Tuning the pion production with Genie version 3

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on behalf of the GENIE Collaboration

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UNIVERSITY OF LIVERPOOL

Genie

Outline

Introduction to GENIE

Modelling the Shallow Inelastic Scattering region

Pion production integrated cross section datasets

Tuning the SIS region against free nucleon data in GENIE v3

Conclusions

GENIE - www.genie-mc.org

Core GENIE mission - from GENIE by-law

Framework	"... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community ..."
Universality	"... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."
Global fit	"... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes ..."

Neutrino MC generators allow to

- Compare data and models
- Compare dataset against dataset
  - Data quality and data sources are increasing ⇒ Tensions
  - ⇒ Comparing results from different experiments
- Global fits
  - A generator is the ideal place for global fits
    - Controls the model implementation
  - Cross Section priors based on data
  - Finding the best parameters

GENIE status overview

- Well established generator
  - Used by many experiments around the world
- Two main efforts
  - Model development
    - Mostly happen during the latest releases of GENIE v2
    - Growing interest from theorists wanting to supply new models
  - **Tuning**

    ⇒ Entering the tuning phase
- The new release v3
  - Interface with the developments

  ⇒ **Tunes against public datasets**
    - E.g. tune against free nucleon data

GENIE Version 3

Interface with the work behind the scenes

⇒ "Comprehensive Model Configurations" (CMC)

- Self-consistent collections of primary process models
- Help cooperation between collaborations
  - Unified model identifications
- Single command-line flag
  - `--tune G18_02a_00_000`
- Complete characterisation against public data
- Possibility to host configurations provided by experiments

- Access to tunes against datasets
  - Same interface
  - Documentation:
    - Manual
    - Dedicated web page – tunes.genie-mc.org/

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

graphics by

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CMC of interest for this talk

G18_01a - Default G00_00a + MEC

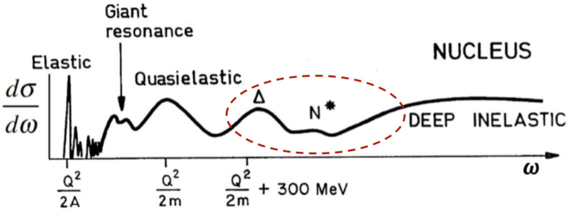
- with Empirical MEC
- CCQE process is Llewellyn Smith Model
- **Rein-Sehgal for resonant interaction**
- Dipole Axial Form Factor - Depending on $M_A = 0.99\,GeV$
- Nuclear model: Fermi Gas Model - Bodek, Ritchie
- Inclusion of diffractive and Lambda production models

G18_02a - Improved pion production models

- Similar to G18_01a and G18_01b
- **Berger-Sehgal for resonant interaction**
- Berger-Sehgal for coherent interaction

Both configurations have been tuned against free nucleon datasets

Scattering mechanisms at the few GeV



Need to model the contributions to pion production for free nucleon

1. The RES contribution to the cross section
2. Shallow Inelastic Scattering transition region (SIS) between the Δ peak and the DIS regime
   – A non-resonant background needs to be added
3. DIS also contributes to RES production after hadronization.

Different models must be merged together while avoiding double counting

RES Models: the Rein-Sehgal Model

- Most widely used model for resonance neutrino production
  [*D.Rein et. al., Annals Phys. 133 (1981)*]
- Only contains resonances up to $W = 2GeV$
- Limit $m_{\mu} = 0$
- Non-resonant background of $I = 1/2$ added incoherently

$$\frac{d\sigma}{dQ^2 dW^2} \propto \left[u^2\sigma_L + v^2\sigma_R + 2uv\sigma_s\right]$$

u and v are kinematical factors
σ_L, σ_R and $\sigma_s \rightarrow$ Helicity cross sections
Depend on:

- $F_{\pm}$ and F_0 dynamical form factors
- Axial and vector transition form factors, $G^{V,A}(q^2) \propto \left(\frac{1}{1-q^2/M^2_{V,A}}\right)^2$
- Original paper values $M_V = 0.84GeV$ and $M_A = 0.95GeV$

RES Models: the Berger-Sehgal Model

- Improved version of the RS model
  [*Bodek, A. et al. Nucl.Phys.Proc.Suppl. hep-ex/0308007*]
- Non zero $m_\mu \Rightarrow$ Final state lepton can have + or - helicity
- Gives a suppressed cross section at small angles

$$\frac{d\sigma}{dQ^2 dW^2} \propto \sum_{\lambda=+,-} \left[\left(c_L^{(\lambda)}\right)^2 \sigma_L^{(\lambda)} + \left(c_R^{(\lambda)}\right)^2 \sigma_R^{(\lambda)} + \left(c_S^{(\lambda)}\right)^2 \sigma_s^{(\lambda)} \right]$$

Depends on:

- $c_L^{(\lambda)}$, $c_R^{(\lambda)}$ and $c_s^{(\lambda)}$ are the new kinematical factors
- Six helicity cross sections that depend on dynamical form factors
- Axial and vector transition form factors also calculated using the dipole approximation

Shallow Inelastic Scattering region

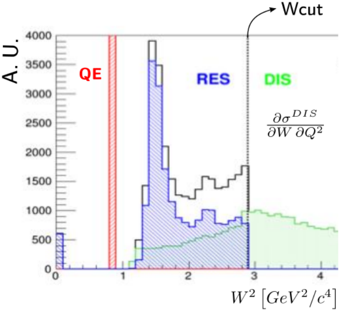
- In the RS model the non-resonant background is computed by introducing incoherently an extra amplitude with I=1/2
  $\rightarrow$ not completely satisfactory approach

