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Intersections of BSM Phenomenology and QCD for New Physics Searches

Weak excitation of baryon resonances and neutrino experiments

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Introduction

- Neutrino interactions with matter are at the heart of many interesting and relevant physical processes
  - Astrophysics
    - Dynamics of the core-collapse in supernovae
    - r-process nucleosynthesis
  - Physics Beyond the Standard Model
    - Non-standard ν interactions
  - Hadronic physics
    - Nucleon and Nucleon-Resonance (N-Δ, N-N*) axial form factors
    - Strangeness content of the nucleon spin
  - Nuclear physics
    - Information about: nuclear correlations, MEC, spectral functions
    - Complement electron scattering studies

Introduction

- Neutrino interactions with matter are at the heart all experiments seeking to unravel its nature.
- Oscillation experiments (with accelerator ν in the few-GeV region): T2K, NOvA, MicroBooNE, Hyper-K, DUNE/LBNF
  - Good understanding of neutrino interactions are important for:
    - ν detection, E_ν reconstruction, ν flux calibration
    - determination of (irreducible) backgrounds
    - reduction of systematic errors
    - needed in the quest for CP violation and ν mass hierarchy
  - Near detectors help to reduce systematic errors but ND vs FD:
    - exposed to different fluxes with different flavor composition
    - Different geometry, acceptance and targets

Introduction

- Neutrino interactions with matter are at the heart all experiments seeking to unravel its nature.
- Oscillation experiments (with accelerator ν in the few-GeV region):

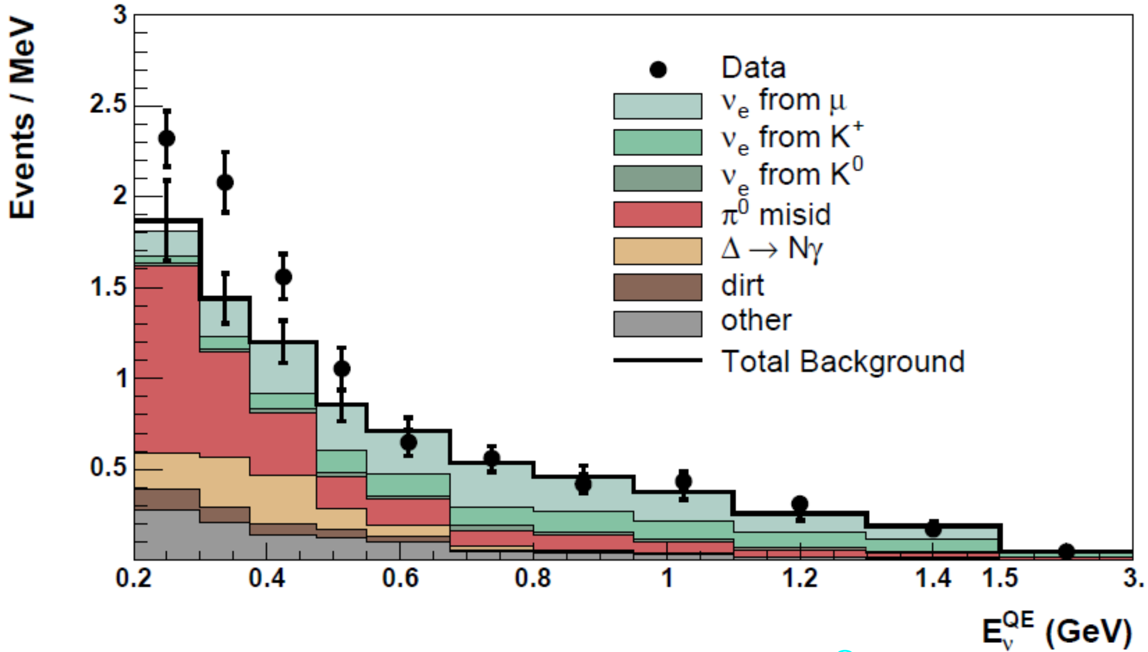
  T2K, NOvA, MicroBooNE, Hyper-K, DUNE/LBNF

  - Good understanding of neutrino interactions are important for:
    - ν detection, E_ν reconstruction, ν flux calibration
    - determination of (irreducible) backgrounds
    - reduction of systematic errors
    - needed in the quest for CP violation and ν mass hierarchy
  - Precision of 1-5% in ν cross sections might be required

Relevance for oscillation experiments

- Backgrounds
  - E.g. in the MiniBooNE $\nu_\mu \to \nu_e$ search

Aguilar-Arevalo et al., PRL102 (2009) 101802

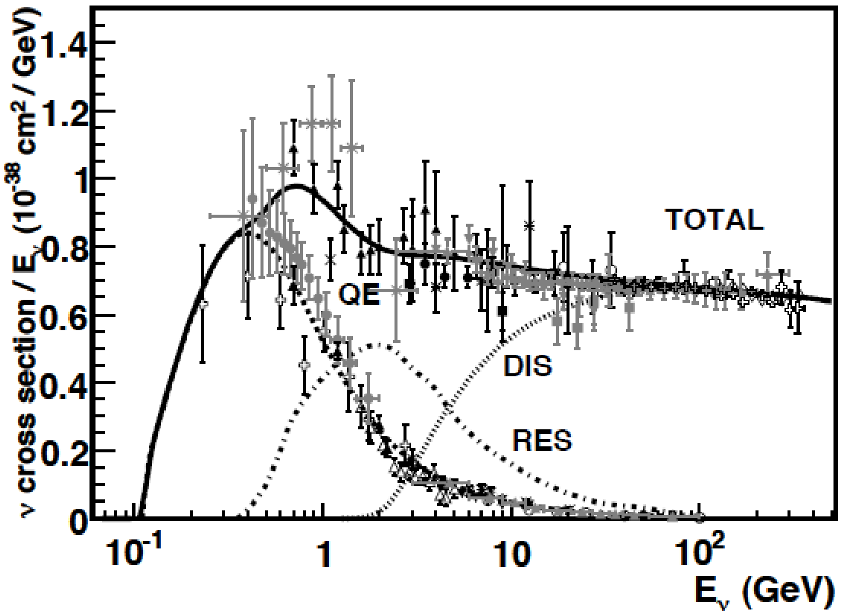


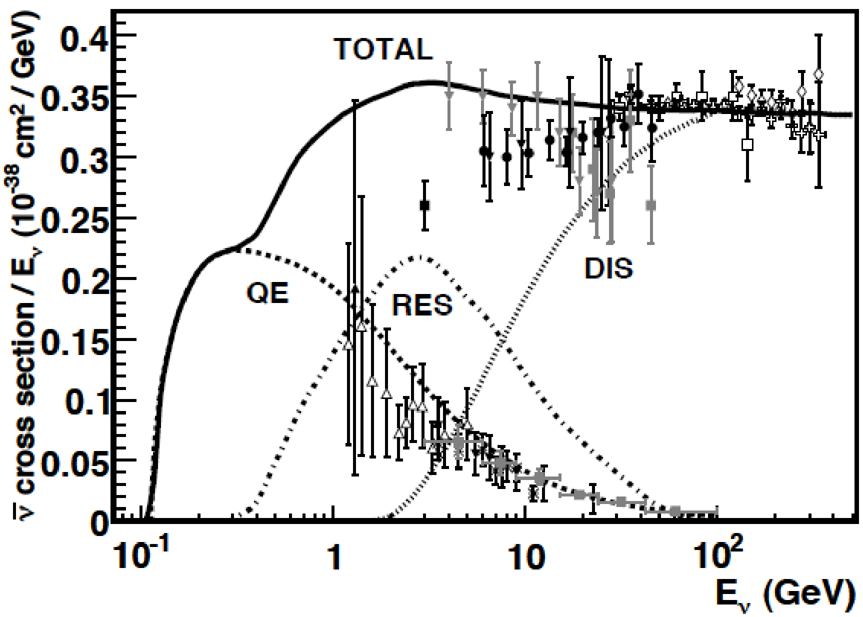
  - NC backgrounds: $\nu_l\, N \to \nu_l\, \pi^0\, N'$

$$\nu_l\, N \to \nu_l\, \gamma\, N'$$

  - Also important for $\nu_\mu \to \nu_e$ measurements at T2K

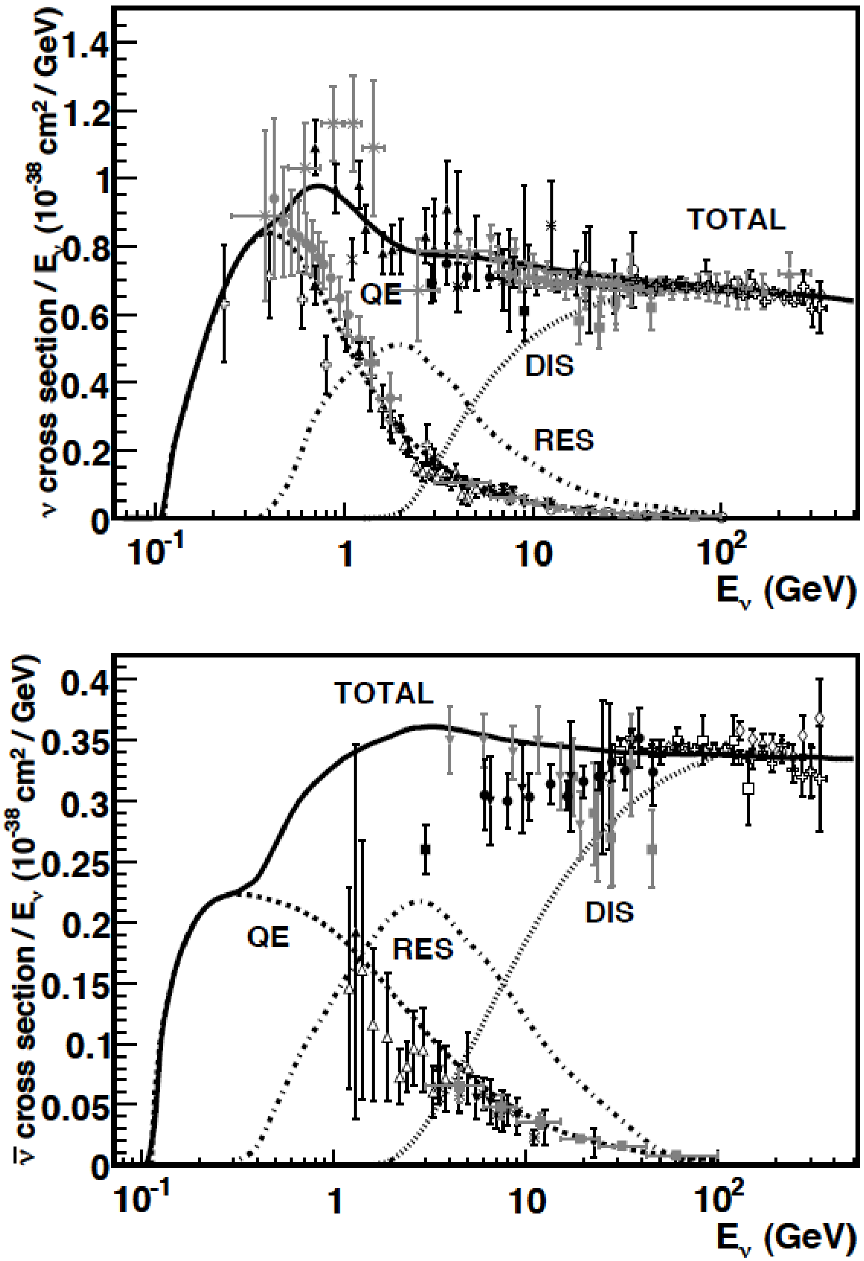
Introduction



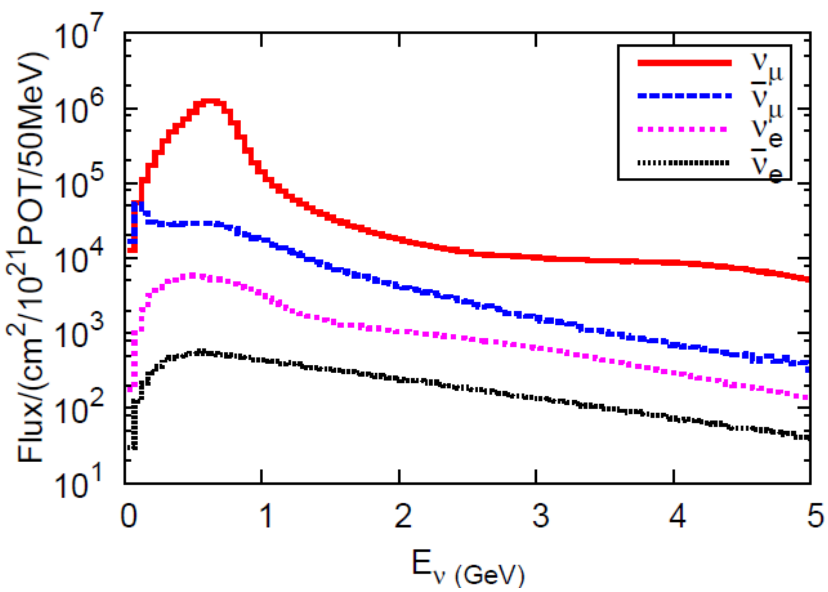


CC cross sections:
world data and NUANCE generator
Formaggio, Zeller, Rev. Mod. Phys. (2012)

Introduction

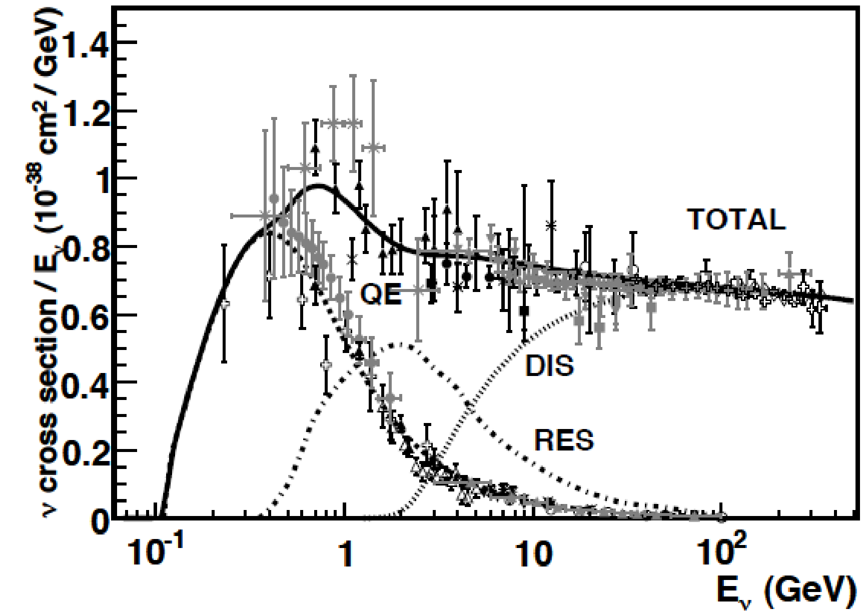


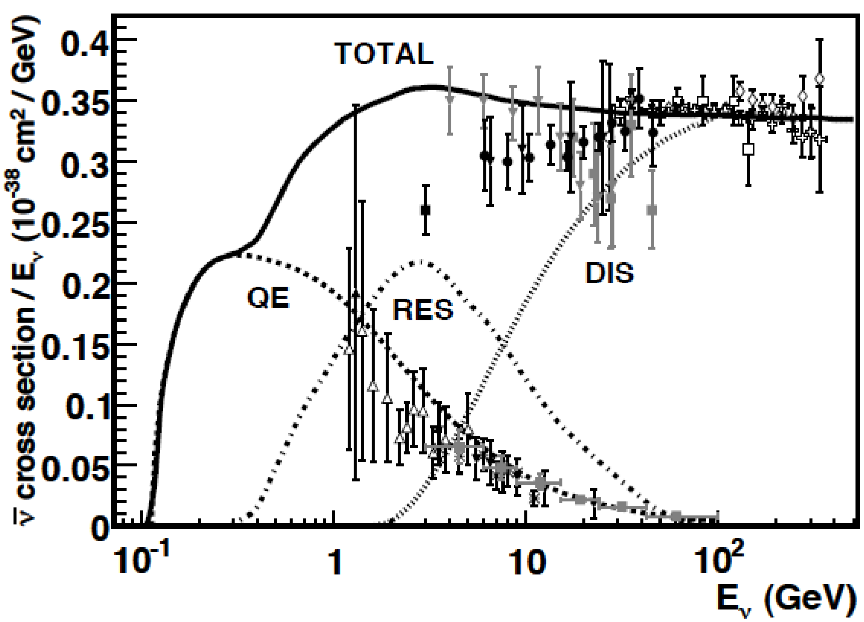
T2K flux



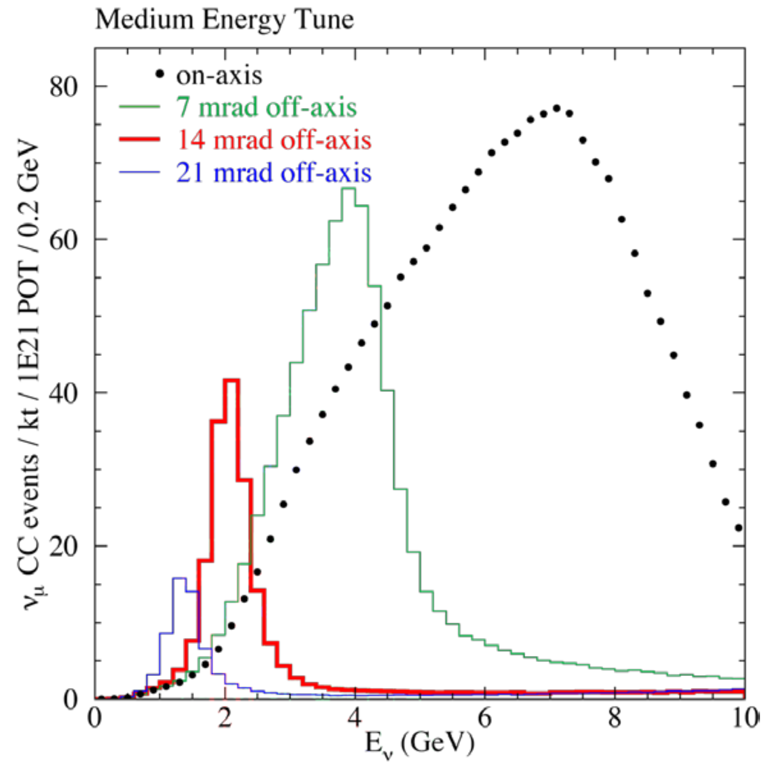
2)

