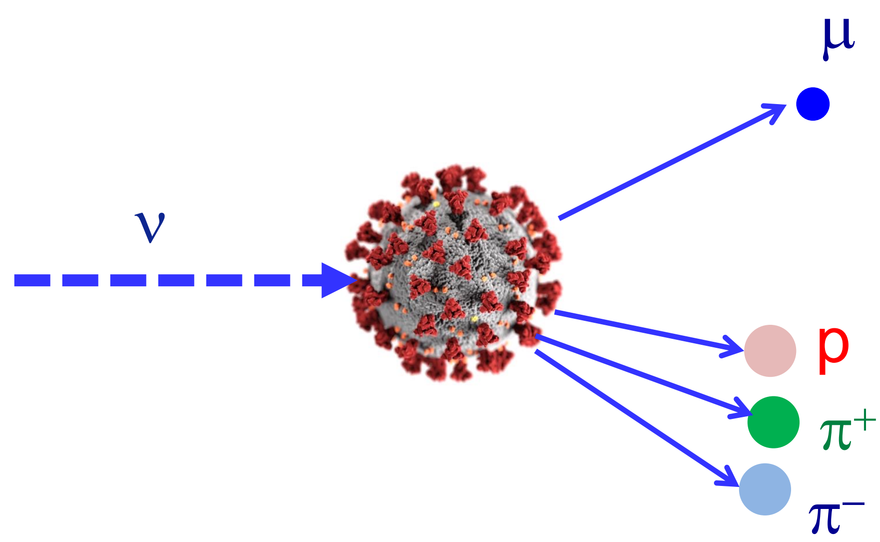
Neutrino-induced Shallow- and Deep-Inelastic Scattering

outline



Resources

NuSTEC nuSIS&DIS workshop, https://nustec.fnal.gov/nuSDIS18/
NuSTEC nuSIS&DIS workshop proceedings, https://arxiv.org/abs/1907.13252
Snowmass LoI on neutrino SIS&DIS, https://arxiv.org/abs/2009.04285
SIS physics review paper (Sajjad Athar and Morfín),https://arxiv.org/abs/2006.08603

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Neutrino–Nucleus Interactions in the Standard Model and Beyond
CERN, Jan. 17, 2022

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Acknowledgement: Luis Alvarez Ruso, Natalie Jachowicz, Jorge Morfin, M. Sajjad Athar

1. Summary

Shallow-Inelastic Scattering (SIS) is an extreme kinematic region. Delta resonance, higher resonances, non-resonant processes, and DIS co-exist and interfere.

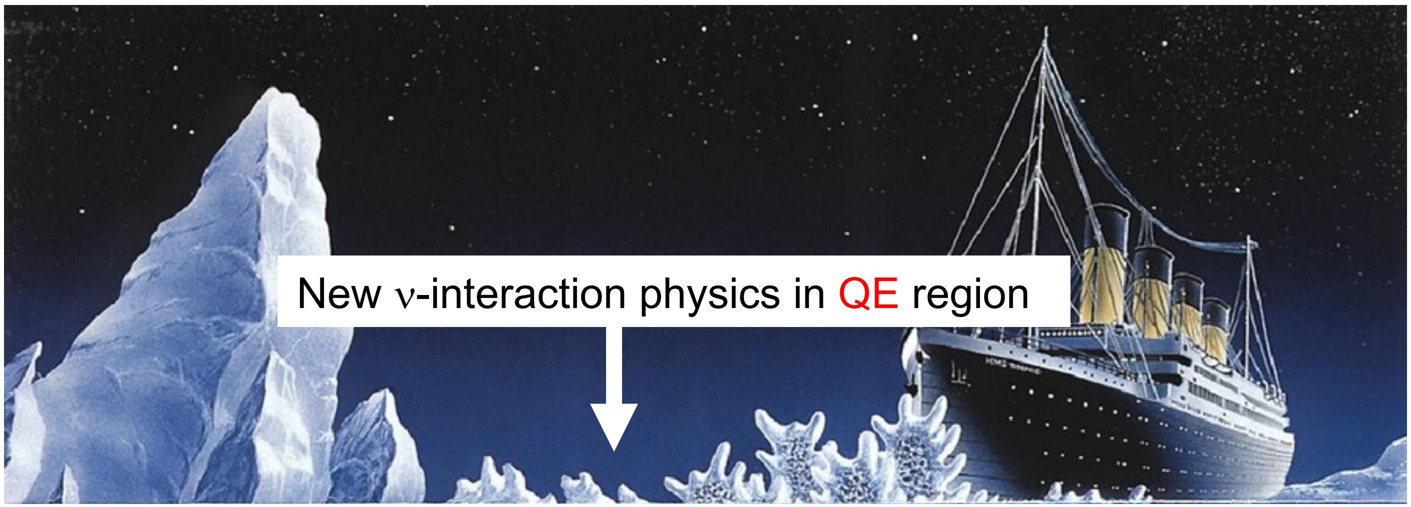
SIS has a rich physics program and active topics to research; interference of resonant and non-resonant processes, quark-hadron duality from SIS to DIS in nuclear environment, etc.

So many unknowns; axial transition form factors for all higher resonances, quark-hadron duality with neutrinos, neutrino nuclear DIS, neutrino low-W hadronization processes, etc.

Naively, ~70% of events in DUNE is SIS, so it's better to pay attention them.

1. Beyond QE peak

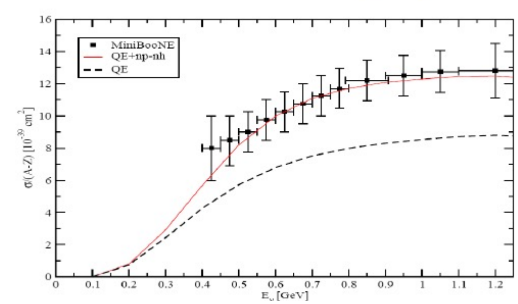
Axial 2-body current in QE region may be a tip of the iceberg…

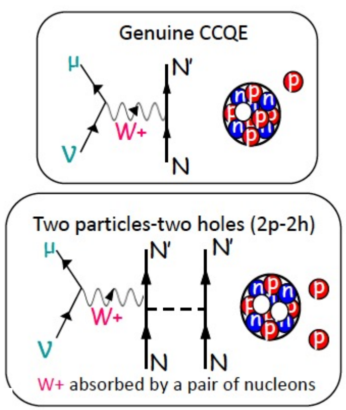


Lots of new results, new understanding
- T2K ND
- MINERvA
- MicroBooNE
- NINJA/WAGASCI, etc

