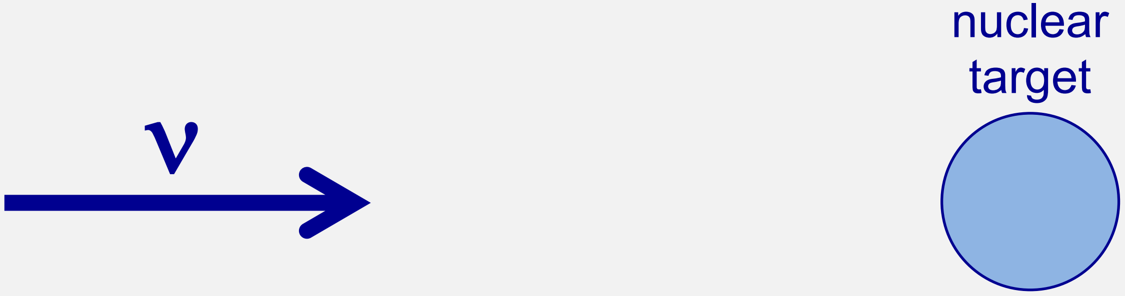
ν
nuclear
target

Fun Timely Intellectual Adorable!

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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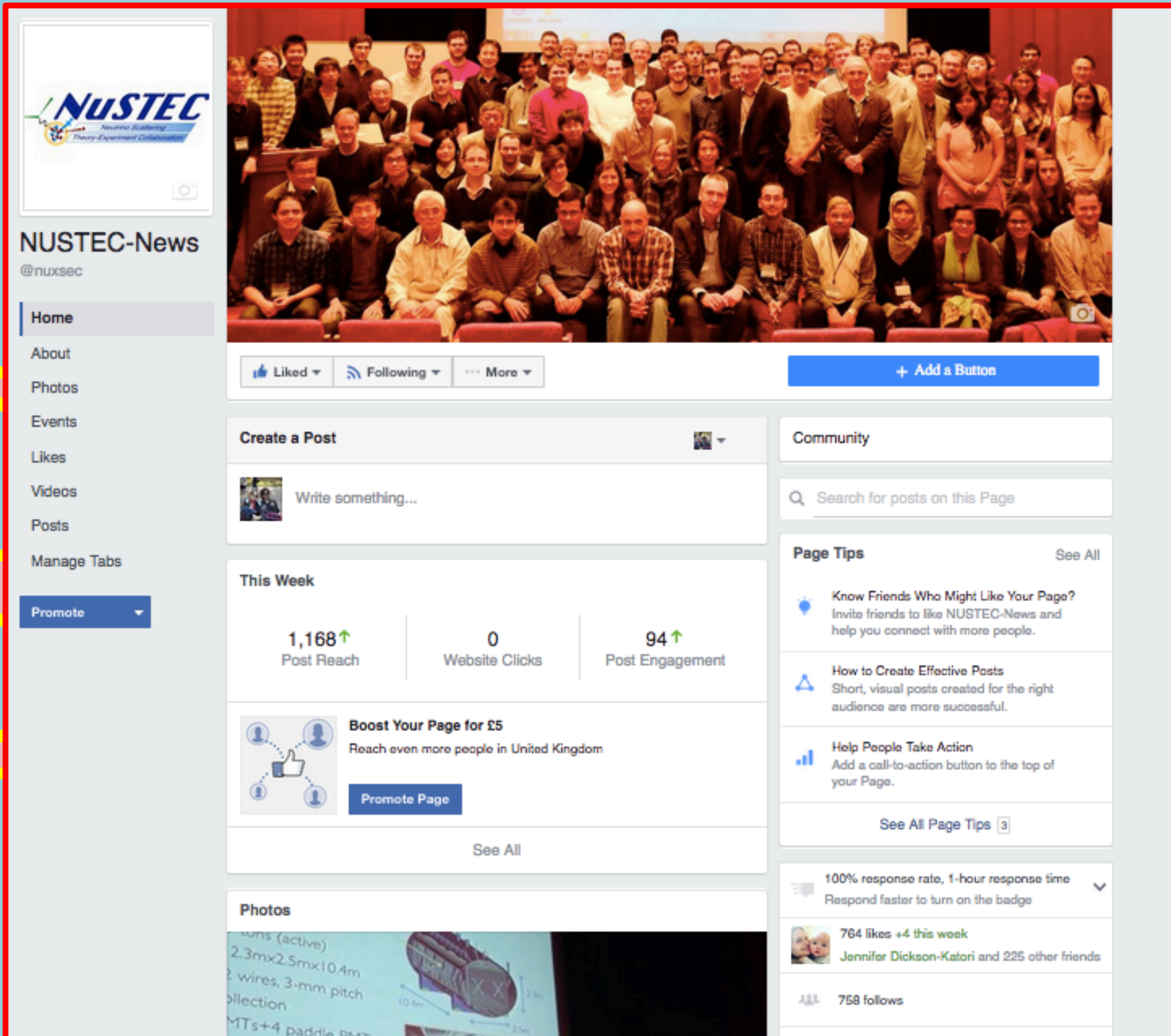
Fun Ti … le!



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TK, Martini, arXiv:1611.07770

Physics of Neutrino Interactions around 1-10 GeV

Teppei Katori
Queen Mary University of London
IPMU seminar, Univ. Tokyo, Feb. 4, 2017