- **Quark-Hadron duality** can give an alternative model to describe the non-resonant background
  - The average over resonances behaves similarly to the valence quark contribution to DIS scaling curve
  - Harari and Freund conjeture suggests the existence of a relationship between non-resonant and sea-quark contributions to structure functions [*Phys. Rev. Lett. 20 (1969) 1395*]

- **If duality is satisfied, the non-resonant background should be proportional to the DIS contribution.**

Swallow Inelastic Scattering region in GENIE

$$\frac{d^2\sigma^{INEL}}{dQ^2 dW} = \frac{d^2\sigma^{RES}}{dQ^2 dW} + \frac{d^2\sigma^{DIS}}{dQ^2 dW}$$



- RES contribution stops at $W = W_{cut}$
  $\rightarrow$ Rein-Sehgal or Berger-Sehgal models

$$\frac{d^2\sigma^{RES}}{dQ^2 dW} = \sum_K \left(\frac{d^2\tilde{\sigma}^{RES}}{dQ^2 dW}\right) \cdot \Theta(W_{cut} - W)$$

- Pure DIS cross section for $W > W_{cut}$
  $\rightarrow$ Bodek-Yang model

$$\frac{d^2\sigma^{DIS}}{dQ^2 dW} = \frac{d^2\tilde{\sigma}^{DIS}}{dQ^2 dW} \cdot \Theta(W - W_{cut}) + \underbrace{\frac{d^2\tilde{\sigma}^{DIS}}{dQ^2 dW} \cdot \Theta(W_{cut} - W) \cdot \sum_m f_m}_{\text{Non-Resonant Background: Scaled DIS}}$$

Shallow Inelastic Scattering region in GENIE

$$\frac{d^2\sigma^{DIS}}{dQ^2dW} = \frac{d^2\tilde{\sigma}^{DIS}}{dQ^2dW} \cdot \Theta(W - W_{cut}) + \underbrace{\frac{d^2\tilde{\sigma}^{DIS}}{dQ^2dW} \cdot \Theta(W_{cut} - W) \cdot \sum_m f_m}_{\text{Non-Resonant Background: Scaled DIS}}$$

- Non-resonant background proportional to DIS
- $f_m = R_m \cdot P_m^{had}$ multiplicity functions
- R_m tunable ad-hoc parameters: they depend on the neutrino flavour, multiplicity of the final state m and nucleon on the initial state
- P_m^{had} is the probability of the final state to be m
  - Obtained from the hadronization model
- This approach couples the DIS with the hadronization models
- Used for both RS and BS models
  - We will see the details of the result done with BS

Cross section datasets on free nucleons

There are two types of free nucleon data

Inclusive cross section on free nucleon

Considers **all possible processes** within the available phase space of the reaction: QEL, RES, DIS

Predictions for pion datasets are very sensitive to

- M_A^{QE}, M_A^{RES}
- Overall scaling factor for RES and DIS applied to the cross section within GENIE

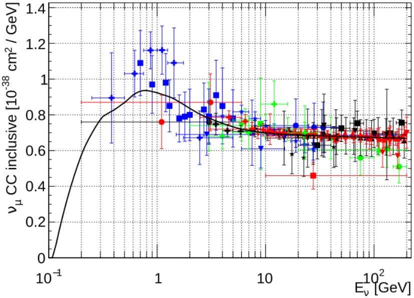
Exclusive cross sections on free nucleon

Considers **a particular process** for a given multiplicity and initial state.
E.g: 1π or 2π production mechanisms.
Predictions are very sensitive to the following GENIE parameters

- W_{cut}, as it determines the end of the SIS region
- R_m for the same multiplicity cross sections

Old default GENIE tune

- The old default configuration (G00_00a) fits well the inclusive cross section
- **More emphasis was given on inclusive data**
- The old tune was driven by MINOS needs



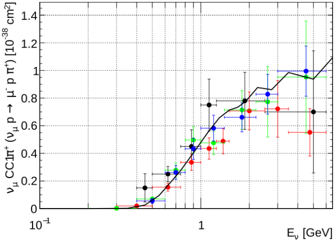
G00_00a default vs ν_μ CC Inclusive datasets. References on the backup

GENIE pion production cross section

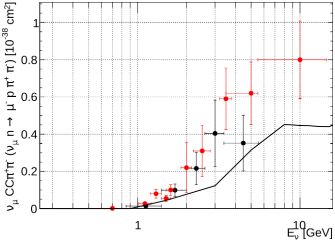
If we use the old tune we lose agreement for exclusive channels

- One pion production was overpredicted
- Underestimating two pion production

⇒ **Tensions exist between inclusive and exclusive data**



G00_00a default vs ν_μ CC pπ^+.
References on the backup



G00_00a default vs ν_μ CC p$\pi^+\pi^-$.
References on the backup

To address this issue, we performed a tune on free nucleon datasets

Tuning the SIS parameters in GENIEv3

The goal is to perform a
global fit to free nucleon integrated cross sections

Datasets used for the tuning

Only cross sections on **deuterium targets** are used:

- ANL_12FT*
- BNL_7FT*
- FNAL
- BEBC

The SIS region is tuned against ν_μ and $\bar{\nu}_\mu$ CC data for the following **topologies**:

- Inclusive
- One pion production
- Two pion production

We are using a total of 169 points for the tune

* Using the ReAnalized datasets [Wilkinson et al., Phys.Rev.D90:112017 (2014)]

Tuning the SIS parameters in GENIEv3

The goal is to perform a
global fit to free nucleon integrated cross sections

Parameters to be tuned within the SIS region ⇒ 8 parameters

1. RES parameters
   - M_A^{RES}: dipole parametrization factor
   - RES-XSecScale
2. SIS non-resonant background parameters
   - W_{cut} to determine the end of the SIS region
   - R_m parameters for proton and neutron, multiplicity 2 and 3
3. DIS parameters
   - DIS-XSecScale

These parameters are common for both G18_01a and G18_02a CMC

Tuning the SIS region in GENIEv3

Systematic treatment

- The datasets from the same experiment are not independent
  $\Rightarrow$ same flux, analysis methodology,...
- The data releases do not contain any correlation
- By adding an **extra nuisance parameters** per experiment we take into account the correlation
  $\rightarrow \nu$ and $\bar{\nu}$ beams have different nuisance parameters
- They are **scaling factors** applied to the prediction
- Each nuisance parameter has a Gaussian prior centered on 1 with $\sigma = 15\%$
- To further constrain the fluxes, **we included quasi-elastic data as well as M_A^{QE} in the fit:**
  $\Rightarrow$ Prior on $M_A^{QE} = 0.89 \pm 0.044$ GeV/c^2 [Eur. Phys. J. C (2008) 54]

Best set of parameters for the G18_02a CMC

Parameter	Default value	Best tune value
M_A^{RES} [GeV/c^2]	1.12	1.065
M_A^{QE} [GeV/c^2]	0.99	0.961
R-vp-m2	0.1	0.008
R-vp-m3	1	0.788
R-vn-m2	0.3	0.128
R-vn-m3	1	2.115
RES-XSecScale	1	0.878
DIS-XSecScale	1.032	1.019
W_{cut} [GeV]	1.7	1.928

- M_A^{RES} and M_A^{QE} agree with the priors we added
- RES-XSecScale dropped a lot as a consequence of the SIS modelling
- DIS-XSecScale describes better the high energy data
- W_{cut} increased $\Rightarrow$ more resonances are included

Priors applied

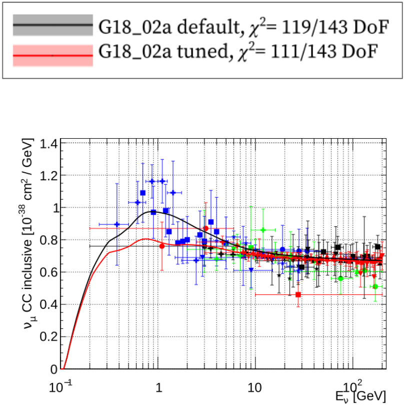
$M_A^{QE} = 0.89 \pm 0.044$ GeV/c^2, fit to just BEBC data [Eur. Phys. J. C (2008) 54]
$M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [ArXiv:0606184]
DIS-XSecScale$= 1 \pm 0.05 \rightarrow$ Motivated by DIS high energy cross section values

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC Inclusive datasets:

- The cross section is reduced at low energies to match the low cross section of pion production
- Pion production is better described without ruining the inclusive cross section

Disclaimer: Not all of these points have been used as just a few of them are on deuterium targets

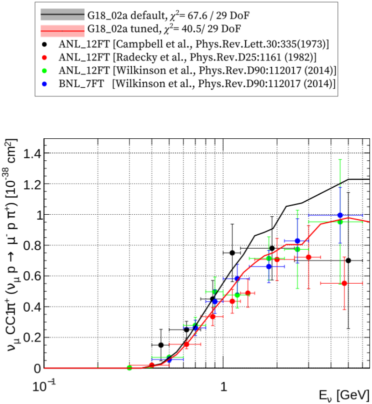


G18_02a default (black) and tuned (red) vs ν_μ CC inclusive. Just BEBC, BNL_7FT and FNAL data was used for the tune. For these datasets, $\chi^2_{default} = 18.8/26$ DoF, $\chi^2_{tuned} = 15.5/26$ DoF. References in the backup.

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC one pion production datasets:

- The description of the data has improved
- The same effect is seen for
  - ν_μ CC $p\pi^+$
  - ν_μ CC $n\pi^+$
  - ν_μ CC $p\pi^0$

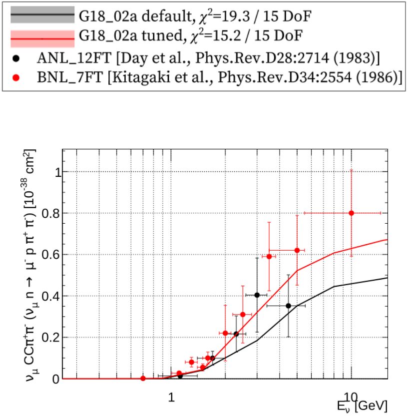


G18_02a default (black) and tuned (red) vs ν_μ CC $1\pi^+$ production data on proton. Just the ReAnalized data has been used. For these datasets, $\chi^2_{default} = 30.3/15$ DoF and $\chi^2_{default} = 16.85/15$ DoF.

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC two pion production datasets:

- The cross section increased



G18_02a default (black) and tuned (red) vs ν_μ CC two pion production data sets. Both datasets are included in the tune.

