Thank you for attending the IoP conference at King's!

This talk is classic old professor style:
"I don't know what you are doing, but this is what I think"

Teppei Katori @teppeikatori
King's College London

Exploring the Physics Opportunities of nuSTORM
IoP building, Apr. 6, 2023

Neutrino interaction physics at HyperK

outline

1. Introduction
2. Electron neutrino cross-sections
3. Shallow-inelastic scattering
4. Higher resonances
5. Quark-Hadron duality
6. DIS in the nuclear environment
7. Hadronization
8. Conclusion

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katori@fnal.gov

KING’S College LONDON

Hyper-Kamiokande

1. Introduction

DUNE and HyperK share the problems for future oscillation programs (except target nuclei specific problems)

1. Lack of electron neutrino cross-section data
2. Lack of axial transition form factors for most of baryonic resonances
3. Lack of good models to predict final state hadron multiplicity and kinematics

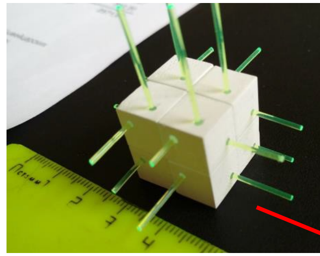
And these problems can be solved by

1. Electron neutrino scattering experiments (nuSTORM)
2. Hydrogen-target neutrino scattering experiments (H/D bubble chamber)
3. High-resolution neutrino scattering experiments

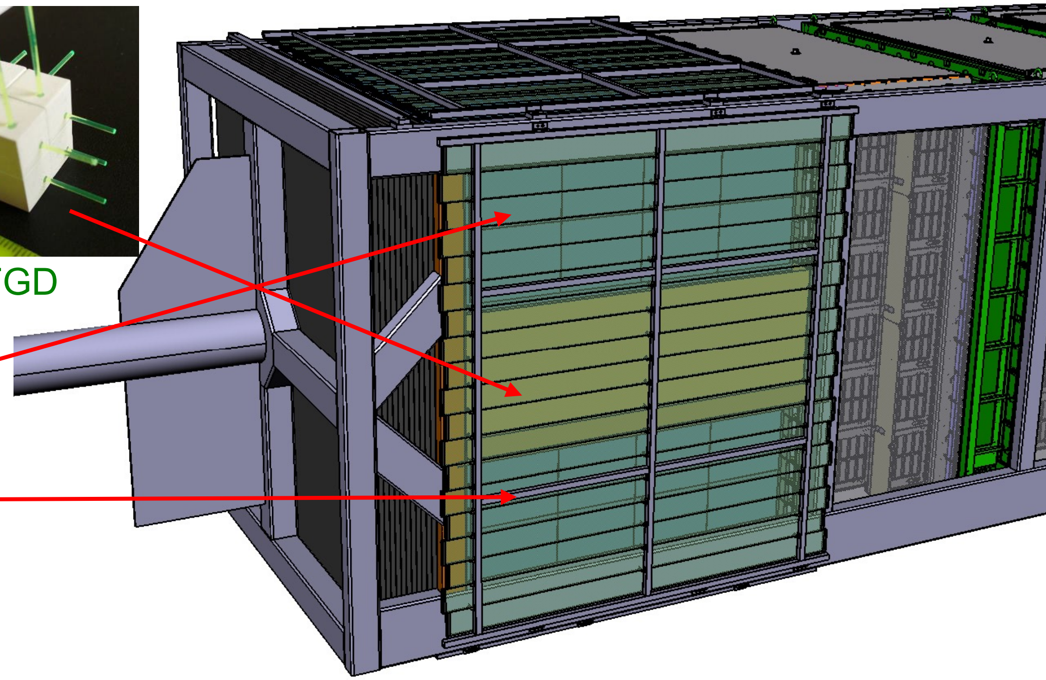
As well as more efficient model development by theory-experiment effort

1. Easy implementation of new models (more modularized generator approach)

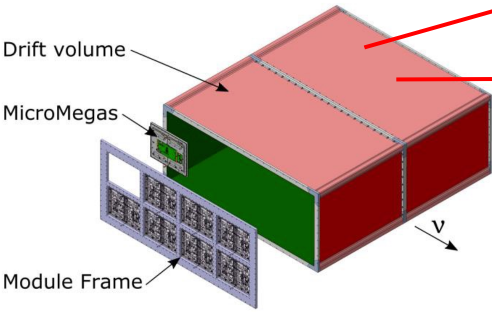
1. ND280 Upgrade



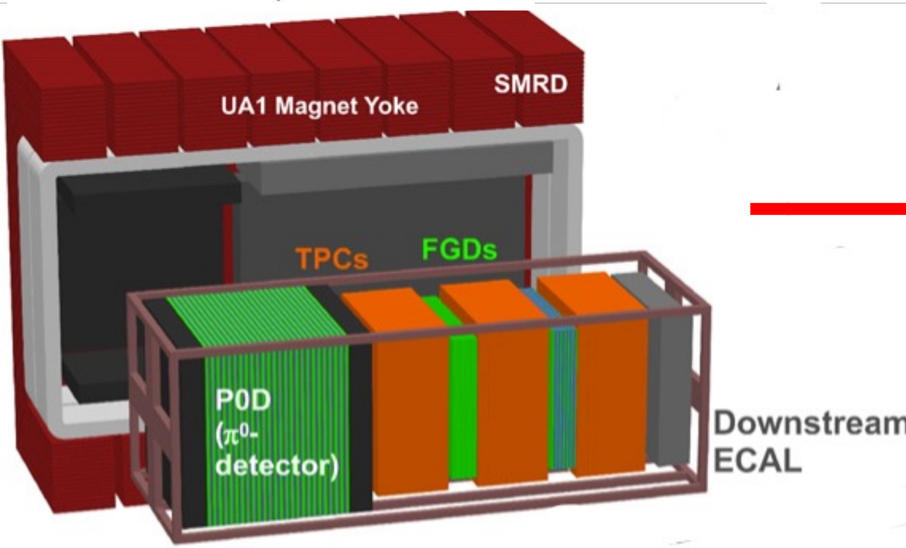
SuperFGD

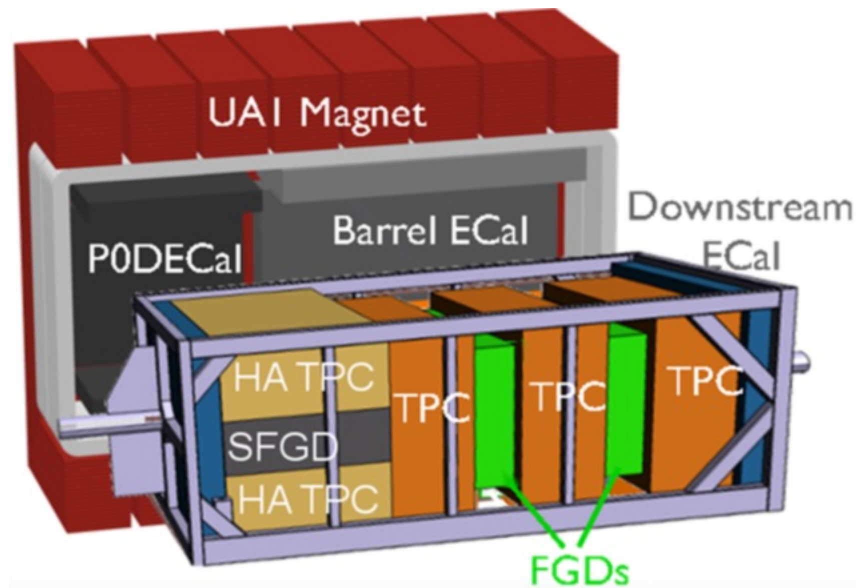


ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD



High Angle TPC





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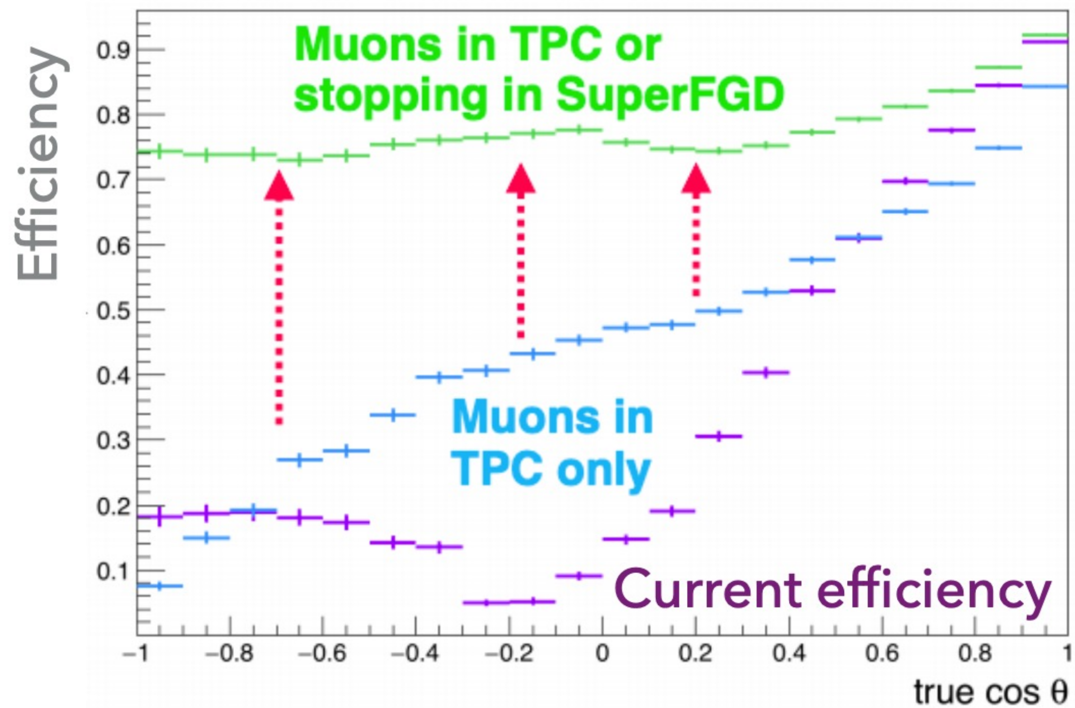
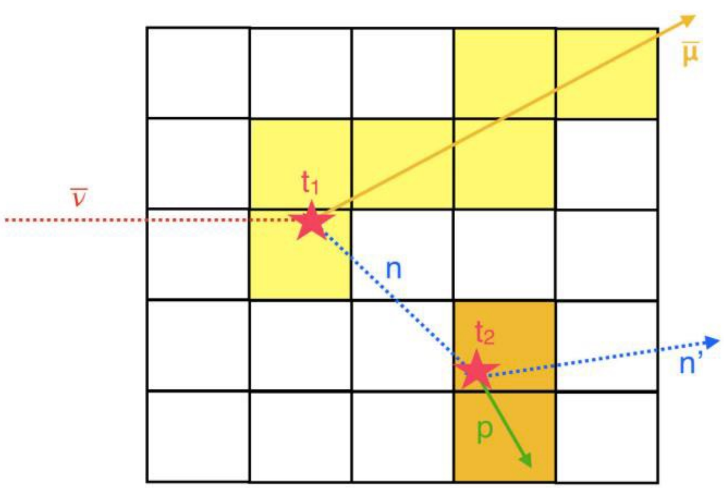
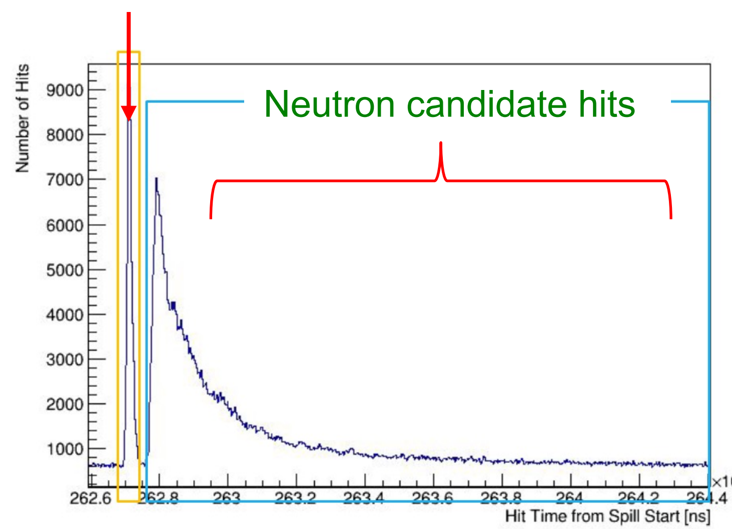


ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD

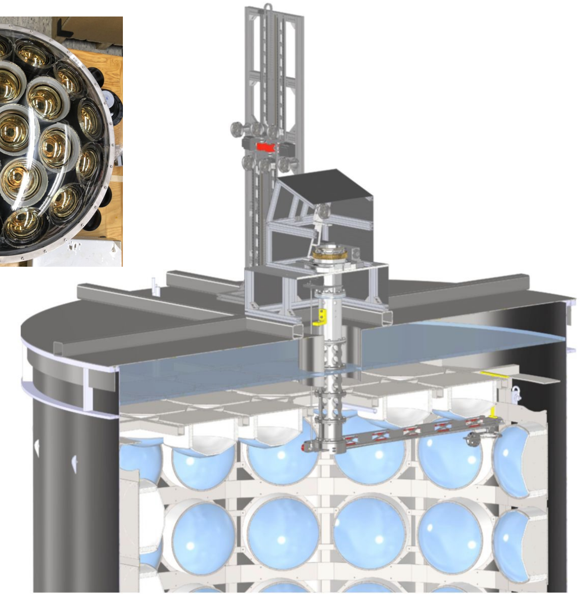
4π coverage
- It matches with Hyper-K phase space

Neutron tagging
- SuperFGD beam test at LANL
- ToF to measure energy



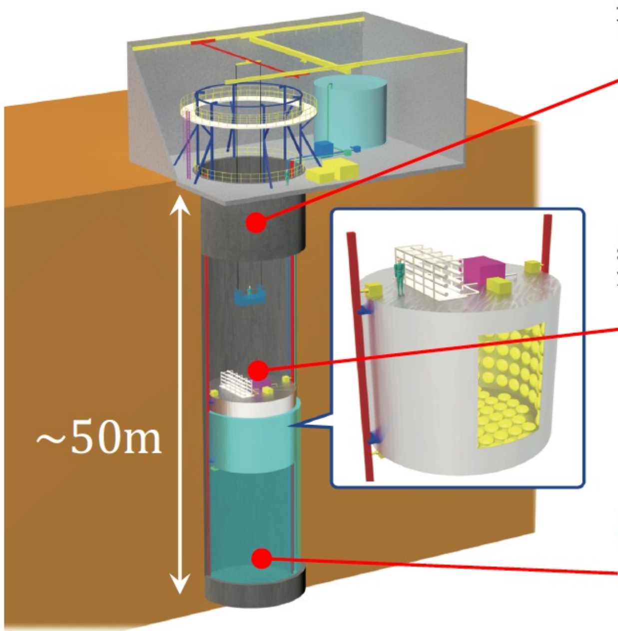


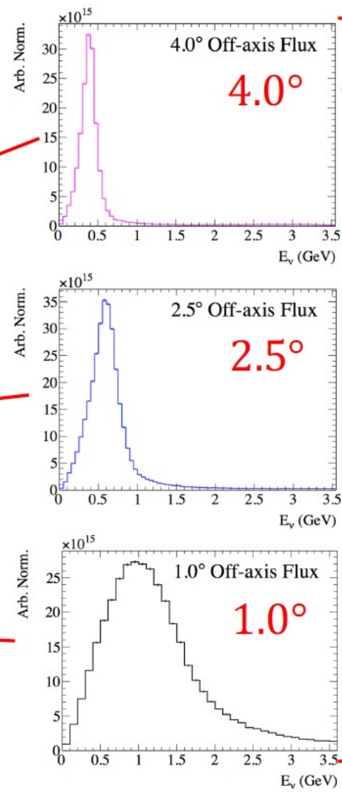
1. IWCD



Intermediate Water Cherenkov Detector

- nuPRISM concept, ~1km from the target
- mPMT units, driving force of HyperK machine learning effort
- Planned test beam at CERN

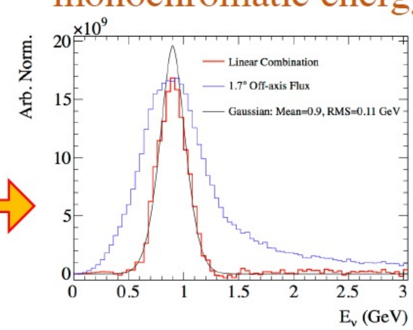




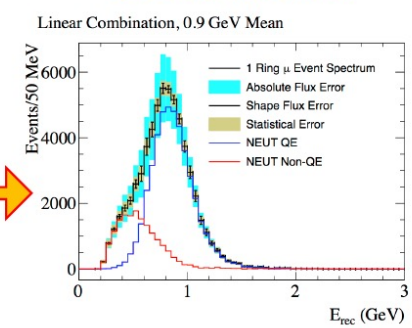
Physics target

- ν-int. measurement by off-axis scanning
- ν_e cross section (3-5% for $\sigma(\nu_e)/\sigma(\nu_\mu), \sigma(\overline{\nu}_e)/\sigma(\overline{\nu}_\mu)$)
- NC and intrinsic ν_e BG measurement (3-4%)
- Neutron multiplicity with Gd loading

Linear sum to make monochromatic energy



Reconstruction



2. Electron neutrino cross-section

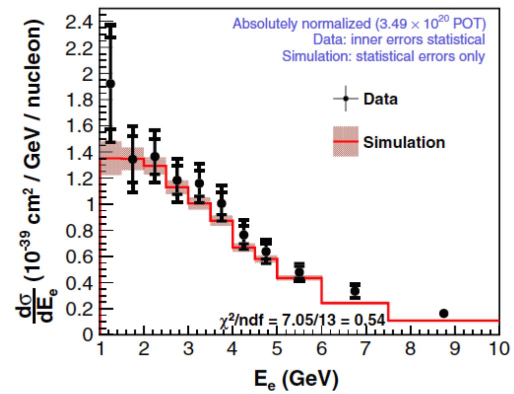
Very limited amount of data

Naively, nuclear structure is the same for ν_e and ν_μ scattering, only the difference is lepton mass

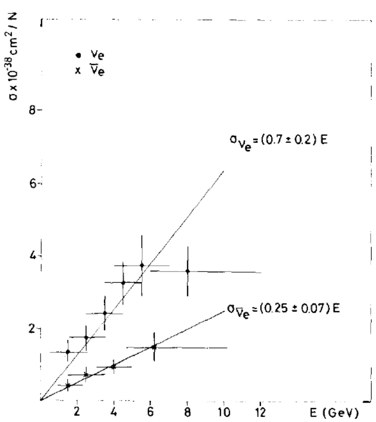
But this sounds similar with "naively, nuclear scattering is the same for neutrino and charged lepton beams, only difference is vector, or V-A current"

We want to confirm if there is any surprise in ν_e scattering or not

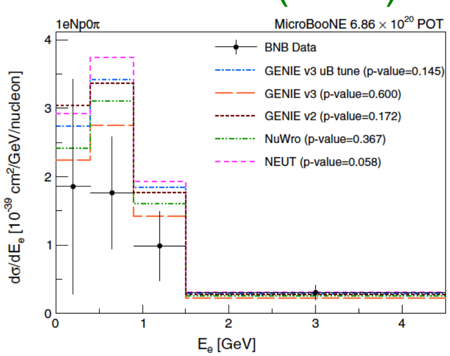
MINERvA (2016)



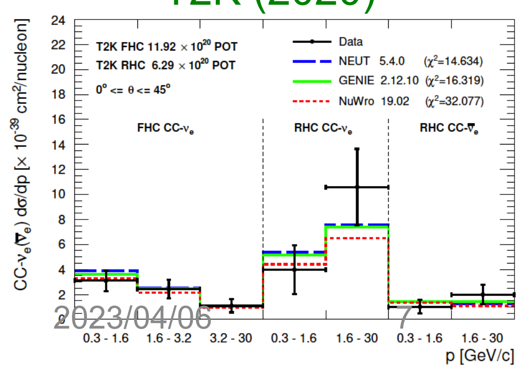
Gargamelle (1978)



MicroBooNE (2022)



T2K (2020)