outline

1. Neutrino Interaction Physics

2. MiniBooNE

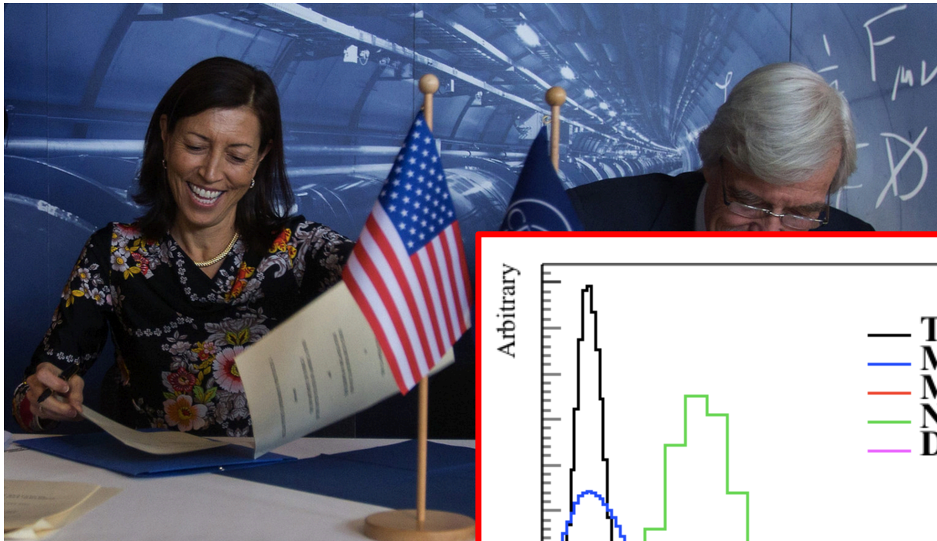
3. T2K near detector

4. MINERvA

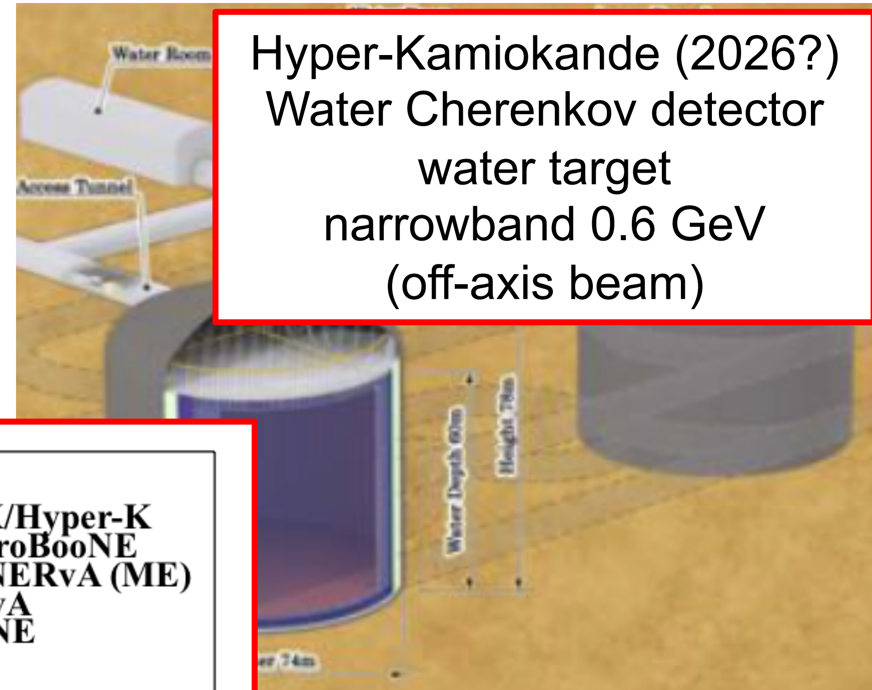
5. LArTPC

6. Conclusion

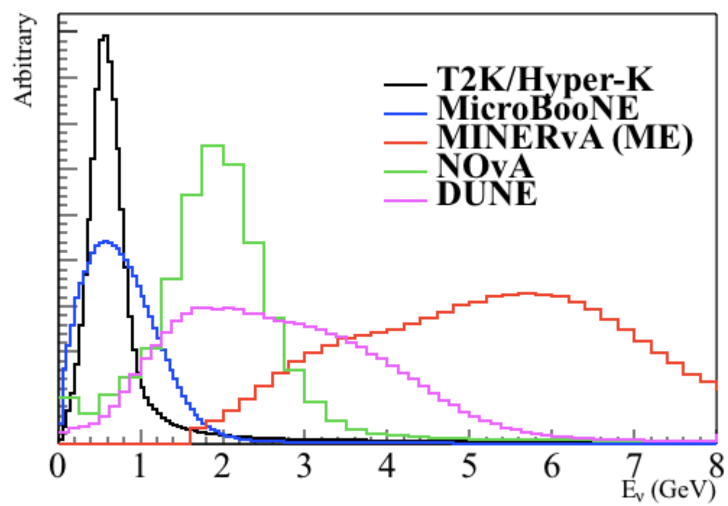
1. DUNE vs. Hyper-K



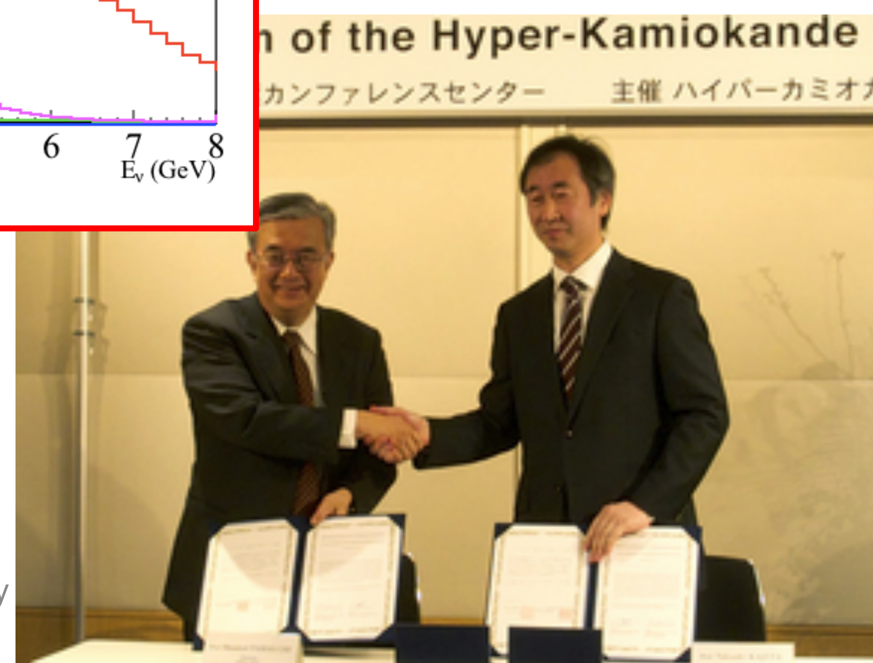