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

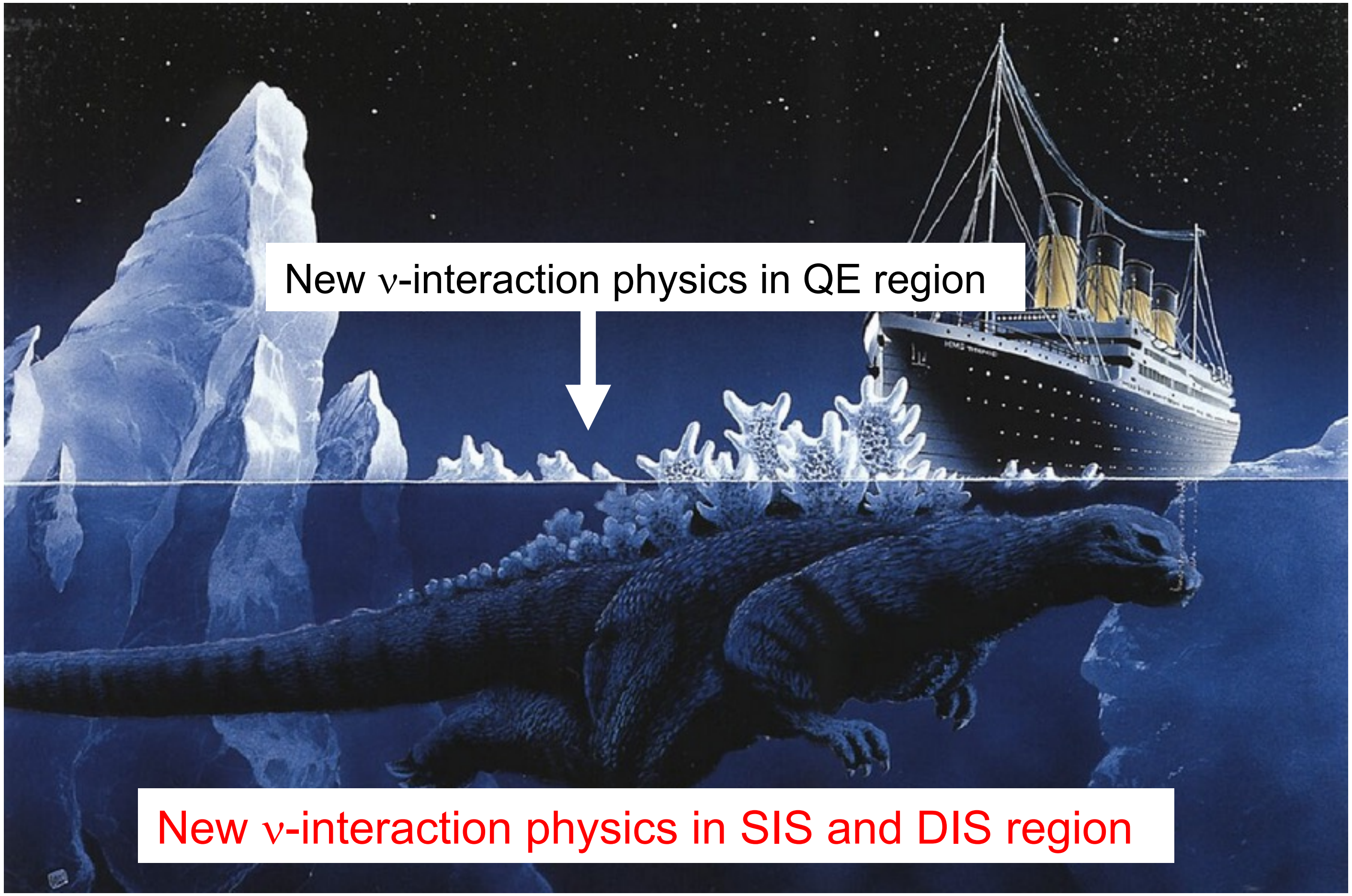




Martini et al,PRC80(2009)065501

1. Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…
or maybe a tip of gozilla!



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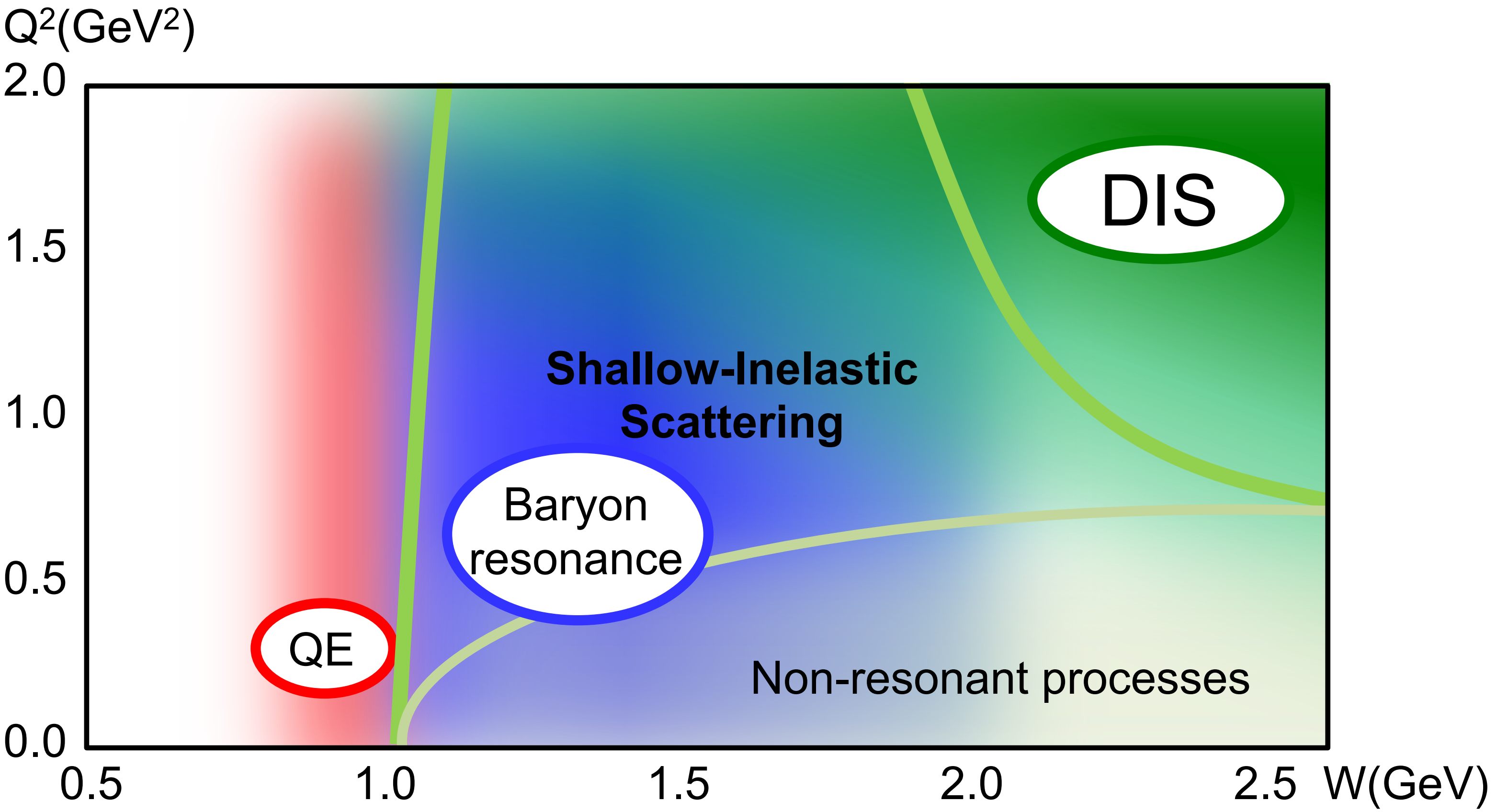
1. Shallow-Inelastic Scattering (SIS)

Shallow-Inelastic scattering region

- Inelastic = not elastic, $W > 1.07$ GeV ($=m_p+m_\pi$)
- Shallow = not deep, $Q^2 < 1$ GeV^2 for $W > 2$ GeV



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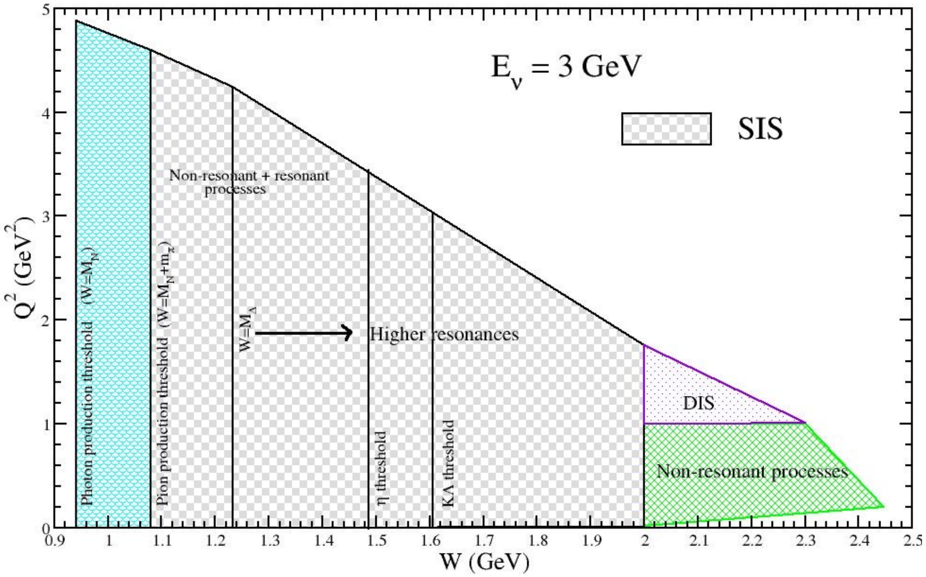
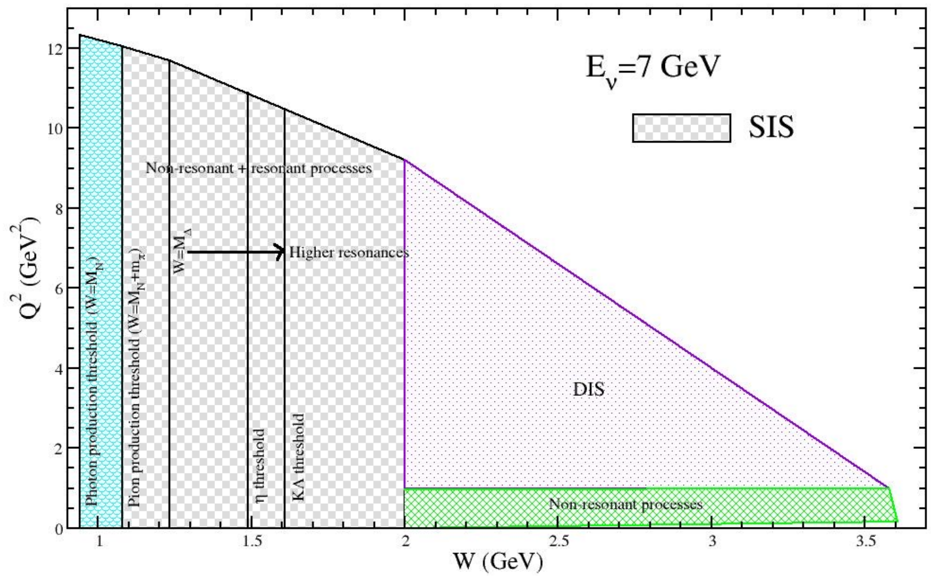
Fraction of SIS changes with energy, it is significant around 3 GeV.





