Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC News

Nucleon correlation

EMC effect

electron scattering

Dark matter

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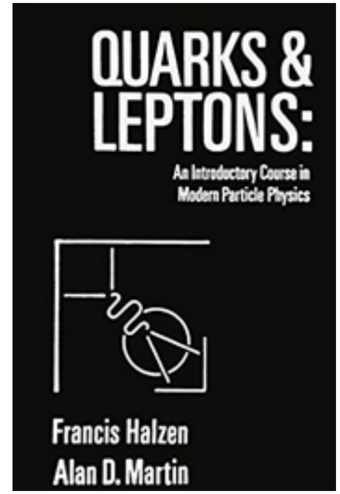
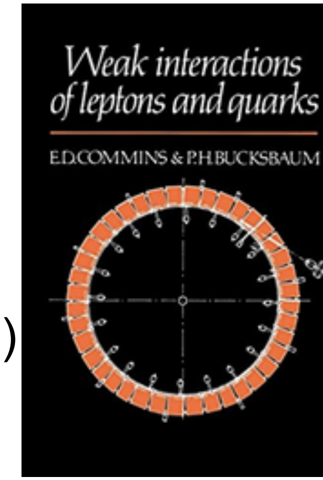
like “@nuxsec” on Facebook page, use hashtag #nuxsec

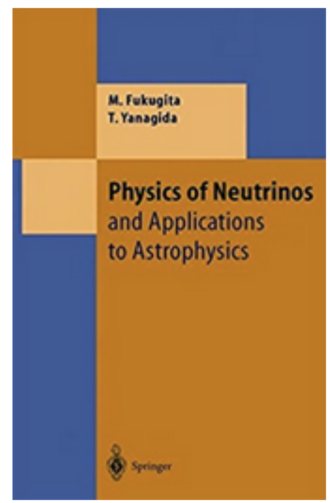
References

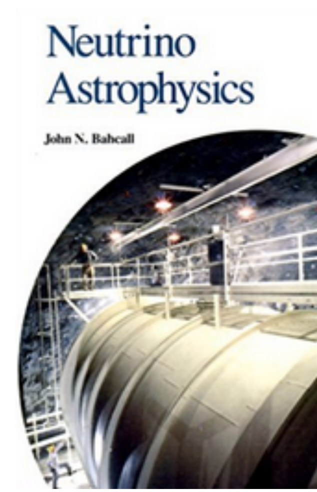




Quarks and Leptons (Halzen and Martin)
- classic
- show many calculations
- solutions for all exercises

Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- classic
- show more details of weak interaction calculations
- too many typos

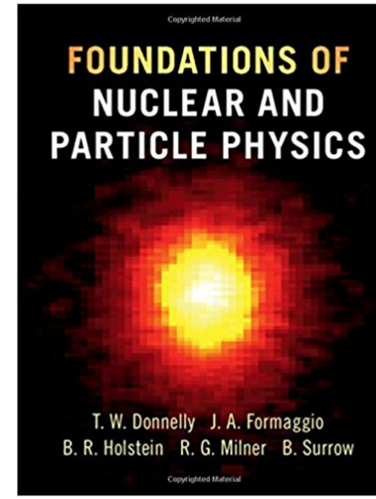




Physics of Neutrinos (Fukugita and Yanagida)
- modern
- very intense
- from solar neutrinos to SUSY

Neutrino astrophysics (Bahcall)
- more likely a novel, honorable mentioning

References



Foundation of Nuclear and Particle Physics (2017)
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- one and only one textbook on this subject
- buy if your PhD thesis topic is about neutrino cross section

"From eV to EeV: Neutrino cross sections across energy scales"
- Authors: Formaggio and Zeller (MicroBooNE spokesperson)
- Rev.Mod.Phys.84(2012)1307, arXiv:1305.7513
- very good summary of neutrino cross sections

"Neutrino-Nucleus Cross Sections for Oscillation Experiments"
- Authors: Katori (me) and Martini (Martini model)
- my paper, a review both theoretical and experimental views
- cite and give me citation number!

"NuSTEC News"
- http://nustec.fnal.gov/
- subscribe mailing list, "like" facebook page, use#nuxsec

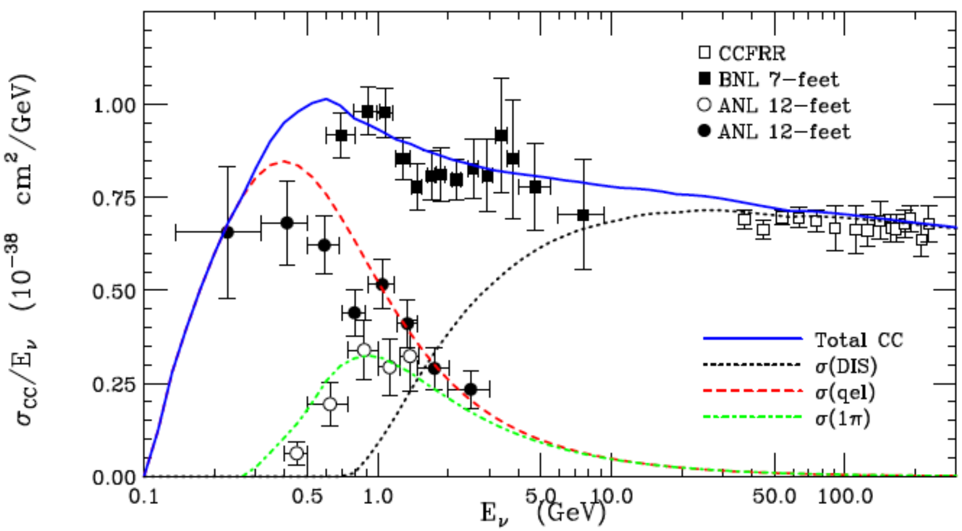
Dark age of neutrino interaction physics

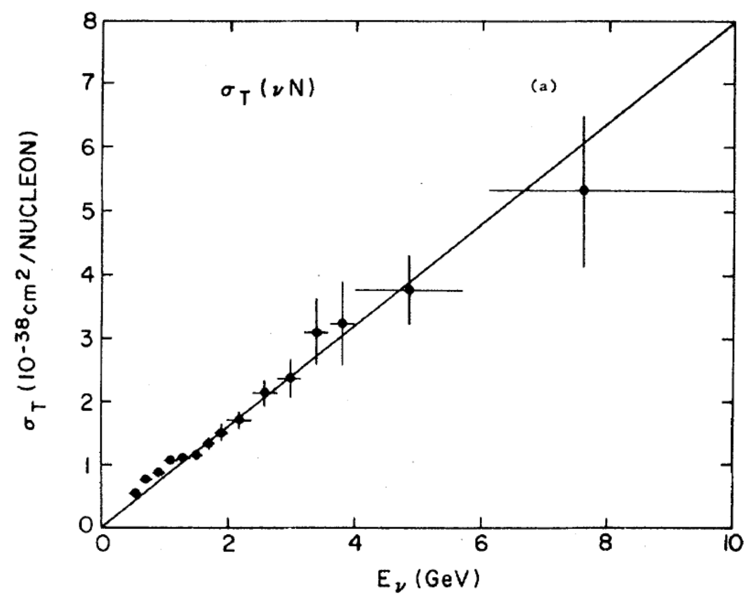
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

What you get? OF COURSE the cross section you assume!

Phys. Rev. D [redacted]

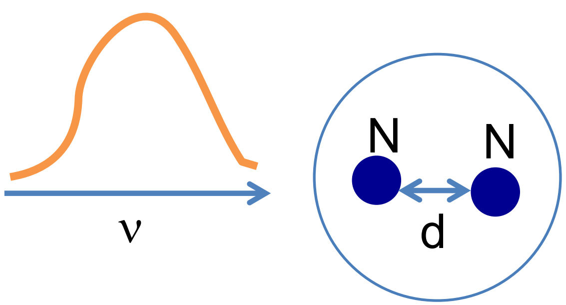
The distribution of events in neutrino energy for the 3C $\nu d \rightarrow \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \rightarrow \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]

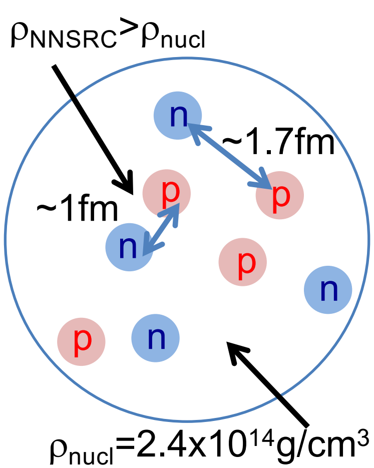




Impulse Approximation is broken at low Q^2 (or low |q|)

$1/q < d$





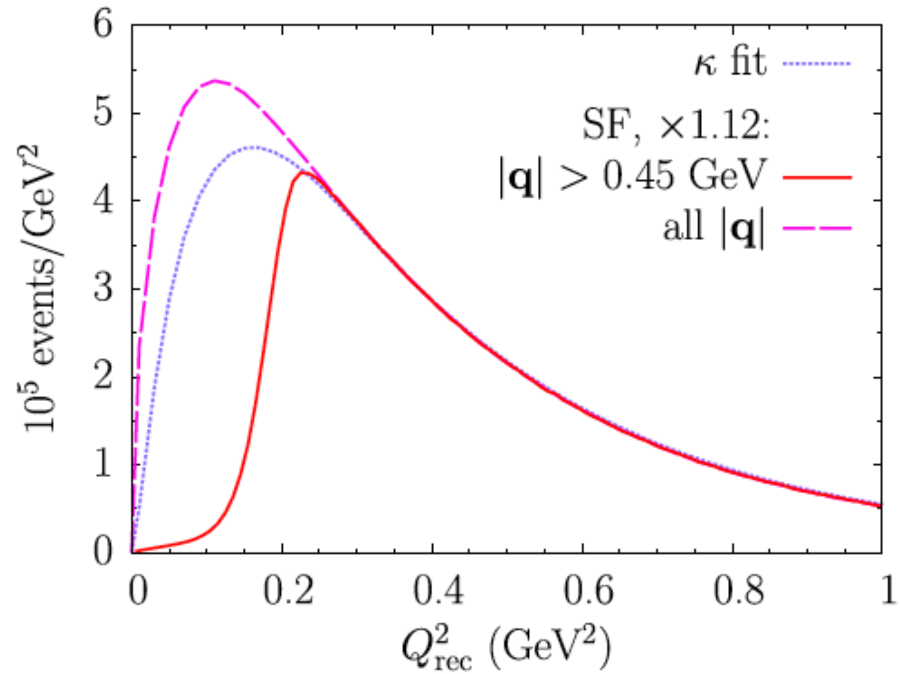


FIG. 6 (color online). Comparison of the MiniBooNE parametrization of the data (dotted line), labeled as the κ fit, to the spectral function calculation (dashed line). The solid line depicts the contribution to the latter from the region where the IA is expected to be valid. The SF results are multiplied by a factor 1.12 to make them match the κ fit.

Nuclear decomposition

PHYSICAL REVIEW C **89**, 024305 (2014)

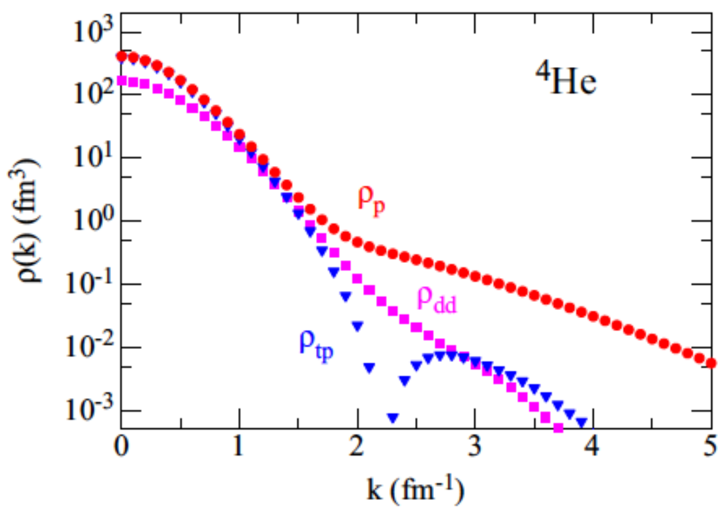


FIG. 4. (Color online) The proton momentum distribution in ^{4}He is shown by the red circles; the *tp* cluster distribution is shown by the blue triangles and the *dd* cluster distribution is shown by the magenta squares.

PHYSICAL REVIEW C **89**, 024305 (2014)

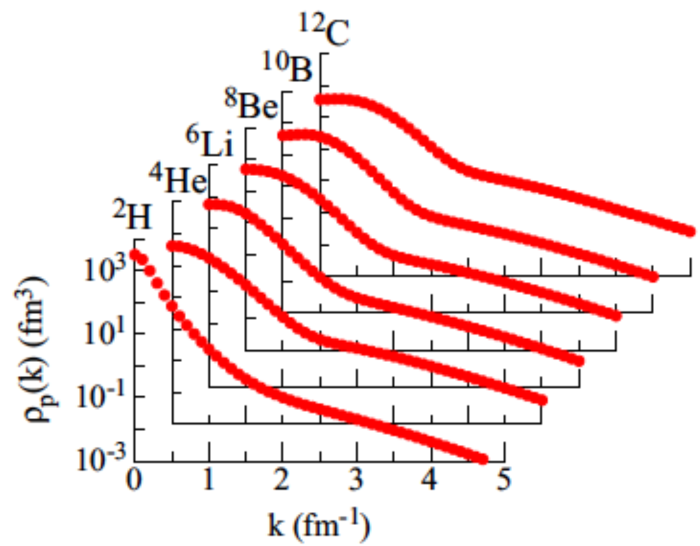
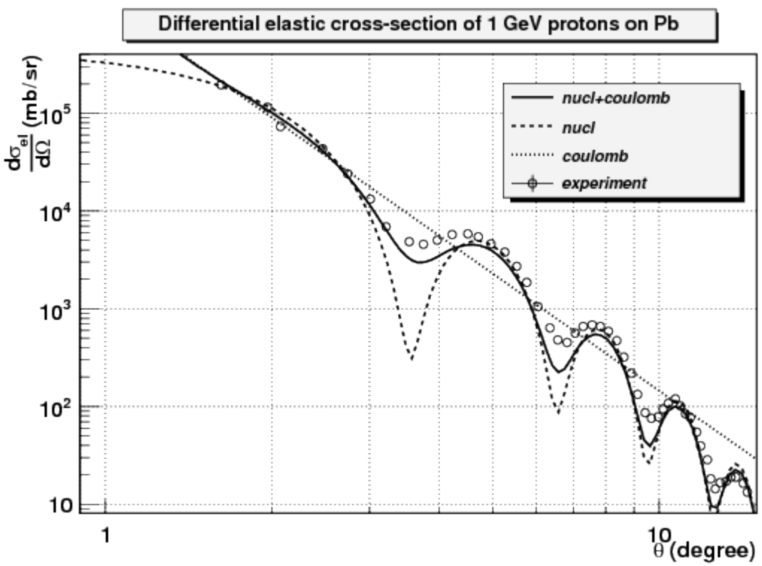


FIG. 10. (Color online) The proton momentum distributions in all $T = 0$ nuclei from $A = 2$–12.

