Neutrino-Nucleon Cross-Sections at Energies of Megaton-Scale Detectors

Part II

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CFA

24.06.2015

Kinematics

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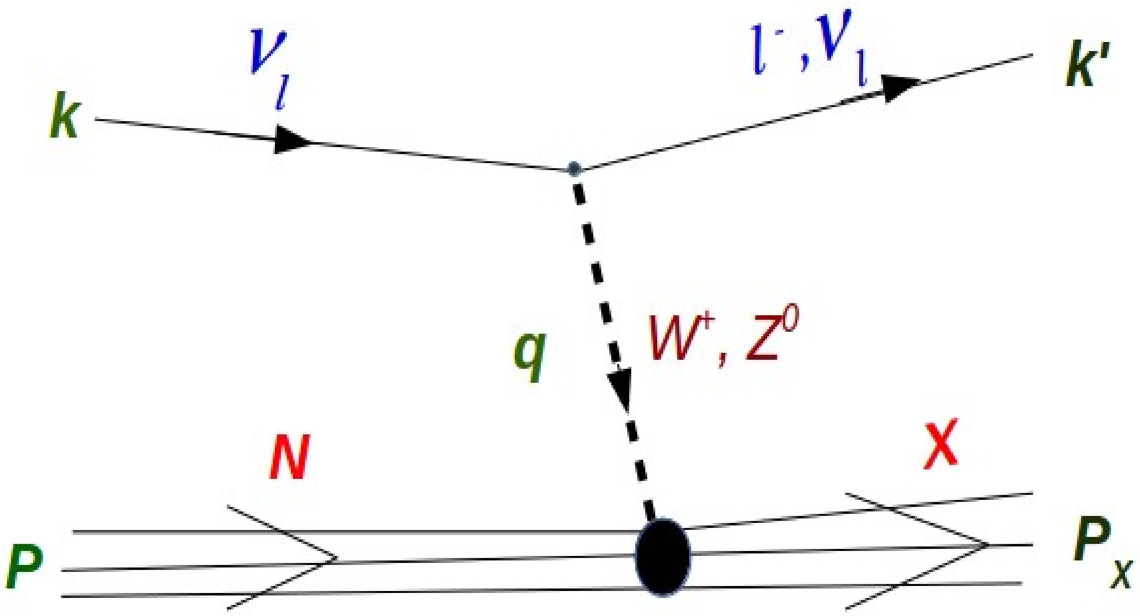

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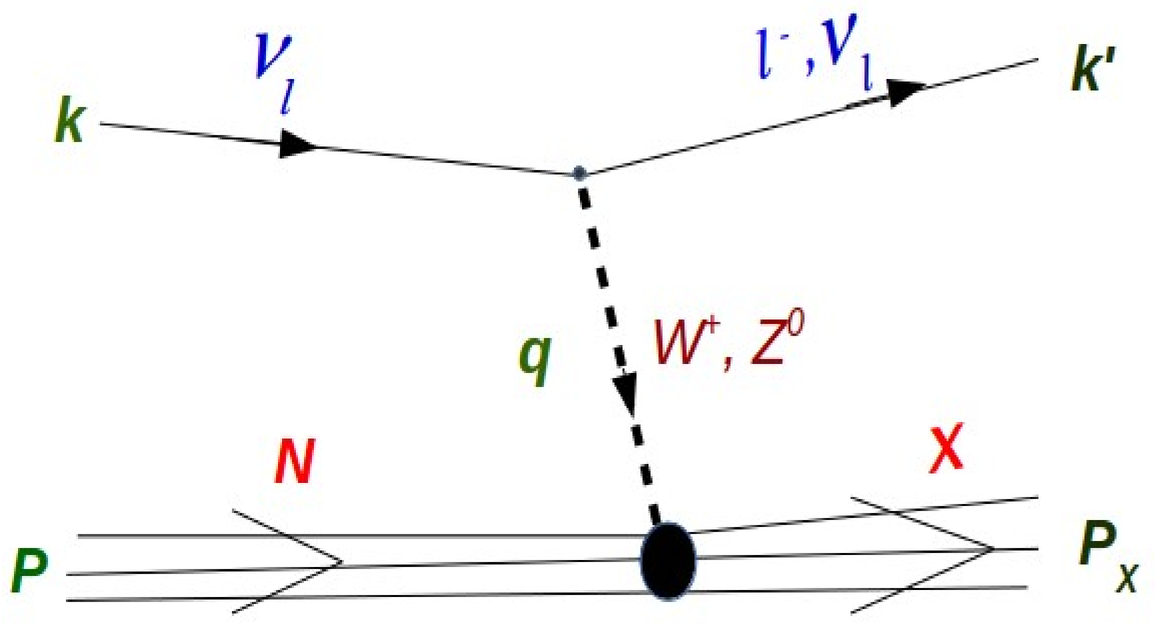

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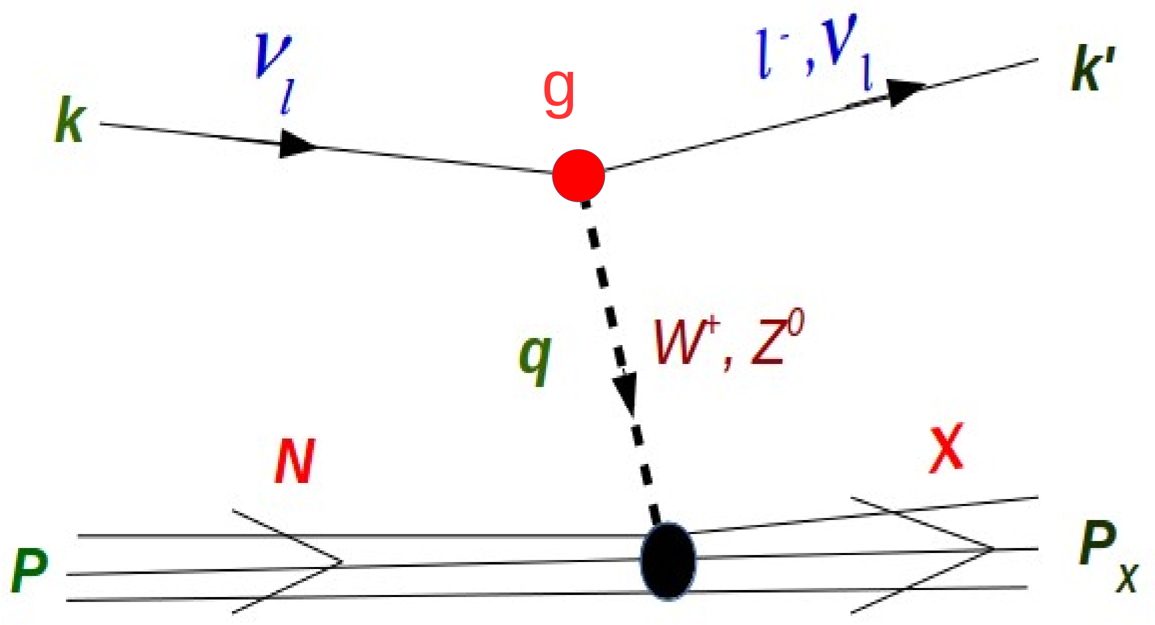

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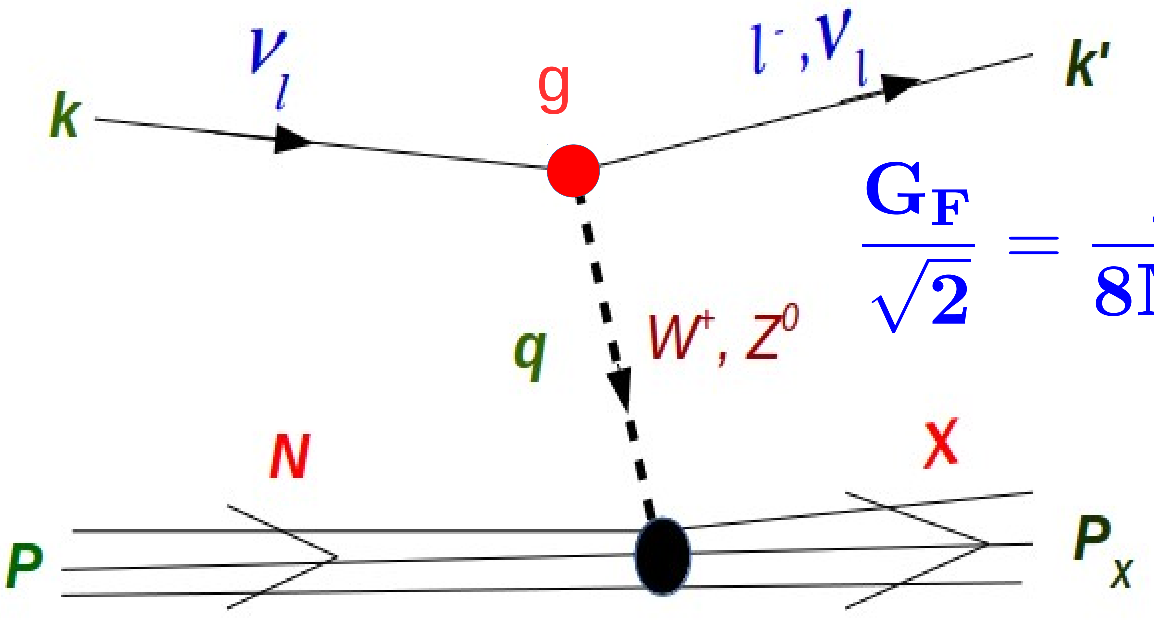

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

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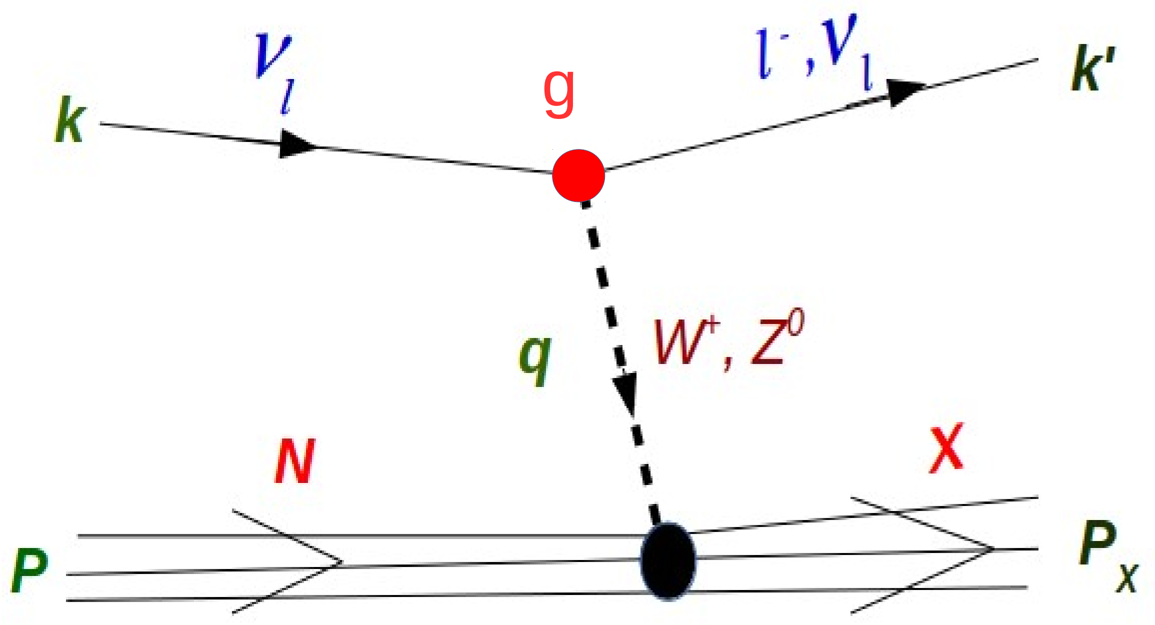

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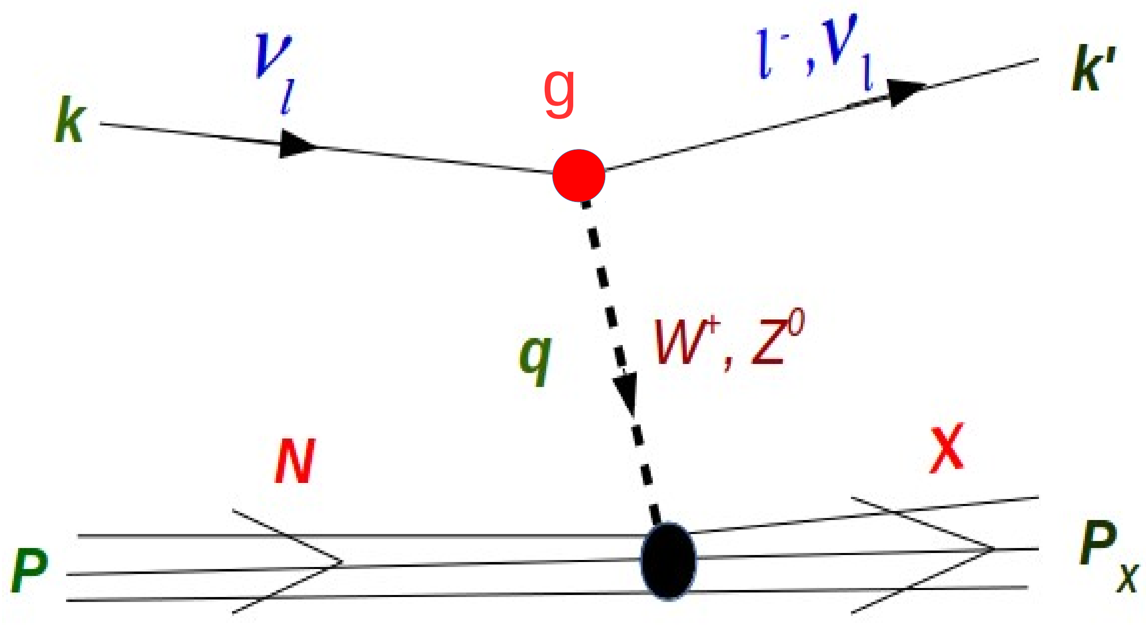

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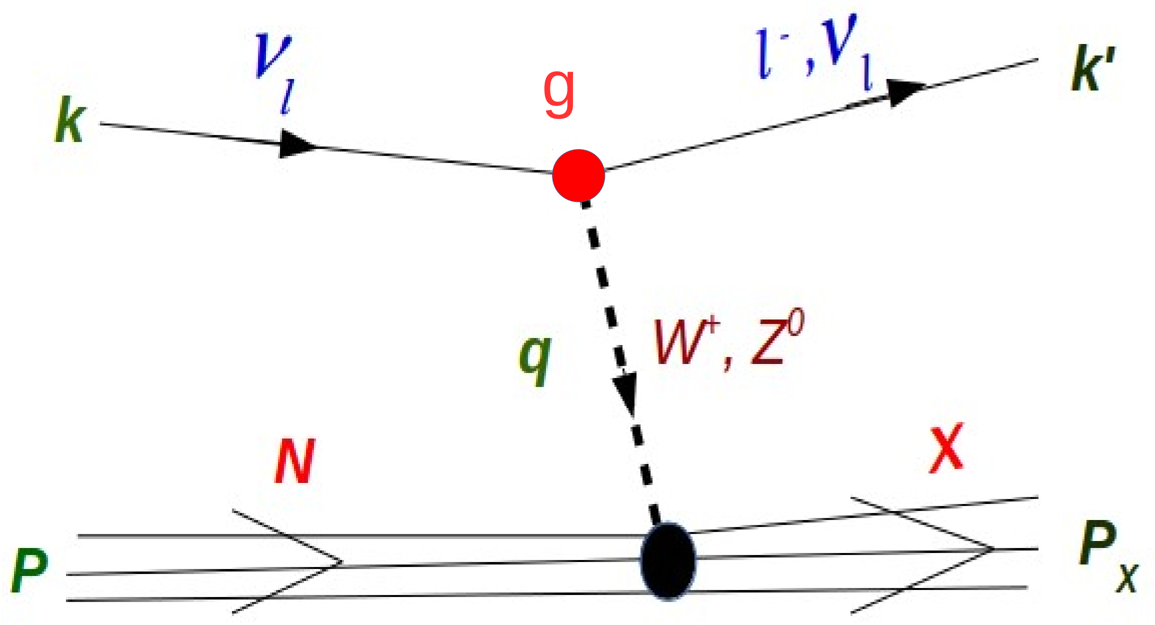

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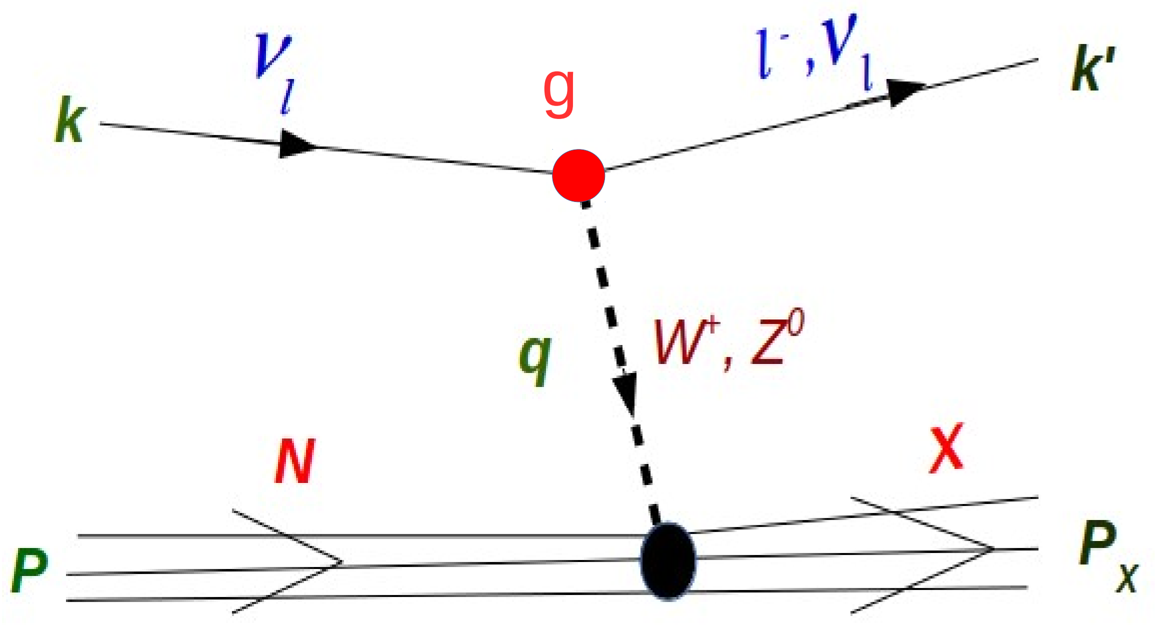

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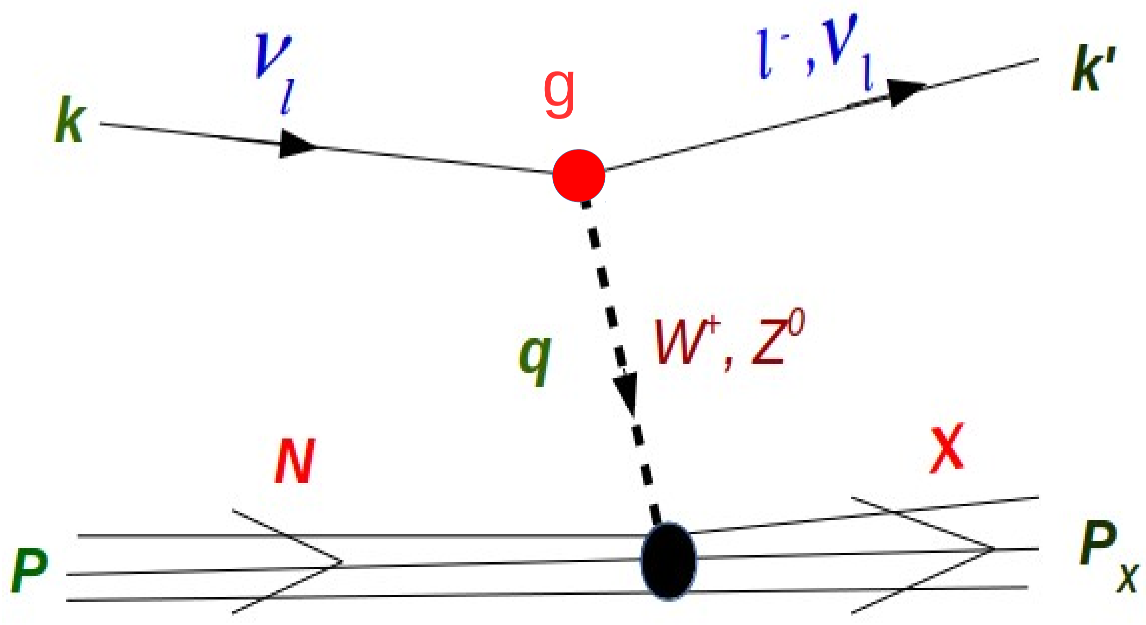

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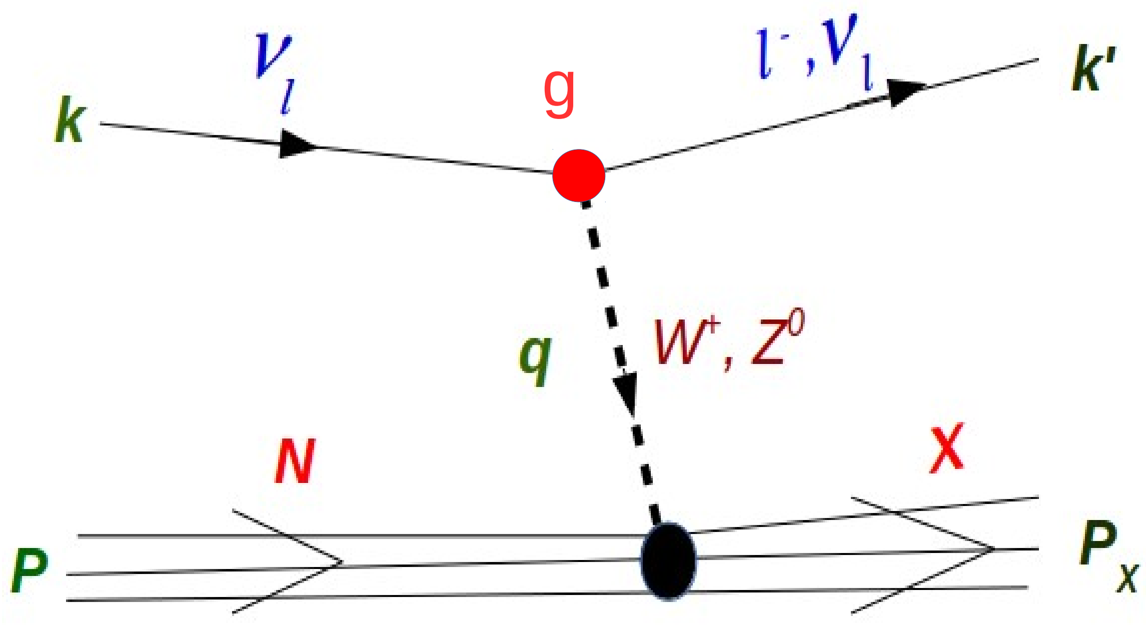

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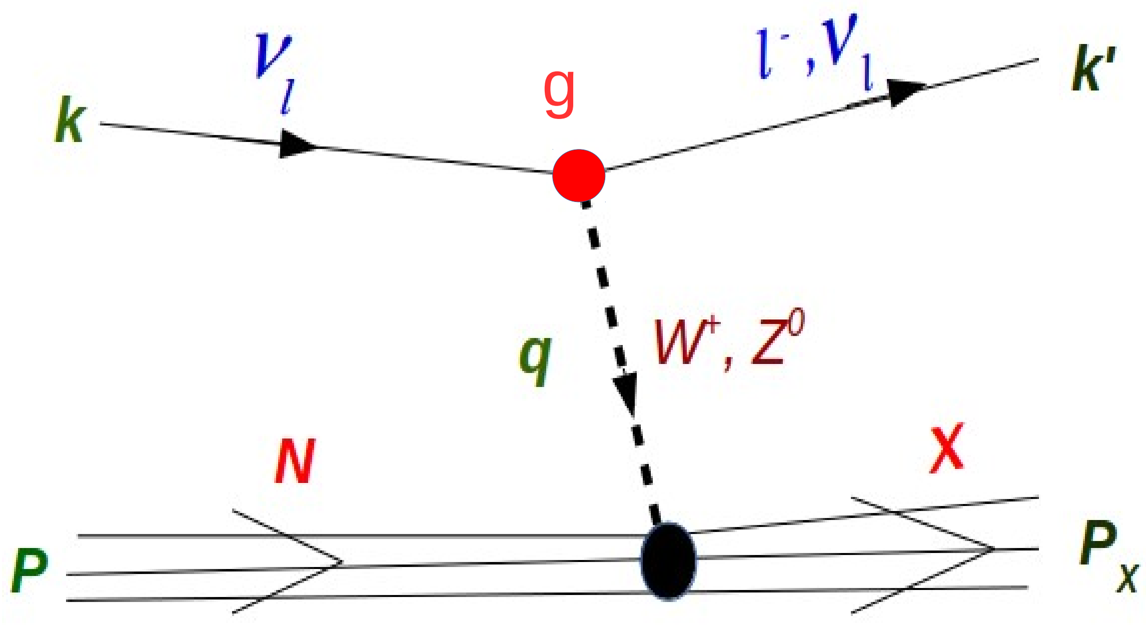

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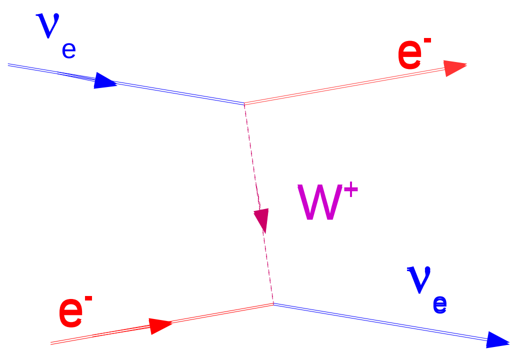

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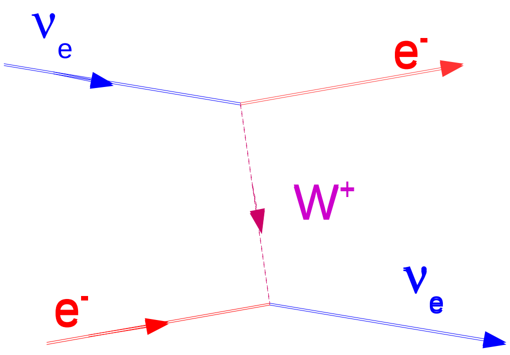

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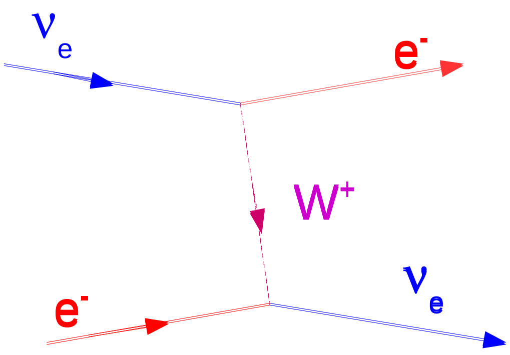

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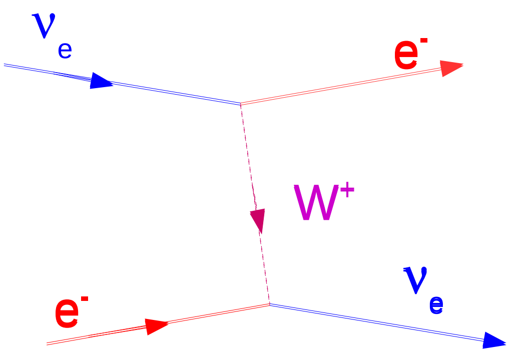

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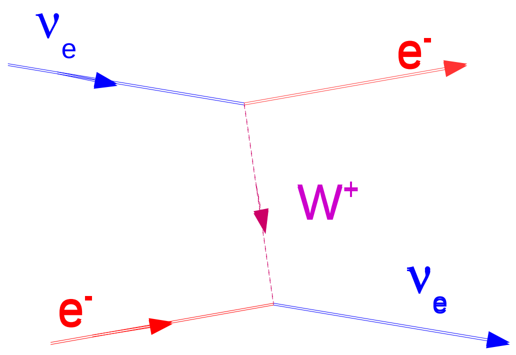

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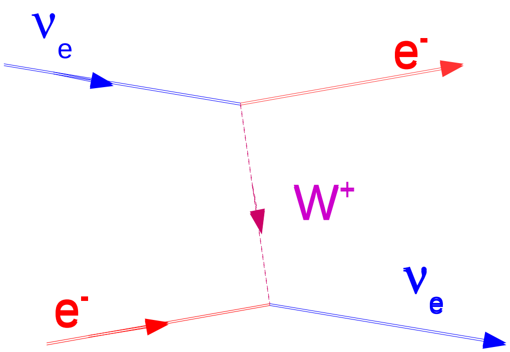

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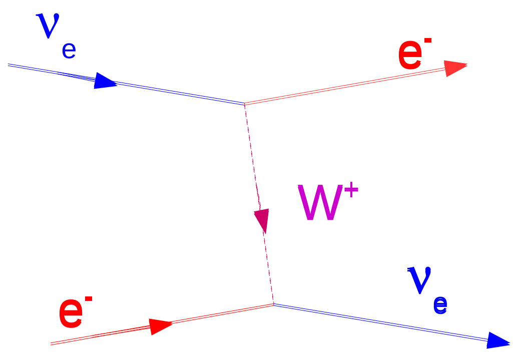

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At LO QCD just put a quark mass m_q instead of the electron for a ν scattering off a nucleon and sum the contributions from all quarks. Valence and sea quarks.