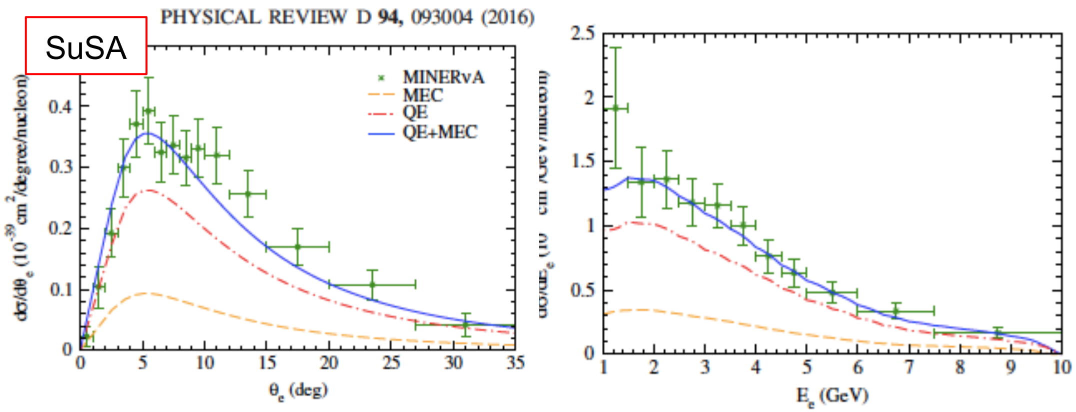
2. Electron neutrino cross-section

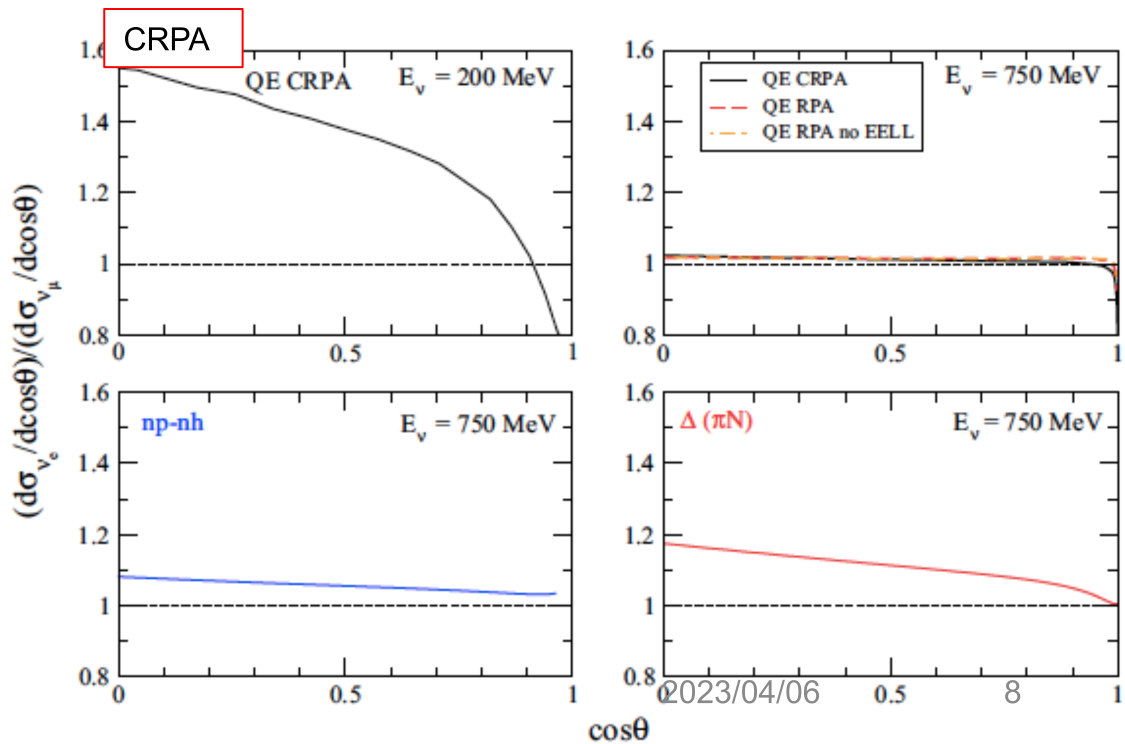
Both T2K(2014) and MINERvA (2016) ν_e cross section data are reproduced by theorists (SuSA, CRPA, GiBUU).

CRPA calculation shows the difference of ν_e and ν_μ cross-section.

At the same beam energy, lepton mass difference ~ 1 pion mass so you expect nuclear effect may be different.

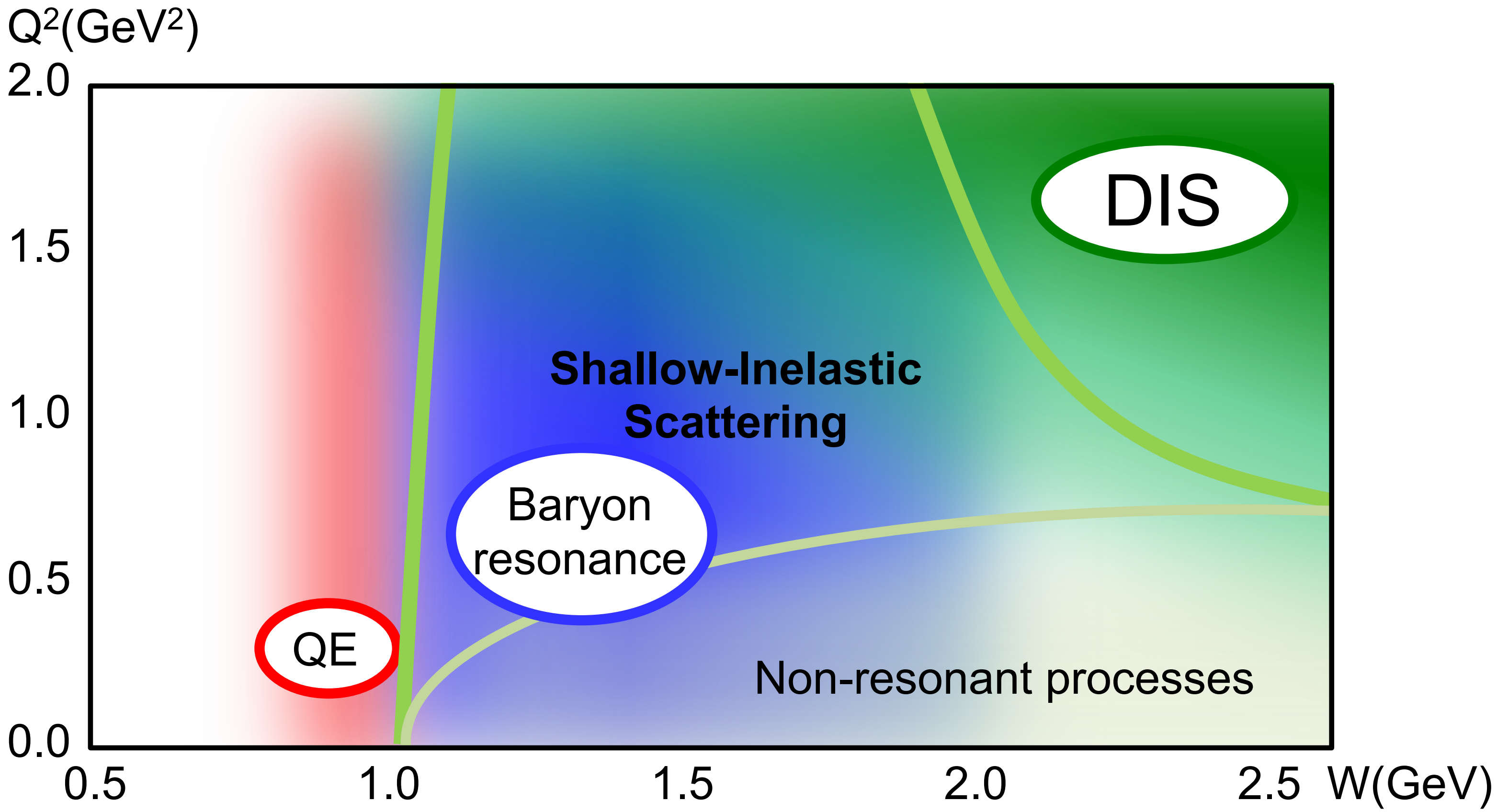
Next step:
We need confirmation of these from other models, first principle calculations, etc, also experimental test





3. Shallow-Inelastic Scattering (SIS)

Shallow-Inelastic scattering region
- Inelastic = not elastic, W > 1.07 GeV (=m_p+m_π)
- Shallow = not deep, Q^2 < 1 GeV^2 for W > 2 GeV



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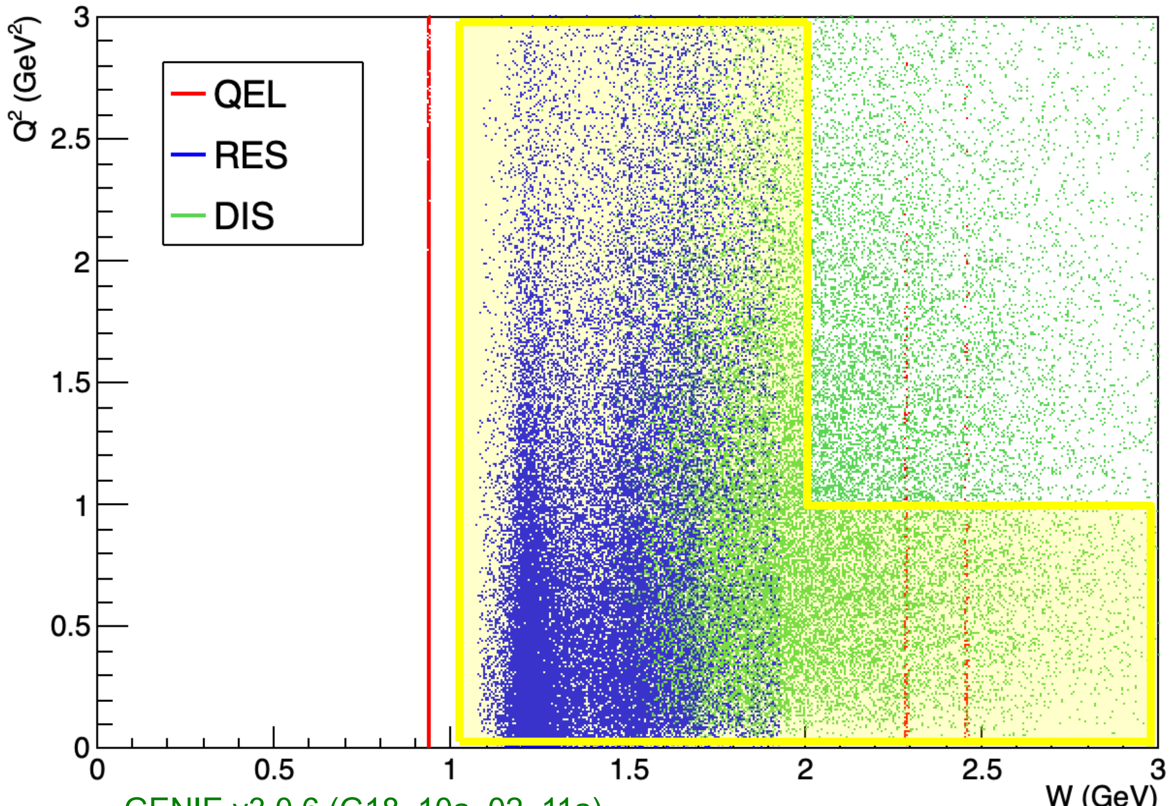
Significant fraction of DUNE beam events (~70%) and multi-GeV atmospheric neutrino events are in SIS kinematic region

Prediction and measurement are both difficult in this region.