Alvarez-Ruso, NuSTEC15 lecture

Form factor

e+Pb → e+Pb



Fourier transformation
charge distribution ←→ form factor

ρ(r)	$\lvert F(q^2) \rvert$	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca
r ⟶	$\lvert q \rvert$ ⟶	

$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu} q_\nu F_2 + \frac{q^\mu}{M} F_S - \gamma^\mu \gamma_5 F_A - \frac{i}{2M}\sigma^{\mu\nu} q_\nu \gamma_5 F_T - \frac{q^\mu}{M}\gamma_5 F_P$$

1. Neutrino cross-section formula

Cross-section

- product of Leptonic and Hadronic tensor

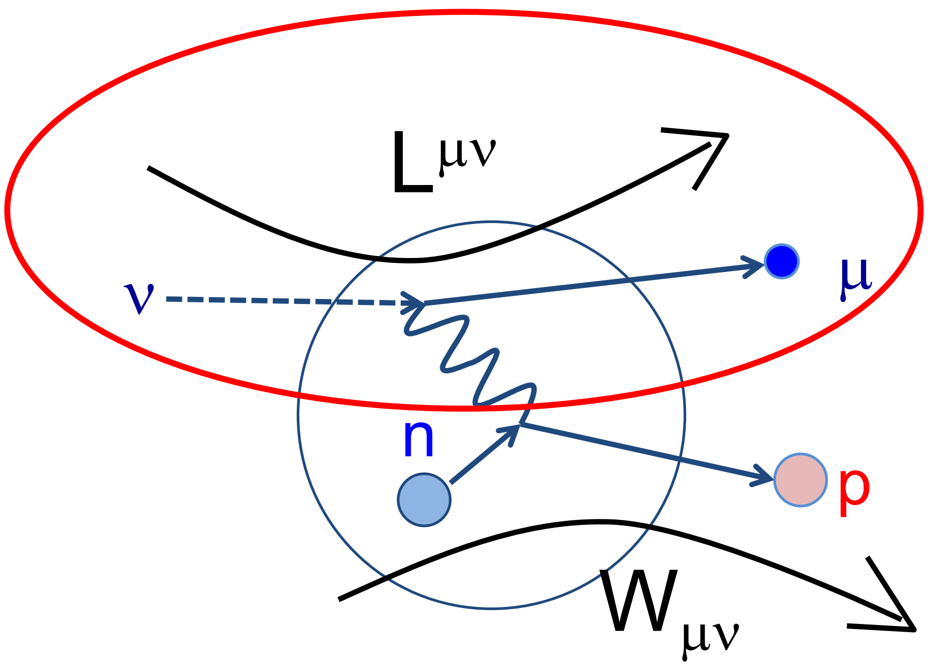
$$d\sigma \sim L^{\mu\nu} W_{\mu\nu}$$

Leptonic tensor

→ the Standard Model (easy)

Hadronic tensor

→ nuclear physics (hard)



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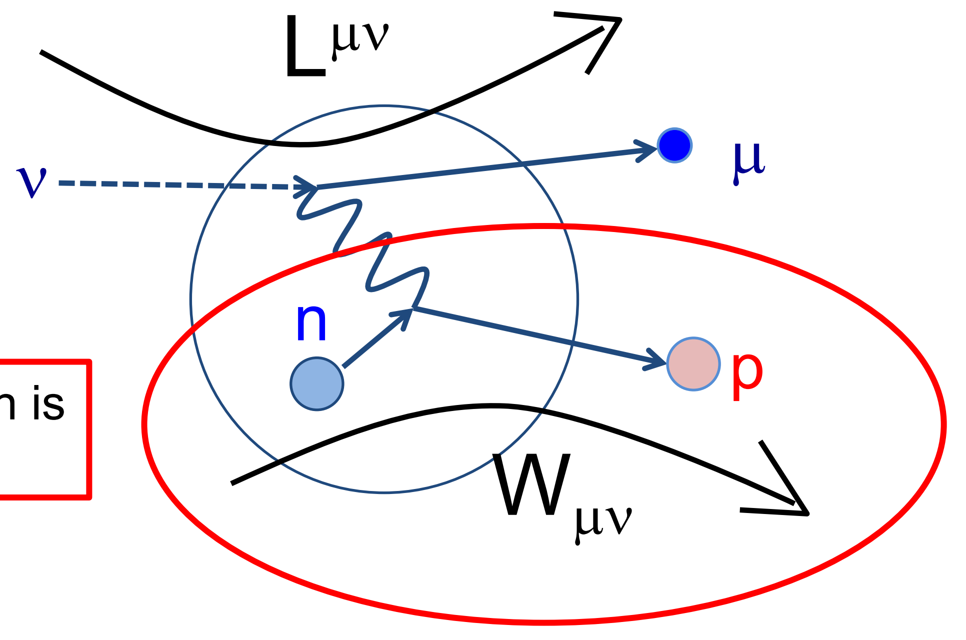
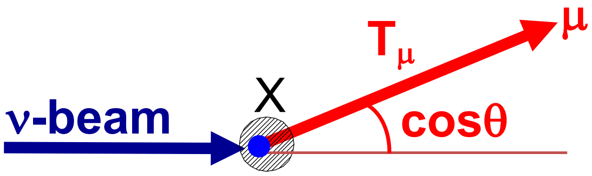


All complication of neutrino cross-section is how to model the hadronic tensor part

2. MiniBooNE phase space



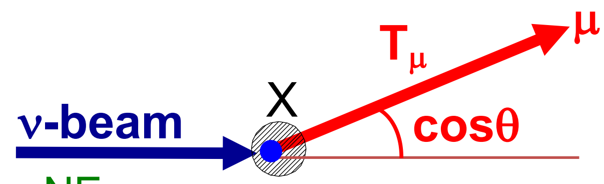
Experiment measure the interaction rate R,

$$R \sim \int \Phi \times \sigma \times \varepsilon$$

- Φ : neutrino flux
- σ : cross section
- ε : efficiency

When do you see data-MC disagreement, how to interpret the result?

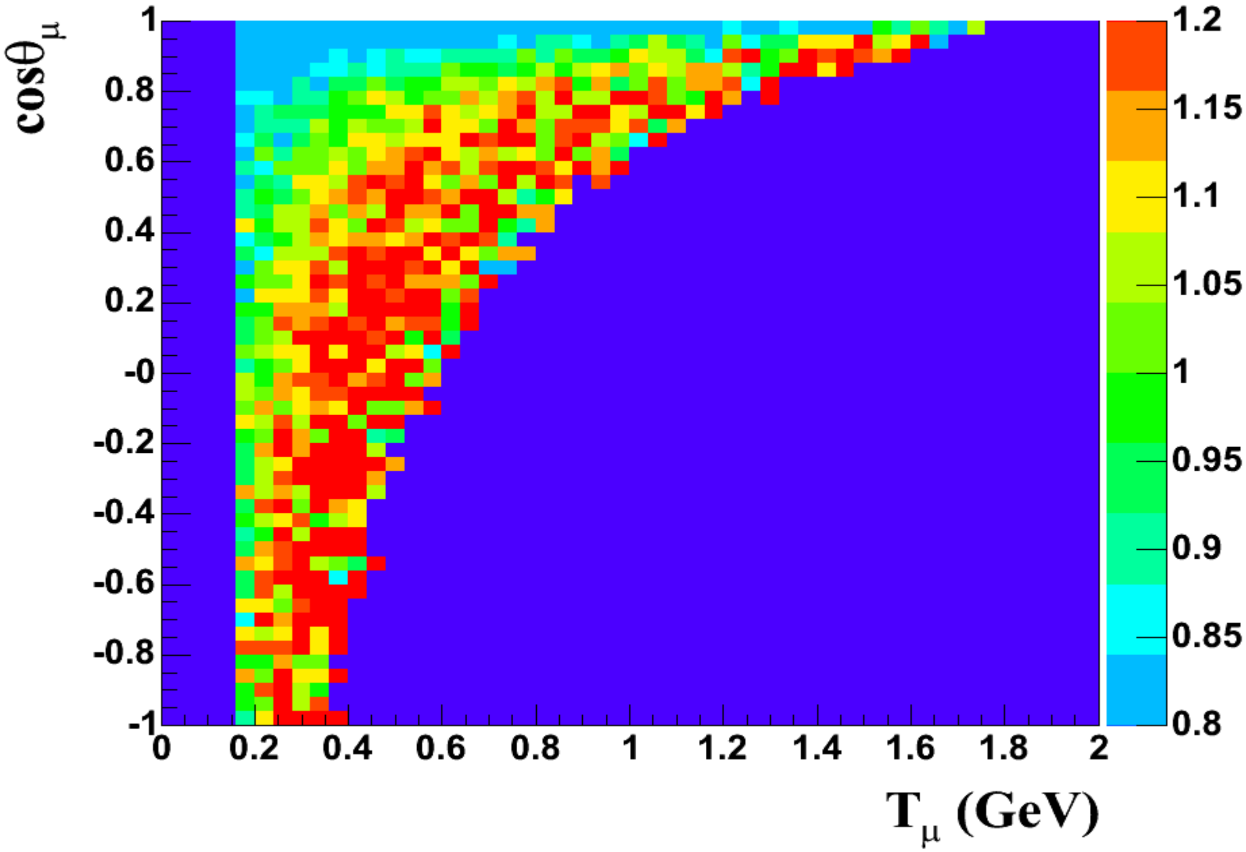
2. MiniBooNE phase space



CCQE kinematic space (T_μ-$\cos\theta_\mu$ plane) in MiniBooNE

Since observables are muon energy (T_μ) and angle ($\cos\theta_\mu$), these 2 variables completely specify the kinematic space.

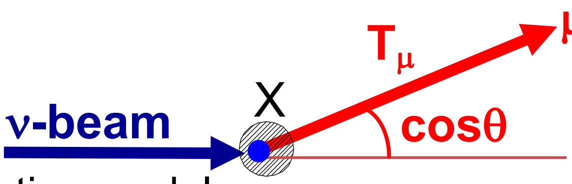
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$



Data-MC ratio for T_μ-$\cos\theta_\mu$ plane (arbitrary normalization).
MiniBooNE MC doesn't describe data very well.

We would like to improve our simulation, but how?

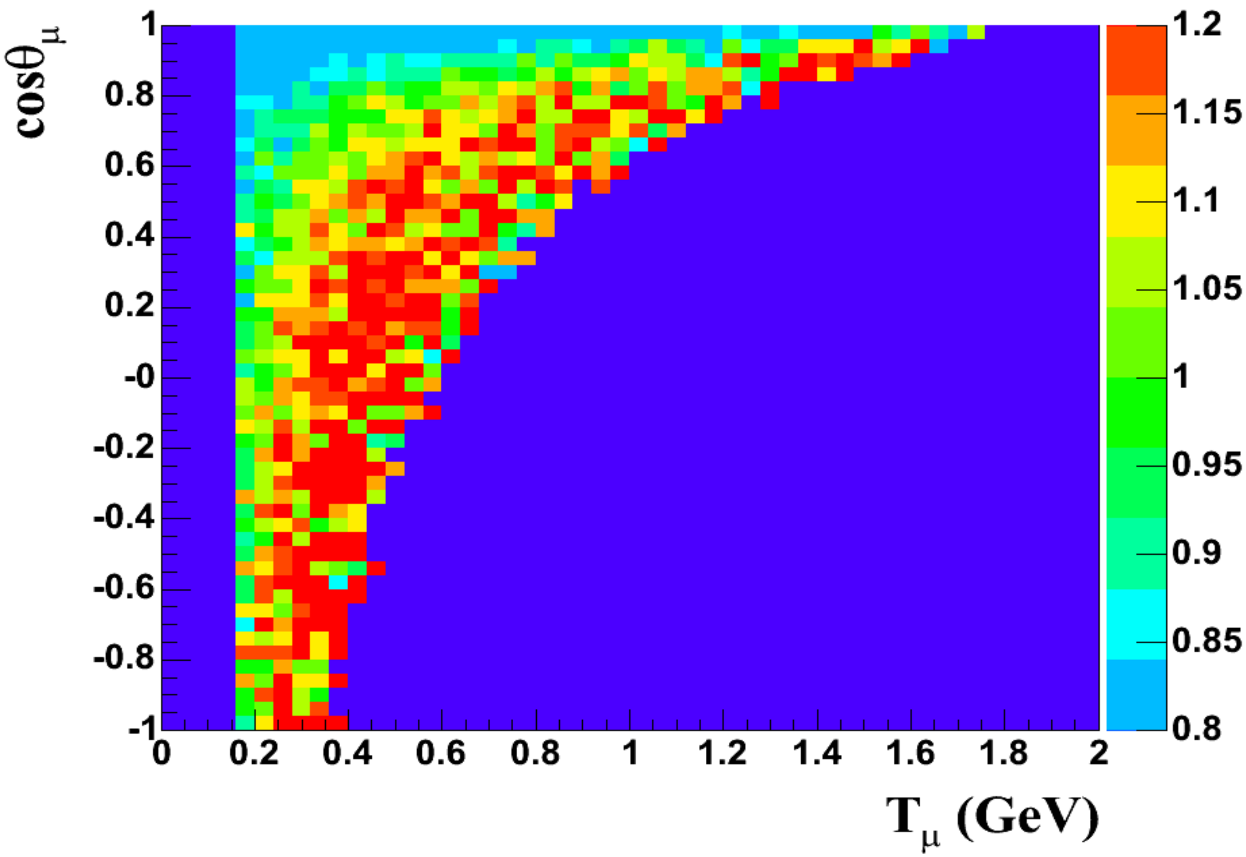
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

$$R \sim \int \Phi \times \sigma$$

$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$



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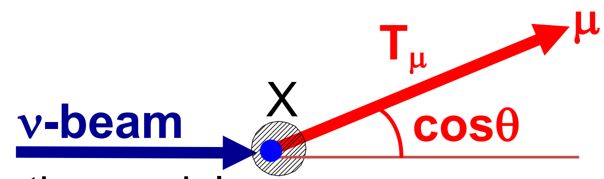

Without knowing flux, you cannot modify cross section model

$$R(E_\nu, Q^2) \sim \int \Phi(E_\nu) \times \sigma(Q^2)$$

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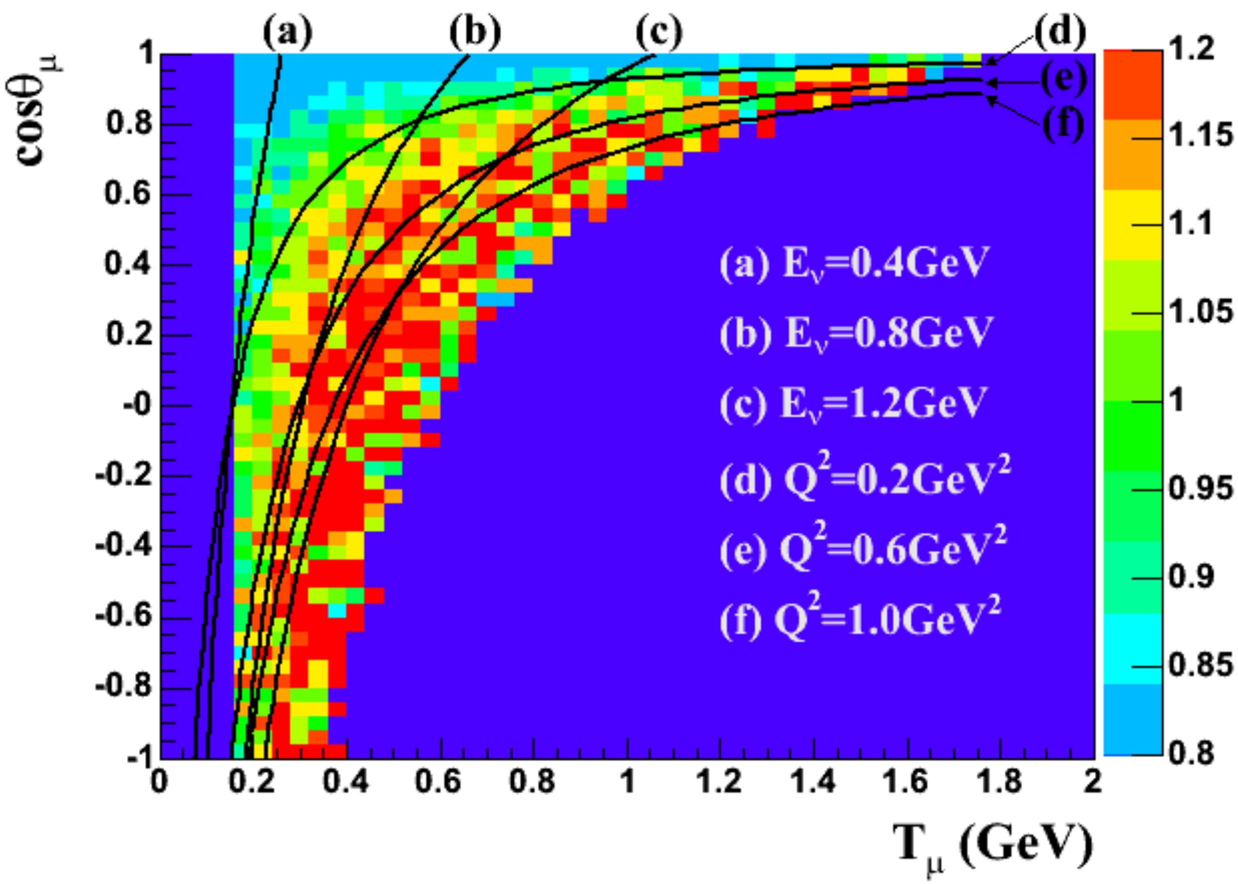
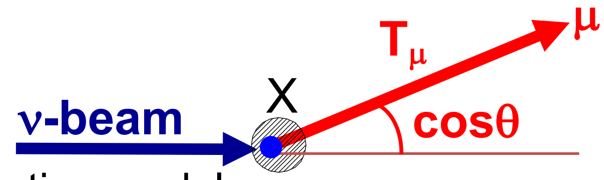


The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

→ Something wrong in cross section model, not flux model.

