# 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. 2, 2021

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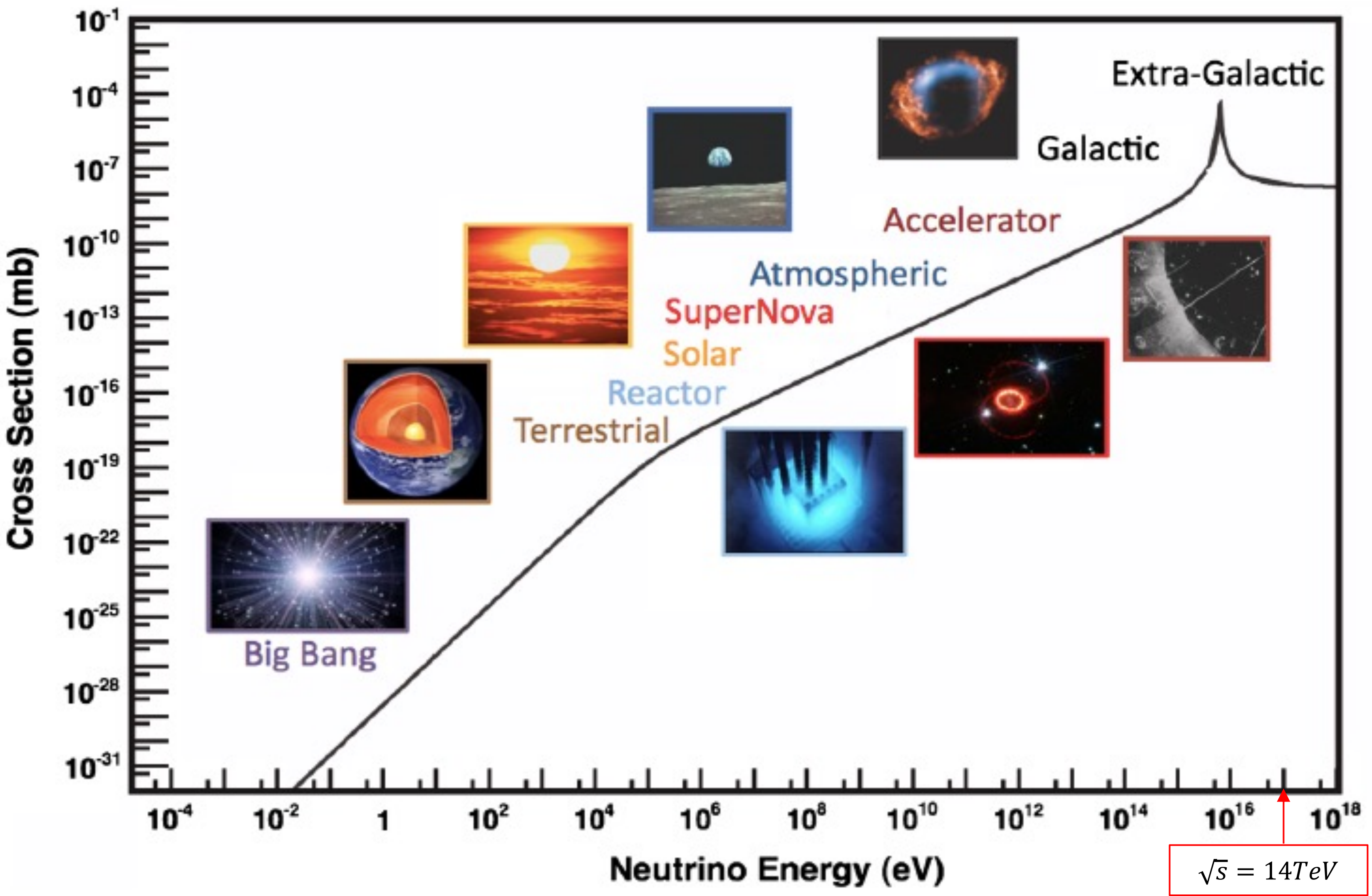
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

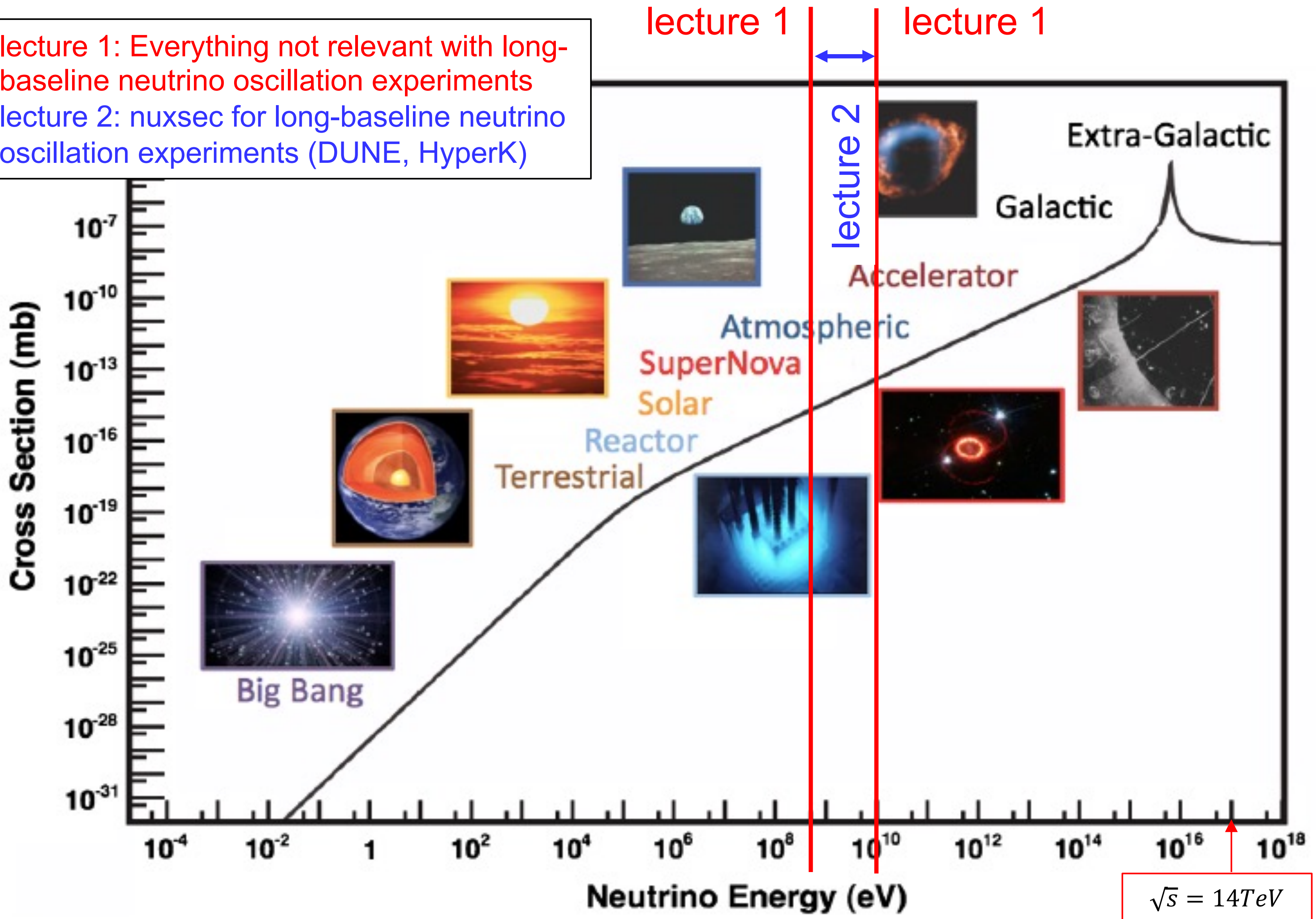
# 1. From eV to EeV: Neutrino cross sections across energy scales



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

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

lecture 1: Everything not relevant with long-baseline neutrino oscillation experiments
lecture 2: nuxsec for long-baseline neutrino oscillation experiments (DUNE, HyperK)

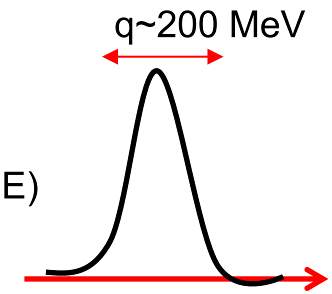


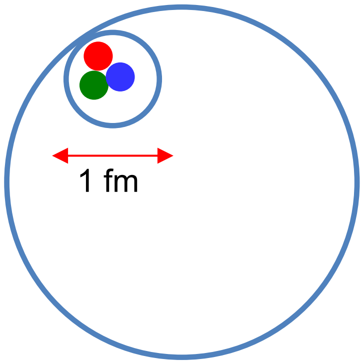
# 1. Scattering measurements

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
(T2K, NOvA, HyperK, DUNE)



# 1. Scattering measurements

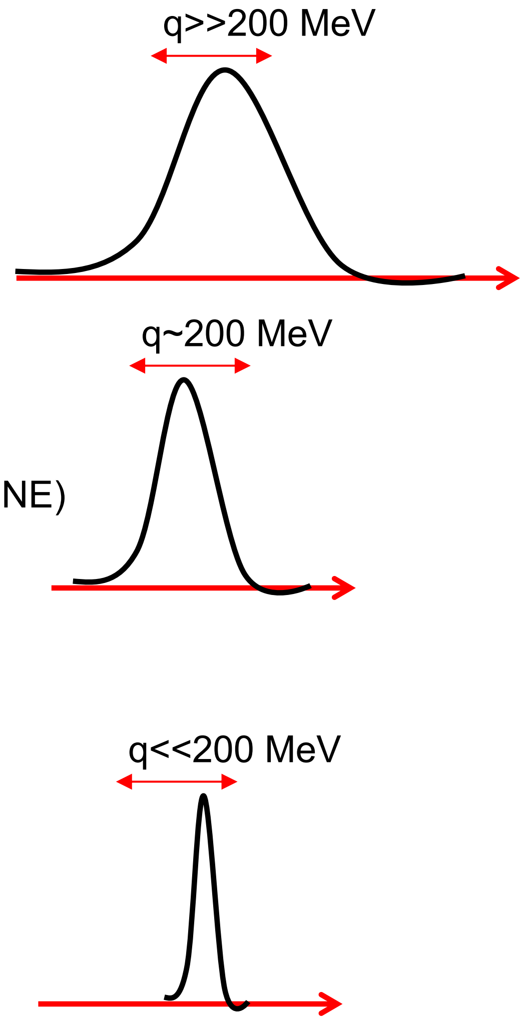
Size of wave packet ~ momentum transfer (~energy)

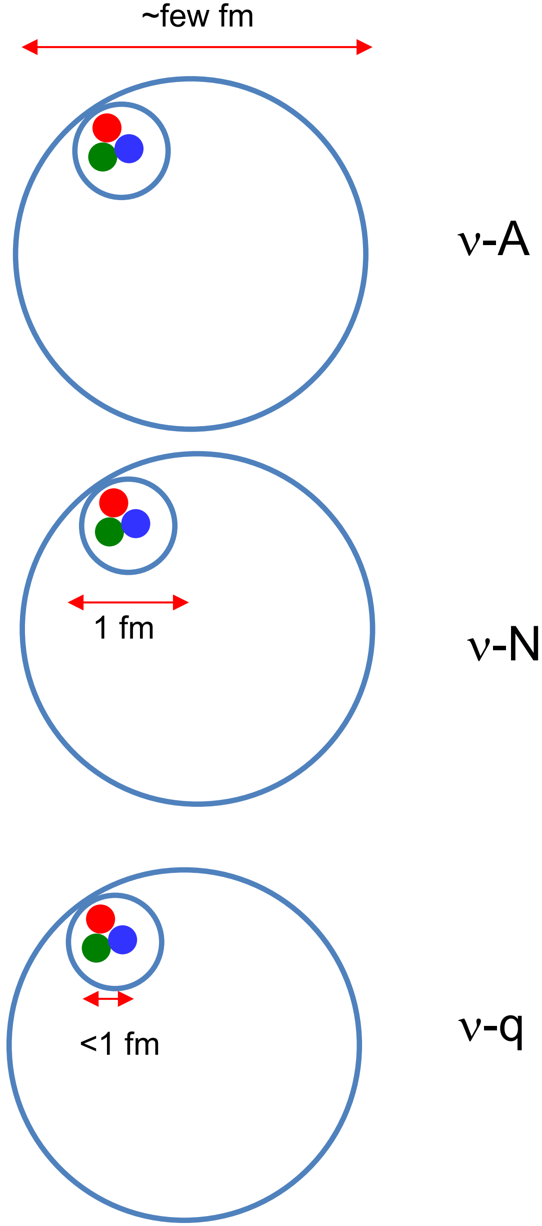
$\hbar c = 197\ MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

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

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

>>1 GeV neutrino beam
(LHC)



# 1. Scattering measurements

Size of wave packet ~ momentum transfer (~energy)

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

Lecture 1: Introduction of neutrino interactions

1. Overview
2. Neutrino lepton scattering (Standard Model)
3. Neutrino quark scattering ($\nu$-q scattering)
4. Neutrino nucleus reactions ($\nu$-A scattering)

Lecture 2: Neutrino interactions for long baseline oscillation experiments ($\nu$-N scattering)

1. Overview
2. CCQE interaction
3. Baryonic resonances
4. Shallow inelastic scattering

# 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 ($\mu_\nu < 3\times10^{-11}\ \mu_B$)

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

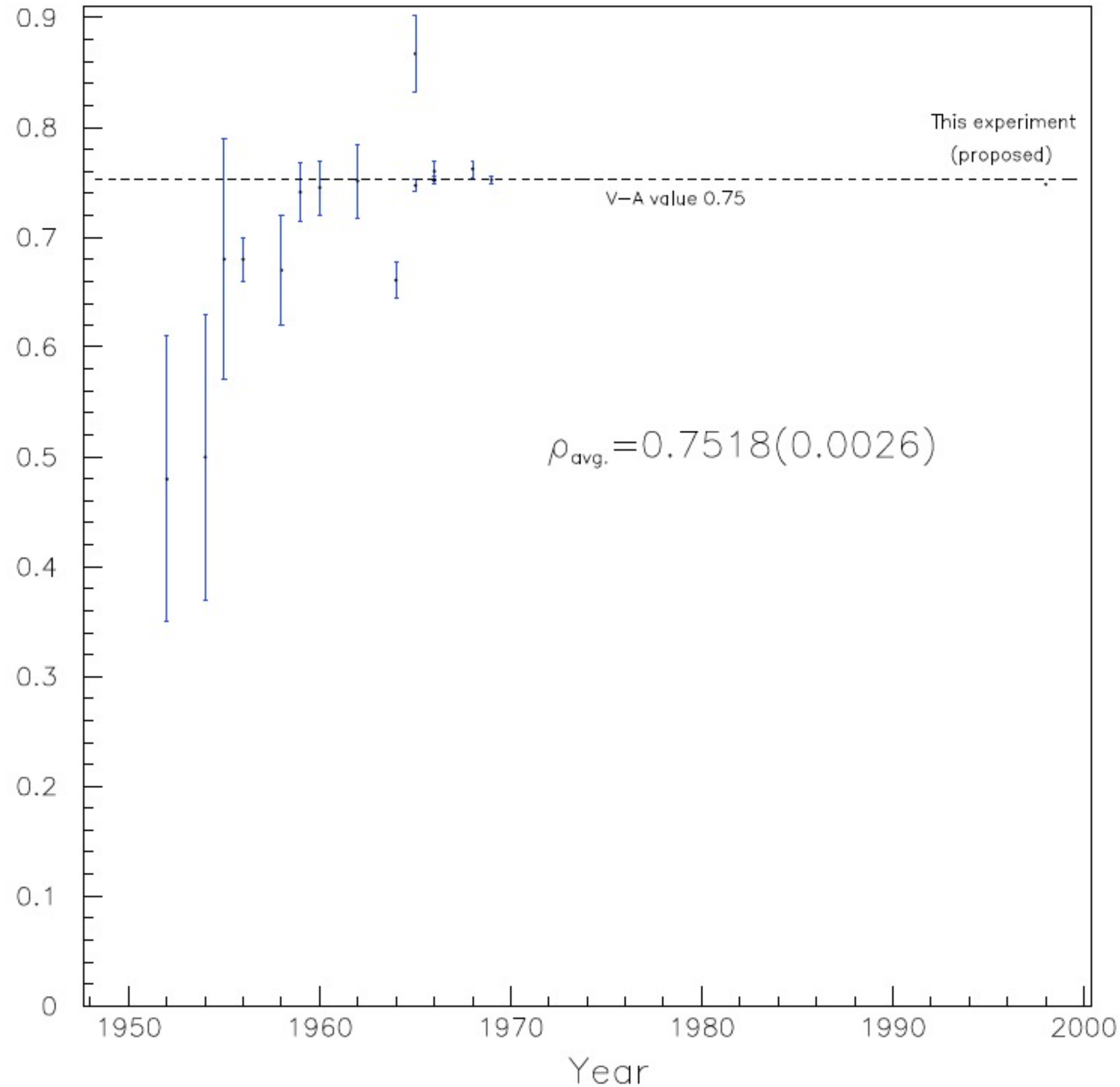
Lepton-only process (pure Standard Model) is often used to test new physics

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

Lee, PhD thesis, Virginia Tech (2001)



# 2. Time dependence of muon decay Michel parameter ρ



# 3. Neutrino-DIS cross section

Neutrino – single d-quark cross section

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

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

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

Neutrino-nucleus DIS cross section with isoscalar assumption

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

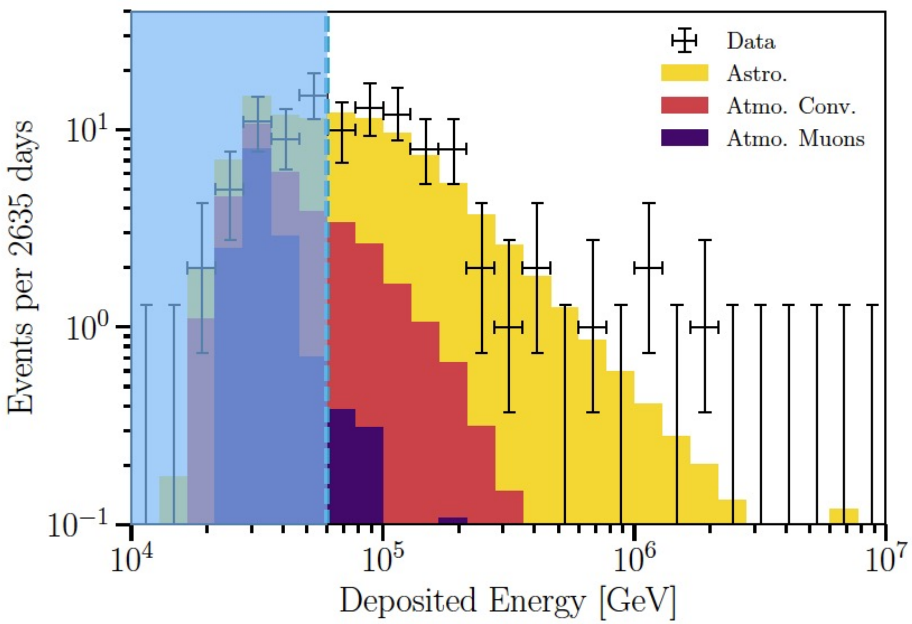
$$u^p(x) + u^n(x) = d^n(x) + d^p(x) = u(x) + d(x) \equiv Q(x)$$
$$\bar{u}^p(x) + \bar{u}^n(x) = \bar{u}^n(x) + \bar{u}^p(x) = \bar{u}(x) + \bar{d}(x) \equiv \bar{Q}(x)$$

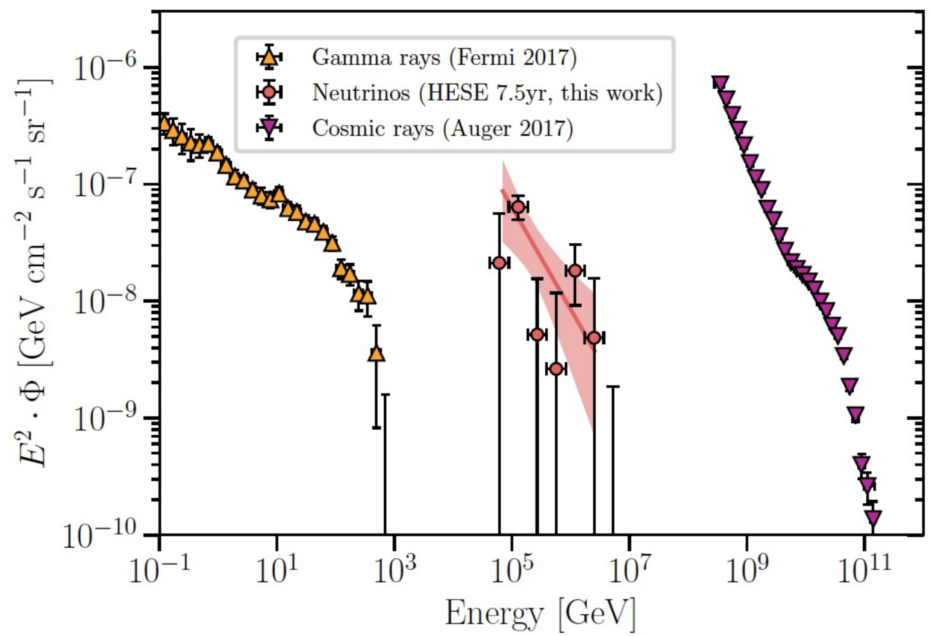
# 3. Astrophysical high-energy neutrino measurement

cross section | efficiency | flux | target

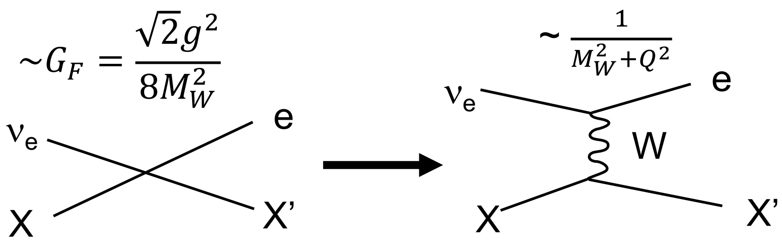
Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Data and MC agree up to ~PeV.
→ We more or less understand neutrino interactions up to ~PeV.