Sajjad Athar (AMU)

1. Shallow-Inelastic Scattering (SIS)

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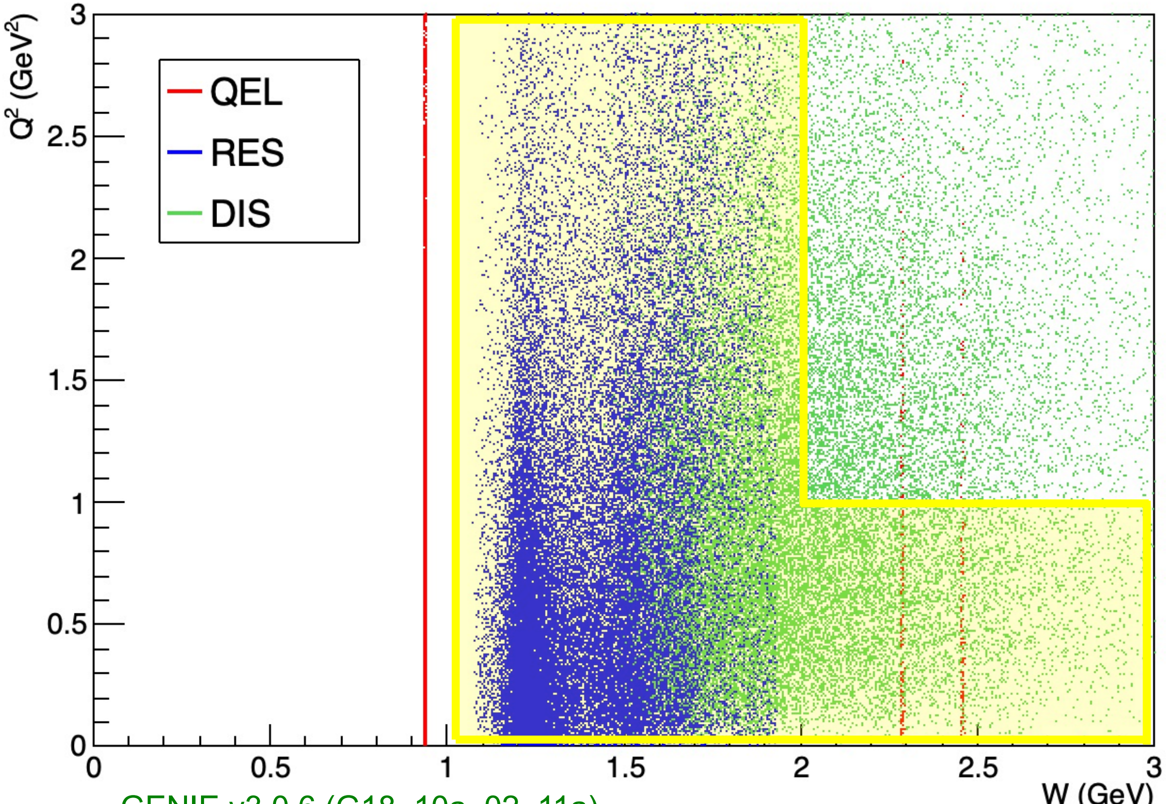
Significant fraction (~70%) of DUNE events are in SIS kinematic region

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)



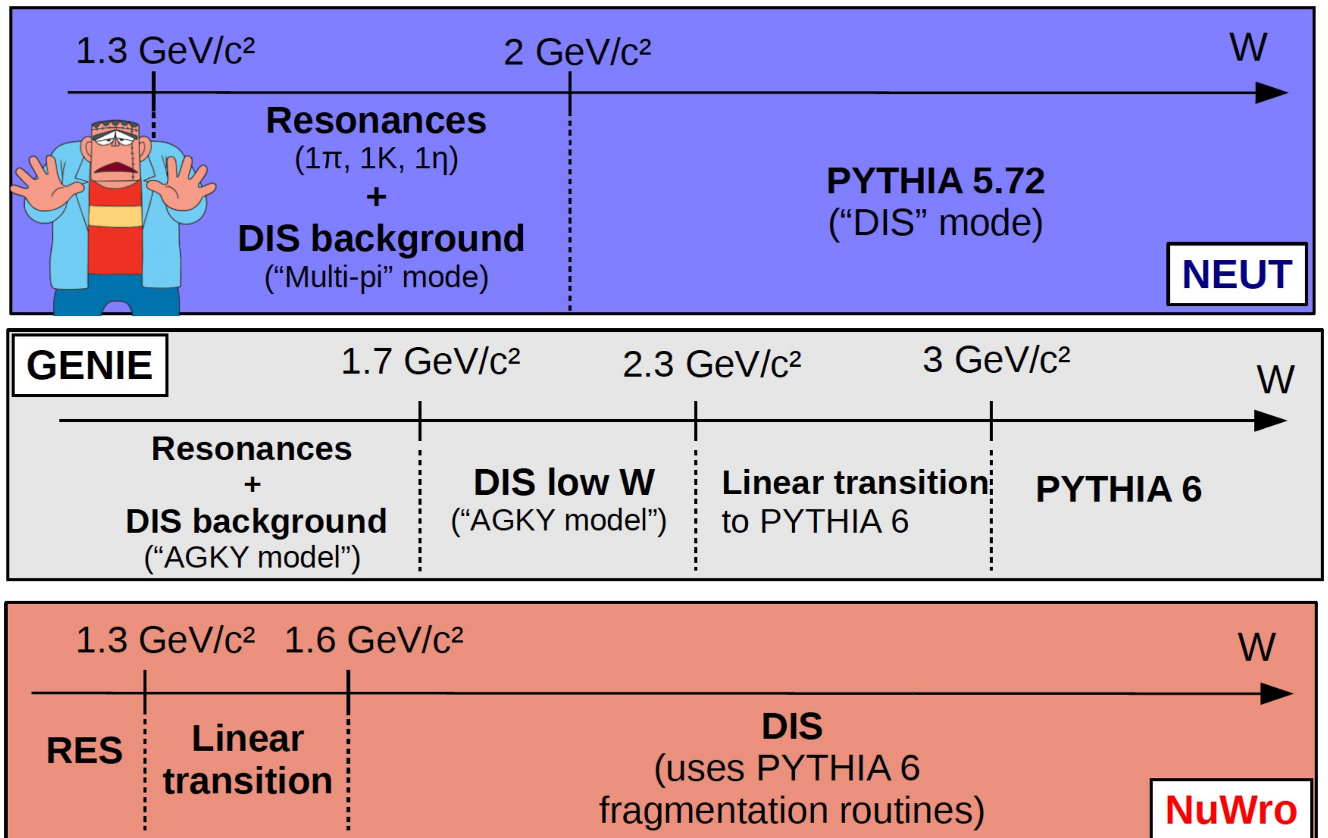
GENIE v3.0.6 (G18_10a_02_11a)