Contributions to the total cross-section

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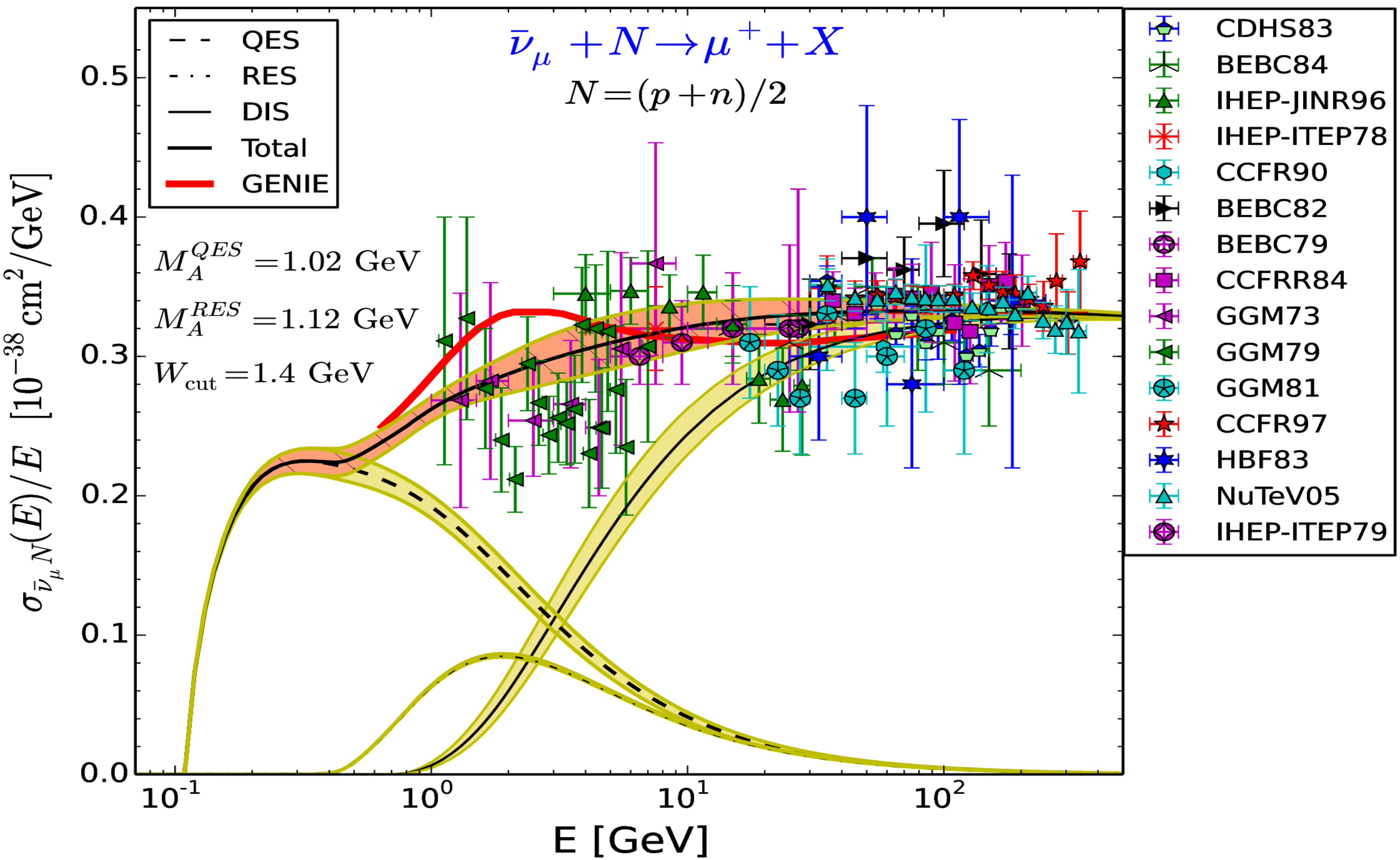
- Deep inelastic scattering ***(DIS)***: > 2π in the final state **X**

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



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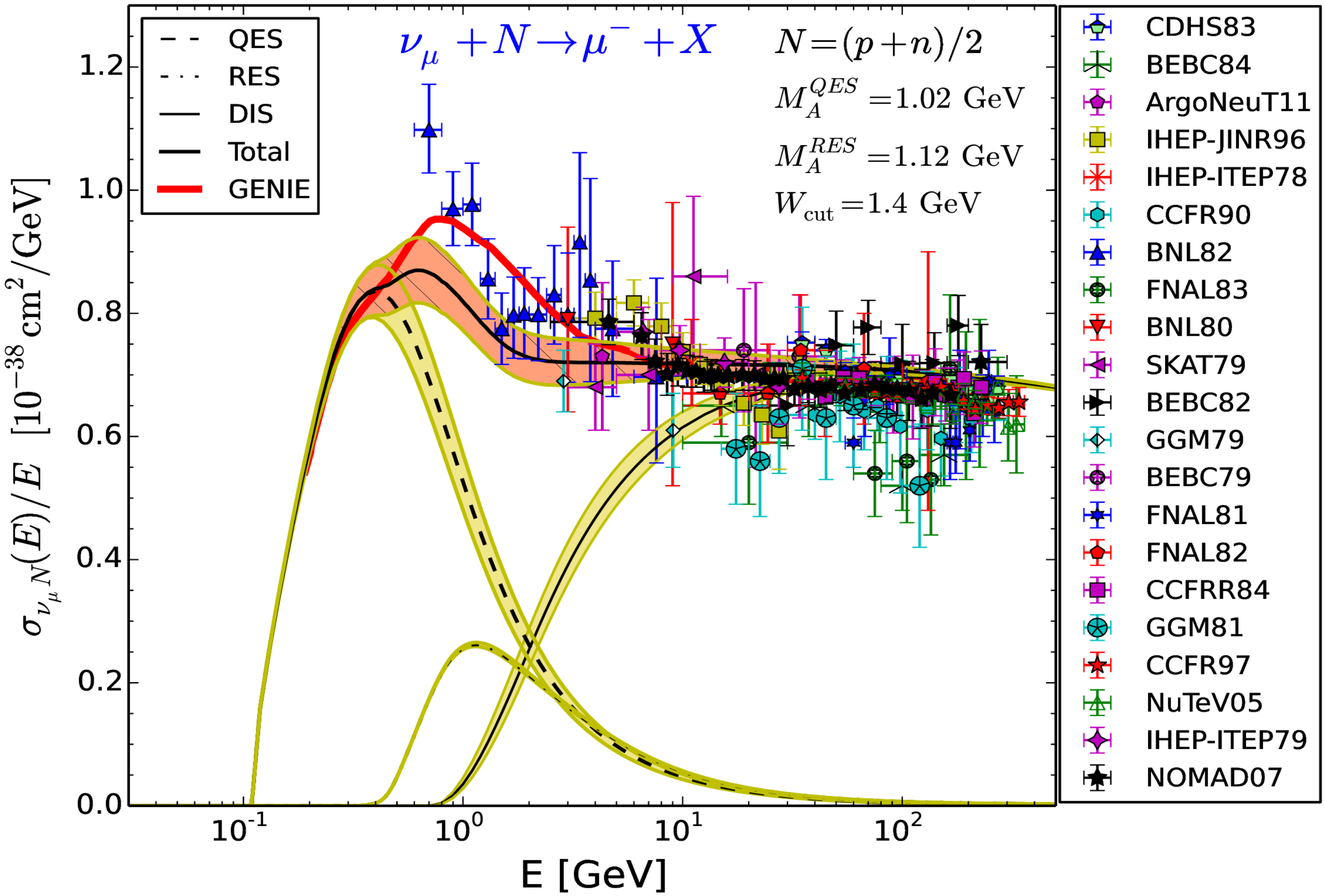
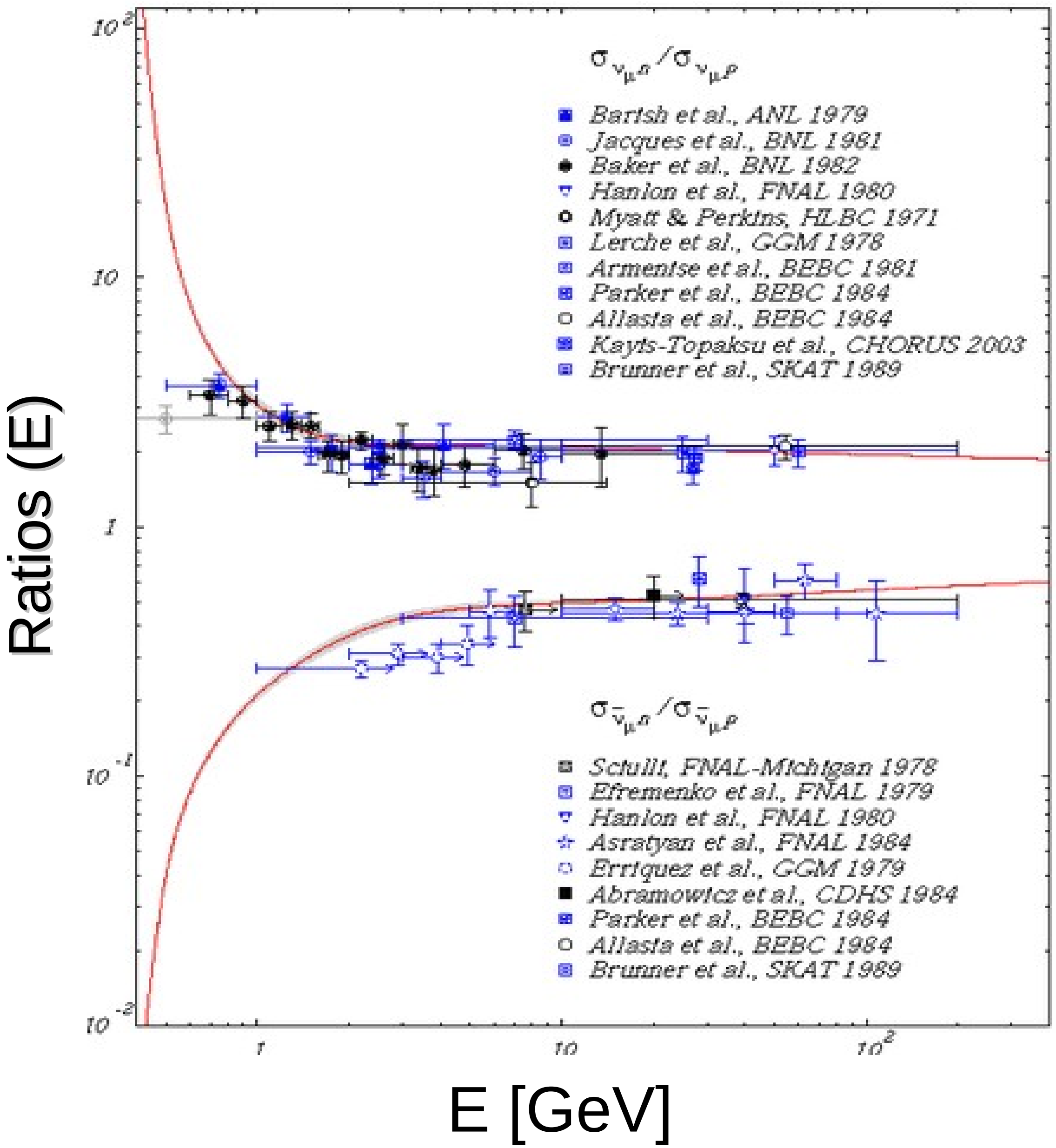
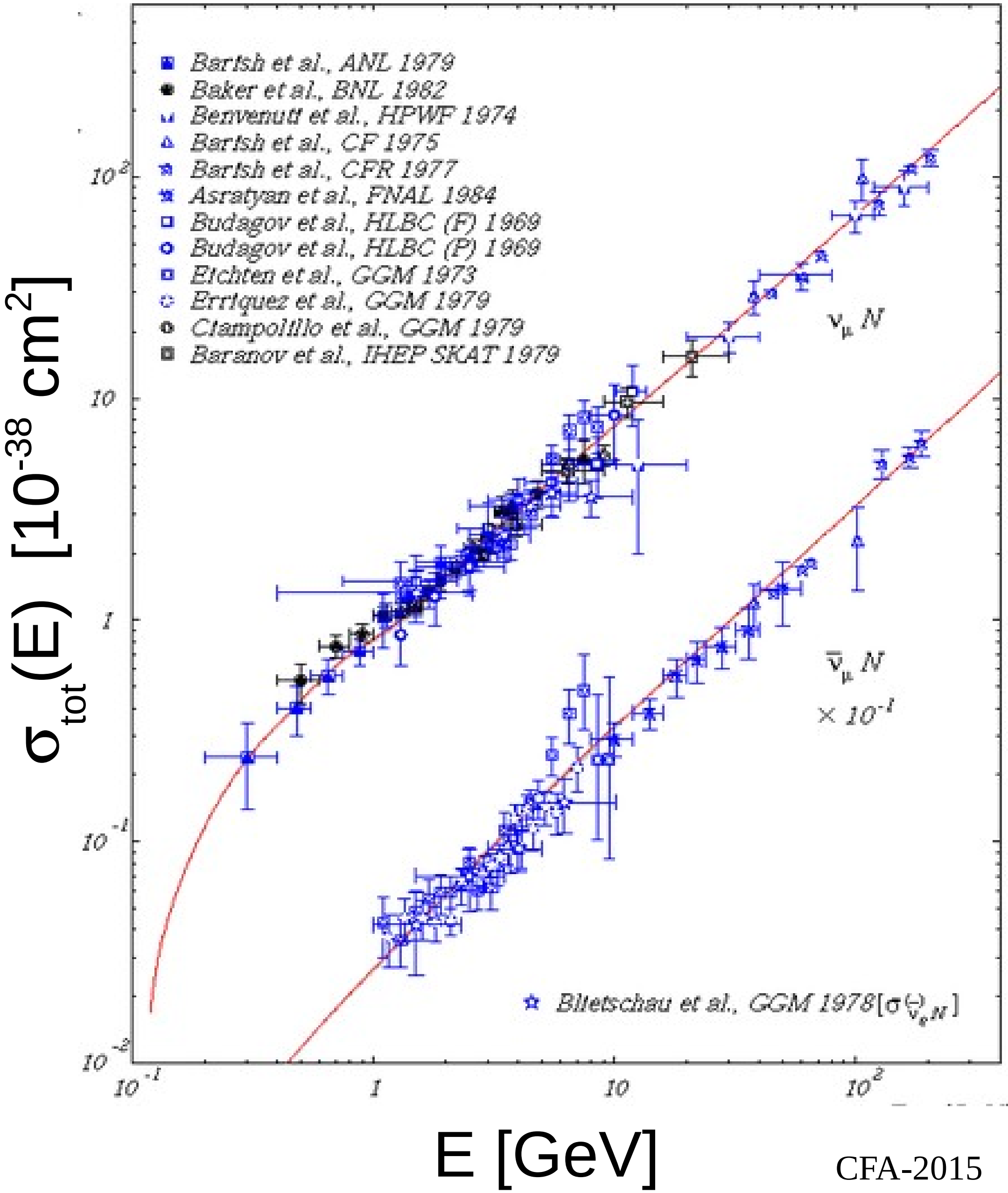


Ratios $\sigma_{\nu n}/\sigma_{\nu p}$ and $\sigma_{\bar{\nu} n}/\sigma_{\bar{\nu} p}$



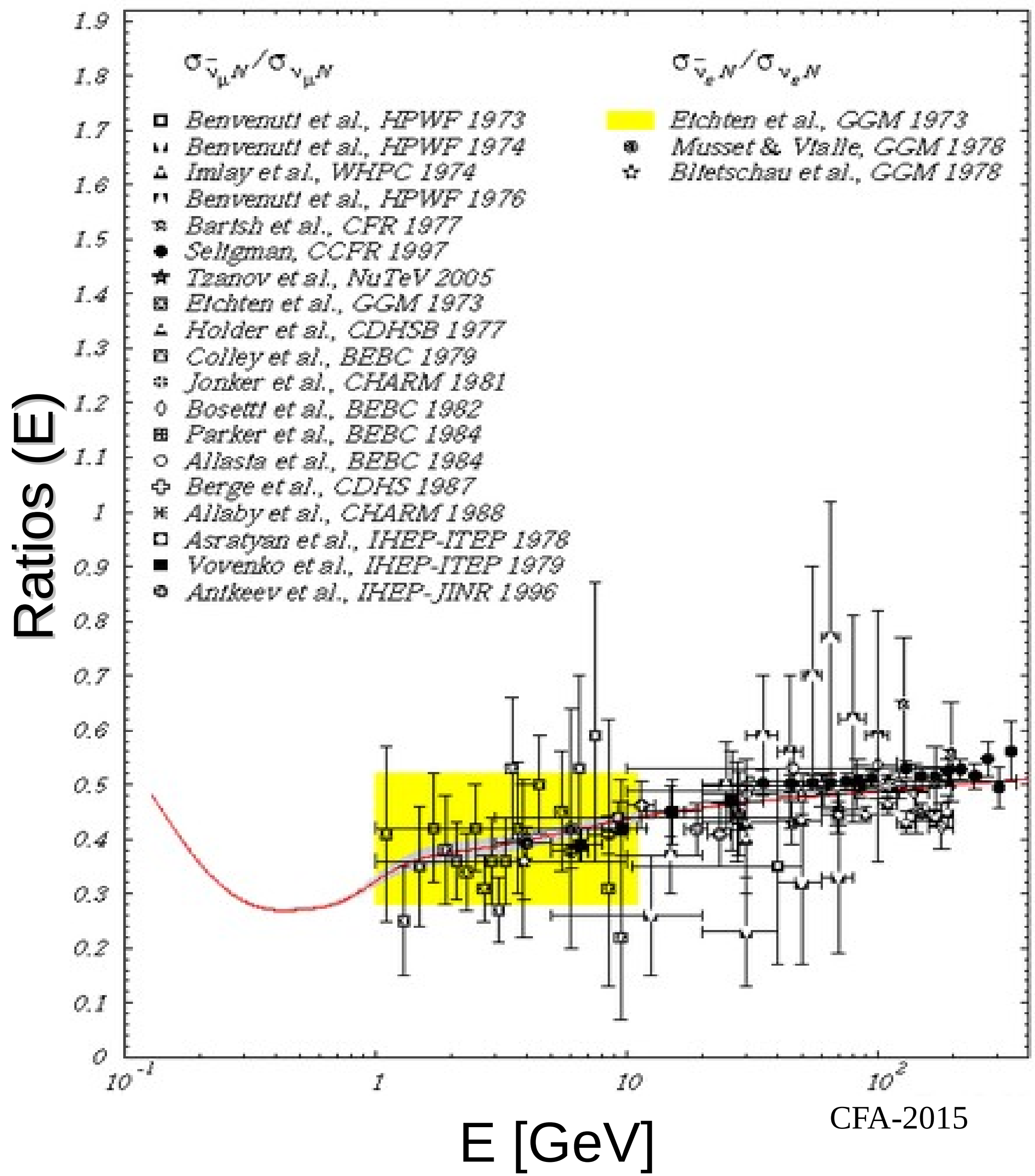
Check model parameteriation using data for such ratios.

Total ν_μN and $\bar{\nu}_\mu$N Cross-Sections



- Cross-sections grow proportional to E.
- At higher energies just power-law growth due to sea-quarks density increase.

$\bar{\nu}N$ / νN Ratios



At low energies ratio is due to kinematics.

Both ν and quark are left-handed: J = 0. Isotropic distribution.

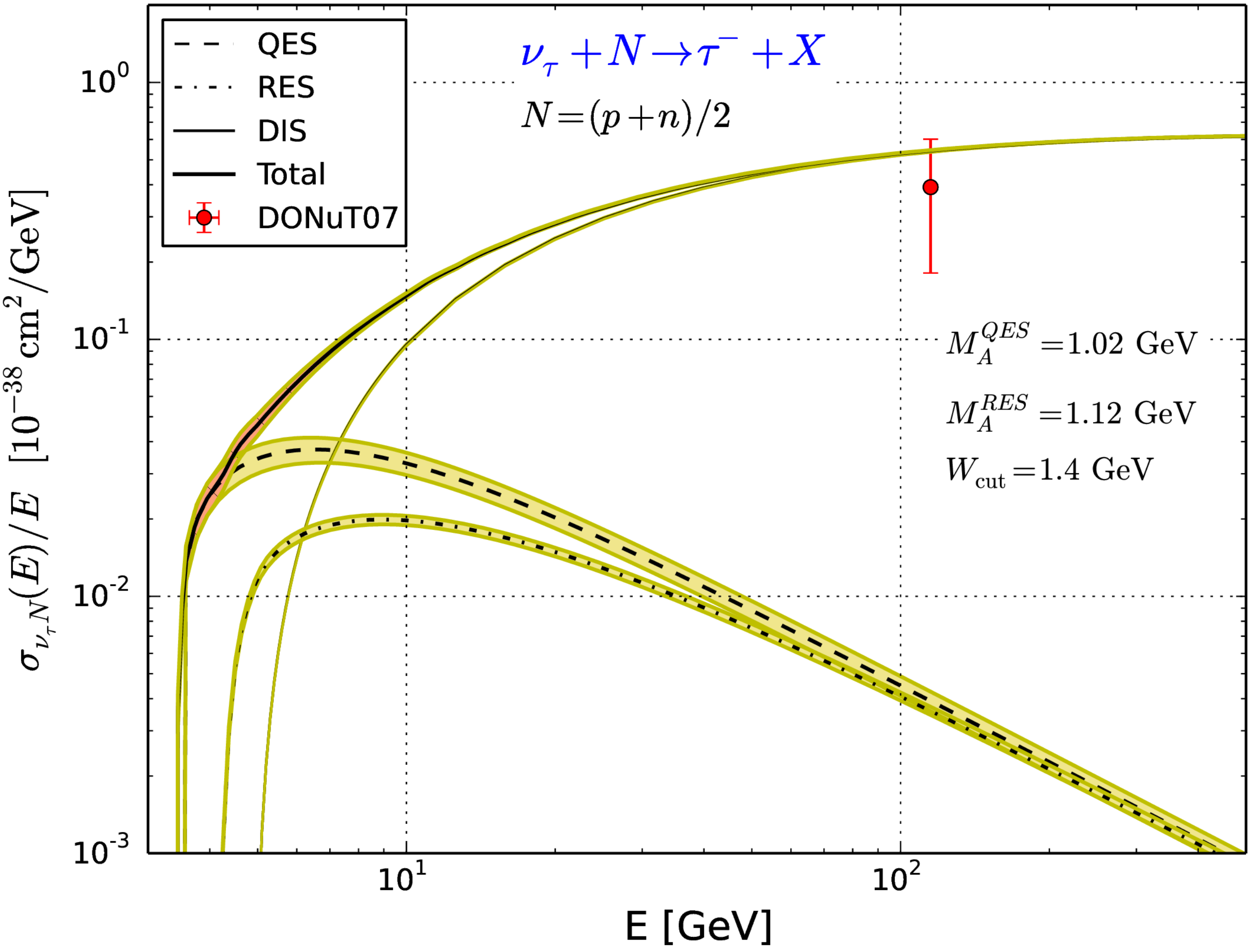
$\bar{\nu}$ is right-handed: J = 1,

$$\frac{\mathbf{d}\sigma(\cos\theta)}{\mathbf{d}\cos\theta} \propto (\mathbf{1} - \cos\theta)^{\mathbf{2}},$$

and $\sigma_{\bar{\nu}}/\sigma_{\nu} \approx 1/3$

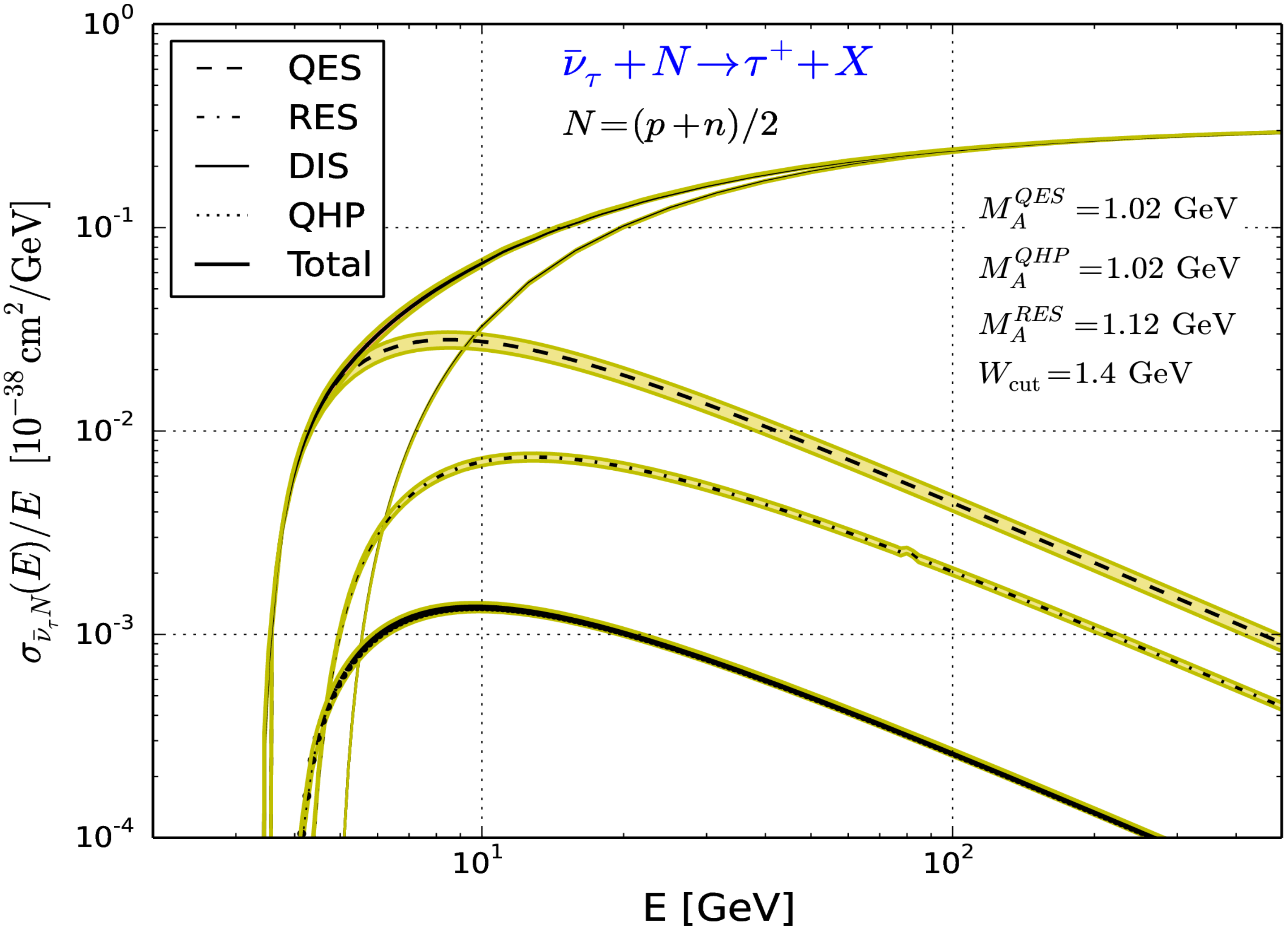
$\nu_\tau + N \rightarrow \tau^- + X$

DONUT – Direct Observation of the NU Tau



- Tevatron protons produce charm mesons.
- ν_τ appears in the charm decays.
- ν_τ produces τ's in the nuclear emulsion.
- 4 τ-events registered, while 0.2 expected if no ν_τ.
- One event with a kink from the τ-decay.

$\bar{\nu}_\tau + N \rightarrow \tau^+ + X$



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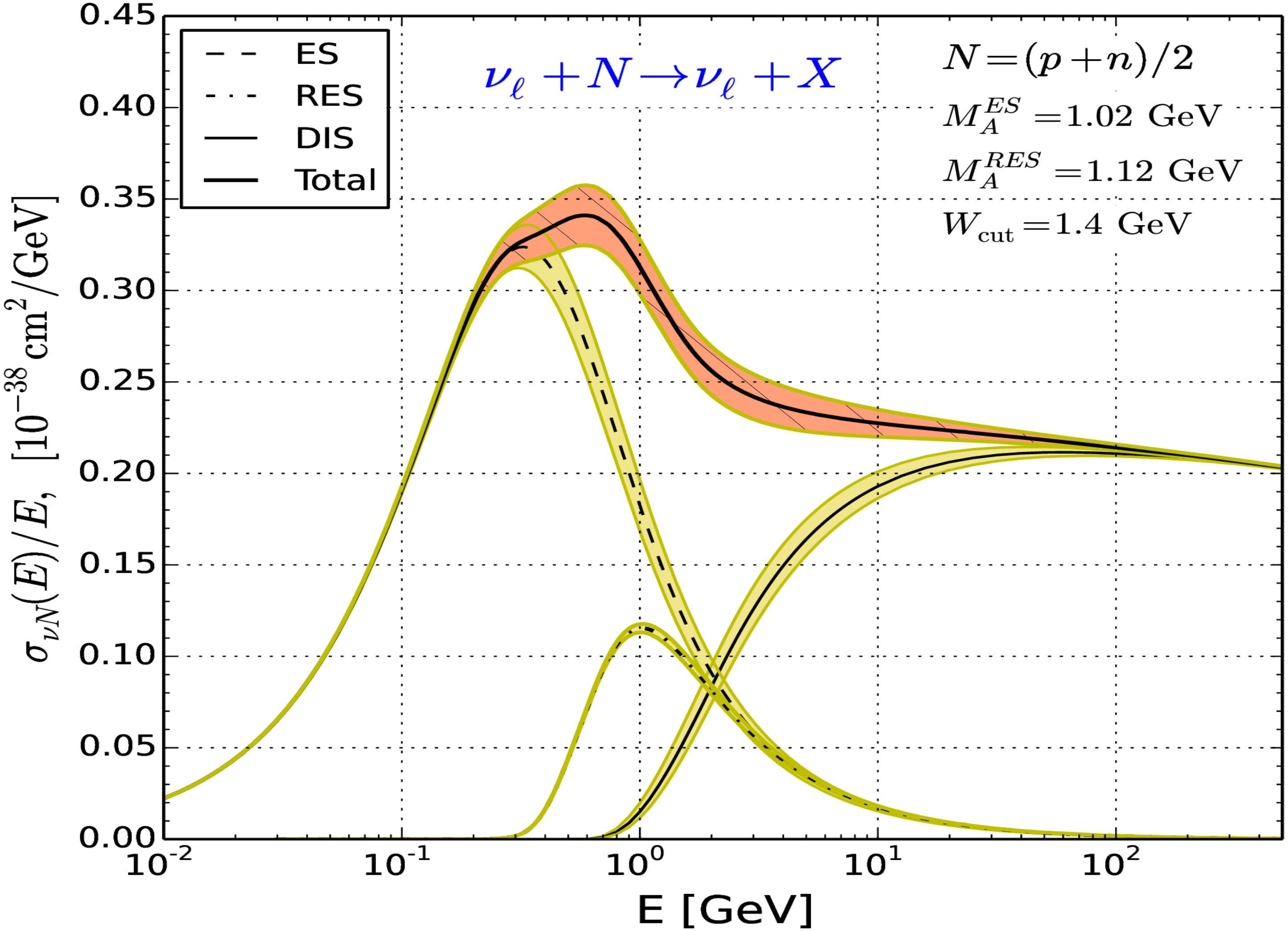

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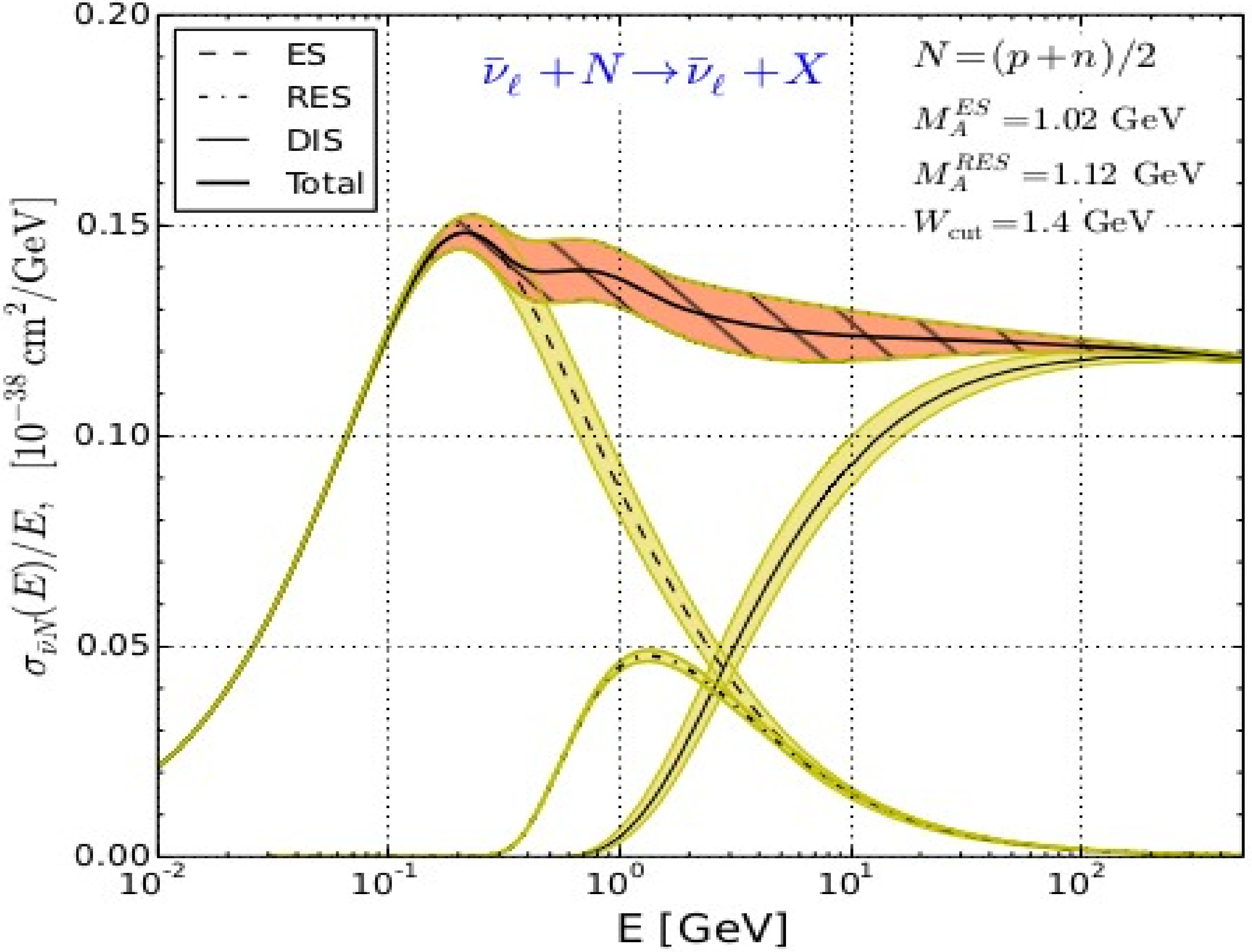