CERN - USA



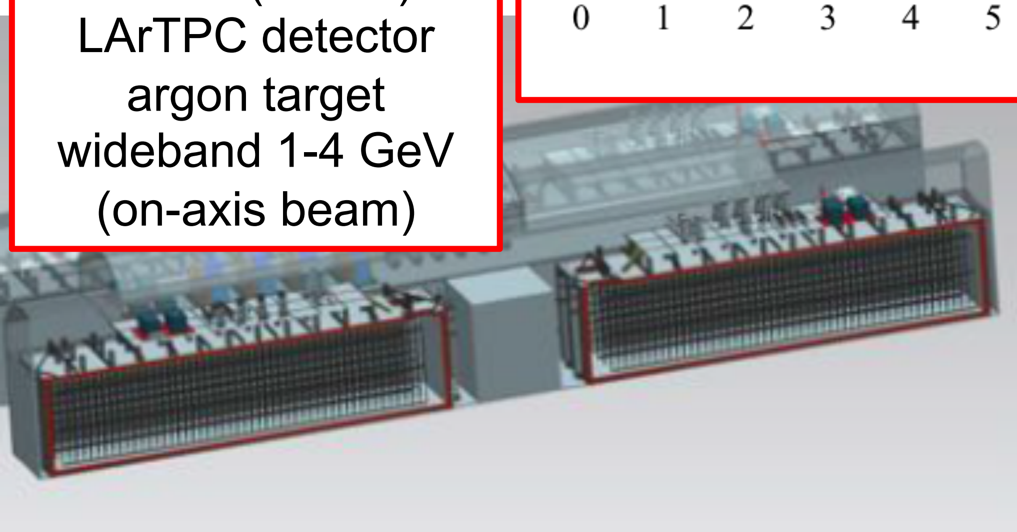
Hyper-Kamiokande (2026?)
Water Cherenkov detector
water target
narrowband 0.6 GeV
(off-axis beam)



KEK - ICRR



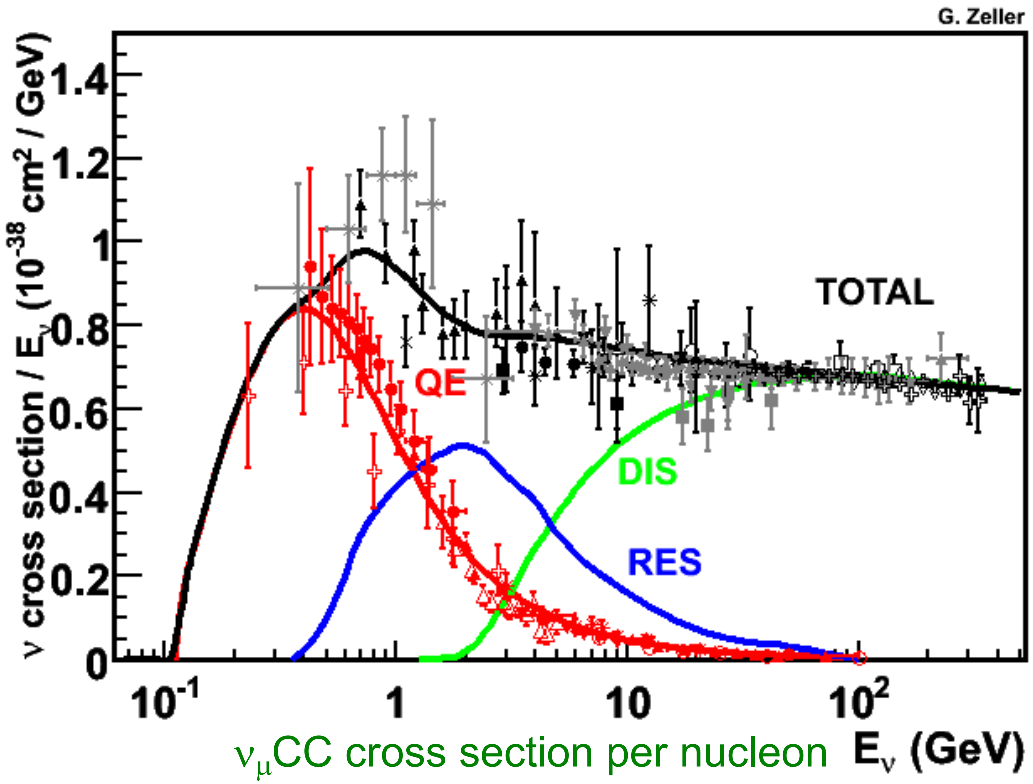
DUNE (2025?)
LArTPC detector
argon target
wideband 1-4 GeV
(on-axis beam)