Introduction

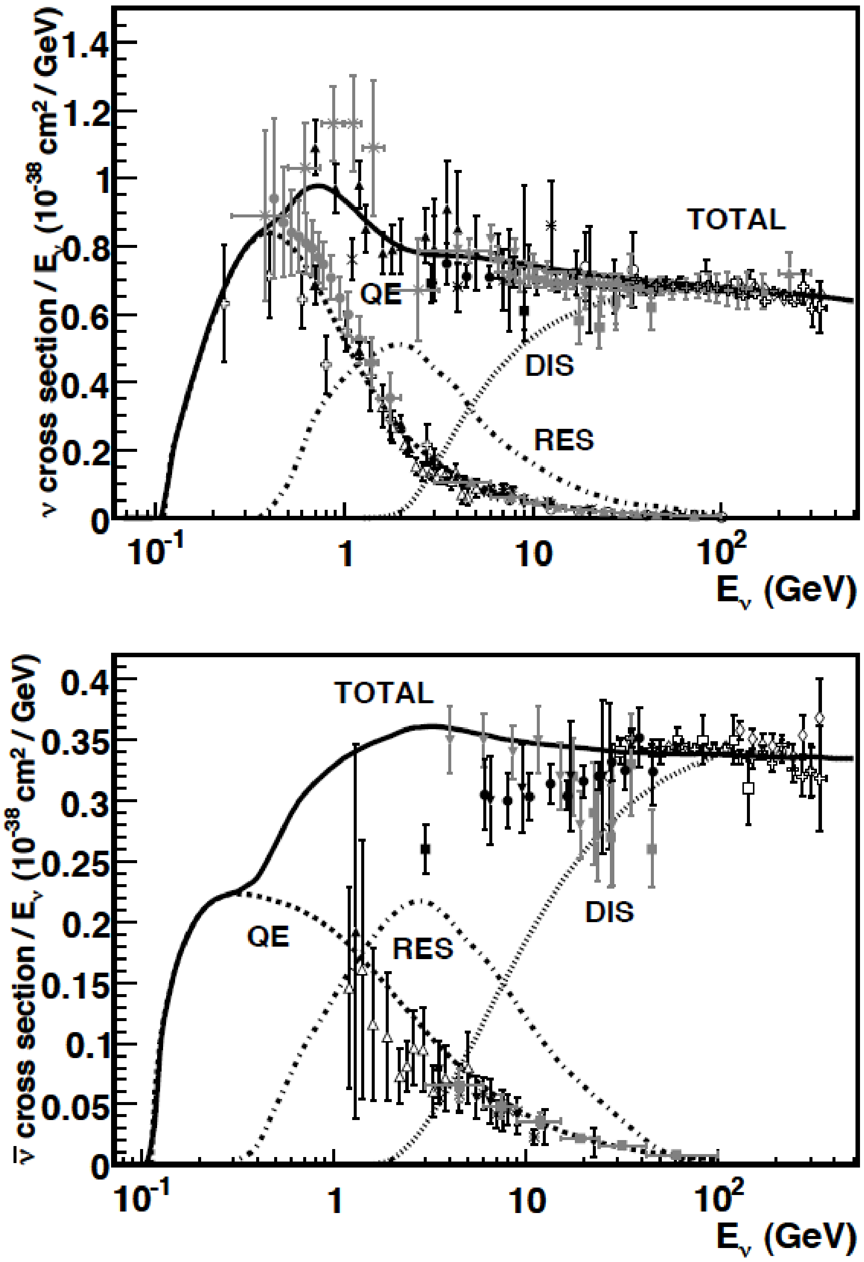




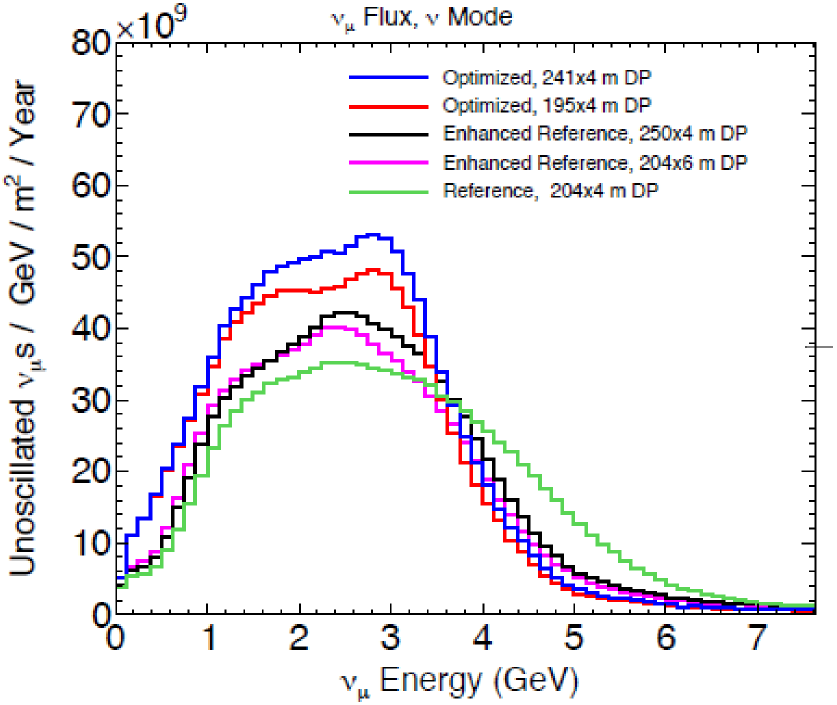
NOvA flux



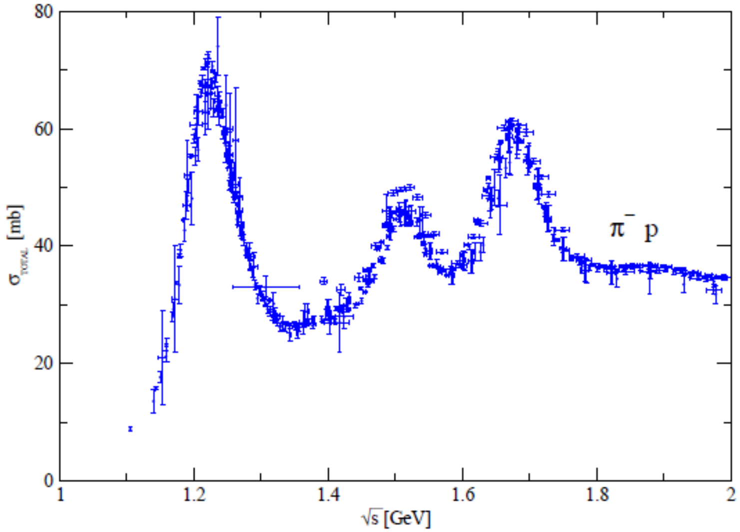
Introduction



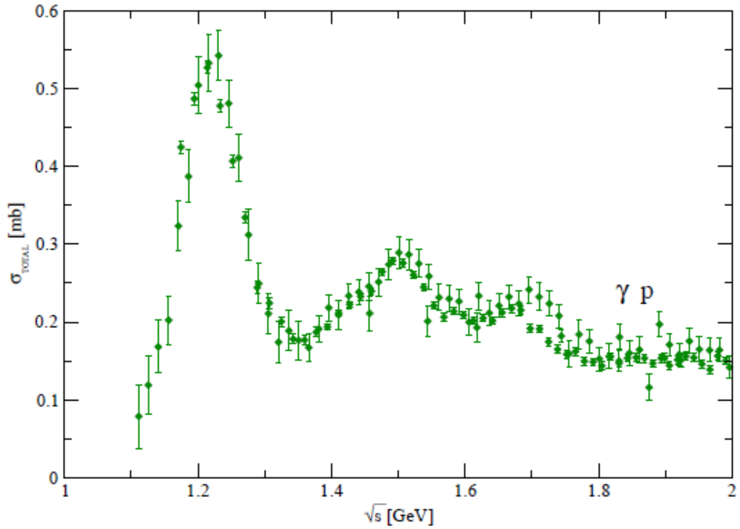
DUNE flux



Baryon resonances



$$\pi N \to R \to \pi N,\ \pi\pi N,\ \eta N,\ \Lambda K\ \ldots$$



$$\gamma N \to R \to \pi N,\ \pi\pi N,\ \eta N,\ \Lambda K\ \ldots$$

From PDG database

Weak Resonance excitation

- CC R excitation: $\nu_l(k)\, N(p) \to l^-(k')\, R(p')$

$$\frac{d\sigma}{dk_0' d\Omega'} = \frac{1}{32\pi^2} \frac{|\vec{k'}|}{k_0 M_N} \mathcal{A}(p') |\bar{\mathcal{M}}|^2$$

← Inclusive cross section

$$\mathcal{A}(p') = \frac{M^*}{\pi} \frac{\Gamma(p')}{(p'^2 - M^{*2})^2 + M^{*2}\Gamma^2(p')}$$

$\Gamma(p')$ ← total momentum dependent width

$$\mathcal{M} = \frac{G_F \cos\theta_C}{\sqrt{2}} l^\alpha J_\alpha$$

$$l^\alpha = \bar{u}(k')\gamma^\alpha(1-\gamma_5)u(k)$$

← leptonic current

$$J_\alpha = V_\alpha - A_\alpha$$

← hadronic current
can be parametrized in terms of
N-R transition form factors

Weak Resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu) \right)\gamma_5 + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu \right] u(p)$$

C^V_{3-5} , C^A_{3-6} $\leftarrow$ N-Δ transition form factors

- Rarita-Schwinger fields: spin 3/2

$$u_\mu(p, s_\Delta) = \sum_{\lambda, s} \left(1\lambda\frac{1}{2}s \middle| \frac{3}{2}s_\Delta \right) \epsilon_\mu(p,\lambda)u(p,s)$$

- Eq. of motion: $(\not{p} - M_\Delta)\, u_\mu = 0$

- with constrains: $\gamma^\mu u_\mu = p^\mu u_\mu = 0$

Weak Resonance excitation

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- Helicity amplitudes are extracted from data on π photo- and electro-production in (model dependent) partial-wave analyses

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}}\left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}}\left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}}\frac{|\mathbf{q}|}{\sqrt{Q^2}}\left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

Weak Resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu) \right)\gamma_5 + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu \right] u(p)$$

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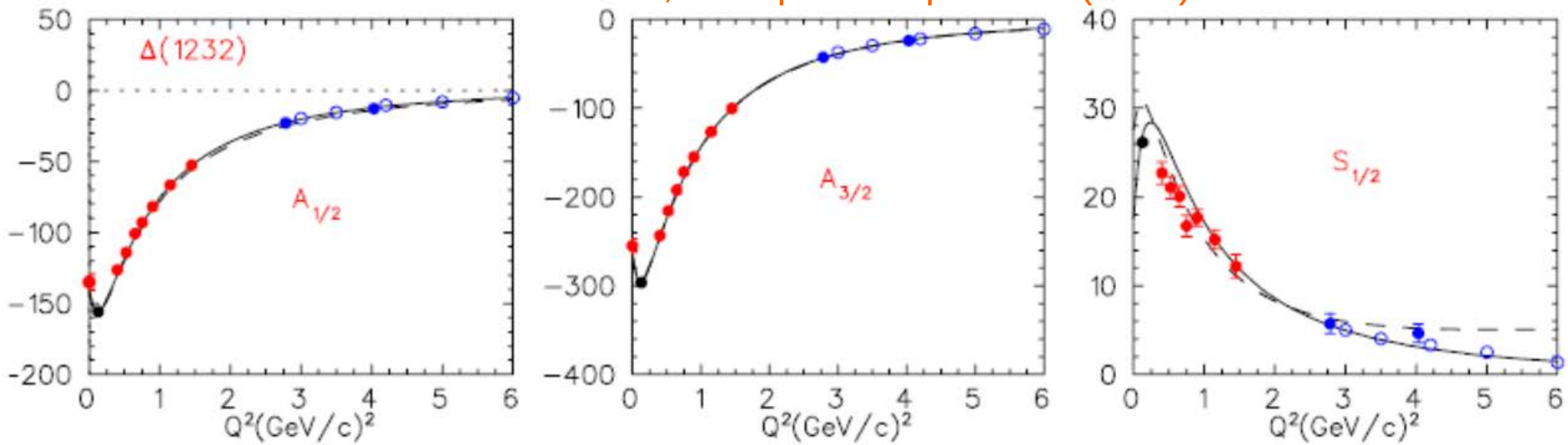
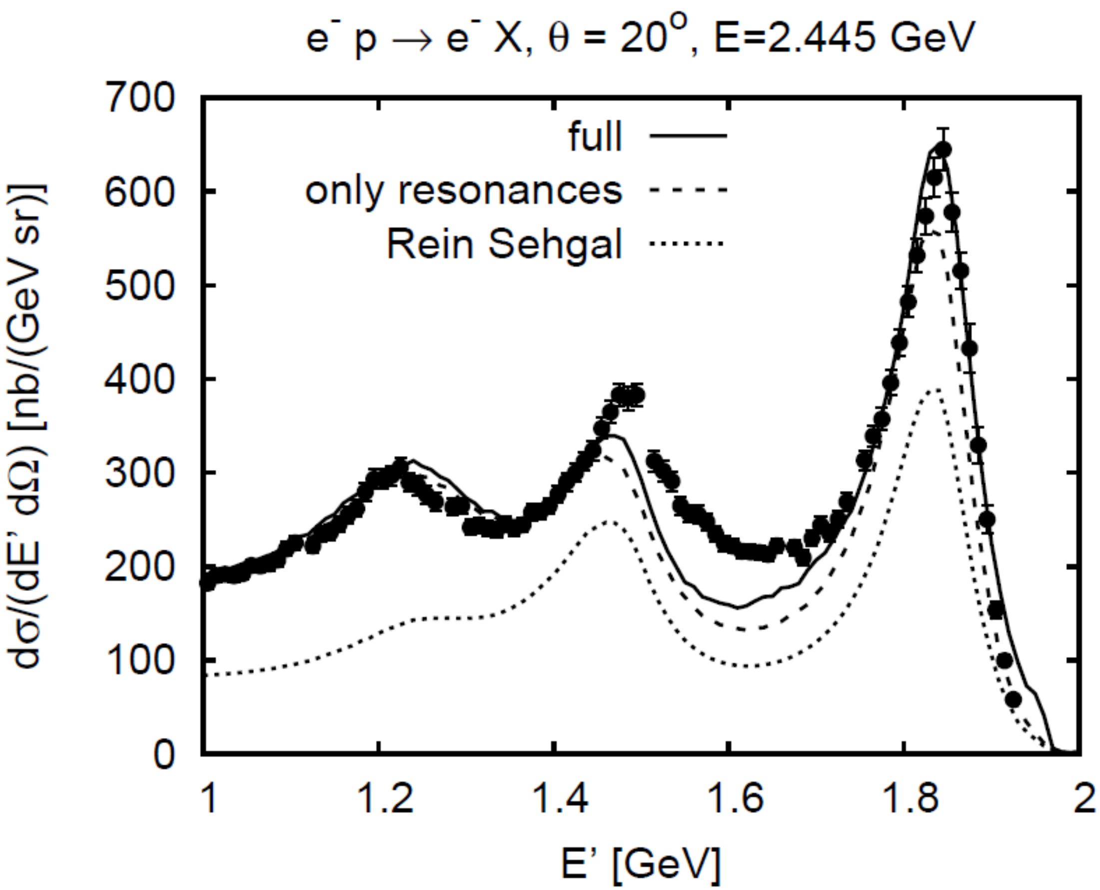
Tiator et al., EPJ Special Topics 198 (2011)



1π production on the nucleon

- Resonance excitation in ν MC generators:

- Rein-Sehgal model: Rein-Sehgal, Ann. Phys. 133 (1981) 79.
- Helicity amplitudes for 18 baryon resonances; relativistic quark model
- Poor description of π electroproduction data on p



Leitner et al., POS NUFACT08

Weak Resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p') \left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu) \right)\gamma_5 \right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu \right] u(p)$$

- Axial form factors

$C_5^A(0) = \sqrt{\frac{2}{3}} g_{\Delta N\pi}$ $\leftarrow$ off diagonal Goldberger-Treiman relation

$$\mathcal{L}_{\Delta N\pi} = -\frac{g_{\Delta N\pi}}{f_\pi}\bar{\Delta}_\mu(\partial^\mu\vec{\pi})\vec{T}^\dagger N \qquad g_{\Delta N\pi} \Leftrightarrow \Gamma(N^* \to N\pi)$$

$$C_5^A = C_5^A(0)\left(1 + \frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$

