Neutrino Interactions

Jyotsna Osta
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Intensity Frontier Department Seminar

A few words before I begin .....

- I view the IF department seminars as a lecture series of sorts ..... meaning that they will be held periodically (gap of some months).
- The subject of "Neutrino Interactions" is too vast and interesting to fit into a single 45 minute discourse (just my opinion).
- I am going to start with the basics today in an effort to lay the foundation for future talks on this subject.
- I hope that each one of us here will be able to walk away with some understanding of weak interactions today. Will be helpful for future talks that detail "quasi-elastic", "resonance", "deep inelastic" interactions with neutrinos.

Outline

- Fundamental properties of neutrino interactions
- Types of Neutrino Interactions
  - Neutrino-Electron Scattering
  - Neutrino-Quark Scattering
  - Neutrino Quasi-Elastic Scattering
- An overview of Charged Current Quasi-Elastic Sc.
- Results from MINERvA
- Conclusions

Weak Interactions

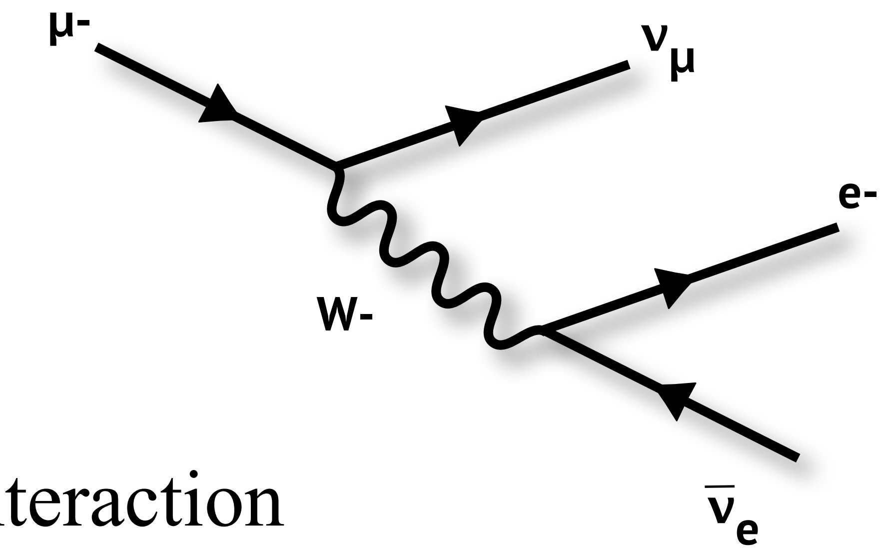
- Neutrinos are unique ! They can only interact by weak interactions !
  - Colorless, electrically neutral, possess a tiny mass
- What are weak interactions ?
- Most interactions we see around us are "strong" and "electromagnetic (EM)"

Nature of Interaction	Lifetimes	Coupling Strengths
Strong	$\sim 10^{-23}$ sec	α_s
Electromagnetic	$\sim 10^{-16}$ sec	α_{EM}
Weak	$\sim 10^{-8}$ sec	α_{WEAK}

$$\alpha_{WEAK} << \alpha_{EM} << \alpha_s$$

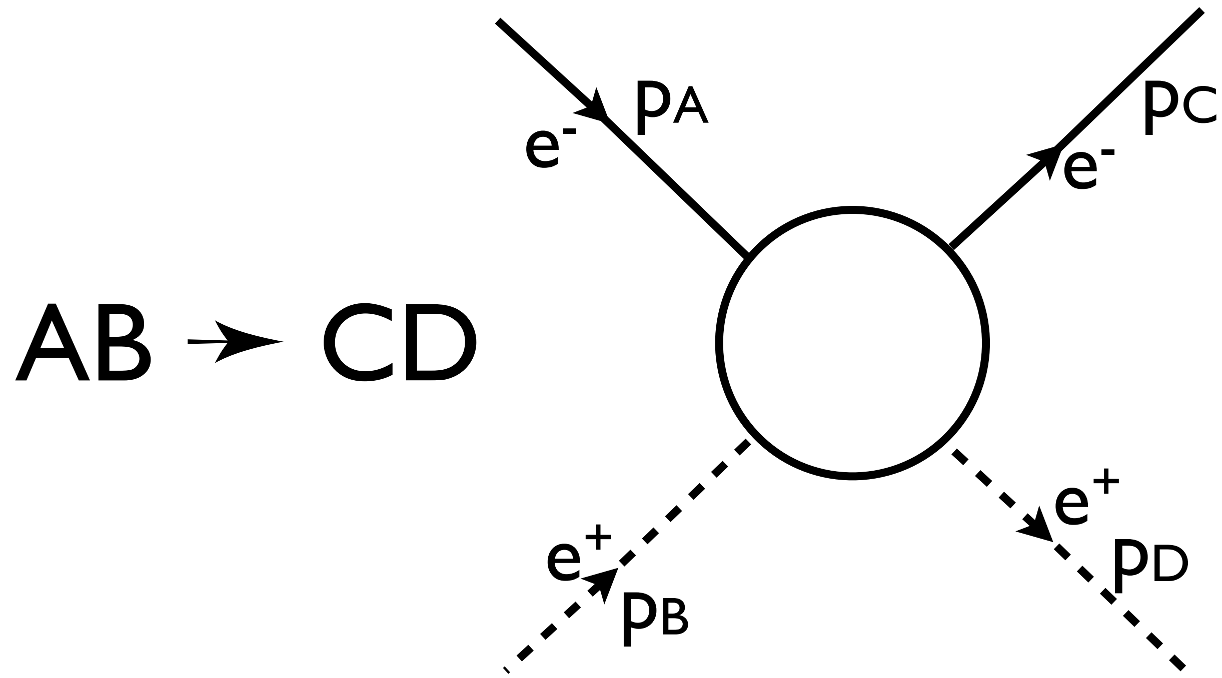
- More on why weak interactions are called "weak" ..... later slides

Weak Interactions



- All hadrons and leptons experience this weak interaction
  - However, they're often hidden by the much more rapid strong and EM interactions !
- Examples of weak interactions:
  - β-decay of atomic nuclei ($n \rightarrow p + e^- + \text{anti-}\nu_e$)
  - $\pi^- \rightarrow \mu^-\ \text{anti-}\nu_\mu$ (pion is lightest charged hadron, no EM decay)
  - $\mu^- \rightarrow e^-\ \text{anti-}\nu_e\ \nu_\mu$ (lepton number conservation)

Mandelstam variables



- Used for expressing invariant amplitude M as a function of variables invariant under Lorentz transformations

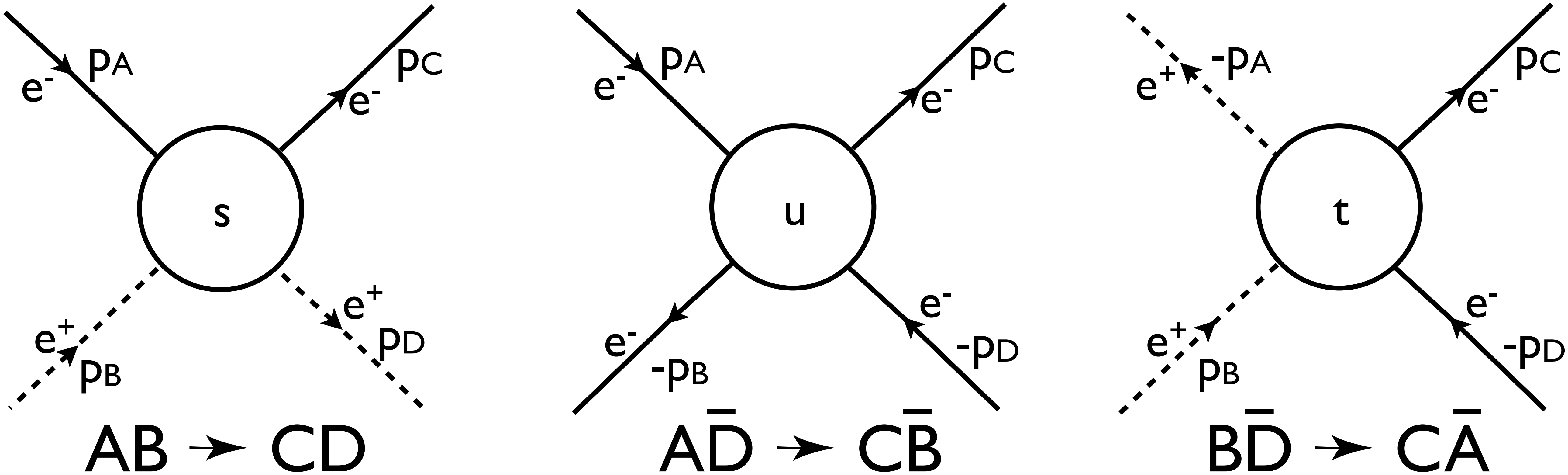
$$s = (p_A + p_B)^2$$

$$t = (p_A - p_C)^2$$

$$u = (p_A - p_D)^2$$

$$s + t + u = m_A^2 + m_B^2 + m_C^2 + m_D^2$$

Mandelstam variables (contd.)



$$s = 4\left(k^2 + m^2\right)$$

$$t = -2k^2\left(1 - \cos\theta\right)$$

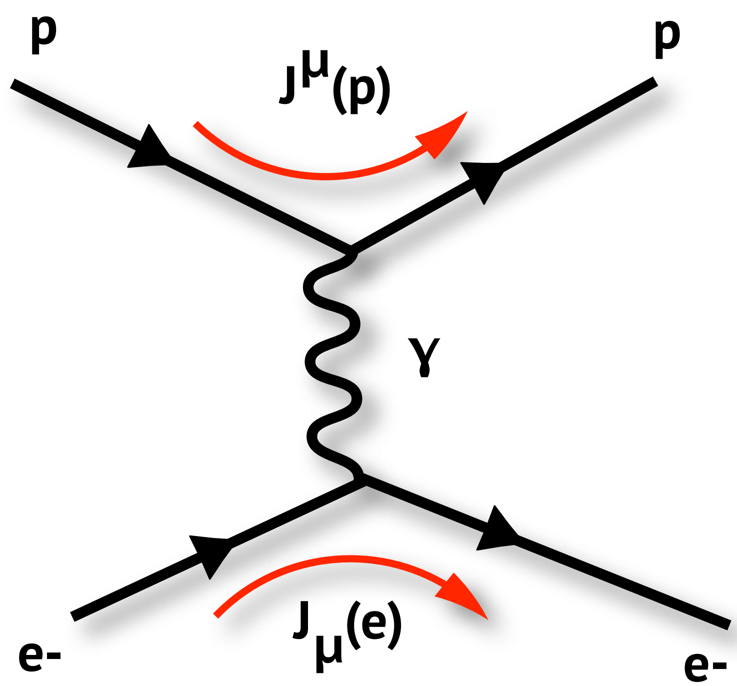
$$u = -2k^2\left(1 + \cos\theta\right)$$

- Here θ is the center-of-mass scattering angle and $k = |\mathbf{k}_i| = |\mathbf{k}_f|$
- $\mathbf{k}_i$ and $\mathbf{k}_f$ are momenta of the incident and scattered electrons in CM frame

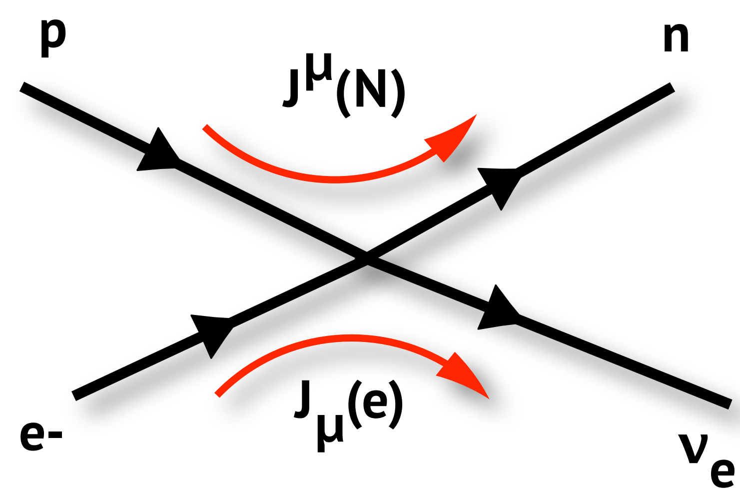
Form of the Weak Current

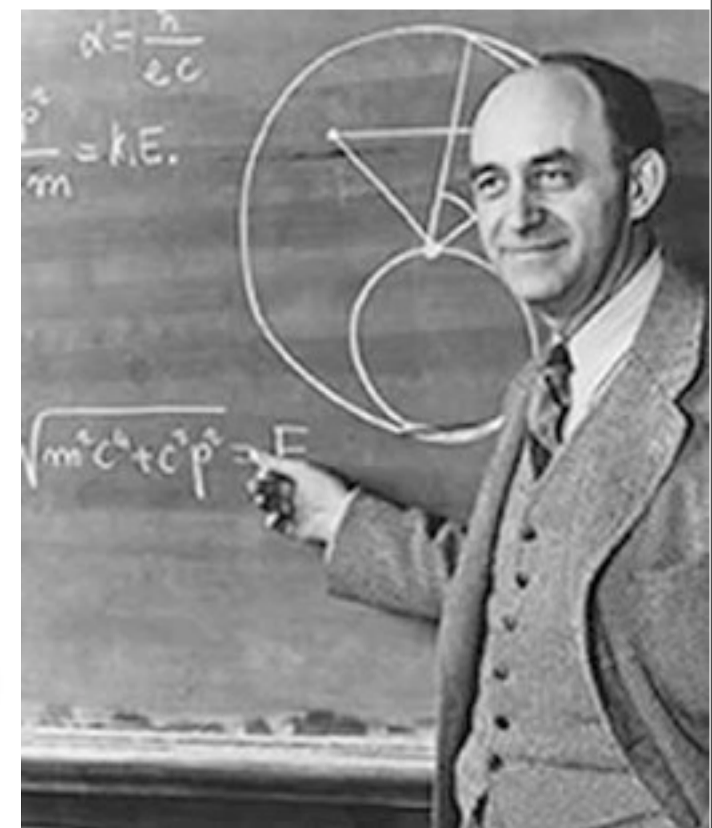
First Attempt: Enrico Fermi, 1932

Electron-proton (EM) scattering



β-decay (Weak) process





$$M_{em} = (e\bar{u}_p\gamma^\mu u_p)\left(\frac{-1}{q^2}\right)(-e\bar{u}_e\gamma^\mu u_e)$$

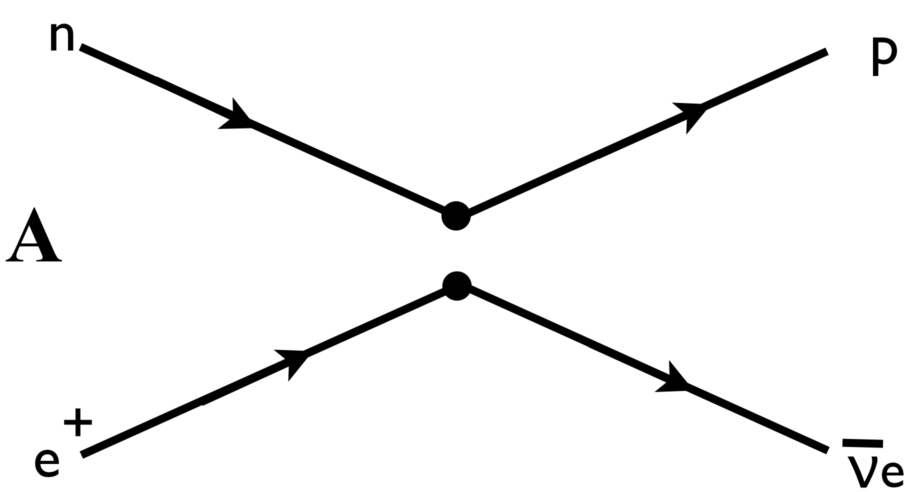
$$M_{weak-CC-Fermi} = G_F\,(\bar{u}_n\gamma^\mu u_p)\,(\bar{u}_\nu\gamma_\mu u_e)$$

G_F is weak coupling constant (Fermi constant)
has dimensions GeV^{-2} (unlike charge, e)
remains to be determined experimentally

V-A Form of Weak Current

$$M_{weak-CC-Fermi} = G_F \left(\bar{u}_n \gamma^\mu u_p\right) \left(\bar{u}_\nu \gamma_\mu u_e\right)$$

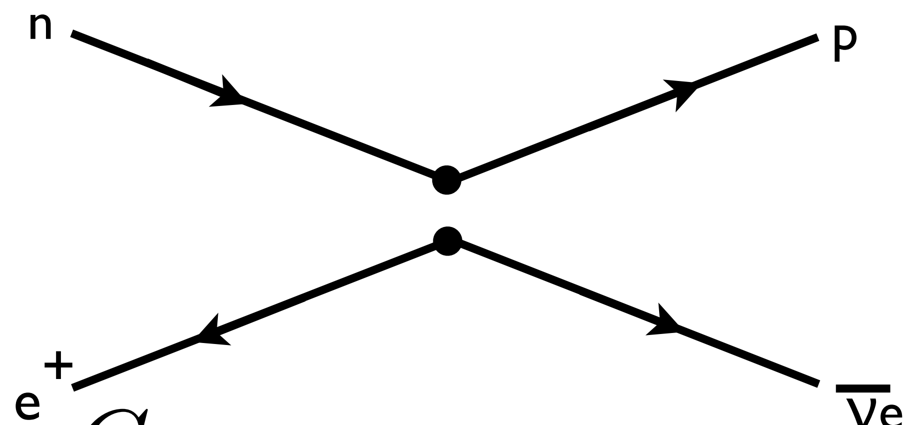
- Fermi's proposed amplitude explained properties of some features of β-decay, but not others!
- For next 25 years, a suite of β-decay experiments were performed to unravel true form of the weak interaction
- Discovery of Parity violation in 1956 !
- Change in Fermi's proposal: γ^μ ➛ $\gamma^\mu(1-\gamma^5)$ ➛ **V - A**
  - γ^μ is vector ➛ inverts under Parity op.
  - γ^5 is pseudoscalar ➛ inverts under Parity op.
  - $\gamma^\mu \gamma^5$ is axial vector ➛ does not invert under Parity op.
- Mixture of γ^μ and $\gamma^\mu \gamma^5$ terms violates Parity in weak interactions !



