O problemach z opisem produkcji pionów w oddziaływaniach neutrin

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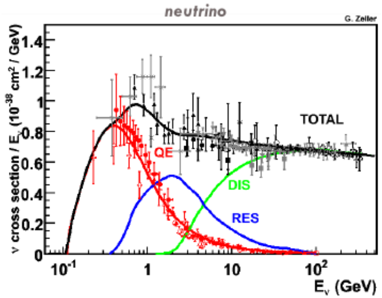
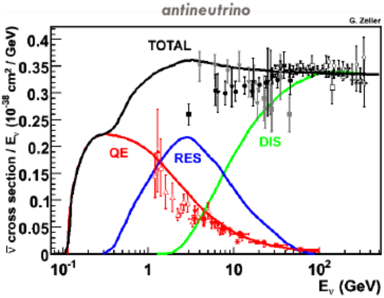
Outline:

- introduction
- puzzle 1: ANL and BNL normalization
- puzzle 2: neutron versus proton π^+ production
- puzzle 3: MiniBooNE π^+ production data
- puzzle 4: MiniBooNE versus MINERvA π^+ production data

Basic interactions modes – vocabulary





Sam Zeller; based on P. Lipari et al

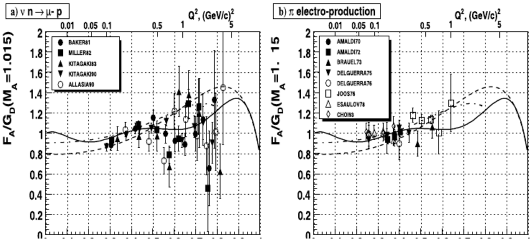
CCQE is $\nu_\mu\ n \to \mu^-\ p$, or $\bar{\nu}_\mu\ p \to \mu^+\ n$.

RES stands for resonance region e.g. $\nu_\mu\ p \to \mu^-\ \Delta^{++} \to \mu^-\ p\ \pi^+$;
one often speaks about SPP - single pion production

DIS stands for: more inelastic than RES.

In the ~ 1 GeV region CCQE and RES are most important.

CCQE and MEC under control?



- older M_A measurements indicate the value of about 1.05 GeV
- independent pion production arguments lead to the similar conclusion

The experimental data is consistent with dipole axial FF and $M_A = 1.015$ GeV.

A. Bodek, S. Avvakumov, R. Bradford, H. Budd

In the near future there should be reliable (5%?) theoretical computations of weak nuclear response (Euclidean response or sum rules) in the QE peak region for carbon, including both one body and two body current contributions.

J. Carlson, R. Schiavilla, A. Lovato et al

Why do we need to understand RES?

- often these are background events
  - if π is absorbed they mimic CCQE (used to measure ν oscillation signal)
  - NC π^0 decay into 2γ and can be confused with ν_e
- pion production channels important at LBNE energies
- theoretical interest, hadronic physics

Neutrino SPP channels

For neutrinos there are three charged current (CC) channels:

$$\nu_l\ p \rightarrow l^-\ p\ \pi^+,$$
$$\nu_l\ n \rightarrow l^-\ n\ \pi^+,$$
$$\nu_l\ n \rightarrow l^-\ p\ \pi^0.$$

The name RES (resonance) reflects an observation that most of the cross section comes from resonance excitation, in the ~ 1 GeV energy region mostly of Δ resonance:

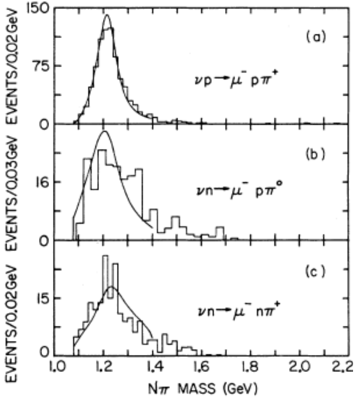
$$\nu_l\ p \rightarrow l^-\ \Delta^{++} \rightarrow l^-\ p\ \pi^+,$$
$$\nu_l\ n \rightarrow l^-\ \Delta^{+} \rightarrow l^-\ n\ \pi^+,$$
$$\nu_l\ n \rightarrow l^-\ \Delta^{+} \rightarrow l^-\ p\ \pi^0.$$

Assuming that the only mechanism is Δ excitation, isospin rules tell us that the cross sections ratio is 9:1:2.

Very little is known about weak current excitation of heavier resonances.

