# Shallow-and-Deep Inelastic Scattering

Shunzo Kumano, Jorge G. Morfin and Roberto Petti

Summary Talk

NuInt15 – Osaka, Japan

November, 2015

# Challenges

- Increasing awareness that SIS and DIS interactions can give significant backgrounds and contributions to the systematics on the scale of the 1% goals in neutrino oscillation experiments.

- In the SIS region the duality based Bodek-Yang model has been fine for giving average strengths of SIS interactions up to now.

- For more detailed studies of systematics from single-and-multi-pion production above the Delta we need models that give us a description of these higher-W resonances, the valleys between them and the non-resonant continuum contribution as well.

- In the DIS region the nPDFs derived from $l^{\pm}$ and D-Y are in reasonable agreement but errors seem underestimated
  - there are indications that the nuclear parton distributions describing $\nu$-A scattering are different than the nPDFs from e-A scattering.

- Clarification and further study of the entire SIS-DIS region is needed.

# PYTHIA Hadronization Program for Neutrino experiments – Teppei Katori

AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

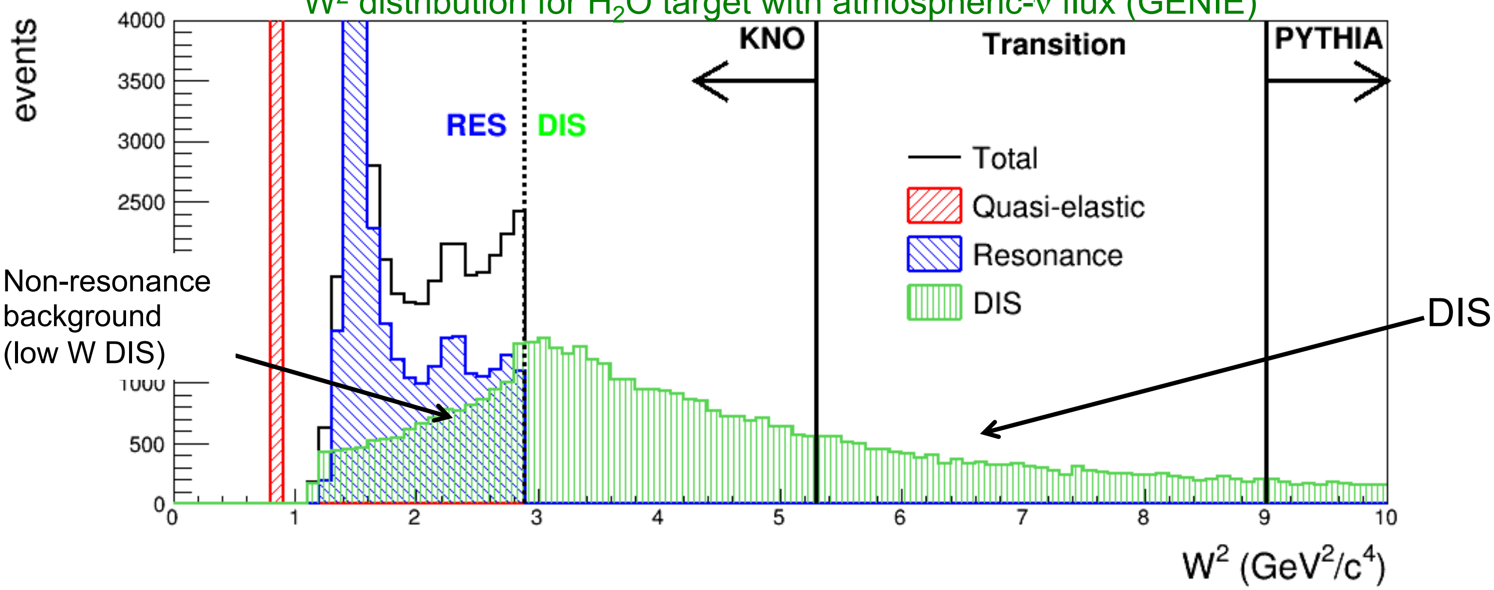


## 1. GENIE hadronization model (AGKY model)

Cross section
$W^2<2.9$ GeV$^2$ : RES
$W^2>2.9$ GeV$^2$ : DIS
Hadronization (AGKY model)
$W^2<5.3$GeV$^2$ : KNO scaling based model
$2.3$GeV$^2<W^2<9.0$GeV$^2$ : transition
$9.0$GeV$^2<W^2$ : PYTHIA6

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

$W^2$ distribution for $H_2O$ target with atmospheric-$\nu$ flux (GENIE)



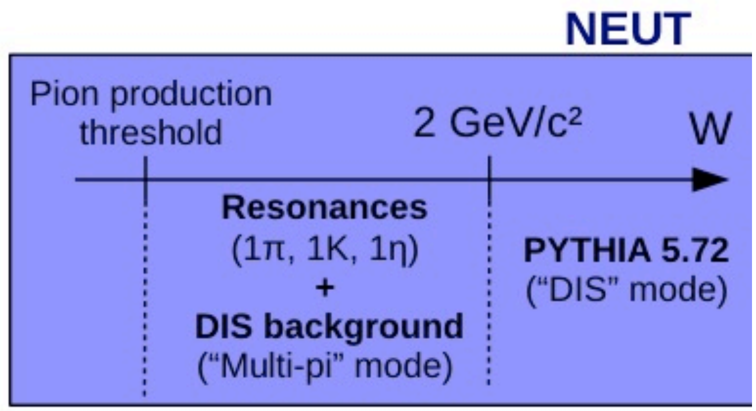
# Generators for the SIS/DIS region

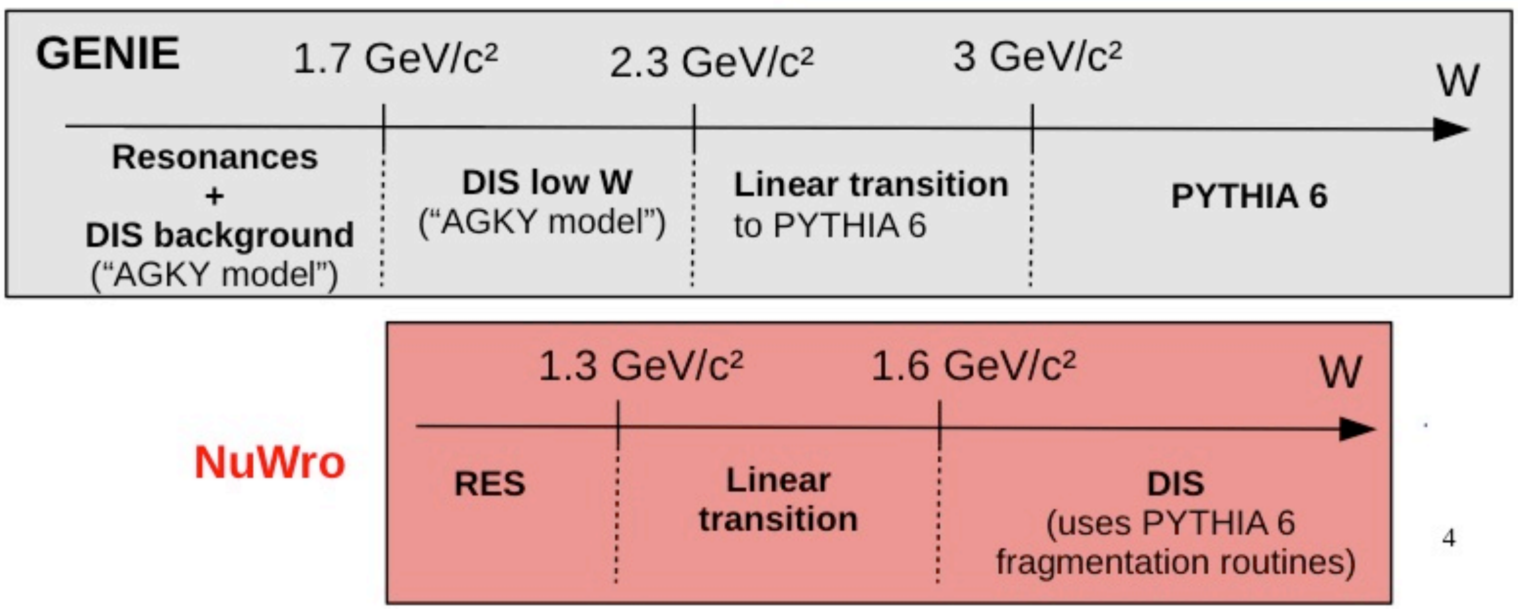
C. Bronner
Kavli IPMU(WPI), Tokyo University

# Generators for the SIS/DIS region

## SIS-DIS region in the generators

- Different models as a function of W
- Combination of resonances and DIS continuous parametrization
- Use GRV98 + Bodek-Yang corrections for cross-sections of the DIS components

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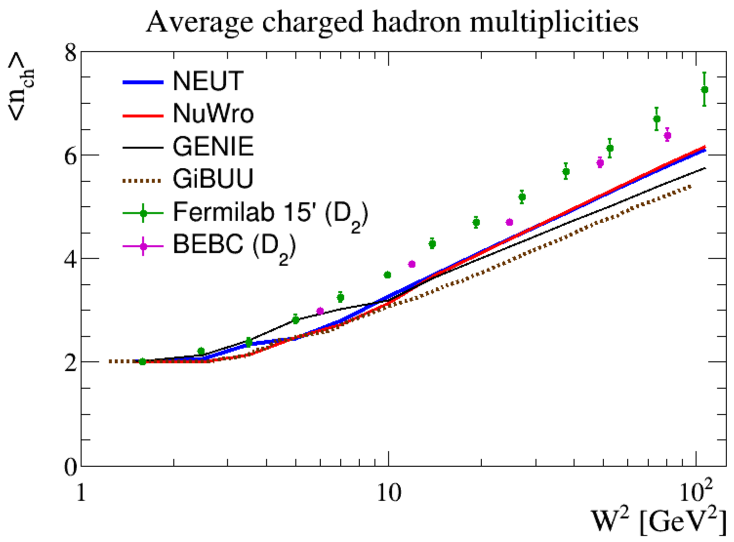
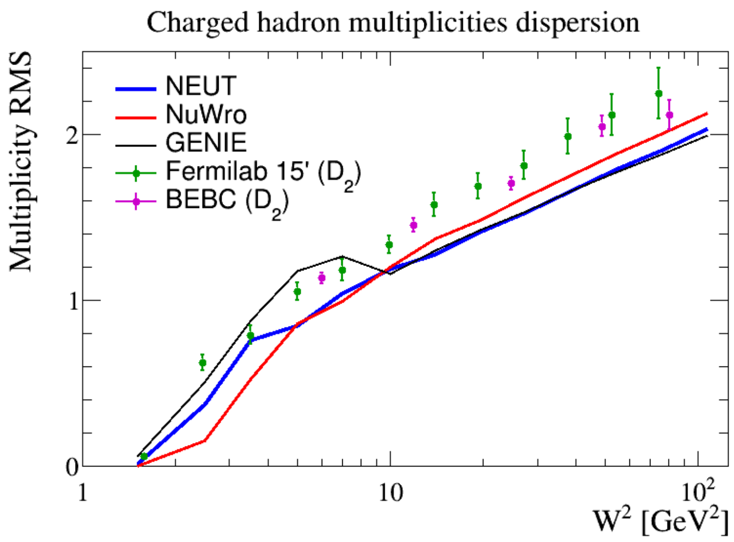
# Generators for the SIS/DIS region

## Charged hadron multiplicities
## **Neutrinos on proton**

- Average charged hadron multiplicity observed to be a linear fonction of log($W^2$) in bubble chamber data
  (K. Kuzmin and V. Naumov argue for a quadratic function at low W in PRC 88, 065501 (2013))



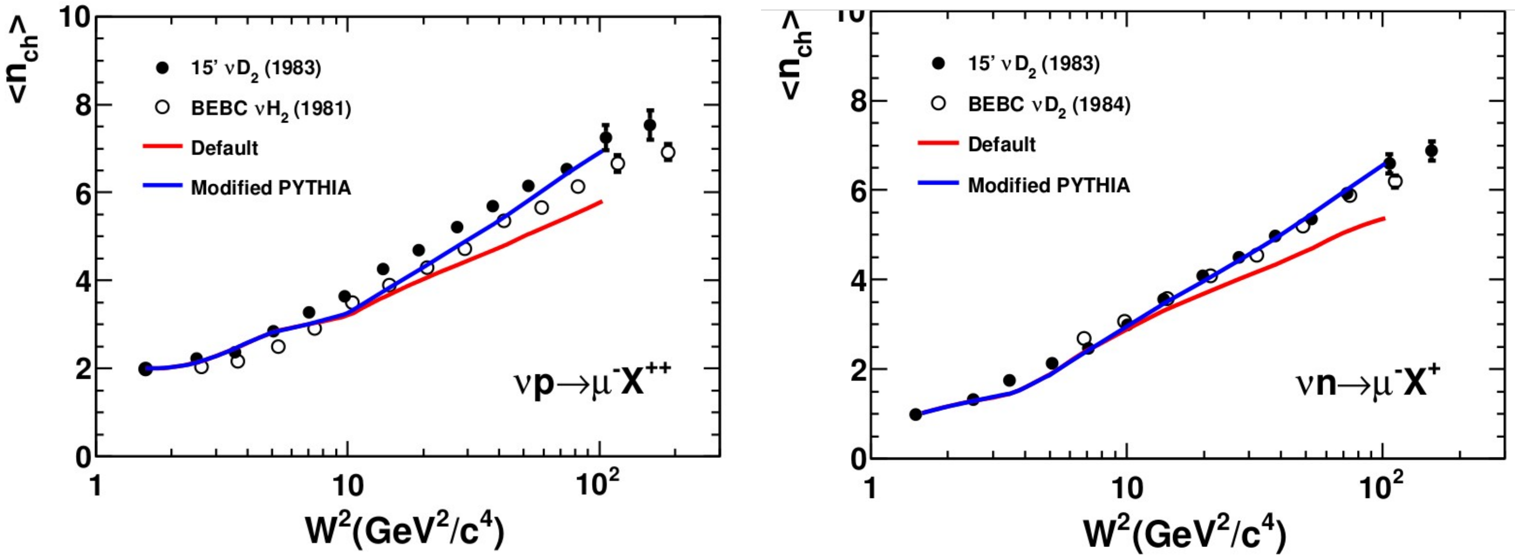




All generators seem to underestimate both average and dispersion of the charged hadron multiplicities

# Generators for the SIS/DIS region

## Tuning charged hadron multiplicities
## Tuning PYTHIA

Tuned PYTHIA parameters using expertise from members of the HERMES collaboration
Allows to properly reproduce average charged hadron multiplicities when tested in GENIE:




<u>Also found some difficulties:</u>

- dispersion of the charged hadron multiplicities
- neutral hadron multiplicities

"Further tuning is ongoing"

T. Katori, S. Mandalia
arxiv: 1412.4301v3

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# Generators for the SIS/DIS region

## Comparisons for different targets and energies

<u>Now moving to the comparisons on different targets at fixed energies:</u>

- **CH at 2 GeV** (6 bound protons, 6 bound neutrons, 1 free proton)
- **Ar at 2.5 GeV** (18 bound protons, 22 bound neutrons, 0 free protons)
- **$H_2O$ at 4 GeV** (8 bound protons, 8 bound neutrons, 2 free protons)
- **Fe at 6 GeV** (26 bound protons, 30 bound neutrons, 0 free protons)

<u>5 different comparisons for each:</u>

- **W** distribution - computed as $W^2=(P_\nu+P_{nuc}-P_\mu)^2$
- **$Q^2$** distribution - computed as $Q^2=(P_\nu-P_\mu)^2$
- **$n_{ch}$**: charged hadron multiplicities
- **$n_\pi$**: pion (charged + neutral) multiplicities
- **$n_{\pi 0}$**: neutral pion multiplicities