1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE



ν_μCC cross section per nucleon

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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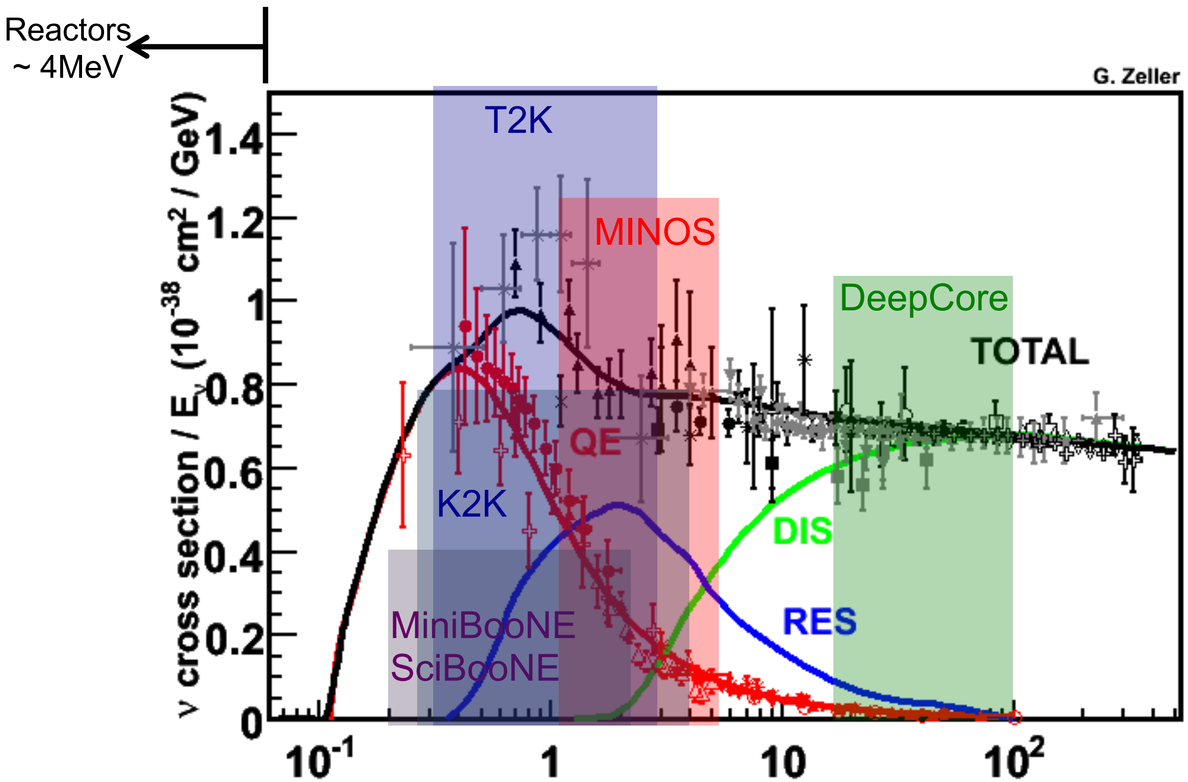

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Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

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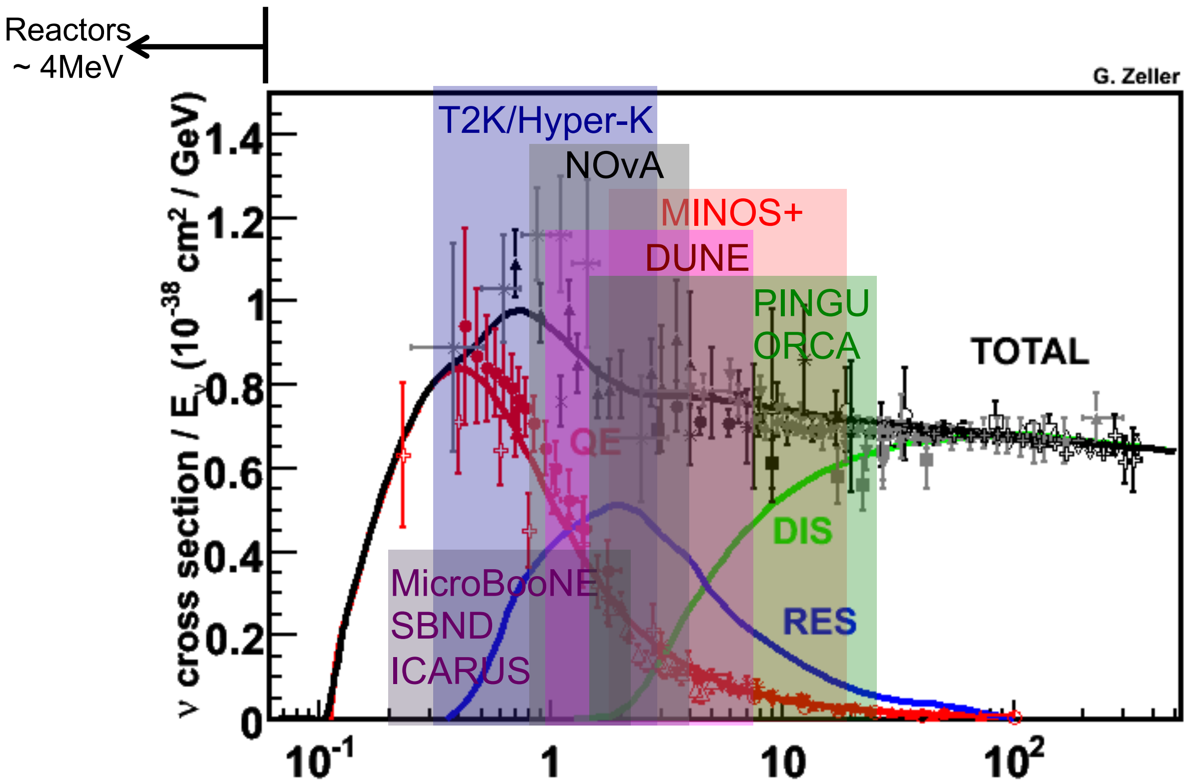

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Jon Link, Fermilab Wine & Cheese seminar (2005)