Conclusions

- We tuned the SIS region on free nucleon
  - Inclusive, exclusive and quasielastic data
  - The correlation between data sets from the same experiment is considered
- The global fit describes both inclusive and exclusive cross section
  - Global agreement with respect to a lot of observables
- We presented the results for the G18_02a CMC
  - Berner-Sehgal to model RES interaction
  - The G18_01a CMC was also tuned with similar procedure
    $\rightarrow$ Rein-Sehgal to model RES interaction
  - Both tunes are deployed in the available version of GENIE v3
    - G18_01a_02_11a
    - G18_02a_02_11a $\Rightarrow$ Default tune

GENIE Collaboration

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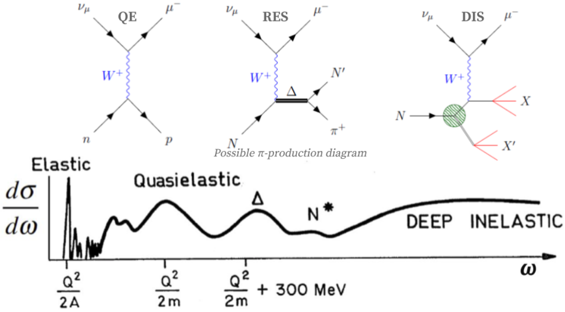
Backup slides

Scattering mechanisms at the few energy range

Broad energy range: several scattering mechanisms are important



- Resonant production is the dominant contribution to single pion processes
- In DUNE, resonance events contribute ∼30% to the CC inclusive rate

GENIE version 2.12.X available models

Models	Default	Alternative models
Nuclear Model	Bodek-Ritchie Relative Fermi Gas (RFG with short-range correlations)	Local Fermi Gas(LFG) effective spectral function model
CCQE	Llewellyn-Smith	Nieves
MEC	Empirica	Nieves
Resonance	**Rein-Sehgal**	**Berger-Sehgal**
FSI	hA	tuned hA
Nonresonant	Scaled Bodek-Yang	Scaled Bodek-Yang
Diffractive		Rein's Model
Charm Production	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model
SingleK Production		DIS-CC: Alam Simo Athar model
LAMBDA Production		QEL: Pais's model

GENIE database for integrated cross sections

Inclusive cross section datasets: 50 points for the tune

ν_μ CC Inclusive

- ANL_12FT
- BEBC
- BNL_7FT
- CCFR
- CCFRR
- CHARM
- MINOS
- FNAL_15FT
- Gargamelle
- IHEP_ITEP
- IHEP_JINR
- SKAT
- SciBooNE
- NOMAD

$\bar{\nu}_\mu$ CC Inclusive

- BEBC
- BNL_7FT
- CCFR
- CHARM
- FNAL_15FT
- Gargamelle
- IHEP_ITEP
- IHEP_JINR
- MINOS

One pion cross section datasets: 67 points for the tune

$\nu_\mu + n \rightarrow \mu^- + n + \pi^+$
– ANL_12FT – SKAT

– BNL_7FT

$\nu_\mu + p \rightarrow \mu^- + p + \pi^0$
– ANL_12FT – SKAT

– BNL_7FT

$\nu_\mu + p \rightarrow \mu^- + p + \pi^+$
– ANL_12FT – BNL_7FT

– FNAL_15FT – SKAT

$\bar{\nu}_\mu + n \rightarrow \mu^+ + n + \pi^-$

– Gargamelle – SKAT

$\bar{\nu}_\mu + p \rightarrow \mu^+ + p + \pi^-$

– FNAL_15FT – SKAT

Two pion cross section datasets: 25 points for the tune

$\nu_\mu + n \rightarrow \mu^- + n + \pi^+ + \pi^+$

– Gargamelle – SKAT

$\nu_\mu + p \rightarrow \mu^- + p + \pi^+ + \pi^0$

– Gargamelle – SKAT

$\nu_\mu + p \rightarrow \mu^- + n + \pi^+ + \pi^-$

Gargamelle – SKAT

We are only using the datasets on deuterium targets

Systematic treatment for ANL and BNL datasets

- Some of the ANL_12FT and BNL_7FT have already been corrected for the flux
  $\Rightarrow$ ReAnalized datasets
- These datasets should have a much more restricted nuisance parameter
  $\Rightarrow$ They consider an unbiased flux but there is still some uncertainty left
- Even though they were reanalized, there is still an existing correlation between i.e. all ANL_12FT datasets
- We consider a **common nuisance parameter** with a prior with $\sigma = 2.5\%$
- **Non reanalized datasets** have an **extra nuisance parameter**
  $\rightarrow$ The total prior applied has $\sigma = 15\%$

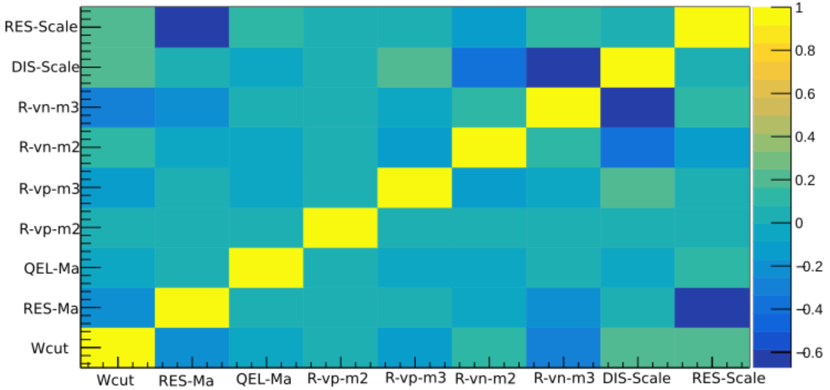
Nuisance parameters

Parameter	Prior width [%]	Best tune value
ANL_12FT_Common	2.5	1.009
ANL_12FT	15	1.021
BNL_7FT_Common	2.5	1.009
BNL_7FT	15	1.064
BNL_7FT_$\bar{\nu}_\mu$_Common	2.5	0.998
BNL_7FT_$\bar{\nu}_\mu$	15	0.916
BEBC	15	0.806
FNAL	15	0.969
FNAL_antinu	15	0.929

