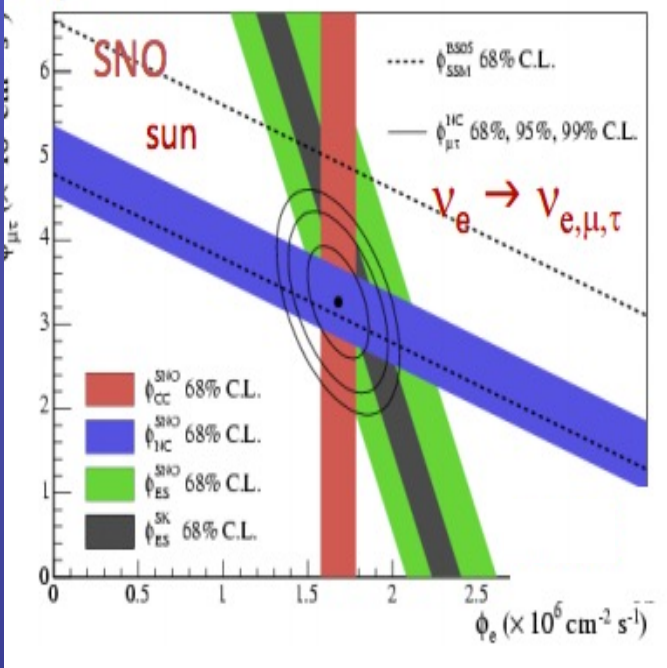
  (d_n vs u_p)
- Asymmetry in strange sea

  (s vs sbar)
- Possible to make an agreement within 1σ : PLB 693 (2010) 462 by Bentz et al.

Neutrino Oscillations discovered



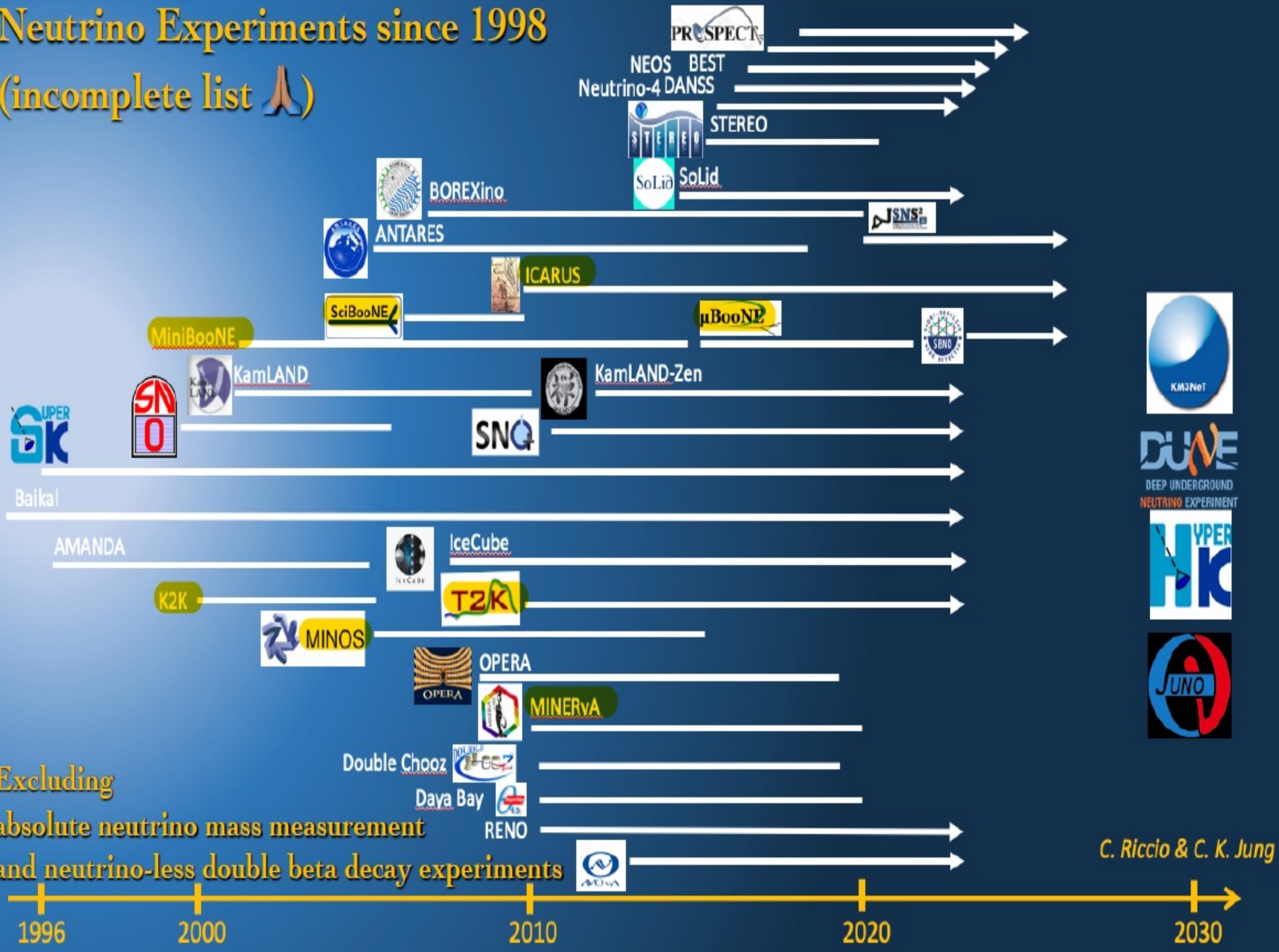
Neutrino 1998 by Kajita



2002 by SNO

- Neutrino Oscillations Brings Precision Neutrino Physics in QCD, but in Eν = few GeV region

Neutrino Experiments since 1998
(incomplete list 🙏)



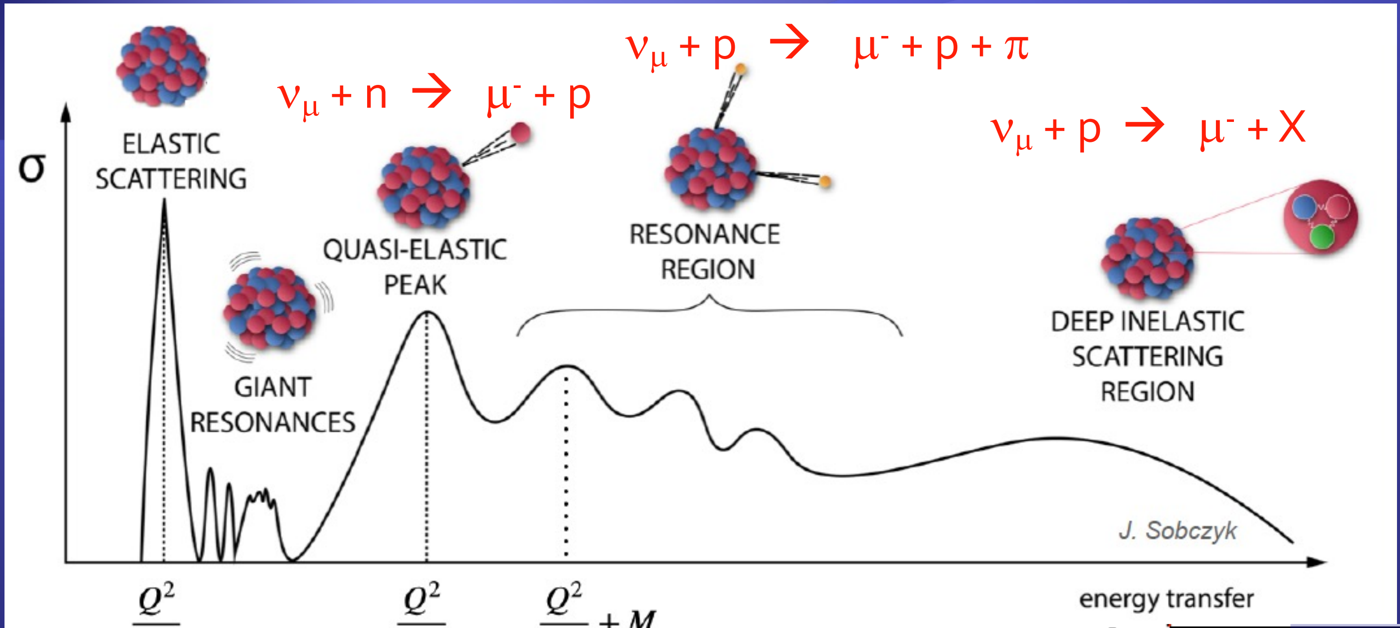
Excluding
absolute neutrino mass measurement
and neutrino-less double beta decay experiments