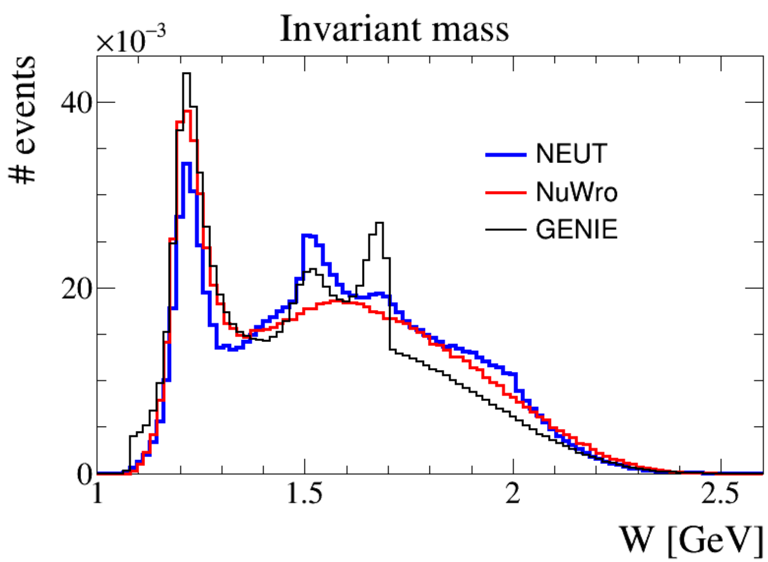
**Except for the W distributions, a cut W>1.7 GeV is applied**
**All plots are normalized by area**

# Generators for the SIS/DIS region

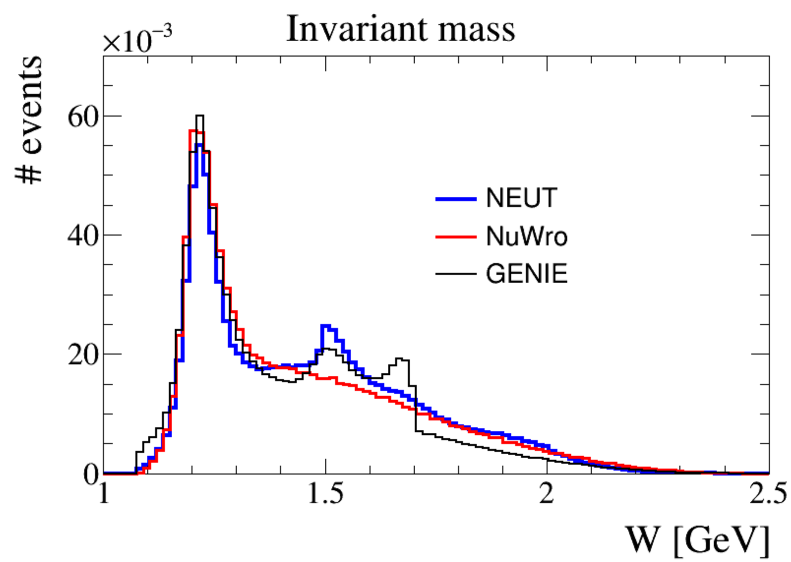
W distributions

Ar, $E_{\nu}$=2.5 GeV

<u>Neutrino</u>




<u>Anti-neutrino</u>




Main differences are presence or absence of certain resonances

Won't affect comparisons at W>1.7 GeV

# Fragmentation studies in NOMAD experiment

Artem Chukanov[1], Roberto Petti[2]

[1]Joint institute for nuclear research, Dubna

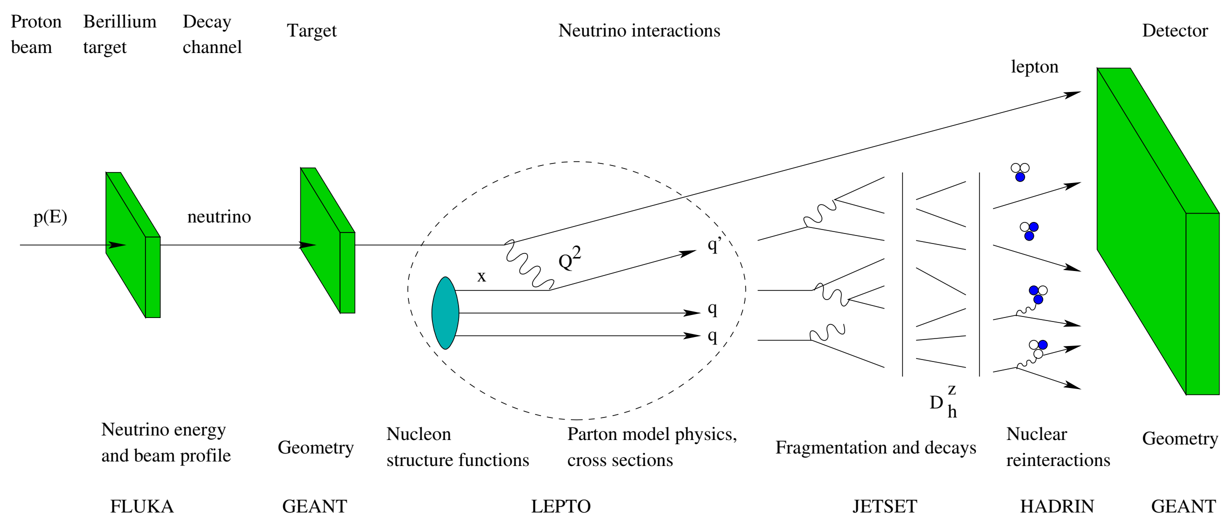
[2]University of South Carolina, USA

NuInt15, Osaka, $19^{th}$ of November 2015

# Fragmentation studies in NOMAD experiment

## NOMAD neutrino event generation library

- LEPTO 6.1
- JETSET 7.4 (string fragmentation)
- GEANT 3 (tracing particles)
- DPMJET II (intranuclear reinteractions)



# Fragmentation studies in NOMAD experiment

## Default JETSET parameters - strange particles production yields. $\nu_\mu$ CC interactions

| Hadrons | MC (%) | Data (%) | MC/Data |
|---|---|---|---|
| $K_S^0$ | 11.4 | $8.99 \pm 0.08$ | $1.27 \pm 0.01$ |
| $\Lambda^0$ | 9.0 | $6.21 \pm 0.08$ | $1.46 \pm 0.02$ |
| $\bar{\Lambda}^0$ | 0.73 | $0.52 \pm 0.02$ | $1.41 \pm 0.08$ |
| $\rho^0(770)$ | | $19.50 \pm 1.90$ | |
| $f_0(980)$ | | $1.80 \pm 0.40$ | |
| $f_2(1270)$ | | $3.80 \pm 0.90$ | |
| Fraction | | | |
| $\frac{N(K^{\star +} \to K_S^0 \pi^+)}{N(K_S^0)}$ | 31.0 | $14.1 \pm 0.9$ | $2.20 \pm 0.04$ |
| $\frac{N(K^{\star -} \to K_S^0 \pi^-)}{N(K_S^0)}$ | 13.5 | $8.9 \pm 0.08$ | $1.5 \pm 0.4$ |
| $\frac{N(\Sigma^{\star +} \to \Lambda \pi^+)}{N(\Lambda)}$ | 16.9 | $4.4 \pm 1.0$ | $3.8 \pm 1.3$ |

The agreement between MC and Data is poor

# Fragmentation studies in NOMAD experiment

**Comparison of tuned NOMAD event generator with GENIE at event generator level for CNGS beam. $\nu_\mu$ CC interactions**

| Hadrons | NOMAD (%) | GENIE (%) | GENIE/NOMAD |
|---|---|---|---|
| $K_S^0$ | 5.31 | 4.38 | 0.82 |
| $\Lambda^0$ | 4.88 | 4.67 | 0.96 |
| $\bar{\Lambda}^0$ | 0.28 | 0.14 | 0.5 |
| $\rho^0(770)$ | 14.27 | 14.76 | 1.03 |
| $f_0(980)$ | 1.39 | 1.56 | 1.12 |
| $f_2(1270)$ | 2.75 | 3.57 | 1.30 |
| $D^0$ | 1.99 | 4.15 | 2.09 |
| $K^+$ | 8.17 | 7.54 | 0.92 |
| $K^-$ | 3.63 | 3.42 | 0.94 |
| Fraction | | | |
| $\frac{N(K^{\star+}\to K_S^0\pi^+)}{N(K_S^0)}$ | 18.19 | 17.32 | 0.95 |
| $\frac{N(K^{\star-}\to K_S^0\pi^-)}{N(K_S^0)}$ | 7.13 | 7.13 | 1.00 |
| $\frac{N(\Sigma^{\star+}\to\Lambda\pi^+)}{N(\Lambda)}$ | 3.47 | 5.49 | 1.58 |

Agreement is much better. Other hidden switches in GENIE

# Fragmentation studies in NOMAD experiment

## Summary

- a tuning of JETSET parameters has been perform with NOMAD data
- the default GENIE-2.8.4 fragmentation parameters disagree with NOMAD results
- the use of the tuned JETSET parameters in GENIE improves the agreement with NOMAD
- additional studies with GENIE event generator are required

NOMAD data offer an excellent tool for the optimization and development of existing event generators!

# Nuclear effects in deep inelastic scattering and transition region

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**Graduate University for Advanced Studies (SOKENDAI)**
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**10th International workshop on Neutrino-nucleus interactions in the few-GeV region,**
**16-21 November 2015, Suita Campus of Osaka University, Japan**
**http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46**

**November 16, 2015**

# Nuclear effects in deep inelastic scattering and transition region

## Recent global analyses on nuclear PDFs

I may miss some papers.

### HKN07

- M. Hirai, S. Kumano, and T. -H. Nagai, Phys. Rev. C 76 (2007) 065207.
- Charged-lepton DIS, DY.

### EPS09

- K. J. Eskola, H. Paukkunen, and C. A. Salgado, JHEP 04 (2009) 065.
- Charged-lepton DIS, DY, $\pi^0$ production in $dAu$.

### CTEQ

- I. Schienbein, J. Y. Yu, C. Keppel, J. G. Morfin, F. I. Olness, J. F. Owens,
  Phys. Rev. D 77 (2008) 054013; D80 (2009) 094004;
  K. Kovarik *et al.*, PRL 106 (2011) 122301; PoS DIS2013 (2013) 274;
  PoS DIS2014 (2014) 047; arXiv:1509.00792.
- Neutrino DIS, Charged-lepton DIS, DY.

### DSZS12

- D. de Florian, R. Sassot, P. Zurita, M. Stratmann, Phys. Rev. D85 (2012) 074028.
- Charged-lepton DIS, DY, RHIC-$\pi$

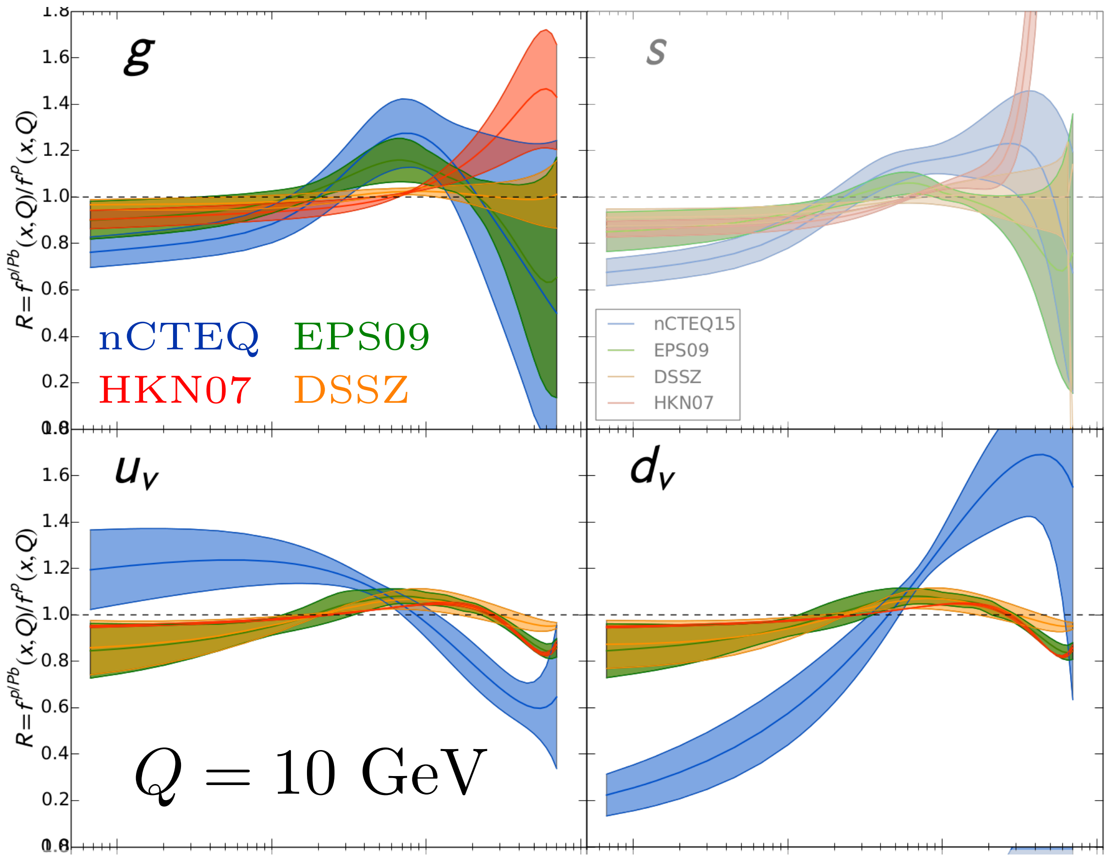
See also L. Frankfurt, V. Guzey, and M. Strikman, Phys. Rev. D 71 (2005) 054001;
Phys. Lett. B687 (2010) 167; Phys. Rept. 512 (2012) 255; arXiv:1310.5879.
S. A. Kulagin and R. Petti, Phys. Rev. D 76 (2007) 094023; C 82 (2010) 054614;
C 90 (2014) 045204.
A. Bodek and U.-K. Yang, arXiv:1011.6592.

# nCTEQ Results

Nuclear correction factors ($Q = 10$ GeV)

$$R_i(Pb) = \frac{f_i^{p/Pb}(x,Q)}{f_i^p(x,Q)}$$

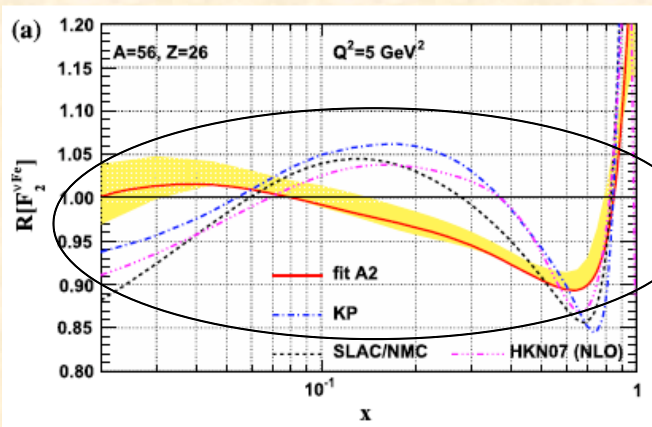
- different solution for $d$-valence & $u$-valence compared to EPS09 & DSSZ
- sea quark nuclear correction factors similar to EPS09
- nuclear correction factors depend largely on underlying proton baseline



# Nuclear effects in deep inelastic scattering and transition region

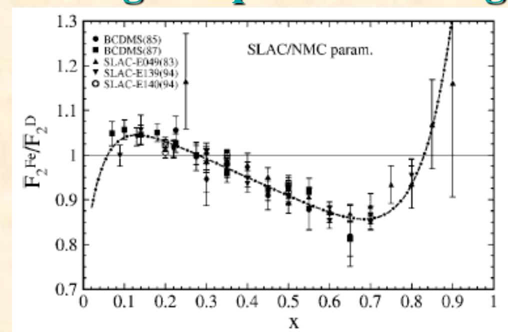
## Analysis of CTEQ-2008 (Schienbein *et al.*)

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

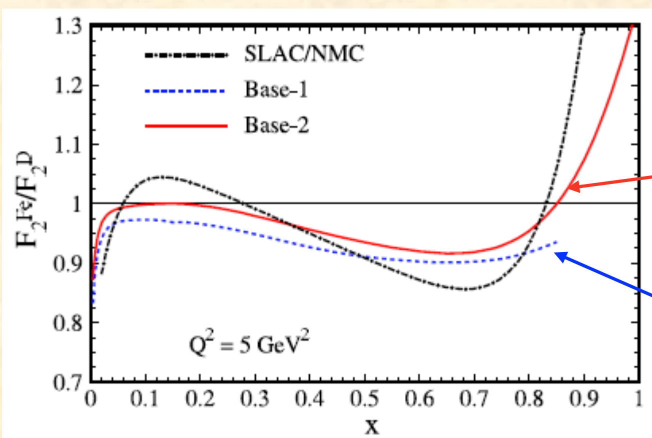



Differences
from typical NPDFs.