Physics of this region is not studied with neutrinos.

Q^2-W distribution with DUNE numu flux on Ar (neutrino model)

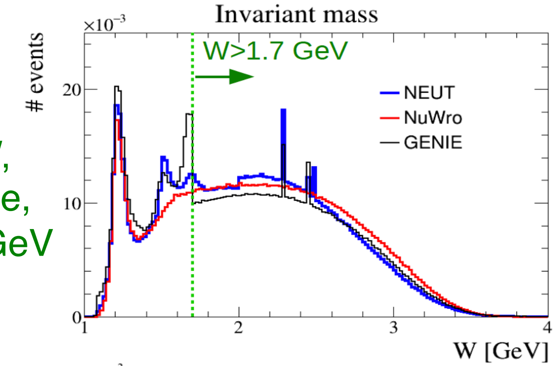


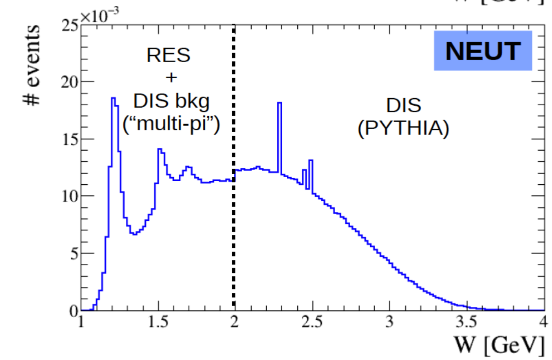
GENIE v3.0.6 (G18_10a_02_11a)

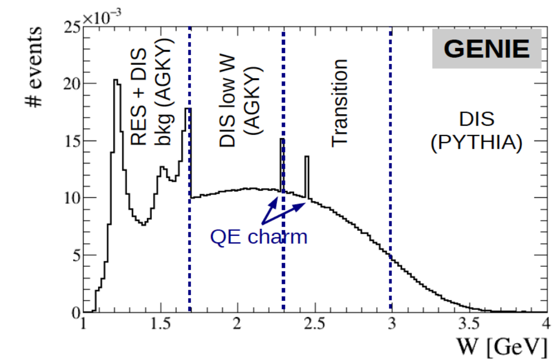
3. SIS in event generators

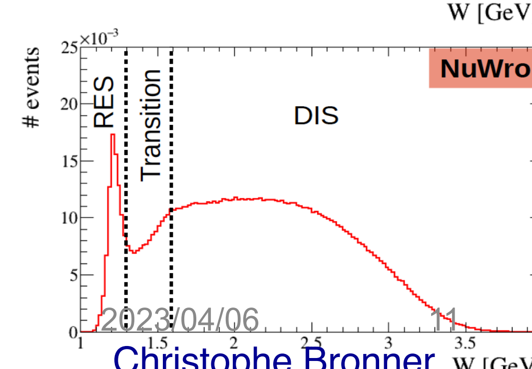
Real Frankenstein part of all generators
- Generators have different approach
- Definition of channels are different in generators
- Very difficult to connect different models
- Need high-statistics tuning samples for verification

True W, ν_μ on Fe, $E\nu$=6 GeV









NEUT

1.3 GeV/c² — 2 GeV/c² — W

Resonances (1π, 1K, 1η) **+ DIS background** (“Multi-pi” mode)

PYTHIA 5.72 (“DIS” mode)

GENIE

1.7 GeV/c² — 2.3 GeV/c² — 3 GeV/c² — W

Resonances + DIS background (“AGKY model”)

DIS low W (“AGKY model”)

Linear transition to PYTHIA 6

PYTHIA 6

NuWro

1.3 GeV/c² — 1.6 GeV/c² — W

RES

Linear transition

DIS (uses PYTHIA 6 fragmentation routines)

Christophe Bronner

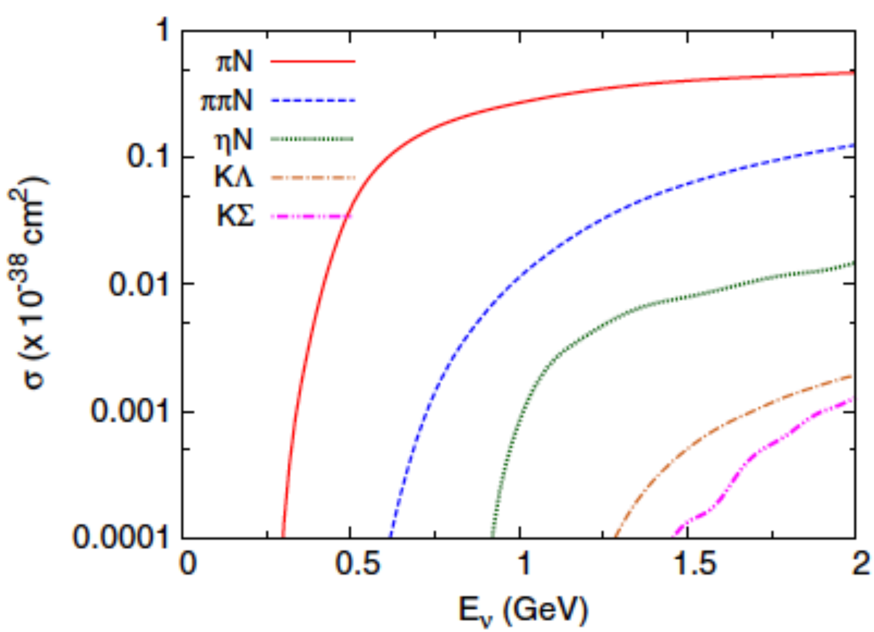
4. Higher resonances

Neutrino higher baryonic resonance

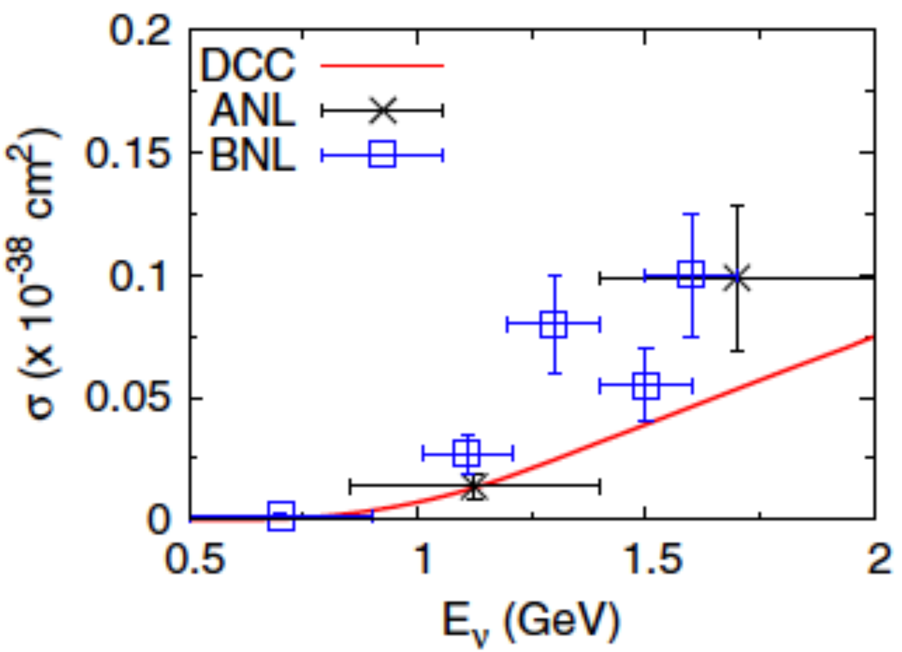
- Single pion production from neutrino-Δ resonance is already problem, but other half has more problem (higher resonance is ~50% of all resonances in DUNE)

e.g.) DCC model

- Many resonances are dynamically coupled to predict final state hadrons.
- Sizable 2 pion production, heavy meson production, etc



ν_μCC(n) total cross section



$\nu_\mu + n \rightarrow \mu^- + \pi^+ + \pi^- + p$

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Q^2 dependence of form factors are obtained from external data

No information of axial form factors

Next step:

- Axial form factors can be provided by lattice QCD, and validated by neutrino H/D target experiments.