2. MiniBooNE phase space

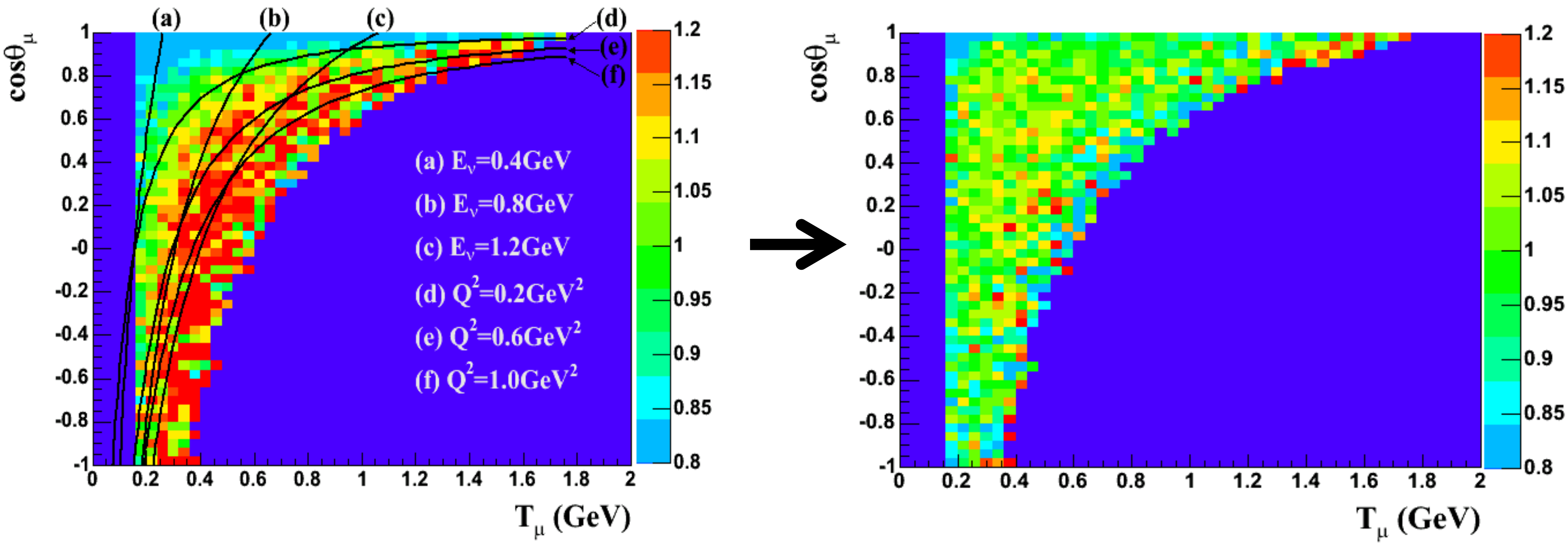


Without knowing flux, you cannot modify cross section model

$$R(E_\nu,Q^2)\sim\int\Phi(E_\nu)\times\sigma(Q^2)$$

After tuning cross section parameters, data and MC agree.

$$\frac{d\sigma^2}{dEd\Omega}\sim\frac{d\sigma^2}{dEd(\cos\vartheta)}$$



Smith and Moniz, Nucl.,Phys.,B43(1972)605

2. Smith-Moniz formalism

Nucleus is described by the collection of incoherent Fermi gas particles.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k},\vec{q},w)T_{\mu\nu}dE \text{ : hadronic tensor}$$

$f(\vec{k},\vec{q},w)$: nucleon phase space distribution

$T_{\mu\nu}=T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon form factors

$F_A(Q^2)=g_A/(1+Q^2/M_A^2)^2$: Axial vector form factor

Ehi : the highest energy state of nucleon

Elo : the lowest energy state of nucleon

Although Smith-Moniz formalism offers variety of choice, one can solve this equation analytically if the nucleon space is simple.

2. Relativistic Fermi Gas (RFG) model

Nucleus is described by the collection of incoherent Fermi gas particles.

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Ehi : the highest energy state of nucleon $=\sqrt{(p_F^2 + M^2)}$

Elo : the lowest energy state of nucleon $= \kappa\left(\sqrt{(p_F^2+M^2)} - \omega + E_B\right)$

Smith and Moniz, Nucl.,Phys.,B43(1972)605

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MiniBooNE tuned following 2 parameters using Q^2 distribution by least χ^2 fit;
M_A = effective axial mass
κ = effective Pauli blocking parameter

MiniBooNE tuned their axial mass to 1.3 GeV!

but axial mass is not 1.3 GeV!

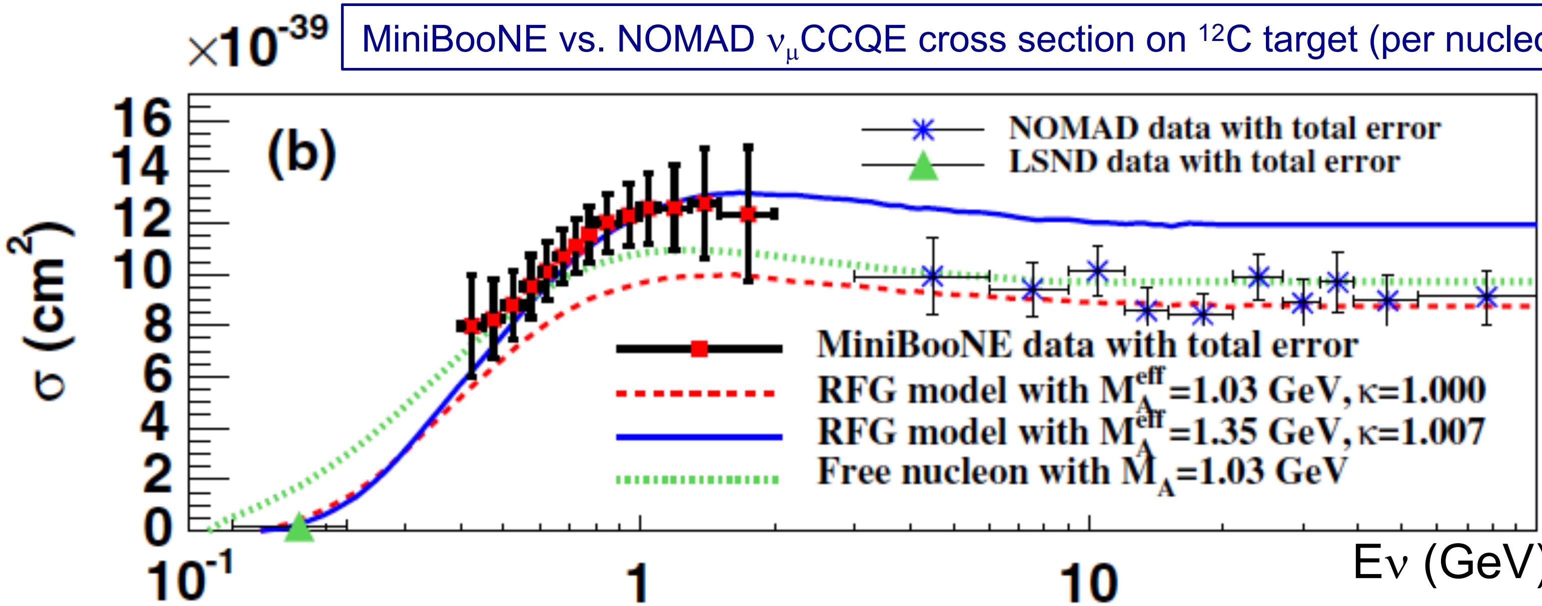
2. Charged Current Quasi-Elastic scattering (CCQE)

CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality → precise prediction for neutrino CCQE cross-section

Simulation disagree with many modern accelerator based neutrino experiment data, neither shape (low Q^2 and high Q^2) nor normalization. By tuning axial mass (M_A) 1.2-1.3 GeV, simulations successfully reproduce data both shape and normalization.

Problem: we know M_A=1 GeV from electron scattering experiments (CCQE puzzle).

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



2. The solution of CCQE puzzle

Presence of 2-body current

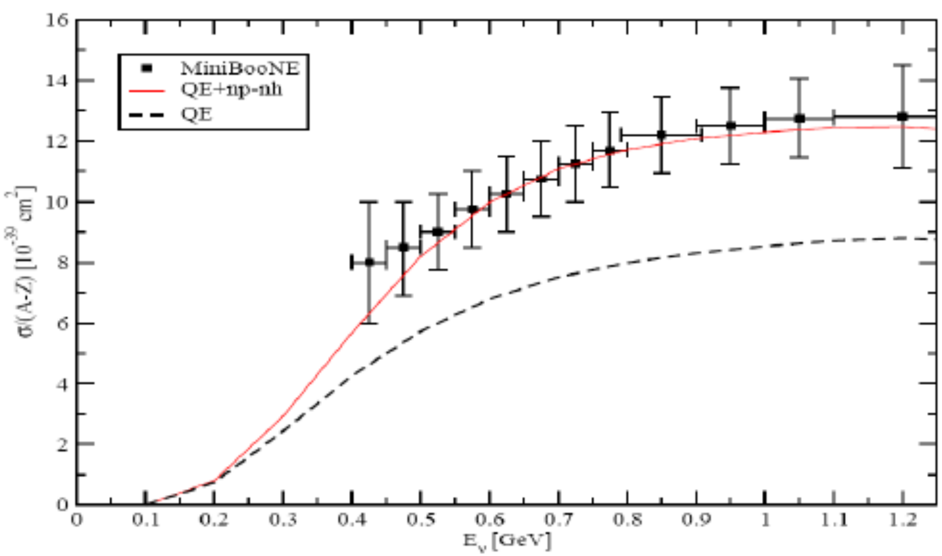
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

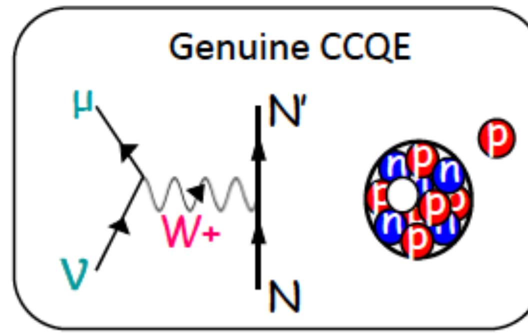
What experimentalists call “CCQE” is not genuine CCQE!

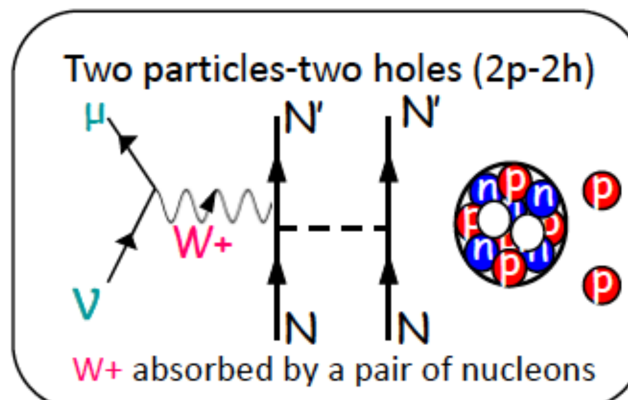
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501
Nieves et al,PLB707(2012)72; NPA627(1997)543

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The model is tuned with electron scattering data (no free parameter)

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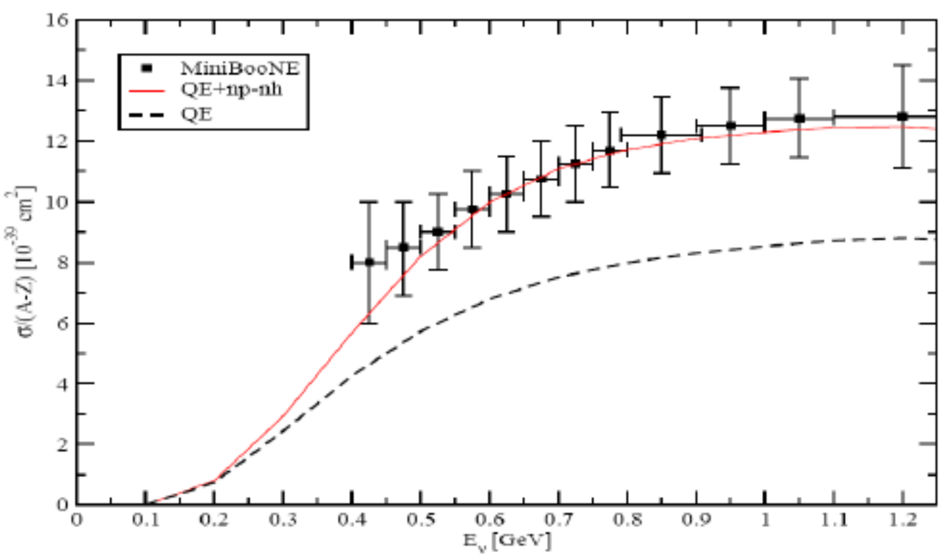
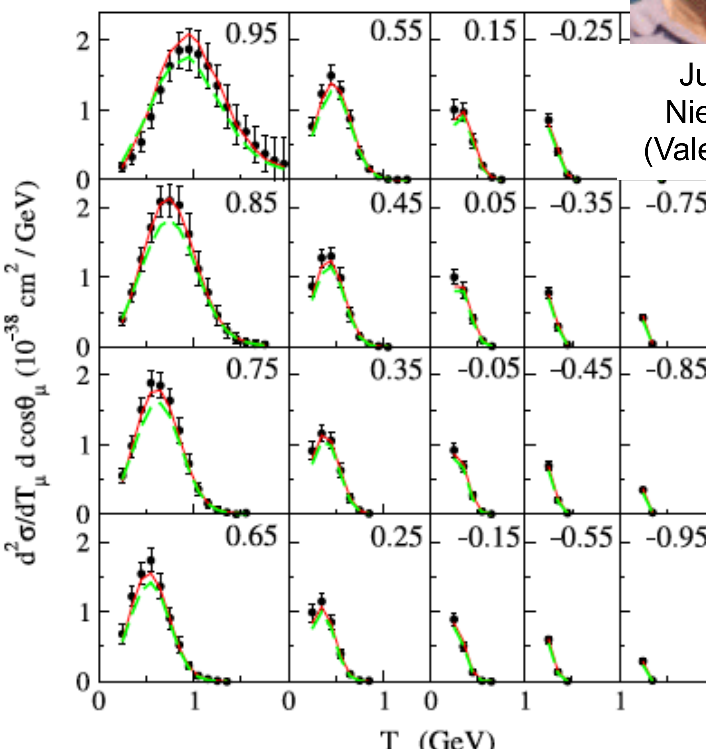


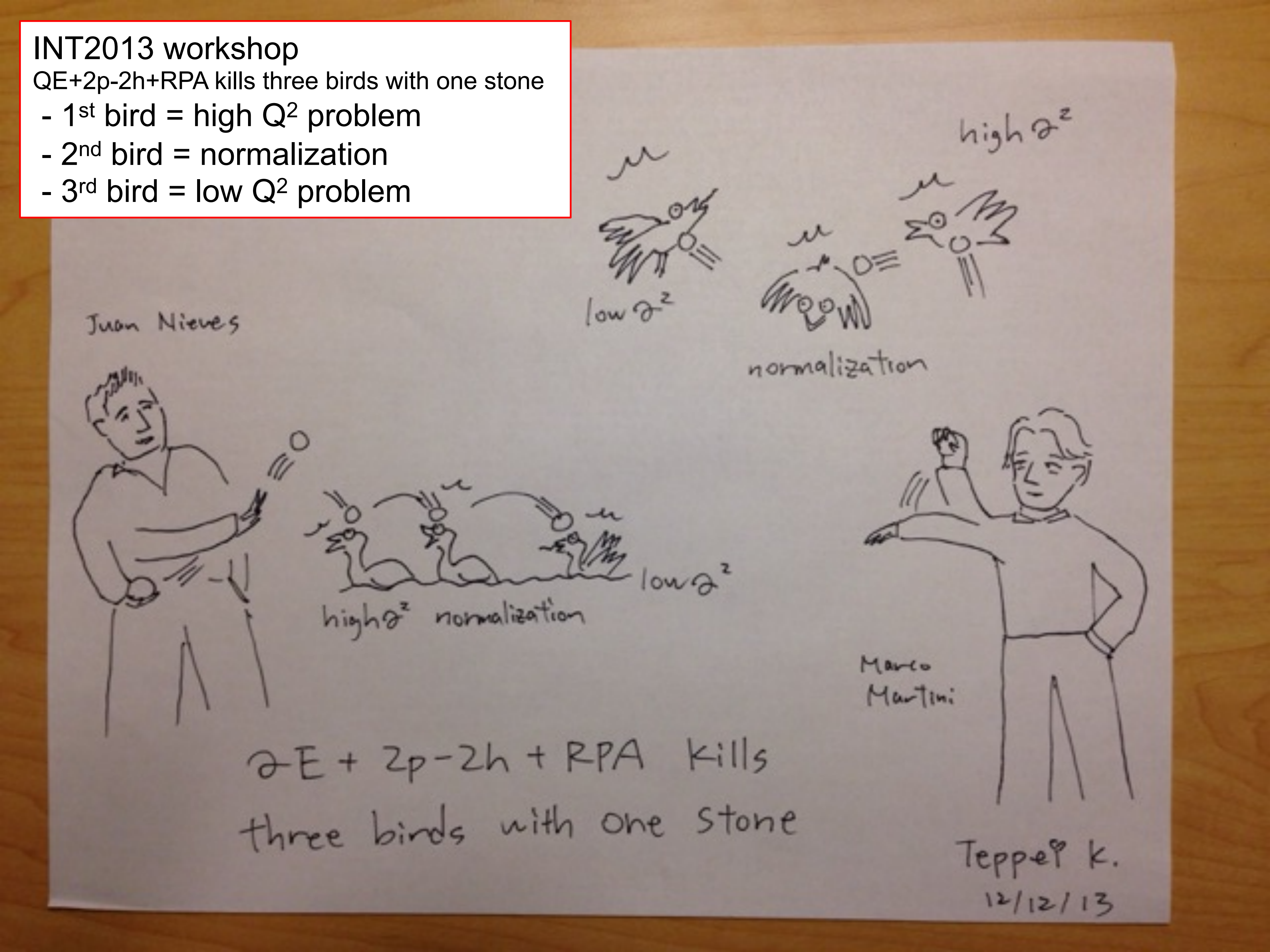


Valencia model vs. MiniBooNE CCQE double differential cross-section data

INT2013 workshop

QE+2p-2h+RPA kills three birds with one stone

- 1^{st} bird = high Q^2 problem
- 2^{nd} bird = normalization
- 3^{rd} bird = low Q^2 problem



Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72

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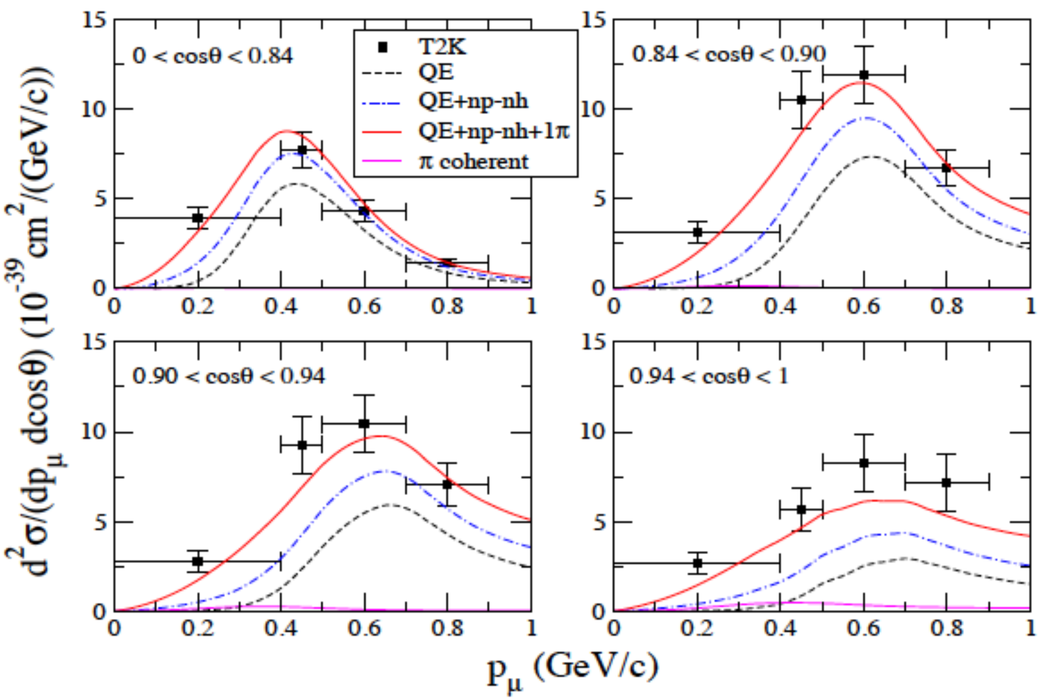
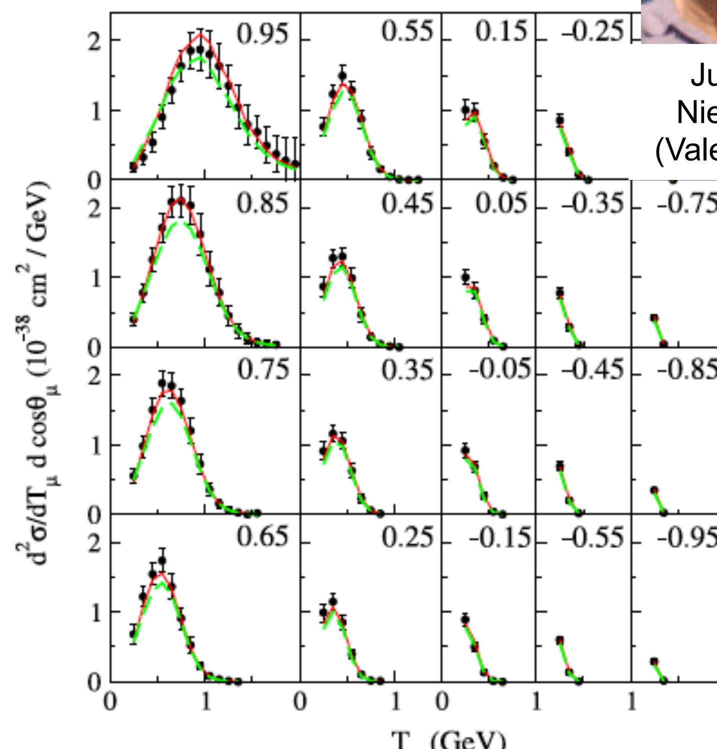
Juan Nieves (Valencia)

Martini model vs. T2K CC double differential cross-section data





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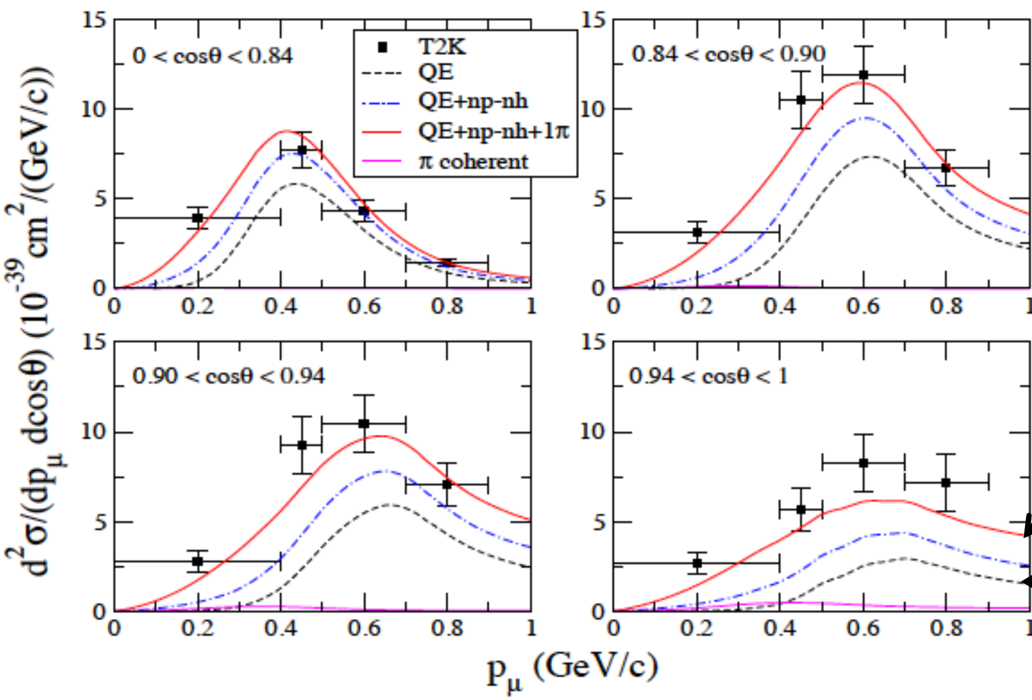
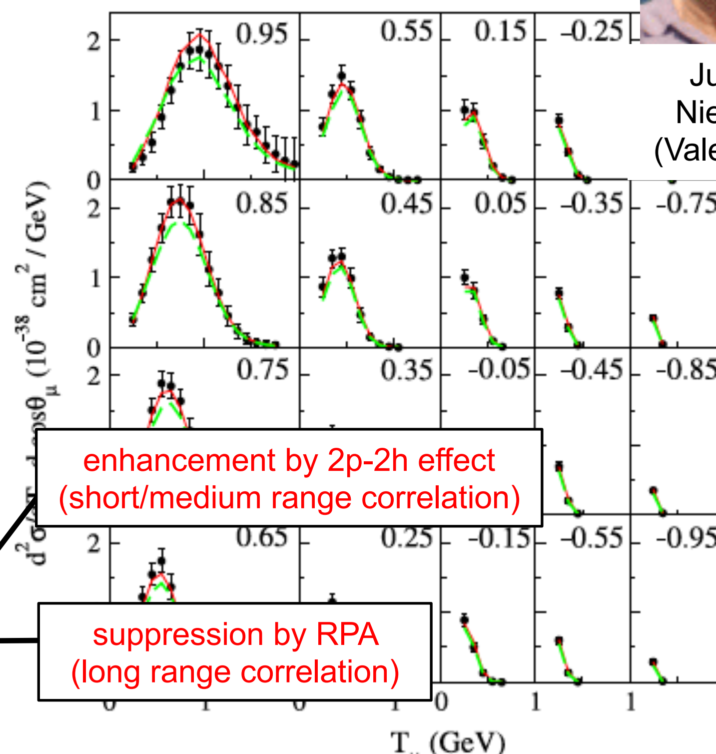




enhancement by 2p-2h effect (short/medium range correlation)

suppression by RPA (long range correlation)

Valencia model vs. MiniBooNE CCQE double differential cross-section data

Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, arXiv:1501.01981

2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato
(Argonne)

Ab initio calculation

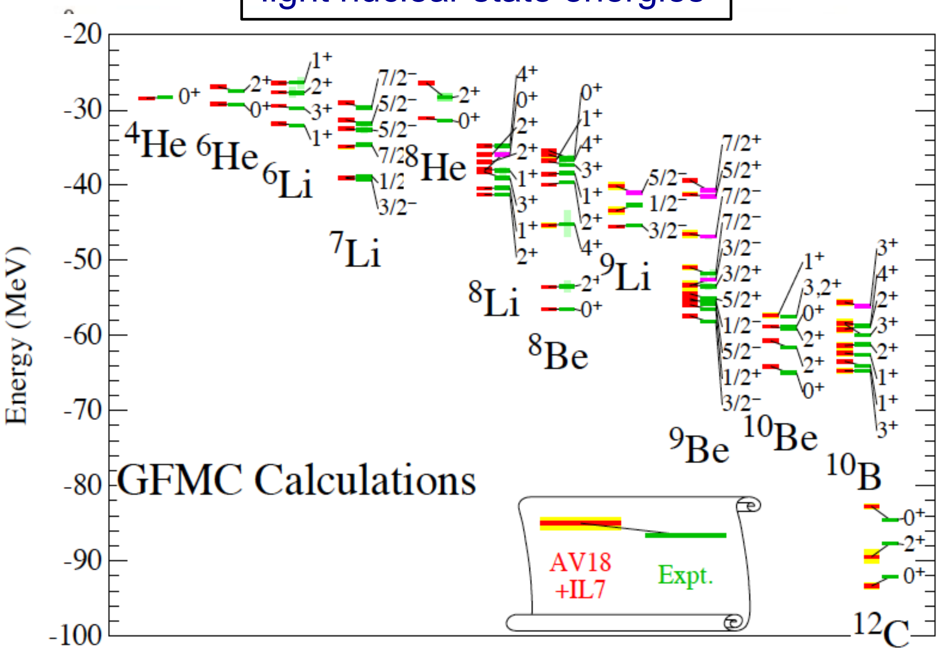
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1 + U_{ij} + \sum_{k\neq i,j}^{A} \tilde{U}_{ijk}^{TNI}\right]|\Psi_J\rangle$$

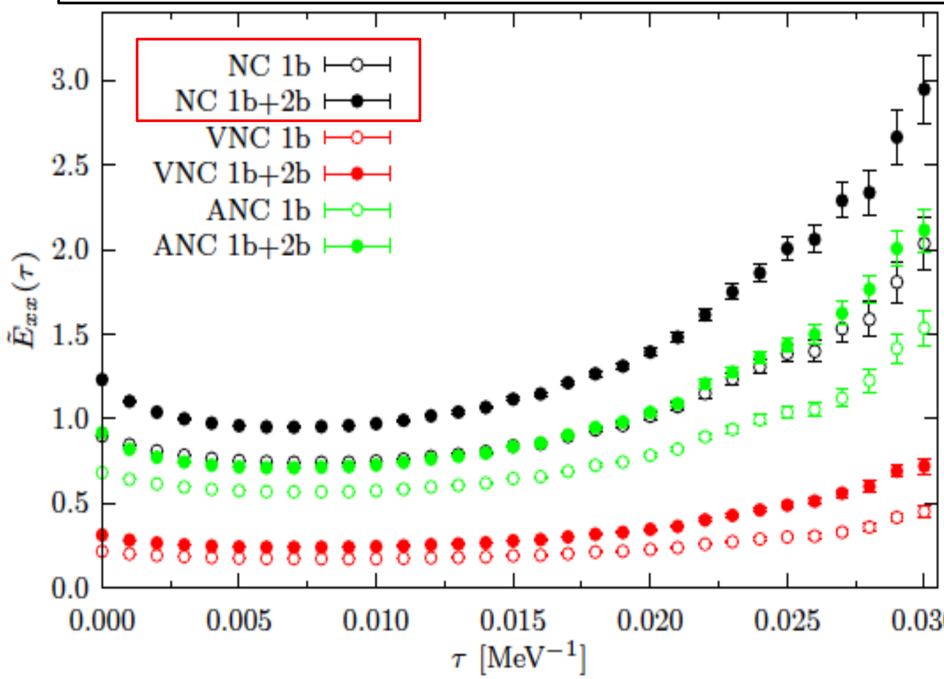
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



Frankfurt et al, IJMPA23(2008)2991, JLab HallA, Science320(2008)1476
Sobczyk, Neutrino2014, Piasetzky et al, PRL106(2011)052301

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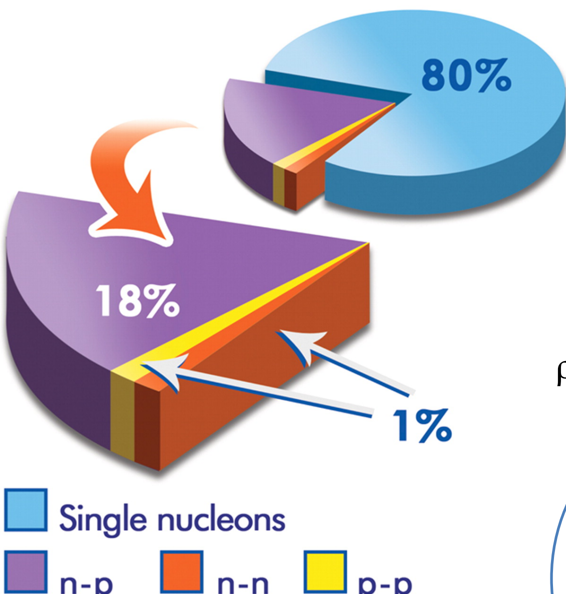
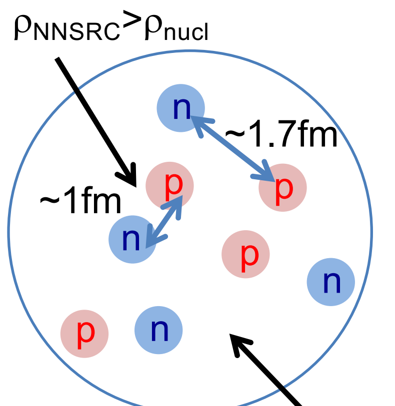
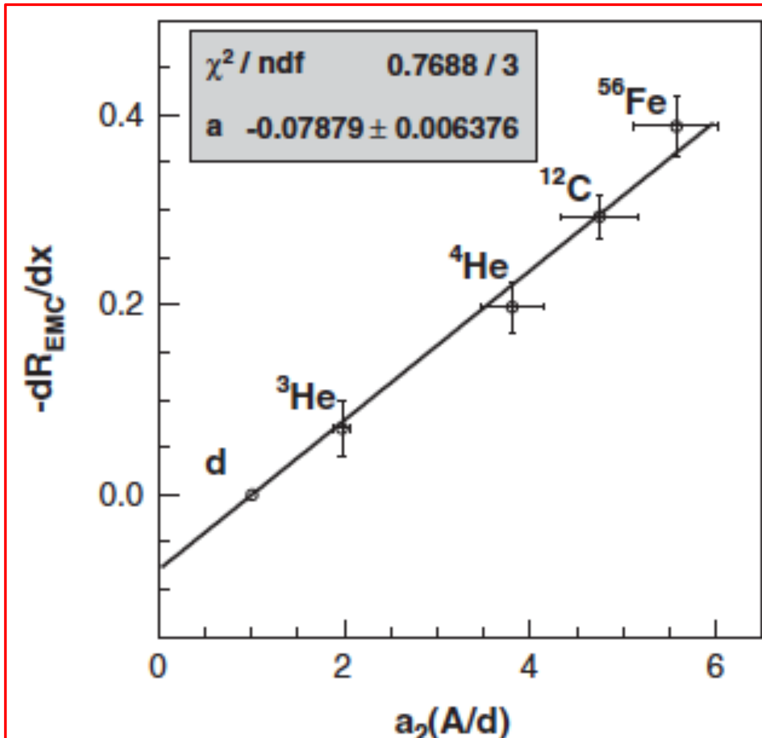
2N potential (Av18) — 3N potential (IL7)



Physics of SRC

- neutrino interaction
- $0\nu\beta\beta$
- astrophysics
- EMC effect
- etc





Nucleon correlation is a very hot topics!