### Charged-lepton scattering




### Neutrino scattering




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

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

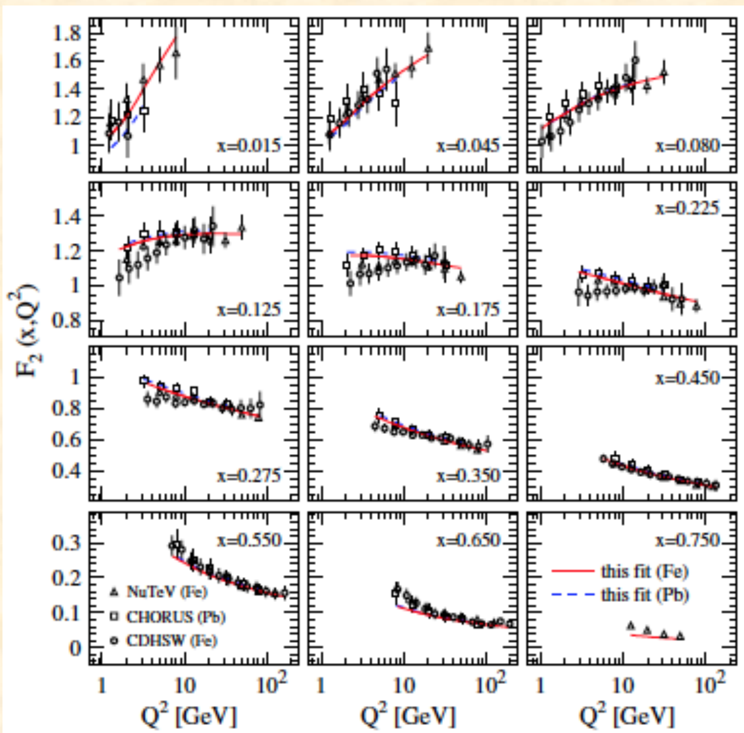
**Base-2: Using current nucleonic PDFs, they (and MRST) obtained very different corrections from charged-lepton data.**

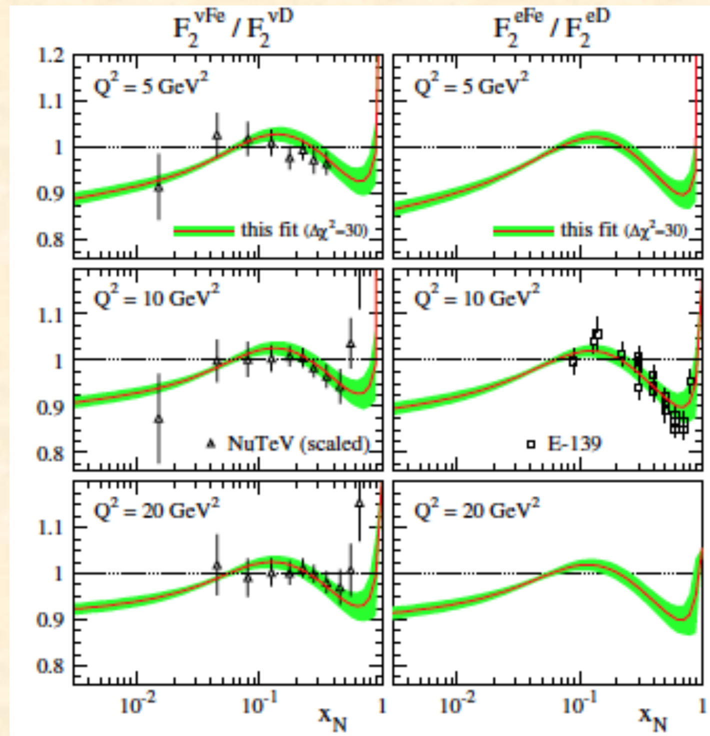
**Base-1: However, it depends on the analysis method for determining "nucleonic" PDFs.**

# Nuclear effects in deep inelastic scattering and transition region

## Neutrino DIS ⇔ Charged DIS issue

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




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

# Update of HKN nuclear PDFs

M. Hirai (NIT)

Collaborators: S. Kumano(KEK), K. Saito (TUS)

nPDFs [HKN07: Nucl. Phys. C76,065207 (2007) ]

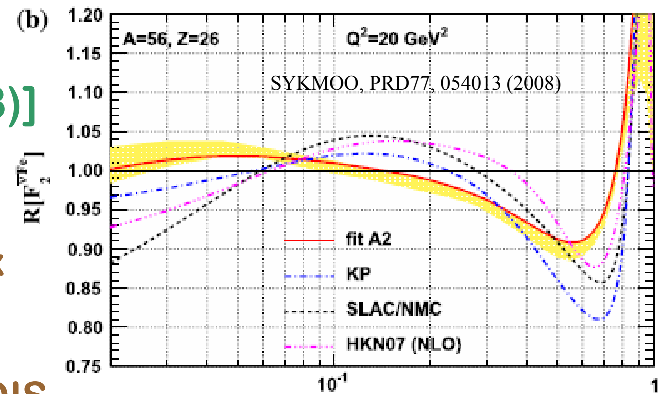
http://research.kek.jp/people/kumanos/nuclp.html

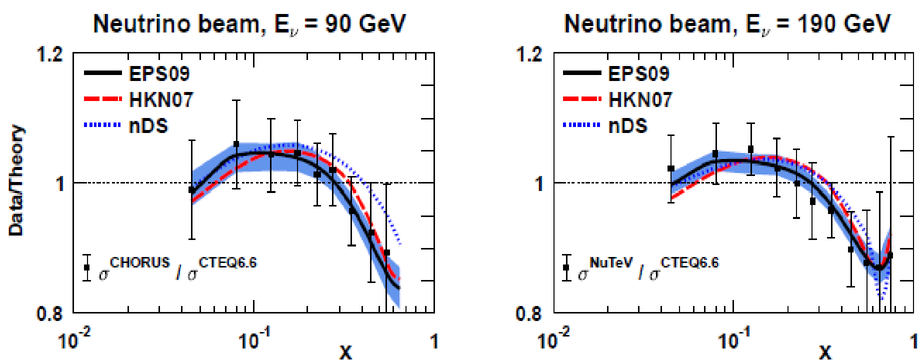
# Update of HKN nuclear PDFs

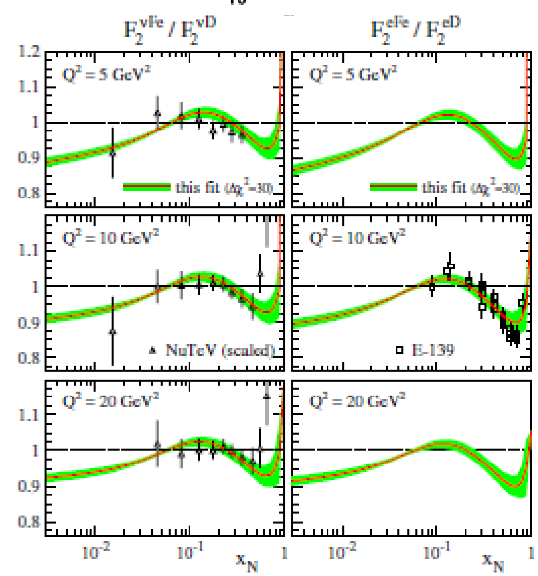
## nPDFs from neutrino DIS

### Discrepancy of nuclear effect ?

- K. Schienbein, et. al [PRD77,054013(2008)]
  - Using (anti-)neutrino DIS data
  - Shallow EMC effect
  - Moving the anti-shadowing peak for small-x
- DSSZ12 [PRD85,0704028 (2012)]
  - Combined data set with lepton & neutrino DIS
    - Using $F_2$ & $xF_3$ data, not x-sect !
  - Showing same effect … ?
- Paukkunen, Salgado [JHEP07,032,(2010)]



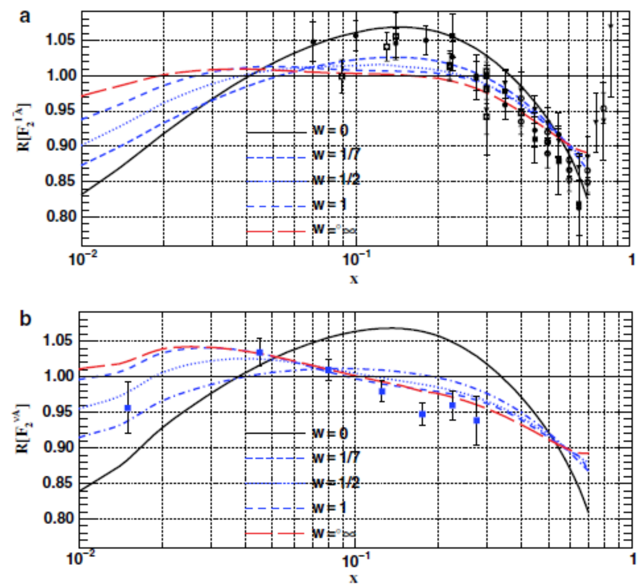



# Update of HKN nuclear PDFs

## An issue of global analysis ($\chi^2$ analysis)

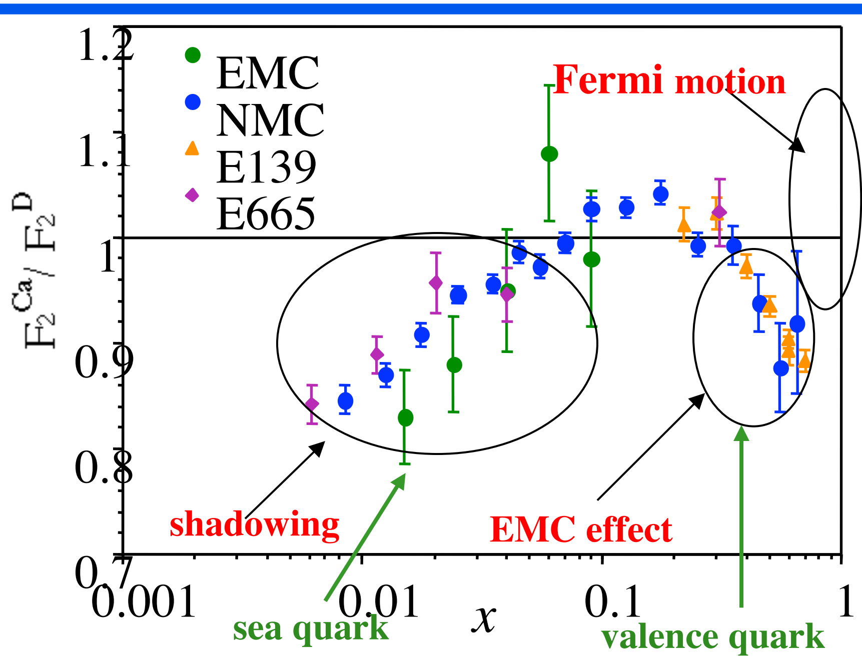
- Assuming the same model when using data sets simultaneously
- Information fall ?
  - larger # of ν-DIS data of Fe, Pb targets
    - 100 (NC-DIS,DY) v.s. 5000 (CC-DIS)
    - Large error data become numerical noise in total $\chi^2$
  - Weight dependence ?
    - Obtained intermediate model which has possibility to reproduce these data sets
- Are nuclear effects different ?
  - Attributing to structure and dynamics in a nucleus, base on strong interaction
  - EW probe dependent ?
  - To answer the equation, test of significance for data set needs




K. Kovarik, et. al, PRL106,122301(2011)

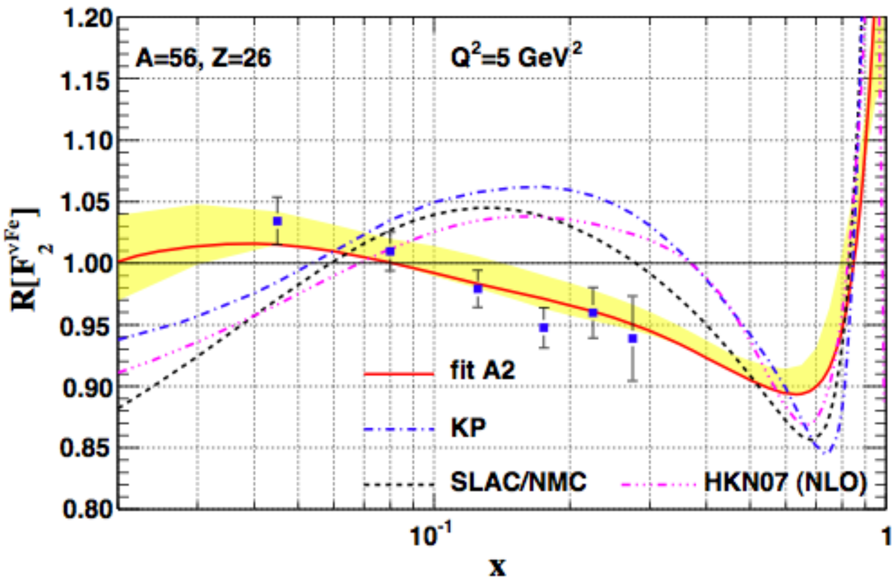
$\chi^2=\chi^2_{lA\text{-DIS}}+w^*\chi^2_{\nu A\text{-DIS}}$

# What about Neutrinos? nCTEQ Analysis

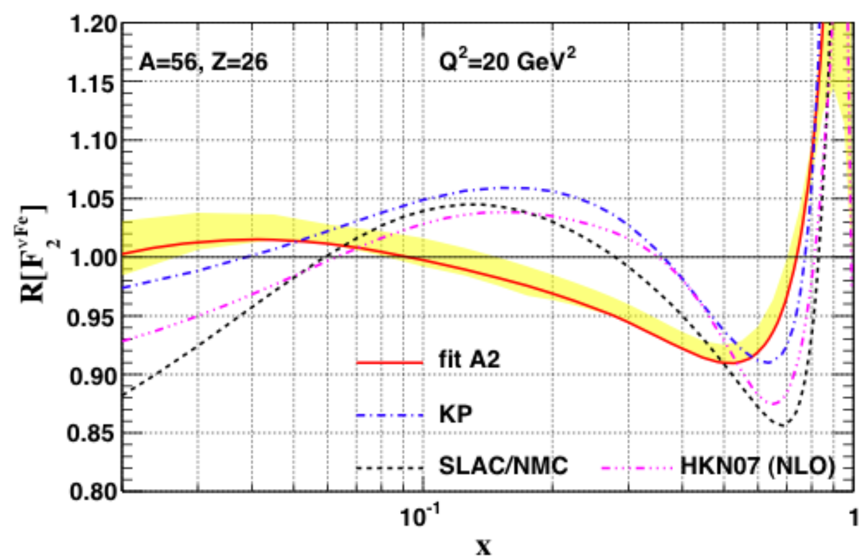



- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> for example different shadowing for $xF_3$ compared to $F_2$.**