V-A Form of Weak Current

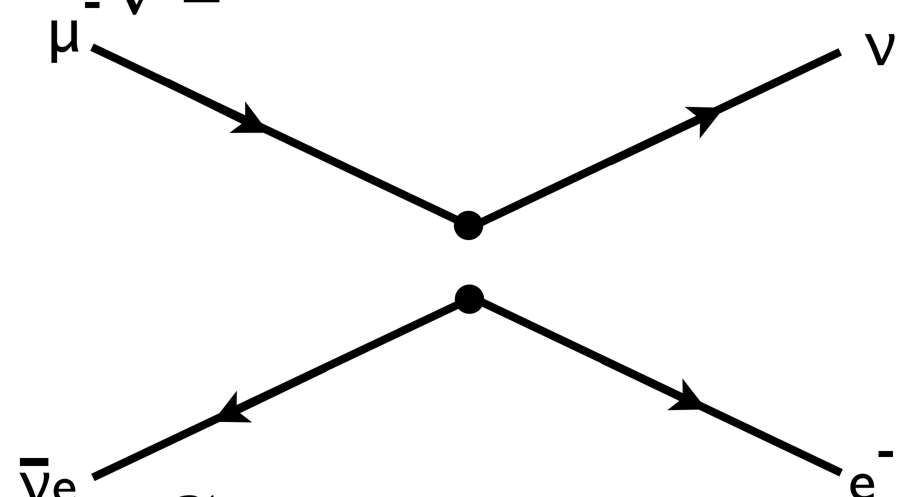
- Parity is not conserved in weak interactions :
  - Lee & Yang, Phys. Rev. 104, 254-258 (1956)
    - Explains K ➛ 2π and 3π; final states have opposite parities !
- Experimental verification : β-transitions of polarized Cobalt nuclei

β-decay



$$M\left(n\rightarrow pe^-\bar{\nu}_e\right)=\frac{G_F}{\sqrt{2}}\left(\bar{u}_n\gamma^\mu\left(1-\gamma^5\right)u_p\right)\left(\bar{u}_{\nu_e}\gamma_\mu\left(1-\gamma^5\right)u_e\right)$$

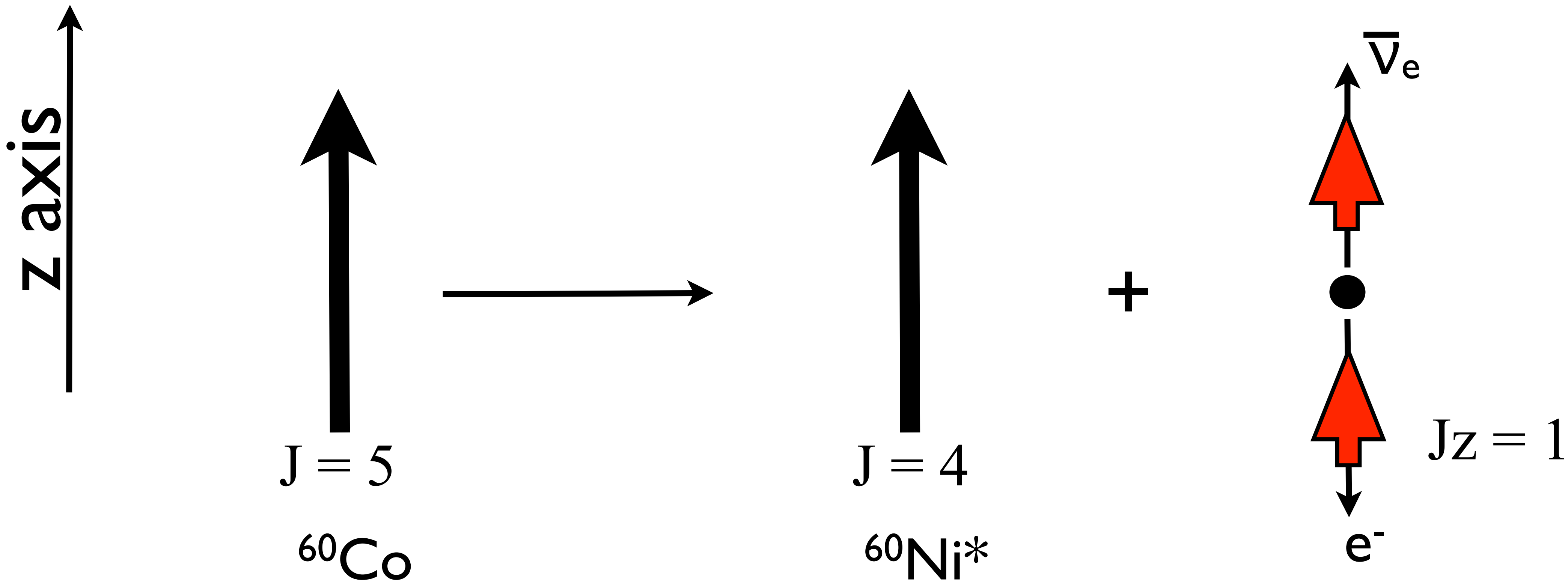
μ-decay



$$M\left(\mu^-\rightarrow e^-\bar{\nu}_e\nu_\mu\right)=\frac{G_F}{\sqrt{2}}\left(\bar{u}_{\nu_\mu}\gamma^\sigma\left(1-\gamma^5\right)u_\mu\right)\left(\bar{u}_e\gamma_\sigma\left(1-\gamma^5\right)u_{\nu_e}\right)$$

Parity Violation Experiment with ^{60}Co

$$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$$



- Electron is emitted opposite in direction to spin of ^{60}Co !
- This asymmetry changed sign upon magnetic field reversal !
- Observed correlation explained by assuming RH(positive helicity) antineutrino and LH(negative helicity) electron !
- $(1-\gamma^5)$ automatically selects a LH neutrino or a RH antineutrino !

Parity Violation Experiment with ^{60}Co

- Weak interactions involve ONLY ν_L & anti-ν_R
  - LH neutrinos and RH antineutrinos couple to charged leptons in weak int.
- Absence of "mirror image" states is a clear violation of Parity
  - NO empirical evidence for anti-ν_L & ν_R
- Charge conjugation invariance is also violated (else ν_L ➛ anti-ν_L)
- Weak interaction is invariant under CP operation

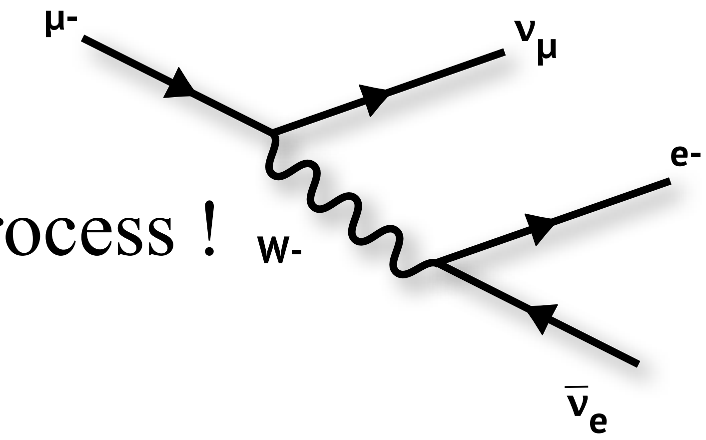
$$\Gamma\left(\pi^+ \to \mu^+ \nu_L\right) \neq \Gamma\left(\pi^+ \to \mu^+ \nu_R\right) \qquad \text{..... P violation}$$

$$\Gamma\left(\pi^+ \to \mu^+ \nu_L\right) \neq \Gamma\left(\pi^- \to \mu^- \bar{\nu}_L\right) \qquad \text{..... C violation}$$

$$\Gamma\left(\pi^+ \to \mu^+ \nu_L\right) = \Gamma\left(\pi^- \to \mu^- \bar{\nu}_R\right) \qquad \text{..... CP invariance}$$

  - Although ..... future experiments will look for CP violation in neutrinos !

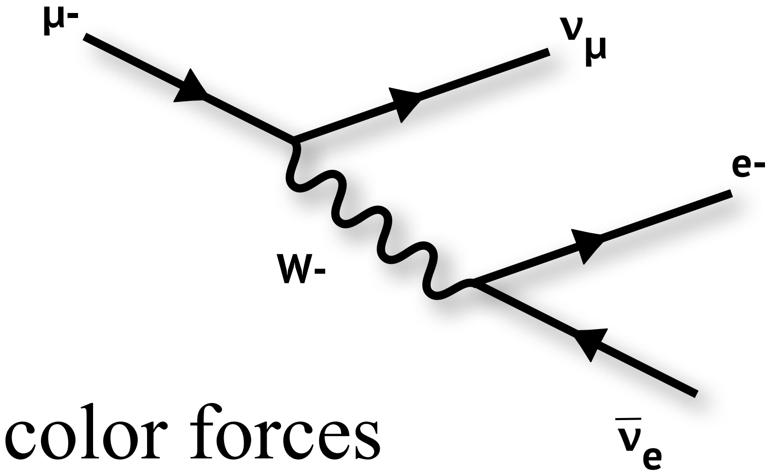
Interpretation of the Coupling Constant G_F



- Crucial check of the universality of the strength of G_F
  - We do not want a new interaction for every weak process !
- In Fermi's model of EM and weak interactions:
  - Analogy: G_F essentially replaces e^2/q^2 ..... (G_F dimensions GeV^{-2})
  - Weak interactions involve emission & absorption of vector bosons
    - Weak bosons Z, $W^{\pm}$

Act of "throwing" or "catching" the boson also transforms the particles !

Interpretation of the Coupling Constant G_F



- $W^{\pm}$ are analogues of γ for EM forces and gluons for color forces

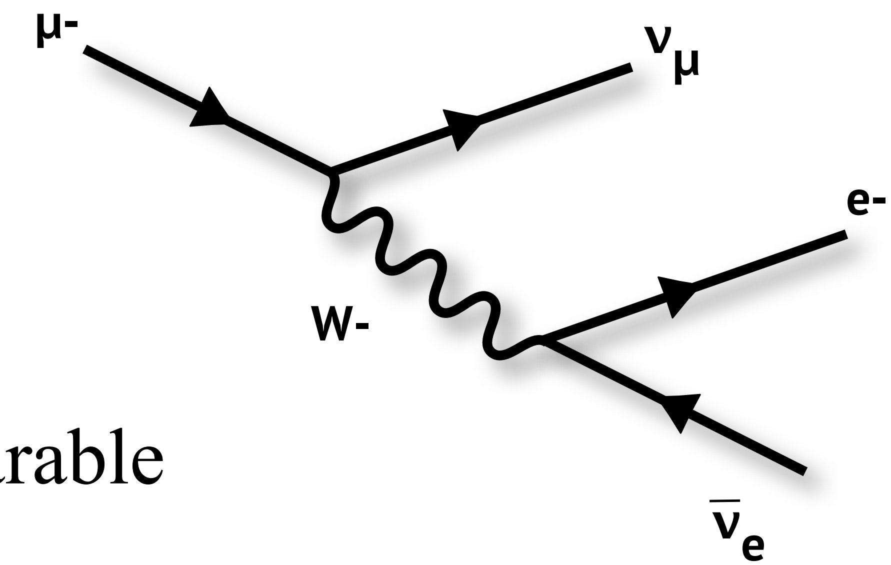
$$M_{MuonDecay} = \left(\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\sigma \frac{1}{2} \left(1 - \gamma^5\right) u_\mu \right) \frac{1}{M_W^2 - q^2} \left(\frac{g}{\sqrt{2}} \bar{u}_e \gamma_\sigma \frac{1}{2} \left(1 - \gamma^5\right) u_{\nu_e} \right)$$

  - $g/\sqrt{2}$ ➛ dimensionless weak coupling; q➛ momentum of W boson
  - $M_W \sim 80$ GeV (else it would be directly produced in weak decays!)
- In β-decay & μ-decay: $q^2 << M^2_W$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Weak interactions are “weak” because M^2_W is large (not because g << e) !

Universality of G_F

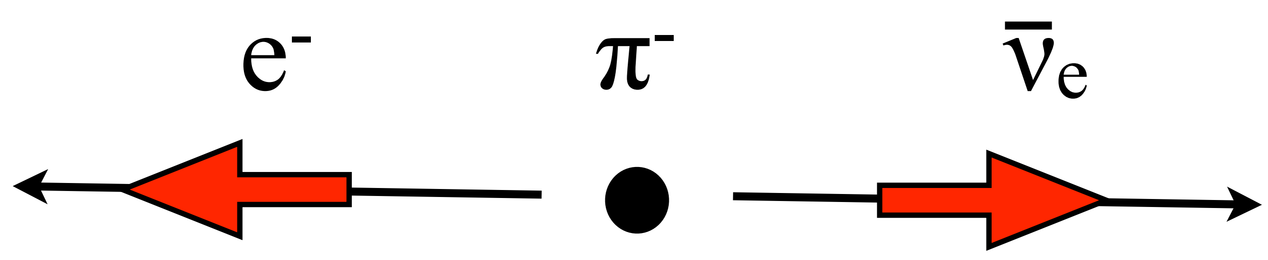


- If g ≈ e: weak & EM interactions will be of comparable strength at energies ≥ $O(M_W)$
    - Unification of weak and EM interactions ➛ electroweak
- Observed rates of β and μ decays can be used to estimate G_F
    - From nuclear β-decays: $G_F = 1.136 \times 10^{-5}\ \mathrm{GeV}^{-2}$
    - From muon decays: $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$
- Supports assertion of the universality of G_F !
    - Nuclear β-decay and muon decay have the same physical origin !
    - Small difference is due to quark-mixing ($\cos\theta_c$)

Pion Decay

$$\frac{\Gamma\left(\pi^- \to e^- \bar{\nu}_e\right)}{\Gamma\left(\pi^- \to \mu^- \bar{\nu}_\mu\right)} = 1.2 * 10^{-4}$$

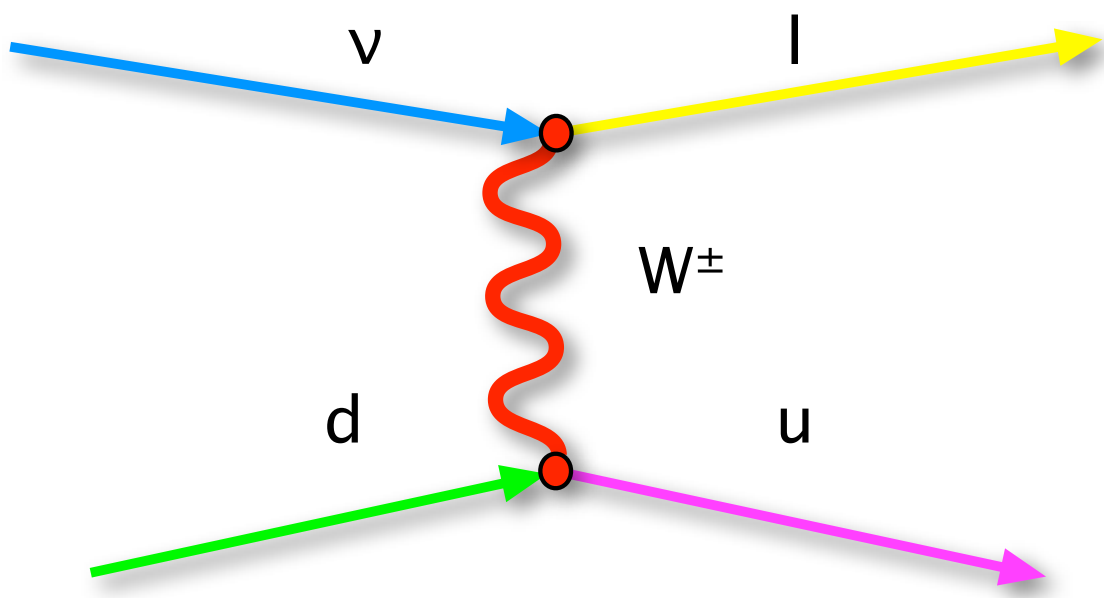
- π^- prefers to decay into a muon (similar mass) rather than electron (much lighter) ! Why ?



- Conservation of angular momentum must have J=0 for outgoing lepton pair
- Forces μ^- (e^-) to have a positive helicity - “wrong” helicity state for μ^- (e^-) !
- As $m_e \to 0$, weak current only couples negative helicity e^-, hence positive helicity coupling is suppressed !
- “Wrong” helicity state is much more likely to happen for μ^- than e^-
- Is a direct consequence of $(1-\gamma^5)$ structure of weak current!

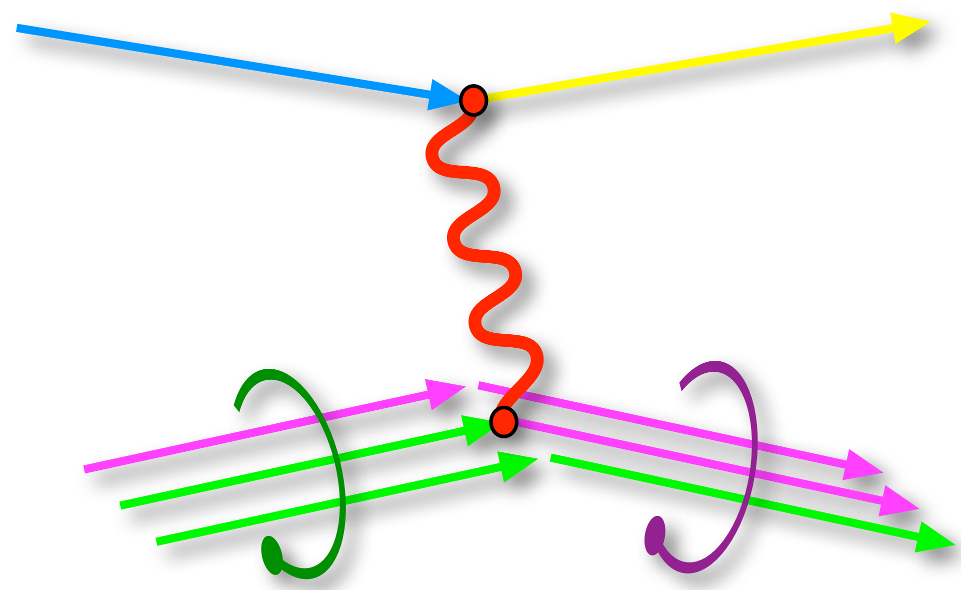
A Recap of Discussions so far .....