C. Riccio & C. K. Jung

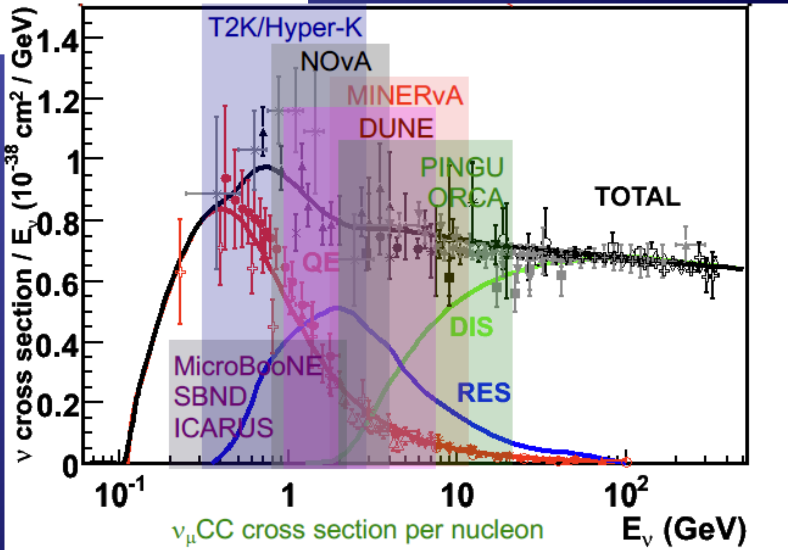
Physics Goals with Neutrinos

- 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



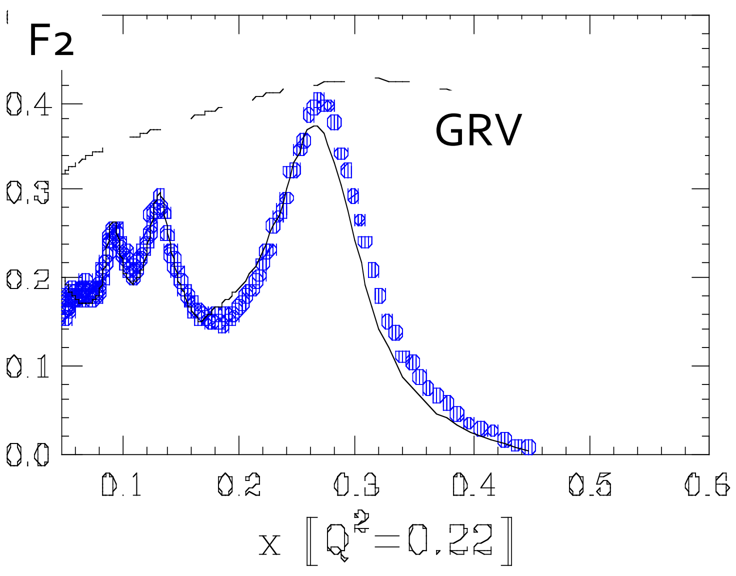
- Neutrino oscillation experiments: beam energies from 0.1 to 10 GeV
- Resonance region overlapped with DIS region
- DIS region is mostly in non-pQCD region



ν_μCC cross section per nucleon

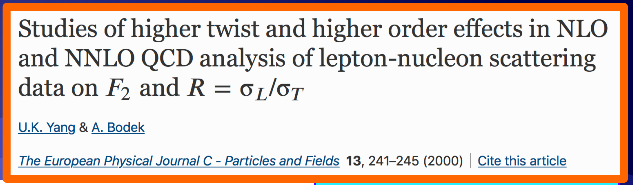
Modeling ν cross sections

- Bodek-Yang model: to describe DIS cross section in all Q^2 regions
- Challenges in e/μ-N DIS
  - High x PDFs at low Q^2
  - Resonance region overlapped with a DIS contribution
  - Hard to extrapolate DIS contribution to low Q^2 region from high Q^2 data due to non-perturbative QCD effects



- NNLO pQCD+TM with NNLO PDFs can describe non-perturbative QCD effects at low Q^2
- Thus, we reverse the approach to build the model: Use LO PDFs and "effective target mass and final state masses" to account for initial, final target mass, and even missing higher orders

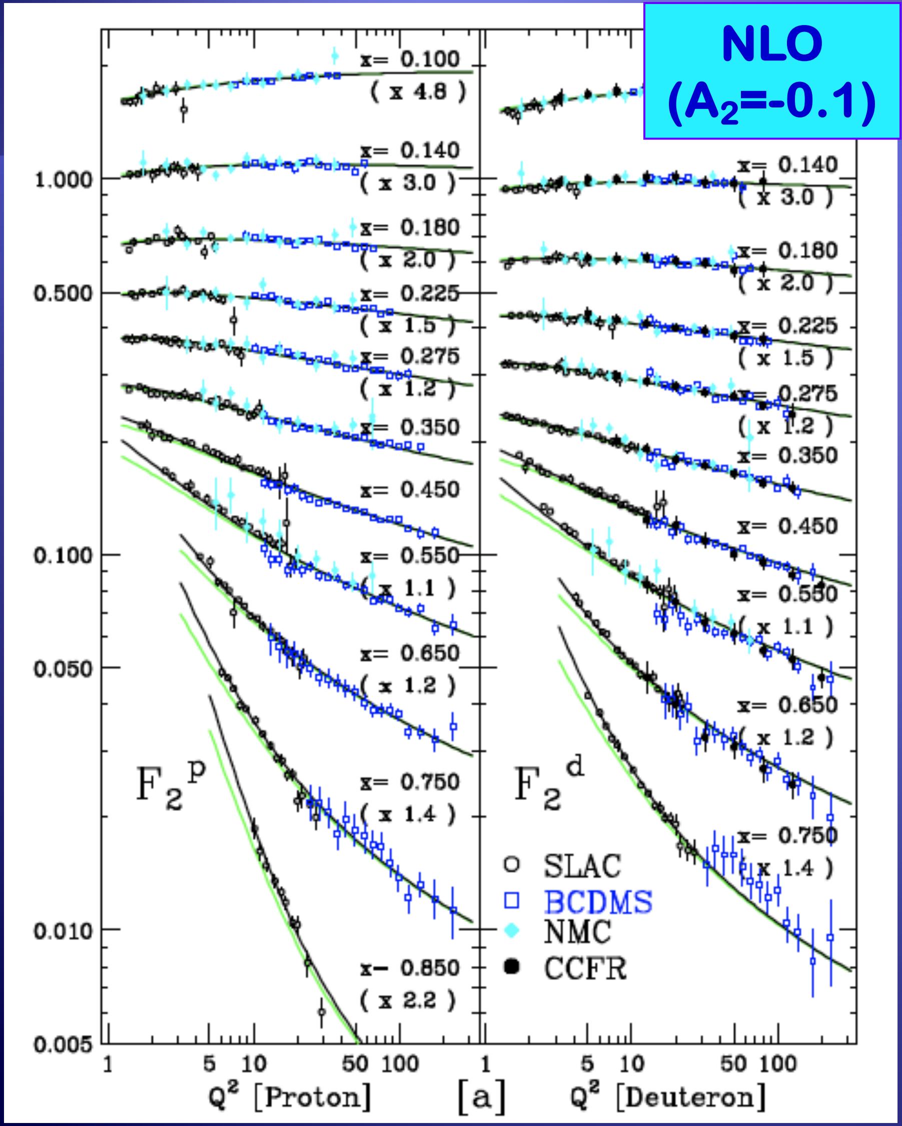
Higher Twist effect: NLO vs NNLO



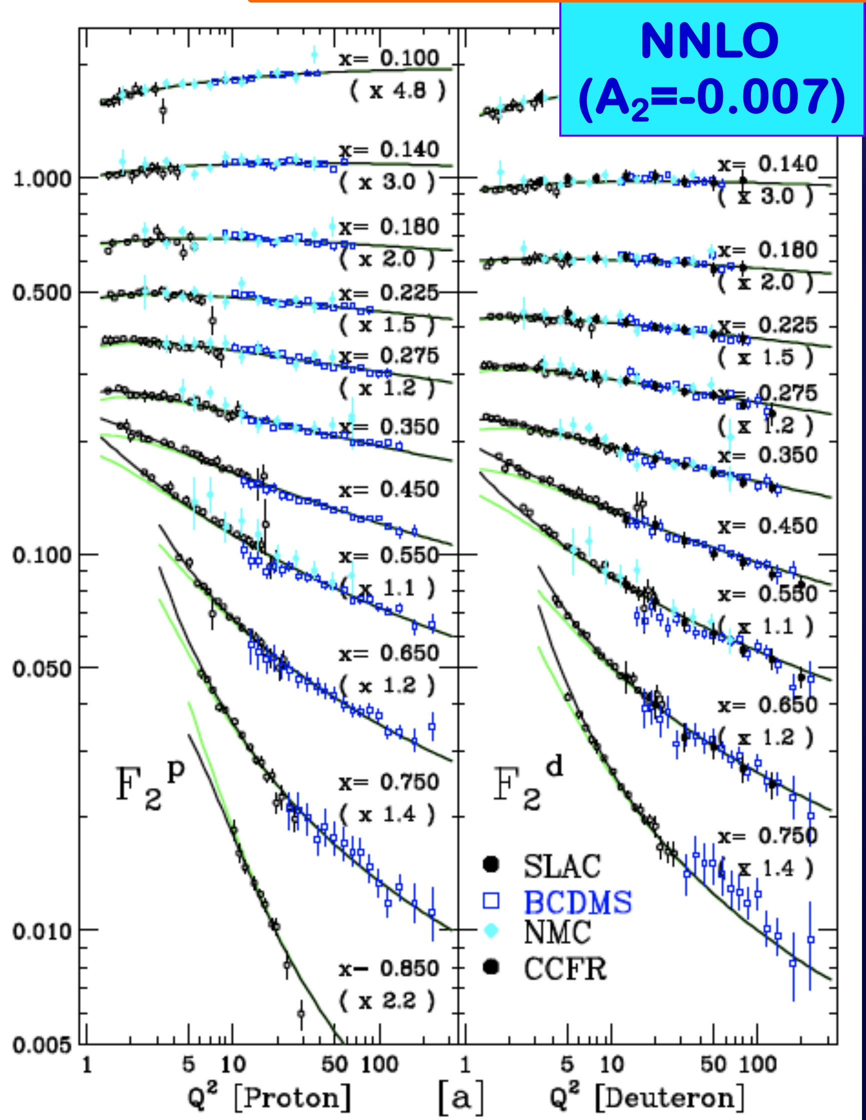
Studies of higher twist and higher order effects in NLO and NNLO QCD analysis of lepton-nucleon scattering data on F_2 and $R = \sigma_L/\sigma_T$