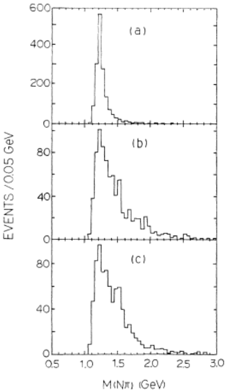
Δ resonance in the weak pion production data

Below, distributions of events in invariant hadronic mass, from old bubble chamber experiments:



ANL

Radecky, et al, PRD 25 1161 (1982)



BNL

Kitagaki, et al, PRD 34 2554 (1986)

The $p\pi^+$ channel is overwhelmingly dominated by the Δ excitation but in other two channels the situation is more complicated.

Theoretical models must include a non-resonant background.

An experimental status of RES – overview:

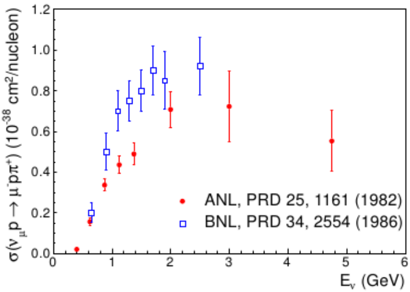
- there are $\sim$ 30 years old deuterium (plus a small fraction of hydrogen – 105 events) bubble chamber data from Argonne (ANL) and Brookhaven (BNL) experiments
  - there is a lot of discussion if ANL and BNL data are consistent in $p\pi^+$ channel
  - problem of consistency between three SPP channels
- there are more recent measurements done on nucleus targets (mostly carbon)
  - difficult to disentangle nuclear (FSI) effects
  - there is an intriguing tension between MiniBooNE and recent MINERvA data

Altogether ...

- ... we can speak about weak pion production puzzles.

ANL and BNL data

It is often claimed there is a tension between both data sets:



from Phil Rodrigues

In the data there is no cut on W.

An apparent discrepancy at $E_\nu \sim 1.5$ GeV.

It seems however, that both experiments did not pay enough attention to overall flux normalization error.

Normalization in ANL

Below, results for $\frac{d\sigma}{dQ^2}$ from ANL experiments.

Q^2	$d\sigma/dQ^2$	$\Delta\sigma/\sigma$	N (events)	$1/\sqrt{N}$
0.01-0.05	0.527± 0.079	15%	51.4	13.9%
0.05-0.1	0.724± 0.084	11.6%	94.5	10.3%
0.1-0.2	0.656± 0.058	8.8%	158.4	7.9%
0.2-0.3	0.546± 0.052	9.5%	133.3	8.7%
0.3-0.4	0.417± 0.045	10.8%	99.2	10%
0.4-0.5	0.307± 0.038	12.4%	70.6	11.9%
0.5-0.6	0.215± 0.032	14.9%	54.8	13.5%
0.6-0.8	0.138± 0.018	13.0%	66.2	12.3%
0.8-1.0	0.069± 0.013	18.8%	33.4	17.3%

The patterns of reported total error and statistical errors are identical, with an overall rescaling by ~ 1.08. Translated into quadrature it gives other error as small as $3.9 - 7.3\%$.

Normalization in ANL

Total ANL cross sections have errors from 8.9% (in the bin $(0.75 - 1)$ GeV) up. It seems they include mostly statistical errors as well.

Another minor point:

In order to investigate Δ region one can use ANL data with an appropriate cut on invariant hadronic mass $W < 1.4$ GeV. The same is impossible with the BNL data.

A realistic assumption is that the flux normalization errors in both experiments are: 20% for ANL and 10% for BNL.

Re-analysis of the ANL and BNL data with a flux renormalization error and deuteron effects was done in

Graczyk, Kiełczewska, Przewłocki, JTS, Phys. Rev D80 093001 (2009).

ANL and BNL data re-analysis

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\sigma_{th}^{diff}(Q_i^2) - p\sigma_{ex}^{diff}(Q_i^2)}{p\Delta\sigma_i} \right)^2 + \left(\frac{p-1}{r} \right)^2,$$

$\sigma_{tot-exp}$ and σ_{tot-th} are the experimental and theoretical flux averaged cross sections measured and calculated with the same cuts, r is a normalization error, p is un unknown flux correction normalization factor (to be found in the fit).

D'Agostini, Nucl. Instrum. Meth. A346 (1994) 306.