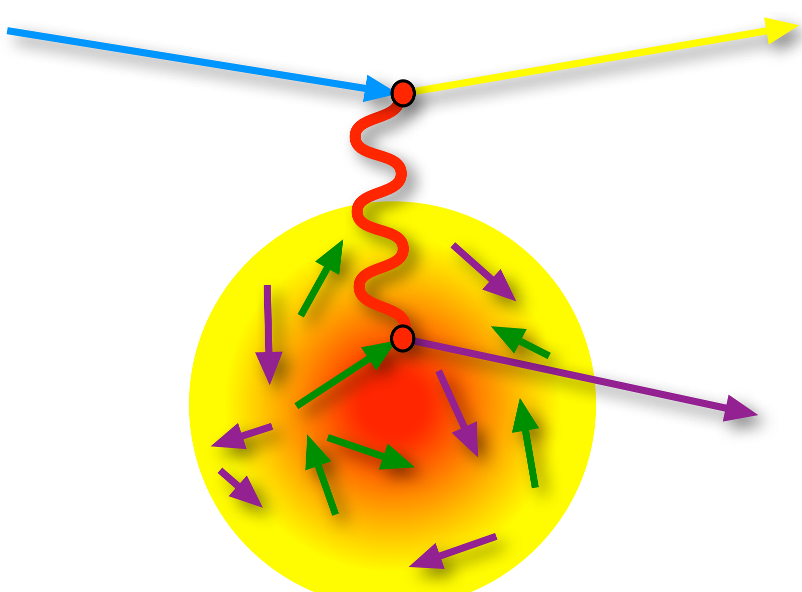
- Neutrinos interact via weak interactions only !
- All hadrons and leptons experience weak interaction
    - But they're often hidden by the strong and EM interactions
- Form of weak current first derived by Fermi (point interaction)
- Discovery of Parity violation in 1956 !
- Change in Fermi's proposal: γ^μ ➛ $\gamma^\mu(1-\gamma^5)$ ➛ **V - A**
- Mixture of γ^μ and $\gamma^\mu \gamma^5$ terms violates Parity in weak interactions !
- Parity violation experimentally confirmed by Madam Wu.
- Weak interactions involve ONLY ν_L & anti-ν_R
- Weak interactions are CP invariant .... until you start looking for CP violation
- Fermi's constant G_F is universal, M_W important contributor
- Pion decays to muon preferentially - positive helicity is suppressed more for electron than muon



Neutrino-lepton and neutrino quark scattering are tractable. Simpler topologies dealing with fundamental particles.

Neutrino-nucleon starts getting complex ! Nuclear medium poses challenges. Parametrization with help of form factors part of recipe.

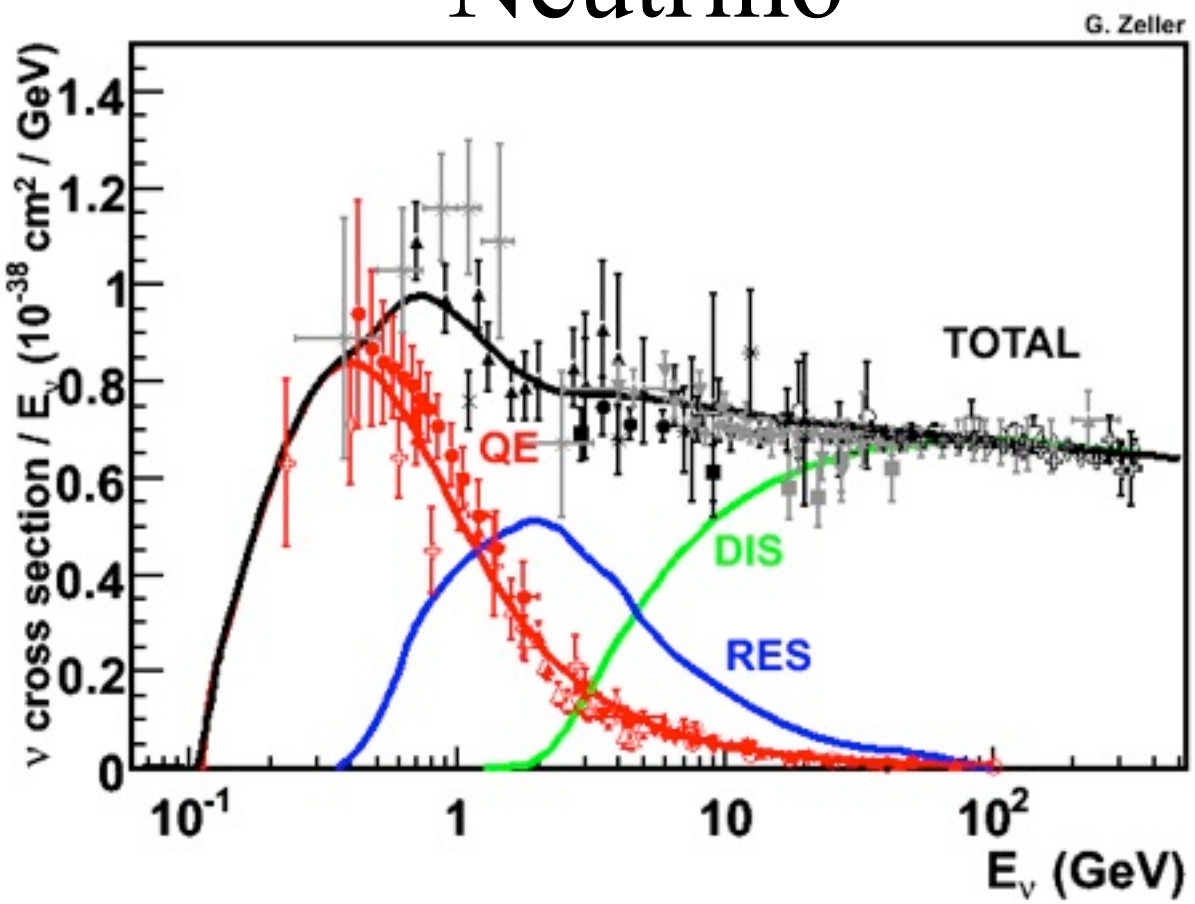




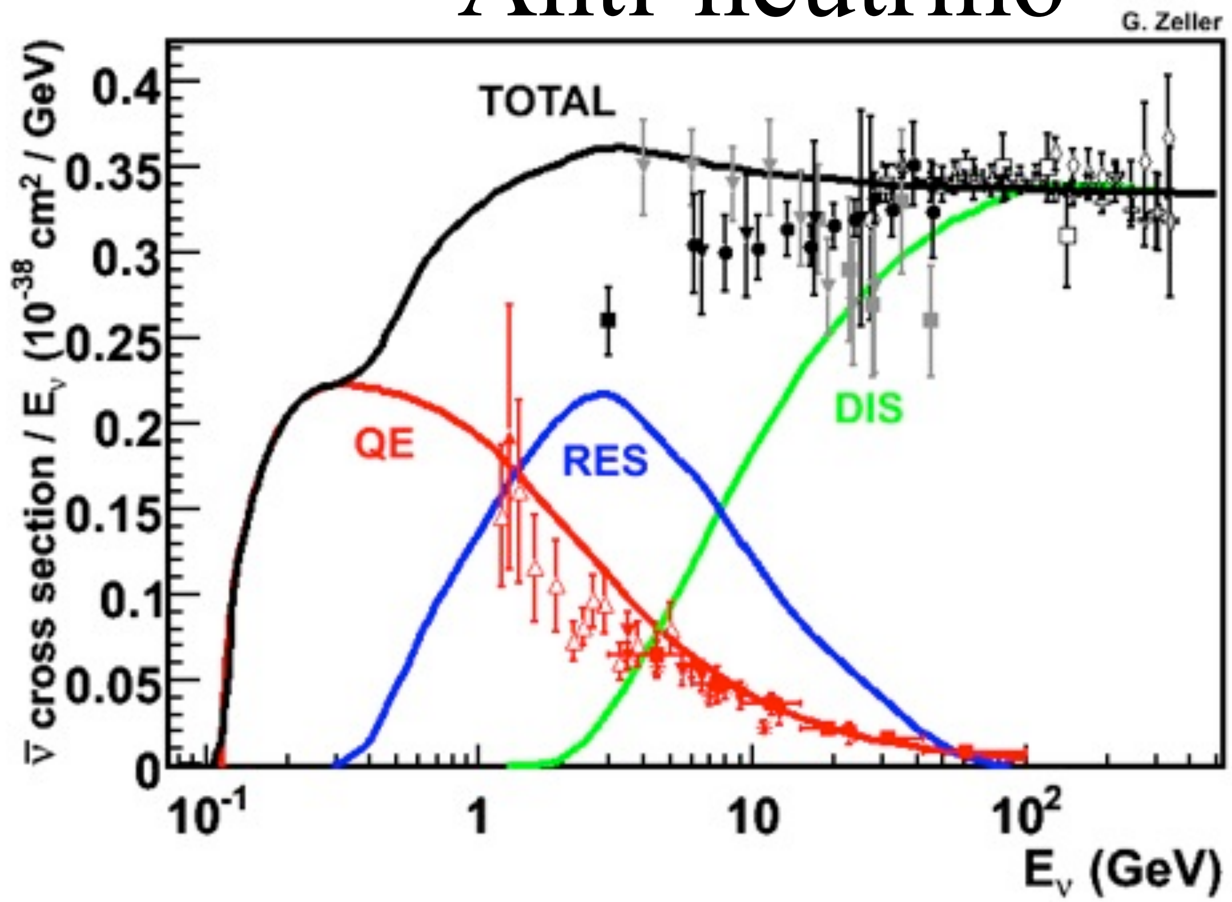
Neutrino-nucleus becomes very complex ! But this is where we want σ ....

Neutrino cross-sections

Neutrino



Anti-neutrino

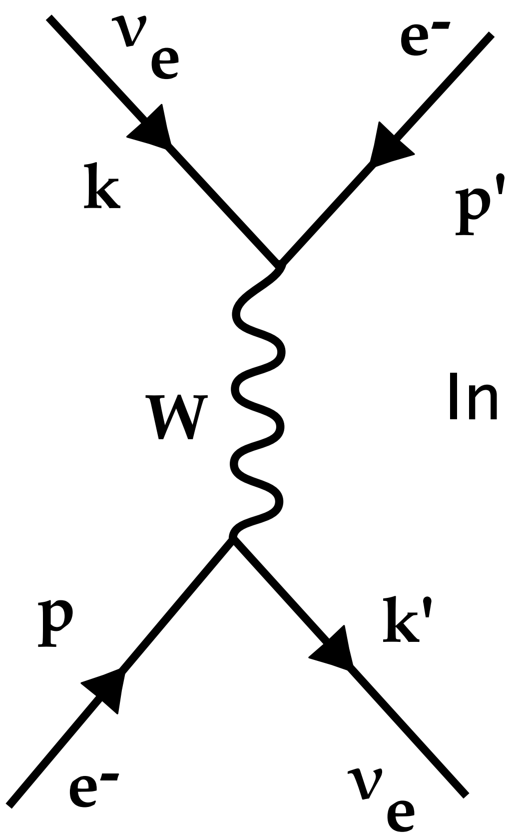


The most important distinctions are with respect to final state multiplicity, pion production and kinematics (Q2, W, etc.)

J.A. Formaggio and G.P. Zeller, "From eV to EeV: Neutrino Cross Sections Across Energy Scales", to be published in Rev. Mod. Phys. 2012

Charged Current Neutrino-Electron Scattering

Neutrino-Electron Scattering



$$\mathcal{M} = \frac{G_F}{2}\left(\bar{u}\left(k'\right)\gamma^{\mu}\left(1-\gamma^5\right)u\left(p\right)\right)\left(\bar{u}\left(p'\right)\gamma^{\mu}\left(1-\gamma^5\right)u\left(k\right)\right)$$

In relativistic limit: $m_e = 0$ & $s = (k+p)^2 = 2k\cdot p = 2k'\cdot p'$

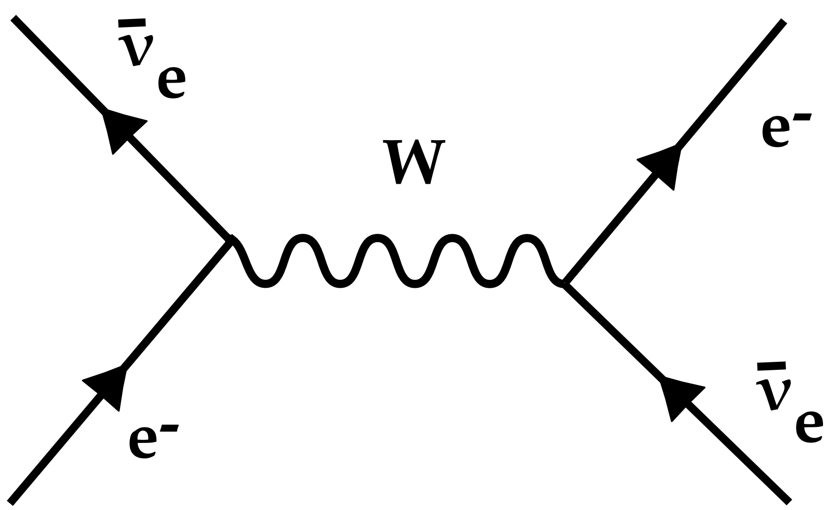
$$\frac{1}{2}\sum_{spins}\left|\mathcal{M}\right|^2 = 64G_F^2\left(k\cdot p\right)\left(k'\cdot p'\right)$$

$$= 16G_F^2 s^2$$

Skip a lot of steps! See: Halzen & Martin Quarks & Leptons or Griffiths Intro. to Elementary Particles.

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\overline{\left|\mathcal{M}\right|^2} = \frac{G_F^2 s}{4\pi^2} \implies \sigma = \frac{G_F^2 s}{\pi}$$

Antineutrino–Electron Scattering



By crossing the neutrinos of previous diagram, we have the result, replacing s with t:

$$\frac{1}{2}\sum_{spins}|\mathcal{M}|^2 = 16G_F^2 t^2$$
$$= 4G_F^2 s^2\left(1-\cos\theta\right)^2$$

θ is the opening angle between incoming $\bar{\nu}_e$ and outgoing e^-

Integrating over angles, we have:

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2 s}{16\pi^2}\left(1-\cos\theta\right)^2 \implies \sigma = \frac{G_F^2 s}{3\pi}$$

Why the factor of 3 ?

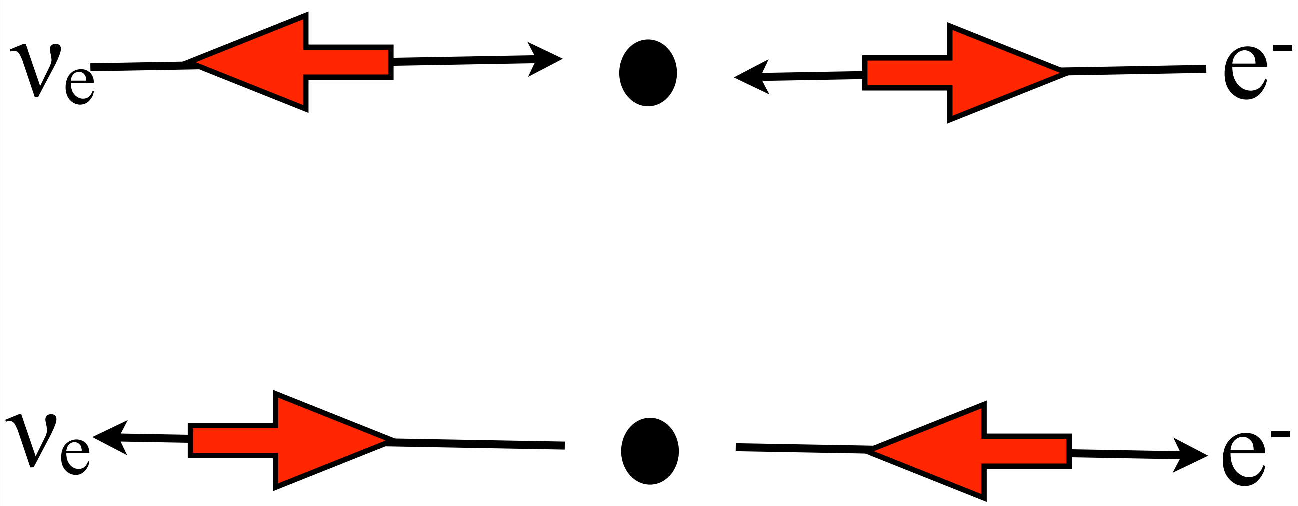
$$\sigma\left(\bar{\nu}_e e^-\right) = \frac{1}{3}\sigma\left(\nu_e e^-\right)$$

$$\frac{d\sigma}{d\Omega}\left(\nu_e e^-\right) = \frac{G_F^2 s}{4\pi^2}$$

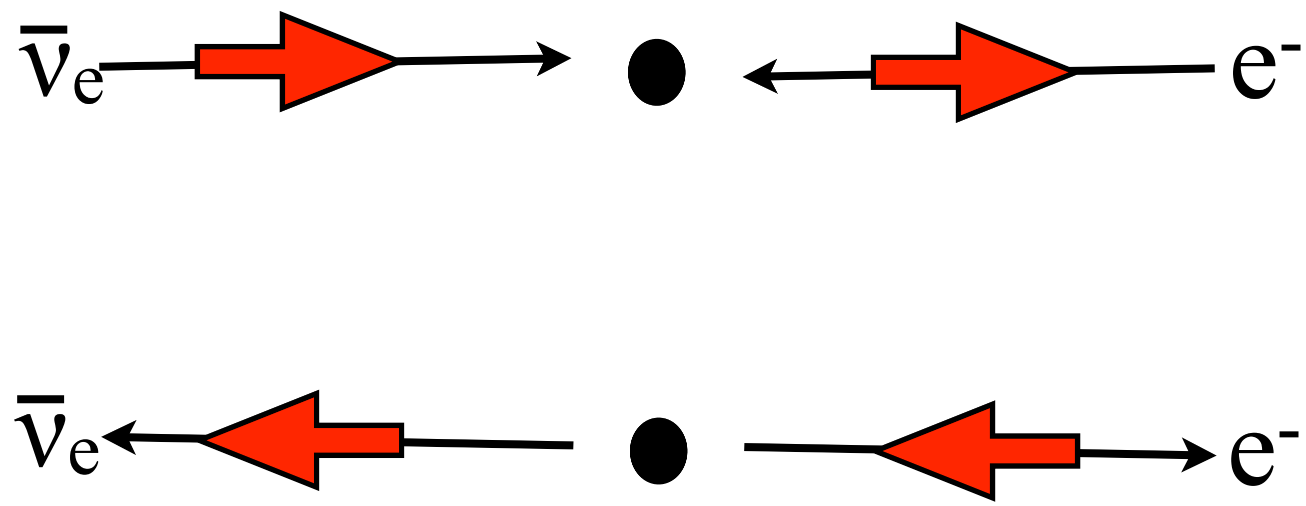
does not vanish !

$$\frac{d\sigma}{d\Omega}\left(\bar{\nu}_e e^-\right) = \frac{G_F^2 s}{16\pi^2}\left(1 - cos\theta\right)^2$$

vanishes for cos θ =1 !