U.K. Yang & A. Bodek

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

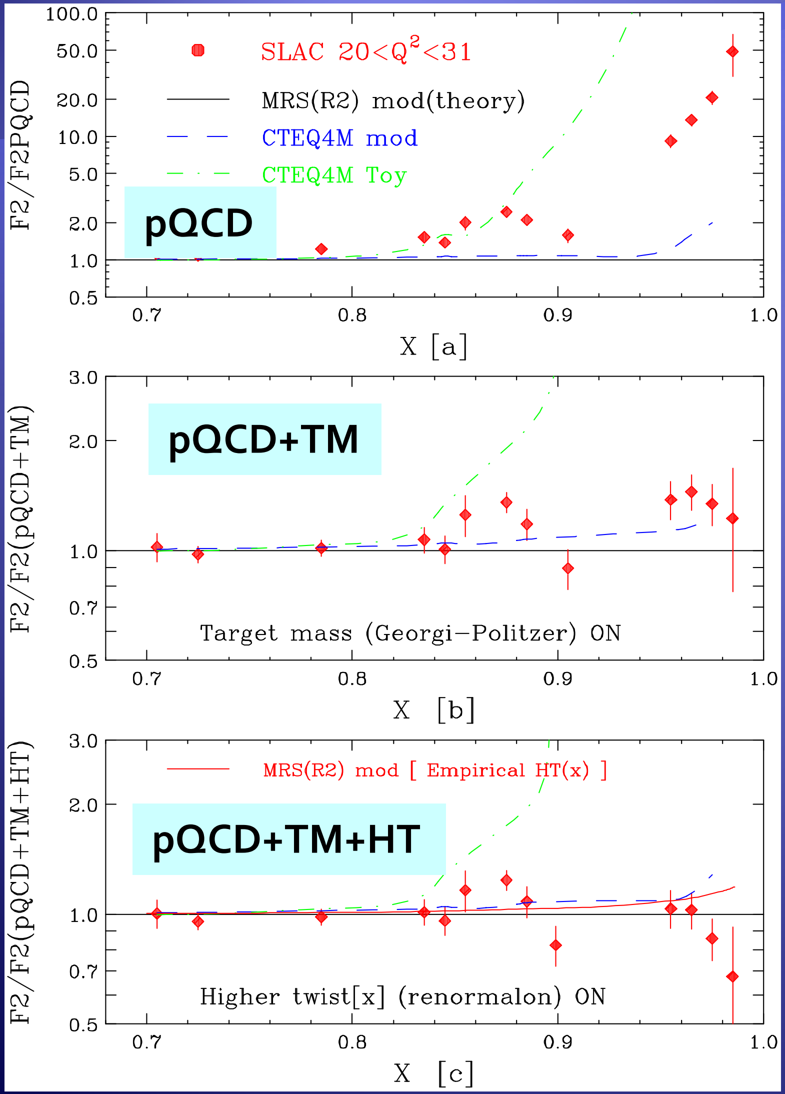


NLO (A_2=-0.1)



NNLO (A_2=-0.007)

Very high x and low Q^2 data



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 (2024)

Modeling ν Cross Sections

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

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

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

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

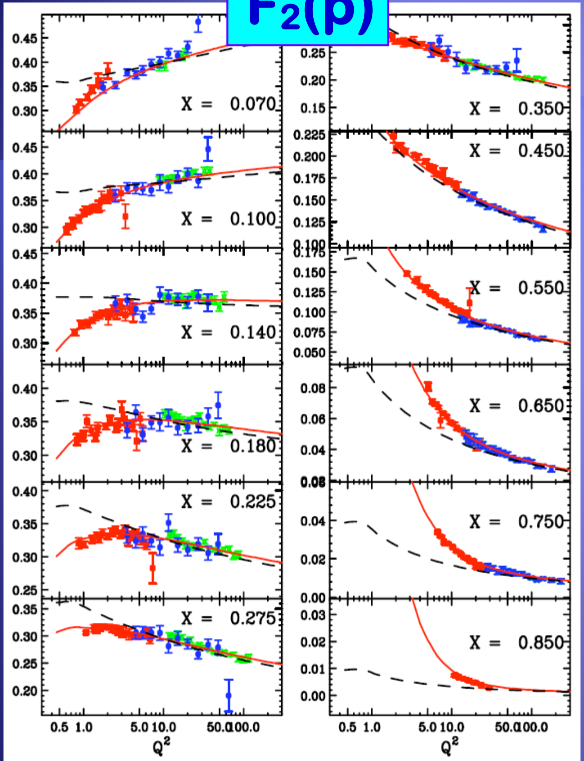
- Kval (u,d) = $[1 - G_D^{\,2}(Q^2)] * [Q^2 + C_{2V}] / [Q^2 + C_{1V}]$,

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

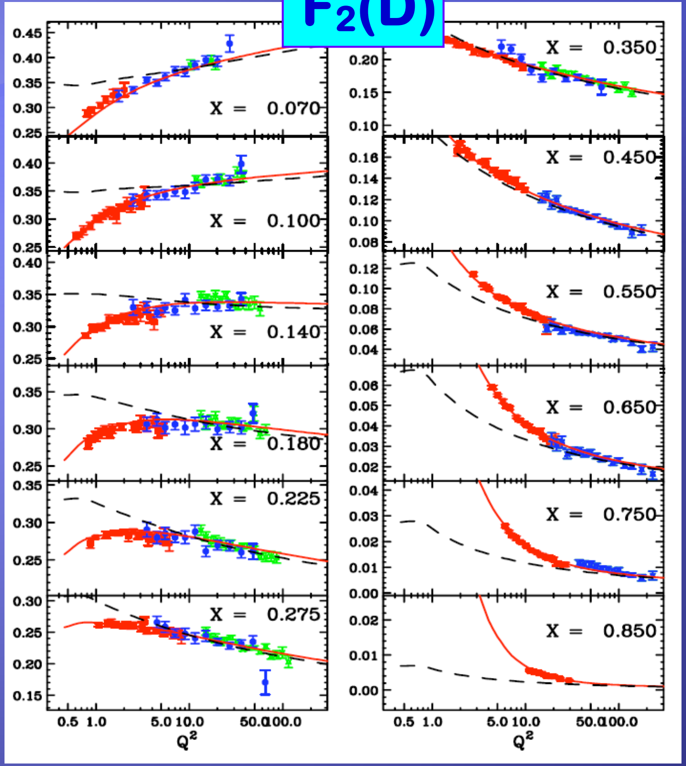
- Ksea (u,d,s) = $Q^2/[Q^2 + Csea]$

Fit Results and Predictions

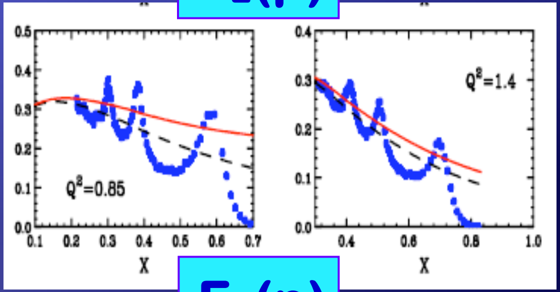
$F_2(p)$



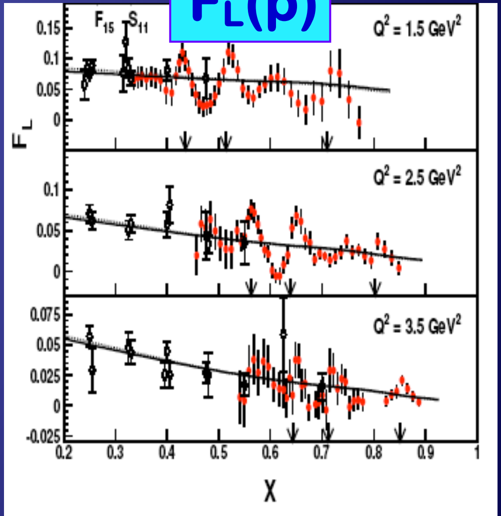
$F_2(D)$

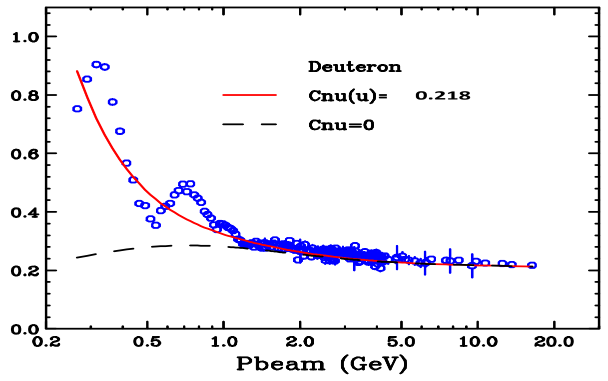


$F_2(p)$



$F_L(p)$





- Excellent Fitting:
  - red solid line: effective LO using ξw
  - black dashed line: x_{bj}

Axial Vector Structure Functions

- At high Q^2 , vector and axial vector contribution are same, but not at low Q2
- K factors for axial contributions: type II