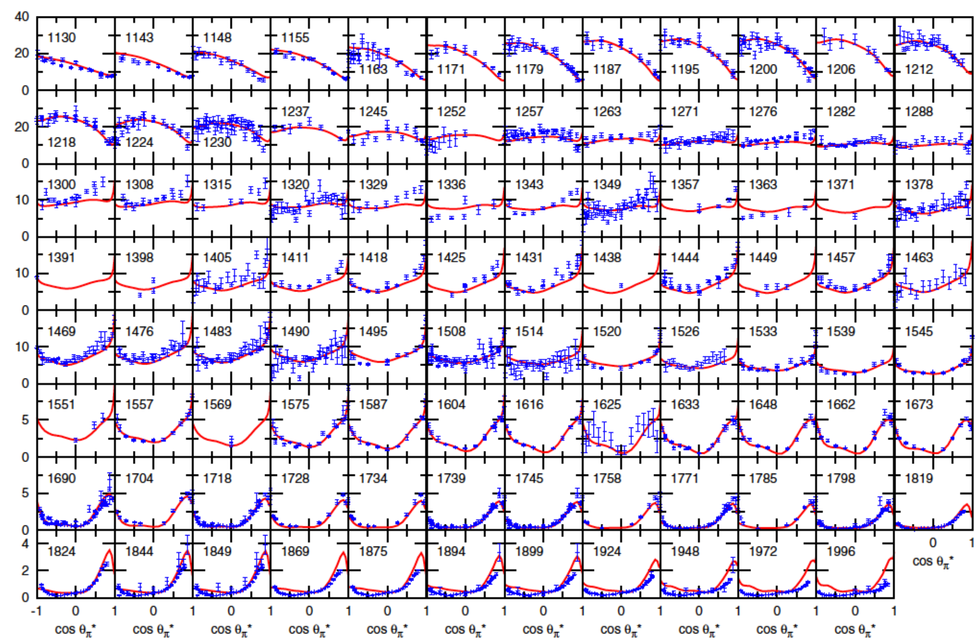


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

Niculescu et al,PRL85(2000),1182,1186

5. Quark-Hadron duality

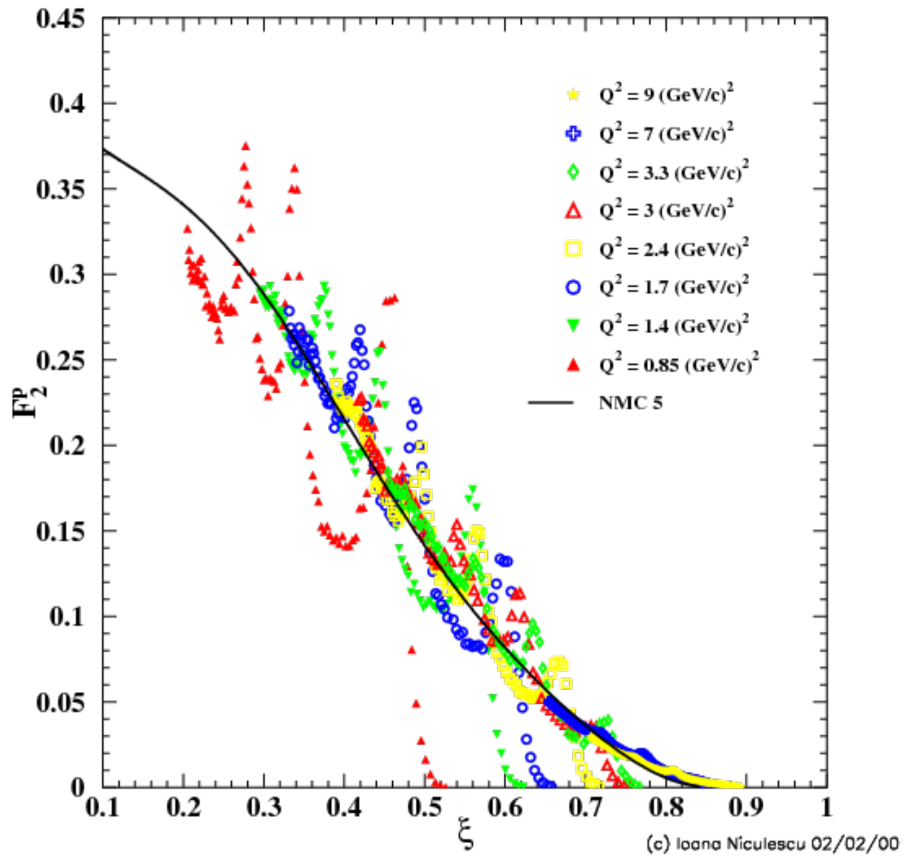
Nachtmann variable

$$\xi = \frac{2x}{\left(1+\sqrt{1+\frac{4x^2M^2}{Q^2}}\right)}$$

Hadron scattering → quark scattering
- Not Bjorken limit (Q^2 is low), but DIS-like
- Scaling law in ξ (Nachtmann variable)

DIS is realized by average of resonance channels. Many confirmation from various structure functions

Not tested with neutrino data



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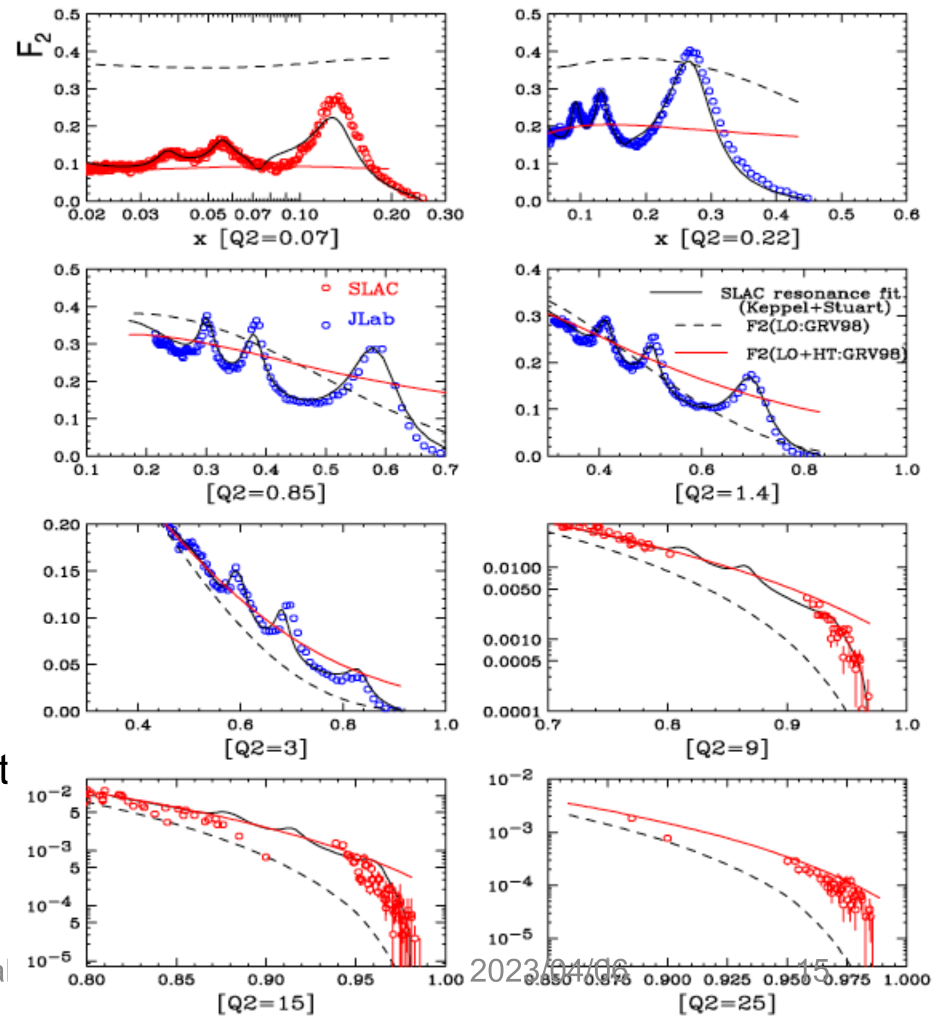
DIS is realized by average of resonance channels. Many confirmation from various structure functions

Not tested with neutrino data

GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality

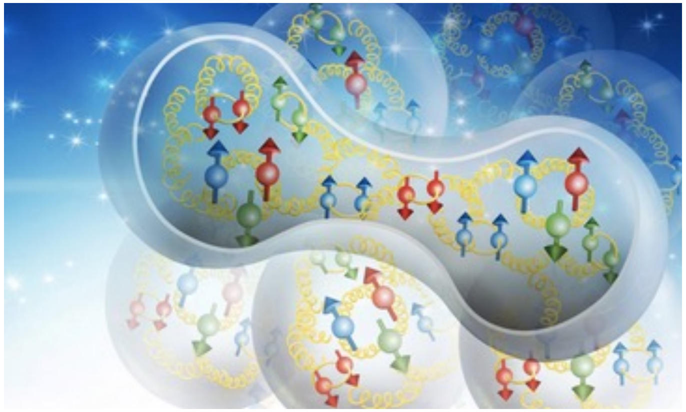
Next step:
We need to test neutrino QH-duality model with neutrino data. Correct model is important to assign correct systematic errors.

