Neutrino Interaction Physics

Lecture 1: Introduction of neutrino interactions
1. Overview
2. Neutrino lepton scattering
3. Neutrino quark scattering (DIS)
4. Neutrino nucleus reactions

Lecture 2: Neutrino interactions for long baseline oscillation experiments
1. Overview
2. CCQE interaction
3. Baryonic resonances
4. Shallow inelastic scattering (SIS)

Teppei Katori
King's College London
Nov. 11, 2019

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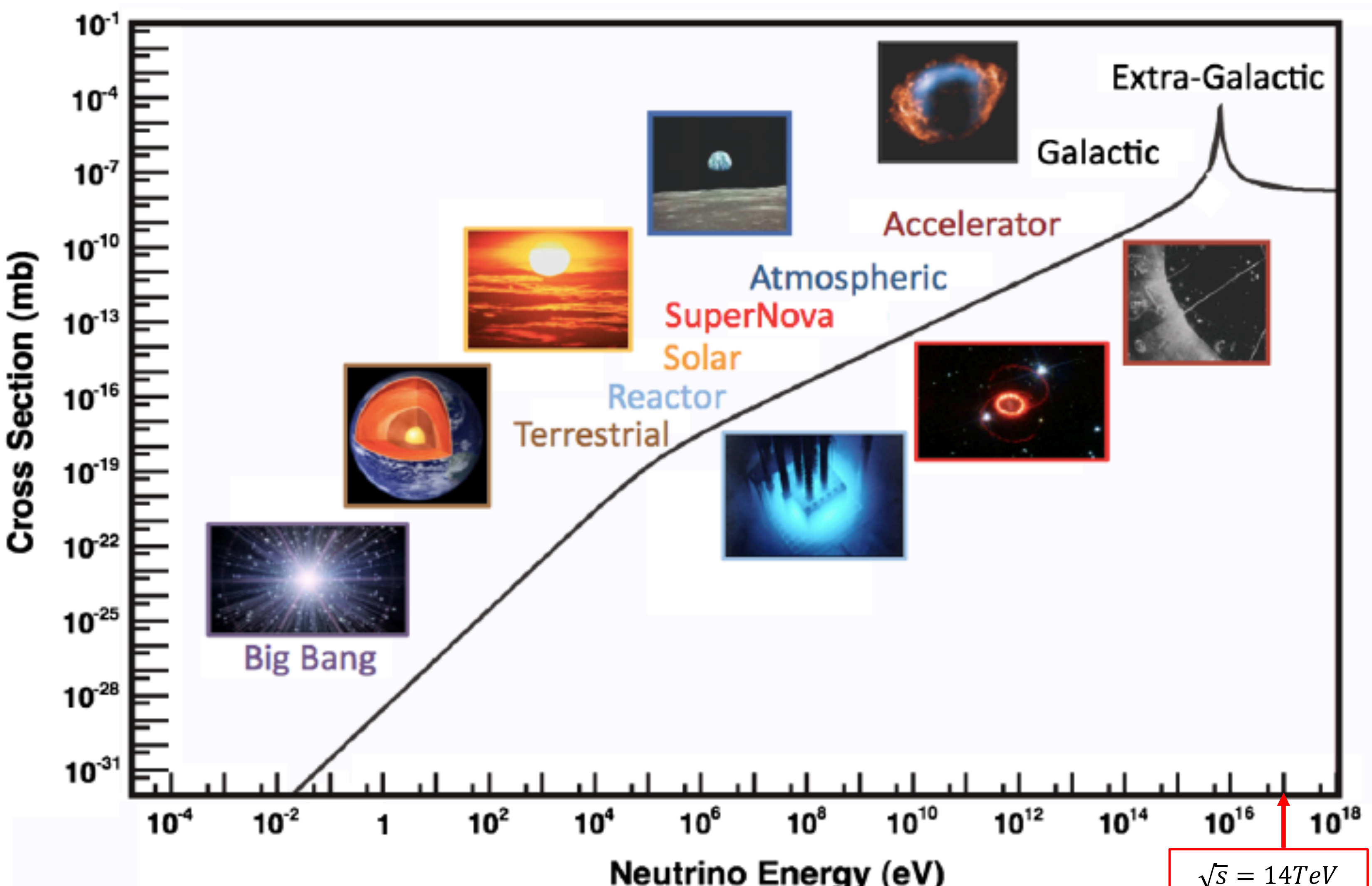
1. From eV to EeV: Neutrino cross sections across energy scales



$\sqrt{s} = 14TeV$

Alexander 2016 J.Phys.:Conf. Ser. 718(2016)062076

2. Neutrino-electron scattering

Neutrino – electron differential cross section

T=recoil electron kinetic energy

E=neutrino energy

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

Neutrino – electron differential cross section with neutrino magnetic moment

($\mu_\nu < 3\text{x}10^{-11}\ \mu_B$)

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

Lepton-only process is often used to test new physics

	C_L	C_R
ν_e - e^-	$\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$
$\overline{\nu_e}$ - e^-	$\sin^2\theta_W$	$\frac{1}{2}+\sin^2\theta_W$
ν_μ - e^-	$-\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$
$\overline{\nu_\mu}$ - e^-	$\sin^2\theta_W$	$-\frac{1}{2}+\sin^2\theta_W$

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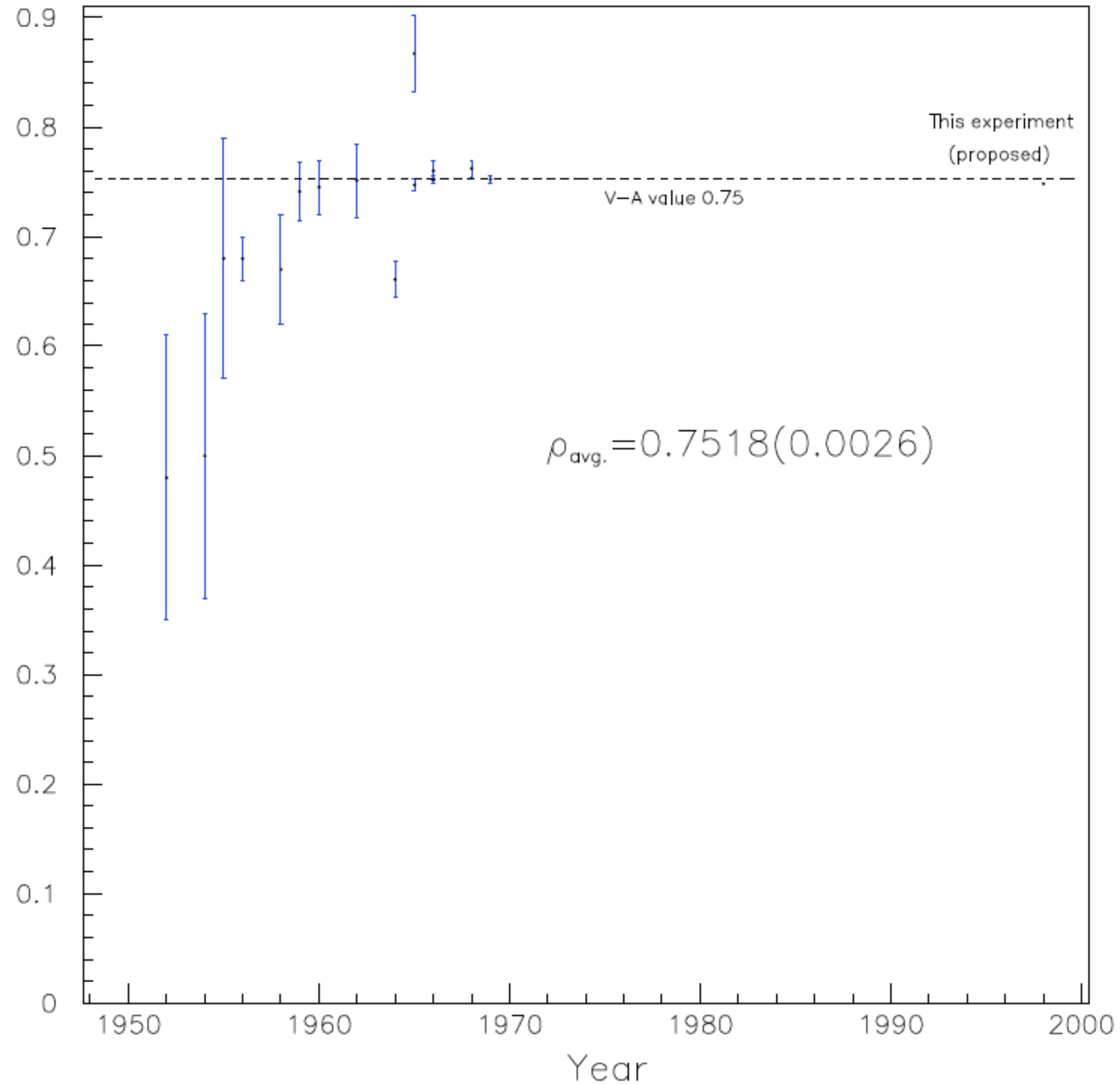
2. Time dependence of muon decay Michel parameter ρ



3. Neutrino-DIS cross section

Neutrino – single d-quark cross section

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

Neutrino – d-quark cross section

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

Neutrino-nucleon DIS cross section

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

Neutrino-nucleus DIS cross section with isoscalar assumption

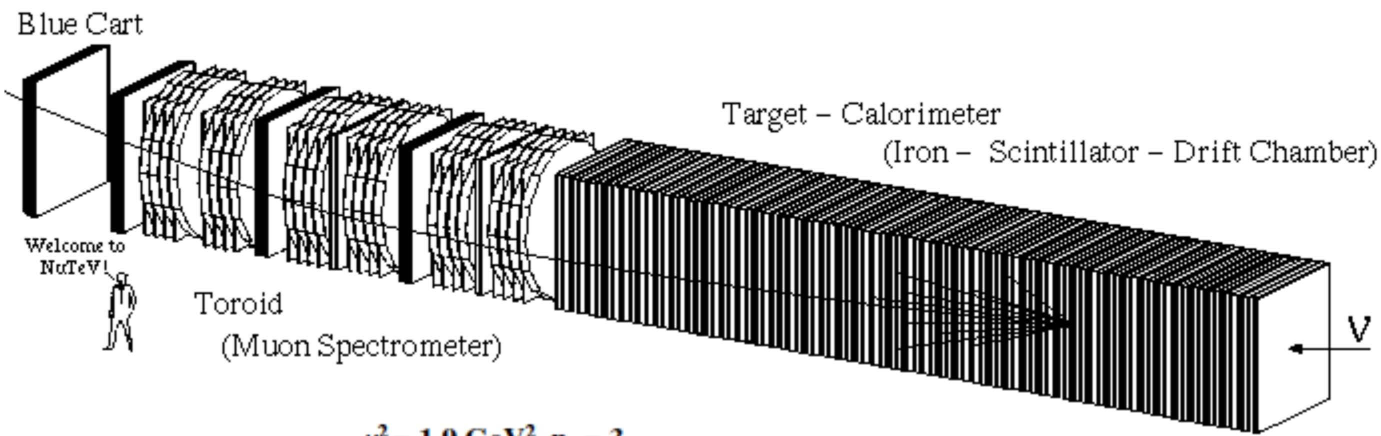
$$\frac{d\sigma}{dy}(\nu A \to \mu X) = A \int_0^1 \frac{G_F^2 xs}{\pi} [Q(x) + \bar{Q}(x)(1-y)^2] dx$$

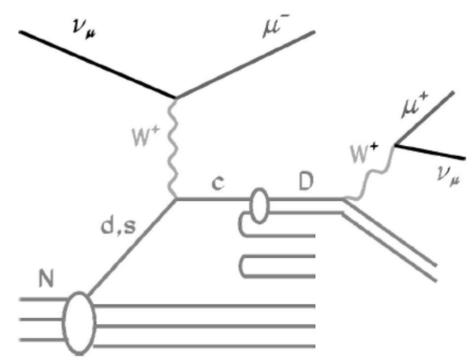
$$u^p(x) + u^n(x) = d^n(x) + d^p(x) = u(x) + d(x) \equiv Q(x)$$

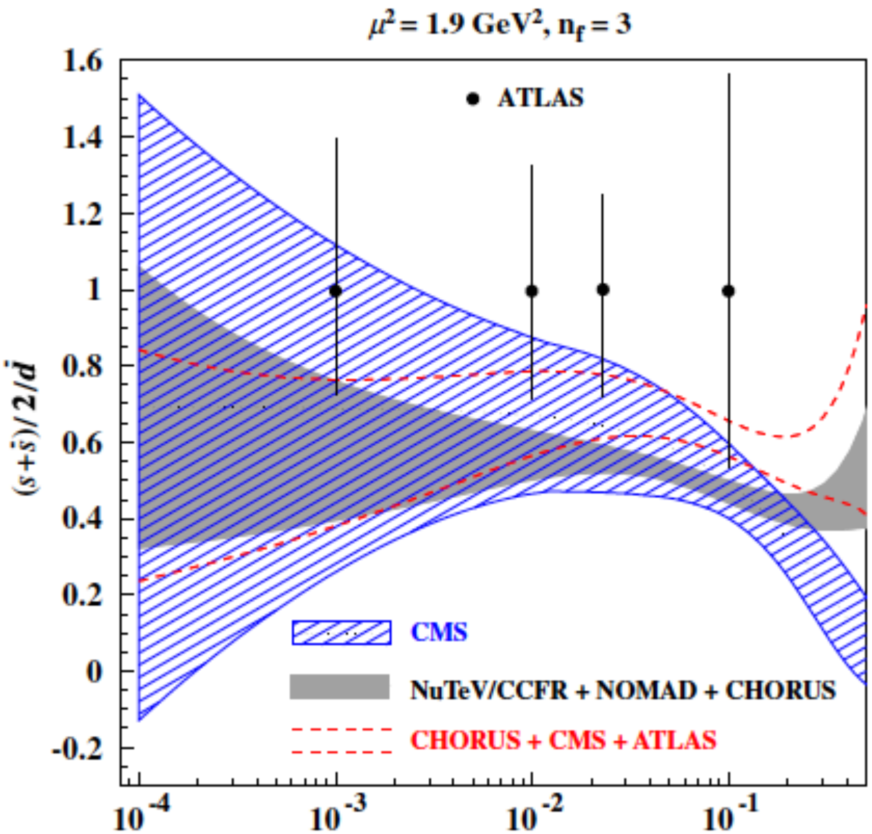
$$\bar{u}^p(x) + \bar{u}^n(x) = \bar{u}^n(x) + \bar{u}^p(x) = \bar{u}(x) + \bar{d}(x) \equiv \bar{Q}(x)$$

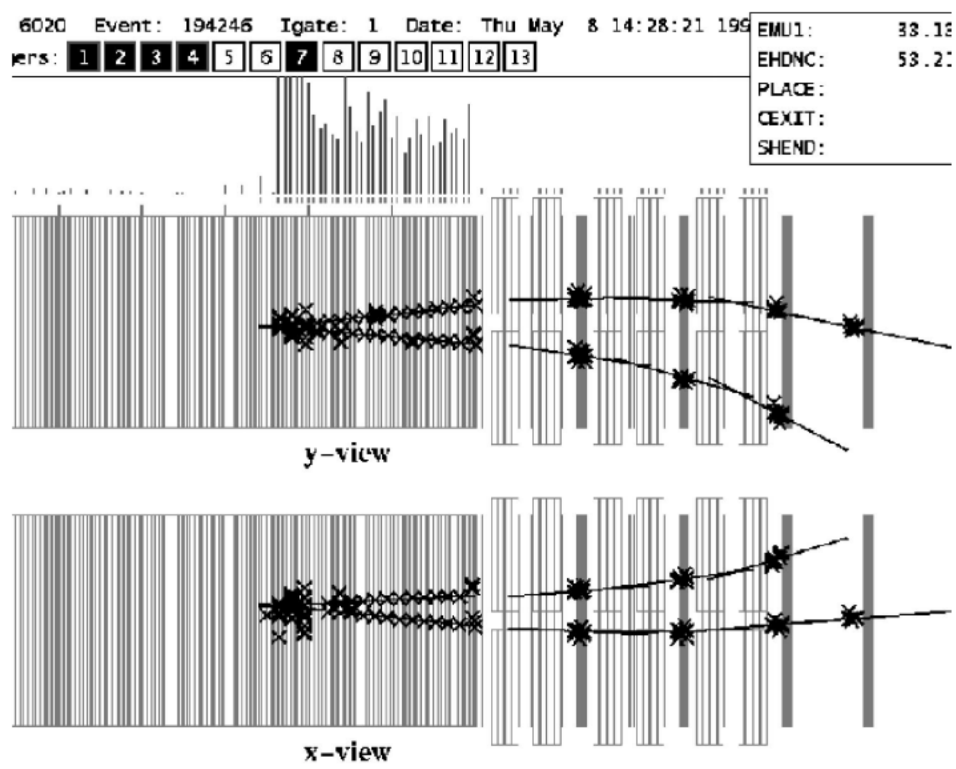
NuTeV, PRD64(2001)112006
Alekhin et al.,PRD91(2015)094002