$(J_z)_i = (J_z)_f = 0$
Allowed



$(J_z)_i = +1;\ (J_z)_f = -1$
Forbidden

- Backward anti-ν_e scattering is forbidden !
- Scattering proceeds entirely in J=1 state, net helicity +1

Charged Current Neutrino-Quark Scattering

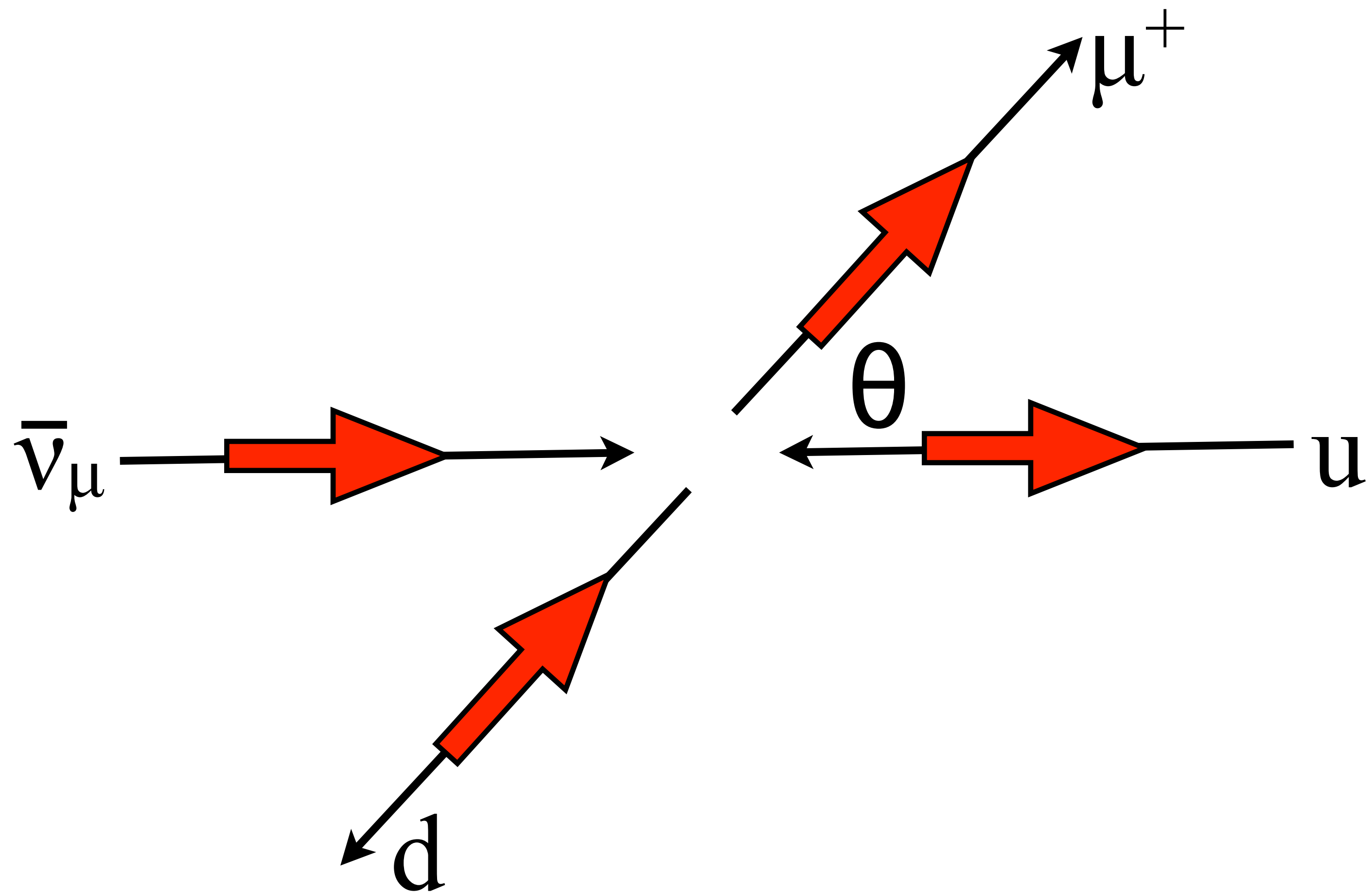
Neutrino Quark Scattering

$$\frac{d\sigma}{d\Omega}\left(\nu_\mu d \to \mu^- u\right) = \frac{G_F^2 s}{4\pi^2}$$

$$\frac{d\sigma}{d\Omega}\left(\bar{\nu}_\mu u \to \mu^+ d\right) = \frac{G_F^2 s}{16\pi^2}\left(1 + cos\theta\right)^2$$

- Backward scattering ($\theta=\pi$) is forbidden by helicity considerations !

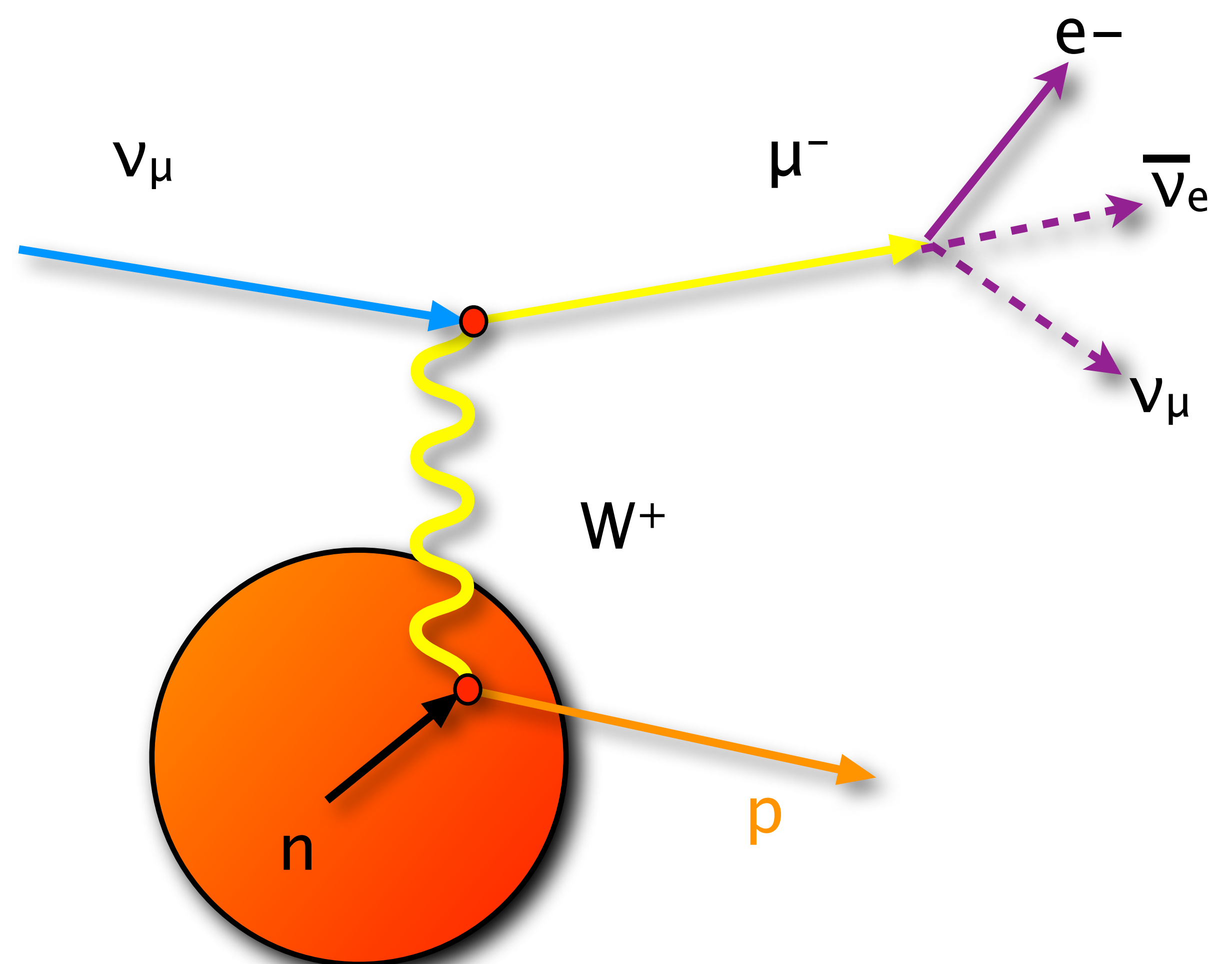
- These constituent x-secs are embedded in νN inclusive cross-sections for comparing with exptl. results (e.g. DIS)



Neutrino Quasi-Elastic Scattering

Why is $\nu(\bar{\nu})$-QE scattering important ?

- Flagship signal channel in current and future generation neutrino oscillation experiments
  - For ν_e appearance we need a simple final state
- Interaction with a free nucleon is tractable (compared to DIS)
  - Actually not that simple when compare results with predictions
  - Nuclear effects and form factors make it challenging
- Improve phenomenological models & dictionaries of events

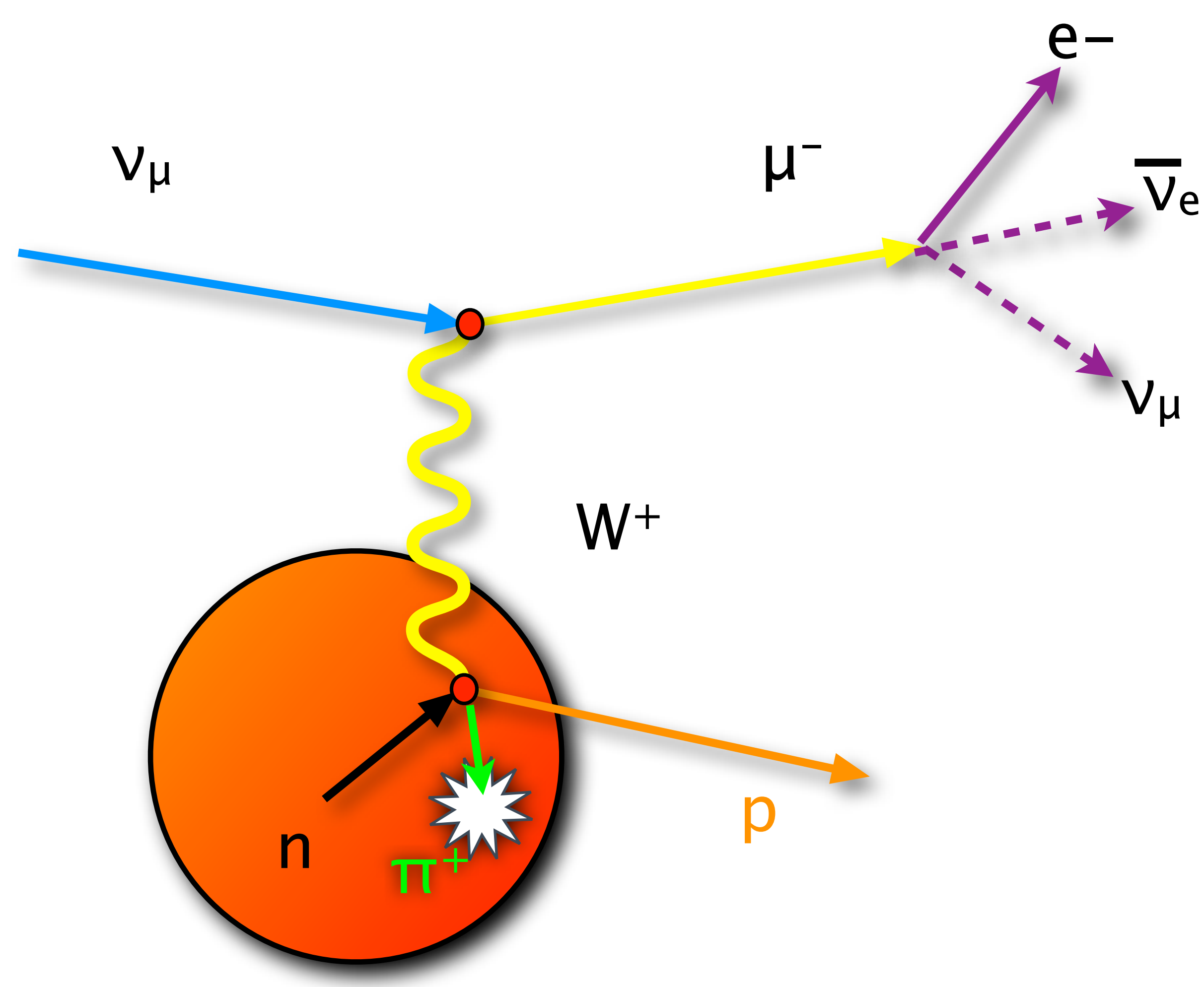


$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

Characteristics of QE Scattering

- Neutrino energy and flavor inferred from just the lepton kinematics !
- Muon decay (Michel) electron helps with particle ID in some detectors
- Main background is CC1π+ (e.g. resonance) where pion is undetected
    - Backgrounds create a bias in parameter estimation for oscillation experiments. They depend on a good understanding of E_ν !



W±

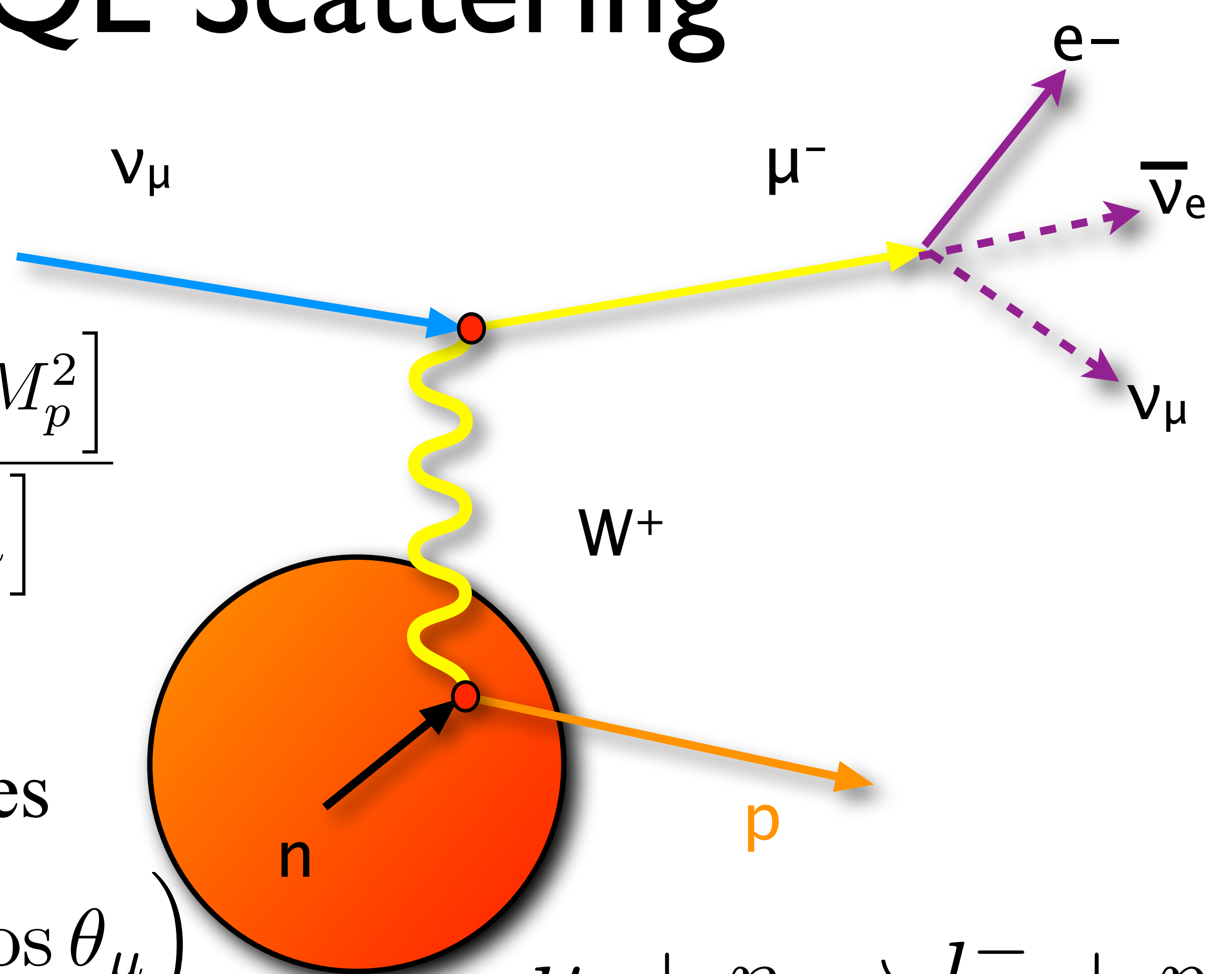
Characteristics of QE Scattering

Neutrino energy from Muon variables

$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right)E_\mu - \left[\left(M_n - E_B\right)^2 + m_\mu^2 - M_p^2\right]}{2\left[\left(M_n - E_B\right) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