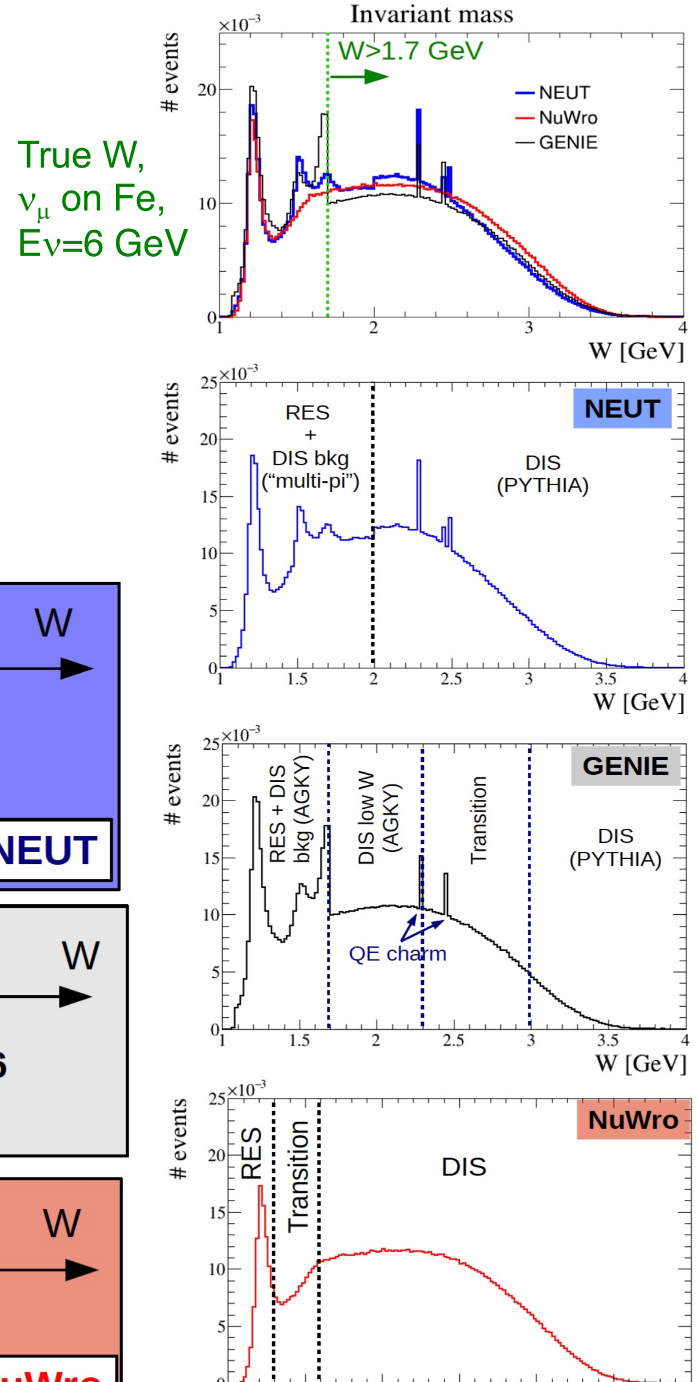
NuSTEC nuSIS workshop, ArXiv:1907.13252

1. 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





Christophe Bronner

1. Introduction

2. Inelastic processes

3. Quark-Hadron duality

4. DIS in the Nuclear Environment

5. Hadronization

6. Conclusion

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Nakamura,Kumano,Sato,PRD92(2015)074024

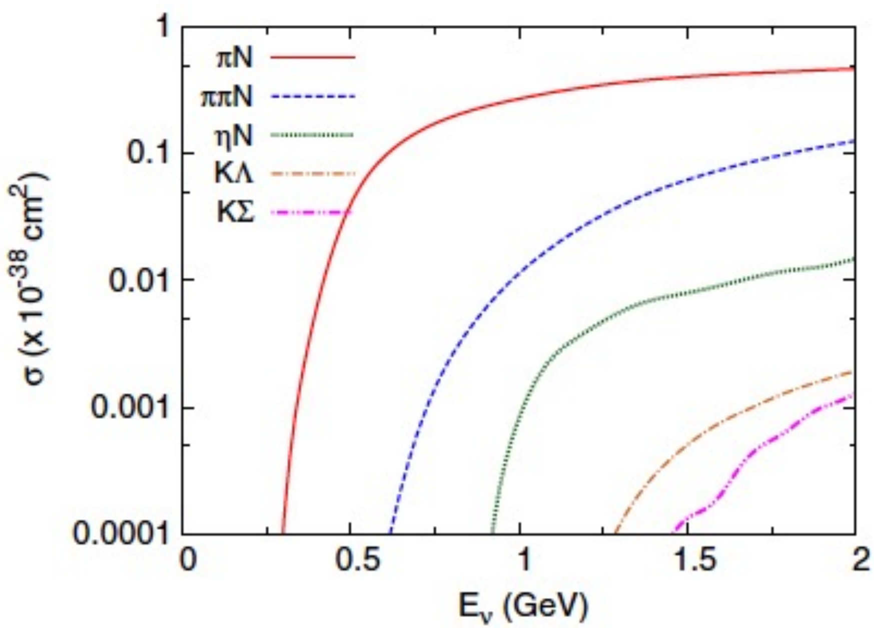
2. Inelastic processes

Neutrino higher baryonic resonance

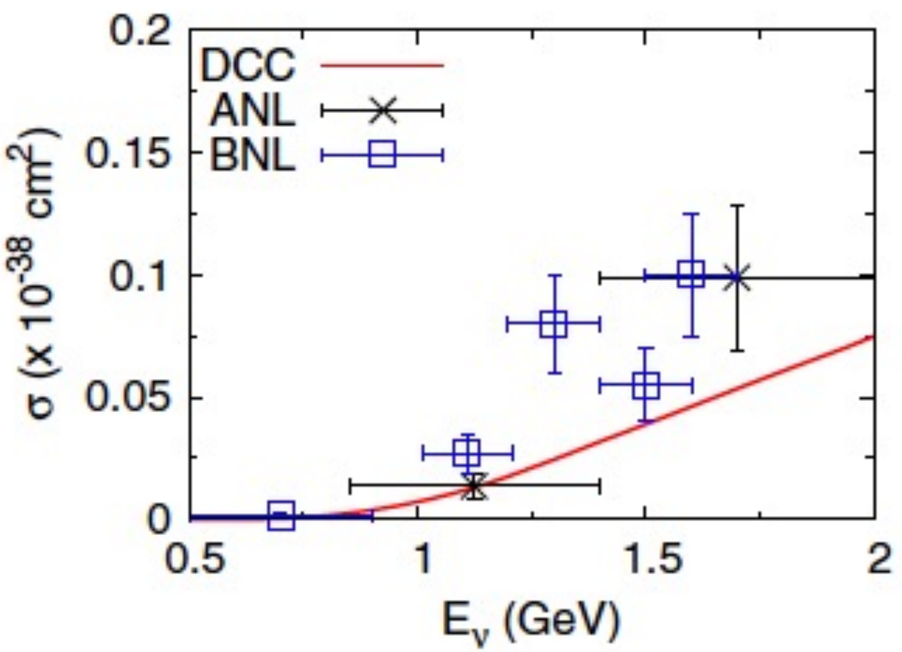
- Single pion production from neutrino-Δ resonance is already problem, but other half has more problem (higher resonance is ~50% of all resonances in DUNE)

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

Solution:

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

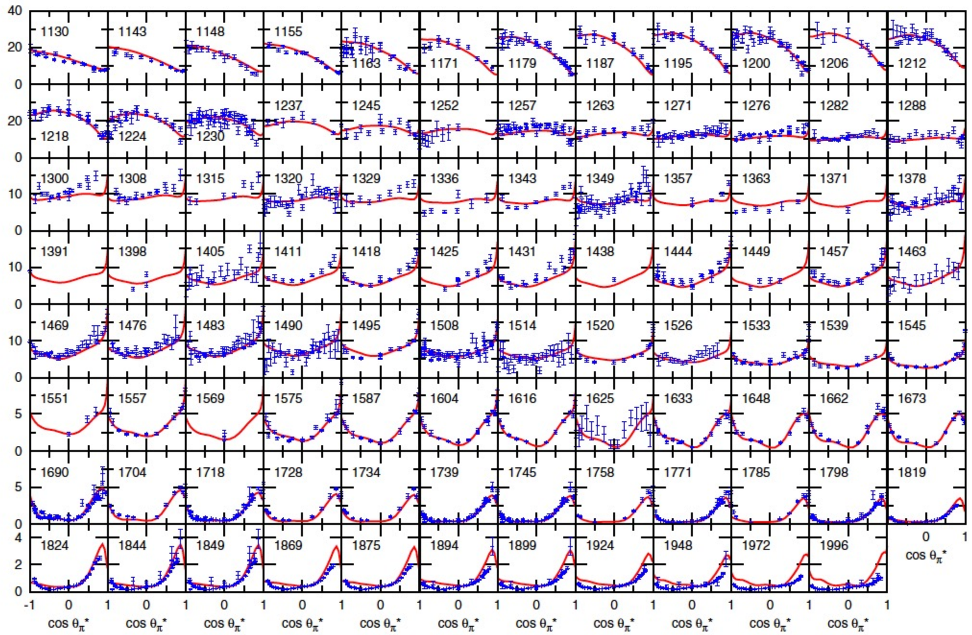

FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

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3. Quark-Hadron duality

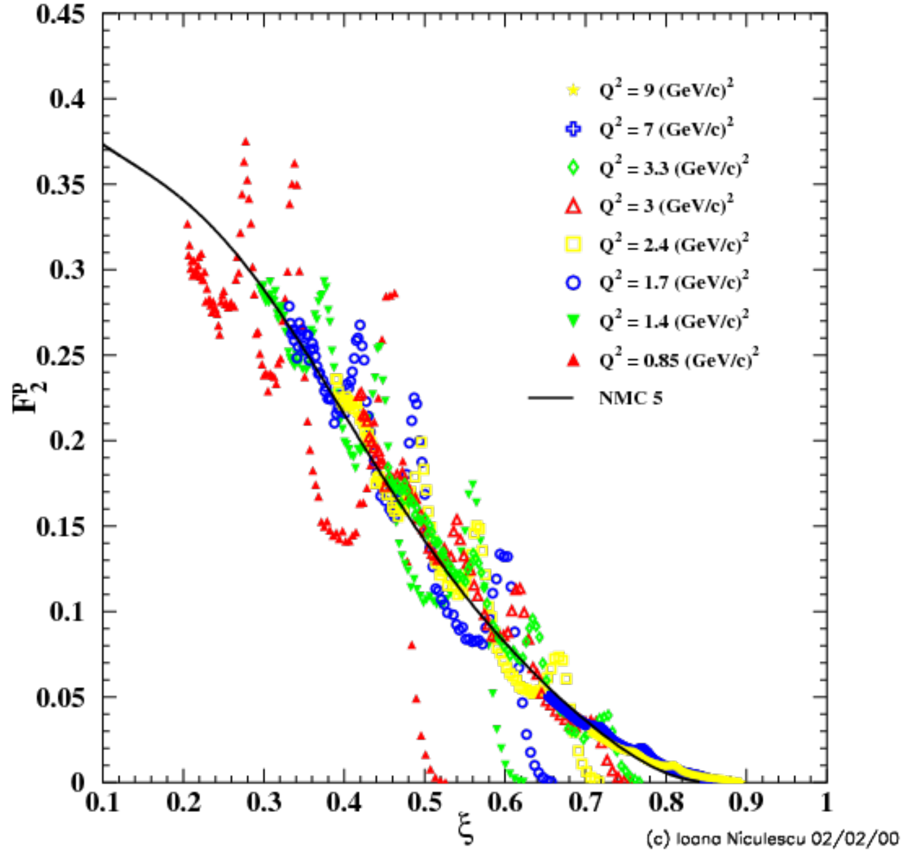
Nachtmann variable

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

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



Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

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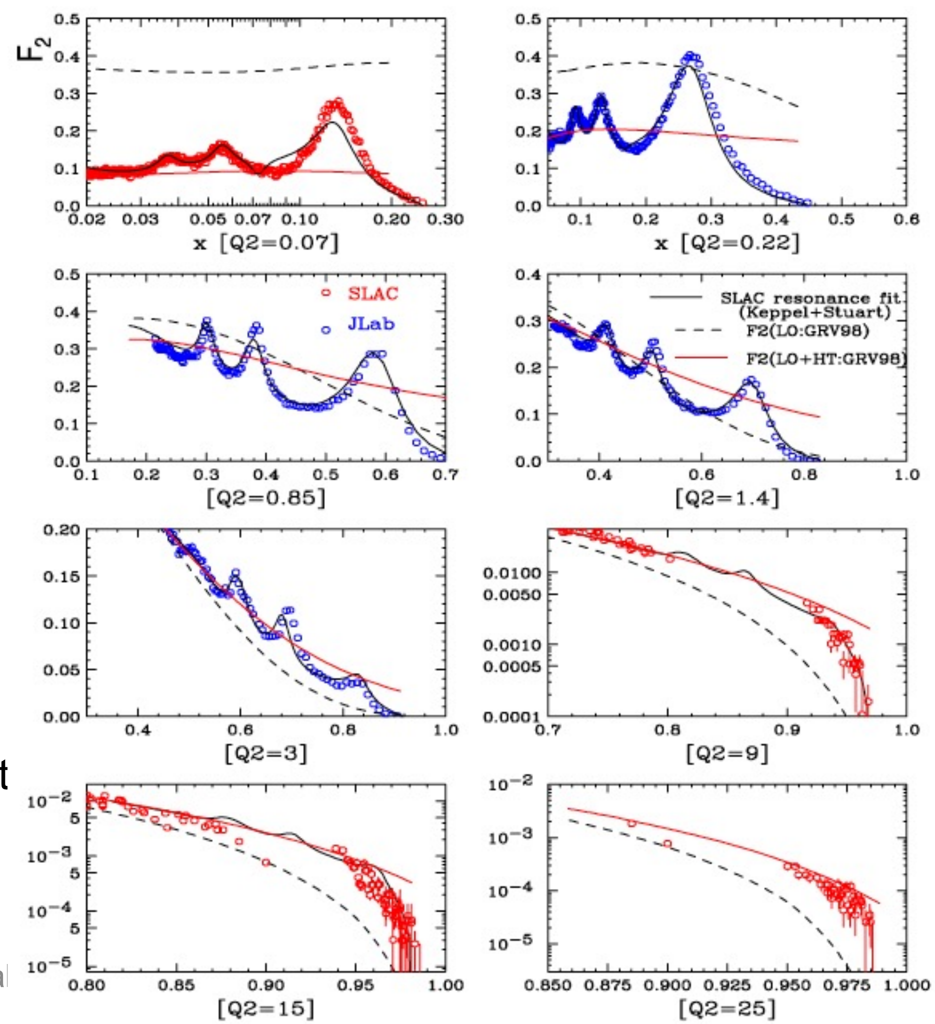
Not tested with neutrino data

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

Solution:
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



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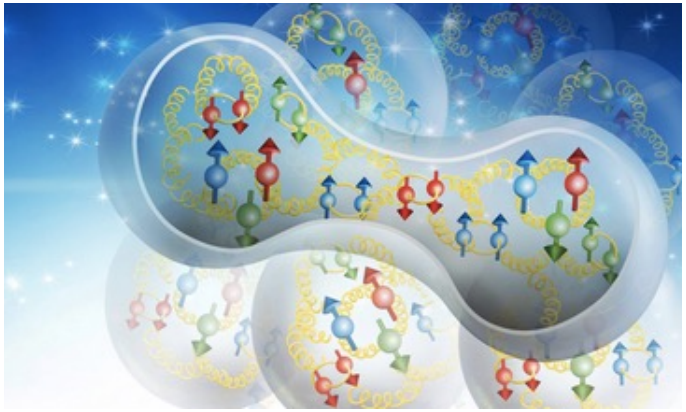
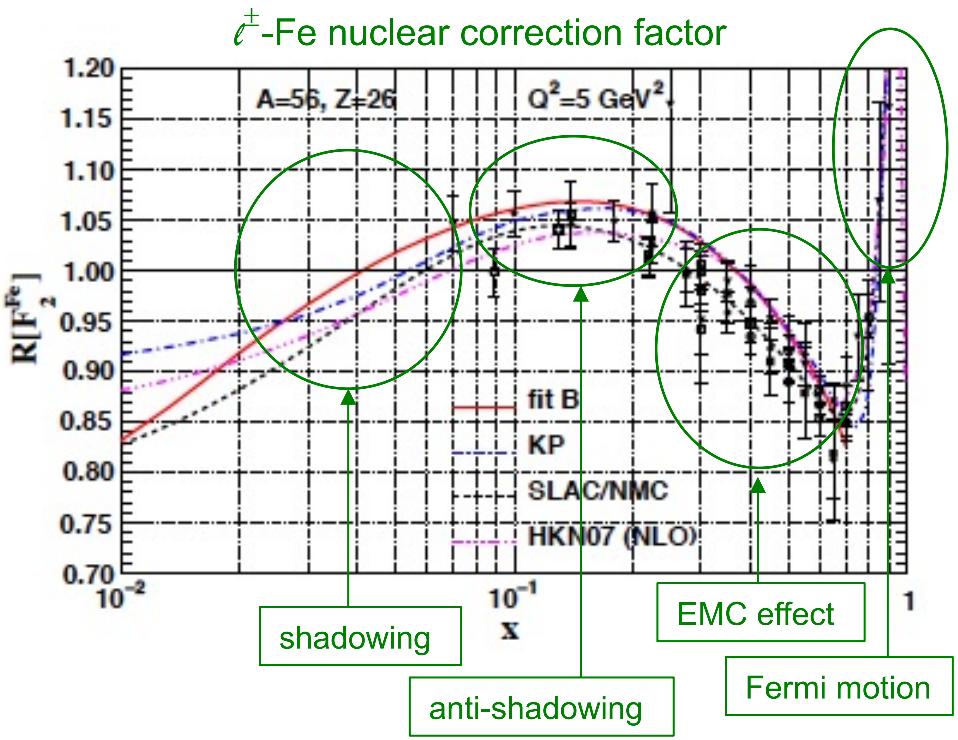
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