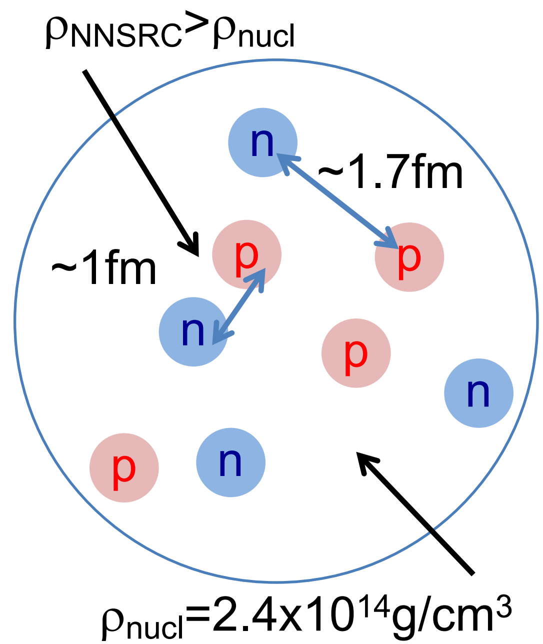
Queen Mary University of London

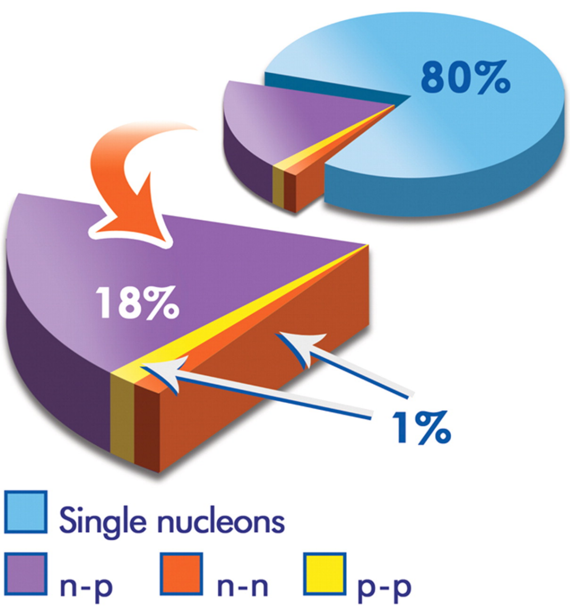
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504
JLab HallA, PRL99(2007)072501, Science320(2008)1476

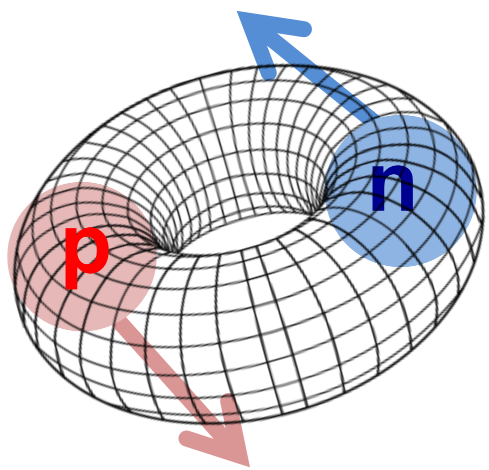
2. Nucleon correlations

Short Range Correlation (SRC)

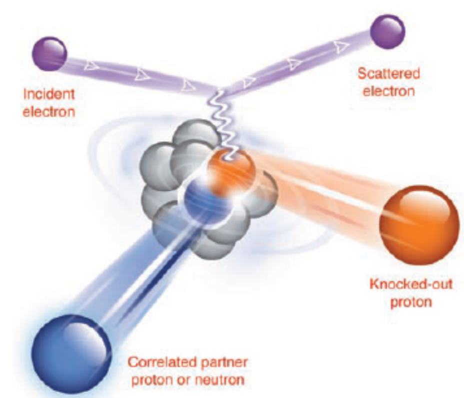
~20% of all nucleons in heavy elements (A>4)
~90% are neutron-proton (n-p) pair
~nucleon pair have back-to-back momentum
~ momentum can be beyond Fermi sea







NNSRC~quasi deuteron



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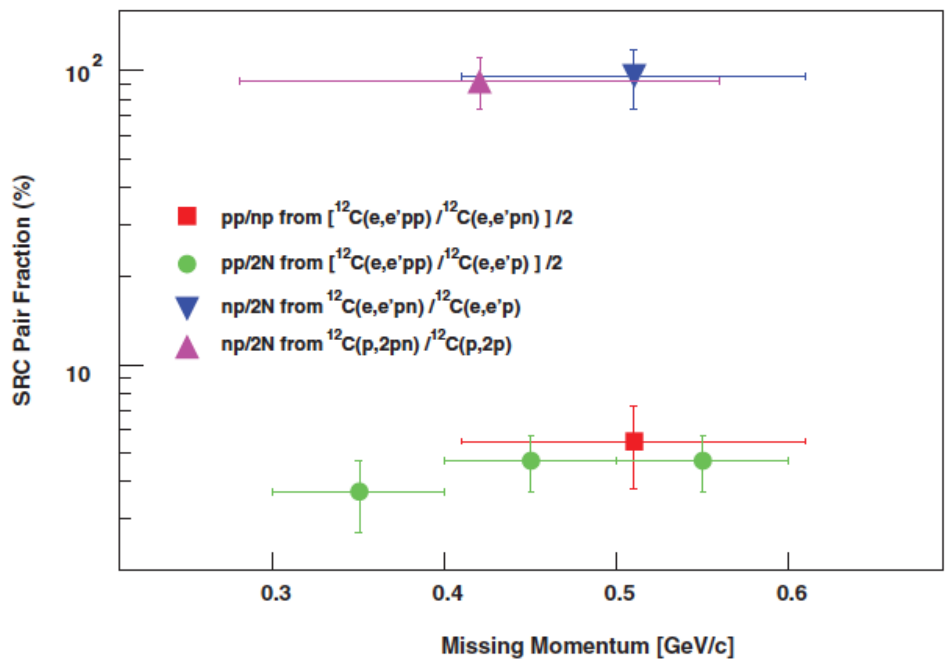


Fig. 2. The fractions of correlated pair combinations in carbon as obtained from the (e,e'pp) and (e,e'pn) reactions, as well as from previous (p,2pn) data. The results and references are listed in table S1.

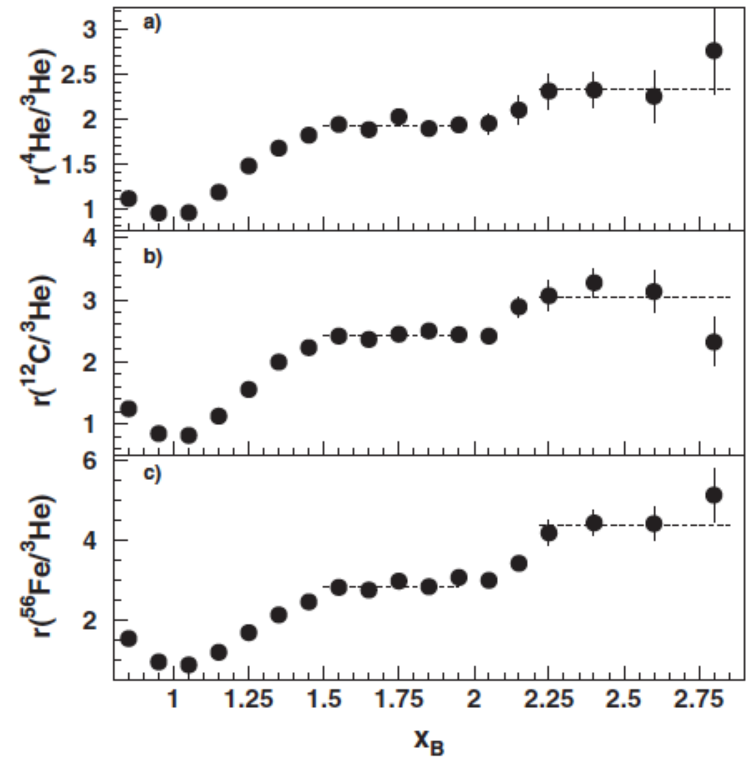


FIG. 1. Weighted cross section ratios [see Eq. (2)] of (a) ^{4}He, (b) ^{12}C, and (c) ^{56}Fe to ^{3}He as a function of x_B for $Q^2 > 1.4$ GeV^2. The horizontal dashed lines indicate the NN ($1.5 < x_B < 2$) and $3N$ ($x_B > 2.25$) scaling regions.

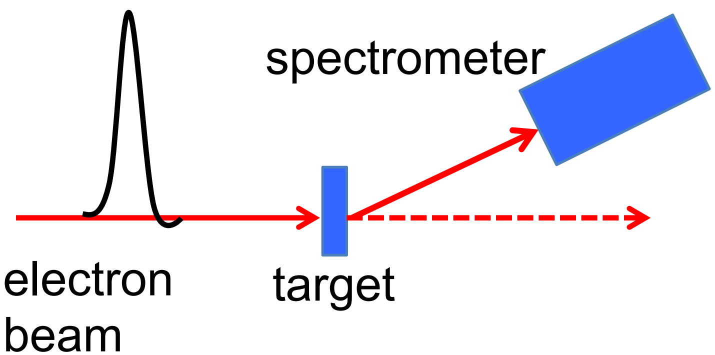
2. Electron scattering vs. Neutrino scattering

Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

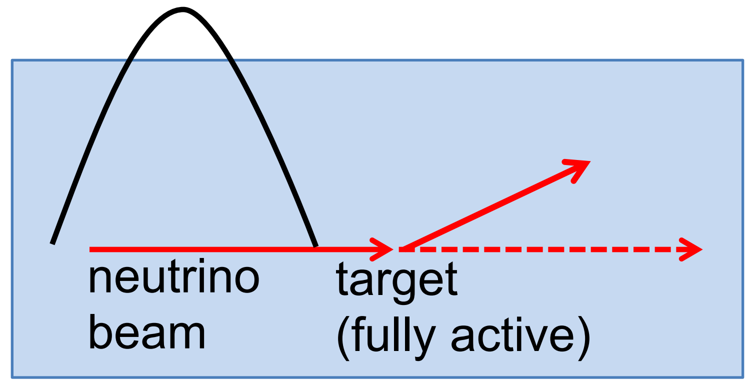
→ kinematics is completely fixed

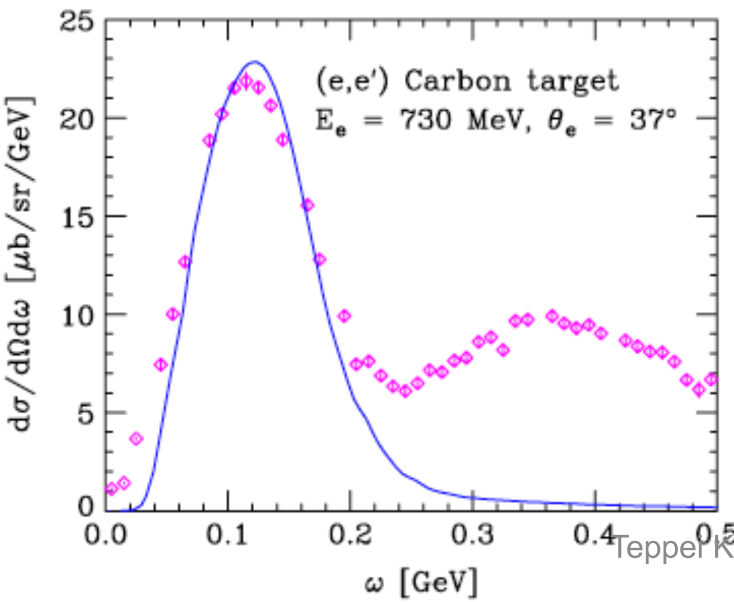


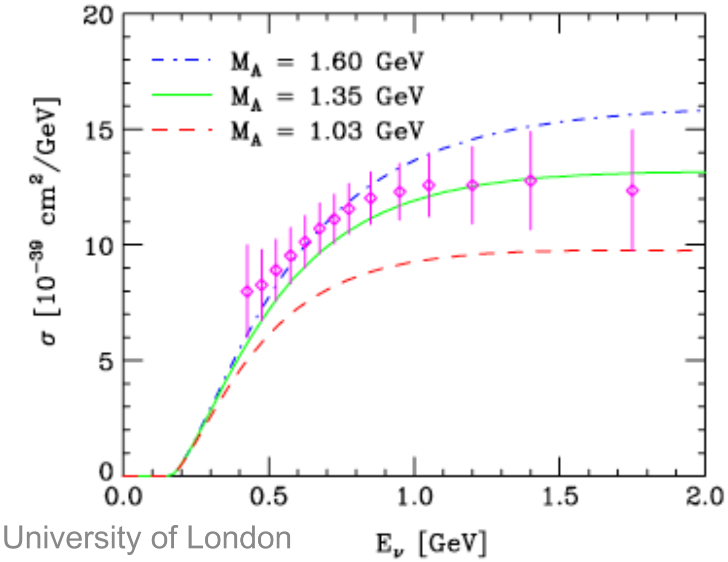
Neutrino scattering

- Wideband beam

→ observables are inclusive







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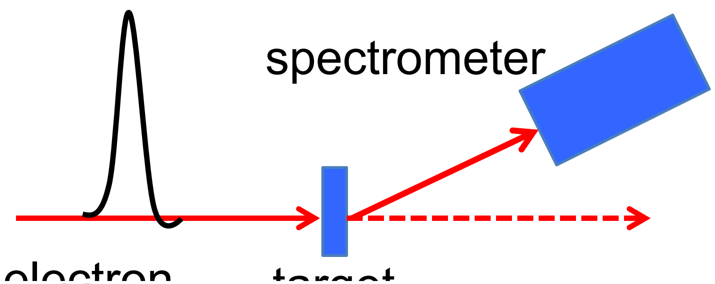

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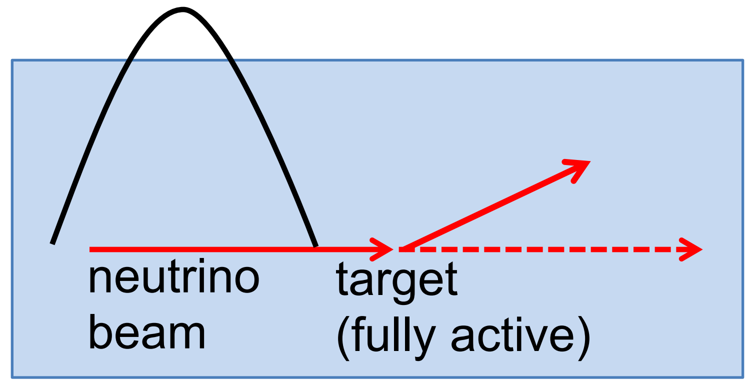
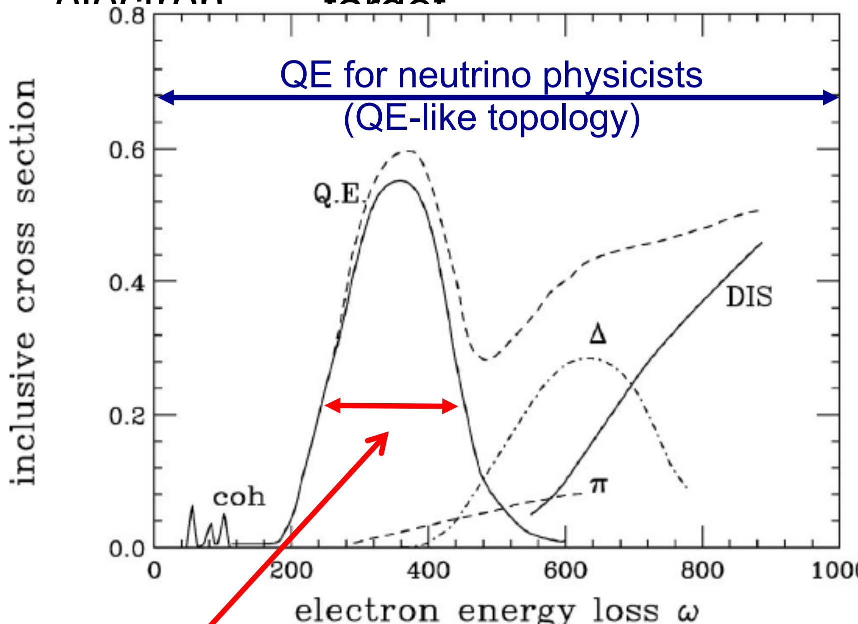
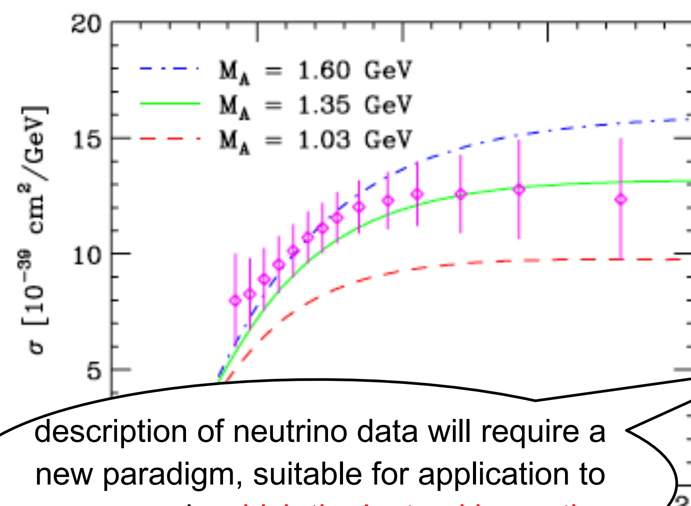
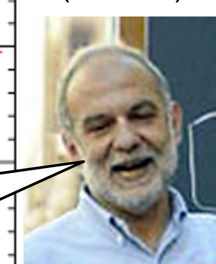




QE for nuclear physicists (genuine QE)



Omar Benhar (Rome I)



description of neutrino data will require a new paradigm, suitable for application to processes in which the lepton kinematics is not fully determined

2. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation
- Valencia MEC model is available in NEUT
- being implemented in GENIE, officially ready for GENIE v2.12

This moment…
Valencia MEC model does not fit T2K (and Super-K) data very well, people are working very hard to understand what is going on

large M_A error → large 2p2h error

It is crucial to have correct CCQE, MEC, pion production models to understand MiniBooNE, MINERvA, T2K data simultaneously. Otherwise M_A error stays around 20-30%.