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

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

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

- 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

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

Neutrino cross sections

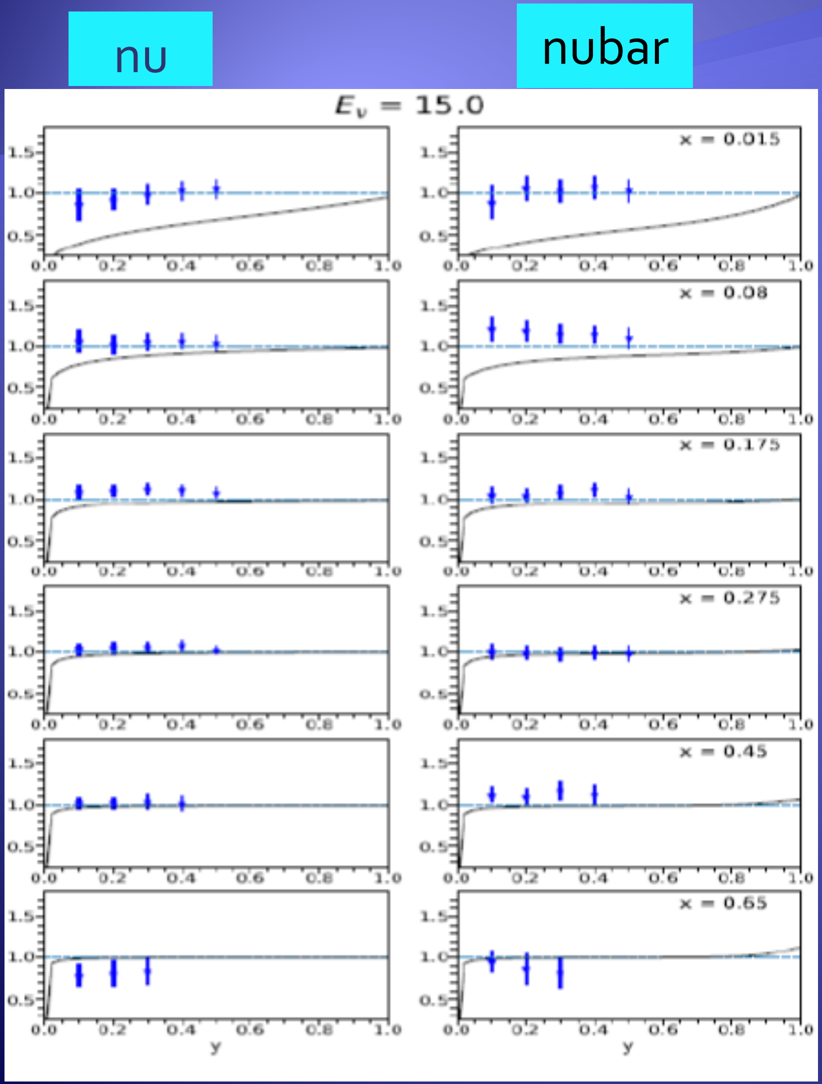
- Effective LO model with ξw describe all DIS and resonance F_2 data as well as photo-production data ($Q^2=0$ limit): vector contribution works well
- Neutrino Scattering:
  - Effective LO model works for xF_3? Yes with NLO f(x)
  - Nuclear correction using e/μ scattering data
  - Axial vector contribution at low Q^2?

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

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

  - Use $R=R_{1998}$ to get $2xF_1$
  - Implement charm mass effect through ξw slow rescaling algorithm for F_2, $2xF_1$, and xF_3

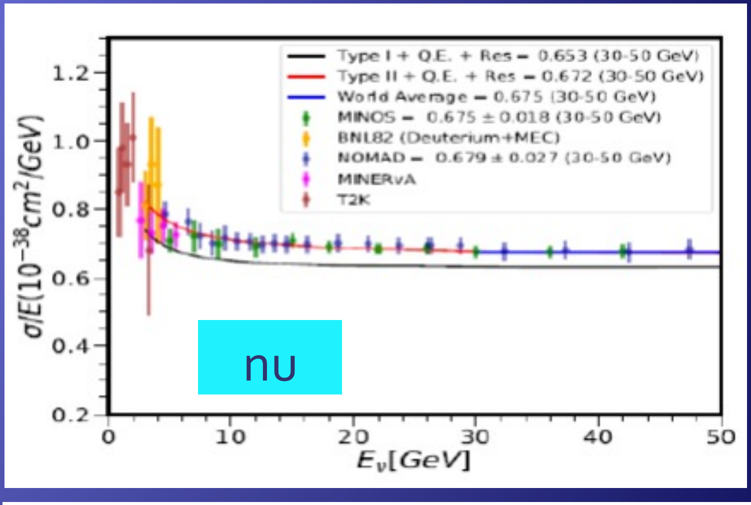
Comparison with CCFR (Fe), CHORUS (Pb) data

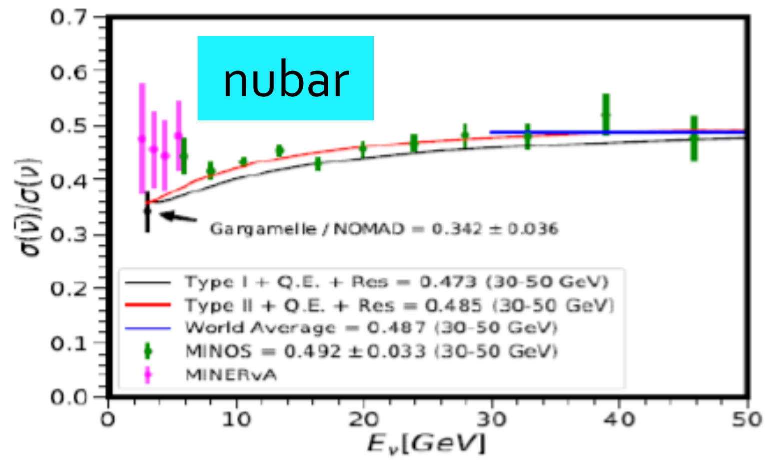


- Blue point: CHORUS/theory (type II)
- Solid line:theory (type I)/(type II)

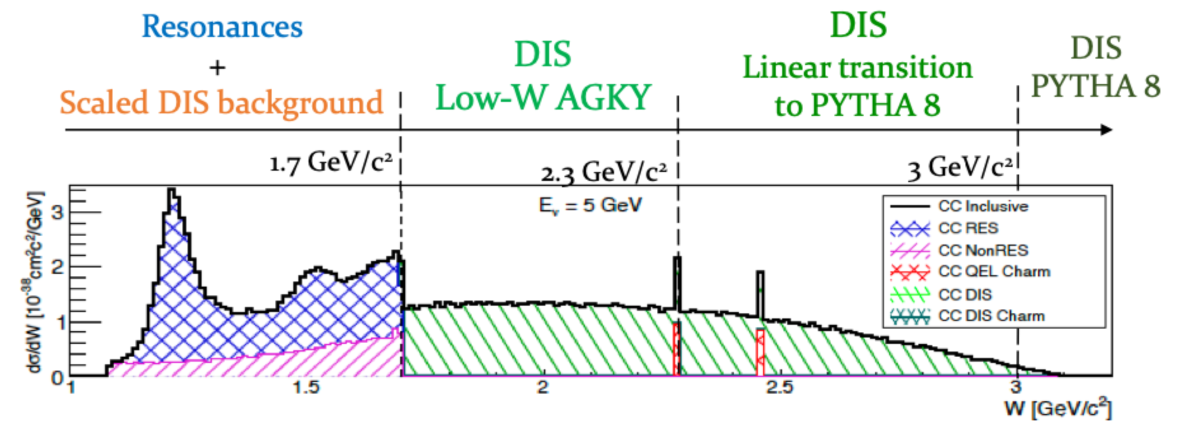
\- Type I (Vector = Axial at low Q^2)

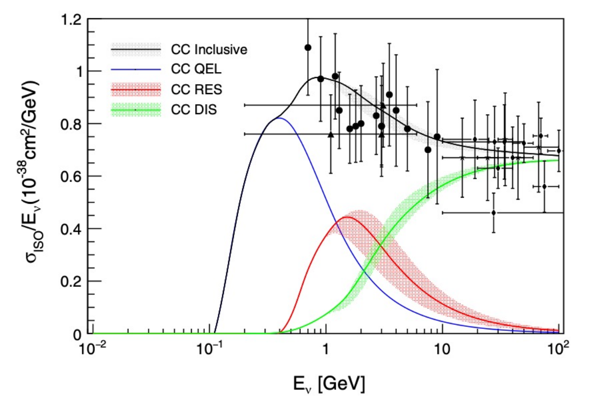
\- Type II (Vector < Axial at low Q^2)





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

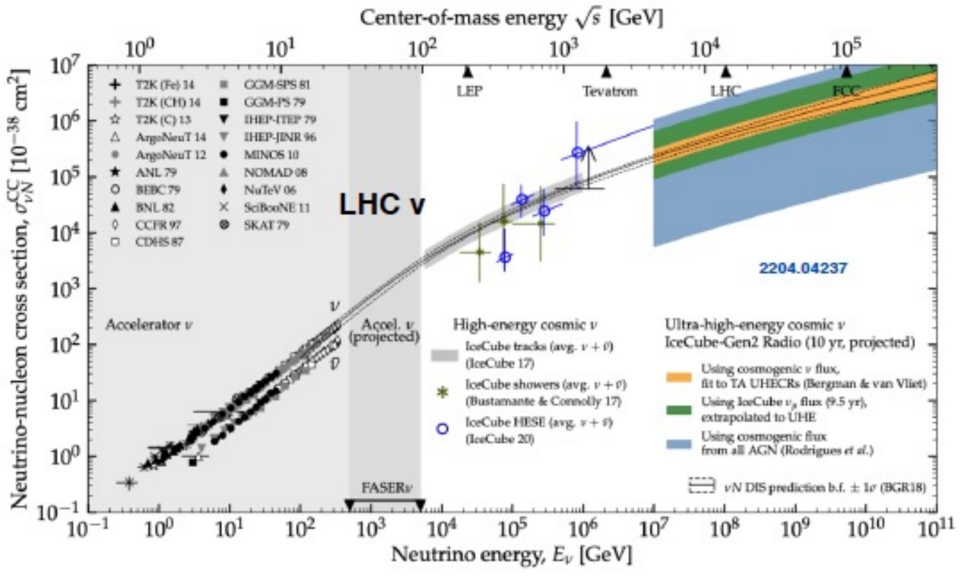
- Duality-based approach
- Scaled Bodek-Yang model
- Scaling factors depend on initial state and hadron multiplicity
- Coupled to low-W AGKY model