$\rightarrow$ We are not using $\bar{\nu}_\mu$ ANL_12FT data for the fit

The effect of the nuisance parameters is to scale the prediction

Correlation between parameters



Correlation between the parameters used in the fit

Inclusive cross section database

ANL_12FT,2 [Barish et al., Phys.Lett.B66:291 (1977)]
BEBC,0 [Bosetti et al., Phys.Lett.B70:273 (1977)]
BEBC,5 [Bosetti et al., Phys.Lett.B110:167 (1982)]
BNL_7FT,0 [Baltay et al., Phys.Rev.Lett.44:916 (1980)]
CCFR,2 [Seligman et al., Nevis Report 292 (1996)]
CHARM,0 [Jonker et al., Phys.Lett.B99:265 (1981)]
FNAL_15FT,1 [Kitagaki et al., Phys.Rev.Lett.49:98 (1982)]
Gargamelle,0 [Eichten et al., Phys.Lett.B46:274 (1973)]
Gargamelle,12 [Morfin et al., Phys.Lett.B104:235 (1981)]
IHEP_ITEP,2 [Vovenko et al., Sov.J.Nucl.Phys.30:528 (1979)]
MINOS,0 [Adamson et al., Phys.Rev.D81:072002 (2010)]
SKAT,0 [Baranov et al., Phys.Rev.B81 255 (1979)]

ANL_12FT,4 [Barish et al., Phys.Rev.D19:2521 (1979)]
BEBC,2 [Colley et al., Zeit.Phys.C2:187 (1979)]
BEBC,8 [Parker et al., Nucl.Phys.B232:1 (1984)]
BNL_7FT,4 [Baker et al., Phys.Rev.D25:617 (1982)]
CCFRR,0 [MacFarlane et al., Zeit.Phys.C26:1 (1984)]
CHARM,4 [Allaby et al., Zeit.Phys.C38:403 (1988)]
FNAL_15FT,2 [Baker et al., Phys.Rev.Lett.51:735 (1983)]
Gargamelle,10 [Ciampolillo et al., Phys.Lett.B84:281 (1979)]
IHEP_ITEP,0 [Asratyan et al., Phys.Lett.B76:239 (1978)]
IHEP_JINR,0 [Anikeev et al., Zeit.Phys.C70:39 (1996)]
NOMAD,5 [Wu et al, Phys.Lett.B660:19 (2008)]
SciBooNE,0 [Nakajima et al., Phys.Rev.D83:012005 (2011)]

Exclusive cross sections: datasets used in the talk

- ANL_12FT [Campbell et al., Phys.Rev.Lett.30:335(1973)]
- ANL_12FT [Radecky et al., Phys.Rev.D25:1161 (1982)]
- ANL_12FT [Wilkinson et al., Phys.Rev.D90:112017 (2014)]
- BNL_7FT [Wilkinson et al., Phys.Rev.D90:112017 (2014)]

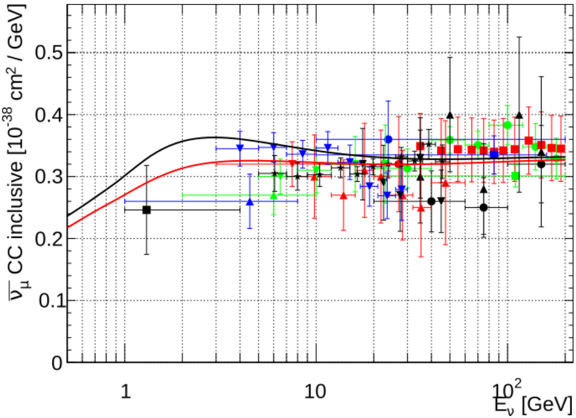
$\nu \rightarrow \mu^- p \pi^+$ datasets and references

- ANL_12FT [Day et al., Phys.Rev.D28:2714 (1983)]
- BNL_7FT [Kitagaki et al., Phys.Rev.D34:2554 (1986)]

$\nu \rightarrow \mu^- p \pi^+ \pi^-$ datasets and references

All the ReAnalized datasets: Wilkinson et al., Phys.Rev.D90:112017 (2014)

Global tune with respect to $\bar{\nu}_\mu$ CC inclusive



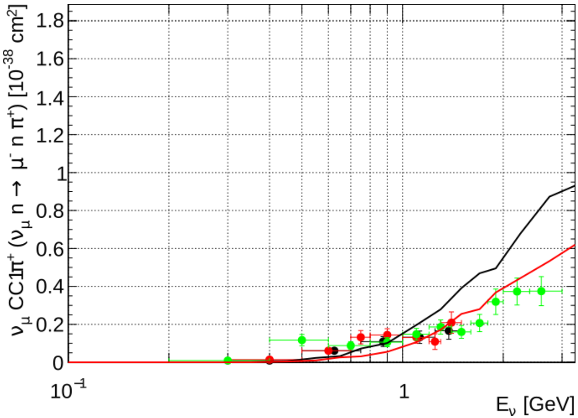
G18_02a default (black) and tuned (red) vs $\bar{\nu}_\mu$ CC inclusive data. $\chi^2_{Total,\,default} = 74.6/69$ DoF, $\chi^2_{Total,\,tuned} = 46.9/69$ DoF. Just BEBC, BNL_7FT and FNAL data used for the tune: $\chi^2_{default} = 17.48/24$ DoF, $\chi^2_{tuned} = 17.45/24$ DoF.