1. pre-modern neutrino cross section measurement

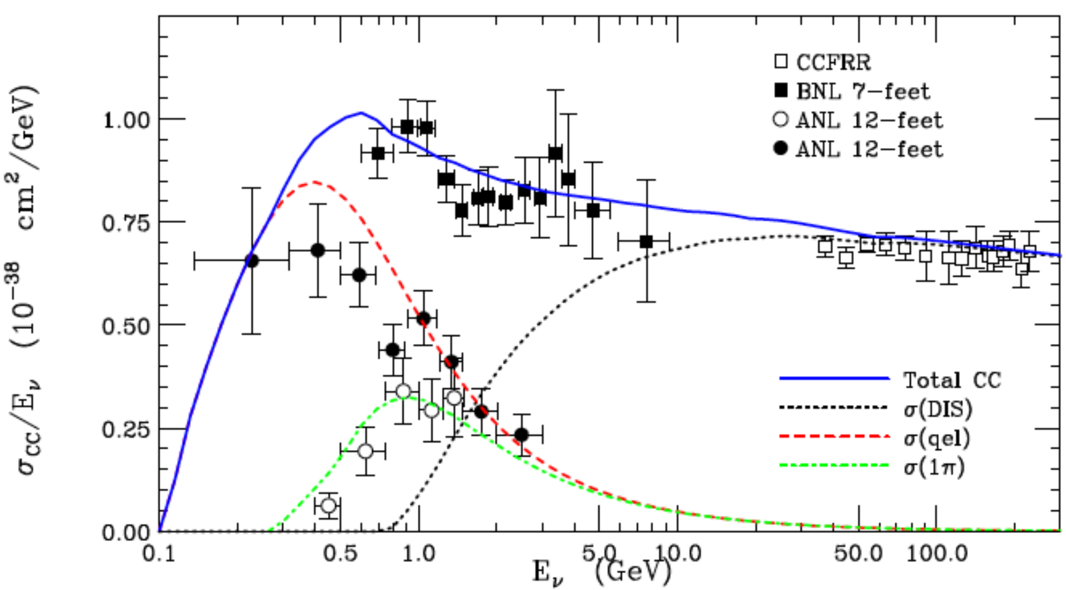
Bubble chamber deuteron data are consistent with M_A~1 GeV
- In general, very poor job to measure the absolute cross-section

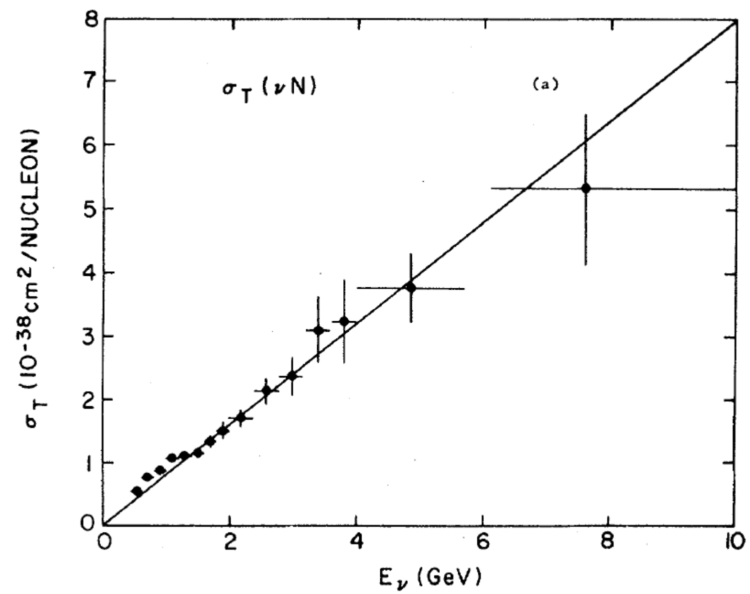
(1) Measure interaction rate
(2) Divide by known cross section to get flux
(3) use this flux, measure cross-section from measured interaction rate

What you get? the known cross section!

Phys. Rev. D [redacted] (1982)

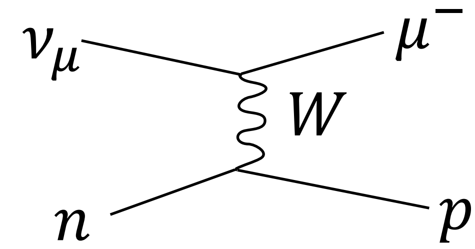
The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections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