DIS

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

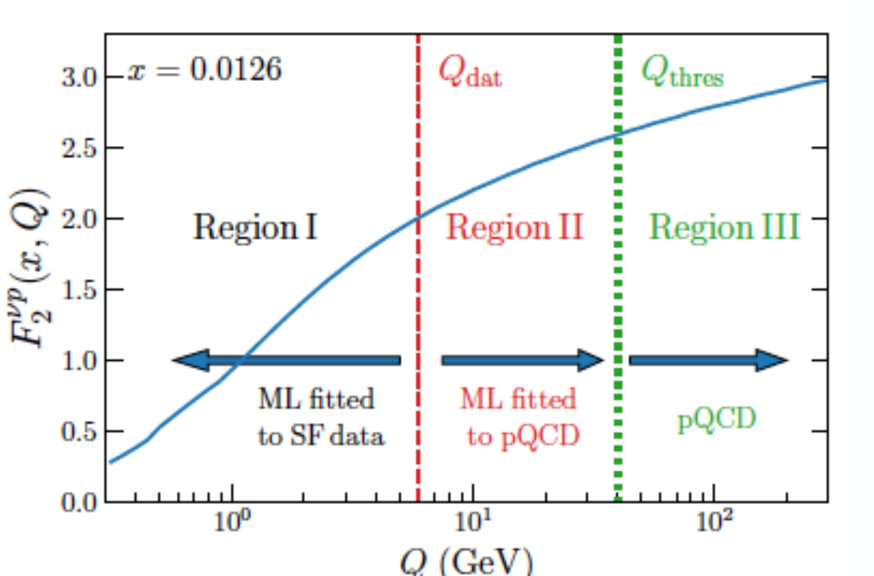
Noble Approach using NN: Neutrino SFs from GeV to EeV

JHEP 05 (2023) 149
By J. Rojo et al

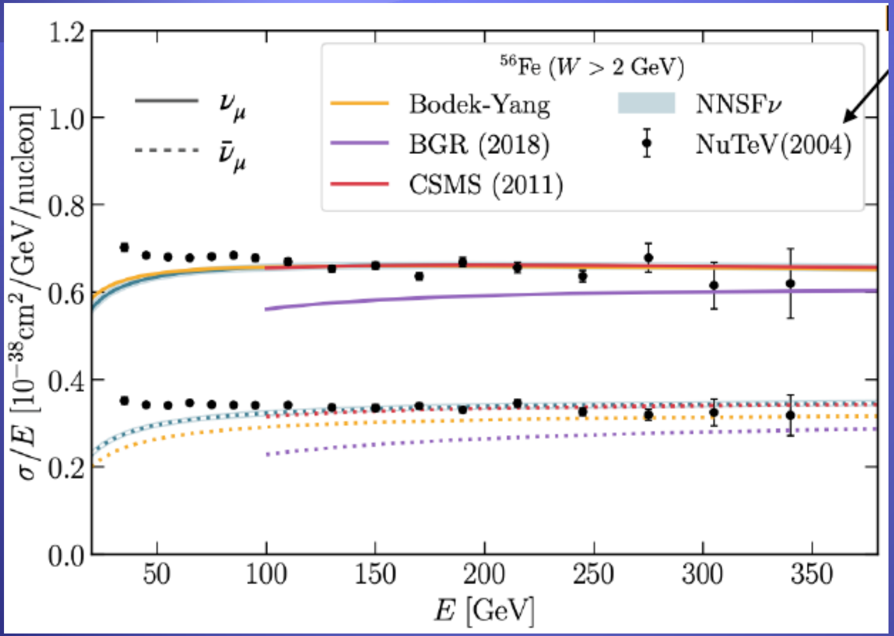


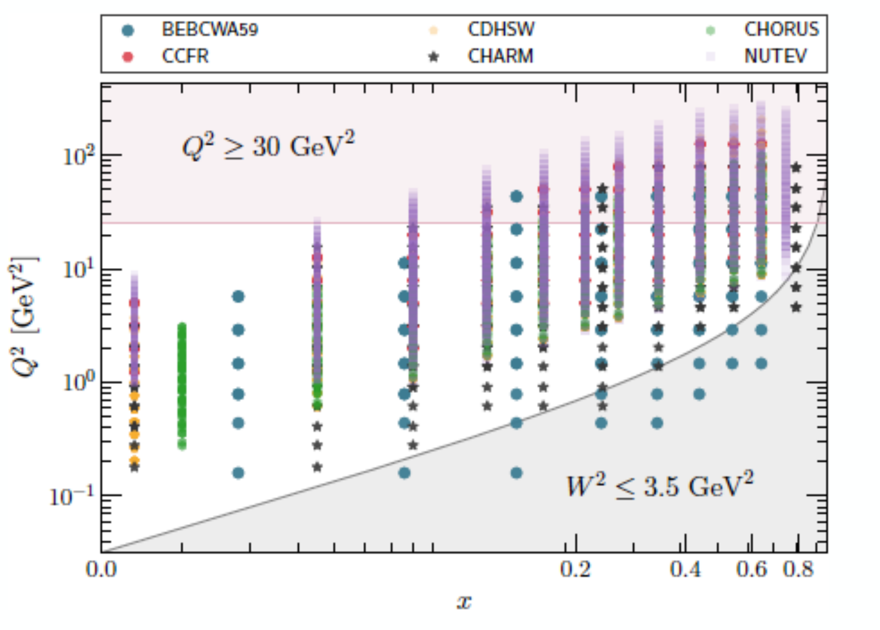
- ➢ Many efforts to model High energy cross
- ➢ For En=10-100 GeV region, 10~20% contribution from Q<1 GeV region, facing non-pQCD problem

- ➢ A new method to account for non-pQCD terms
  - Machine learning parameterization of low Q2 using neutrino data
  - High Q2 regions from pQCD



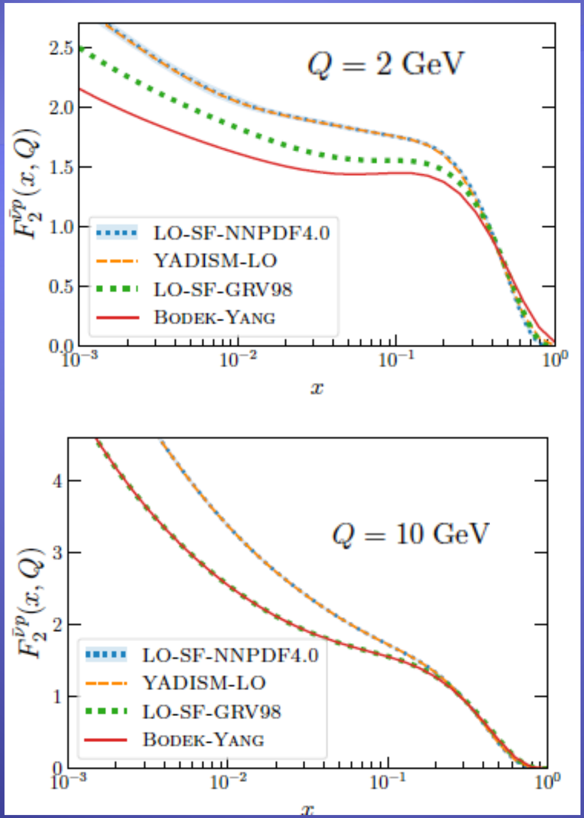
Noble Approach using NN: NNSFν

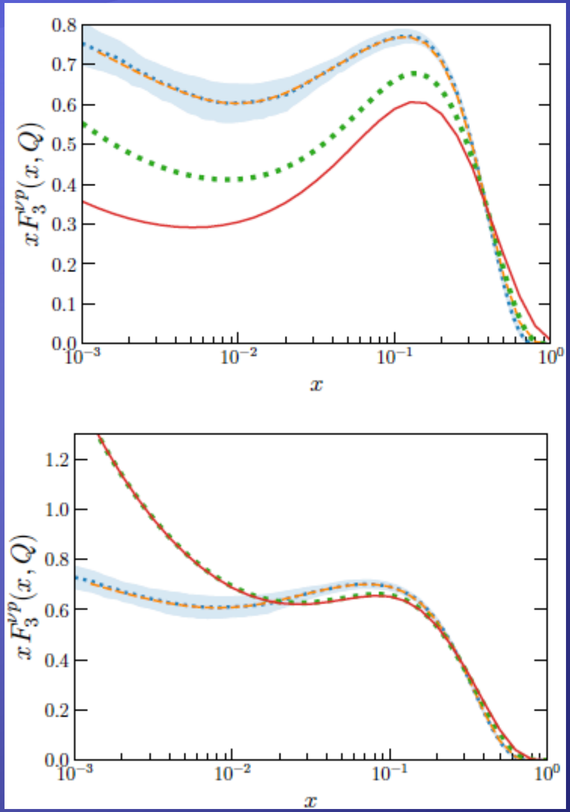




- ➢ NNSFν :good agreement with NuTeV data
- ➢ Bodek-Yang: lower in anti-neutrino data (perhaps due to mixing NLO correction f(x)