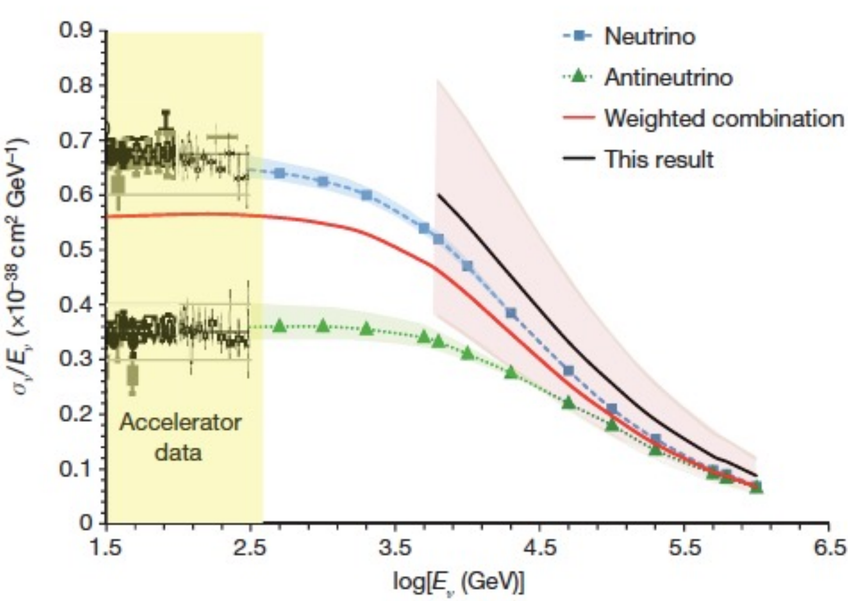



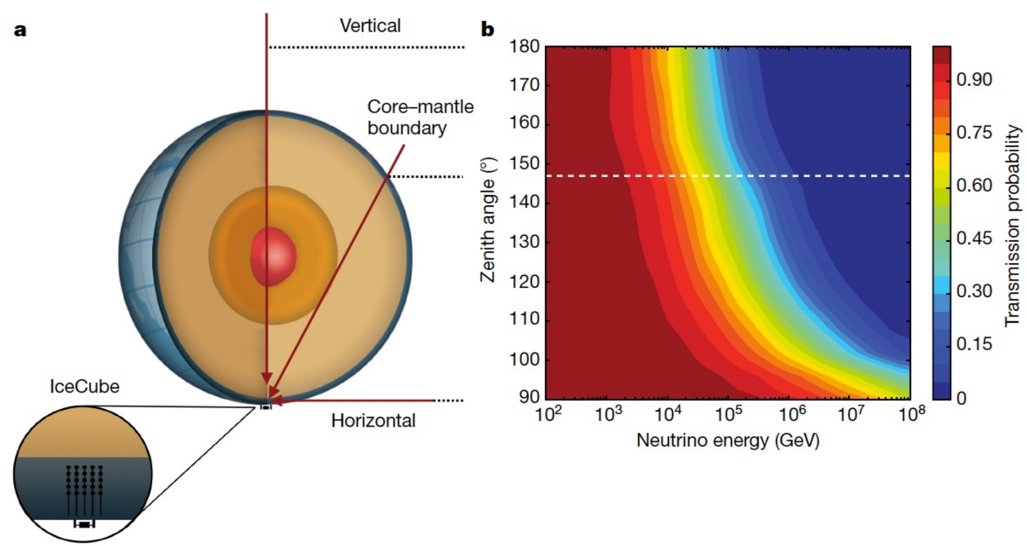
# 3. Neutrino DIS saturation




cross section | efficiency | flux | target

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



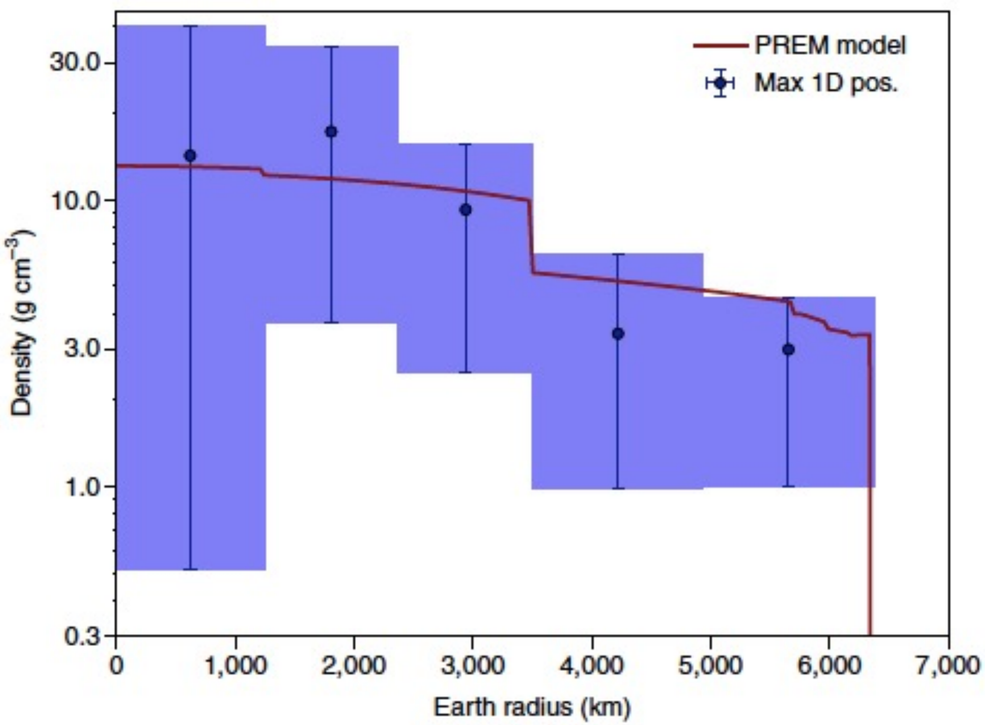



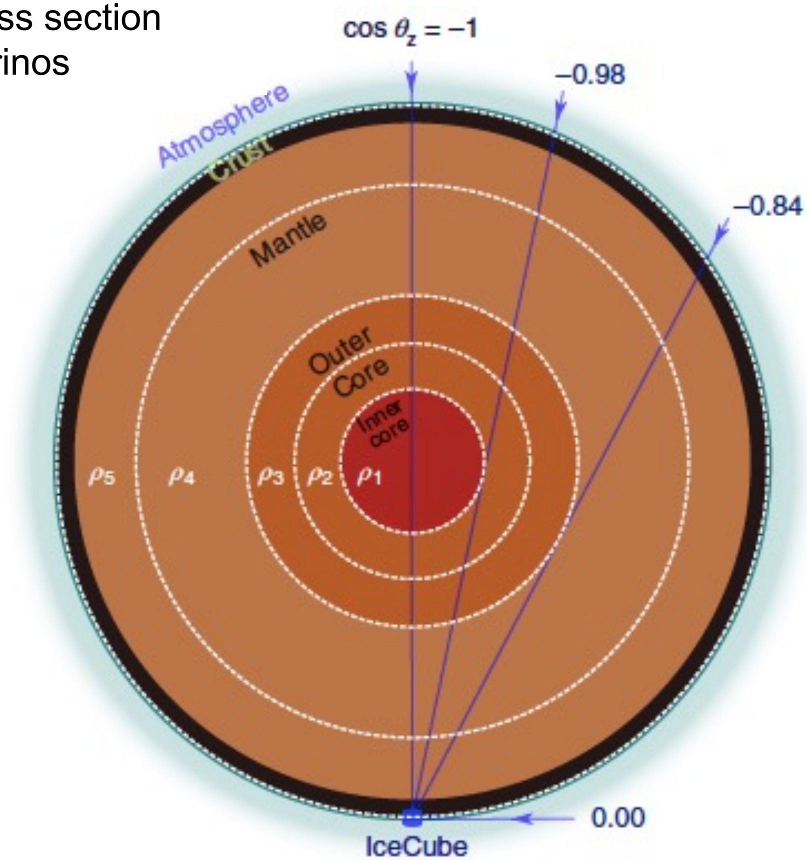
# 3. Earth tomography

cross section | efficiency | flux | target

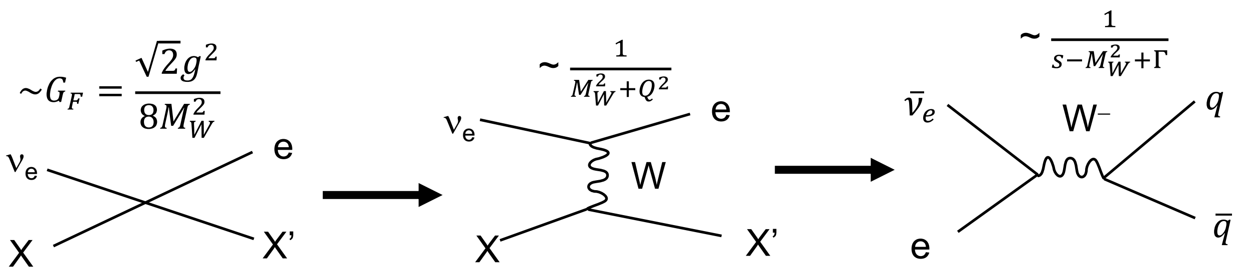
Event rate $\mathrm{N} = \Phi \times \sigma \times T \times \varepsilon$

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

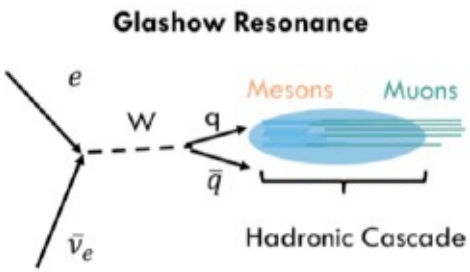


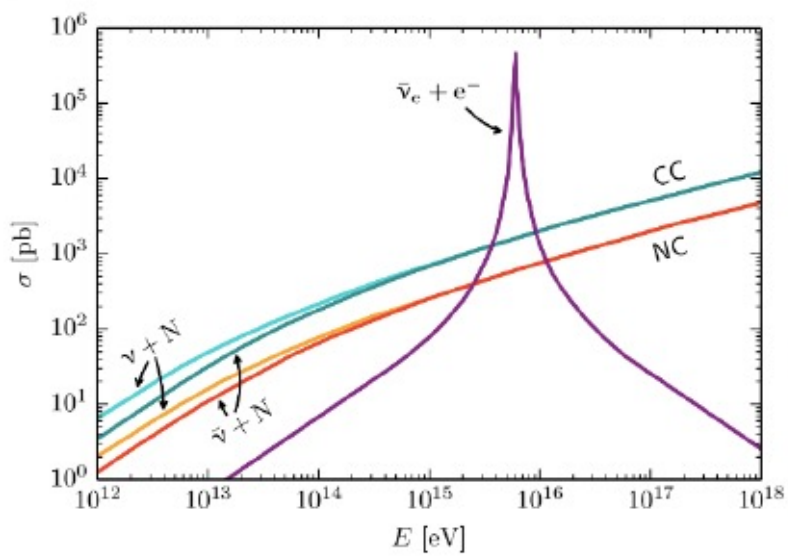
# 3. Glashow resonance

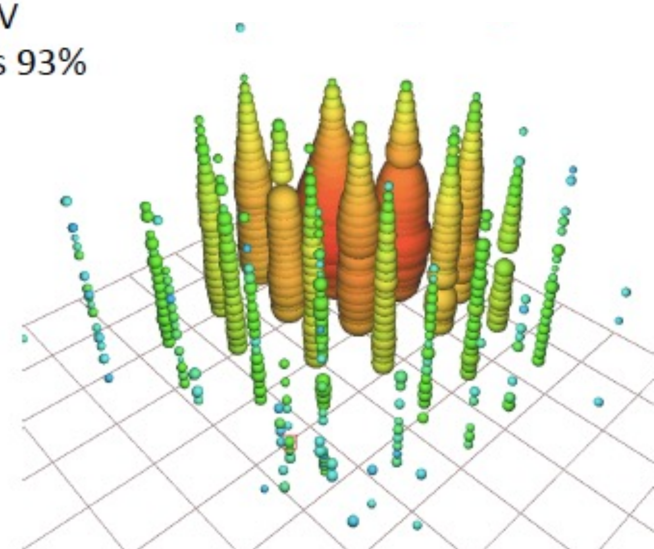



## A 5.9 PeV event in IceCube




Resonance: $E_\nu$ = 6.3 PeV
Typical visible energy is 93%



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

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

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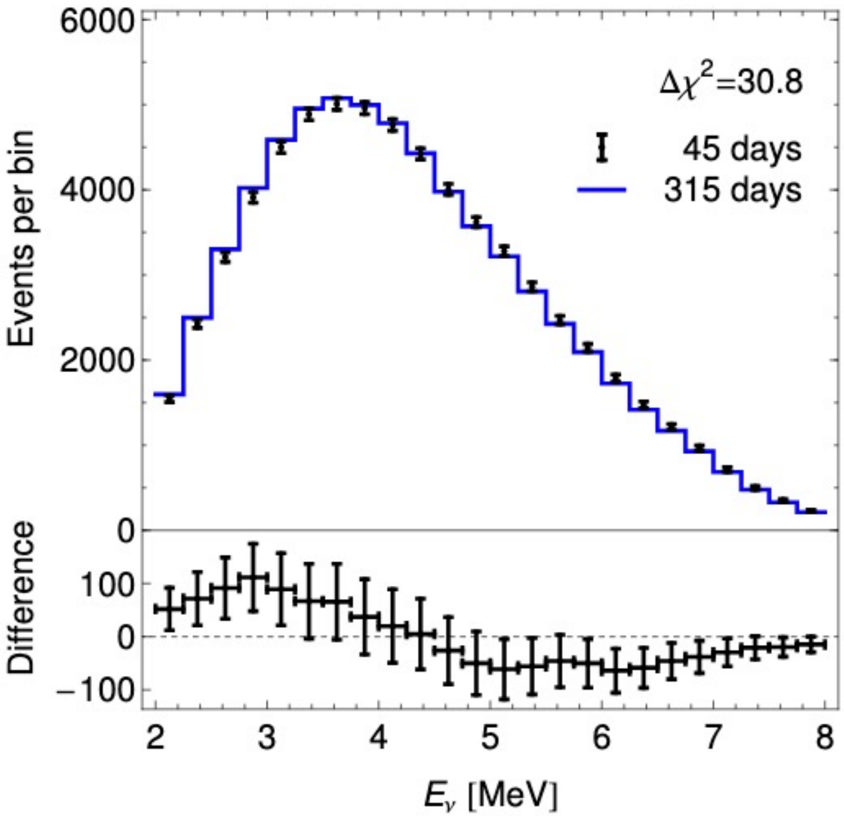
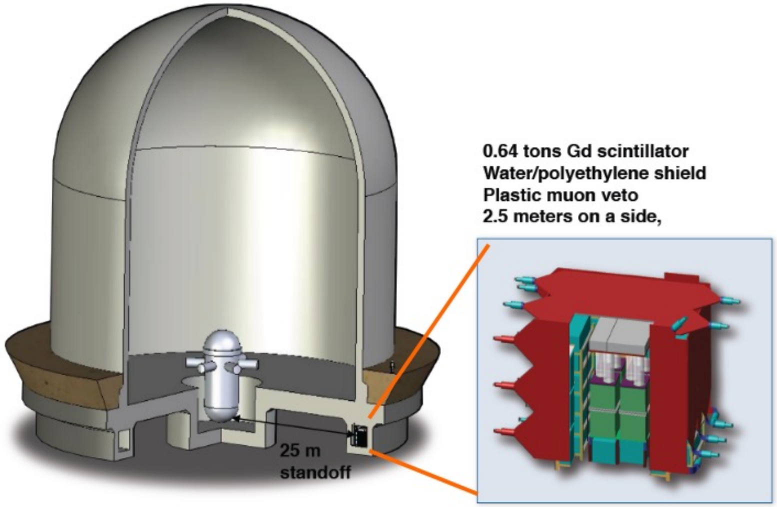
Akindele (Neutrieno2020), https://zenodo.org/record/3959532
SONGS, Journal of Applied Physics, 105(6), 064902 (2009)

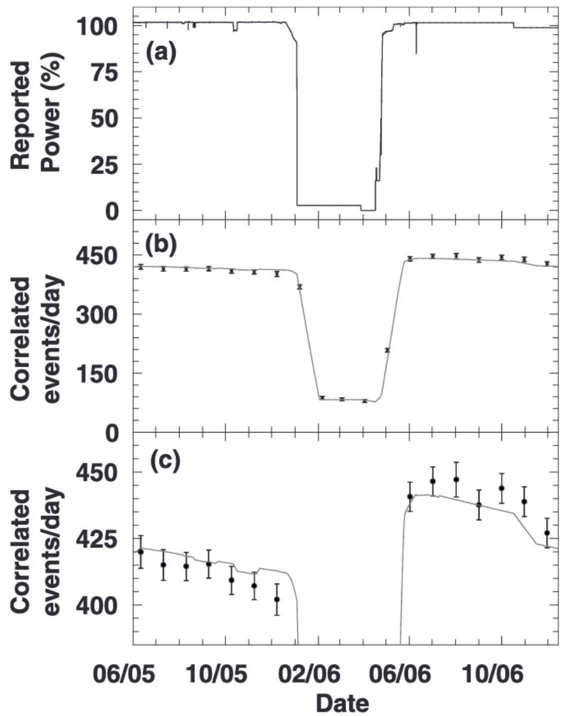


# 4. Reactor neutrino

Low energy electron anti-neutrinos
- High-precision spectrum prediction
- Monitoring fission reactor



