Neutrino Interactions - Experiment

1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

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King's College London
INSS 2026, UCSB, USA
June 30 – July 1, 2026

KING'S College LONDON

photo by Reidar Hahn, Fermilab

Hi, my name is Teppei!

- Born and raised in Japan
- PhD (Indiana), MiniBooNE
- Postdoc (MIT), MicroBooNE
- Reader (King's College London, UK), Super-Kamiokande, Hyper-Kamiokande (and bits of IceCube-Gen2, T2K, NINJA, neutron beam, nanoparticles, etc)

NuSTEC: Neutrino Scattering Theory-Experiment Collaboration

https://nustec.fnal.gov

- We provide community service about neutrino interaction physics
- Online seminars, conference, papers
- Please subscribe "NuSTEC-News"!

1. Past

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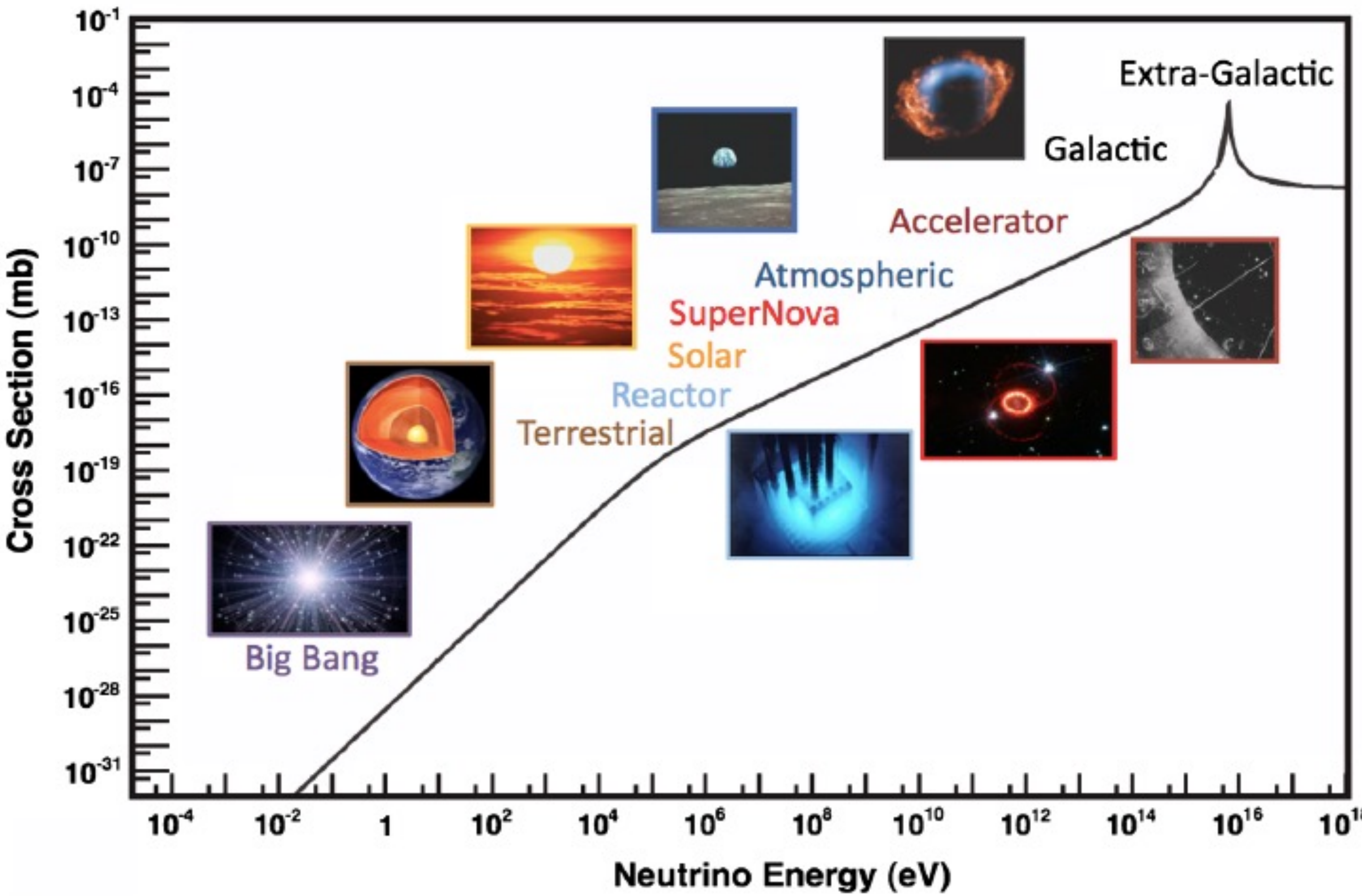
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

1.1 From eV to EeV: Neutrino cross sections across energy scales



Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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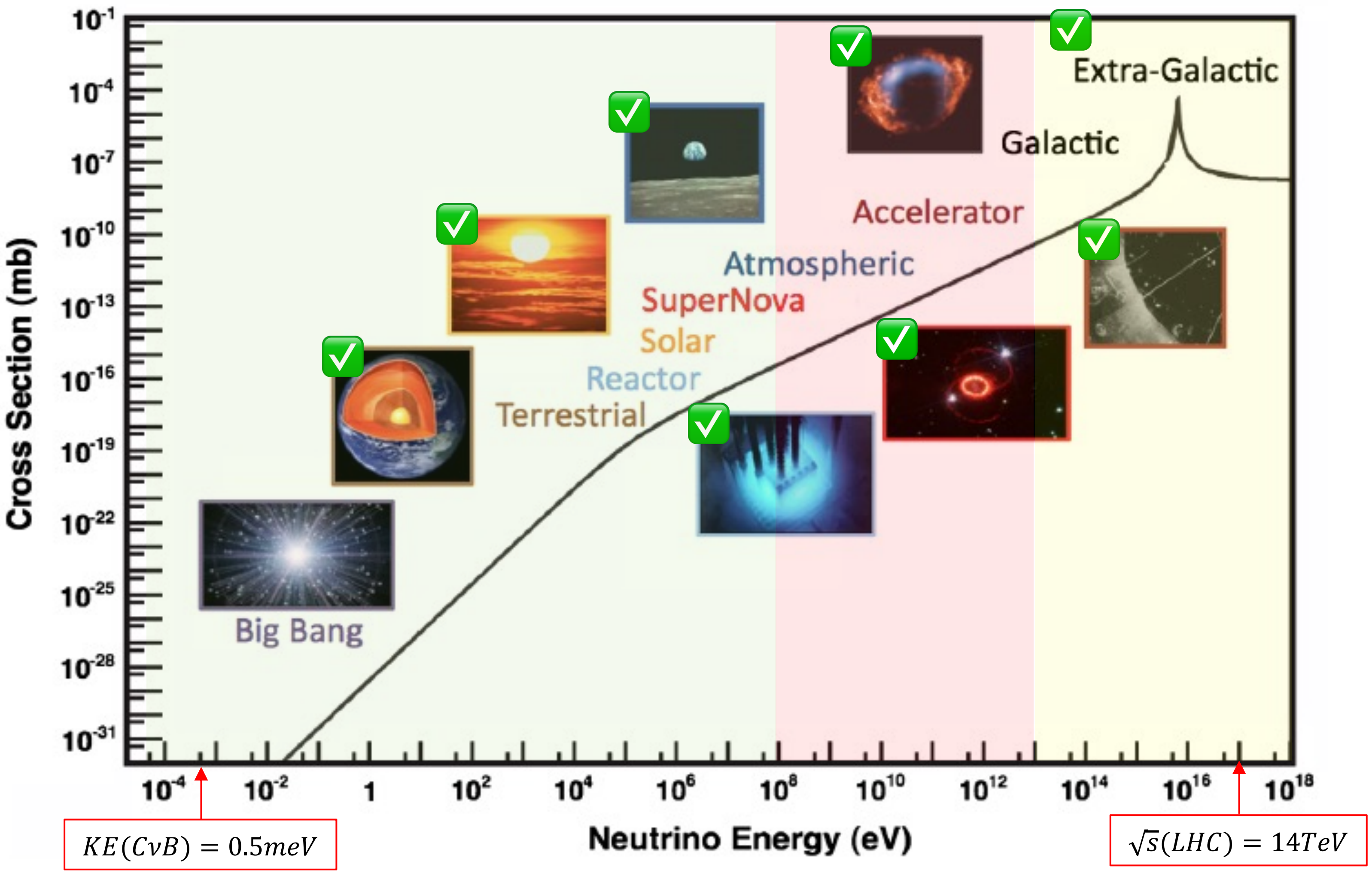

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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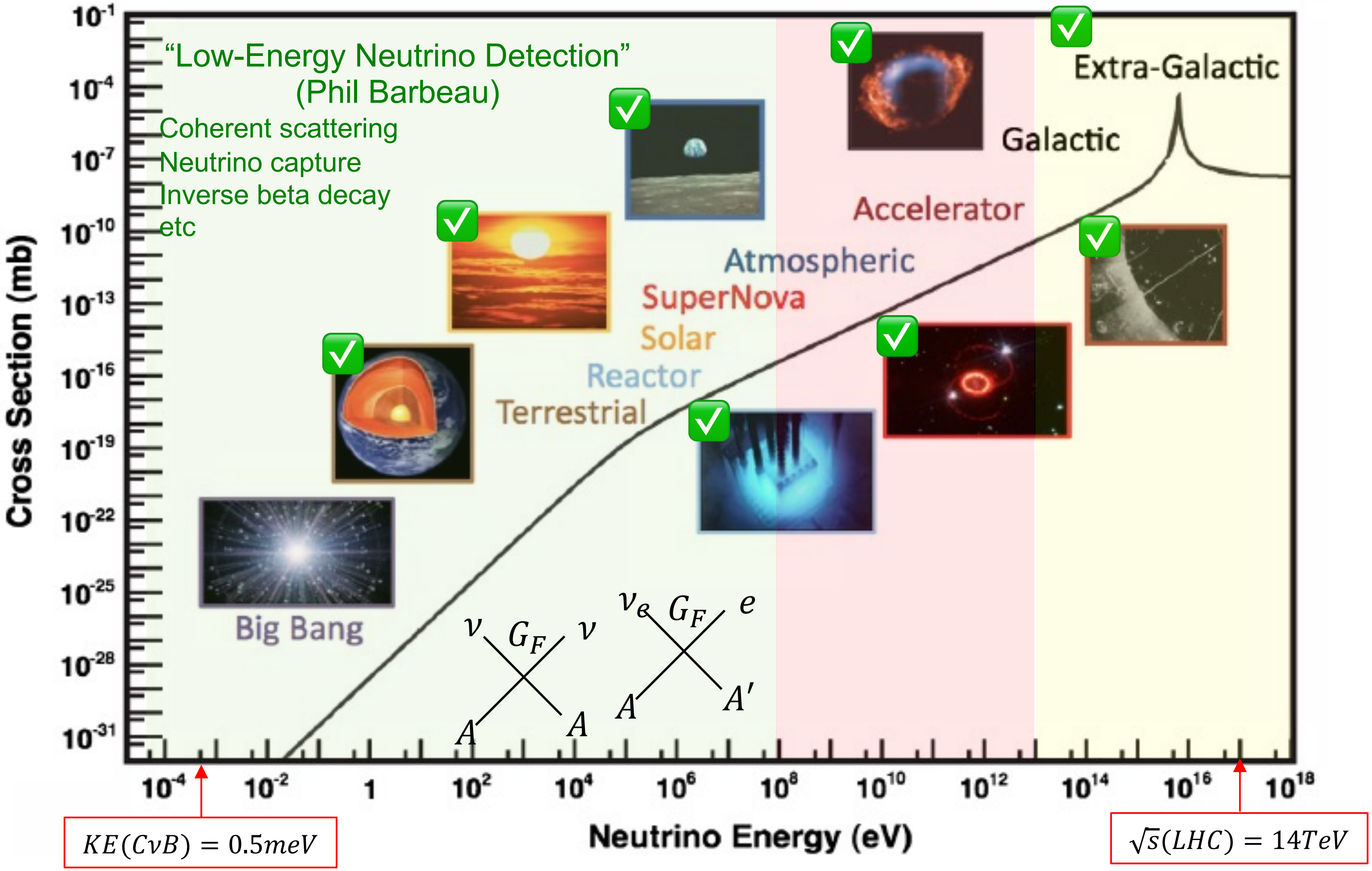
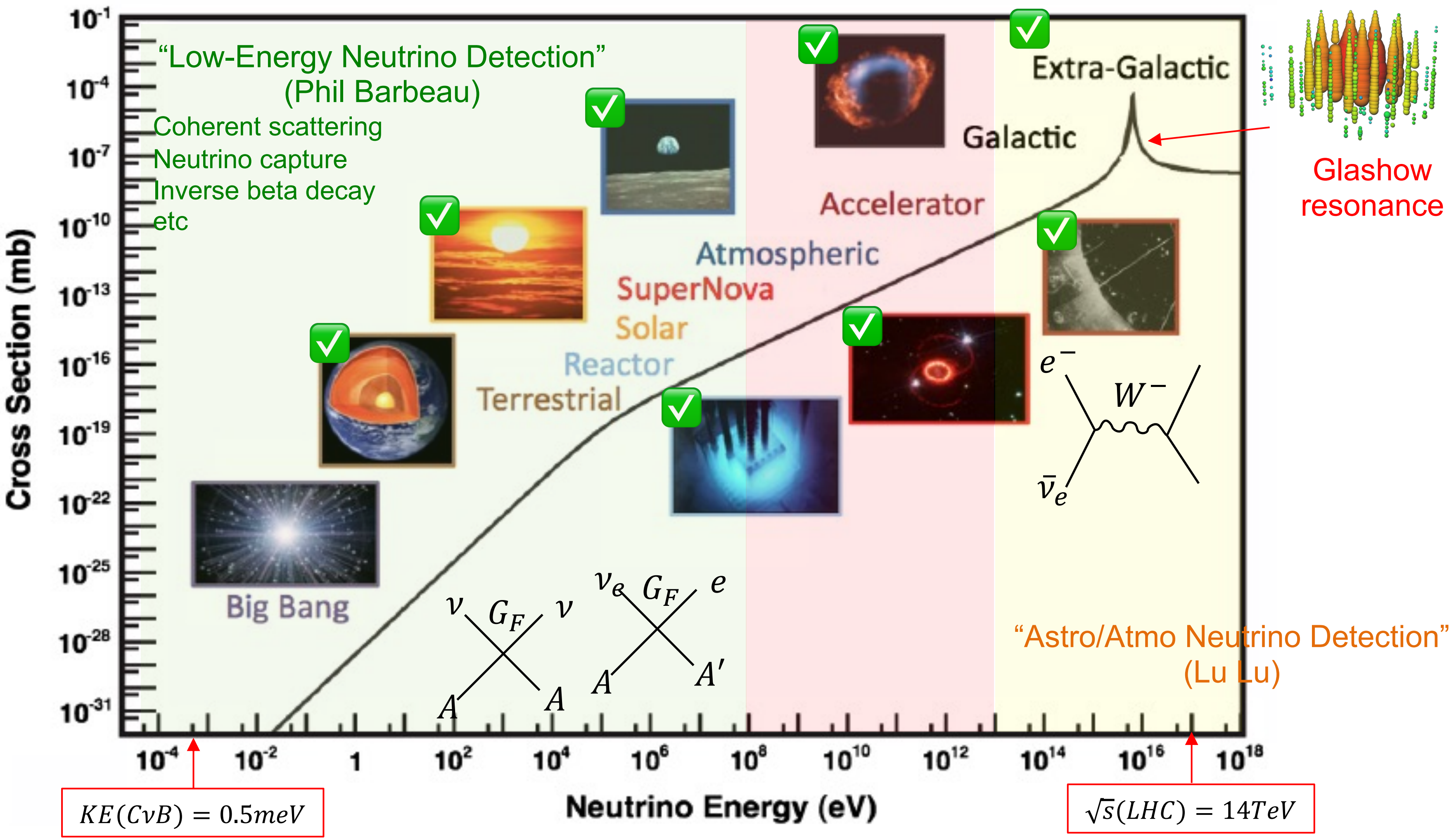


Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

1.1 From eV to EeV: Neutrino cross sections across energy scales

IceCube, Nature591(2021)220



Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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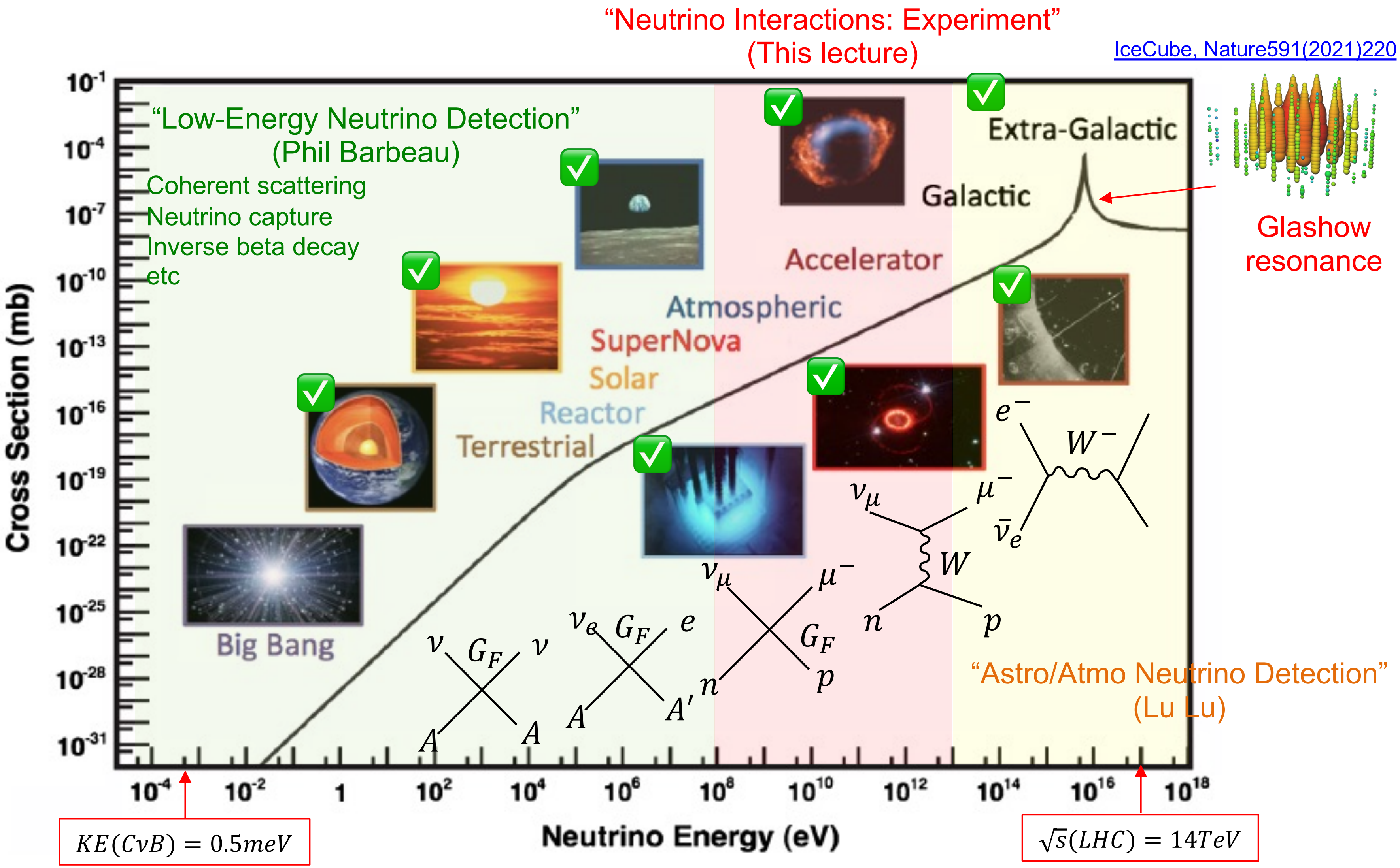
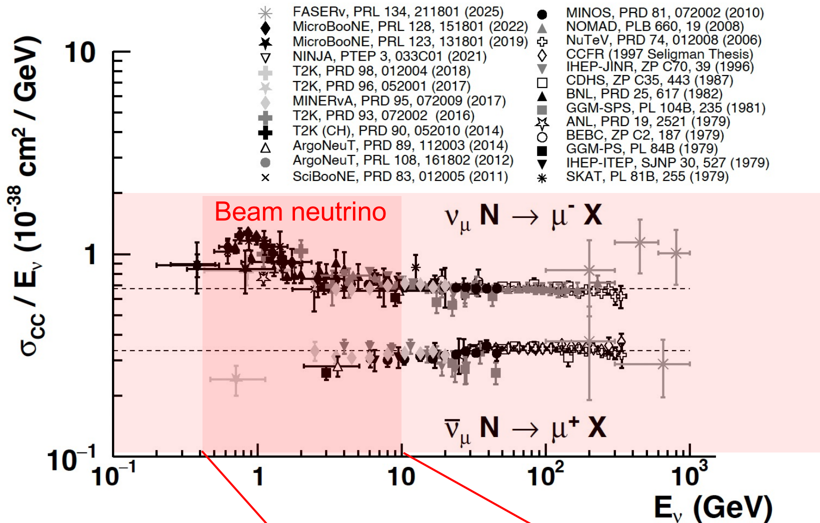


1.1 PDG: Neutrino Cross Section Measurements

PDG has a summary of neutrino cross-section data since 2012!

Strong focus on neutrino interactions around a few GeVs



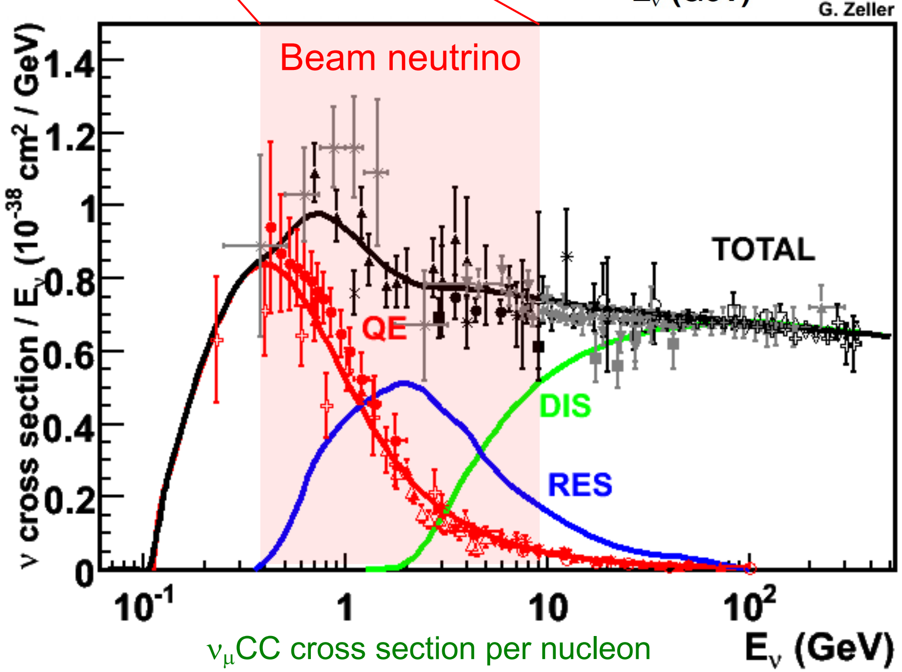


Table 52.2: Published measurements of muon neutrino and antineutrino CC inclusive cross sections from modern neutrino experiments.

experiment	measurement	target
ArgoNeuT	ν_μ [22, 23], $\overline{\nu}_\mu$ [23]	Ar
FASERν	ν_μ [17], $\overline{\nu}_\mu$ [17]	W, emulsion
IceCube	$\nu + \overline{\nu}$ [20]	H_2O
MicroBooNE	ν_μ [10, 24–27]	Ar
MINERνA	ν_μ [8, 9, 12, 13, 28–31], $\overline{\nu}_\mu$ [28, 31], $\overline{\nu}_\mu/\nu_\mu$ [32]	C, CH, Fe, Pb
MINOS	ν_μ [33], $\overline{\nu}_\mu$ [33]	Fe
NINJA	ν_μ [34, 35], $\overline{\nu}_\mu$ [34]	H_2O, Fe
NOMAD	ν_μ [36]	C
NOvA	ν_μ [37–39]	CH_2
SciBooNE	ν_μ [40]	CH
T2K	ν_μ [41–45], $\overline{\nu}_\mu/\nu_\mu$ [11]	CH, H_2O, Fe

1.1 Neutrino interaction physics around 1-10 GeV

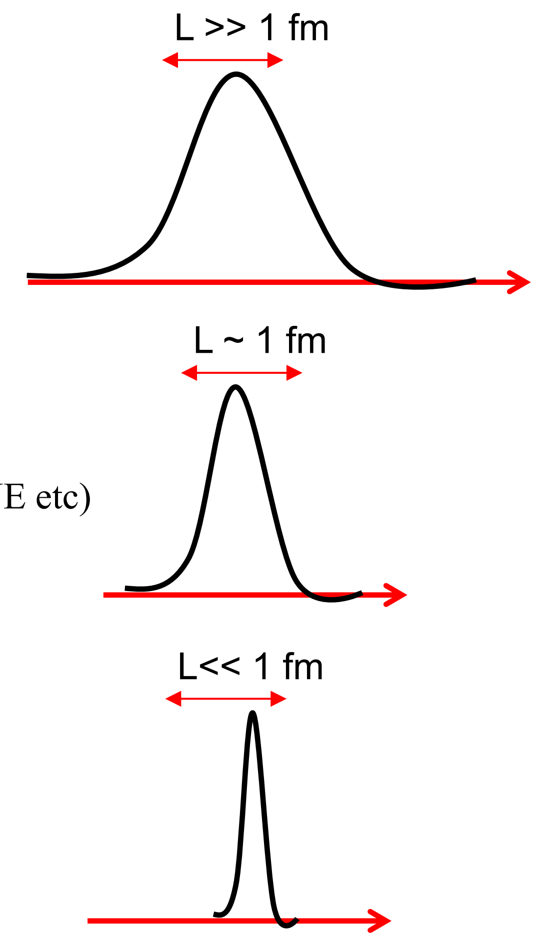
Size of wave packet ~ momentum transfer (~energy)

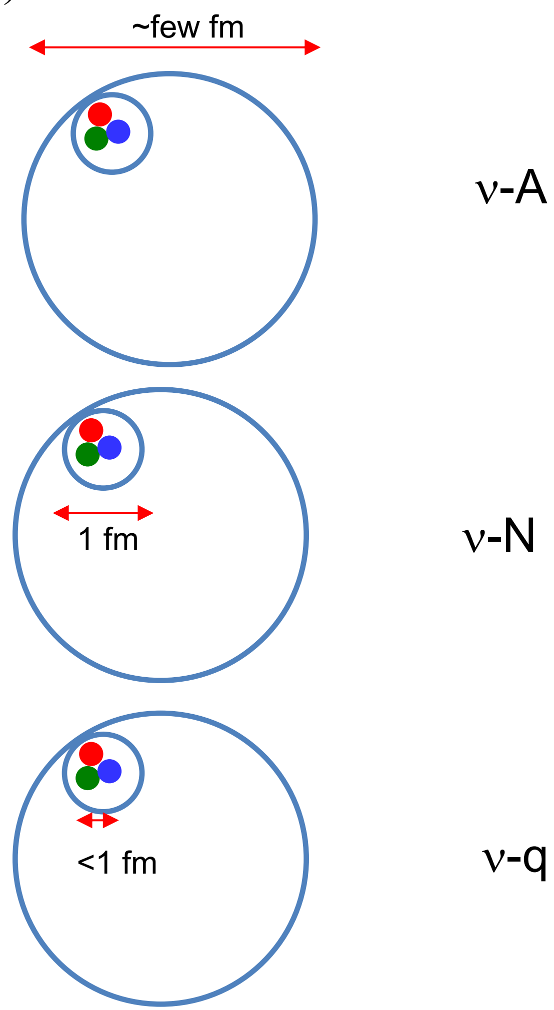
$\hbar c = 197\ MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

<<1 GeV neutrino beam
(solar neutrinos, etc)

~1 GeV neutrino beam
(T2K, NOvA, HyperK, DUNE etc)

>>1 GeV neutrino beam
(collider, astro/atmo)





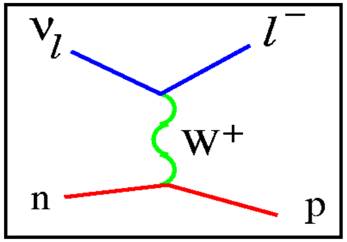
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

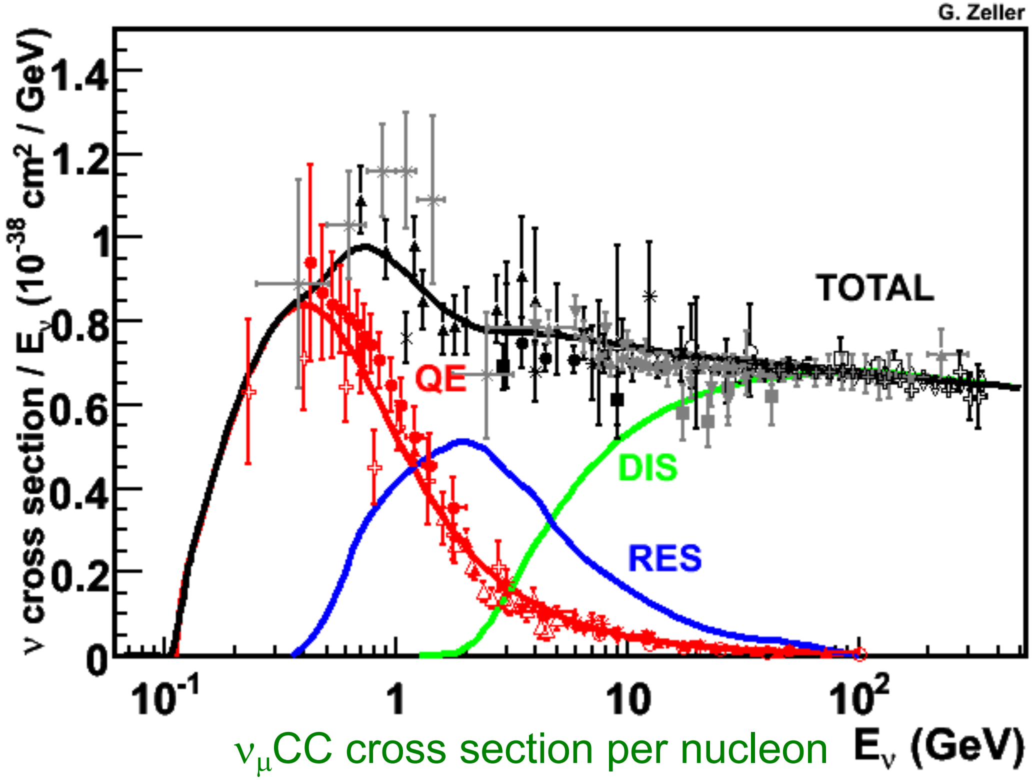
1.1 Neutrino interaction physics around 1-10 GeV

Neutrino interaction physics around 1-10 GeV

- degree of freedom change from nucleus → nucleon → parton
- There is no cut off (they all interfere), all processes co-exist

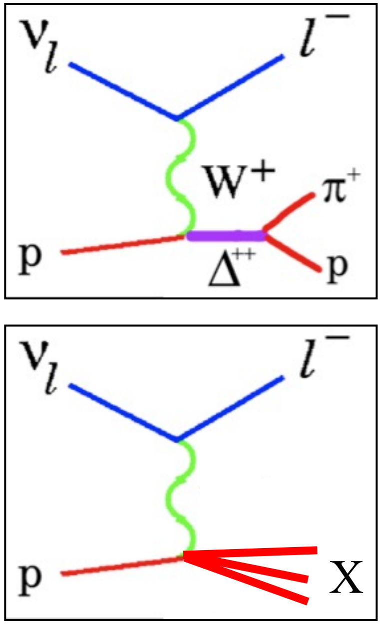
Quasi Elastic (QE)





ν_μCC cross section per nucleon

Baryonic Resonance (RES)



Deep Inelastic Scattering (DIS)

Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

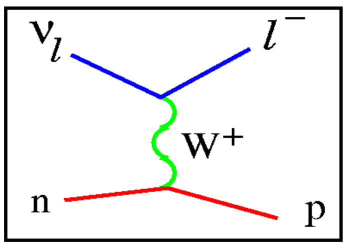
1.1 Next generation neutrino oscillation experiments

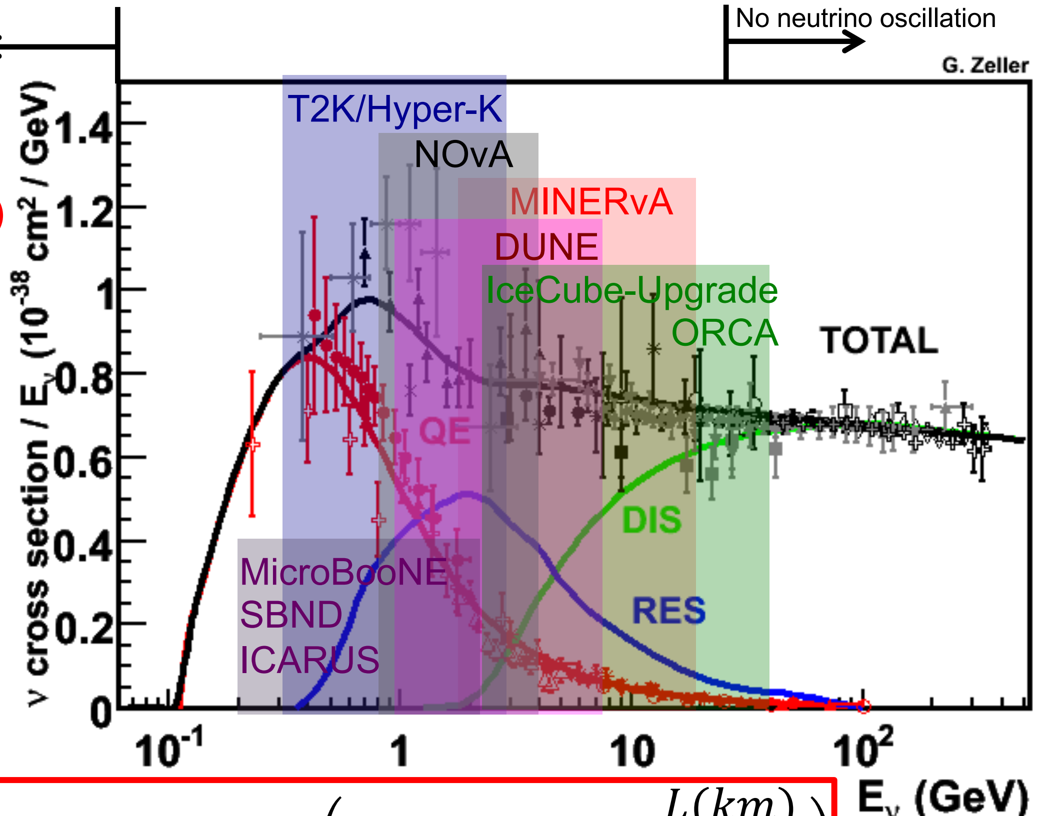
Current and future neutrino oscillation experiments

- J-PARC: T2K, Hyper-Kamiokande, etc
- Fermilab: MicroBooNE/SBND/ICARUS, MINERvA, NOvA, DUNE, etc
- Atmospheric: Hyper-Kamiokande, ORCA, IceCube-Upgrade, etc

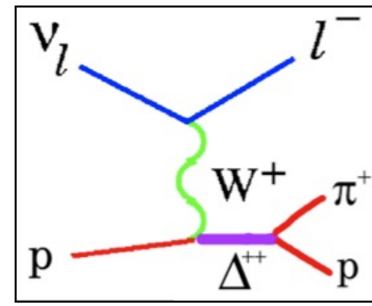
Reactor and Solar neutrino oscillation

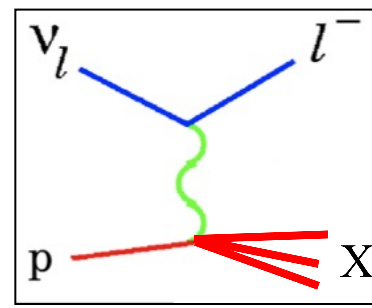
Quasi Elastic (QE)





Baryonic Resonance (RES)





Deep Inelastic Scattering (DIS)

$$P(L/E) = sin^2 2\theta sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1.1 Next generation neutrino oscillation experiments

Current and future neutrino oscillation experiments

- J-PARC: T2K, Hyper-Kamiokande
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- Atmospheric: Hyper-Kamiokande, ORCA, IceCube-Upgrade

Number of detected $\nu_\alpha \rightarrow \nu_\beta$ oscillation events are;

$$N_\beta = \left(\int \Phi(E_\nu^\alpha) \otimes P_{\alpha\rightarrow\beta}(L, E_\nu^\alpha) \otimes \sigma\left(E_l, \vec{k}_l \middle| E_\nu^\beta\right) \otimes \varepsilon\left(E_l, \vec{k}_l\right) \right) \times target \times exposure$$

- $\Phi(E_\nu^\alpha)$: Neutrino flux
- $P_{\alpha\rightarrow\beta}(L, E_\nu^\alpha)$: Neutrino oscillation probability
- $\sigma\left(E_l, \vec{k}_l \middle| E_\nu^\beta\right)$: Neutrino interaction cross-section (to produce charged lepton with E_l and $\vec{k}_l$)
- $\varepsilon\left(E_l, \vec{k}_l\right)$: Efficiency to detect charged lepton with E_l and $\vec{k}_l$

Neutrino interaction cross-sections (all relevant neutrinos, targets, and final states) must be known to measure neutrino oscillation probability.

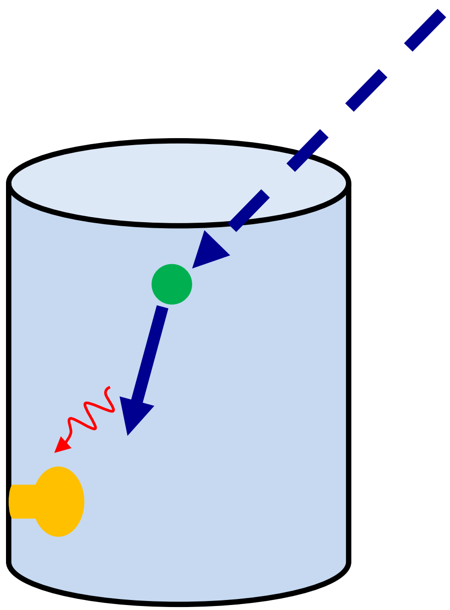
$$P(L/E) = sin^2 2\theta sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1.1 Neutrino event generator

Data

- Neutrinos interact with target materials
- Particles propagate, and emit photons
- Photons are recorded by sensors

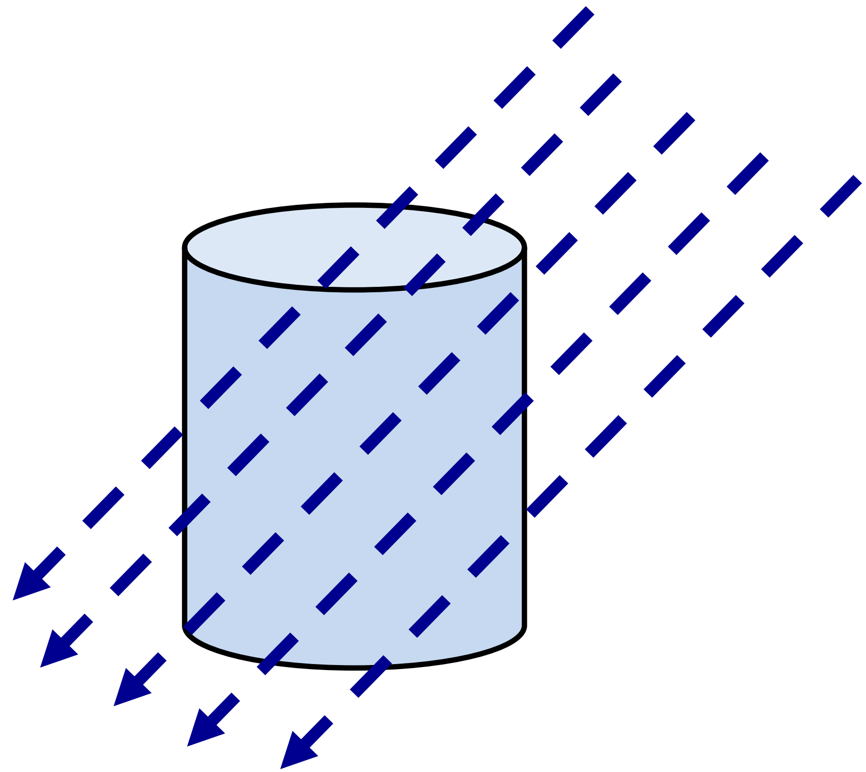
→ 1 event = 1 data trigger



Simulation

- If you try to simulate neutrino interaction by propagating neutrinos, you wait very long time to make 1 neutrino interaction

→ very inefficient simulation



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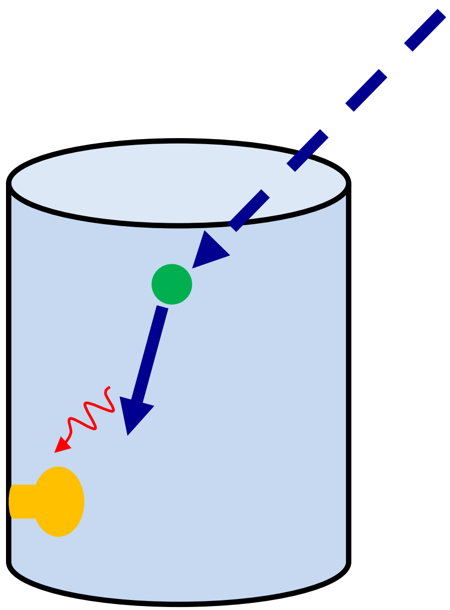
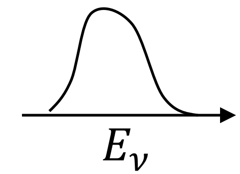


Simulation

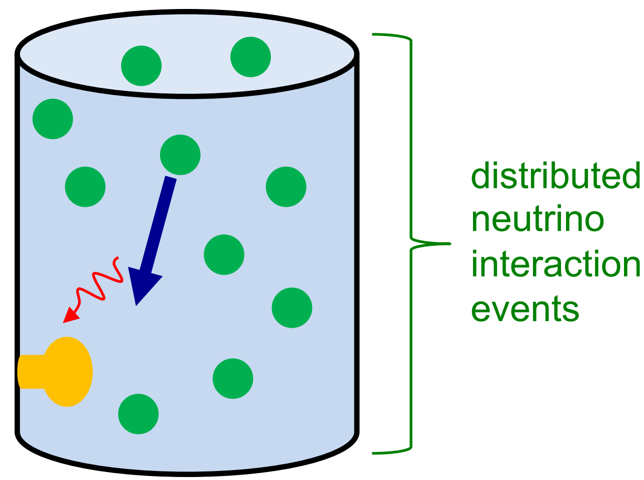
- Flux prediction $\Phi(E_\nu)$ define PDF



- Neutrino events are generated based on this PDF and cross-section $\sigma(E_l, \vec{k}_l | E_\nu)$

→ Neutrino event generator

$$Events = \int \Phi \otimes \sigma \, dE_\nu$$



- Generated events are distributed in volume
- Particle & photon propagation by Geant4

→ 1 event = 1 neutrino interaction

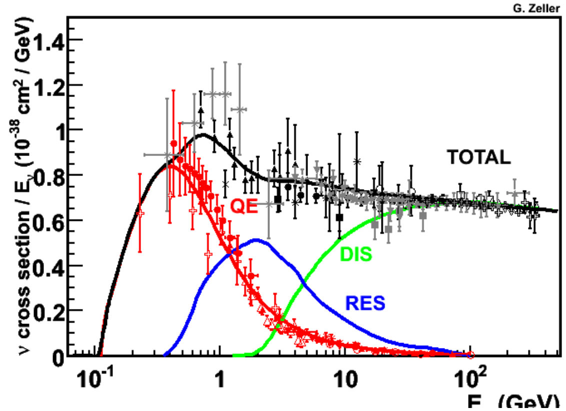
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307
NuSTEC, Prog.Part.Nucl.Phys.100(2018)1

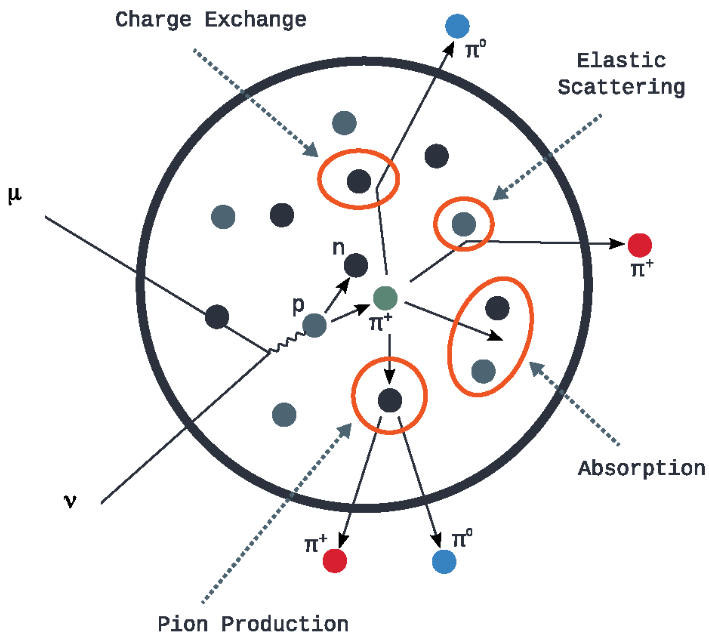
1. Why neutrino event generator?