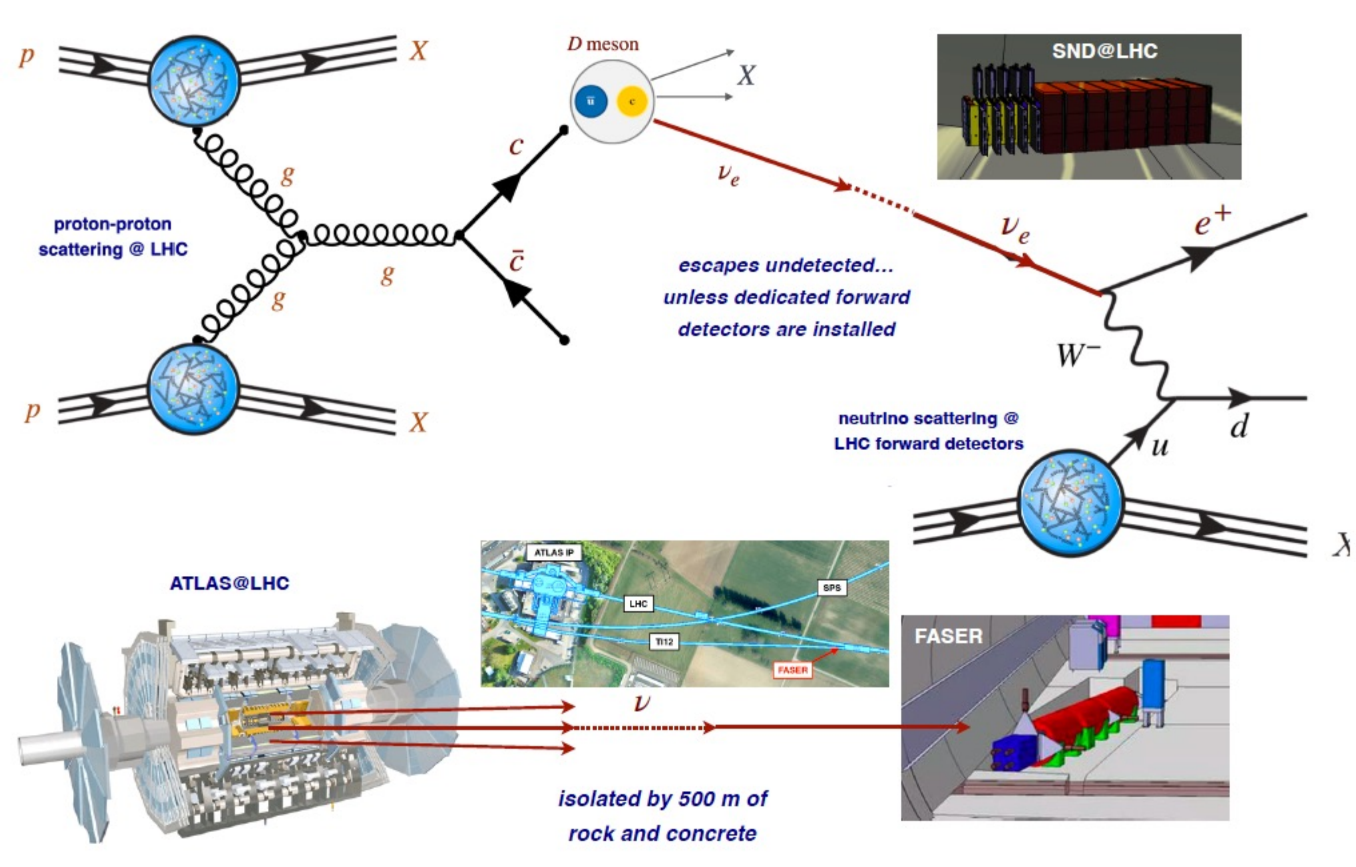
Precision Neutrino Physics Era

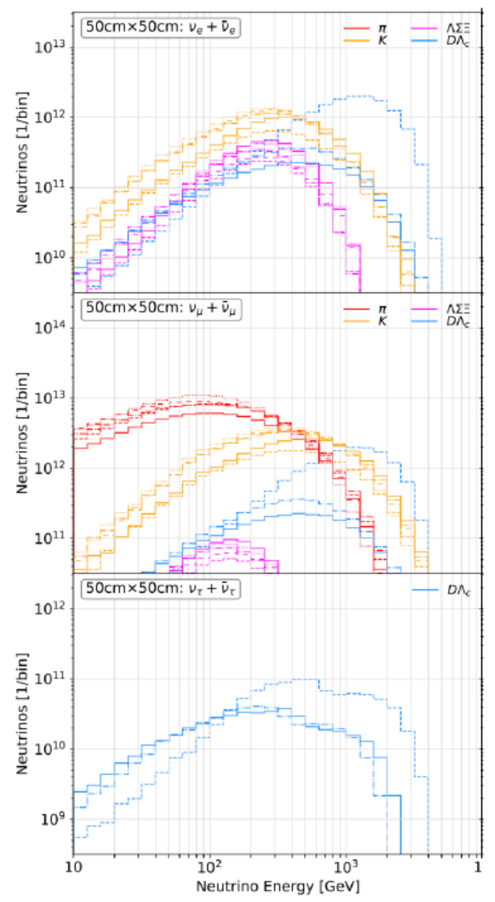




- ➢ Bodek-Yang: lower than NNSFν for x=0.1
  - Developed for neutrino oscillation experiments in few GeV region (x>0.1 and low Q^2 region)
  - Charm contribution needs to be added by FFS calculation in GRV98
- ➢ NNSFν : lower at very high x than BY for Q= 2GeV (not enough data trained for target mass effect?