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

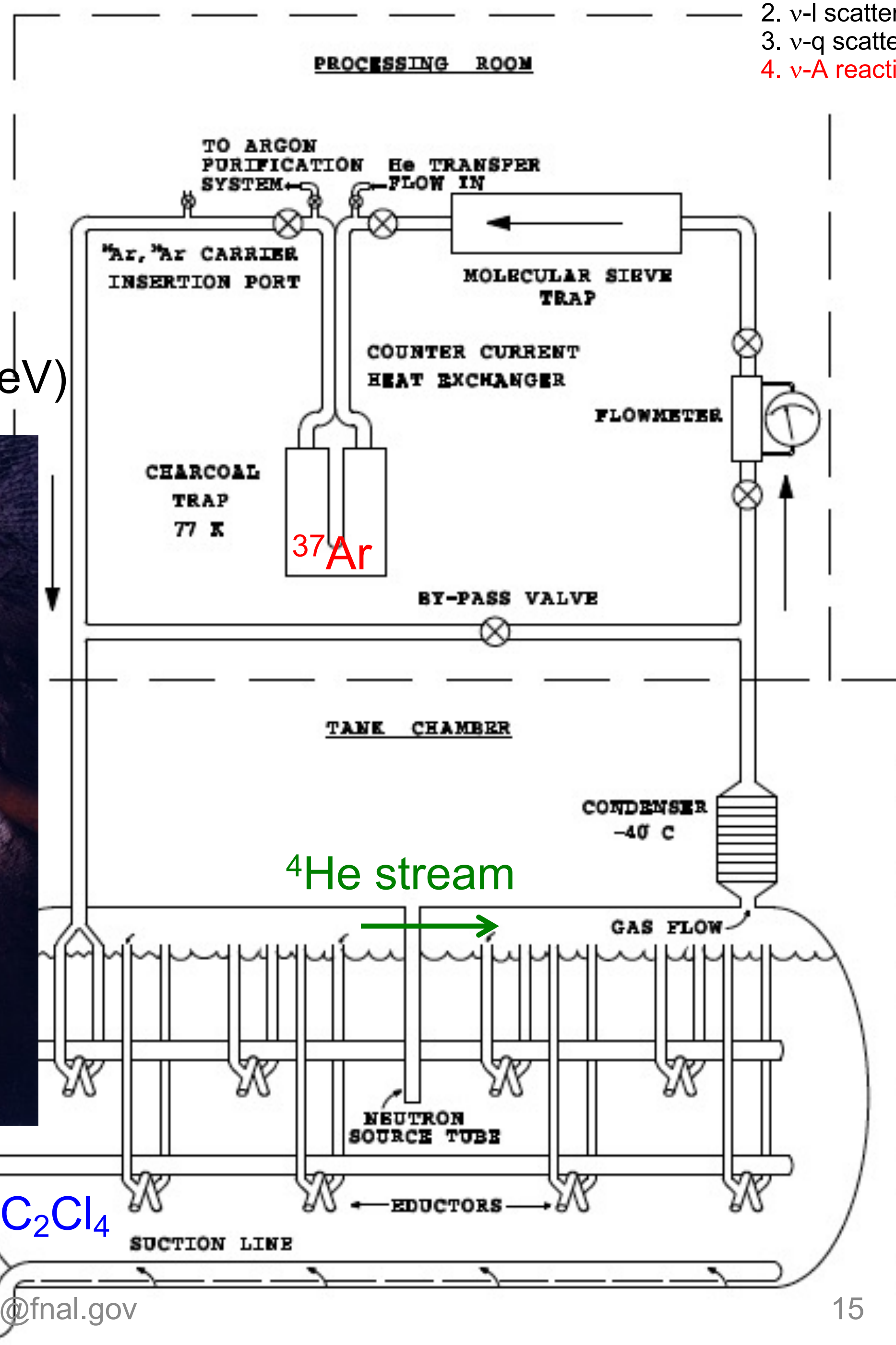
# 4. Solar neutrino

## Homestake experiment

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

(proposed by Pontecorvo)

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

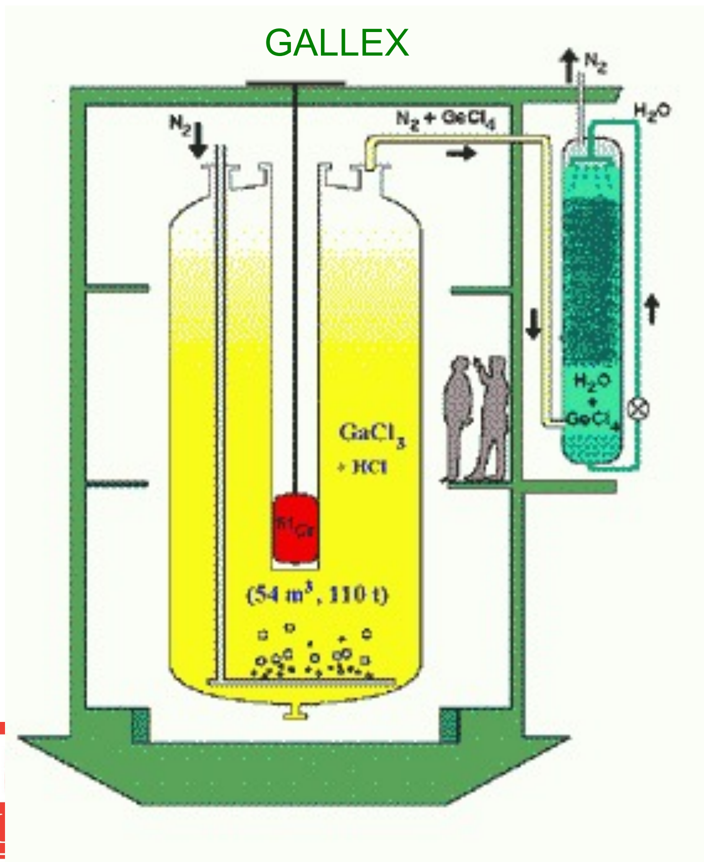


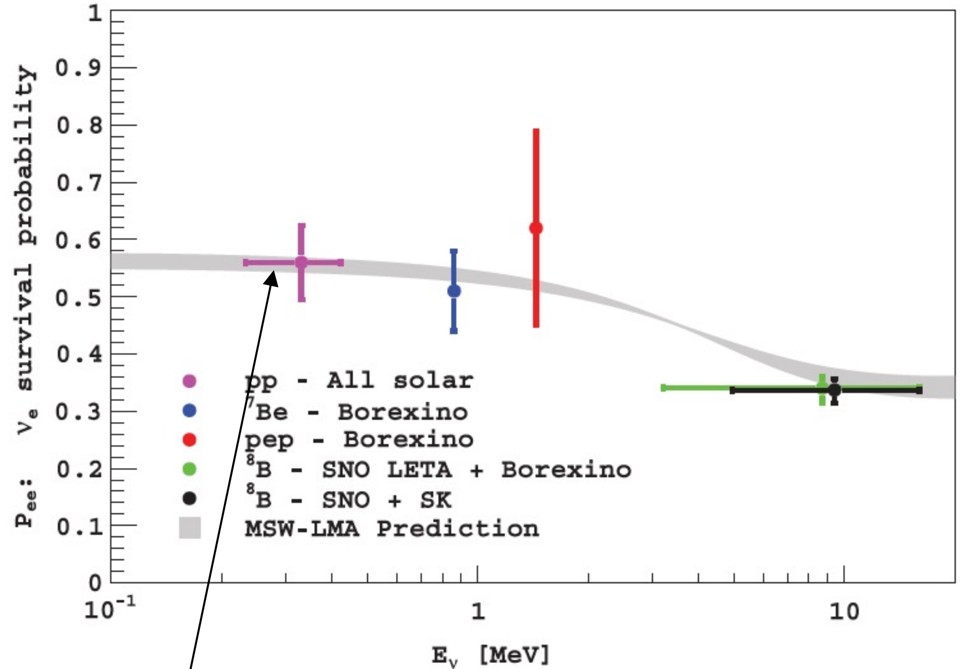
# 4. Solar neutrino

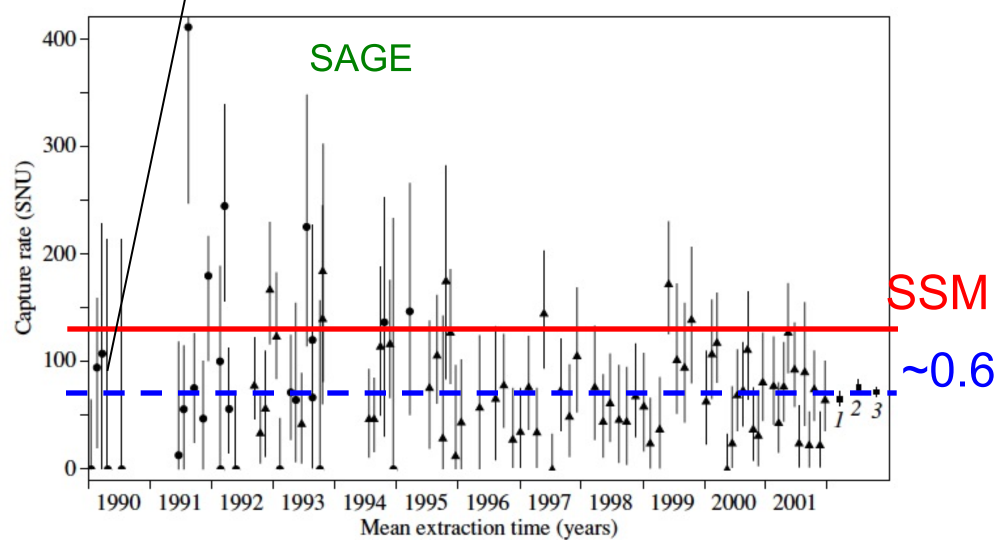
## Gallium experiment

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

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



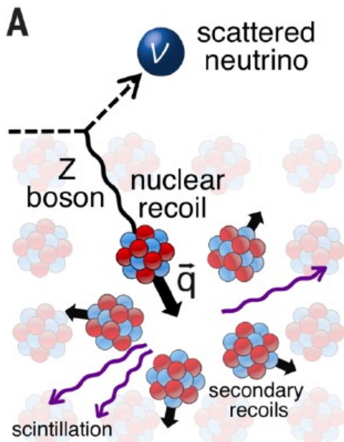
COHERENT, Science10.1126/science.aao0990 (2017).

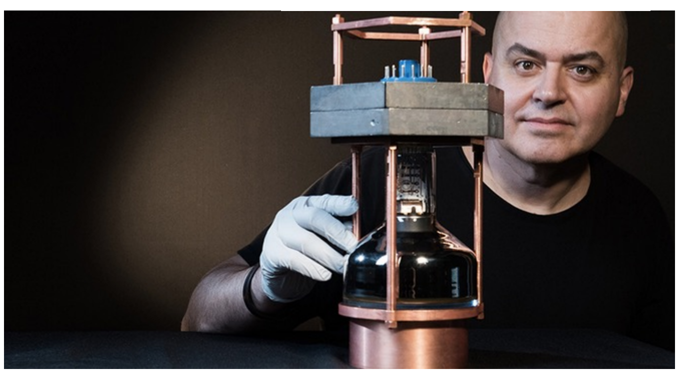
2. ν-l scattering
3. ν-q scattering
4. ν-A reaction

# 4. Neutrino-Nucleus coherent scattering

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

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

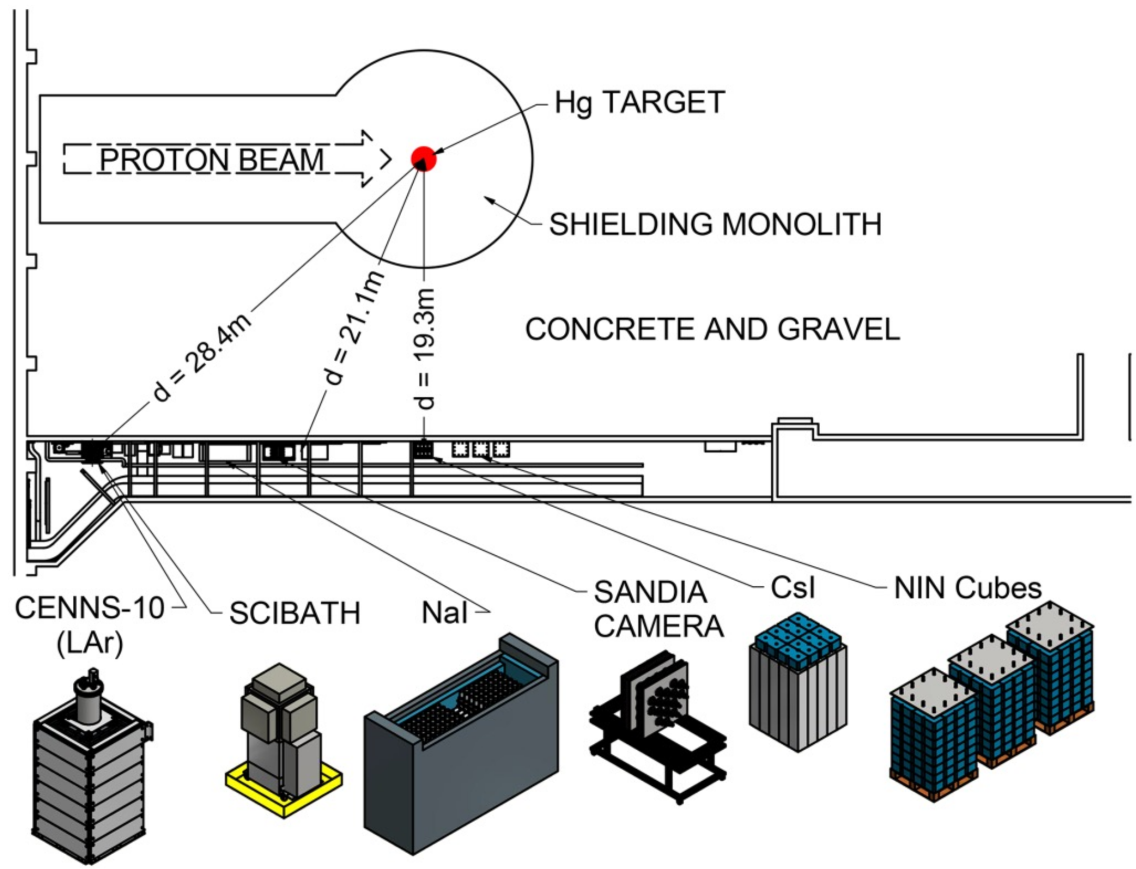



Science REPORTS

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

**Observation of coherent elastic neutrino-nucleus scattering**

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# Conclusion

Neutrinos interact by weak force

$\nu$-l scattering : test of weak theory

- Neutrino-electron scattering
- Muon decay

$\nu$-q scattering : test of weak theory, test of quark model

- DIS cross sections
- Di-muon production
- Paschos-Wolfenstein ratio
- Astrophysical neutrinos

$\nu$-A scattering :

- Reactor neutrino experiments
- Neutrino nuclear capture by Cl and Ga, important for solar neutrinos
- Neutrino coherent scattering, important for supernova (2017)

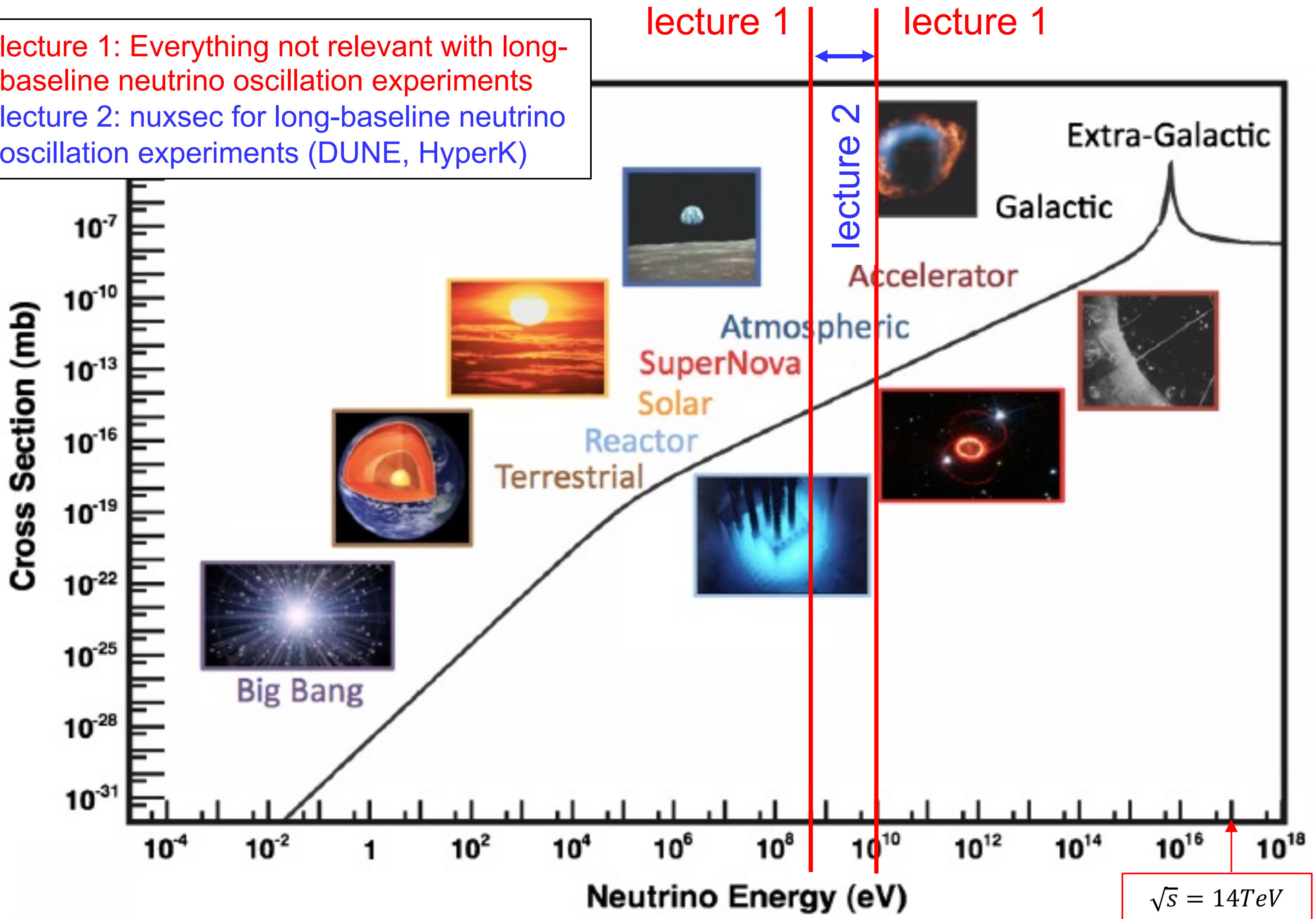
$\nu$-N scattering : important reactions for long baseline neutrino oscillation experiment

(T2K, NOvA, DUNE, Hyper-Kamiokande)

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

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

lecture 1: Everything not relevant with long-baseline neutrino oscillation experiments
lecture 2: nuxsec for long-baseline neutrino oscillation experiments (DUNE, HyperK)



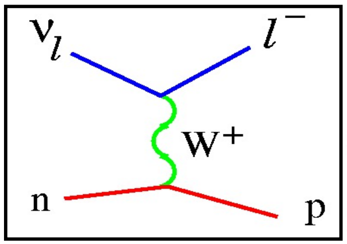
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