Four Momentum Transfer from Muon variables

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

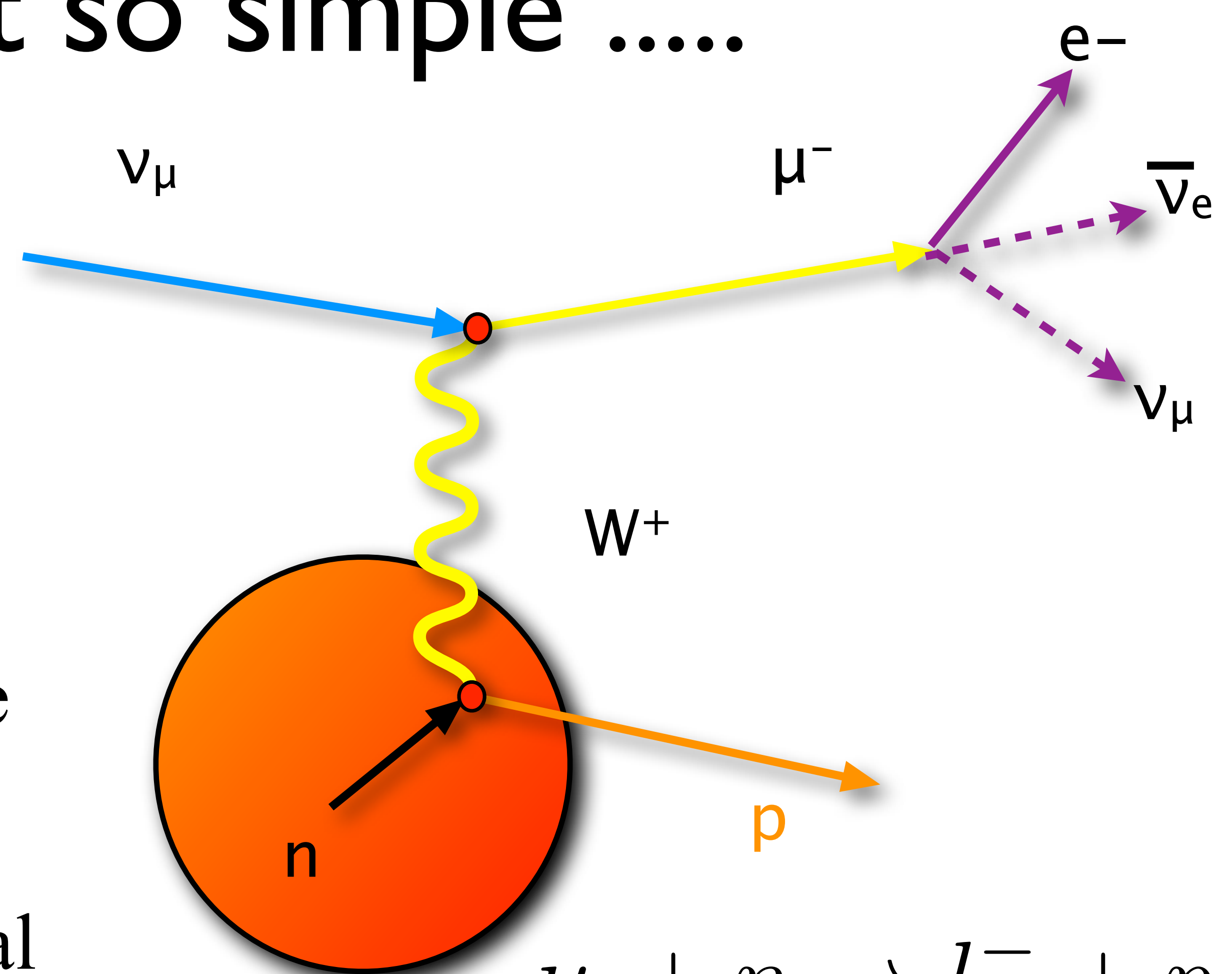


$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

QE Scattering - not so simple .....

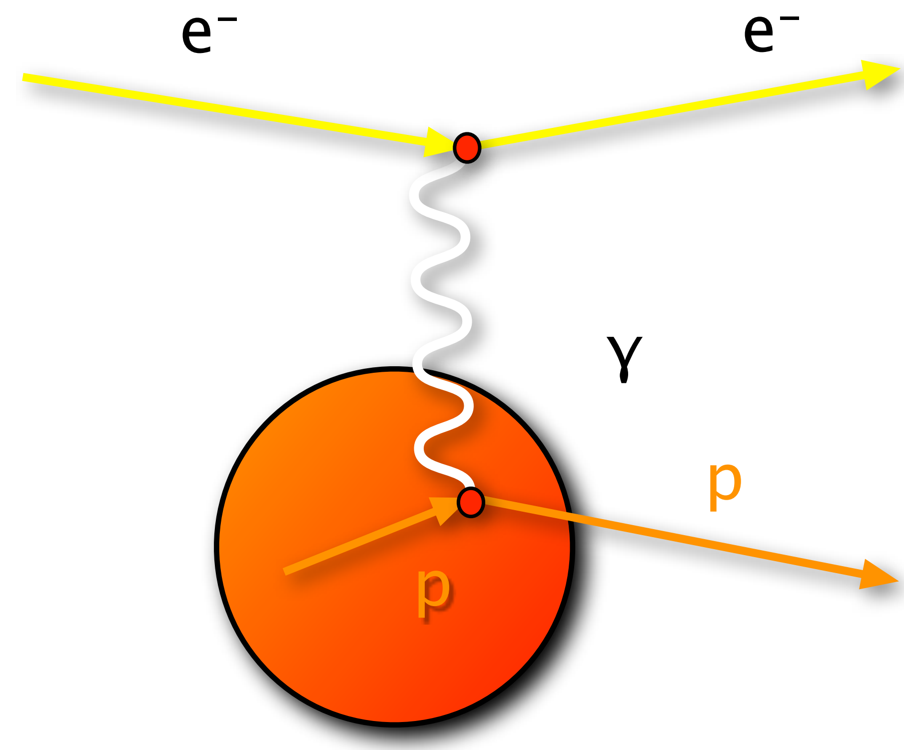


$$\nu_l + n \rightarrow l^- + p$$

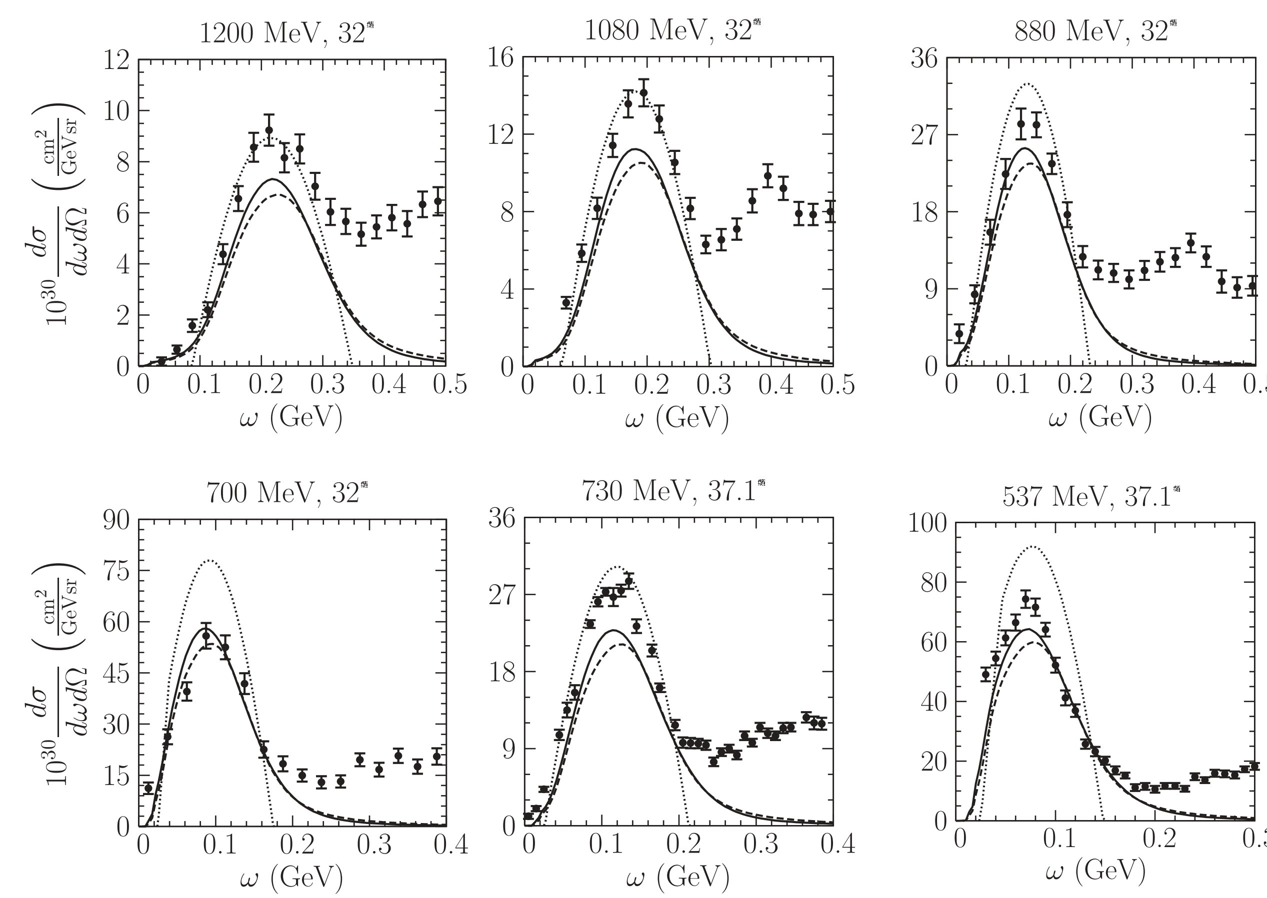
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

- Formalism works for free nucleons
- Nuclear medium makes it complex
- What structure does the neutrino resolve in the nucleus ?
- What would be a consistent experimental definition ?
- Different for nucleon & nucleus ?
- We also assume that nucleons are at rest
  - Not true ! Moreover nucleons are off-shell & transition matrix elements are not known !

QE Scattering in electrons



- We know incoming and outgoing electron energies - great advantage !
- Very clear signature in electron scattering.
- Energy transfer is very sharply peaked as a function of angle and electron energy, with broadening due to initial state momentum.



Ankowski et al, Phys. Rev. C 77, 044311 (2008)

QE Scattering - Llewellyn Smith formalism

ν Cross Section: $$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right)\frac{s-u}{M^2} + C\left(Q^2\right)\frac{\left(s-u\right)^2}{M^4}\right]$$

- Early formalism by Llewellyn Smith
- Vector and Axial-Vector components
  - Vector piece can be lifted from well-studied electron scattering data.
  - Neutrino experiments determine the Axial piece !

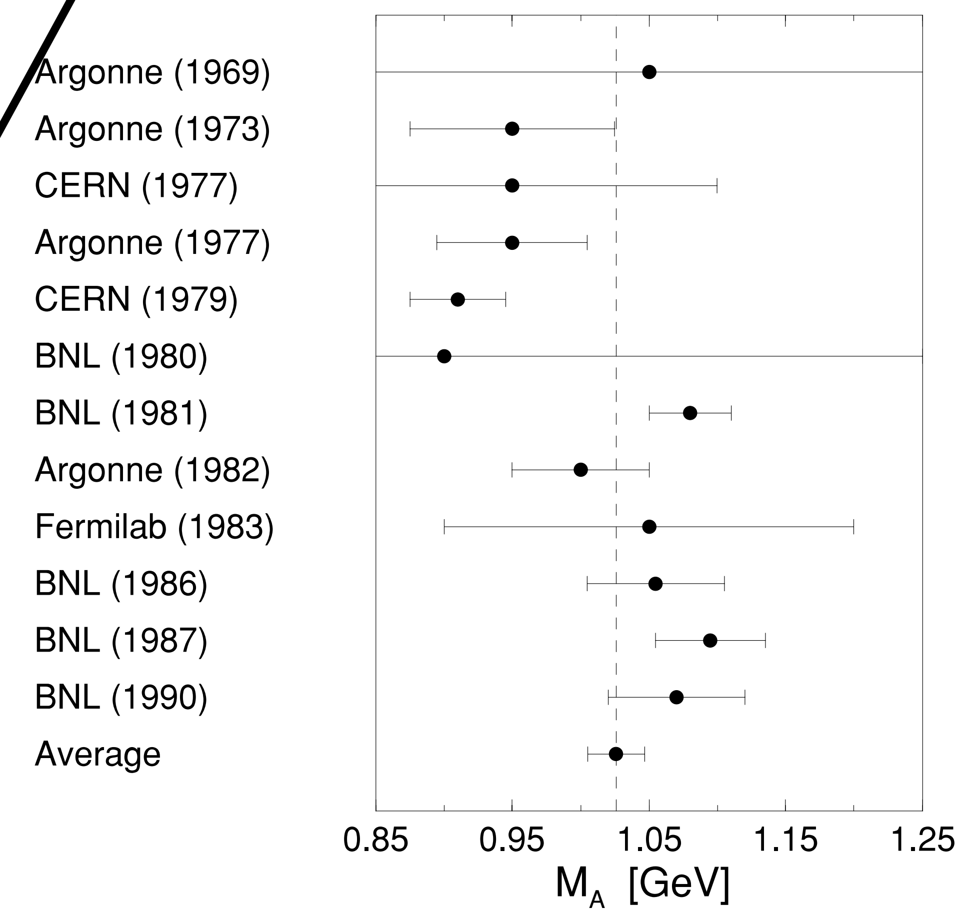
- Q2 is the four-momentum transfer
- s and u are Mandelstam variables
- Lepton vertex is known. Nucleon structure is parameterized with 2 vector (F_1, F_2) and 1 axial-vector (F_A) form factors

C. H. Llewellyn Smith, Phys. Rep. C3 261 (1972).

Llewellyn Smith & CCQE Cross Sections

- Standard Application:
  - Assume a Fermi Gas Model with parameters from electron scattering (or a favorite nuclear model).
    - Typically (FGM) assume the Impulse Approximation.
  - Vector form factors from electron scattering.
  - Assume dipole form for Axial-vector form factor. Everything now follows from M_A. Measure the x-section, get M_A.
  - $F_A(0)$ is measured in beta-decay.
- Early measurements of F_A involved low statistics on light targets (deuterium) at high energy.

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



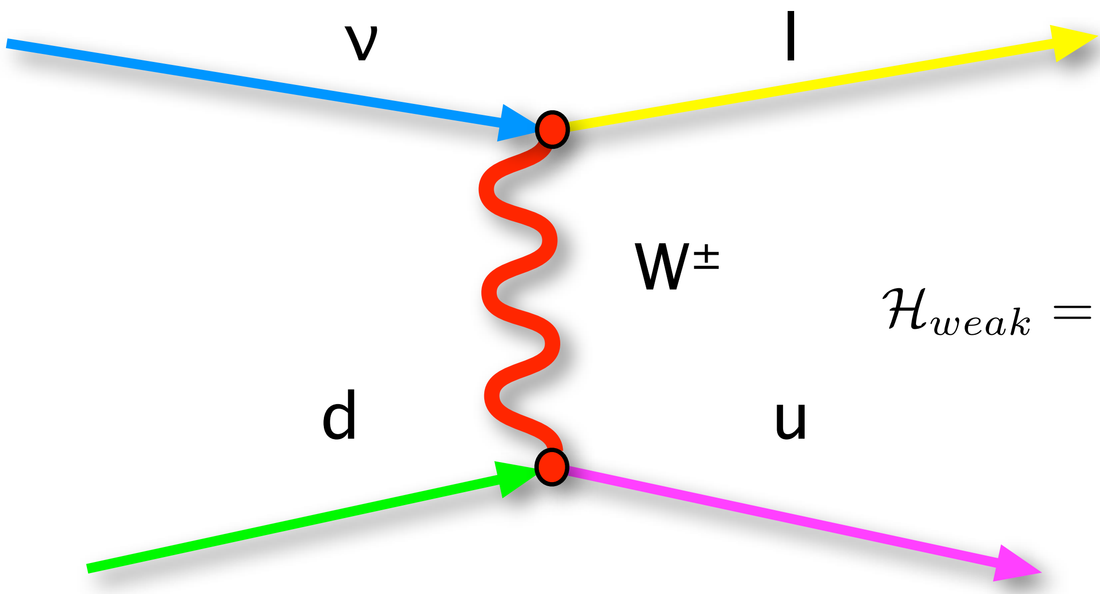
Bernard et al 2002 J. Phys. G: Nucl. Part. Phys. 28 R1

Relativistic Fermi Gas: Smith, Moniz, NPB 43, 605 (1972)

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

Axial Form Factor & M_A

"Intuition" for the axial form factor & M_A .....