3. Di-muon production

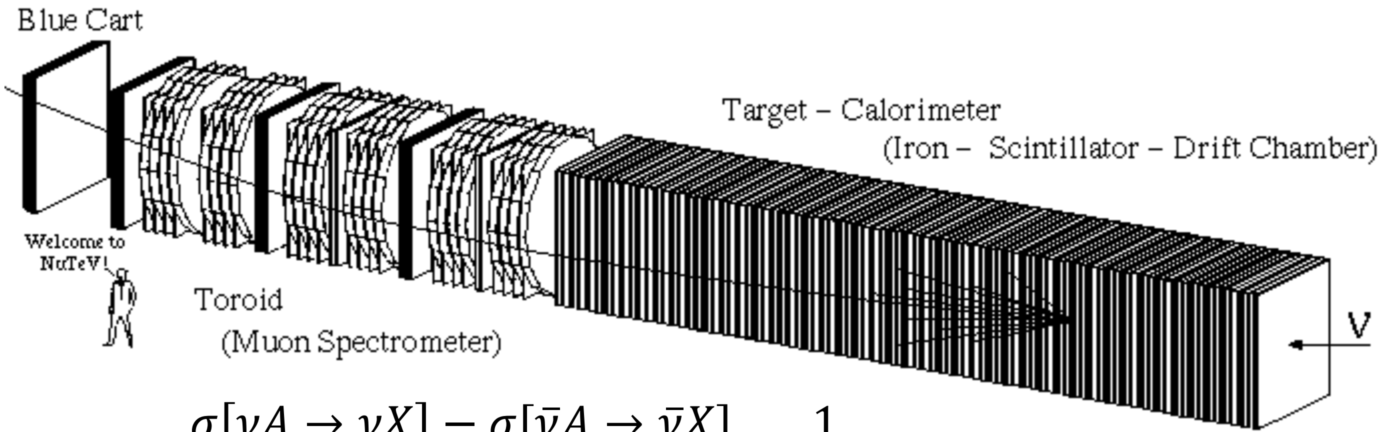








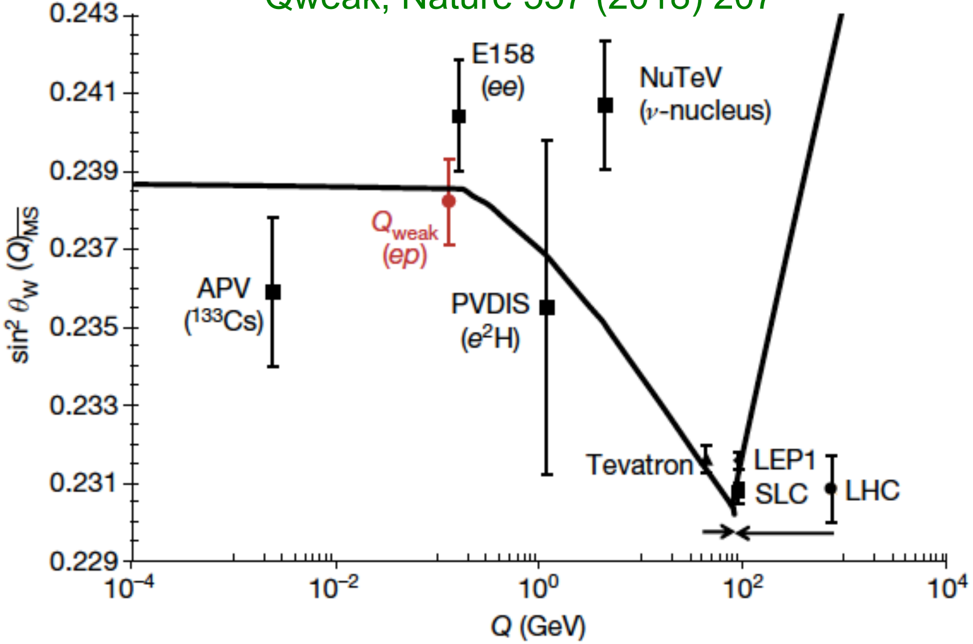
3. Paschos-Wolfenstein ratio and NuTeV anomaly



Manny Paschos (Dortmund)

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

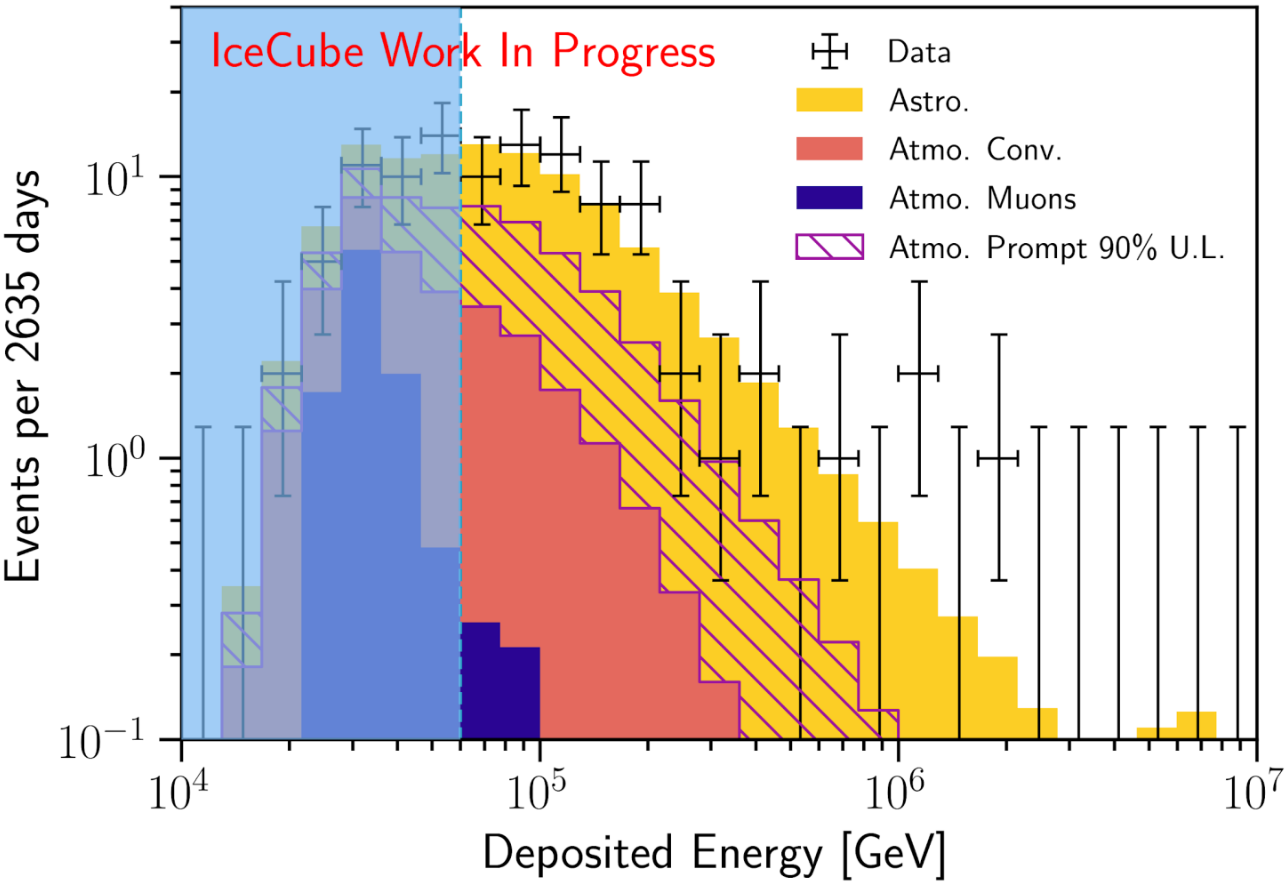
Qweak, Nature 557 (2018) 207



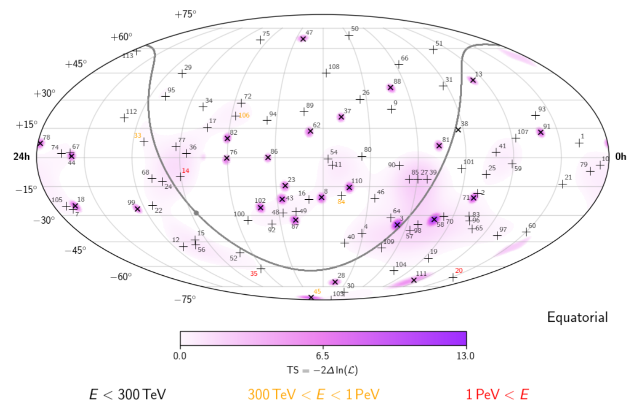
3. Astrophysical high-energy neutrino measurement

cross section, efficiency, flux, target

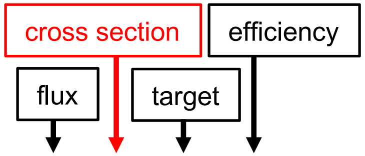
Event rate $N = \Phi \times \sigma \times T \times \varepsilon$



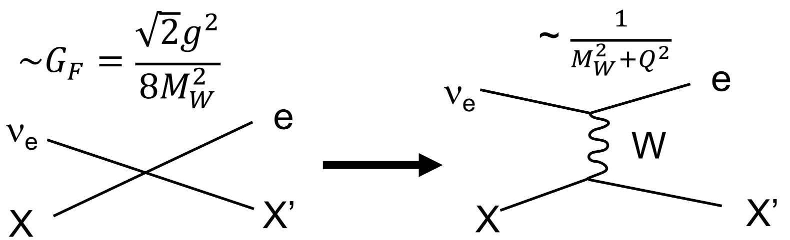
IceCube preliminary 2018

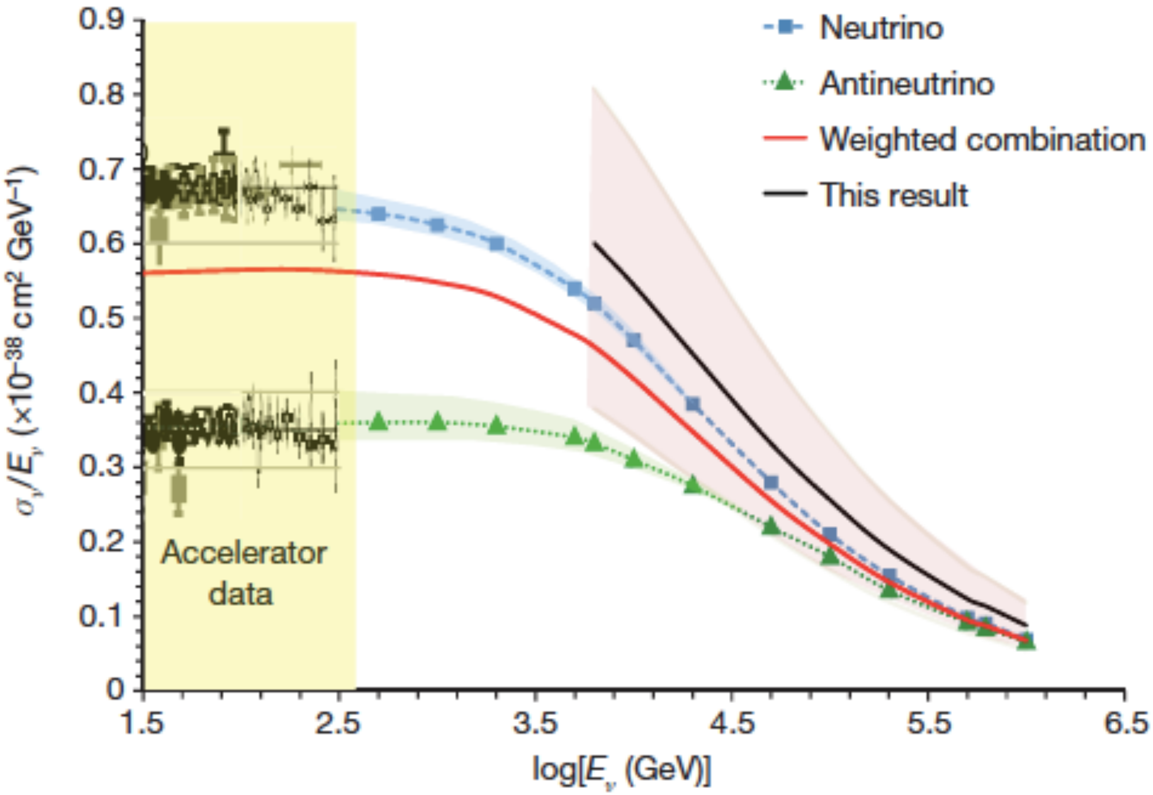


3. Neutrino DIS saturation



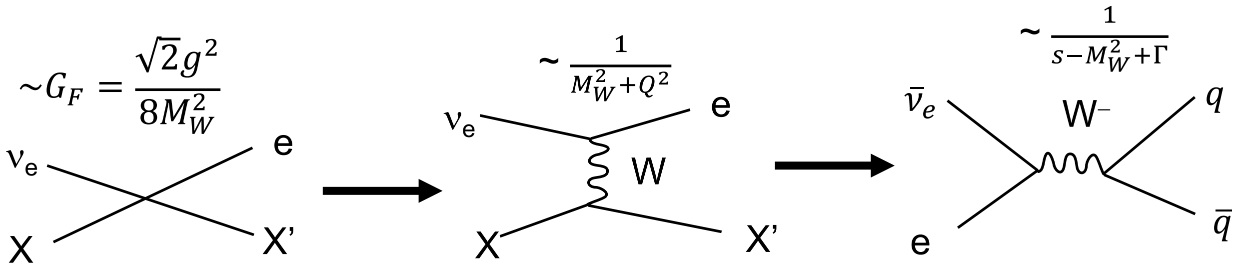
Event rate $\mathrm{N} = \Phi \times \sigma \times T \times \varepsilon$



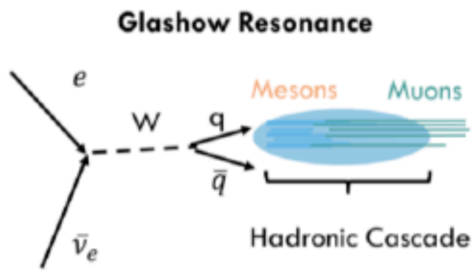


IceCube preliminary

3. Glashow resonance

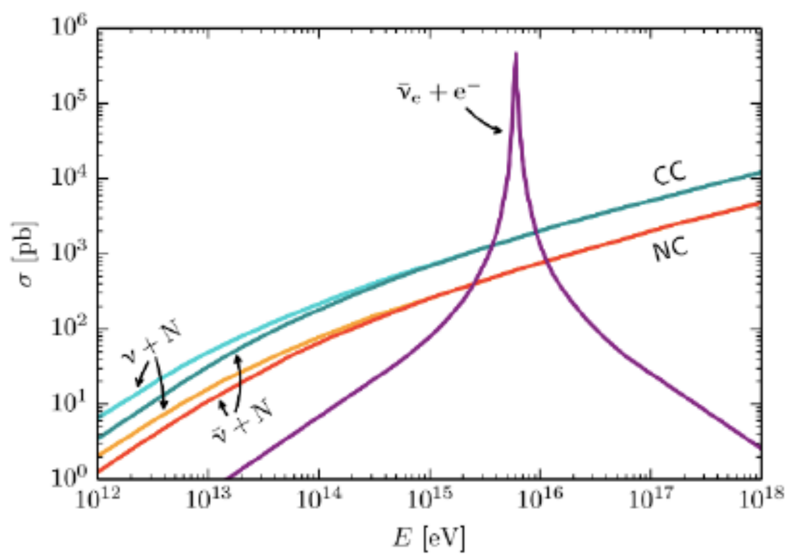


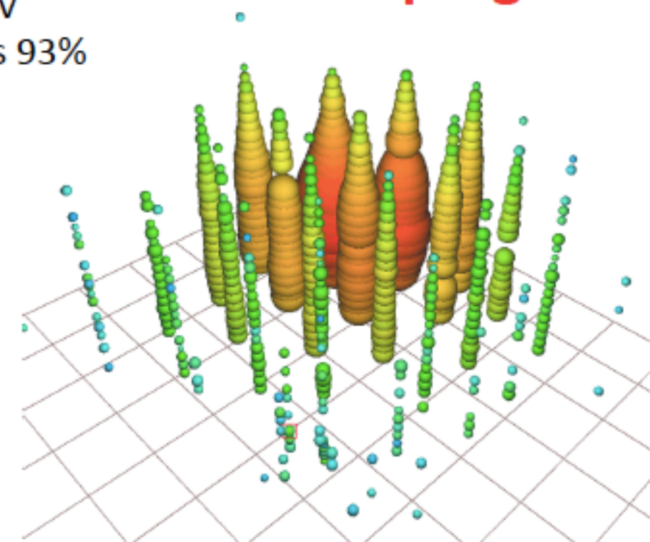
A 5.9 PeV event in IceCube



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

Work in progress





Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

Dziewonski, Anderson (PREM), Phys. Earth Planet.Inter.25,(1981)297
Donini, Palomares-Ruiz, Salvado, Nature Physics 15(2019)37