Fast simulation
- Monte Carlo method

Merge models to cover all kinematic phase space
- Charged-current quasi-elastic (CCQE)
- Resonance baryon production (RES)
- Deep-inelastic scattering (DIS)
- etc

Simulate nuclear effects
- Pauli blocking
- Fermi motion
- Final state interactions (scattering, absorption, etc)
- Nucleon correlations
- etc





1.1 Neutrino event generator

GENIE
https://github.com/GENIE-MC
- Used by Fermilab experiments (C++)

NEUT
(no public website)
- Used by Japanese neutrino experiments (F77)

Unofficial NEUT logo made by Clarence Wret

NuWro
https://nuwro.github.io/user-guide/
- Independent generator (C++)

GIBUU
https://gibuu.hepforge.org/trac/wiki
- BUU transport to simulate hadron final states (F77)

Achilles
https://github.com/AchillesGen/Achilles
- Theory-driven better factorization (C++)

NUISANCE
https://nuisance.hepforge.org/
- Data-Neutrino generator comparison framework

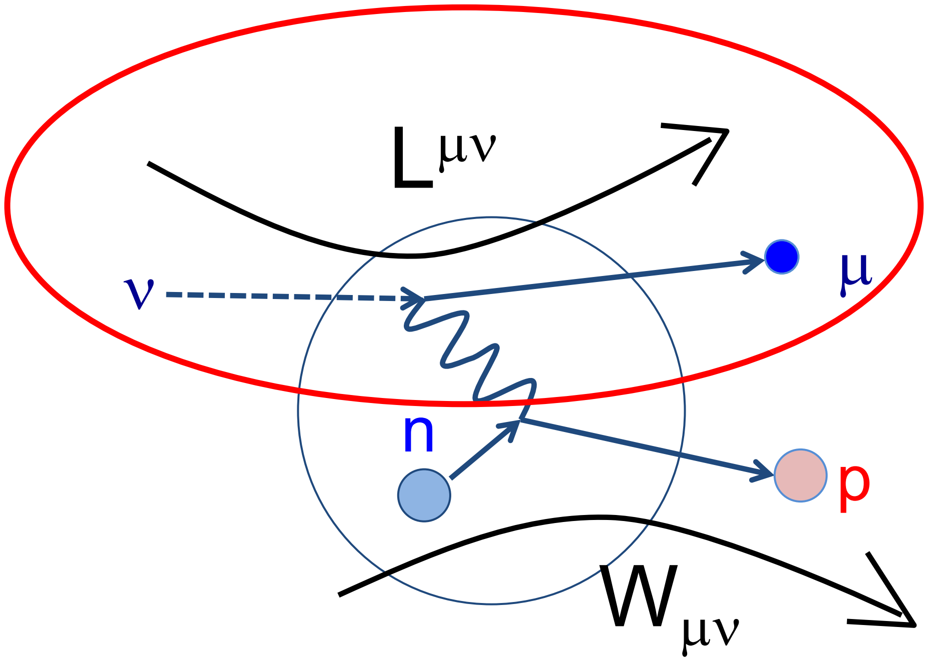
1.1 Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

$$d\sigma \sim L^{\mu\nu}W_{\mu\nu}$$

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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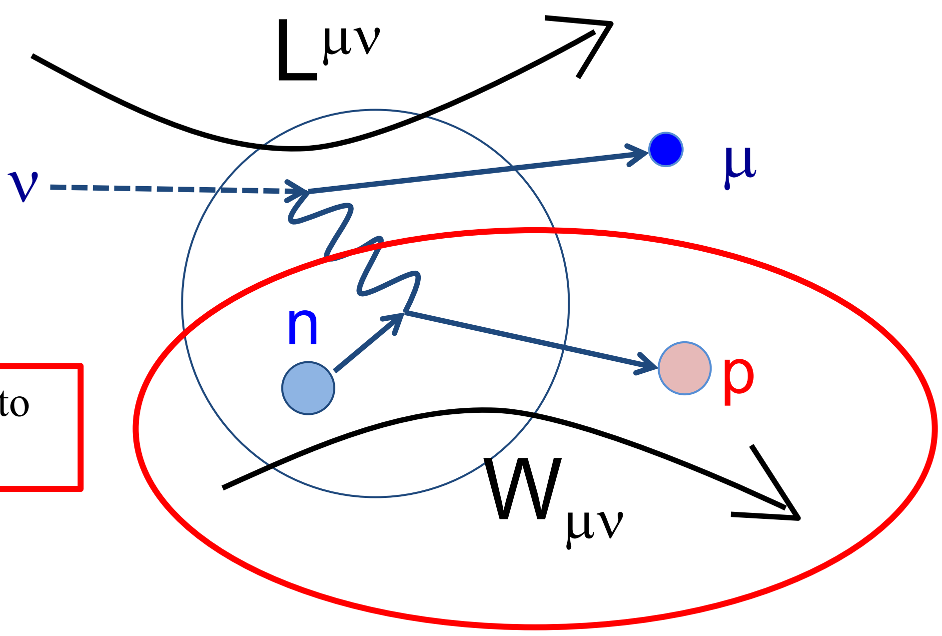
All complication of neutrino cross-section is how to model the hadronic tensor part



1. Past

2. Presence

3. Future

1.2 Neutrino interactions for Discovery physics

Neutrino interaction = Weak theory = you know it
- You know the cross section from theory
- No QED background
- No QCD background

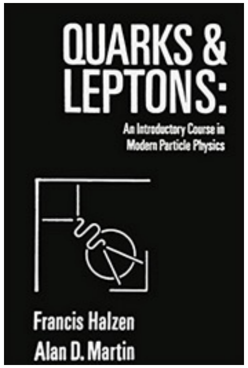
T=recoil electron kinetic energy
E=neutrino energy

Neutrino – electron differential cross section

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E-T}{E}\right)^2 - C_L C_R \frac{m_e T}{E^2}\right]$$

	C_L	C_R
ν_e - e^-	$\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$
$\bar{\nu}_e$ - e^-	$\sin^2\theta_W$	$\frac{1}{2}+\sin^2\theta_W$
ν_μ - e^-	$-\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$
$\bar{\nu}_\mu$ - e^-	$\sin^2\theta_W$	$-\frac{1}{2}+\sin^2\theta_W$

Quarks and Leptons (Halzen and Martin)
- If you don't know how to calculate this



“Low-Energy Neutrino Detection” (Phil Barbeau)

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T=recoil electron kinetic energy
E=neutrino energy

	C_L	C_R
ν_e - e^-	½+$\sin^2\theta_w$	$\sin^2\theta_w$
$\overline{\nu_e}$ - e^-	$\sin^2\theta_w$	½+$\sin^2\theta_w$
ν_μ - e^-	-½+$\sin^2\theta_w$	$\sin^2\theta_w$
$\overline{\nu_\mu}$ - e^-	$\sin^2\theta_w$	-½+$\sin^2\theta_w$

Neutrino – electron differential cross section

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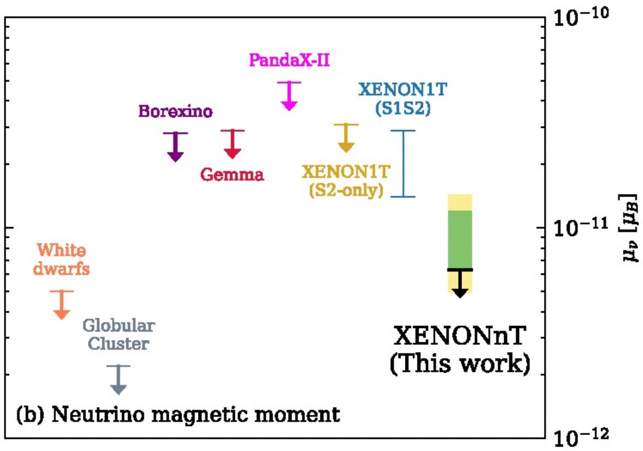
Search of neutrino magnetic moment

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E-T}{E}\right)^2 - C_L C_R \frac{m_e T}{E^2}\right] + \frac{\pi\alpha\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E}\right)$$

XENONnT: Best limit, $\mu_\nu < 6.4\times10^{-12}\mu_B$



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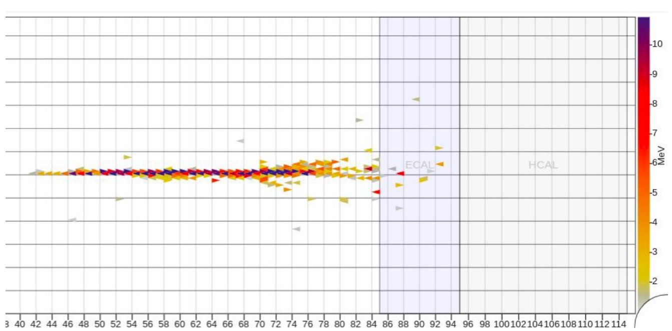
ν_μ - e^-	$-\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$
$\bar{\nu}_\mu$ - e^-	$\sin^2\theta_W$	$-\frac{1}{2}+\sin^2\theta_W$

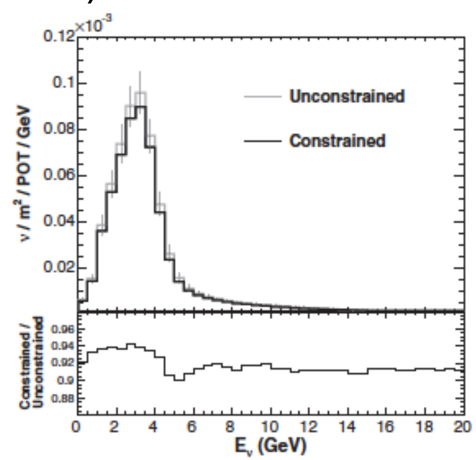
MINERvA neutrino flux calibration

$$\#events = \left(\int flux \otimes cross\ section \otimes efficiency\right) \times target \times exposure$$

From known cross-section, you constrain the neutrino flux



Luis Zazueta (Syracuse)



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1. Discovery of Weak Neutral Current
2. Discovery of Weak Theory
3. Studies of constituent quark model
4. Measurements of neutrino interaction cross-sections

Gargamelle, PLB46(1973)138 , https://en.wikipedia.org/wiki/Gargamelle
Benvenuti et al, PRL32(1974)800

1.2.1 Discovery of Neutral Current

Gargamelle bubble chamber detector (CERN)

$$\nu_\mu + N \rightarrow \nu_\mu + X \quad \bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + X$$

By the way, Fermilab also claimed they discovered neutral current...

OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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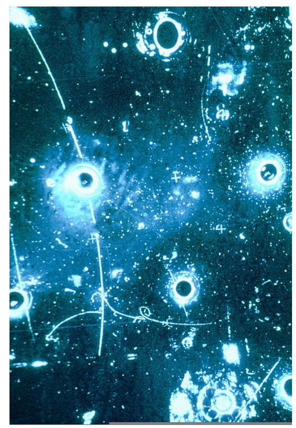
Received 25 July 1973



Observation of Muonless Neutrino-Induced Inelastic Interactions

A. Benvenuti, D. C. Cheng,* D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, F. Messing, R. L. Piccioni, J. Pilcher,† D. D. Reeder, C. Rubbia, R. Stefanski, and L. Sulak
Department of Physics, Harvard University,‡ Cambridge, Massachusetts 02138, and Department of Physics, University of Pennsylvania,‡ Philadelphia, Pennsylvania 19174, and Department of Physics, University of Wisconsin,‡ Madison, Wisconsin 53706, and National Accelerator Laboratory, Batavia, Illinois 60510

(Received 3 August 1973)

1.2.2 Discovery of Weak Theory

Gargamelle bubble chamber detector (CERN)

$$\nu_\mu + N \rightarrow \nu_\mu + X \quad \bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + X$$

and

$$\nu_\mu + N \rightarrow \mu^- + X \quad \bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

NC/CC (neutrino) ~ 0.21±0.02
NC/CC (anti-neutrino) ~ 0.45±0.09

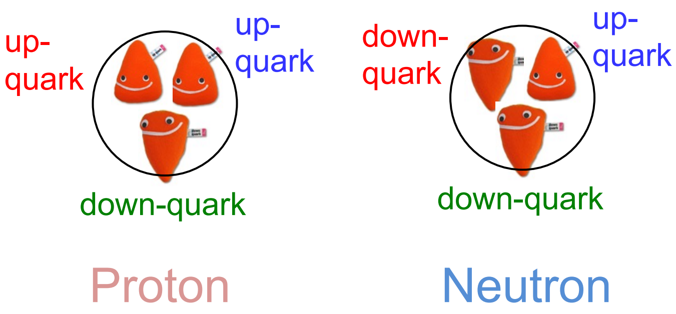
Constituent quark model

- Naive quark model

NC/CC(neutrino) $= \frac{1}{2} - sin^2\theta_W + \frac{20}{27} sin^4\theta_W \sim 0.308$

NC/CC(anti-neutrino) $= \frac{1}{2} - sin^2\theta_W + \frac{20}{9} sin^4\theta_W \sim 0.388$

(ignore sea quark contribution)



Data is consistent with Electroweak theory prediction

Electroweak theory has been established by neutrino interaction long before discoveries of W and Z bosons

FNAL 15ft, PRD24(1981)1071 and others
https://www.particlezoo.net/

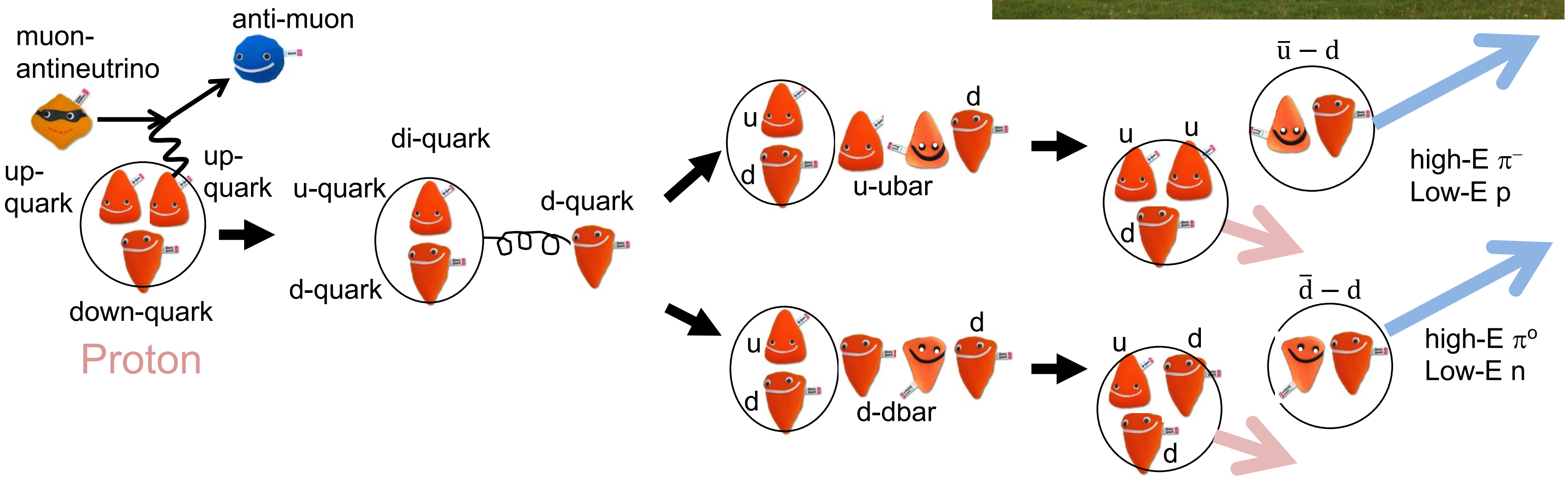
1.2.3 Studies of Constituent Quark Model

Fermilab 15” bubble chamber detector (Fermilab)

$$\bar{\nu}_\mu + p(uud) \rightarrow \mu^+ + X$$

Constituent quark model

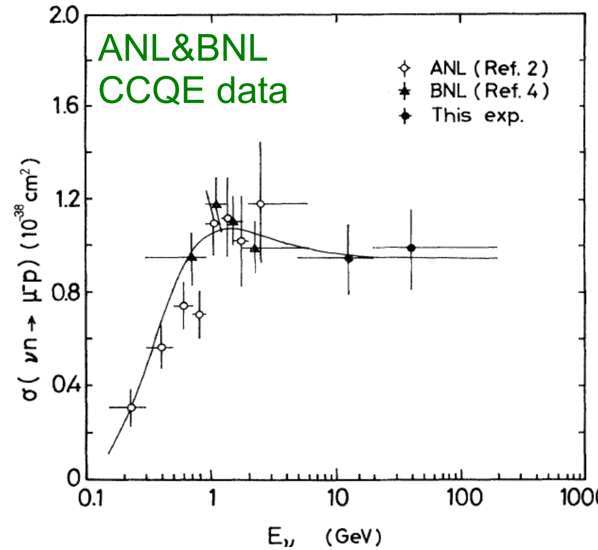
- Forward going d-quark and slow u-d pair (di-quark)
- Characteristic kinematics for final state hadrons



Quark model is confirmed by neutrino interactions

FNAL 15ft, PRD28(1983)436 and others
Gargamelle, NPB133(1978)205

1.2.4 Measurements of neutrino interaction cross-sections



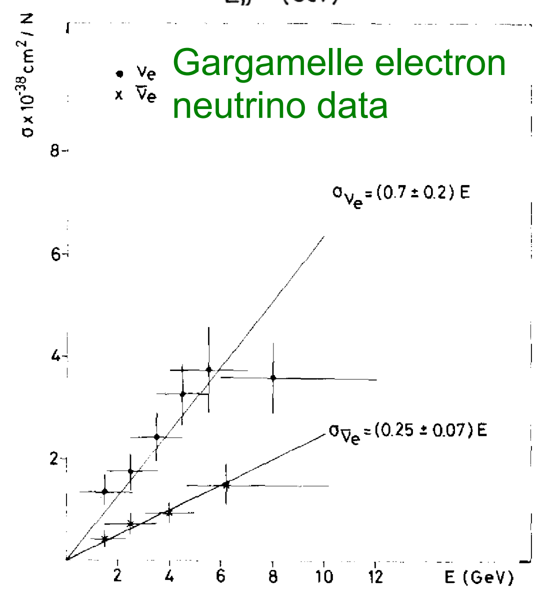
Charged current quasi-elastic (CCQE) measurement

$$\nu_\mu + D \to \mu^- + p + p$$

- No free neutrons, deuteron is the closest to pure CCQE

$$\nu_\mu + n \to \mu^- + p$$

- Total xs agrees with a model and other data (within large error) with Axial mass (M_A~1.0 GeV).



Gargamelle bubble chamber detector (CERN)

$$\nu_e + N \to e^- + X \quad \bar{\nu}_e + N \to e^+ + X$$

- First electron-neutrino cross-section measurements (and only one in next 36 years).
- Total xs agrees with a model (within large error)

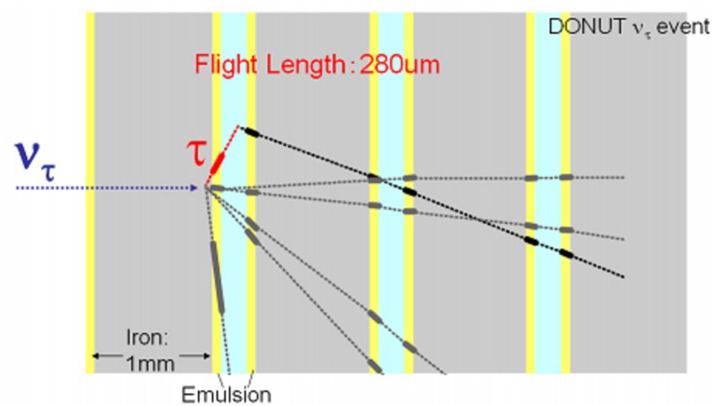
Neutrino cross-section measurement in 1970-1990s

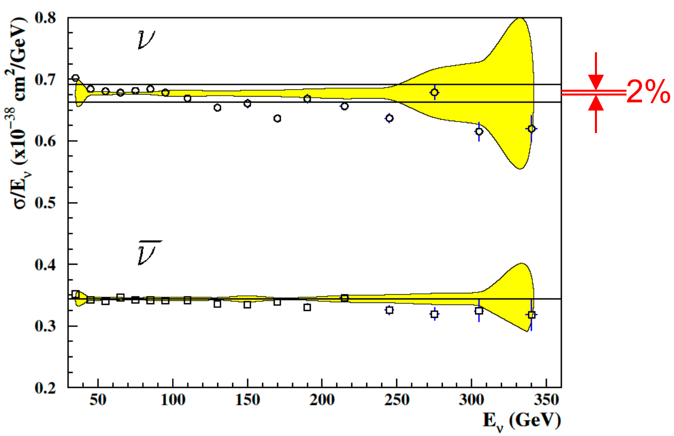
1. You don't measure neutrino cross-section because you know it. You just need to check it.
2. You cannot measure neutrino cross-section with high-precision because of low statistics and large neutrino flux error.
3. Conclusion: everything agrees within the error

[DONUT, PLB504(2001) 218](#)
[NuTeV, PRD74(2006)012008](#)

Time skip in neutrino interaction physics, 1980s → 2000s

Some important results with beam neutrinos
- Tau neutrino discovery (DONUT, 2001)
- High-energy neutrino cross-sections (NuTeV, 2006)





Meantime, neutrino oscillation physics moves to precision era with GeV neutrinos

Neutrino interaction physics around a few GeVs have no new results from 1980s to 2000s...

1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

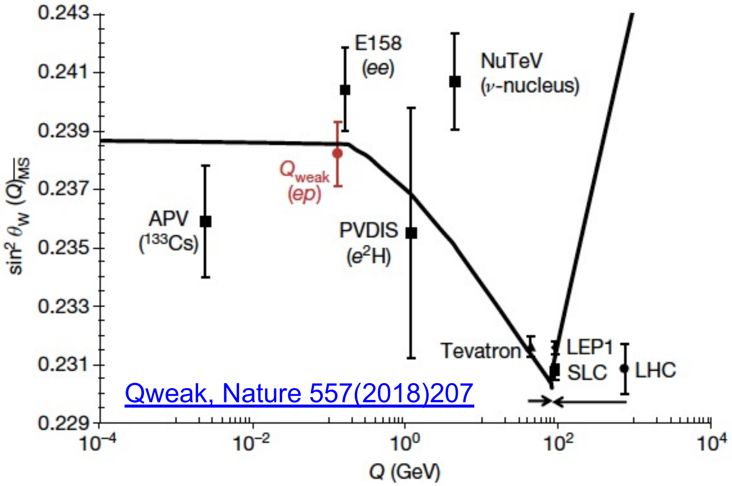
3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

1.3 Measurements of Weak mixing angle

Paschos-Wolfenstein ratio

$$R_{PW} = \frac{\sigma[\nu A \to \nu X] - \sigma[\bar{\nu} A \to \bar{\nu} X]}{\sigma[\nu A \to \mu X] - \sigma[\bar{\nu} A \to \mu^+ X]} = \frac{1}{2} - \sin^2\theta_W$$

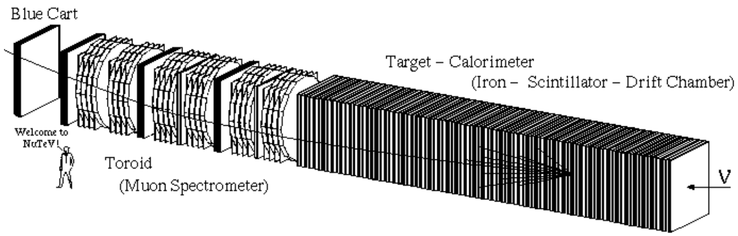
- Clean way to measure Weak mixing angle (sea quark contribution cancels)



NuTeV anomaly

$$\nu_\mu + Fe \to \mu^- + X \quad \bar{\nu}_\mu + Fe \to \mu^+ + X$$

$$\nu_\mu + Fe \to \nu_\mu + X \quad \bar{\nu}_\mu + Fe \to \bar{\nu}_\mu + X$$



- Nuclear target (iron)
- Many explanations are based on nuclear physics

cf. Isoscalar violation
- proton +1, up-quark +1
- neutron -1, down-quark -1
- This symmetry is broken: $M_p < M_n$, $m_u < m_d$

(this symmetry is used in many interaction models in all neutrino interaction generators)

Neutrino interaction experiments start to hit a limitation with ignoring precise nuclear physics...

1.3 Charged Current Quasi-Elastic scattering (CCQE)

The simplest and the most abundant interaction around ~1 GeV.

$$\nu_\mu + n \to \mu^- + p \;(\nu_\mu + X \to \mu^- + X')$$

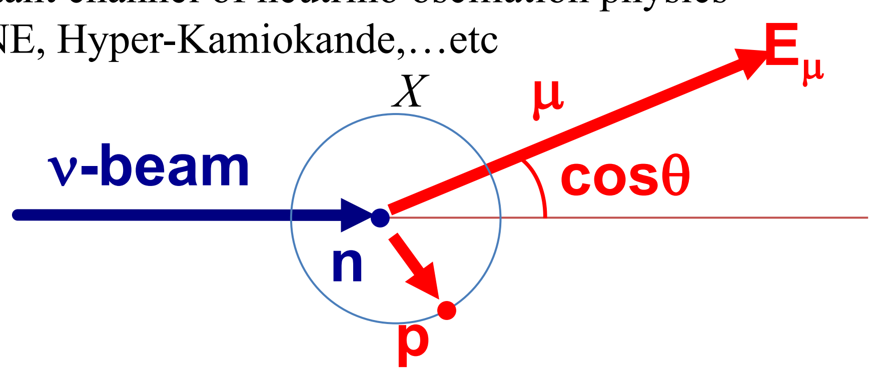
Neutrino energy (E_ν^{QE}) and 4-momentum transfer (Q_{QE}^2) are reconstructed from the observed lepton kinematics with CCQE assumption

1. assuming neutron at rest
2. assuming 2-body kinematics

$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

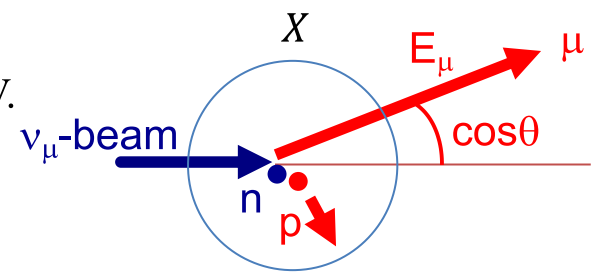
$$Q_{QE}^2 = 2E_\nu^{QE}\left(E_\mu - p_\mu cos\theta\right) - m_\mu^2$$

CCQE is the most important channel of neutrino oscillation physics
T2K, NOvA, MicroBooNE, Hyper-Kamiokande,…etc



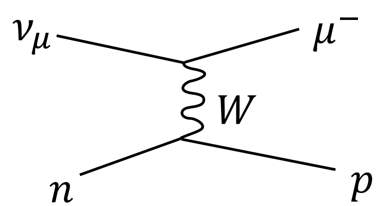
“Neutrino Interactions: Theory”
(Natalie Jachowicz)

1.3 Charged Current Quasi-Elastic scattering (CCQE)



The simplest and the most abundant interaction around ~1 GeV.

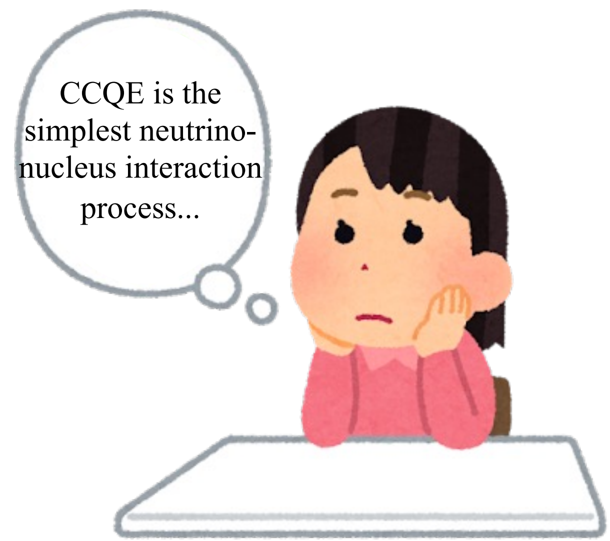
$$\nu_\mu + n \to \mu^- + p \; (\nu_\mu + X \to \mu^- + X')$$



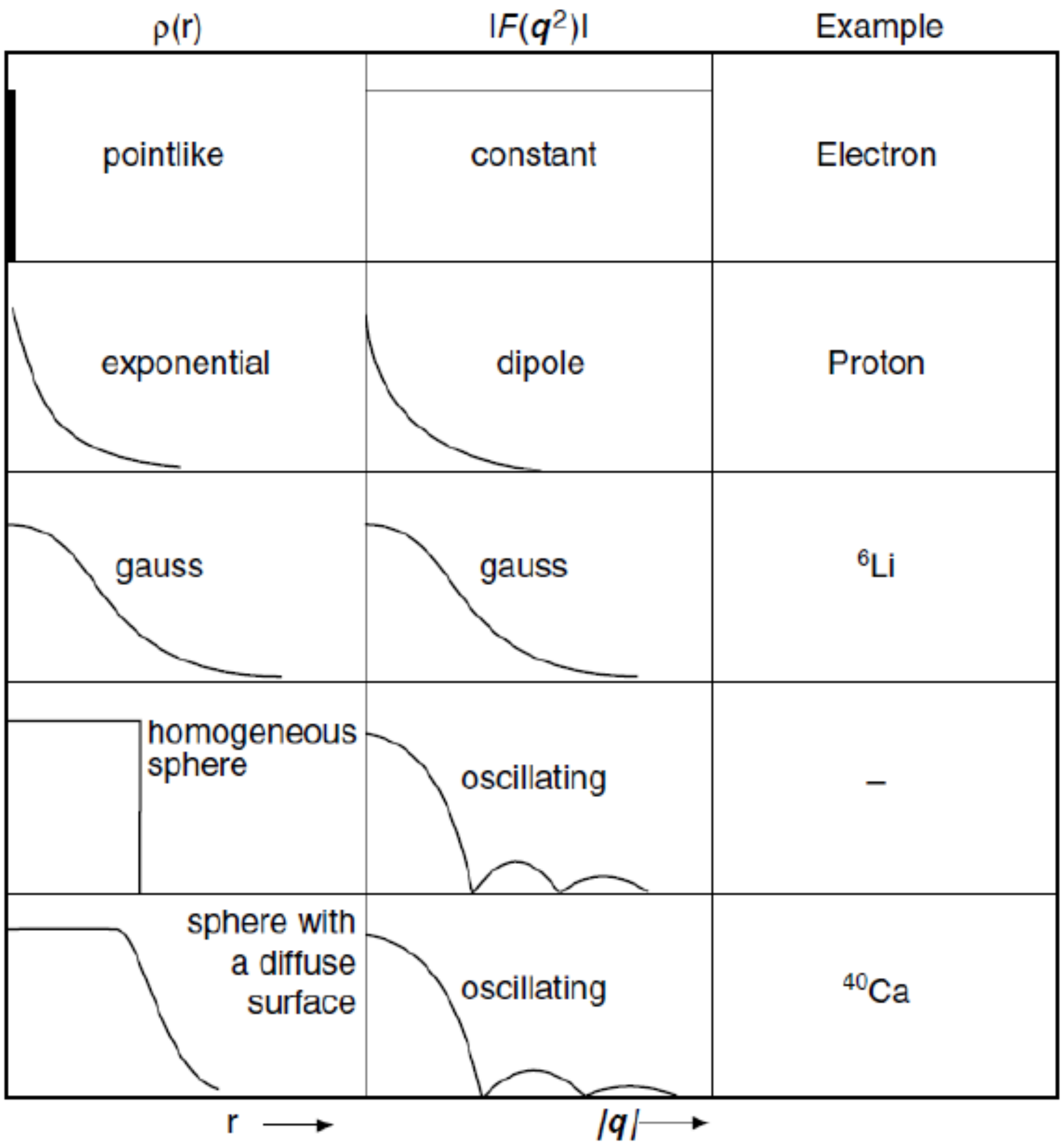
$d\sigma \sim L_{\mu\nu} W^{\mu\nu}$
$L_{\mu\nu} \sim J_\mu J_\nu$: Lepton tensor
$W_{\mu\nu} = \int f(\vec{k}, \vec{q}, \omega) T_{\mu\nu} dE$: hadronic tensor
$f(\vec{k}, \vec{q}, \omega)$: nucleon phase space
$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon tensor
F_1, F_2, F_A, F_P : form factors (F_1, F_2 are known, F_P is small)

Axial Vector form factor can be parameterized with
dipole form with M_A (axial mass) ~ 1.0 GeV

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



1.3 Form factors



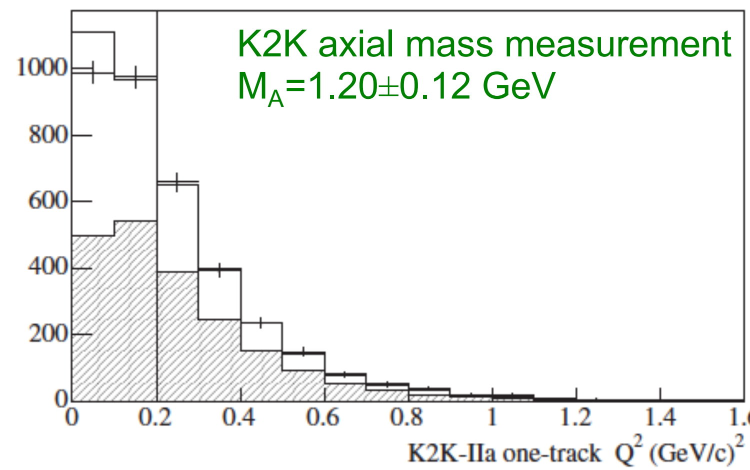
Fourier transformation

- Dipole FF = Exponential charge

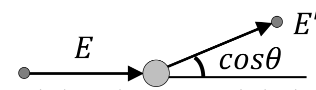
$$F(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$

- All charge distributions are more or less exponential distribution

M_A>1.0 GeV disagrees with bubble chamber result



1.3 K2K CCQE measurement



cf. small particle – large particle interaction

$$Q^2 = 4EE'sin^2\frac{\theta}{2}$$

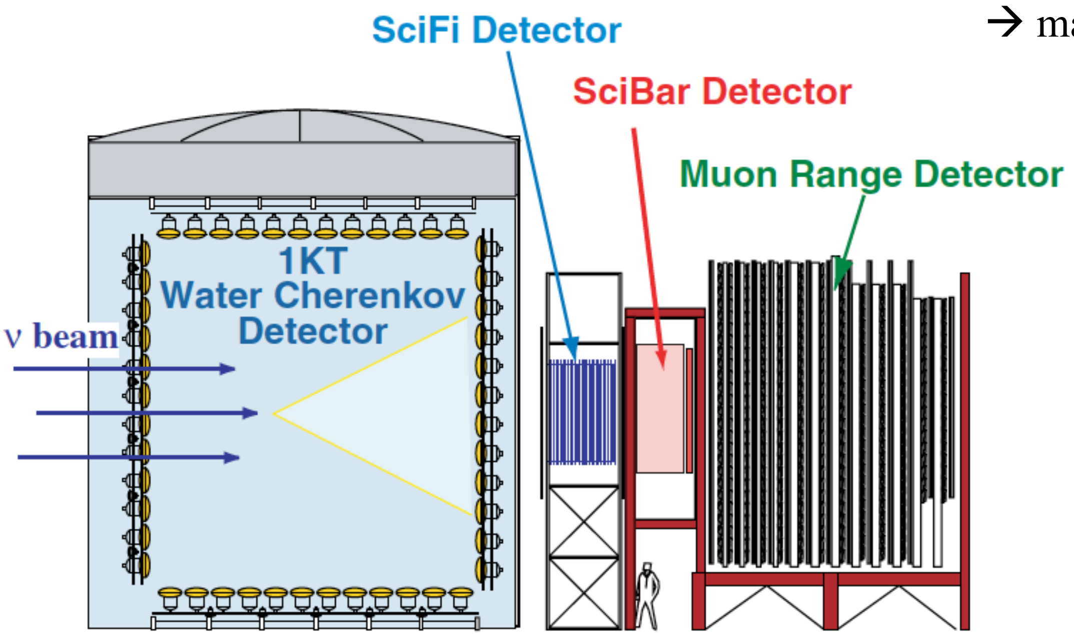
First long-baseline neutrino oscillation experiment

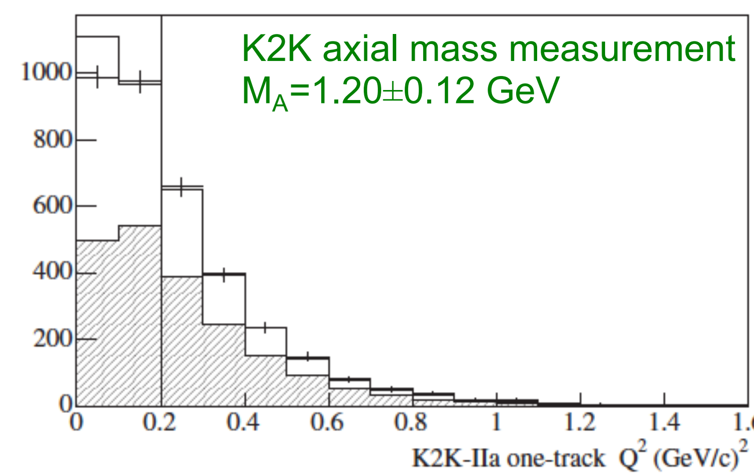
$$\nu_\mu + {}^{12}C \rightarrow \mu^- + X$$

- Forward-type near detector
- M_A=1.20±0.12 GeV
- Origin of CCQE puzzle

CCQE puzzle

1. low Q2 suppression
→ efficiency of forward going muon is wrong?
2. high Q2 enhancement
→ maybe flux prediction is wrong?





MiniBooNE, PRL100(2008)032301

1.3 MiniBooNE CCQE measurement

Short-baseline neutrino oscillation experiment

$$\nu_\mu + {}^{12}C \rightarrow \mu^- + X$$

- 4π Cherenkov detector
- M_A=1.23±0.20 GeV
- Confirmation of CCQE puzzle

CCQE puzzle

1. low Q2 suppression

-→ ~~efficiency of forward going muon is wrong?~~

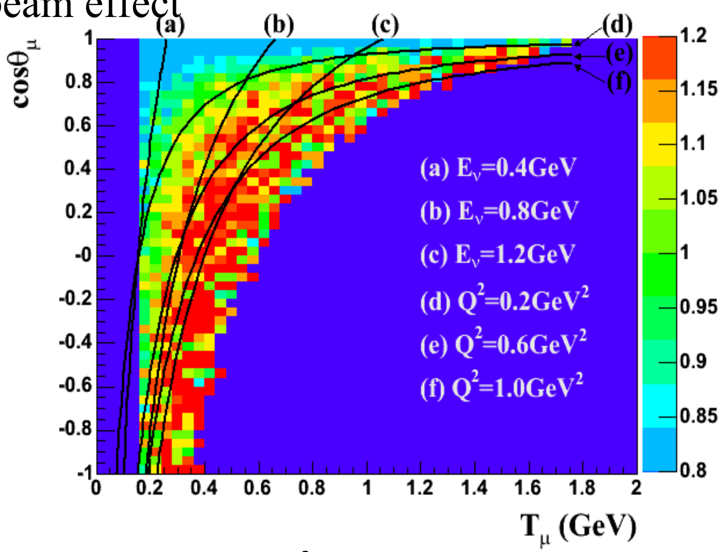
2. high Q2 enhancement

-→ ~~maybe flux prediction is wrong?~~

MiniBooNE T_μ-$\cos\theta_\mu$ space

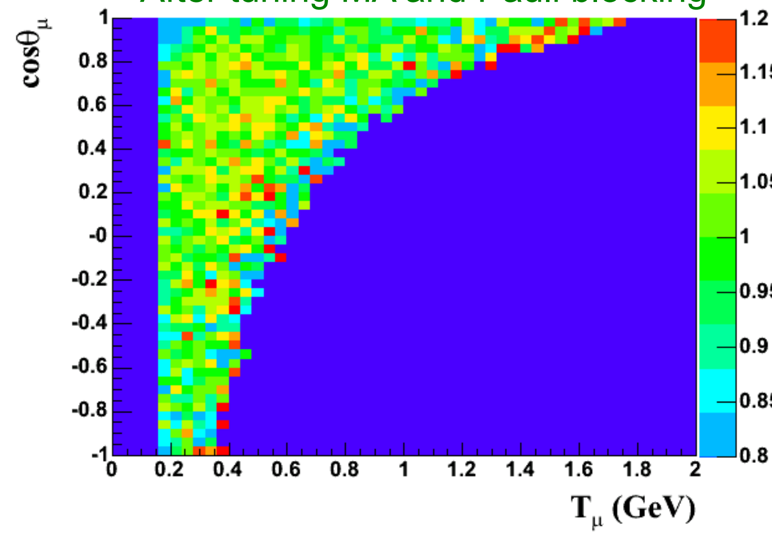
Data-MC ratio is wrong along constant Q2

→ It looks CCQE puzzle is not detector or beam effect



→

After tuning MA and Pauli blocking



$$Events\ (T_\mu, cos\theta_\mu) \sim \int flux(E_\nu) \otimes cross\ section(Q^2)$$

MiniBooNE, PRD81(2010)092005

1.3 MiniBooNE CCQE measurement

MiniBooNE CCQE measurement

$$\nu_\mu + {}^{12}C \rightarrow \mu^- + X$$

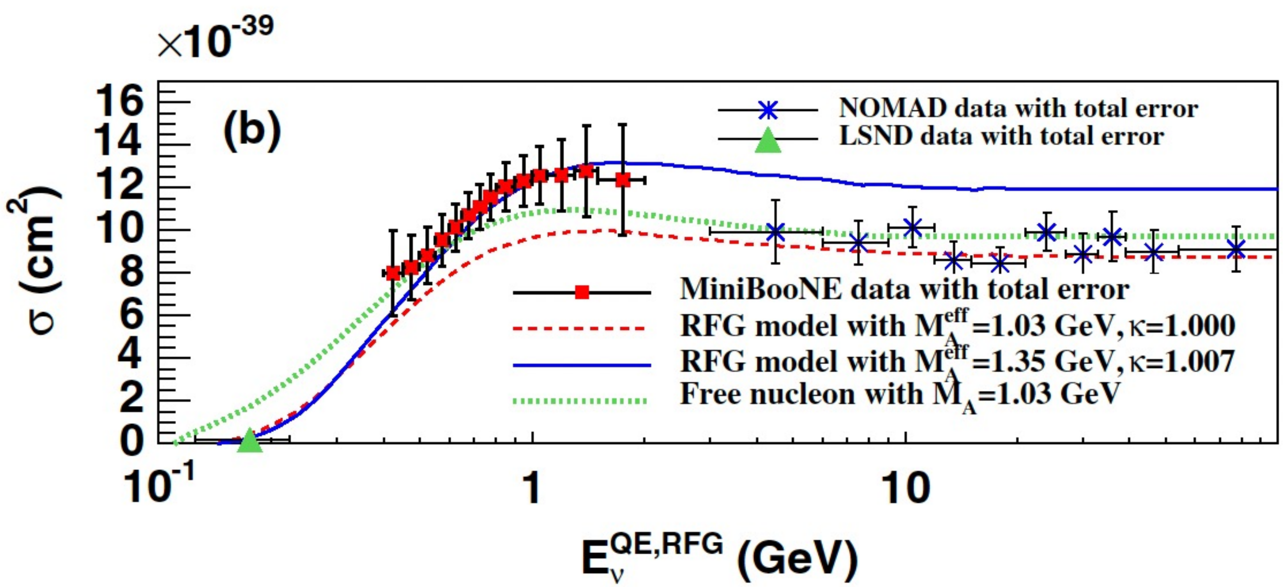
MiniBooNE CCQE cross-section is higher than free nucleon CCQE cross-section.

Nuclear effect = phase space suppression
→ reduction of cross-section.

Nuclear effect cannot explain high event rate

CCQE puzzle

1. low Q2 suppression
~~→ efficiency of forward going muon is wrong?~~
2. high Q2 enhancement
~~→ maybe flux prediction is wrong?~~
3. high normalization
→ maybe flux normalization prediction is wrong?



MiniBooNE, PRD79(2009)072002
NA61/SHINE, EPJC79(2019)100 , T2K, EPJC83(2023)782

"Neutrino sources and beams"
(Laura Fields)

1.3 Neutrino flux systematic error reduction

Low energy flux error was in general over 30% (~2009)

- Based on phenomenological parametrization
- e.g.) Sanford-Wang parametrization

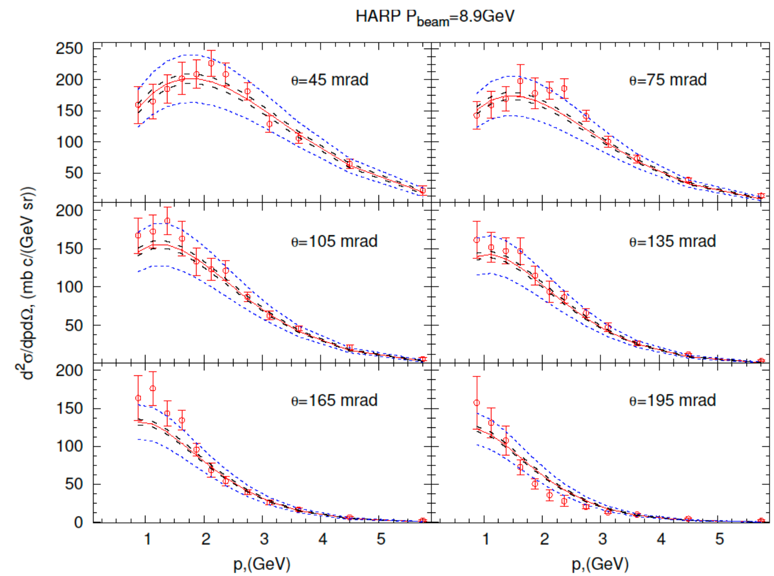
$$\frac{d^2\sigma}{dpd\Omega} = c_1\left(1 - \frac{p}{p_B - c_9}\right) exp\left[-c_3\frac{p^{c_4}}{p_B^{c_5}} - c_6\theta(p - c_7 p_B cos^{c_8}\theta)\right]$$

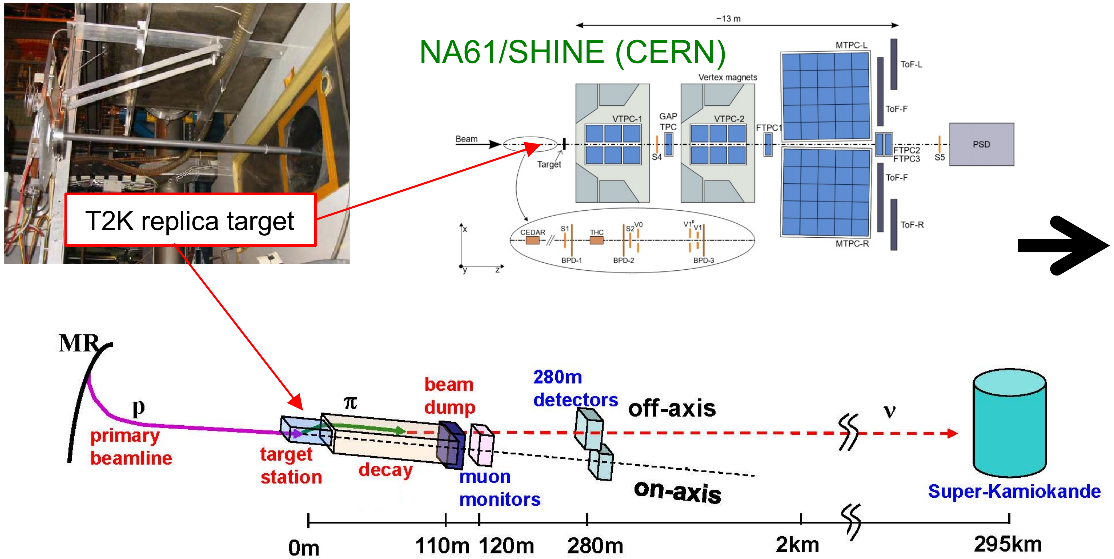
- Not great fit, parameter tensions propagate and give neutrino flux normalization error on neutrino cross-section

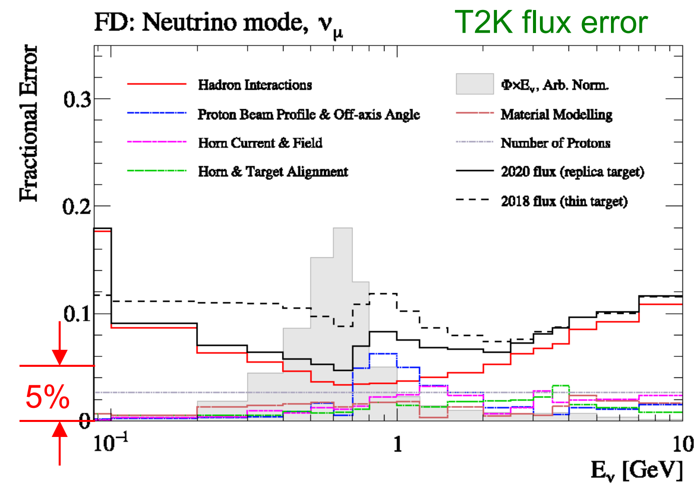
Modern oscillation experiment, flux error ~5-8% (2009~)

- Directly propagate hadron production data taken from replica target to neutrino experiments

HARP pion data fit with Sanford-Wang formula







1.3 Community effort to understand the problem

Model parameters are tuned within experimental simulations (M_A etc). Theorists have no idea how to interpret the data if they are compared with experimental simulations.