MiniBooNE

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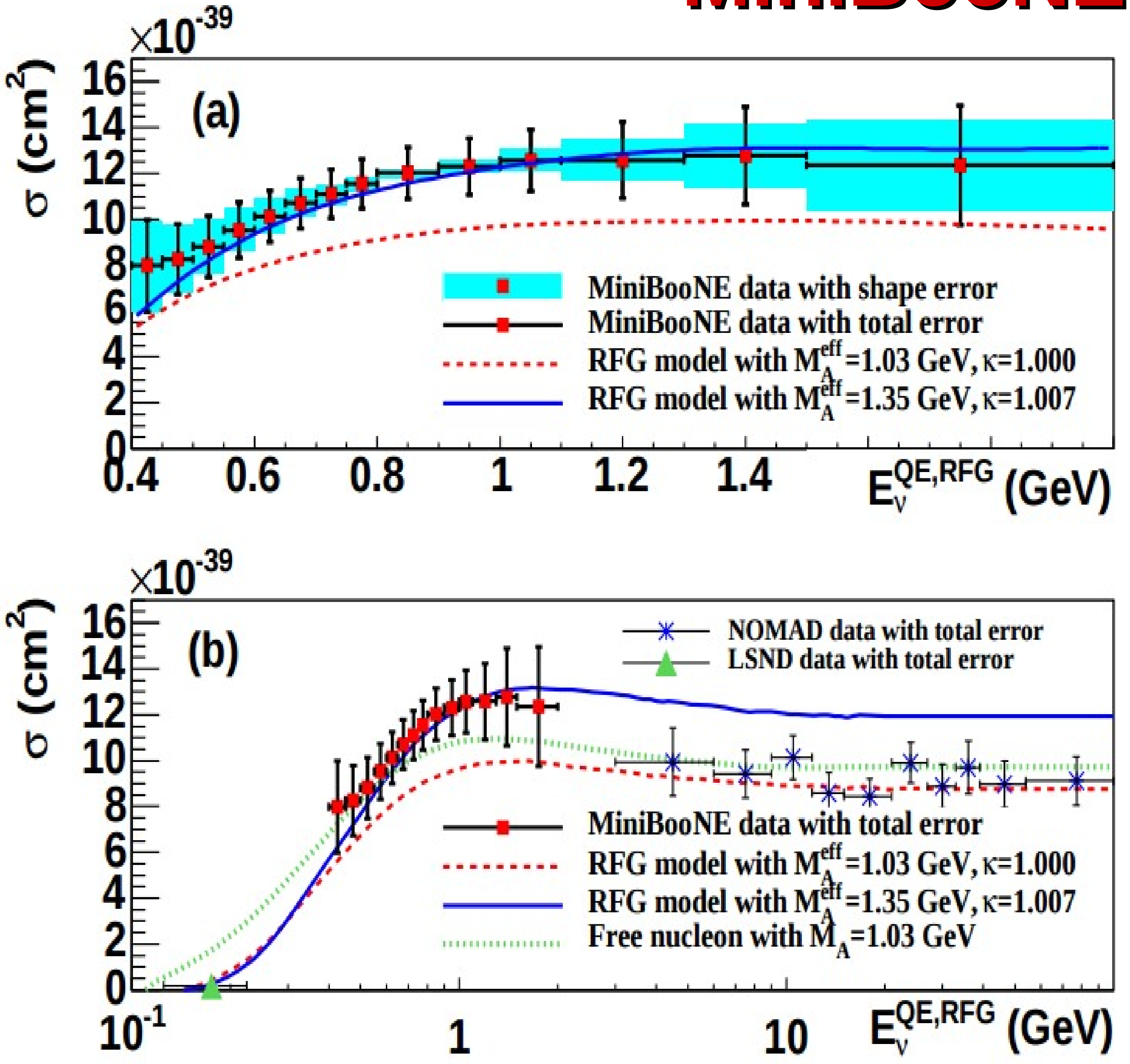
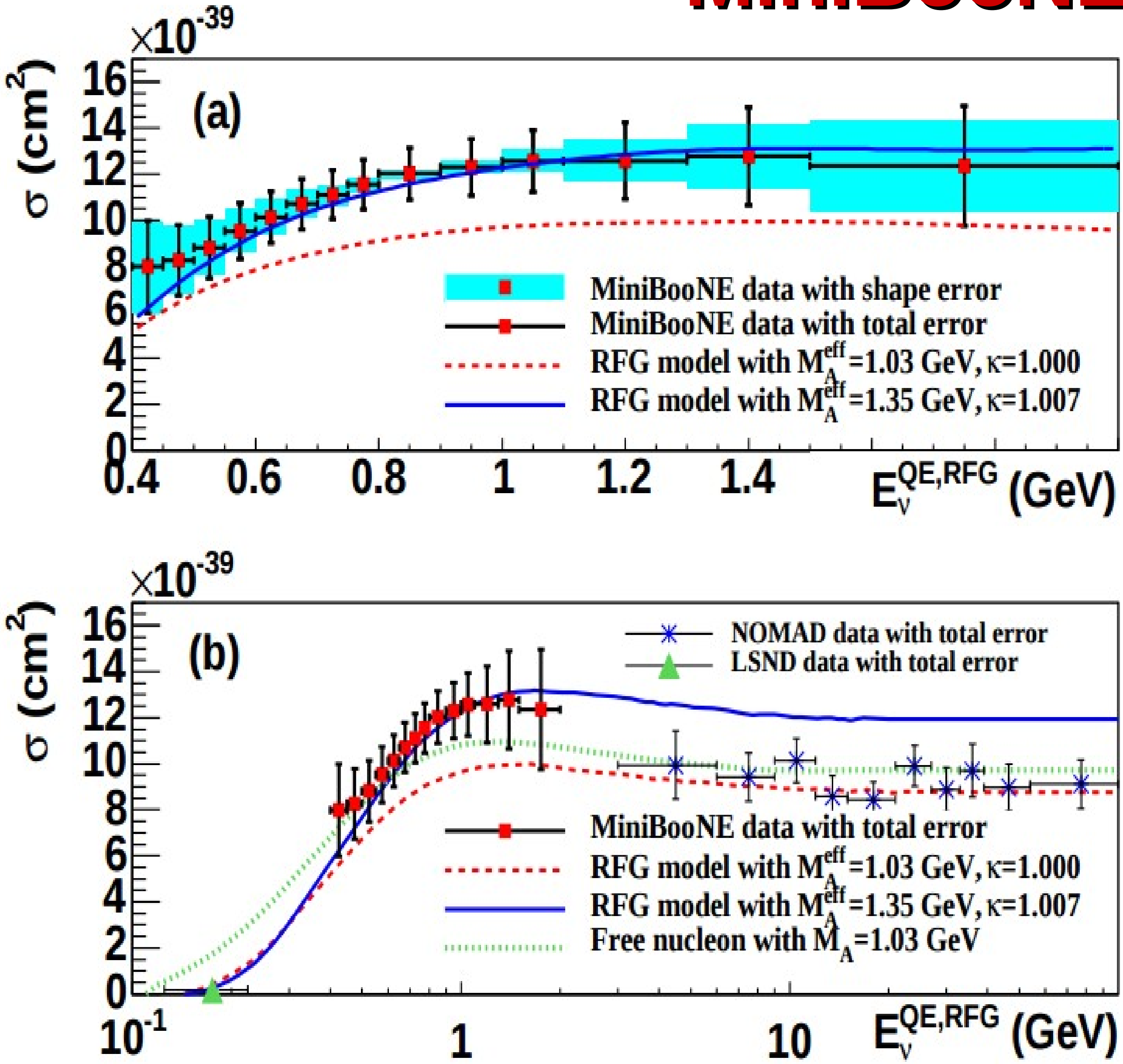


(a)
MiniBooNE data with shape error
MiniBooNE data with total error
RFG model with M_A^{eff}=1.03 GeV, κ=1.000
RFG model with M_A^{eff}=1.35 GeV, κ=1.007
σ (cm²)
$E_\nu^{QE,RFG}$ (GeV)
(b)
NOMAD data with total error
LSND data with total error
MiniBooNE data with total error
RFG model with M_A^{eff}=1.03 GeV, κ=1.000
RFG model with M_A^{eff}=1.35 GeV, κ=1.007
Free nucleon with M_A=1.03 GeV

MiniBooNE



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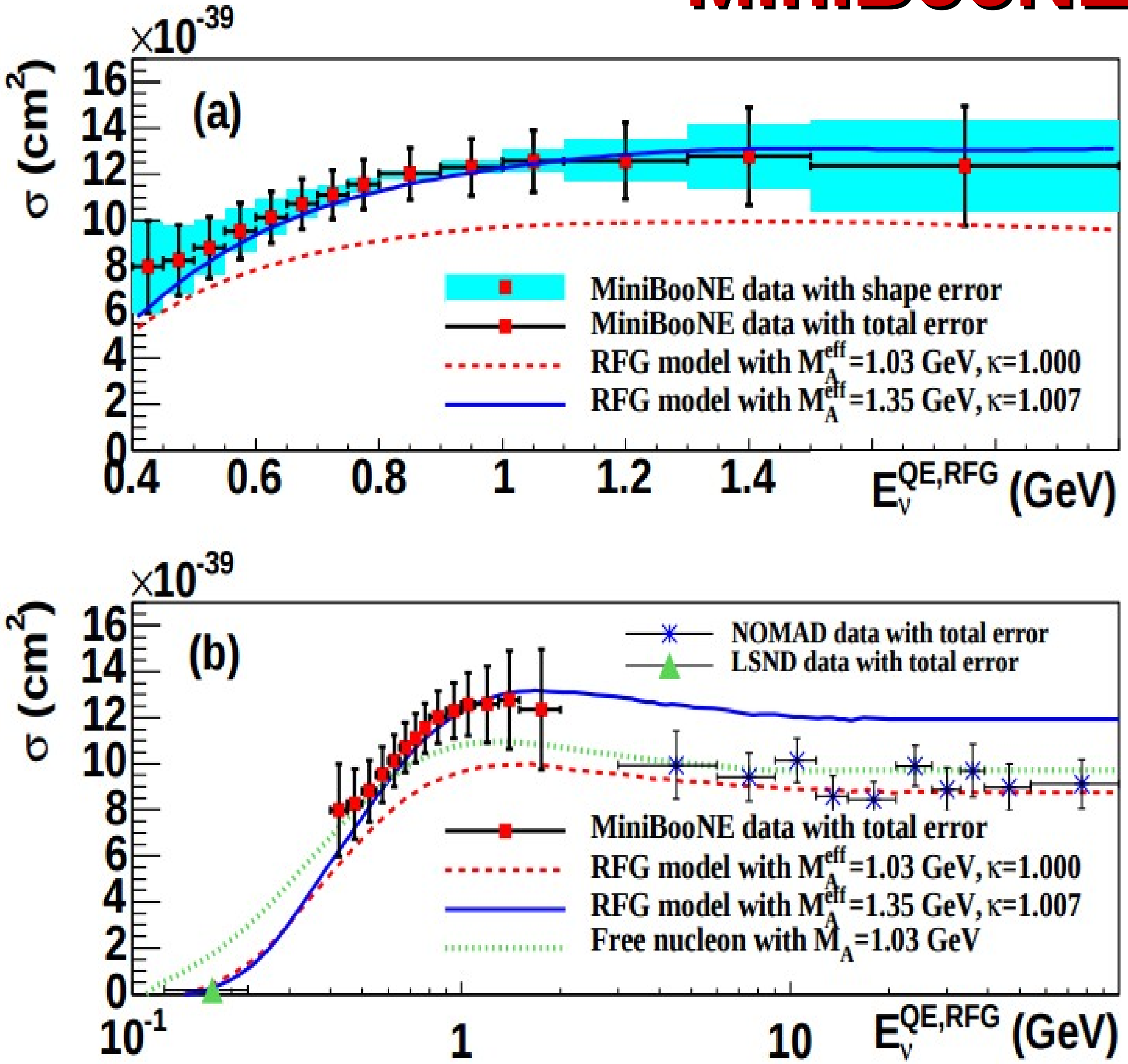

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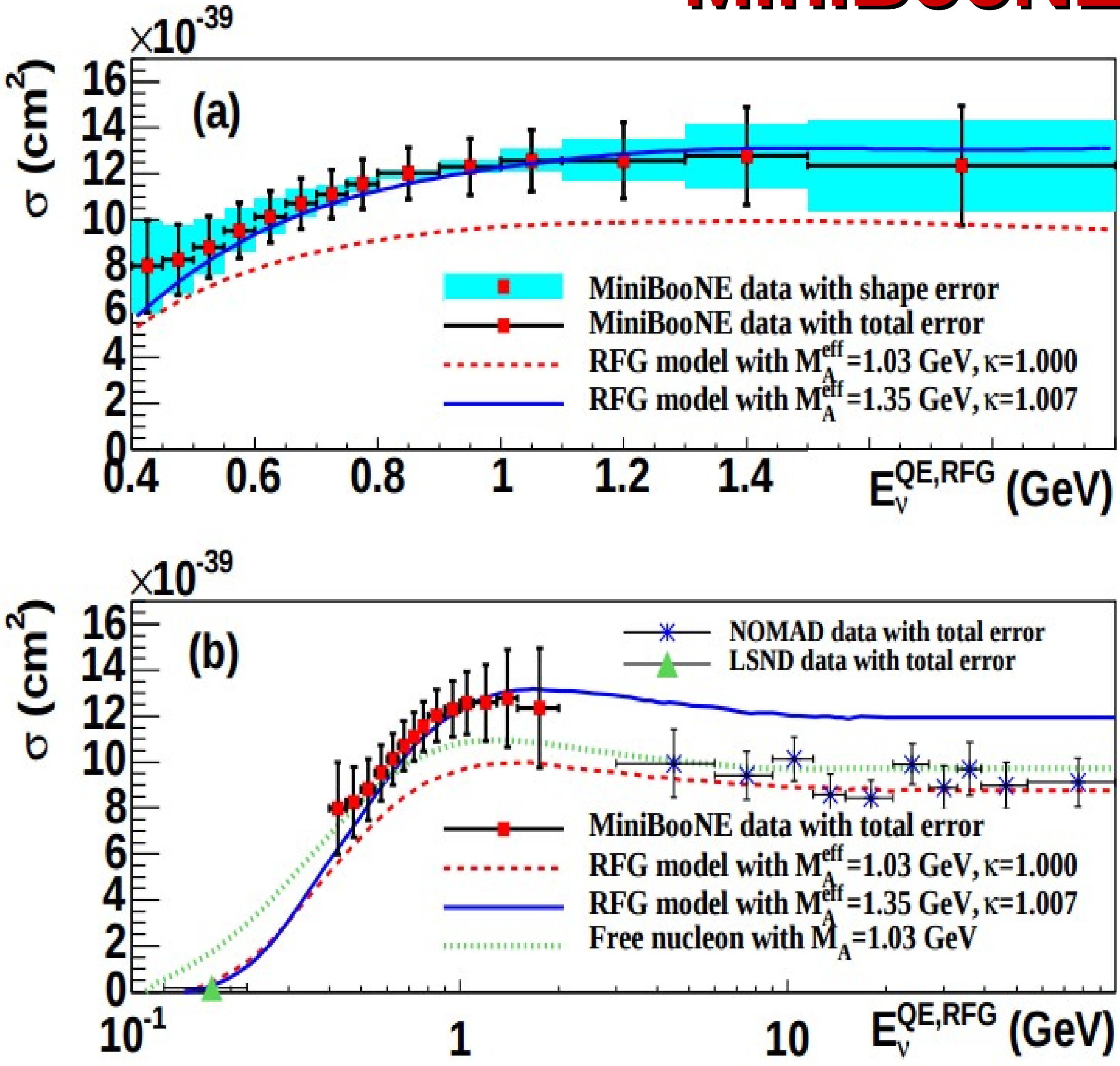

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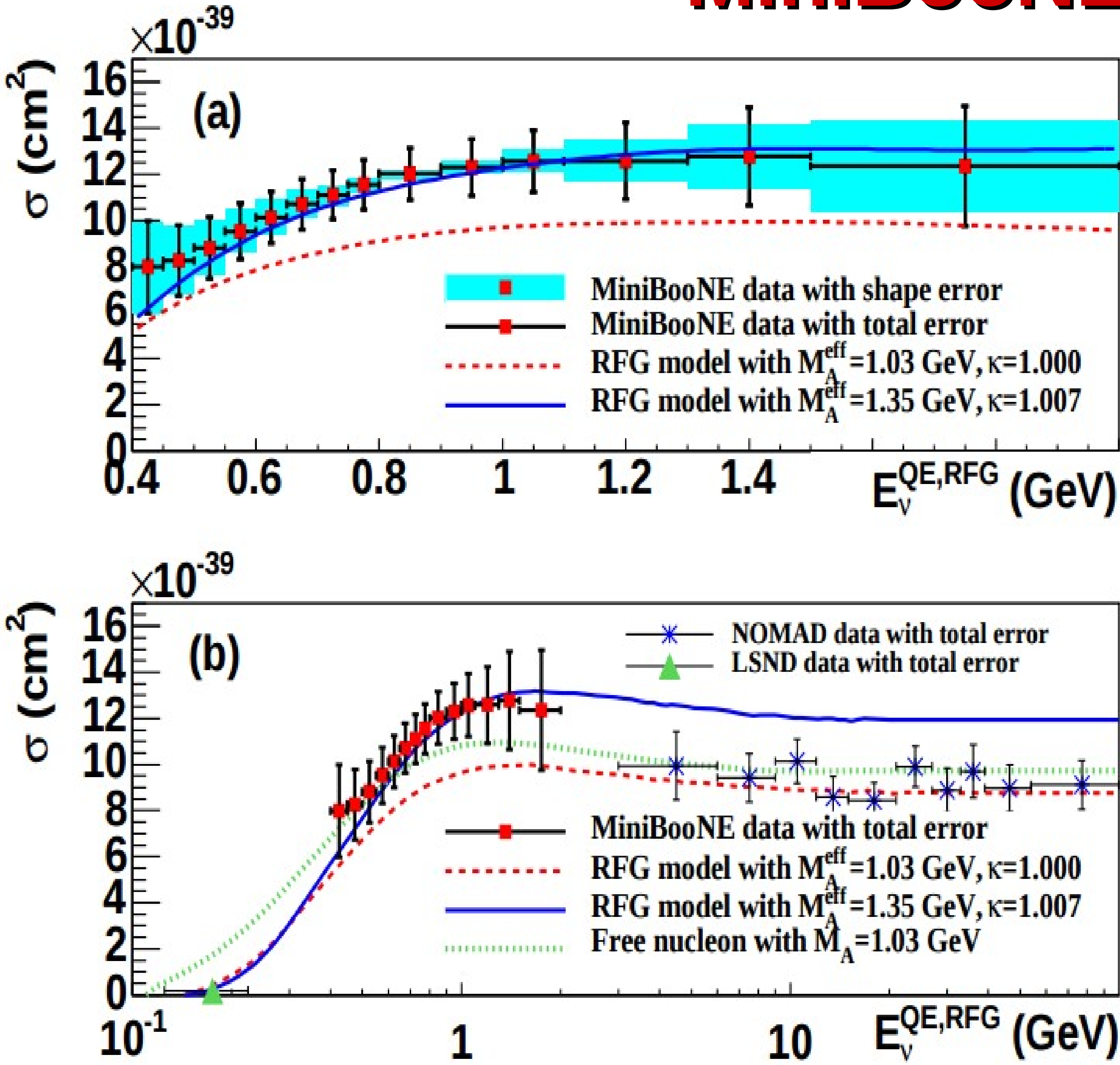

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- The most precision expe-riment. 2-differential cross-sections.
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- We avoided discussion of low energies.Irrelevant for the future PINGU / ORCA megaton experi-ments.

ES and QES off proton/neutron

QES

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

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

$$\nu_l + p/n \rightarrow \nu_l + p/n$$

ES

- These processes dominate at low energies.
- There is practically no threshold energy for the *ES*.
- The threshold energy for QES with $M_N = m_p$ or m_n

($m_n - m_p \approx 1.293$ MeV)

$$E_{\nu,th} \geqslant \frac{(m_l + M_{N'})^2 - M_N^2}{2\, M_N} \simeq m_l \left(1 + \frac{m_l}{2\, M_N}\right)$$

- For τ-lepton production with $m_\tau/m_\mu \approx 16.8$, $m_\tau/m_N \approx 1.9$

$$\mathbf{E_{\nu_\tau,th}/E_{\nu_\mu,th} \simeq 30}.$$

Theoretical approach to QES

In terms of the Mandelstam variables

$$s = (k+p)^2,\ t = -Q^2 = (k-k')^2,\ u = (k-p')^2$$

the differential cross-section of *QES*

$$\frac{d\sigma}{d|t|} = \frac{G_F^2 \cos^2\theta_C}{2\pi(s - M_N^2)^2} |\mathcal{M}^2|$$

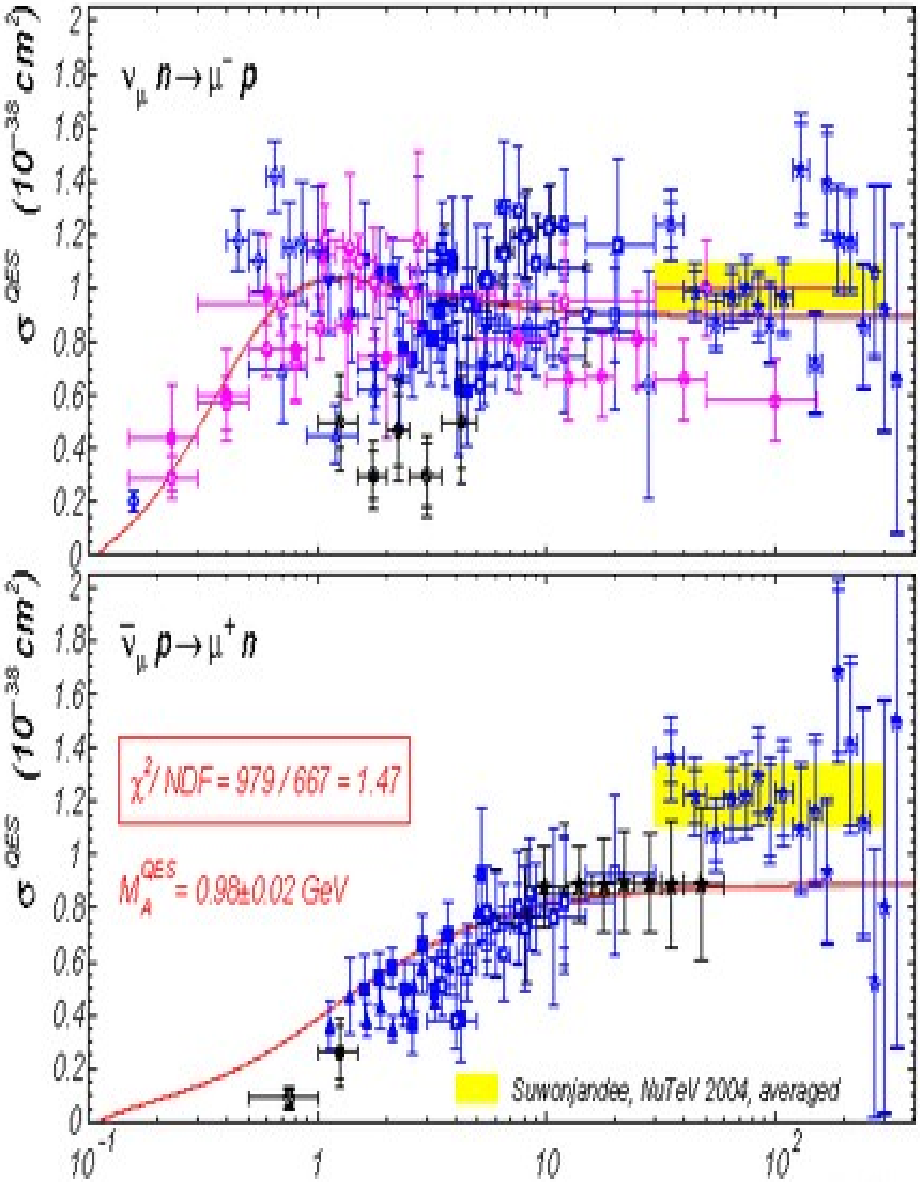
where $|\mathcal{M}^2| = A(t) - (s-u)B(t) + (s-u)^2 C(t)$.

See e.g. A. Strumia & F. Vissani, Phys. Lett. B564:42-54, 2003

A(t), B(t) and C(t) may be expressed in terms of vector and axial vector form factors. They are parametrized by the vector mass $M_V^2 = 0.71\ \mathrm{GeV}^2$ and the axial-vector mass $M_A^{QES} \approx 1.02\ \mathrm{GeV}$

$$F_A(Q^2) = \frac{F_A(0)}{(1+Q^2/M_A^2)^2}$$ with **$F_A(0) \approx -1.267$**

QES Cross Sections vs. Data



E [GeV]

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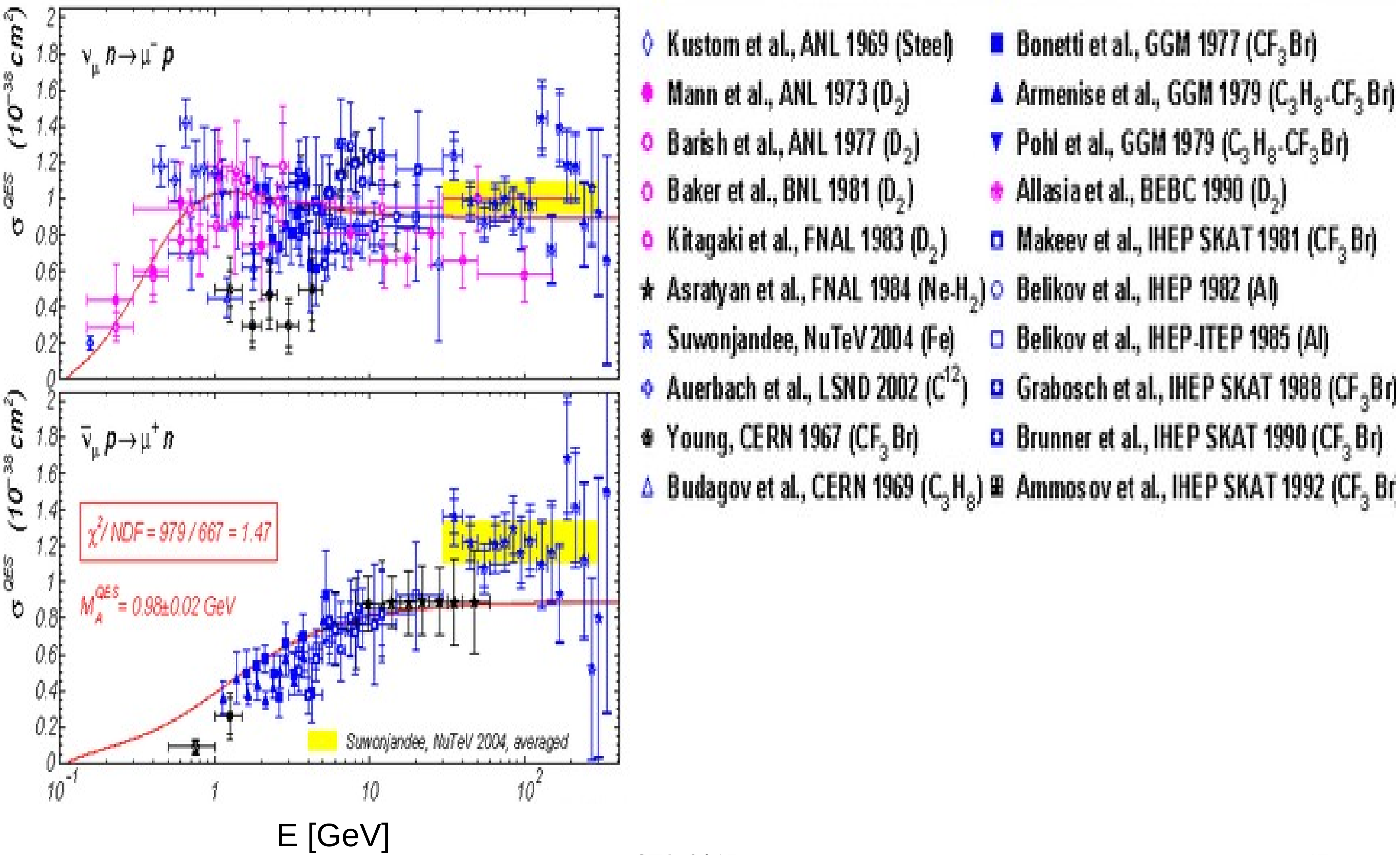

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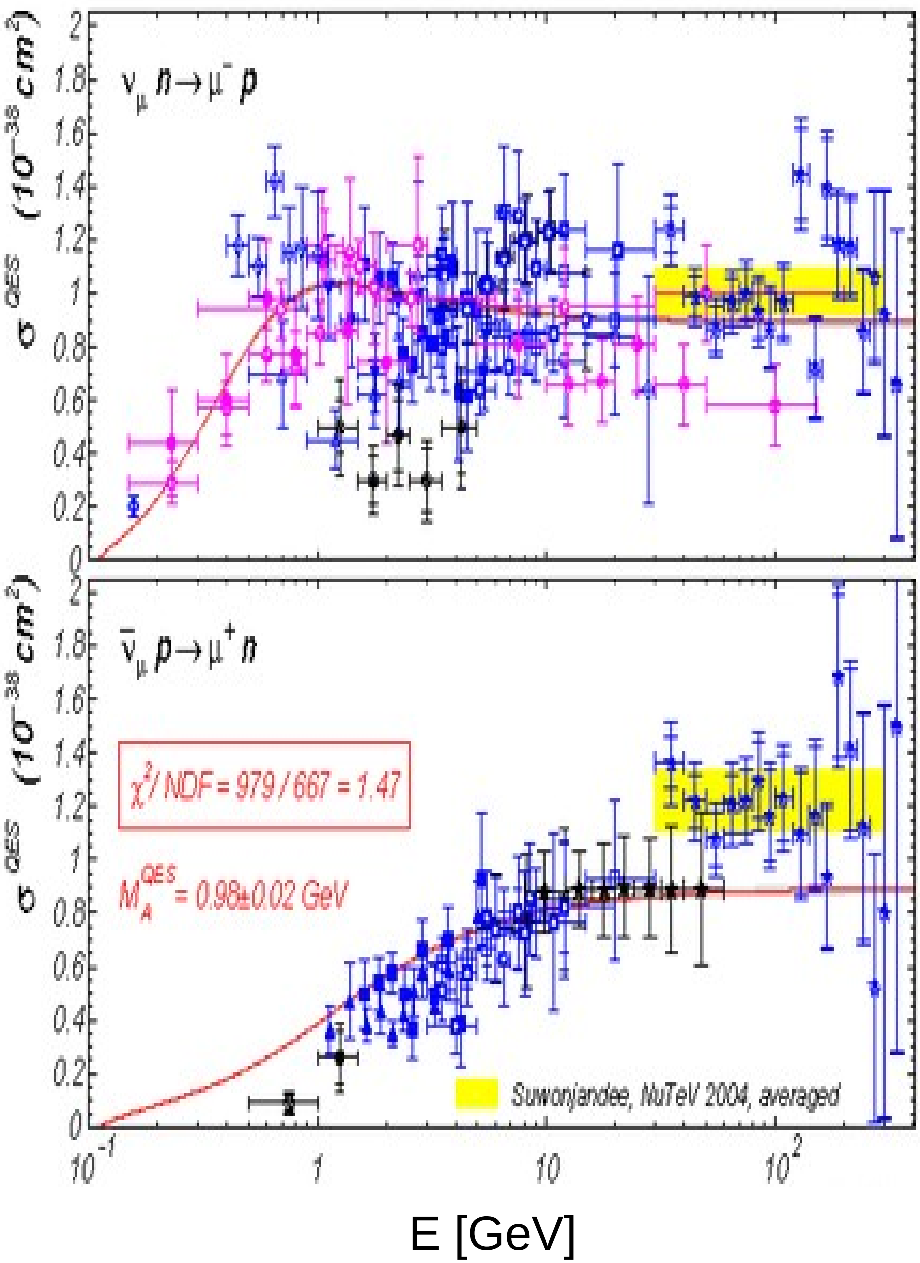