Global tune with respect to $\bar{\nu}_\mu$ CC inclusive

- BEBC,1 [Bosetti et al., Phys.Lett.B70:273 (1977)]
- BEBC,6 [Bosetti et al., Phys.Lett.B110:167 (1982)]
- BNL_7FT,1 [Fanourakis et al., Phys.Rev.D21:562 (1980)]
- CHARM,1 [Jonker et al., Phys.Lett.B99:265 (1981)]
- FNAL_15FT,4 [Taylor et al., Phys.Rev.Lett.51:739 (1983)]
- Gargamelle,1 [Eichten et al., Phys.Lett.B46:274 (1973)]
- Gargamelle,13 [Morfin et al., Phys.Lett.B104:235 (1981)]
- IHEP_ITEP,3 [Vovenko et al., Sov.J.Nucl.Phys.30:528 (1979)]
- MINOS,1 [Adamson et al., Phys.Rev.D81:072002 (2010)]
- BEBC,3 [Colley et al., Zeit.Phys.C2:187 (1979)]
- BEBC,7 [Parker et al., Nucl.Phys.B232:1 (1984)]
- CCFR,3 [Seligman et al., Nevis Report 292 (1996)]
- CHARM,5 [Allaby et al., Zeit.Phys.C38:403 (1988)]
- FNAL_15FT,5 [Asratyan et al., Phys.Lett.B137:122 (1984)]
- Gargamelle,11 [Erriquez et al., Phys.Lett.B80:309 (1979)]
- IHEP_ITEP,1 [Asratyan et al., Phys.Lett.B76:239 (1978)]
- IHEP_JINR,1 [Anikeev et al., Zeit.Phys.C70:39 (1996)]

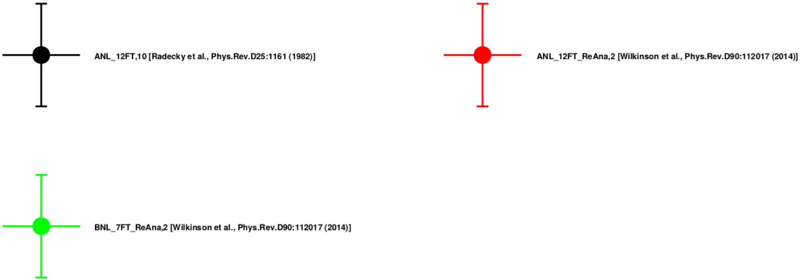
References for $\bar{\nu}_\mu$ CC inclusive datasets.

Global tune with respect to $\nu_\mu n \to \mu^- n\pi^+$



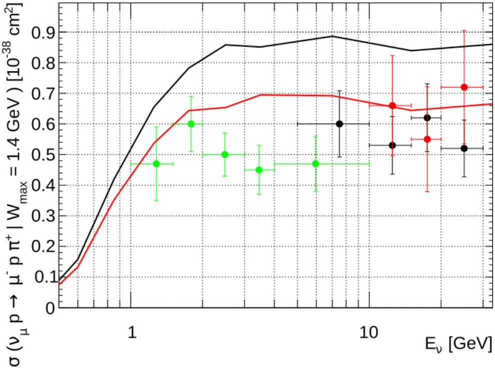
G18_02a default (black) and tuned (red) vs $\nu_\mu n \to \mu^- n\pi^+$ data. All the datasets have been used for the tune. $\chi^2_{Total,default} = 187/23$ DoF, $\chi^2_{Total,tuned} = 98.7/23$ DoF.

Global tune with respect to $\nu_\mu n \to \mu^- n \pi^+$



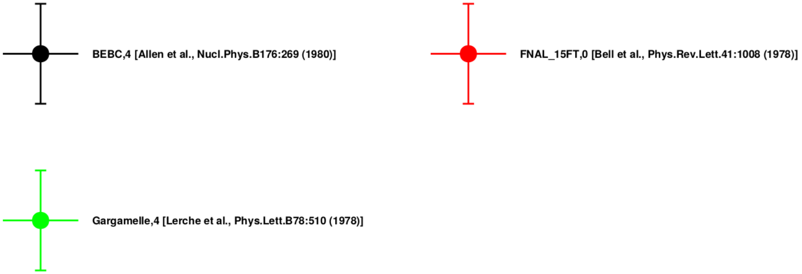
Datasets references for $\nu_\mu n \to \mu^- n \pi^+$.