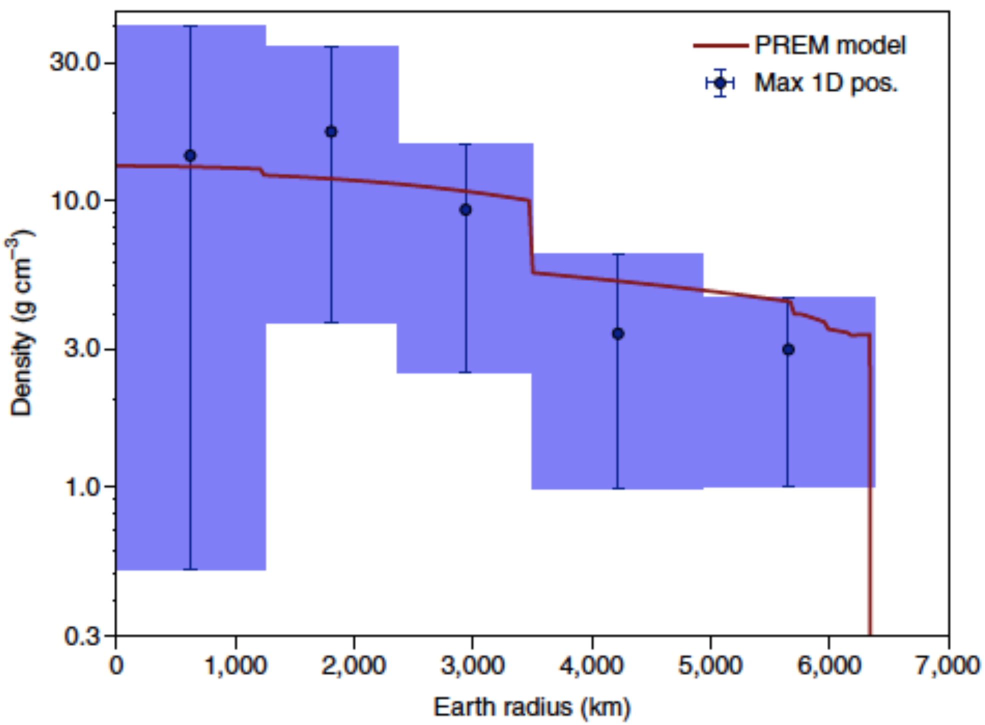
3. Earth tomography

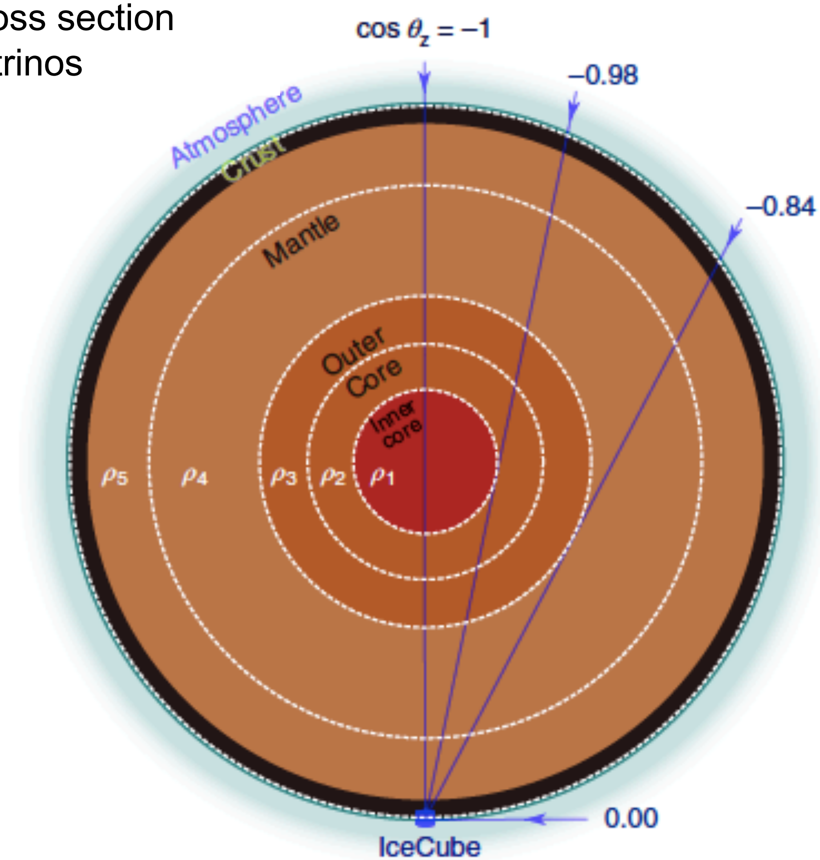
cross section | efficiency | flux | target

Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Earth absorption for Earth density measurement

- PREM (Preliminary reference Earth model)
- Standard earth density model used by T2K, NOvA, etc
- Earth density profile is extracted by assuming flux and cross section
- Measure Earth moment of inertia and Earth mass by neutrinos





Cleveland et al.,Astrophys.J.496(1998)505
Pontecorvo,Phys.Lett.28B(1969)493

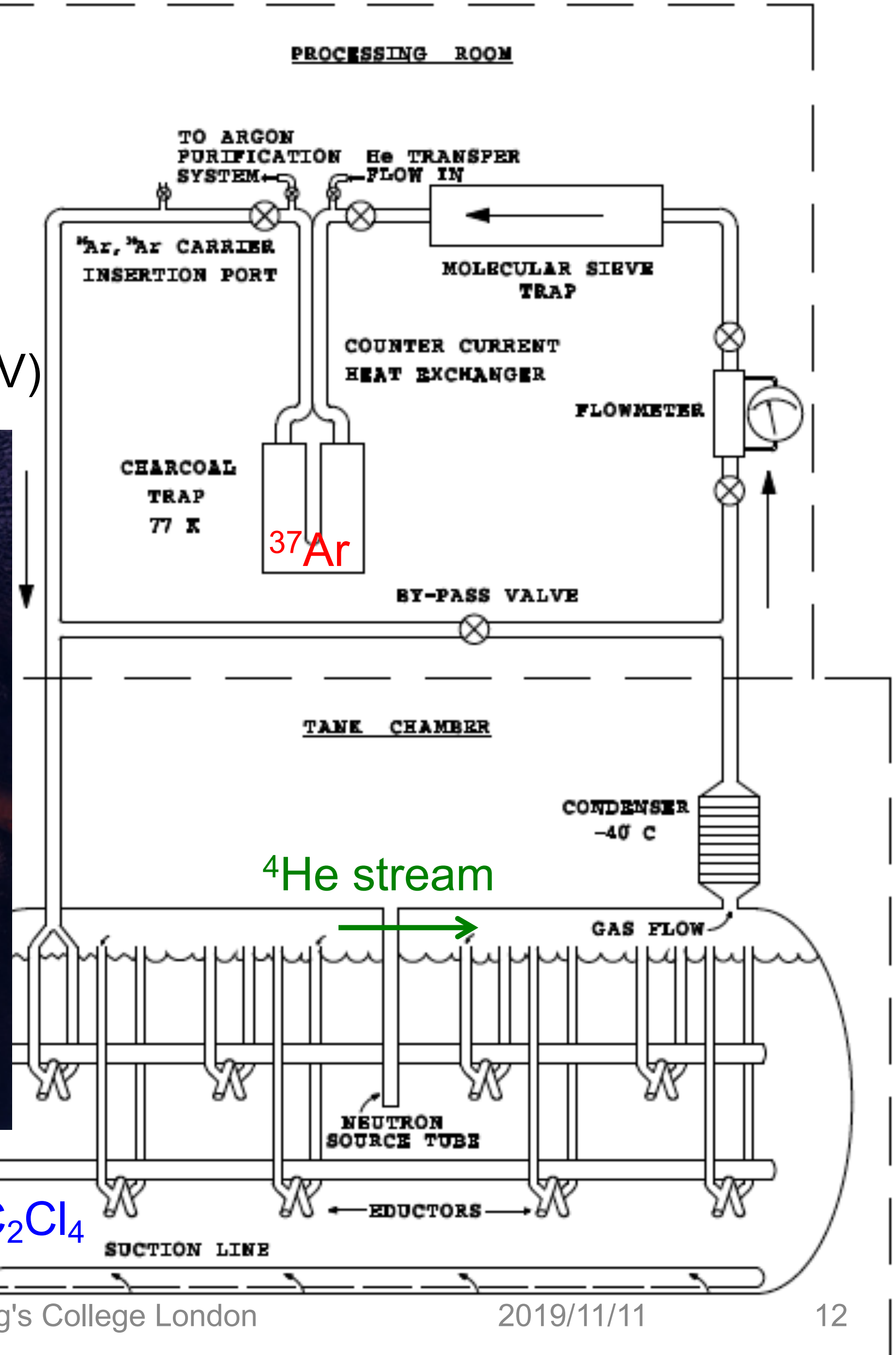
4. Solar neutrino

Homestake experiment

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

(proposed by Pontecorvo)

- mainly sensitive to ^{8}B neutrino (~10 MeV)



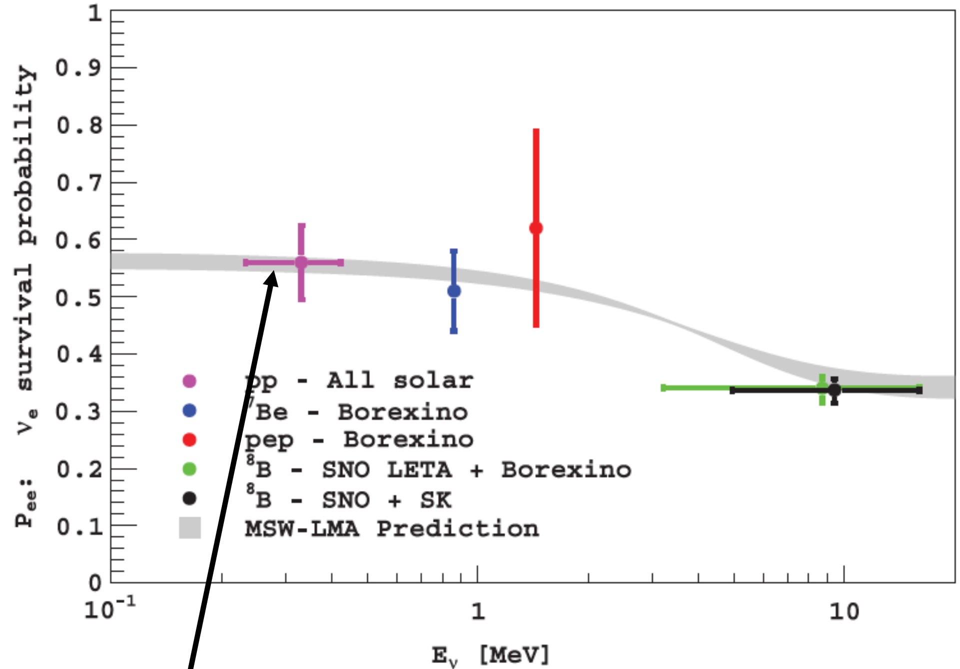
GALLEX, PLB490(2000)16;SAGE, J.Expt.Theor.Phys.95(2002)181
Borexino, PRL 108(2012)051302

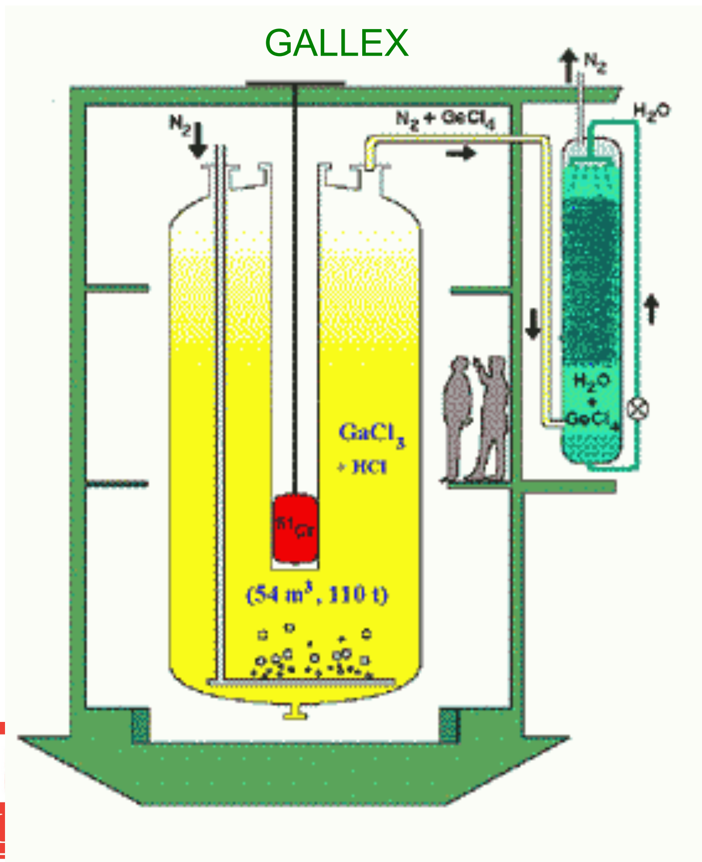
4. Solar neutrino

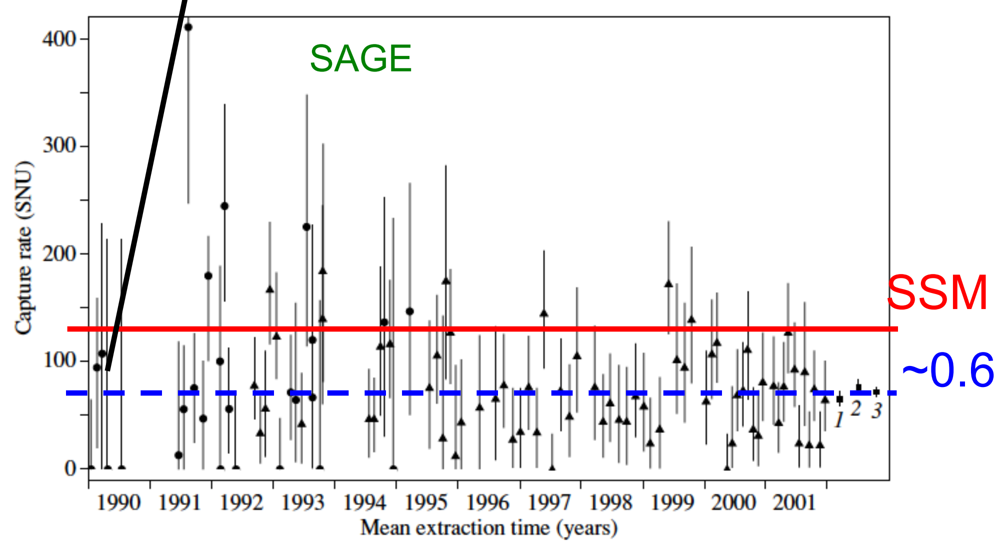
Gallium experiment

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

- Sensitive to pp-neutrino (0.42 MeV), 90% of total solar neutrino flux.
- Both experiments observed deficit, but higher than Homostake result





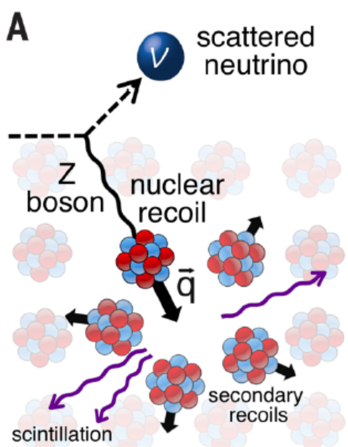


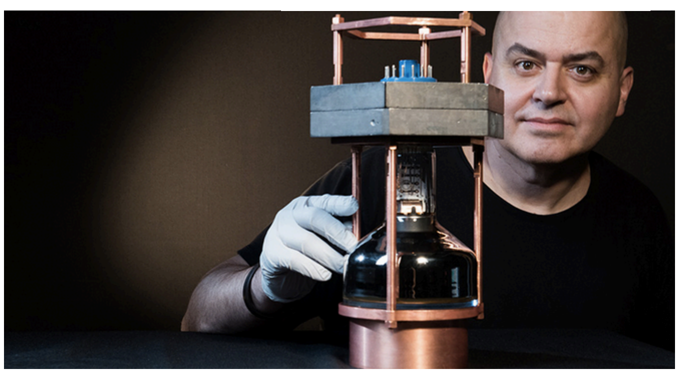
COHERENT, Science10.1126/science.aao0990 (2017).