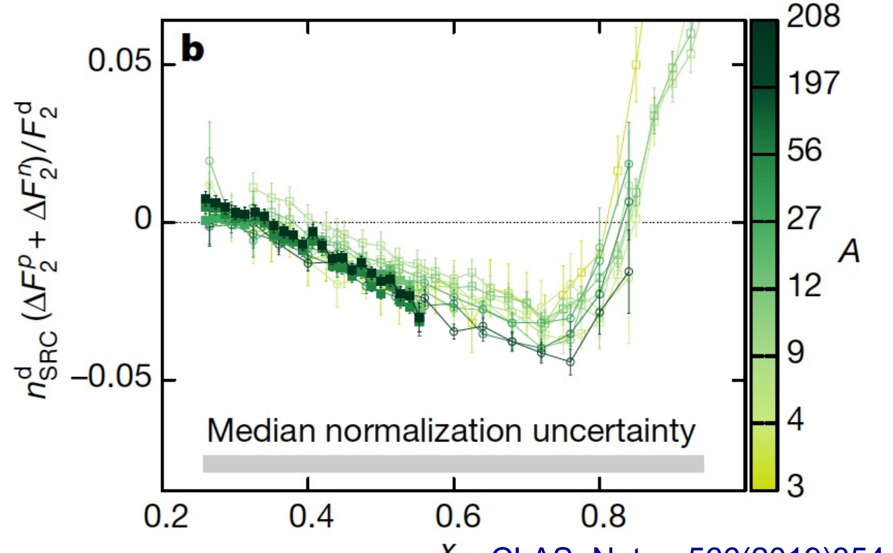
4. DIS in the Nuclear Environment



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

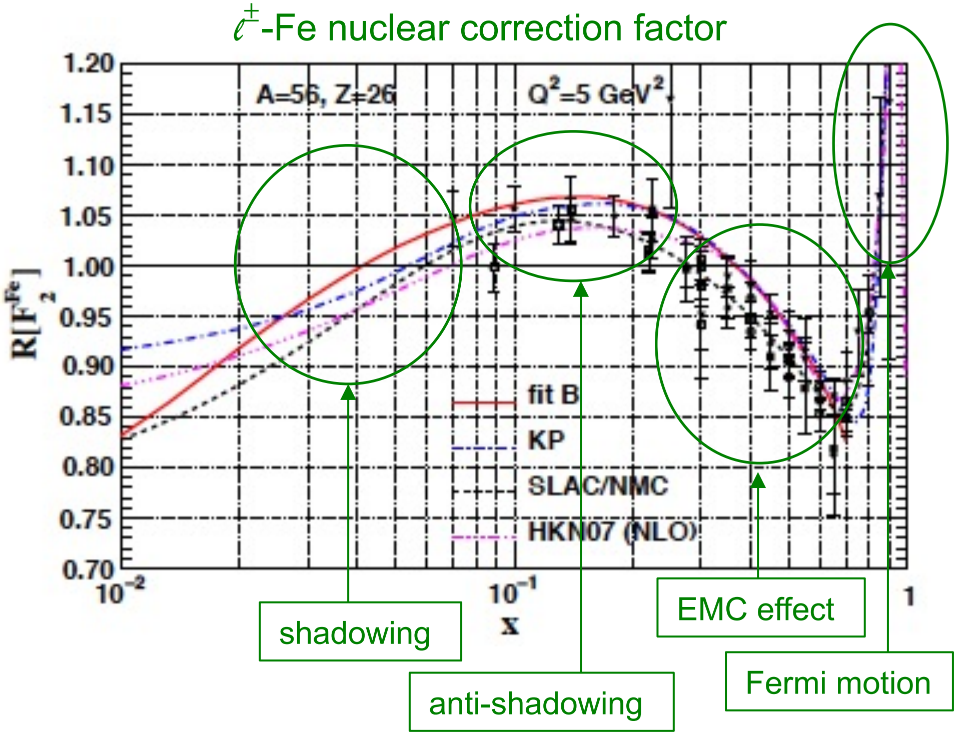
4. DIS in the Nuclear Environment

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

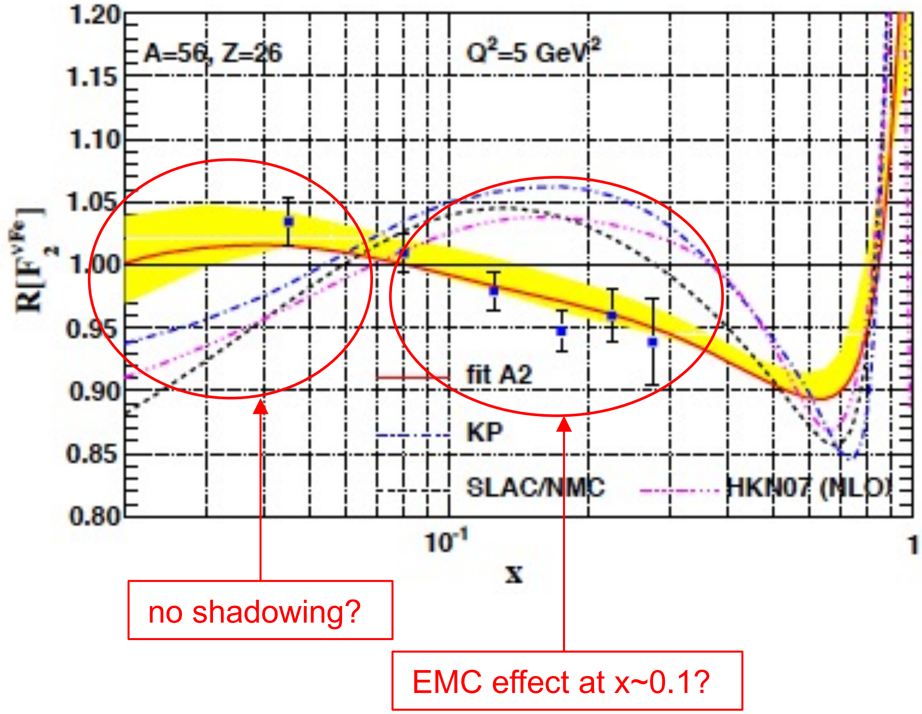
Charged lepton nPDF cannot describe neutrino data well

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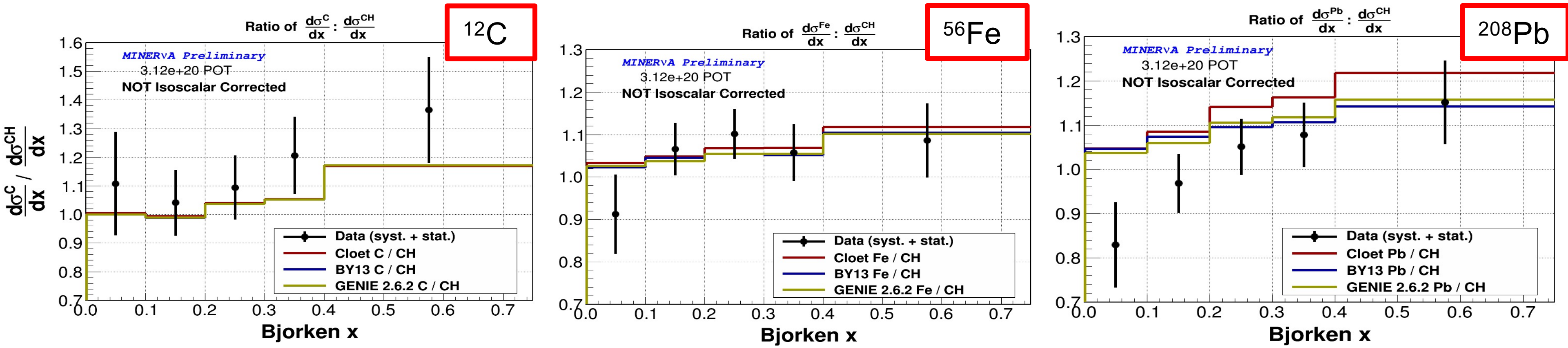
MINERvA DIS cross-section ratio
- Most recent data on this topic
- Data suggest shadowing