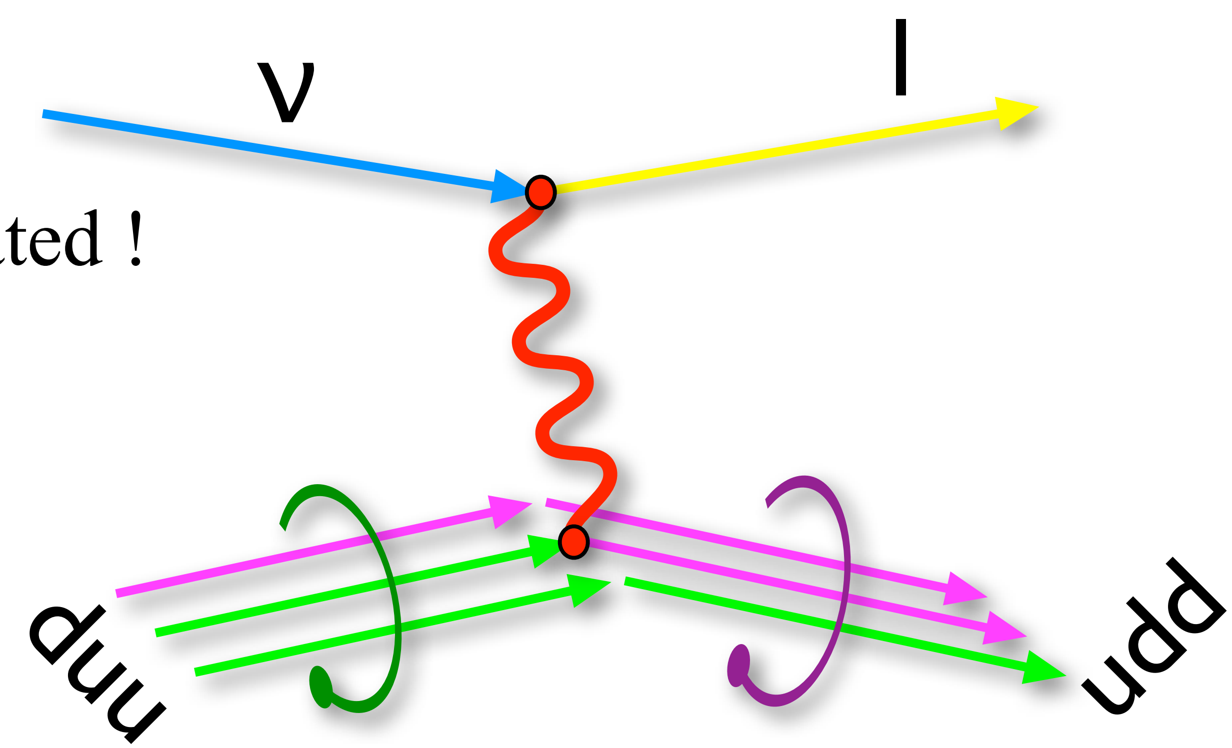
We know how to handle scattering for Dirac particles:

$$\mathcal{H}_{weak} = \frac{4\,G_F}{\sqrt{2}}\left[\bar{l}/\bar{\nu}\gamma_\mu \frac{1-\gamma_5}{2}\nu\right]\left[\bar{f}'\gamma_\mu\left(g_L\frac{1-\gamma_5}{2} + g_R\frac{1+\gamma_5}{2}\right)f\right] + h.c.$$

In real protons ..... things get more complicated !

Form Factor : Fourier Transform of the Charge Distribution

$$\rho\left(r\right) = \rho_0 e^{-mr}$$



Form Factor :
Fourier Transform of the Charge Distribution

$$\rho(r) = \rho_0 e^{-mr}$$

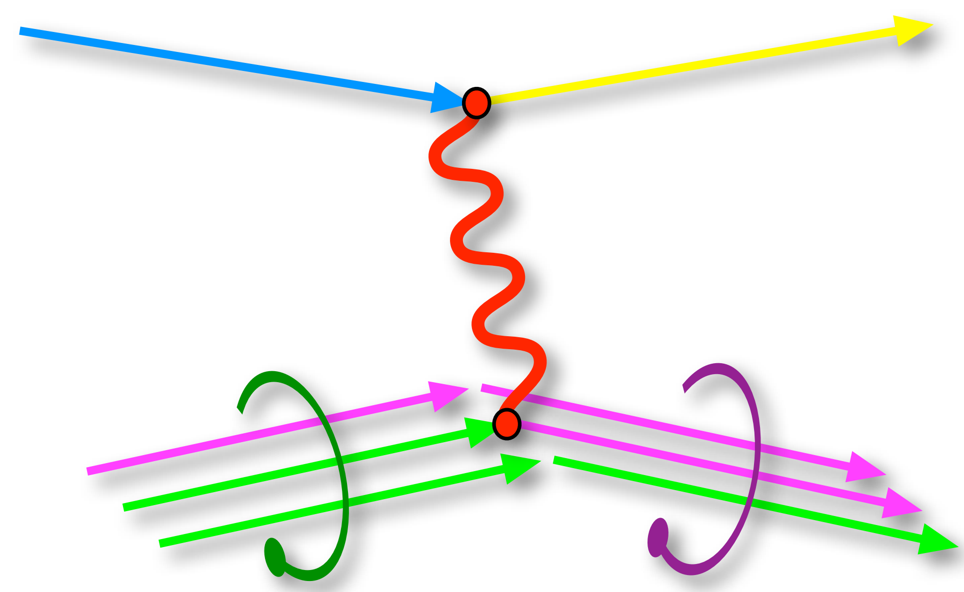
m is a constant

$$F\left(|q|^2\right) = N\int e^{-mr} e^{i\vec{q}\cdot\vec{x}} d^3x$$

$$= 2\pi N\int r^2 e^{-mr} e^{i|q|r\cos\theta} dr d(\cos\theta)$$

$$= \frac{2\pi N}{i|q|}\int_0^\infty r\left[e^{-(m-i|q|)r} - e^{-(m+i|q|)r}\right] dr$$

$$= \frac{8\pi N}{m^3\left(1+\frac{|q|^2}{m^2}\right)^2}$$



Normalization:

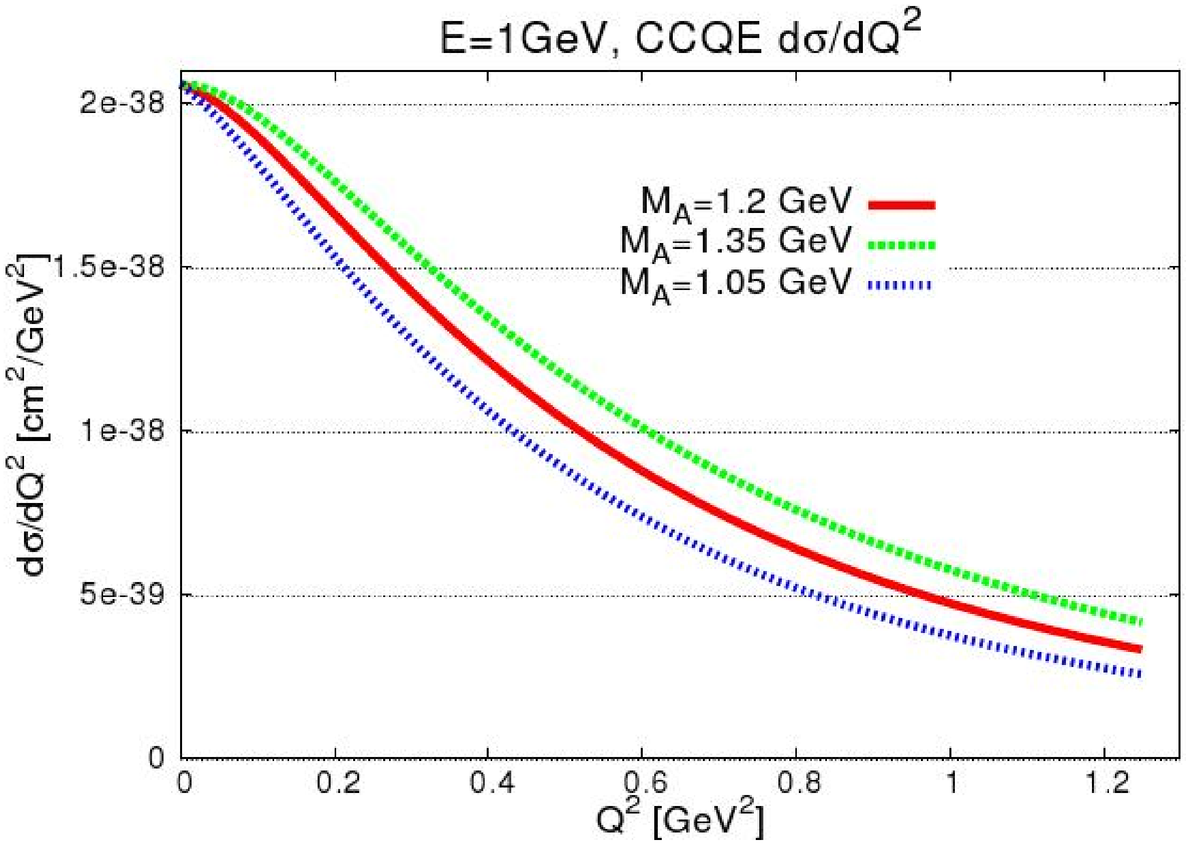
$$N\int e^{-mr} d^3x = 1 \Rightarrow N = m^3/8\pi$$

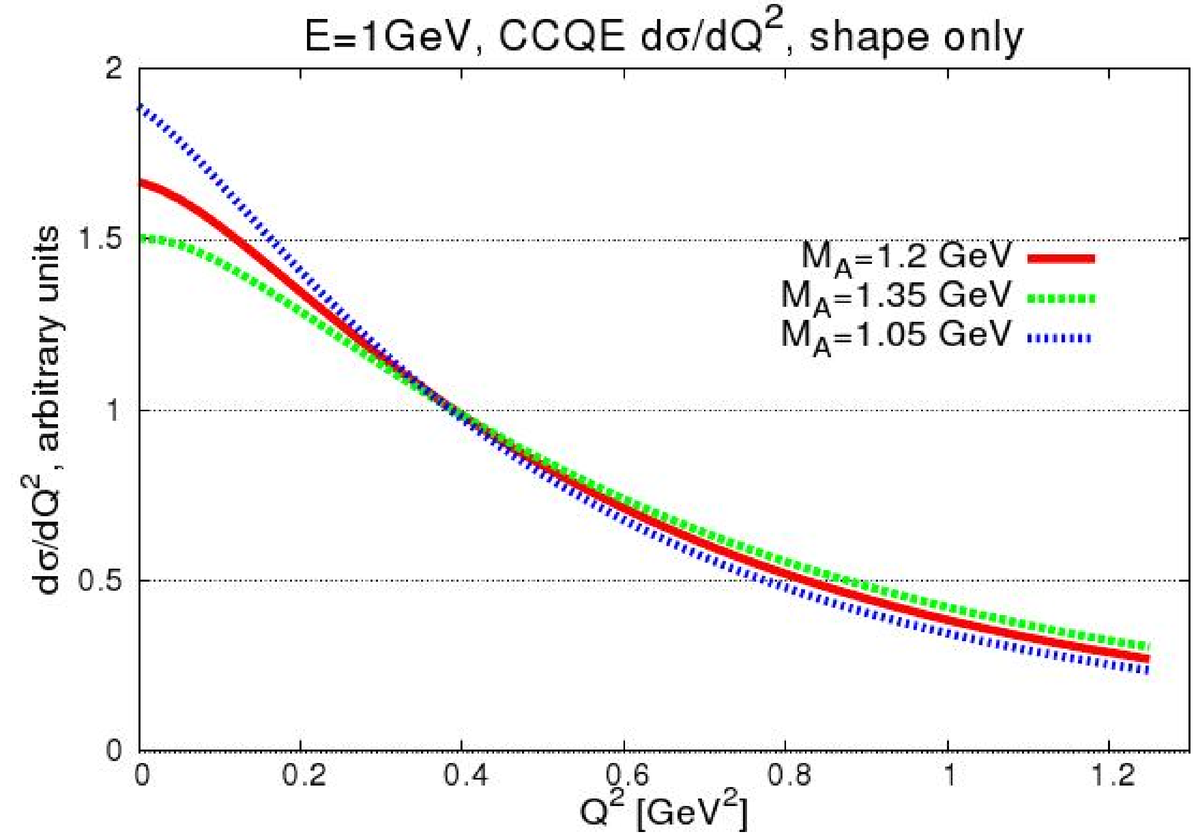
$$\Rightarrow F\left(q^2\right) = \frac{1}{\left(1-\frac{q^2}{m^2}\right)^2}$$

m=M_A

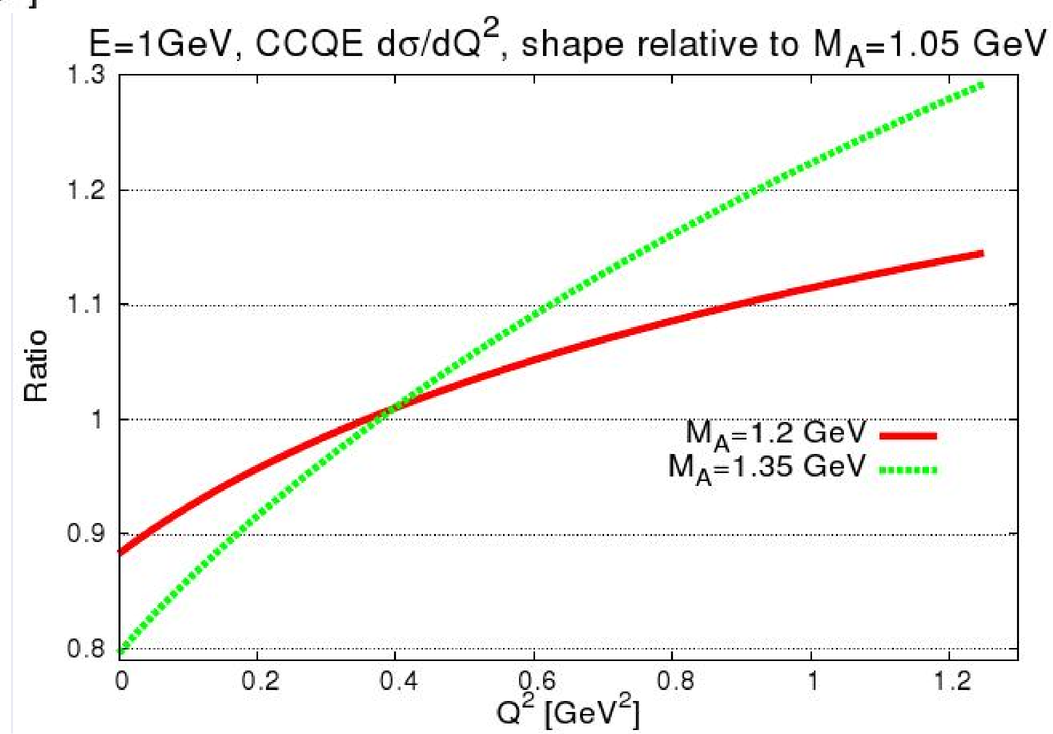
Q² dependence ⟺ Finite nucleon size

The Effect of M_A





Higher absolute cross section for higher M_A.



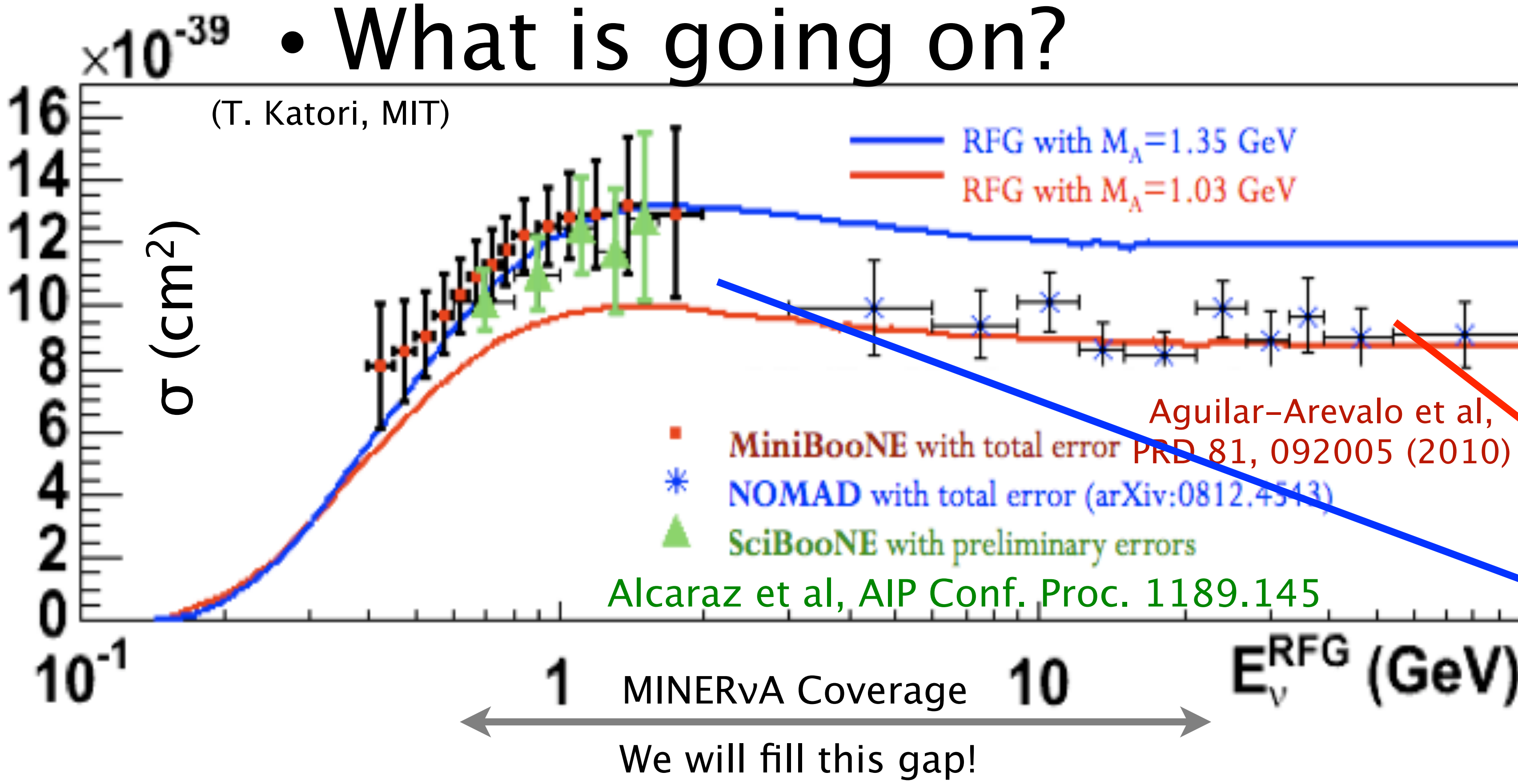
Relatively higher at high Q^2 for higher M_A.