We have good theorists who make models, and good experimentalists who measure data, but we are still lacking people between them.

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Garvey et al.,Phys.Rept.580 (2015) 1

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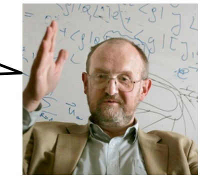

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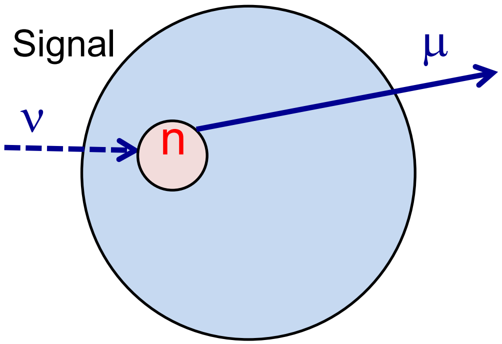
Baryon resonance, pion production by neutrinos

3. non-QE background

non-QE background → shift spectrum



Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

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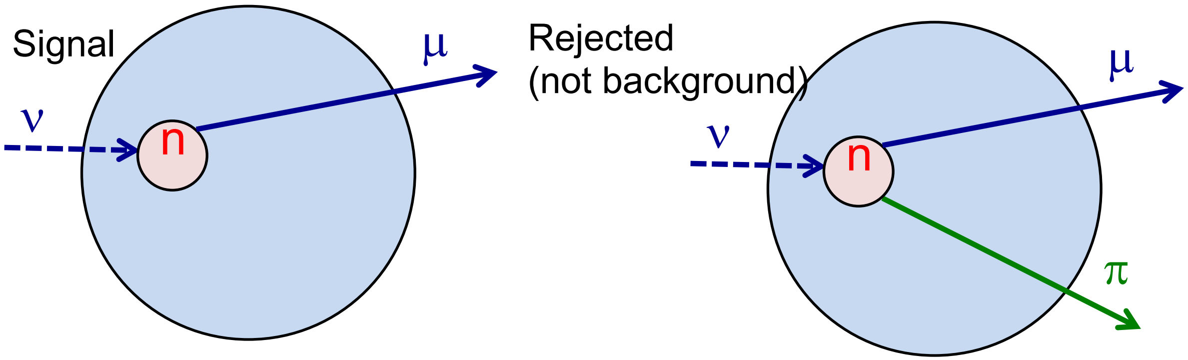

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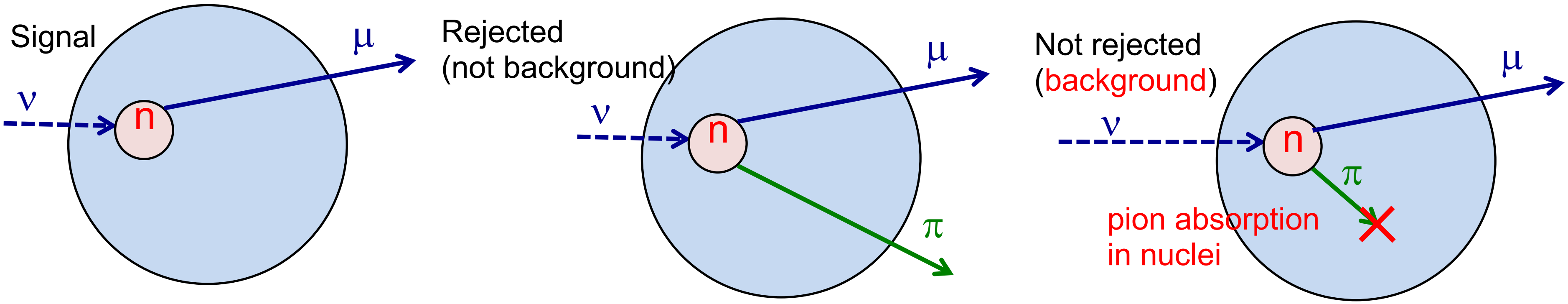

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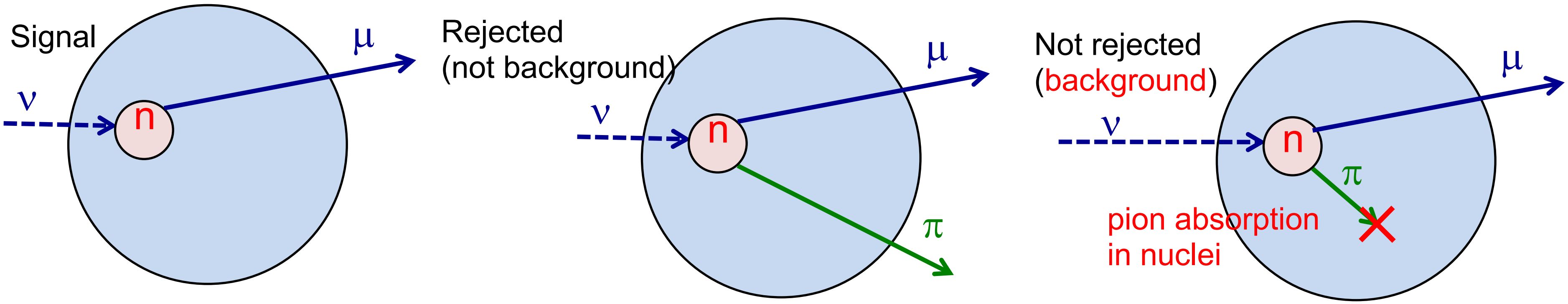
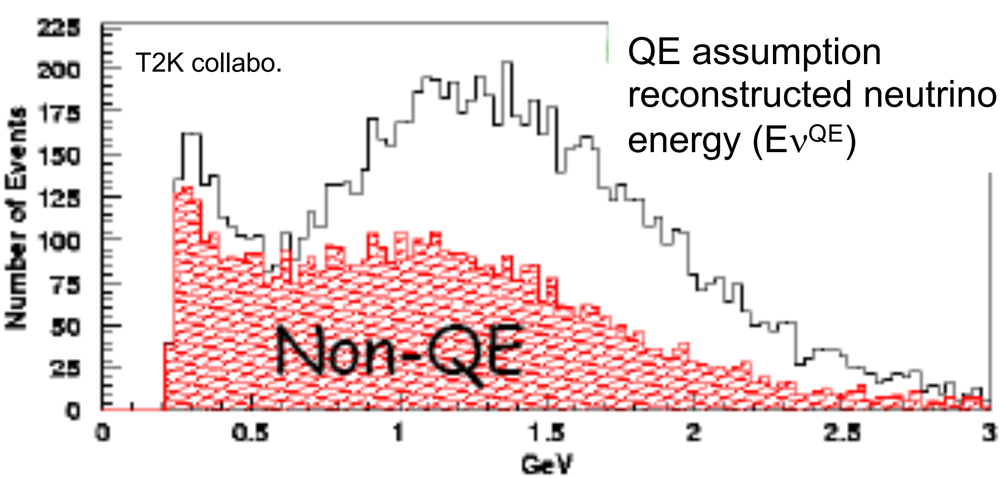
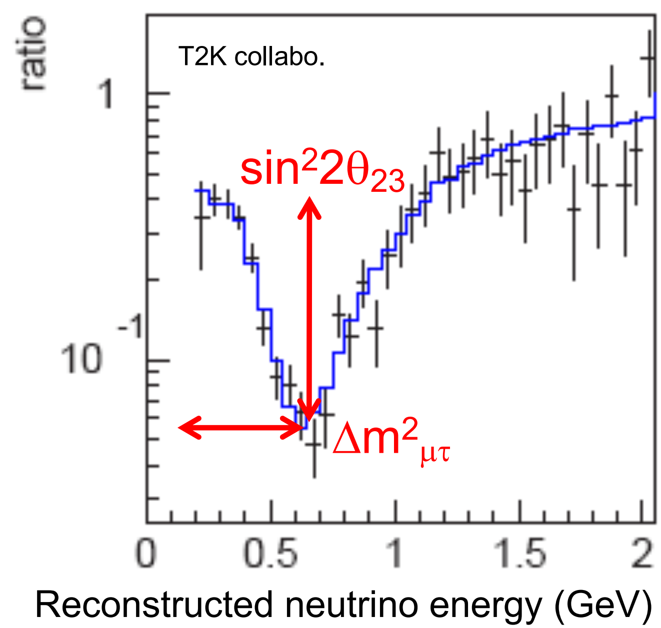




QE assumption reconstructed neutrino energy ($E\nu^{QE}$)



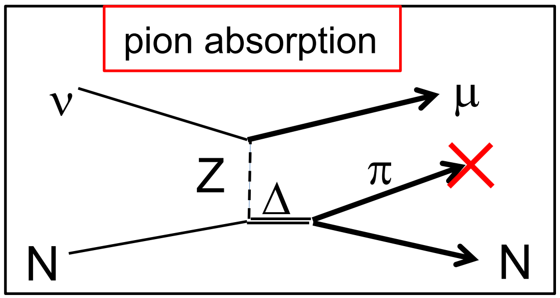
Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

3. non-QE background

Understanding of neutrino pion production is important for oscillation experiments

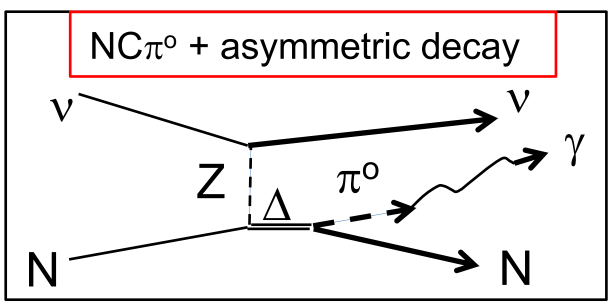
Pion production for ν_μ disappearance search

- Source of mis-reconstruction of neutrino energy

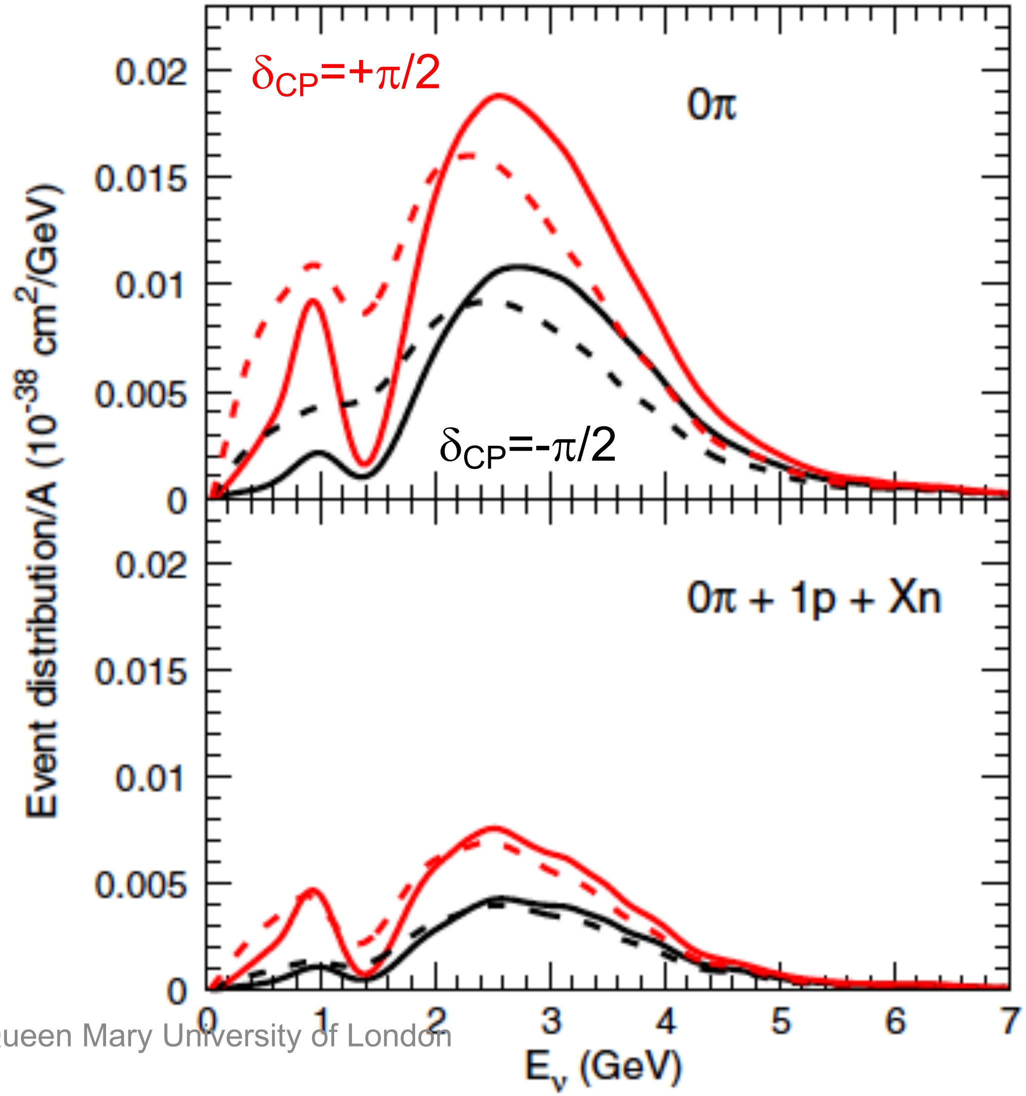


Neutral pion production in ν_e appearance search

- Source of misID of electron



DUNE true vs. reconstructed Eν spectrum



Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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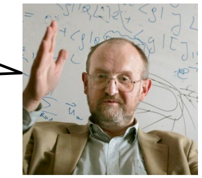
The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



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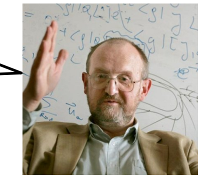

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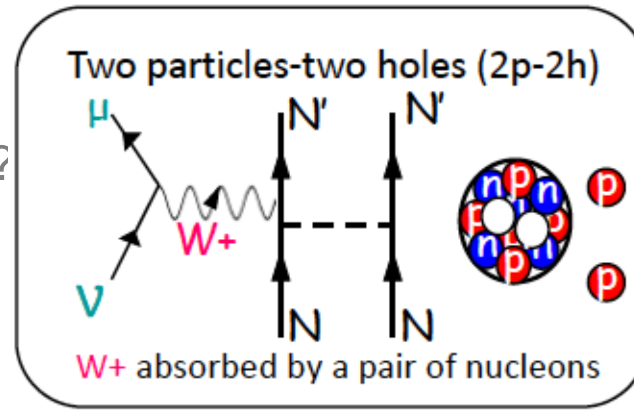

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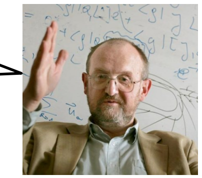

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Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