The fit was done to $\nu_\mu p \to \mu^- p \pi^+$ channel with a model that contained only Δ^{++}, and no non-resonant background. The results were surprising: both data sets are in agreement! Best fit values of renormalization factors were found to be: $p_{ANL} = 1.08 \pm 0.1$ and $p_{BNL} = 0.98 \pm 0.03$.

ANL (left) and BNL (right) data re-analysis

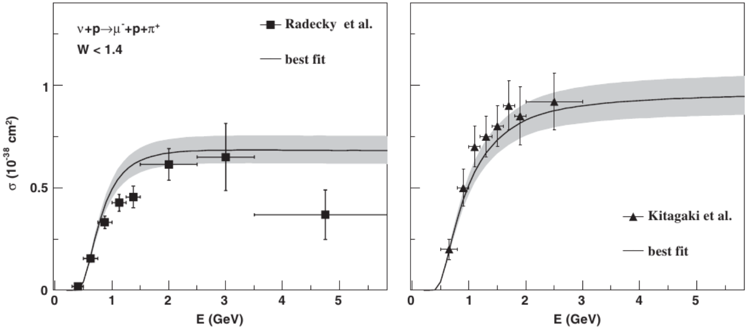
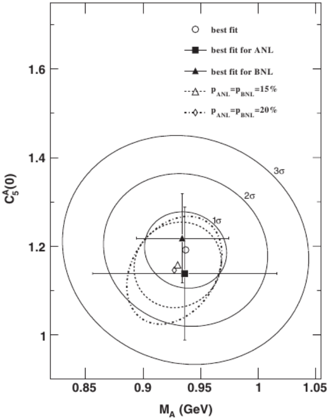


FIG. 5. Total cross section for $\nu + p \rightarrow \mu^- + p + \pi^+$. In the left panel the ANL data [5] with the cut $W = 1.4$ are shown (black squares), while the right panel presents the BNL data [42] (without cuts in W)—black triangles. The overall normalization error is not plotted. The best fit curves were obtained with a corresponding cut in W. The theoretical curves were obtained with dipole parametrization Eq. (32) with $M_A = 0.94$ GeV and $C_5^A(0) = 1.19$. The shaded areas denote the 1σ uncertainties of the best fit. The theoretical curves are not modified by the deuteron correction effect.

ANL and BNL data re-analysis

Parameter goodness of fit also showed a good agreement between both data sets.



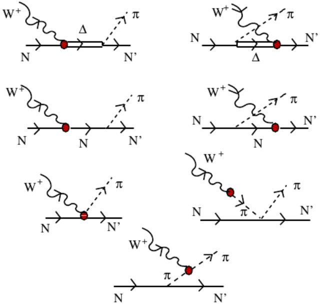
The idea parameter goodness of fit is to compare seperate ANL and BNL fits with a joint fit.

Maltoni, Schwebs

Neutron SPP channels, non-resonant background

As seen before in the neutron SPP channels non-Δ contribution is very important.

A possible strategy: take a model based on Chiral Field Theory:



Hernandez, Nieves, Valverde, Phys.Rev. D76 (2007) 033005

The same set of diagrams is used in MEC computations.

Neutron SPP channels, non-resonant background

In phenomenological studies one makes a fit to $N \to \Delta$ transition matrix element form-factors:

$$\left\langle \Delta^{++}(p') \right| V_\mu \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_\lambda(p') \left[g^\lambda_{\ \mu} \left(\frac{C_3^V}{M}\gamma_\nu + \frac{C_4^V}{M^2}p'_\nu + \frac{C_5^V}{M^2}p_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^V}{M}\gamma_\mu + \frac{C_4^V}{M^2}p'_\mu + \frac{C_5^V}{M^2}p_\mu \right) \right] \gamma_5 u(p)$$

$$\left\langle \Delta^{++}(p') \right| A_\mu \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_\lambda(p') \left[g^\lambda_{\ \mu} \left(\gamma_\nu \frac{C_3^A}{M} + \frac{C_4^A}{M^2}p'_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^A}{M}\gamma_\mu + \frac{C_4^A}{M^2}p'_\mu \right) + g^\lambda_{\ \mu} C_5^A + \frac{q^\lambda q_\mu}{M^2} C_6^A \right] u(p).$$

$\Psi_\mu(p')$ is Rarita-Schwinger field, and $u(p)$ is Dirac spinor.

Typically, one fits values of $C_5^A(0)$ and M_A, where $C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$, imposing reasonable conditions on remaining ones. Vector FF are taken from electroproduction experiments.