Proton F2 function GRV98-BY correction vs. data

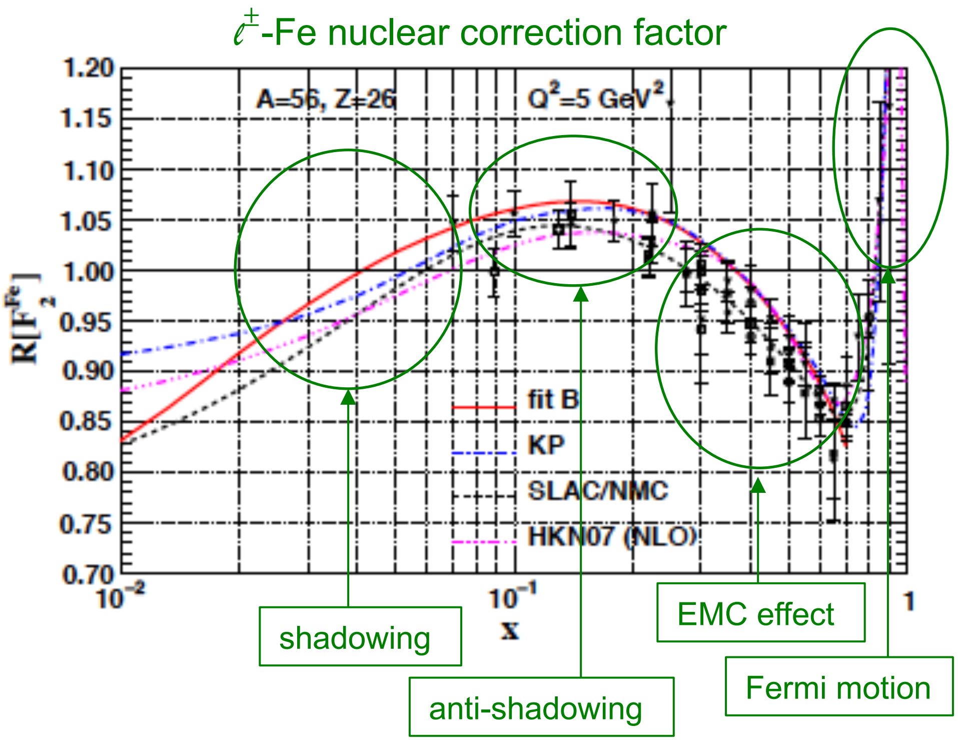


HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

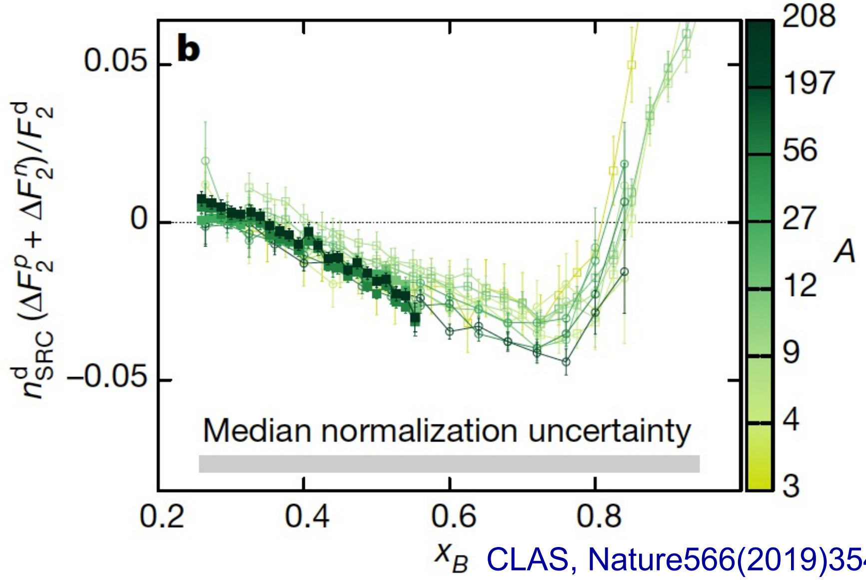
6. DIS in the Nuclear Environment



Nuclear PDF
- Shadowing, anti-shadowing, EMC effect
- Various models describe charged lepton data



EMC effect can be modeled from the amount of correlated pairs in nuclei (CLAS in JLab).



CLAS, Nature566(2019)354

HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

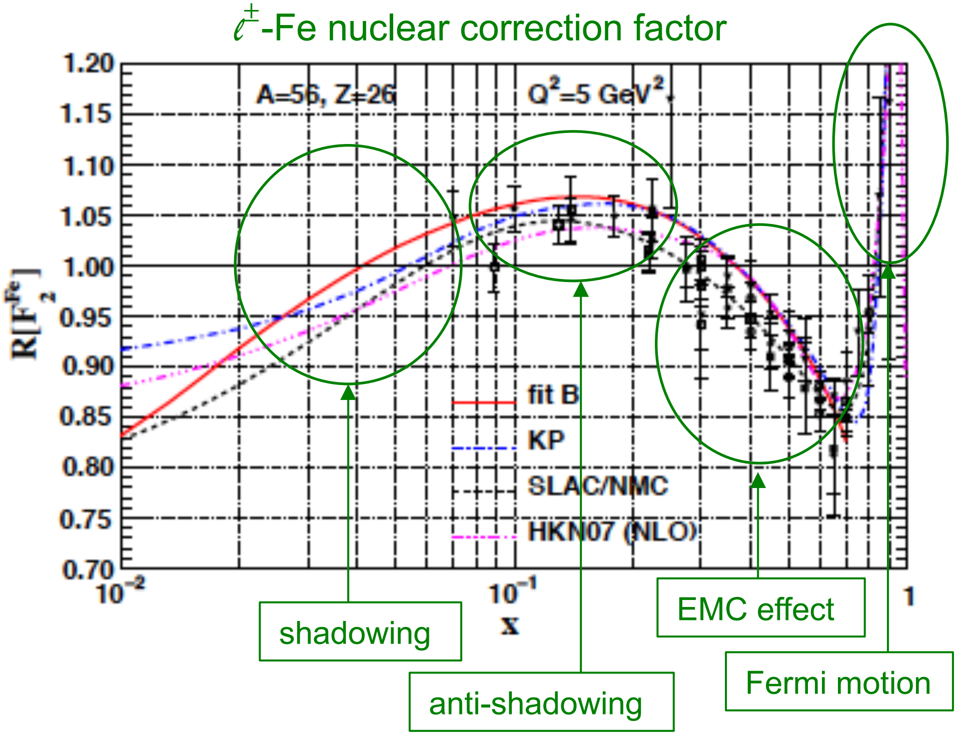
6. DIS in the Nuclear Environment

Nuclear PDF
- Shadowing, anti-shadowing, EMC effect
- Various models describe charged lepton data

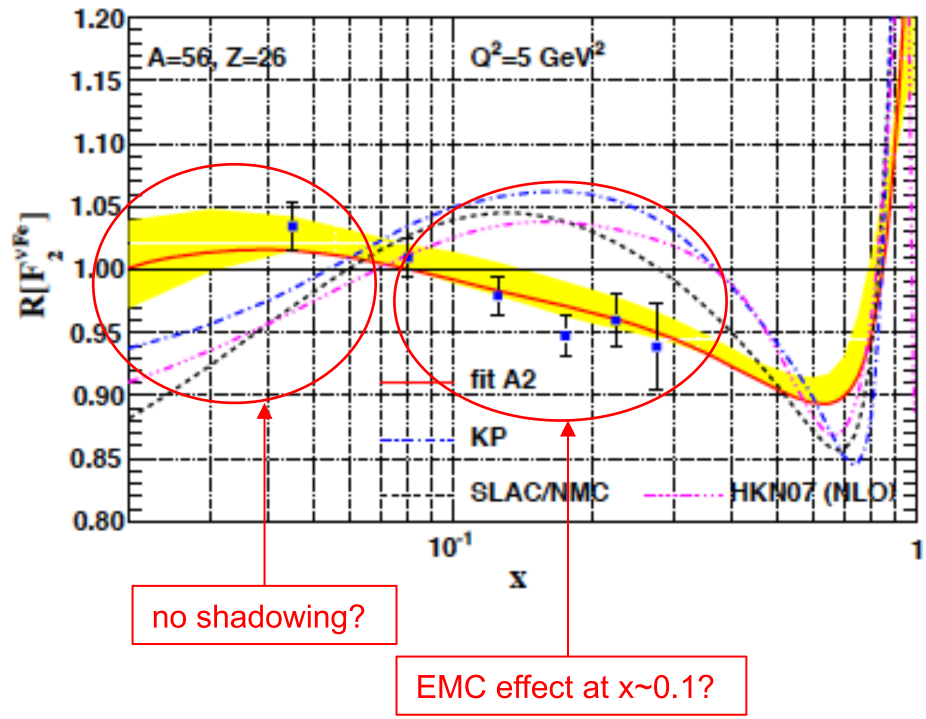
Charged lepton nPDF cannot describe neutrino data well

Next step: we need more DIS experiments with nuclear target to develop nPDF for neutrinos

$\ell^{\pm}$-Fe nuclear correction factor



ν-Fe nuclear correction factor



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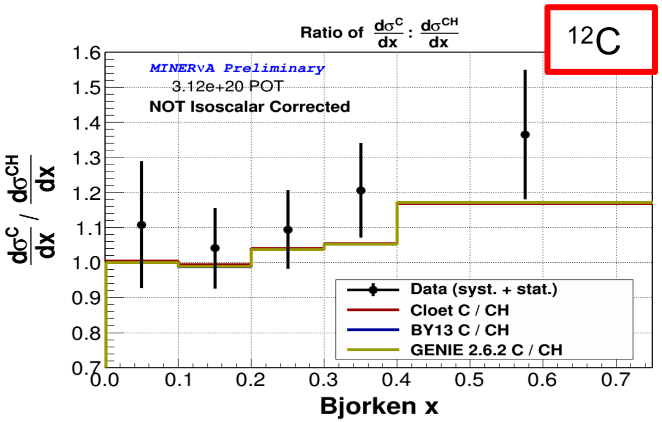
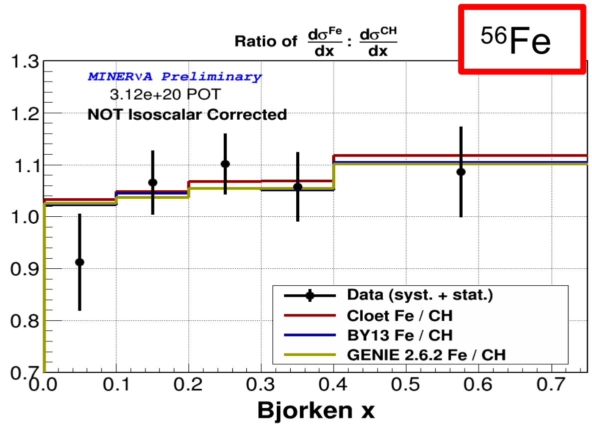
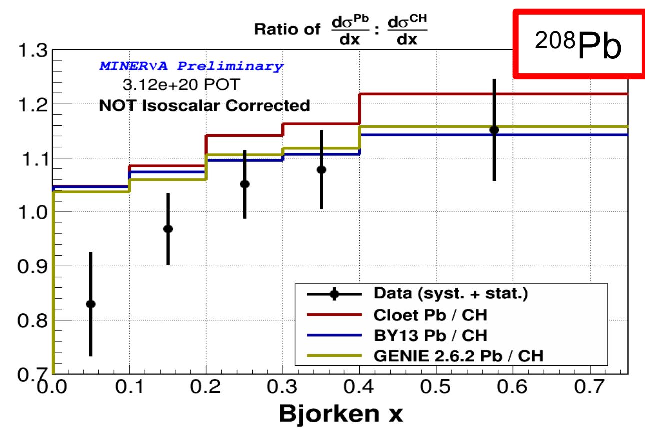
MINERvA DIS cross-section ratio
- Most recent data on this topic
- Data suggest shadowing