But if experimentalists publish corrected data, the data are model-dependent and biassed, and theorists have no idea how to interpret them.

We need "a common language" which theorists and experimentalists can discuss with the data.

→ Flux-averaged differential cross-section (2010)

1.3 Flux-averaged differential cross-section

Flux-averaged differential cross-section data allow theorists and experimentalists talk directly

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

Theorists

Theoretical cross-section is integrated with given neutrino flux so that theorists predict experimental data

Experimentalists

$$\frac{d^2\sigma}{dT_l \cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta\cos\theta)_i}$$

Experimental data have correction of detector effect (minimum bias) but not neutrino flux

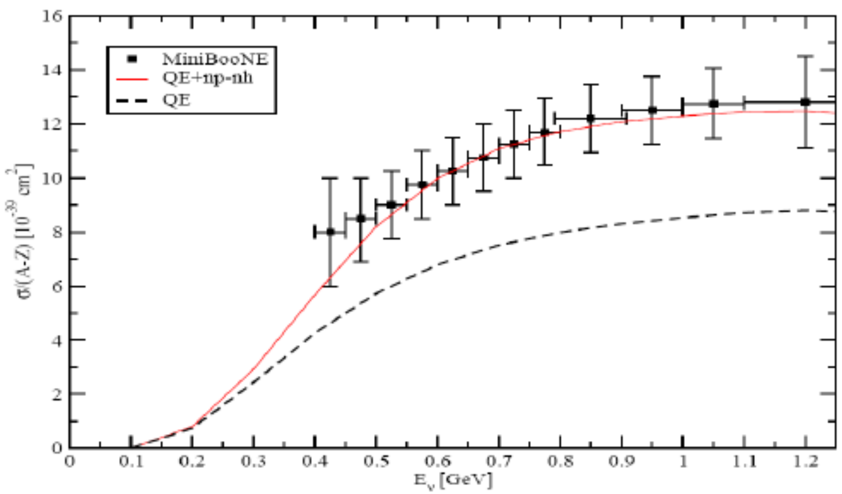
1.3 The solution of CCQE puzzle

Presence of 2-body current

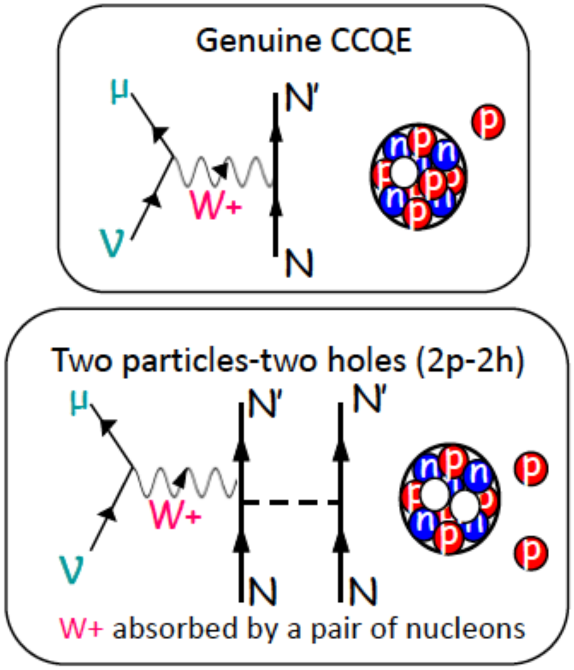
- Martini et al showed 2p2h effect can add up more cross section
- Consistent result by Nieves et al (Valencia 2p2h model)
- Phenomenological model results are supported by nuclear ab initio calculation

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



Martini model vs. MiniBooNE CCQE total cross-section

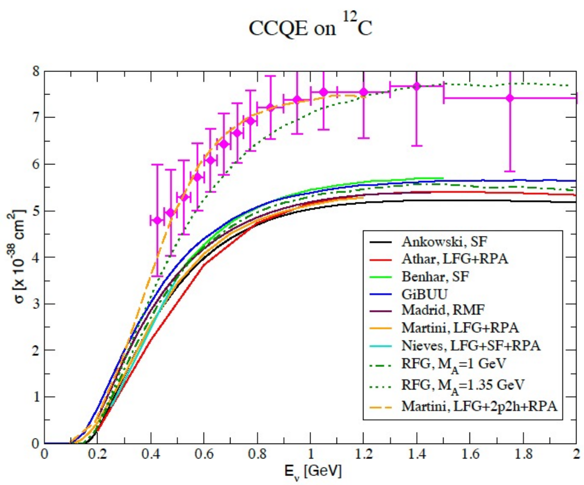


1.3. Models using 2p2h

Flux-averaged differential cross-sections allow nuclear theorists to compare their models with data without implementing models in simulation

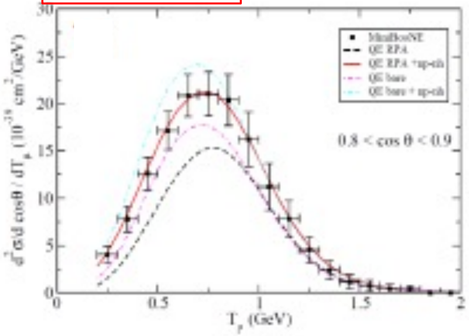
This boosts model development work by theorists

Martini et al – Lyon 2p2ph model
Nieves et al – Valencia 2p2h model
SuSAv2 – Superscaling+MEC
Giusti et al – Relativistic Green's function
Butkevich et al – RDWIA+MEC
Lovato et al – GFMC
Jachowicz et al – CRPA+MEC
etc

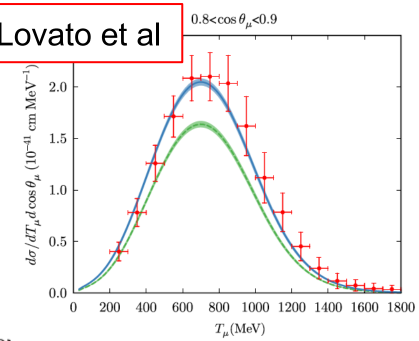


Alvarez-Ruso, NuInt 2010

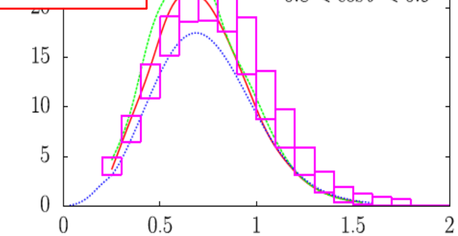
Martini et al



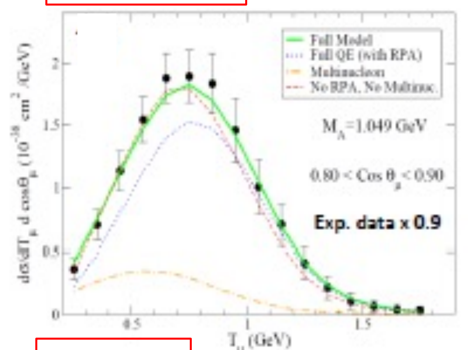
Lovato et al



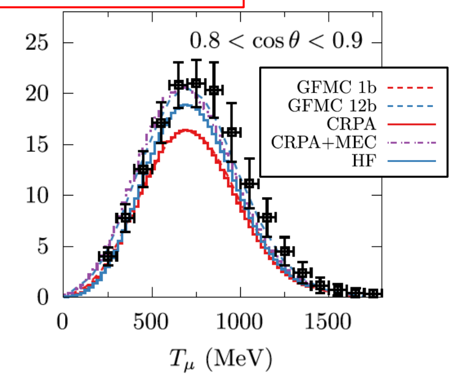
Giusti et al



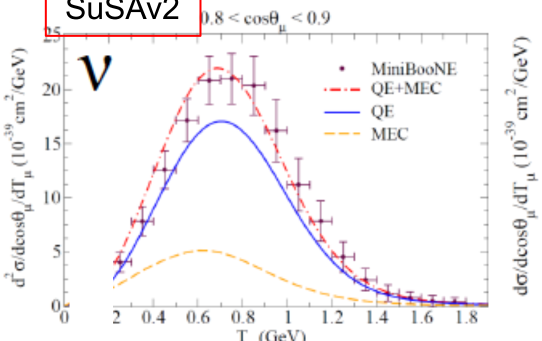
Nieves et al



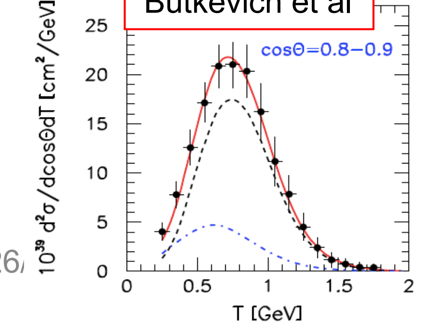
Jachowicz et al



SuSAv2



Butkevich et al



1. Neutrino Interactions: Experiment – Past, Summary

Neutrino interactions has been used to look for new physics from the beginning of particle physics
- Weak Theory
- Quark Model, etc

Data and predictions always agree because of low statistics and large flux error.

Modern experiments start to show data-prediction deviation due to nuclear physics
- Neutrino flux prediction dramatically improved, >30% error → ~5% error
- Nuclear physics is not a small correction, need new data to improve theoretical understandings

Flux-averaged differential cross-section is a new language to discuss data
- Minimally model dependent

It turned out modern experiments do not measure CCQE, instead CCQE-like final states
~~CCQE measurement~~ → CC0π measurement (1 muon + 0 pion + any number of protons)

Final state interactions (FSI) change out-going hadrons, so CC0π data include both CCQE, CCRES with pion absorption, and CC2p2h

1. Neutrino Interactions: Experiment – Past, Summary

K2K

PHYSICAL REVIEW D **74,** 052002 (2006)

Measurement of the quasielastic axial vector mass in neutrino interactions on oxygen

They try to measure "CCQE" interaction

MiniBooNE

PRL **100,** 032301 (2008) PHYSICAL REVIEW LETTERS

Measurement of Muon Neutrino Quasielastic Scattering on Carbon

Eur. Phys. J. C (2009) 63: 355–381
DOI 10.1140/epjc/s10052-009-1113-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

NOMAD

A study of quasi-elastic muon neutrino and antineutrino scattering in the NOMAD experiment

↓

They measure "CCQE-like" final state (muon + any number of nucleons but no pions) or more specific.

T2K

PHYSICAL REVIEW D **93,** 112012 (2016)

Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam

PHYSICAL REVIEW D **112,** 072007 (2025)

MicroBooNE

Measurement of charged-current muon neutrino-argon interactions withou pions in the final state using the MicroBooNE detector

PHYSICAL REVIEW LETTERS **124,** 121801 (2020)

MINERvA

High-Statistics Measurement of Neutrino Quasielasticlike Scattering at 6 GeV on a Hydrocarbon Target

Flux-averaged differential cross-section is defined by the final state particles

1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

2.1 Flux-averaged differential cross-section

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data
b_j: background
R_{ij}^{-1}: unsmearing matrix
ε_i: efficiency
N: number of target
Φ: Integrated total flux
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}\left(d_j - b_j\right)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

1. Signal definition
2. Background subtraction
3. Unsmearing
4. Efficiency correction
5. Normalization correction
6. Systematic error

The equation can be used, but it is symbolistic

2.1.1 Signal definition

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

b_j: background

R_{ij}^{-1}: unsmearing matrix

ε_i: efficiency

N: number of target

Φ: Integrated total flux

Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

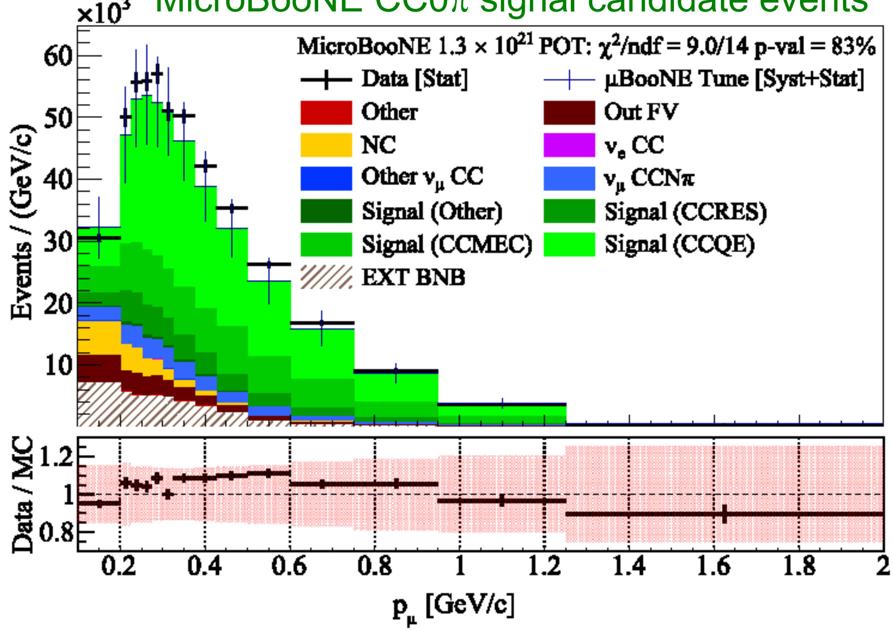
Signal definition

- Final state particles and morphology

e.g.) CC0π measurement (~~CCQE channel~~)

- One and only one muon
- No pions in the final state
- Pions produced in the target nuclei but failed to escape it → signal
- Pions produced and escape the target nuclei, but failed to detect → background

MicroBooNE CC0π signal candidate events



(a) Reconstructed p_μ.

2.1.1 Signal definition

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

b_j: background

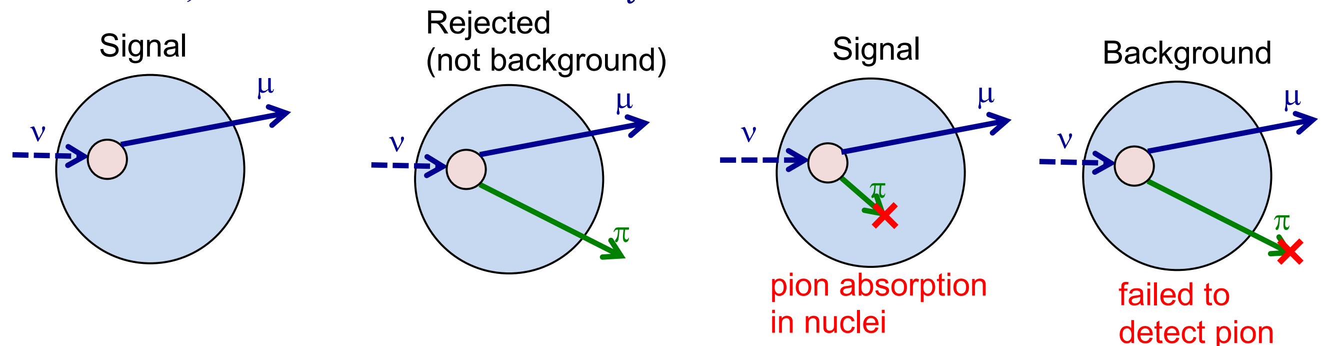
R_{ij}^{-1}: unsmearing matrix

ε_i: efficiency

N: number of target

Φ: Integrated total flux

Δx_i: bin width



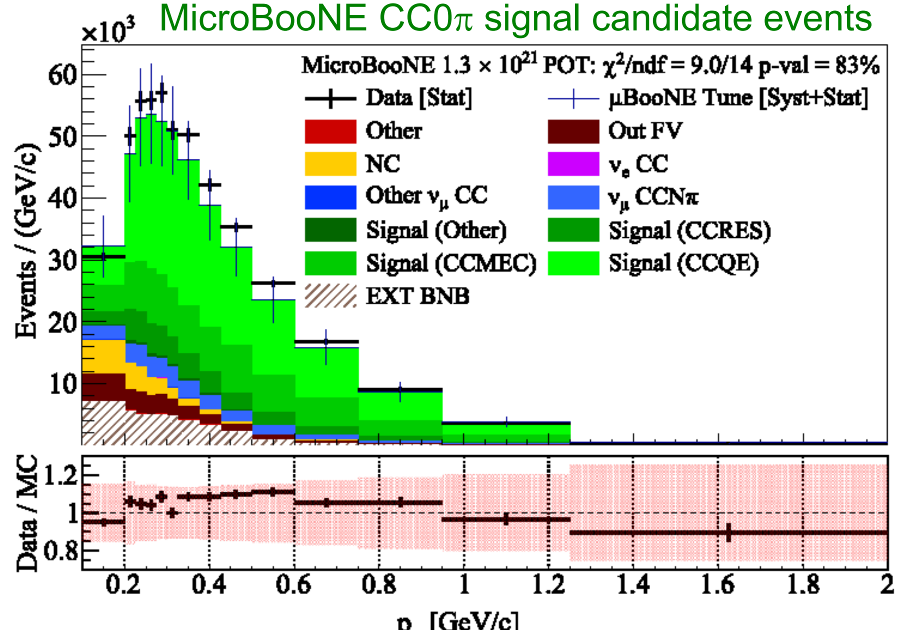
Signal definition

- Final state particles and morphology

e.g.) CC0π measurement (~~CCQE channel~~)

- One and only one muon
- No pions in the final state
- Pions produced in the target nuclei but failed to escape it → signal
- Pions produced and escape the target nuclei, but failed to detect → background

MicroBooNE CC0π signal candidate events



(a) Reconstructed p_μ.

2.1.2 Background subtraction

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

b_j: background

R_{ij}^{-1}: unsmearing matrix

ε_i: efficiency

N: number of target

Φ: Integrated total flux

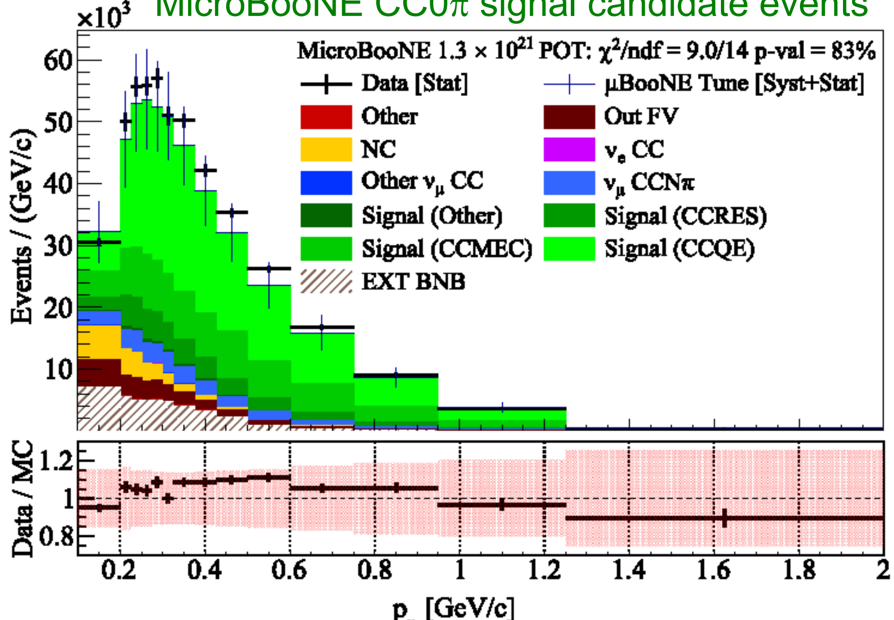
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

2.1.2 Background subtraction

- Background imitates signal final state particles and morphology

MicroBooNE CC0π signal candidate events



(a) Reconstructed p_μ.

T2K, PRD93(2016)112012

2.1.2 Background subtraction

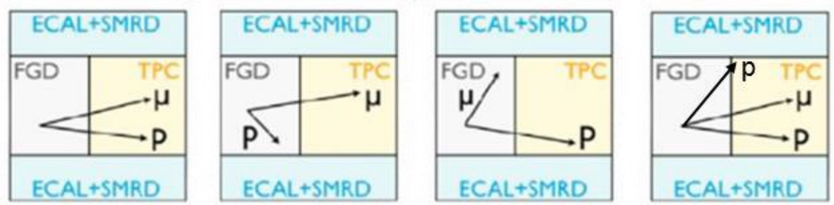
"Neutrino Detection"
(Brooke Russel)

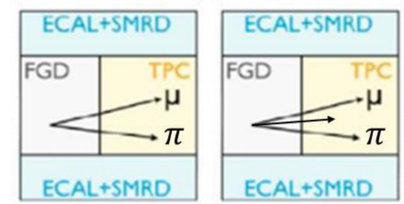
PHYSICAL REVIEW D **93**, 112012 (2016)

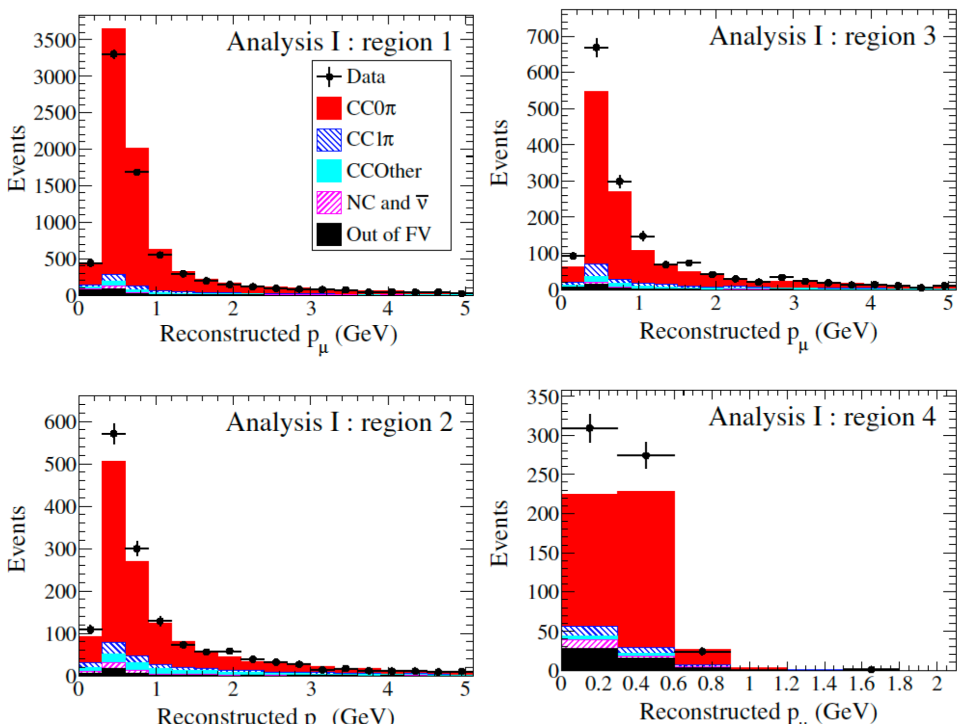
Measurement of double-differential muon neutrino charged-current interactions on C_8H_8 without pions in the final state using the T2K off-axis beam

Sideband constraints

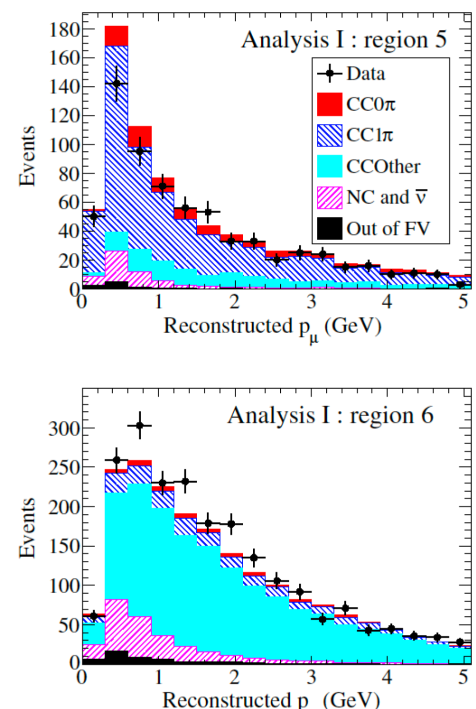
- Background dominant samples (control samples) to correct background components in the signal region







T2K CC0π signal candidate events



T2K CC0π background candidate events

2.1.3 Unsmearing

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

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ε_i: efficiency

N: number of target

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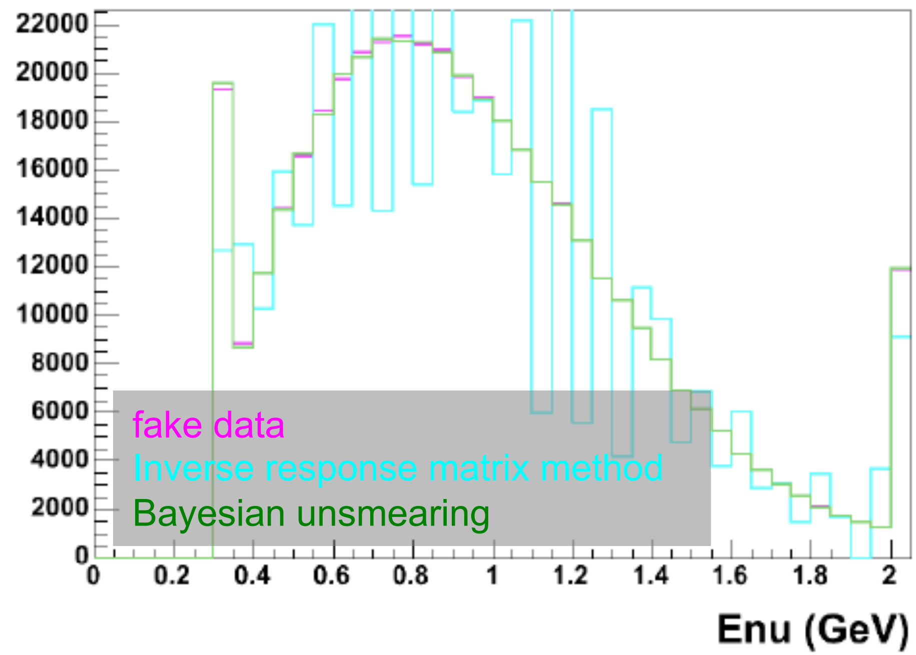
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Unsmearing

- Unfolding process removes detector responses by transformation from measured spectrum to true spectrum
  1. Unsmearing
  2. Efficiency correction
- Naive inverse of matrix doesn't work

$M_j^{meas} = R_{ij} M_j^{True} \rightarrow M_j^{True} = R_{ij}^{-i} M_j^{meas}$



2.1.3 Unsmearing

Flux-averaged differential cross-section, function of kinematics x_i

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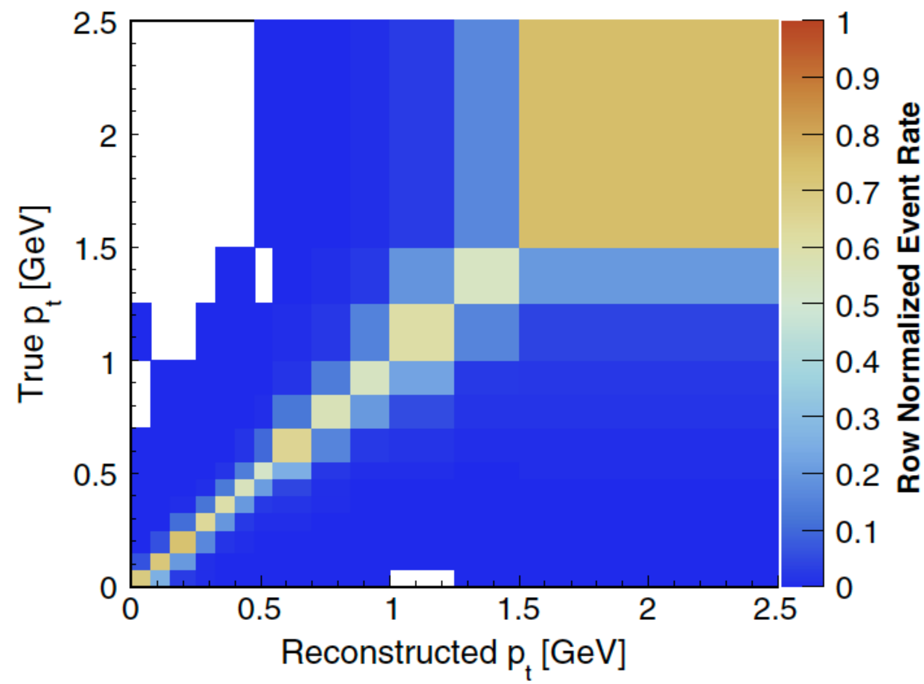
$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Unsmearing
- Many techniques of unsmearing
1. Iterative Bayesian method (MINERvA)
2. Wiener-SVD unfolding (MicroBooNE)
3. Binned likelihood method (T2K)

(1) uses migration matrix to transform the measured spectrum to true spectrum. Repeat this to remove biases.



2.1.3 Unsmearing

Flux-averaged differential cross-section, function of kinematics x_i

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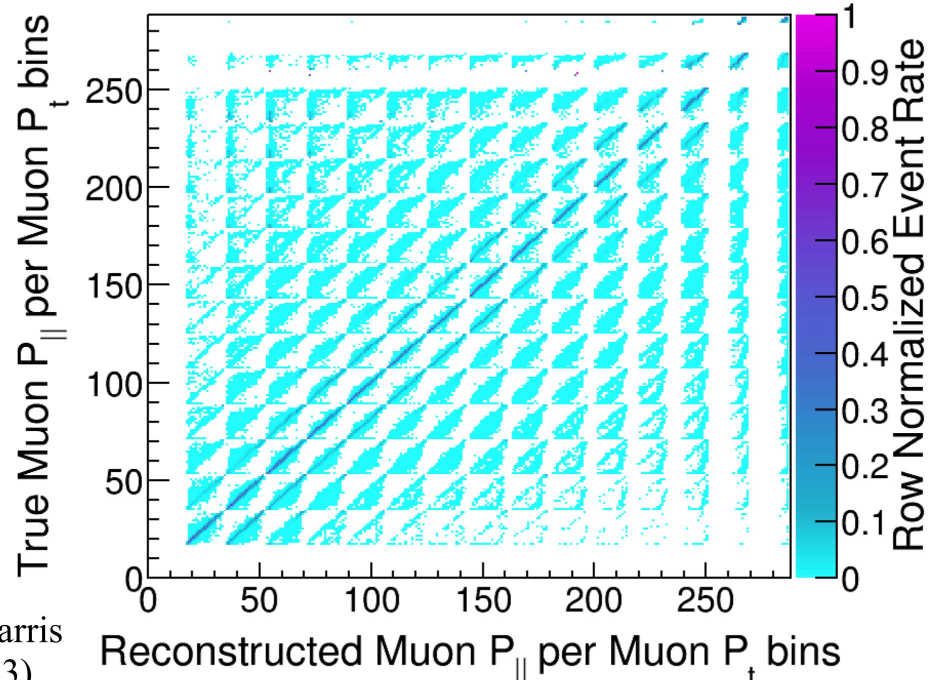

Debbie Harris (INSS2023)

2.1.3 Unsmearing

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

b_j: background

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ε_i: efficiency

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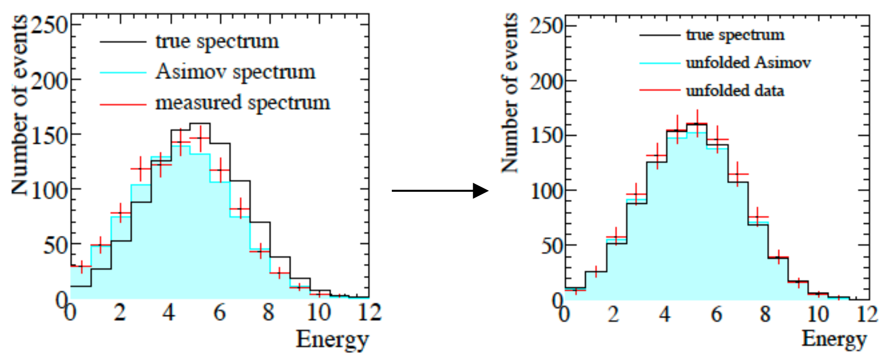
$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Unsmearing

- Many techniques of unsmearing

1. Iterative Bayesian method (MINERvA)
2. Wiener-SVD unfolding (MicroBooNE)
3. Binned likelihood method (T2K)



(2) uses response matrix with regularization based on Wiener filter (no manual tuning of regularization parameters)

$$s^{Asimov} = R \cdot s^{True}$$

$$s^{unfolded} = R^{Wiener-SVD} \cdot (s^{measured} - b)$$

2.1.3 Unsmearing

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data
b_j: background
R_{ij}^{-1}: unsmearing matrix
ε_i: efficiency
N: number of target
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Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Unsmearing
- Many techniques of unsmearing
1. Iterative Bayesian method (MINERvA)
2. Wiener-SVD unfolding (MicroBooNE)
3. Binned likelihood method (T2K)

$$-2\log\mathcal{L}_{\text{stat}} = 2\sum_j^{\text{reco bins}}\left(\beta_j N_j^{\text{MC}} - N_j^{\text{obs}} + N_j^{\text{obs}}\log\frac{N^{\text{obs}_j}}{\beta_j N_j^{\text{MC}}} + \frac{\beta_j^2 - 1}{2\sigma_j^2}\right)$$

$$N_j^{\text{MC}} = \sum_i^{\text{true bins}}\left(c_i w_{ij}^{\text{sig}}(\vec{p}) N_{ij}^{\text{sig}} + w_{ij}^{\text{bkg}}(\vec{p}) N_{ij}^{\text{bkg}}\right)$$

(3) fits both background and signal, in signal and control samples
→ Constrain background, find signal fraction, and unsmear

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_i} = \frac{\hat{N}_i^{\text{sig}}}{\epsilon_i \Phi N_{\text{nucleons}} \Delta x_i}$$

2.1.4 Efficiency correction

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data

b_j: background

R_{ij}^{-1}: unsmearing matrix

ε_i: efficiency

N: number of target

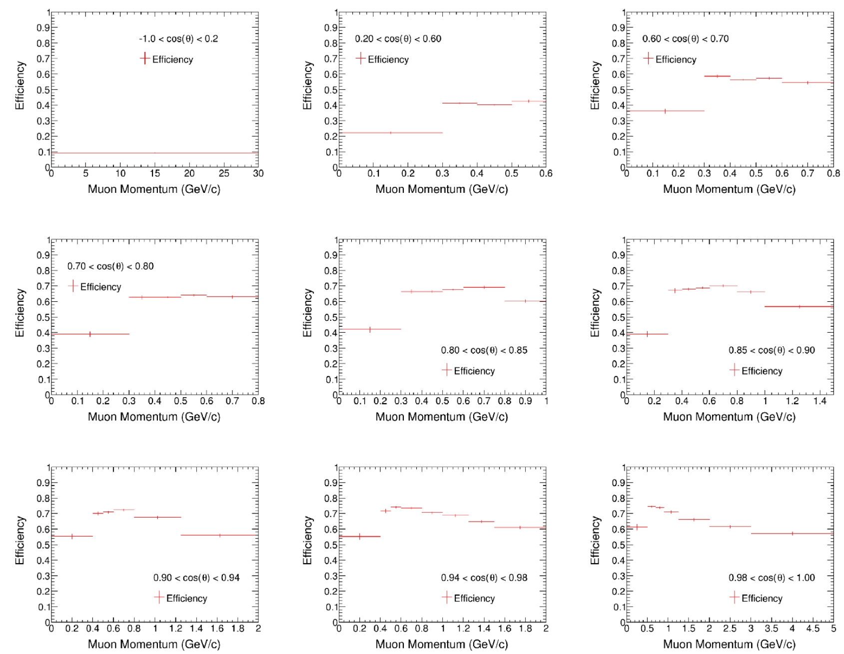
Φ: Integrated total flux

Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Efficiency correction

- Unfolding process removes detector effects by transformation from measured spectrum to true spectrum
   1. Unsmearing
   2. Efficiency correction



T2K detection efficiency of CC0π signal candidates by ND280 detector

T2K, PRD108(2023)112009

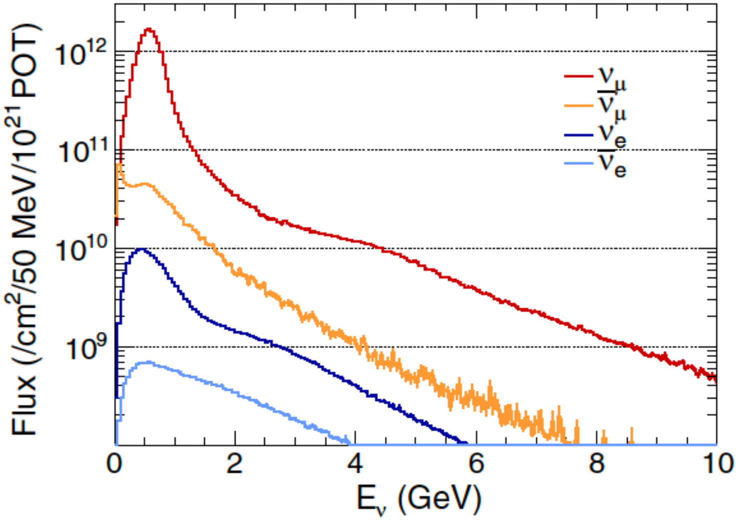
2.1.5 Normalization

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data
b_j: background
R_{ij}^{-1}: unsmearing matrix
ε_i: efficiency
N: number of target
Φ: Integrated total flux
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Normalization
- $N \sim$ fiducial volume × density × N_A
- $\Phi = \int \Phi_\nu(E_\nu) dE_\nu$
- Δx_i : $\sum_{i=1}^{all} \frac{d\sigma}{d_{x_i}} \cdot \Delta x_i < \sigma(total)$ due to limited phase space
- cross-section is quoted to average neutrino energy or peak neutrino energy



T2K neutrino flux prediction at ND280 detector

2.1.6 Systematic error

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data
b_j: background
R_{ij}^{-1}: unsmearing matrix
ε_i: efficiency
N: number of target
Φ: Integrated total flux
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}\left(d_j - b_j\right)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Systematic error: multi-universe approach

$$V_{ij} = \frac{1}{N}\sum_k^N \left(M_i^k - M_i^{CV}\right)\left(M_j^k - M_j^{CV}\right)$$

- Change systematic parameter k to generate a kth MC (reweighting)
- Average many covariance matrix
- Propagate systematic parameter correlations to bin-by-bin correlation of measured kinematic variables

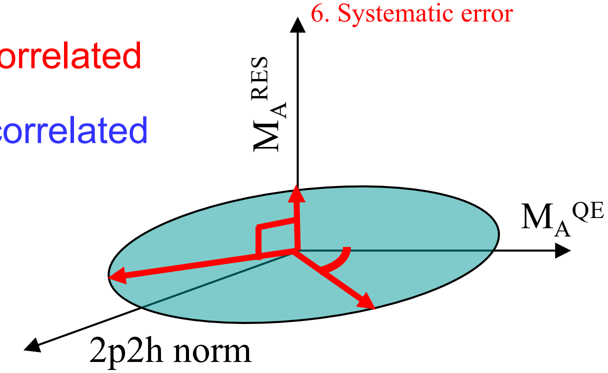
2.1.6 Multi-universe covariance matrix construction

e.g.) Systematic errors of cross-section models

M_A^{QE}, 2p2h norm — correlated

M_A^{RES} — uncorrelated

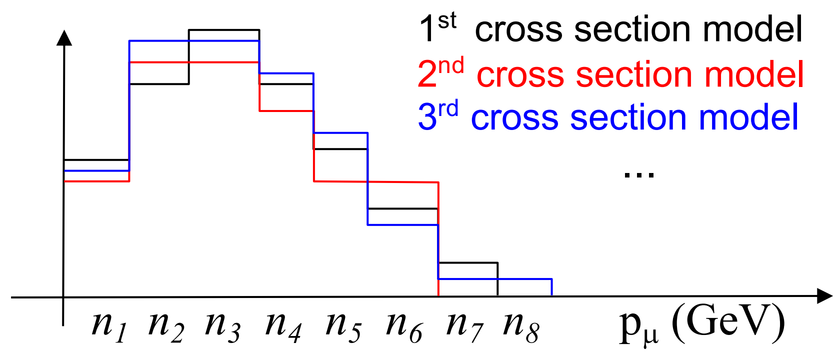
$$V_{input}(XS)=V_{input}^{XS}=\begin{pmatrix} var(M_A^{QE}) & cov(M_A^{QE},norm) & 0 \\ cov(M_A^{QE},norm) & var(norm) & 0 \\ 0 & 0 & var(M_A^{RES}) \end{pmatrix}$$



Sample parameters from this parameter space, and generate new MC (N~100),

$$V_{output}^{XS}=\frac{1}{N}\sum_k^N\left(M_i^k-M_i^{CV}\right)\left(M_j^k-M_j^{CV}\right)$$

$$=\begin{pmatrix} var(n_1) & cov(n_1,n_2) & cov(n_1,n_3) & \cdots \\ cov(n_1,n_2) & var(n_2) & cov(n_2,n_3) & \cdots \\ cov(n_1,n_3) & cov(n_2,n_3) & var(n_3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$



Repeat this to all systematics of all categories, and add all covariance matrix

$$V^{total}=V^{flux}+V^{XS}+V^{detector}+\cdots$$

uBooNE, PRD112(2025)072007

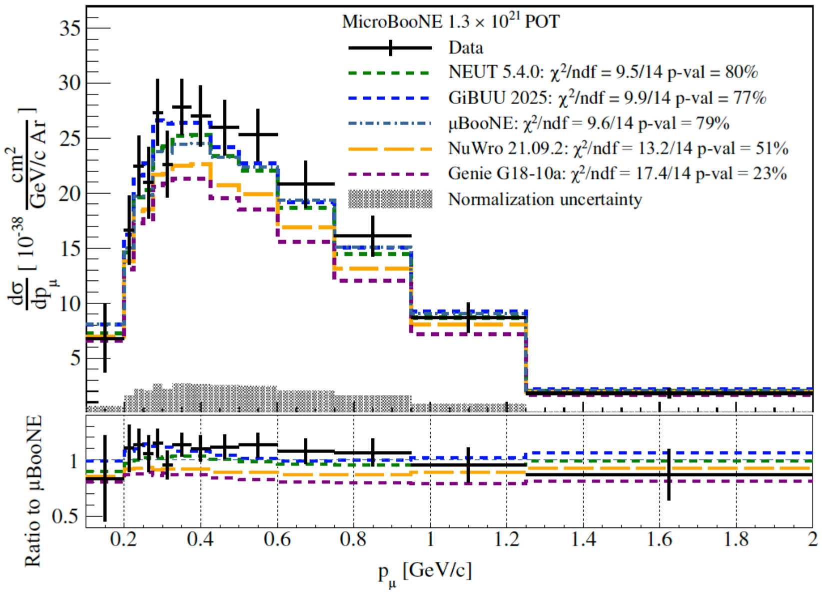
2.1 Flux-averaged differential cross-section

Flux-averaged differential cross-section, function of kinematics x_i

d_j: data
b_j: background
R_{ij}^{-1}: unsmearing matrix
ε_i: efficiency
N: number of target
Φ: Integrated total flux
Δx_i: bin width

$$\frac{d\sigma}{dx_i} = \frac{\sum_j R_{ij}^{-1}(d_j - b_j)}{\varepsilon_i \cdot N \cdot \Phi \cdot \Delta x_i}$$

Cross-section results
- Function of measurable kinetic variables
- Cross-section results have the right order and unit
- Quoted at average or peak neutrino energy
- Not directly comparable to data with different flux (total cross-section is model-dependent)



(a) p_μ differential cross section.