Neutron SPP channels, non-resonant background

Such a study has been done recently using ANL data with a cut $W < 1.4$ GeV. Deuteron effects in plane wave impulse approximation (neglecting FSI) are included.

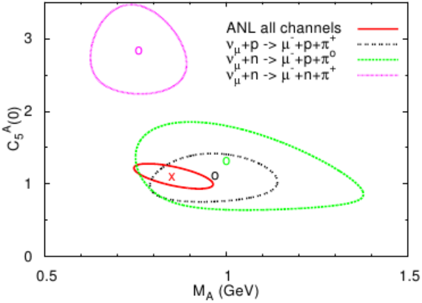
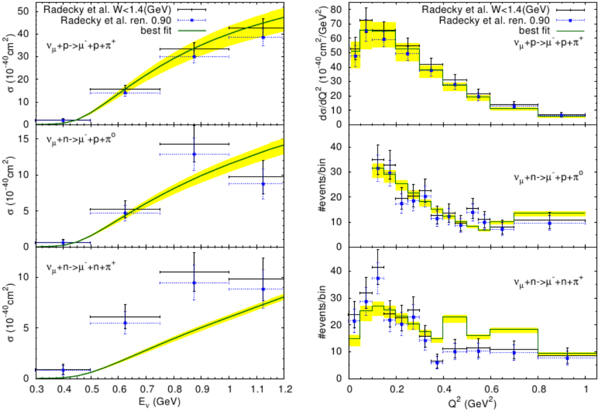


FIG. 5. (Color online) 1σ uncertainty contours for fits on deuteron target.

Graczyk, Żmuda, JTS PRD90 (2014) 9, 093001

The $n\pi^+$ channel prefers much larger value of $C_5^A(0)$ and seems to be inconsistent with the other two.

Neutron SPP channels, non-resonant background



In the $n\pi^+$ channel the measured cross section is much larger than the calculated one.

Neutron SPP channels, non-resonant background

What goes wrong may be a lack of unitarity in the model.

- unitarity and time invariance relate weak pion production matrix element phase with a pion-nucleon interaction matrix element (Watson theorem)
- study done by L. Alvarez-Ruso, E.Hernandez, J. Nieves, M. Valverde, and M.J. Vicente Vacas.

Nuclear target SPP measurements

- typically, one measures cross section for 1π in the final state
- not the same as free nucleon SPP
  - pion absorption
  - pion charge exchange

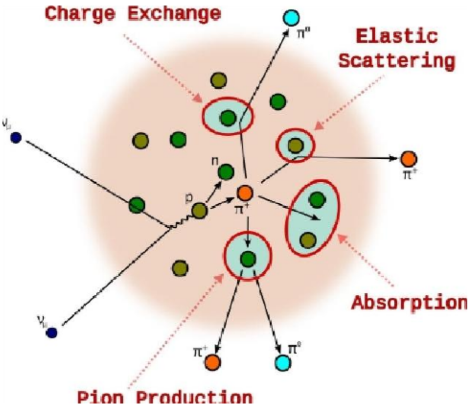
Important advantage vrt old measurements:

- much better statistics

Theoretical computations should include Δ in-medium self energy broadening, see backup slides.

Final state interactions:

What is observed are particles in the final state.



from T. Golan

Pions...

- can be absorbed
- can be scattered elastically
- (if energetically enough) can produce new pions
- can exchange electic charge with nucleons

Nuclear target SPP measurements

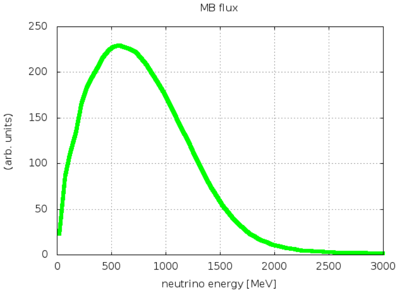
- typically, one measures cross section for 1π in the final state
- not the same as free nucleon SPP
  - pion absorption
  - pion charge exchange

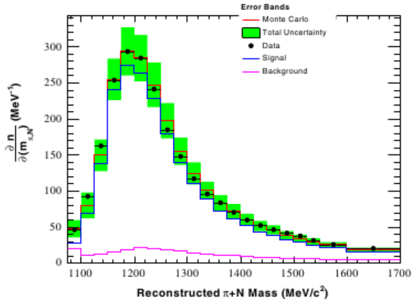
Important advantage vrt old measurements:

- much better statistics

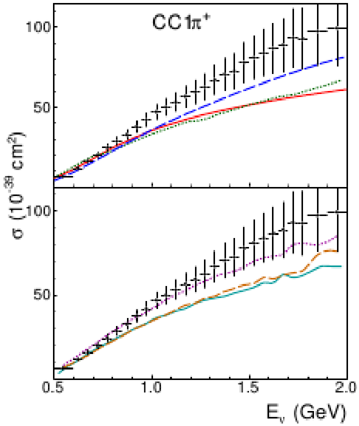
MiniBooNE CC π^+ production measurement

- target is CH_2
- flux peaked at 600 MeV, without high energy tail $\Rightarrow$ the relevant dynamics is in the Δ region
- coherent π^+ production is a part of the signal
- signal defined as $1\pi^+$ and no other pions in the final state.

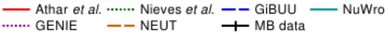




MiniBooNE SPP data and theoretical models

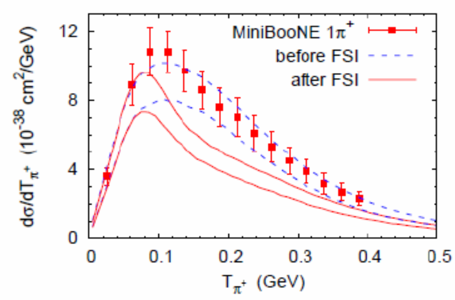


Typically, the measured cross section is underestimated.



MiniBooNE data and FSI effects

GIBUU results

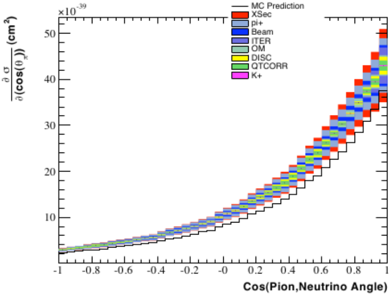


U. Mosel

Better agreement with computations without FSI. But we know, FSI must be there.

MiniBooNE CC1π^+ angular distribution

There is also less known π^+ angular distribution data:



M. Wilkins, PhD Thesis

The data is not official. For π with $T_\pi < 70...150$ MeV direction is poorly reconstructed and MC NUANCE) predictions were used.

MINERvA CC π^+ production measurement

- target is CH
- NuMi flux $(1.5 - 10)$ GeV with $< E_\nu > \sim 4$ GeV
- a cut $W < 1.4$ GeV
- as a result, the Δ region is investigated, like in the MiniBooNE experiment
- coherent π^+ production is a part of the signal
- signal is defined as $1\pi^\pm$ (almost always it is π^+) in the final state
    - contrary to MiniBooNE there can be arbitrary number of π^0 in the final state

MinoBooNE and MINERvA

Does it make sense to compare MiniBooNE and MINERvA results?

- very different energy

But...

- the same Δ mechanism

The only relevant difference can come from slightly different definitions of the signal, and perhaps from relativistic effects.

- at larger energy more momentum is transfered to the hadronic system, and Δ is more relativistic

MinoBooNE and MINERvA

Composition of the signal in two experiments
MiniBooNE

- RES: 87.1%
- COH: 6.7%
- DIS: 3.6%
- QEL and MEC: 2.7%

MINERvA

- RES: 84.7%
- COH: 10.7%
- QEL and MEC: 4.6%

MinoBooNE and MINERvA

FSI effects are expected to be very similar:

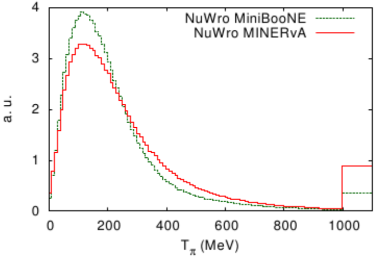
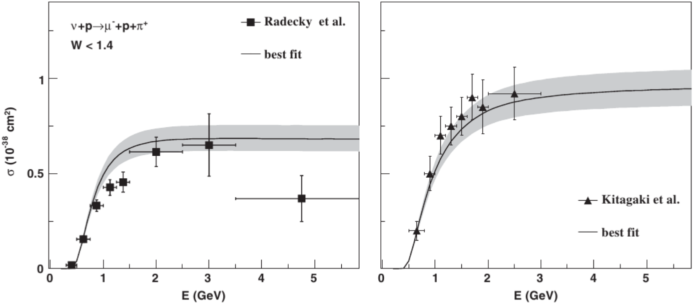


FIG. 9. (Color onlne) Spectrum of pion kinetic energy distribution for both experiments predicted by NuWro without FSI effects. Last bin includes pions with kinetic energies above 1 (GeV).