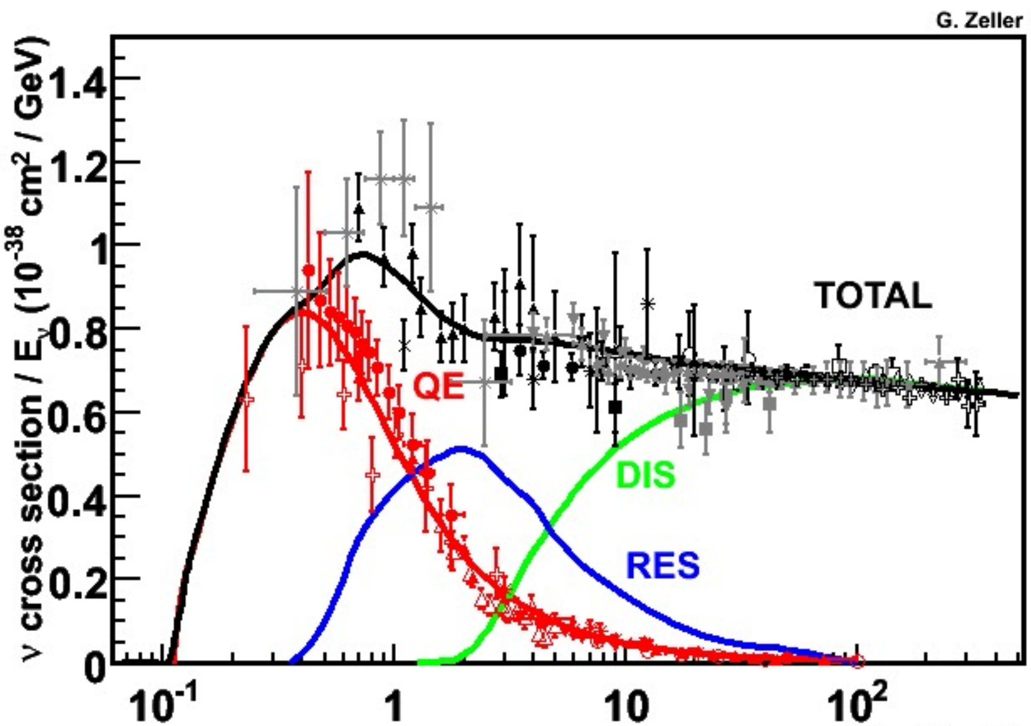
# 1. Next generation neutrino oscillation experiments

## Accelerator-based neutrino oscillation experiments

- Present to Future: T2K, NOvA, Hyper-Kamiokande, DUNE

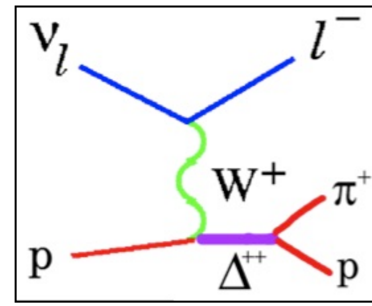
Quasi Elastic

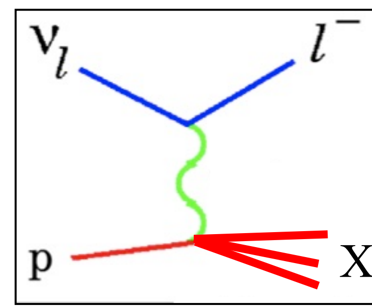



$\nu_\mu$CC cross section per nucleon

baryonic RESonance




Deep Inelastic Scattering

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

# 1. Next generation neutrino oscillation experiments

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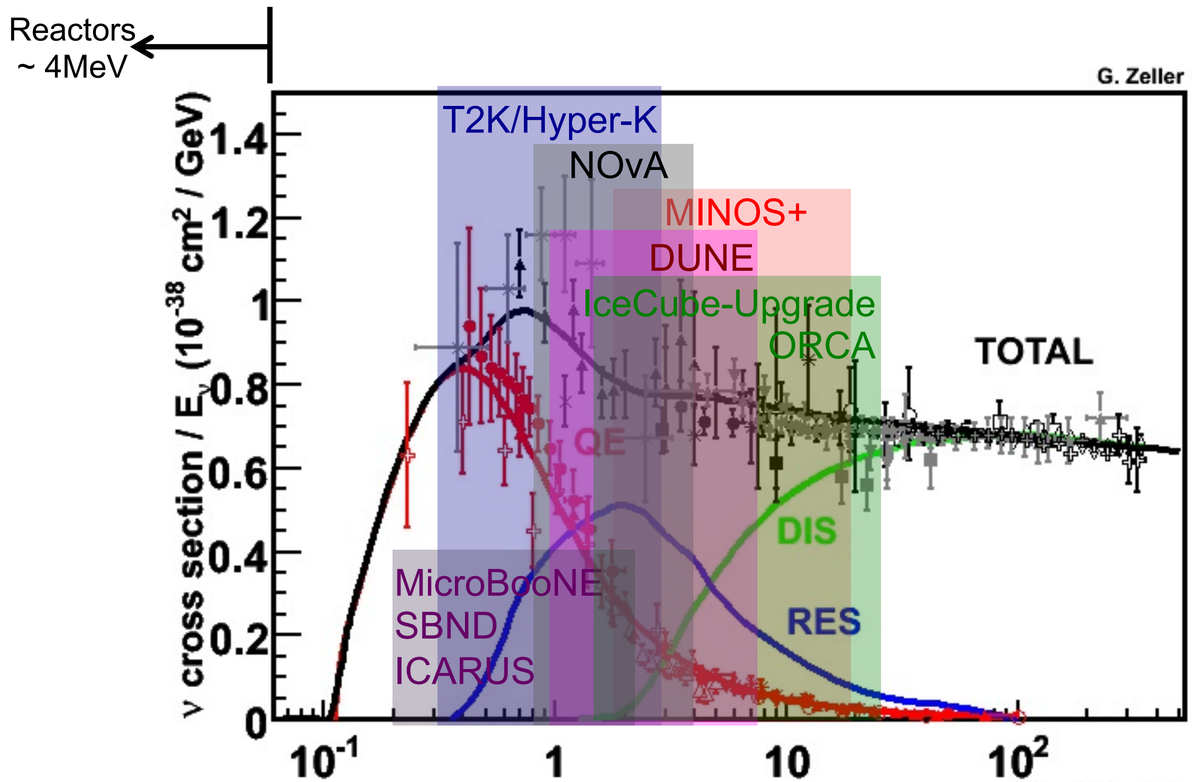
- Present to Future: T2K, NOvA, Hyper-Kamiokande, DUNE…




$\nu_\mu$CC cross section per nucleon

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

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# 1. Next generation neutrino oscillation experiments

## Accelerator-based neutrino oscillation experiments

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

## Most of data are from muon neutrino beam

- create by $\pi$-DIF, K-DIF (pion and kaon decay-in-flight)
- $\Phi(\nu_\mu) > \Phi(\bar{\nu}_\mu)$: more $\pi^+$ and $K^+$ than $\pi^-$ and $K^-$ (for low energy)
- $\mu$-decay can make electro-neutrinos but they are background
- $\delta_{CP}$ study need electro-neutrino and antineutrino cross-sections ($\nu_e$ appearance)

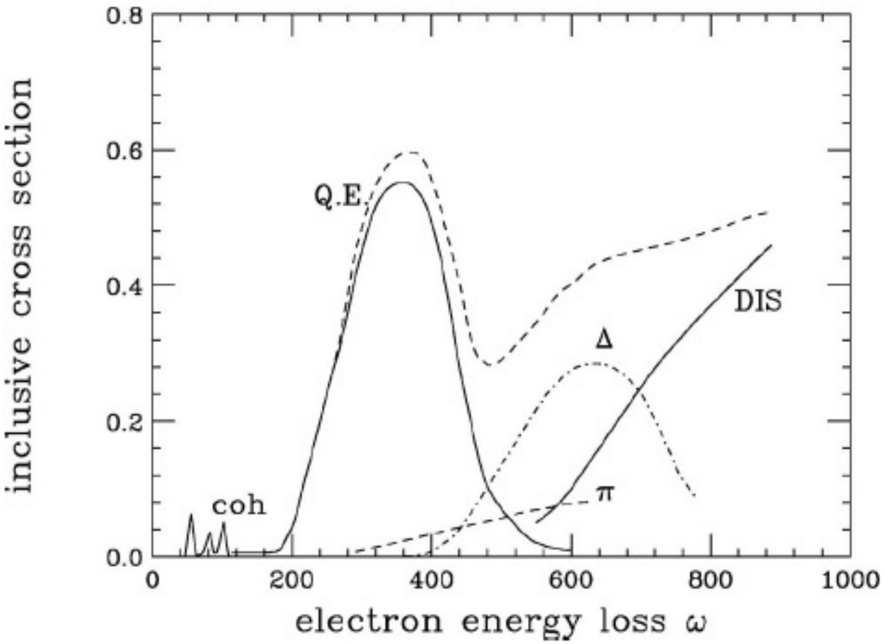
## Nuclear physics sucks

- 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…

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

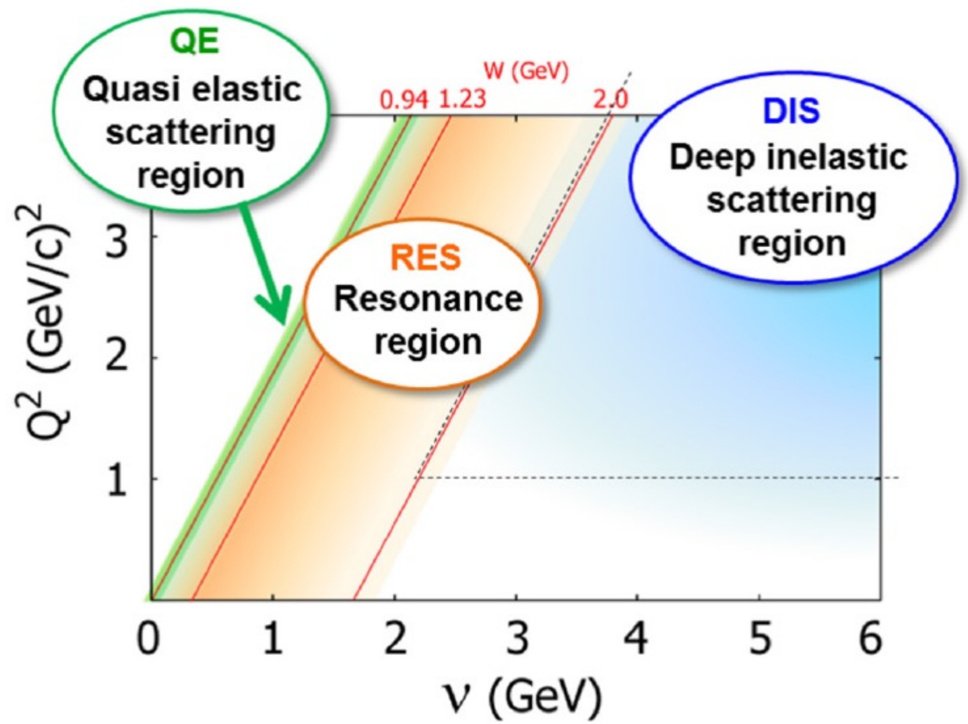
Benhar,Day,Sick,Rev.Mod.Phys.80(2008)189
Nakamura et a;,Rep.Prog.Phys.80(2017)056301

# 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)

katc

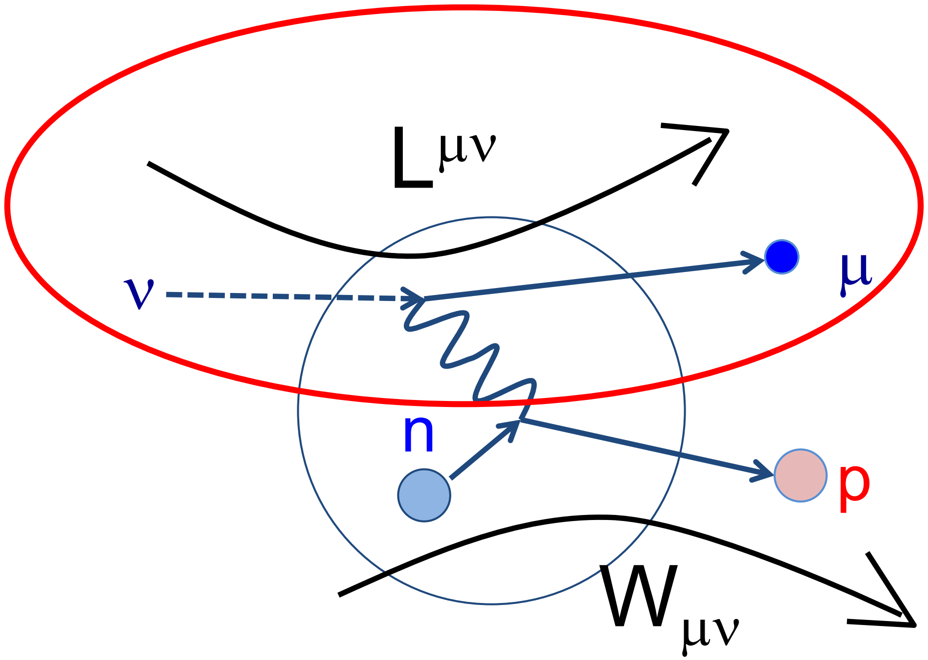
# 1. Neutrino cross-section formula

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)



# 1. Neutrino cross-section formula

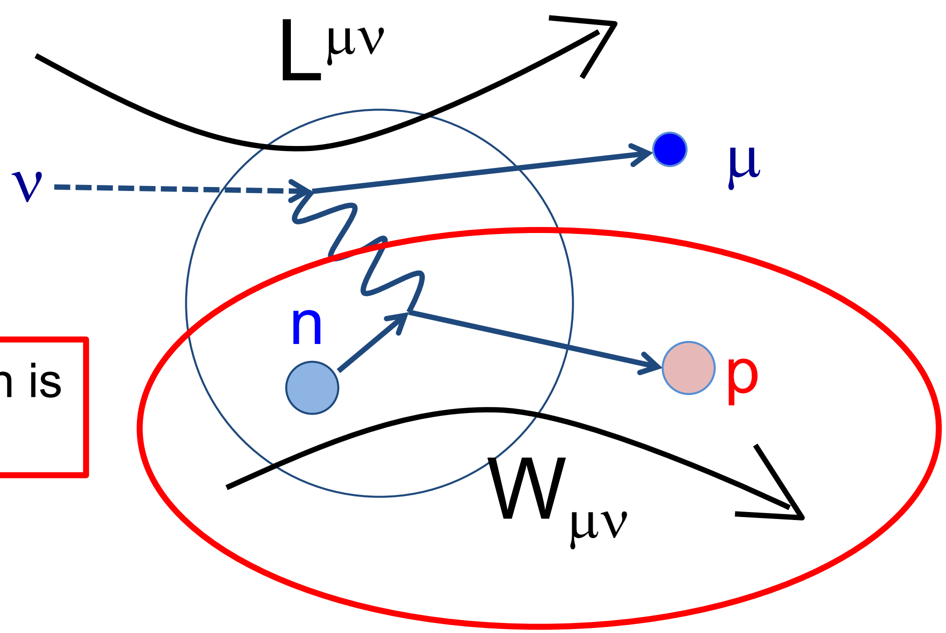
Cross-section
- product of Leptonic and Hadronic tensor

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

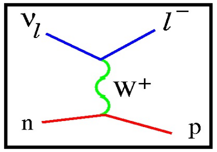
Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)

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



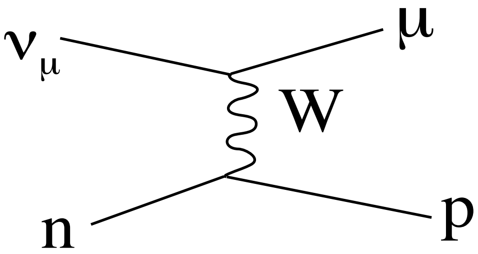
Quasi Elastic




# 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 parameterized with dipole form

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

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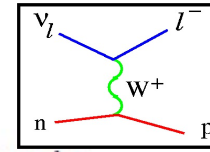
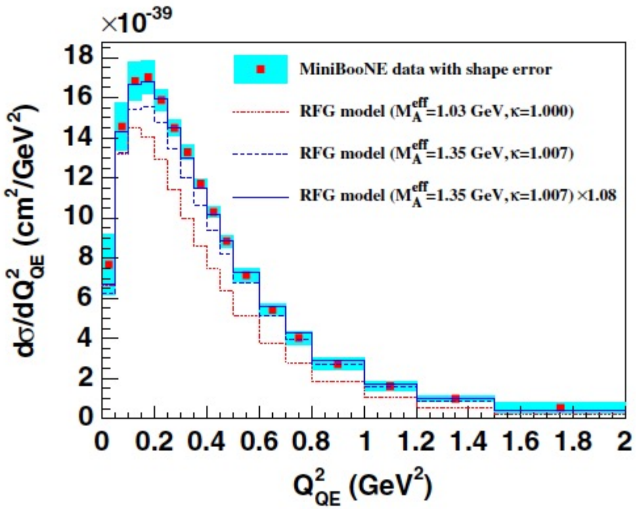
Quasi Elastic




# 2. Form factors

MiniBooNE CCQE cross section
PRD81(2010)092005




Form factors can be parameterized with dipole form

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

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

r ⟶ $|q|$ ⟶

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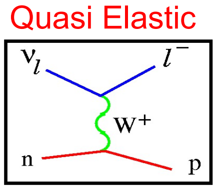
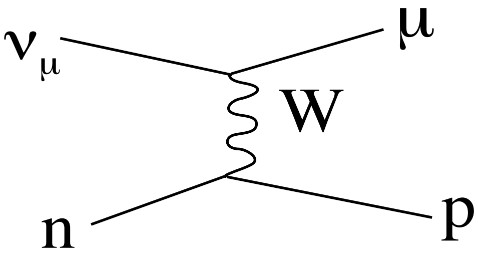



# 2. Charged Current Quasi-Elastic scattering (CCQE)

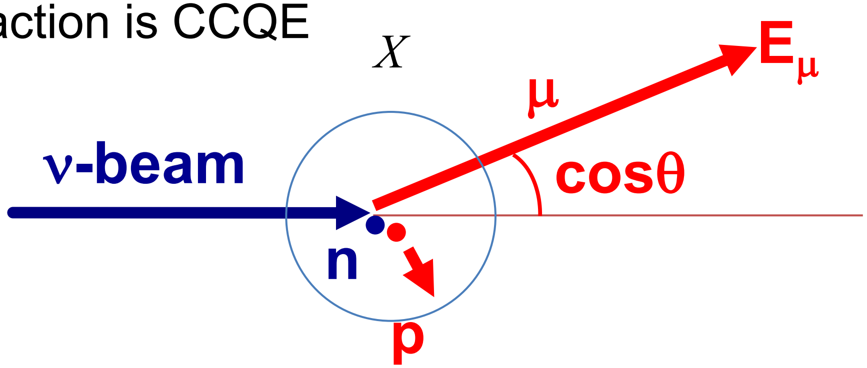
The simplest and the most abundant interaction around ~1 GeV.