MicroBooNE CC0π flux-averaged differential cross-section

1. Past

2. Presence

3. Future

Benhar et al, PRL105(2010)132301 , EPJST230(2021)4309
TK and Martini, JPhysG45(2017)1

2.2 Incomplete lepton kinematic measurements

Flux-averaged differential cross-section

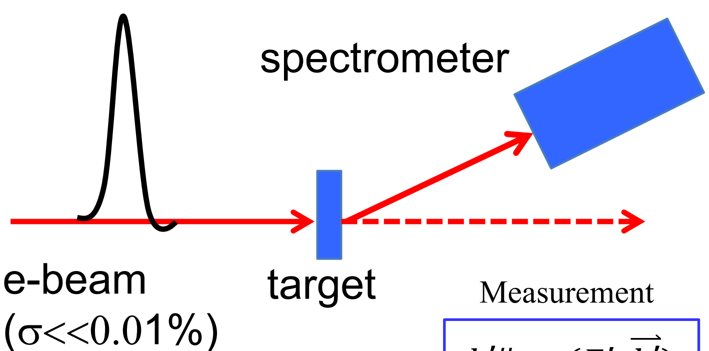
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models

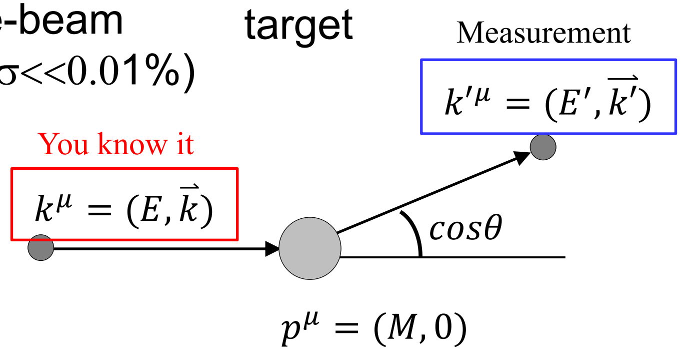
Electron scattering

- Well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ Measure cross-section of each process (QE, etc)





Energy transfer

$$q_0 = E - E'$$

ν : particle physicist
ω : nuclear physicist

3-momentum transfer

$$q_3 = |\vec{q}| = \sqrt{\left(\vec{k} - \vec{k}'\right)^2} = \sqrt{Q^2 + q_0^2}$$

Negative 4-momentum transfer

$$Q^2 = -q^2 = (k^{\mu} - k'^{\mu})^2$$

Invariant mass

$$W^2 = (k^{\mu} + p^{\mu})^2$$

Bjorken x

$$x = \frac{Q^2}{2M\nu}$$

Inelasticity y

$$y = \frac{\nu}{E}$$

2.2 Incomplete lepton kinematic measurements

Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models

Electron scattering

- Well defined energy, well known flux

→ reconstruct energy-momentum transfer

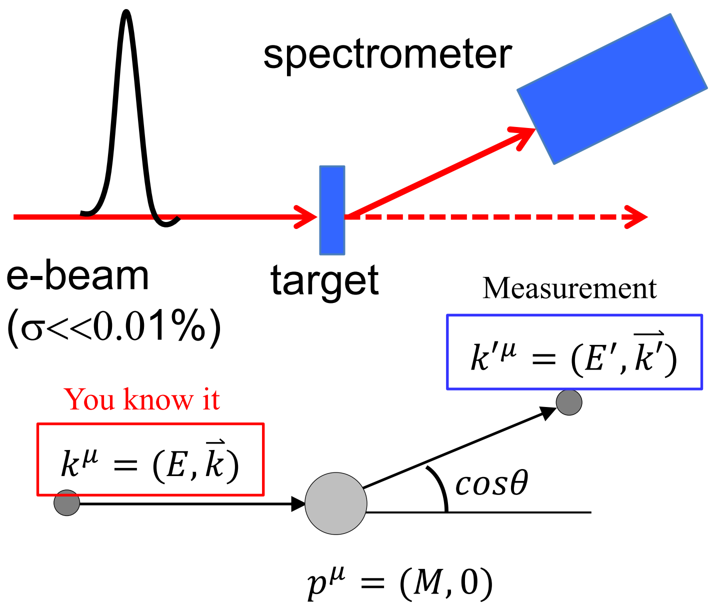
→ Measure cross-section of each process (QE, etc)

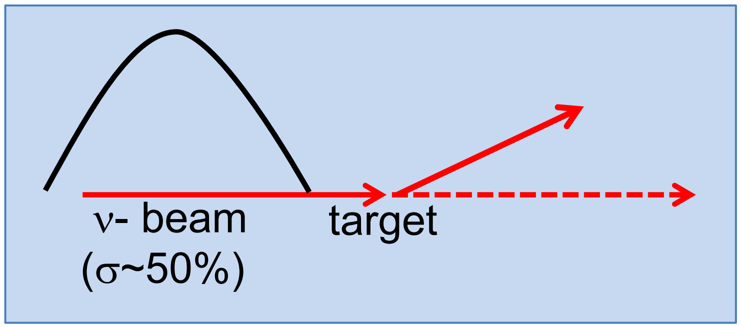
Neutrino scattering

- Wideband beam (unknown Ev)

→ cannot fix kinematics

→ inclusive measurement (CCQE, RES...)





Benhar et al, PRL105(2010)132301 , EPJST230(2021)4309
TK and Martini, JPhysG45(2017)1

2.2 Incomplete lepton kinematic measurements

Flux-averaged differential cross-section

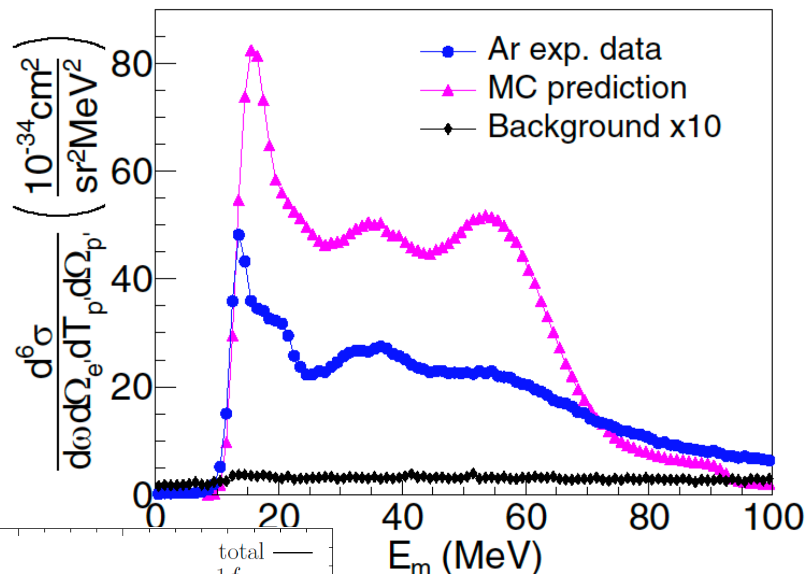
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models

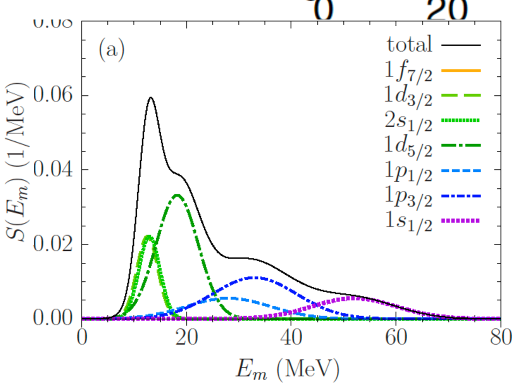
PHYSICAL REVIEW C **103**, 034604 (2021)

JLab Hall A (e,e')

JLab Hall A, PRC103 (2021) 034604

Measurement of the Ar($e, e'p$) and Ti($e, e'p$) cross sections in Jefferson Lab Hall A





$$(E_m = E - E' - T_{p'} - T_R)$$

outgoing proton energy

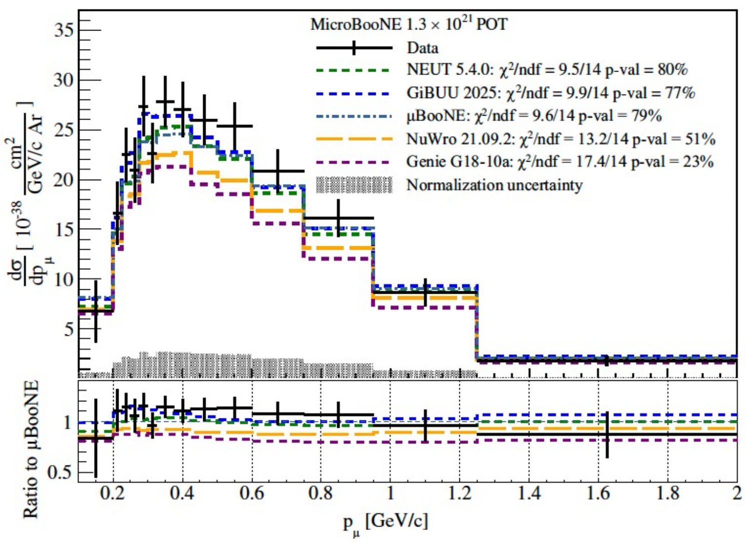
recoil nucleus energy

PHYSICAL REVIEW D **112**, 072007 (2025)

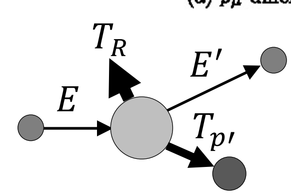
MicroBooNE

uBooNE, PRD112(2025)072007

Measurement of charged-current muon neutrino-argon interactions without pions in the final state using the MicroBooNE detector



(a) p_μ differential cross section.

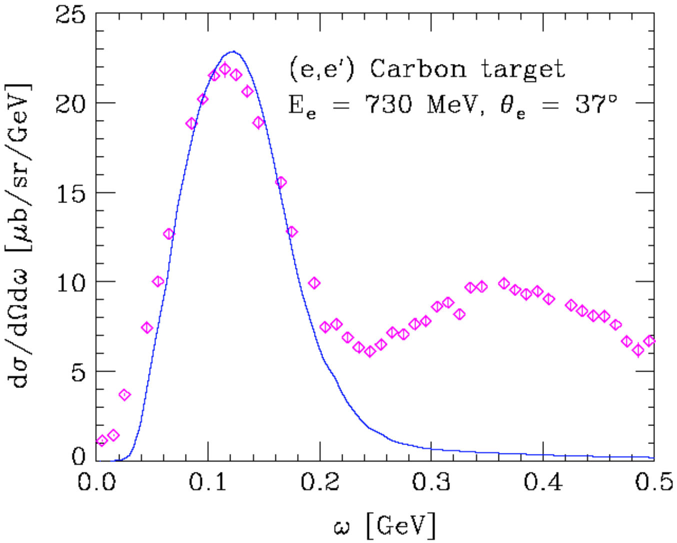


Benhar et al, PRL105(2010)132301 , EPJST230(2021)4309
TK and Martini, JPhysG45(2017)1

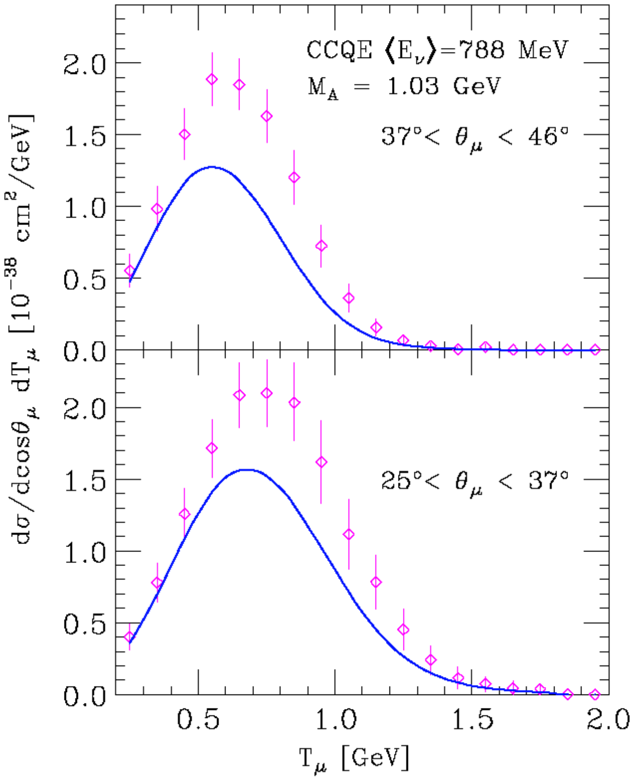
2.2 Incomplete lepton kinematic measurements

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models

Measured variables are minimally biased, but integrated to neutrino flux, and inclusive of all processes
- Detailed nuclear structure is not visible
- Not easy to separate each process



Spectral function model and inclusive (e,e') scattering on carbon (E=730 MeV, θ=37°)



Spectral function model and MiniBooNE CCQE-like flux-averaged differential cross-section

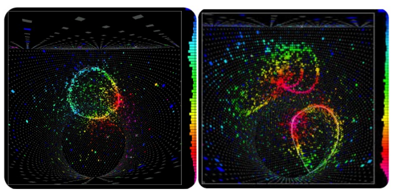
2.2 Incomplete lepton kinematic measurements

Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models

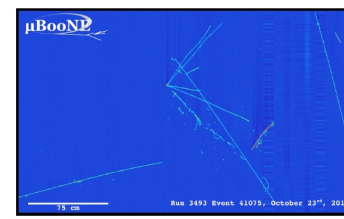
Neutrino energy reconstruction

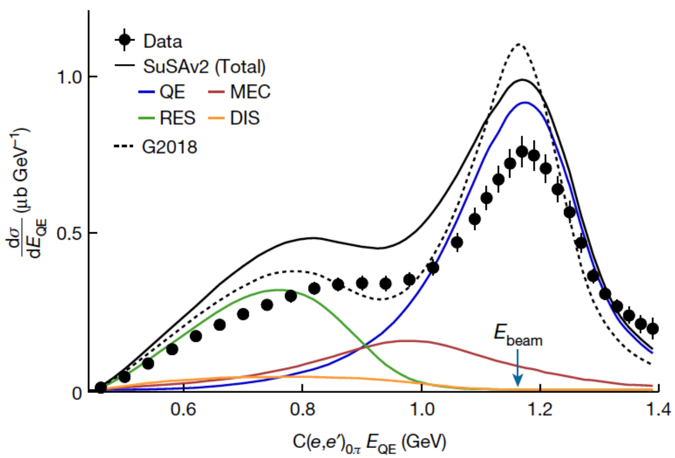
- QE kinematics (T2K, Hyper-K): Based on CCQE assumption
- Calorimetric (NOvA, DUNE): Sum of all visible energy
- CLAS+e4ν study electron scattering data to "imitate" neutrino energy reconstruction
- E_ν^{Cal} is higher resolution than E_ν^{QE}, but sensitive to hadron systematic errors

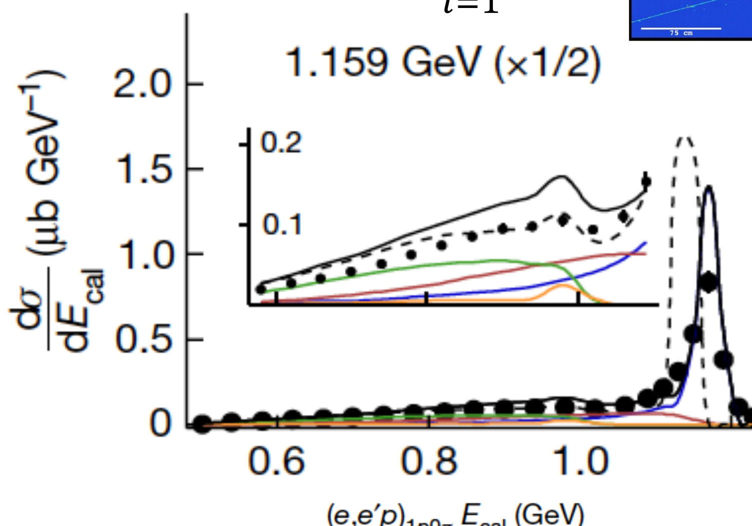


$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

$$E_\nu^{Cal} = E_\mu + \sum_{i=1}^{all} E_{had}^i$$







1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

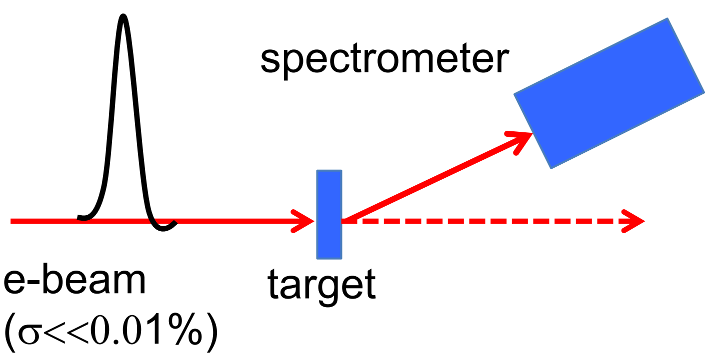
TK and Martini, JPhysG45(2017)1

"Neutrino Detection"
(Brooke Russel)

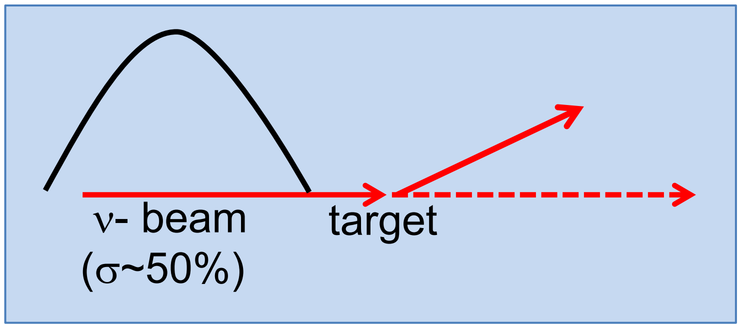
2.3 Fully active 4π detector

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

Electron scattering
- Precise measurement, but limited acceptance



Neutrino scattering
- 4π detector coverage to maximize event rate
- Suitable to measure extra hadrons



TK and Martini, JPhysG45(2017)1

"Neutrino Detection"
(Brooke Russel)

2.3 Fully active 4π detector

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models
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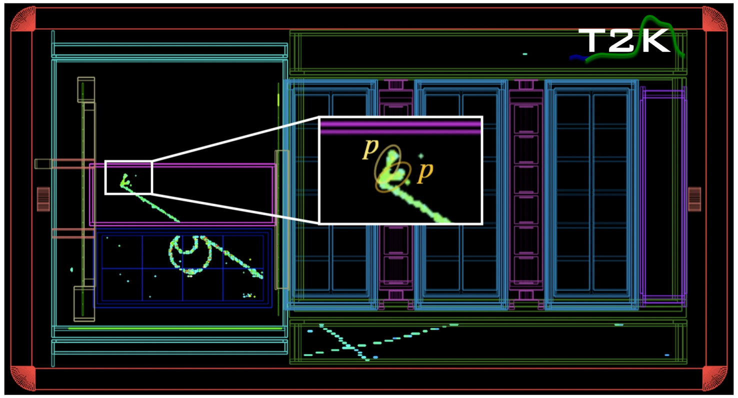
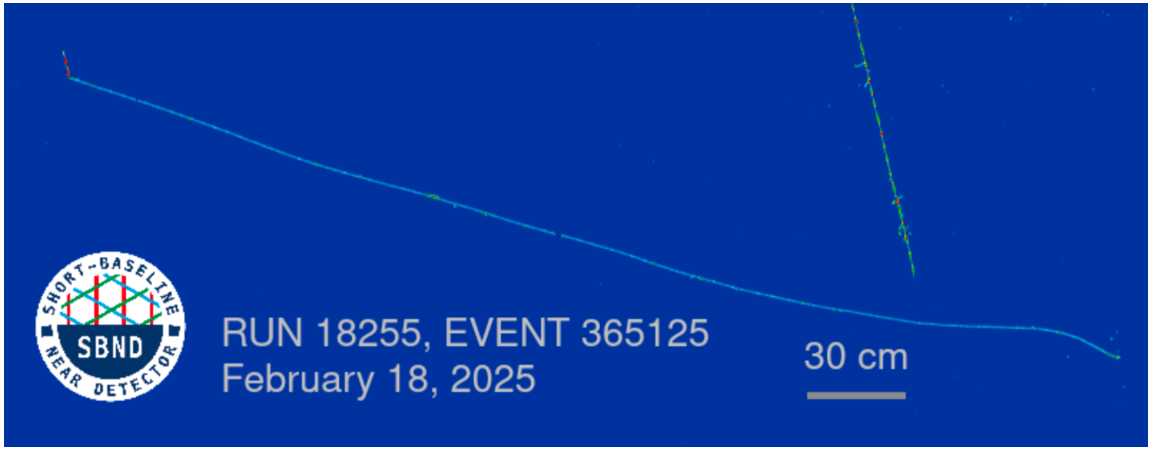
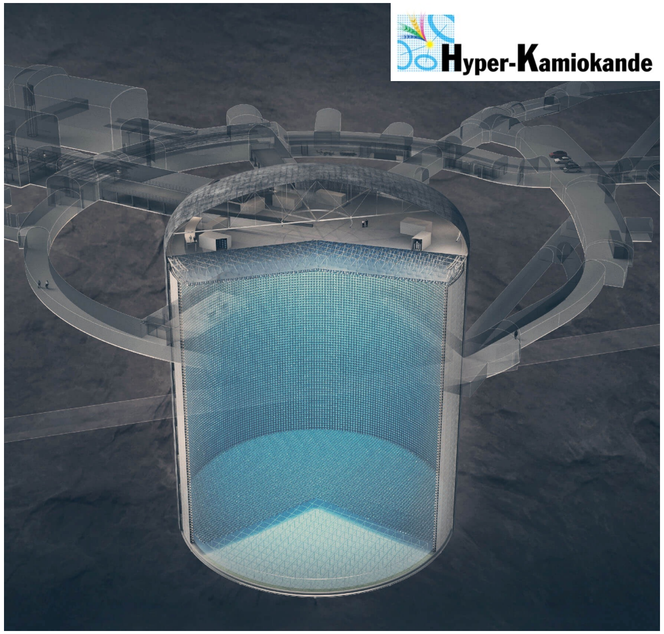


Neutrino scattering
- 4π detector coverage to maximize event rate
- Suitable to measure extra hadrons

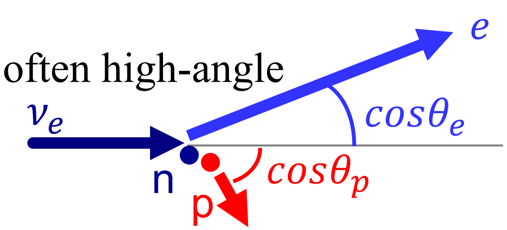


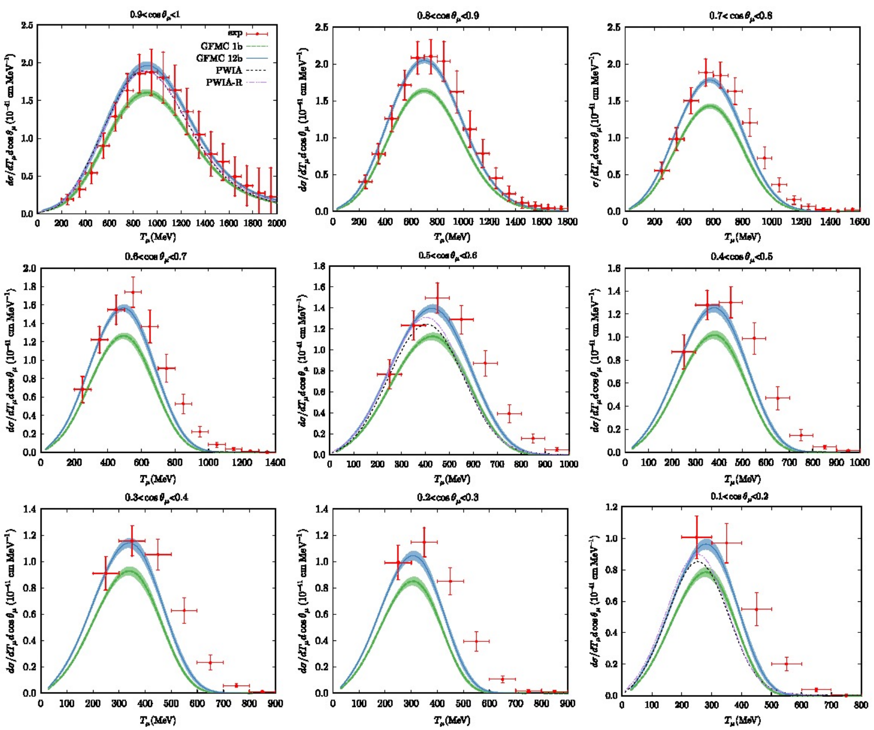


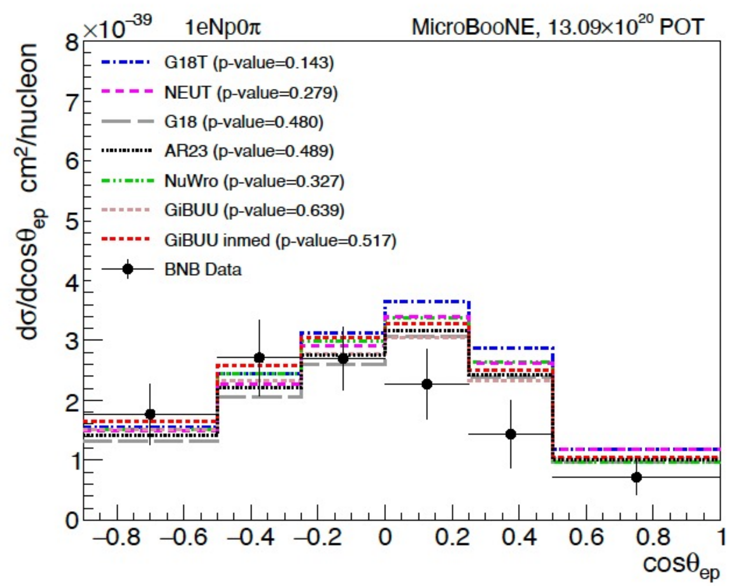
2.3 Fully active 4π detector

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

High-angle events
- 2p2h events have characteristic high-angle contribution
- Opening angle between outgoing charged lepton and leading hadron are often high-angle







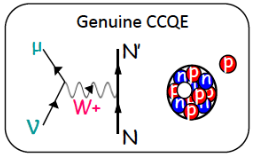
2.3 Fully active 4π detector

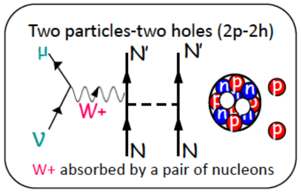
Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Eν, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

Visible hadron energy (E_{had}^{vis})

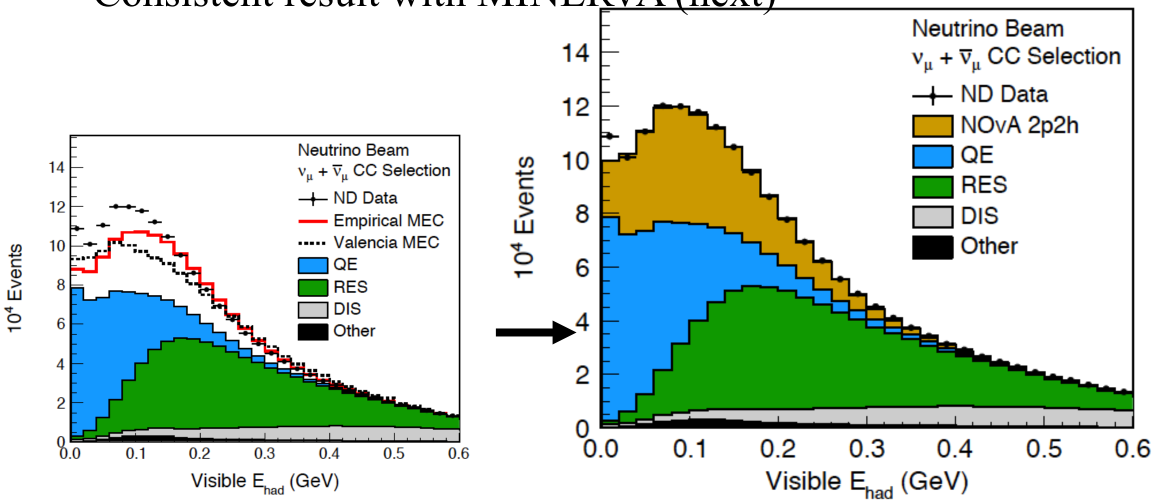
- All visible hadronic energy deposit
- $E_{\nu}^{Cal} = E_{\mu} + E_{had}^{vis}$

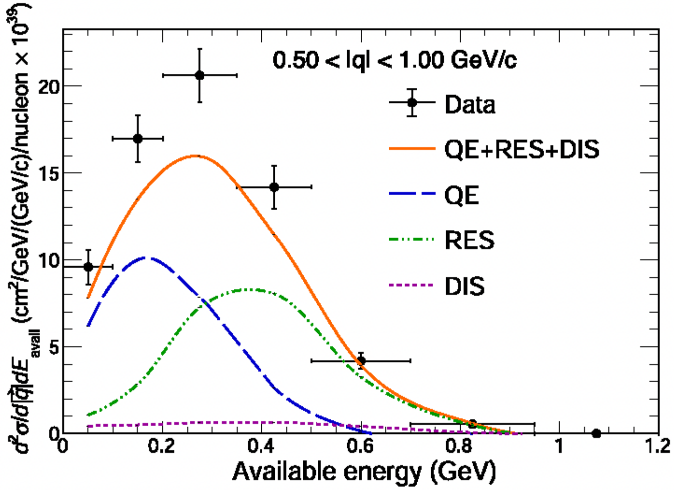




NOvA 2p2h tuning

- Visible Ehad data-MC disagreement is interpreted lack of 2p2h
- 2p2h component is reweighted to agree with data
- Consistent result with MINERvA (next)





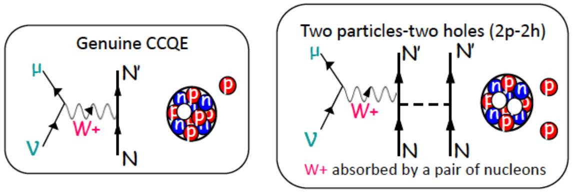
2.3 Fully active 4π detector

Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

Available energy, Eavail

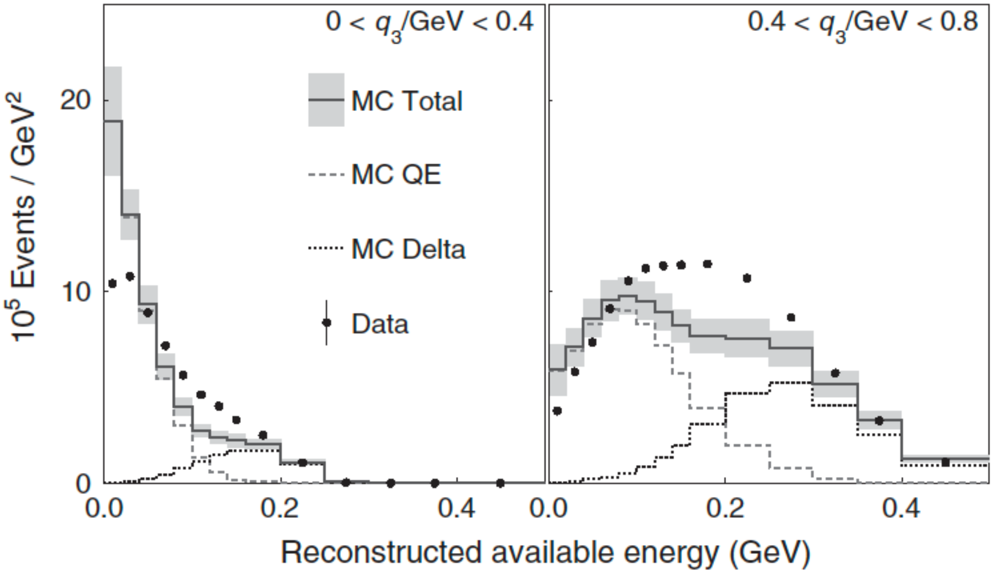
- Sum of visible hadron energy (=truth level of visible Ehad)
- $E_{avail} \equiv \sum(T_p + T_{\pi\pm} + E_{\pi 0} + E_{e\pm} + E_\gamma)$
- Proxy of energy transfer q0
- $E_{avail} \xrightarrow{MC} q_0 \rightarrow q_3 = \sqrt{Q^2 + q_0^2}$



MINERvA 2p2h search

- Eavail-q3 space to separate CCQE and Delta
- Large excess between 2 bumps

→ indication of an additional channel? (2p2h?)

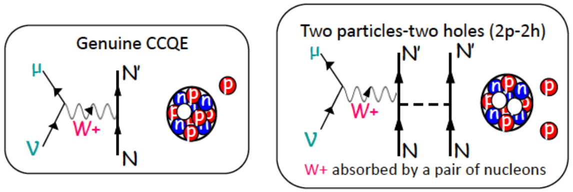


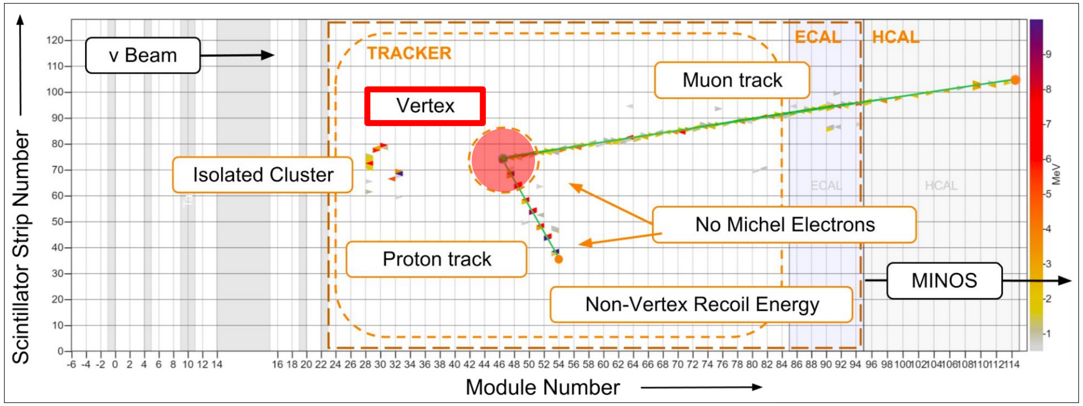
2.3 Fully active 4π detector

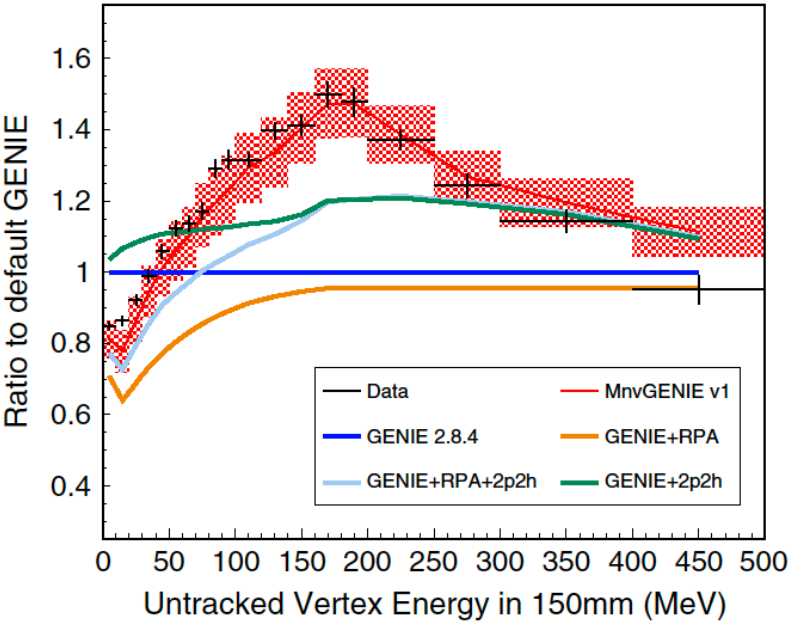
Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Eν, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

Vertex activity
- Hadronic energy deposit around vertex

MINERvA search of extra nucleon emission
- Excess of energy deposit around the vertex due to 2p2h?
- Default 2p2h model doesn't describe data
- Data prefer models with RPA and 2p2h





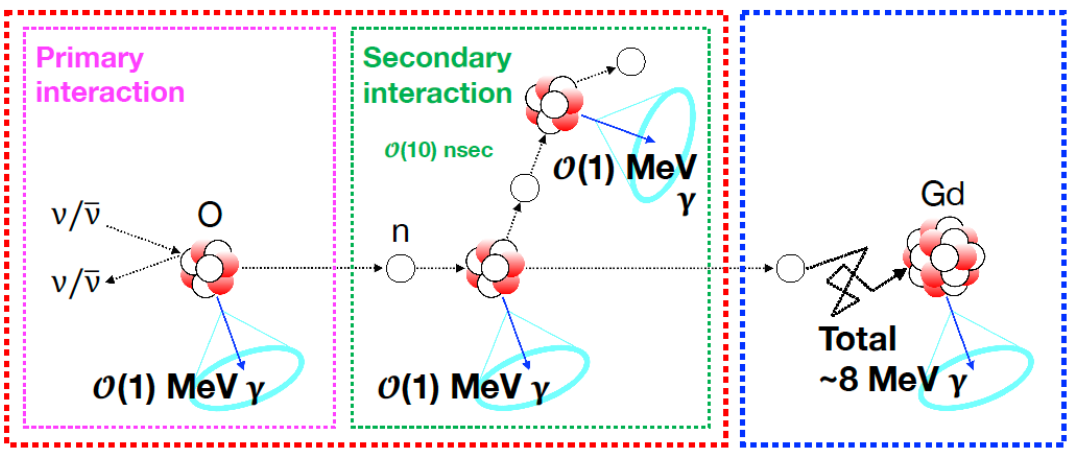


2.3 Fully active 4π detector

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q0, q3, W, x, y,… depends on models
- Fully active target, 4π measurements of many out-going particles

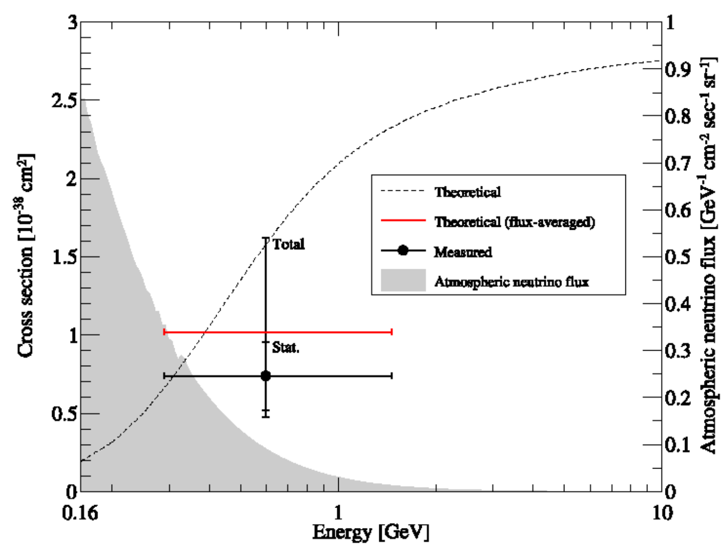
Nucleon counting
- Number of protons and neutrons identified from neutrino interactions

Super-Kamiokande NCQE cross-section measurements
- QE (particle physics): $\nu_\mu(E) + n \rightarrow \mu(E') + p$
- QE (nuclear physics): $\nu(E) + {}^{16}O \rightarrow \nu(E') + {}^{15}O + n$ ←NCQE



S. Sakai

Prompt signal → Delayed signal
~115 μsec (0.011% mass conc. of Gd)



MicroBooNE, PRD110(2024)013006
NINJA, PRD106(2022)032016

2.3 Fully active 4π detector

Flux-averaged differential cross-section
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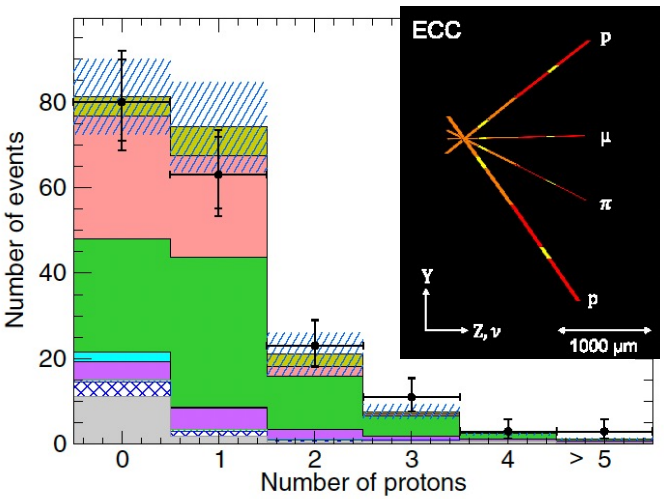
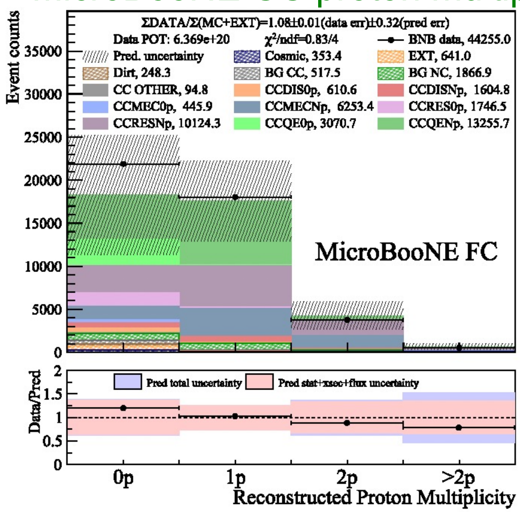
Nucleon counting
- Number of protons and neutrons identified from neutrino interactions

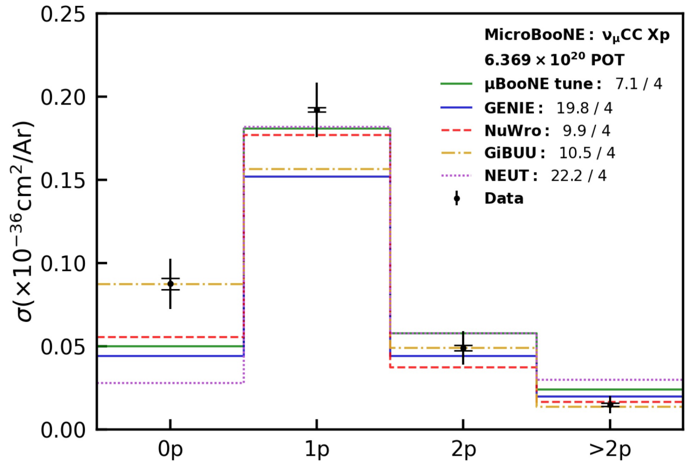
MicroBooNE CCXp cross-section measurement and NINJA proton counting
- High-resolution detectors: NINJA(emulsion) and MicroBooNE (LArTPC) can count protons
- Differential cross-section is reproducible by theorists (but not easy)

NINJA CC proton multiplicity



MicroBooNE CC proton multiplicity and differential cross-section





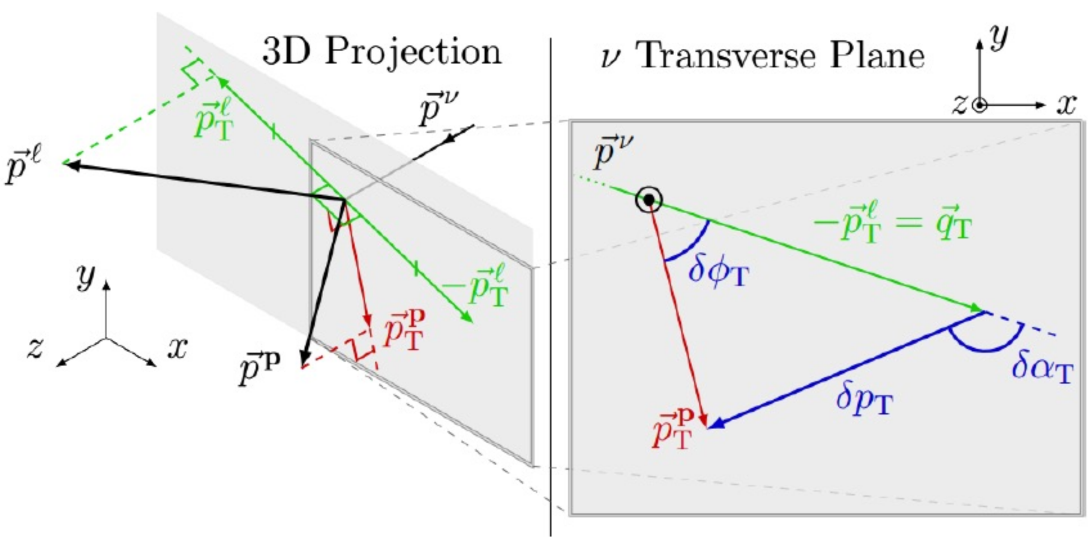
T2K, PRD98(2018)032003
Lu et al, PRC94(2016)015503

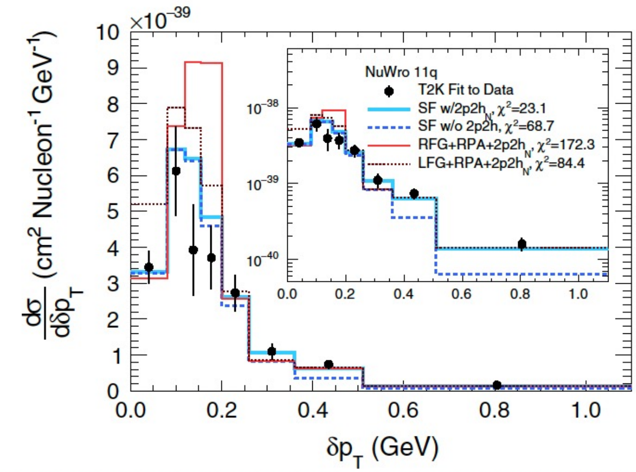
2.3 Fully active 4π detector

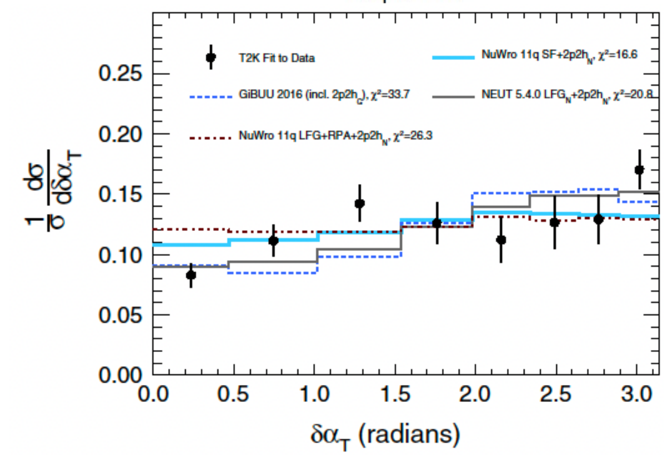
Transverse kinematic imbalance variables (TKIs)

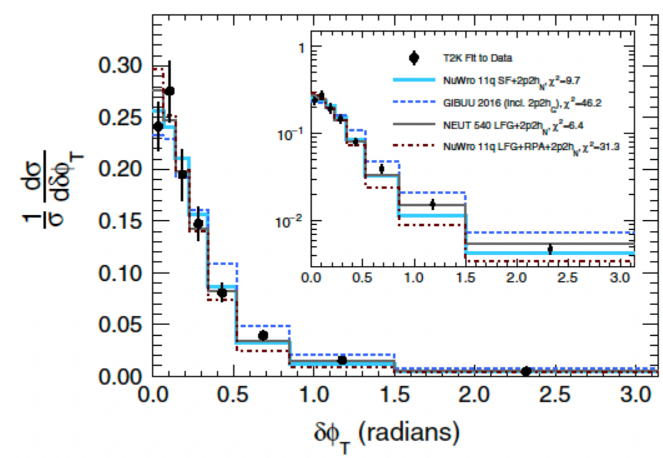
- Mostly independent with the beam neutrino energy
- $\delta P_T \equiv \left|\vec{P}_T^l + \vec{P}_T^p\right|$: transverse momentum imbalance
- $\delta \alpha_T \equiv arccos \frac{-\vec{P}_T^l \cdot \delta \vec{P}_T}{P_T^l \delta P_T}$: transverse boosting angle
- $\delta \phi_T \equiv arccos \frac{-\vec{P}_T^l \cdot \vec{P}_T^p}{P_T^l \cdot P_T^p}$: opening angle in transverse plane