- Constraints from ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$

Weak Resonance excitation

- $\Delta(1232)$ $J^P=3/2^+$

$$J_\alpha = \bar{u}^\mu(p')\left[\left(\frac{C_3^V}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^V}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\alpha p'_\mu) + \frac{C_5^V}{M_N^2}(g_{\alpha\mu}q\cdot p - q_\alpha p_\mu)\right)\gamma_5\right.$$
$$\left. + \frac{C_3^A}{M_N}(g_{\alpha\mu}\not{q} - q_\alpha\gamma_\mu) + \frac{C_4^A}{M_N^2}(g_{\alpha\mu}q\cdot p' - q_\beta p'_\mu) + C_5^A g_{\alpha\mu} + \frac{C_6^A}{M_N^2}q_\alpha q_\mu\right]u(p)$$

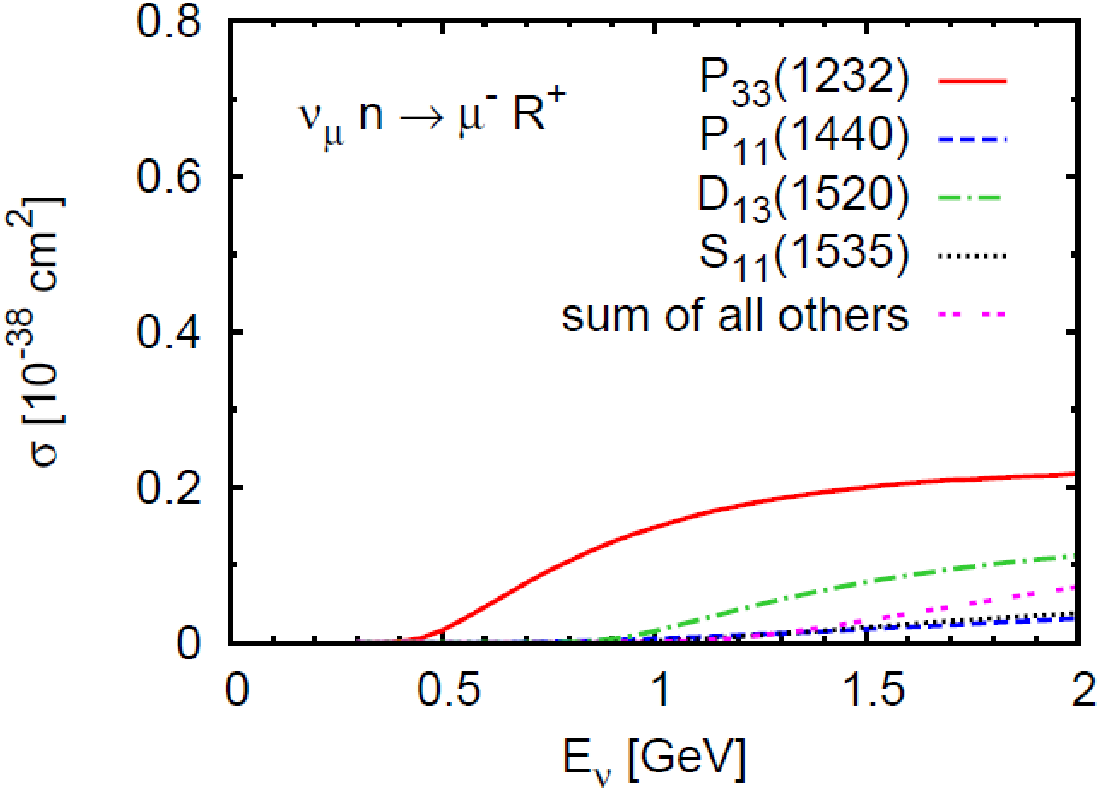
- Axial form factors

$$C_6^A = C_5^A\,\frac{M^2}{m_\pi^2+Q^2} \leftarrow \text{PCAC}$$

$$C_4^A = -\frac{1}{4}C_5^A \qquad C_3^A = 0 \leftarrow \text{Adler model}$$

  - ANL and BNL data do not allow to extract $C^A_{3,4}$: consistent with zero
    Hernandez et al., PRD81(2010)

Inclusive resonance production



T. Leitner, O. Buss, LAR, U. Mosel, PRC 79 (2009)
T. Leitner, PhD Thesis, 2009

- At E_ν = 2 GeV, CCN*(1520)/CCΔ $\sim$ 0.5, CCN*(1440,1535)/CCΔ $\sim$ 0.22
- N*(1520) is important for $\nu_l\, N \to l\, N'\, \pi$

Weak Resonance excitation

- Baryon resonances contribute to:
  - the inclusive $\nu_l \, N \to l \, X$ cross section
  - several exclusive channels: $\nu_l \, N \to l \, N' \, \pi$

$$\nu_l \, N \to l \, N' \, \gamma$$

$$\nu_l \, N \to l \, N' \, \eta$$

$$\nu_l \, N \to l \, \Lambda(\Sigma) \, \bar{K}$$

  - At $E_\nu \sim 1$ GeV (MiniBooNE, SciBooNE, T2K) Δ(1232) is dominant
  - At E_ν>1 GeV (MINOS, NOvA, DUNE) N* become also important

Weak meson production

$$\nu_l\, N \to l\, \pi\, N'$$

- CC: $\nu_\mu\, p \to \mu^-\, p\, \pi^+ , \quad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^-$

  $\nu_\mu\, n \to \mu^-\, p\, \pi^0 , \quad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0$

  $\nu_\mu\, n \to \mu^-\, n\, \pi^+ , \quad \overline{\nu}_\mu\, n \to \mu^+\, n\, \pi^-$

  - source of CCQE-like events (in nuclei)
  - needs to be subtracted for a good E_ν reconstruction

- NC: $\nu_\mu\, p \to \nu_\mu\, p\, \pi^0 , \quad \overline{\nu}_\mu\, p \to \overline{\nu}_\mu\, p\, \pi^0$

  $\nu_\mu\, p \to \nu_\mu\, n\, \pi^+ , \quad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$

  $\nu_\mu\, n \to \nu_\mu\, n\, \pi^0 , \quad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, n\, \pi^0$

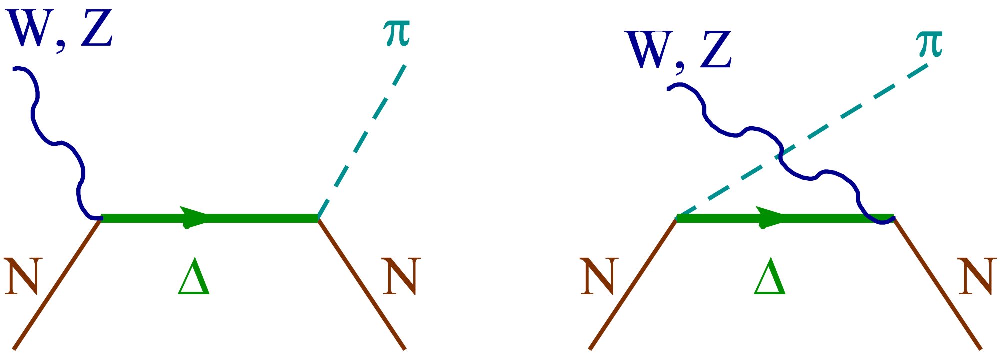
  $\nu_\mu\, n \to \nu_\mu\, p\, \pi^- , \quad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, p\, \pi^-$

  - e-like background to $\nu_\mu \to \nu_e$ (T2K)

1π production on the nucleon

$$\nu_l \, N \rightarrow l \, \pi \, N'$$

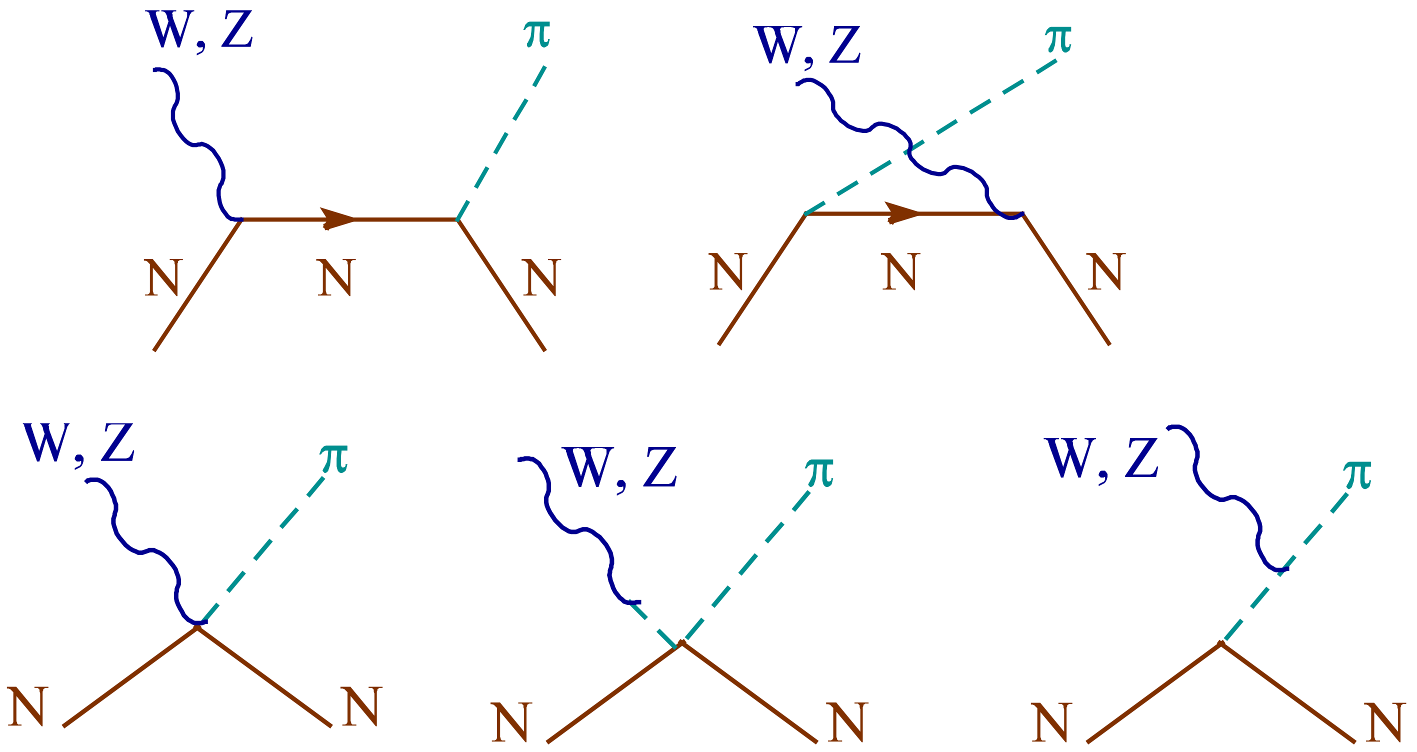
- Δ (1232) excitation:



1π production on the nucleon

$$\nu_l \, N \rightarrow l \, \pi \, N'$$

- From Chiral symmetry:



1π production on the nucleon

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\Delta}$
- $$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$
- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$

- Graczyk et al., PRD 80 (2009)
  - Deuteron effects
  - Non-resonant background absent
  - $C^A_5(0) = 1.19 \pm 0.08$, $M_{A\Delta} = 0.94 \pm 0.03$ GeV

- Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - $C^A_5(0) = 1.00 \pm 0.11$, $M_{A\Delta} = 0.93 \pm 0.07$ GeV
  - 20% reduction of the GT relation $C_5^A(0) = 1.15 - 1.2$

1π production on the nucleon

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\Delta}$
- $C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$
- From ANL and BNL data on $\nu_\mu \, d \rightarrow \mu^- \, \pi^+ \, p \, n$
- Graczyk et al., PRD 90 (2014)
  - Deuteron effects
  - Non-resonant background present
  - N-Δ e.m. form factors fitted to F_2 data (e-p scattering)
  - $C_5^A(0) = 1.10^{+0.15}_{-0.14}\,,\; M_{A\Delta} = 0.85^{+0.09}_{-0.08}$ GeV

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

$$\sum_M \langle M|T|F\rangle^* \langle M|T|I\rangle = -2\mathrm{Im}\langle F|T|I\rangle \in \mathbb{R}$$

- For W N $\rightarrow$ π N
  - assuming that |M⟩ = |F⟩ = |π N⟩
  - schematically:

$$\langle \pi N|T|\pi N\rangle^* \langle \pi N|T|W N\rangle = -2\mathrm{Im}\langle \pi N|T|W N\rangle \in \mathbb{R}$$

$$\langle \pi N|T|\pi N\rangle \approx \langle \pi N|T_{\mathrm{strong}}|\pi N\rangle$$

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

- For W N $\to \pi$ N

$$\sum_\rho \sum_L \frac{2L+1}{2J+1} (L,1/2,J;0,-\lambda')(L,1/2,J;0,-\rho) \langle J,M;L,1/2|T_{\rm str}|J,M;L,1/2\rangle^* \langle J,M;0,\rho|T|0,0;r,\lambda\rangle \in \mathbb{R}.$$

- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

writing $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction

  Olsson, NPB78 (1974)
  Carrasco, Oset, NPA536 (1992)
  Gil, Nieves, Oset, NPA627 (1997)

1π production on the nucleon

- Watson's theorem
  - Unitarity
  - Time reversal invariance

- For W N $\rightarrow$ π N

$$\sum_\rho \sum_L \frac{2L+1}{2J+1}(L,1/2,J;0,-\lambda')(L,1/2,J;0,-\rho)\langle J,M;L,1/2|T_{\rm str}|J,M;L,1/2\rangle^* \langle J,M;0,\rho|T|0,0;r,\lambda\rangle \in \mathbb{R}$$

- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

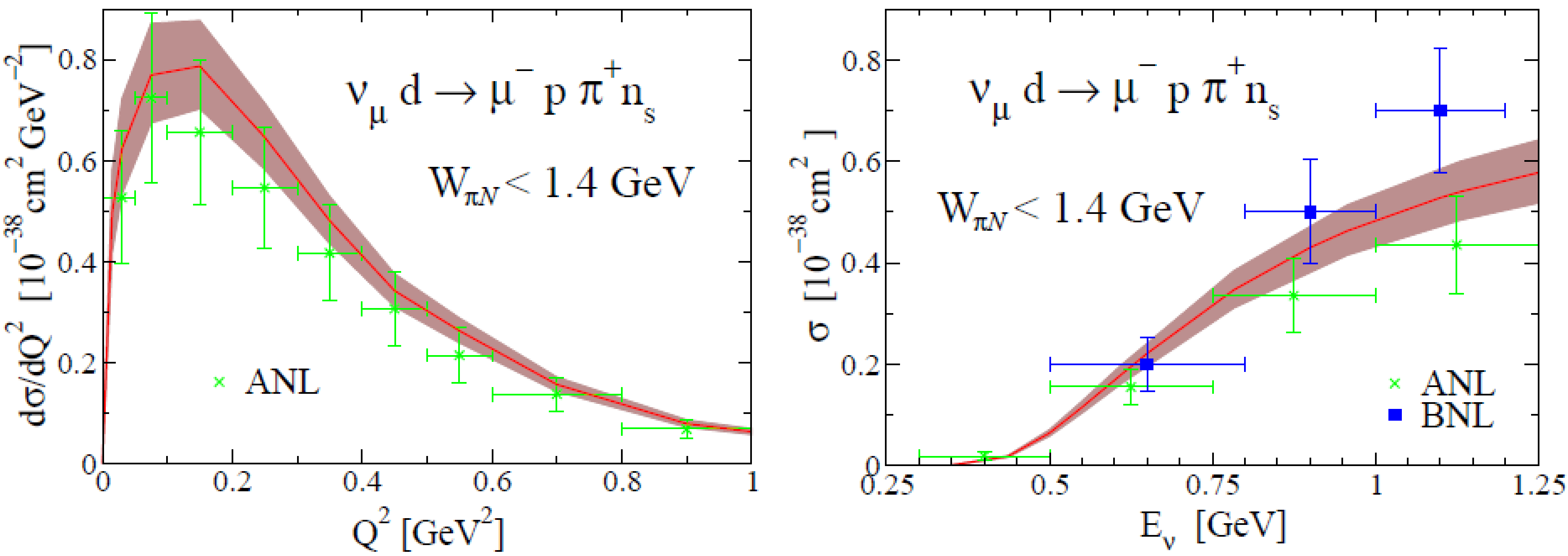
$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

writing $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction
- In weak production two phases δ_V and δ_A are needed