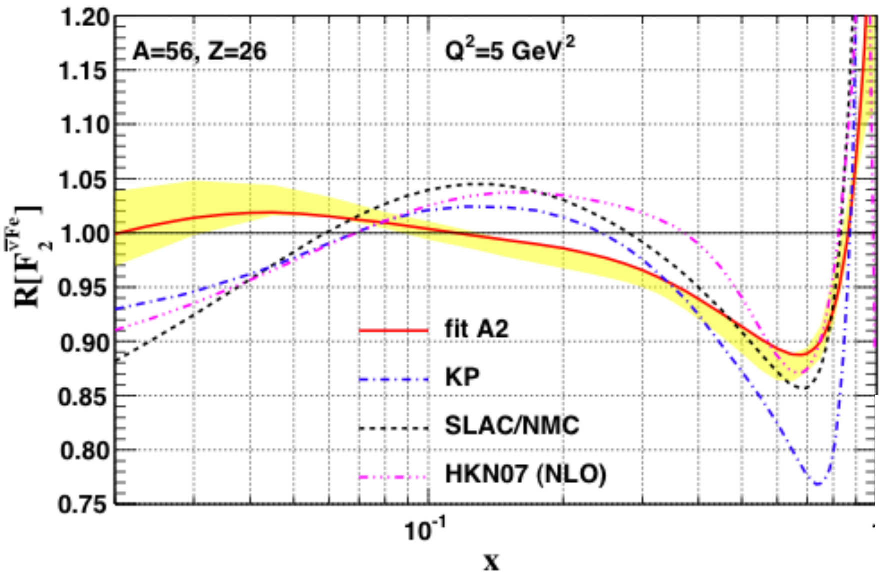
# $F_2$ Structure Function Ratios: ν-Iron



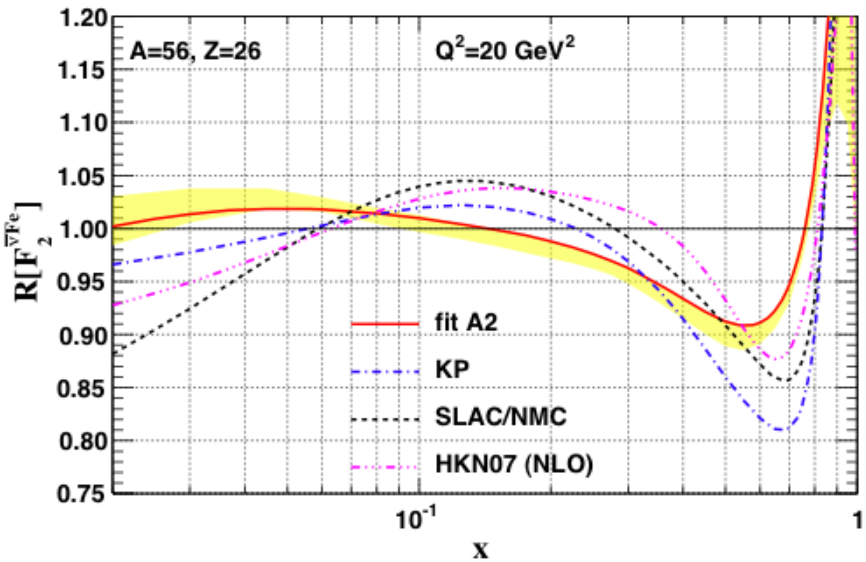

$$\frac{F_2(\nu + \mathrm{Fe})}{F_2(\nu + [n+p])}$$



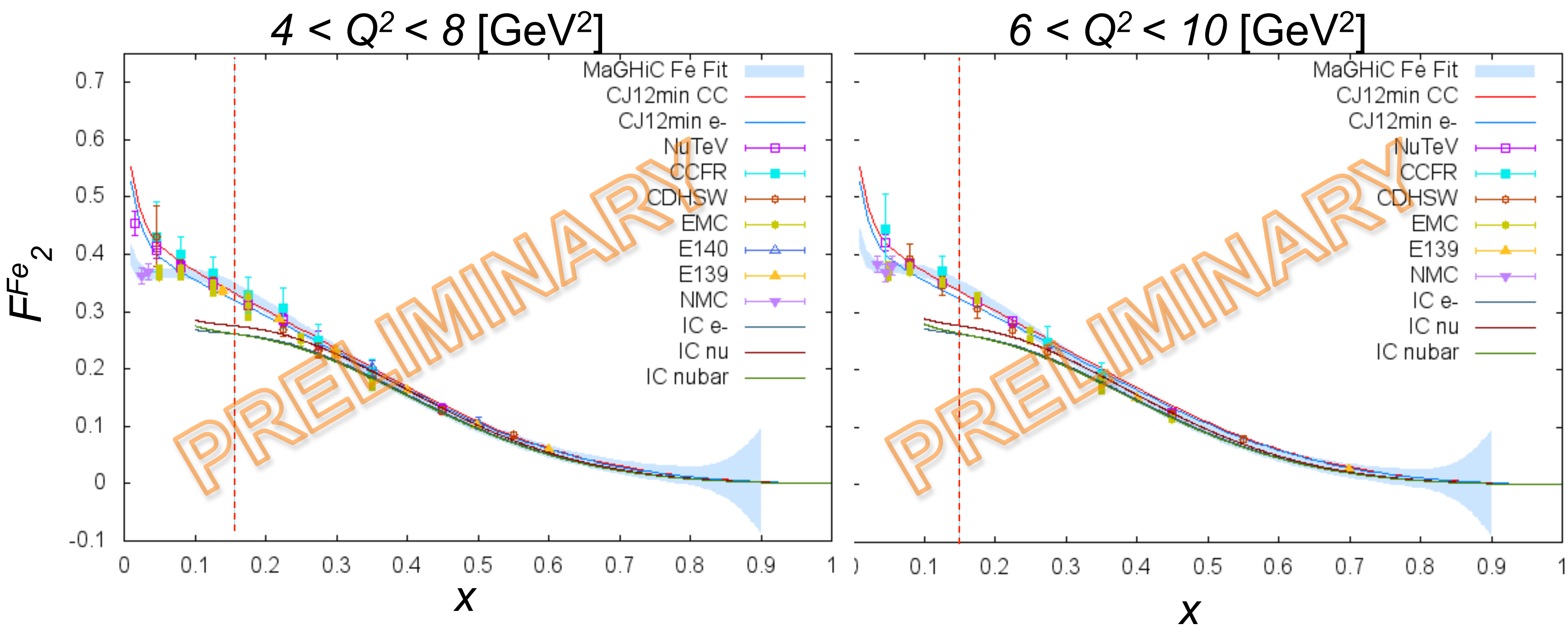
# $F_2$ Structure Function Ratios: $\overline{\nu}$-Iron




$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



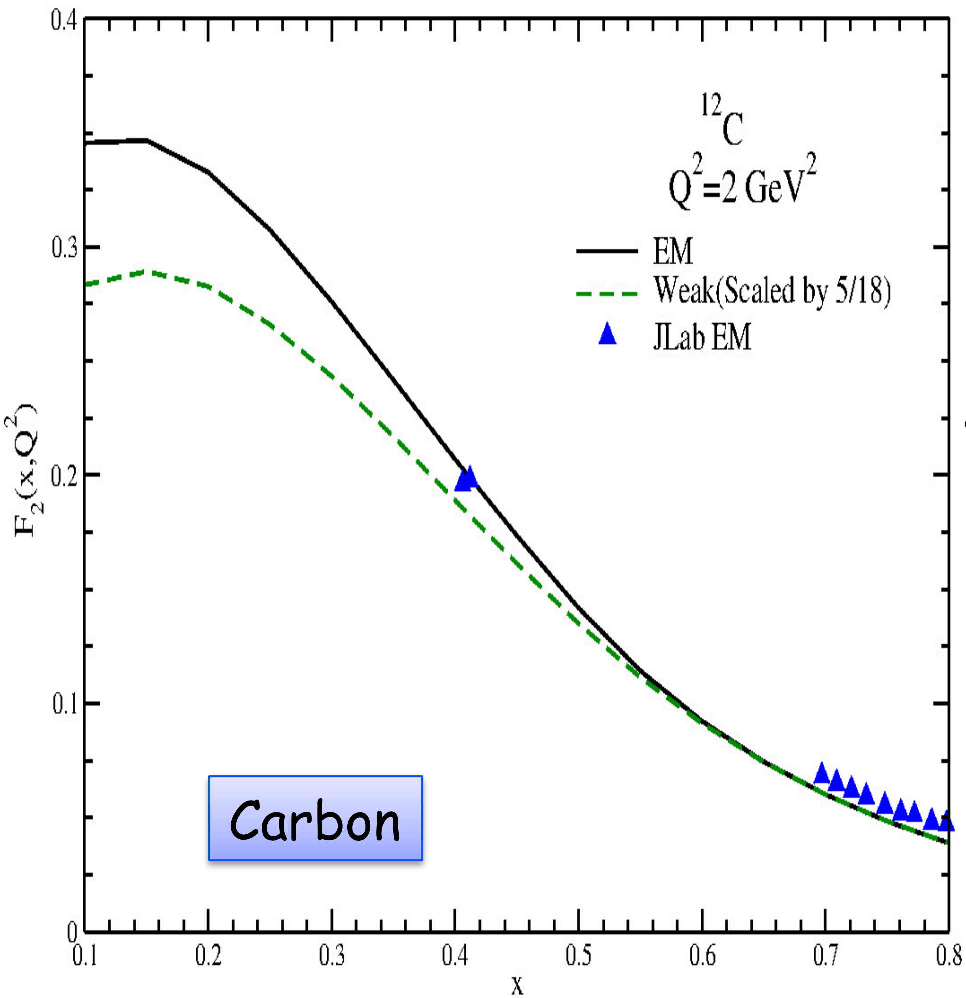
# Comparison of the $F_2$ Structure Function in Iron as Measured by Charged Lepton and Neutrino Probes

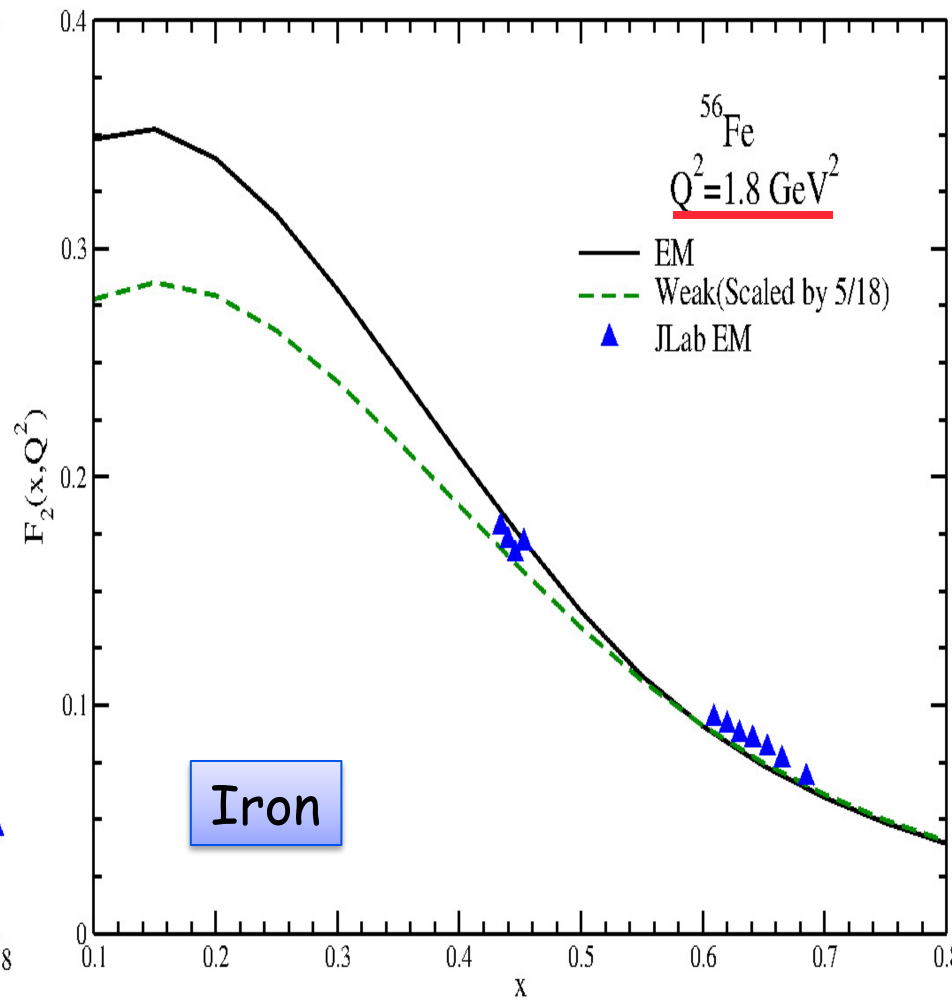



- "CJ12min fit" Phys.Rev. D **87** 094012 (2013)
- "MaGHiC" Intl. Journ. Mod. Phys. E **23** 1430013 (2014)
- Difference between Charged lepton and neutrino data at $x$ < ~0.15
- Neutrino data seems to be in agreement with CJ -CJ has no nuclear effects taken in to account.

H.Haider et al. in a field theoretical model have studied medium effects in nuclear structure functions $F_i^{EM}$ (i=1,2) and $F_j^{Weak}$ (j=1,2,3)

## $F_i^{EM}(x,Q^2)$(i=2) vs x | $F_i^{Weak}(x,Q^2)$(i=2,3) vs x



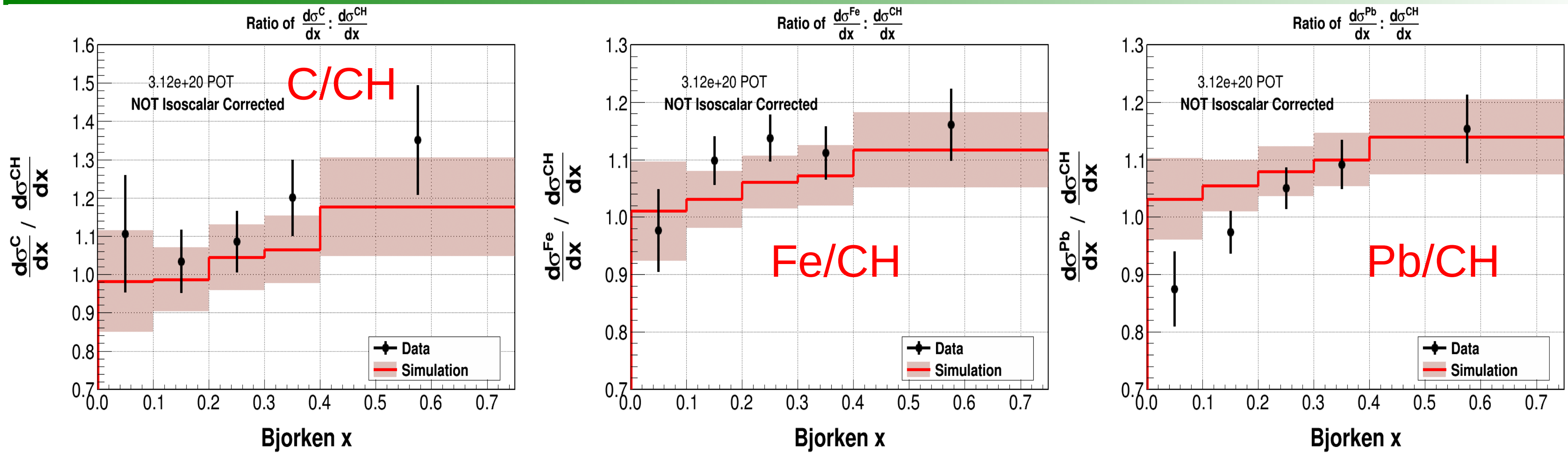
# Others Do NOT Find this Difference between $l^{\pm}$ and $\nu$

- The analyses of K. Eskola et al. and D. de Florian et al. do not find this difference between $l^{\pm}$–A and $\nu$–A scattering.
- They do not use the full covariant error matrix rather adding statistical and systematic errors in quadrature.
- They do not use the full double differential cross section rather they use the extracted structure functions which involve assumptions:
  - Assume a value for $\Delta x F_3$ (= $F_3^{\nu}$ - $F_3^{\bar{\nu}}$) from theory.
  - Assume a value for R = $F_L$ / $F_T$.
- If nCTEQ makes these same assumptions, than a combined solution of $l^{\pm}$–A and $\nu$–A scattering can be found.