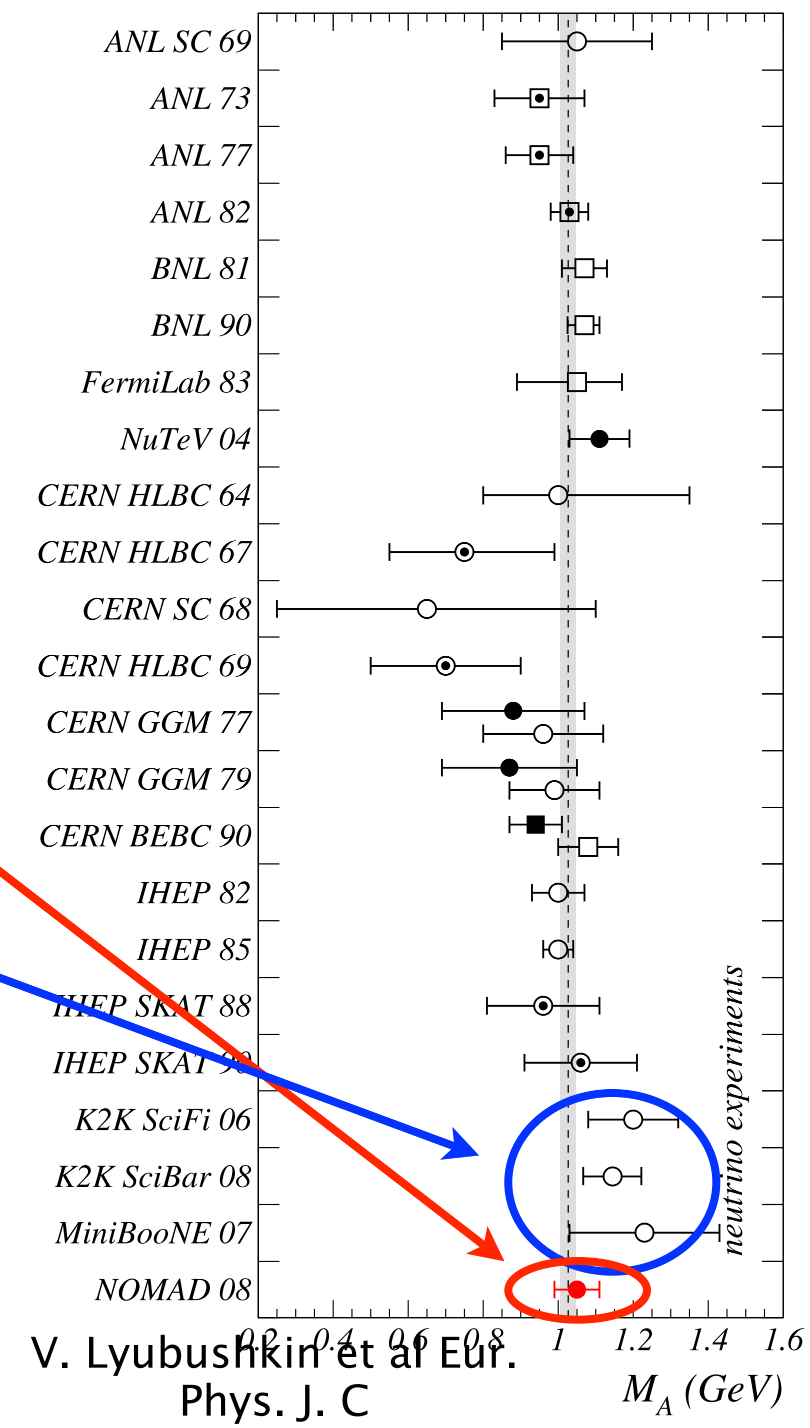
Figures courtesy of J. Sobczyk

Is this picture of QE scatt. good enough ?

Modern experiments are high statistics measurements on heavy targets at low E.

- What is going on?



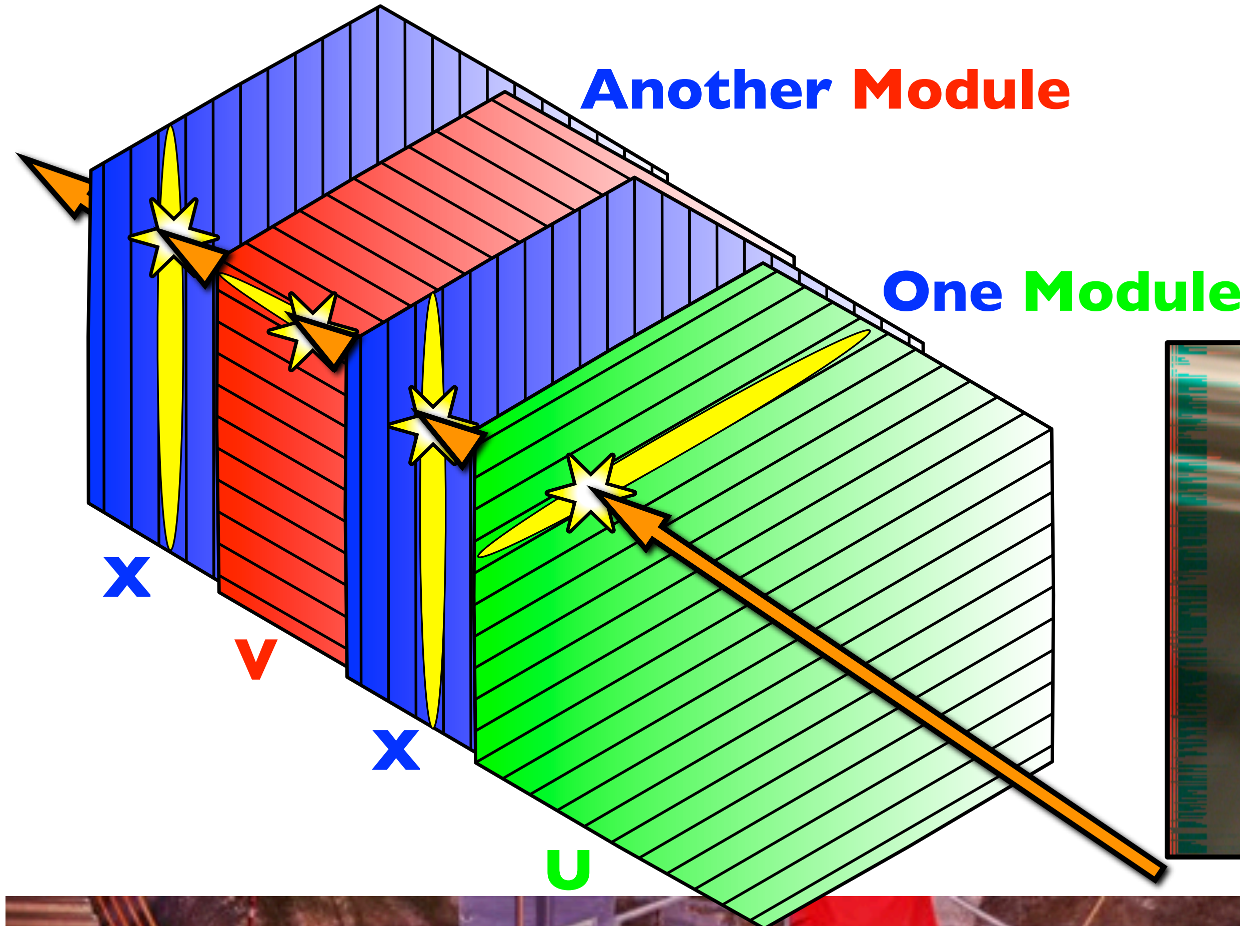


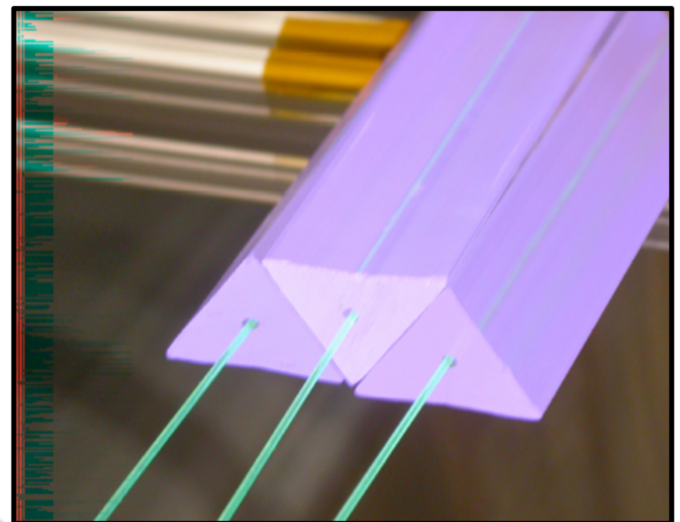
V. Lyubushkin et al Eur. Phys. J. C (2009) 63: 355-381 (NOMAD)

What is going on?

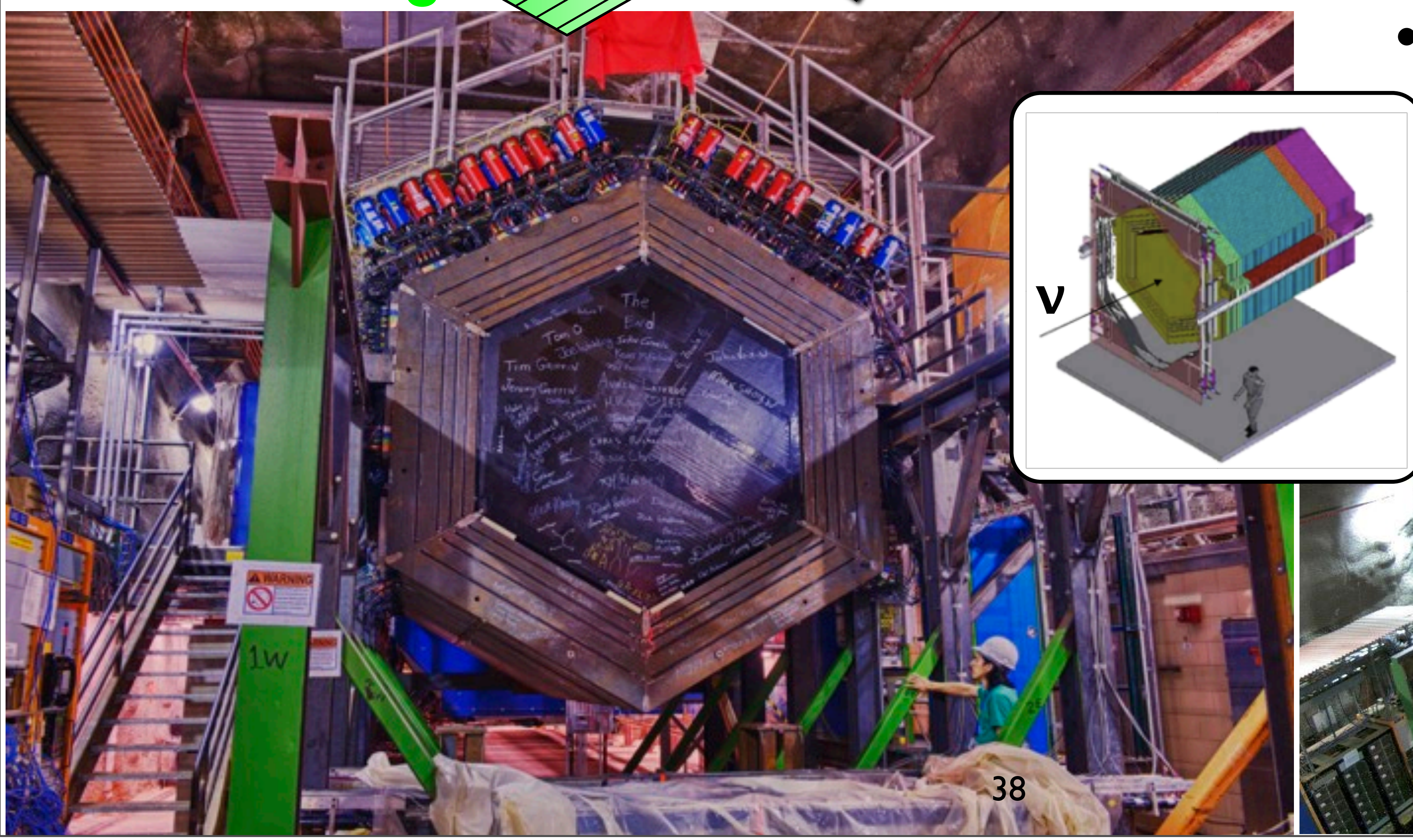
???

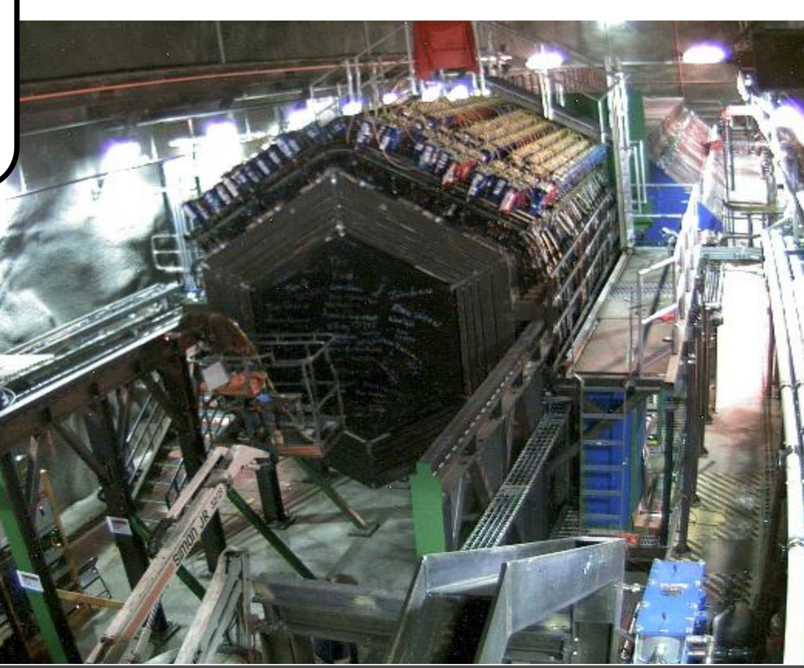
MINERνA



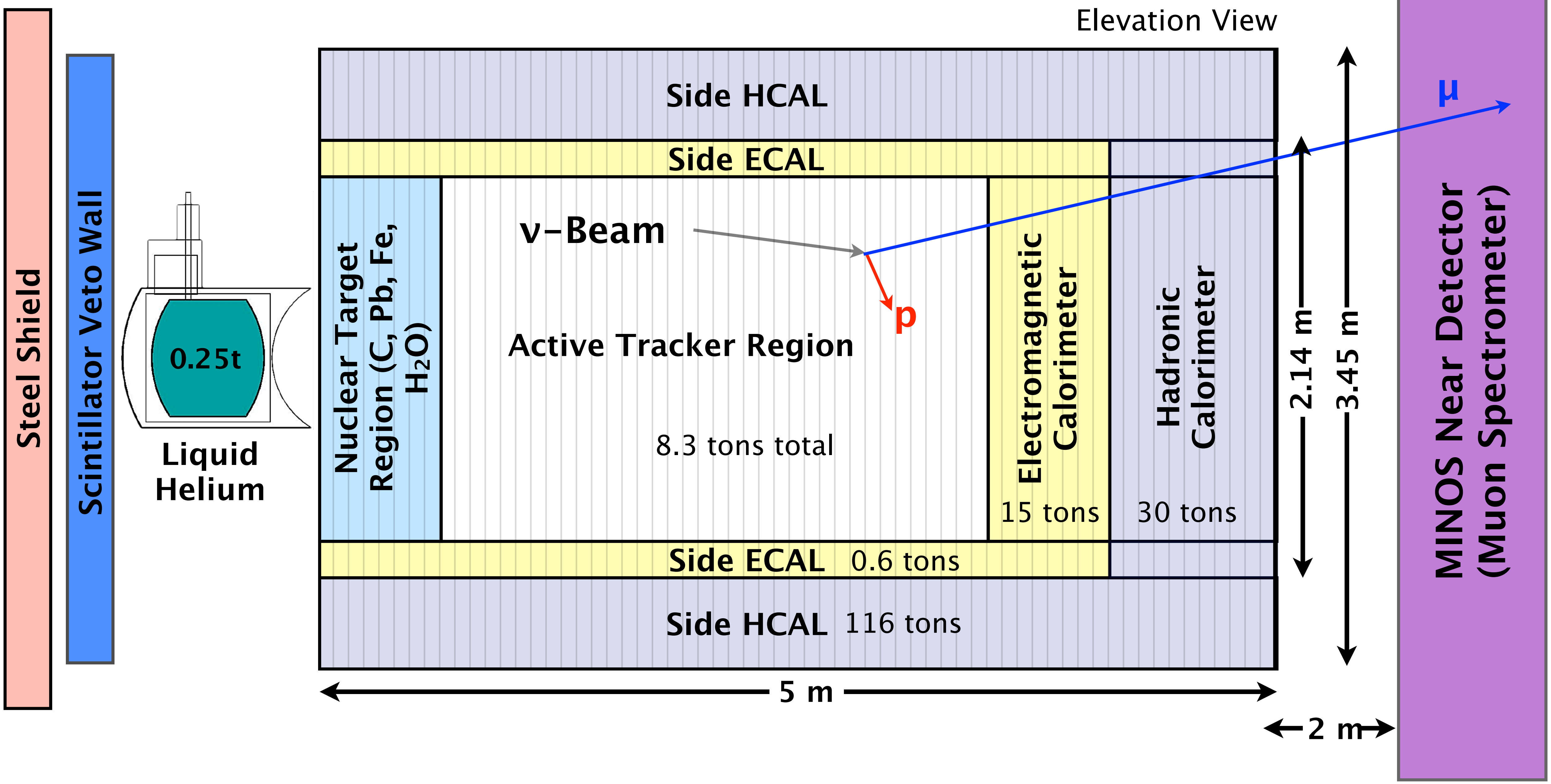


- Fine-grained resolution for excellent kinematic measurements.
- Low-energy cross-section program well-suited to next-generation oscillation experiments.
- Nuclear effects with a variety of target materials ranging from Helium to Lead. Especially important for ME run.