4. Neutrino-Nucleus coherent scattering

Low energy neutrinos from neutron sources at SNS (spallation neutron source), ORNL (Oak Ridge National Lab)

$$\nu + A \rightarrow \nu + A$$

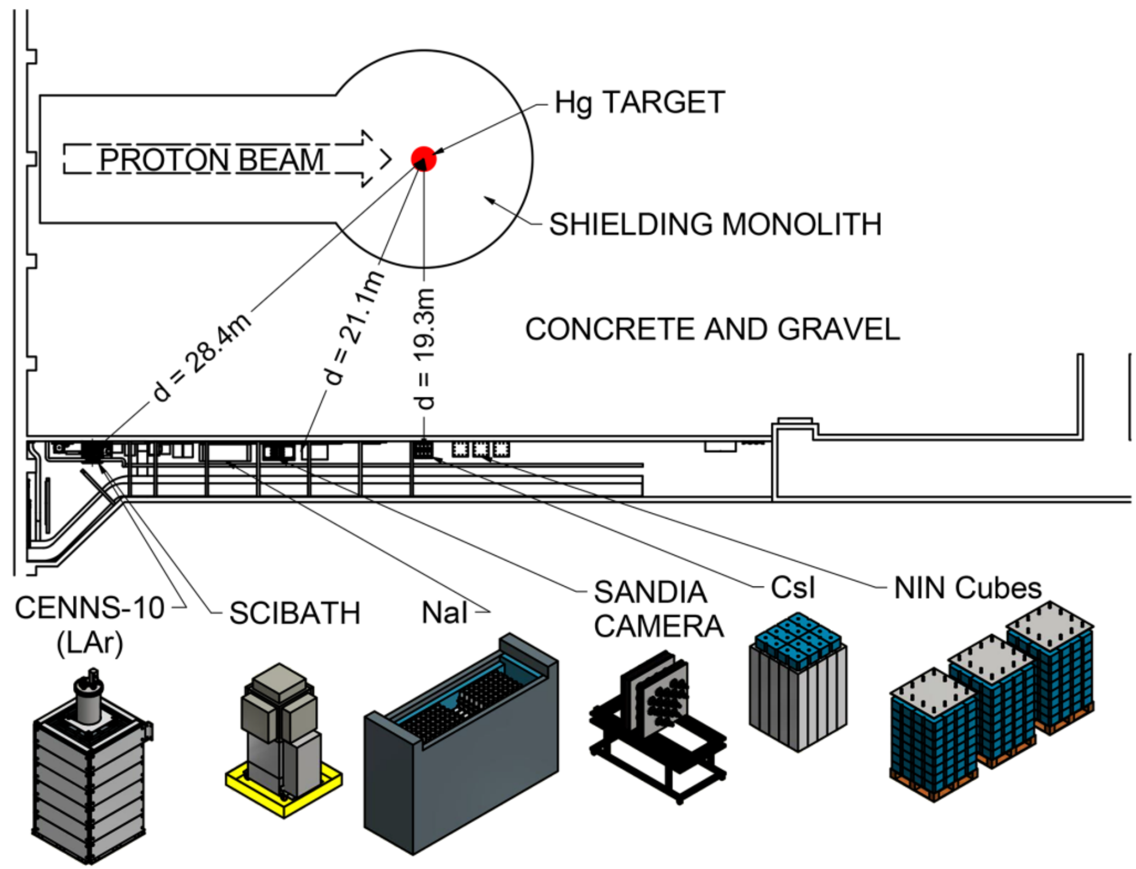




Science
REPORTS
Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9*] R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13†] D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9‡] W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9§] M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3||] S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13¶] S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#



Conclusion

Neutrinos interact by weak force

ν-l scattering : test of weak theory
- Neutrino-electron scattering
- Muon decay

ν-q scattering : test of weak theory, test of quark model
- DIS cross sections
- Di-muon production
- Paschos-Wolfenstein ratio
- Astrophysical neutrinos

ν-A scattering :
- Neutrino nuclear capture by Cl and Ga, important for solar neutrinos
- Neutrino coherent scattering, important for supernova (first observation, Aug. 2017)

ν-N scattering : important reactions for long baseline neutrino oscillation experiment
- (T2K, NOvA, DUNE, Hyper-Kamiokande)

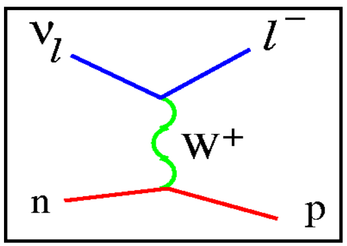
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

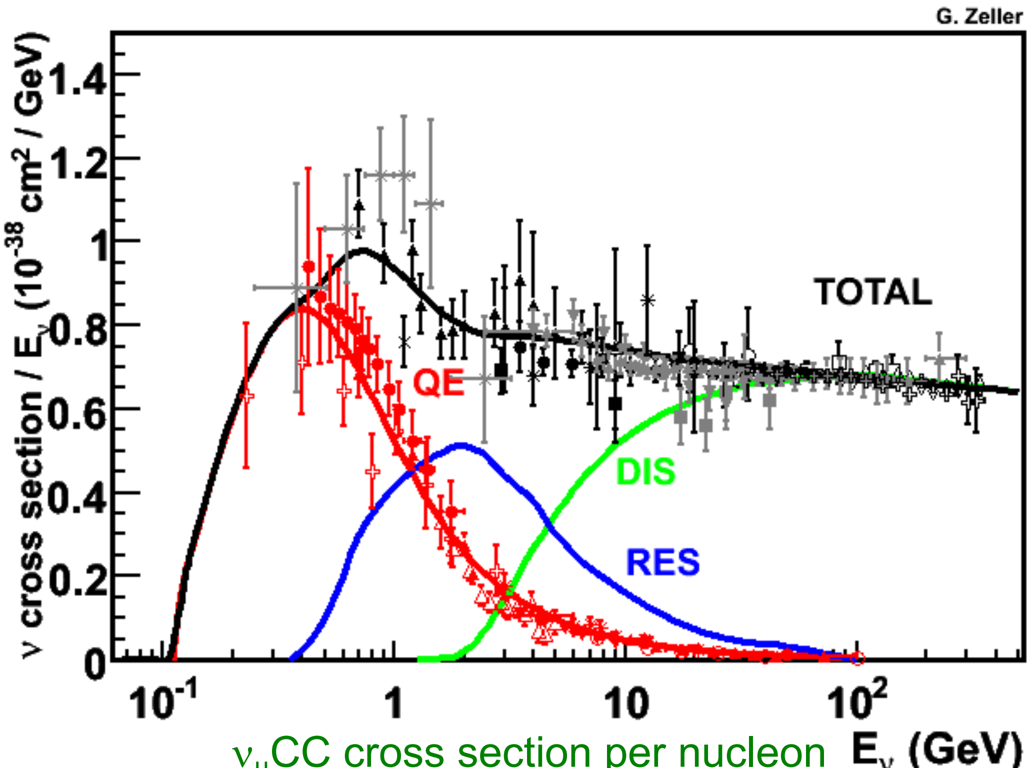
1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE

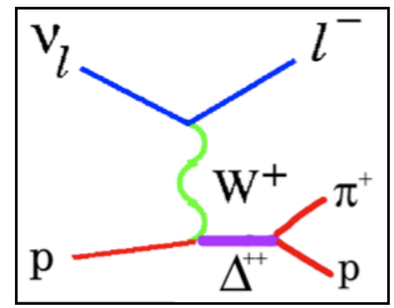
Quasi Elastic

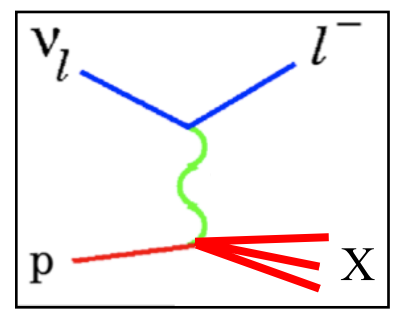




ν_μCC cross section per nucleon

baryonic RESonance





Deep Inelastic Scattering

1. Next generation neutrino oscillation experiments

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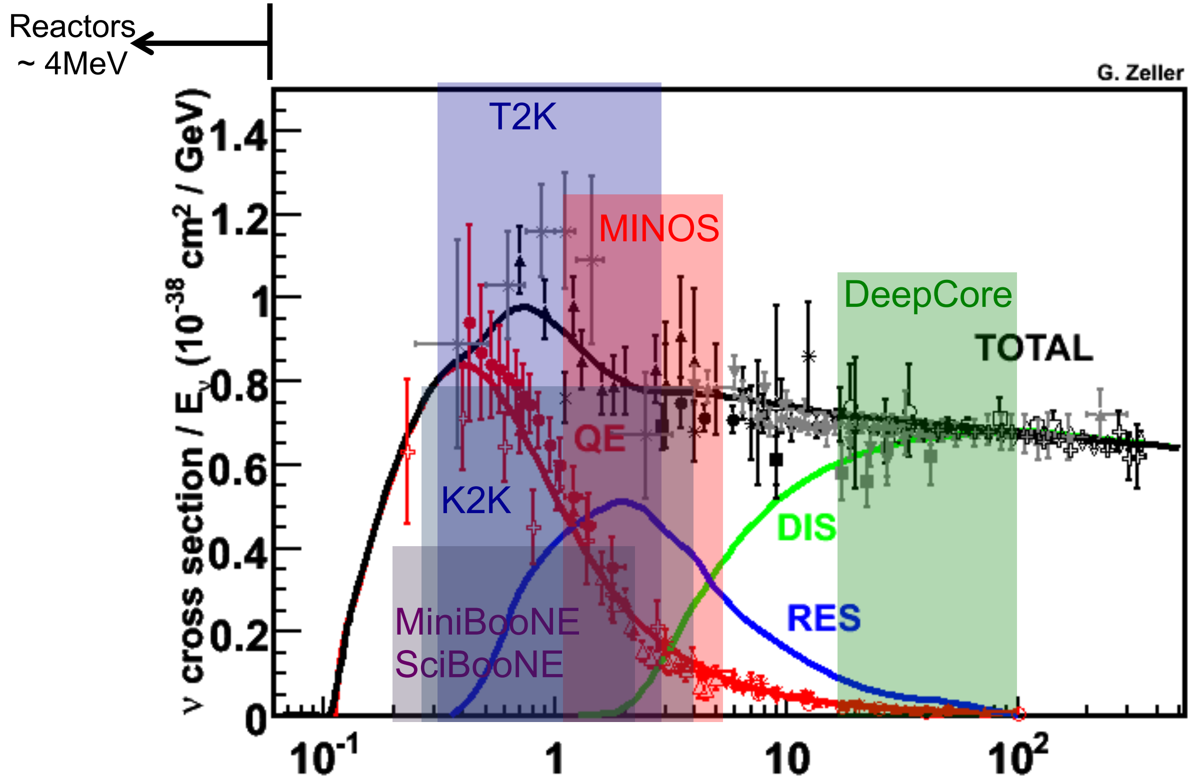
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE…



ν_μCC cross section per nucleon

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

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

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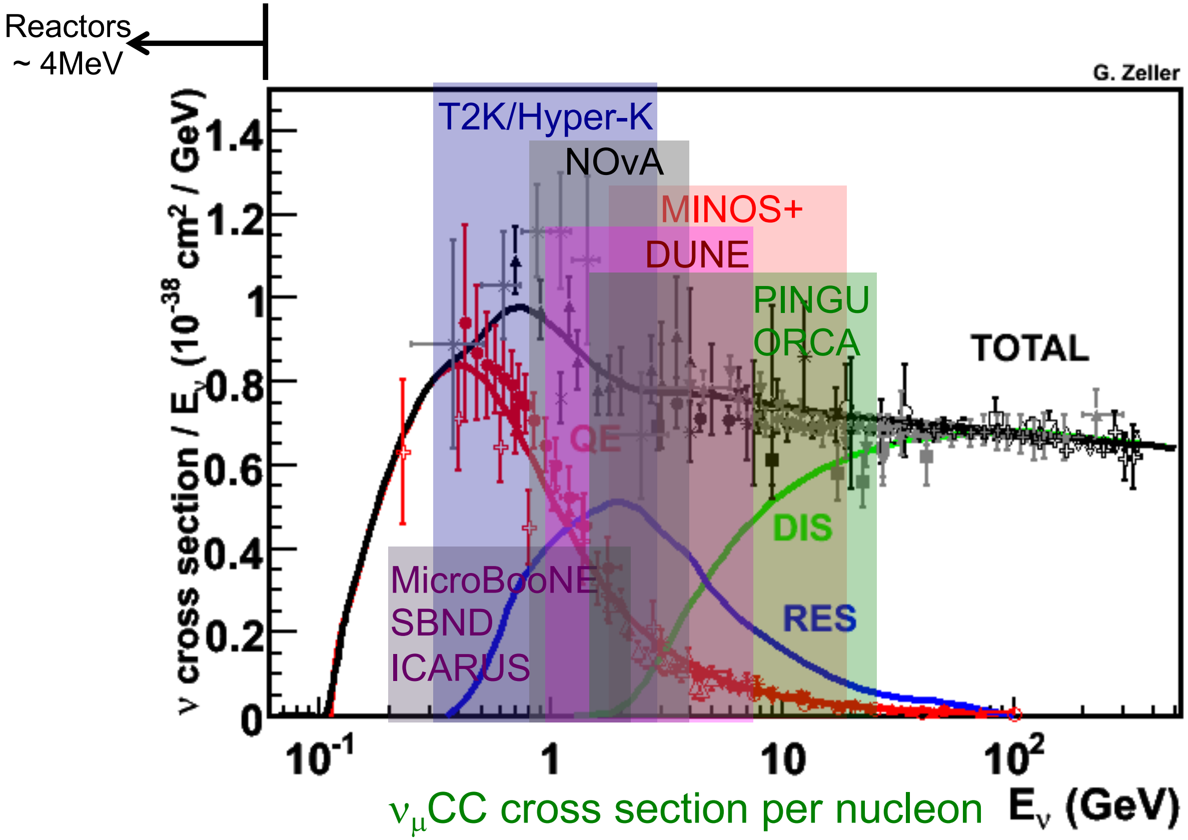

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1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE…

Most of data are from muon neutrino beam, why?

- create by π-DIF (pion decay-in-flight)
- $\Phi(\nu_\mu) > \Phi(\bar{\nu}_\mu)$: more π^+ than π^- (because they are made by protons)
- d_{CP} study need electro-neutrino cross-section (ν_e appearance) and anti-neutrino cross-section (CP violation)

Nuclear physics sucks

- Simple extrapolation may be broken due to nuclear physics
- We are not good at nuclear physics because we are not nuclear physicists
- Nuclear physics = non-perturbative QCD (many models, no theory)
- Particle physics is developed by avoiding nuclear physics…

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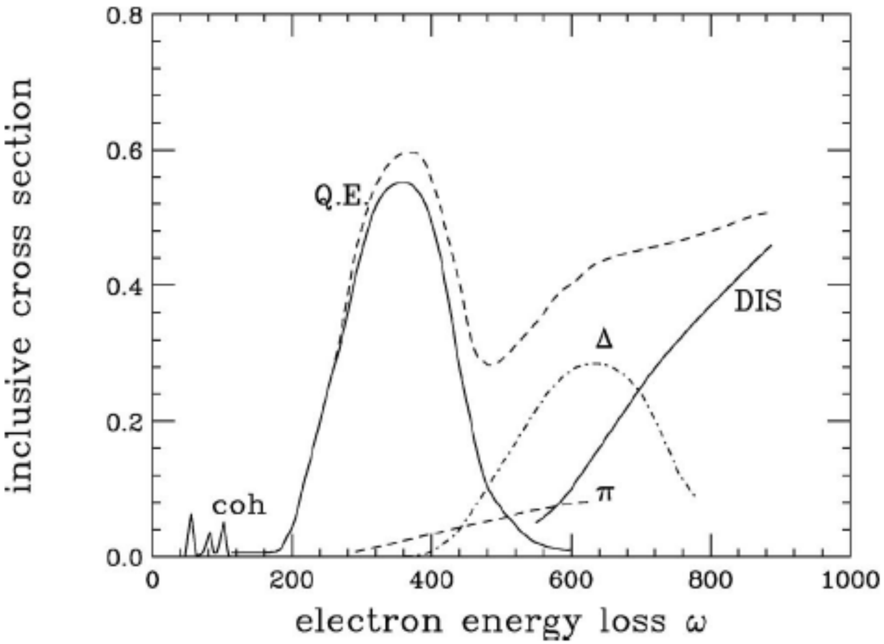
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

Benhar,Day,Sick,Rev.Mod.Phys.80(2008)189
Nakamura et a;,Rep.Prog.Phys.80(2017)056301

1. Particle Physics vs. Nuclear Physics

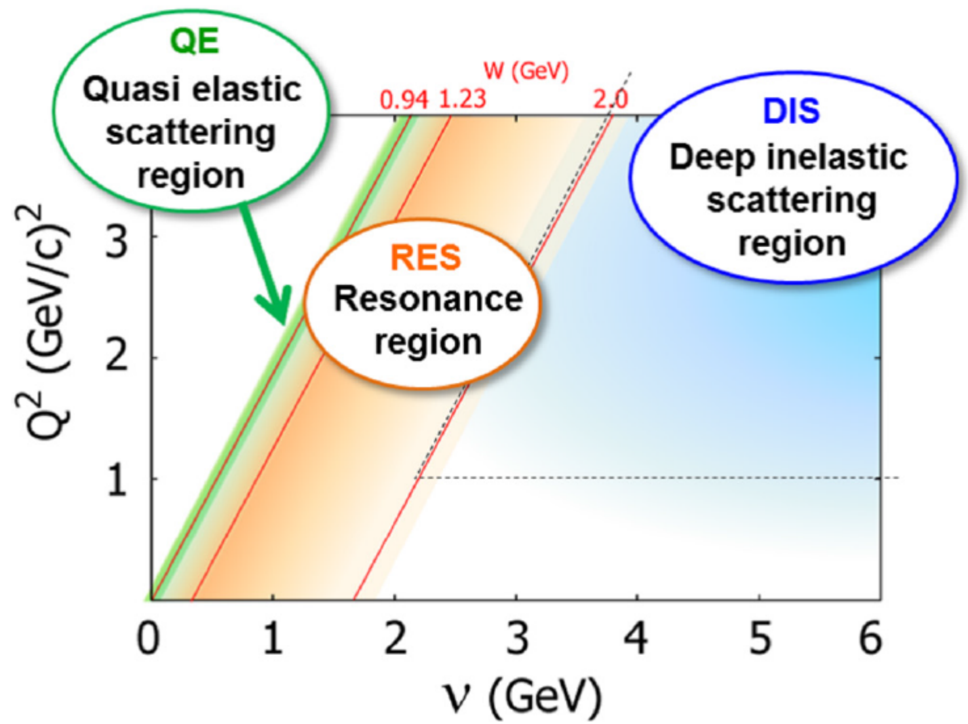


Nuclear physics

Interactions are classified in q (3-momnetum transfer) and ω (energy transfer)

Particle physics (neutrino physics)

Interactions are classified in Q^2 (4-momentum transfer) and ν (energy transfer) or W^2 (invariant mass)