# Neutrino-nucleus deep inelastic scattering with MINERvA

**Joel A. Mousseau**
**University of Michigan /**
**University of Florida**
**10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region**
**11/19/15**

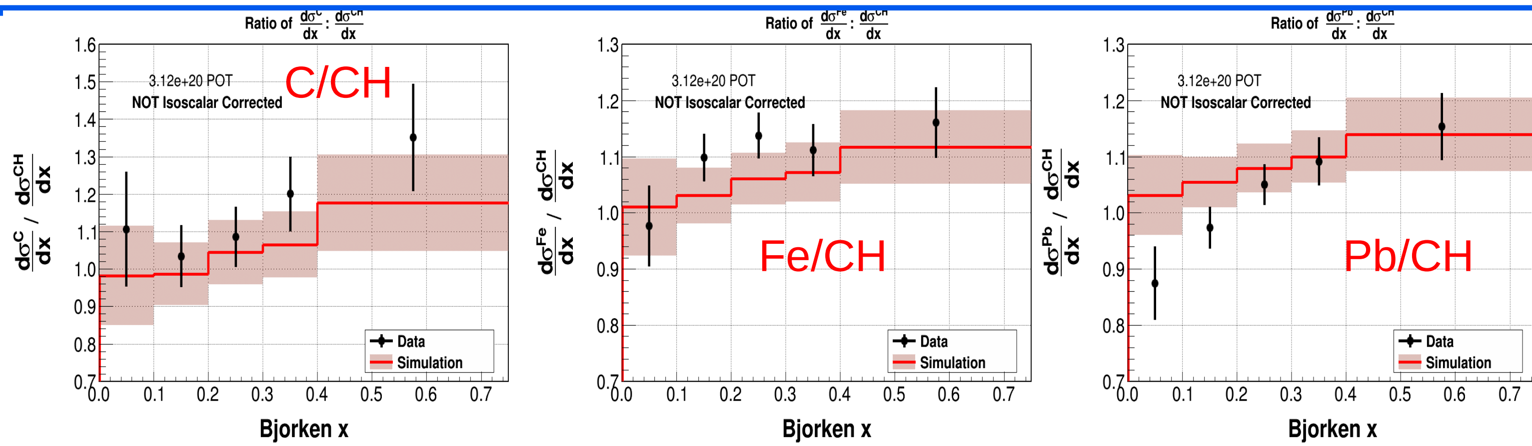
# DIS Ratios: dσ /dx




- X dependent ratios directly translate to x dependent nuclear effects.
- Currently, our simulation assumes the *same* x-dependent nuclear effects for C, Fe and Pb tuned to $e^-$ scattering.
- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing.
- The intermediate x range of (0.3 < x <0.75) shows good agreement between data and simulation.

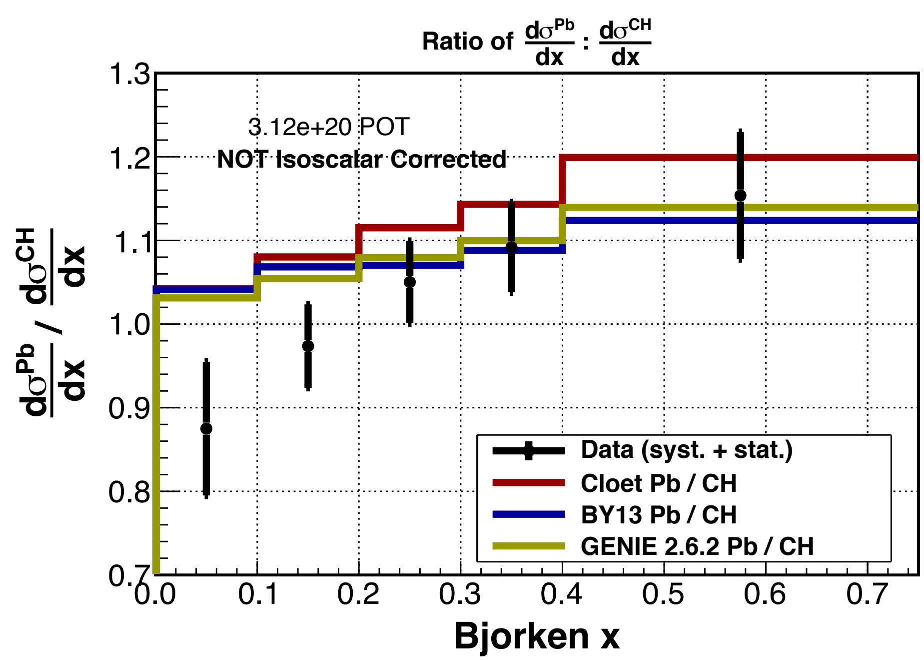
# We Now Have A New DIS Player - What does MINERvA see?

# DIS Cross Section Ratios – $d\sigma/dx$




J. Mousseau

- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing. **at an <x>** (0.07) **& <$Q^2$ >** (2 $GeV^2$) - **where negligible shadowing is expected with $l^{\pm}$.**



# Shadowing - continued

- Why low x?
- The lifetime of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters:

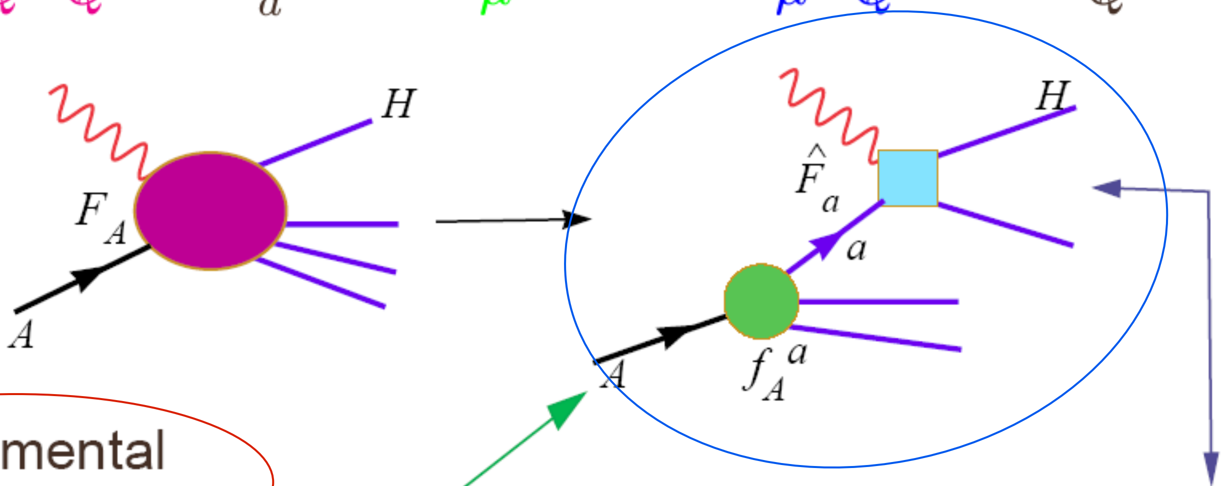
$$t_c = 2E_{had} \;/\; (Q^2 + m^2)$$

- For a given $Q^2$ need large $E_{had}$ to yield sufficient $t_c$ which implies small x.
- m is larger for the vector current than the axial vector current $\rightarrow$ for a given $Q^2$ you need more $E_{had}$ for the vector current than the axial vector current to have sufficient $t_c$.
- This implies you can have shadowing at higher x with neutrinos than with charged leptons

# Global QCD Analysis in a Nutshell

## Master Equation for QCD Parton Model – the Factorization Theorem

$$F_A^\lambda\left(x,\frac{m}{Q},\frac{M}{Q}\right) = \sum_a f_A^a\left(x,\frac{m}{\mu}\right) \otimes \hat{F}_a^\lambda\left(x,\frac{Q}{\mu},\frac{M}{Q}\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$




Experimental Input

Theoretical Calculations

Hard Cross-section perturbative calculable (may contain $\alpha_s^n \mathrm{Log}^n(M/Q)$)

universal Parton Dist. Fn.
Non-Perturbative Parametrization at $Q_0$
GLAP Evolution to Q

extracted by applying global analysis methods

**What do the concepts of "factorization" and "universal (nuclear) parton distributions" mean in the nuclear environment?**

# Backup

# Generators for the SIS/DIS region

- Generator comparison: run the different generators at different fixed energies for different targets and compare the ouputs
- Focus on **charged current interactions**
  Assume SIS/DIS region = **W>1.7 GeV**
  All interactions from **muon neutrinos and anti-neutrinos**
- Comparisons will be mainly multiplicities (charged hadrons, pions and neutral pions) and some kinematical variables (W, Q2, leading pion momentum)
- Also have a look at particle content for the “custom models” used by generators to model DIS interactions where PYTHIA cannot be used
- Start by describing how the generators treat the transition and DIS regions

# PYTHIA Hadronization Program for Neutrino experiments – Teppei Katori

AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

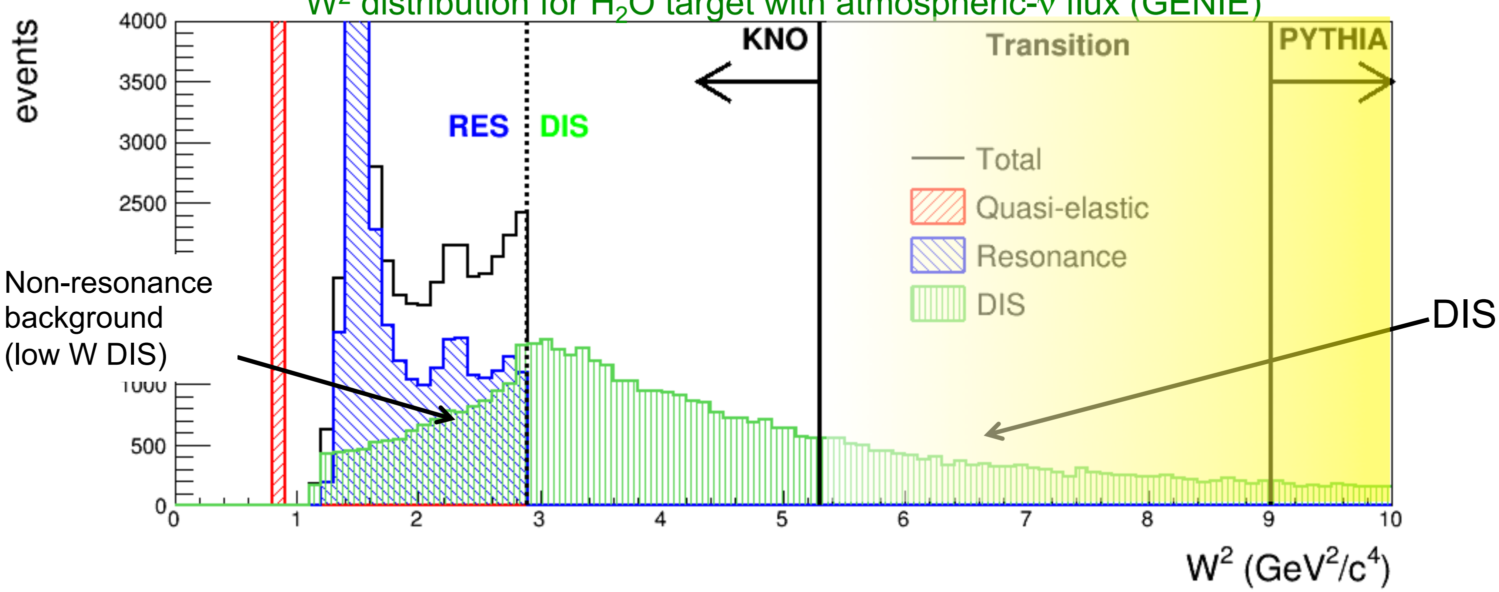
## 1. GENIE hadronization model (AGKY model)



Cross section
$W^2$<2.9 $GeV^2$ : RES
$W^2$>2.9 $GeV^2$ : DIS
Hadronization (AGKY model)
$W^2$<5.3$GeV^2$ : KNO scaling based model
2.3$GeV^2$<$W^2$<9.0$GeV^2$ : transition
9.0$GeV^2$<$W^2$ : PYTHIA6

PYTHIA hadronization
- It is used only for high W ($W^2$>5.3$GeV^2$)
- It may be important for future experiments, especially PINGU, ORCA, Hyper-K, DUNE

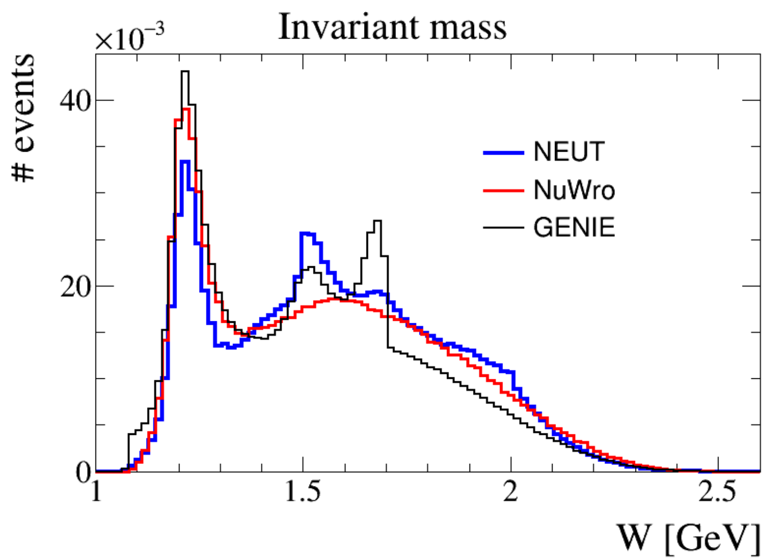
$W^2$ distribution for $H_2O$ target with atmospheric-ν flux (GENIE)



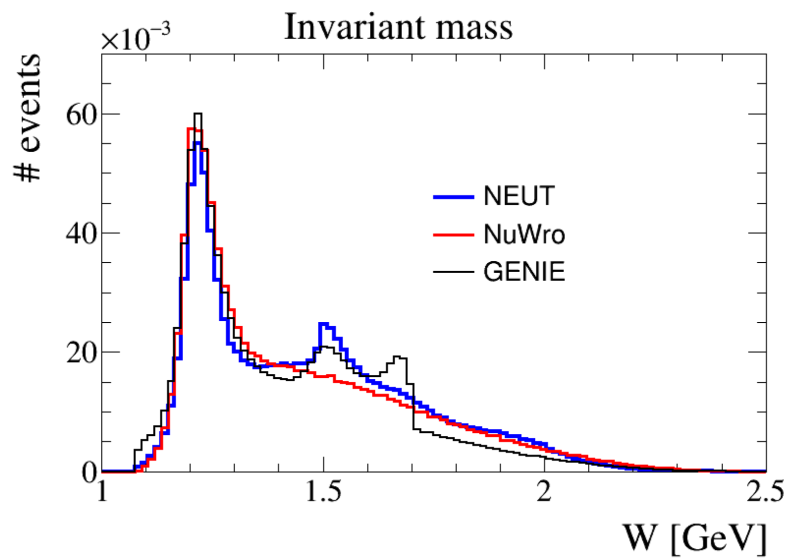
# Generators for the SIS/DIS region

W distributions
Ar, $E_\nu$=2.5 GeV

Neutrino




Anti-neutrino



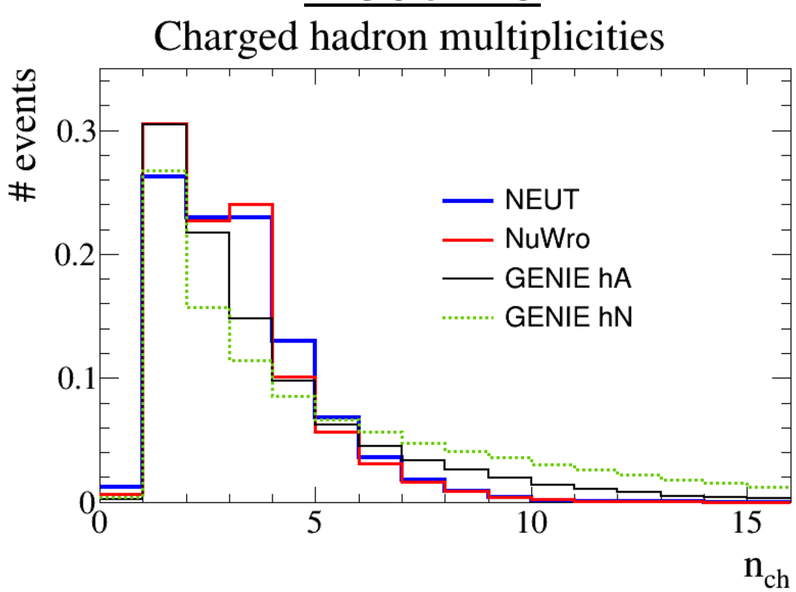

Main differences are presence or absence of certain resonances
Won't affect comparisons at W>1.7 GeV