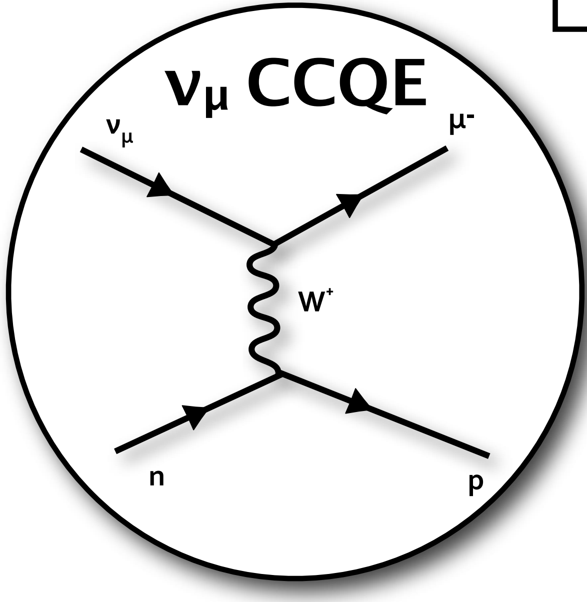
MINERvA - the detector design

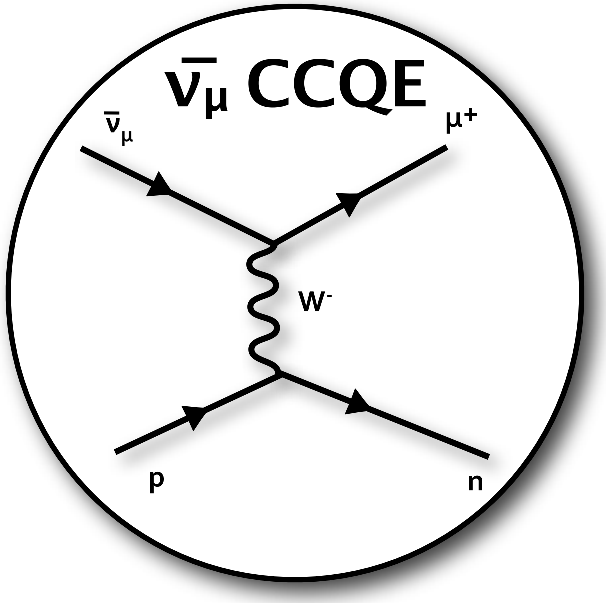


- Detector composed of 120 stacked modules of varying composition.
- Finely segmented (~32 K readout channels), side ECAL & HCAL well instrumented
- MINOS near detector acts as magnetic spectrometer ➛ muon charge and momentum

CCQE Physics Results

PRL 111, 022501 (2013) & PRL 111, 022502 (2013)





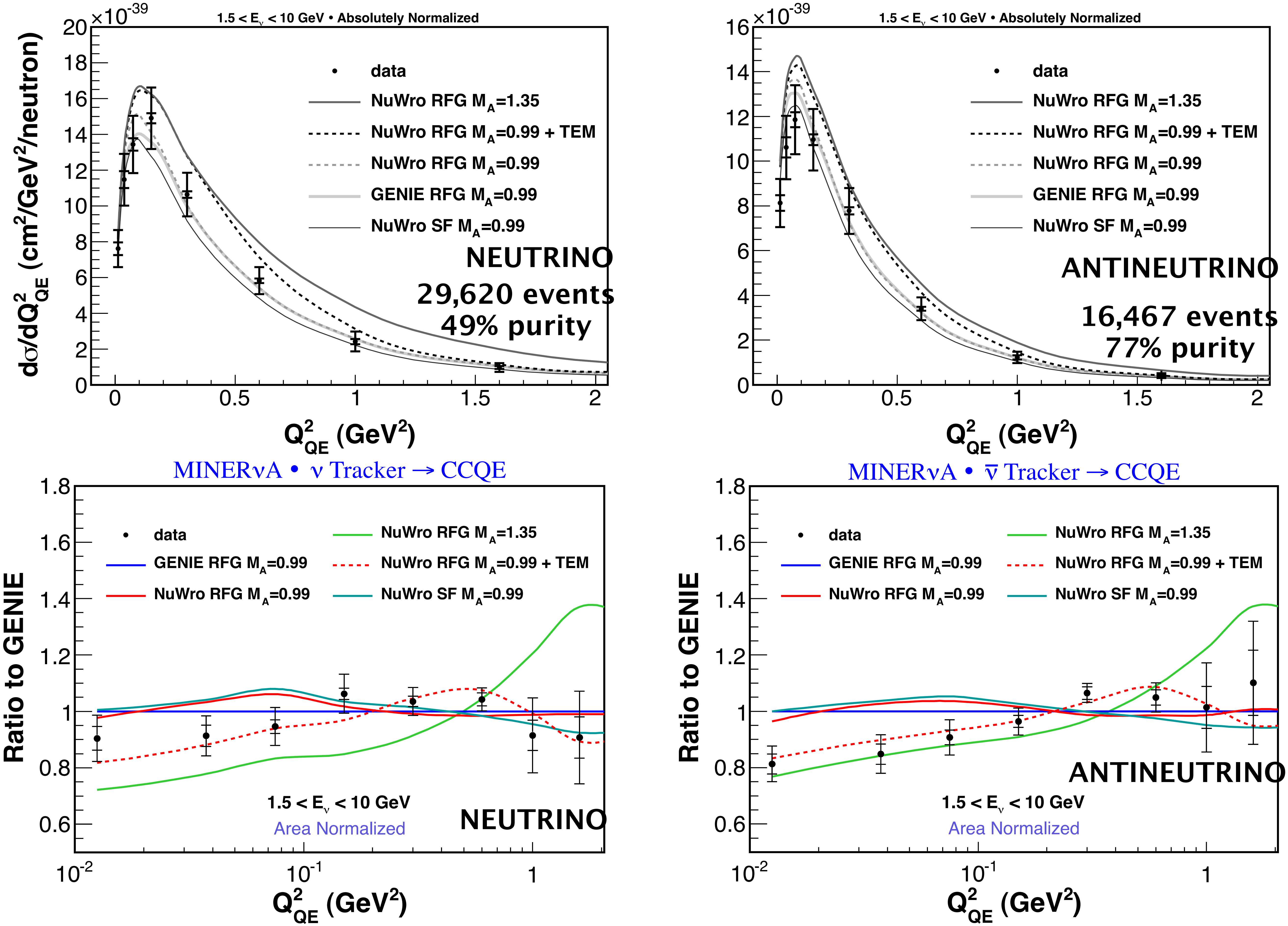
- $d\sigma/dQ^2$ on a (mostly) hydrocarbon target.
- Flux integrated over 1.5 to 10 GeV in the NuMI "Low Energy" Configuration.
- Muons are sign and momentum analyzed in the MINOS Near Detector (puts a lower-bound on momentum).
- See FNAL Wine & Cheese (D. Schmitz) on 10 May 2013 for more details.

$$Q^2_{QE} = -m^2_\mu + 2E^{QE}_\nu \left(E_\mu - \sqrt{E^2_\mu - m^2_\mu} \cos\theta_\mu \right)$$

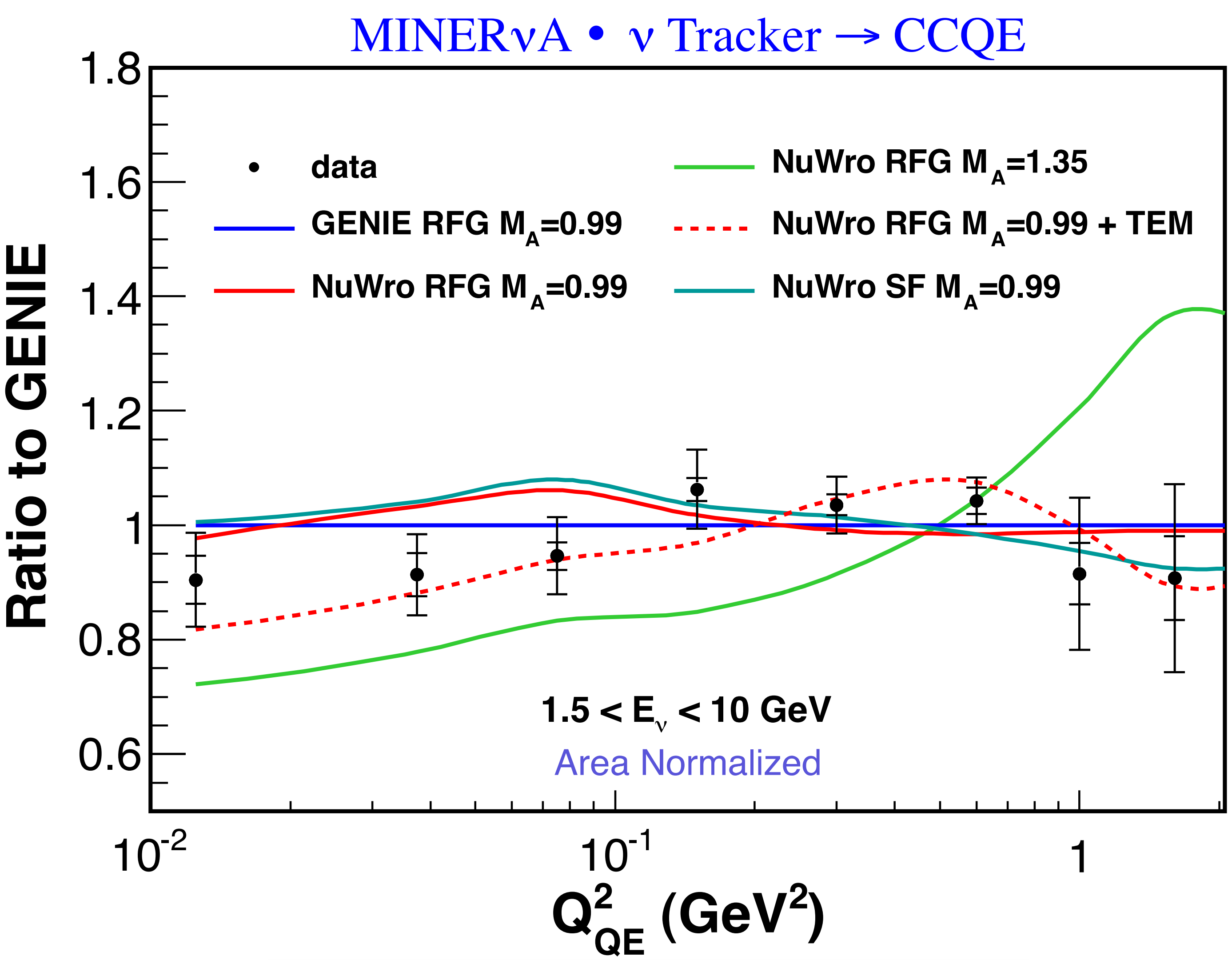
= Four momentum transfer

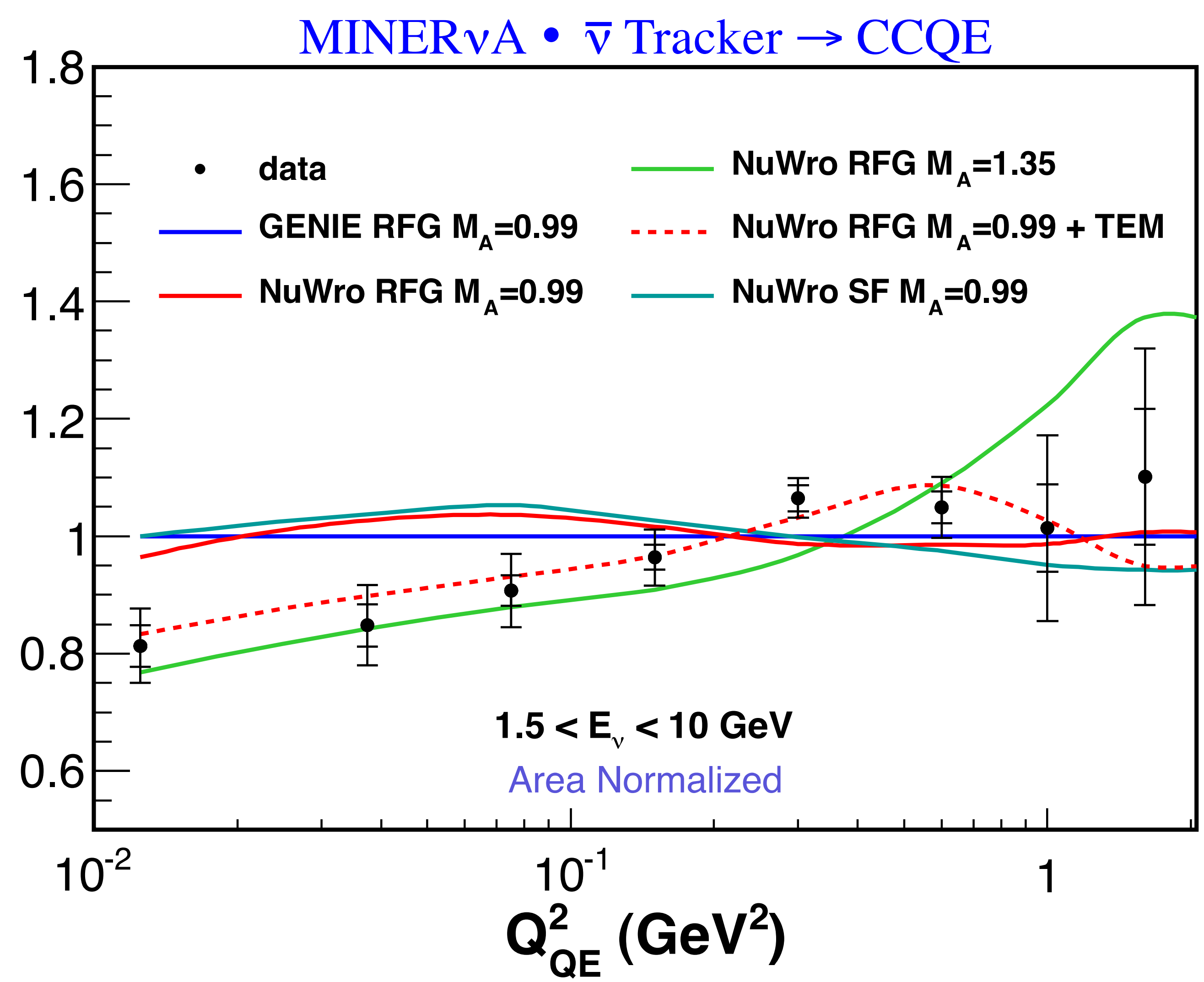
Nuclear Models

- Relativistic Fermi Gas (RFG), $M_A = 0.99$ GeV/c^2
  - The standard used in essentially all event generators.
- Relativistic Fermi Gas (RFG), $M_A = 1.35$ GeV/c^2
  - Motivated by recent measurements & successful at low Q^2.
- Nuclear Spectral Function (SF), $M_A = 0.99$ GeV/c^2
  - A more realistic model of the nucleon momentum distribution.
- Transverse Enhancement Model (TEM), $M_A = 0.99$ GeV/c^2
  - Empirical model modifying the magnetic form factors of bound nucleons to create the enhancement in the transverse cross-section observed in electron scattering (attributed to correlated pairs of nucleons).
- Vary one thing at a time in our comparisons...


1.5 < E_ν < 10 GeV • Absolutely Normalized
×10^-39
dσ/dQ²_QE (cm²/GeV²/neutron)
data
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99 + TEM
NuWro RFG M_A=0.99
GENIE RFG M_A=0.99
NuWro SF M_A=0.99
NEUTRINO
29,620 events
49% purity
Q²_QE (GeV²)
ANTINEUTRINO
16,467 events
77% purity
MINERνA • ν Tracker → CCQE
MINERνA • ν̄ Tracker → CCQE
Ratio to GENIE
1.5 < E_ν < 10 GeV
Area Normalized

Neutrino (Left), Antineutrino (Right)





Neutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

Antineutrino

NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

A Recap of Discussions so far .....

- Neutrino-nucleon interactions are complex from a theoretical and experimental understanding point of view. Neutrino-nucleus gets even more difficult !
- Neutrino-electron and anti-neutrino-electron scattering cross-secs. have a factor of 3 difference. Backward ($\theta=0$) anti-ν_e scattering is forbidden due to helicity considerations !
- Neutrino-quark and anti-neutrino-quark scattering cross-secs. also have a factor of 3 difference. $\theta=\pi$ scattering is forbidden again !
- Neutrino Quasi-Elastic scattering is flagship signal channel in current and future generation neutrino oscillation experiments
- Neutrino energy and flavor inferred from just the lepton kinematics !
- However, it is not so simple - nuclear medium adds complexity
- Llewellyn Smith formalism uses simple model, assumes non-interacting nucleons, dipole form-factor, etc.
- MINERvA has published results on neutrino and anti-neutrino scattering on a mostly hydrocarbon target (PRL 111, 022501 (2013) and PRL 111, 022502 (2013) ! NuMI flux integrated over 1.5-10.0 GeV.
- Results presented in comparison to various nuclear models.

Lots of topics left uncovered today .....

- I gave hints of certain topics today, that need more time and slides for a better understanding of the physics involved in neutrino scattering, e.g. :
    - Free non-interacting nucleons inside the nucleus ?
        - Multi-nucleon ejection, short range correlations, etc. are some of the existing theories that attempt to model a more realistic picture of nucleons inside a nuclear medium.
    - Relativistic Fermi Gas model used in most current MC event generators
        - Ongoing work in theoretical field for improving nuclear models in event generators. Better models of final state interactions.
    - Flux is very crucial to neutrino cross-section measurements. Different methods adopted by different experiments at estimating their flux. Often multiple methods used for a better estimation.
    - Deep Inelastic Scattering, Resonance Processes
        - Complex topologies compared to QE scattering. Probe into affects like EMC, shadowing, anti-shadowing, etc. An exclusive talk will do justice to these topics.
- Please visit http://minerva.fnal.gov/ - will answer a lot of the above questions

Other experimental results

- Unfortunately I could not cover results from other experiments today.....
  - MiniBooNE (http://www-boone.fnal.gov/publications/)
  - ArgoNeut (http://t962.fnal.gov/Publications.html)
  - MINOS (http://www-numi.fnal.gov/pr_plots/index.html)
  - SciBooNE (http://www-sciboone.fnal.gov/documents/papers/papers.html)
  - NOMAD (http://www.nu.to.infn.it/exp/all/nomad/)
  - LSND (http://www.nu.to.infn.it/exp/all/lsnd)
  - Expts. done at Jefferson Lab, SLAC - e.g. on Deep Inelastic Scattering
- Please visit the above websites for more information on neutrino scattering results

Thank you for your time !

Many thanks to all the slide & idea lenders for this talk !

Backup Slides