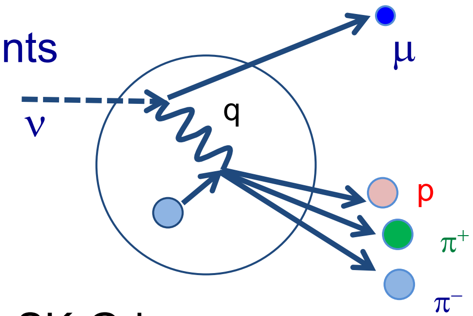


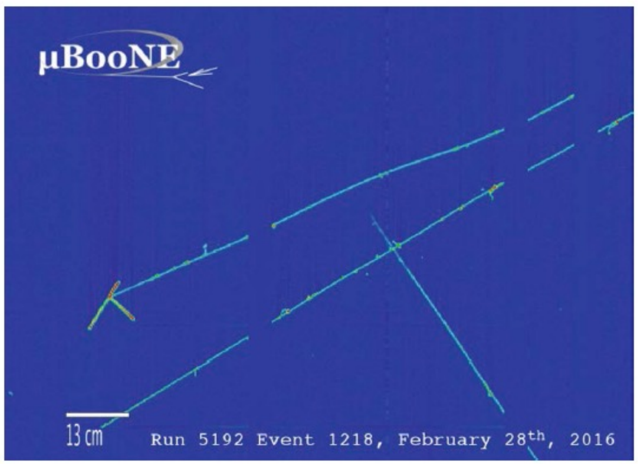


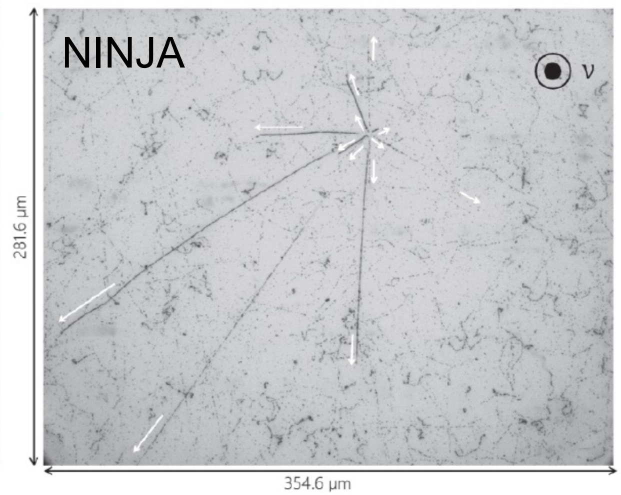
MicroBooNE, EPJC79(2019)248, NINJA, PRD102(2020)072006, Jones et al, Instruments4(2020)3,21
SuperK, ArXiv:2112.00092

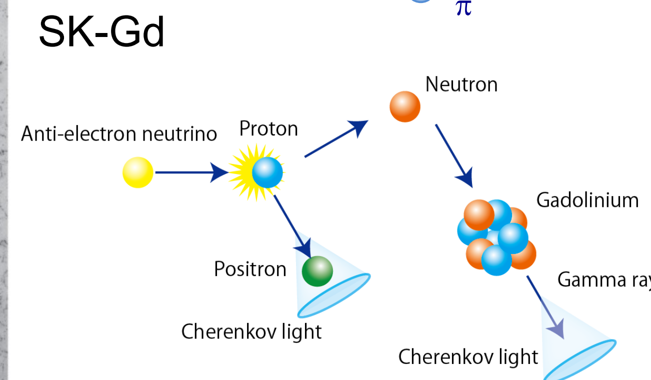
7. Neutrino induced hadron final state measurements

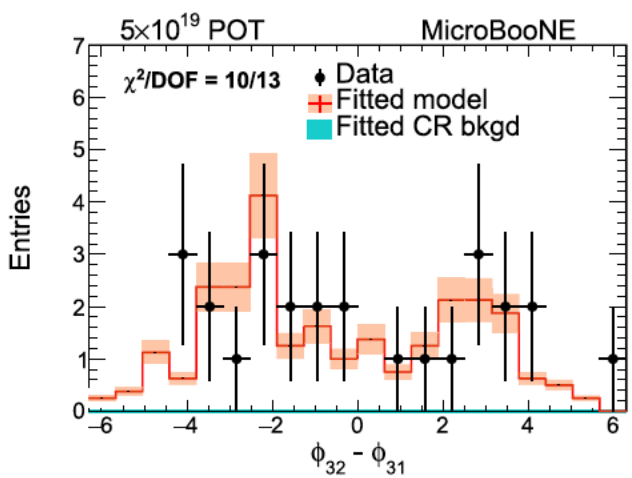
Next generation detectors focus on hadron final state measurements
- LArTPC (liquid argon time projection chamber)
- ECC (emulsion cloud chamber)
- Gd-loaded water Cherenkov, etc

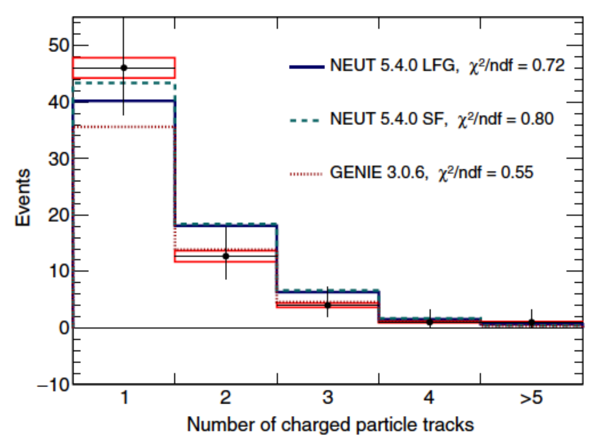


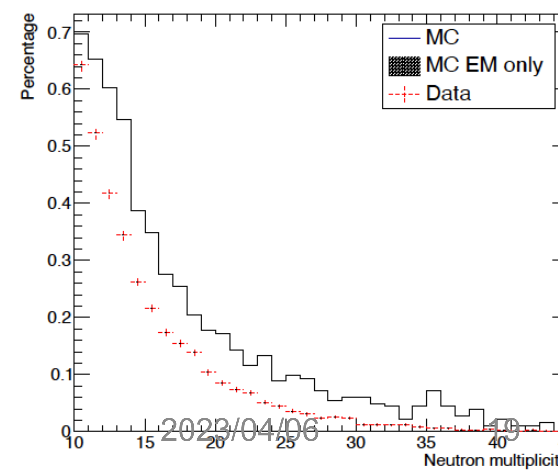




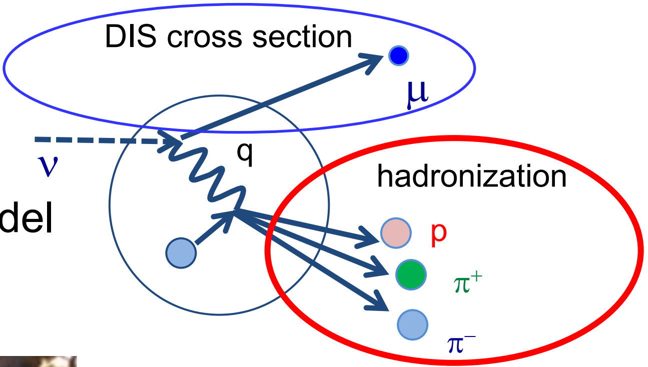








7. Neutrino cross section ≠ Hadron final states



Neutrino cross-section only predict lepton kinematics
- lepton kinematics → cross-section model
- hadron multiplicity and kinematics → not cross-section model

Cross-section model
- Lepton kinematics
(current focus)

Hadron production model
- Conservation laws
- Isotropic phase space decays (no model)

FSI, hadron media effects
- Complicated
(rough surface to move)

Studying neutrino-induced hadrons are hard

7. Neutrino hadronization

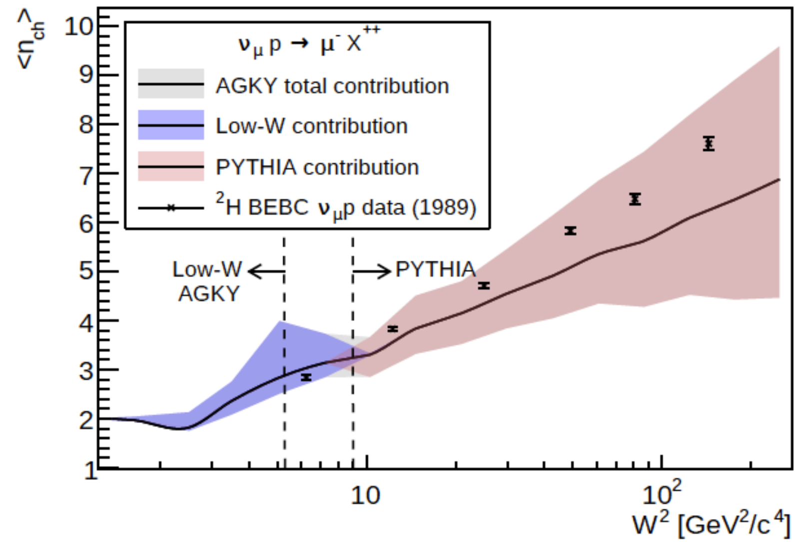
Low W multiplicity → empirical model
High W multiplicity → PYTHIA

Low W multiplicity dispersion → KNO scaling
High W multiplicity dispersion → PYTHIA

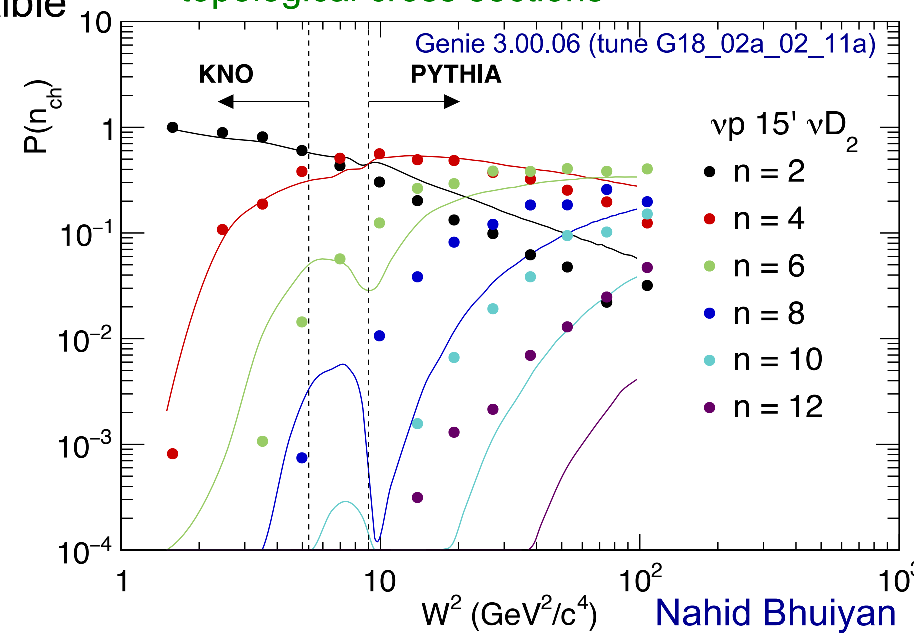
Averaged multiplicity has a large error to accommodate data tensions