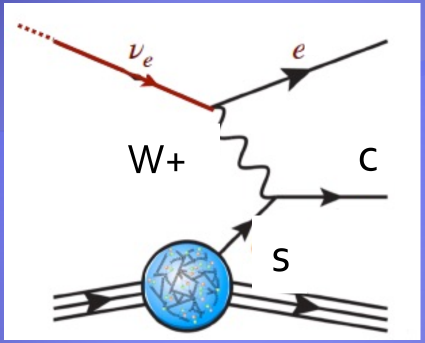
Neutrinos at the LHC

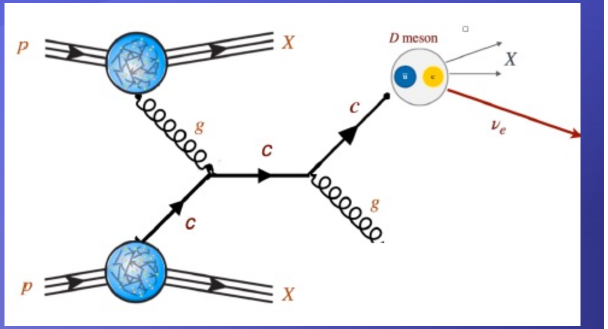


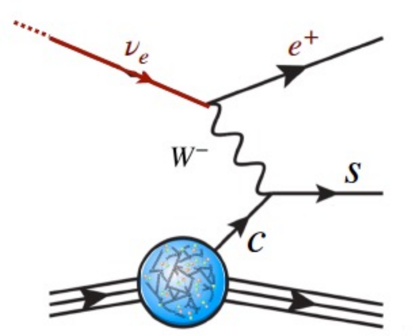


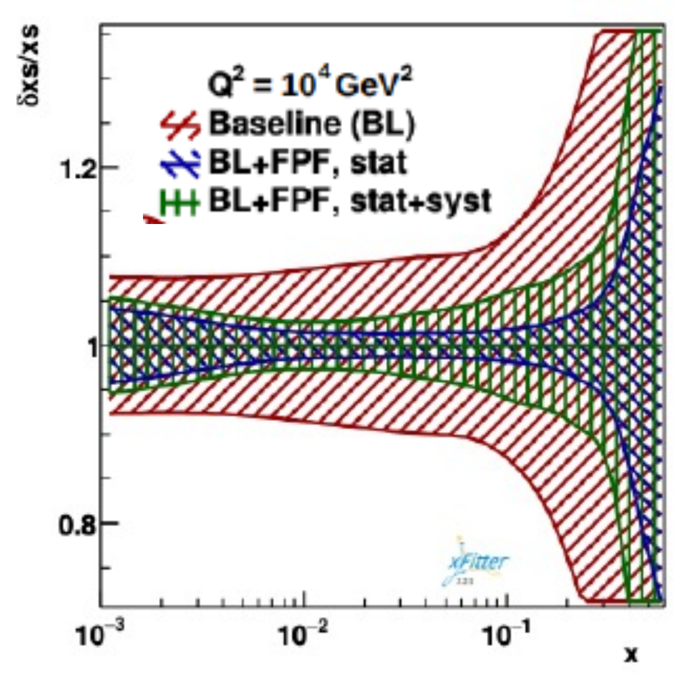
Slide by Rojo

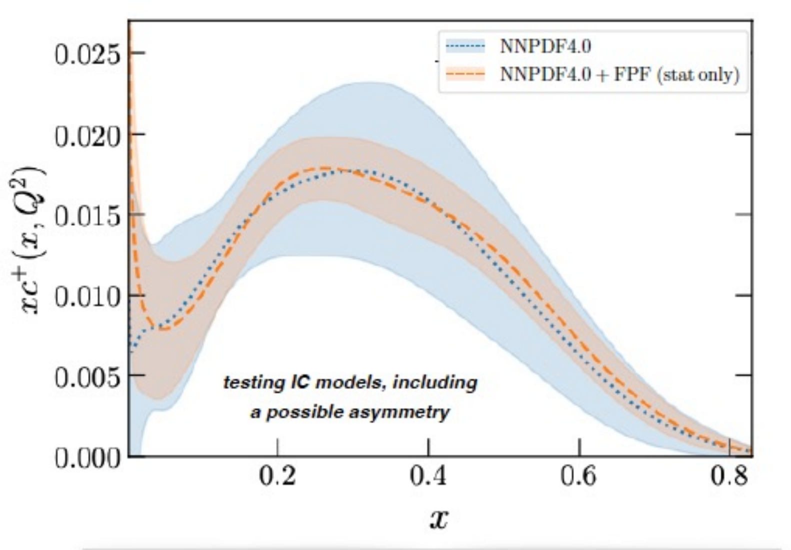
Impact of the LHC Neutrinos



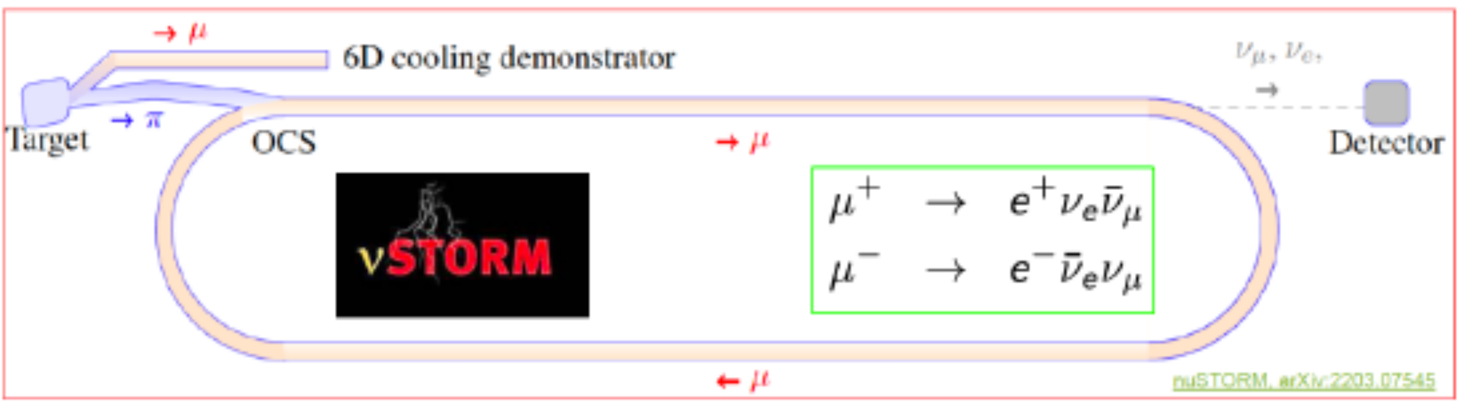








νSTORM



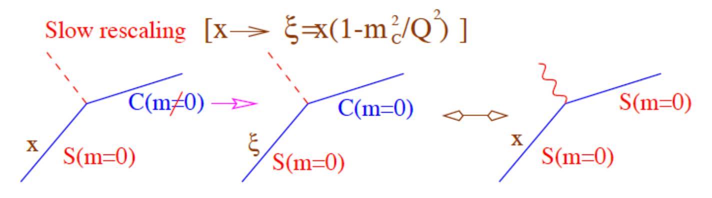
nuSTORM, arXiv:2203.07545

- Neutrino Factory (νSTORM) and Muon Collider in Fermilab
- Excellent physics potential with high intensity neutrino beam with high energy
- And muon collider for precision Higgs and BSM physics

Precision, Precision… but systematic effect: theory and experiment

- Discrepancy between CCFR (ν) and NMC(μ) data at low x region (0.01<x<0.1)
  - Resolved by the proper handling of massive charm treatment (VFS, FFS): Model Ind. CCFR F2, xF3, δxF, *Phys.Rev.Lett.* 86 (2001) 2742
- Discrepancy in QCD analysis between CCFR(ν) and CDHSW (ν)
  - Problem appeared in the CDHSW diff. cross section, overall level fine, but wrong y-dependence, *Phys.Rev.Lett.* 87 (2001) 251802
- Discrepancy in diff. cross section between CCFR(ν) and NuTeV (ν) at high x region (x>0.5), making a new discrepancy at high region
  - Problem appeared in the toroidal magnet calibration of the CCFR detector: *Phys.Rev.D* 74 (2006) 012008
- Different neutrino effect in neutrino: MINERvA saw a different nuclear effect?
- d/u at high x and asymmetry in strange sea
  - Updated d/u→0.2 or 0 at x=1
  - Asymmetry measurement in strange sea: correlated with d/u issue

Effect of heavy quark: PMI F2


Slow rescaling $[x \rightarrow \xi = x(1-m_c^2/Q^2)]$

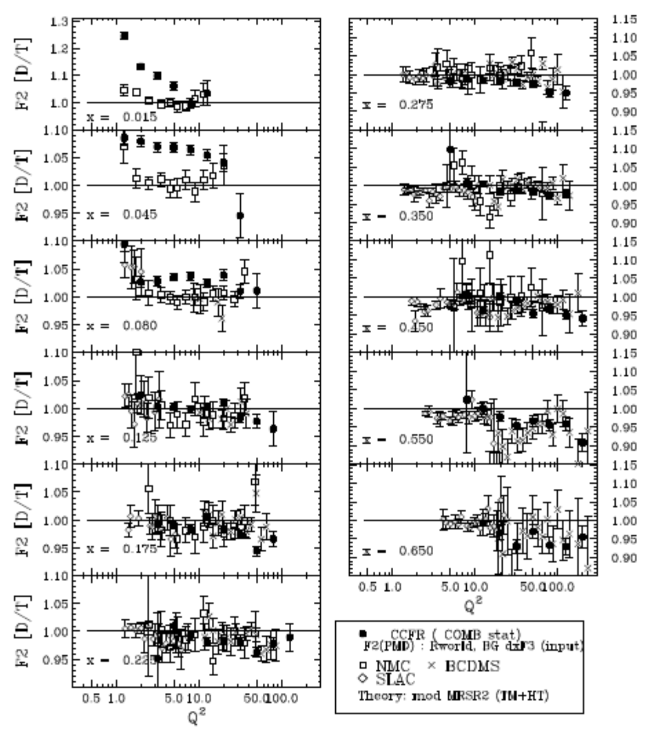
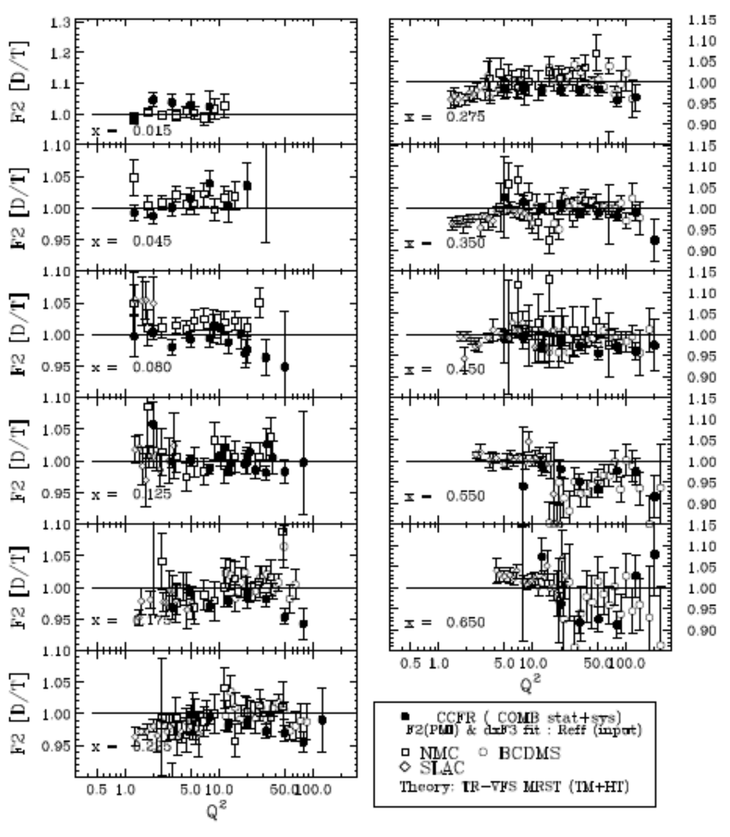


Figure 6.27: The ratio (data/theory) of the previous F_2^ν (PMD) data (and also F_2^μ (NMC) and F_2^e (SLAC)) divided by the predictions of the MRSR2 light-flavor PDFs (with nuclear, target mass and higher twist corrections).

Figure 6.22: The ratio (data/theory) of the F_2^ν (PMI) data divided by the predictions of the TR-VFS(MRST) theory (with nuclear, target mass and higher twist corrections). Both statistical and systematic errors are included. Also shown are the ratios of the F_2^μ (NMC) and F_2^e (SLAC) to the TR-VFS(MRST) predictions.



Phys.Rev.Lett. 86 (2001) 2742

A good observable for heavy quark

$$\frac{10}{3}F_2^{\nu} - 12F_2^{\mu} \;=\; \Delta x F_3.$$

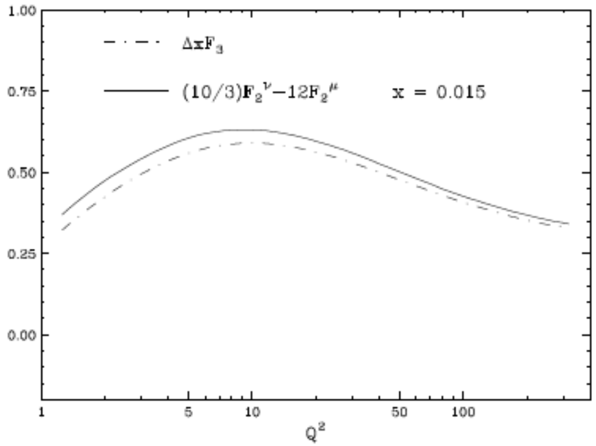


Figure 6.25: Comparison of the NLO light flavor predictions for $\frac{10}{3}F_2^{\nu} - 12F_2^{\mu}$ and ΔxF_3 at $x = 0.015$ calculated using the MRSR2 PDFs