1π production on the nucleon

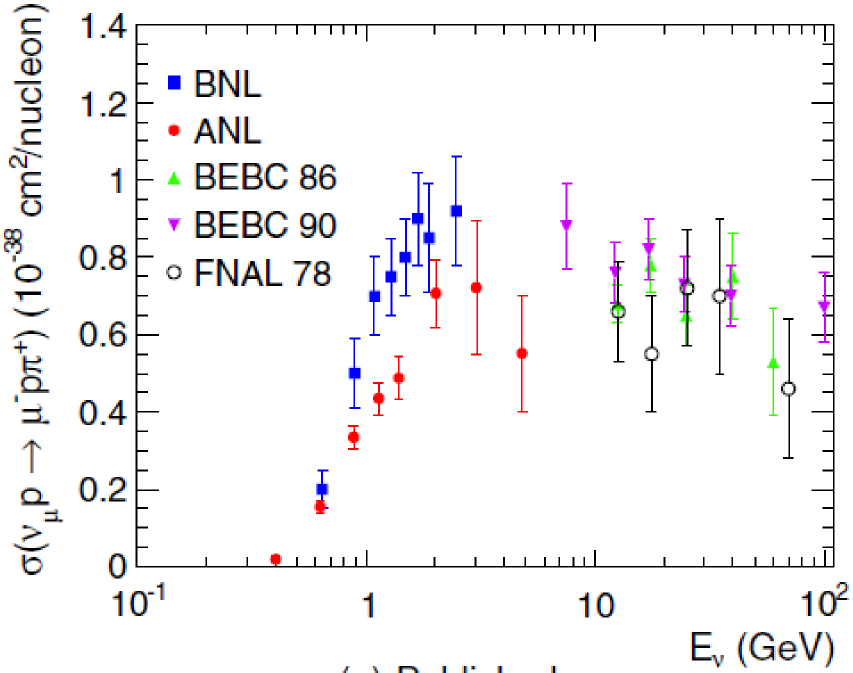
- Fit to ANL and BNL data with W < 1.4 GeV



- $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\,\Delta} = 0.95 \pm 0.06$ GeV
- Consistent with the off-diagonal GT relation $C_5^A(0) = 1.15 - 1.2$

1π production on the nucleon

- Discrepancies between ANL and BNL datasets

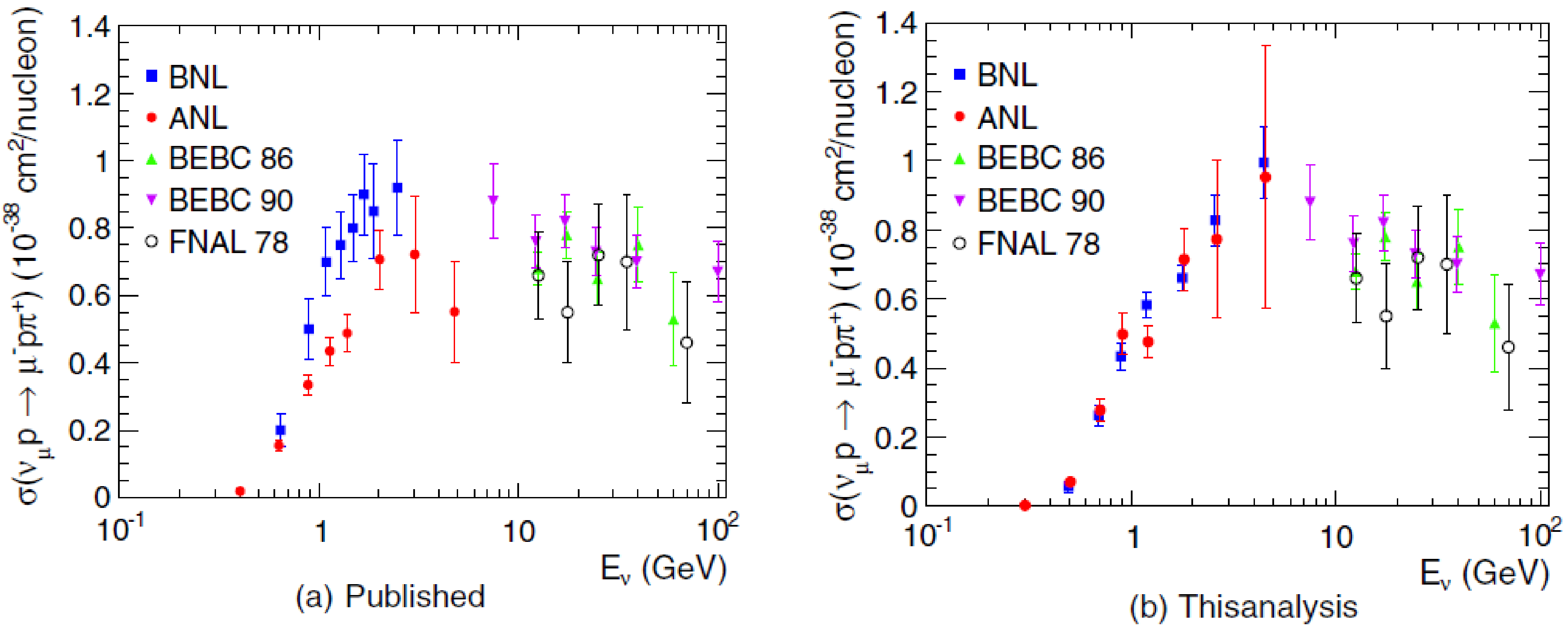


(a) Published

- Reanalysis by Wilkinson et al., PRD90 (2014)
  - Flux normalization independent ratios: $CC1\pi^+$/ CCQE
  - Good agreement for ratios
  - Better understood CCQE cross section used to obtain the $CC1\pi^+$ one

1π production on the nucleon

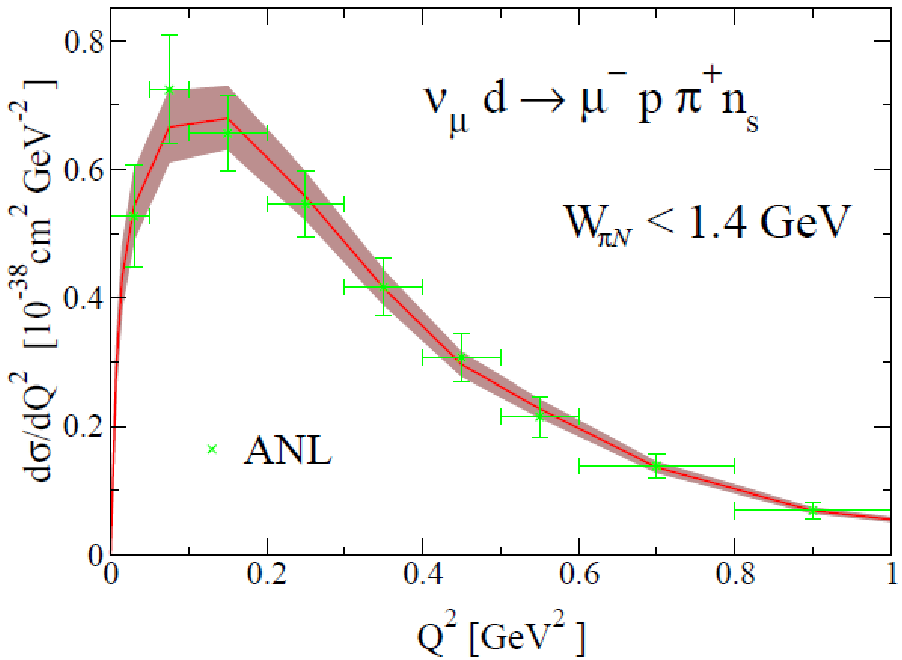
- Discrepancies between ANL and BNL datasets

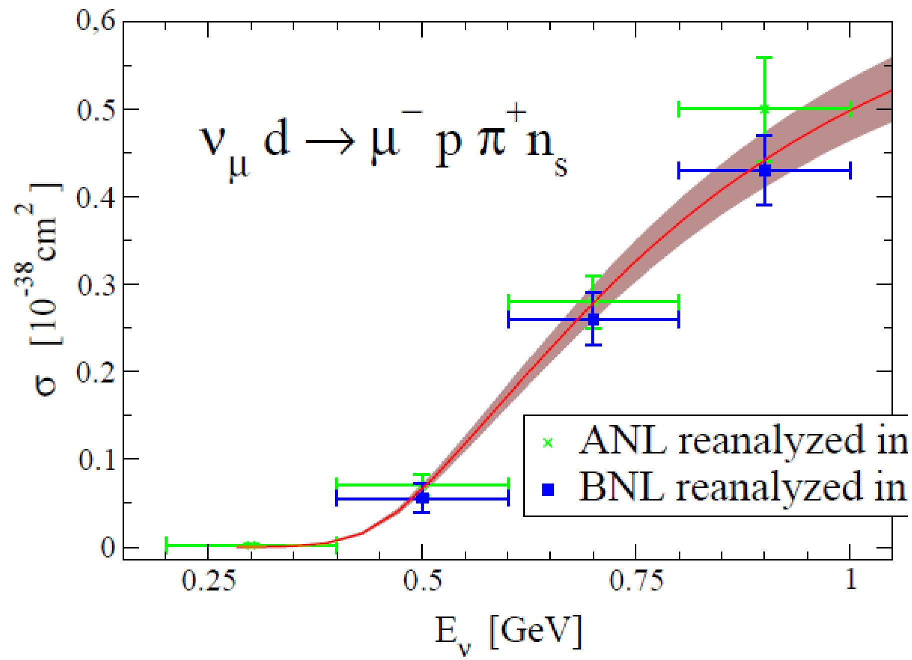


- Reanalysis by Wilkinson et al., PRD90 (2014)
  - Flux normalization independent ratios: CC1π^+/ CCQE
  - Good agreement for ratios
  - Better understood CCQE cross section used to obtain the CC1π^+ one

1π production on the nucleon

- New fit to ANL and BNL data
  - Shape from original ANL $d\sigma/dQ^2$
  - Integrated σ from Wilkinson et al.: points with E_ν < 1 GeV





- $C^A_5(0)$ =1.14 $\pm$ 0.07, $M_{A\,\Delta}$ = 0.96 $\pm$ 0.07 GeV
- $C^A_5(0)$ =1.12 $\pm$ 0.11, $M_{A\,\Delta}$ = 0.95 $\pm$ 0.06 GeV $\leftarrow$ former fit
- $C^A_5(0)$ =1.15 – 1.20 $\leftarrow$ GT

1π production on the nucleon

- Fits to ANL and BNL data
  - $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\Delta} = 0.95 \pm 0.06$ GeV $\leftarrow$ original data (A)
  - $C^A_5(0) = 1.14 \pm 0.07$, $M_{A\Delta} = 0.96 \pm 0.07$ GeV $\leftarrow$ reanalysis (B)
- Relative error: $r_A = 10\ \%$ $\Rightarrow$ $r_B = 6\ \%$
- Is this precision enough?
- Should ν-N cross sections be measured again?

NCγ

- Photon emission in NC interactions:
  - on nucleons $\nu(\bar{\nu})\,N \to \nu(\bar{\nu})\,\gamma\,N$
  - on nuclei $\nu(\bar{\nu})\,A \to \nu(\bar{\nu})\,\gamma\,X$ $\leftarrow$ incoherent

    $\nu(\bar{\nu})\,A \to \nu(\bar{\nu})\,\gamma\,A$ $\leftarrow$ coherent

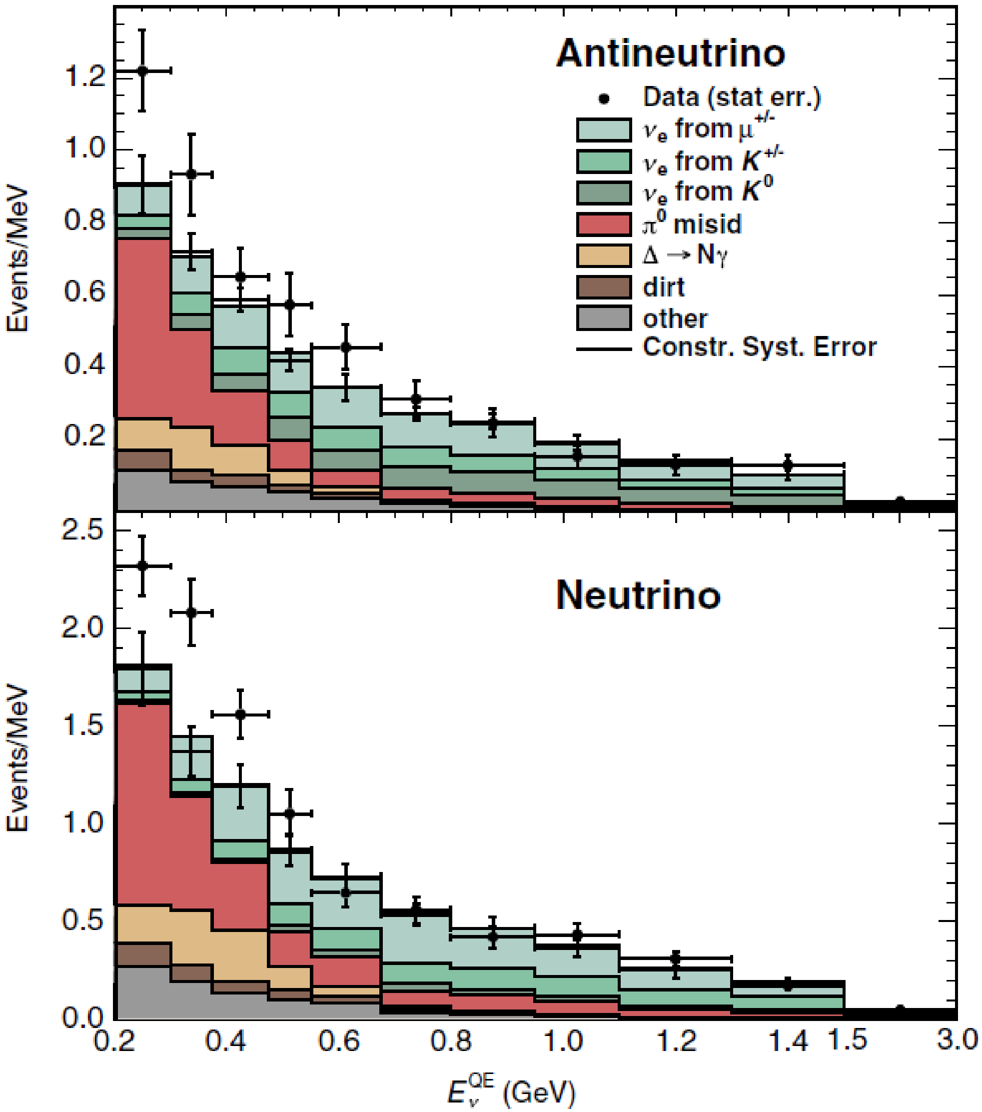
  - Small cross section (weak & e.m.)

  but

  - Important background for $\nu_\mu \to \nu_e$ studies (θ_{13} , δ) if γ is misidentified as $e^\pm$ from CCQE $\nu_e\,n \to e^-\,p$ or $\bar{\nu}_e\,p \to e^+\,n$

NCγ

- Photon emission in NC interactions:



$\gamma\, N$

$\gamma\, X$ $\leftarrow$ incoherent

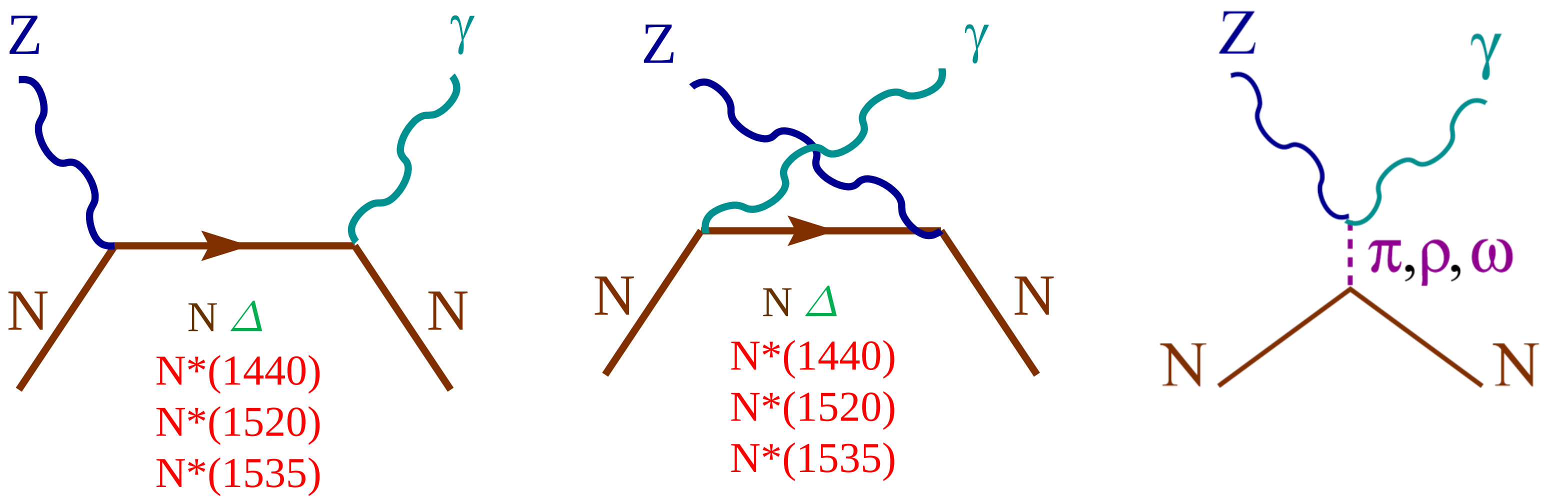
$\gamma\, A$ $\leftarrow$ coherent

studies (θ_{13} , δ) if γ is misidentified

r $\bar{\nu}_e\, p \to e^+\, n$

NCγ

- Feynman diagrams:

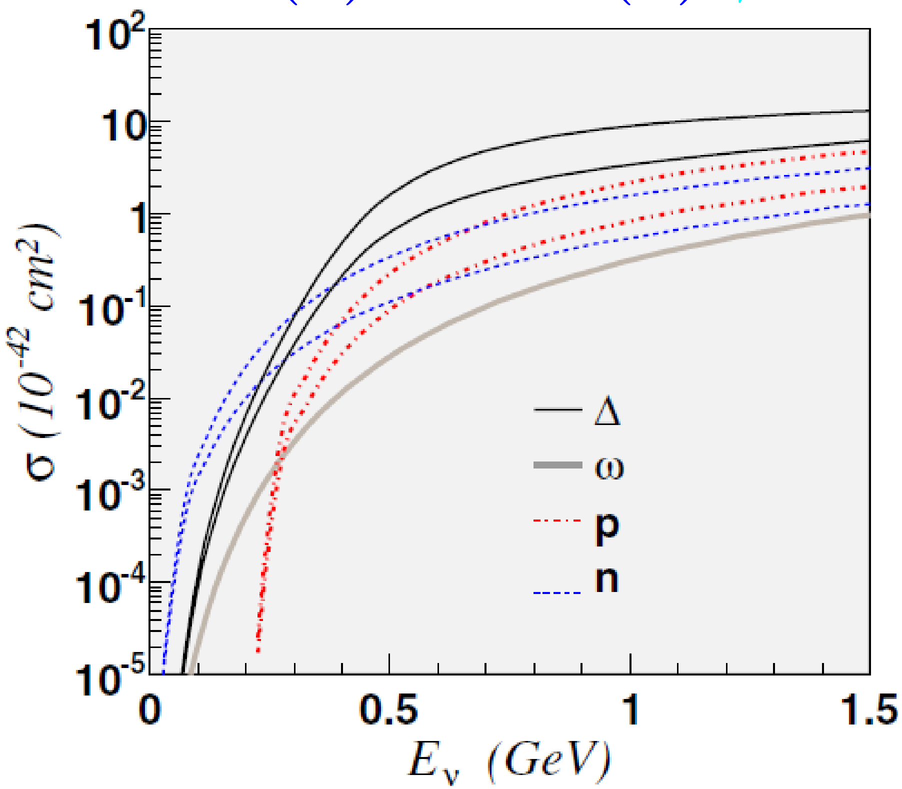


R. Hill, PRD 81 (2010)
Zhang & Serot, PRC 86 (2012)
Wang, LAR, Nieves, PRC 89 (2014)

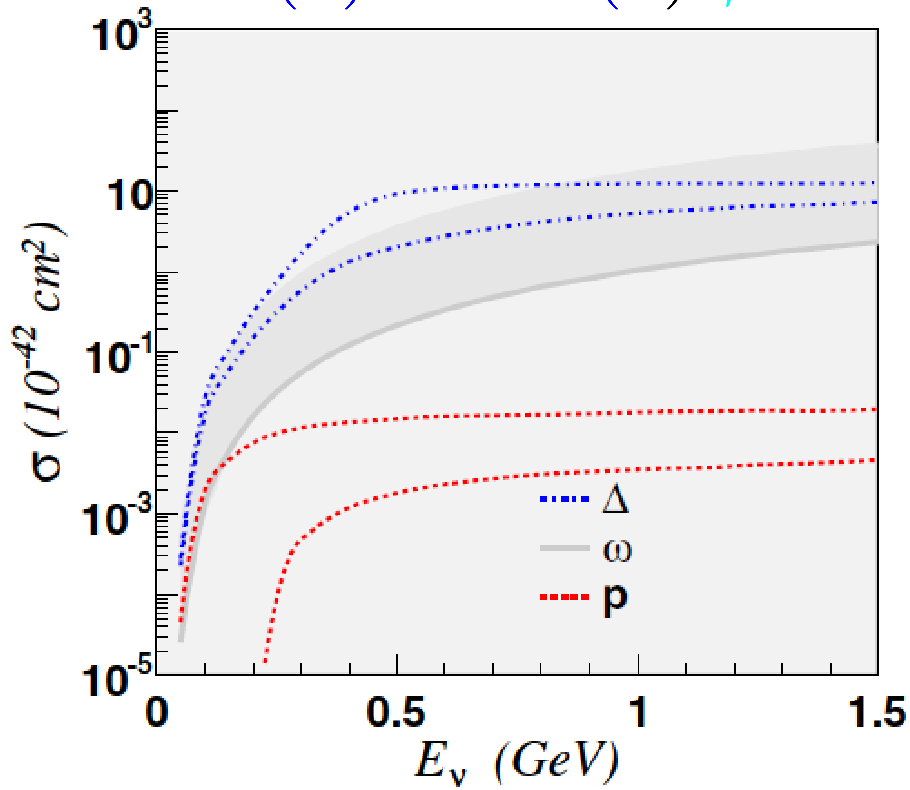
NCγ

- R. Hill, PRD 81 (2010)

$\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$



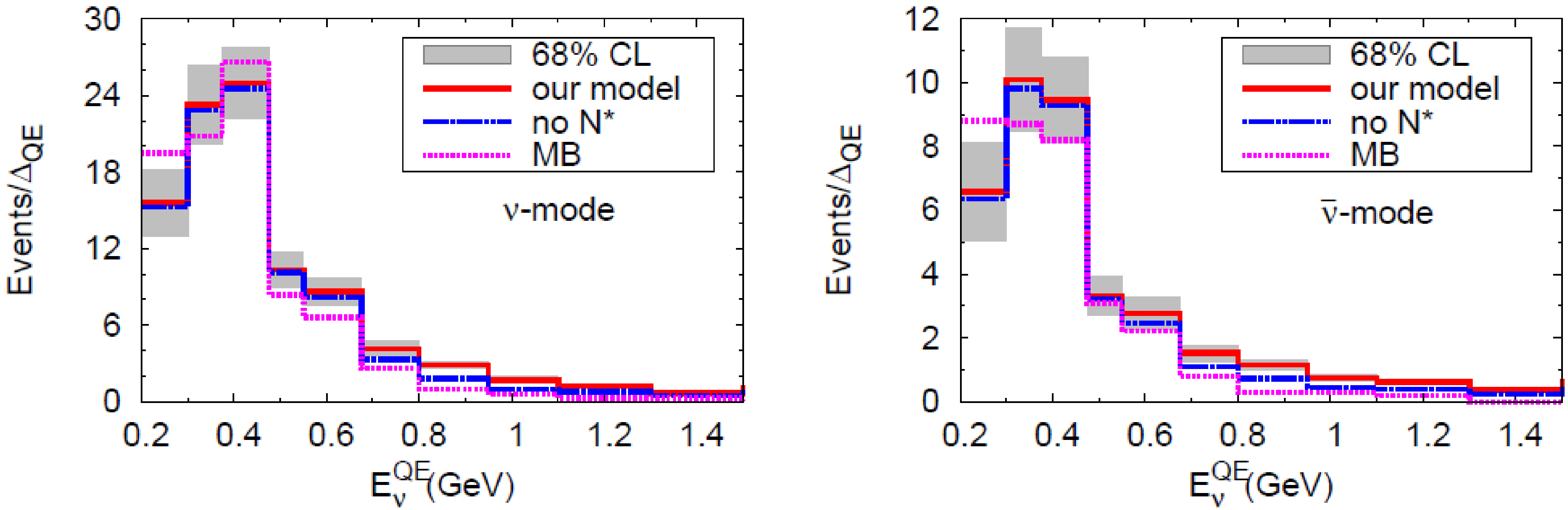
$\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, A$



- The ω exchage contribution is very small
- J. Rosner, PRD 91 (2015) ⇒ ¼ smaller
  - Z-ω-γ vertex calibrated by $\tau \to \nu_\tau$ a_1 and $f_1 \to \rho\, \gamma$ decays

NCγ events at MiniBooNE

- Comparison to the MiniBooNE estimate
  - Resonance model (R&S) tuned to π production data
  - Only R -> N γ



E. Wang, LAR, J. Nieves, PLB 740 (2015)

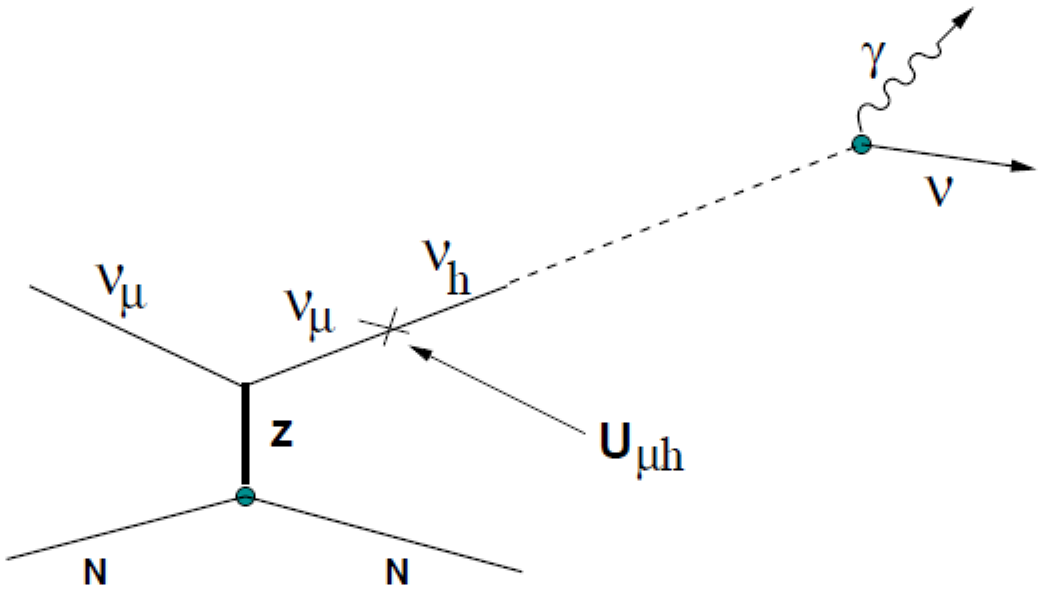
- NCγ : insufficient to explain the excess of e-like events at MiniBooNE
- Same conclusion as Zhang, Serot, PLB 719 (2013)

e-like events at MiniBooNE

- Oscillations: not explained by 1, 2, 3 families of sterile neutrinos

  J. Conrad et al., Adv. High Energy Phys. 2013, C. Giunti et al., PRD88 (2013)

- Heavy neutrinos S. Gninenko, PRL 103 (2009), M. Masip et al, JHEP 1301 (2013)
  - $m_h \approx 50$ MeV, $|U_{\mu h}|^2 \approx 10^{-3}$- 10^{-2}, $\tau_h < 10^{-9}$ s



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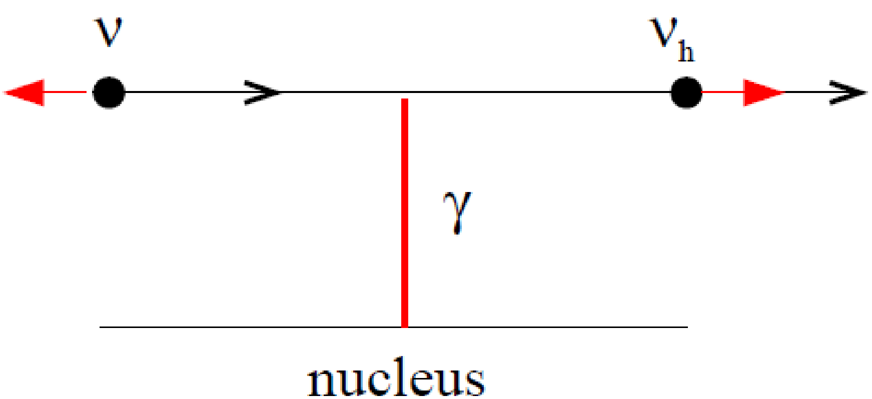
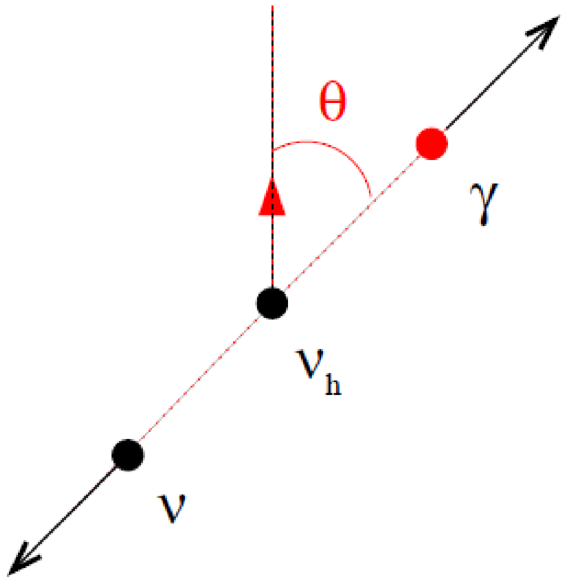
  - m_h= 50 MeV, τ_h = 5×10^{-9} s, BR($\nu_h \to \nu_\mu \gamma$)= 0.01





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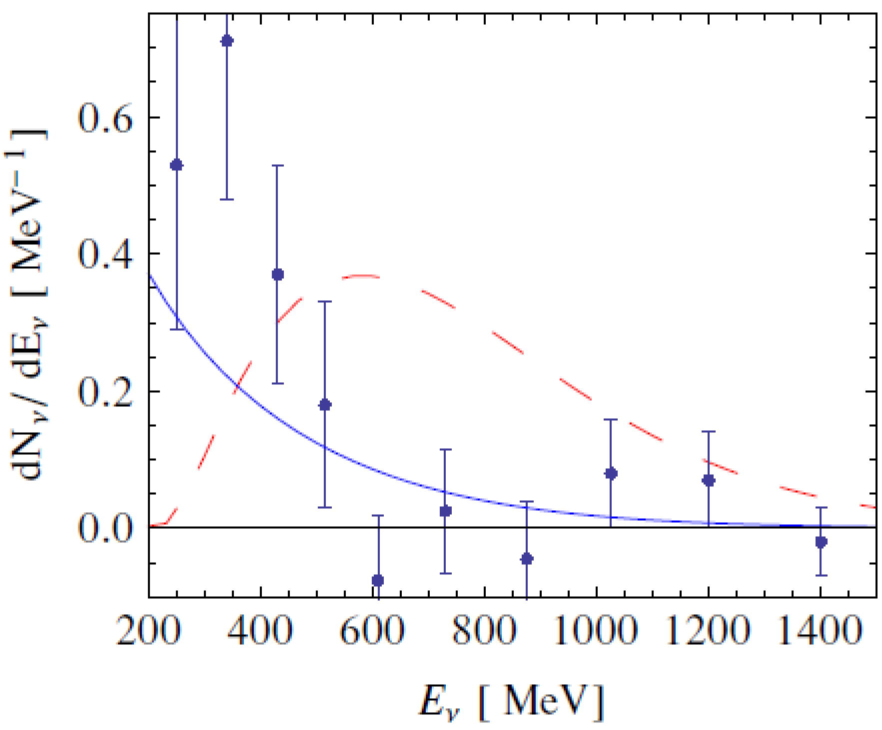
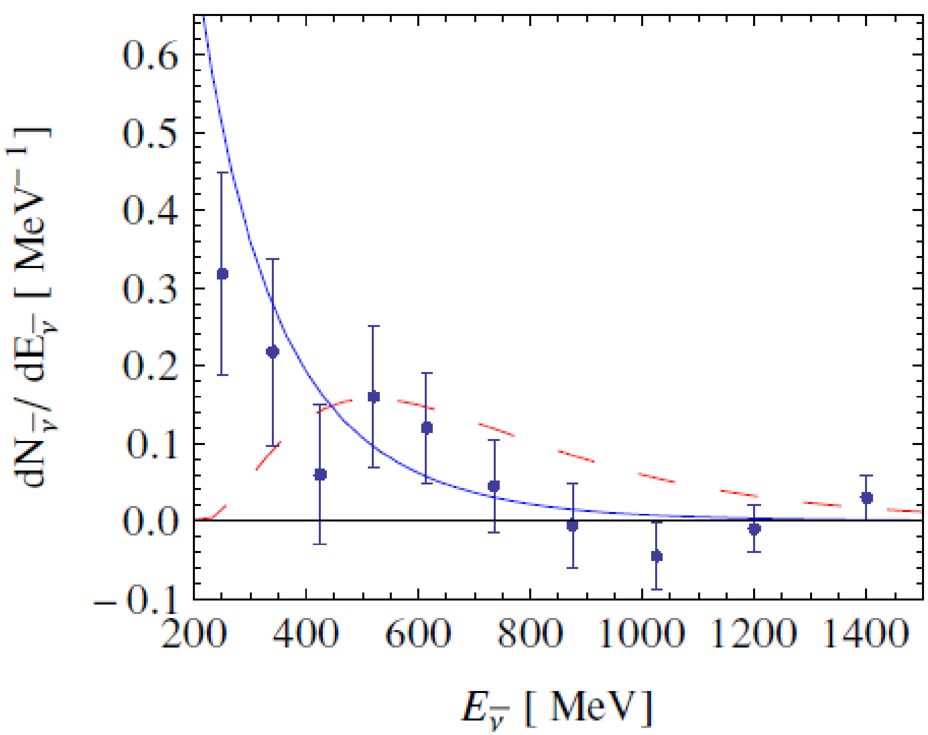
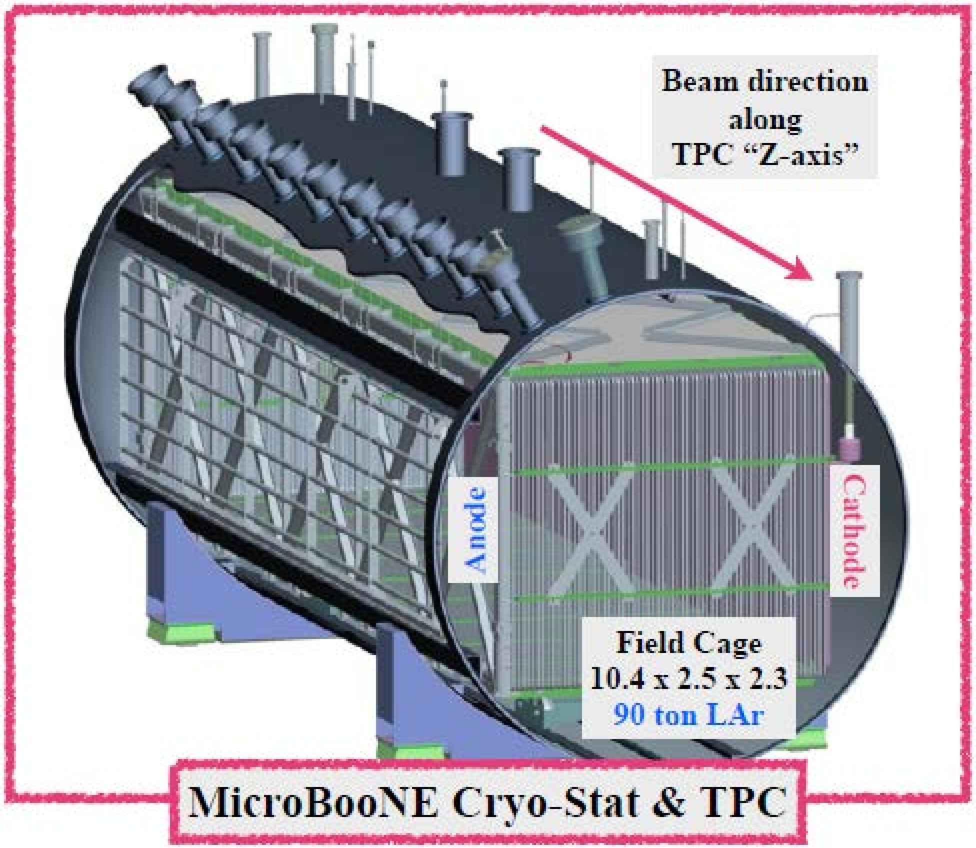