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




Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"

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

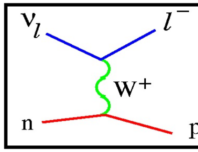



$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

Martini et al, PRC80(2009)065501

Quasi Elastic



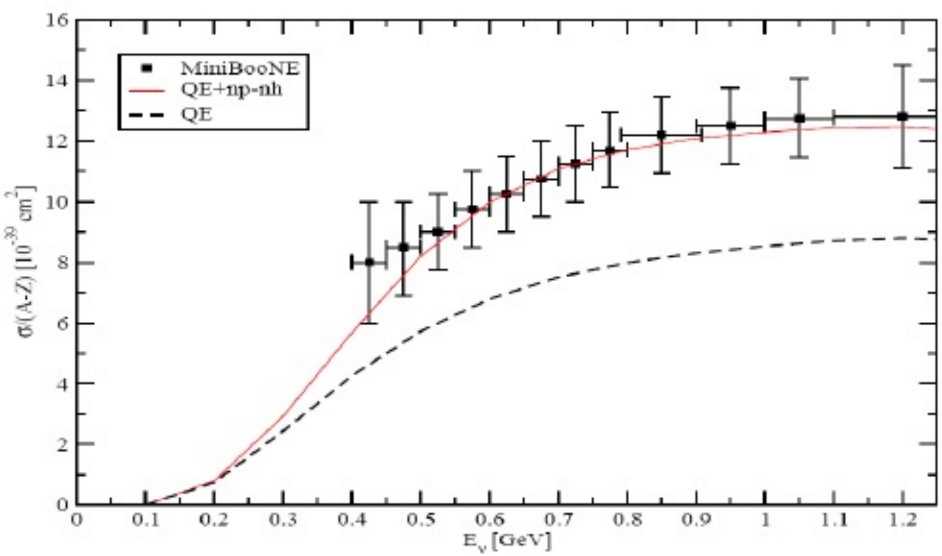

# 2. Nucleon correlations

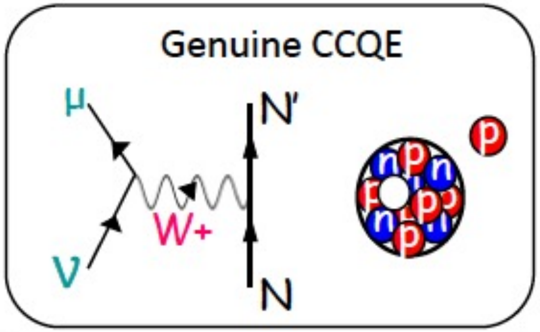
2-particle 2-hole (2p2h) effect

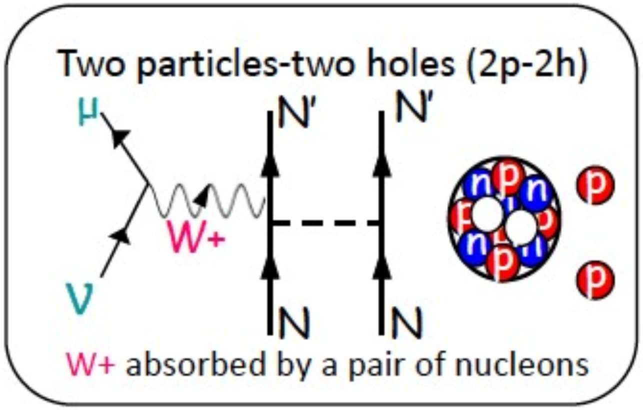
- Mimic CCQE interaction, significant change cross section (both shape and normalization)
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



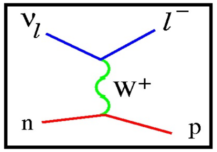



Martini et al, PRC80(2009)065501
NOvA, EPJC80,1119(2020)

# 2. Nucleon correlations

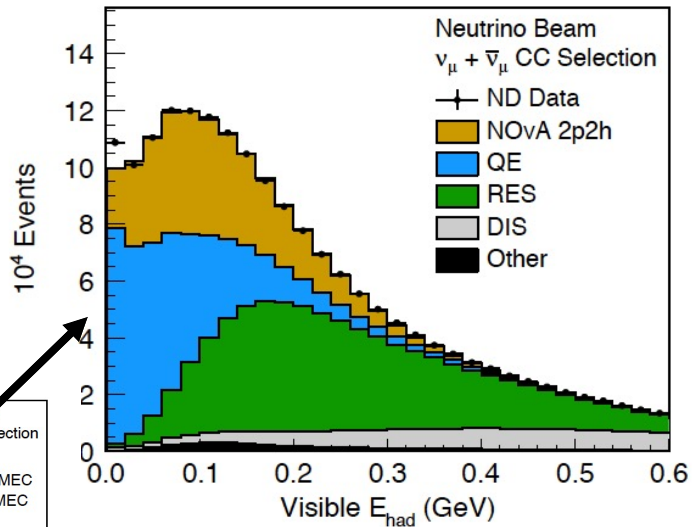
Quasi Elastic

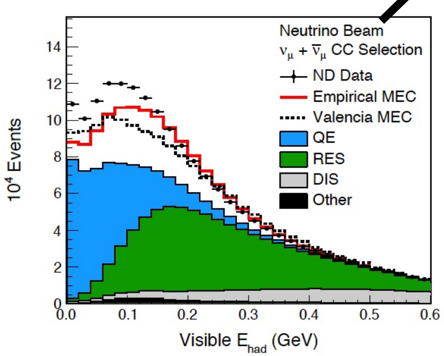


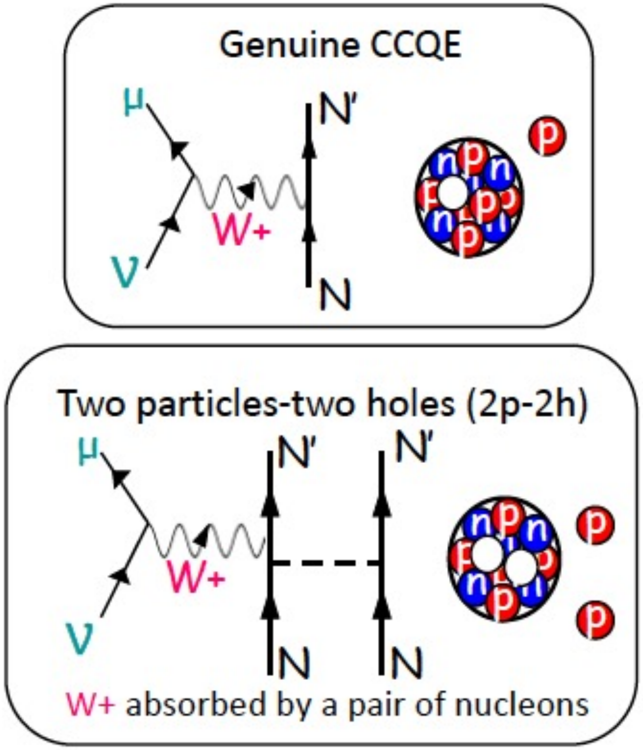

## 2-particle 2-hole (2p2h) effect

- Mimic CCQE interaction, significant change cross section (both shape and normalization)
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE)
- 2p2h models in generators don't describe data well?
- High resolution detector (LArTPC, emulsion, etc) can find what is going on?

NOvA near detector data-MC comparison after fit



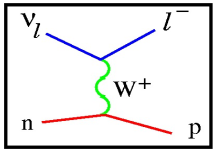



Smith and Moniz, NPB43(1972)605
Ashkenazi (Neutrino 2020), https://zenodo.org/record/3959538

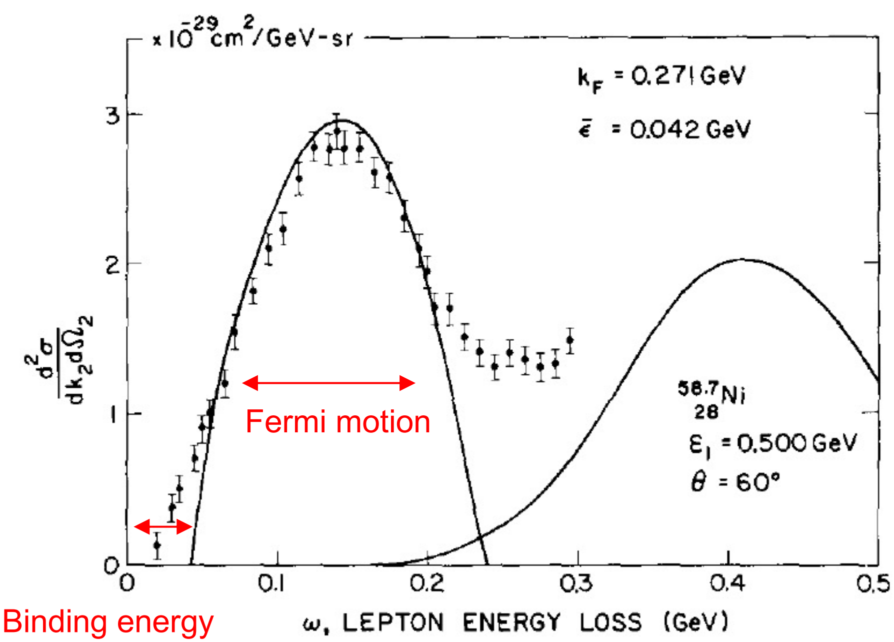
# 2. Fermi motion

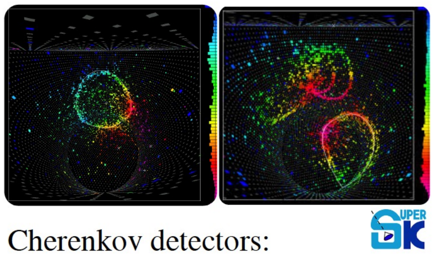
Quasi Elastic




## 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)



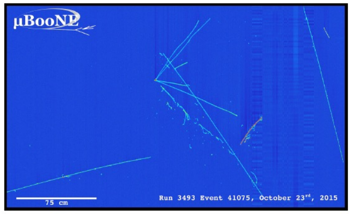



Cherenkov detectors:

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

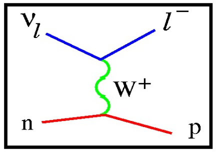
$$E_{\rm cal} = E_l + E_p^{\rm kin} + \epsilon$$

[1p0π]

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

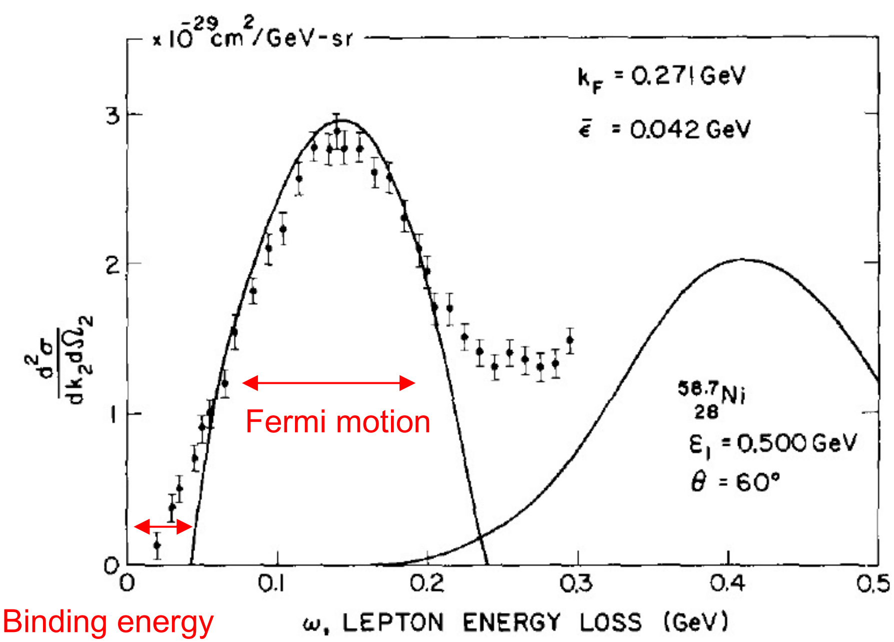
# 2. Pauli blocking

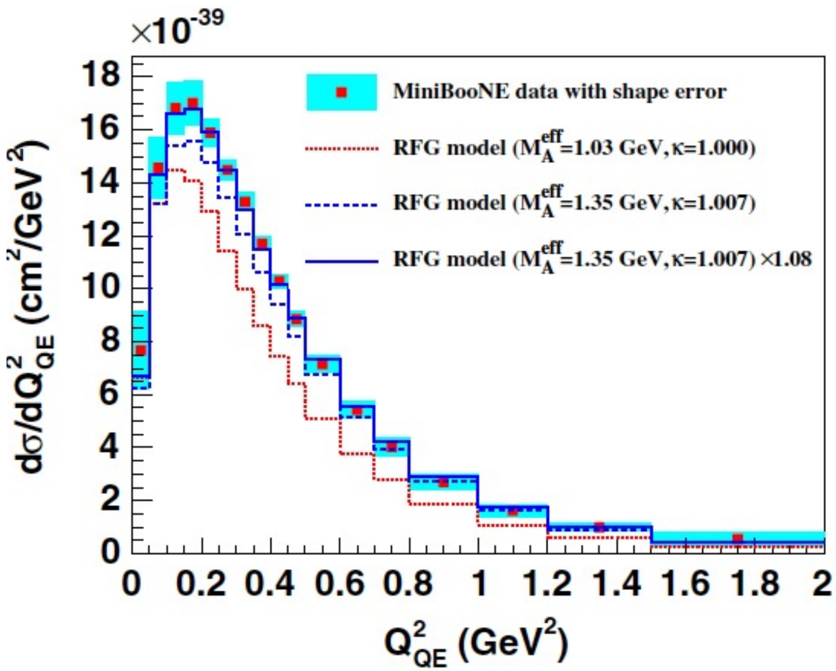
Quasi Elastic




### 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

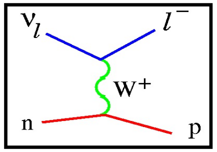


Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

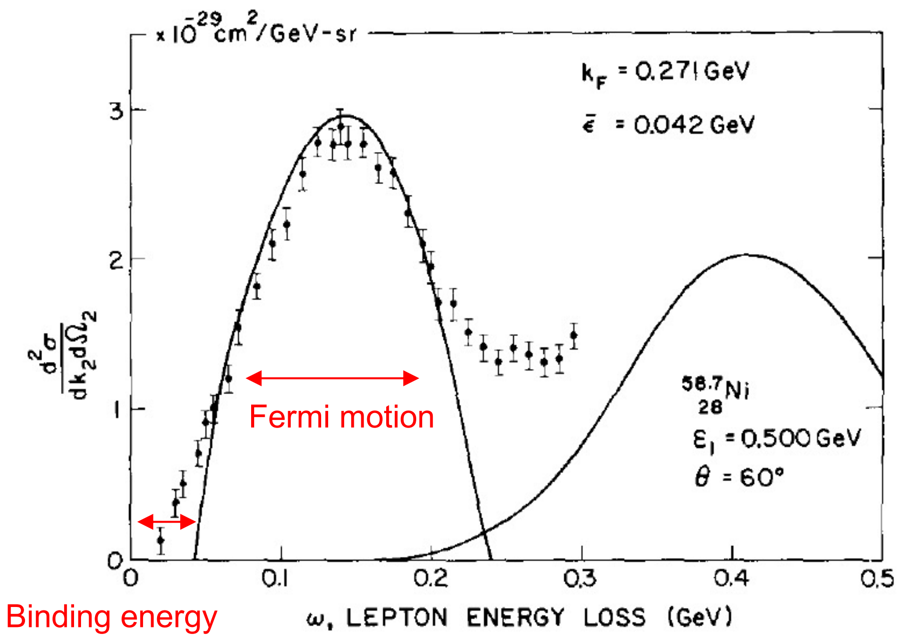
# 2. Nuclear Shell structure and binding energy

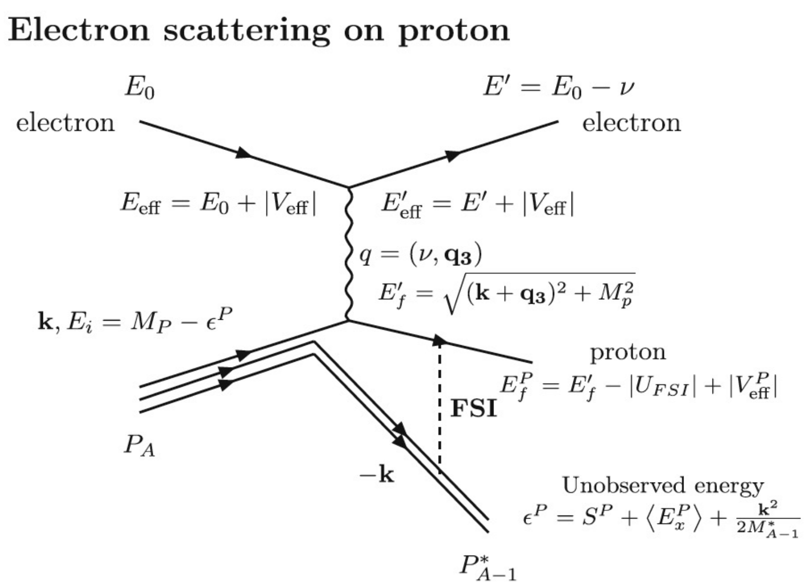
Quasi Elastic




Binding energy ~ unobserved energy

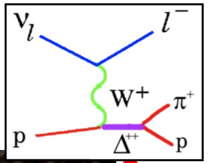
- Energy to cost to release 1 nucleon, not constant
- Separation energy + excitation energy + recoil energy
  - Separation energy: energy to release 1 nucleon from the shell (~15 MeV, depends)
  - Excitation energy: energy used to excite leftover target nucleus (~1 MeV)
  - Recoil energy: kinetic energy of recoil target nucleus (~2-3 MeV)



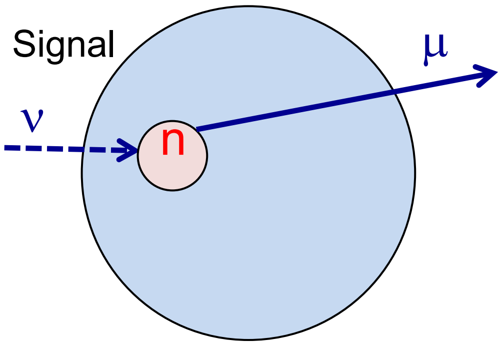



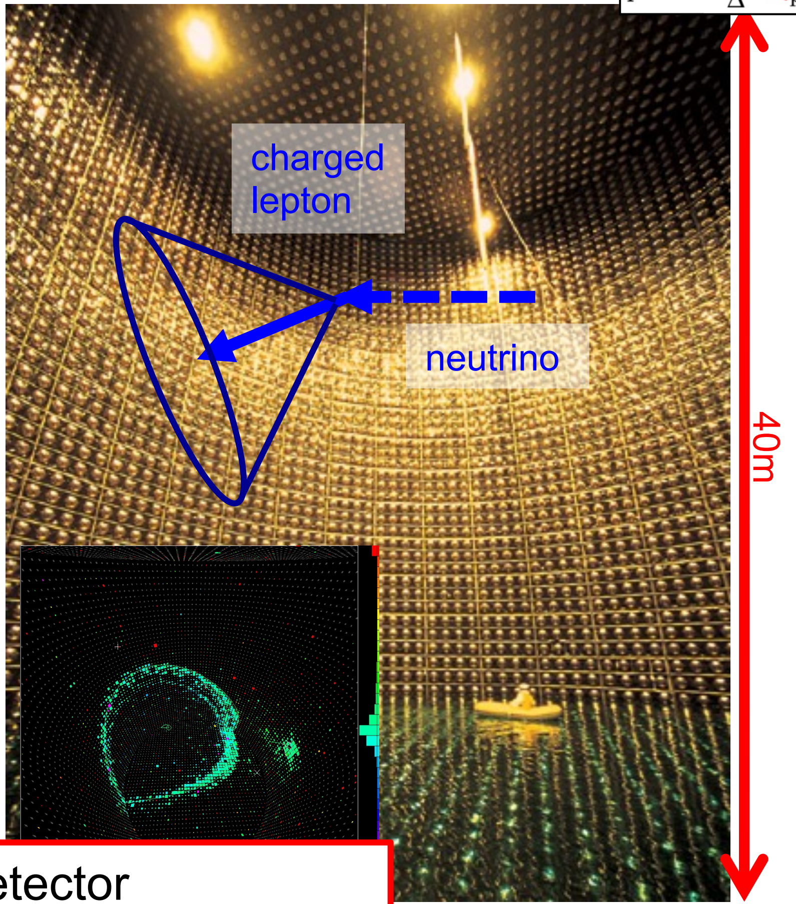
# 3. non-QE background (resonance pion production)