# Generators for the SIS/DIS region

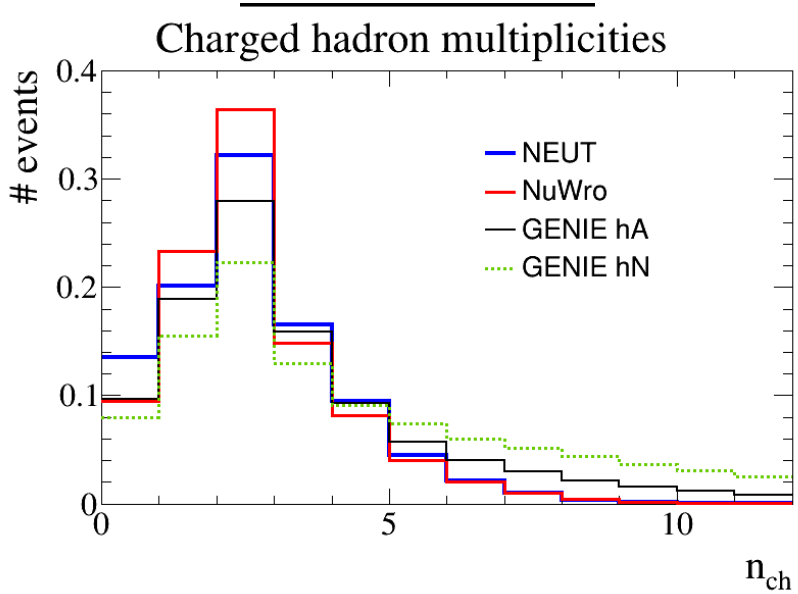
Charged hadron multiplicities
Ar, $E_\nu$=2.5 GeV

W>1.7 GeV

## Neutrino




## Anti-neutrino



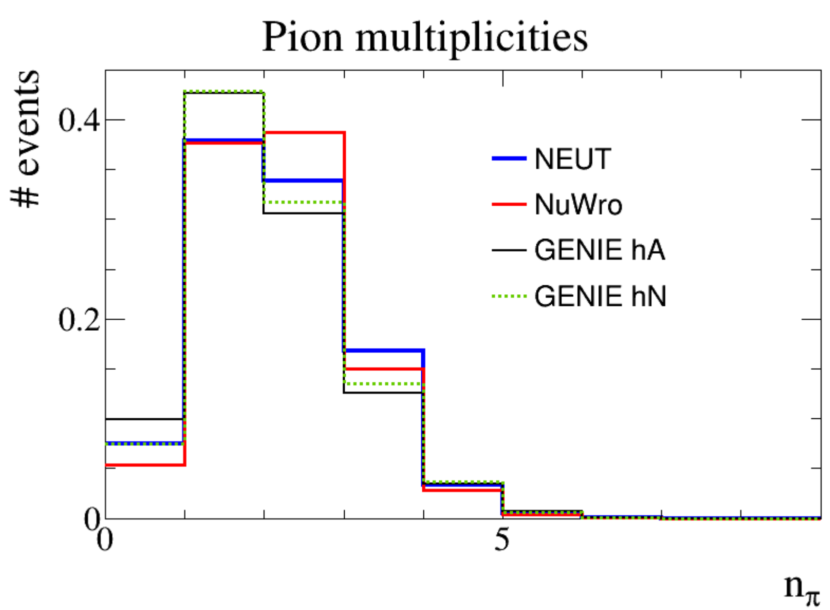

Relative agreement between NEUT and NuWro
GENIE predicts more charged hadrons than others

# Generators for the SIS/DIS region

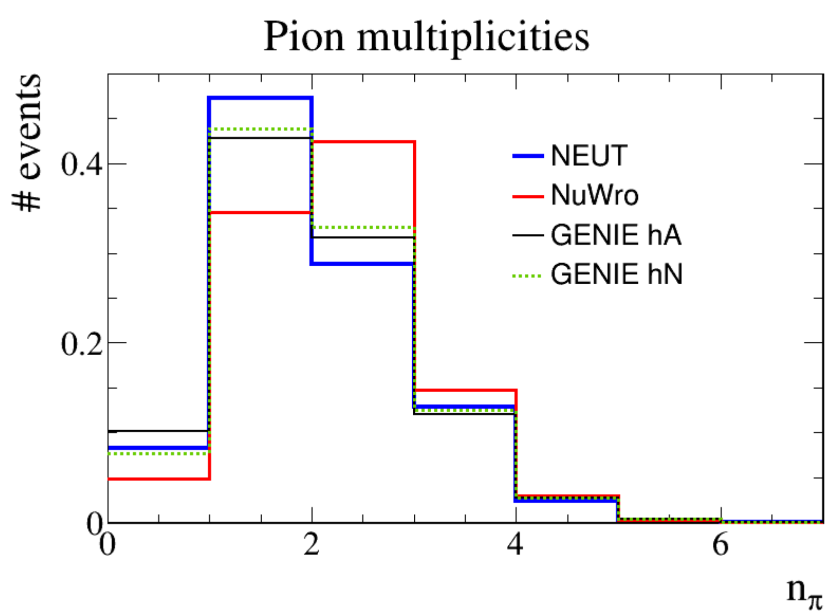
Pion multiplicities
Ar, $E_\nu$=2.5 GeV

W>1.7 GeV

Neutrino




Anti-neutrino



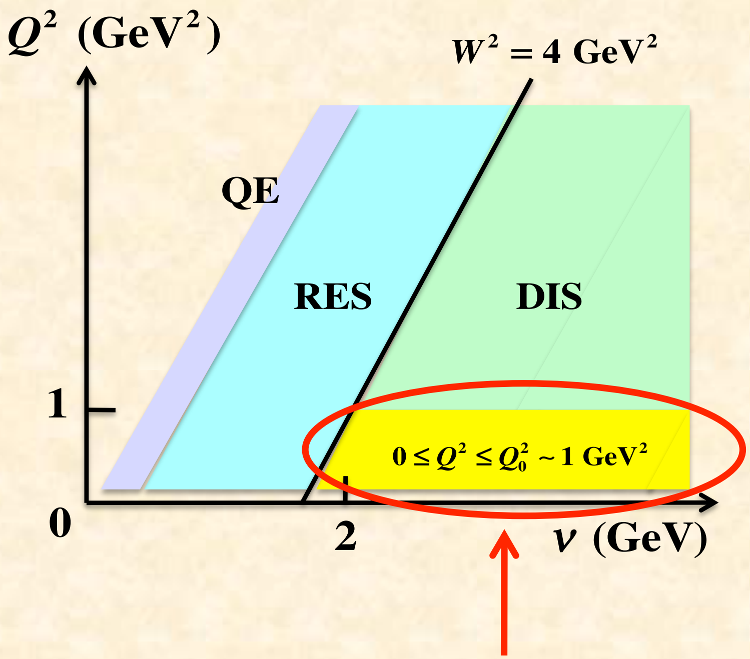

Similar pattern, difference between NEUT and NuWro slightly smaller

# Fragmentation studies in NOMAD experiment

**Comparison of tuned NOMAD event generator with GENIE at event generator level for CNGS beam.**
**$\nu_\mu$ CC interactions**

| Hadrons | NOMAD (%) | GENIE (%) | GENIE/NOMAD |
|---|---|---|---|
| $K_S^0$ | 5.31 | 6.46 | 1.21 |
| $\Lambda^0$ | 4.88 | 7.63 | 1.56 |
| $\bar{\Lambda}^0$ | 0.28 | 0.25 | 0.89 |
| $\rho^0(770)$ | 14.27 | 19.30 | 1.35 |
| $f_0(980)$ | 1.39 | 0 | - |
| $f_2(1270)$ | 2.75 | 0 | - |
| $D^0$ | 1.99 | 4.11 | 2.07 |
| $K^+$ | 8.17 | 11.91 | 1.46 |
| $K^-$ | 3.63 | 4.88 | 1.34 |
| Fraction | | | |
| $\frac{N(K^{\star +} \to K_S^0 \pi^+)}{N(K_S^0)}$ | 18.19 | 25.97 | 1.42 |
| $\frac{N(K^{\star -} \to K_S^0 \pi^-)}{N(K_S^0)}$ | 7.13 | 9.09 | 1.27 |
| $\frac{N(\Sigma^{\star +} \to \Lambda \pi^+)}{N(\Lambda)}$ | 3.47 | 13.4 | 3.86 |

# $Q^2 \to 0$ region: Theoretical background




$$F_{T,L} = \frac{\gamma}{\pi} Q^2 \sigma_{T,L}, \quad \gamma = \frac{|\vec{q}|}{q_0} = \sqrt{1 + \frac{Q^2}{\nu^2}}$$

$\sigma_{T,L}$ = Total $\nu$ cross section

$$\sim \sum_f (2\pi)^4 \delta(p + q - p_f) \left| \langle f | \varepsilon_{T,L} \cdot J(0) | p \rangle \right|^2$$

$F_{T,L}$ = transverse, longitudinal cross section

Vector current conservation: $q_\mu W^{\mu\nu} = 0$

$\Rightarrow F_L^V \sim Q^2 F_T^V$ as $Q^2 \to 0$

---

PCAC (Partially Conserved Axial-vector Current):

$\partial_\mu A^\mu(x) = f_\pi m_\pi^2 \pi(x)$, $A^\mu$ = Axial-vector current,

$f_\pi$ = Pion-decay constant, $\pi$ = Pion field

$\Rightarrow F_L^A \sim \dfrac{f_\pi^2}{\pi} \sigma_\pi$ as $Q^2 \to 0$,

Pion-scattering cross section: $\sigma_\pi$


References:
A. Donnachie and P. V. Landshoff, Z. Phys. C 61 (1994) 139
B. Z. Kopeliovich, Nucl. Phys. B 139 (2005) 219;
S. A. Kulagin, Phys. Rev. D 76 (2007) 094023

# $Q^2 \rightarrow 0$ region: Practical description

$F_{1,2,3}^{\nu A}(x, Q^2 \to 0)$

(1) **FLUKA**, G. Battistoni *et al.*,
Acta Phys. Pol. B 40 (2009) 2431

$$F_{2,3}(x,Q^2) = \frac{2Q^2}{Q_0^2 + Q^2} F_{2,3}(x,Q_0^2)$$

(2) **A. Bodek and U.-K. Yang**, arXiv:1011.6592

**charged-lepton**:

$$F_2^{e/\mu}(x,Q^2 < 0.8\ \mathrm{GeV}^2) = K_{valence}^{vector}(Q^2) F_{2,LO}^{valance}(\xi_w, Q^2 = 0.8\ \mathrm{GeV}^2) + K_{sea}^{vector}(Q^2) F_{2,LO}^{sea}(\xi_w, Q^2 = 0.8\ \mathrm{GeV}^2)$$

$$K_{valence}^{vector}(Q^2) = \frac{Q^2}{Q^2 + C_s}, \quad K_{sea}^{vector}(Q^2) = \left[1 - G_D^2(Q^2)\right] \frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}$$

$$G_D(Q^2) = \frac{1}{(1 + Q^2/0.71)^2}, \quad \xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2\left[1 + \sqrt{1 + 4M^2x^2/Q^2}\right] + 2Ax}$$

**neutrino**:

Separate $F_i^{\nu}(x,Q^2)$ into vector and axial-vector parts.

$F_i^{\nu}(x,Q^2)_{\text{vector}} \to Q^2 \to 0 \quad (Q^2 \to 0)$ as the charged-lepton case.

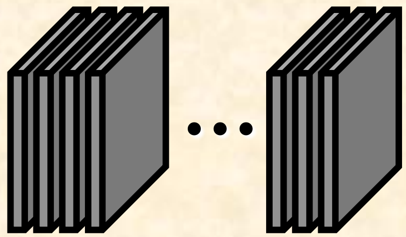
$F_i^{\nu}(x,Q^2)_{\text{axial-vector}} \neq 0 \quad (Q^2 \to 0)$ due to PCAC.

Actual expressions are slightly complicated (see the original paper).

# Neutrino DIS experiments

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

$E$ = 30 ~ 500 GeV

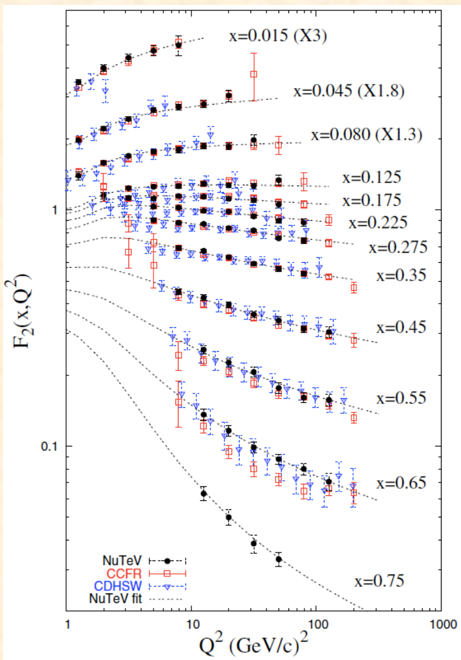


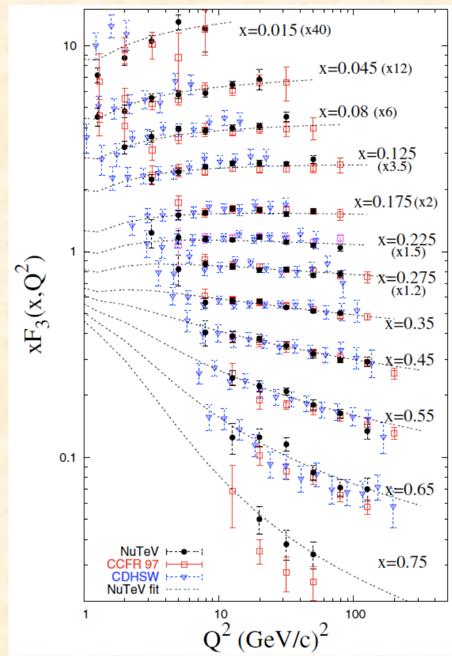
Huge Fe target (690 ton)

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

**MINERνA (He, C, Fe, Pb), …**

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



# Charged-lepton Nuclear Parton Distribution Functions

## Experimental data

(1) $F_2^A / F_2^D$

- NMC: p, He, Li, C, Ca
- SLAC: He, Be, C, Al, Ca, Fe, Ag, Au
- EMC: C, Ca, Cu, Sn
- E665: C, Ca, Xe, Pb
- BCDMS: N, Fe
- HERMES: N, Kr