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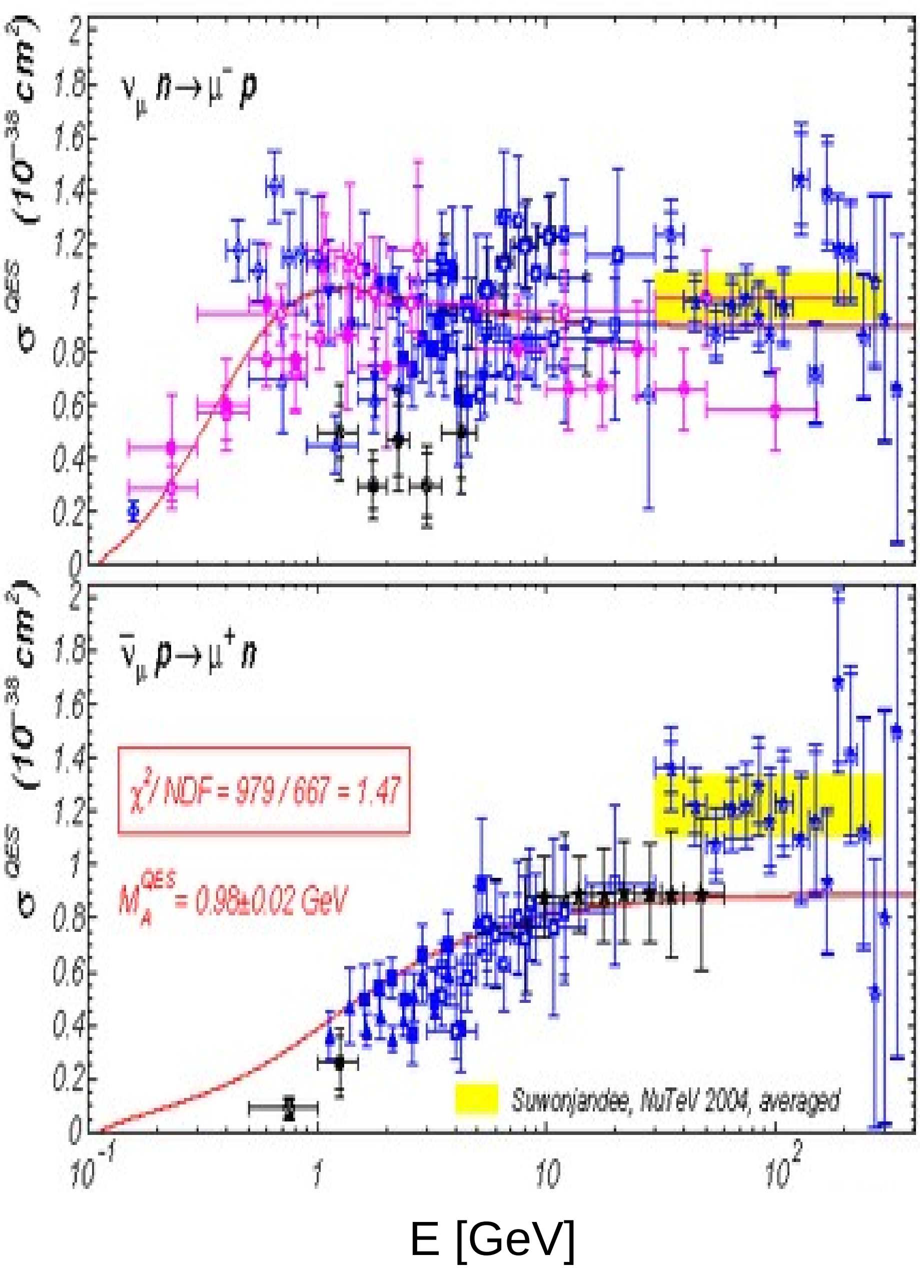

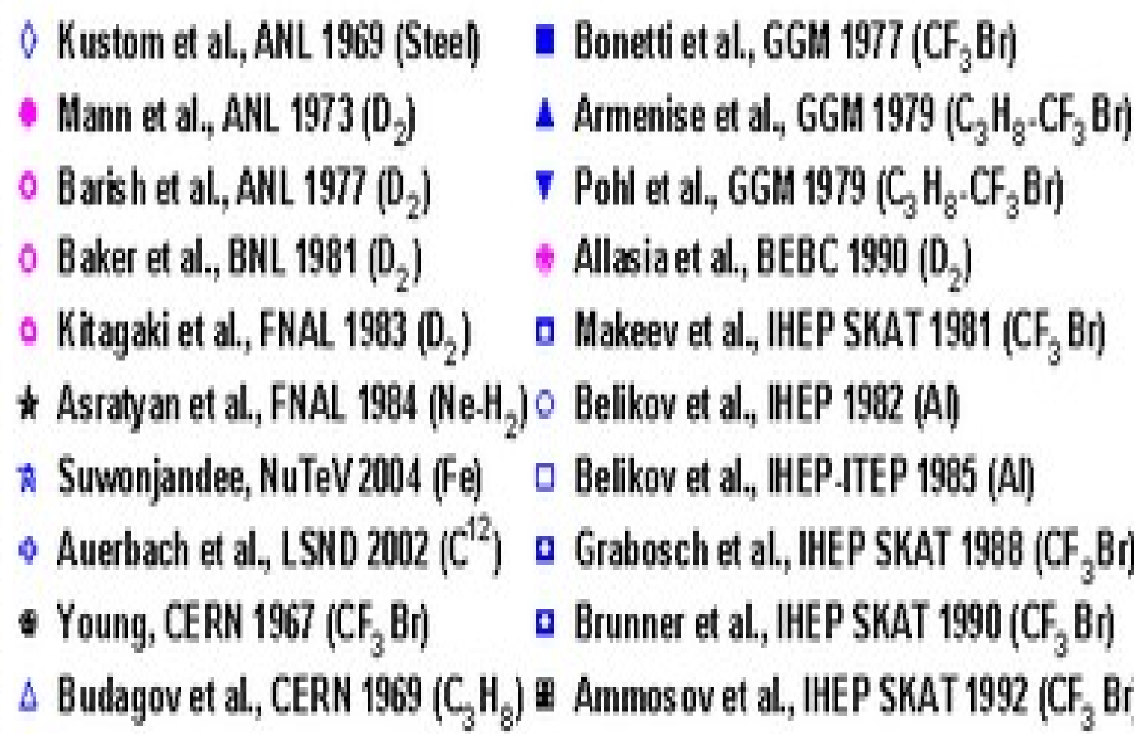

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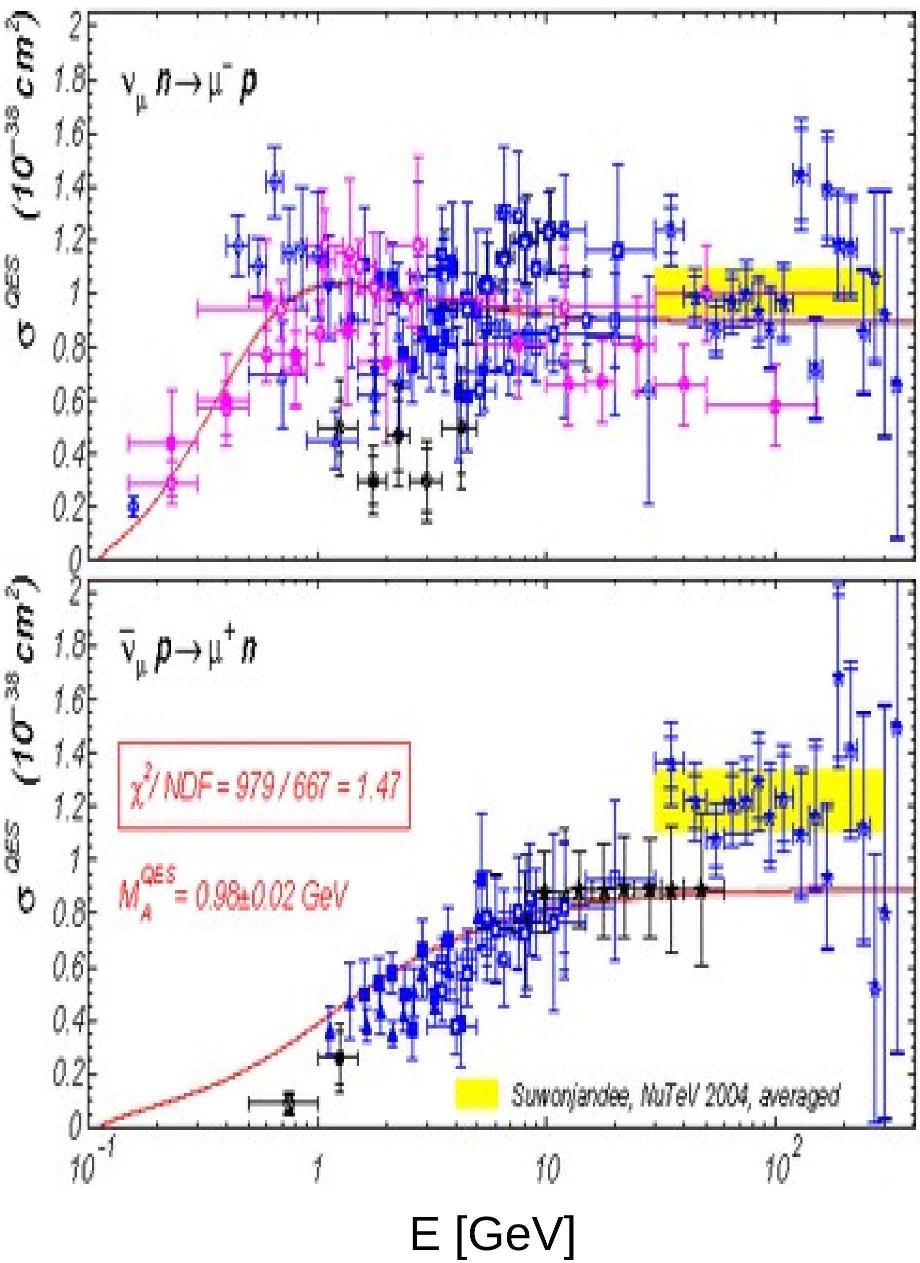

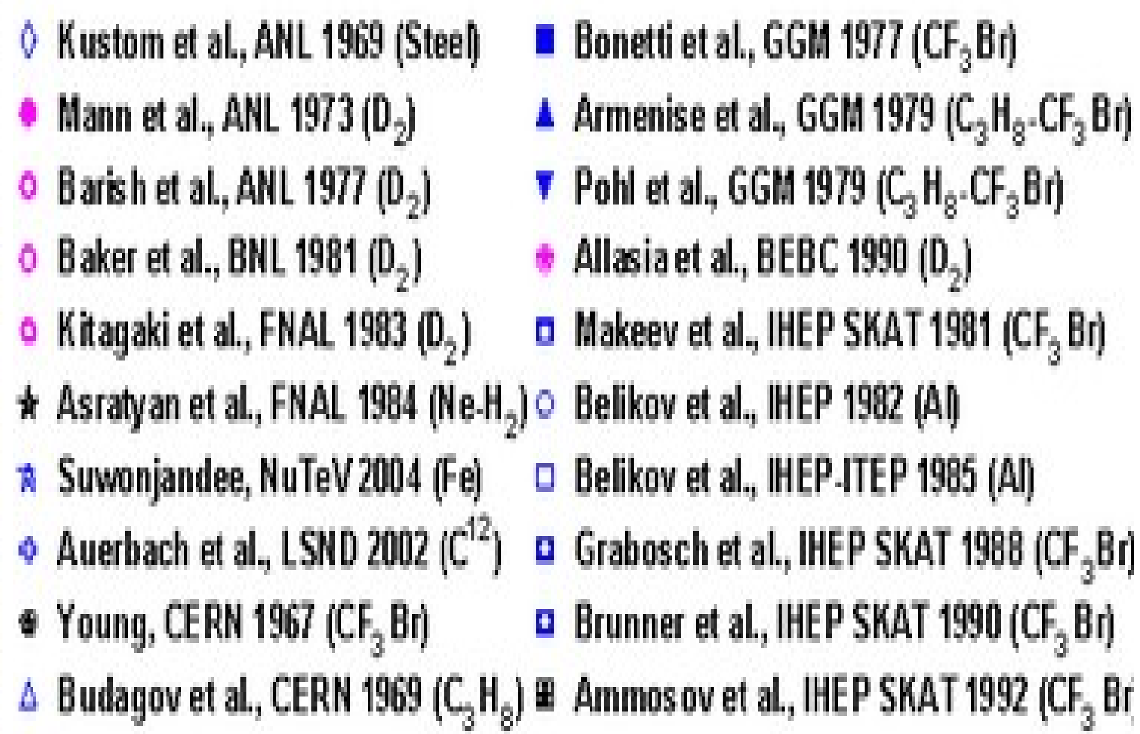

- Many experimental data differ.
- Different targets, different ν-flux-es, different methods.
- A global fit needs a careful choice of data to be included.

Sensitivity of QES to M_A

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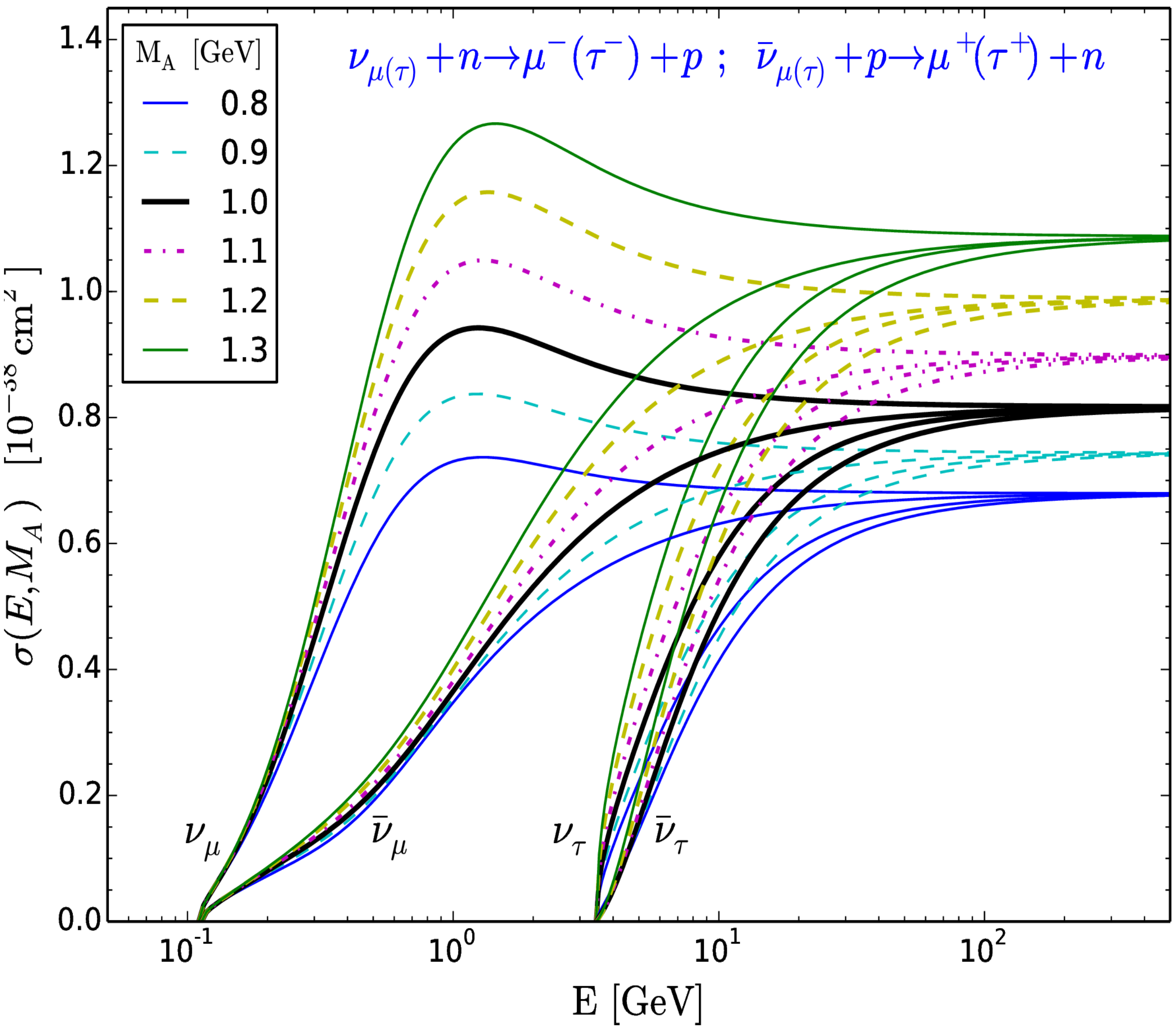

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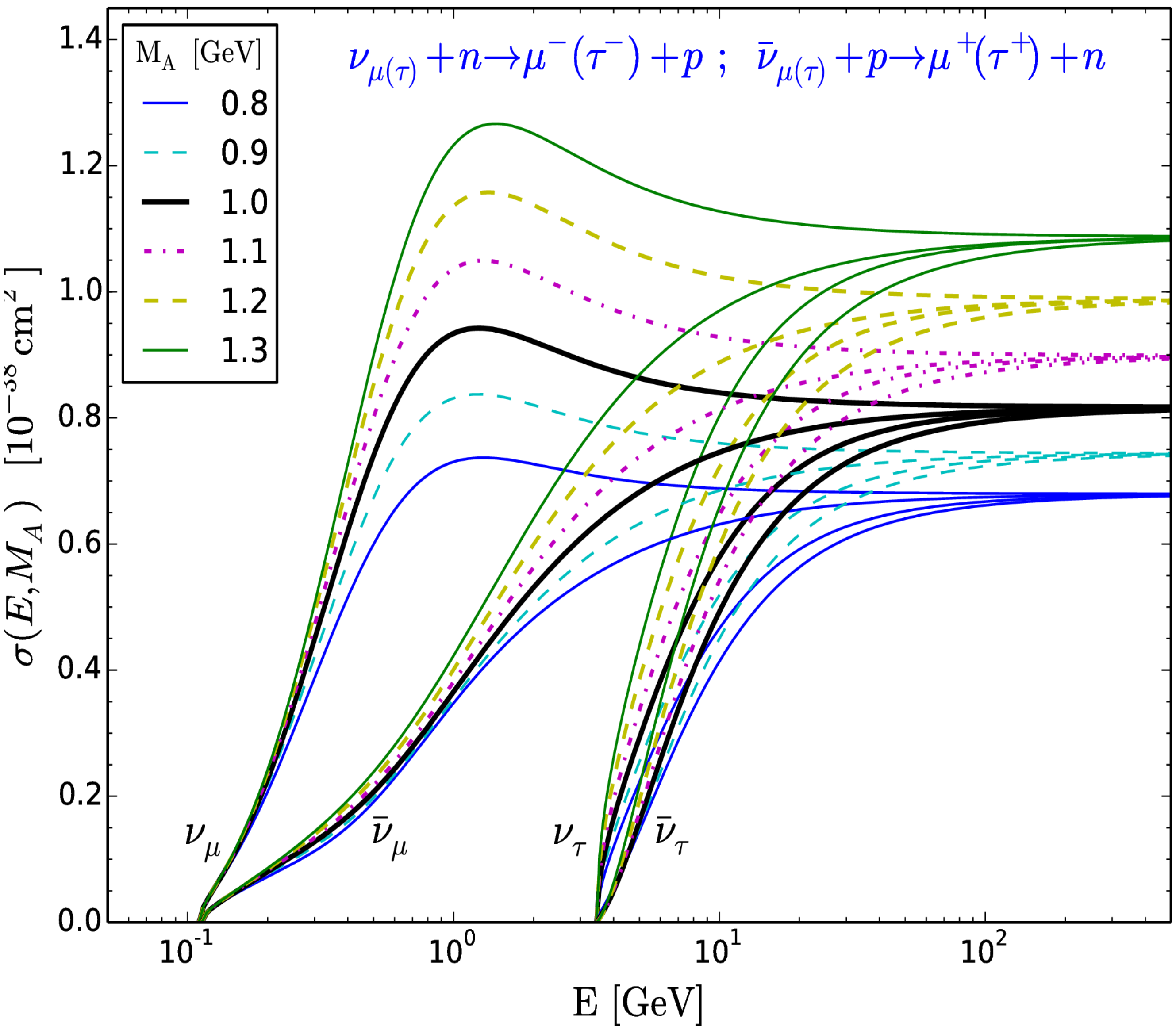

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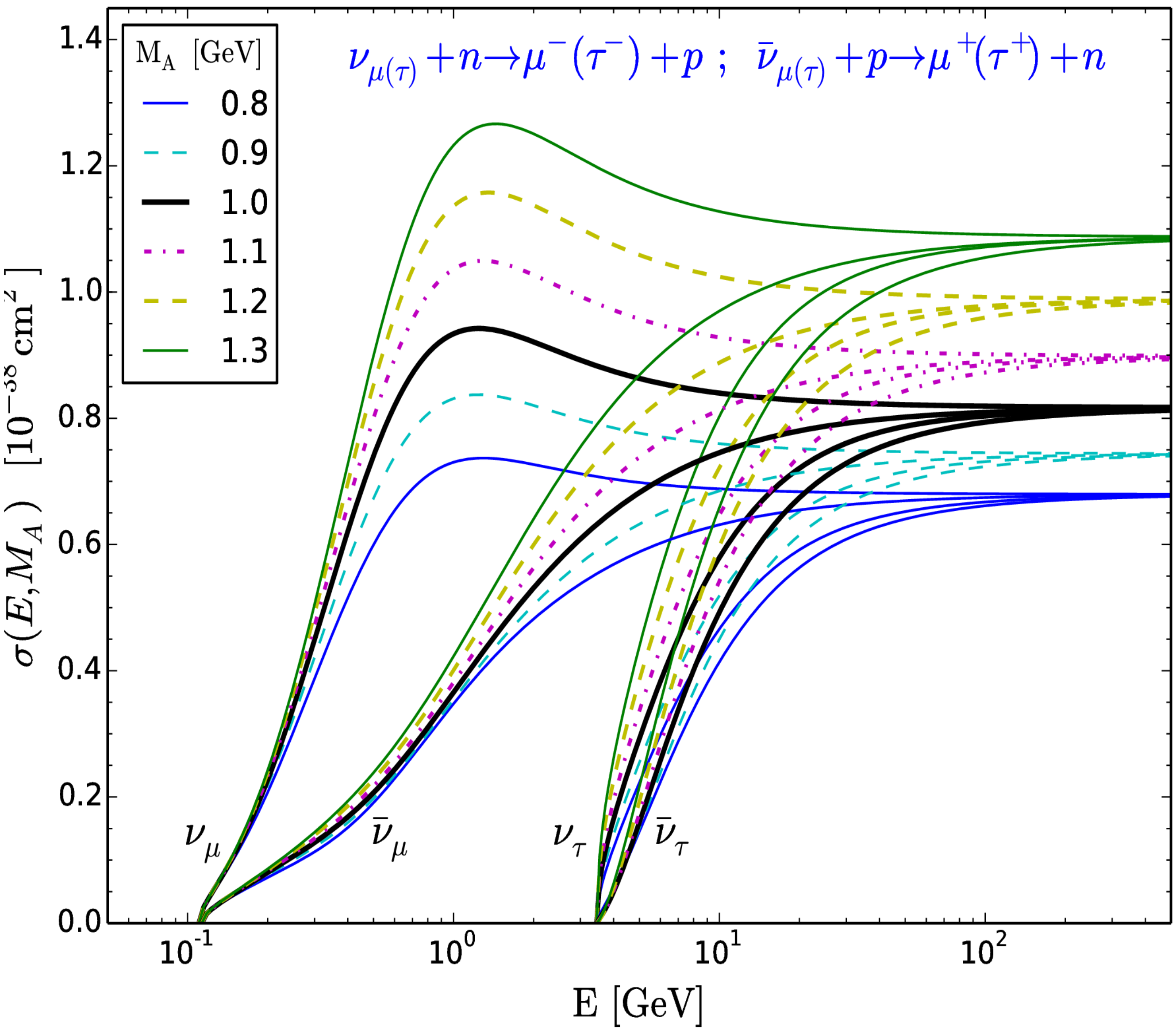

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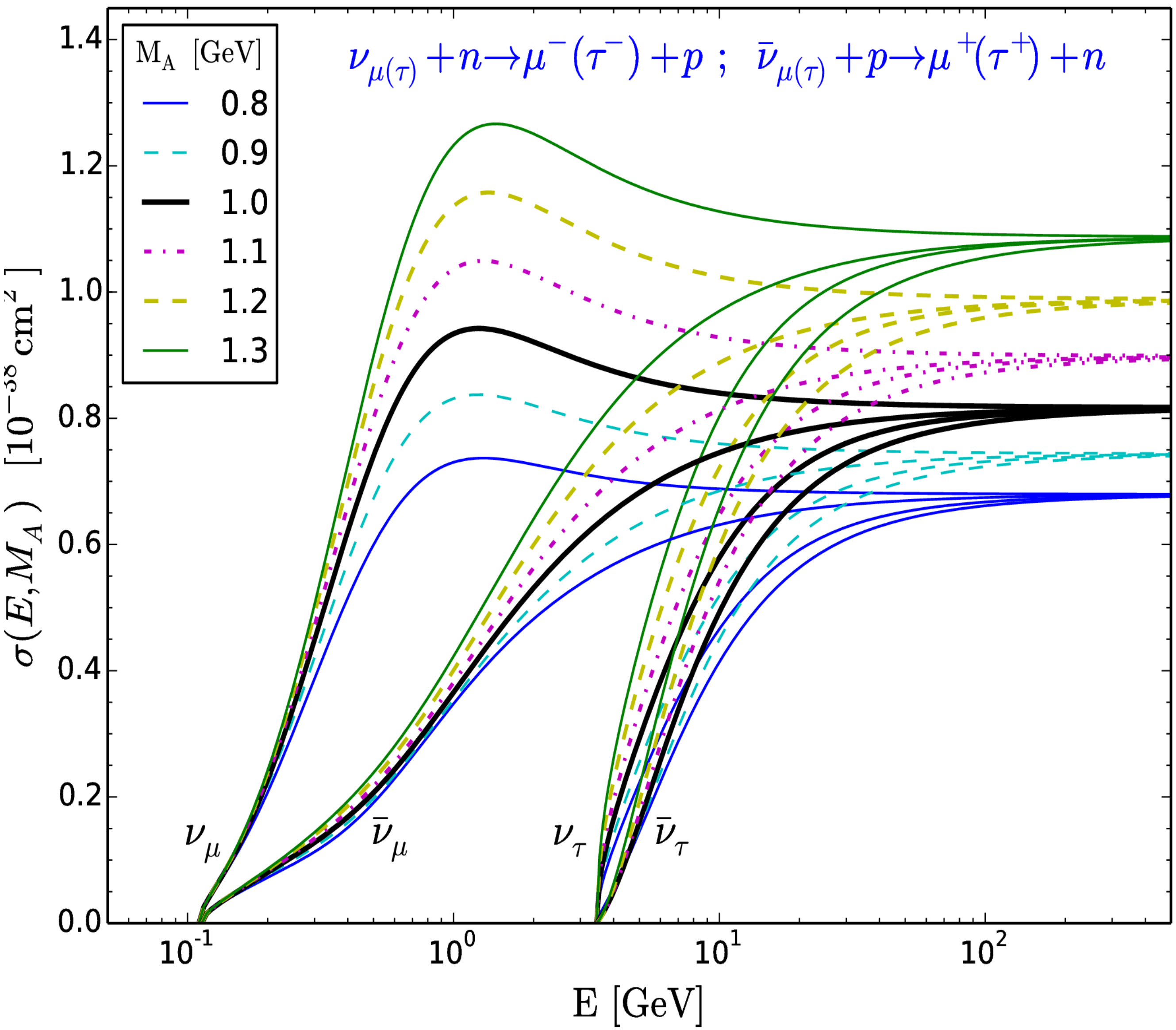

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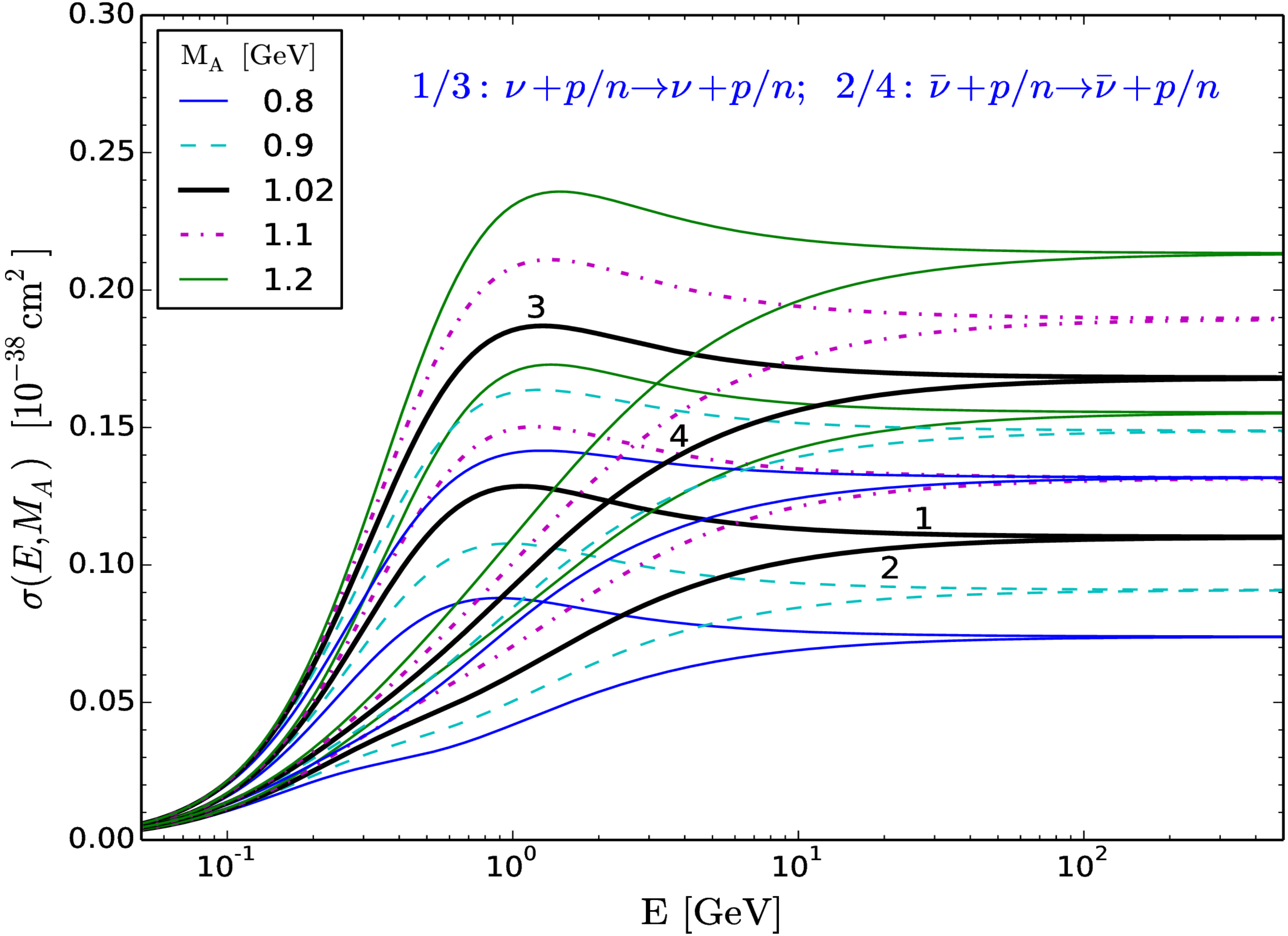
- At high energies QES cross-sections for ν and $\bar{\nu}$ coincide.