Dispersion of PYTHIA at low W is not compatible with KNO scaling

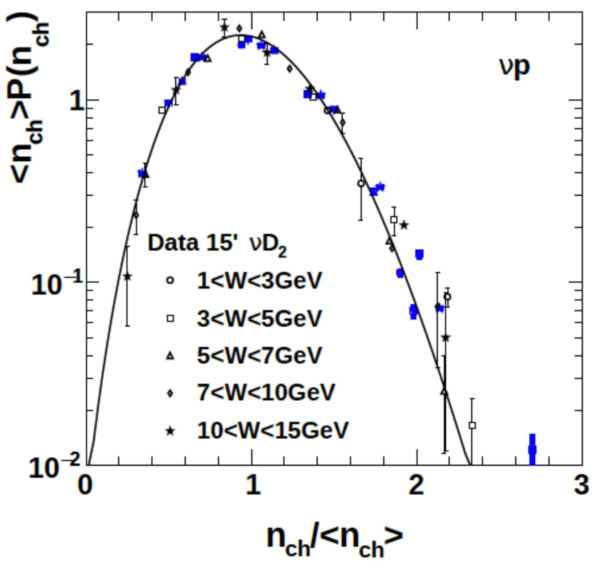
averaged charge hadron multiplicity



topological cross sections



KNO scaling



Nahid Bhuiyan

7. Neutrino hadronization

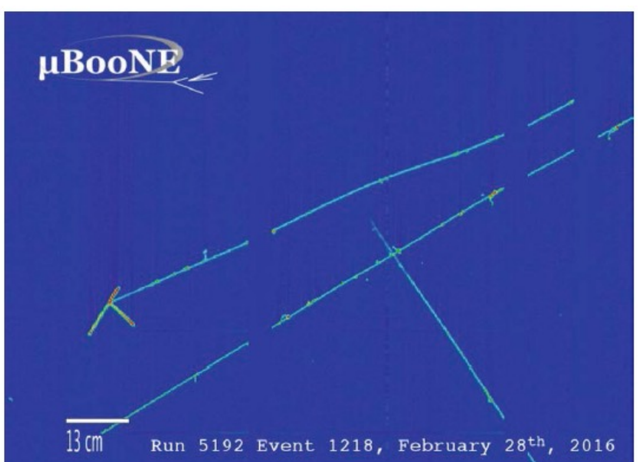
Hadrons in neutrino interaction

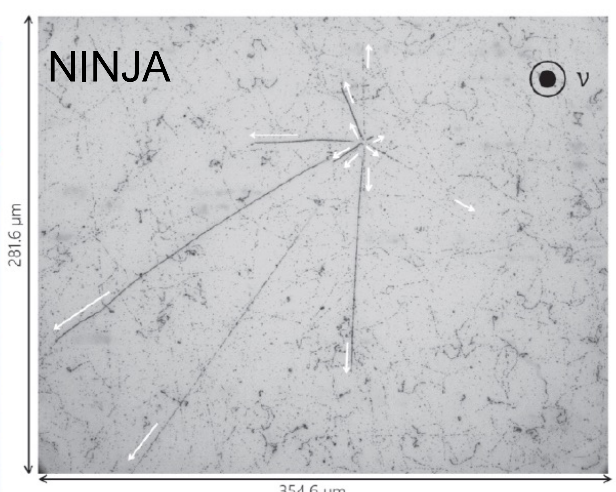
1. Kinematics reconstruction
 - Hadron energy measurement can specify energy transfer ν, then others: $E\nu$, y, Q^2, W, x, |q|

2. Interaction process identification
 - number of hadrons can be used for process ID: $\bar{\nu}/\nu$, 2p-2h, resonance, DIS

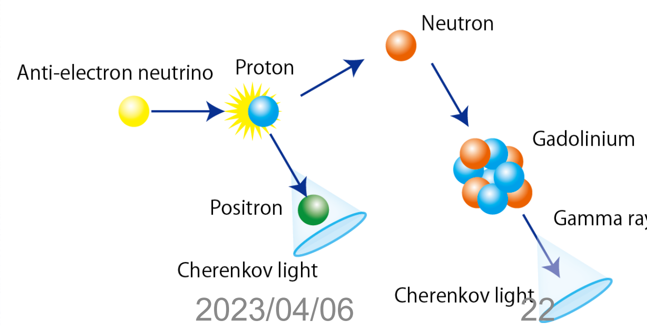
3. Rare process search
 - BSM physics for rare hadron topology

We need a good event-by-event prediction of hadron final states





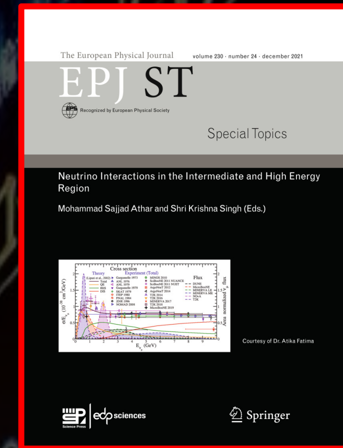
SK-Gd



https://link.springer.com/journal/11734/volumes-and-issues/230-24

Conclusion

EPJ Special Topic
Neutrino Interactions in the Intermediate and High Energy Region



So many unknowns
- high-precision electron neutrino differential cross section
- axial transition form factors for all higher resonances
- quark-hadron duality with neutrinos
- neutrino nuclear DIS
- neutrino low-W hadronization processes,
- etc.

These are not only important systematics, but also extremely interesting science with discovery potential

Thank you for your attention!

Backup

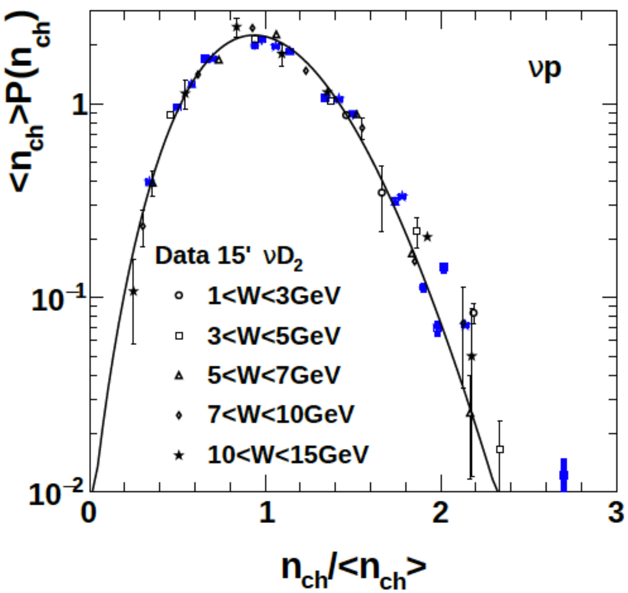
AGKY, EPJC63(2009)1, GENIE, ArXiv:2106.05884

5. Hadronization

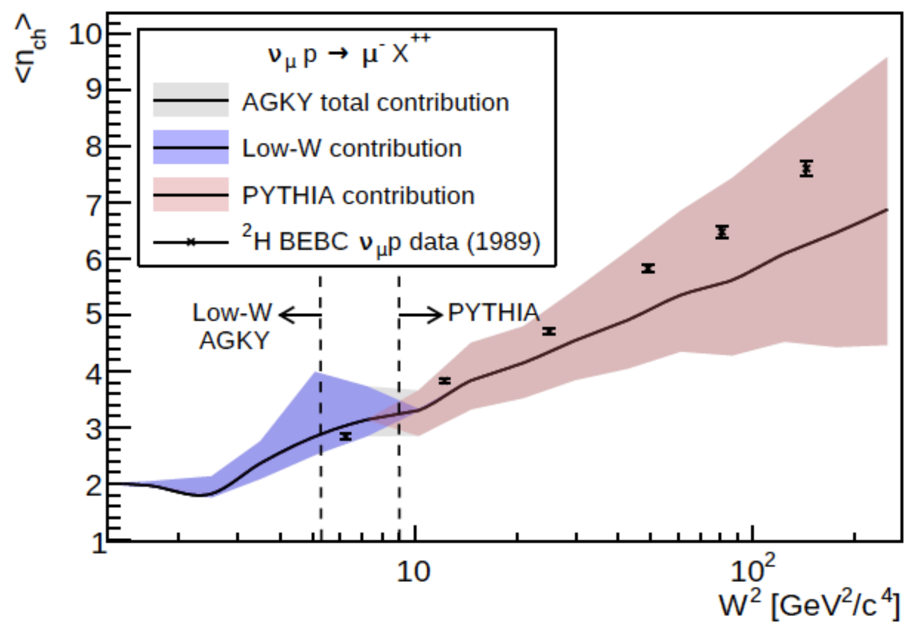
Hadron multiplicity tuning for low W DIS event

- Fix averaged charged hadron multiplicity from external data $\langle n_{ch} \rangle = a_{ch} + b_{ch} \cdot \ln(W^2)$
- Use isospin symmetry to obtain averaged neutral pion multiplicity
- Use KNO scaling to derive dispersion of hadron multiplicity from external data
- MC simulation for event-by-event prediction

$$\langle n \rangle \cdot P(n) = \frac{2e^{-c} c^{cn/\langle n \rangle + 1}}{\Gamma(cn/\langle n \rangle + 1)}$$



(a) KNO distribution for νp interactions.



5. Hadronization

Neutrino kinematic reconstruction

lepton energy E_l, lepton scattering angle $cos\theta_l$, hadron energy $E_{had} = \sum_i T^i_{nucl} + \sum_j E^j_{meson}$

$\nu = E_{had}$
$E_\nu = E_\mu + E_{had}$
$y = \nu / E_\nu$
$Q^2 = m_l^2 - 2E_\nu(E_\mu - P_\mu cos\theta_l)$
$W^2 = M^2 + 2M\nu - Q^2$
$x = Q^2/2M\nu$
$|q| = \sqrt{\nu^2 + Q^2}$

5. Topological cross section

Nahid Bhuiyan
Genie 3.00.06 (tune G18_02a_02_11a)