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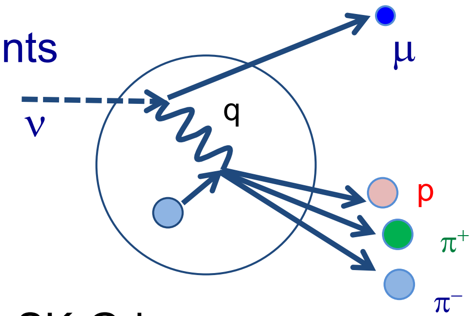
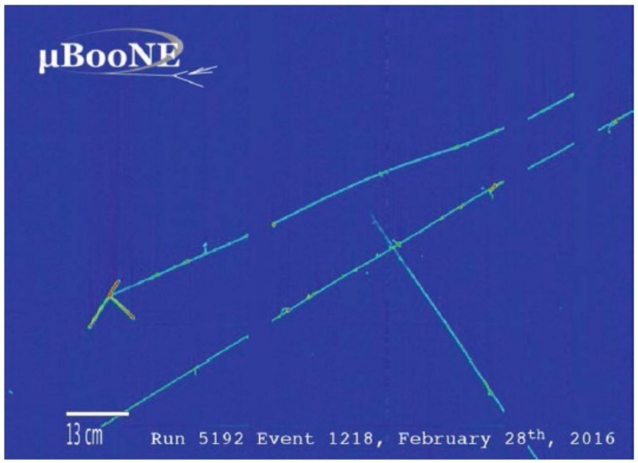
MicroBooNE, EPJC79(2019)248, NINJA, PRD102(2020)072006, Jones et al, Instruments4(2020)3,21
SuperK, ArXiv:2112.00092,2112.00092

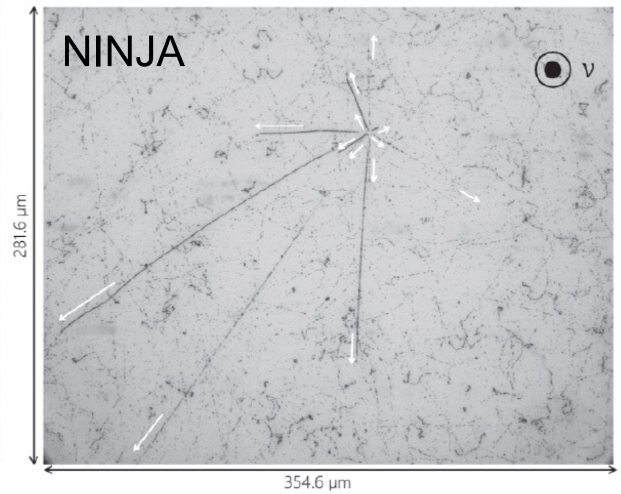
5. Neutrino induced hadron final state measurements

Next generation detectors focus on hadron final state measurements

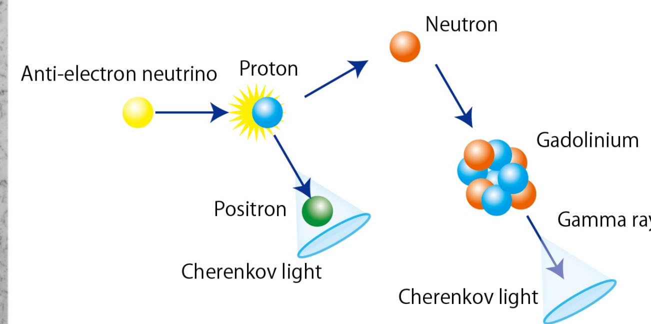
- LArTPC (liquid argon time projection chamber)
- ECC (emulsion cloud chamber)
- Gd-loaded water Cherenkov
- HPgTPC (high-pressure gas TPC), etc

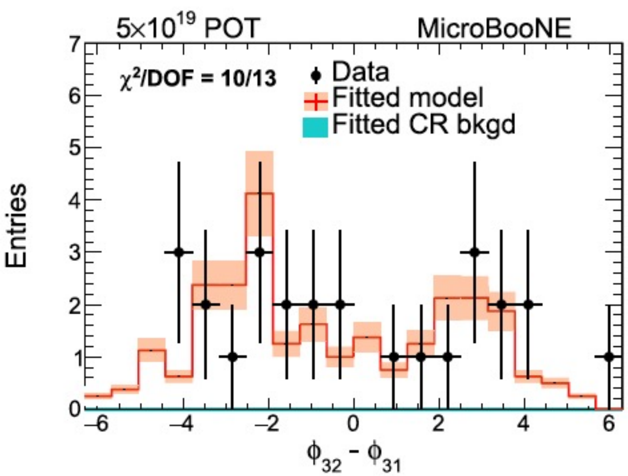


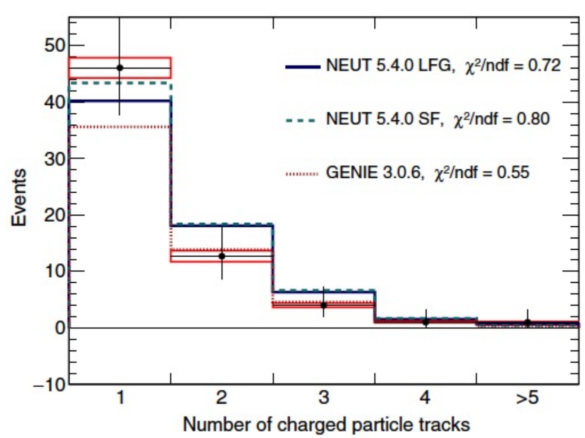


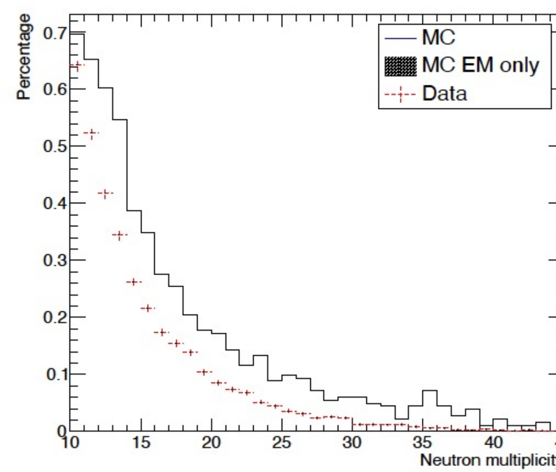


SK-Gd

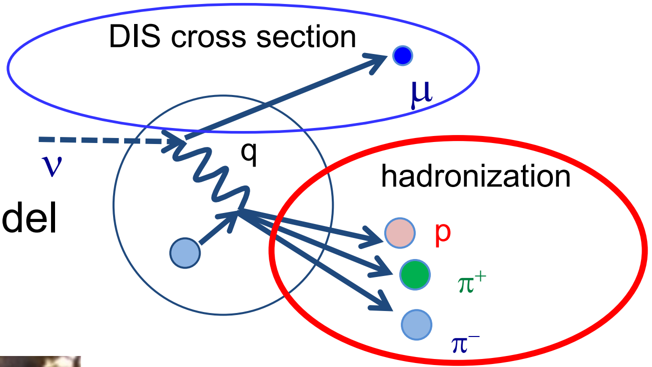








5. Neutrino cross section ≠ Hadron final states



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

Cross-section model
- Many development in past years, providing full power to move toward the future!

Hadronization model
- Not much effort

Neutrino experimentalist
- Driving a car with beautiful front wheels, no back wheels

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5. Neutrino hadronization

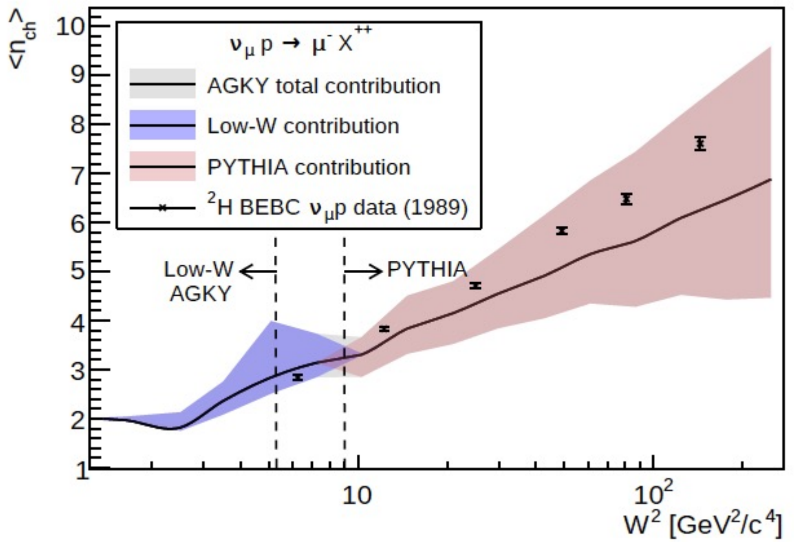
Low W multiplicity → empirical model
High W multiplicity → PYTHIA