δP_T shape → Fermi motion model
$\delta \alpha_T$ shape → proton deceleration due to FSIs ($\delta \alpha_T > 1.5$)





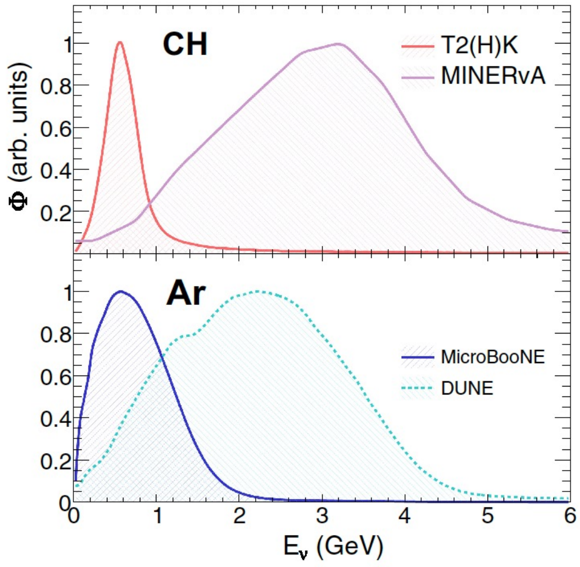




teppei.katori@kcl.ac.uk

T2K, PRD98(2018)032003 , MINERvA, PRL121,(2018)022504 , MicroBooNE, PRL131(2023)101802
Lu et al, PRC94(2016)015503 , Filali, Munteanu, Dolan, PRD111(2025)032009

2.3 Fully active 4π detector



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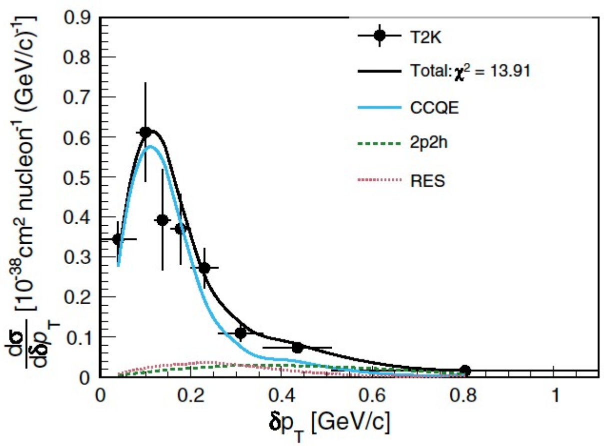
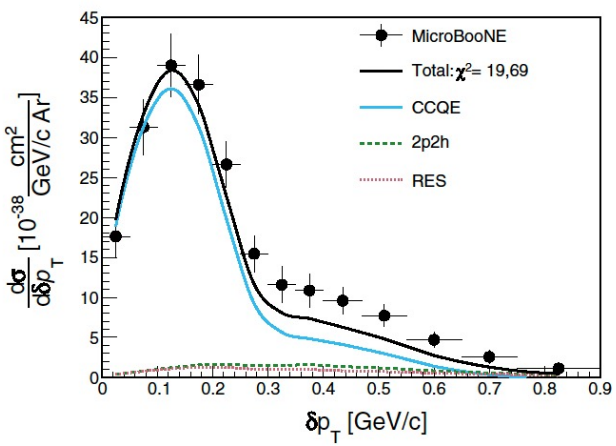
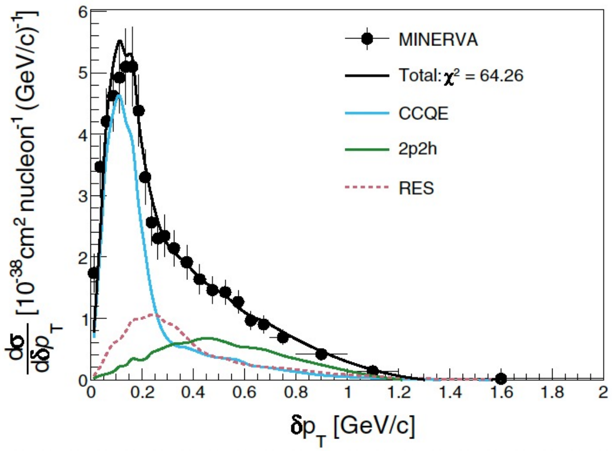
- $\delta \phi_T \equiv arccos\frac{-\vec{P}_T^l \cdot \vec{P}_T^p}{P_T^l \cdot P_T^p}$: opening angle in transverse plane

T2K vs MINERvA vs MicroBooNE

- Different energy and nuclear target
- Energy-scaling of 2p2h looks ok (T2K vs. MINERvA)
- A-scaling of 2p2h is not modeled correctly (T2K vs. MicroBooNE)







2. Neutrino Interactions: Experiment – Presence, Summary

Flux-averaged differential cross-section is currently accepted as a standard way to compare data and simulation to understand neutrino interaction physics

1. Signal definition
2. Background subtraction
3. Unsmearing
4. Efficiency correction
5. Normalization correction
6. Systematic error

Neutrino interaction physics study with flux-averaged differential cross-section implies;

1. Incomplete lepton kinematics (bad)
 → No direct comparison with nuclear physics models
2. Fully active 4π detector (good)
 → New hadron kinematic variables

1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

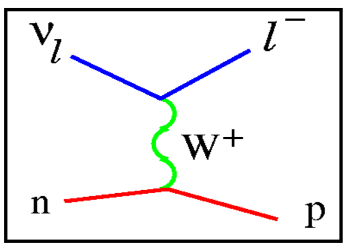
3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

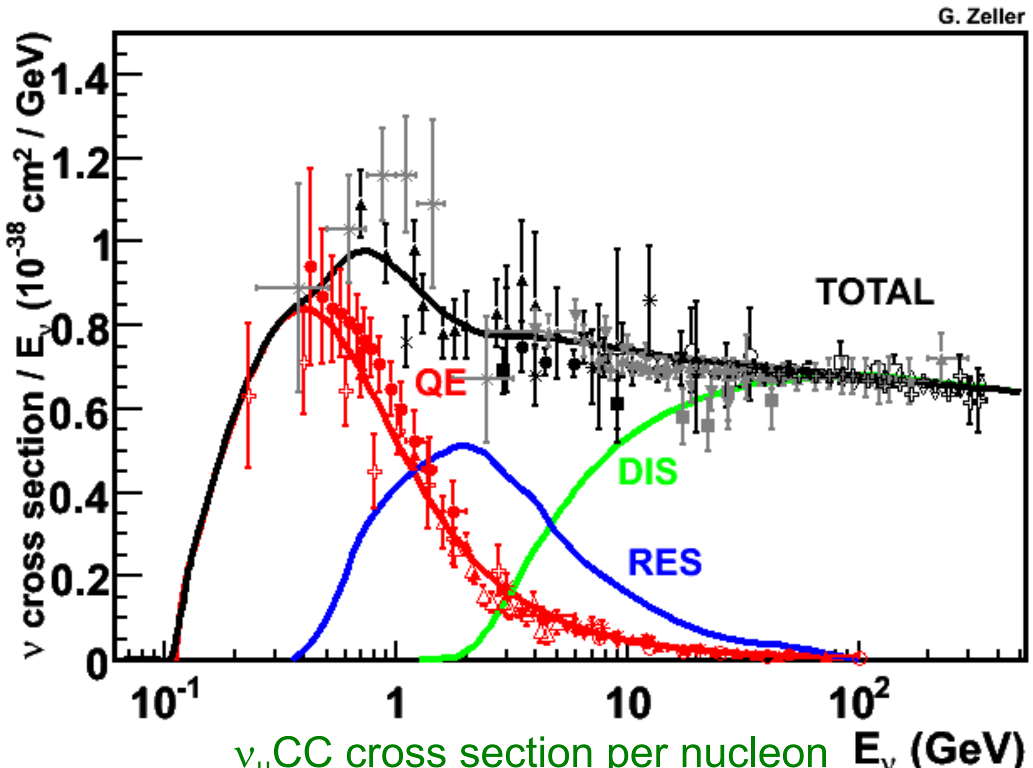
3. Neutrino interaction physics around 1-10 GeV

Neutrino interaction physics around 1-10 GeV

- Data-simulation agreement status for QE, RES, DIS

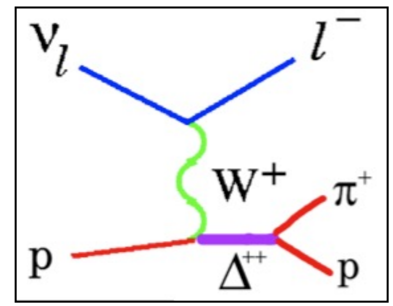
Quasi Elastic (QE)

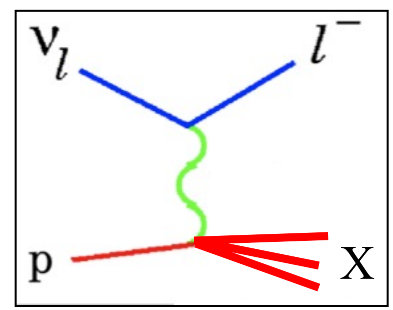




ν_μCC cross section per nucleon

Baryonic Resonance (RES)





Deep Inelastic Scattering (DIS)

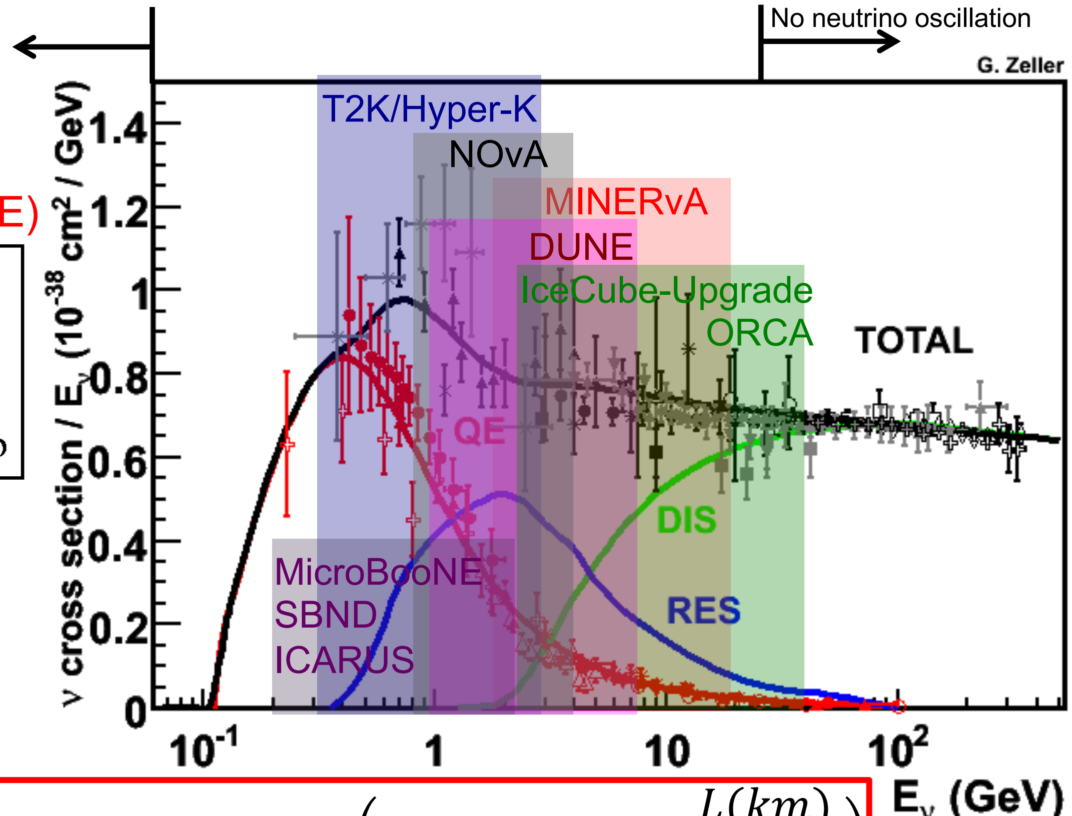
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

3. Next generation neutrino oscillation experiments

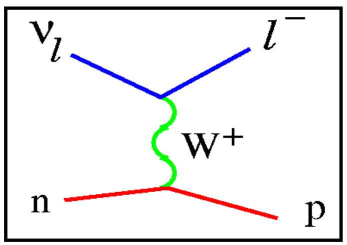
Current and future neutrino oscillation experiments

- J-PARC: T2K, Hyper-Kamiokande, etc
- Fermilab: MicroBooNE/SBND/ICARUS, MINERvA, NOvA, DUNE, etc
- Atmospheric: Hyper-Kamiokande, ORCA, IceCube-Upgrade, etc

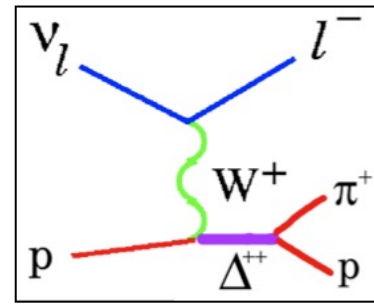
Reactor and Solar neutrino oscillation

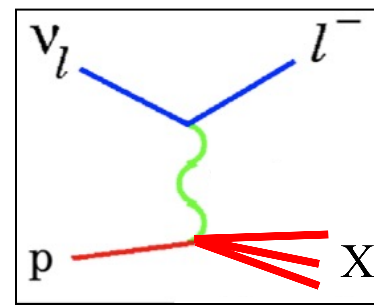


Quasi Elastic (QE)



Baryonic Resonance (RES)





Deep Inelastic Scattering (DIS)

$$P(L/E) = sin^2 2\theta sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Past

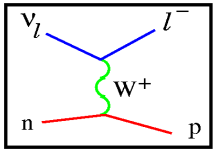
2. Presence

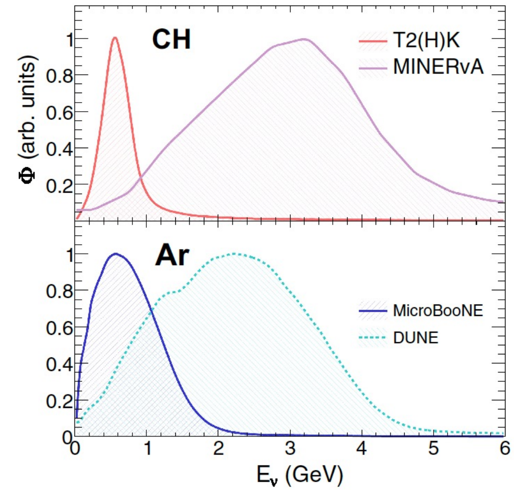
3. Future

TENSION2016, Phys.Rep.773(2018)1.
TENSION2018, PRD105(2022)092004

3.1 Path forward: QE (CC0π)

Quasi Elastic

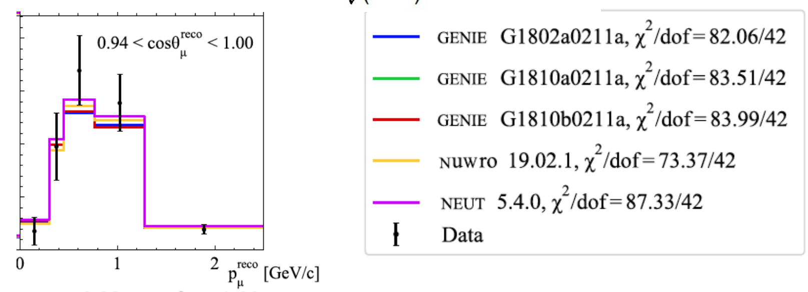




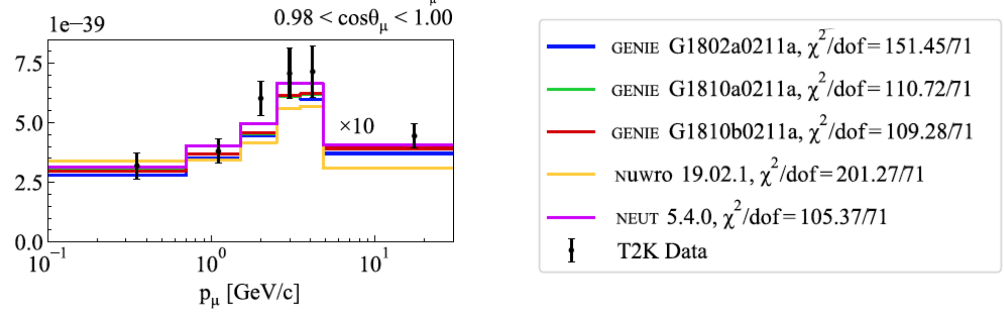
Data tension, no generator describes all data

- T2K vs. MINERvA vs. MicroBooNE
- Different kinematic coverage due to different beams
- Different target (in general, argon is harder to simulate)
- In general, very difficult to fit all data simultaneously

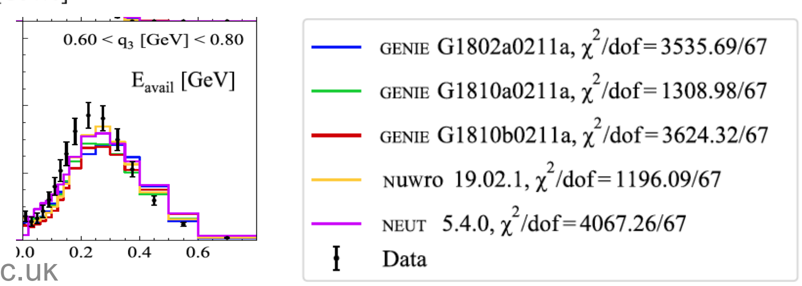
MicroBooNE CC inclusive double differential cross-section



T2K CC inclusive double differential cross-section

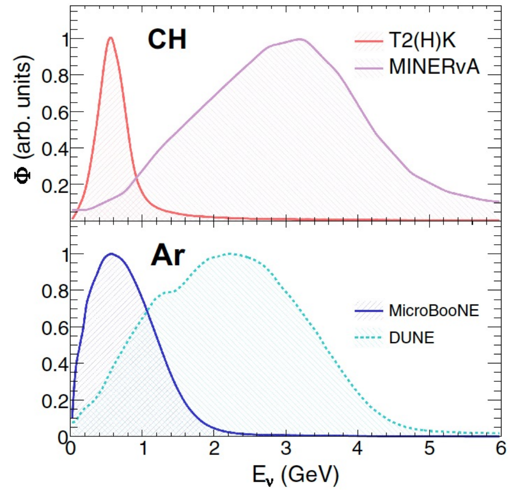


MINERvA CC inclusive double differential cross-section

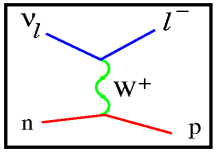


Filali, Munteanu, Dolan, PRD111(2025)032009

3.1 Path forward: QE (CC0π), 2p2h

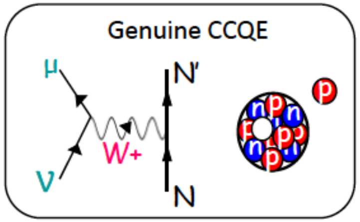


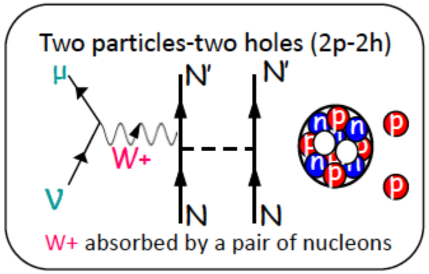
Quasi Elastic

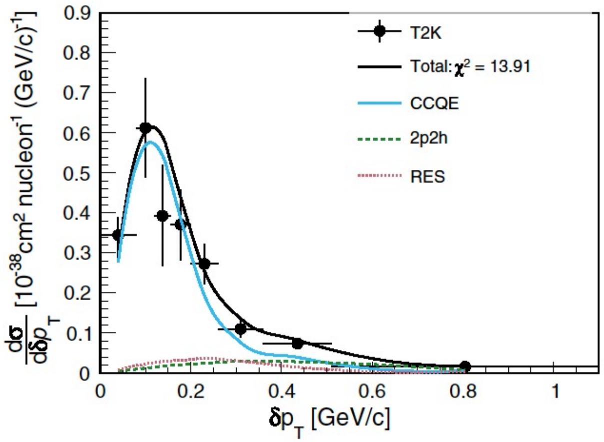


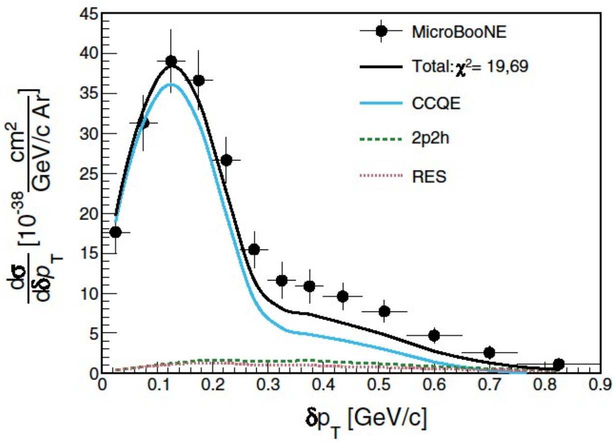
2p2h model is preferred, but not much details

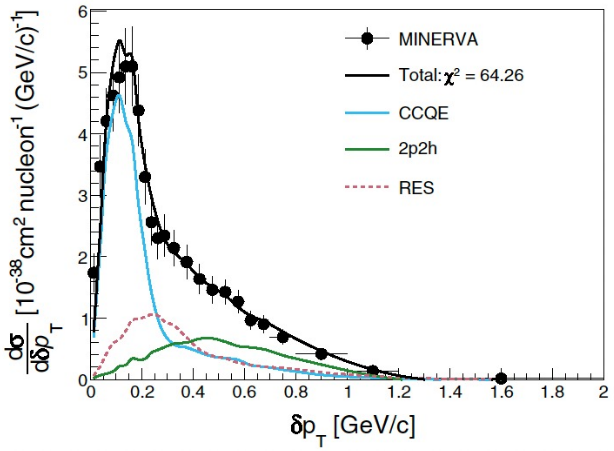
- TKIs show 2p2h contribution is necessary
- Energy scaling may be ok
- A-scaling is probably not ok



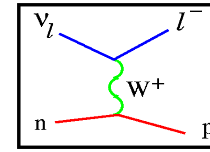








Quasi Elastic



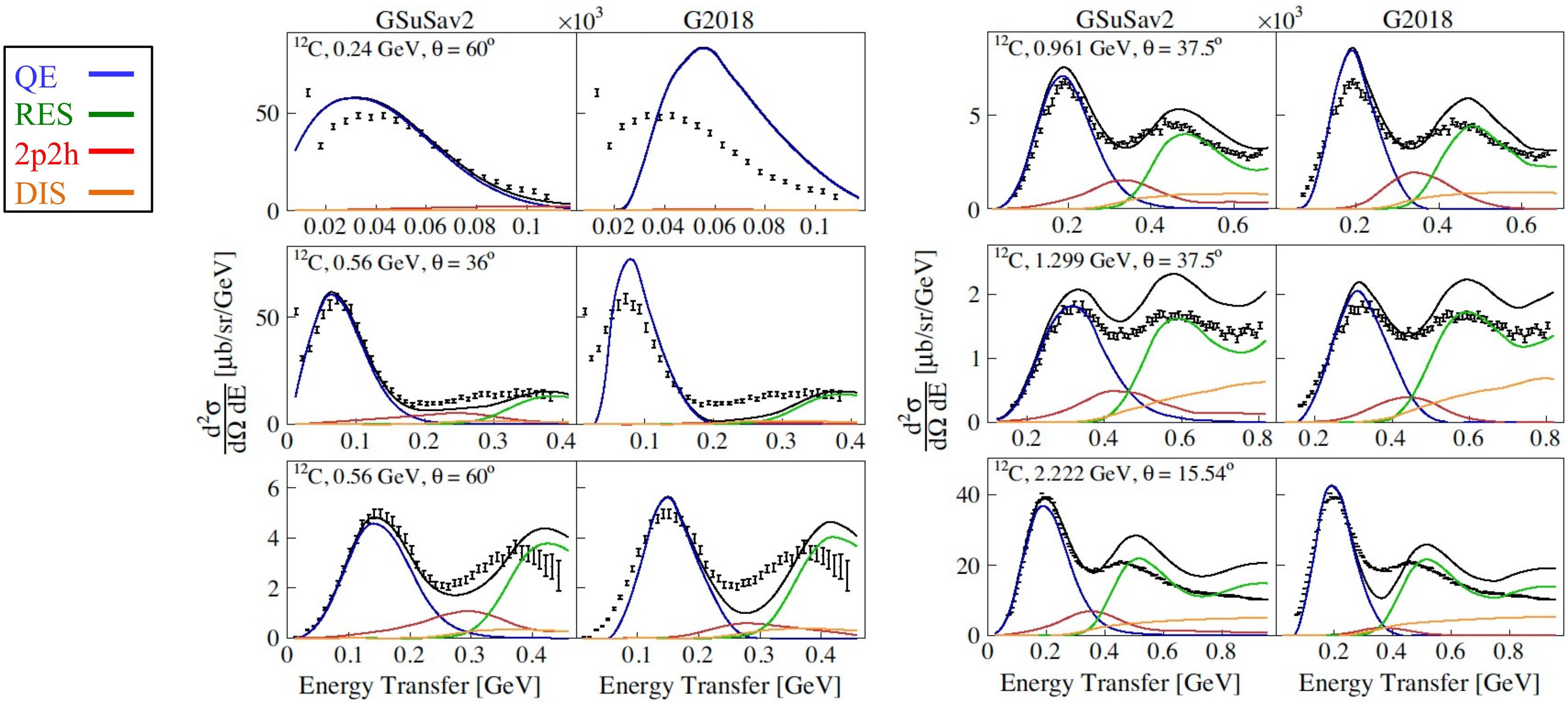
3.1 Path forward: QE (CC0π), 2p2h

Electron scattering

- Use neutrino event generator to reproduce high-statistics high-precision electron scattering data
- Very difficult to describe data in wide kinematic range

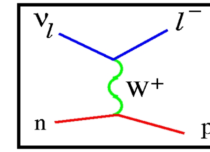
→ Neutrino experiment is incomplete lepton kinematics, integrated with full energy transfer spectrum

- Gaps between QE and RES interpreted as 2p2h



uBooNE, PRD110(2024)013006

Quasi Elastic



3.1 Path forward: QE (CC0π), 2p2h

2p2h model is preferred, but not much details

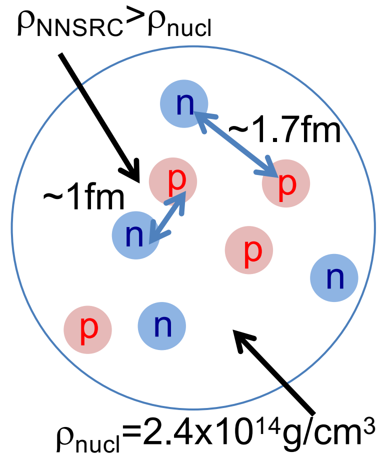
- TKIs show 2p2h contribution is necessary
- Energy scaling may be ok
- A-scaling is probably not ok

Nucleon cluster model Sobczyk, PRC86(2012)015504

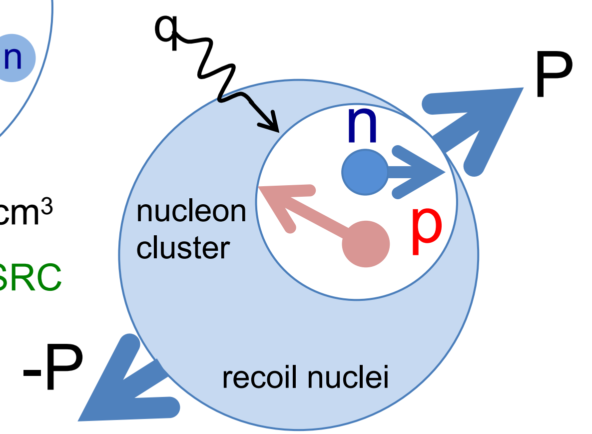
$$\nu_\mu + {}^{12}C(n-p) \rightarrow \mu^- + p + p + X$$

- Motivated from short range correlation (SRC)
- n-p pair dominant (n-p : n-n: p-p?) PRL97(2006)162504
- momentum distribution (back-to-back?) PRL99(2007)072501
- No confirmation from proton data

(nucleon cluster model small effect?)

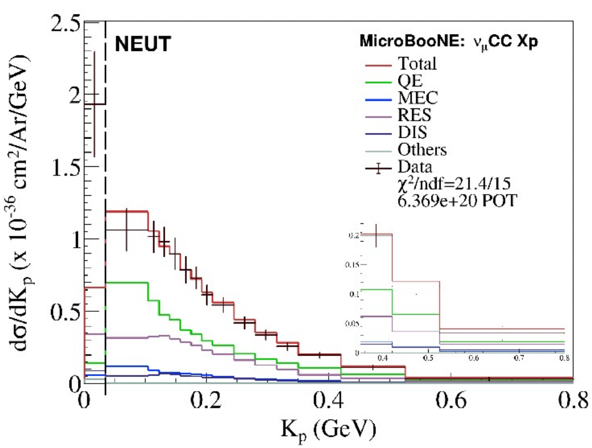


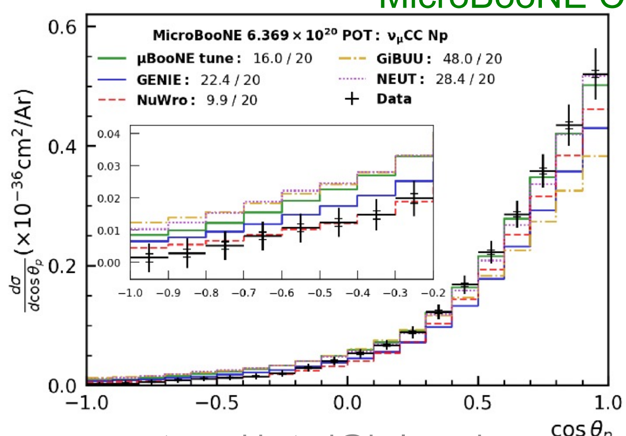
nucleon-nucleon SRC

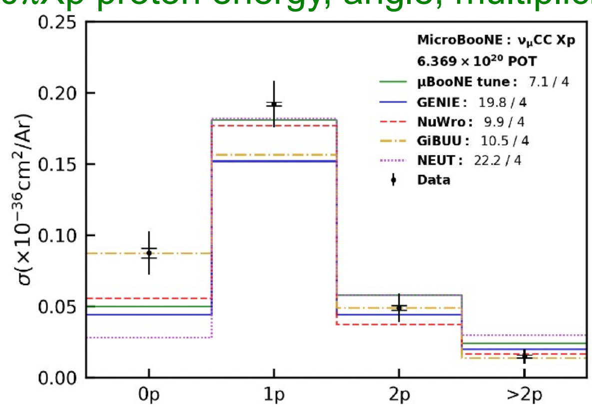


nucleon cluster model

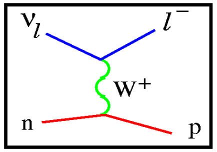
MicroBooNE CC0πXp proton energy, angle, multiplicity







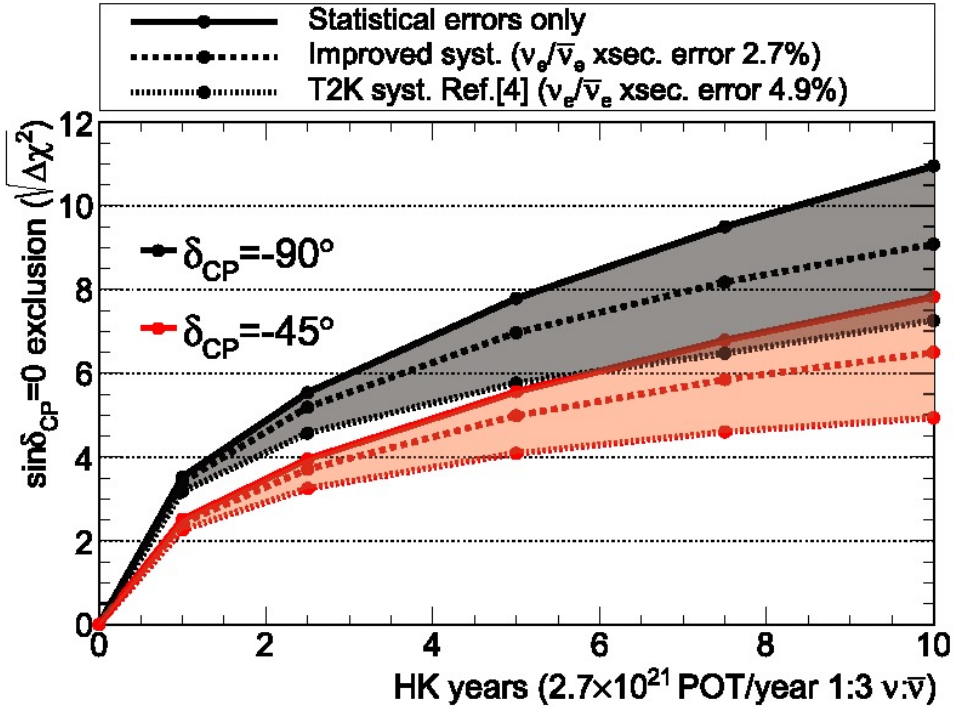
Quasi Elastic



3.1 Path forward: QE (CC0π), electron neutrinos

$\nu_e/\bar{\nu}_e$ systematics

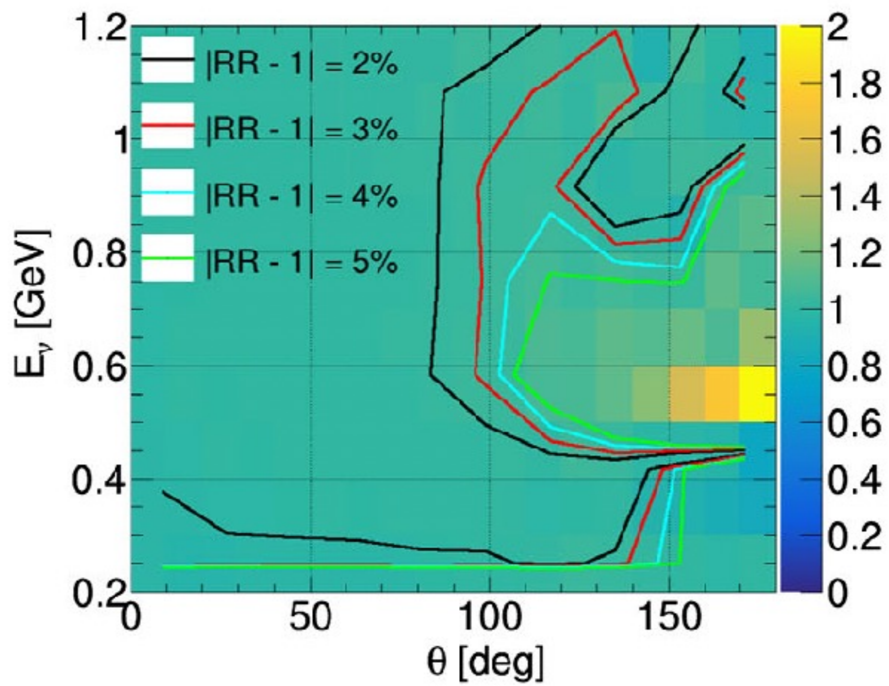
- δ_{CP} measurement = $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$
- T2K oscillation error analysis uses: 4.9%
- Expected HyperK oscillation error: 2.7%



Theoretical error $\nu_e/\bar{\nu}_e$ estimation

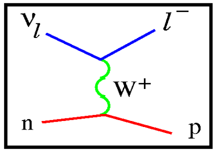
- Model comparison (double ratio) gives >5% deviation in some kinematic space
- estimated impact on oscillation parameter is ~2% errors

$\nu_e/\bar{\nu}_e$ ratio comparison for HF-CRPA and SF



T2K, PRL113(2014)241803 :135(2025)151802, JHEP10(2020)114 , NOvA, PRL130(2023)051802
ArgoNeuT, PRD102(2020)011101(R) , uBooNE, ArXiv:2603.13593

Quasi Elastic



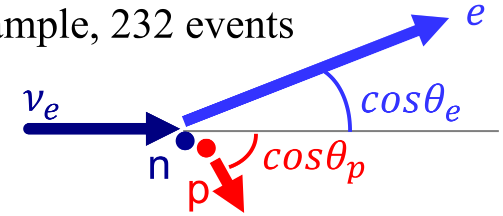
3.1 Path forward: QE (CC0π), electron neutrinos

T2K

- 2014: Second data since Gargamelle (1978)
- 2020: 23% error (under-estimate)
- 2025: $\nu_e CC1\pi^+$, 24% error (over-estimate)

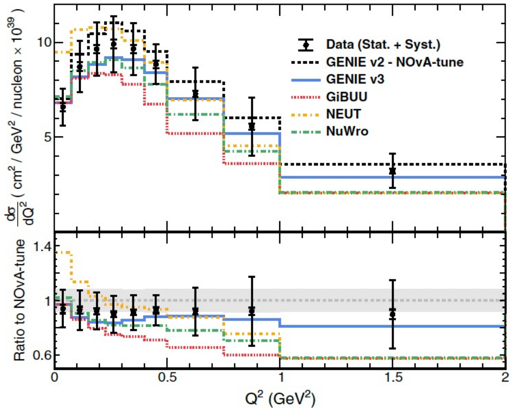
LArTPC

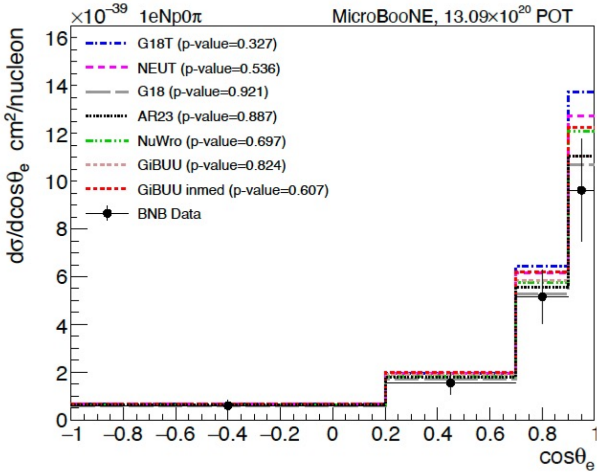
- ArgoNeuT 2020: First $\nu_e \& \bar{\nu}_e$ data on Argon
- MicroBooNE 2026: 1eNp0π sample, 232 events
- SBND: >10k events in 3yrs

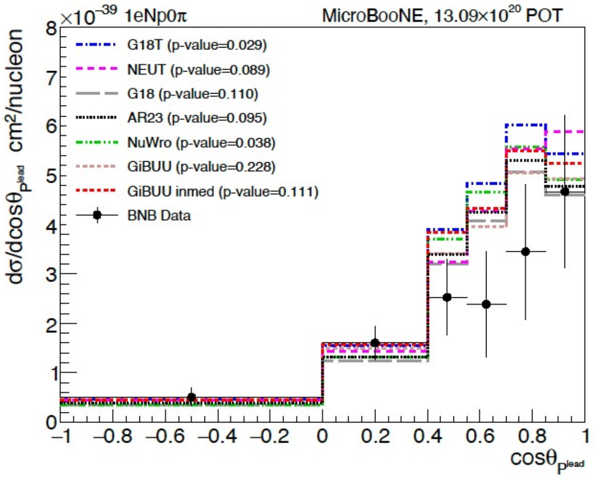


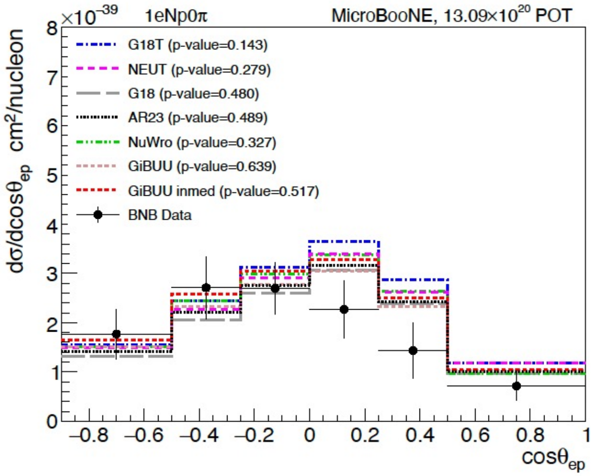
NOvA

- 2023: 19% error
- No model describes data well

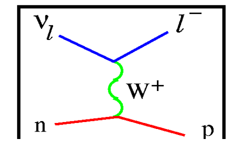






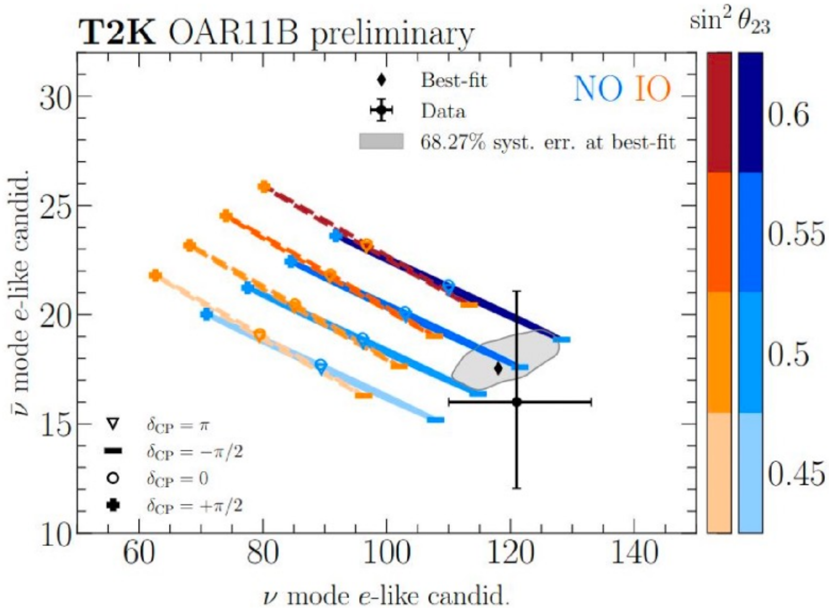


Quasi Elastic

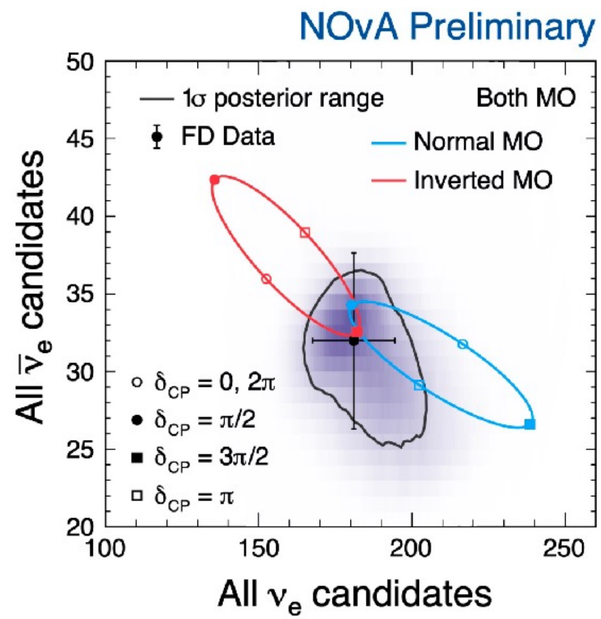


3.1 Path forward: QE (CC0π), electron neutrinos

Long-Baseline Accelerator Data

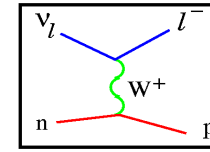


S. King for T2K, Neutrino 2026



Z. Vallari for NOvA, Neutrino 2026

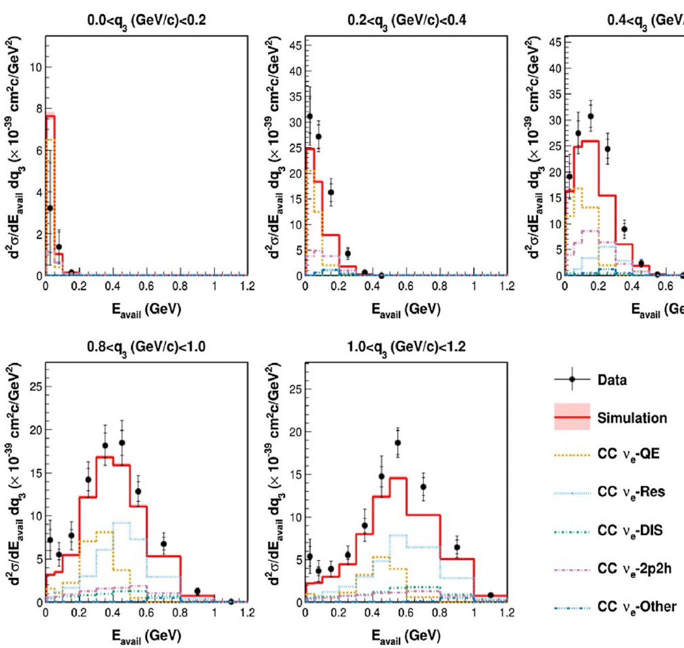
Quasi Elastic



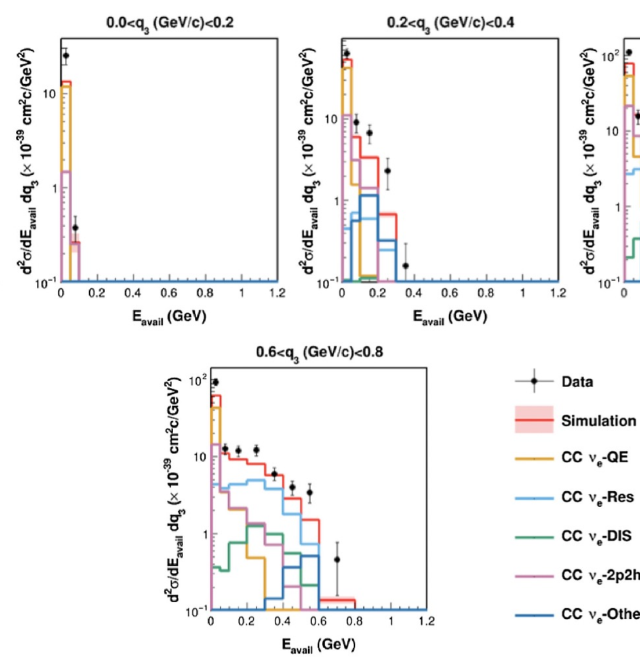
3.1 Path forward: QE (CC0π), electron neutrinos