Global tune with respect to $\nu_\mu p \rightarrow \mu^- p \pi^+$ with 1.4 GeV cut on W



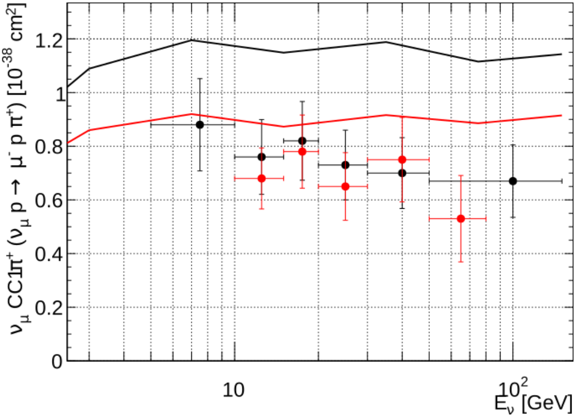
G18_02a default (black) and tuned (red) vs $\nu_\mu p \rightarrow \mu^- p \pi^+$ data. In the analysis of these datasets they applied a cut on W at 1.4 GeV. $\chi^2_{Total,\ default} = 94.5/12$ DoF, $\chi^2_{Total,\ tuned} = 25/12$ DoF. Just BEBC and FNAL data used for the tune: $\chi^2_{default} = 19.65/8$ DoF and $\chi^2_{tuned} = 5.054/8$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- p\pi^+$



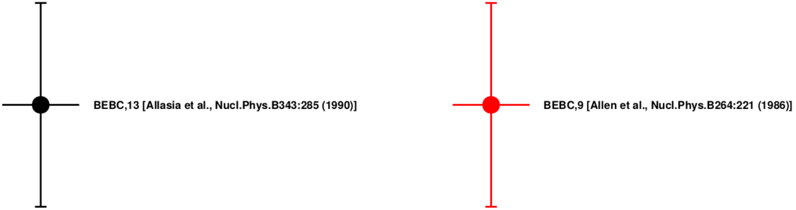
Datasets references for $\nu_\mu p \to \mu^- p\pi^+$ with a cut on W at 1.4 GeV.

Global tune with respect to $\nu_\mu p \to \mu^- p\pi^+$ with 2 GeV cut on W



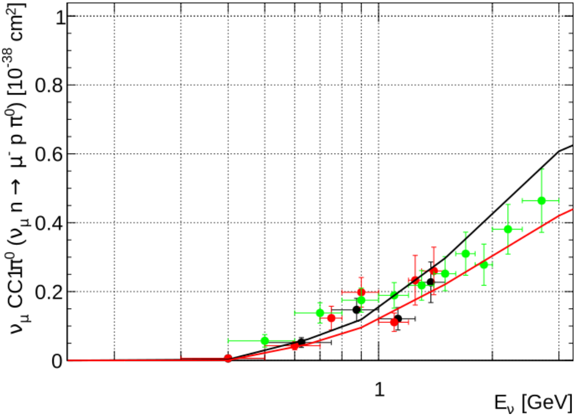
G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- p\pi^+$ data. All data was used for the tune. In the analysis of these datasets they applied a cut on W at 2 GeV. $\chi^2_{Total,\, default} = 44.9/11$ DoF, $\chi^2_{Total,\, tuned} = 15.3/11$ DoF.

Global tune with respect to $\nu_\mu p \rightarrow \mu^- p \pi^+$



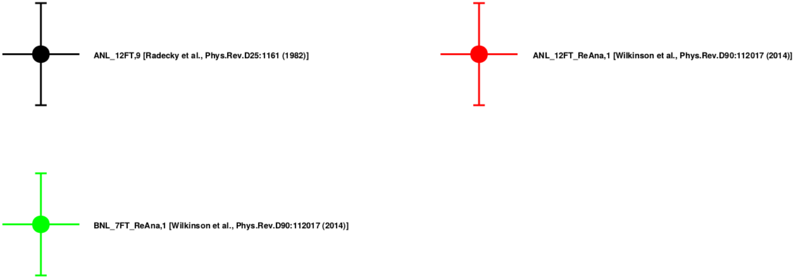
Datasets references for $\nu_\mu p \rightarrow \mu^- p \pi^+$ with a cut on W at 2 GeV.

Global tune with respect to $\nu_\mu p \rightarrow \mu^- n\pi^0$



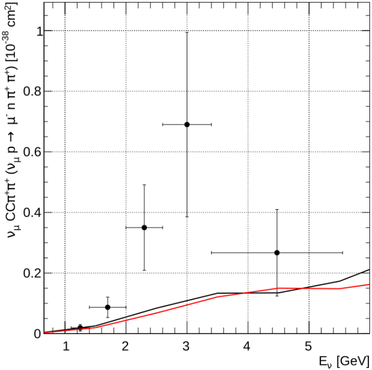
G18_02a default (black) and tuned (red) vs $\nu_\mu p \rightarrow \mu^- n\pi^0$ data. All data was used for the tune. $\chi^2_{Total,\, default} = 66.7/22$ DoF, $\chi^2_{Total,\, tuned} = 42.1/22$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- n\pi^0$



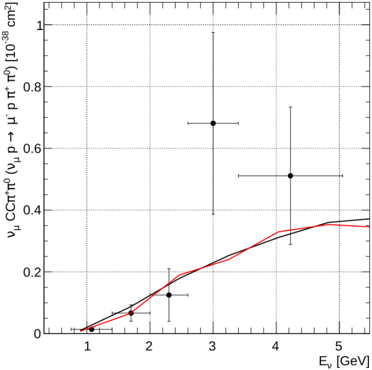
Datasets references for $\nu_\mu p \to \mu^- n\pi^0$.