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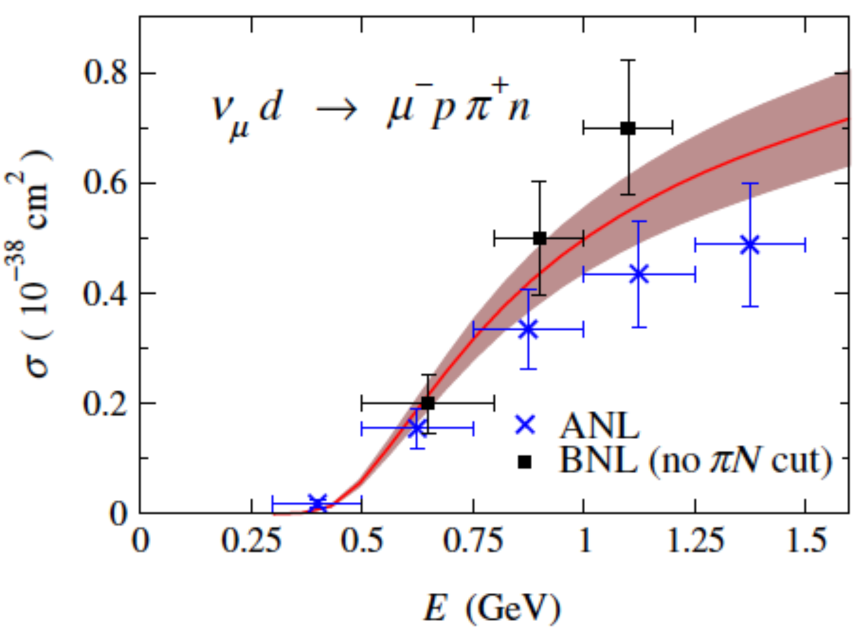
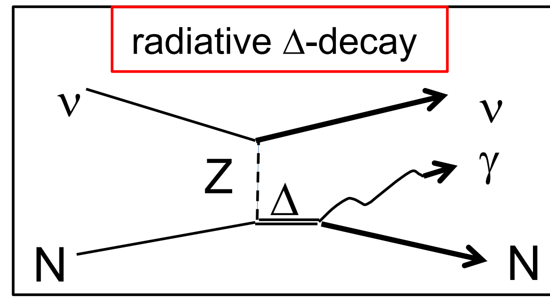
Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

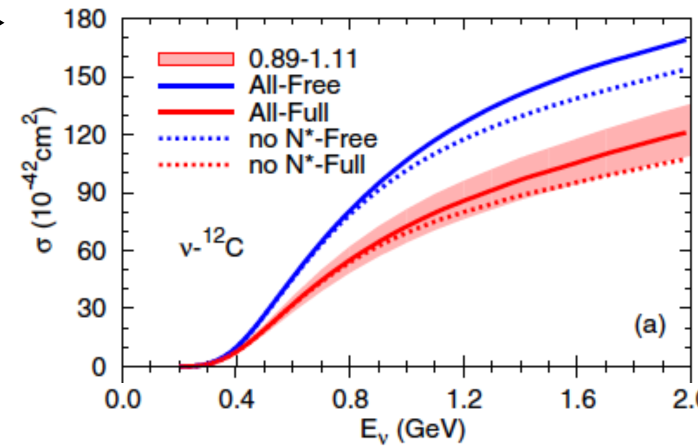
→ this propagates to every interactions with baryon resonance

ANL vs. BNL



e.g.) NCγ production model





Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001
Wu et al,PRC91(2015)035203

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Reanalysis by Sheffield-Rochester group found a normalization problem on BNL

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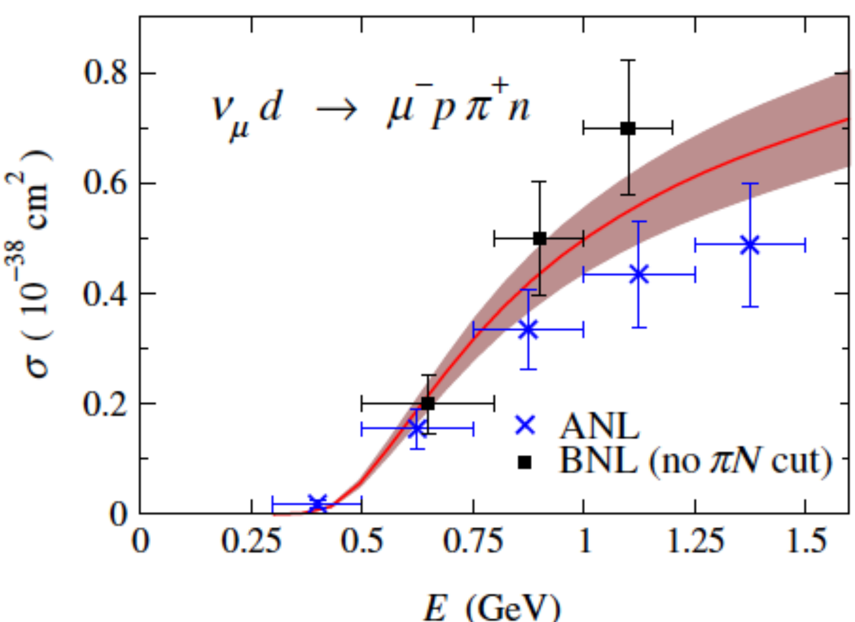

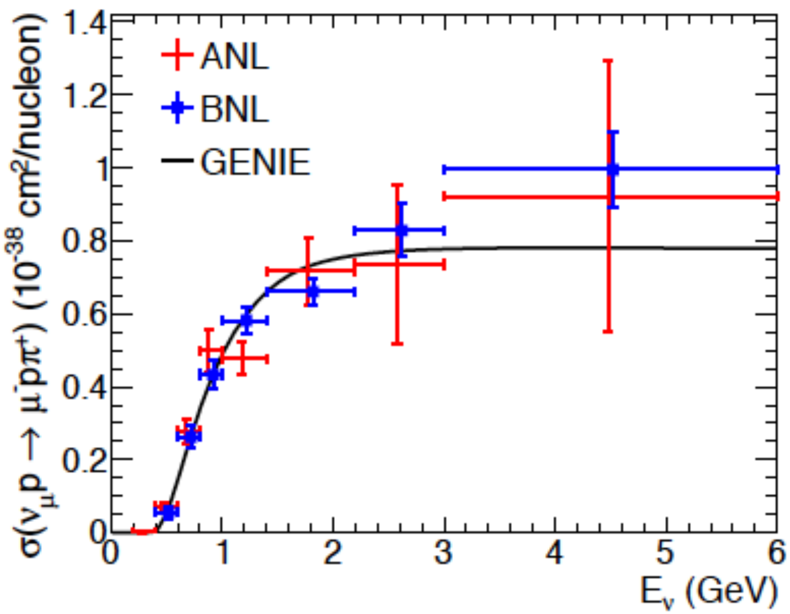

Remained task, was nuclear effect correctly taken into account to extract these data? (Wu. et al)

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Garvey et al.,Phys.Rept.580 (2015) 1

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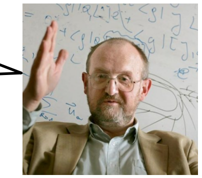

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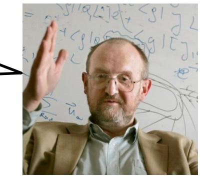

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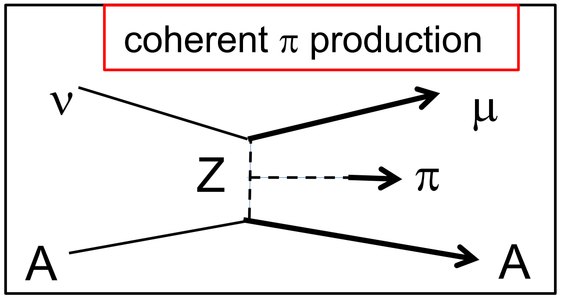
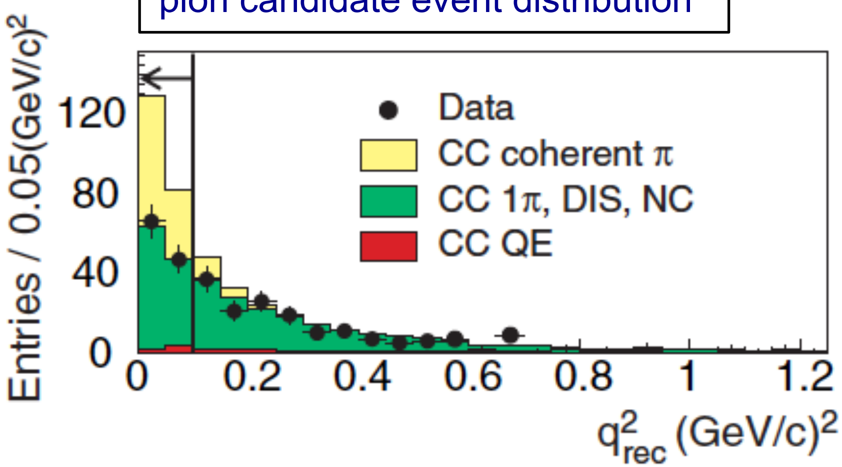


K2K muon neutrino CC coherent pion candidate event distribution



K2K,PRL95(2005)252301, SciBooNE, PRD78(2008)112004
Suzuki, NuFact2014, ArgoNeuT, PRL114(2015)039901, MINERvA, PRL113(2014)261802, T2K, PRL117(2016)192501

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ArgoNeuT, T2K, and MINERvA discovered nonzero CC coherent pion production, but details of kinematics are not understood.

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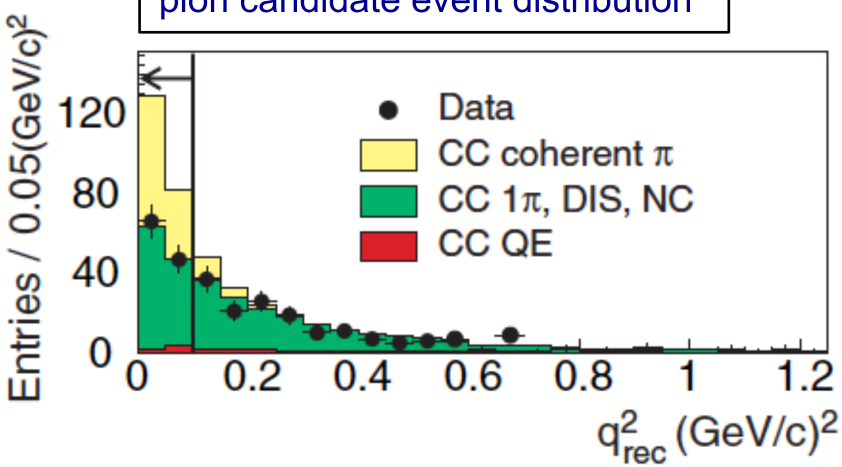
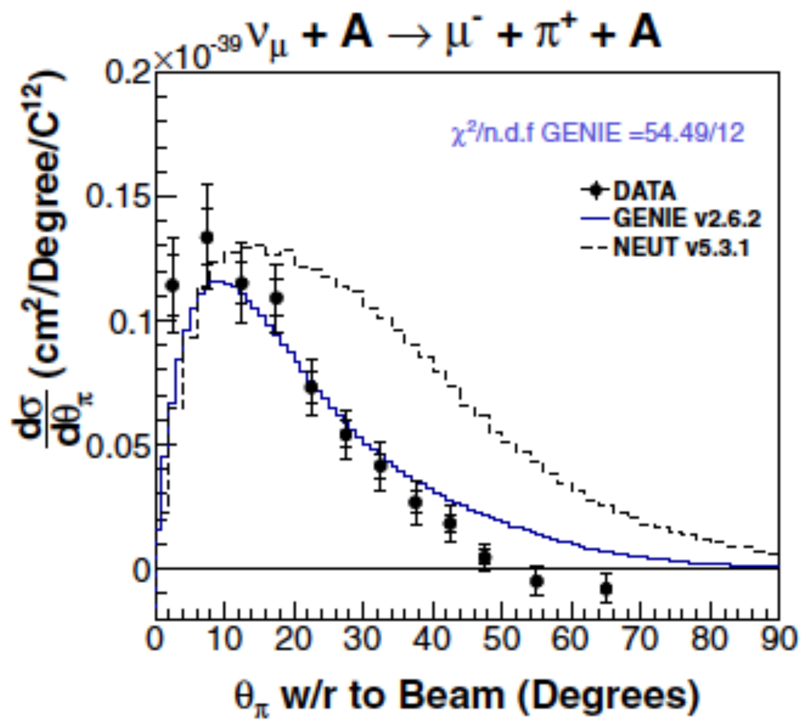


MINERvA muon neutrino CC coherent pion production differential cross-section



T2K (on-axis): Suzuki, NuFact2014
MINERvA: PRL113(2014)261802
ArgoNeuT: PRL114(2015)039901
T2K (off-axis): PRL117(2016)192501

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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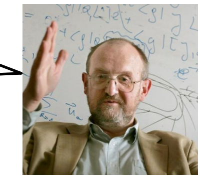

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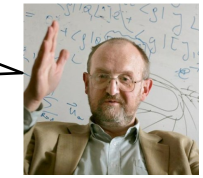

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MiniBooNE,PRD83(2011)052007
MINERvA,arXiv:1406.6415

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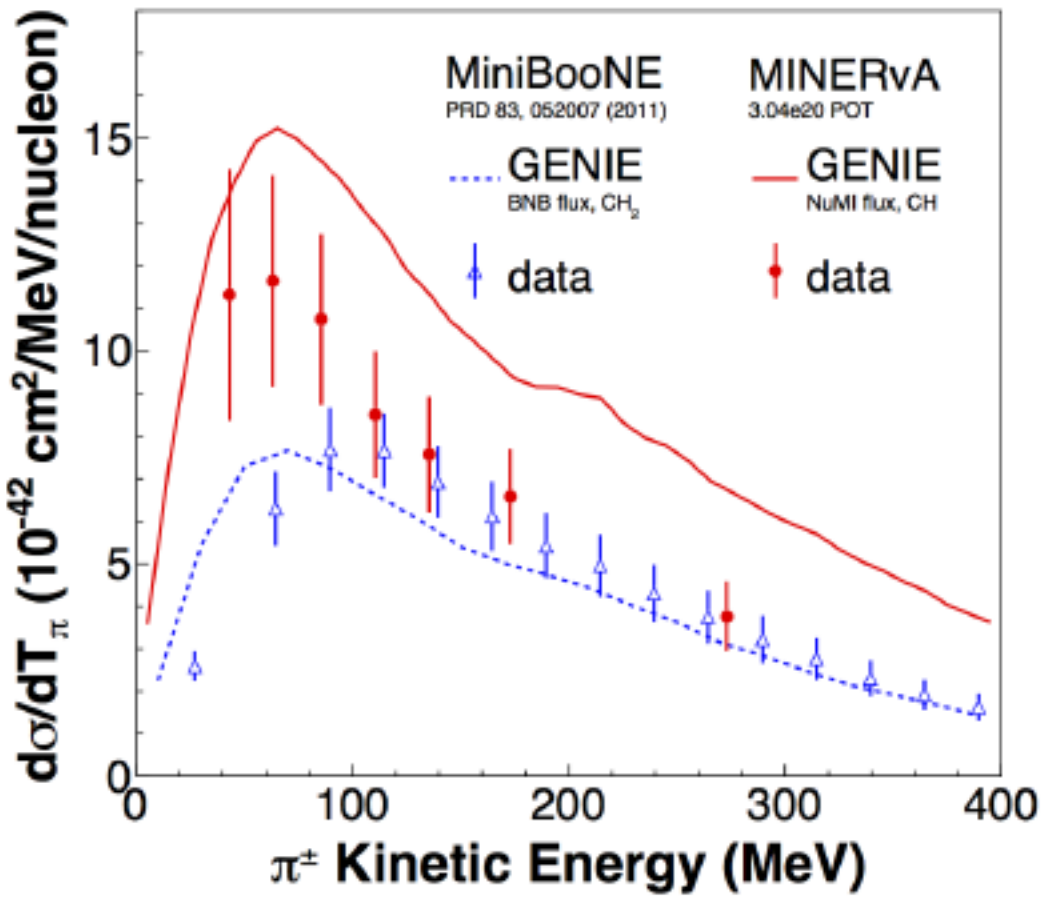
Data from MiniBooNE and MINERvA and simulation are all incompatible

Flux-integrated differential cross-section are not comparable (unless 2 experiments use same neutrino beam)

Two data set are related by a model (=GENIE neutrino interaction generator).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…



MiniBooNE,PRD83(2011)052007
MINERvA,arXiv:1406.6415, Sobczyk and Zmuda,PRC91(2015)045501