RESonance




non-QE background → shift spectrum




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

Typical neutrino oscillation detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

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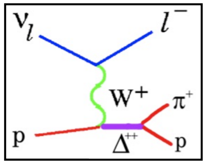
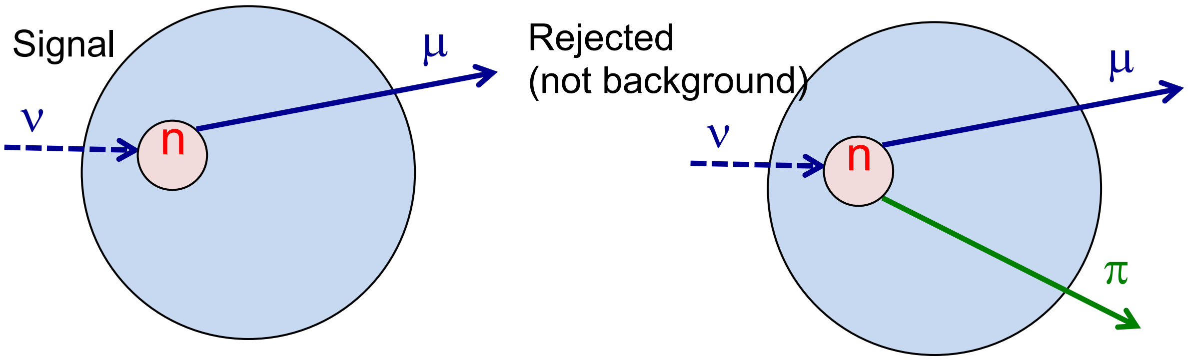



non-QE background → shift spectrum

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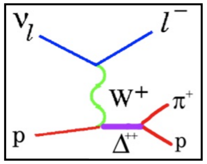


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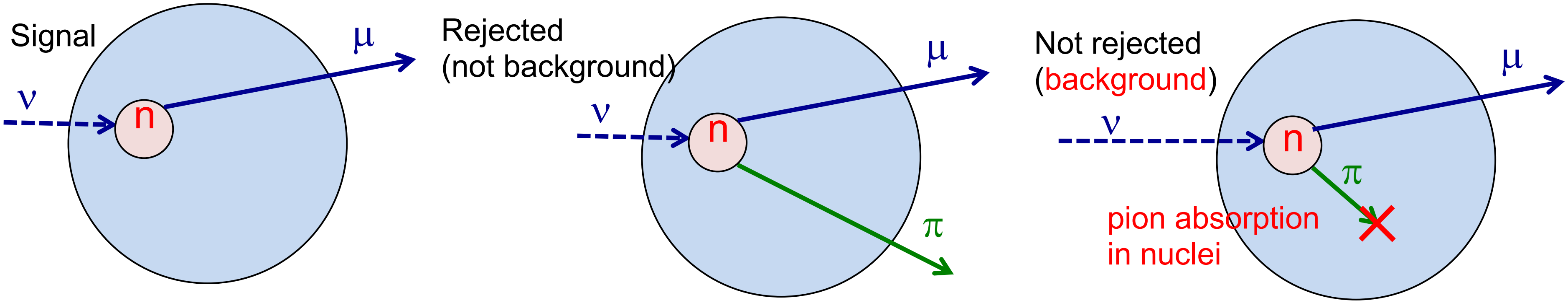


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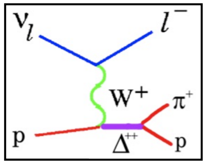


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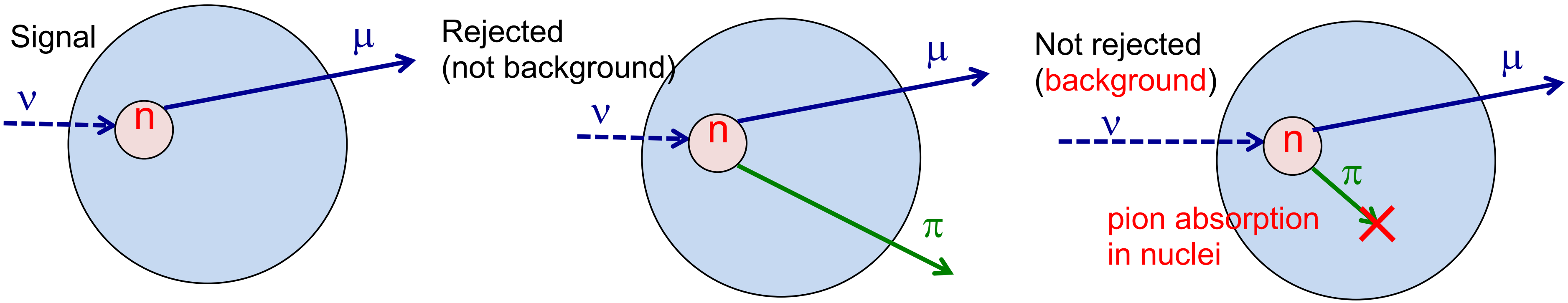
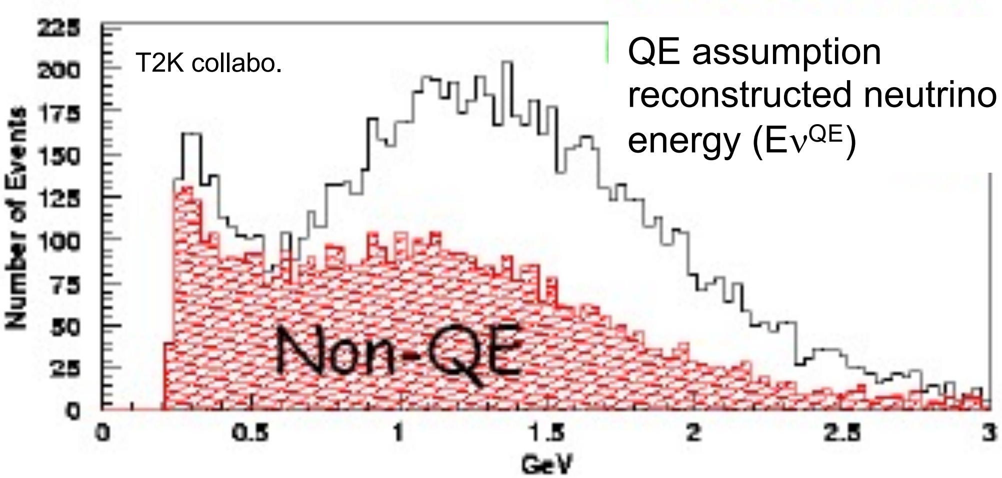
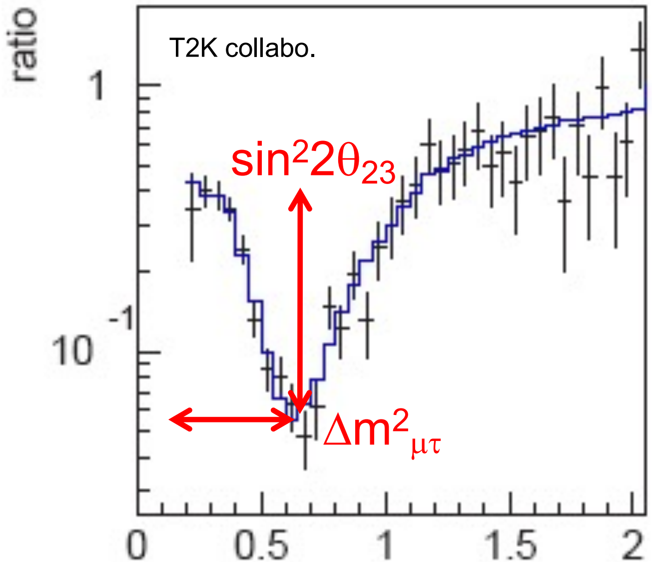
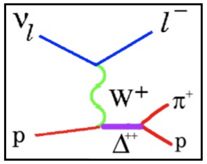


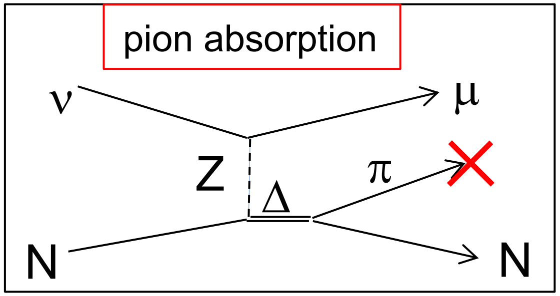
Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

RESonance

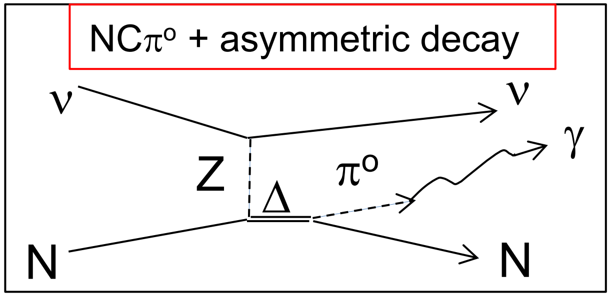



# 3. non-QE background (resonance pion production)

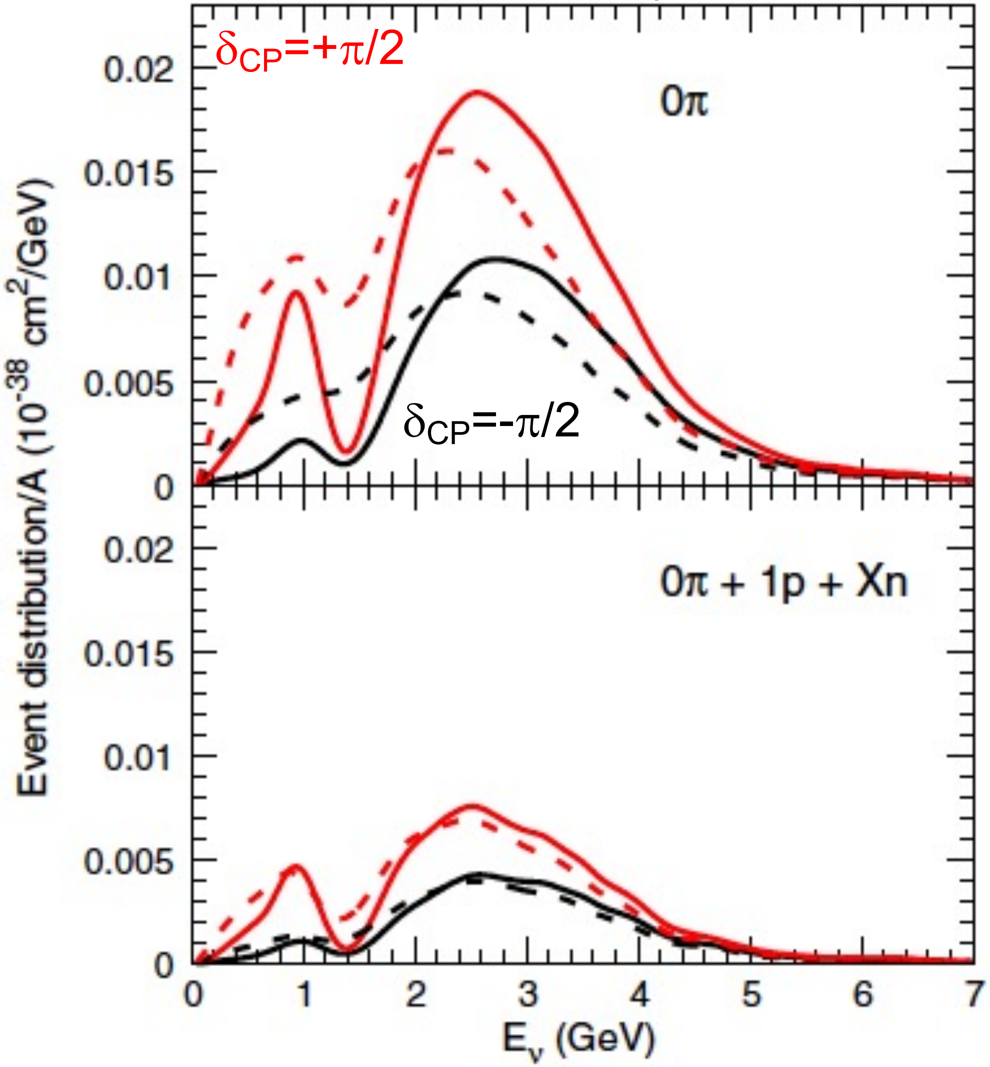
Pion production for $\nu_\mu$ disappearance search
- Source of mis-reconstruction of neutrino energy



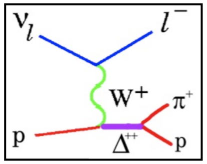

Neutral pion production in $\nu_e$ appearance search
- Source of misID of electron




DUNE true vs. reconstructed Eν spectrum

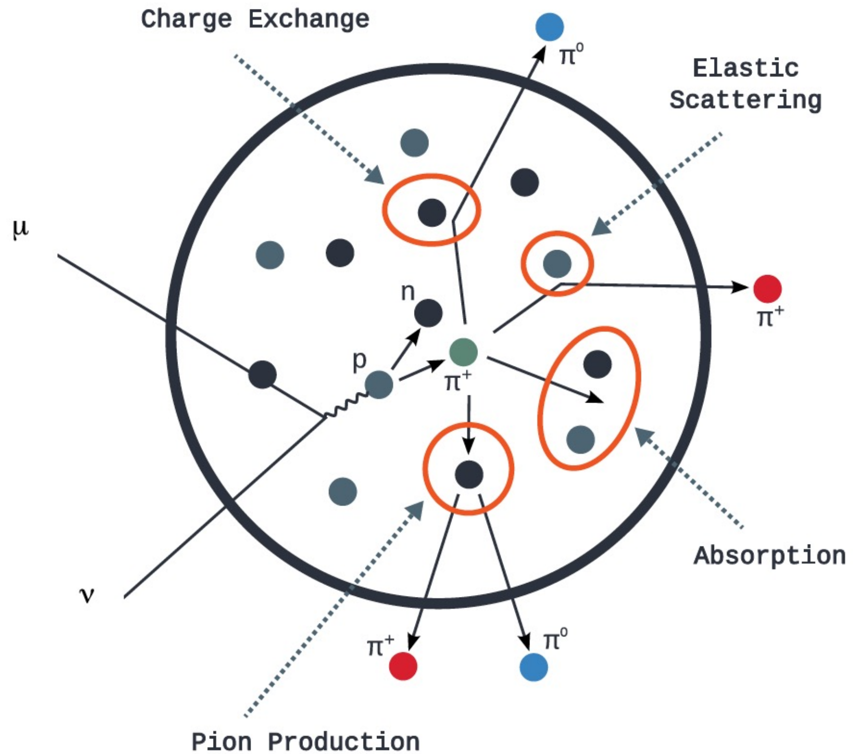


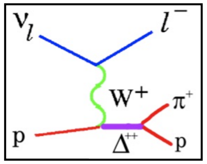

Understanding of neutrino baryonic resonance meson production is important for oscillation experiments




# 3. Final state interaction

Cascade model
- Elastic scattering: Nucleon elastic scattering, pion elastic scattering
- Inelastic scattering: Nucleon inelastic scattering, pion inelastic scattering
- Charge exchange: Nucleon charge exchange, pion charge exchange
- Absorption: Nucleon absorption, pion absorption

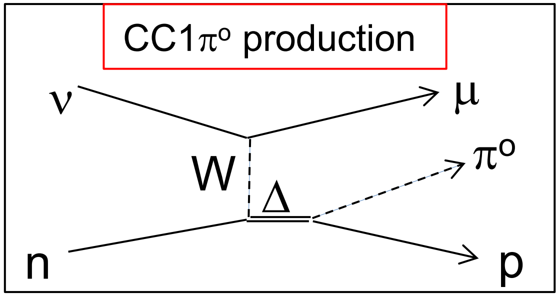


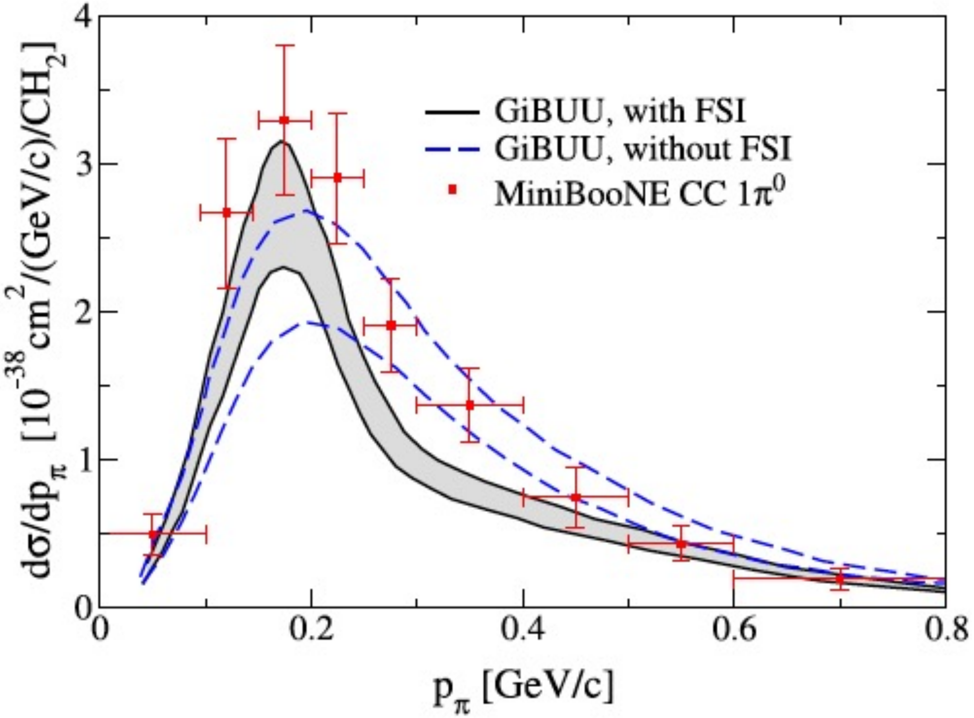



# 3. Neutrino Baryonic resonance data

## Final state interaction

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

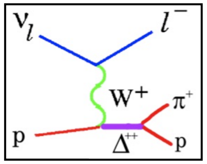



MiniBooNE $\pi^o$ momentum vs simulation

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



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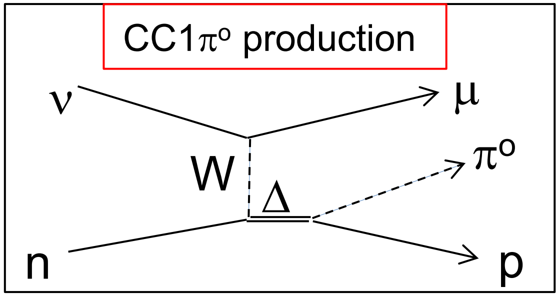