Global tune with respect to $\nu_\mu p \to \mu^- n\pi^+\pi^-$



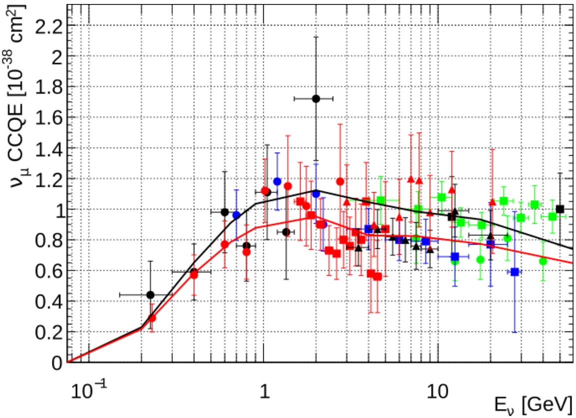
G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- n\pi^+\pi^-$ data. ANL_12FT,13 [Day et al., Phys.Rev.D28:2714 (1983)] used in the tune. $\chi^2_{Total,\,default} = 8.61/5$ DoF, $\chi^2_{Total,\,tuned} = 9.54/5$ DoF.

Global tune with respect to $\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0$



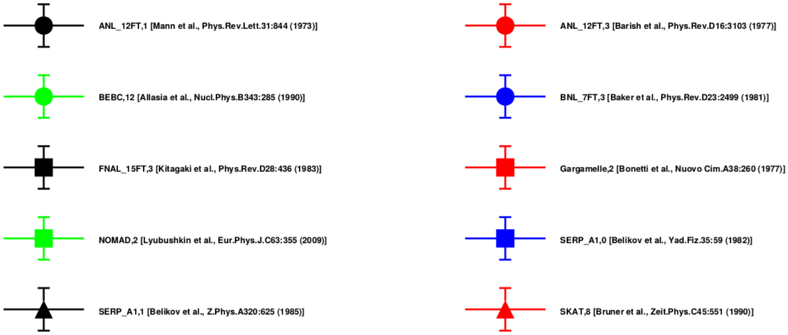
G18_02a default (black) and tuned (red) vs $\nu_\mu p \rightarrow \mu^- p \pi^+ \pi^0$ data. ANL_12FT,12 [Day et al., Phys.Rev.D28:2714 (1983)] used in the tune. $\chi^2_{Total,\, default} = 4.21/5$ DoF, $\chi^2_{Total,\, tuned} = 4.4/5$ DoF.

Global tune with respect to ν_μ CC QEL



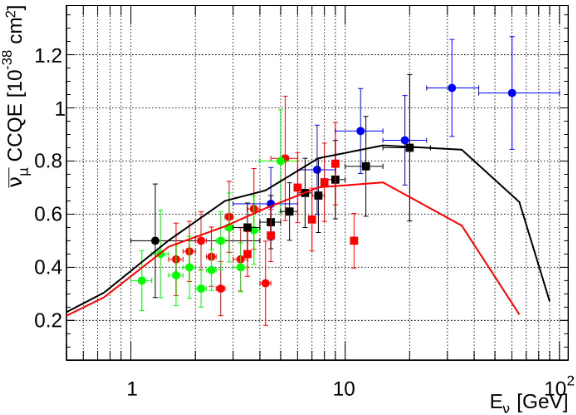
G18_02a default (black) and tuned (red) vs ν_μ CC QEL data. $\chi^2_{Total,\, default} = 85.1/70$ DoF, $\chi^2_{Total,\, tuned} = 79.7/70$ DoF. Only ANL_12FT, BEBC, BNL_7FT and FNAL data used for the fit: $\chi^2_{default} = 28.85/26$ DoF, $\chi^2_{tuned} = 22.84/26$ DoF.

Global tune with respect to ν_μ CC QEL



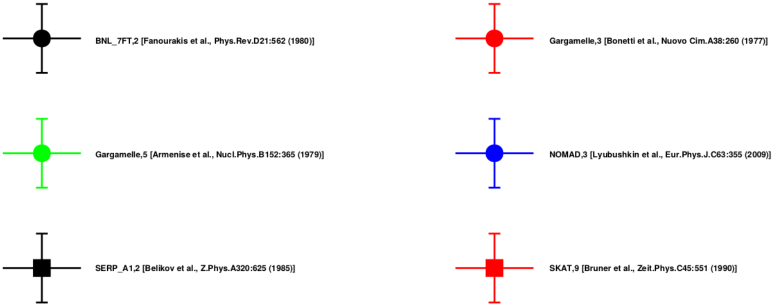
Datasets references for ν_μ CC QEL.

Global tune with respect to $\bar{\nu}_\mu$ CC QEL



G18_02a default (black) and tuned (red) vs $\bar{\nu}$ CC QEL data. $\chi^2_{Total,\,default} = 86.2/43$ DoF, $\chi^2_{Total,\,tuned} = 69.9/43$ DoF. Only BNL_7FT data used for the fit: $\chi^2_{default} = 0.125/1$ DoF, $\chi^2_{tuned} = 0.00566/1$ DoF.

Global tune with respect to $\bar{\nu}_\mu$ CC QEL



Datasets references for $\bar{\nu}$ CC QEL.

Previous studies results

Previous studies

- $M_A^{QE} = 0.99 \pm 0.044$ GeV/c^2, global fit which considers Al data
  Eur. Phys. J. C (2008) 54
- $M_A^{QE} = 0.89 \pm 0.044$ GeV/c^2, fit to just BEBC data
  Eur. Phys. J. C (2008) 54
- $M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [S.Konstantin et. al. arXiv:0606184v1]
- $M_A^{RES} = 0.94 \pm 0.05$ GeV/c^2, [P.Rodrigues et. al. arXiv:1601.01888]