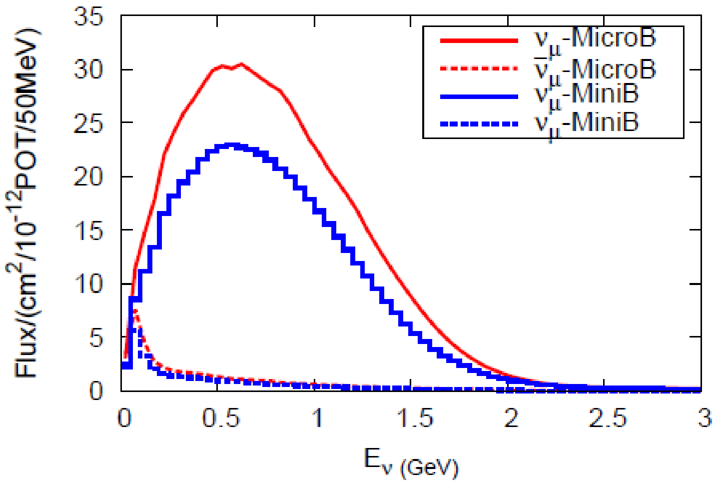
MicroBooNE

- 170 ton LArTPC
- Located along the Booster neutrino beam line
- Distinguishes electrons from photons



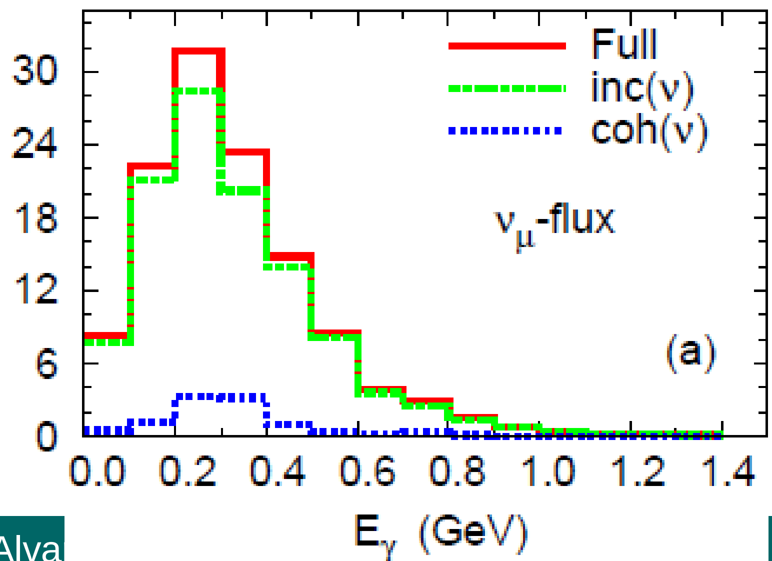
MicroBooNE

- 6.6×10^{20} POT
- Active mass = 86.6 tons
- Flux prediction:

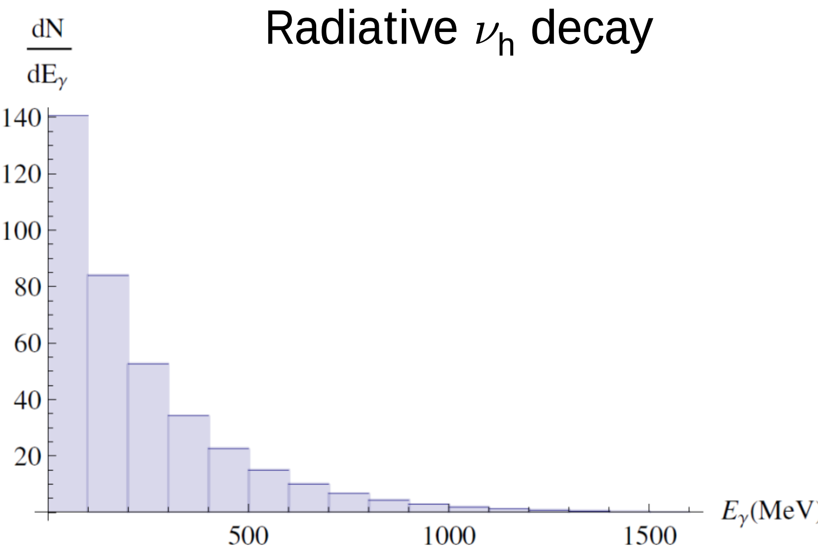


- LAR, E. Saul, E. Wang, preliminary

Standard



Radiative ν_h decay



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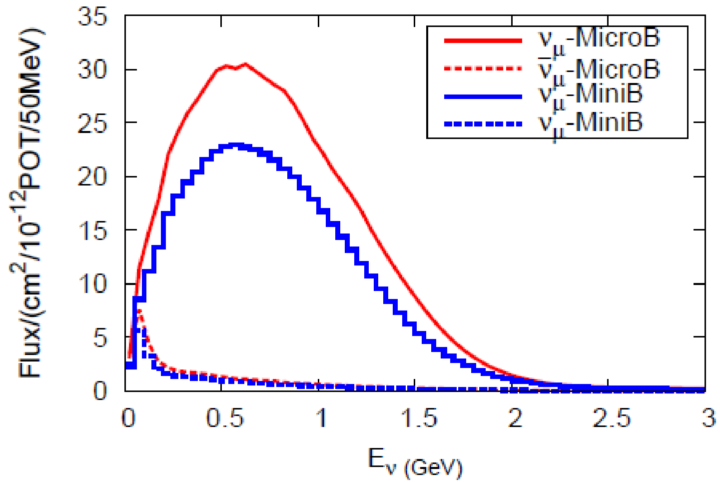

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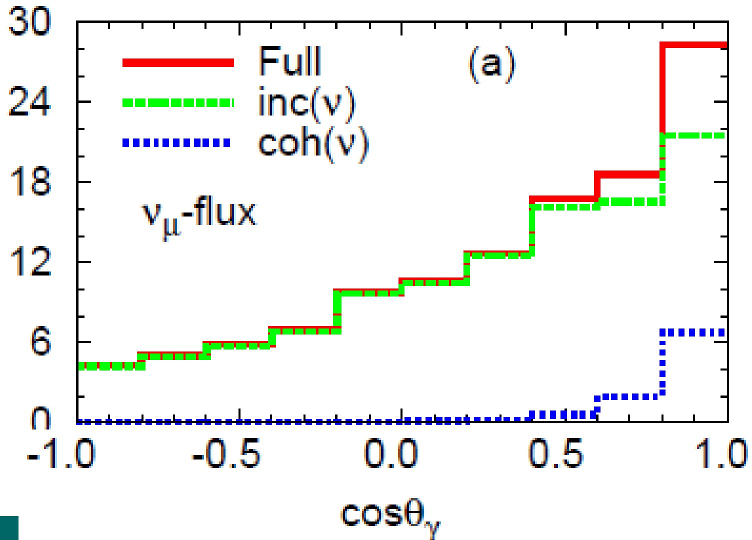

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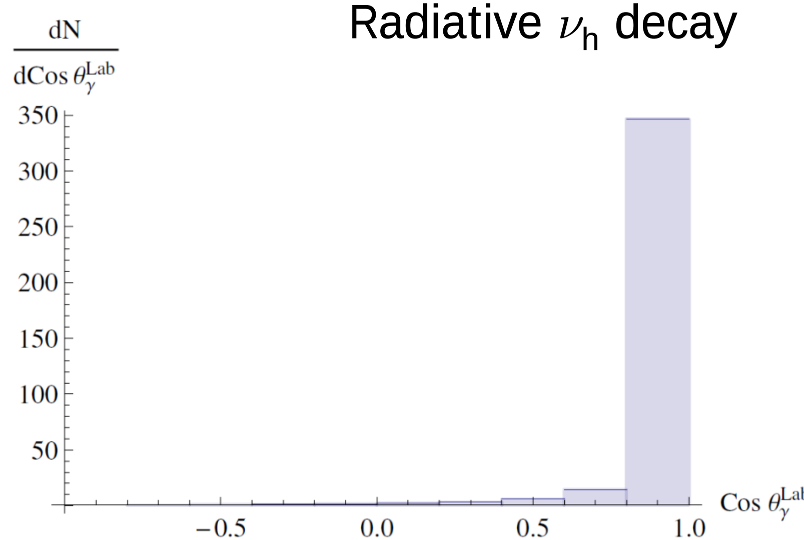
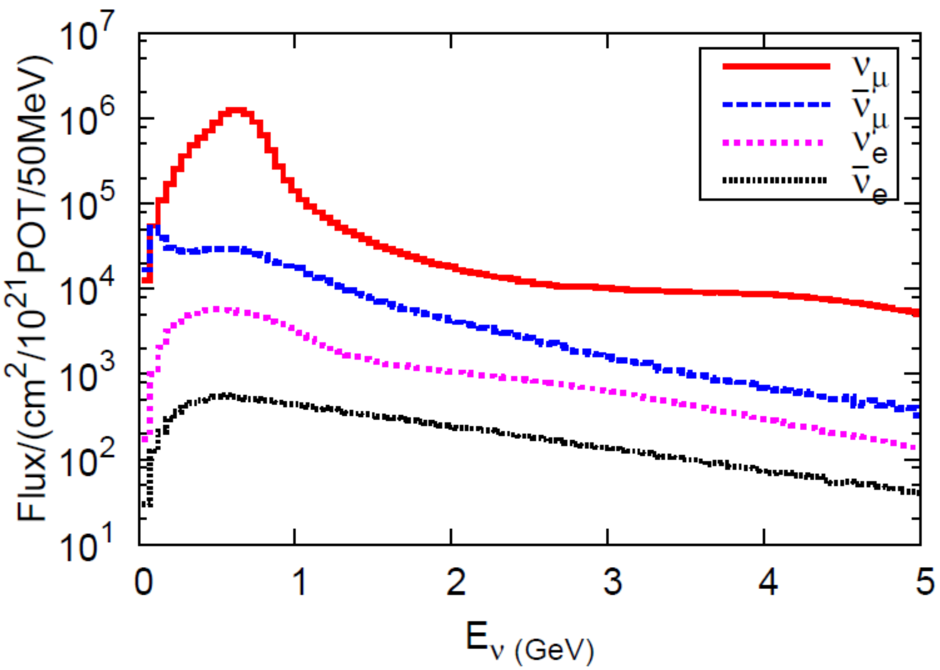
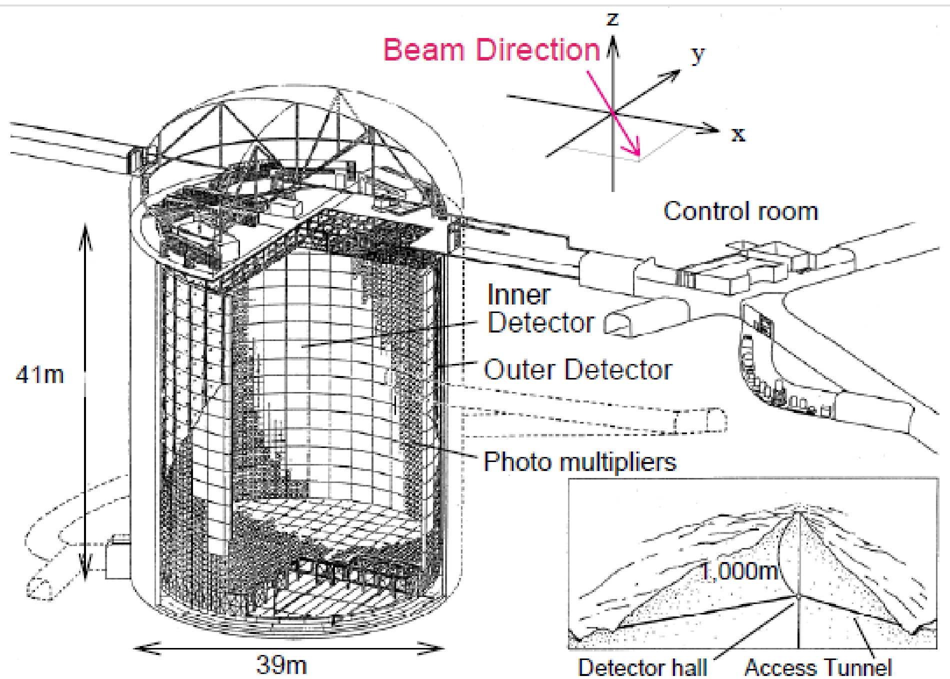


NCγ events at T2K

- Target: H_2O — Abe et al, PRL 112 (2014) 061802
- Mass: 22.5 ktons
- POT: 6.57 x 10^{20} (ν mode)
- Fluxes: SK250 100 MeV < E_ν < 3 GeV — Abe et al, PRD 87 (2013)





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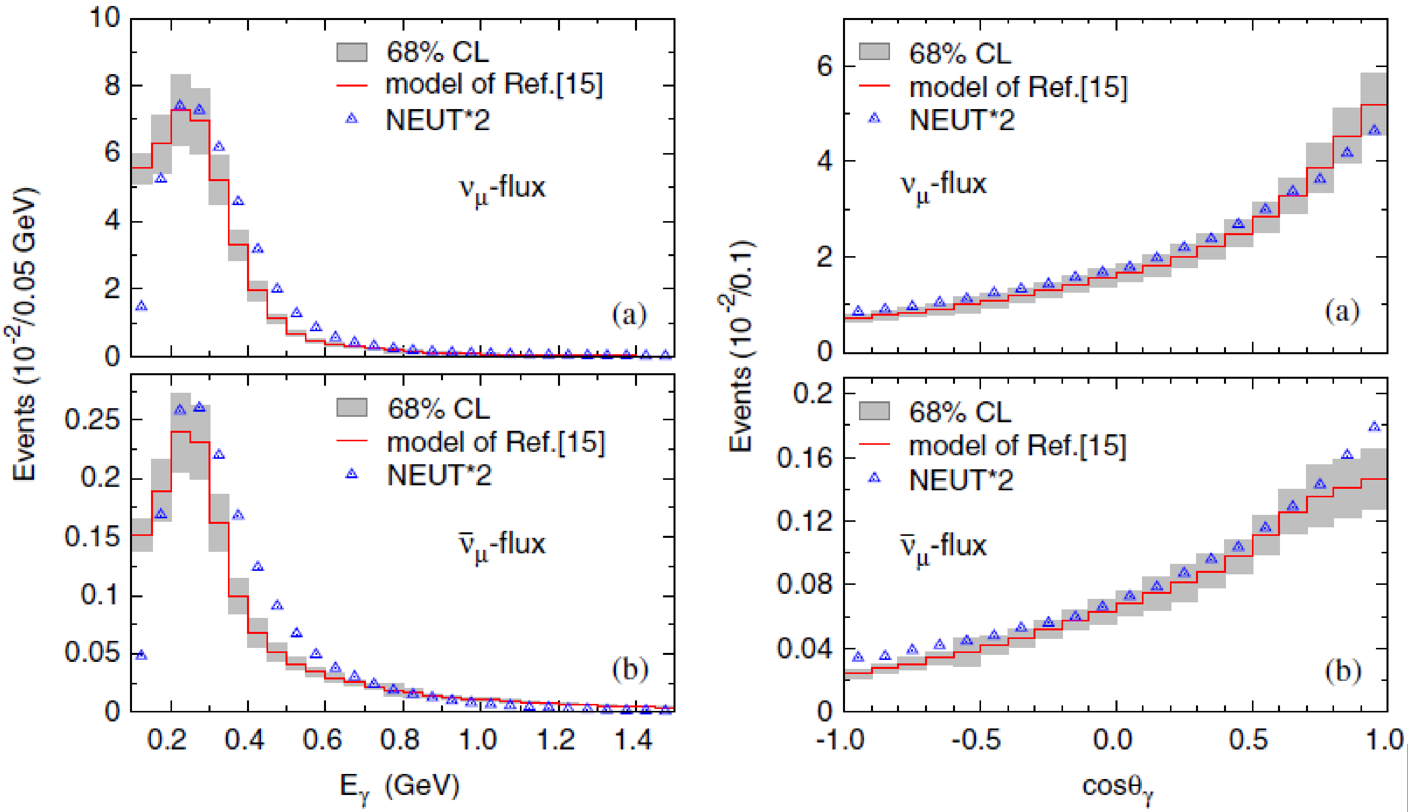

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$$N_{tot} = 0.427 \pm 0.050 \quad \text{vs} \quad N_{NEUT} = 0.217$$

- Does this discrepancy matter?
  - For θ_{13}?: probably not.