MINERvA medium energy electron neutrino and antineutrino results

- 2024: high statistics $\nu_e\&\bar{\nu}_e CC$ Eavail-q3 distribution
- So many structures and data-simulation discrepancies are not understood
- The model underpredicts ν_e but not $\bar{\nu}_e$, simple 2p2h scaling cannot explain the discrepancy
- Comparisons of $\nu_e\&\bar{\nu}_e CC$ and $\nu_\mu\&\bar{\nu}_\mu CC$ Eavail-q3 distributions are also complicated



ν_eCC



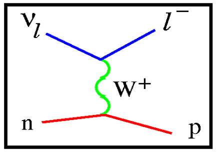
$\bar{\nu}_e$CC

Meyer,Walker-Loud,Wilkinson,Annu.Rev.Nucl.Part.Sci.2022.72:205–32
Alexandrou et al., PRD96(2017)054507

3.1 Path forward: QE (CC0π), M_A puzzle

M_A=1.3 T-shirts official going away party (NuInt 2015)

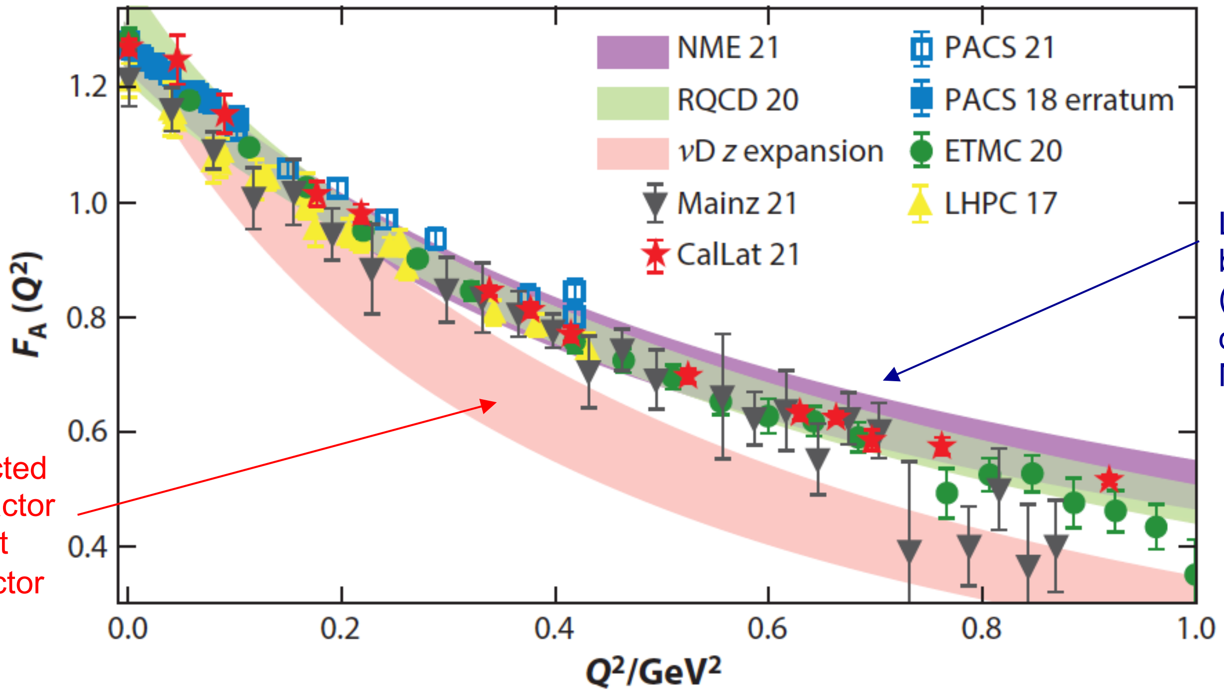
Quasi Elastic



Lattice QCD in neutrino physics

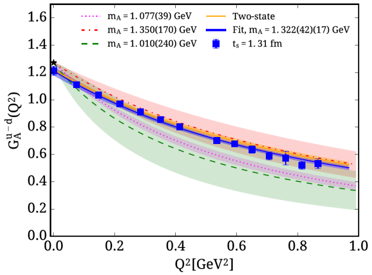
- We have developed QE model by assuming large M_A result (MiniBooNE etc) can be interpreted 2p2h
- M_A^{QE} = 1.0 GeV is supported by pion photoproduction data
- Recent Lattice QCD calculations start to converge axial form factor with longer tail

→ Similar with large M_A^{QE} with dipole form factor

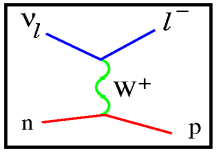


Lattice QCD calculations by different groups (which is consistent with dipole form factor with M_A^{QE}~1.3GeV)

Z-expansion extracted axial vector form factor (which is consistent with dipole form factor with M_A^{QE}~1GeV)



Quasi Elastic



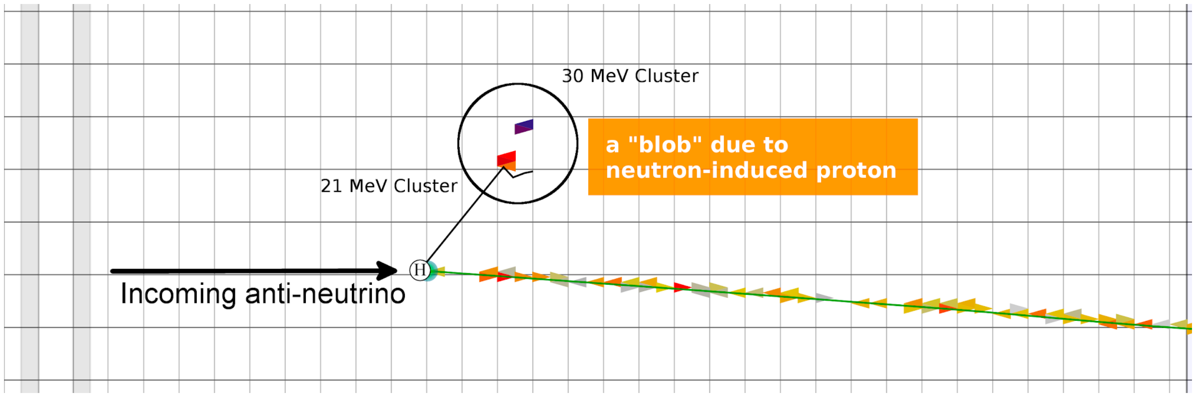
3.1 Path forward: QE (CC0π), M_A puzzle

MINERvA charged current elastic scattering

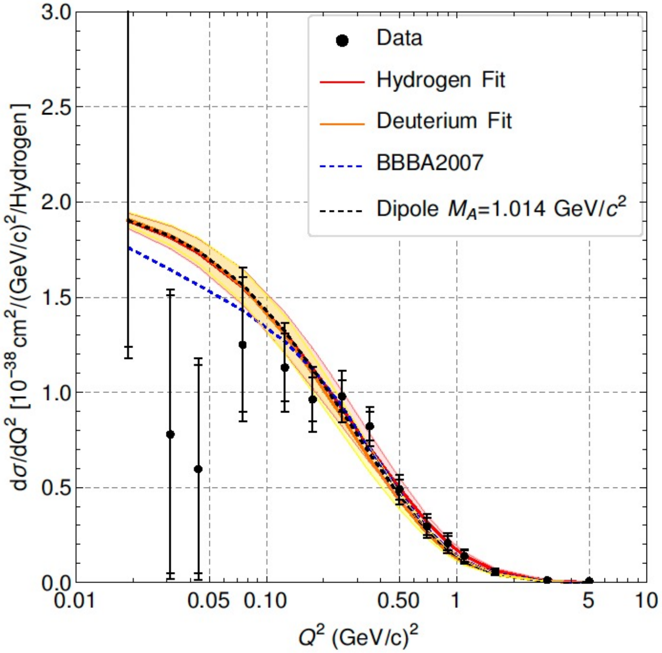
- Look for neutrino interaction with hydrogen from kinematics (no nuclear effect)

$$\bar{\nu}_\mu + p \to \mu^+ + n \text{ (signal)}$$
$$\bar{\nu}_\mu + {}^{12}C \to \mu^+ + X \text{ (background)}$$
$$\nu_\mu + {}^{12}C \to \mu^- + X \text{ (rejected)}$$

- Precise extraction of axial vector form factor without nuclear effect
- Data compatible to axial form factor with M_A~1 GeV?

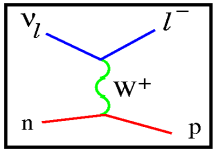


Tejin Cai (NuInt 2022)



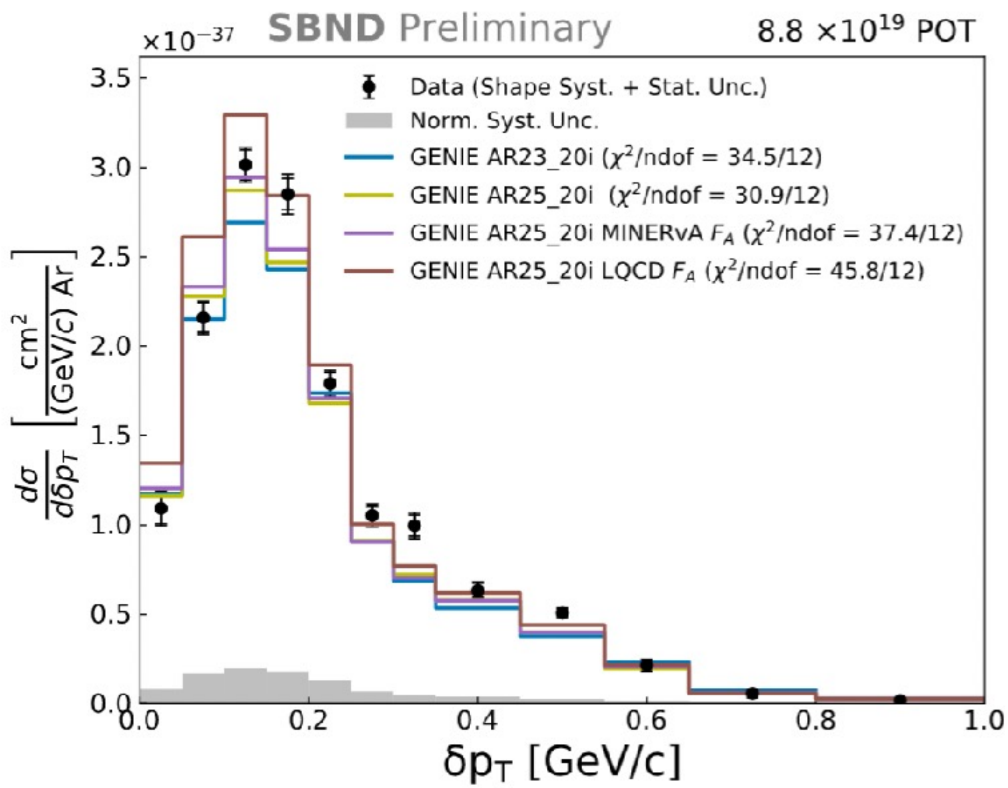
3.1 Path forward: QE (CC0π), M_A puzzle

Quasi Elastic



First SBND result

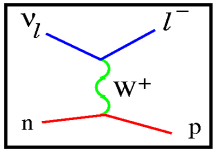
- The highest statistics modern neutrino interaction experiment
- Both Lattice QCD and MINERvA axial vector is compatible
- Axial vector form factor doesn't solve all data-MC discrepancy



Neutrino data anomalies are (mostly) by Strong interaction

DUNE, ArXiv:2605.2509.07664
ENUBET, EPJC83(2023)964 , NuTag, EJC84(2024) , nuSCOPE, ArXiv:2503.21589

Quasi Elastic



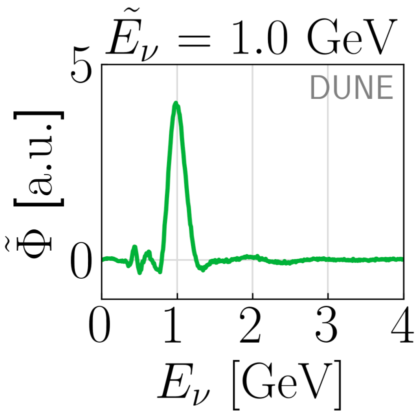
3.1 Path forward: QE (CC0π), kinematic reconstruction

PRISM

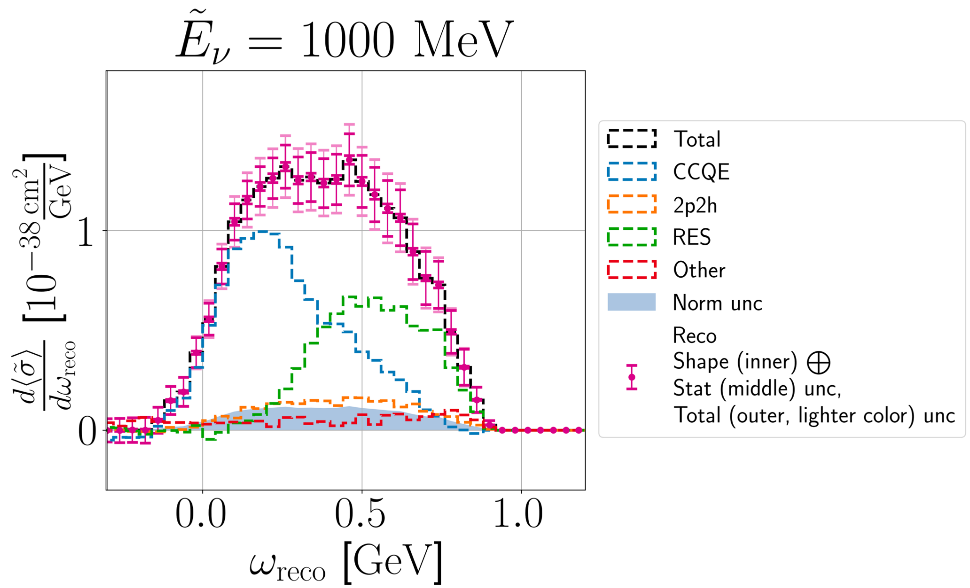
- Move detector to sample different neutrino energy
- Combine data to produce pseudo-monoenergetic virtual flux

NuScope

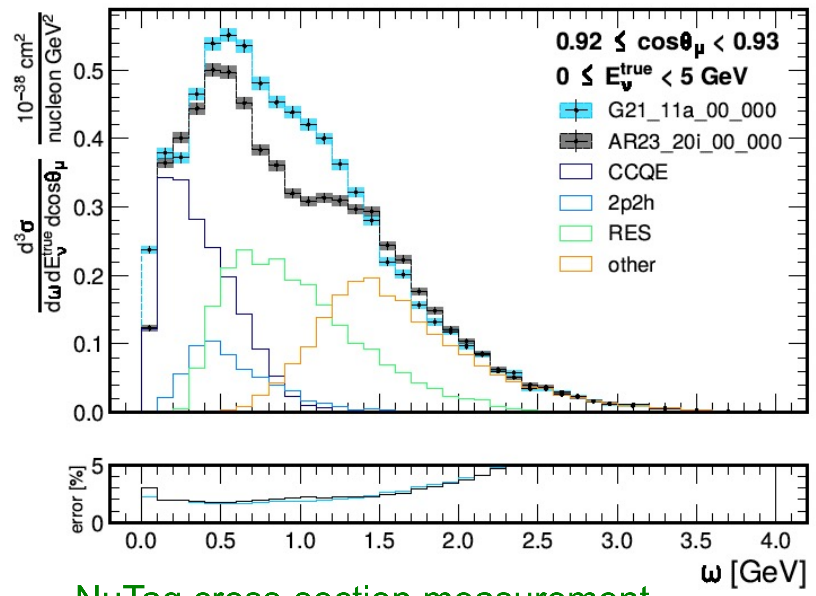
- ENUBET: monitoring neutrino beam (easier)
- NuTag: tagged neutrino beam (challenging)



PRISM virtual flux

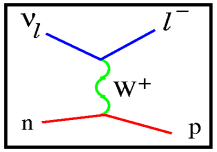


PRISM cross-section measurement



NuTag cross-section measurement

Quasi Elastic

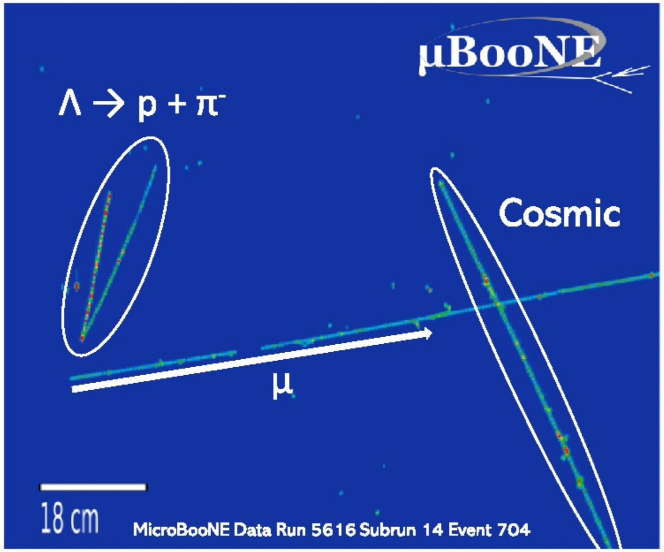


3.1 Path forward: QE (CC0π), Cabibbo-suppressed CCQE

MicroBooNE hyperon CCQE production

$$\bar{\nu}_\mu + p \to \mu^+ + \Lambda^0$$
$$\bar{\nu}_\mu + p \to \mu^+ + \Sigma^0$$
$$\bar{\nu}_\mu + n \to \mu^+ + \Sigma^-$$

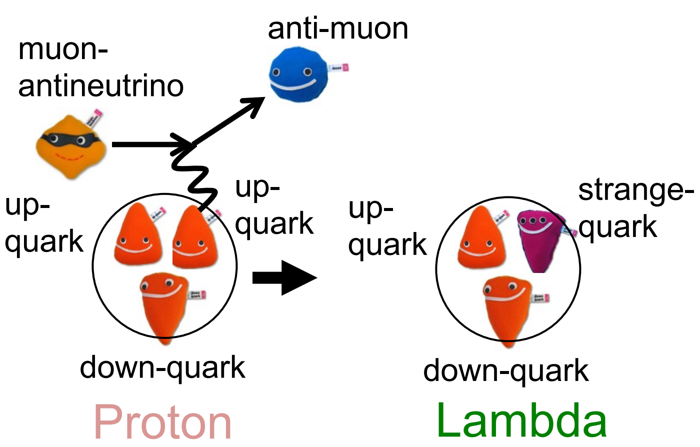
- Another forgotten subject since bubble chamber time
- Poorly measured outside of SU(2) framework



Cabibbo-suppressed charm production?

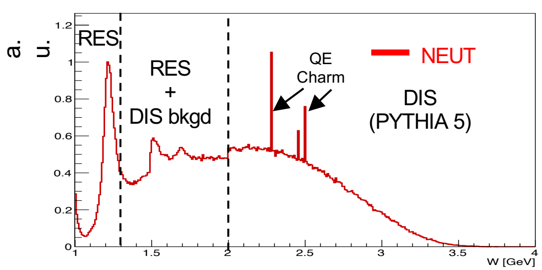
$$\nu_\mu + n \to \mu^- + \Lambda_c^+$$

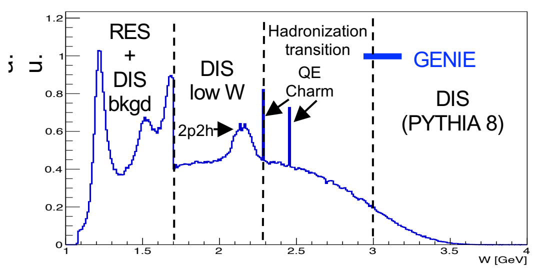
- Theoretically possible channel
- This exists in generators...



$\nu_\mu + H_2O$, 6 GeV, CC-only
True W-distribution
$W^2 = (p^\mu + q^\mu)^2$

NEUT v5.6.4.3
GENIE v3.06.00, G18_01a





1. Past

2. Presence

3. Future

3.2 Final state interaction

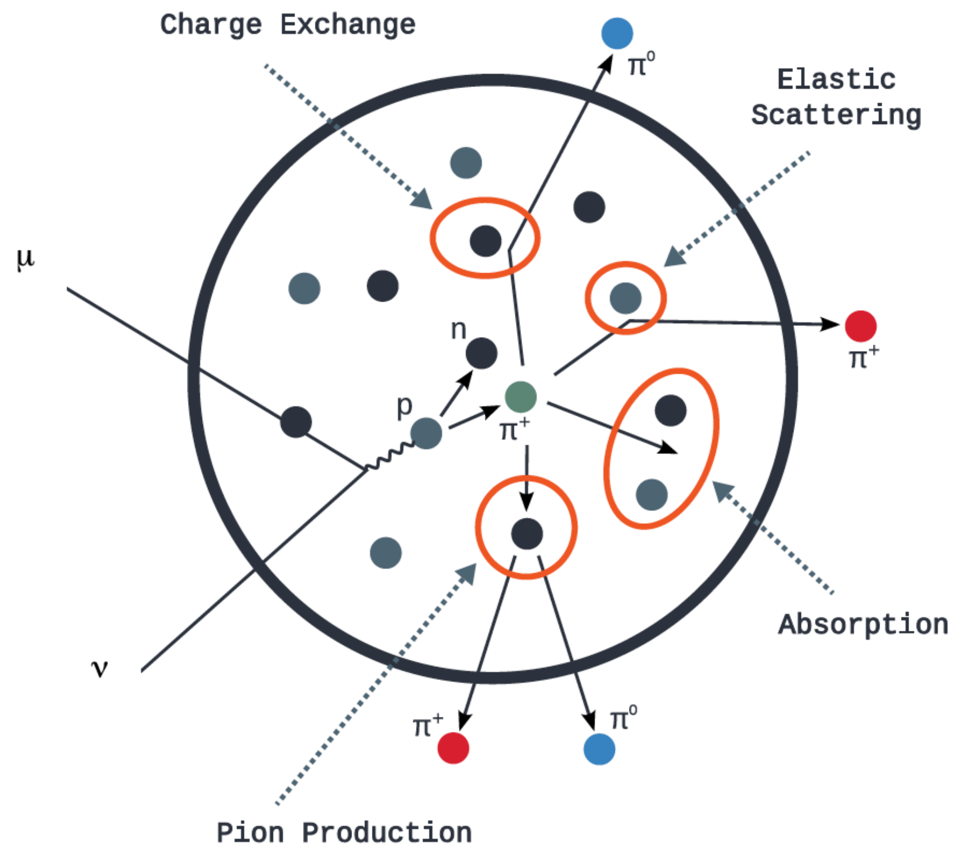
Cascade model

- Elastic scattering: hadron direction changes
- Inelastic scattering: hadron direction and energy changes
- Charge exchange: $\pi^+ + n \leftrightarrow \pi^0 + p$, $\pi^0 + n \leftrightarrow \pi^- + p$
- Absorption: Nucleon absorption, pion absorption
- Production: Pion production

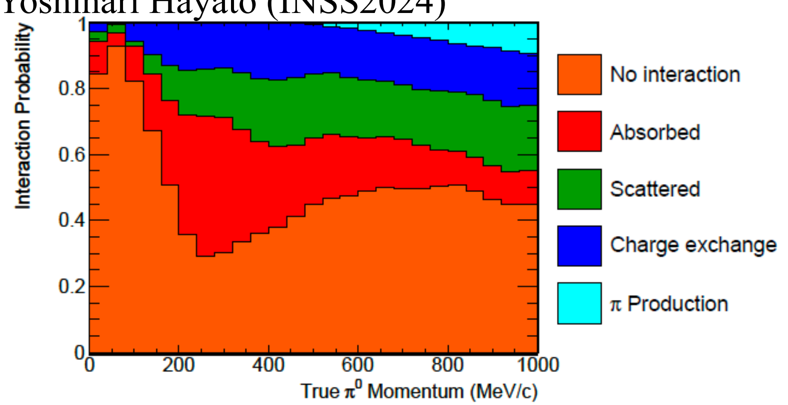
It's difficult to measure hadron final states

It's difficult to understand the primary processes from the final state hadrons

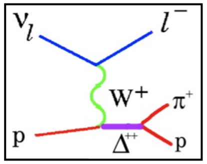
(it's difficult to predict final state hadron multiplicity and kinematics)



Yoshinari Hayato (INSS2024)



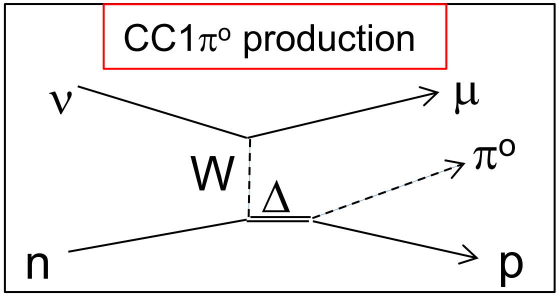
RESonance

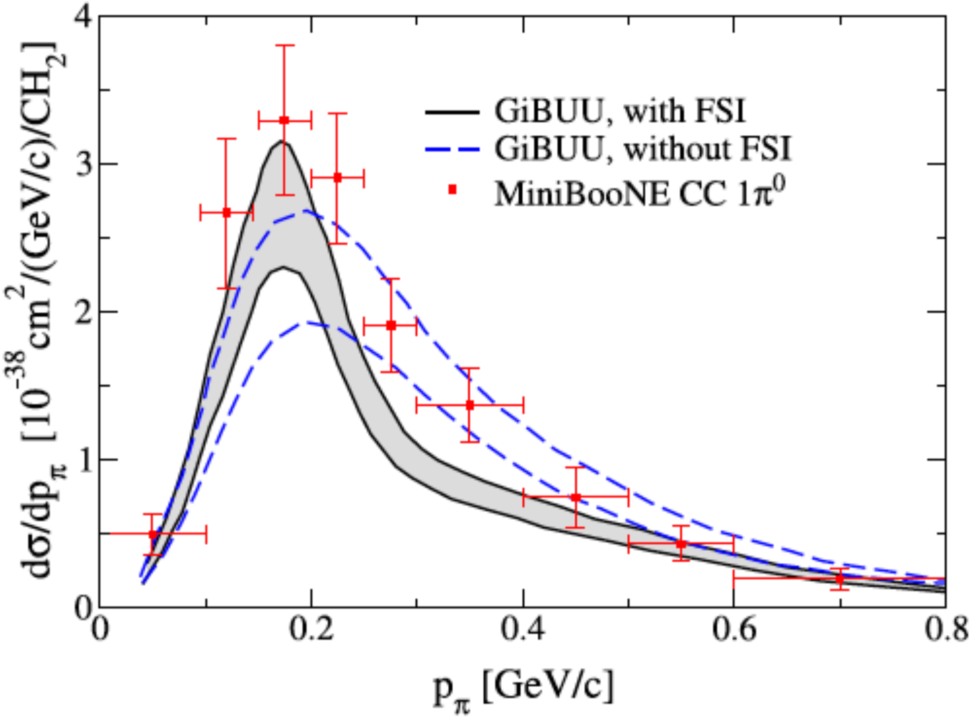


3.2 Path forward: RES (CC1π)

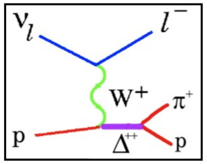
MiniBooNE CC1π^o data

- FSIs change pion kinematics



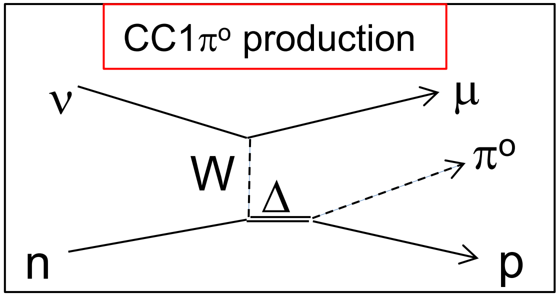


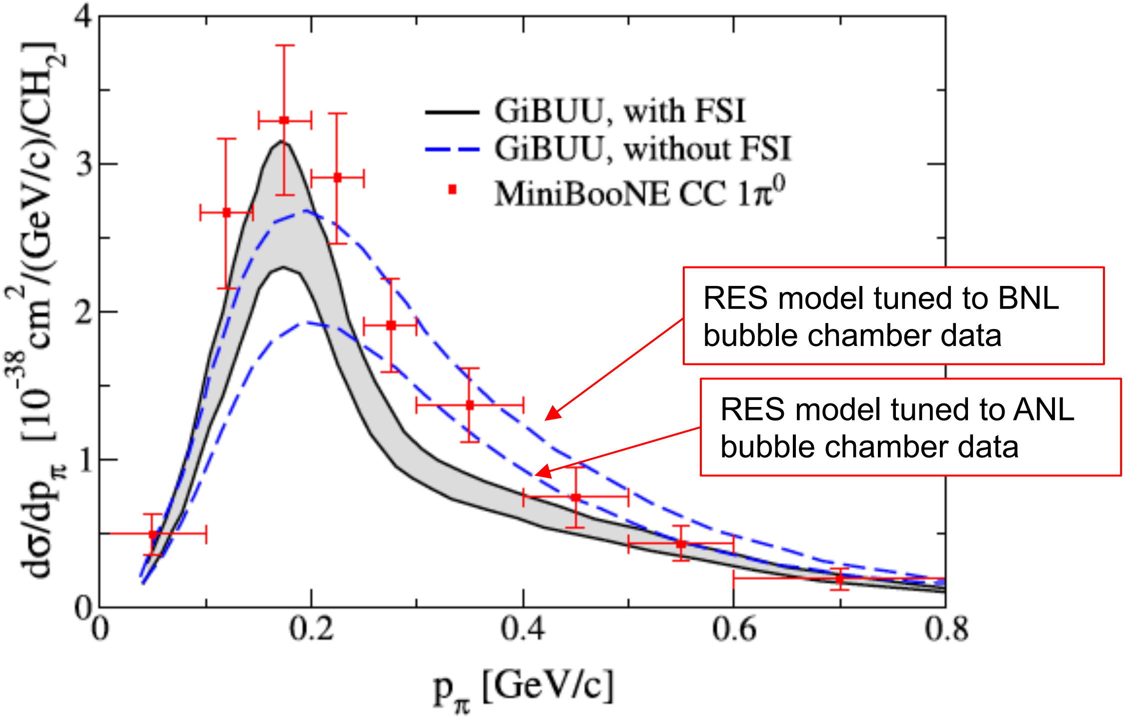
MiniBooNE π^o momentum vs simulation



3.2 Path forward: RES (CC1π)

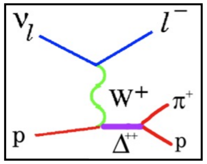
MiniBooNE CC1π° data
- FSIs change pion kinematics



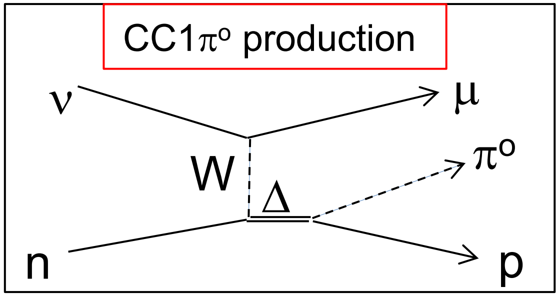


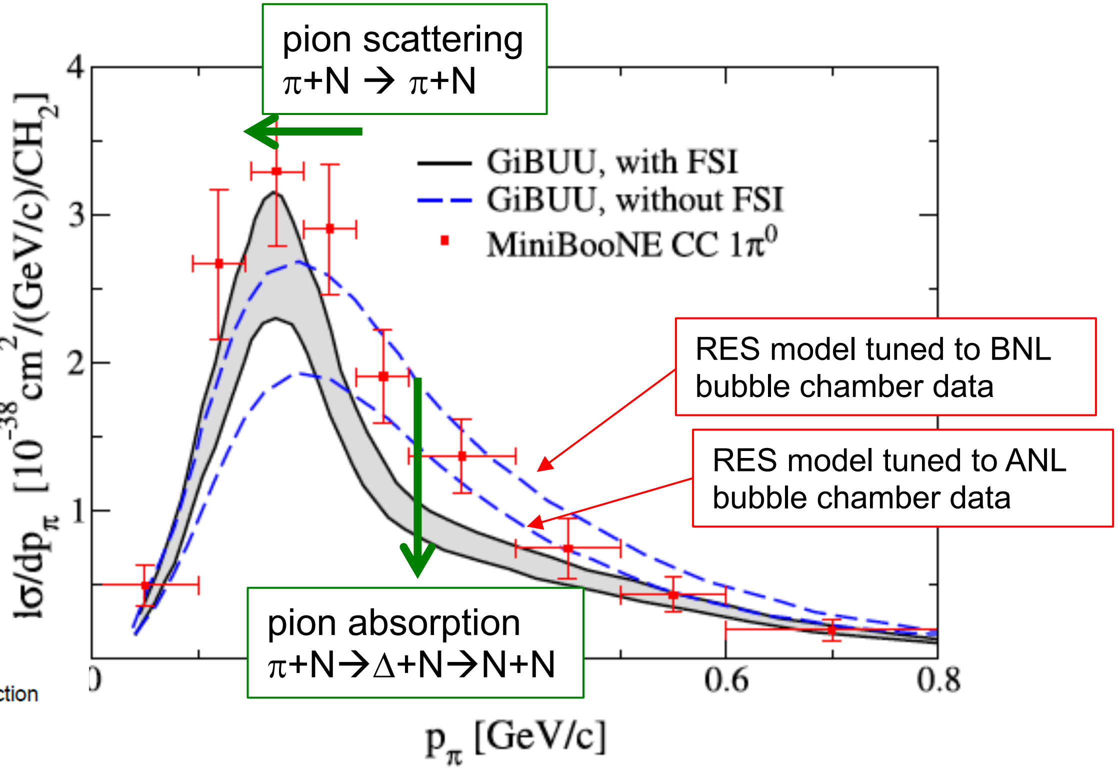
MiniBooNE π° momentum vs simulation

3.2 Path forward: RES (CC1π)

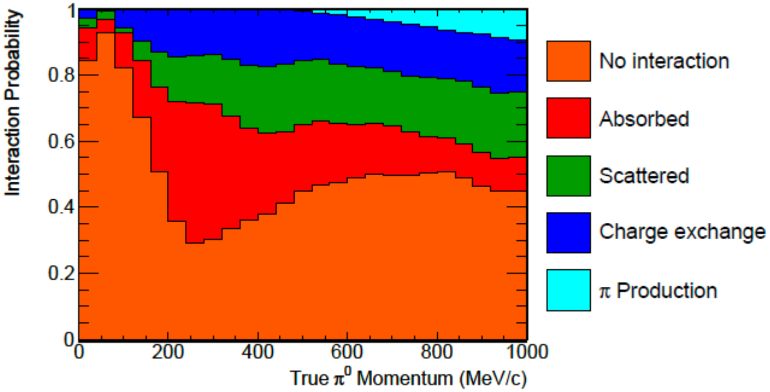


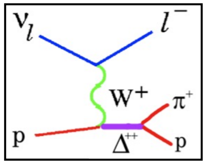
MiniBooNE CC1π° data
- FSIs change pion kinematics





MiniBooNE π° momentum vs simulation

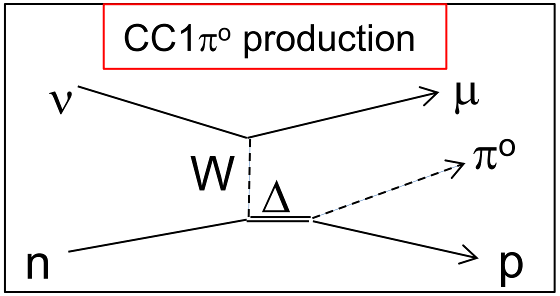


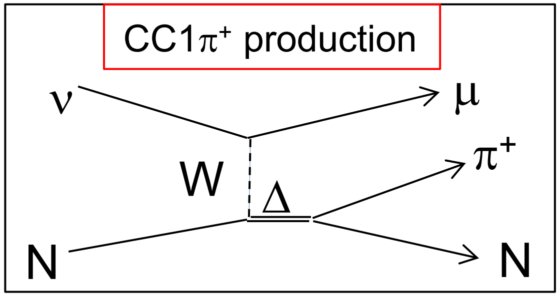


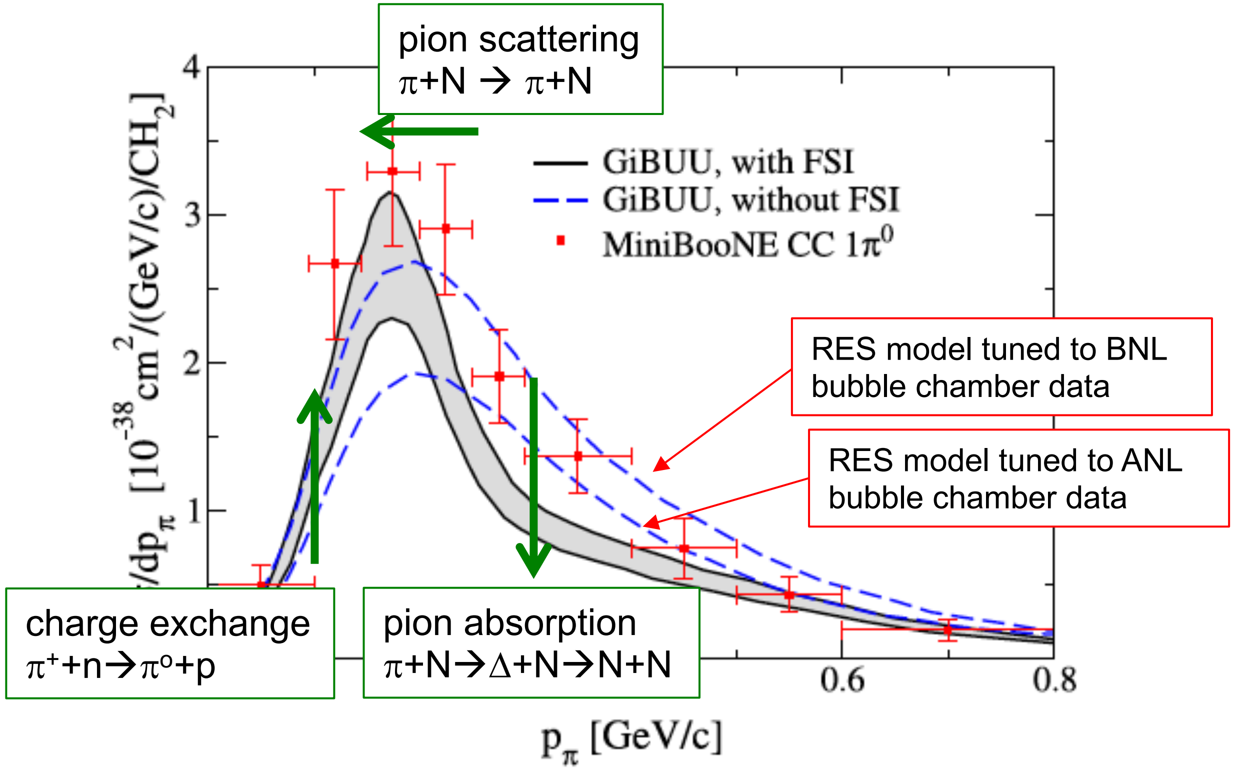
3.2 Path forward: RES (CC1π)

MiniBooNE CC1π^o data

- FSIs change pion kinematics
- data-simulation comparison requires to calculate all pion channels and all FSI processes



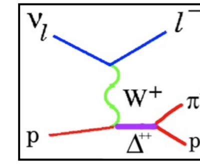




MiniBooNE π^o momentum vs simulation

It is very difficult to learn details of FSIs from data-simulation comparison

Wilkinson et al.,PRD90(2014)112017, Mosel and Gallmeister, PRC96(2017)015503, GENIE, EPJST230(2021)4449
TENSION2016, Phys.Rep.773(2018)1 , TENSION2018, PRD105(2022)092004

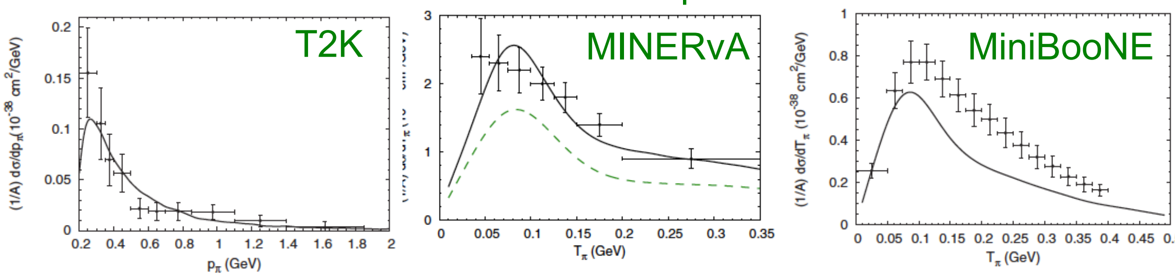


3.2 Path forward: RES (CC1π)

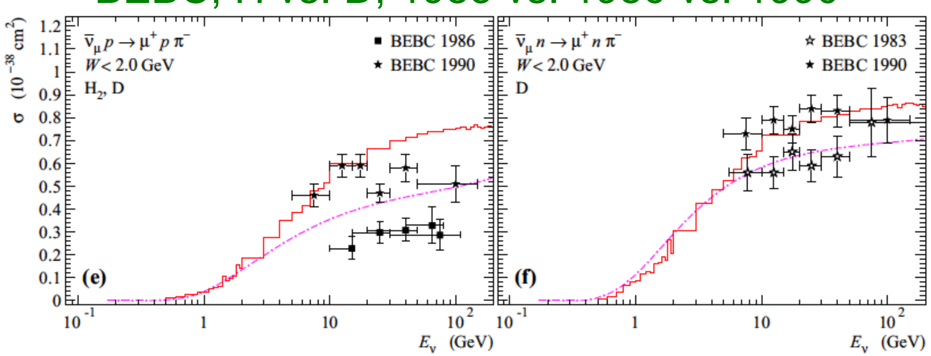
Data tension

- Tension between different experiments
- Tension between different targets
- Tension between different analyses
- Reanalysis supports ANL result

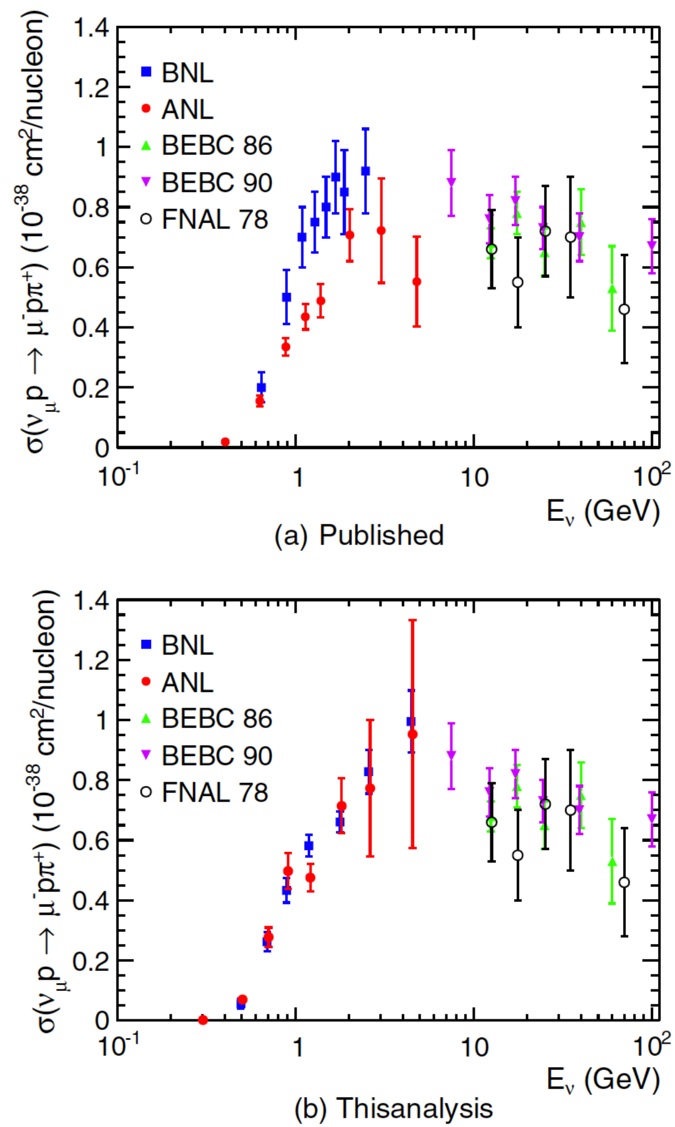
data-GiBUU comparison

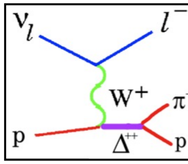


BEBC, H vs. D, 1983 vs. 1986 vs. 1990



ANL vs. BNL data





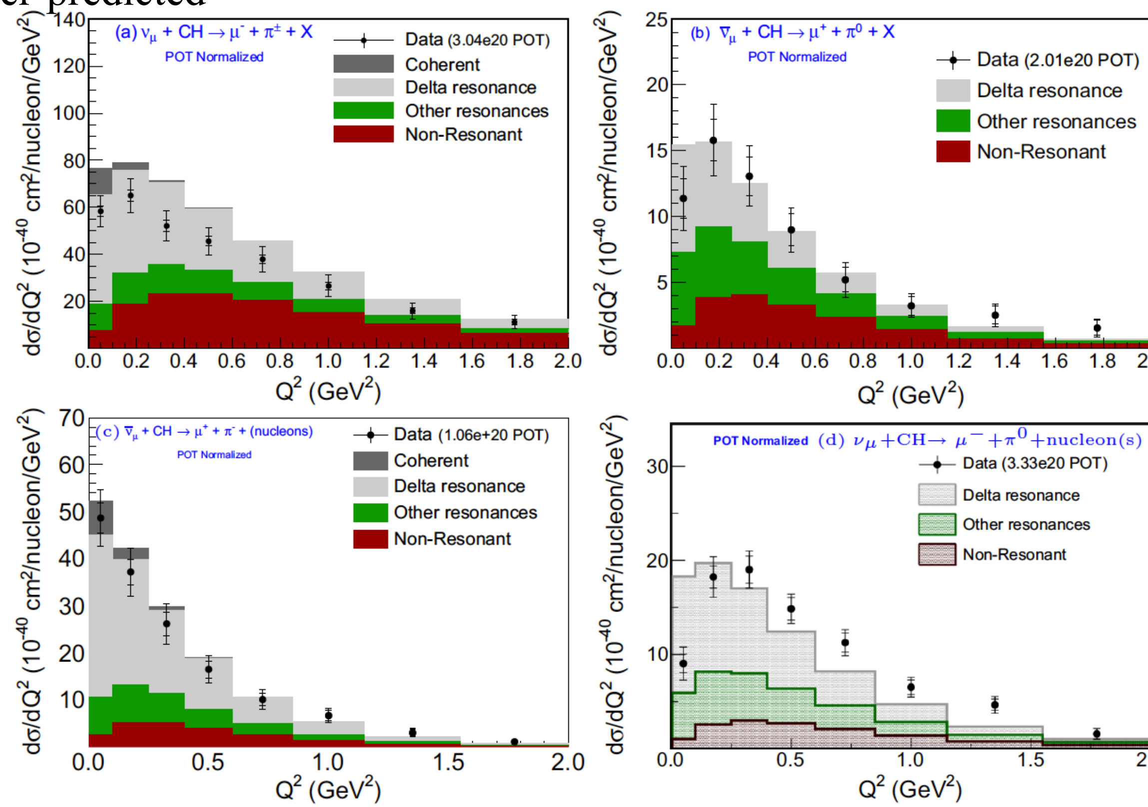
3.2 Path forward: RES (CC1π)

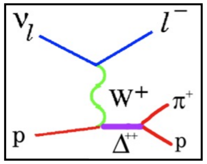
Data tension – internal: MINERvA CC1π data

- It is extremely difficult to tune pion and/or FSI parameters to fit all pion data
  - $\nu_\mu CC\pi^\pm$, low Q2 suppression, over-predicted
  - $\nu_\mu CC\pi^0$, strong low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^-$, no low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^0$, low Q2 suppression, under-predicted

The study relies of available knobs in the generator

It looks the simulation doesn't have good knobs to tune





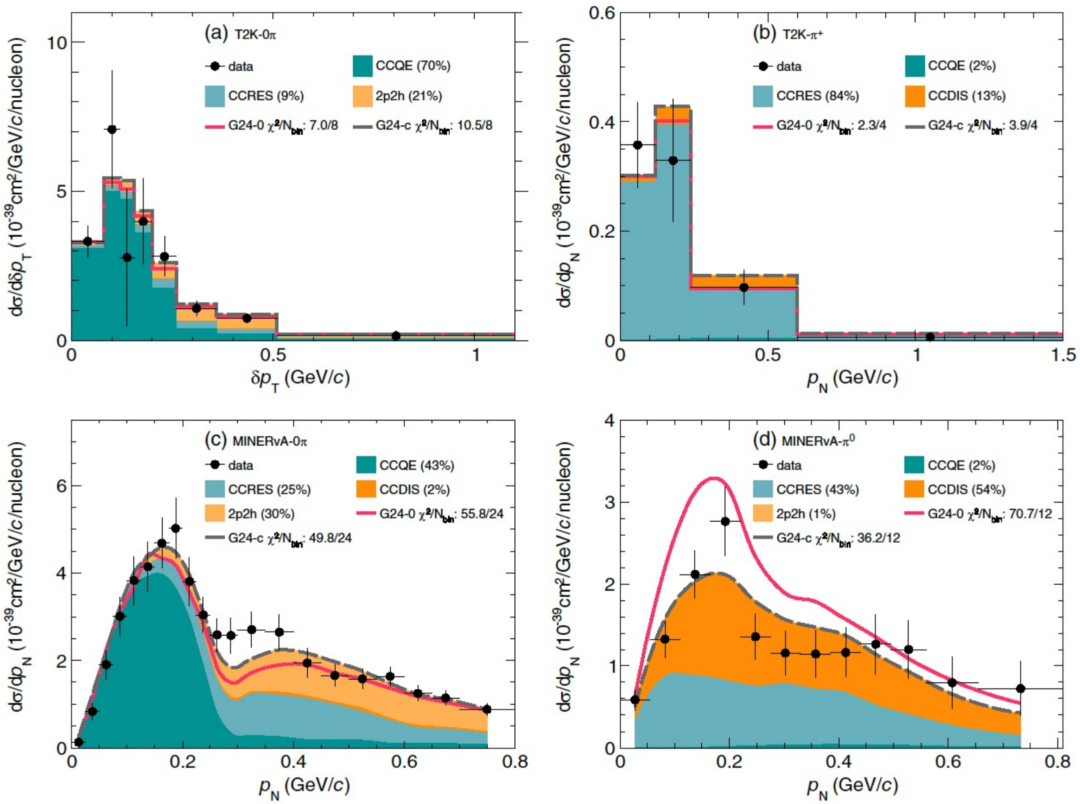
3.2 Path forward: RES (CC1π)

Data tension – external: T2K vs. MINERvA pion data

- MINERvA π^o data makes a large tension
- Tuning to reduce this (reduce charge exchange $\pi^+ \rightarrow \pi^0$, reduce π^o m.f.p)

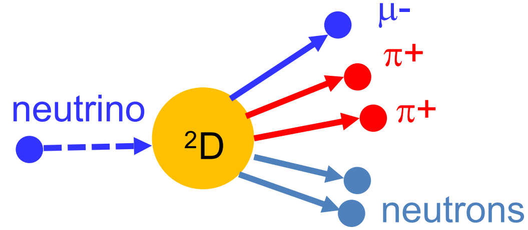
Simulation cannot reproduce the MINERvA "gap" between CCQE and RES
→ stronger 2p2h is required?