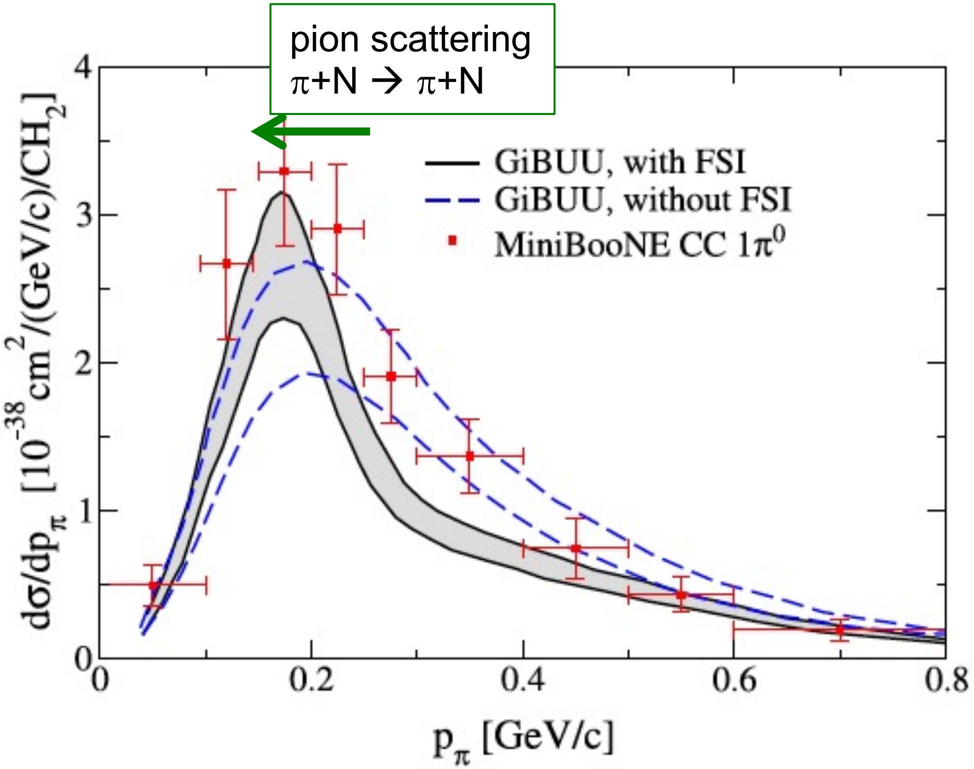


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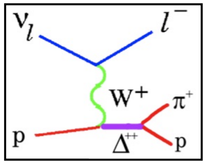
RESonance

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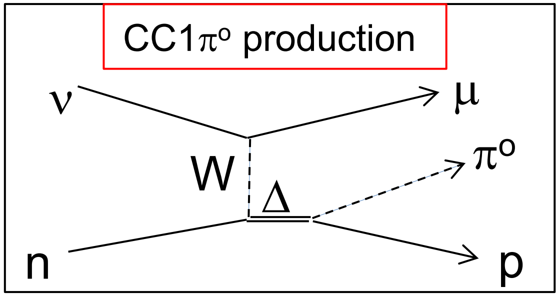


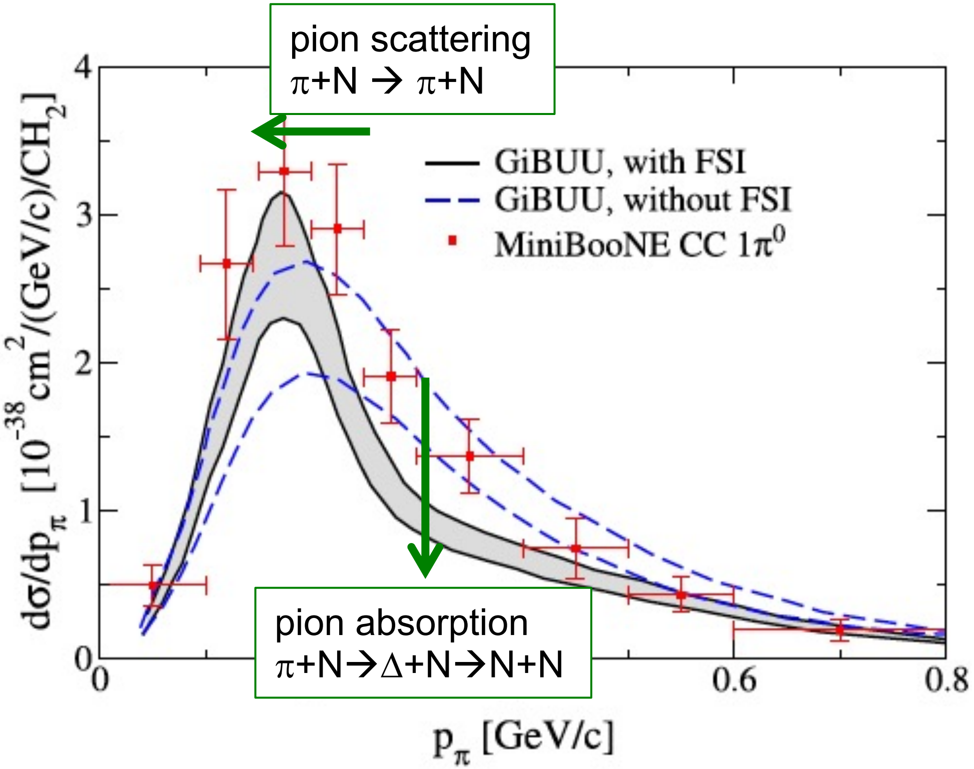


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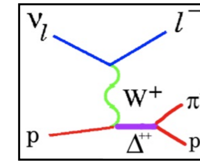


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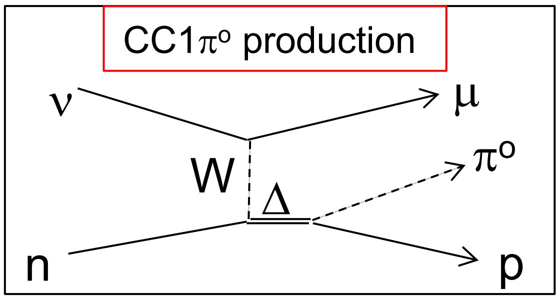
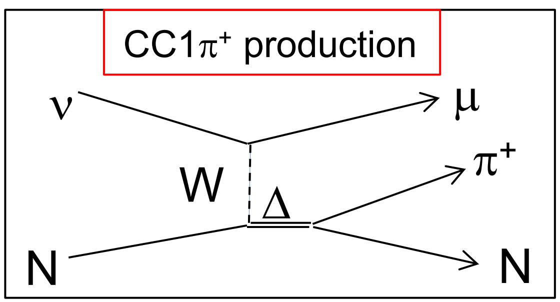
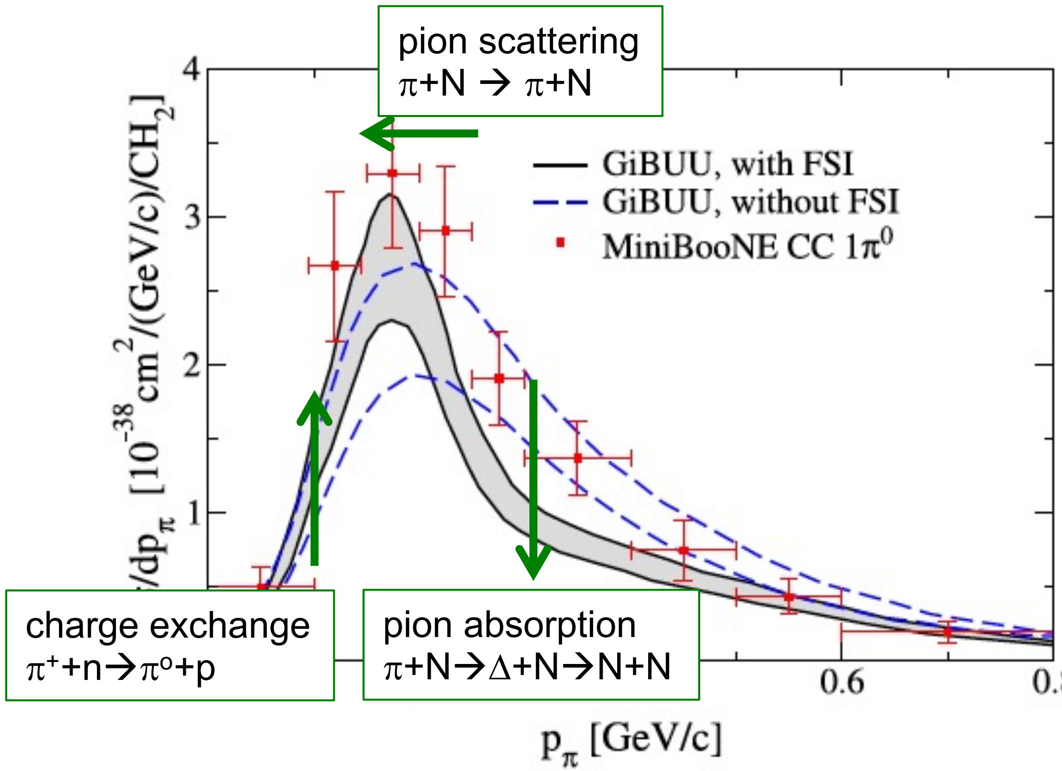


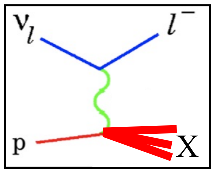




MiniBooNE πo momentum vs simulation

**All neutrino baryonic resonance processes have ~30% errors**

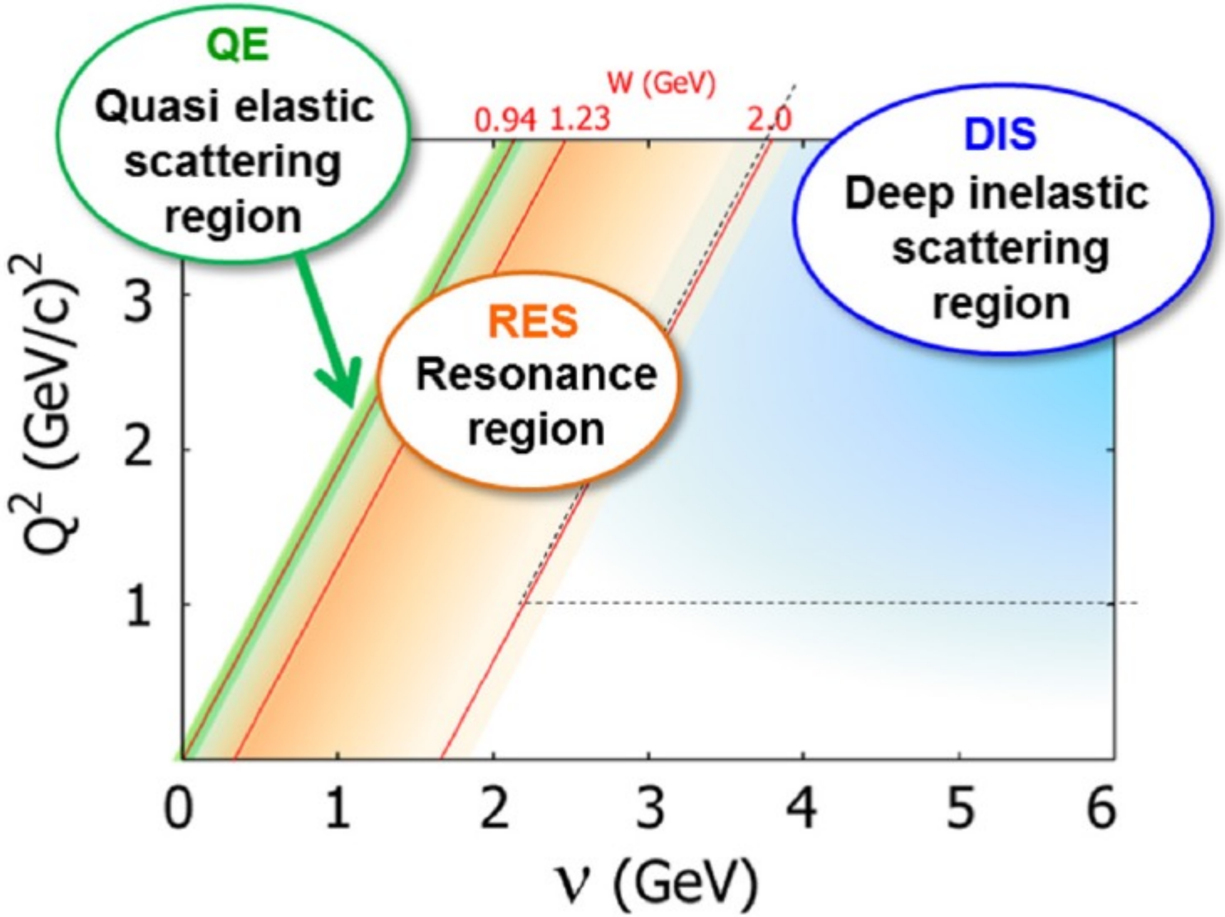
Nakamura et al,Rep.Prog.Phys.80(2017)056301

# 4. Shallow Inelastic Scattering (SIS)




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

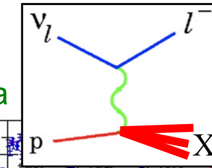
Neutrino experiment around 1-10 GeV is not quite DIS yet



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

# 4. Higher baryonic resonances

DIS




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 ($\pi N$, $\pi\pi N$, etc)
- 2 pion productions ~10% at 2 GeV

DCC model vs. electro-pionproduction data

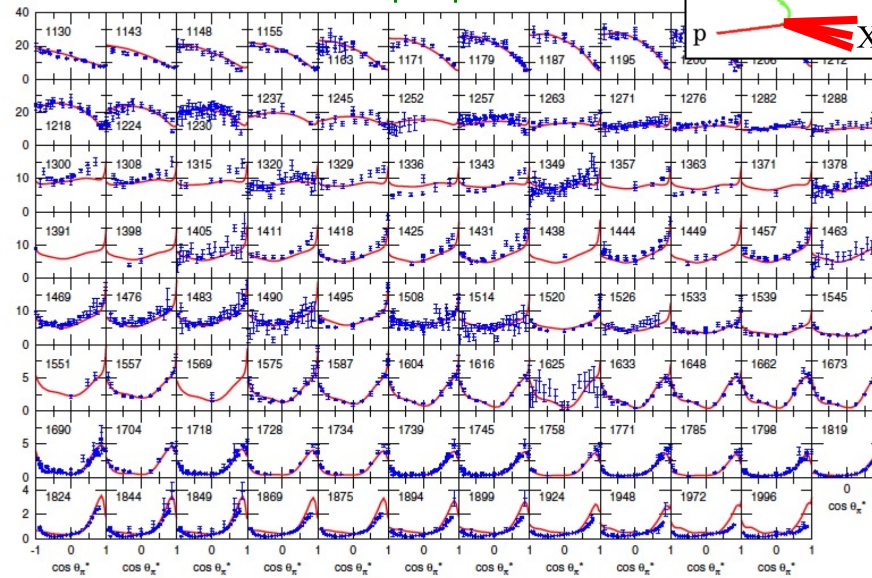
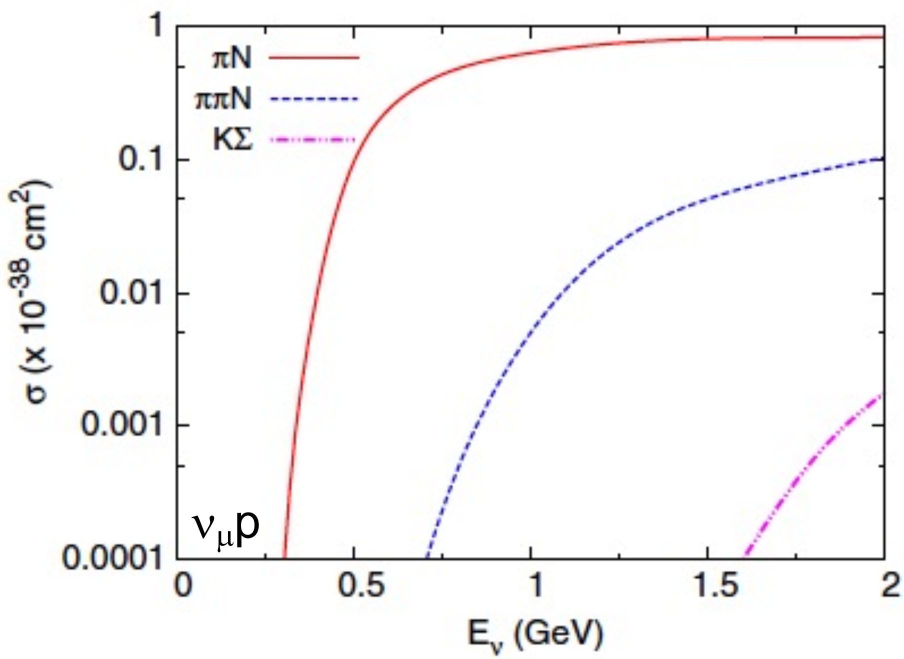
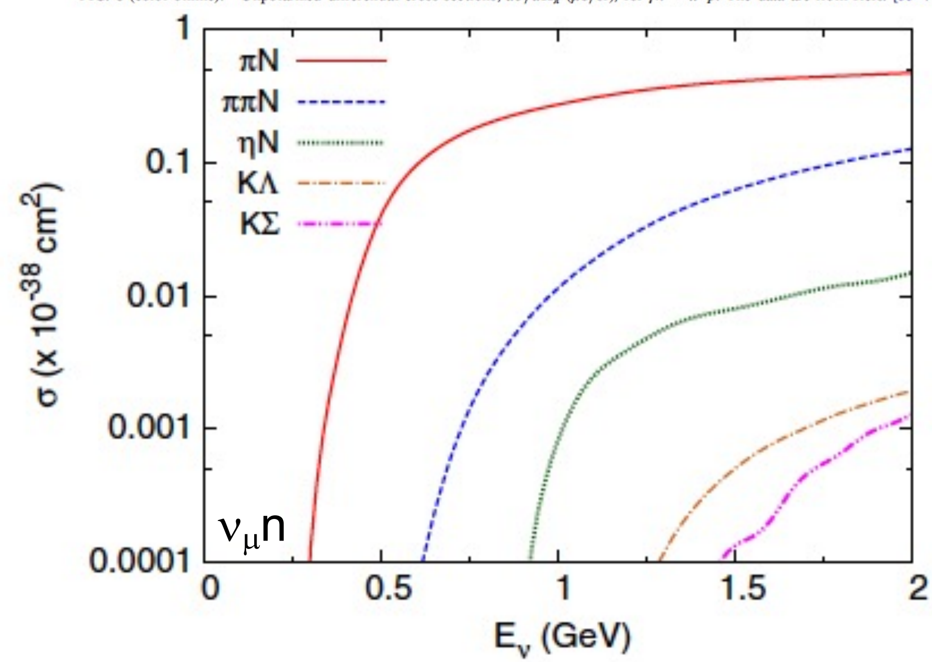



FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ ($\mu$b/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

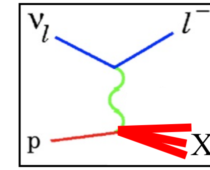


# 4. Quark-Hadron duality

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

DIS




### Cross section

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- Quark-Hadron duality (low $Q^2$, low W DIS)
- Nuclear dependent DIS