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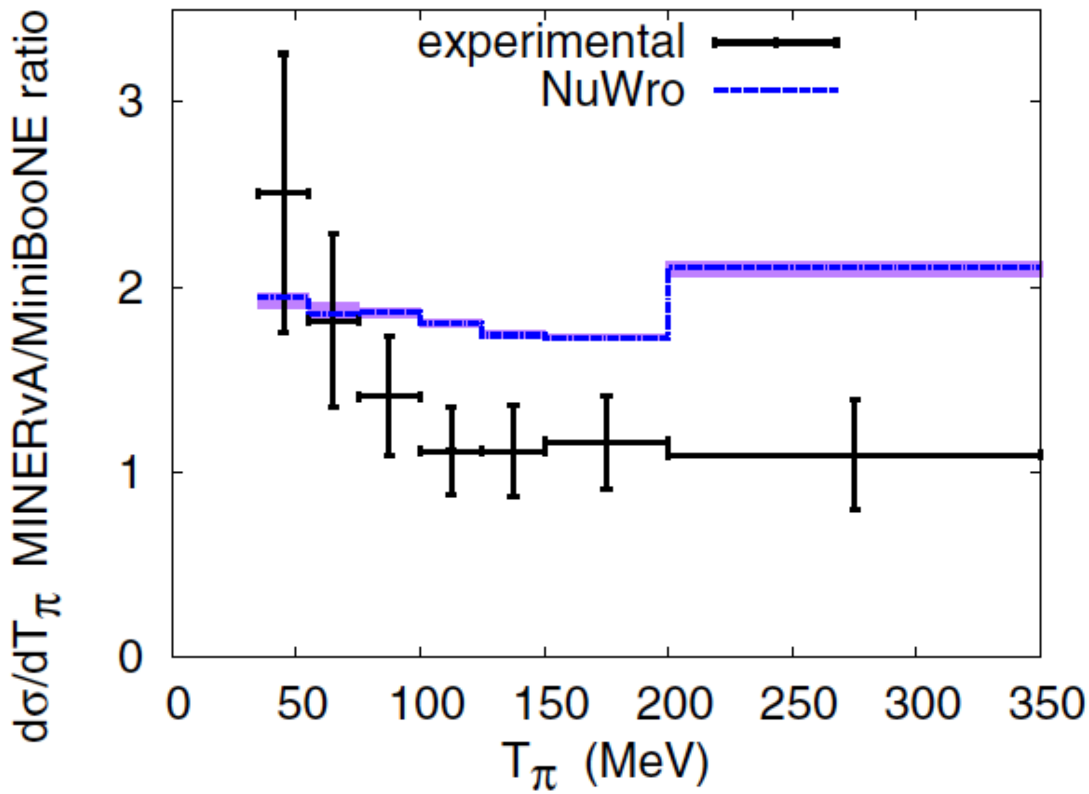
Two data set are related by a model (=GENIE neutrino interaction generator).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…



MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602, Buss et al,Phys.Rept.512(2012)1

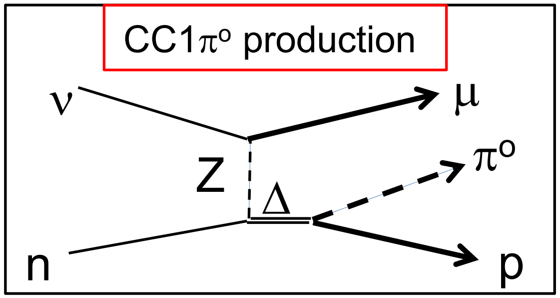
3. Pion puzzle

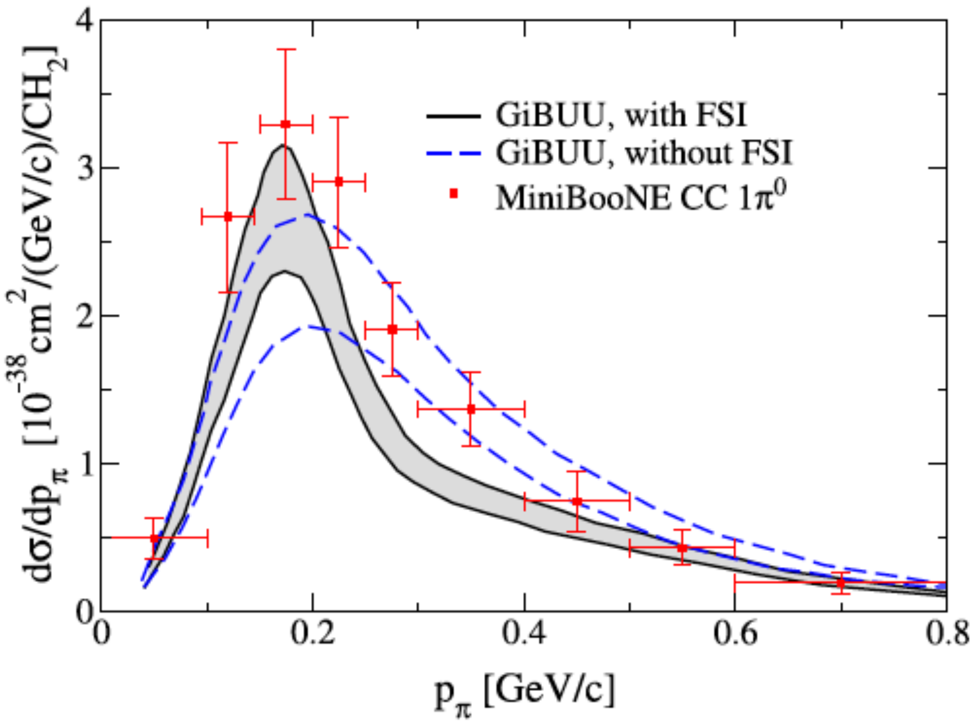
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation





ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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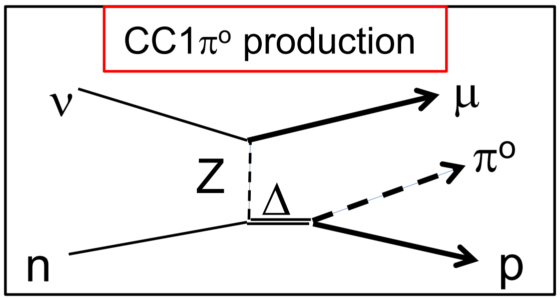

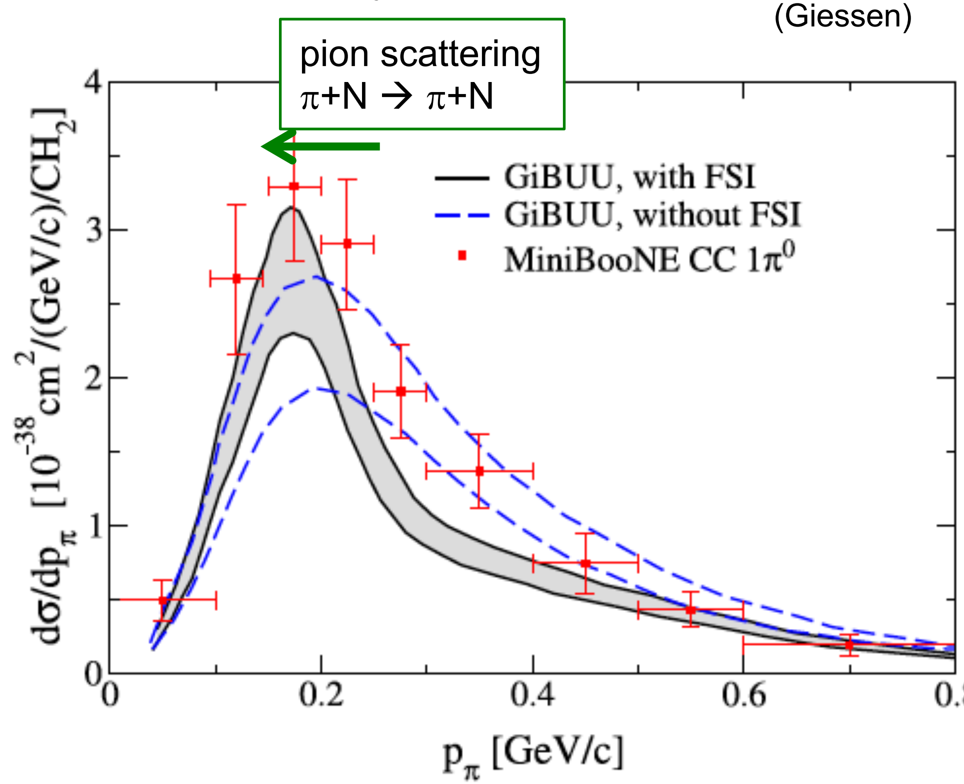

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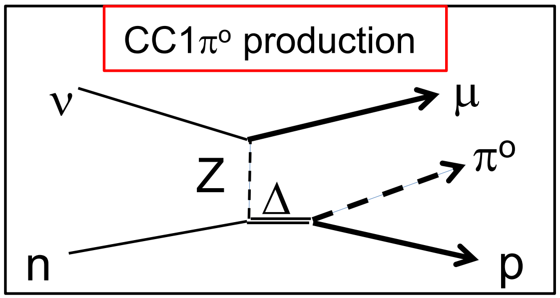

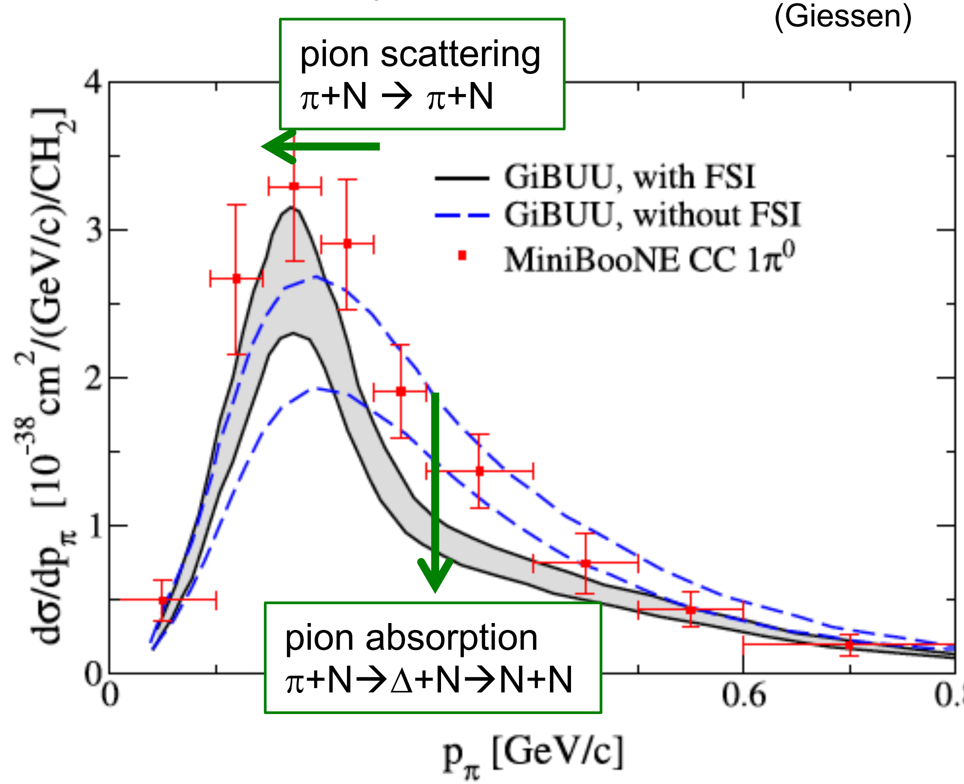

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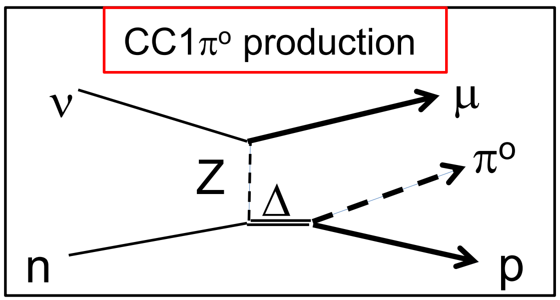
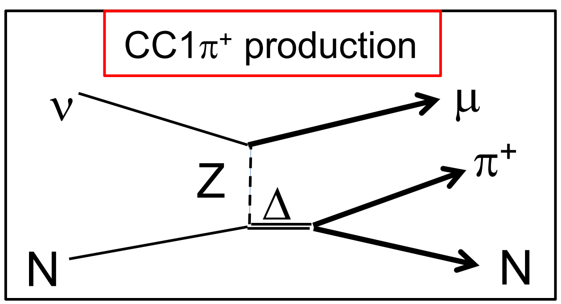
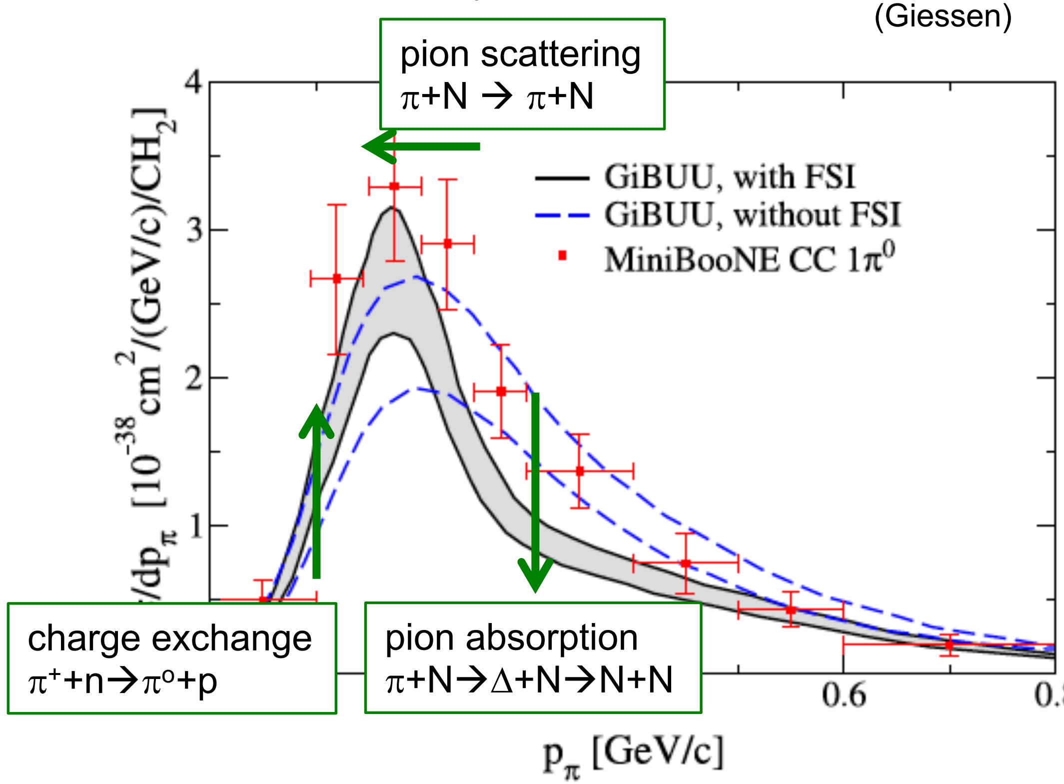






To get right prediction, you need…

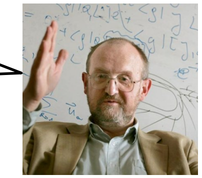
1. neutrino flux prediction
2. pion production model
3. final state interaction

ex) Giessen BUU transport model

- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

3. Open question of neutrino interaction physics

The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



Jan Sobczyk (Wroclaw)

CCQE puzzle

- Low Q2 suppression, high Q2 enhancement, high normalization

→ presence of short and long range nucleon correlations

ANL-BNL puzzle

- Normalization difference between ANL and BNL bubble chamber pion data

→ After correcting BNL normalization, ANL and BNL data agree

Coherent pion puzzle

- Is there charged current coherent pion production?

→ yes it is, but details of kinematic need to be studied more

Pion puzzle

- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

→ ???

Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001
Wu et al,PRC91(2015)035203, Alvarez-Ruso, arXiv:1510.06266

3. Summary of resonance region for oscillation

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25% (ANL-BNL puzzle).
→ origin of 20-30% error on M_A^{RES}
Recent re-analysis found a normalization problem on BNL

Recent fit on re-analyzed ANL-BNL data shows on $C^A_5(0)$ error is 6%. This would give ~6-10% error on M_A^{RES} for experimentalist.

…However, Wu et al pointed out there might be significant contribution of nuclear effect in bubble chamber data. This mean, perhaps, cross section extracted by re-analyzed ANL-BNL would be underestimated?!

M_A^{RES} imitates all normalization errors associated with SPP data ($C^A_5(0)$, M_A^{RES}, nuclear effect, etc). Unless all mysteries are solved (including MiniBooNE-MINERvA tension, pion puzzle), M_A^{RES} error stays ~20-30%.

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Conclusion

Tremendous amount of activities, new data, new theories… (NuInt series)
http://nustec.fnal.gov/nuint-conference-series/

Check slides from NuSTEC schools for further studies
http://nustec.fnal.gov/nustec-school/

1 to 10 GeV neutrino interaction measurements are crucial to successful next-generation neutrino oscillation experiments (DUNE, Hyper-K)

This moment, data from MiniBooNE, T2K, MINERvA, and ArgoNeuT play major roles to develop neutrino interaction models

Thank you for your attention!

Backup