Sensitivity of ES to M_A



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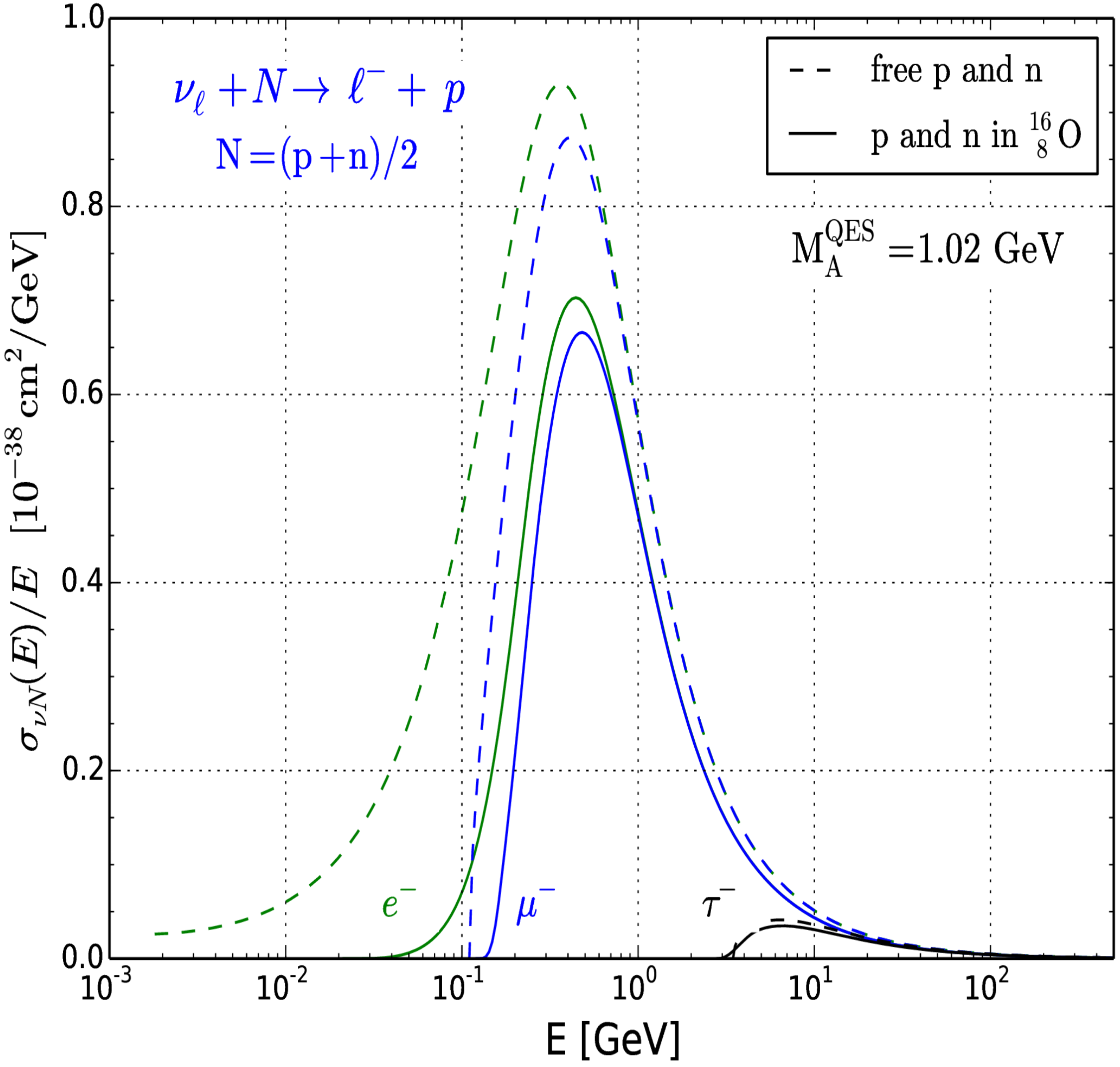

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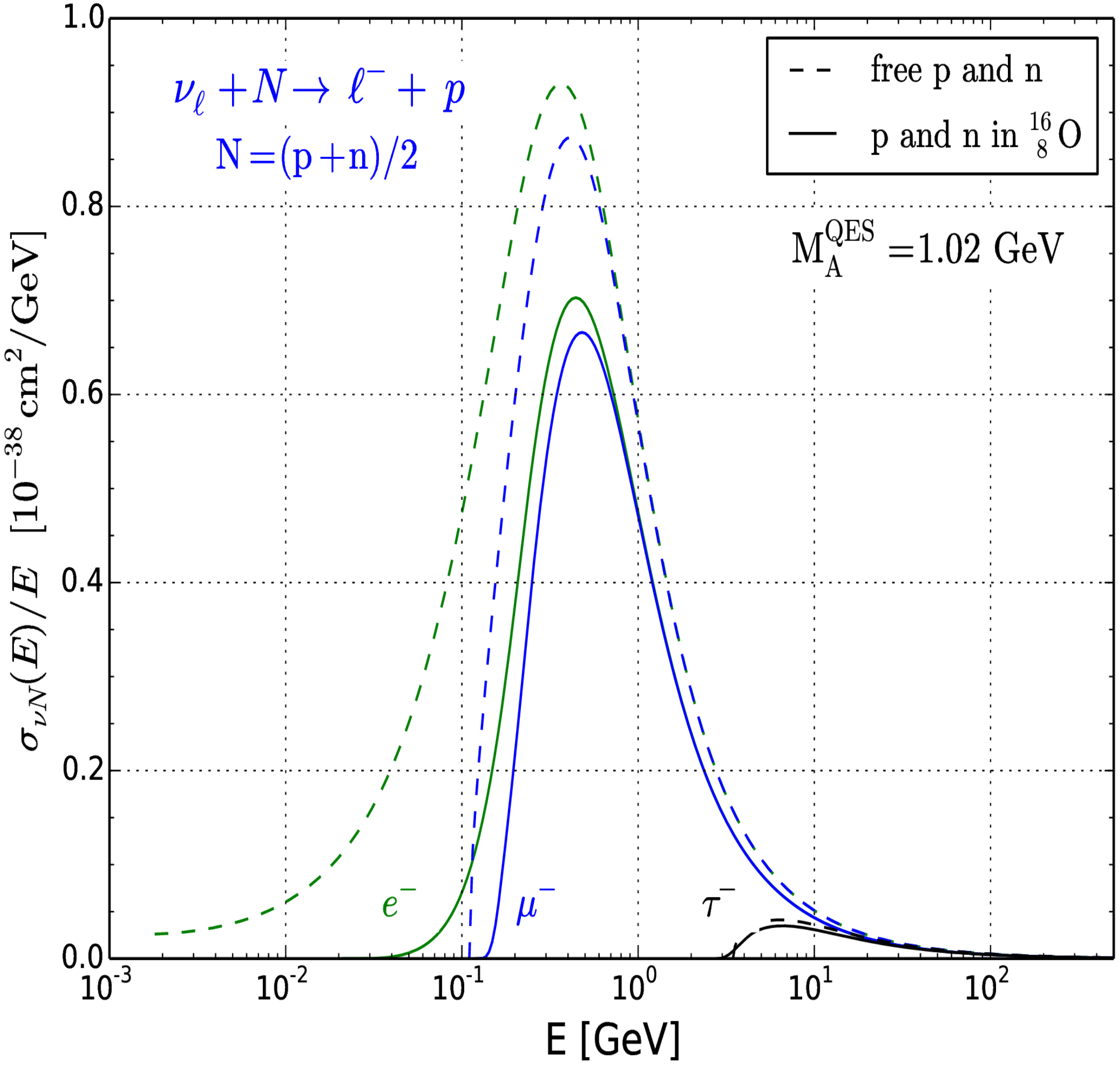

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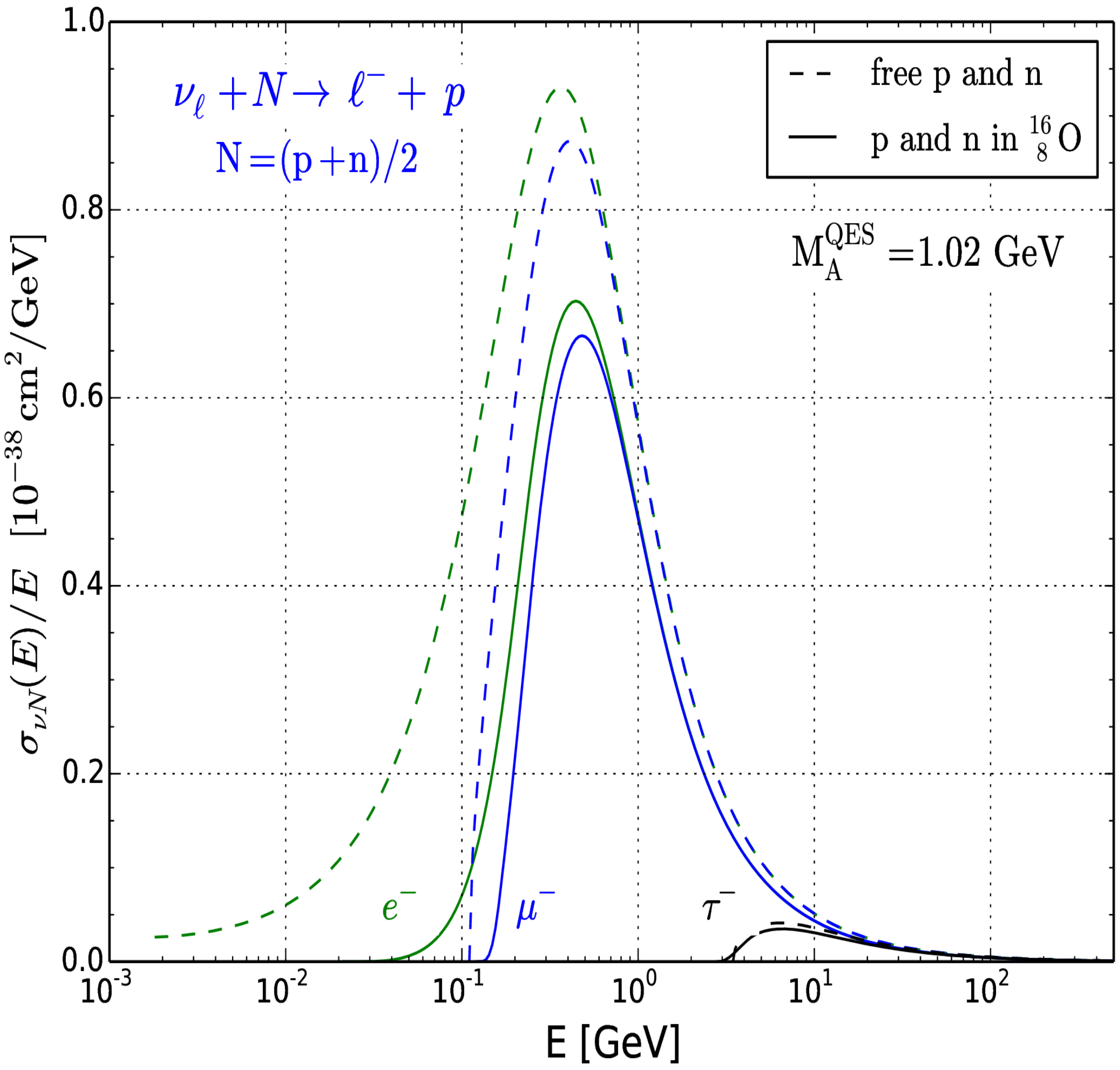

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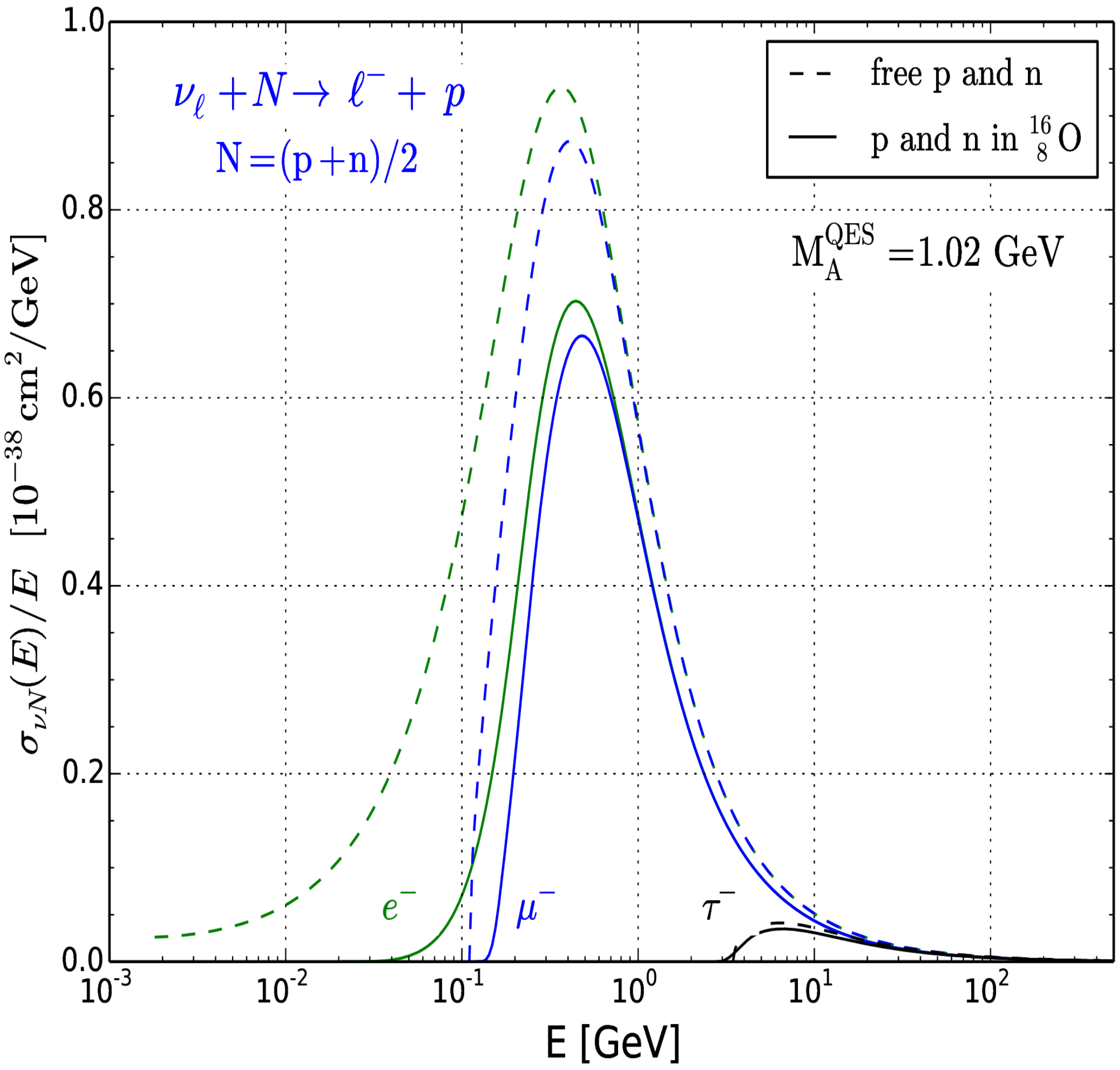

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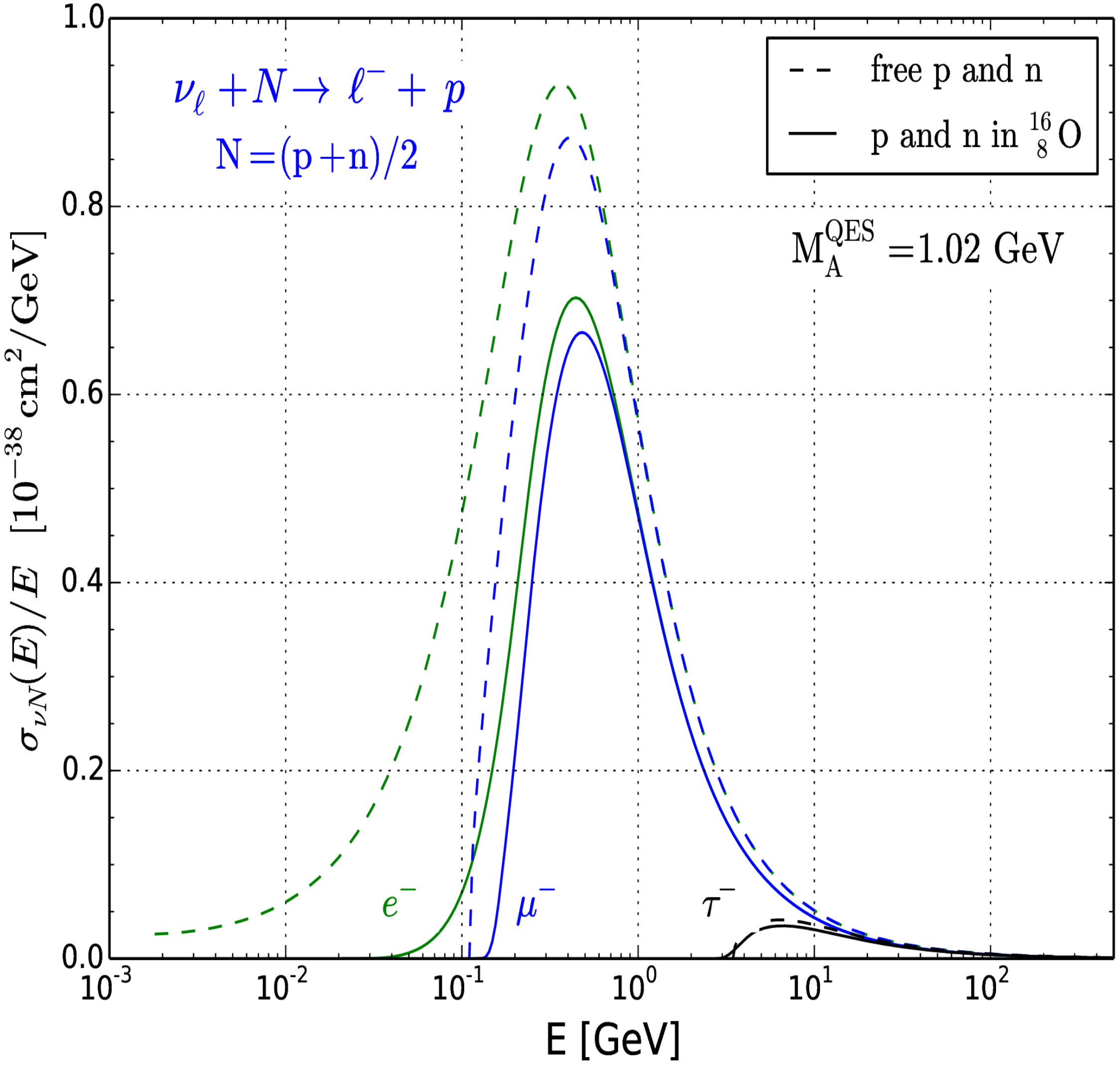

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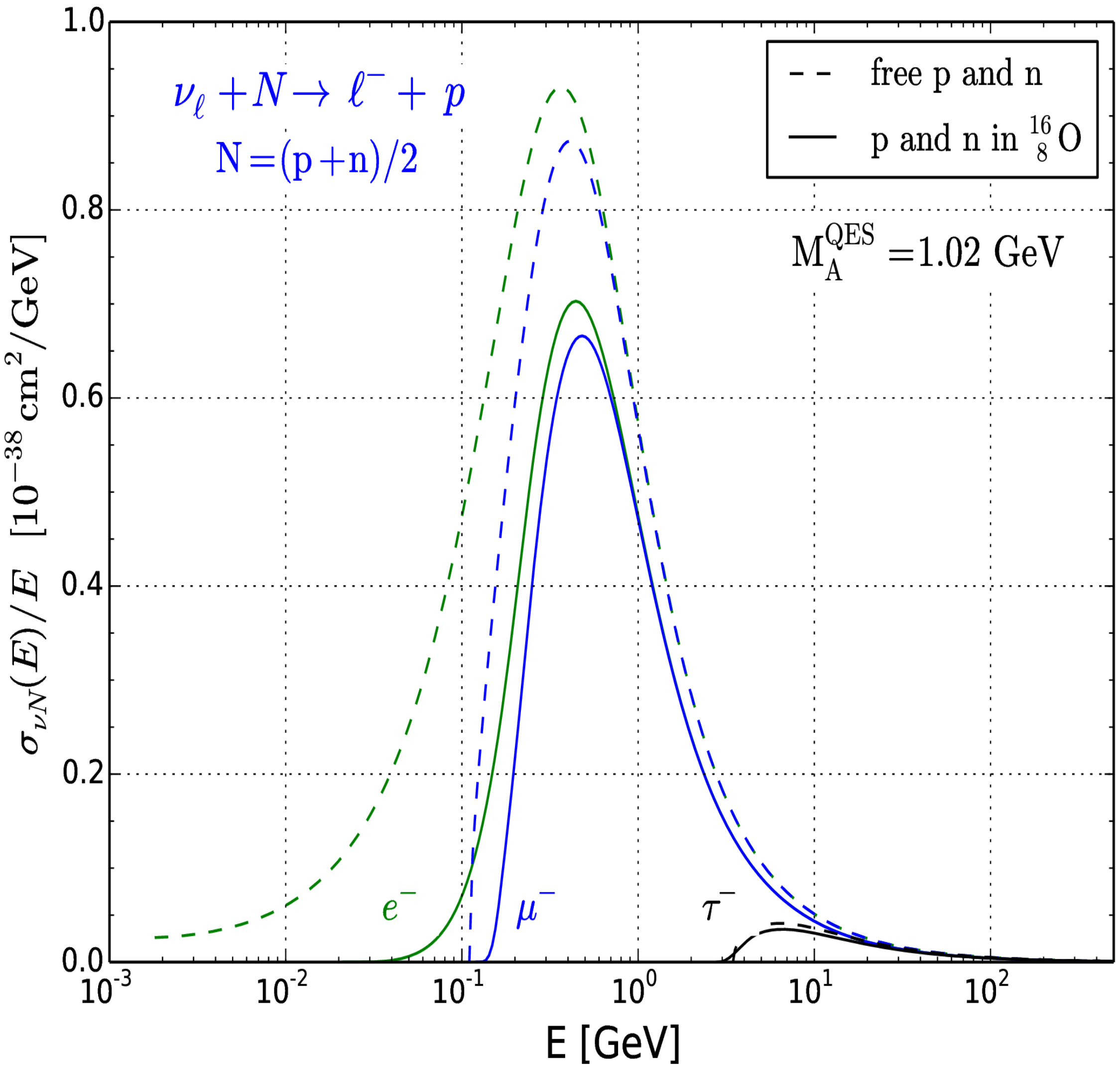

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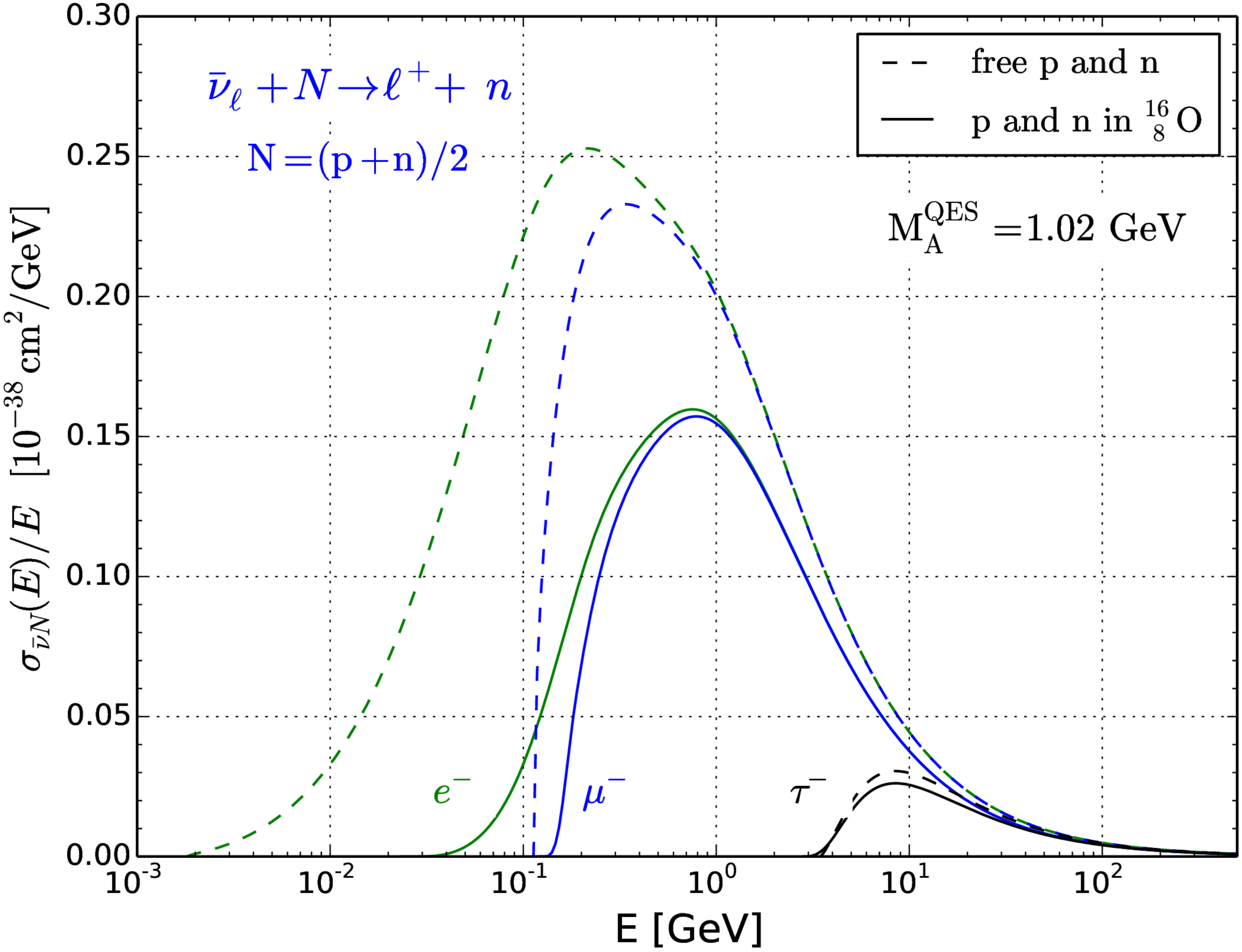
- The difference is just at small energies lower than interesting for PINGU.
- But for future HyperK lower energies are important.

ES off Oxygen Target



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- The RS model was extended (ExRS) to account for the finite mass of secondary leptons in the case of CC-scattering.

Nucleon Resonances with M < 2 GeV

according to PDG-2014

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S_{11}	$N(1650)$	$[70, 1^-]_1$	1645–1670 (1655)	110–170 (140)	50–90 (70.0)	+
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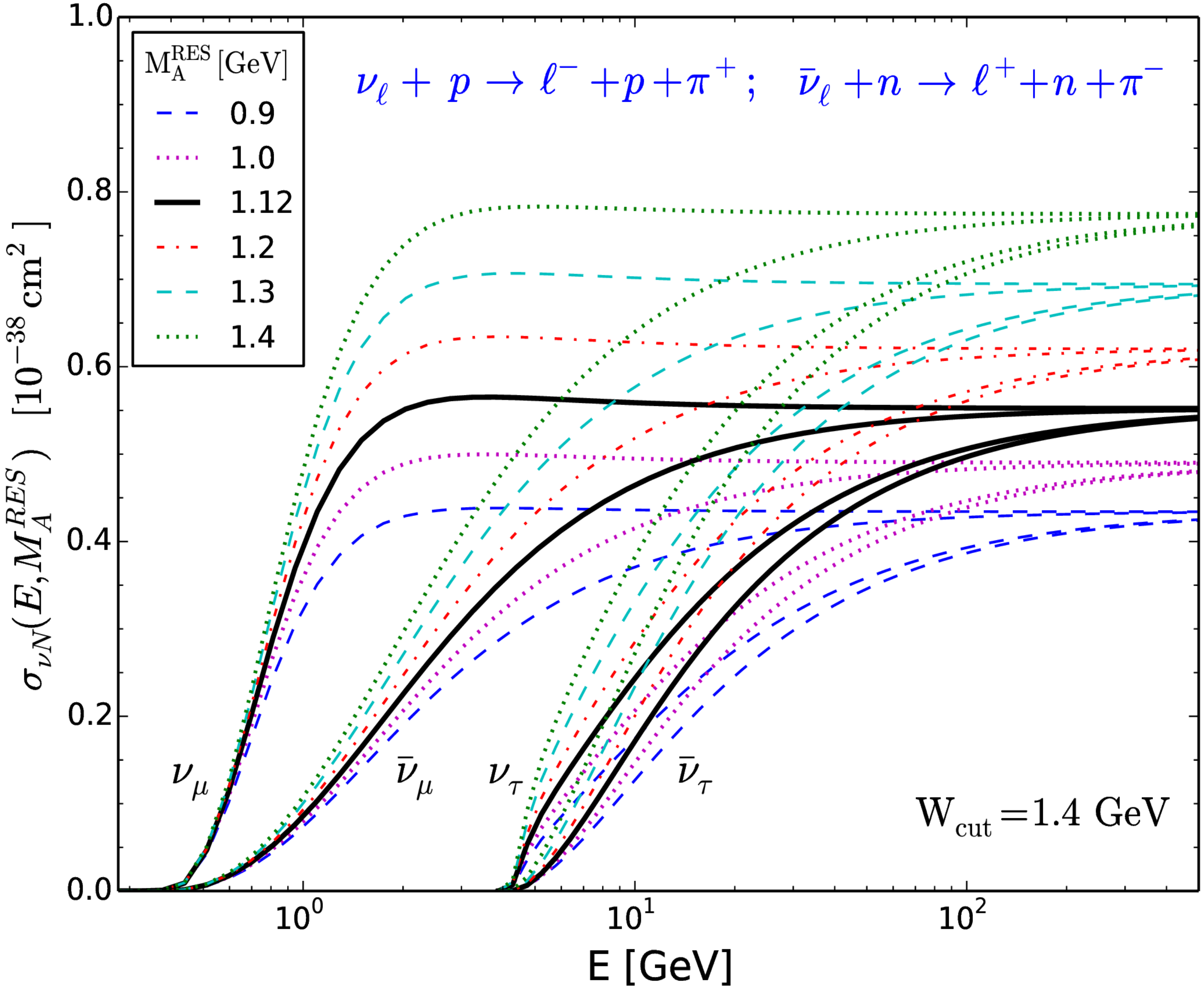
Single Pion Production (RES), cont.

- Besides resonances, a non-resonance background is to be added (general problem!).
- Relative normalization of contributions from different resonances is a problem, though **Δ(1232)** dominates.
- To avoid a double counting with DIS, the maximum mass of the bound πN state is to be defined – the **W_{cut}**.
- We find W_{cut} = 1.4 GeV to be the best fit in our approach.
- It's choice is a general problem as well. Experiments also present date for different W_{cut} from 1.1 GeV up to 2 GeV.
- It will be discussed later.