K2K, PRD74(2006)052002,PRD74(2006)072003

1. K2K

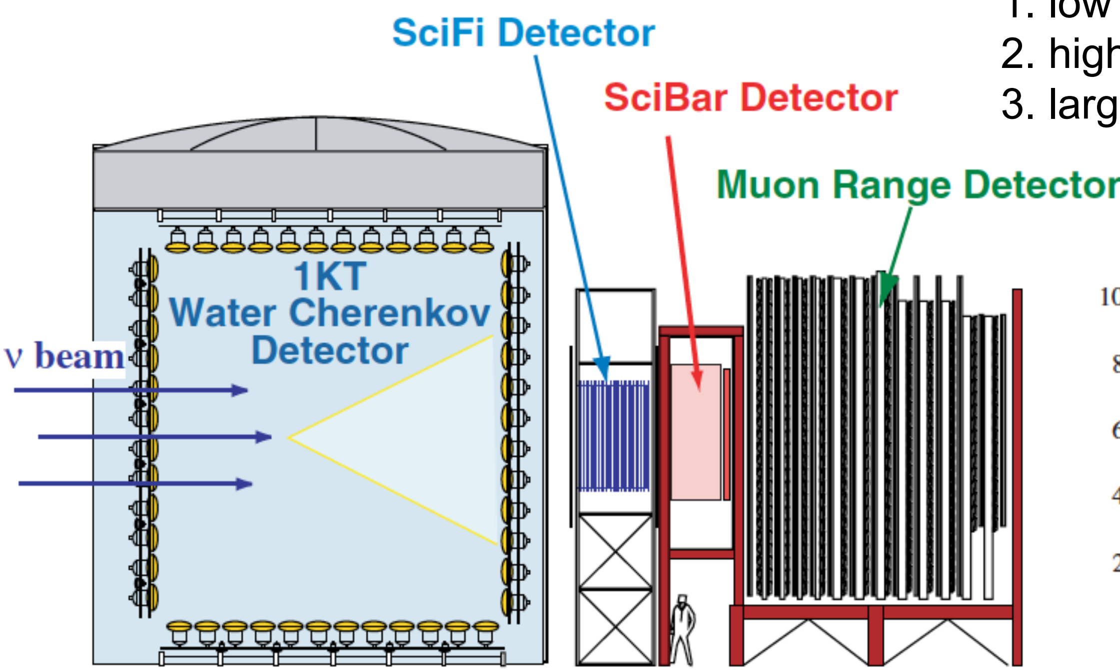


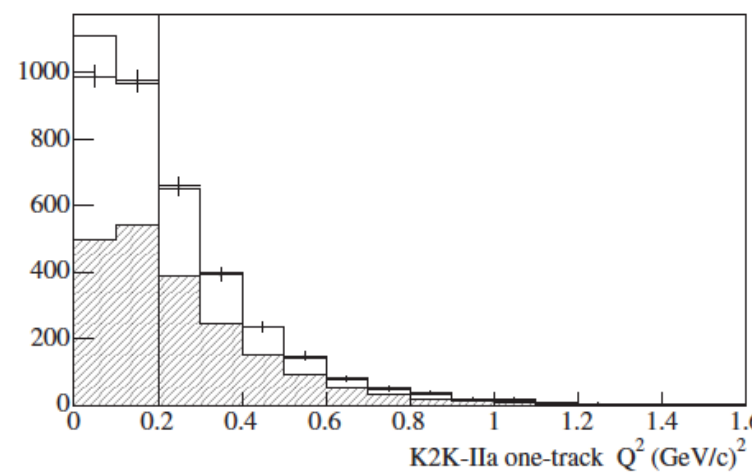
Scintillation tracker

- Tracker, <E>~1.3 GeV
- The first long baseline oscillation experiment
- Modern neutrino interaction experiment to "discover" Origin of all neutrino interaction problems…

CCQE puzzle

1. low Q2 suppression → Pauli blocking?
2. high Q2 enhancement → MA=1.2 GeV
3. large normalization → Beam normalization?





Cross section models are really wrong!
→ we need more experiments to improve models

1. Flux-integrated differential cross-section

We want to study the cross-section model, but we don't want to implement every models in the world in our simulation…

We want theorists to use our data, but flux-unfolding (model-dependent process) loses details of measurements…

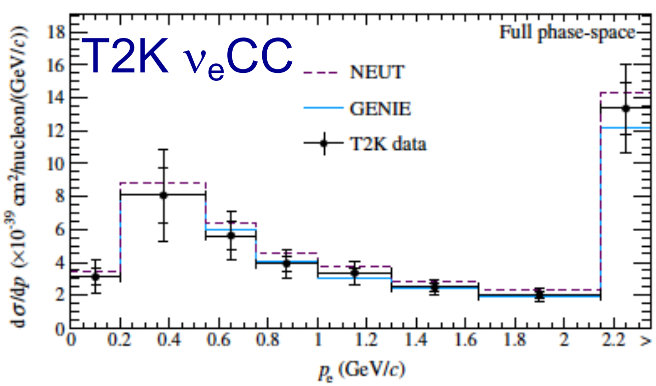
Now, all modern experiments publish flux-integrated differential cross-section
→ Detector effect corrected event rate (R=Φ x σ x ε)
→ Theorists can reproduce the data with neutrino flux tables from experimentalists
→ Minimum model dependence, useful for nuclear theorists

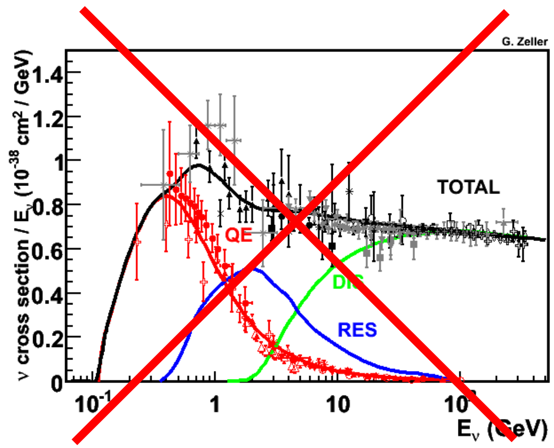
These data play major roles to study/improve neutrino interaction models by theorists

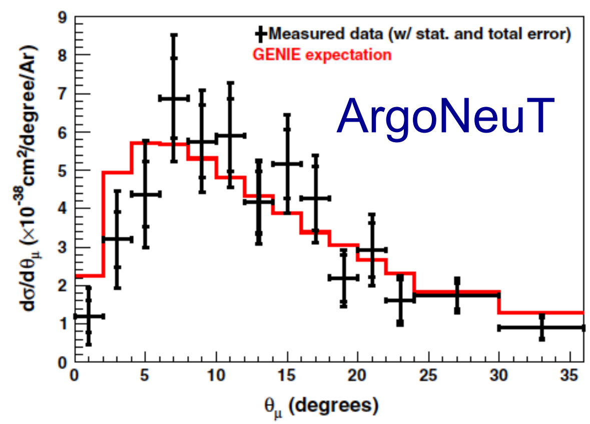
1. Flux-integrated differential cross-section

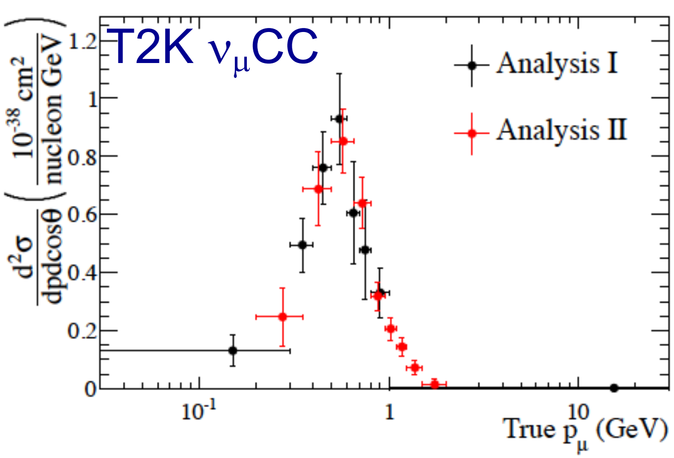
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

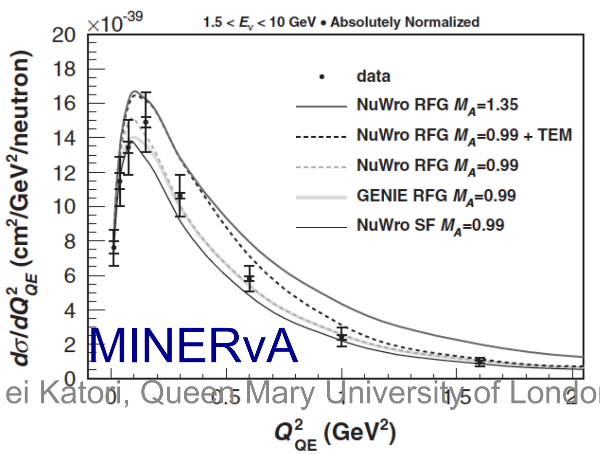
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