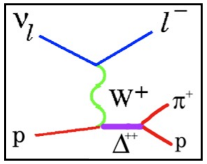
RES are background of QE-based oscillation experiment (T2K, MicroBooNE, HyperK), but the main channel for other experiments (NOvA, DUNE)



Nakamura et al,Rep.Prog.Phys.80(2017)056301

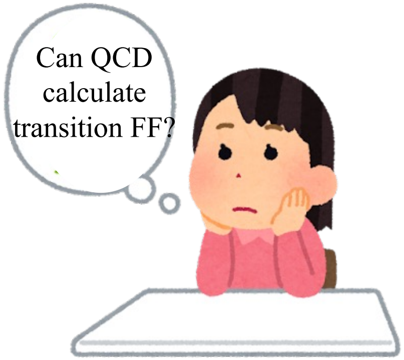
3.2 Path forward: RES (CC2π etc)





2-pion production

- Very limited amount of data
- Higher-resonance, mostly



Higher-resonance

- GENIE has ~15 additional resonances
- Each resonance have 4 vectors and 4 axial vector form factors
- Almost all axial vector FFs are unmeasured

DCC model vs. electro-pionproduction data (Vector FF)

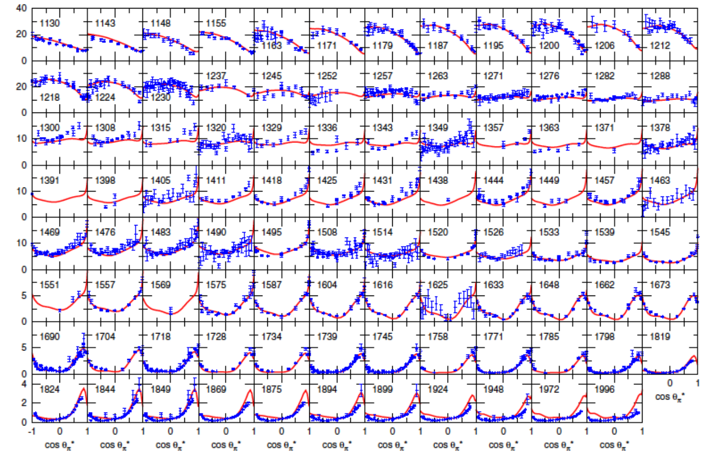
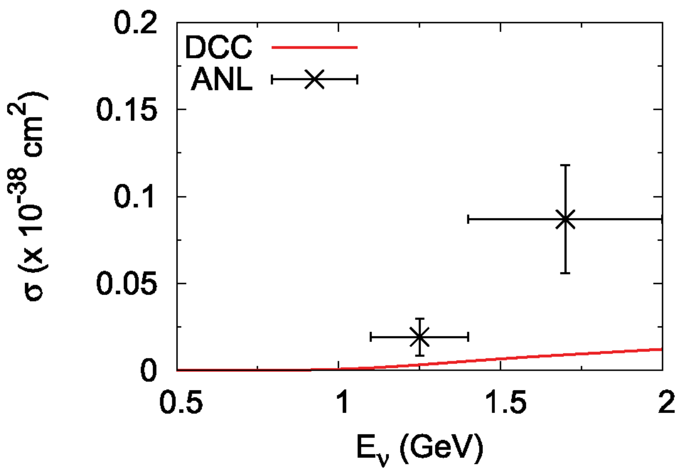
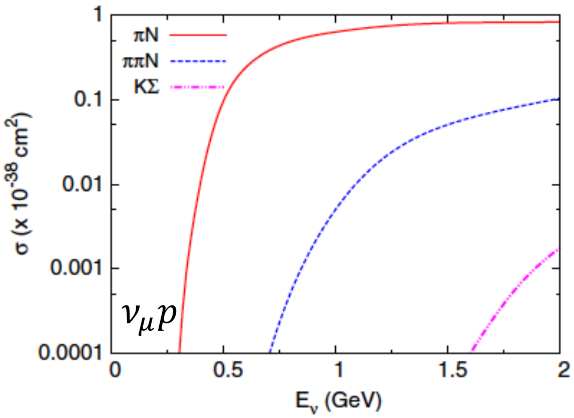
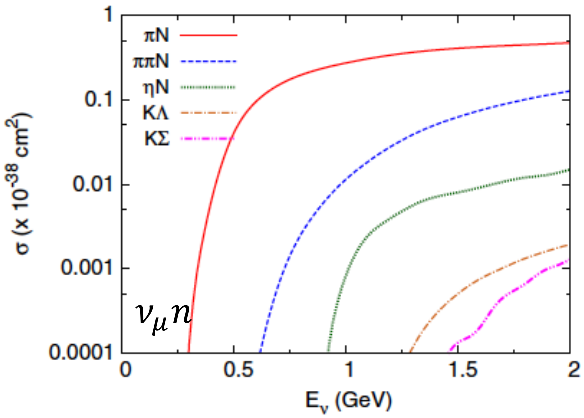


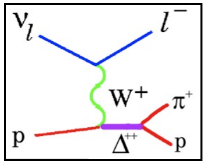
FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

Neutrino induced 2-pion production



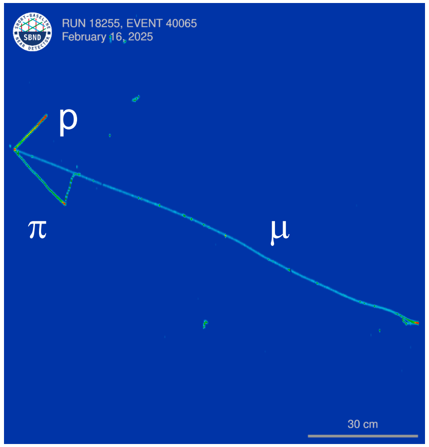






3.2 Path forward: RES (CC2π etc)

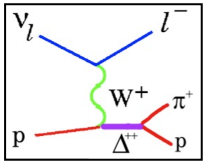
First SBND result
- The highest statistics modern neutrino interaction experiment
- We expect new knowledge of multi-track events
  - Resonance channels
  - FSIs



SBND CC1π candidate

Process		No. Events	Events/ ton	Stat. Uncert.
	ν_μ *Events (By Final State Topology)*			
CC Inclusive		5,212,690	46,542	0.04%
CC 0 π	$\nu_\mu N \to \mu + Np$	3,551,830	31,713	0.05%
	· $\nu_\mu N \to \mu + 0p$	793,153	7,082	0.11%
	· $\nu_\mu N \to \mu + 1p$	2,027,830	18,106	0.07%
	· $\nu_\mu N \to \mu + 2p$	359,496	3,210	0.17%
	· $\nu_\mu N \to \mu + \geq 3p$	371,347	3,316	0.16%
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ 1\pi^\pm$	1,161,610	10,372	0.09%
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 2\pi^\pm$	97,929	874	0.32%
CC $\geq 1\pi^0$	$\nu_\mu N \to \mu +$ nucleons $+ \geq 1\pi^0$	497,963	4,446	0.14%
NC Inclusive		1,988,110	17,751	0.07%
NC 0 π	$\nu_\mu N \to$ nucleons	1,371,070	12,242	0.09%
NC 1 $\pi^\pm$	$\nu_\mu N \to$ nucleons $+ 1\pi^\pm$	260,924	2,330	0.20%
NC $\geq 2\pi^\pm$	$\nu_\mu N \to$ nucleons $+ \geq 2\pi^\pm$	31,940	285	0.56%
NC $\geq 1\pi^0$	$\nu_\mu N \to$ nucleons $+ \geq 1\pi^0$	358,443	3,200	0.17%

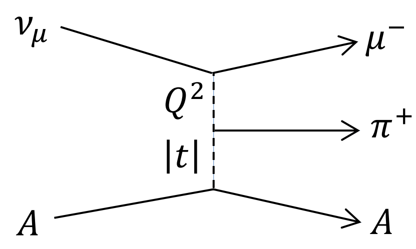
SBND expected number of events

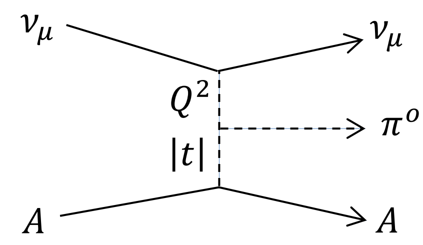


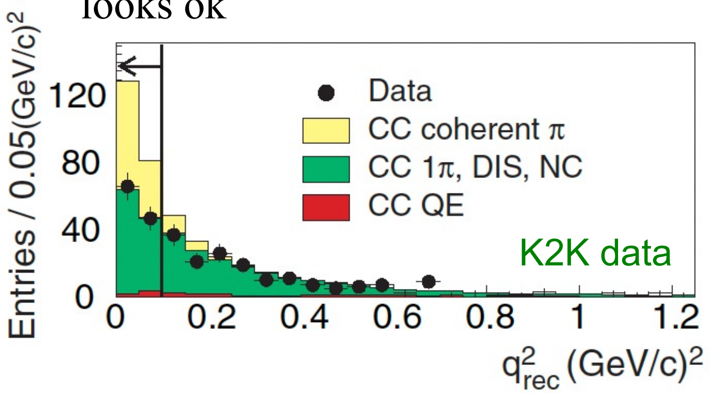
3.2 Path forward: RES, coherent and diffractive production

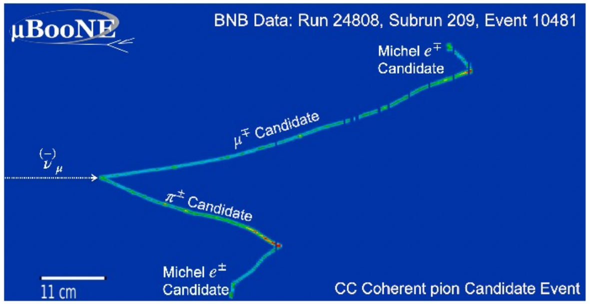
Coherent pion production

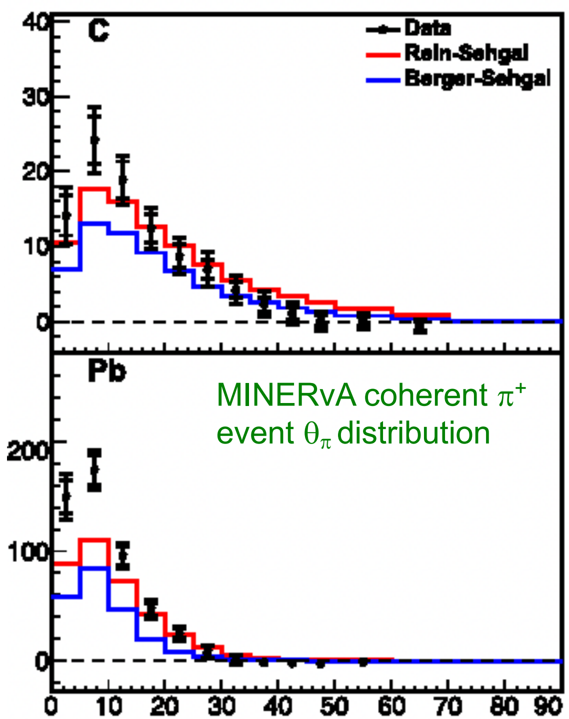
- Low momentum transfer pion production processes
- Forward going π^o(EM shower) is ν_e background
- K2K, SciBooNE → No coherent pion production
- T2K, MINERvA, MicroBooNE → They exists
- MINERvA → Model underestimate, but A-scaling looks ok





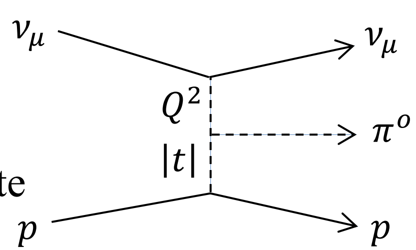






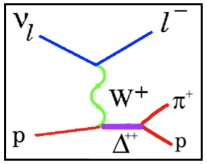
Diffractive NC pion production

- Coherent pion-like process with hydrogen
- Very similar to $\nu_e CC$ but photon.
- Once thought as low-energy excess candidate
- MINERvA had measured



MINERvA, PRL117(2016)061802 , PRD94(2016)012002 , PRL119(2017)011802
MicroBooNE, PRL135(2025)251804

RESonance



3.2 Path forward: RES, Kaon production

Kaon papers

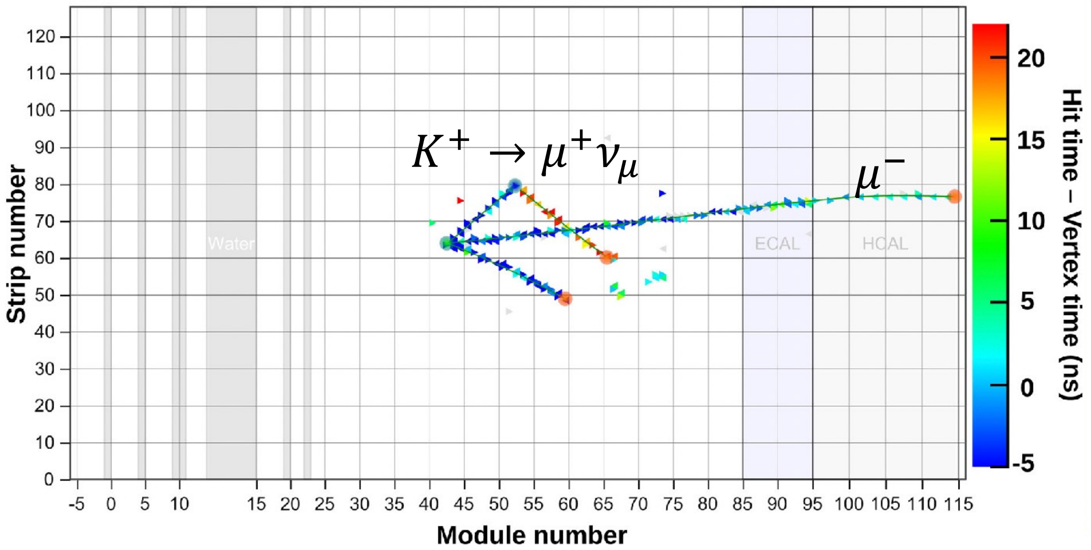
- Below 2 GeV, Cabibbo-suppressed production dominant

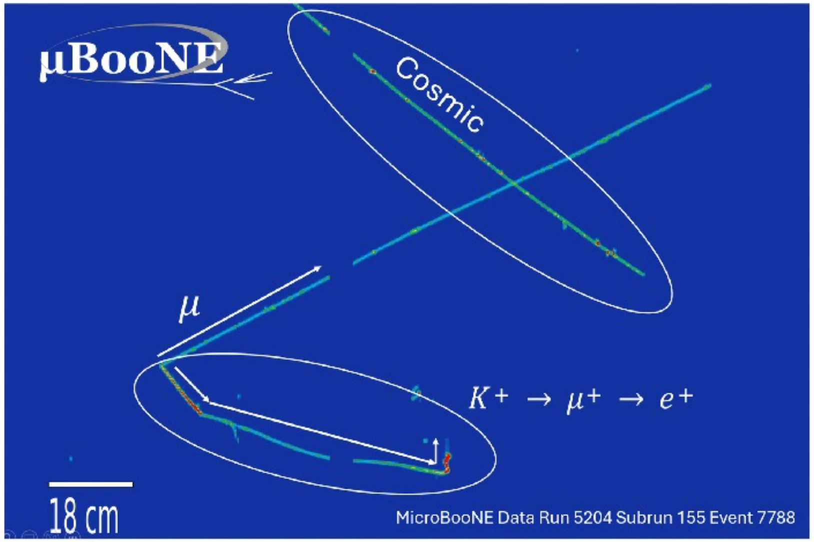
$$\nu_\mu + X \rightarrow \mu^- + K^+ + X'$$

- Above, associate production

$$\nu_\mu + X \rightarrow \mu^- + K^+ + \Lambda^0 + X' \text{ , etc}$$

- NC kaon production is proton decay background ($p \rightarrow K^+\nu$)
- MINERvA measured coherent kaon production measurement
- Study FSI (strangeness conservation), higher resonances etc





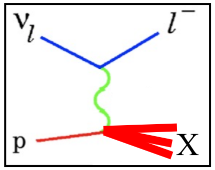
1. Past

2. Presence

3. Future

NuTeV, PRD74(2006)012008

DIS

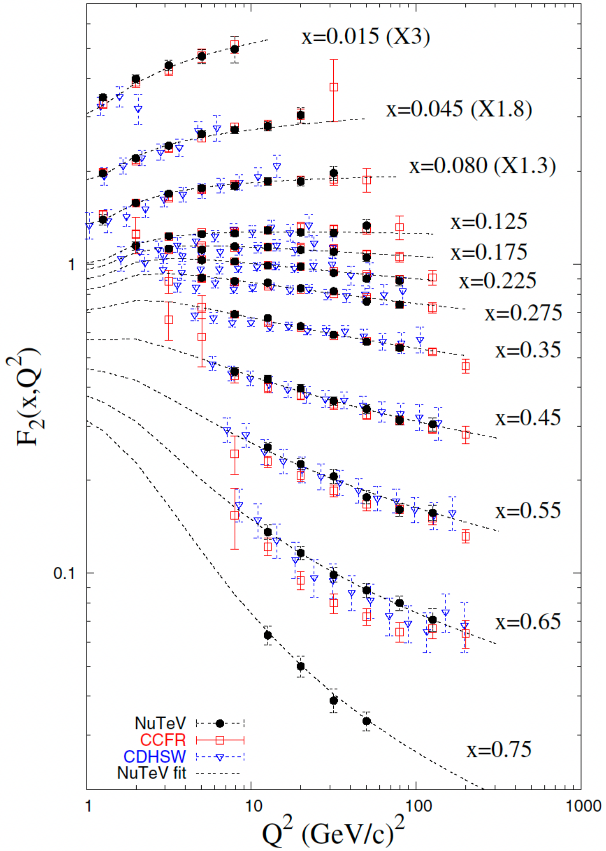


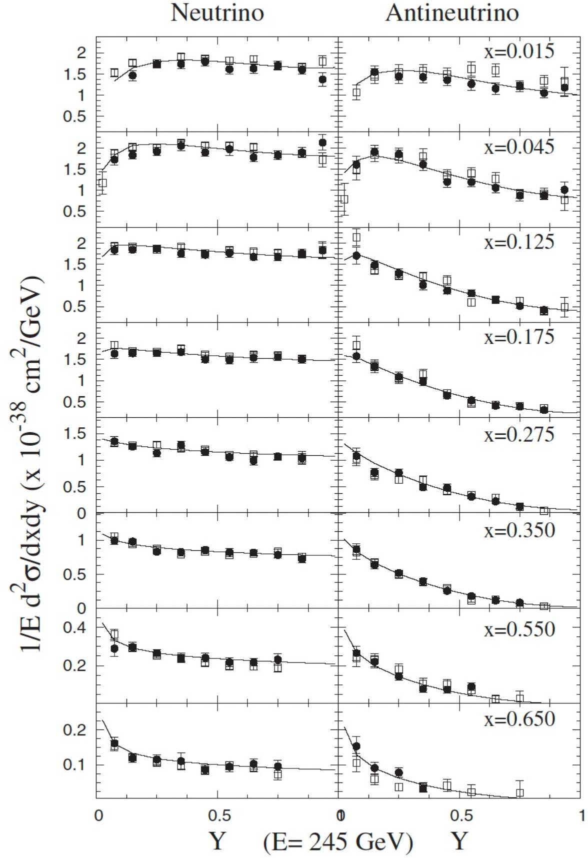
3.3 Path forward: DIS

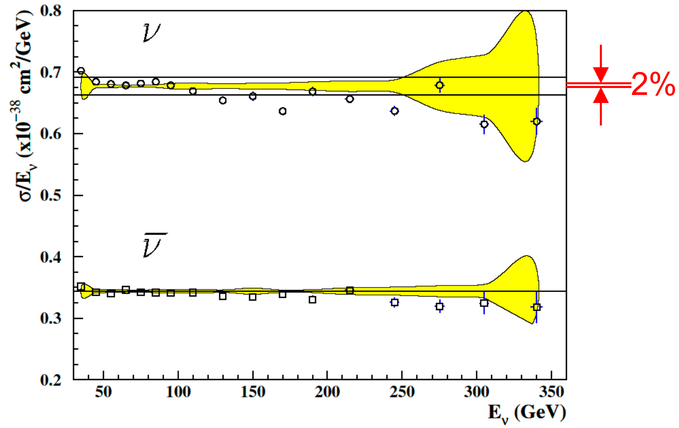
DIS cross-sections have been understood up to 360 GeV by accelerator neutrino experiments

NuTeV

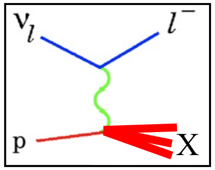
- Precise (not flux-averaged) differential cross section measurements
- $E_\nu^{Cal} = E_\mu + E_{had}$







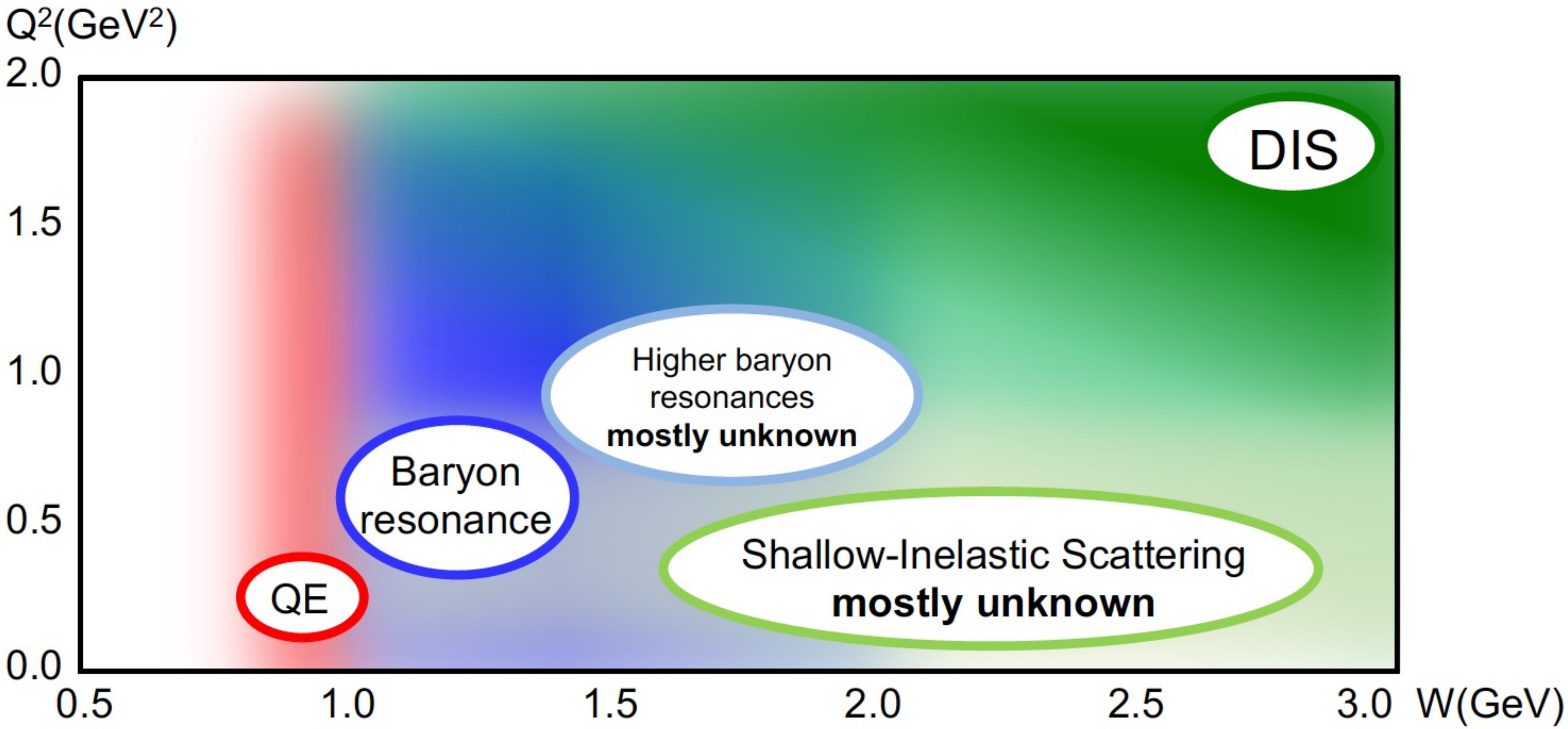
DIS



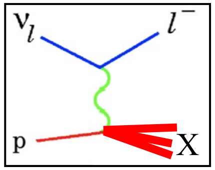
3.3 Path forward: SIS

Shallow-inelastic scattering (SIS)

- Neutrino experiments around 1-10 GeV are not quite DIS yet
  - Shallow → low Q^2
  - Inelastic → large W



DIS



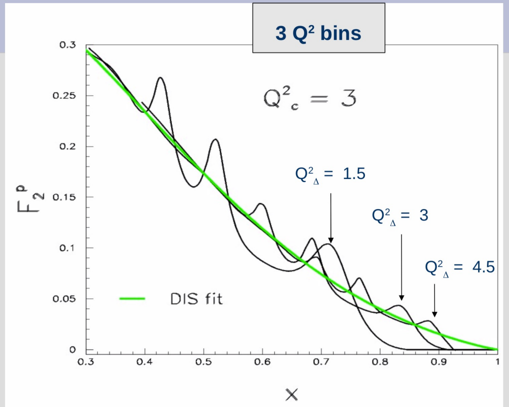
3.3 Path forward: SIS: Quark-Hadron duality

Bodek-Yang correction is a phenomenological model to reproduce duality-like behavior, accepted by all neutrino simulation

DIS ≠ Bjorken limit
DIS = Q^2 average of all resonances

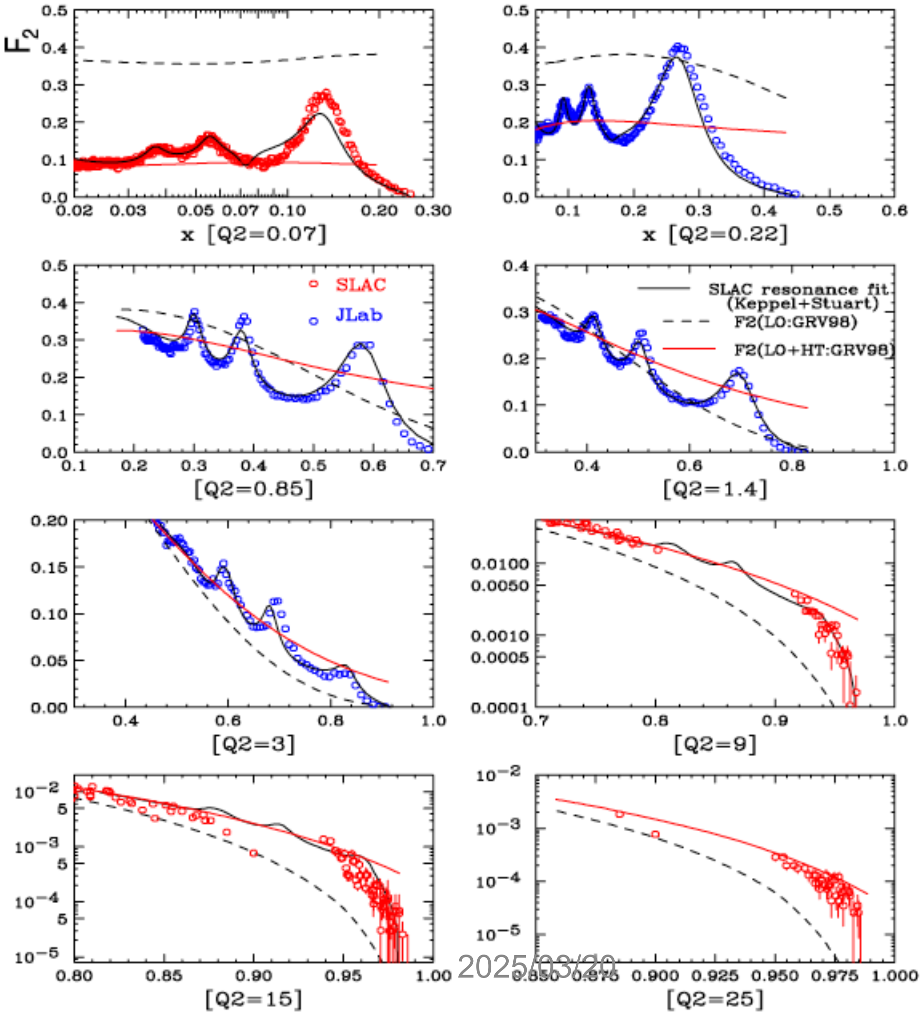
Many few GeV DIS events are affected by duality

'DIS-like' duality averaging procedure

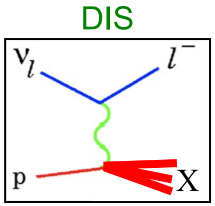


Christy, NuSTEC SIS workshop
https://nustec.fnal.gov/nuSDIS18/

Proton F2 function GRV98-BY correction vs. data

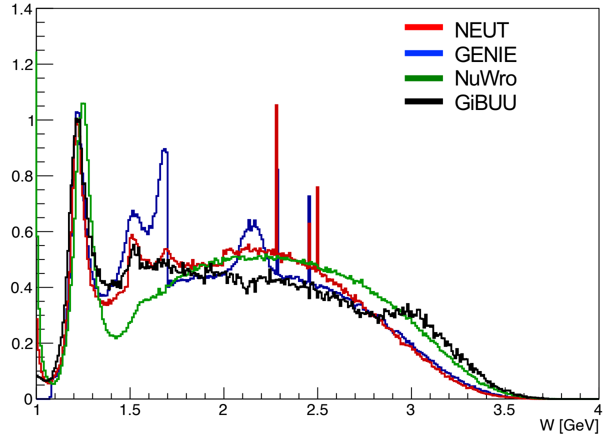


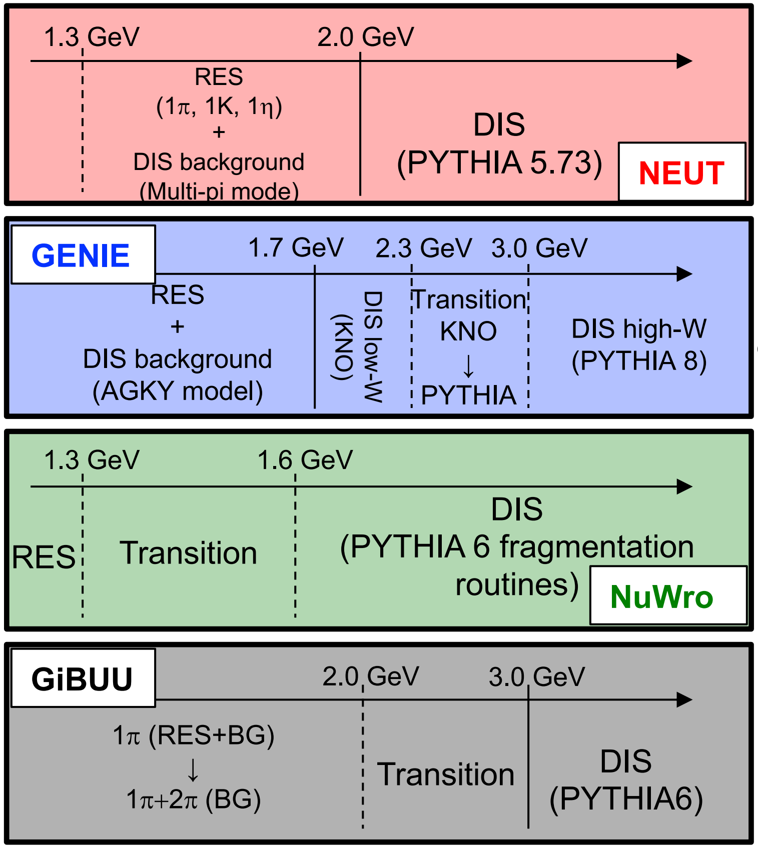
3.3 Path forward: SIS, Neutrino event generator



Shallow-inelastic scattering (SIS)

- Neutrino experiments around 1-10 GeV are not quite DIS yet
- Generators disagree how to model SIS
- Predicted cross-sections are not continuous

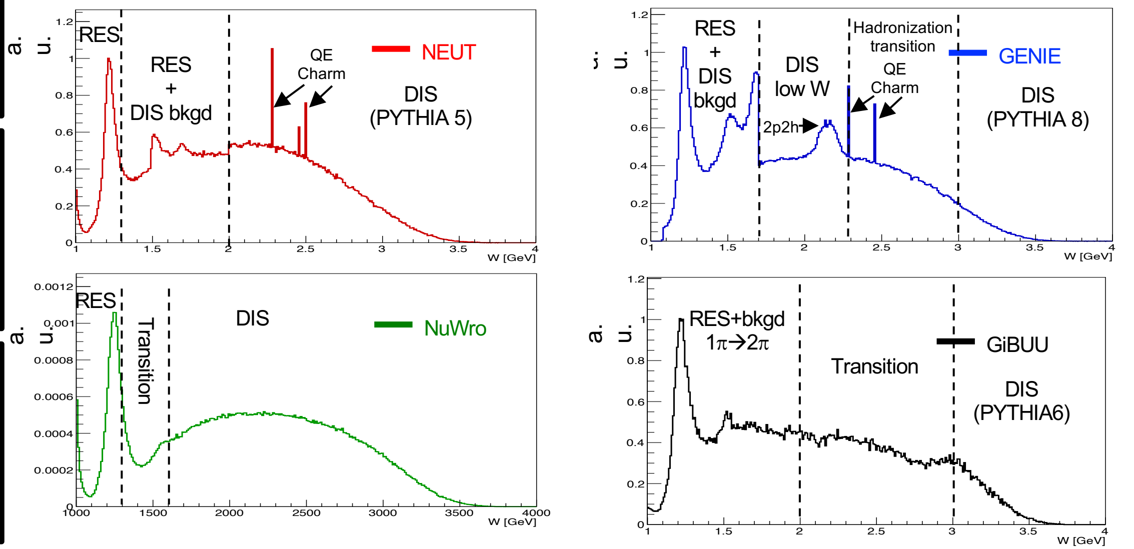




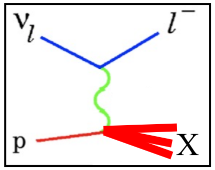
$\nu_\mu + H_2O$, 6 GeV, CC-only
True W-distribution

$W^2 = (p^\mu + q^\mu)^2$

NEUT v5.6.4.3
GENIE v3.06.00, G18_01a
NuWro nuwro_25.01
GiBUU 5.1.2025



DIS



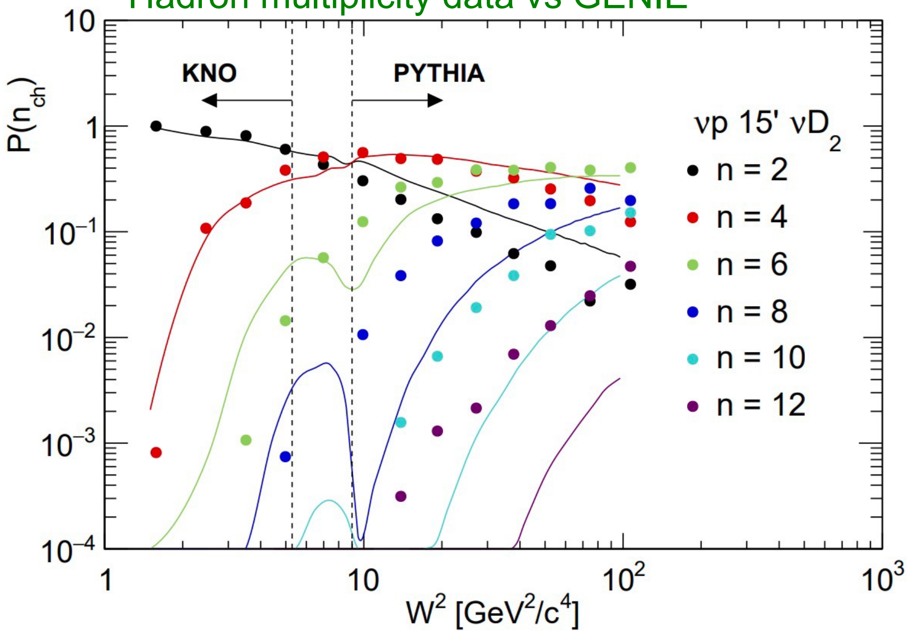
3.3 Path forward: SIS, Hadronization

Shallow-inelastic scattering (SIS)

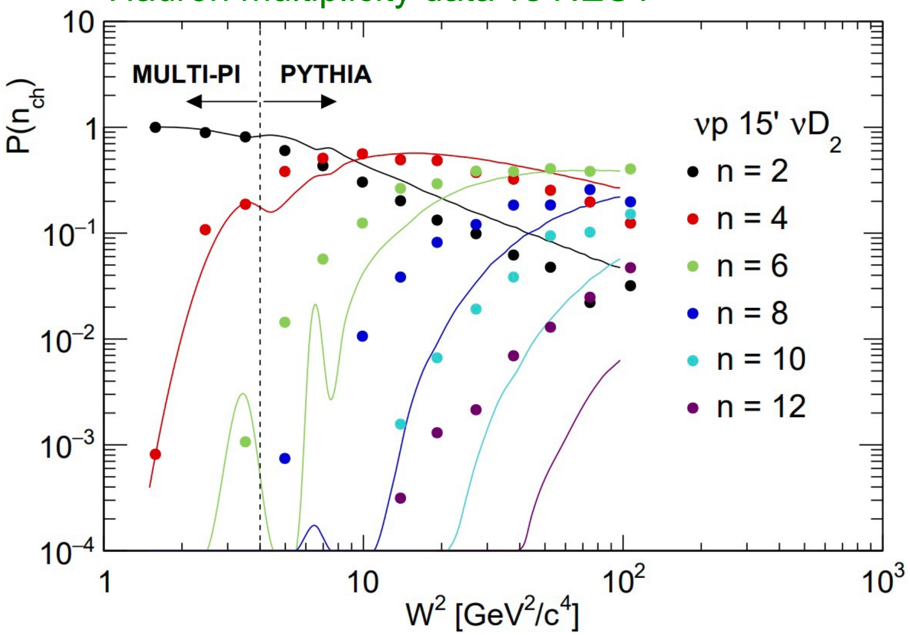
- Neutrino experiments around 1-10 GeV are not quite DIS yet
- Generators disagree how to model SIS
- Predicted cross-sections are not continuous
- Predicted hadron multiplicities are not continuous

PYTHIA cannot reproduce bubble chamber hadron multiplicity dispersion data
→ event-by-event hadron simulation is very difficult

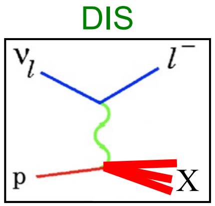
Hadron multiplicity data vs GENIE



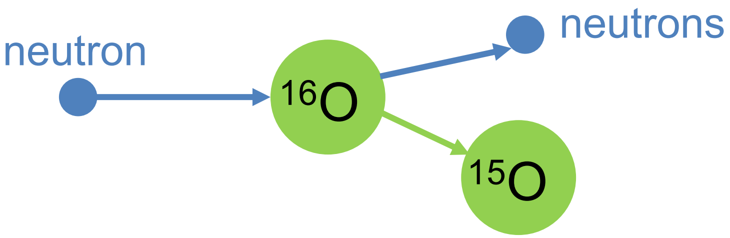
Hadron multiplicity data vs NEUT



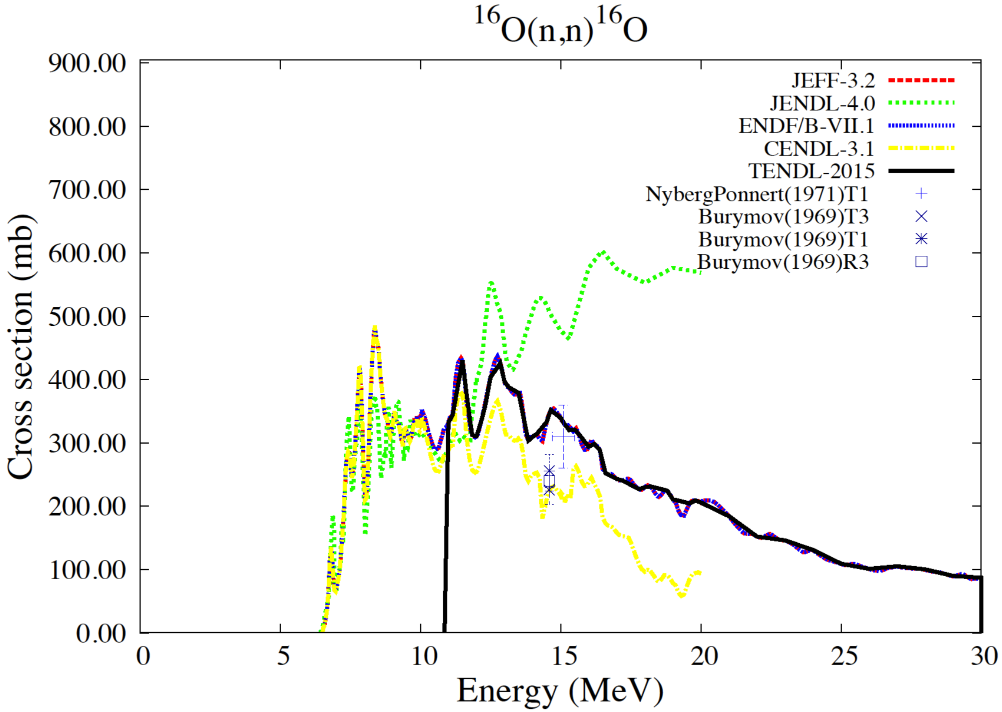
3.3 Path forward: SIS, Hadron propagation