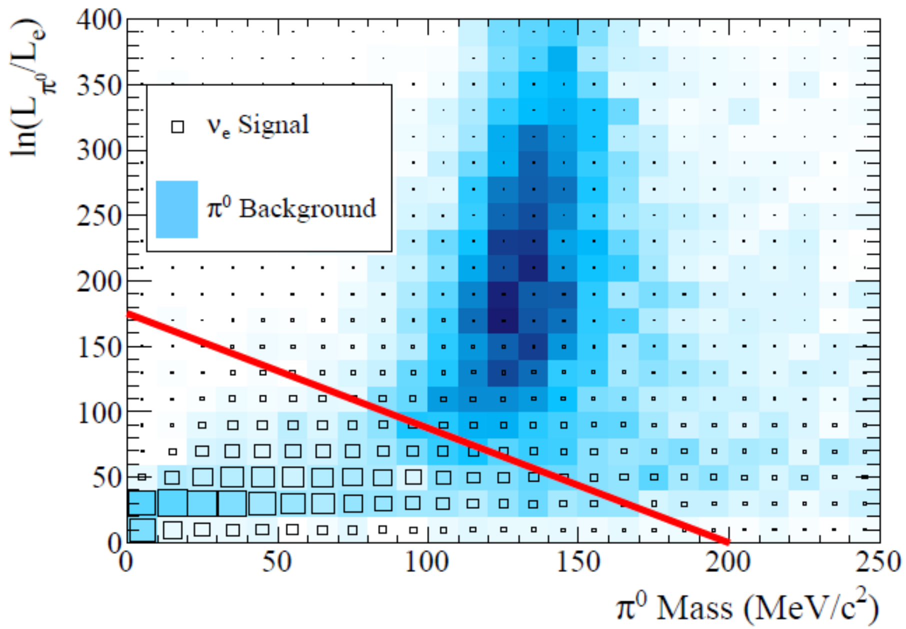
NCγ events at T2K

- **Target**: H_2O
- **Mass**: 22.5 ktor
- **POT**: 6.57 x 10
- **Fluxes**: SK250

- **Comparison** to

$N_{tot} = 0.427$

Abe et al, PRL 112 (2014) 061802



37 (2013)

, PRD92 (2015)

- Does this **discrepancy** matter?
  - For θ_{13}?: probably not.
  - Better π^o rejection cut $\Rightarrow$ NCγ relatively more important
  - For CP violation searches? perhaps...

Weak meson production

- ΔS = 0 e.g. $\nu_l \, p(n) \rightarrow l^- \, K^+ \, \Sigma^+(\Lambda)$ Nakamura et al.,arXiv:1506.03403
- ΔS = 1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - Kaon:
    $$\begin{aligned} \nu_l \, p &\rightarrow l^- \, K^+ \, p \\ \nu_l \, n &\rightarrow l^- \, K^0 \, p \\ \nu_l \, n &\rightarrow l^- \, K^+ \, n \end{aligned}$$
    - Background for proton decay p $\rightarrow \nu$ K^+

Weak strangeness production

- ΔS = -1 :
  - Cabibbo suppressed but with lower thresholds than ΔS = 0
  - antiKaon: $$\begin{aligned} \bar{\nu}_l\, p &\rightarrow l^+\, K^-\, p \\ \bar{\nu}_l\, p &\rightarrow l^+\, \bar{K}^0\, n \\ \bar{\nu}_l\, n &\rightarrow l^+\, K^-\, n \end{aligned}$$
  - $\Sigma\,\pi$: $$\begin{aligned} \bar{\nu}_l\, p &\rightarrow l^+\, \Sigma^0\, \pi^0 \\ \bar{\nu}_l\, p &\rightarrow l^+\, \Sigma^+\, \pi^- \\ \bar{\nu}_l\, p &\rightarrow l^+\, \Sigma^-\, \pi^+ \end{aligned}$$
  - can proceed through the excitation of Λ or Σ resonances
    - in particular: Λ(1405)

Weak strangeness production

- $\bar{\nu}_l \, p \rightarrow l^+ \, \phi \, B$ Ren et al., PRC91 (2015)

$$\phi \, B = K^- \, p, \, \bar{K}^0 \, n, \, \pi^0 \, \Lambda, \, \pi^0 \, \Sigma^0, \, \eta \, \Lambda, \, \eta \, \Sigma^0, \, \pi^+ \, \Sigma^-, \, \pi^- \, \Sigma^+, \, K^+ \, \Xi^-, \, K^0 \, \Xi^0$$

- SU(3) symmetric chiral Lagrangian
- Physical hadron masses
- Couplings depend on V_{us} and D, F, f_π $\leftarrow$ fixed by semileptonic decays
- Global dipole form factor

$$F(q^2) = \left(1 - \frac{q^2}{M_F^2}\right)^{-2}$$ $M_F = 1 \pm 0.1$ GeV

- s-wave projection
- Unitarization in coupled channels

Weak strangeness production

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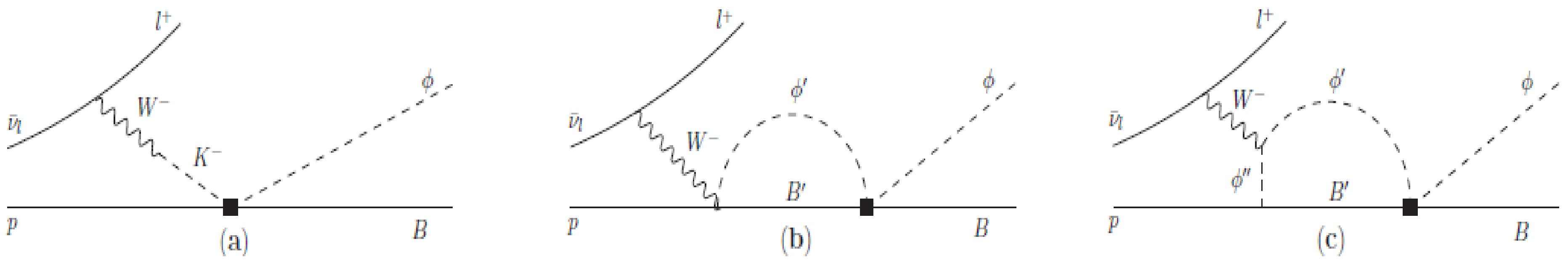
- Unitarization in coupled channels



- T: Solution of the Bethe-Salpeter eq. in coupled channels

$$T = V + VGT = [1 - VG]^{-1} V$$

- V: from leading order chiral Lagrangian
- Cut-off regularization of the loop functions with q_{max} = 630 MeV
- Oset, Ramos, NPA635 (1998)

Weak strangeness production

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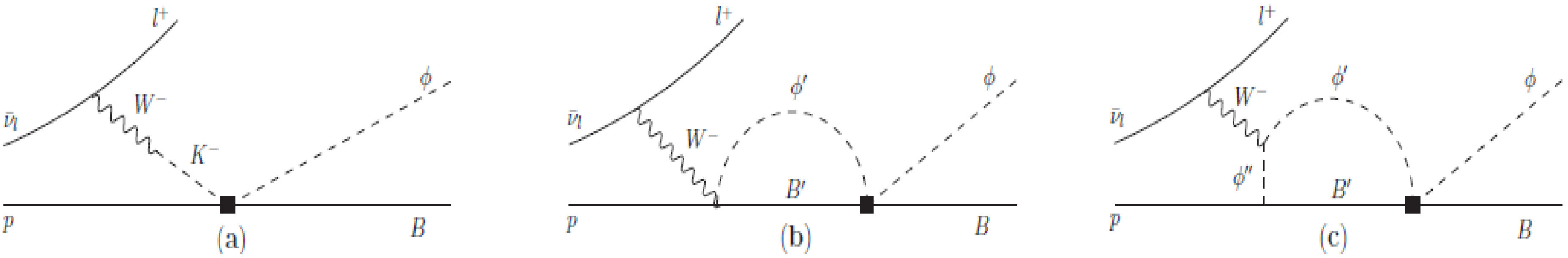
$$\phi\, B = K^- p,\ \bar{K}^0 n,\ \pi^0 \Lambda,\ \pi^0 \Sigma^0,\ \eta \Lambda,\ \eta \Sigma^0,\ \pi^+ \Sigma^-,\ \pi^- \Sigma^+,\ K^+ \Xi^-,\ K^0 \Xi^0$$

- Unitarization in coupled channels



- Λ(1405) dynamically generated
- Two poles: M$\approx$ 1385 MeV, $\Gamma \approx$ 150 MeV
  M$\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- Suggested by Dalitz et al.(60ies) and obtained in many theoretical studies

Oller, Meissner, PLB500(2001); Jido et al. NPA725(2003); Borasoy et al. PRC74(2006);
Geng, Oset, EPJA34(2007; Hyodo, Jido, Prog.Part.Nucl.Phys.67(2012);
Guo, Oller PRC87(2013); Roca, Oset PRC87(2013); Mai, Meissner, EPJA51(2015); ...

Weak strangeness production

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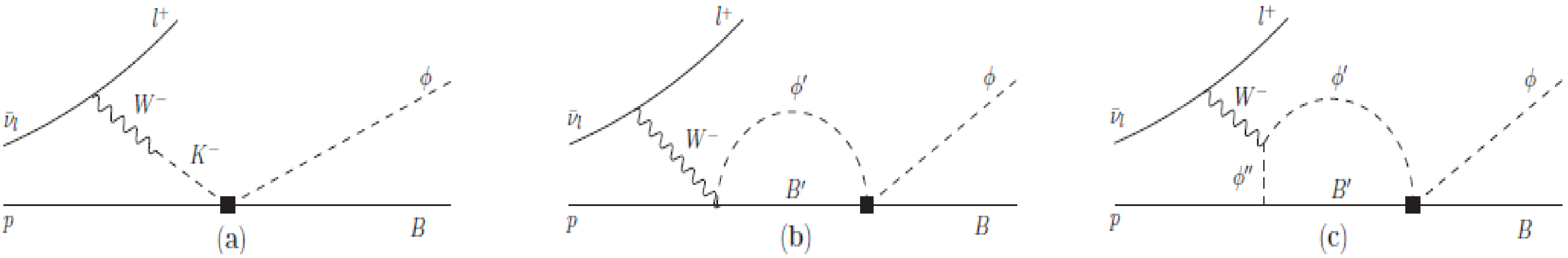
- Unitarization in coupled channels



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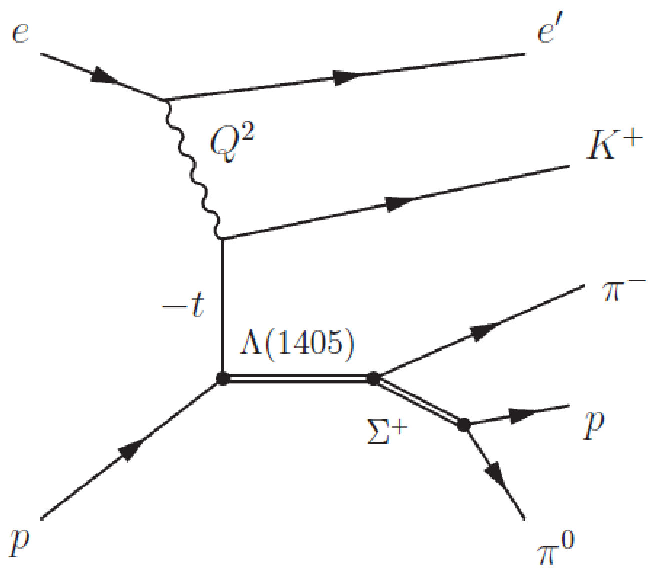
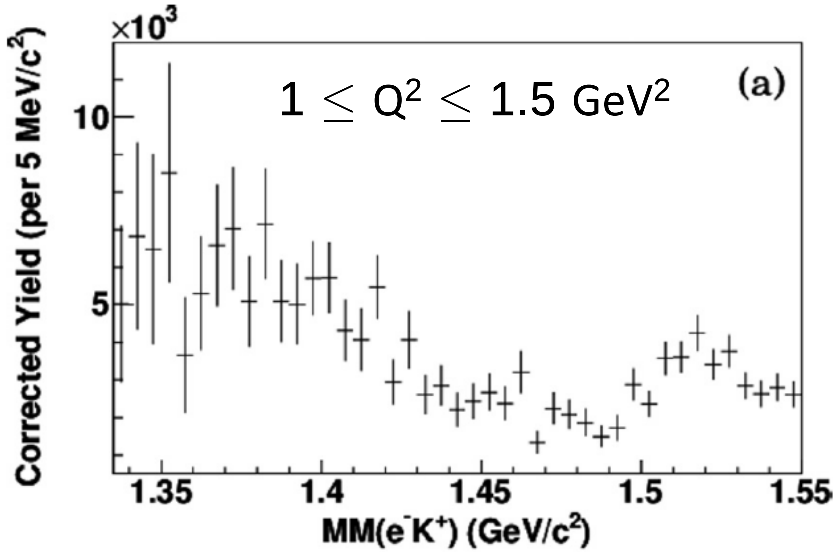
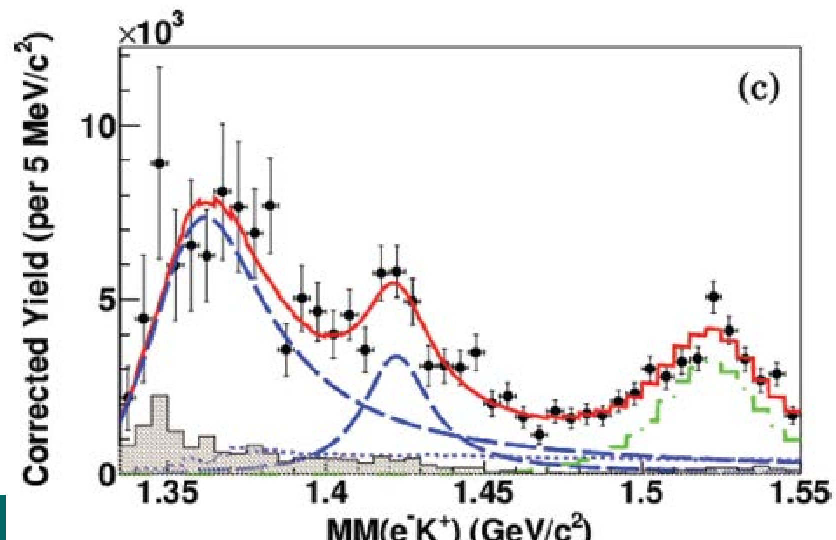
- Two poles: M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  M≈ 1420 MeV, $\Gamma \approx$ 40 MeV
- Suggested by Dalitz et al.(60ies) and obtained in many theoretical studies
- Consistent with data:
  $K^- \, p \rightarrow \phi \, B$, $K^- \, p \rightarrow \pi^0 \, \pi^0 \, \Sigma^0$, $p \, p \rightarrow p \, K^- \, \Lambda(1405)$, $\gamma \, p \rightarrow K^+ \, \pi \, \Sigma$, $e \, p \rightarrow e' \, K^+ \, \Lambda(1405)$

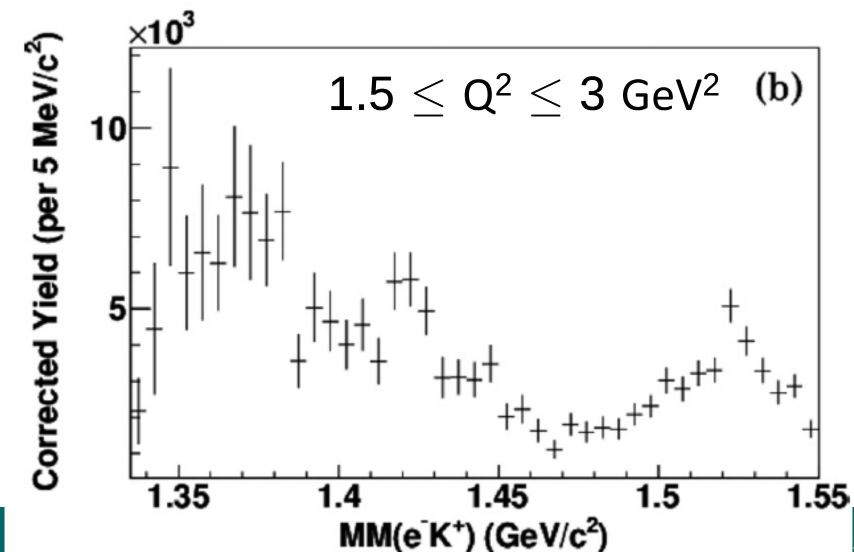
Weak strangeness production

- $e\, p \rightarrow e'\, K^{+}\, \Lambda(1405)$ Lu et al. (CLAS), PRC88(2013)