Sensitivity of RES to M_A (CC 1)



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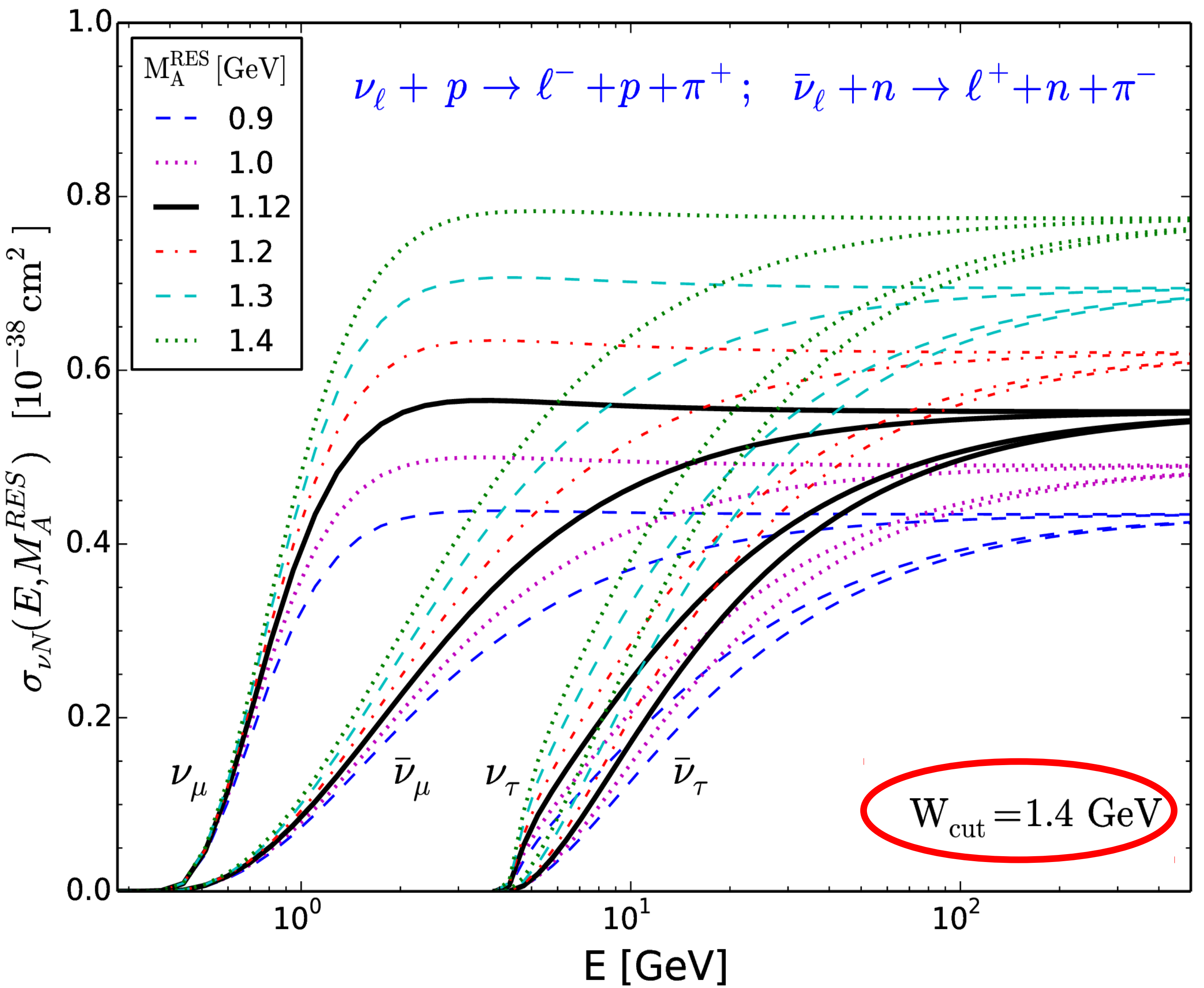

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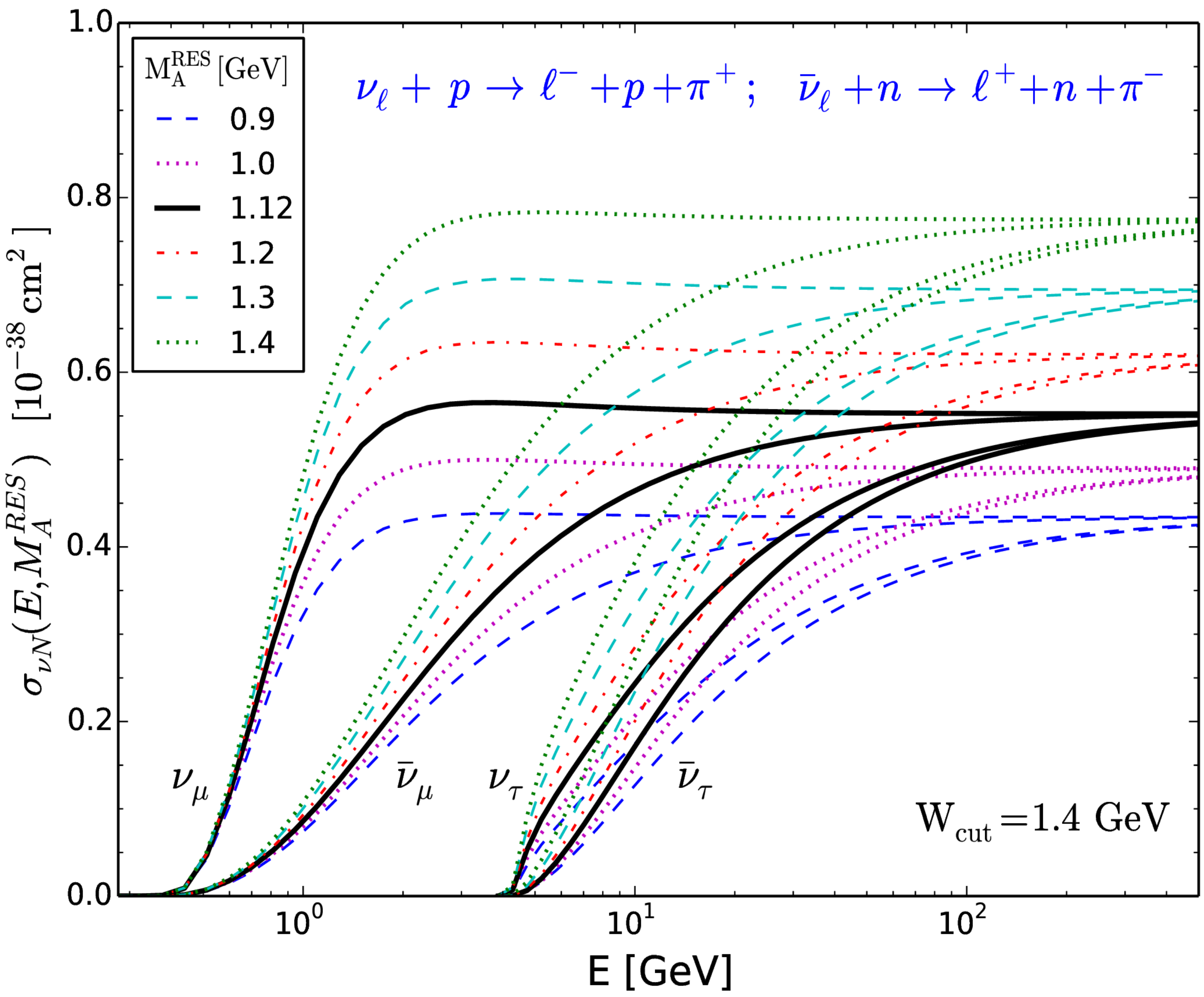
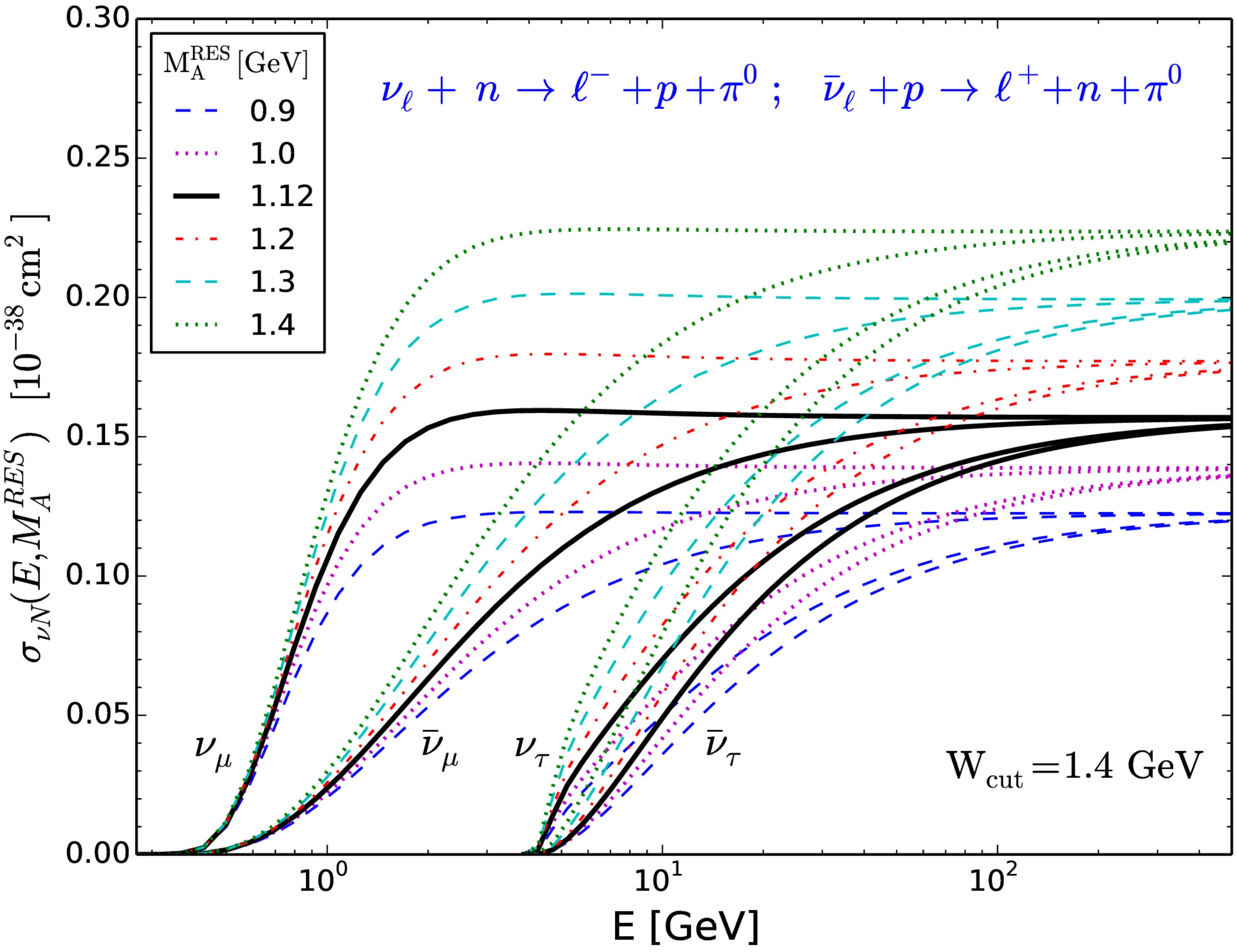
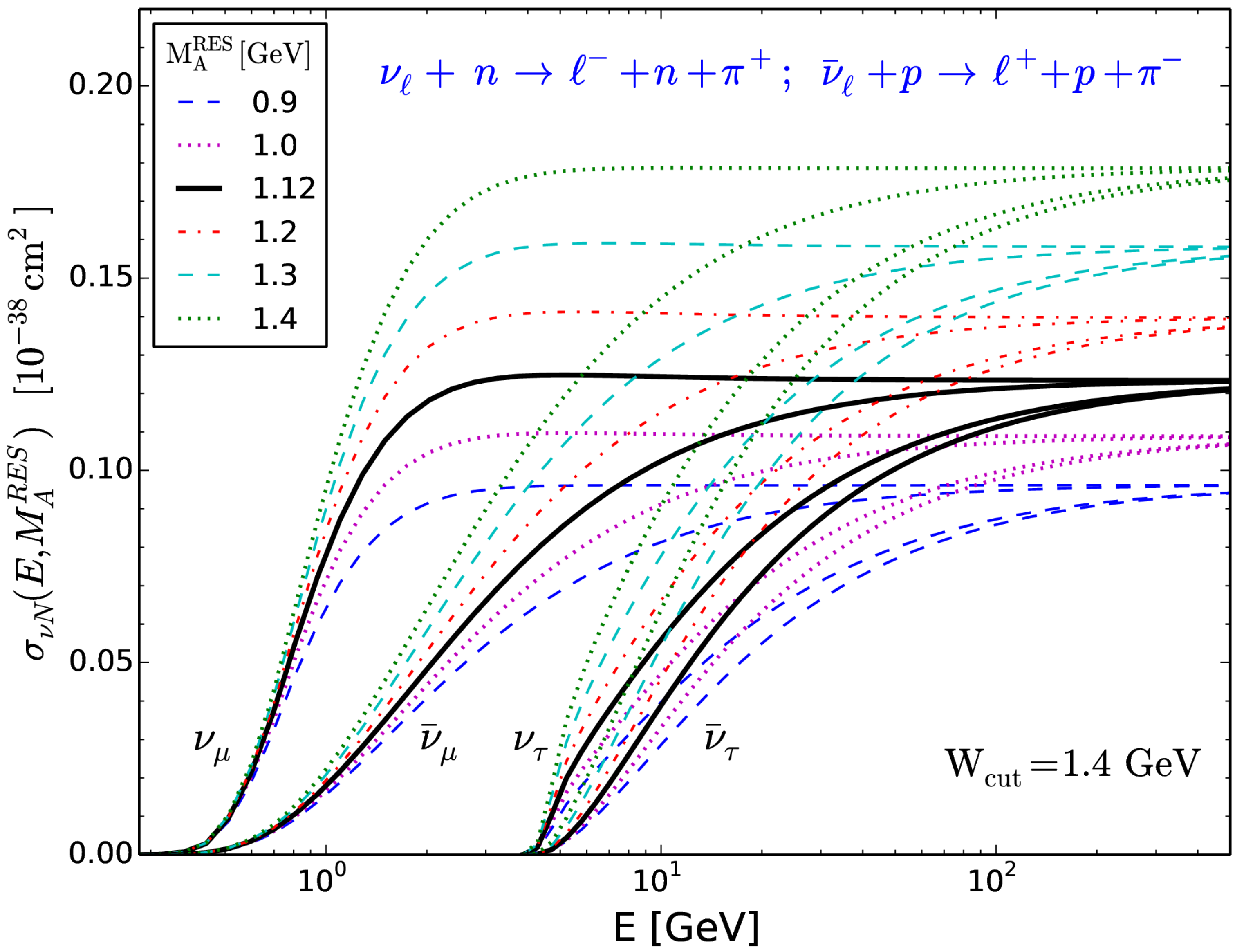


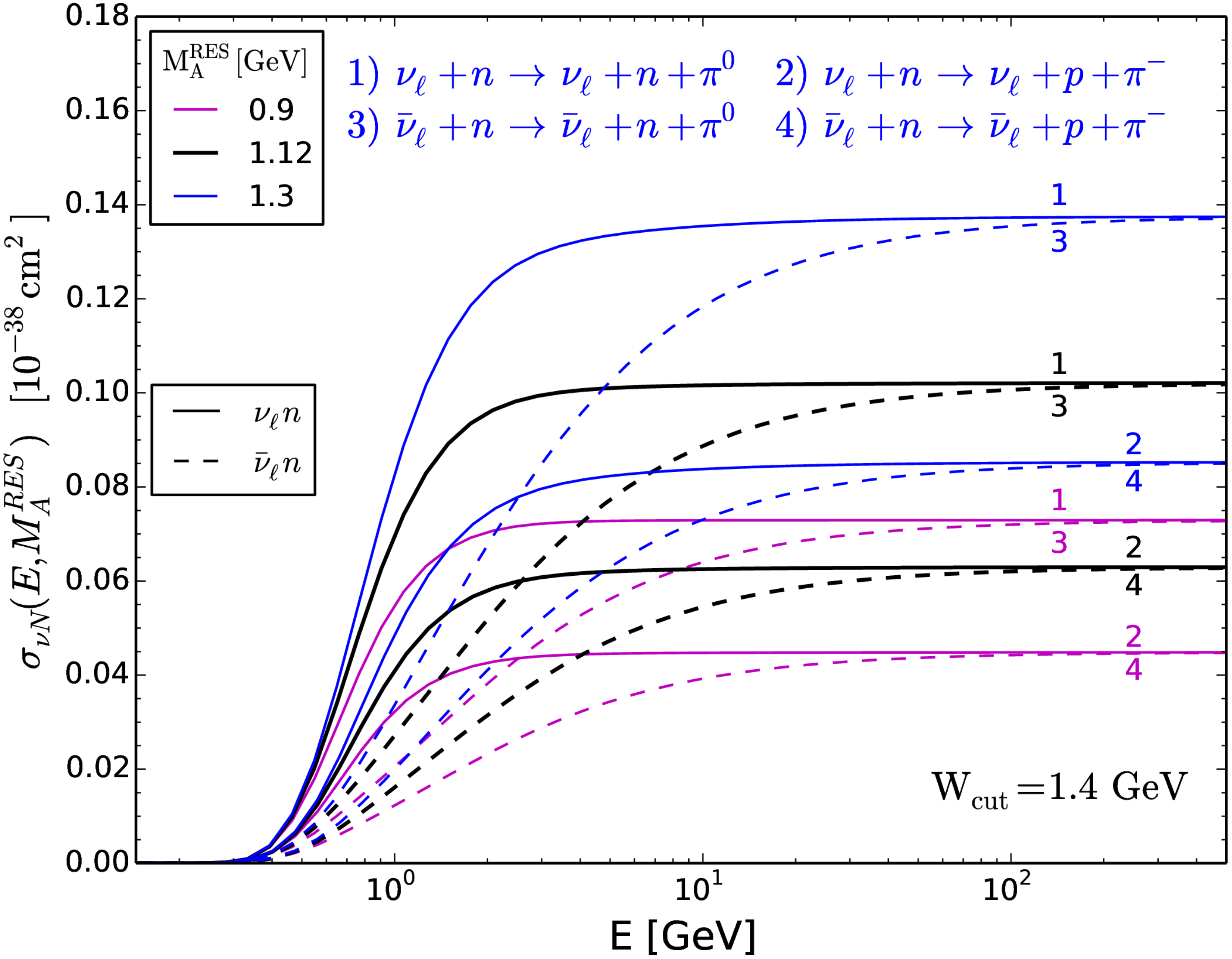
Sensitivity of RES to M_A (CC 2)



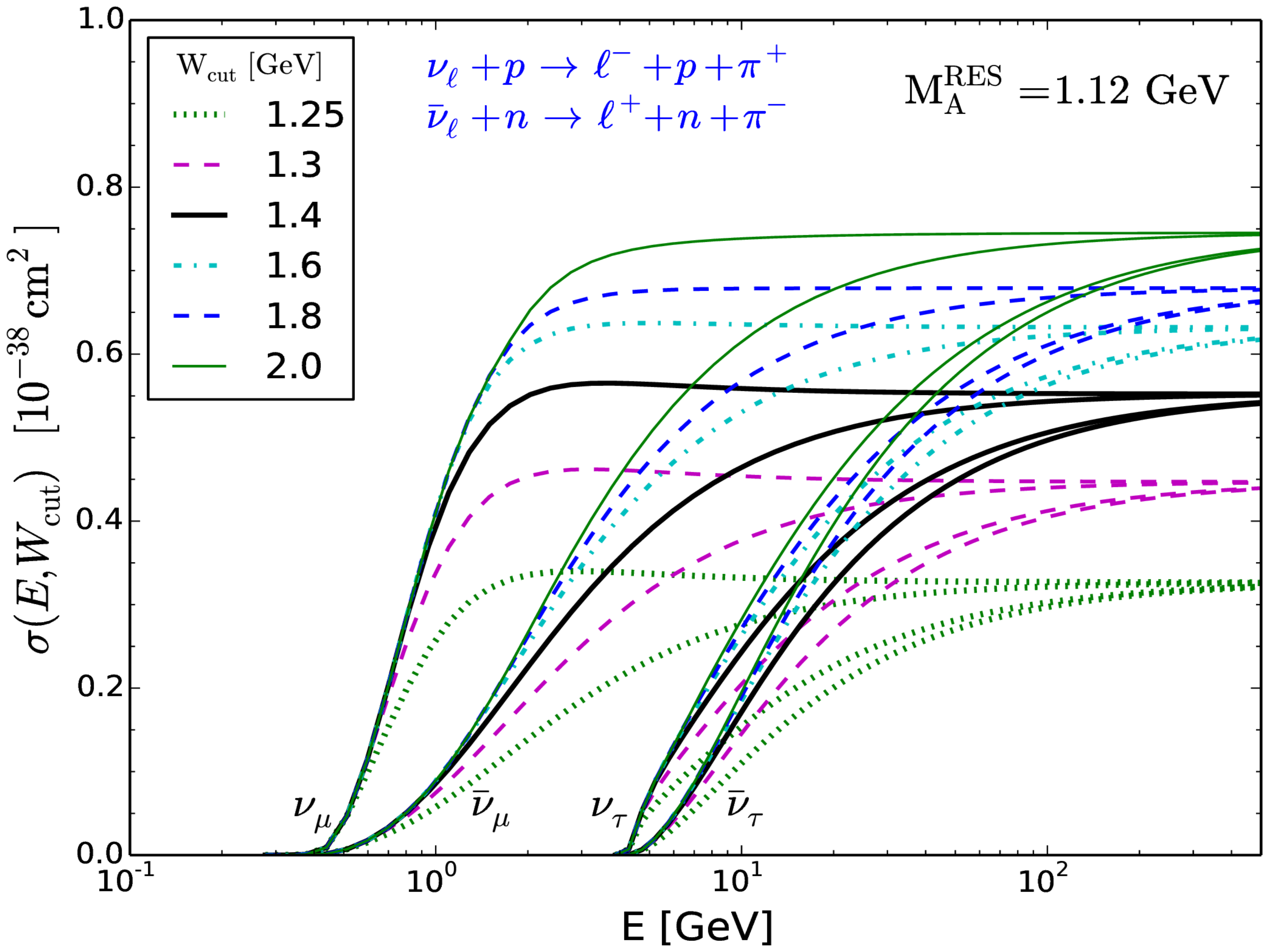
Sensitivity of RES to M_A (CC 3)



Sensitivity of RES to M_A (NC)



Sensitivity of CC RES to W_{cut}



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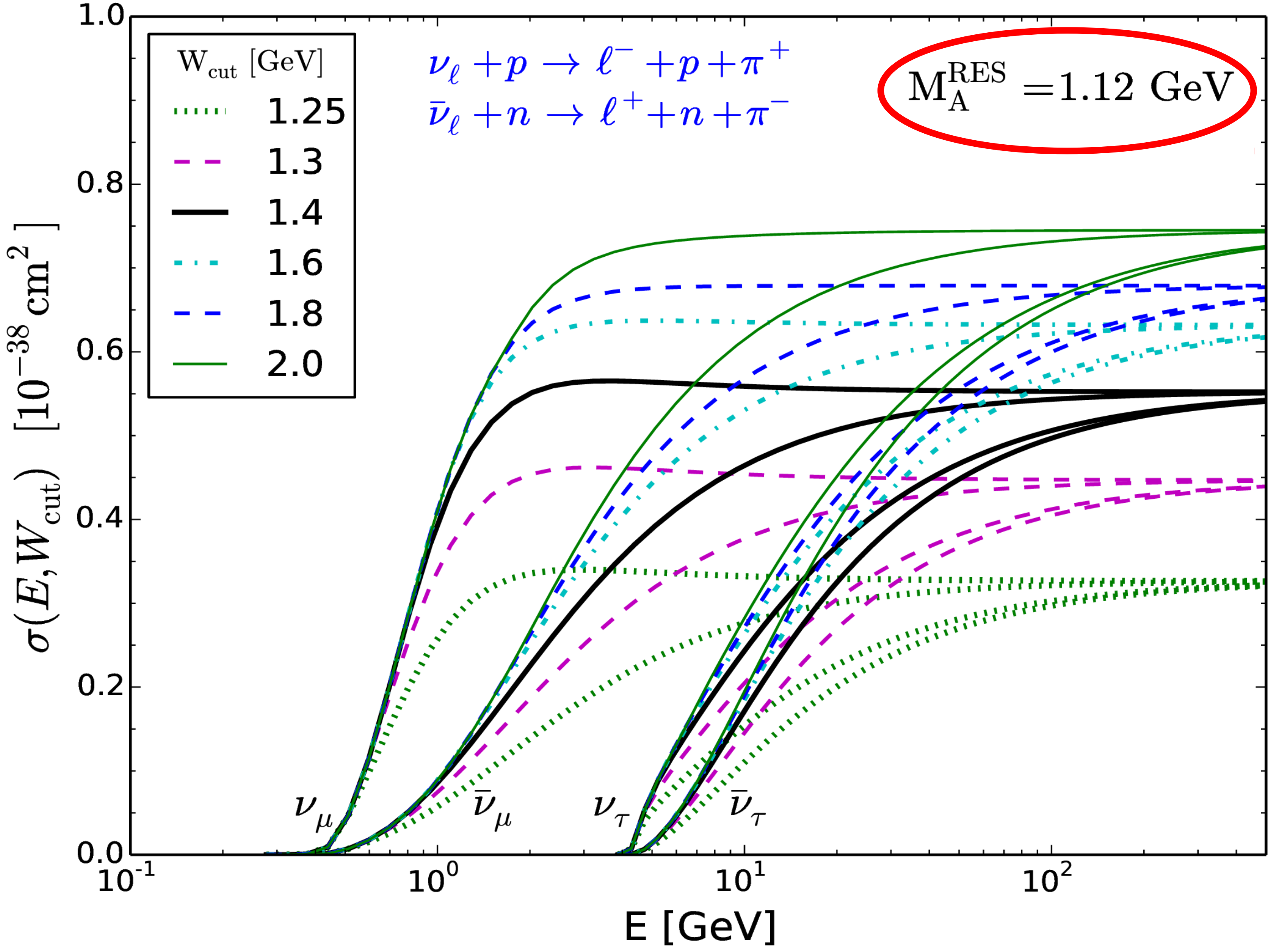

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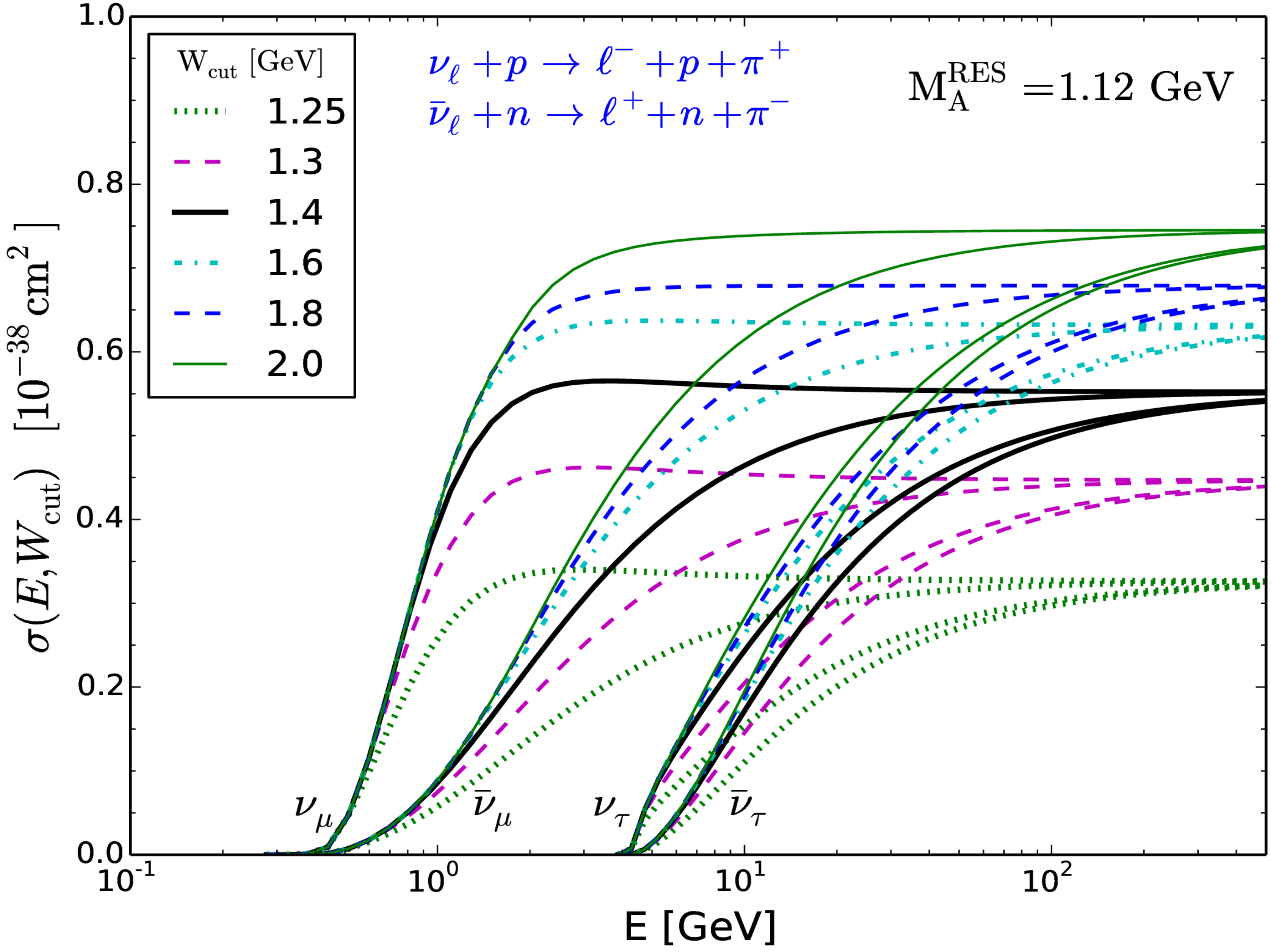
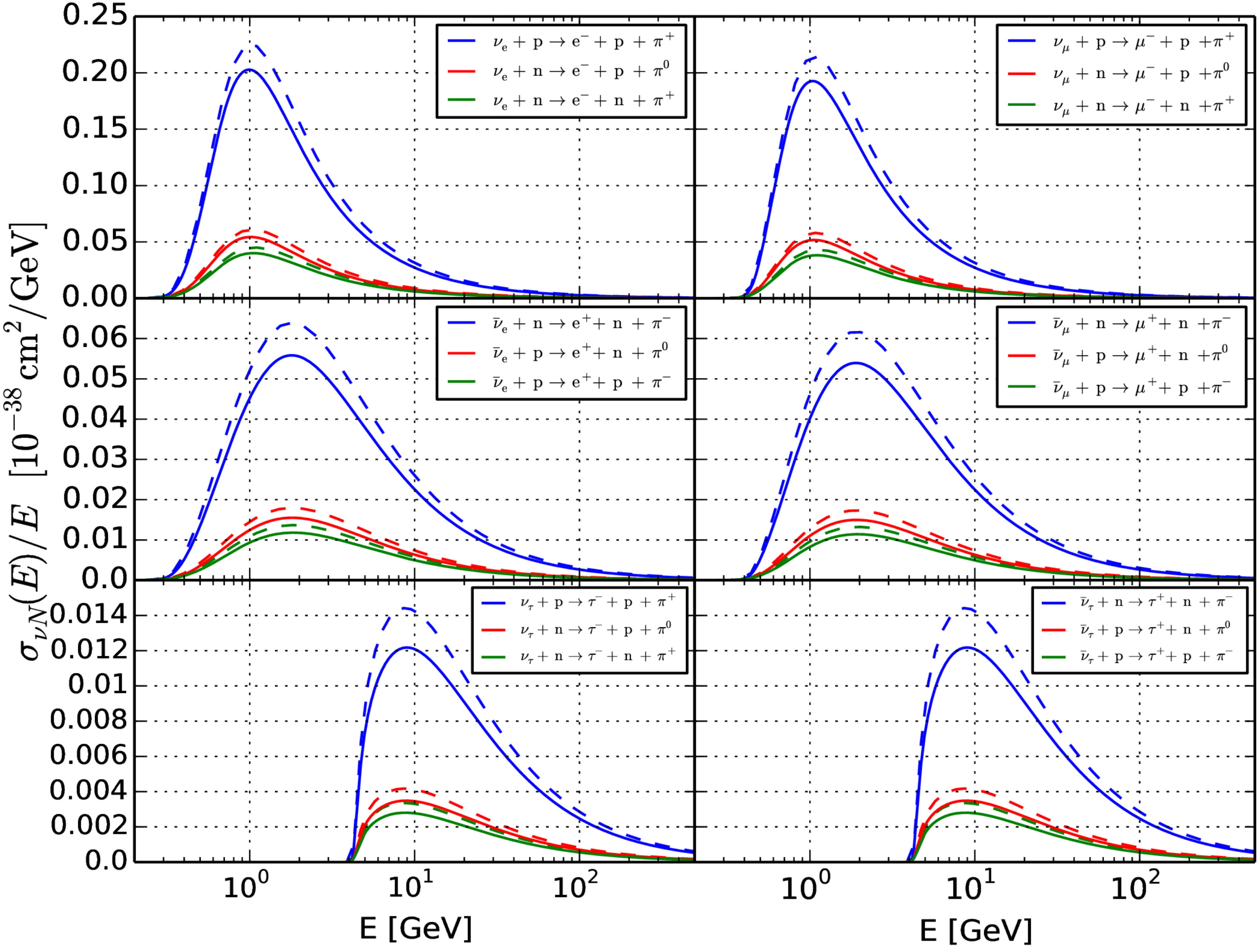


RES off Oxygen Target



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- DIS is the sum of cross-sections on all quarks in a nucleon.

QCD and Structure Functions

- At *LO* of perturbative QCD nucleon consists of valence quarks, “sea”-quarks and gluons.
- Sea quarks are $q\bar{q}$-pairs.They arise from qg- and gg-interactions.
- For unpolorized nucleons – 5 Sfs.