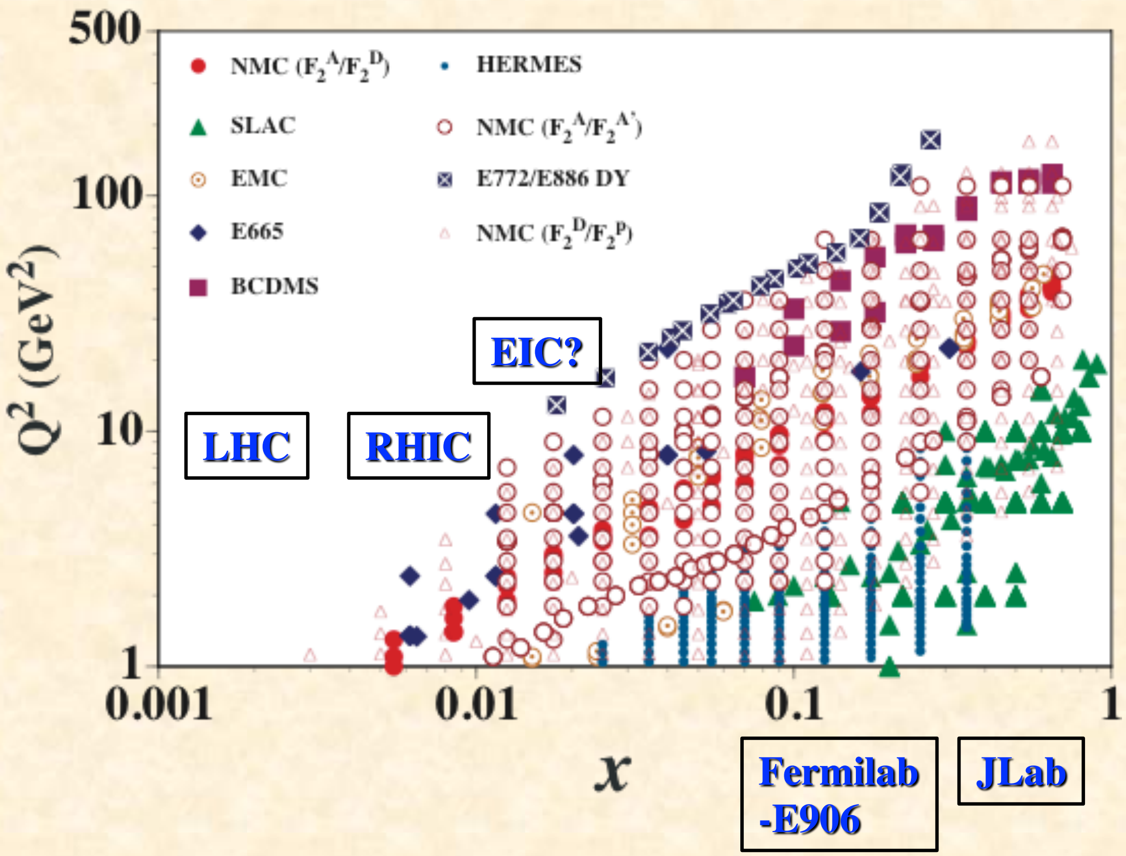
+ JLab data

(2) $F_2^A / F_2^{A'}$

- NMC: Be / C, Al / C, Ca / C, Fe / C, Sn / C, Pb / C, C / Li, Ca / Li

(3) $\sigma_{DY}^A / \sigma_{DY}^{A'}$

- E772: C / D, Ca / D, Fe / D, W / D
- E866: Fe / Be, W / Be



# Current nuclear data are kinematically limited.

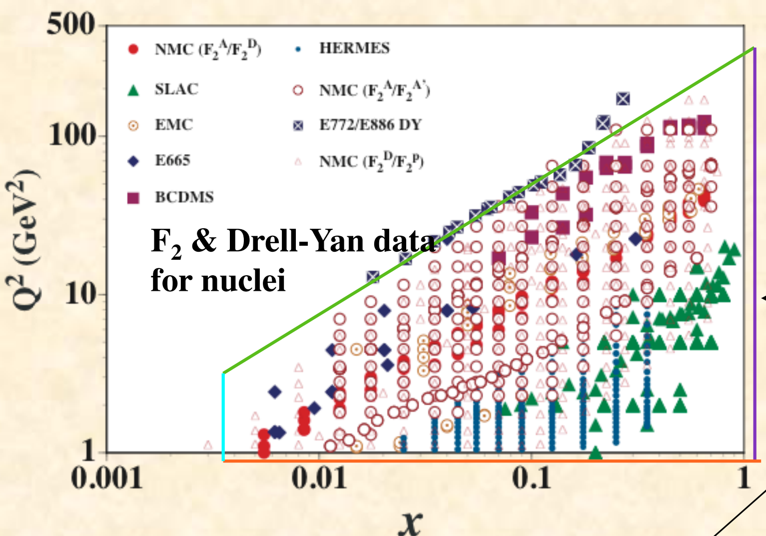
$$x = \frac{Q^2}{2p\cdot q} \simeq \frac{Q^2}{ys}$$

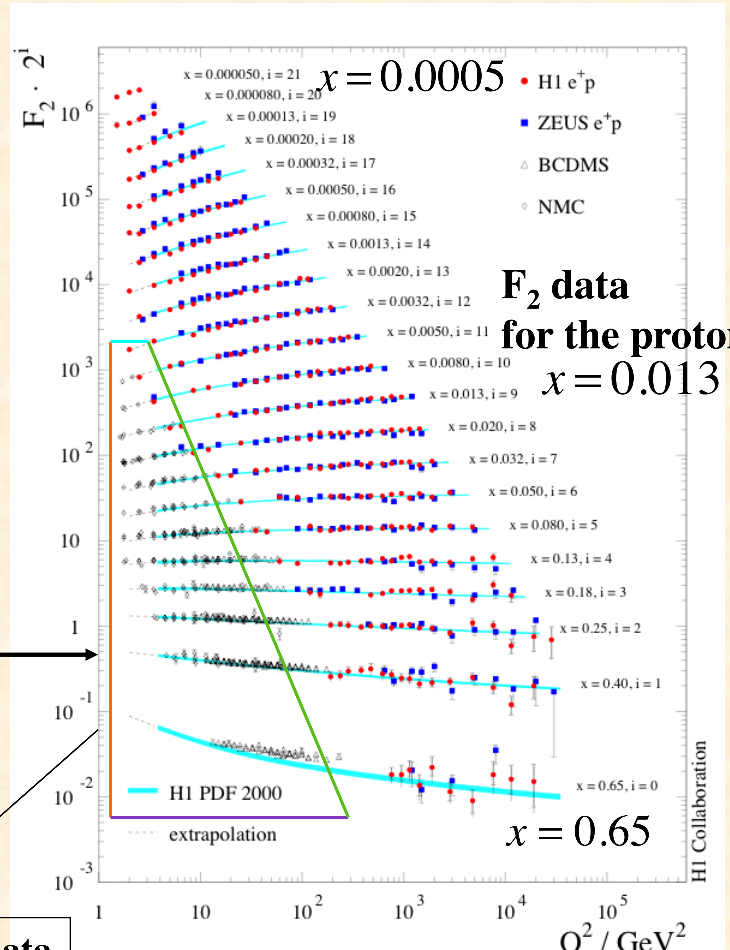
(from H1 and ZEUS, hep-ex/0502008)

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

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

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




region of nuclear data

# Functional form of initial distributions at $Q_0^2$

- **Definition of NPDF ( as initial condition of the DGLAP eq.)**
  - $f_i^A(x) = \frac{1}{A}\left(Z\, f_i^{p/A}(x) + (A-Z) f_i^{n/A}(x)\right), \left[ f_i^{N/A}(x): \text{ PDF of bound nucleon in the nucleus} \right]$
  - **Assuming isospin symmetry:** $u \equiv d^n = u^p,\ d \equiv u^n = d^p$
- **Functional forms**
  - **HKN07 ($Q_0^2$=1 GeV$^2$)**

$$\boxed{f_i^A(x) = w_i(x,A,Z)\frac{1}{A}\left(Z\, f_a^p(x) + (A-Z) f_a^n(x)\right),\ w_i(x,A,Z) = 1 + \left(1 - \frac{1}{A^{1/3}}\right)\frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{0.1}}}$$

  - **EPS09 ($Q_0^2$=1.69 GeV$^2$)**

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

  - **nCTEQ15 ($Q_0^2$=1.69 GeV$^2$)**

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

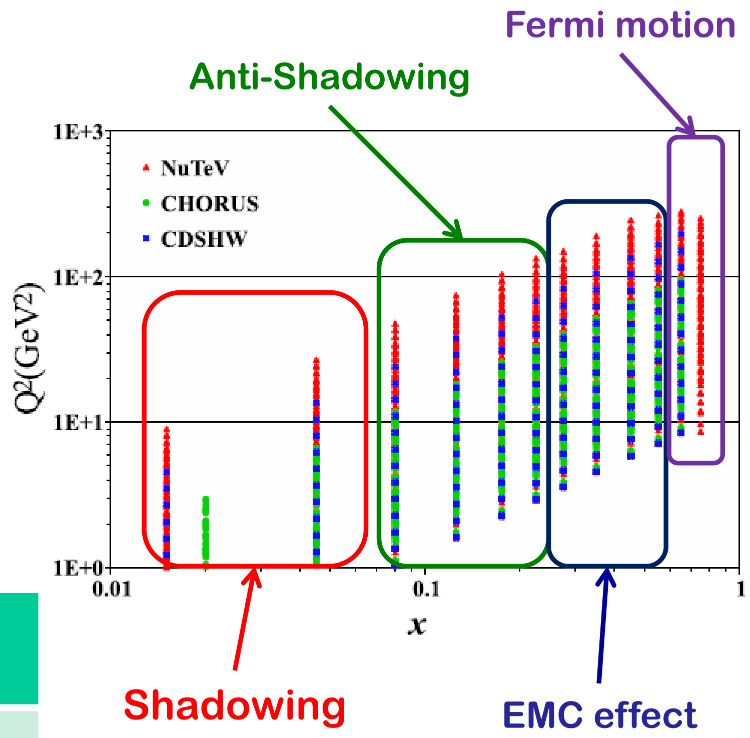
  - **DSSZ ($Q_0^2$=0.4 GeV$^2$)**

$$f_i^{N/A}(x_N) = \int_x^A \frac{dy}{y} W_i(y,A,Z)\ f_i^N\left(\frac{x_N}{y}, Q_0^2\right), \begin{cases} W_v(y,A,Z) = \left[ a_v\, \delta(1 - \bullet_v - y) + (1-a_v)\,\delta(1 - {}_{v'} - y)\right] + n_v \left(\frac{y}{A}\right)^{\alpha_v}\left(1 - \frac{y}{A}\right)^{\beta_v} + n_s \left(\frac{y}{A}\right)^{\alpha_s}\left(1 - \frac{y}{A}\right)^{\beta_s}, \\ W_{s,g}(y,A,Z) = A\,\delta(1-y) + \frac{a_{s,g}}{N_{s,g}}\left(\frac{y}{A}\right)^{\alpha_{s,g}}\left(1 - \frac{y}{A}\right)^{\beta_{s,g}} \end{cases}$$

# Kinematics of the neutrino DIS experiment

- **Kinematic in Lab frame**
  - $X=Q^2/2\langle M_N\rangle\nu$
  - $\nu=E_{had}$: energy of outgoing hadron
  - $y=E_{had}/(E_{had}+E_l)$
  - $Q^2=2\langle M_N\rangle xyE_\nu$, ($E_\nu= E_{had}+E_l$)
  - $W=\langle M_N\rangle^2+Q^2(1-x)/x$
- $Q^2> 4\ \text{GeV}^2$, $W>3.5\ \text{GeV}$

| Experiment | Target | Beam energy (GeV) | # of data $\nu$ & $\bar{\nu}$ |
|---|---|---|---|
| NuTeV | Fe | 35-340 | 2604 |
| CHORUS | Pb | 25-130 | 1204 |
| CDHSW | Fe | 23-187 | 1602 |



# Neutrino: CTEQ vs. Other nPDF sets

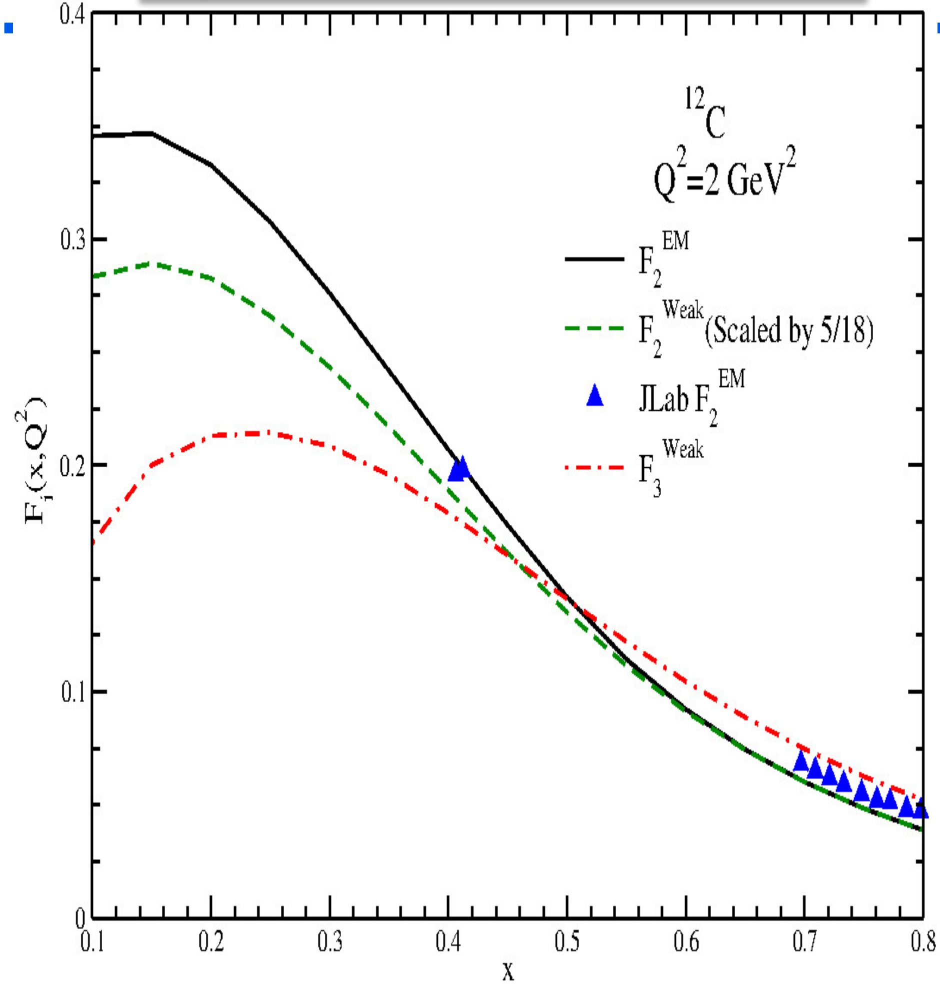
- CTEQ uses the double differential cross sections NOT the structure functions $F_2$ and $xF_3$ that require additional theoretical assumptions to extract.

- CTEQ uses the full NuTeV covariant error matrix rather than adding systematics and statistical errors in quadrature.