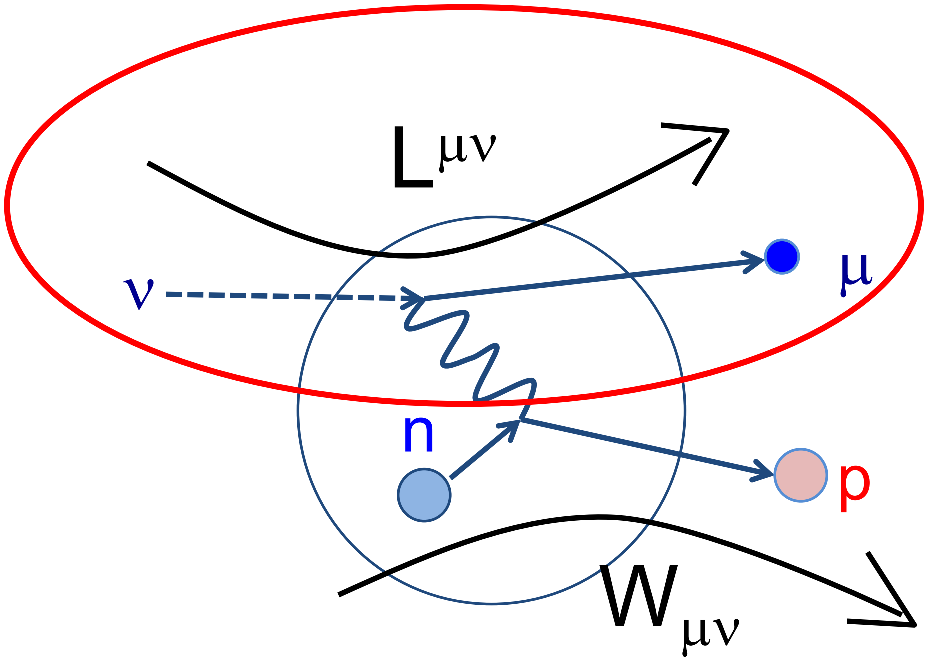
1. Neutrino cross-section formula

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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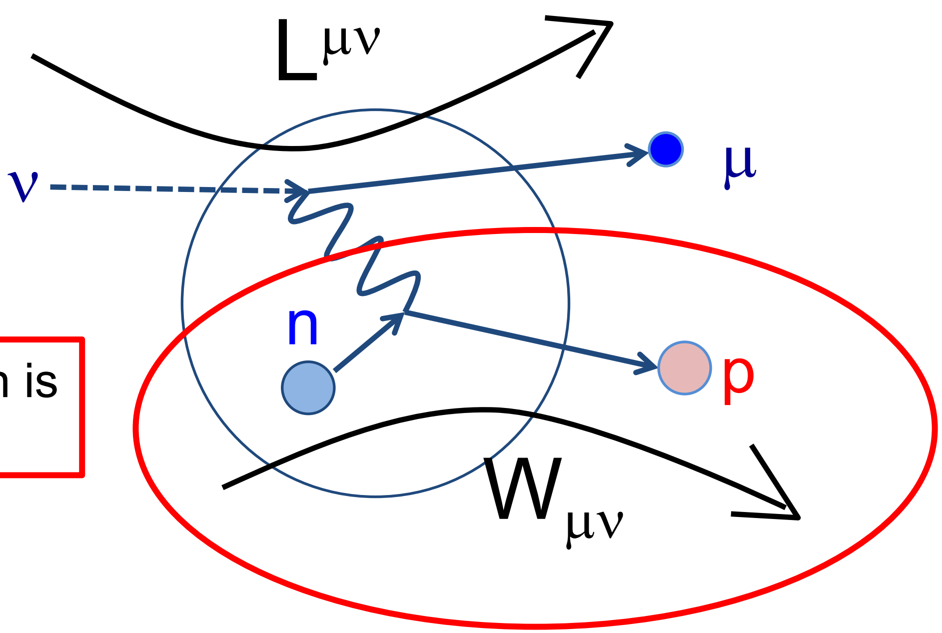
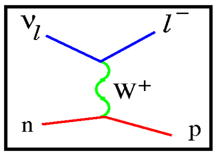


All complication of neutrino cross-section is how to model the hadronic tensor part

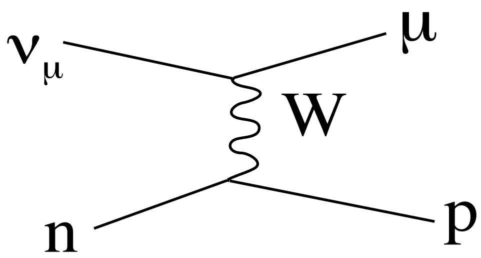
Quasi Elastic



2. Charged Current Quasi-Elastic scattering (CCQE)

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

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



$d\sigma \sim L_{\mu\nu} T^{\mu\nu}$

$L_{\mu\nu} \sim J_\mu J_\nu$: 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

$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$: form factors

Form factors can be parameterize with dipole form

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

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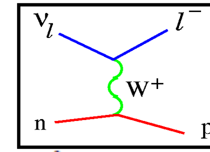
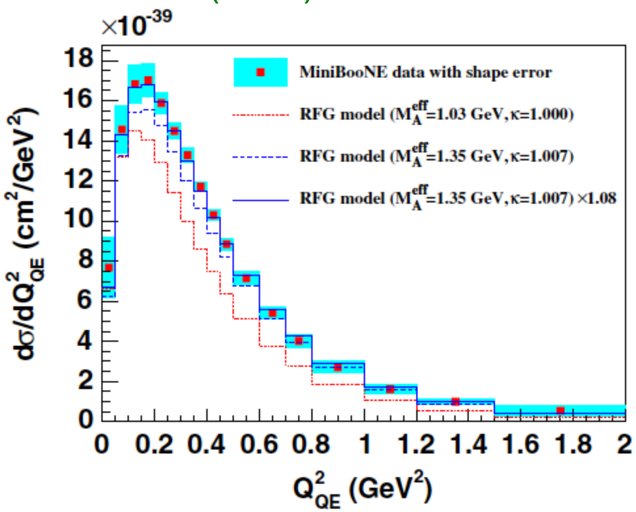
2. Form factors

Quasi Elastic



MiniBooNE CCQE cross section
PRD81(2010)092005



Form factors can be parameterize with dipole form

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

ρ(r)	$\lvert F(q^2) \rvert$	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca
r →	$\lvert q \rvert$ →	

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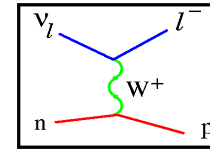
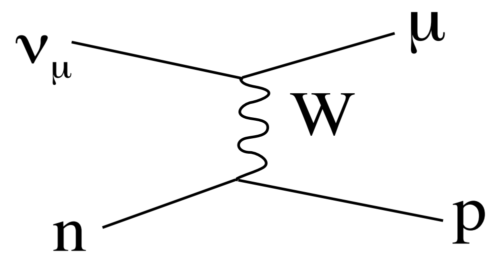
Quasi Elastic



2. Charged Current Quasi-Elastic scattering (CCQE)

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

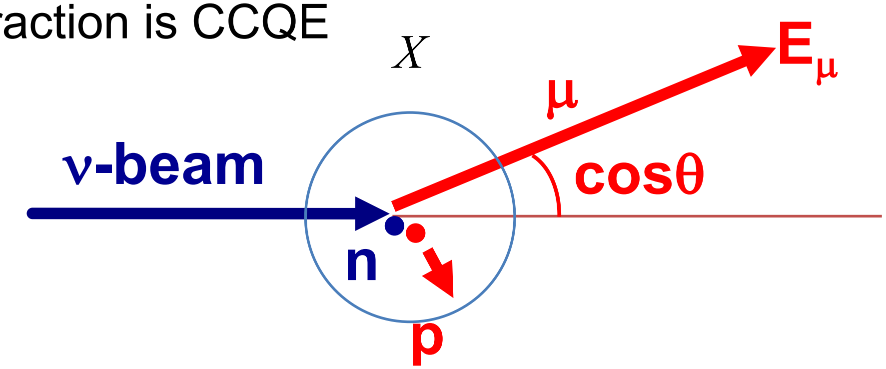
$$\nu_\mu + n \to p + \mu^- \quad (\nu_\mu + X \to X' + \mu^-)$$



Neutrino energy is reconstructed from the observed lepton kinematics

"QE assumption"

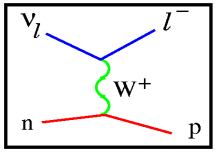
1. assuming neutron at rest
2. assuming interaction is CCQE



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

Neutrinos hit nucleons inside of nucleus, and the energy reconstruction is possible only with QE assumption

Quasi Elastic

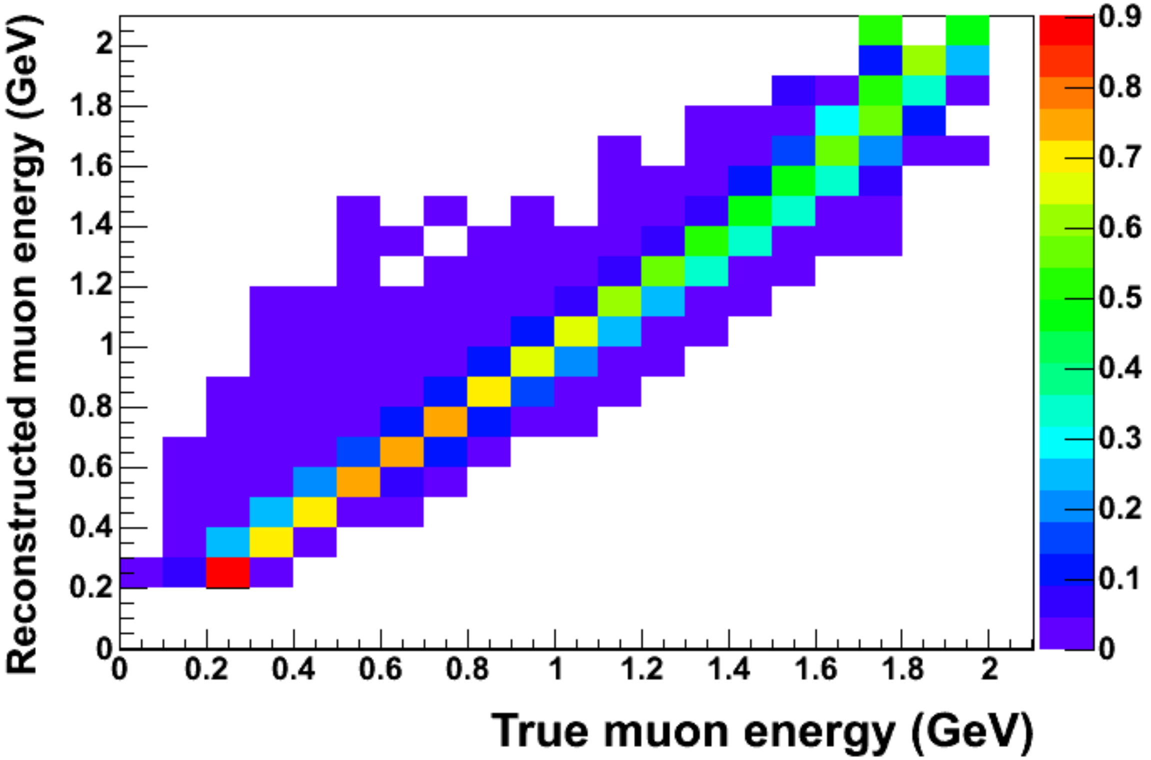


2. Basic nuclear physics in nucleus

Fermi motion

- Nucleons move with ~200 MeV/c momentum in the nucleus.
  → This smear neutrino energy reconstruction.

Even if you have a perfect measurement of CCQE, measured neutrino energy doesn't represent the true neutrino energy due to Fermi motion.



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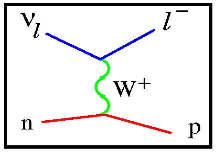

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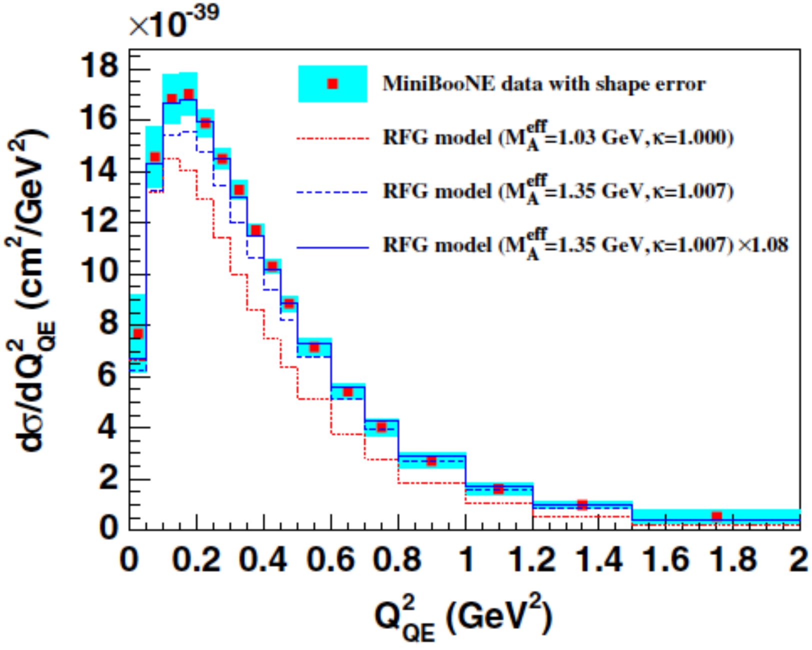
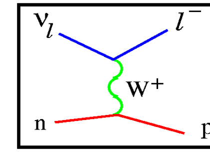
Pauli blocking
- Nucleon Fermi sea is occupied.
  → Low momentum transfer transition (<200 MeV/c) is forbidden.



Quasi Elastic



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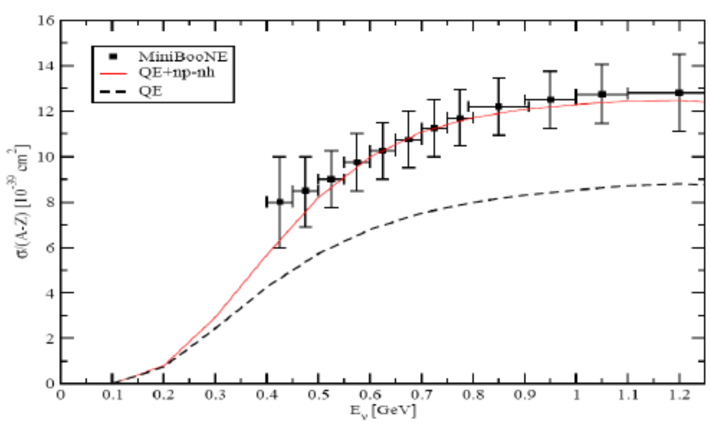
- Nucleons move with ~200 MeV/c momentum in the nucleus.
  → This smear neutrino energy reconstruction.

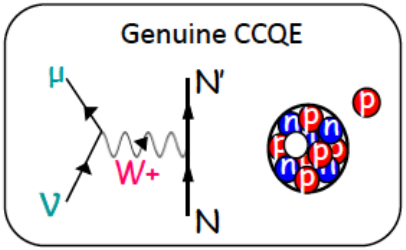
Pauli blocking
- Nucleon Fermi sea is occupied.
  → Low momentum transfer transition (<200 MeV/c) is forbidden.

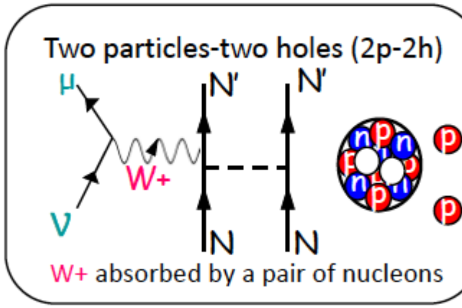
Nuclear correlation
- Neutrinos can interact 2 or more correlated nucleons (=mimic CCQE interaction)
- Cross section can be modified order 30% (both shape and normalization).

Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"
1. assuming neutron at rest
2. assuming interaction is CCQE

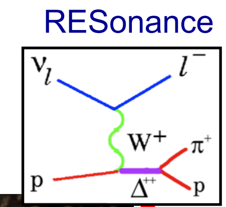
Inclusion of the multinucleon emission channel (np-nh)



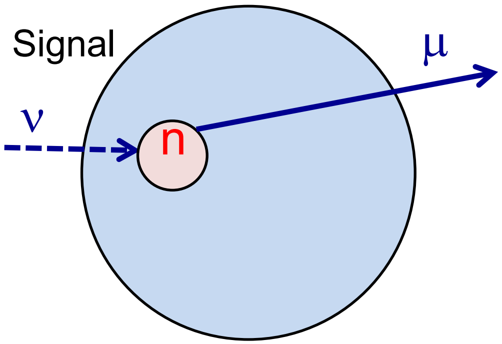




3. non-QE background (resonance pion production)



non-QE background → shift spectrum



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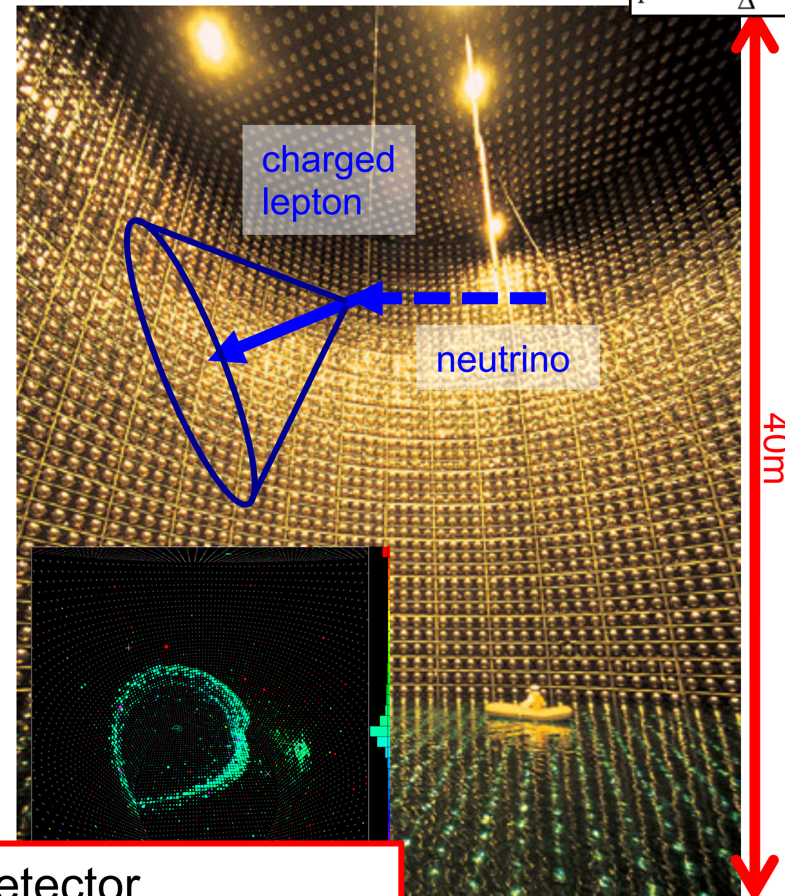
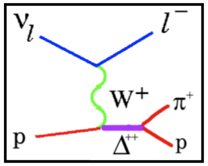


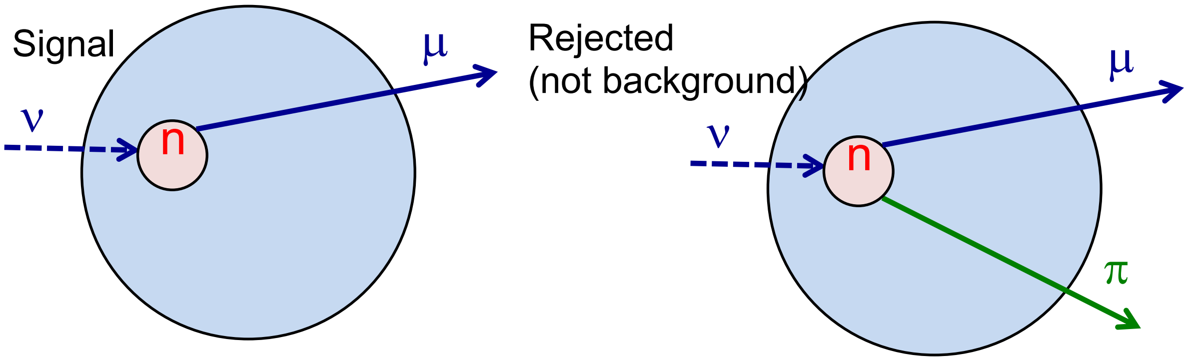
Typical neutrino oscillation detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost
(not great detector to measure hadrons)

3. non-QE background (resonance pion production)

RESonance



non-QE background → shift spectrum



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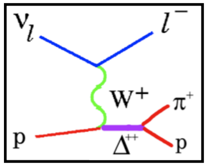

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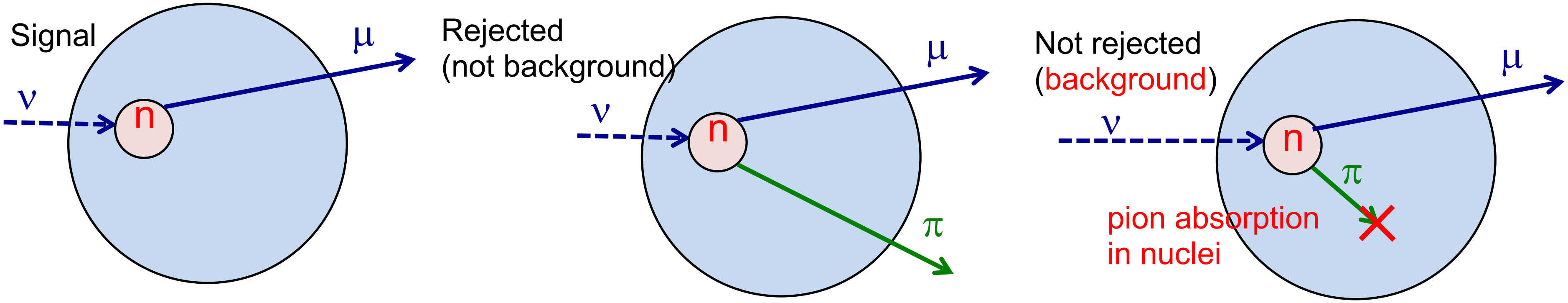

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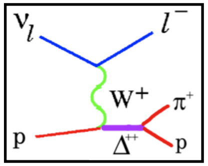

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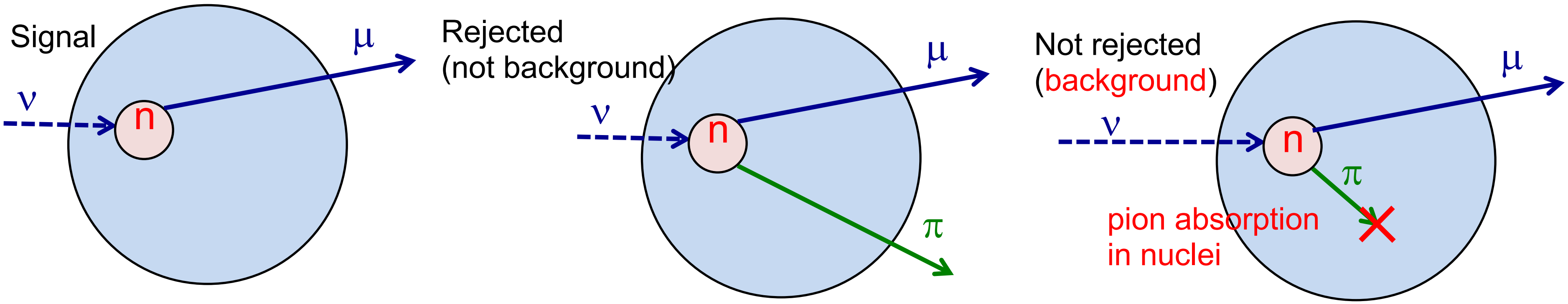
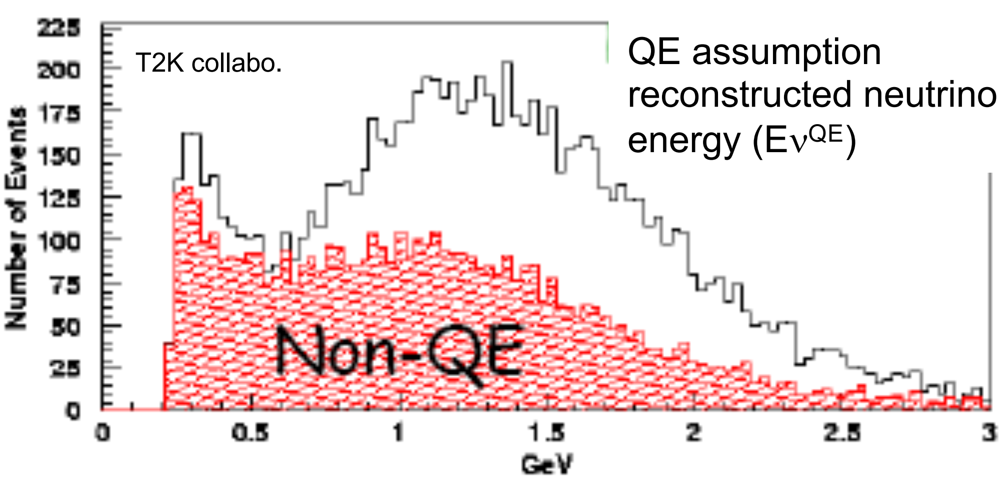
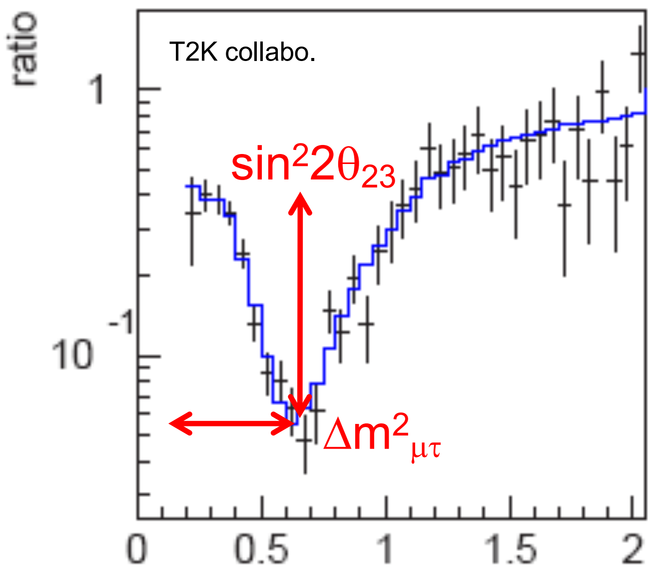
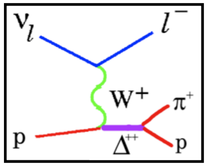






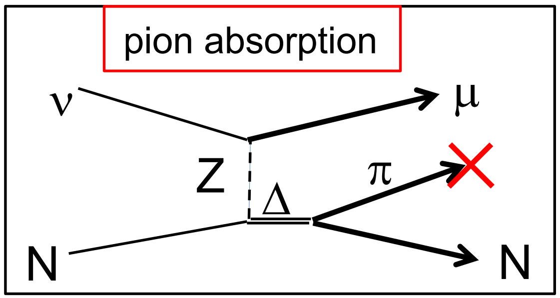
Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

RESonance

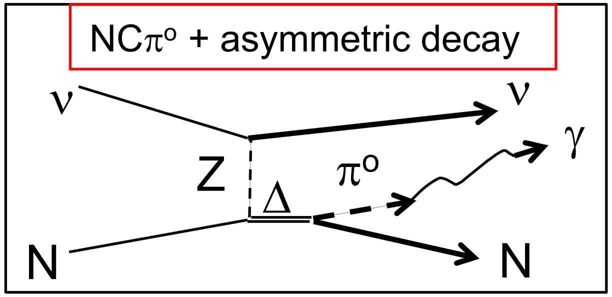


3. non-QE background (resonance pion production)

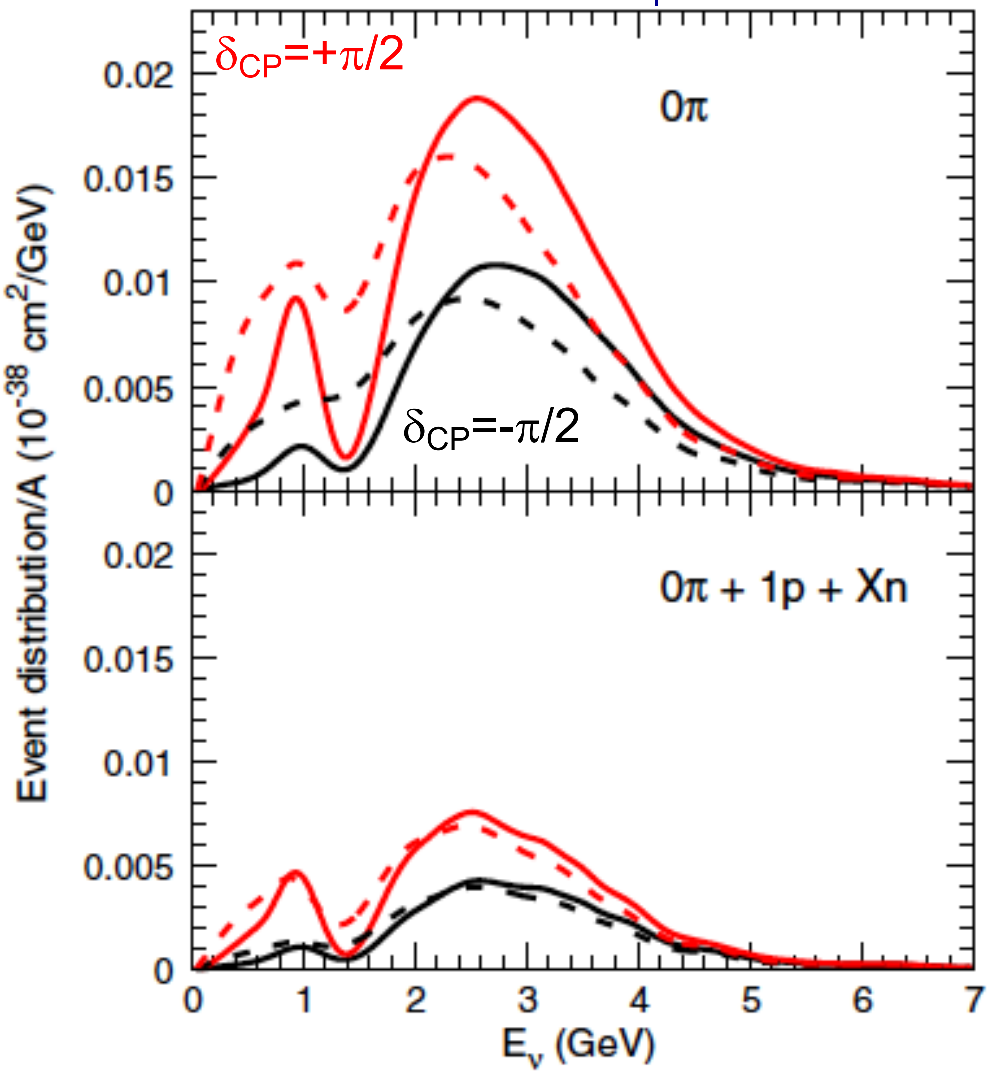
Pion production for ν_μ disappearance search
- Source of mis-reconstruction of neutrino energy



Neutral pion production in ν_e appearance search
- Source of misID of electron



DUNE true vs. reconstructed Eν spectrum



Understanding of neutrino baryonic resonance meson production is important for oscillation experiments

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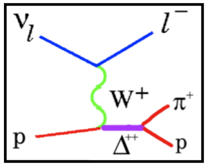
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

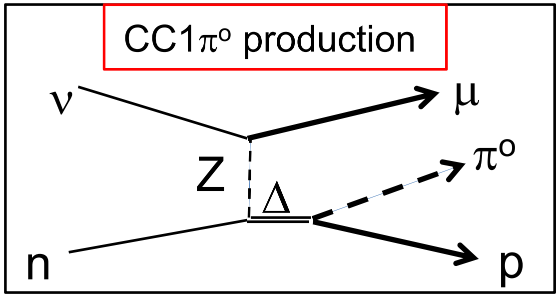
RESonance

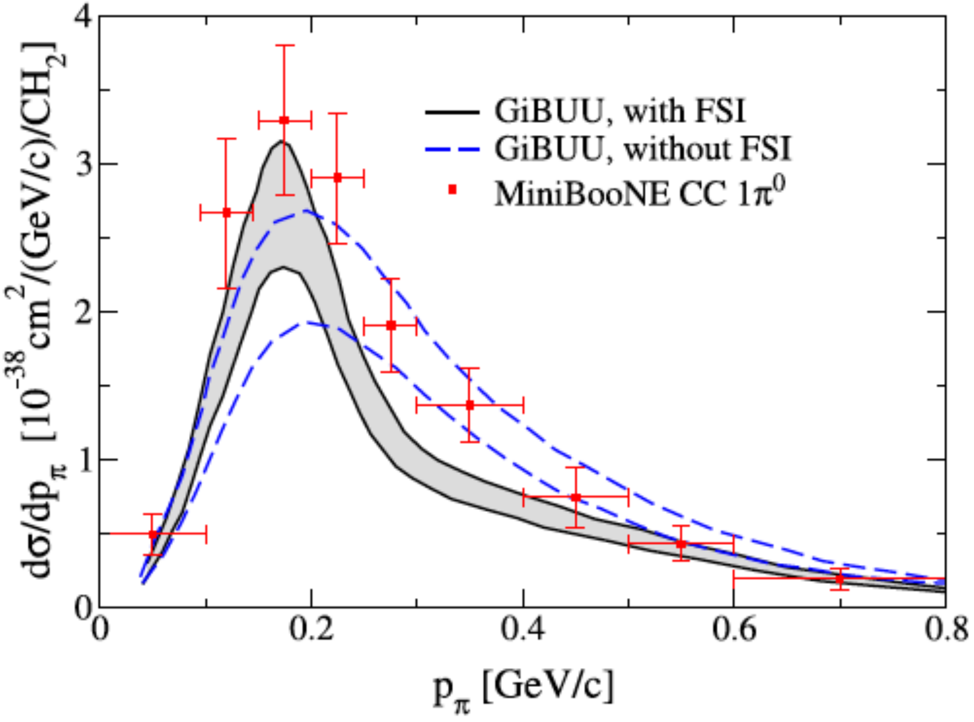


3. Neutrino Baryonic resonance data

Final state interaction

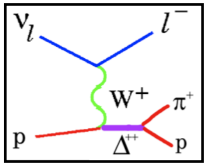
- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation





MiniBooNE π^o momentum vs simulation

3. Neutrino Baryonic resonance data



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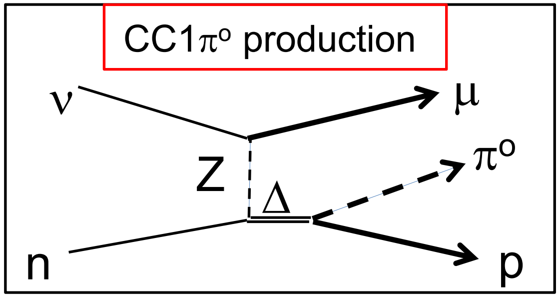