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dx\ dy}(E_\nu, x, y) = \frac{G_F^2 M_N E_\nu}{\pi(1+Q^2/M_W^2)^2}$$

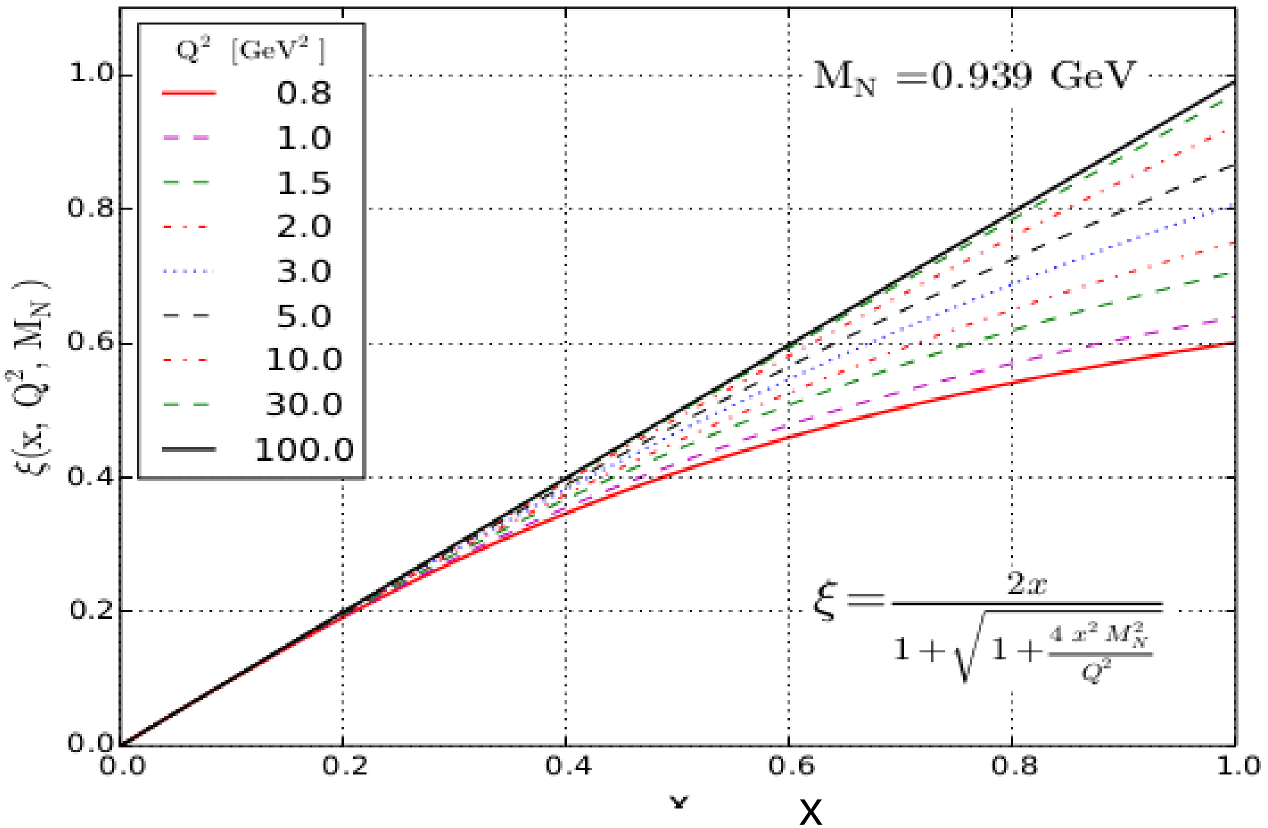
$$\times \sum_{i=1}^{5} a_i(E_\nu, x, y, M_N, m_\ell)\, F_i^{TMC}(x, Q^2),$$

$$a_1 = y^2 x + \frac{m_\ell^2 y}{2E_\nu M_N},\ a_2 = 1 - \frac{m_\ell^2}{4E_\nu^2} - \left(1 + \frac{M_N x}{2E_\nu}\right) y,$$

$$a_3 = \pm\left[xy\left(1 - \frac{y}{2}\right) - \frac{m_\ell^2 y}{4E_\nu M_N}\right],$$

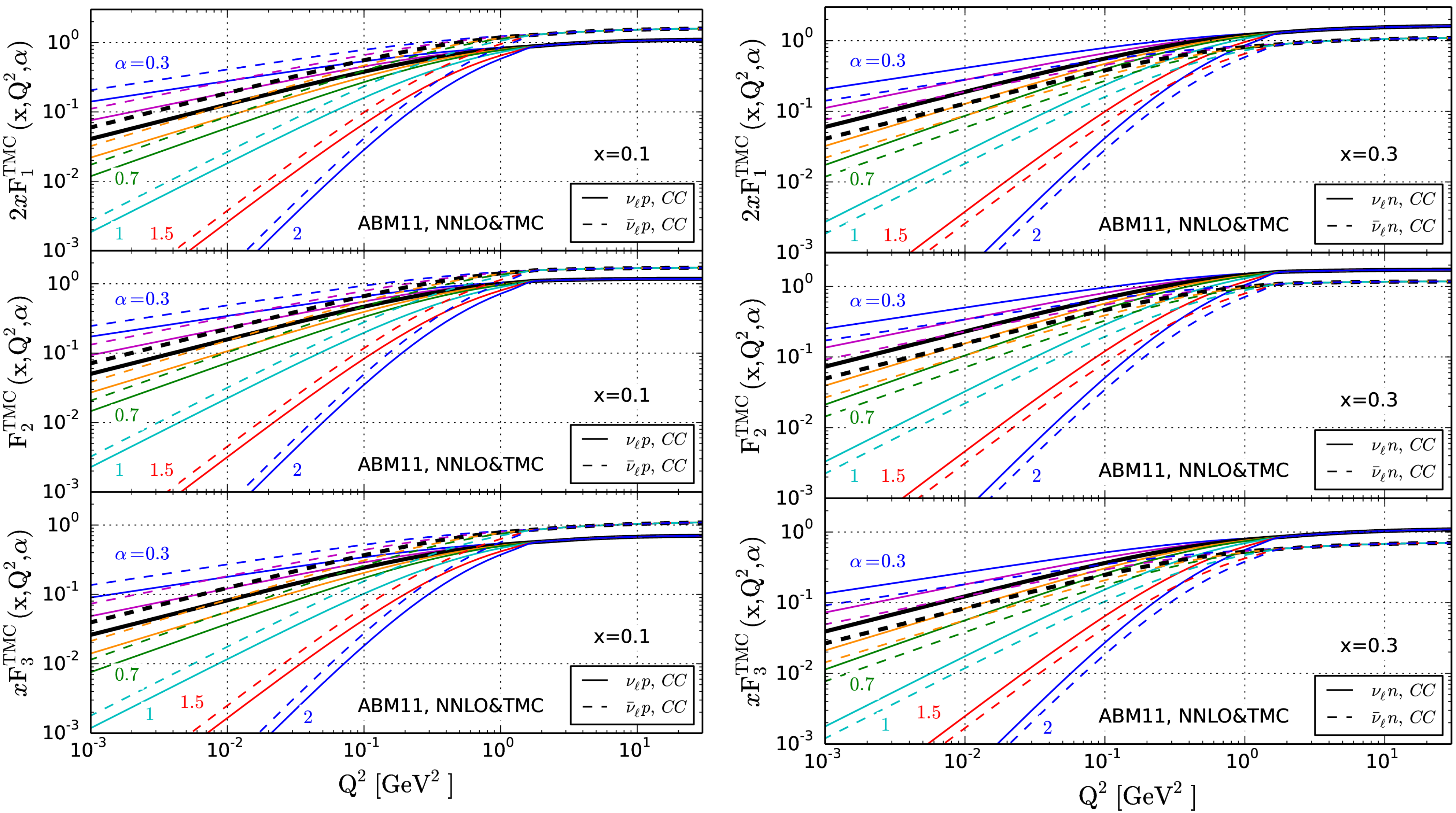
$$a_4 = \frac{m_\ell^2(m_\ell^2+Q^2)}{4E_\nu^2 M_N^2 x}, \quad a_5 = -\frac{m_\ell^2}{E_\nu M_N}.$$

Nachtmann Variable

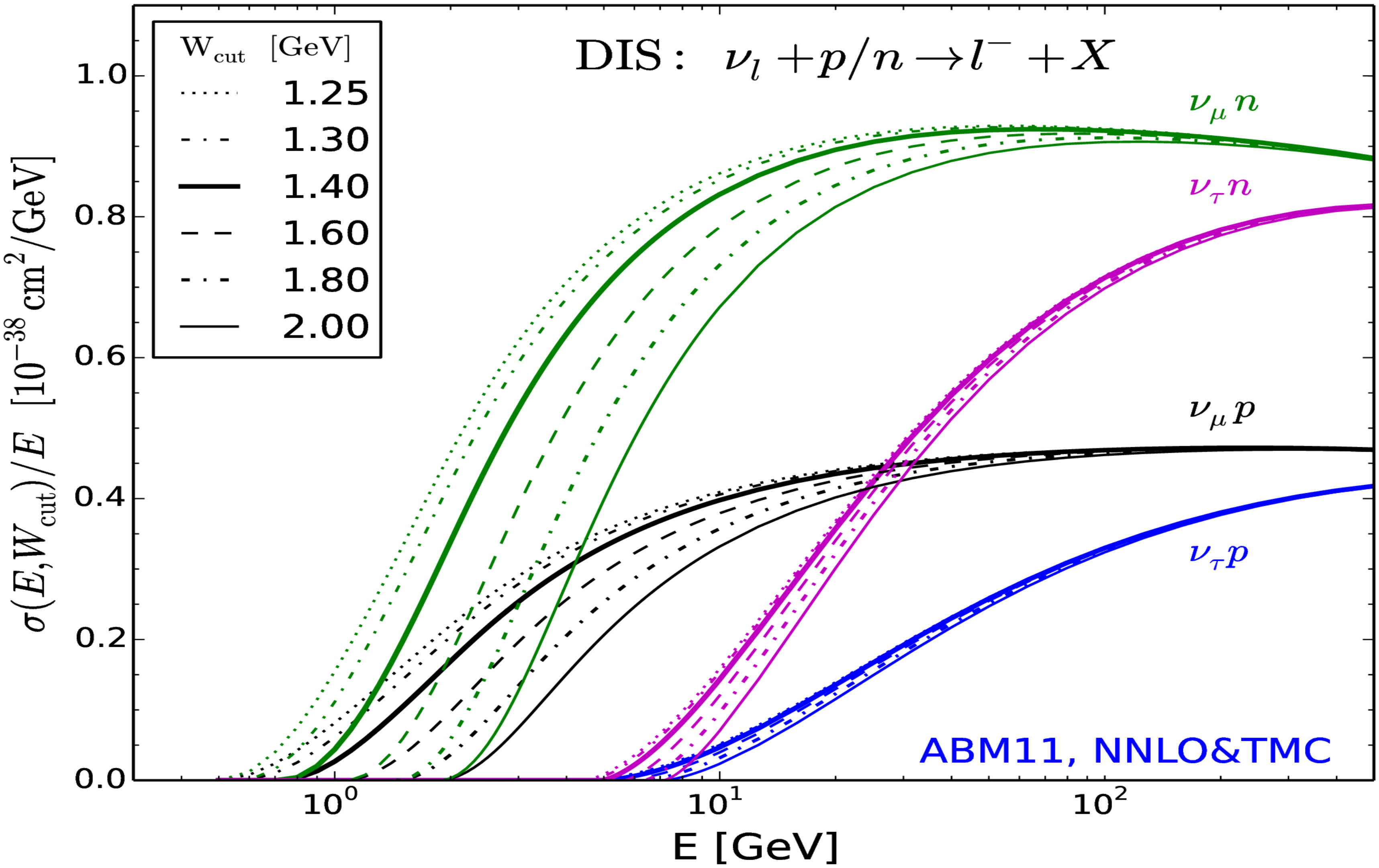


$$F_j^{\mathrm{TMC}}(x,Q^2) = \sum_{i=1}^{5} A_j^i F_i(\xi,Q^2) + B_j^i h_i(\xi,Q^2) + C_j g_2(\xi,Q^2).$$

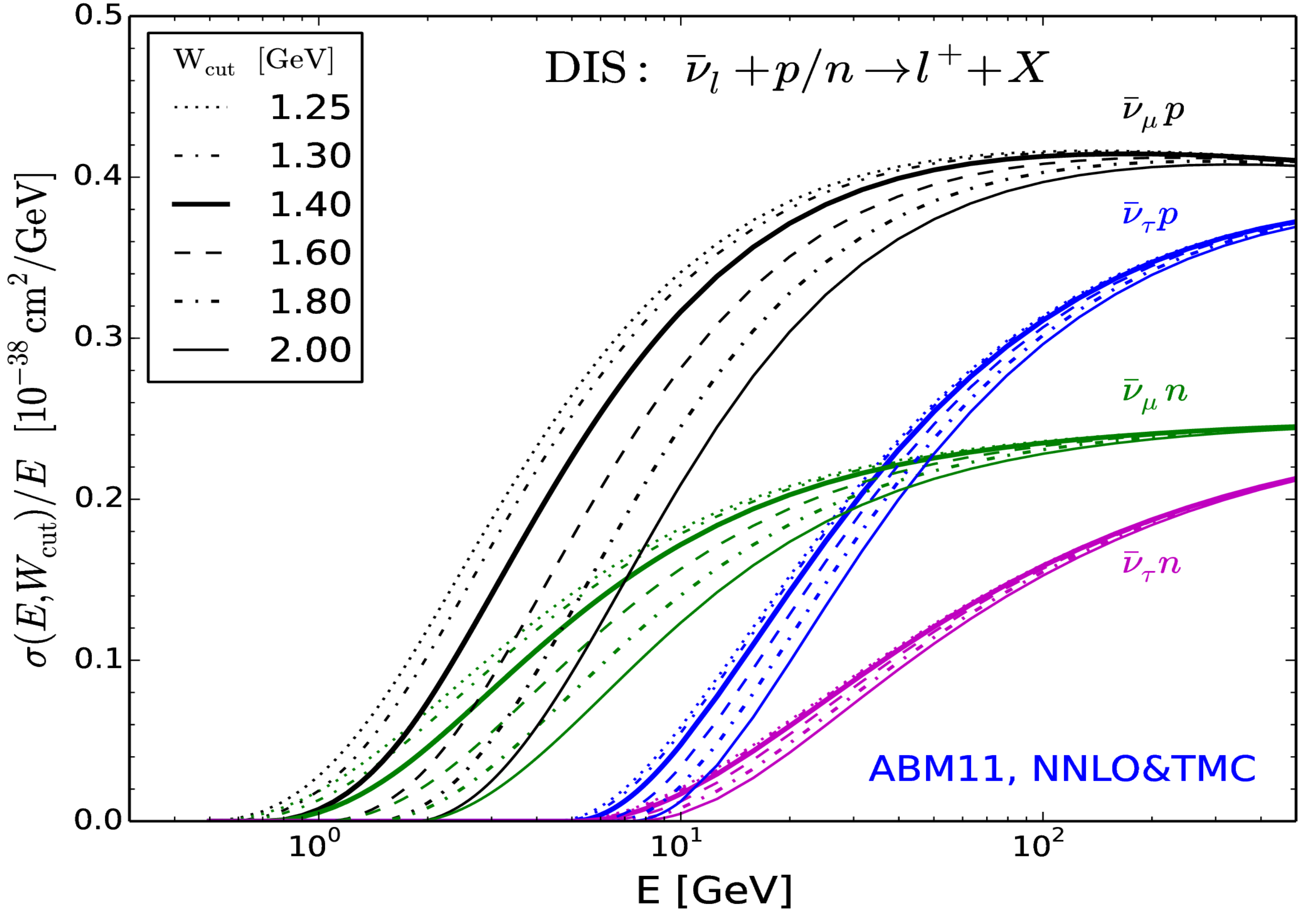
Extrapolations of SFs to small Q^2



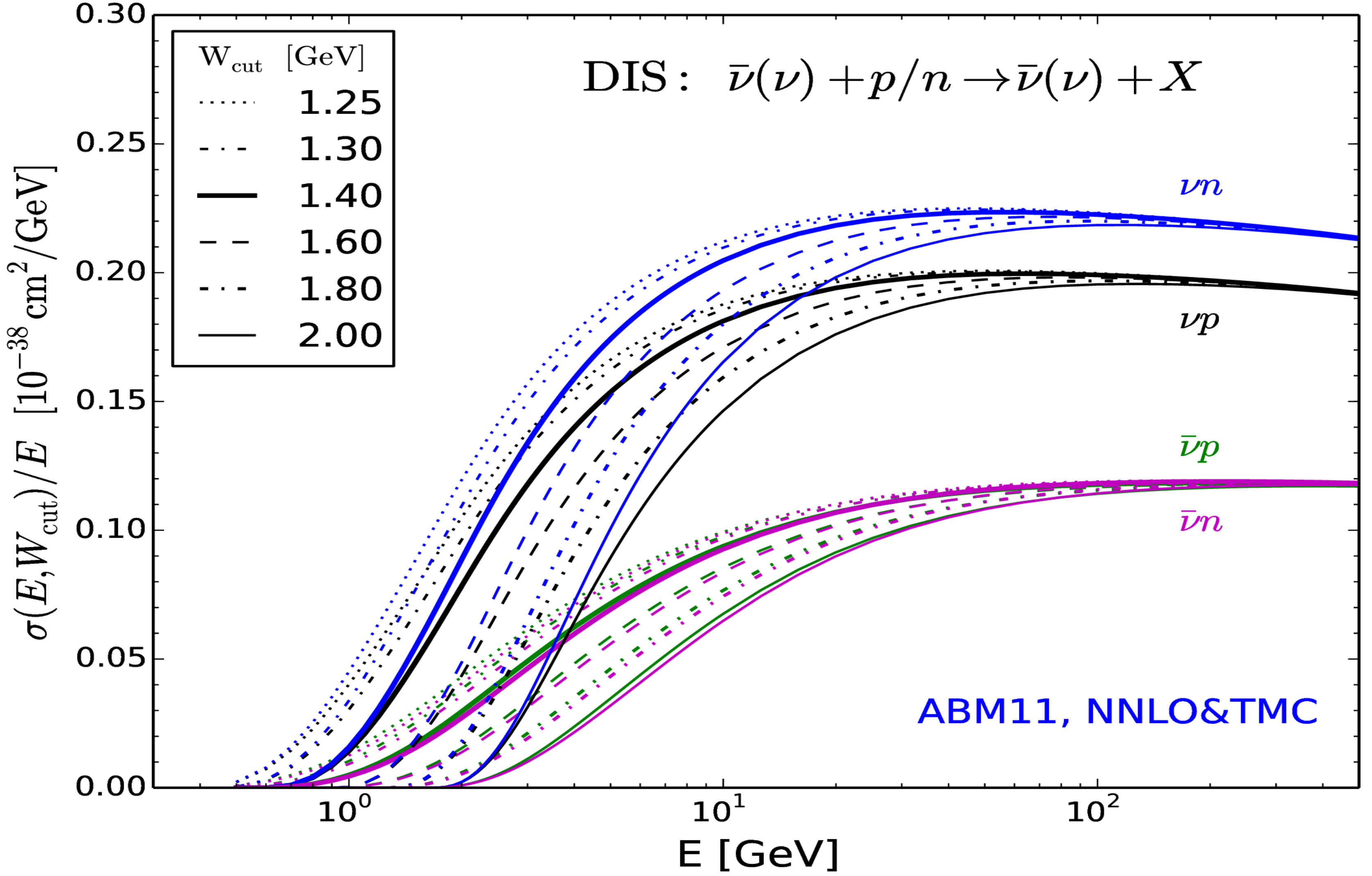
Dependence of νN CC DIS on W_{cut}



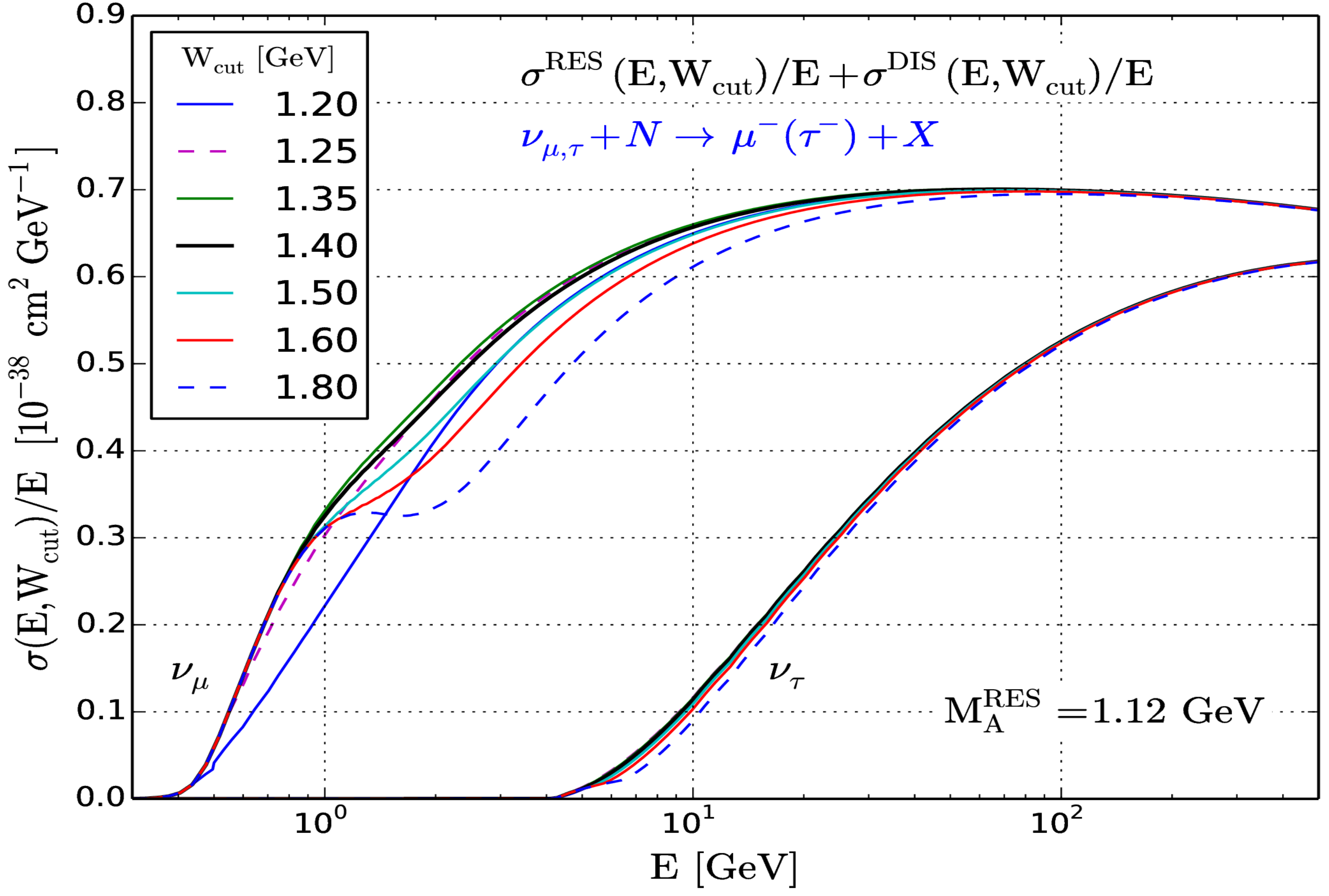
Dependence of $\bar{\nu}$N CC DIS on W_{cut}



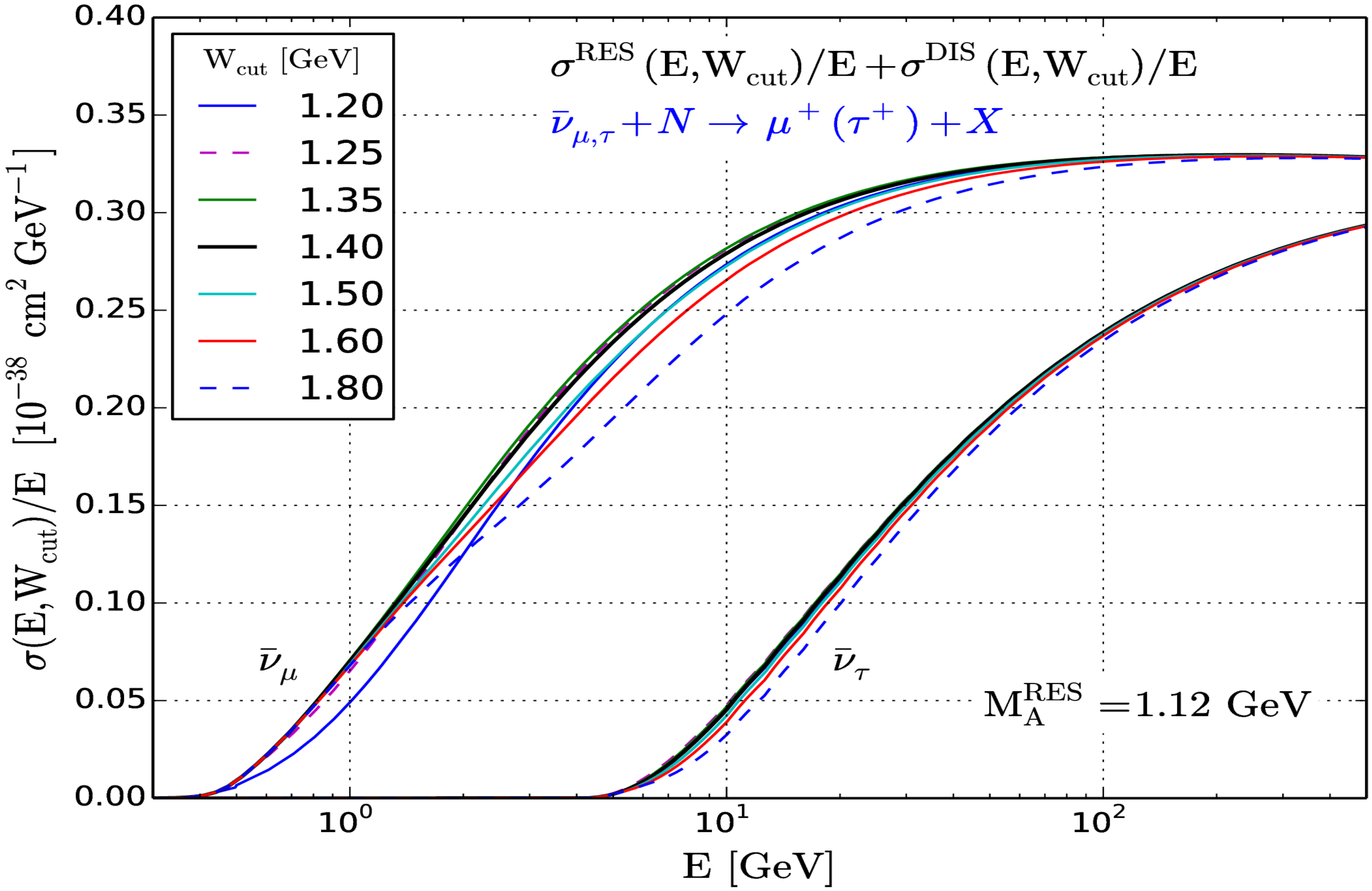
Dependence of ν($\bar{\nu}$)N NC DIS on W_{cut}



Optimization of W_{cut} for νN



Optimization of W_{cut} for $\bar{\nu}N$



Kinematic Limits

$$y = 1 - E_\ell / E_\nu$$

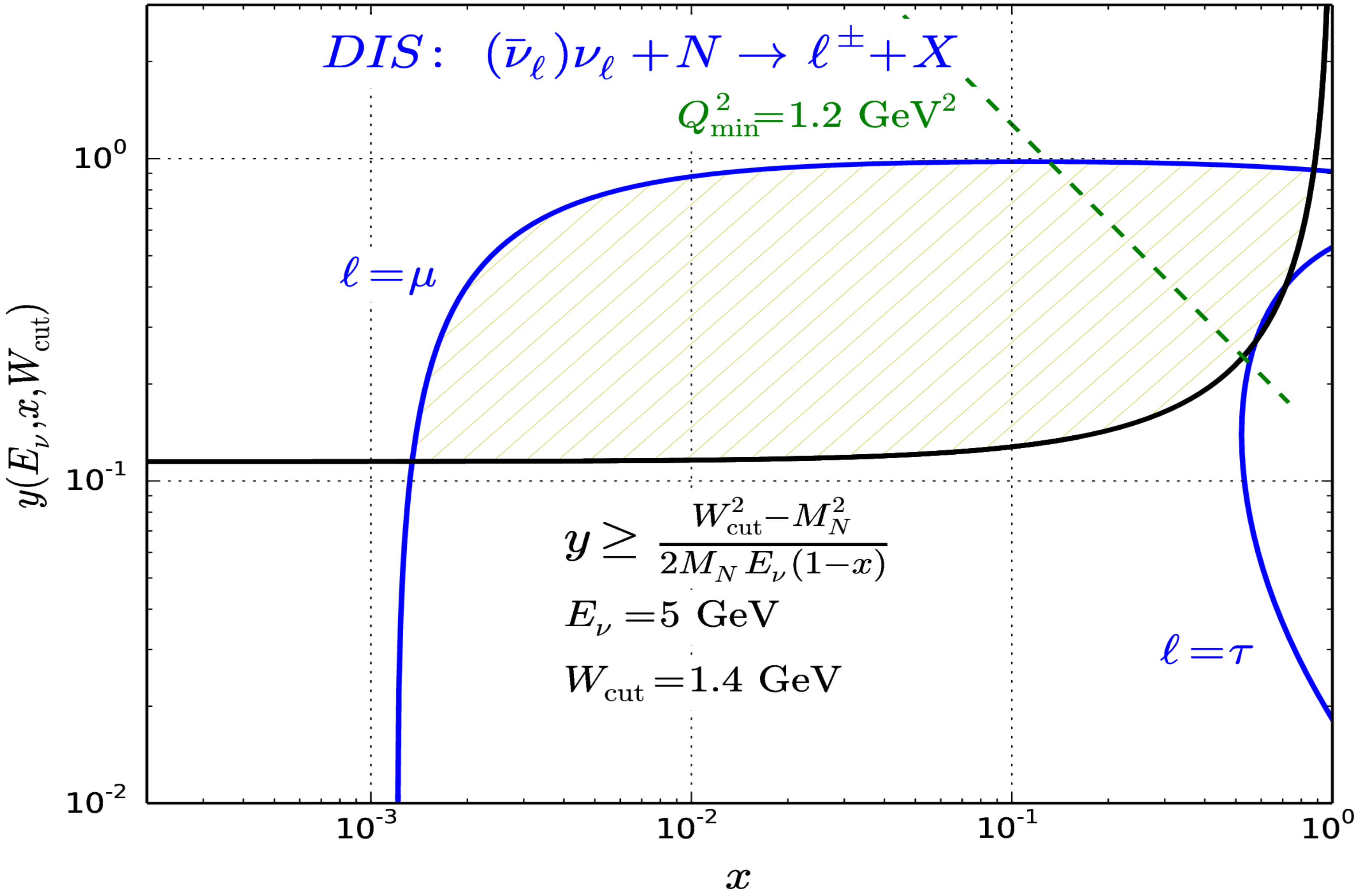
$$W^2 = M_N^2 + 2M_N E_\nu y(1-x) \qquad y \geq \frac{W_{\rm cut}^2 - M_N^2}{2M_N E_\nu (1-x)}$$

$$\frac{m_\ell^2}{2M_N(E_\nu - m_\ell)} \leq x \leq 1,$$

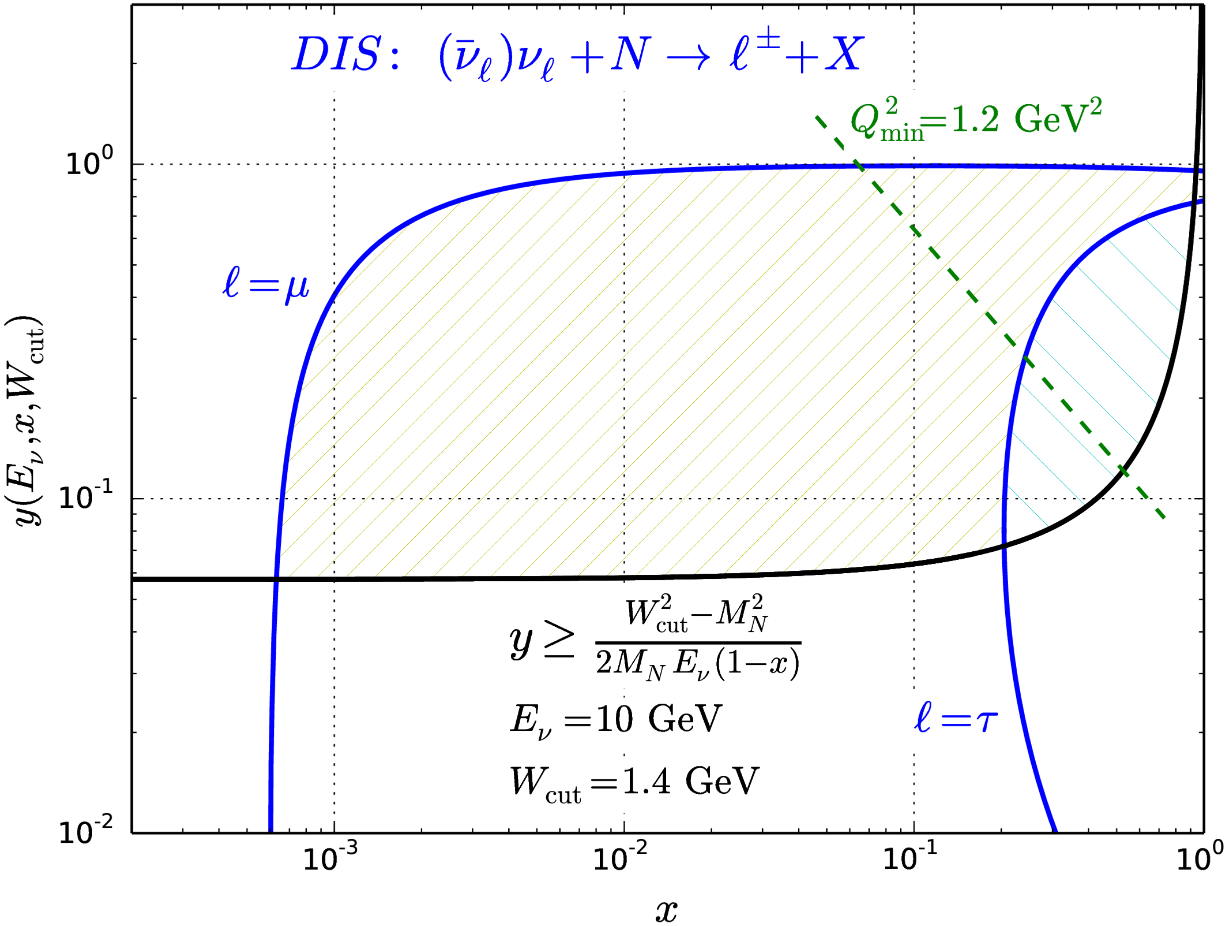
$$A - B \leq y \leq A + B$$

$$A = \frac{1 - \frac{m_\ell^2}{2M_N E_\nu x} - \frac{m_\ell^2}{2E_\nu^2}}{2 + M_N x/E_\nu}, B = \frac{\sqrt{\left(1 - \frac{m_\ell^2}{2M_N E_\nu x}\right)^2 - \frac{m_\ell^2}{E_\nu^2}}}{2 + M_N x/E_\nu}$$