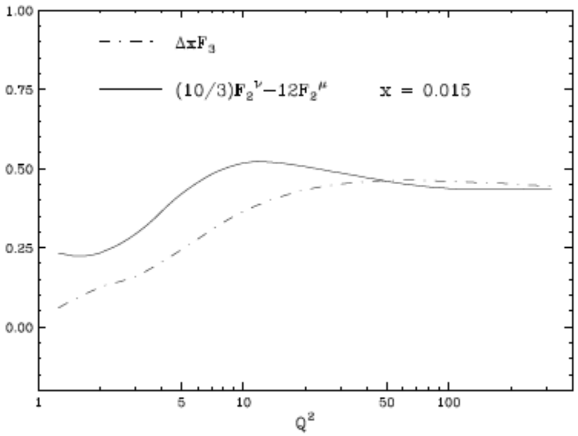


Figure 6.26: Comparison of NLO TR0-VFS predictions $\frac{10}{3}F_2^{\nu} - 12F_2^{\mu}$ (solid) and ΔxF_3 (dashed) predictions with MRST99 PDFs at $x = 0.015$, the difference between solid and dashed line is very sensitive to the input charm quark mass

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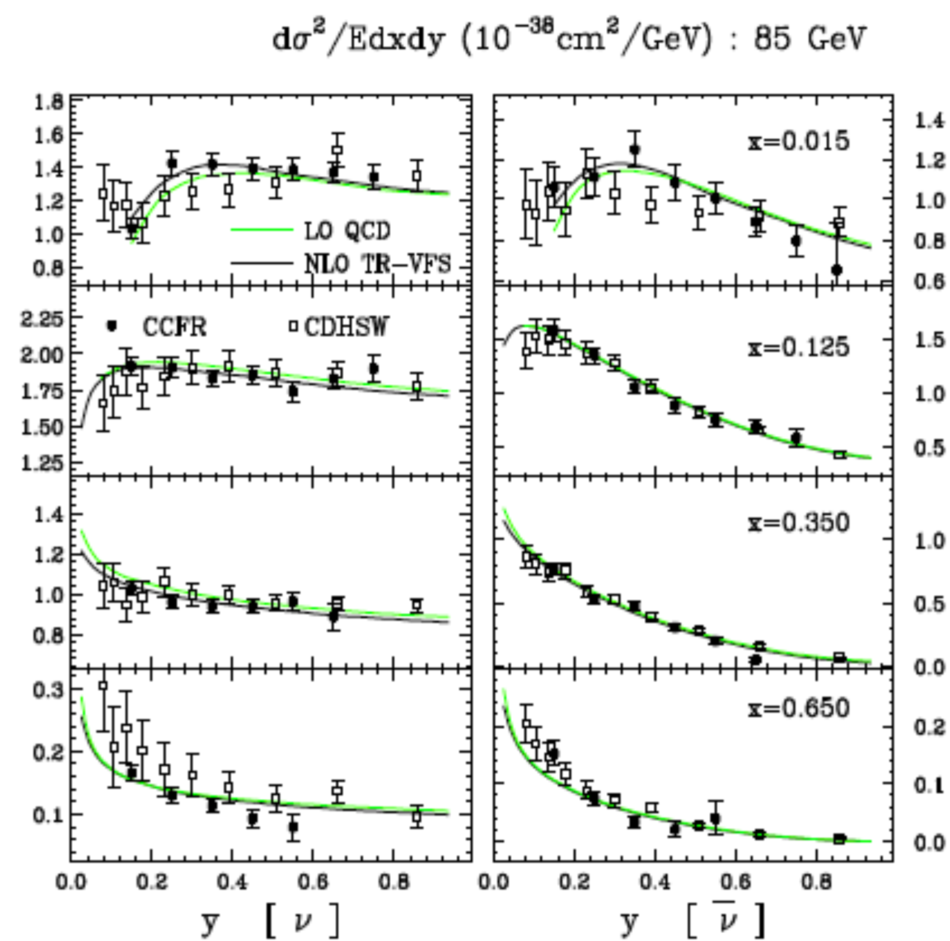
CCFR vs CDHSW data



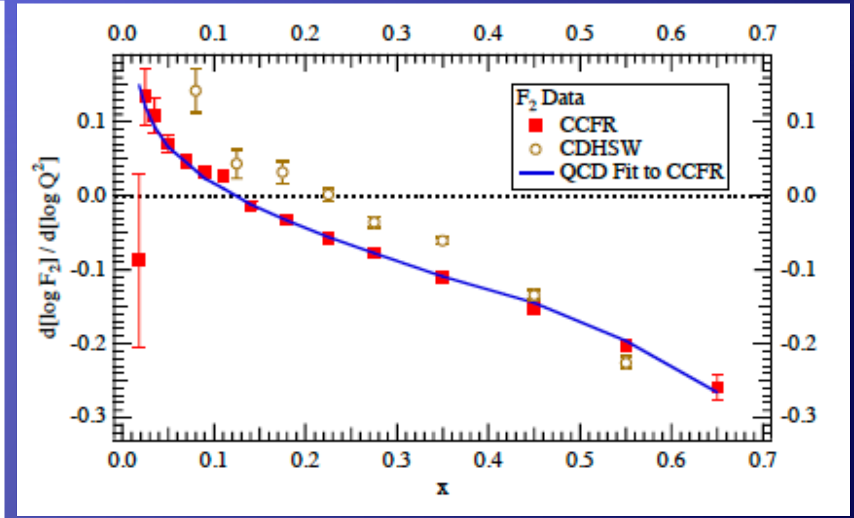


FIG. 1. Some of the CCFR and CDHSW differential cross section data at $E_\nu = 85$ (both statistical and systematic errors are included). The data are in good agreement with the NLO TR-VFS QCD calculation using MRST99 (extended) PDFs (dashed line). The solid line is a leading order CCFR QCD inspired fit used for acceptance and radiative corrections. A disagreement between the CCFR data and CDHSW data is observed in the slope of the y distribution at small x, and in the level of the cross sections at large x.

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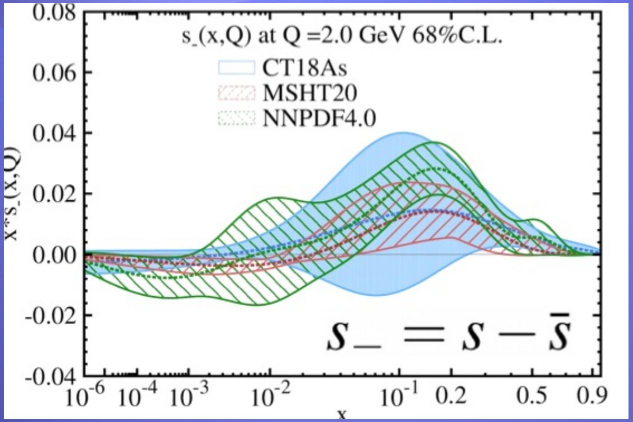
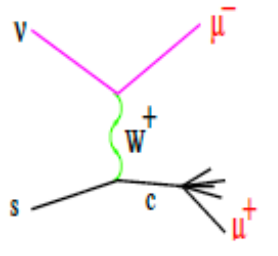
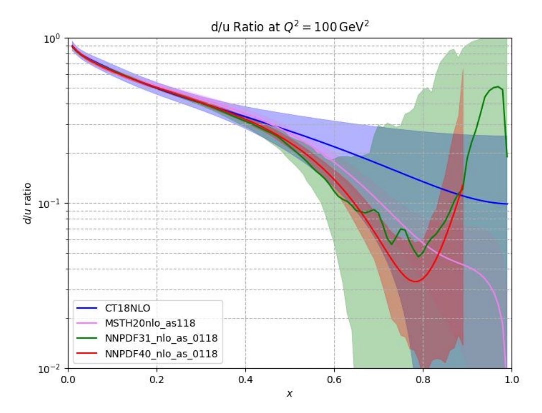
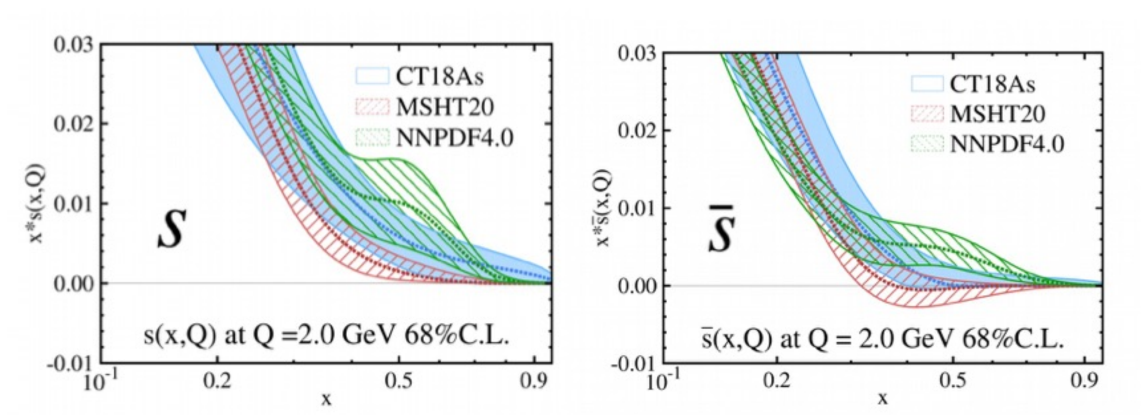
Asymmetry in strange Quark

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









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Summary and Outlook

- Neutrino experiments have provided in understanding QCD 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
- For future neutrino oscillation experiments for DUNE, HyperK, it is important to understand following effects
  - Different nuclear effect in neutrino
  - Axial vector contribution
  - Asymmetry in strange sea
  - Non-perturbative effects (HT, target mass etc)
  - Proper systematic treatments in old dataset is important
- LHC FPF (and NuSTORM) will provide a precise study on QCD and can resolve serval issues