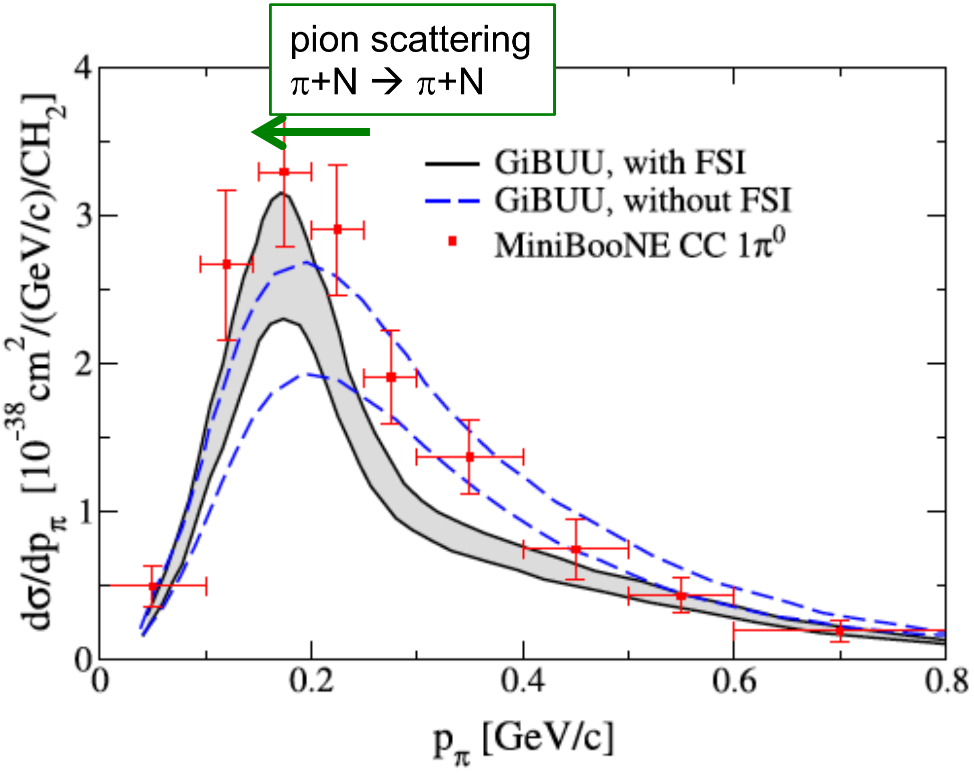

MiniBooNE πº momentum vs simulation

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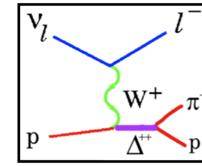

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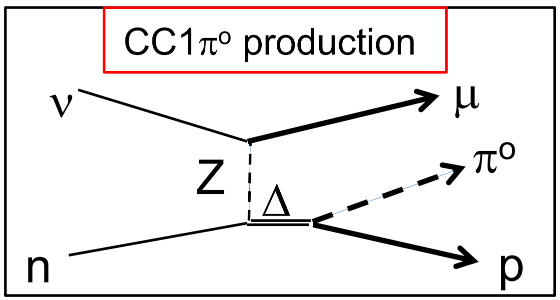

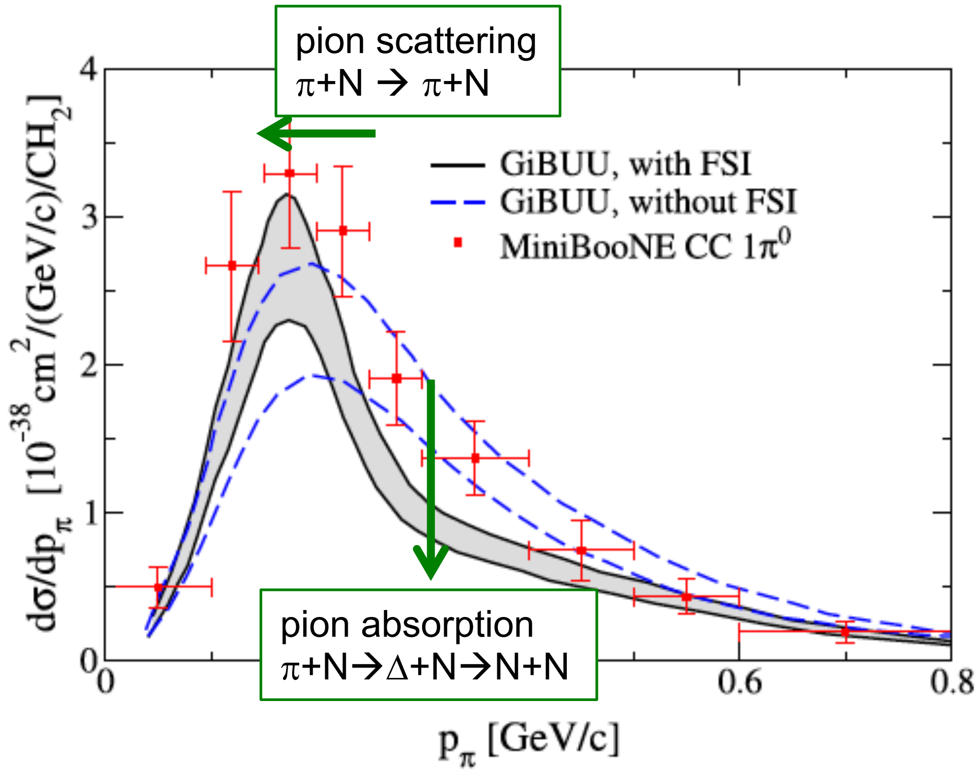

MiniBooNE πº momentum vs simulation

MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

3. Neutrino Baryonic resonance data

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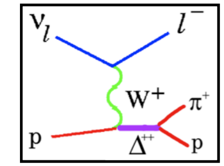

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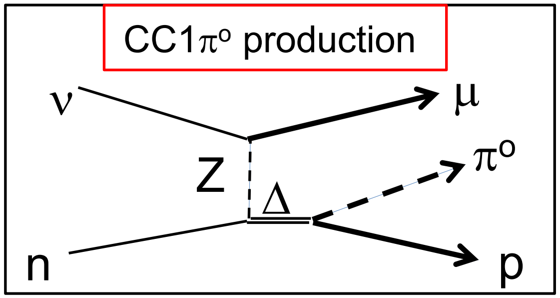

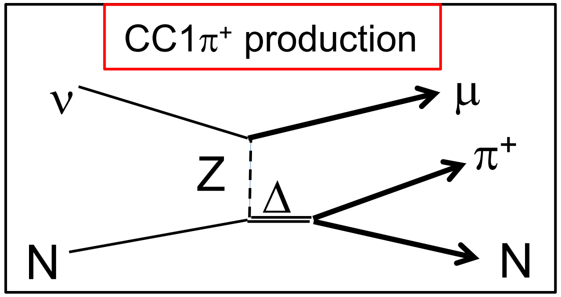

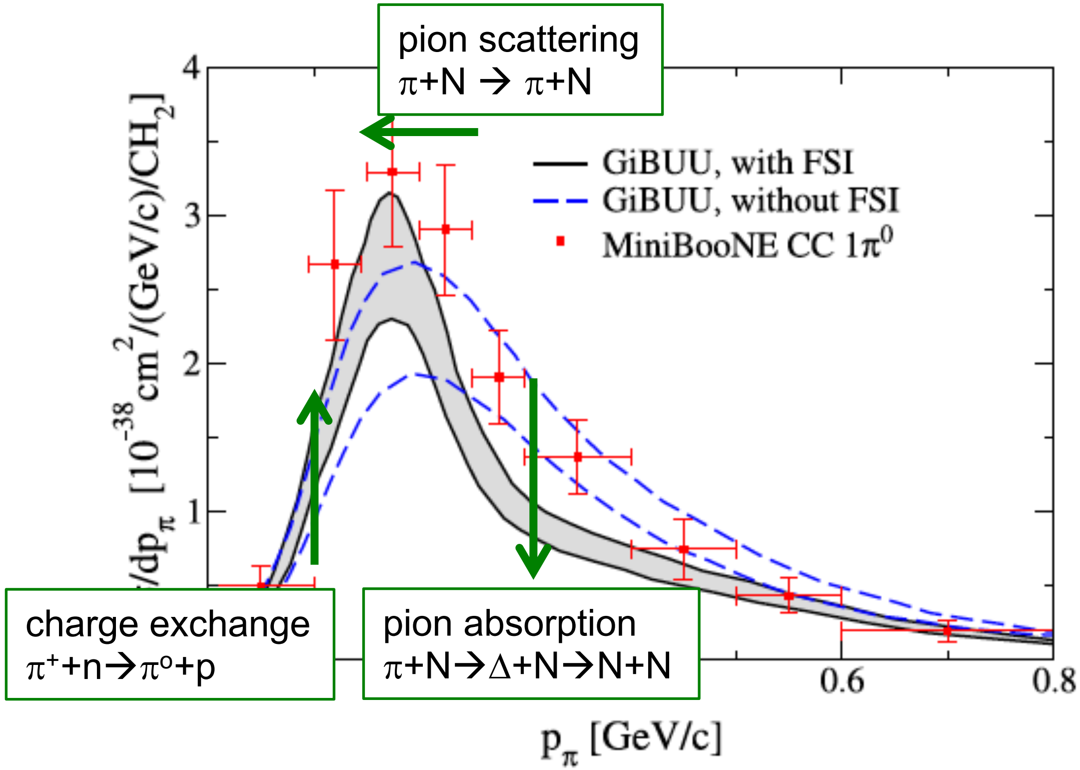

MiniBooNE π° momentum vs simulation

All neutrino baryonic resonance processes have ~30% errors

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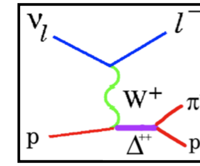
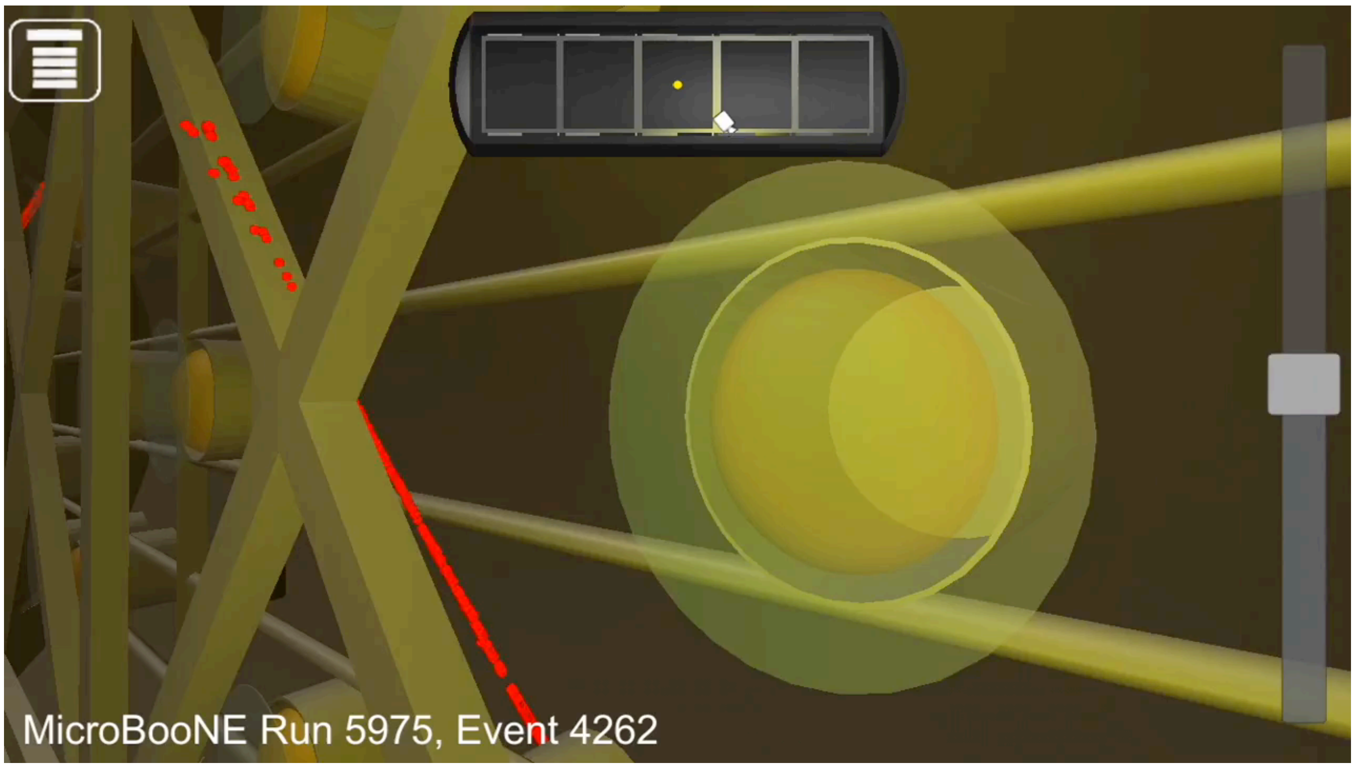


3. LArTPC

Exclusive hadron final state measurements from neutrino interactions?

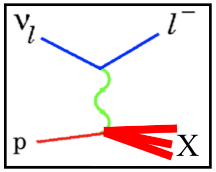
- Neutrino energy can be reconstructed using total hadron energies
- Inefficiencies of hadron measurements (neutrons) cause energy mis-reconstruction
- Fermilab SBN programs will provide a lot of new information



VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app to take a look MicroBooNE data

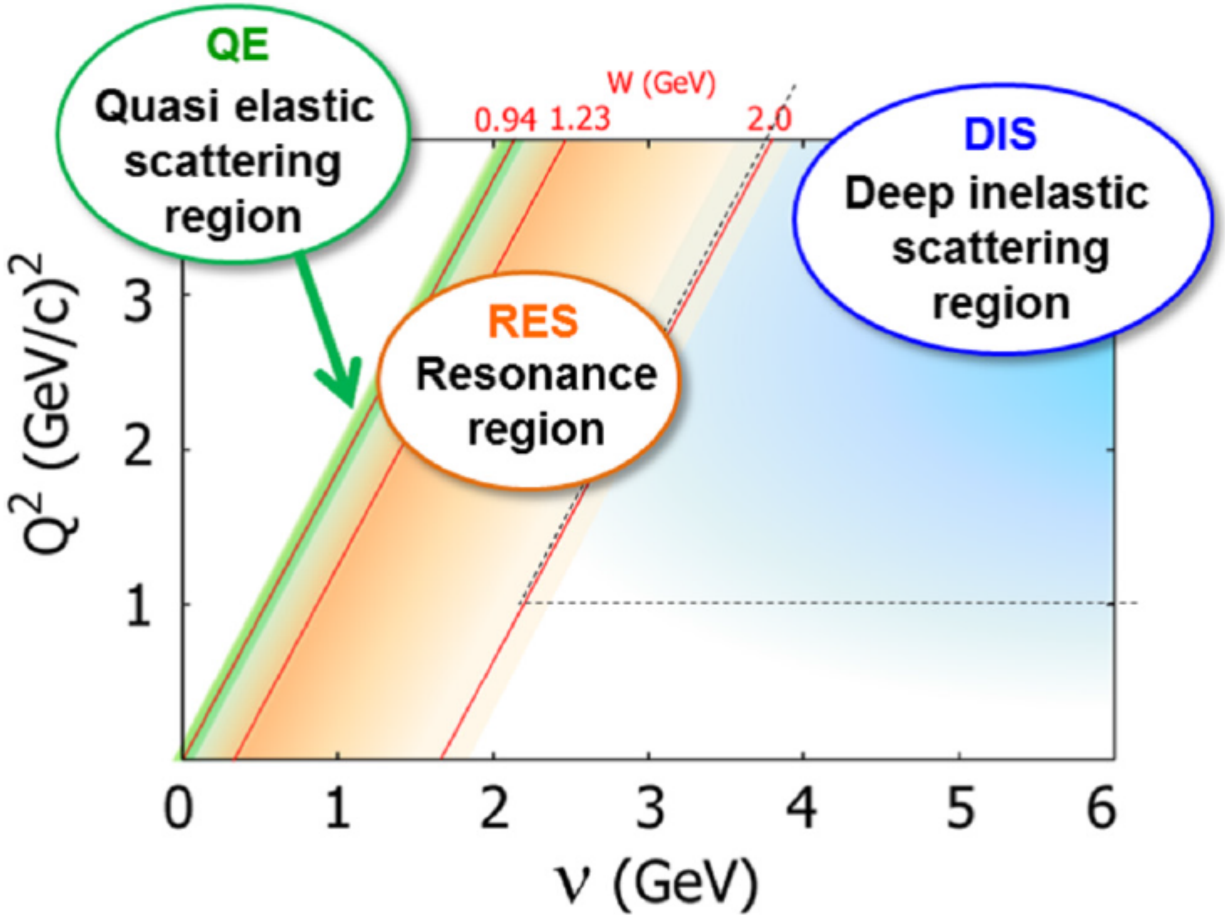
4. Shallow Inelastic Scattering (SIS)

DIS



Cross section

- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS



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

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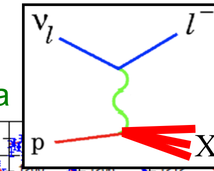