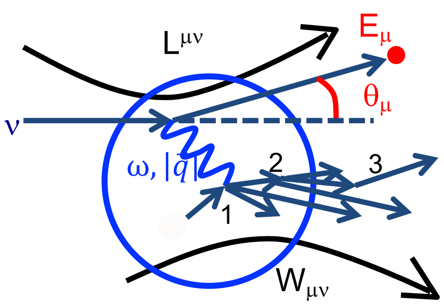
Hadron library
- Geant4 high-precision mode use <20 MeV hadron simulation from hadron library
- Most of inelastic process data are empty (neutron cross-section data > 1 MeV is very sparce, because nobody cares)



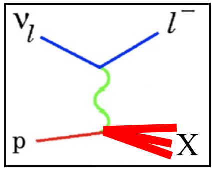
Neutron total inelastic cross section on oxygen



How to simulate final state hadrons
1. Hadronization
2. Final state interactions
3. Hadron propagation in media



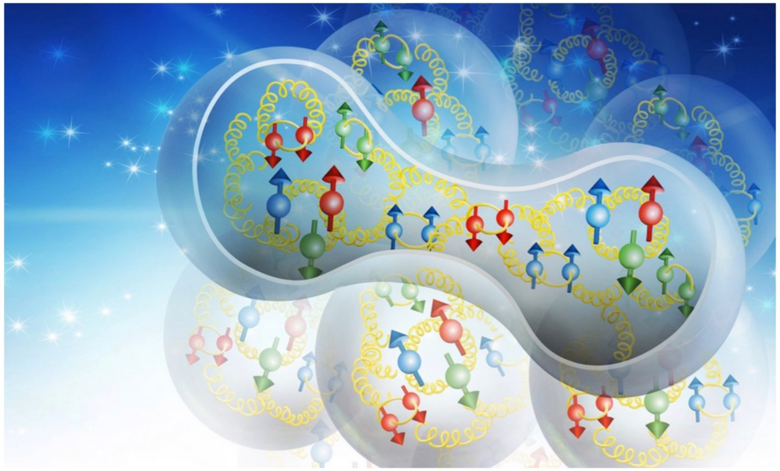
DIS



3.3 Path forward: SIS, Nuclear dependent DIS

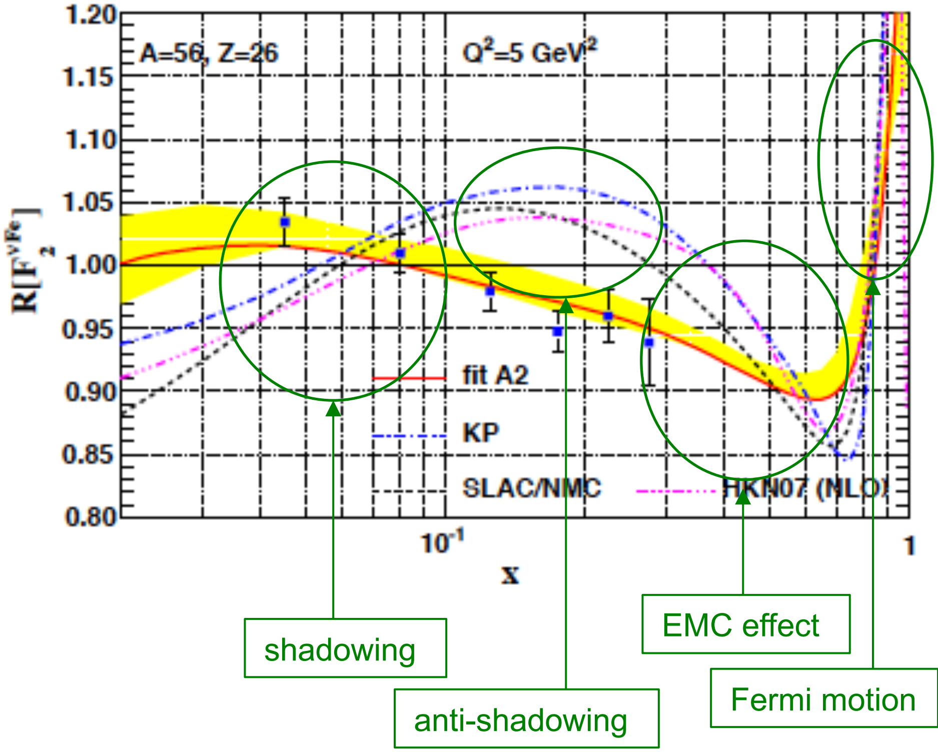
Nuclear dependent DIS
- IF quarks are confined in each nucleon, PDF doesn't depend on nucleus
→ PDF depends on nucleus

CORRELATED NUCLEONS MAY SOLVE 35-YEAR-OLD MYSTERY

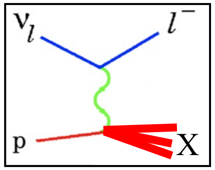


Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Likely due to nucleon dynamics in nucleus
- Various models describe charged lepton data well
- Neutrino data look very different

ν-Fe nuclear correction factor



3.3 Path forward: SIS, systematic error



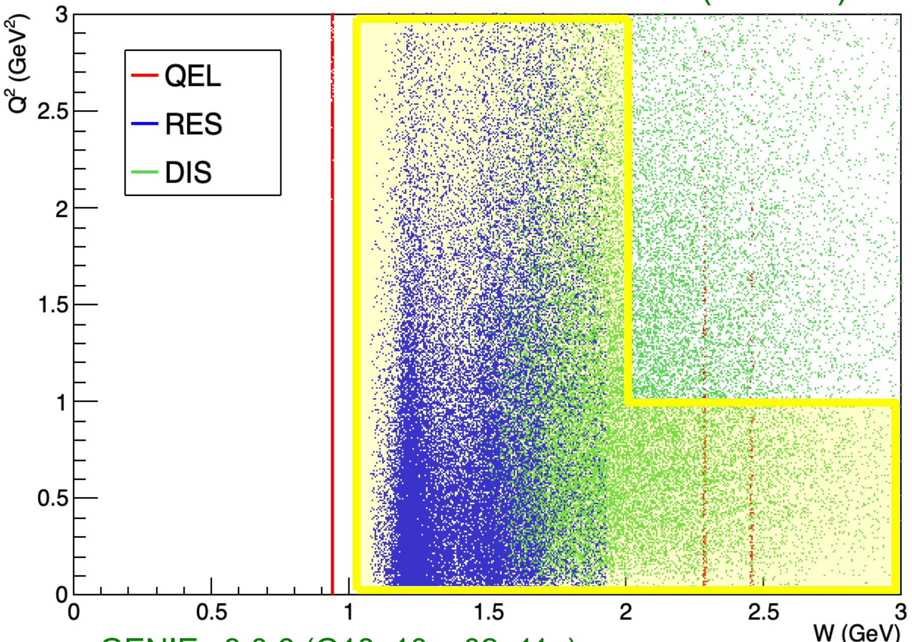
Shallow-inelastic scattering (SIS)
- Neutrino experiments around 1-10 GeV are not quite DIS yet
- Generators disagree how to model SIS
- Predicted cross-sections are not continuous
- Predicted hadron multiplicities are not continuous
  → SIS systematic errors are not easy to evaluate

(Important for DUNE and ν_{atm} oscillation experiments)

Shallow-Inelastic scattering region
- Inelastic: W > 1.07 GeV (= $m_p + m_\pi$)
- Shallow: $Q^2 < 1$ GeV^2 for W > 2 GeV
- Up to 70% of events with DUNE flux fall in this
- Not sure how to estimate errors
  - NOvA motivated multi-hadron errors
  - GENIE motivated Bodek-Yang model

parameter errors, etc

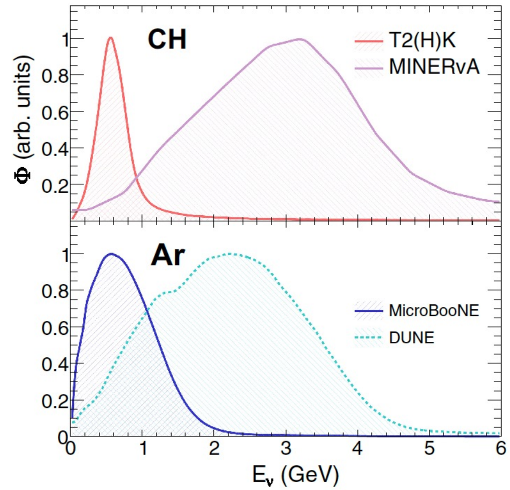
Q²-W with DUNE numu flux on Ar (ν-mode)

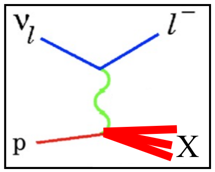


GENIE v3.0.6 (G18_10a_02_11a)

[SBND, ArXiv:2504.00245](https://arxiv.org/abs/2504.00245)

3.3 Path forward: SIS





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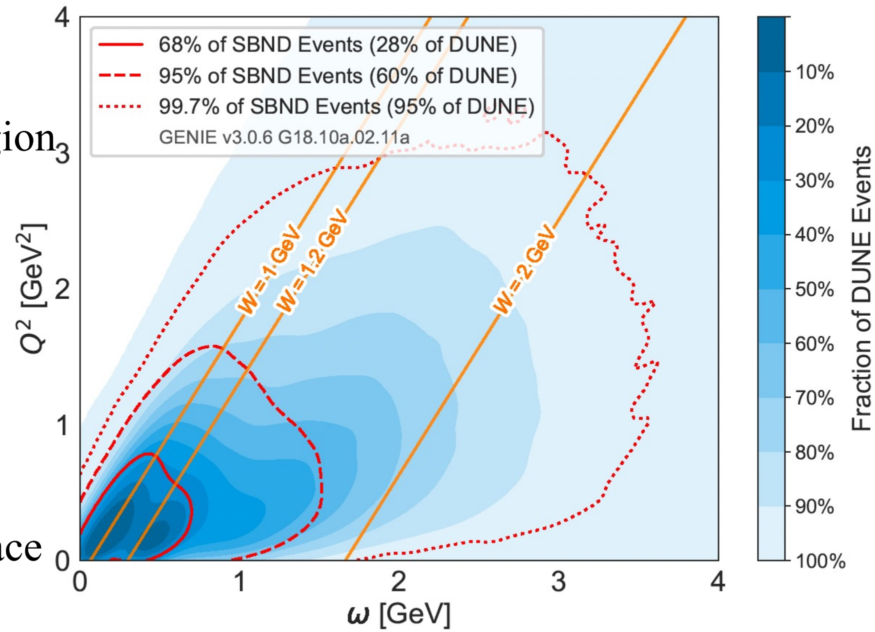
- Shallow: $Q^2 < 1\ GeV^2$ for W > 2 GeV
- Up to 70% of events with DUNE flux fall in this region
- Not sure how to estimate errors
  - NOvA motivated multi-hadron errors
  - GENIE motivated Bodek-Yang model

parameter errors, etc

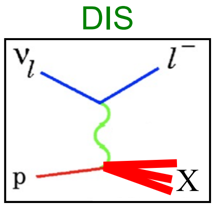
SBND

- BNB energy is much lower than DUNE, but SBND

has very good coverage of DUNE kinematic phase space



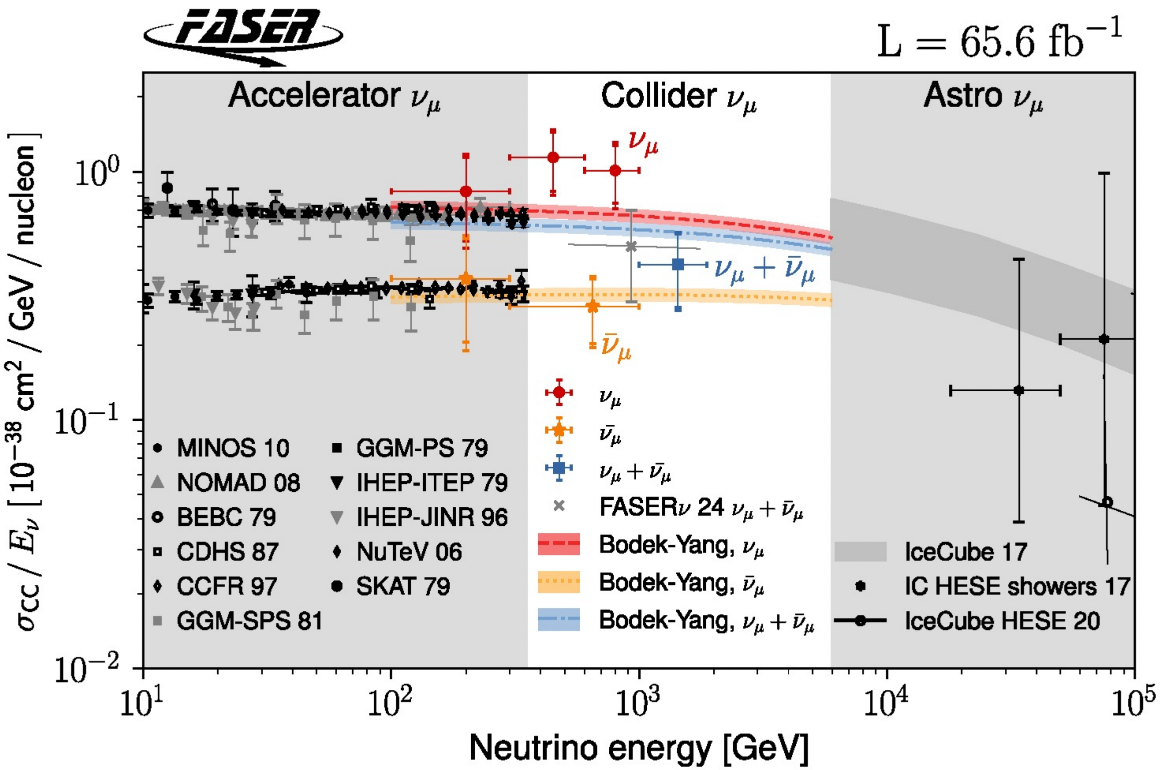
Neutrino data anomalies are (mostly) by Strong interaction

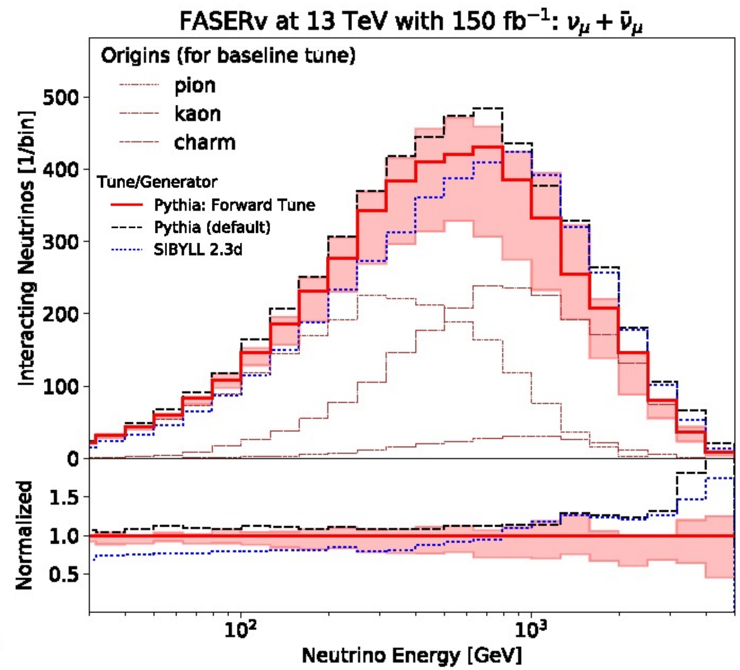


3.3 Path forward: DIS, collider neutrinos

Collider neutrinos

- Man-made neutrino beam up to ~ 2 TeV



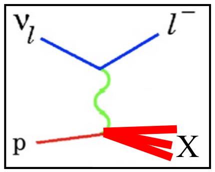


Forward production

- PYTHIA forward physics tune for collider neutrino flux prediction
- Relevant for cosmic rays, LHCb, and neutrino experiments (4π detector)
- Foward physics facility, lake Geneva neutrino experiments, etc

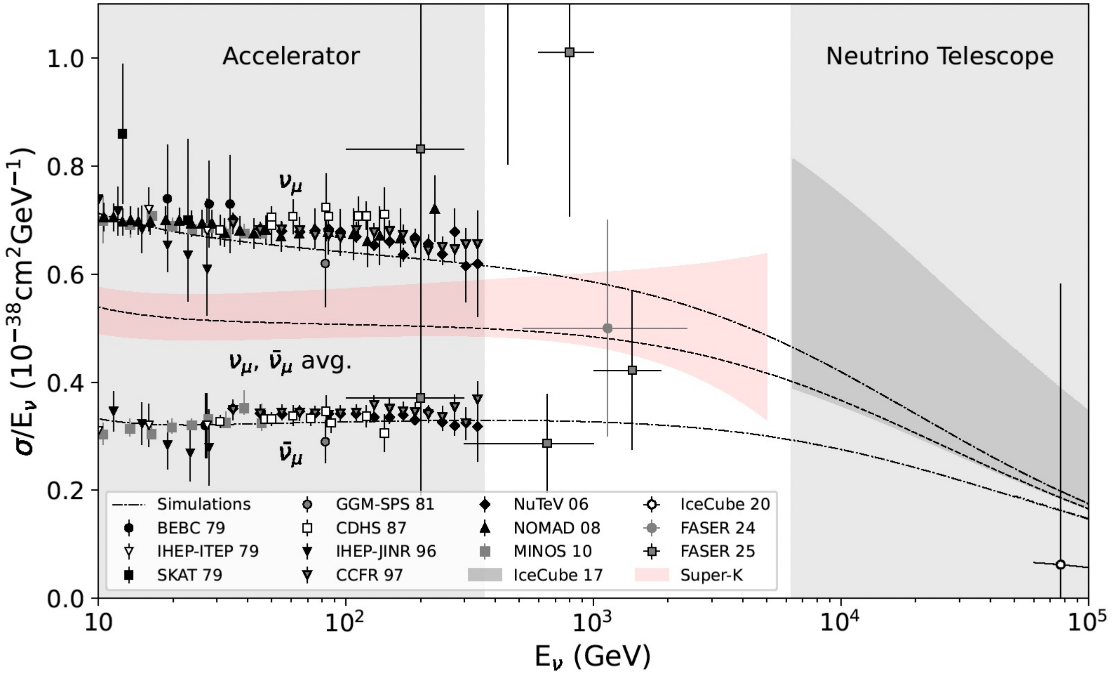
SuperK, PRD94(2016)052001 , SuperK, ArXiv:2605.10221

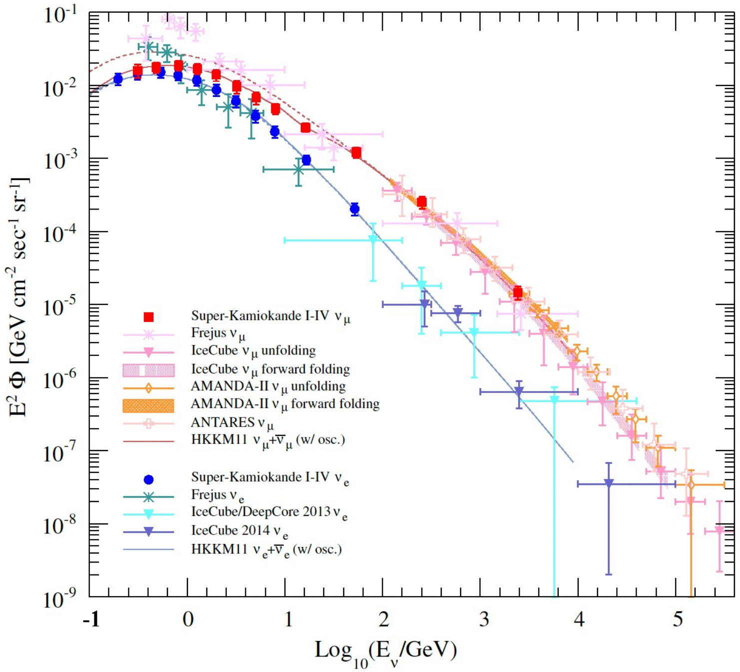
3.3 Path forward: DIS, atmospheric neutrinos



Atmospheric neutrinos

- Natural continuous source up to ~10 TeV
- Relatively well-understood around 10 GeV to 10 TeV (sweet spot for new physic search)





Why ν_{atm} flux understood above 10 GeV

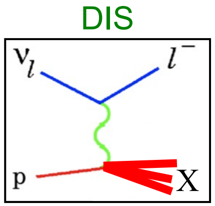
- 1-d cascade model works
- Geomagnetic field effect is weak
- More hadron production data for tuning

Why ν_{atm} flux NOT understood above 10 TeV

- Earth absorption is large
- Prompt (charm decay) ν_{atm} not known
- Astrophysical neutrino contribution

Argüelles et al., PRX13 (2023) 041055, Giner Olavarrieta et al, PRD110(2024)L051101

3.3 Path forward: DIS, inelasticity



Inelasticity

Bjorken $x = \frac{Q^2}{2M\nu}$, $Q^2 = 4EE' sin^2 \frac{\theta}{2} \rightarrow x \sim Q^2 \sim \theta$

Inelasticity $y = \frac{\nu}{E} \rightarrow y \sim \frac{E_{had}}{E}$,

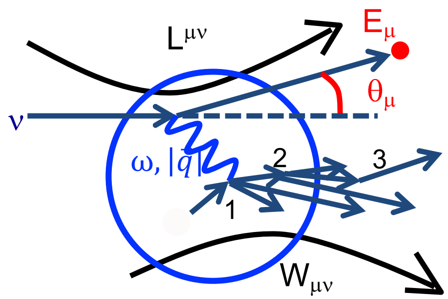
→ Inelasticity can be estimated from sources without direction information

Statistical $\nu_\mu - \bar{\nu}_\mu$ separation using inelasticity

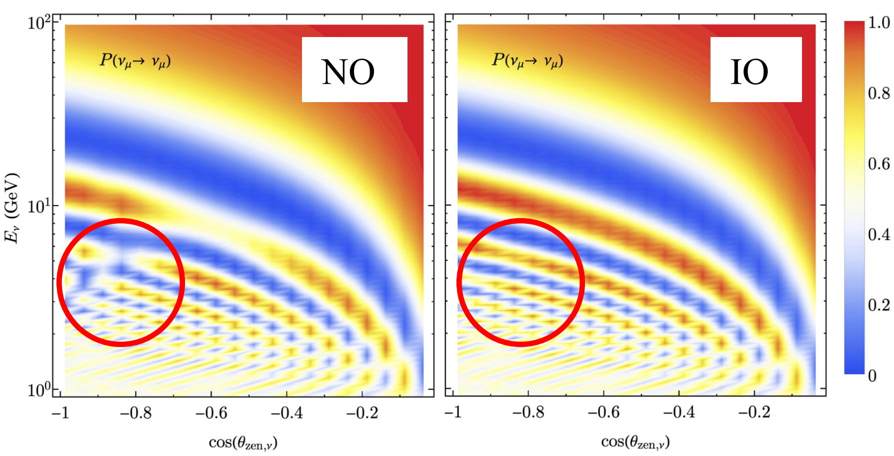
- MSW resonance at 6 GeV
- Neutrino mass hierarchy from atmospheric neutrinos

Challenges

0. Good detector to measure hadronic energy deposit
1. Hadronization
2. Final state interactions
3. Hadron propagation in media

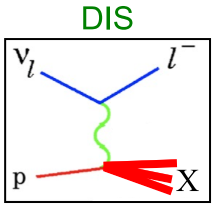


νμ-disappearance oscillogram



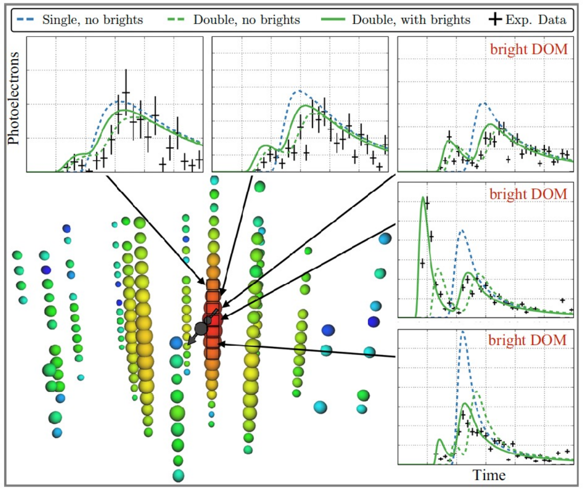
Snowmass 2021 report, J.Phys.G49(2022)110501 , FPF NPB1026(2026)117398
DONUT, PLB504(2001) 218, IceCube, EPJC82 (2022)1031

3.3 Path forward: DIS, tau neutrinos



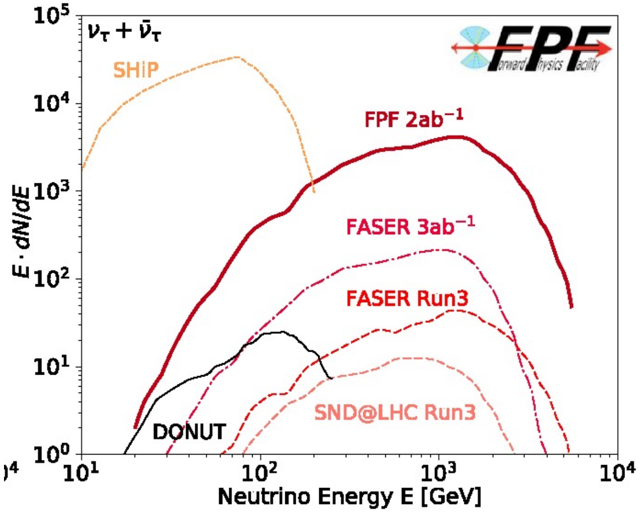
Tau neutrinos

- Least understood, first detection 2001
- Heaviest charged lepton
  → access to cross-section terms proportion to $\propto m_l \ /M \quad , m_l^2/M^2$
- Second class form factors
- F4 and F5 structure functions



PID is challenging

- ν_τCCQE threshold ~3.5 GeV
- 1 PeV tau travels 50 m (IceCube double bang) → Too rare
  → ~100 TeV tau with ~20 m elongated cascade (IceCube)
  → ~20 GeV tau travel 0.5mm track (DONUT)
- ~100 TeV tau production and decay ~100 ns (IceCube)
  → ~100 GeV tau production and decay, ~100 ps
- 2/3 multi-hadronic decay
- 1/3 leptonic decay



Challenging to extract a good kinematic information (cross-section measurement)
- Dedicated facility (SHiP, FASER, SND@LHC etc)

1. Past

1.1 Overview of neutrino interaction physics
1.2 Brief history of neutrino interaction for discovery physics
1.3 Anomalies in neutrino interaction physics

2. Presence

2.1 Flux-averaged differential cross-section
2.2 Incomplete lepton kinematics
2.3 Fully active 4π detector

3. Future

3.1 Path forward: QE
3.2 Path forward: RES
3.3 Path forward: DIS

4. Summary

Summary

Past:
Neutrino interaction physics is a successful sub-field of particle physics for many discoveries. Modern neutrino experiments revealed non-negligible nuclear effects.

Presence:
Flux-averaged differential cross-section is currently used as a successful tool to study neutrino interactions with nuclear effects. This requires the community to accept incomplete lepton kinematics with new hadron kinematic variables. T2K, MINERvA, MicroBooNE data are actively used to study neutrino interactions.

Future:
Neutrino interaction physics has many challenges, both theory and experiment. RES and DIS become more important for future experiments and SBND seems very important for these.
- QE region: nucleon form factors, 2p2h
- RES region: pion production models, FSIs
- DIS region: SIS, hadronization

Thank you for your attention!

Backup

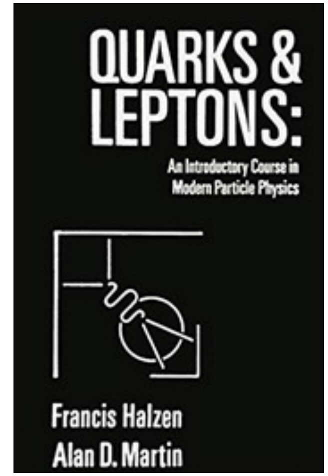
References (books)

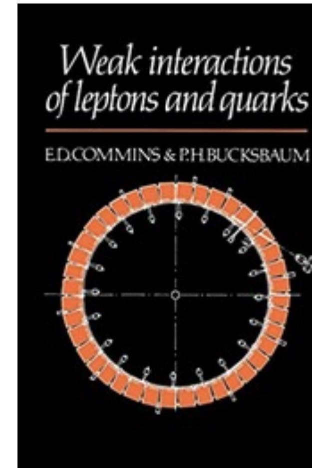
Quarks and Leptons (Halzen and Martin)
- many derivations of famous formula
- solutions for all exercises

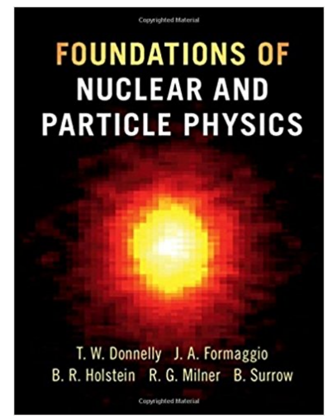
Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- details of weak interaction calculations
- too many typos

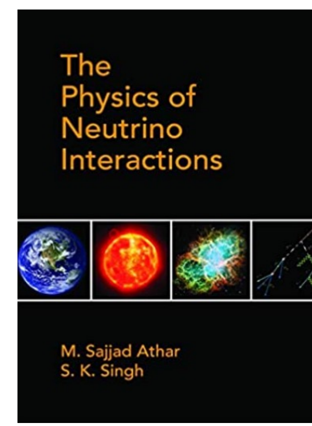
Foundation of Nuclear and Particle Physics (2017)
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- buy if your PhD thesis topic is about neutrino cross section measurements in T2K, NOvA, SBN, etc

The Physics of Neutrino interactions (2020)
- The newest book in this kind (970 pages!)





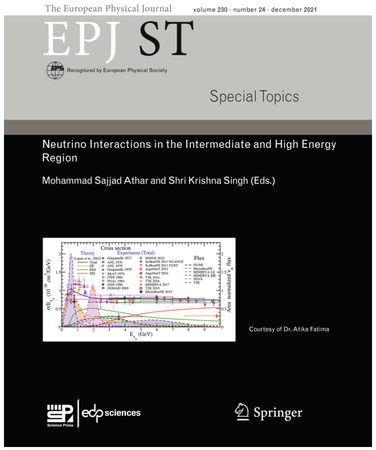




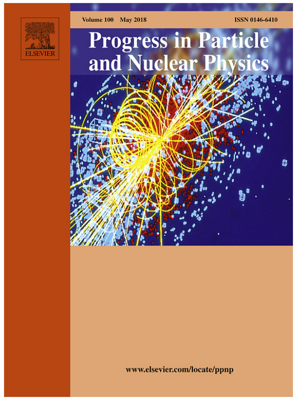
References (papers)

“Neutrino Interactions in the Intermediate and High Energy Region”
- EPJ Special Topic (2021)

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



“NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering”
- NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)
- Prog.Part.Nucl.Phys. 100 (2018) 1-68, https://arxiv.org/abs/1706.03621
- Cover all open issues in the community



“Neutrino-Nucleus Cross Sections for Oscillation Experiments”
- Authors: Katori (me) and Martini (Martini model)
- J.Phys. G45 (2018) no.1, 013001, https://arxiv.org/abs/1611.07770
- A review both theoretical and experimental views

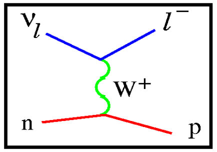
“From eV to EeV: Neutrino cross sections across energy scales”
- Authors: Formaggio and Zeller (MicroBooNE spokesperson)
- Rev.Mod.Phys.84(2012)1307, https://arxiv.org/abs/1305.7513
- very good summary of neutrino cross sections

“NuSTEC News”
- http://nustec.fnal.gov/
- subscribe mailing list, “like” facebook page, use #nuxsec

Smith and Moniz, NPB43(1972)605
Ashkenazi (Neutrino 2020), https://zenodo.org/record/3959538

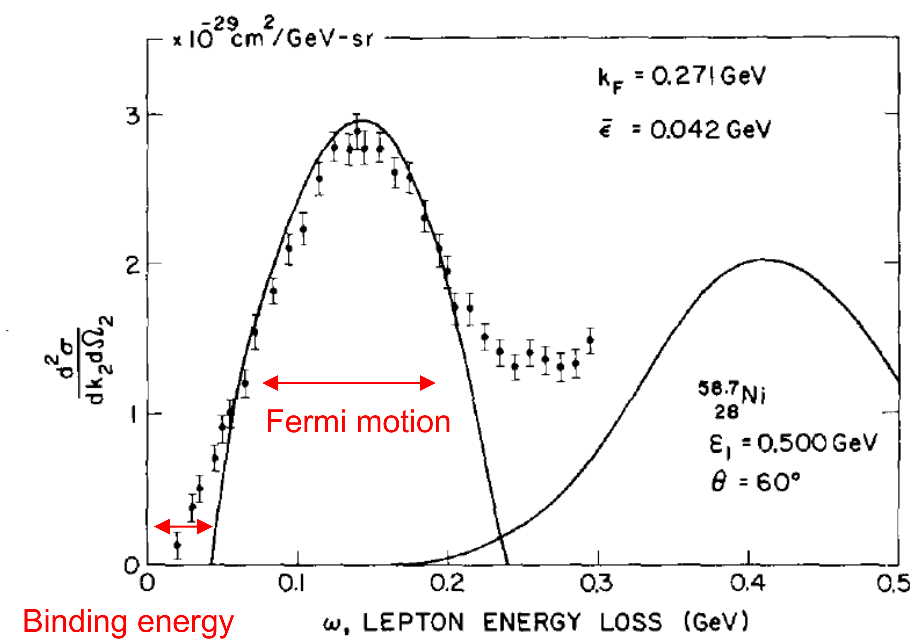
1.1. Fermi motion

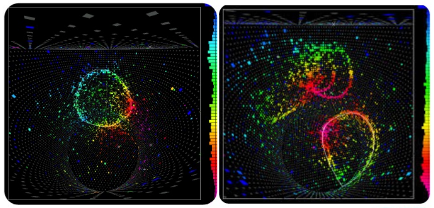
Quasi Elastic



Fermi motion

- Measured energy is smeared from the true energy if you assume nucleon at rest
- High resolution detector can measure all outgoing hadrons
  → initial nucleon momentum can be reconstructed (no Fermi motion smearing)



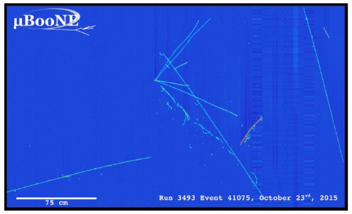


Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$



Tracking detectors:

Calorimetric sum

Using All detected particles

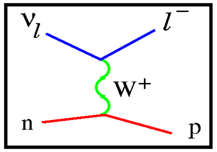
$$E_{cal} = E_l + E_p^{kin} + \epsilon$$

[1p0π]

Smith and Moniz, NPB43(1972)605
MiniBooNE, PRD81(2010)092005

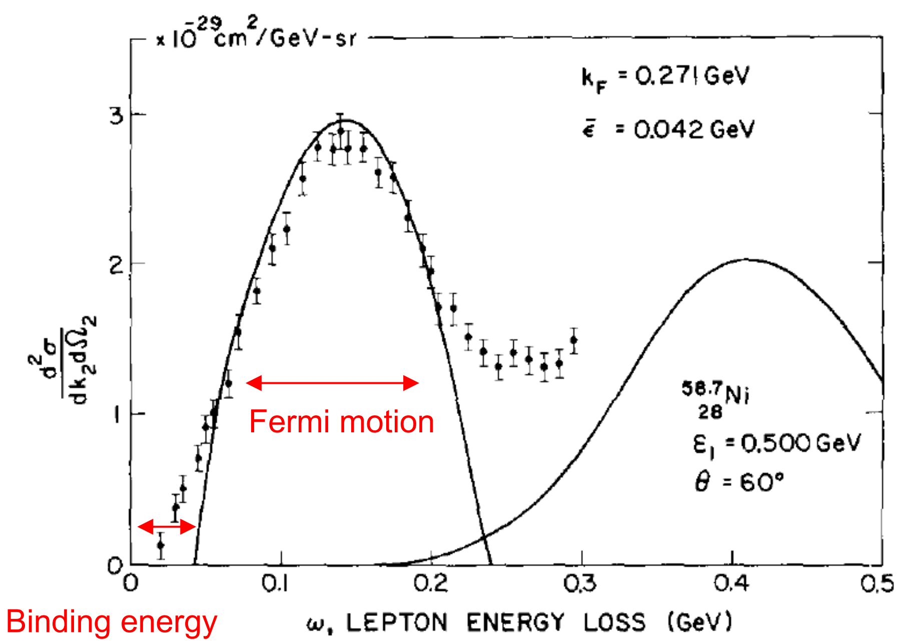
1.1. Pauli blocking

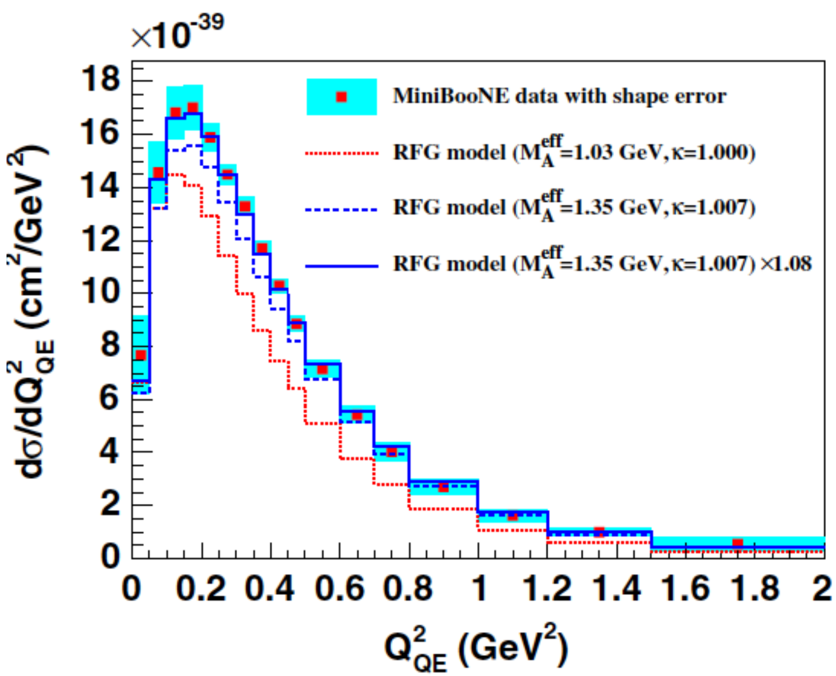
Quasi Elastic



Pauli blocking

- Low momentum transfer reaction is forbidden.
- data show more suppression than what Pauli blocking can → RPA(?)
- In the global Fermi gas model, Pauli blocking looks unphysical

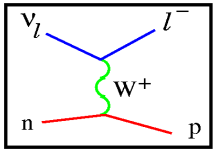




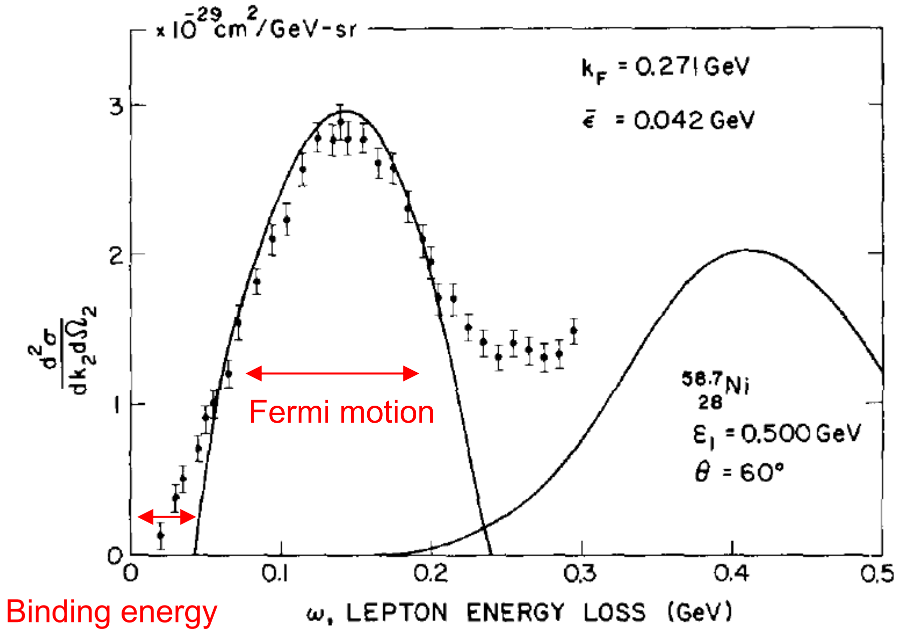
Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

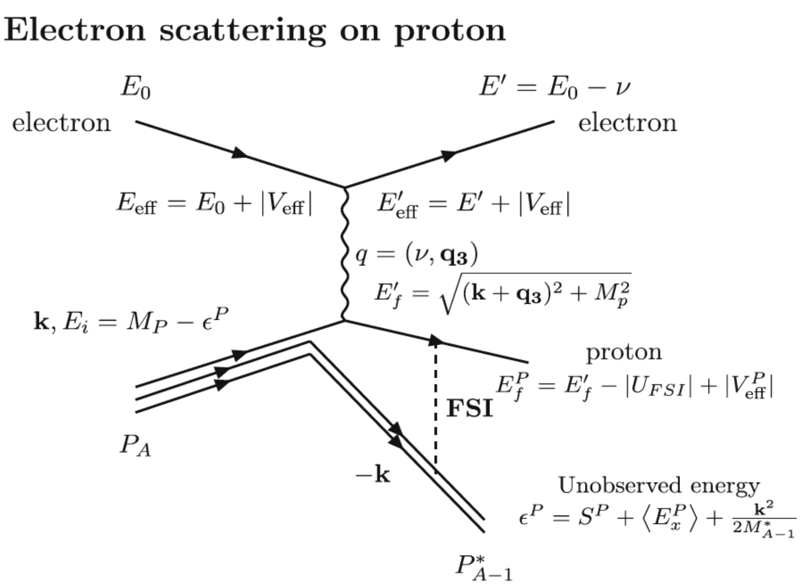
1.1. Nuclear Shell structure and binding energy

Quasi Elastic



Binding energy ~ unobserved energy
- Energy to cost to release 1 nucleon, not constant
- Separation energy + excitation energy + recoil energy
  - Separation energy: energy to release 1 nucleon from the shell (~15 MeV, depends)
  - Excitation energy: energy used to excite leftover target nucleus (~1 MeV)
  - Recoil energy: kinetic energy of recoil target nucleus (~2-3 MeV)
- In general, neutrino interaction generators violate energy-momentum conservation





1.2 Neutrino-DIS cross section

Neutrino – single d-quark cross section

$$\frac{d\sigma}{dy}(\nu d \rightarrow \mu u) = \frac{G_F^2 xs}{\pi}$$

Neutrino – d-quark cross section

$$\frac{d\sigma}{dy}(\nu d \rightarrow \mu u) = \int_0^1 \frac{G_F^2 xs}{\pi} d(x) dx$$

Neutrino-nucleon DIS cross section

$$\frac{d\sigma}{dy}(\nu N \rightarrow \mu X) = \int_0^1 \frac{G_F^2 xs}{\pi} [(d(x) + s(x) \dots) + [\bar{u}(x) + \bar{c}(x) \dots](1-y)^2] dx$$

Neutrino-nucleus DIS cross section with isoscalar assumption

$$\frac{d\sigma}{dy}(\nu A \rightarrow \mu X) = A \int_0^1 \frac{G_F^2 xs}{\pi} [Q(x) + \bar{Q}(x)(1-y)^2] dx$$

$$u^p(x) + u^n(x) = d^n(x) + d^p(x) = u(x) + d(x) \equiv Q(x)$$
$$\bar{u}^p(x) + \bar{u}^n(x) = \bar{u}^n(x) + \bar{u}^p(x) = \bar{u}(x) + \bar{d}(x) \equiv \bar{Q}(x)$$

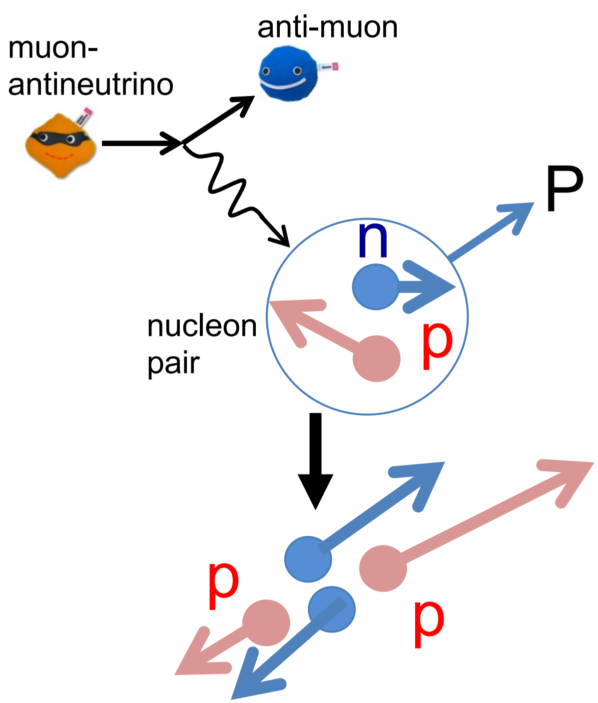
1.2 Studies of nuclear effect

Fermilab 15" bubble chamber detector (Fermilab)

$$\bar{\nu}_\mu + Ne \rightarrow \mu^+ + X + pp \ldots$$

Backward protons due to nuclear effect
→ nucleon correlations

Proton-Neutron pair
- If one is struck forward, others can move backward
- Proton multiplicity is ~1 higher with backward going p



PHYSICAL REVIEW D VOLUME 18, NUMBER 5 1 SEPTEMBER 1978

Probing nuclei with antineutrinos

Variable[a]	Backward-proton events	Charged-current events
Number of events	36	837
$\langle E_{\bar{\nu}} \rangle$ (GeV)	25.48 ± 2.82	28.78 ± 0.71
$\langle P_\mu \rangle$ (GeV/c)	18.10 ± 2.36	19.02 ± 0.53
$(1-\cos\theta_\mu)$	$(2.87 \pm 0.60) \times 10^{-3}$	$(5.96 \pm 0.31) \times 10^{-3}$
$\langle \nu \rangle$ (GeV)	7.38 ± 1.47	9.71 ± 0.44
$\langle Q^2 \rangle$ [(GeV/c)^2]	1.43 ± 0.25	3.58 ± 0.15
$\langle x \rangle$	0.17 ± 0.02	0.23 ± 0.01
$\langle y \rangle$	0.26 ± 0.03	0.33 ± 0.01
$\langle n \rangle$	7.42 ± 0.64	6.20 ± 0.11
$\langle C \rangle$	2.14 ± 0.17	1.25 ± 0.04
$\langle C_1 \rangle$	0.81 ± 0.28	0.98 ± 0.04