### GRV98 LO PDF + Bodek-Yang correction

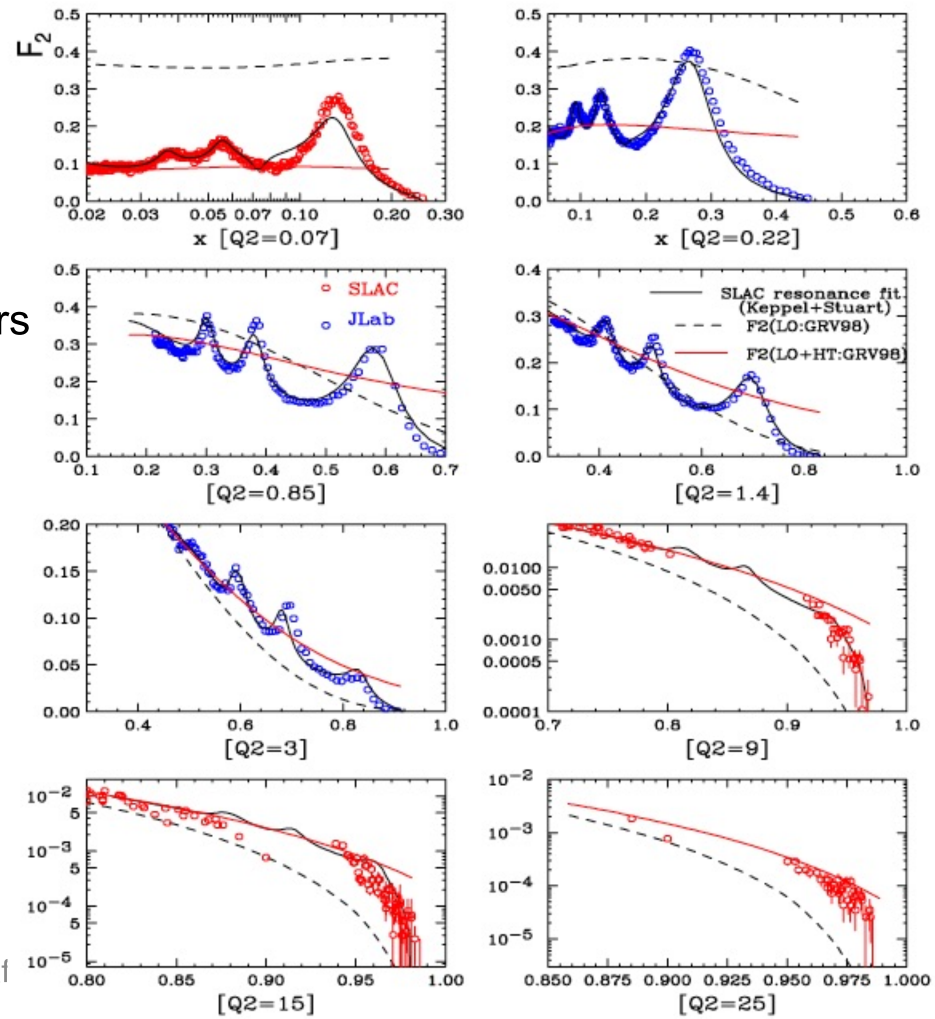
- GRV98 for low $Q^2$ DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data

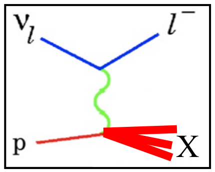



KING'S College LONDON

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

# 4. Nuclear dependent DIS

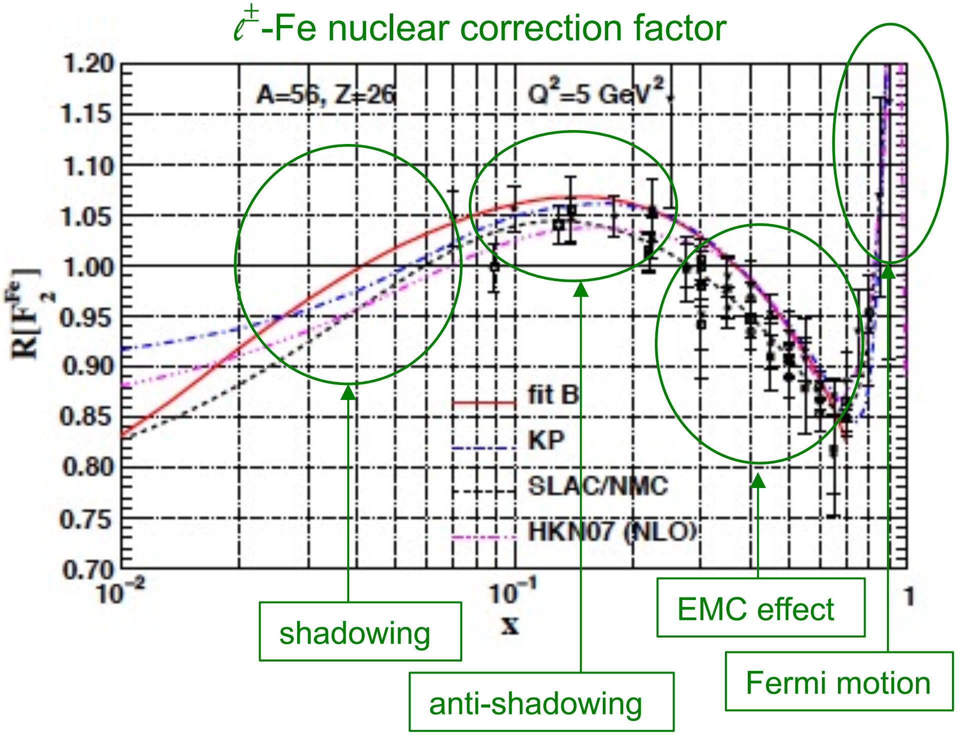
DIS



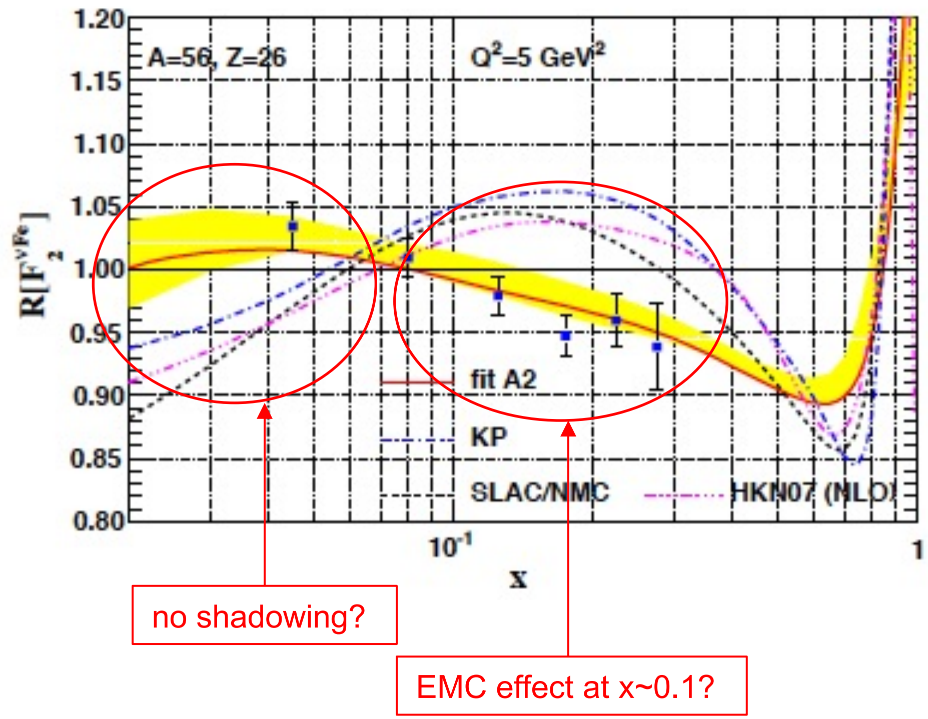

Cross section
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low $Q^2$, low W DIS)
- Nuclear dependent DIS

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

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

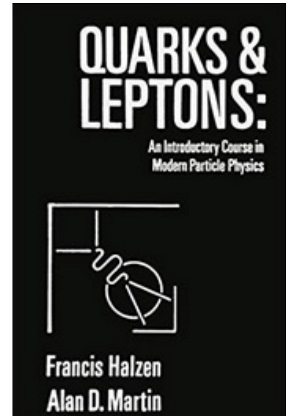
CCQE: charged-current quasi-elastic, around 1 GeV
RES: baryonic resonance, around 2 GeV
DIS: deep inelastic scattering, 3 GeV to higher

Nuclear physics sucks
- Fermi motion: nucleon motion smears kinematic reconstruction
- Pauli blocking: It limits low momentum transfer reaction
- Nuclear shell structure: separation energy (missing energy) for different nucleons
- Baryonic resonance: Often misidentified as CCQE
- Final state interaction: RES looks like CCQE, DIS looks like RES, etc
- Nucleon correlation: Physics between $\nu$-N and $\nu$-A interaction
- Quark-Hadron duality: Physics between $\nu$-q and $\nu$-N interaction
- Nuclear dependent PDF: Physics between $\nu$-q and $\nu$-A interaction

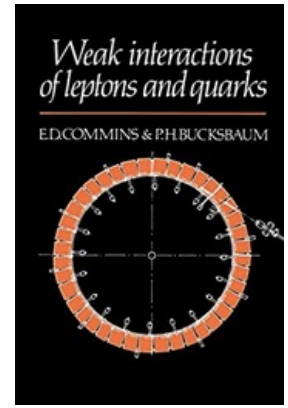
Currently, ~30% error is acceptable for many processes

# References (books)

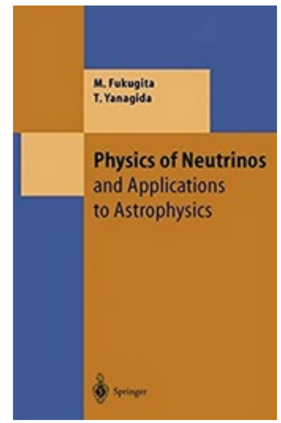
Quarks and Leptons (Halzen and Martin)
- show many calculations
- solutions for all exercises



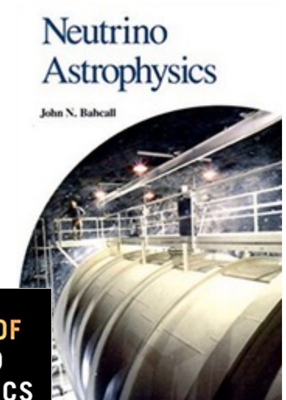

Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- show details of weak interaction calculations
- too many typos



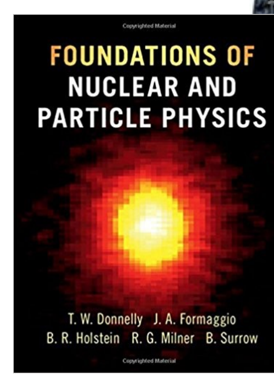

Physics of Neutrinos (Fukugita and Yanagida)
- very intense
- from solar neutrinos to SUSY




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



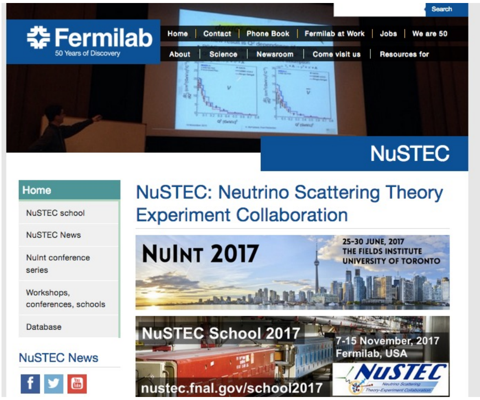
# References (papers)

"From eV to EeV: Neutrino cross sections across energy scales"
- Authors: Formaggio and Zeller (MicroBooNE spokesperson)
- Rev.Mod.Phys.84(2012)1307, https://arxiv.org/abs/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, https://arxiv.org/abs/1611.07770
- 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, https://arxiv.org/abs/1706.03621
- Cover all open issues in the community

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

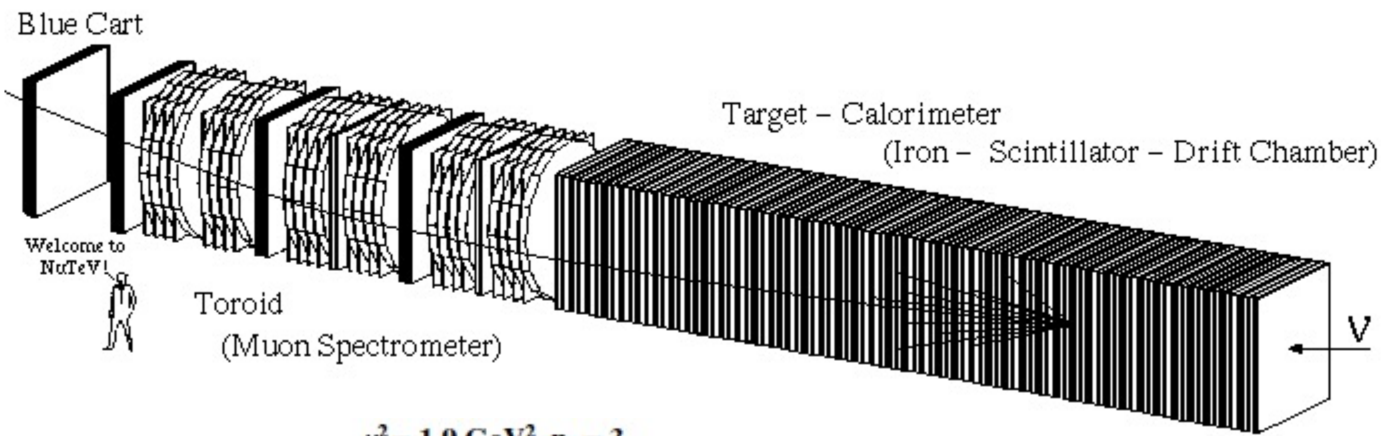


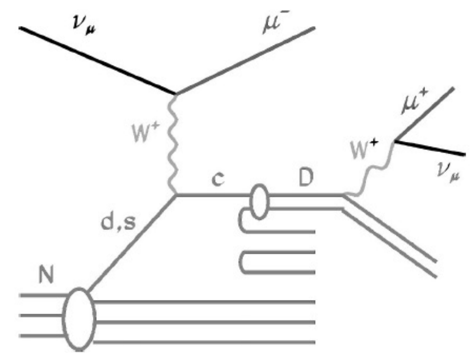
Backup

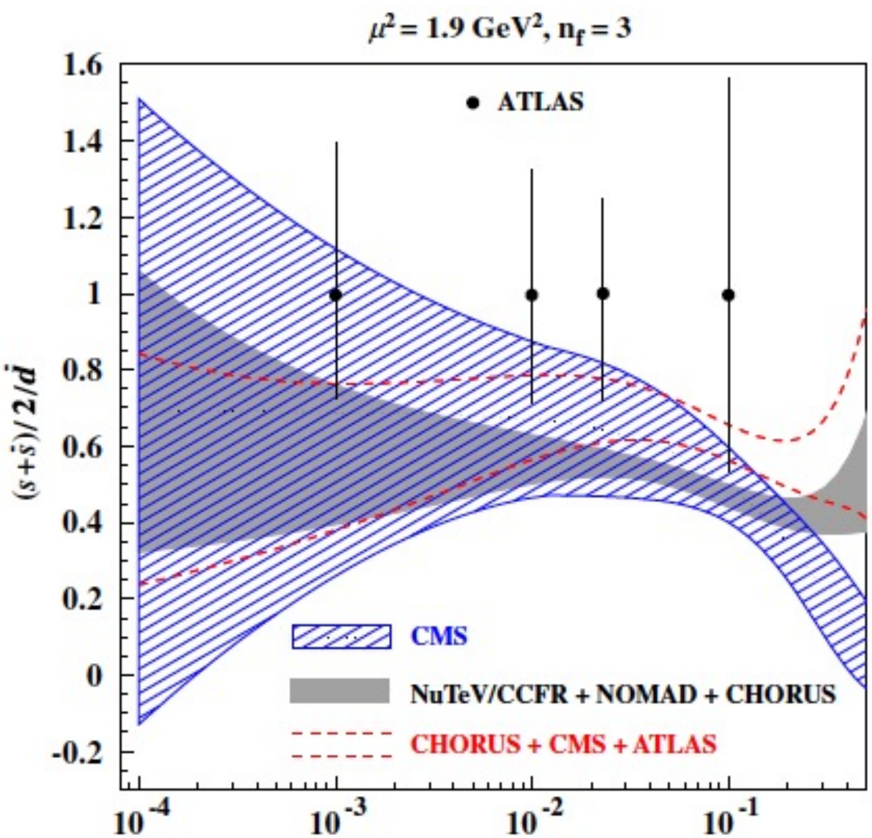
NuTeV, PRD64(2001)112006
Alekhin et al.,PRD91(2015)094002

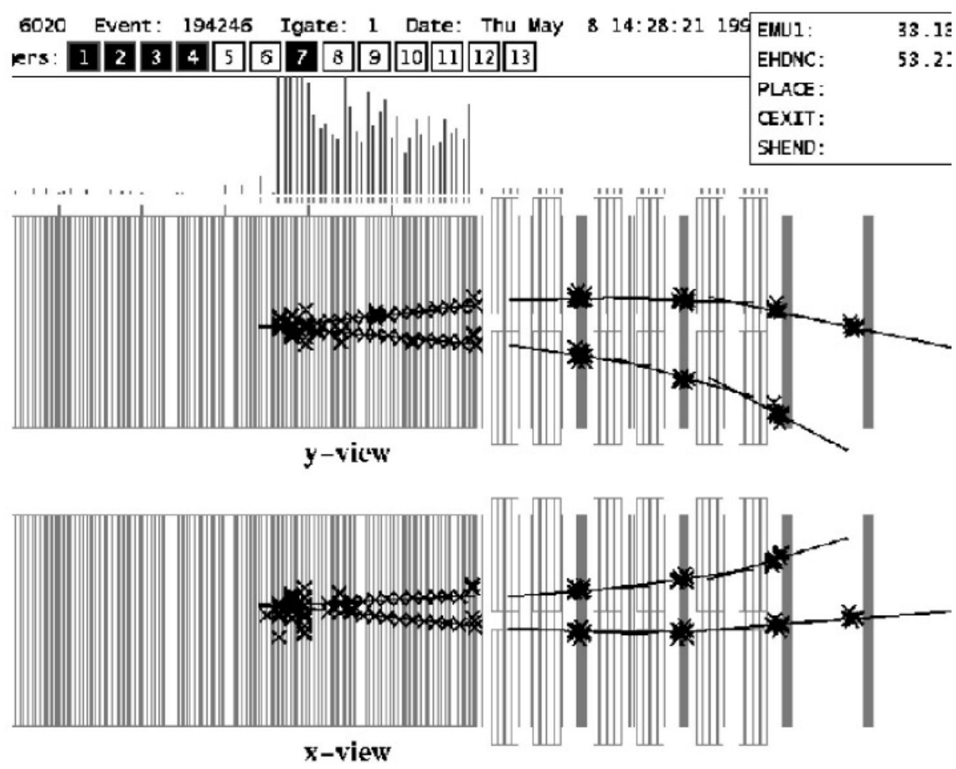


# 3. Di-muon production

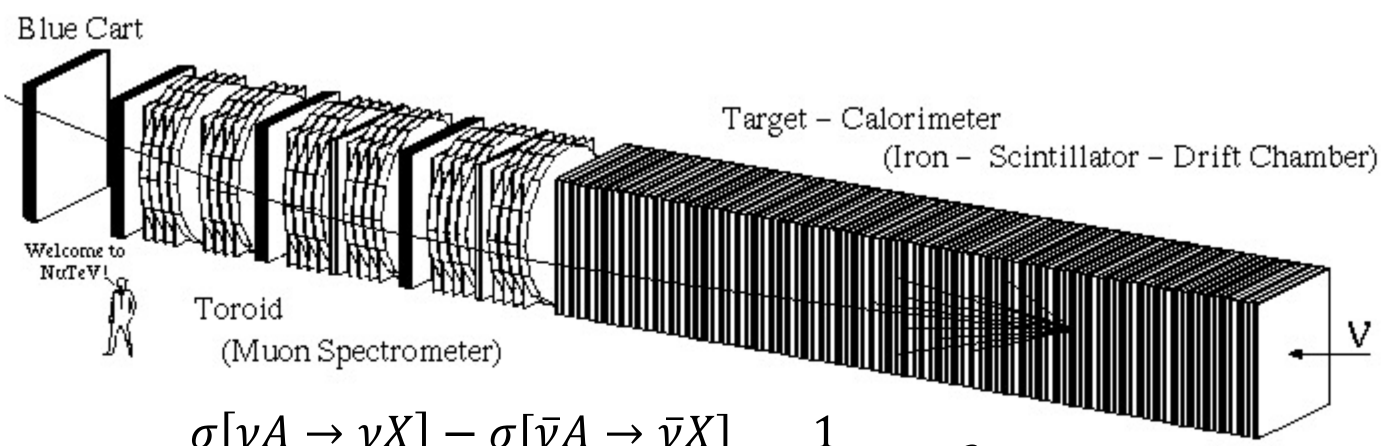


# 3. Paschos-Wolfenstein ratio and NuTeV anomaly




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