DCC model vs. electro-pionproduction data

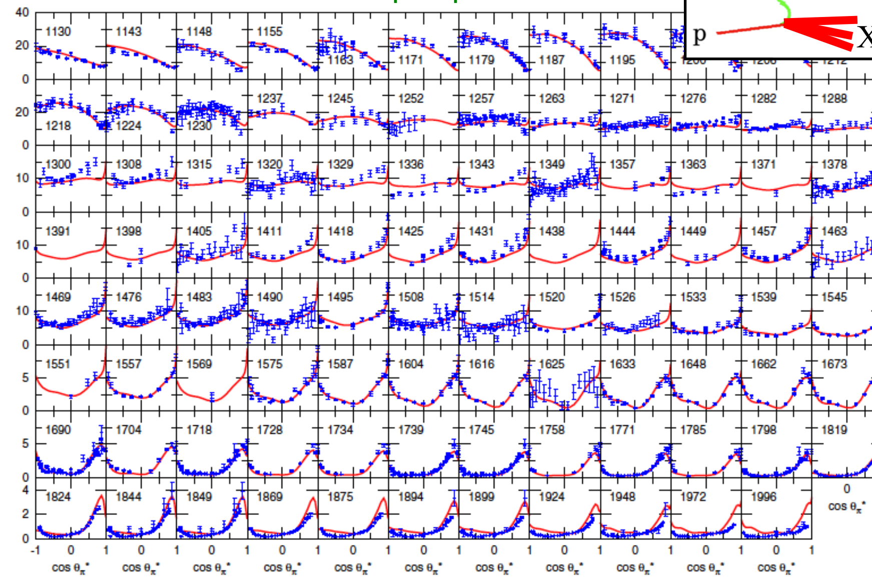


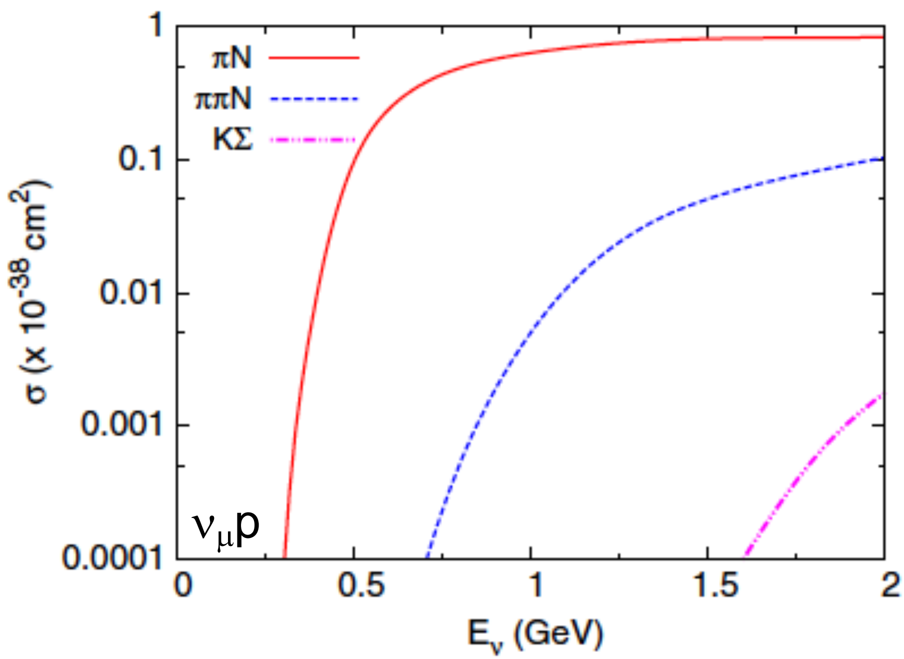
FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

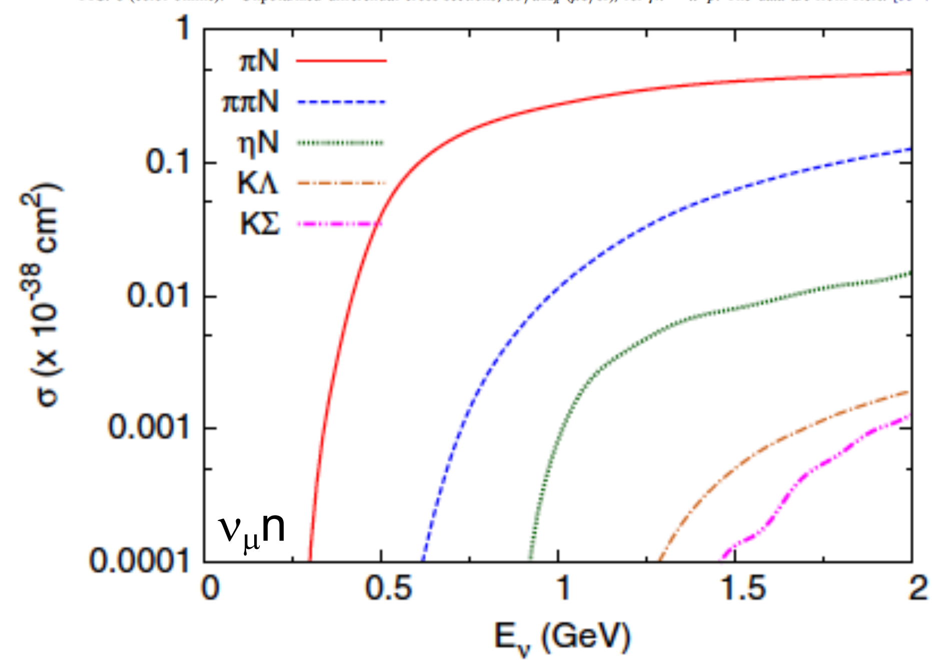
Cross section

- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

DCC model

- Total amplitude is conserved
- Channels are coupled (πN, $\pi\pi$N, etc)
- 2 pion productions ~10% at 2 GeV



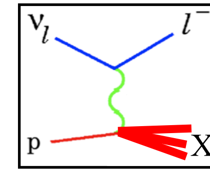


4. Shallow Inelastic Scattering (SIS)

Nachtmann variable

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

DIS



Cross section
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

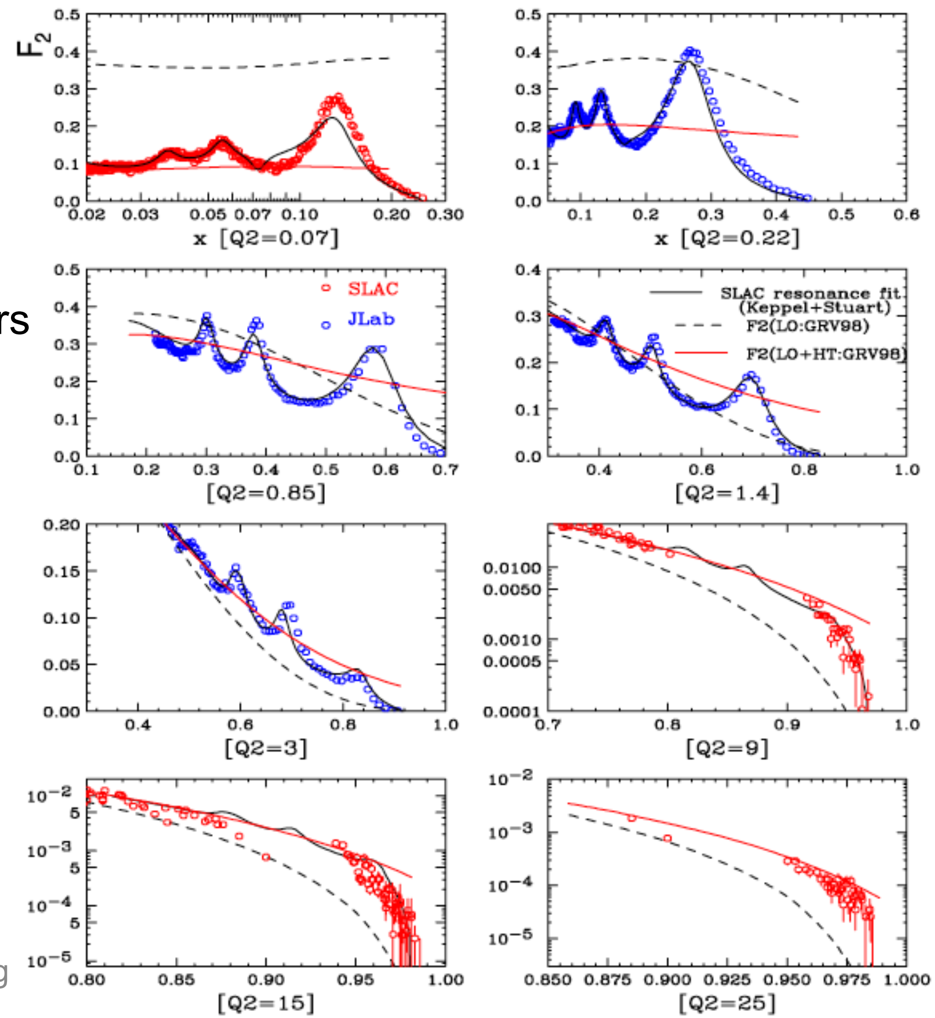
GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

$$\xi \to \xi_\omega = \frac{2x\left(1+\frac{M_f^2+B}{Q^2}\right)}{\left(1+\sqrt{1+\frac{4x^2M^2}{Q^2}}\right)+\frac{2Ax}{Q^2}}$$

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

$$K_{sea}(Q^2) = \frac{Q^2}{Q^2+C_{s1}}$$

Proton F2 function GRV98-BY correction vs. data



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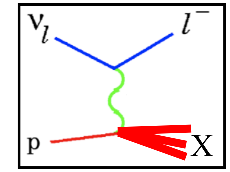
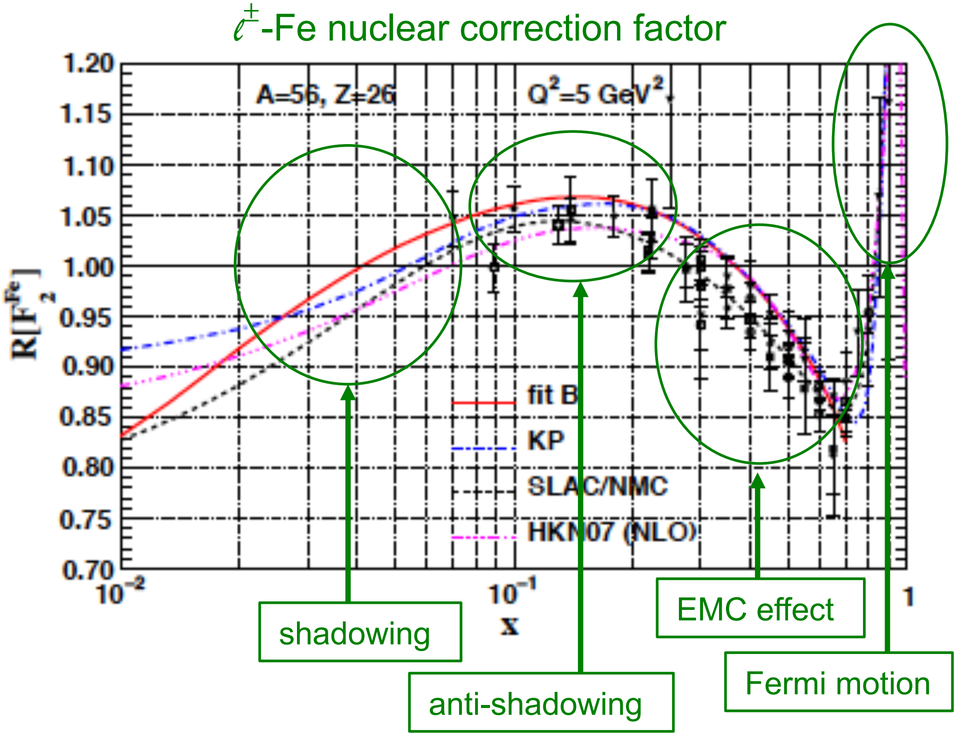
DIS



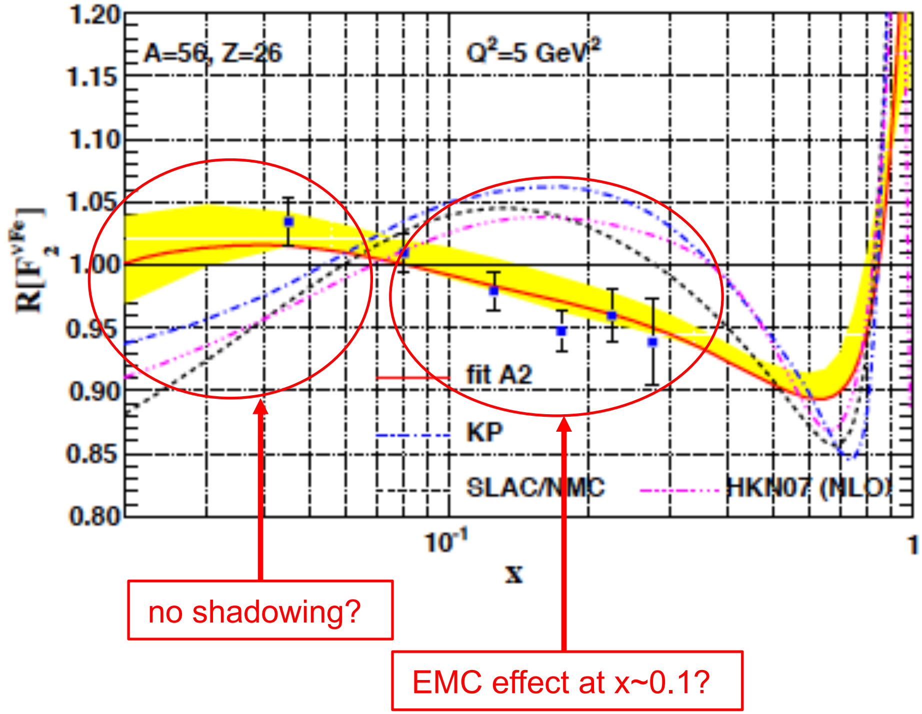
Cross section
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

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

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



ν-Fe nuclear correction factor



Conclusion

Neutrinos interact by weak force

ν-N scattering : important reactions for long baseline neutrino oscillation experiment
(T2K, NOvA, DUNE, Hyper-Kamiokande)

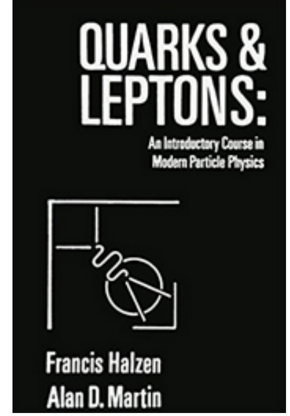
CCQE: charged-current quasi-elastic, around 1 GeV
RES: baryonic resonance, around 2 GeV
DIS: deep inelastic scattering, 3 GeV to higher

Nuclear physics sucks
- Fermi motion: nucleon motion smears kinematic reconstruction
- Pauli blocking: It limits low momentum transfer reaction
- Baryonic resonance: if you fail to tag outgoing mesons, get incorrect neutrino energy
- Nucleon correlation: Physics between ν-N and ν-A interaction
- Quark-Hadron duality: Physics between ν-q and ν-N interaction
- Nuclear dependent PDF: quarks inside of nucleons depend on nucleus

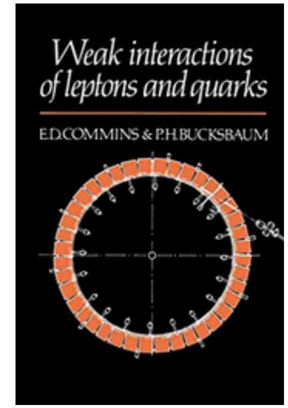
Currently, ~30% error is acceptable for many processes… (future experiments will be systematically limited)

References (books)

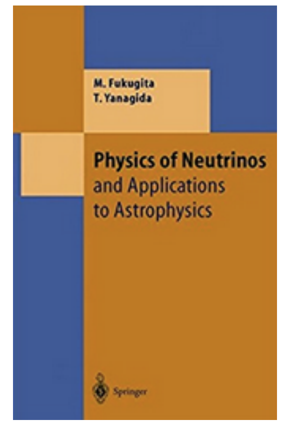
Quarks and Leptons (Halzen and Martin)
- show many calculations
- solutions for all exercises



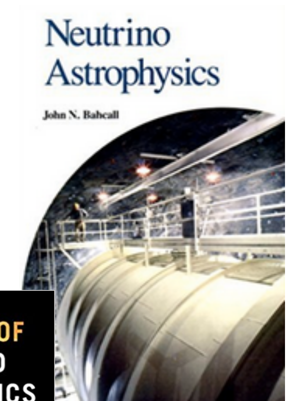
Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- show details of weak interaction calculations
- too many typos



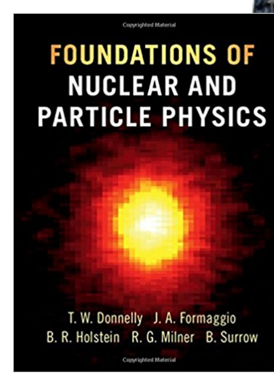
Physics of Neutrinos (Fukugita and Yanagida)
- very intense
- from solar neutrinos to SUSY



Neutrino astrophysics (Bahcall)
- good book to read



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



References (papers)

"From eV to EeV: Neutrino cross sections across energy scales"
- Authors: Formaggio and Zeller (MicroBooNE spokesperson)
- Rev.Mod.Phys.84(2012)1307, arXiv:1305.7513
- very good summary of neutrino cross sections

"Neutrino-Nucleus Cross Sections for Oscillation Experiments"
- Authors: Katori (me) and Martini (Martini model)
- J.Phys. G45 (2018) no.1, 013001
- A review both theoretical and experimental views

"NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering"
- NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)
- Prog.Part.Nucl.Phys. 100 (2018) 1-68
- Cover all open issues in the community

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