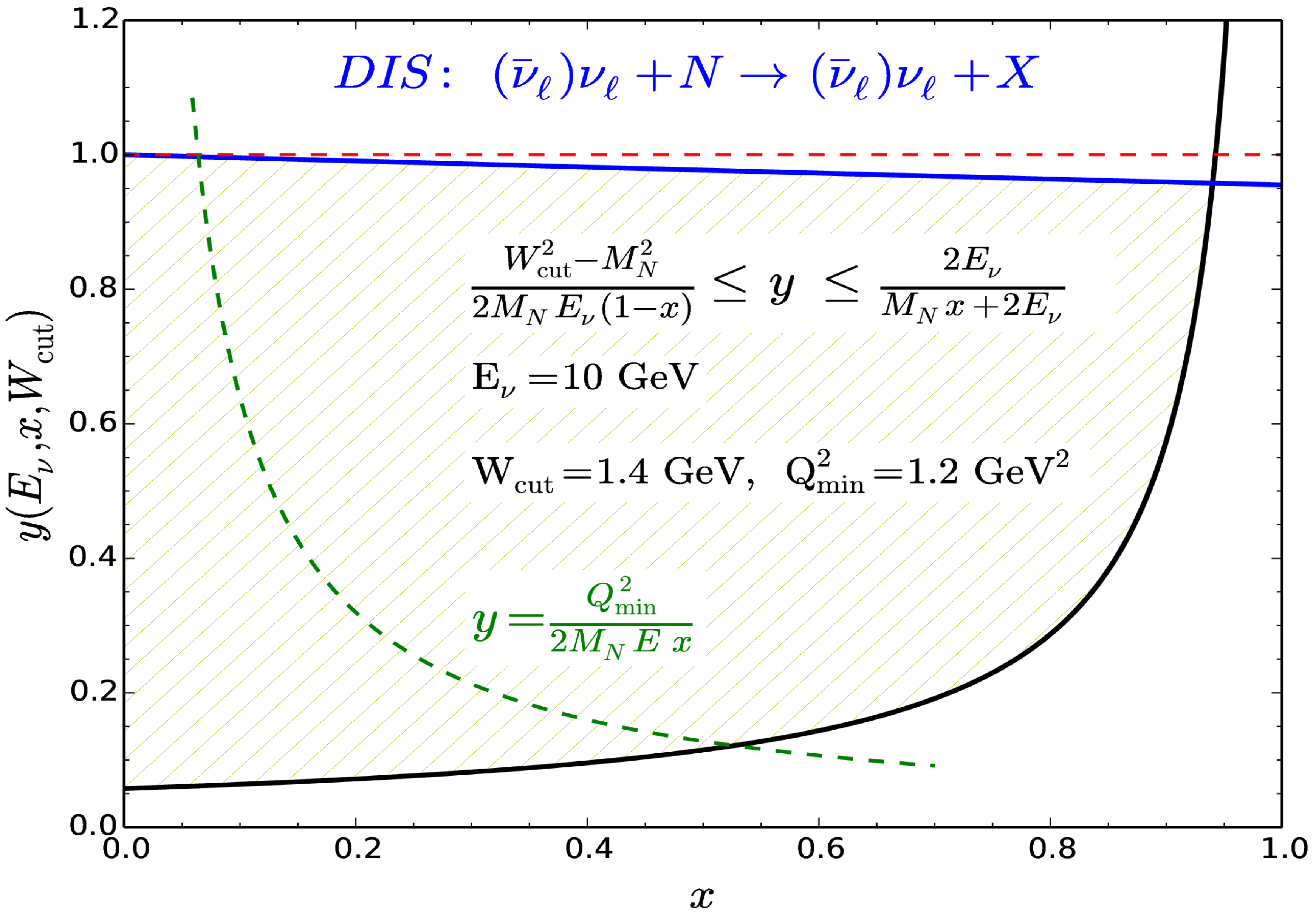
Kinematic Limits for CC DIS at E=5 GeV



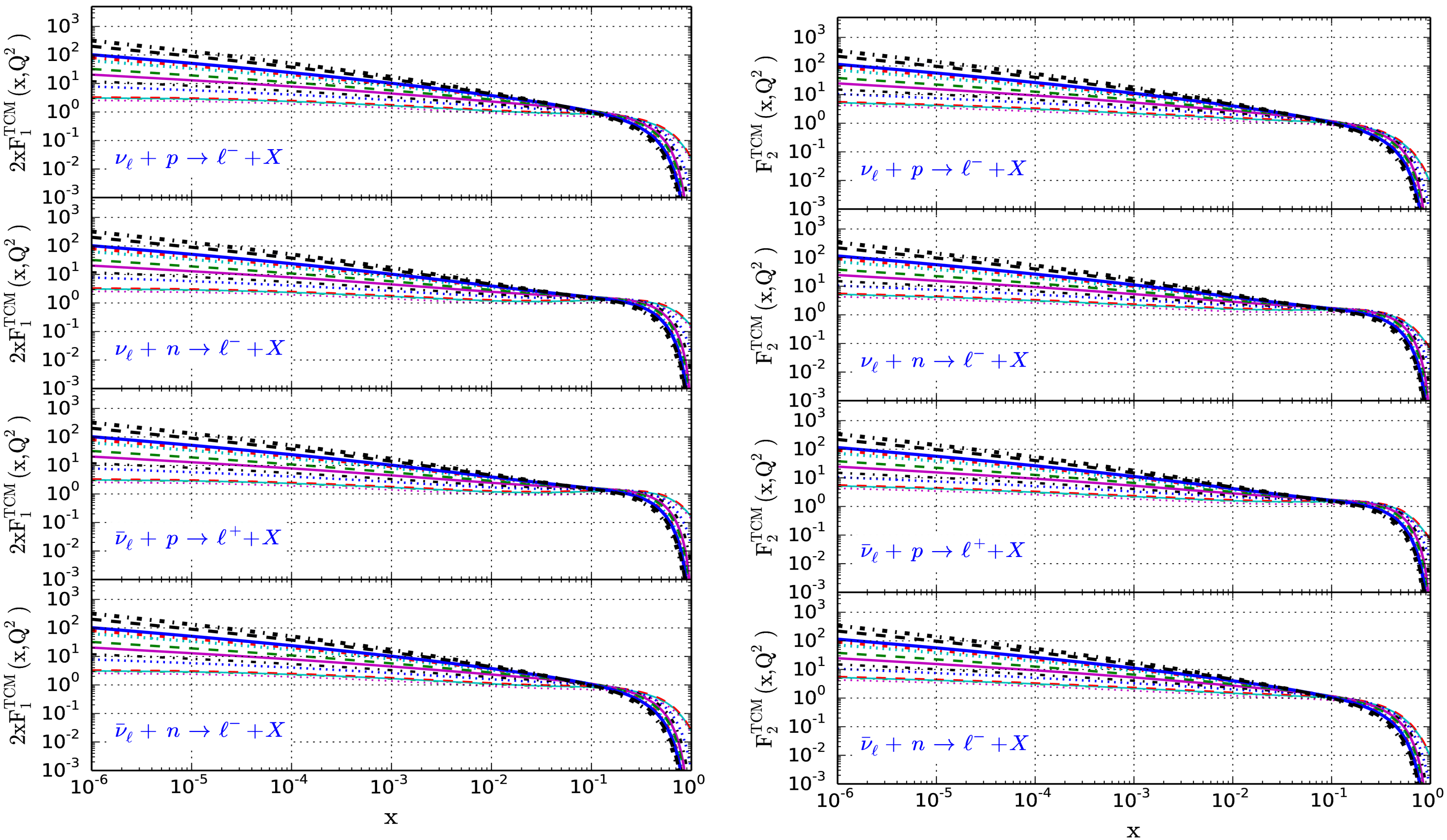
Kinematic Limits for CC DIS at E=10 GeV



Kinematic Limits for NC DIS at E=10 GeV



TMC SFs Dependence on x

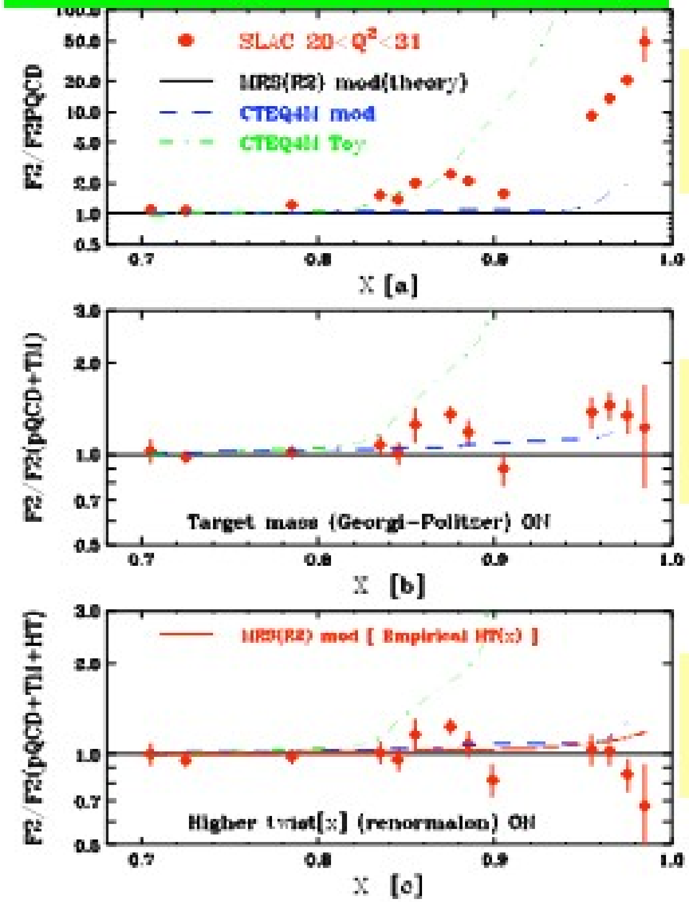


PDF are from **ABM-11** and **OPENQCDRAD** by Alekhin, Bluemlein, Moch.

Approach of Bodek&Yang

Very high x F_2 proton data (DIS + resonance)

SLAC high x data/theory

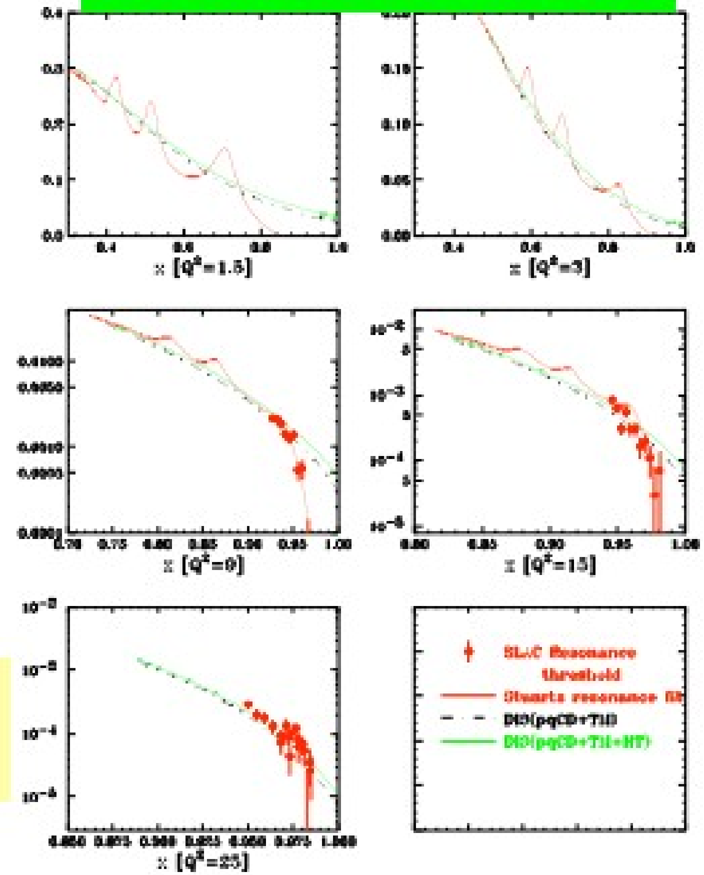


pQCD only

pQCD +TM

pQCD +TM+HT

SLAC resonance data



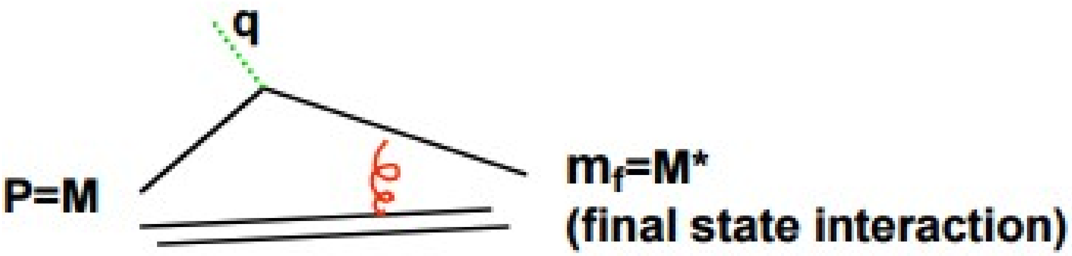
The data are well described by the predictions (duality works!)

https://www.jlab.org/conferences/neutrino/talks/yang_uk.pdf

B&Y Pseudo NLO

Original approach (NNLO pQCD+TM) was to explain the non-perturbative QCD effects at low Q^2, but now we reverse the approach:

- Use LO PDFs and "effective target mass and final state masses" to account for initial target mass, final target mass, and even missing higher orders



$$\xi_W = \frac{Q'^2}{M\nu[1+\sqrt{(1+Q^2/\nu^2)}]},$$

where $2Q'^2 = (Q^2 + m_f^2 - m_i^2) + \sqrt{(Q^2 + m_f^2 - m_i^2)^2 + 4Q^2(m_i^2 + P_t^2)}$

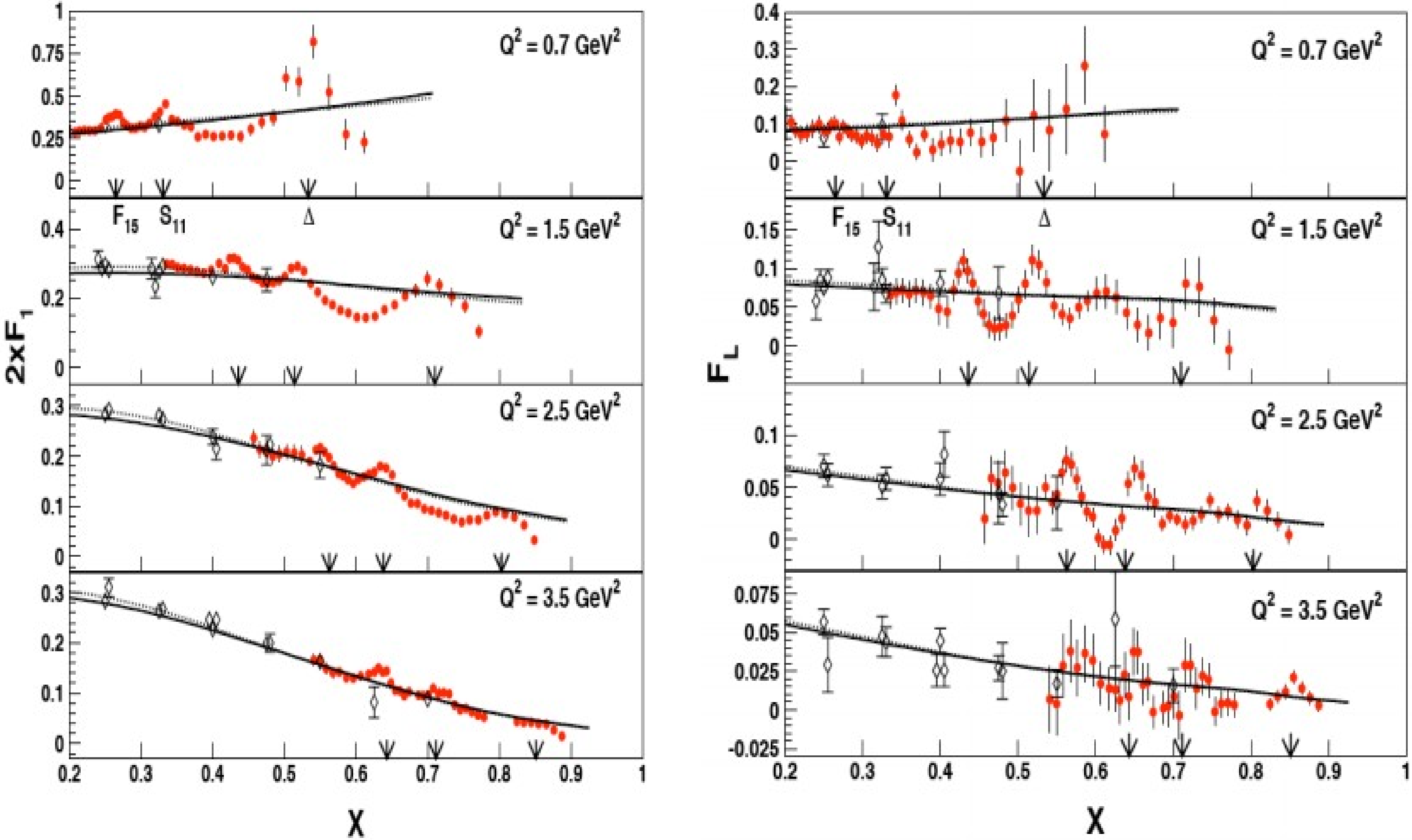
resonance, higher twist, and TM

$$\xi_W = \frac{Q^2 + B}{\{M\nu[1+\sqrt{(1+Q^2/\nu^2)}] + A\}}$$

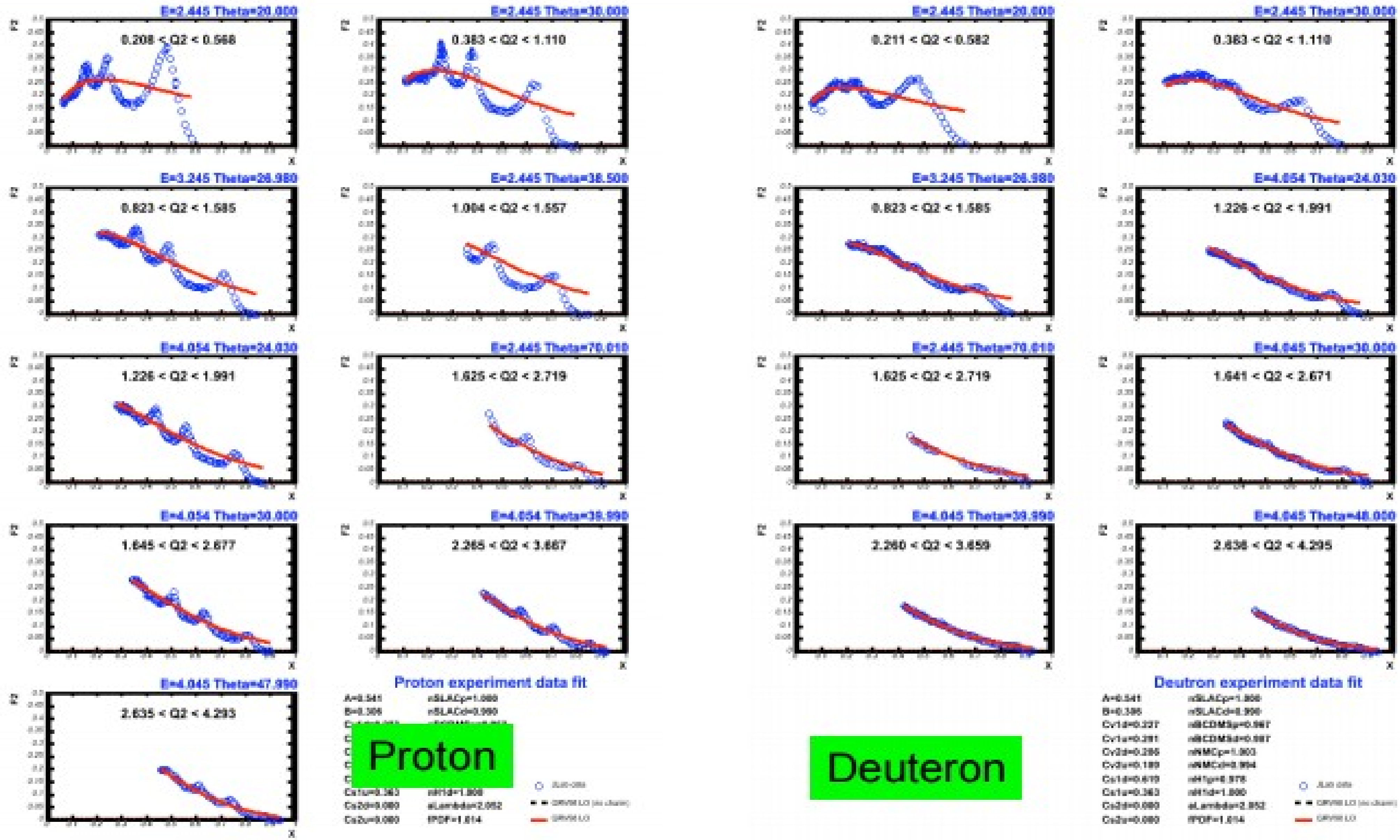
A : initial binding/target mass effect plus higher order term

B: final state mass m_f^2 , Δm^2 and photo-protduction

$2xF_1$ and F_L in B&Y Approach



Comparison of B&Y Model with Resonances



MC Generators

Neutrino event generators available in the market.

- **NEUT** – developed for Kamiokande and used by Super-Kamiokande, K2K, SciBooNE, T2K.
- **NUANCE** – developed for the IMB experiment and used by MiniBooNE.
- **NEUGEN** - developed for the SOUDAN and updated for MINOS.
- **ANIS** – developed for AMANDA and used by IceCube.

General purpose MC generators

- **FLUKA**
- **GENIE** – ArgoNeut, MicroBooNE, MINOS, MINERνA, T2K. Continuously updated.

MC Generators, cont.

- **GIBUU** – theorist group approach. It provides an unified transport framework at MeV - GeV energies. Numerous nuclear effects included.
- **NuWro** - developed by the Wroclaw group. Accounts for the impact of nuclear effects on directly observable quantities with all the final state interactions included.

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- An account for TMC, lepton mass, pQCD corrections are important.
- New precision data may change the set of parameters.

Thank you!

QES: from Strumia&Vissani

$$\mathcal{M} = \bar{v}_{\nu_e}\gamma^a(1-\gamma_5)v_e \cdot \bar{u}_n\left(f_1\gamma_a + g_1\gamma_a\gamma_5 + if_2\sigma_{ab}\frac{q^b}{2M} + g_2\frac{q_a}{M}\gamma_5\right)u_p$$

where $q = p_\nu - p_e = p_n - p_p$. A straightforward calculation yields[2]:

$$|\mathcal{M}^2| = A(t) - (s-u)B(t) + (s-u)^2C(t)$$

where $s = (p_\nu + p_p)^2$, $t = (p_\nu - p_e)^2$, $u = (p_\nu - p_n)^2$ are the usual Mandelstam variables and

$$\begin{aligned}
16\ A &= (t-m_e^2)\ \Big[4|f_1^2|(4M^2+t+m_e^2) + 4|g_1^2|(-4M^2+t+m_e^2) + |f_2^2|(t^2/M^2+4t+4m_e^2) + \\
&\quad +4m_e^2t|g_2^2|/M^2 + 8\mathrm{Re}[f_1^* f_2](2t+m_e^2) + 16m_e^2\mathrm{Re}[g_1^* g_2]\Big] \\
&\quad -\Delta^2\Big[(4|f_1^2| + t|f_2^2|/M^2)(4M^2+t-m_e^2) + 4|g_1^2|(4M^2-t+m_e^2) + 4m_e^2|g_2^2|(t-m_e^2)/M^2 + \\
&\quad +8\mathrm{Re}[f_1^* f_2](2t-m_e^2) + 16m_e^2\mathrm{Re}[g_1^* g_2]\Big] - 32m_e^2 M\Delta\mathrm{Re}[g_1^*(f_1+f_2)] \\
16\ B &= 16t\mathrm{Re}[g_1^*(f_1+f_2)] + 4m_e^2\Delta\left(|f_2^2| + \mathrm{Re}[f_1^* f_2 + 2g_1^* g_2]\right)/M \\
16\ C &= 4(|f_1^2| + |g_1^2|) - t|f_2^2|/M^2.
\end{aligned}$$

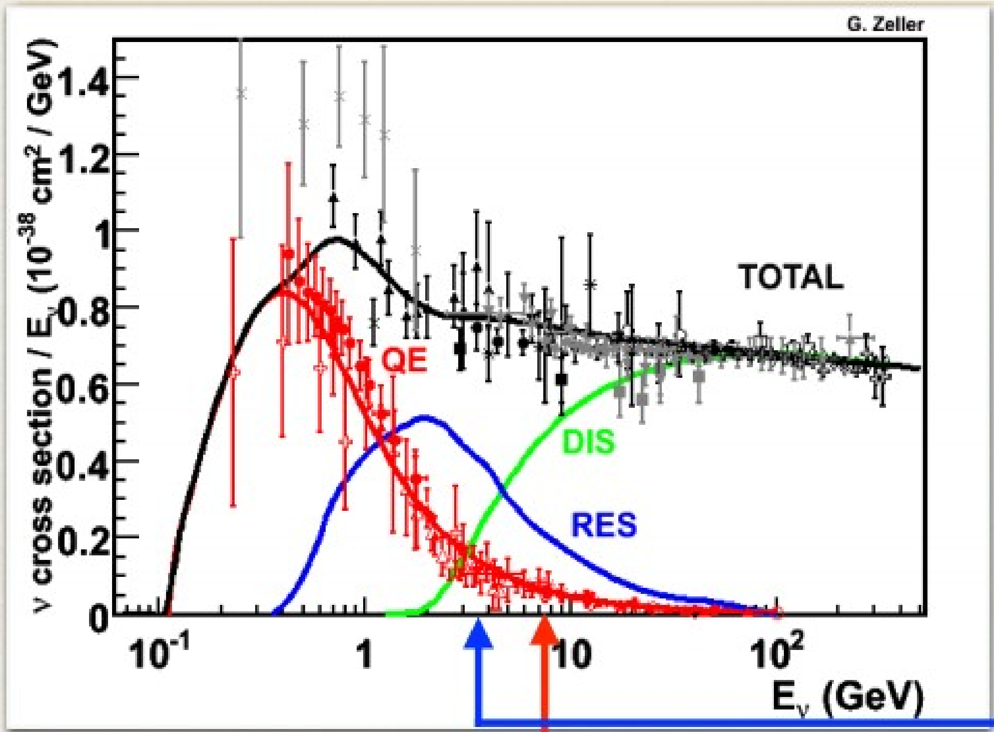
f_i and g_i are real function of $t = -Q^2$. Approximation:

$$\{f_1, f_2\} = \frac{\{1-(1+\xi)t/4M^2, \xi\}}{(1-t/4M^2)(1-t/M_V^2)^2}, \quad g_1 = \frac{g_1(0)}{(1-t/M_A^2)^2}, \quad g_2 = \frac{2M^2 g_1}{m_\pi^2 - t}$$

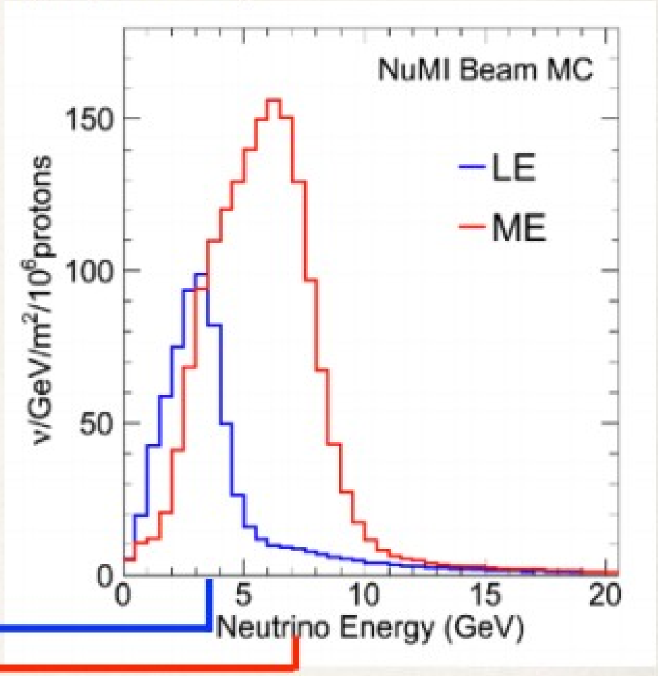
$$\xi = k_p - k_n = 3.706$$

where k_p and k_n – anomalous magnetic moments in units of nuclear magneton $\mu_N = e\hbar/2m_p$

The MINERvA energy range



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012



Low-energy run, 2010-2012
3.98x10^{20} POT (ν)
1.7x10^{20} POT ($\bar{\nu}$)

Medium-energy run, 2013-
Already exceeded low-energy POT in ν mode

BooNE experiments, T2K

MINERvA, DUNE, NOνA, MINOS

PINGU