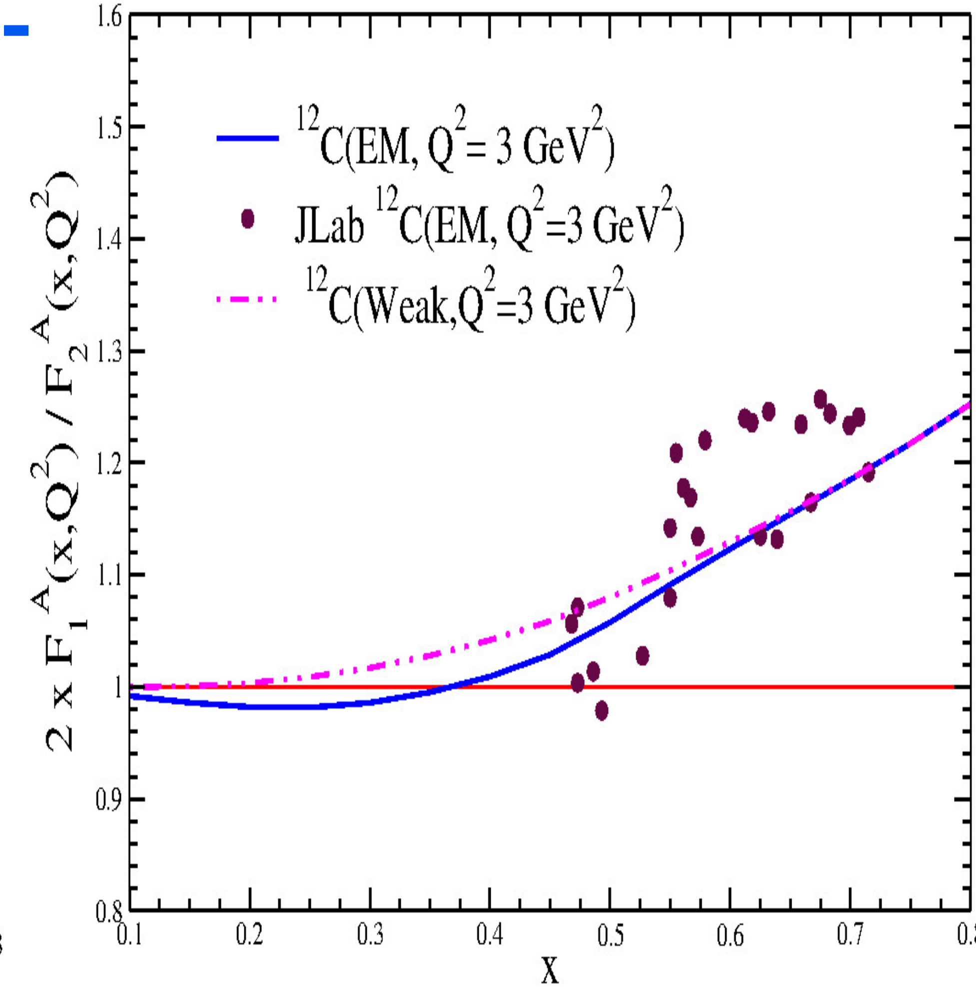
- Use **8 Neutrino data sets**
  - NuTeV cross section data: $\nu\, Fe,\ \nu\, Fe$
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: $\nu\, Pb,\ \nu\ Pb$
  - CCF*R* dimuon off Fe data

$F_i^{EM}(x,Q^2)(i=2)$ vs x

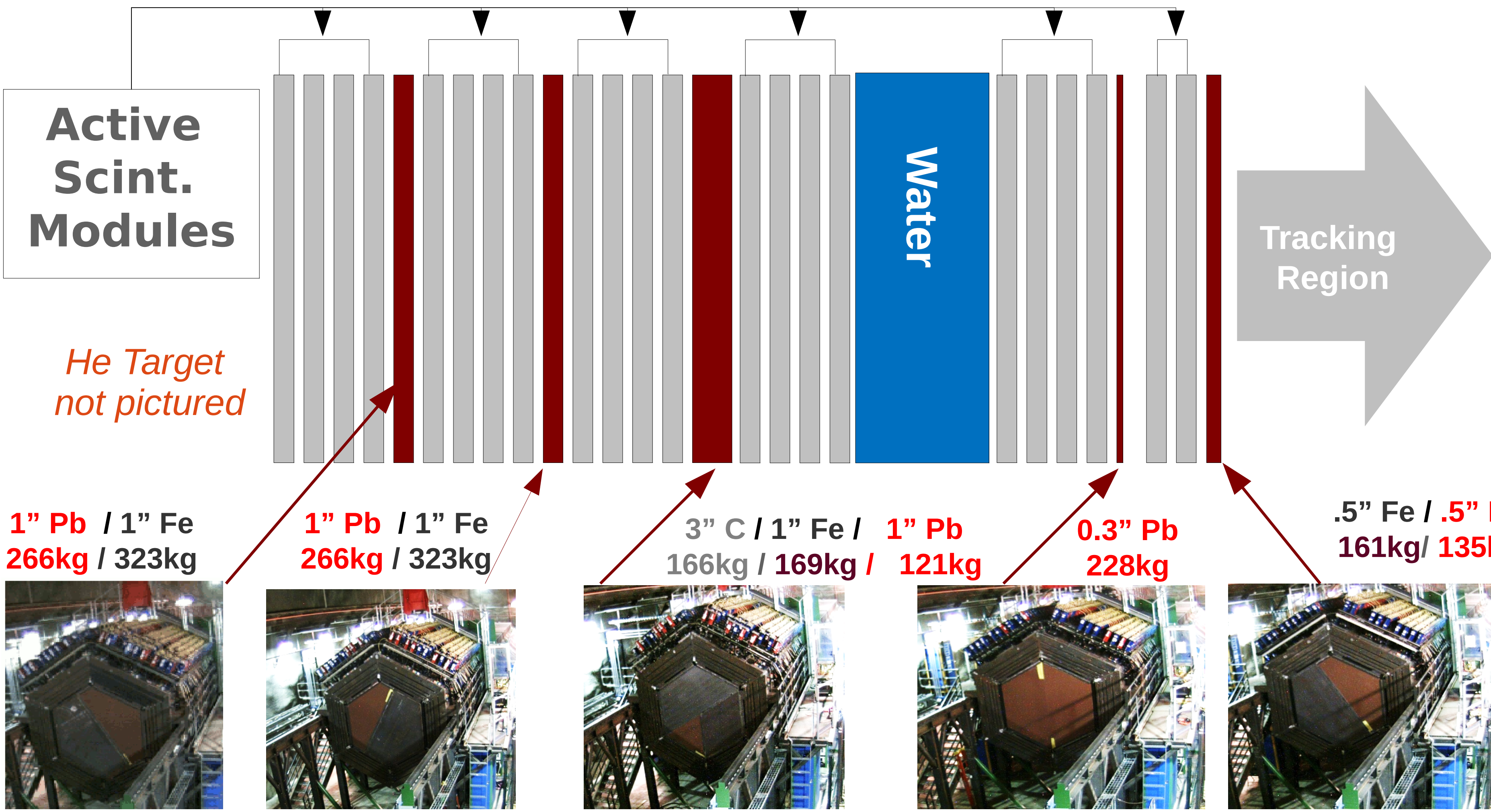
$F_i^{Weak}(x,Q^2)(i=2,3)$ vs x



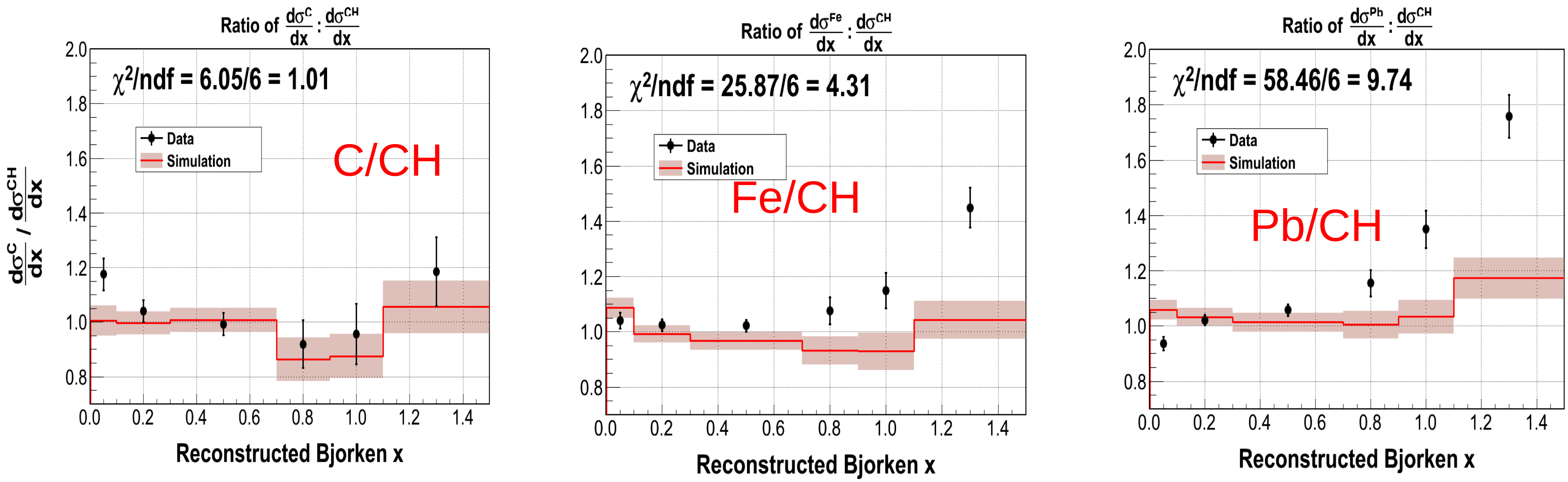

Callan-Gross relation in nuclei



# MINERvA Nuclear Targets



# Inclusive Ratios: dσ /dx

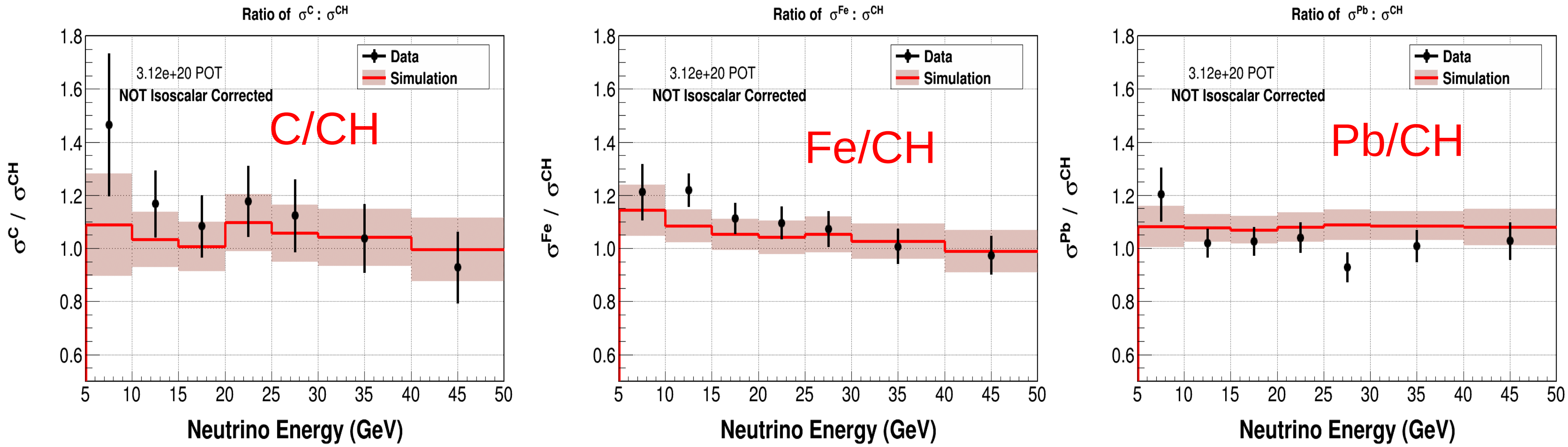



•Data are presented as differential cross-section ratios in reconstructed x: we do not correct for detector smearing.

•We observe an *excess* in the data at large x, and a *deficit* at low x, which grows with the size of the nucleus.

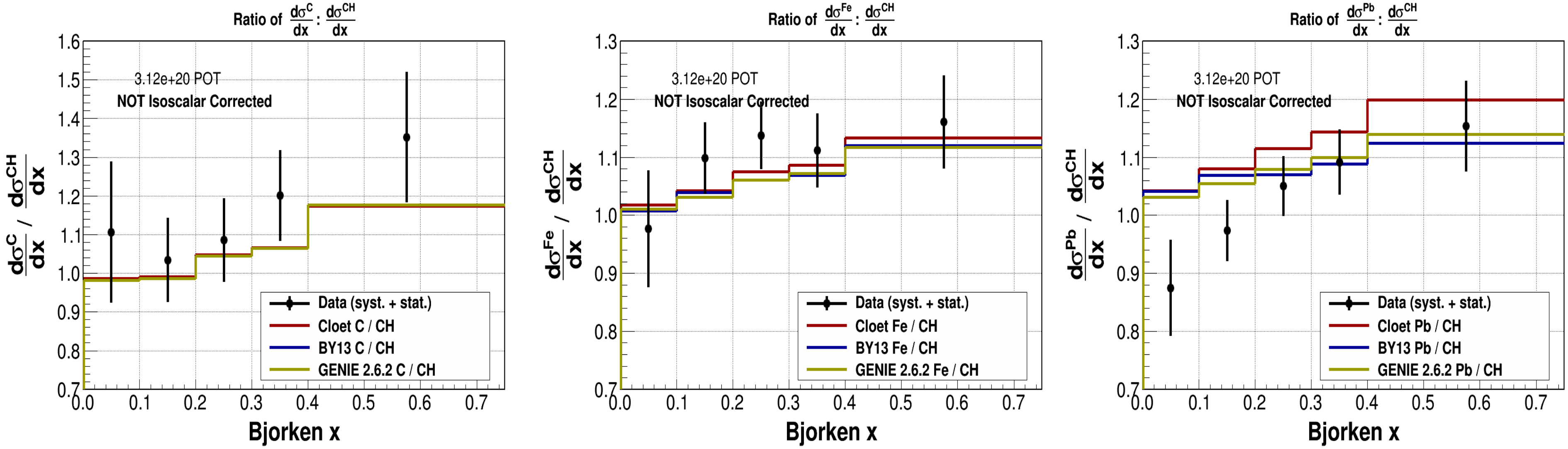
- The low x events are at a low $Q^2$ (0.5 $(\text{GeV}/c)^2$ ), where the theory complicated.
- High x events are a mixture between quasi-elastic and resonant.

# DIS Ratios: $\sigma(E_\nu)$




- Ratios of the heavy nuclei (Fe, Pb) to lighter CH are evidence of nuclear effects.
- There is a general trend of the data being below the MC at high energy.
- This trend is larger in the lead than in the iron.

# Alternative x-Dependent Effects

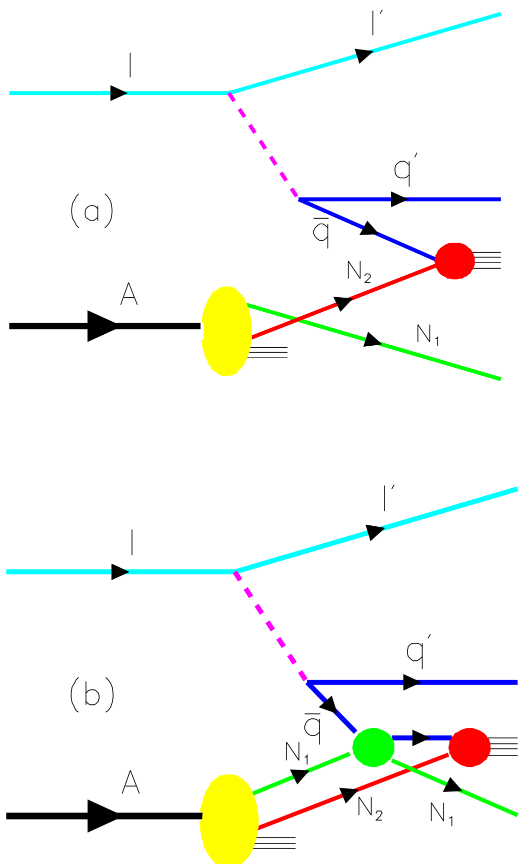



- Our data currently lacks statistical precision to differentiate between different effects, particularly on the edges of the distribution.
- But the models themselves show significant disagreements from each other, especially in the EMC region (0.3 < x < 0.7).
- This is strong motivation to accumulate and analyze additional medium energy neutrino and anti-neutrino data, which will be able to resolve these discrepancies.
- Additionally, better observe these differences in shadowing between $e^-$ and $\nu_\mu$

# Shadowing in Neutrino Interactions
# Difference expected compared to $l^{\pm}$ A

Nuclear Shadowing in Electro-Weak Interactions - Kopeliovich, JGM and Schmidt arXiv:1208.6541

- Several theoretical models successfully describe the shadowing effects observed in charged-lepton nucleus scattering.
- Most are based on hadronic fluctuations of the $\gamma$ (or W/Z for neutrinos)
- These fluctuations then undergo multiple diffractive scattering off leading nucleons in the the nucleus.
- The multiple scatters interfere destructively leading to no flux making it to downstream nucleons resulting in a depletion of cross section at low values of x.



# Generators for the SIS/DIS region

- No summary from the talk itself however,
- The obvious summary is that this is a very informative and useful comparison of existing generators in their treatments of the higher W part of SIS and the DIS kinematic regimes.

# Fragmentation studies in NOMAD experiment

## Tuning NOMAD event generator - $\nu_\mu$ CC even

Reweighting for the cross-sections
Events selection: $Q^2 > 0.8\ GeV^2, E_{had} > 3GeV$

Analizing the following variables:

- Transverse size of the hadronic system
- Momentum and angle distributions of hadrons
- Primary tracks multiplicity
- Particles and resonances yields: $\Lambda^0$, $\bar{\Lambda}^0$, $K_S^0$, $K^{\star\pm}, \Sigma^{\star+}, D^0, D^{\star 0}, \rho^0, f_0, f_2$, di-muon events
- Formation length

Tuning: JETSET, DPMJET