Weak strangeness production

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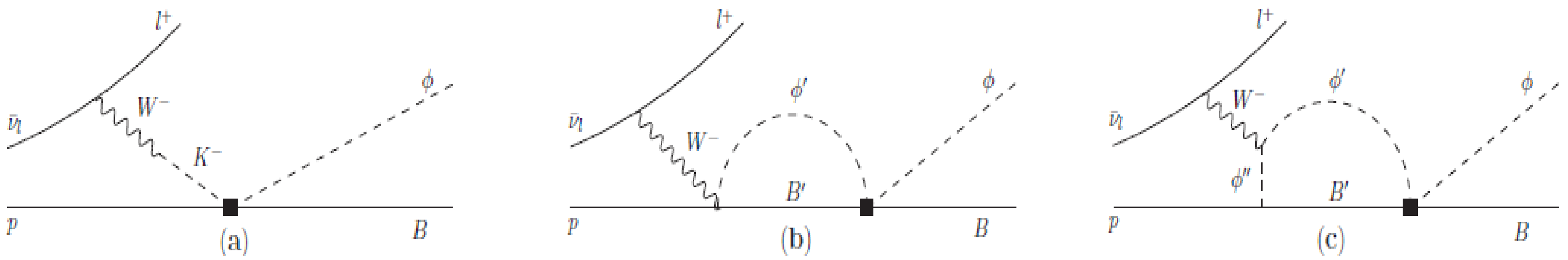
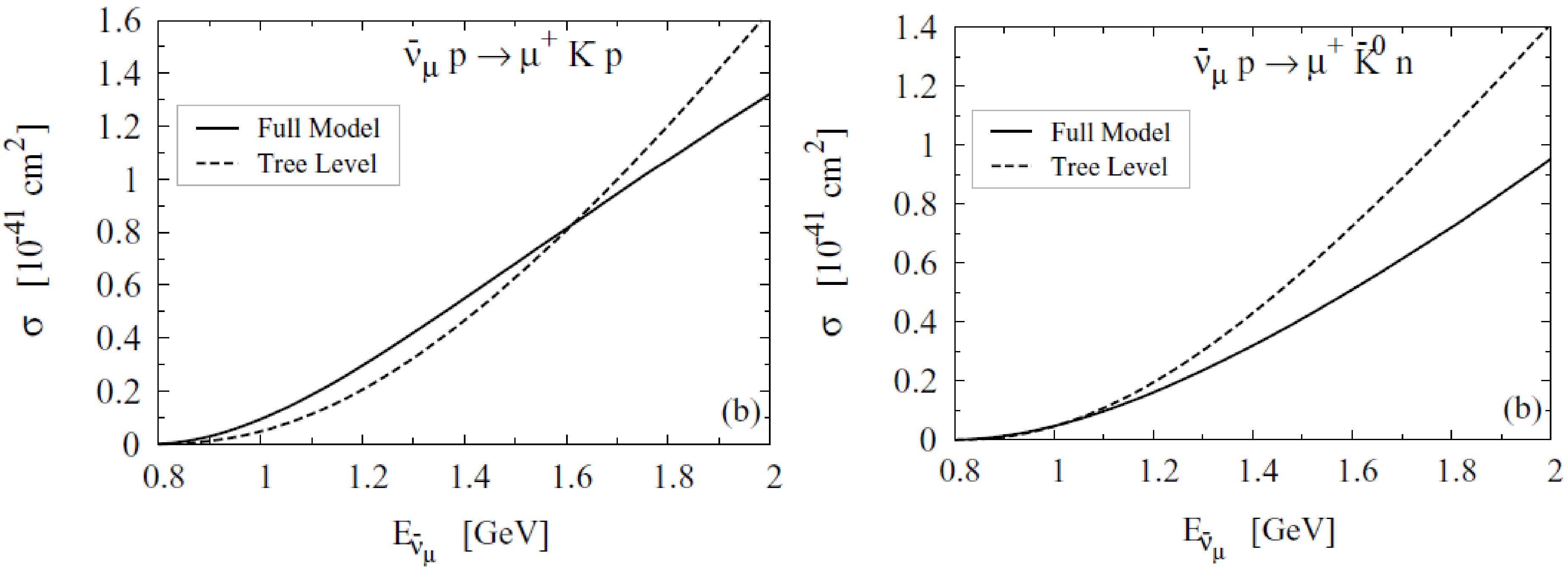


- Λ(1405) dynamically generated
- Two poles: M≈ 1385 MeV, $\Gamma \approx$ 150 MeV
  M≈ 1420 MeV, $\Gamma \approx$ 40 MeV
- $\bar{\nu}_l \, p \to l^+ \, \Lambda(1405)$ vs $\gamma \, p \to K^+ \, \pi \, \Sigma, \; e \, p \to e' \, K^+ \, \Lambda(1405)$
  - no lineshape distortion due to $K^+ \Lambda(1405)$ FSI
  - but Cabibbo suppressed

Weak strangeness production

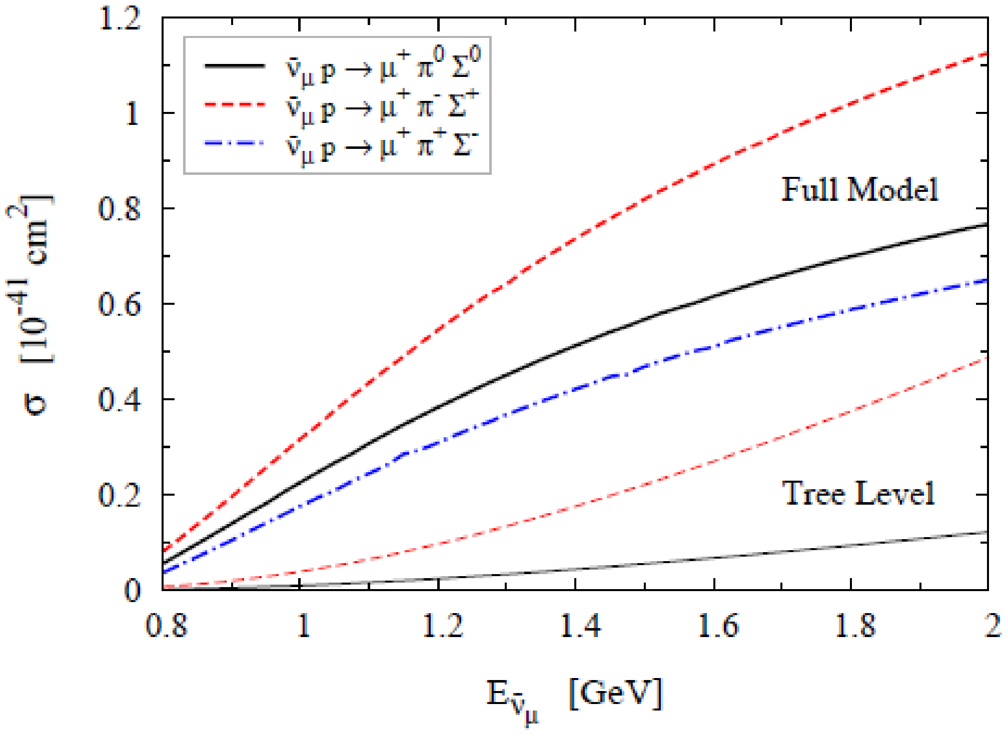
- $\bar{\nu}_l \, p \rightarrow l^+ \, \bar{K} \, N$ Ren et al., PRC91 (2015)



- Unitarization effects are not large: mostly a reduction of the cross section

Weak strangeness production

- $\bar{\nu}_l \, p \rightarrow l^+ \, \Sigma \, \pi$ Ren et al., PRC91 (2015)



- Cross sections largely driven by the $\Lambda(1405)$ resonance

Weak strangeness production

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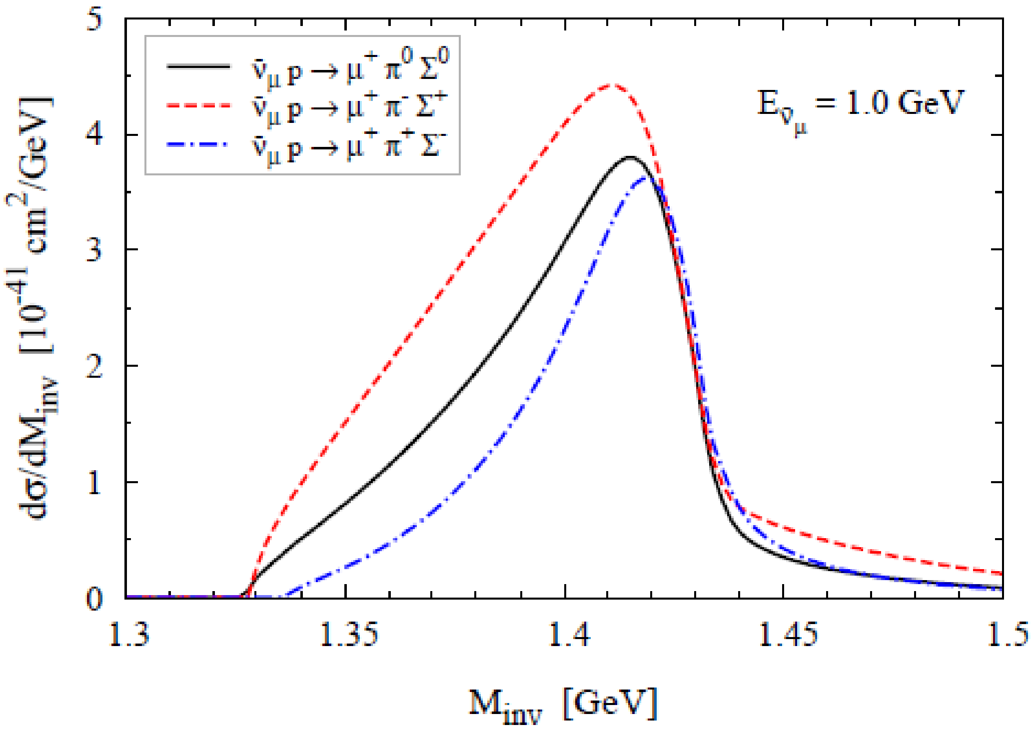
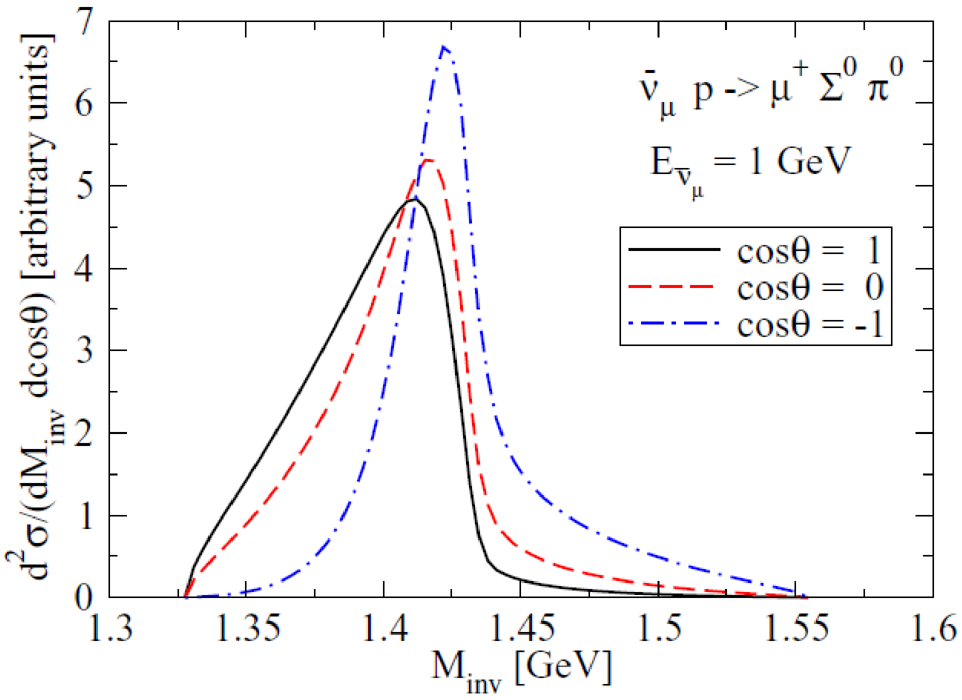


- Cross sections largely driven by the Λ(1405) resonance
- Differences in strength vs the $\pi^0\Sigma^0$ channel from the I=1 amplitude
- Single asymmetric peak with more weight from the 1420 MeV pole

Weak strangeness production

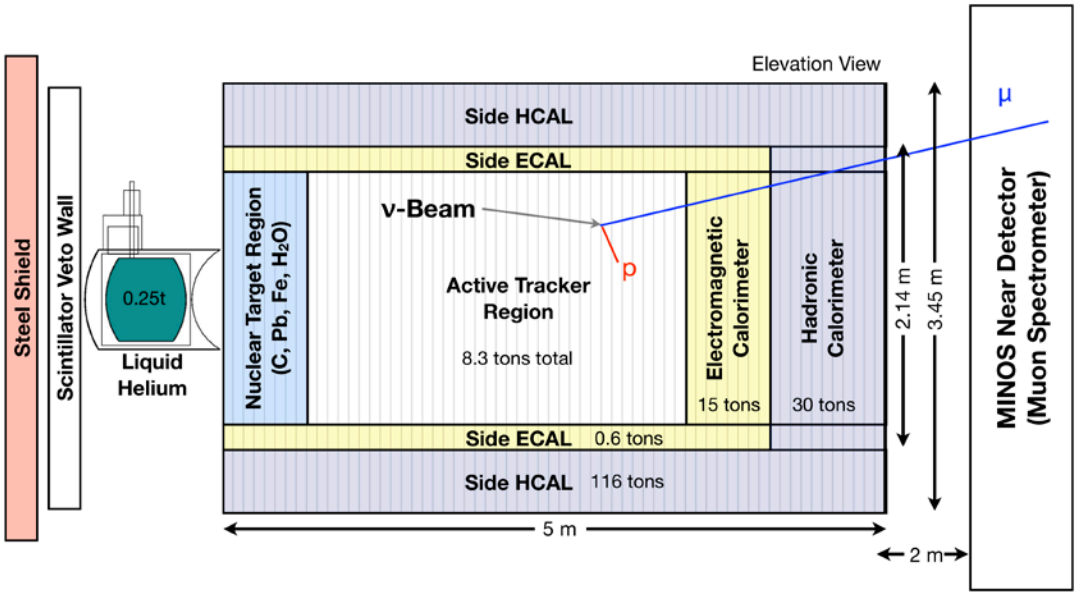
- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ Ren et al., PRC91 (2015)

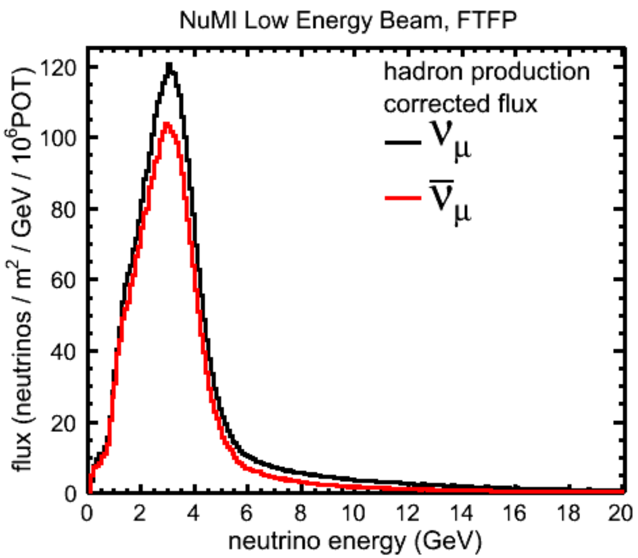


- Single asymmetric peak with more weight from the 1420 MeV pole
- Backwards: $\sim$ Breit-Wigner resonance with M $\approx$ 1420 MeV, $\Gamma \approx$ 40 MeV
- Although $d^2\sigma(\cos\theta = -1) \sim d^2\sigma(\cos\theta = 1)/14$

Weak strangeness production

- $\bar{\nu}_l \, p \to l^+ \, \Sigma \, \pi$ @ MINERvA (FNAL)





- $\approx$ 2000 $\pi\Sigma$ pairs @ scintillator

Conclusions

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- This is the case, in particular, for weak meson production
  - dominated by baryon resonance excitation

Conclusions

- ν scattering on nucleons and nuclei is relevant for oscillation studies
- Interesting for hadron and nuclear physics
- Weak pion production, photon emission and $|\Delta S| = 1$ reactions discussed
- Weak pion production: consistency with the off-diagonal G-T relation for the N-Δ transition is restored by imposing the Watson's theorem
- NC photon emission:
  - results agree with MiniBooNE's estimate $\rightarrow$ insufficient to explain the excess of e-like events at MiniBooNE
  - implications for T2K: twice more NCγ events predicted vs NEUT
- Weak production of Λ(1405) studied for the first time. Events at MINERvA predicted