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

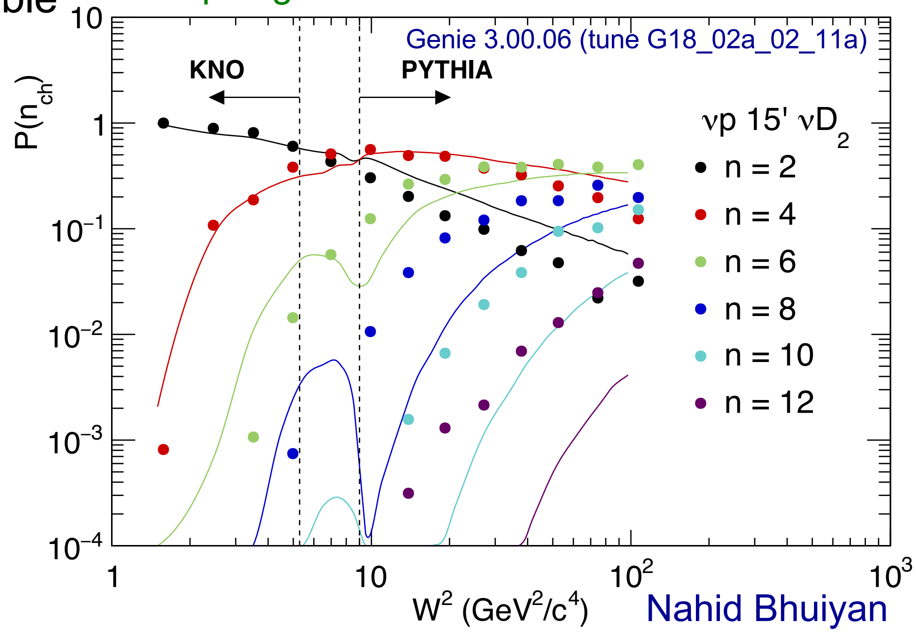
Averaged multiplicity has a large error to accommodate data tensions

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

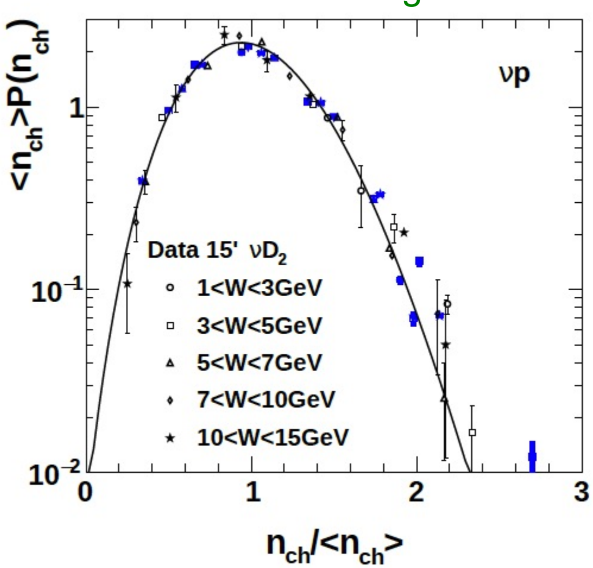
averaged charge hadron multiplicity



topological cross sections



KNO scaling



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5. 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

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6. Path forward: SIS physics

Path forward: Inelastic scattering

Axial form factors can be provided by lattice QCD, and validated by neutrino hydrogen/deuterium target experiment

Path forward: Quark-Hadron duality

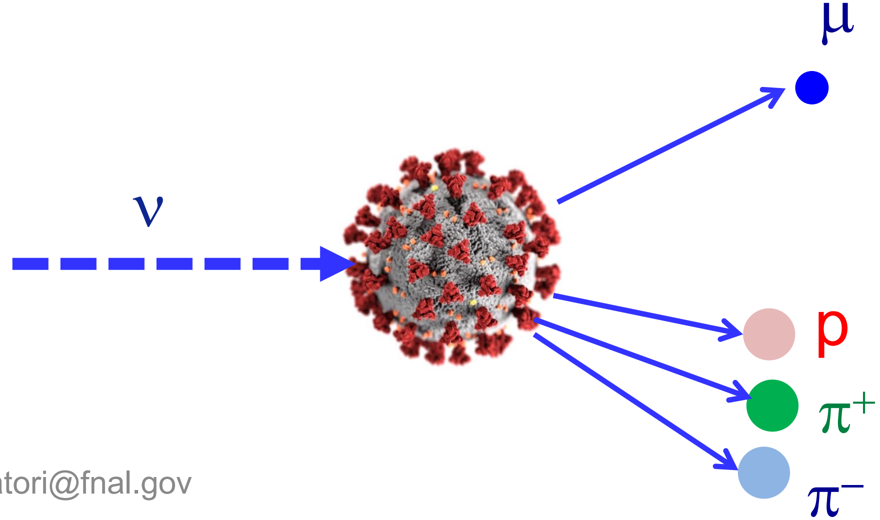
Develop neutrino QH-duality model and test with neutrino data

Path forward: DIS in Nuclear environment

Neutrino nuclear target DIS experiments to develop nPDF for neutrinos

Path forward: hadronization

Neutrino hadron production experiments to measure hadron final states to validate neutrino hadronization model



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So many unknowns; axial transition form factors for all higher resonances, quark-hadron duality with neutrinos, neutrino nuclear DIS, neutrino low-W hadronization processes, etc.

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Snowmass LoI on neutrino SIS&DIS, https://arxiv.org/abs/2009.04285
SIS physics review paper (Sajjad Athar and Morfín),https://arxiv.org/abs/2006.08603

Thank you for your attention!

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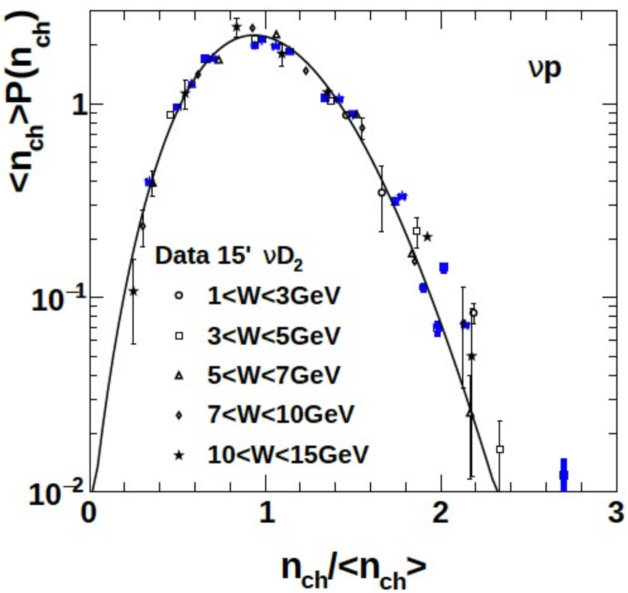
Backup

5. Hadronization

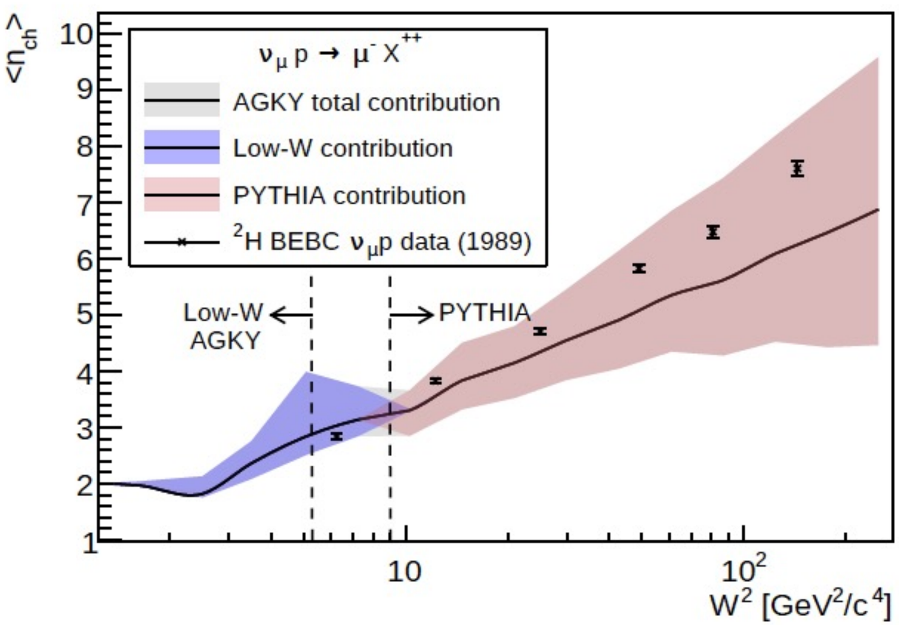
Hadron multiplicity tuning for low W DIS event

- 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 $E_{had} = \sum_i T^i_{nucl} + \sum_j E^j_{meson}$

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

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5. Topological cross section

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