MinoBooNE and MINERvA

The only relevant difference is in normalization: at MINERvA energies cross section is larger by a factor of ~ 2!



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Graczyk, Kiełczewska, Przewłocki, JTS, Phys. Rev D80 093001 (2009).

MinoBooNE and MINERvA

The most obvious consistency test is to look at the cross sections ratios from both experiments and compare with Monte Carlo.

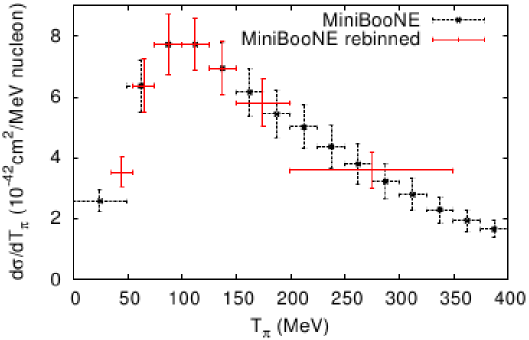
$$\frac{\left(\frac{d\sigma}{dT_\pi}\right)^{MINERvA}}{\left(\frac{d\sigma}{dT_\pi}\right)^{MiniBooNE}} \quad \text{and} \quad \frac{\left(\frac{d\sigma}{d\theta_\pi}\right)^{MINERvA}}{\left(\frac{d\sigma}{d\theta_\pi}\right)^{MiniBooNE}}$$

Some work must be done:

- both experiments have different binning
- MiniBooNE data is for $\cos\theta_\pi$ and MINERvA for θ_π
- error of experimental ratio must be estimated
- error of NuWro ratio predictions must be estimated as well

A few technicalities:

Rebinning:



A few technicalities:

- for ratios the processed data points are treated as random variables X and Y with known expected values and variances

$$E(X\cdot Z) = E(X)E(Z),$$
$$Var(X\cdot Z) = Var(X)Var(Z) + E(X)^2 Var(Z) + E(Z)^2 Var(X)$$

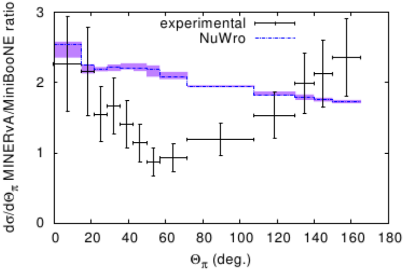
- replacement $Z=\frac{1}{Y}$; $E(\frac{1}{Y}) \neq \frac{1}{E(Y)}$ unless $P(Y)=\delta(Y-Y_0)$
- several assumptions for $P(Y)$ were investigated, results are similar,
- we chose the log-normal distributions:

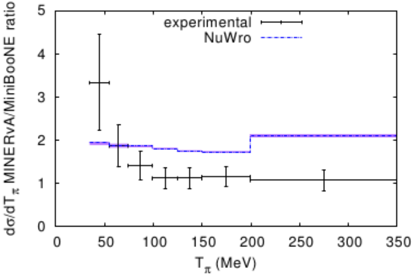
$$P(Y) = \frac{1}{\sqrt{2\pi}bY}\exp\left[-\frac{(\ln(Y)-a)^2}{2b^2}\right]\Theta(Y)$$
$$E(Y) = \exp(b^2/2+a), \quad Var(Y) = \exp(2b^2+2a).$$

We get $E(\frac{1}{Y}) = \exp(b^2/2-a)$ and $Var(\frac{1}{Y}) = \exp(b^2-2a)\left[\exp(b^2)-1\right]$.

MinoBooNE and MINERvA

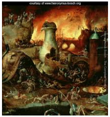
Results:





Large data/Monte Carlo discrepancy in shapes.
Difference in scale can be due to flux normalization uncertainties.
Rememer that MB data for angular distributon is not official. Impact of MC assumptions must be estmated.

Conclusions (green≡ understood/paradise, red ≡ not understood/hell):

- puzzle 1: ANL and BNL normalization 
- puzzle 2: neutron versus proton π^+ production 
- puzzle 3: MiniBooNE π^+ production data 
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