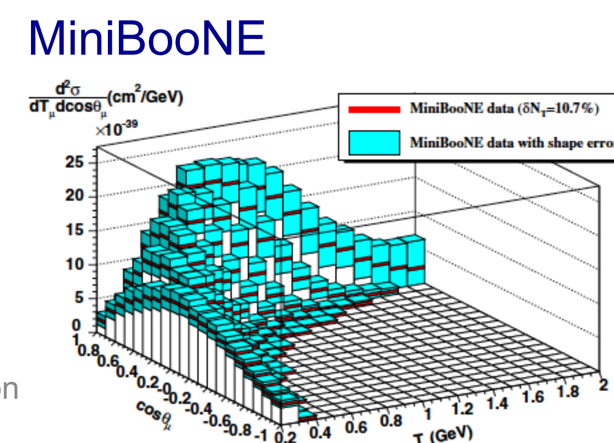












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Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

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$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

Theorists

Experimentalists

$$\frac{d^2\sigma}{dT_l \cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta\cos\theta)_i}$$

Flux-integrated differential cross-section data allow theorists and experimentalists talk first time in modern neutrino interaction physics history

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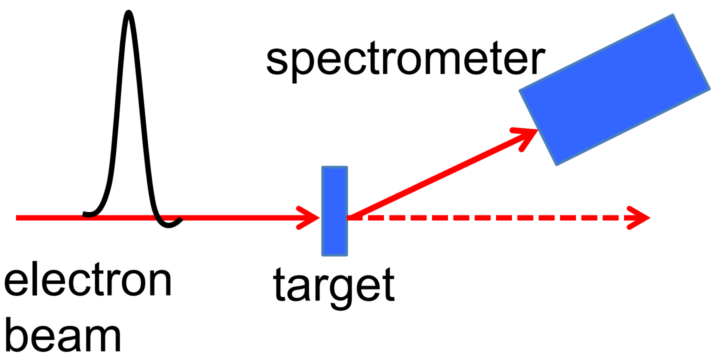
1. Electron scattering vs. Neutrino scattering

Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

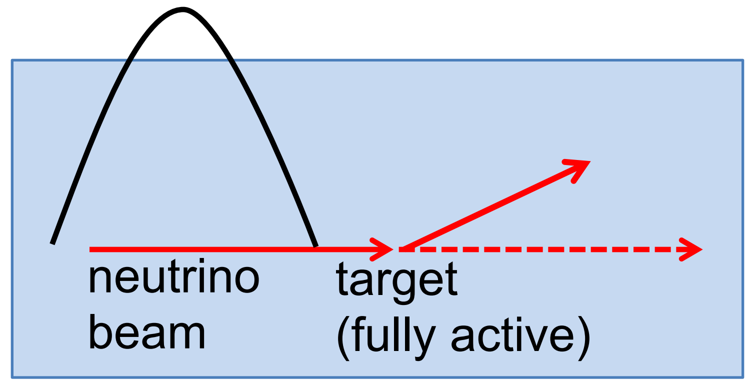
→ kinematics is completely fixed

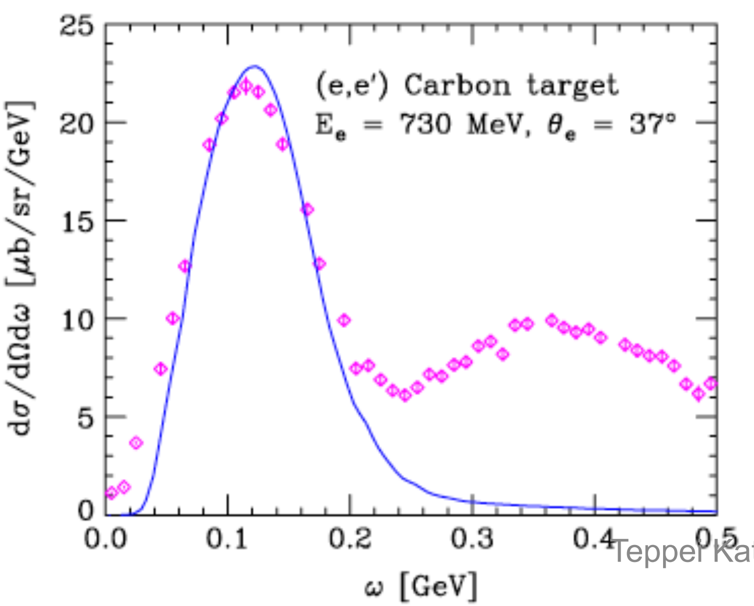


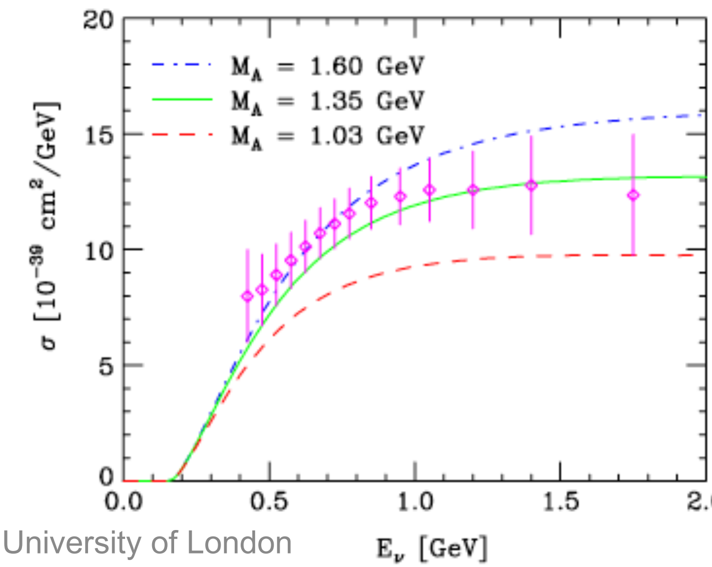
Neutrino scattering

- Wideband beam

→ observables are inclusive







Benhar et al, Rev.Mod. Phys.80(2008)189, PRL105(2010)132301

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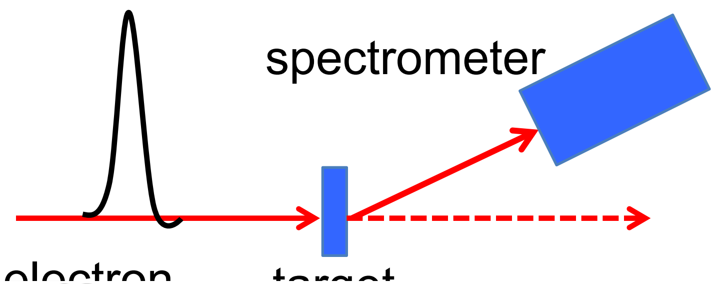

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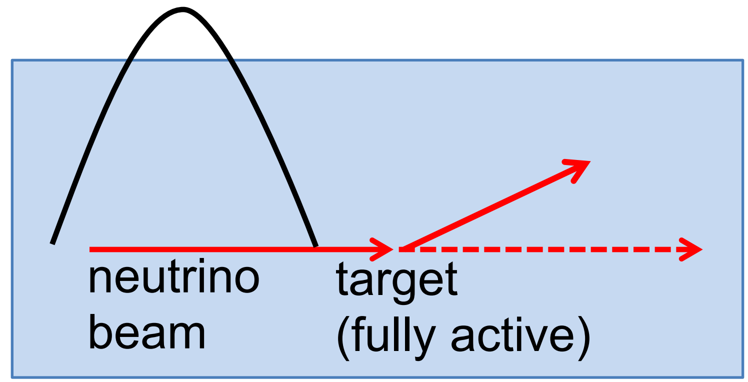
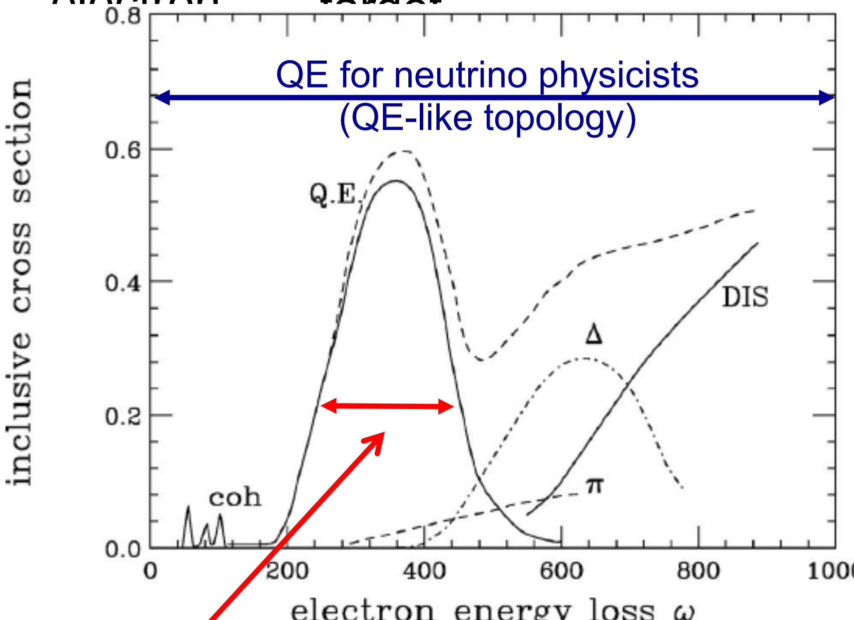
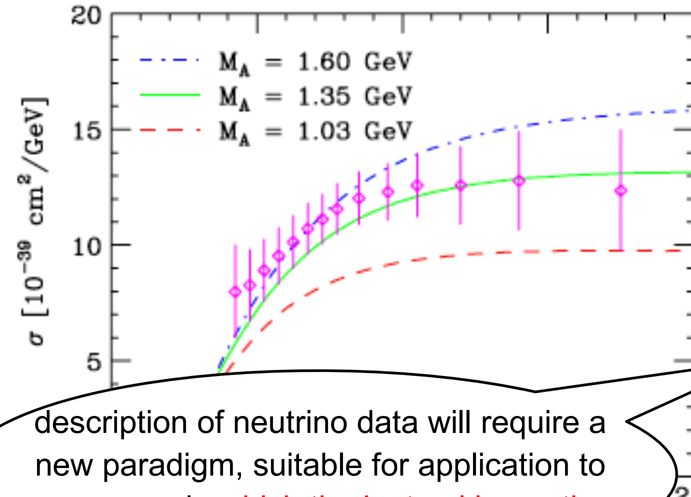
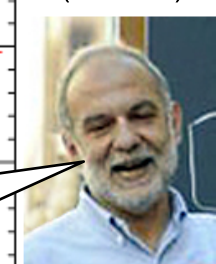




QE for nuclear physicists (genuine QE)



Omar
Benhar
(Rome I)

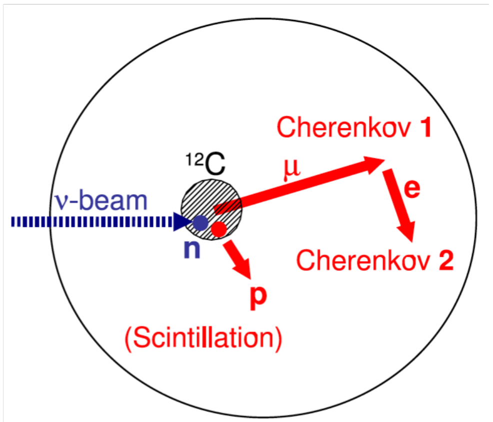


description of neutrino data will require a new paradigm, suitable for application to processes in which the lepton kinematics is not fully determined

MiniBooNE,PRD81(2010)092005
Redij (T2K), NuInt15

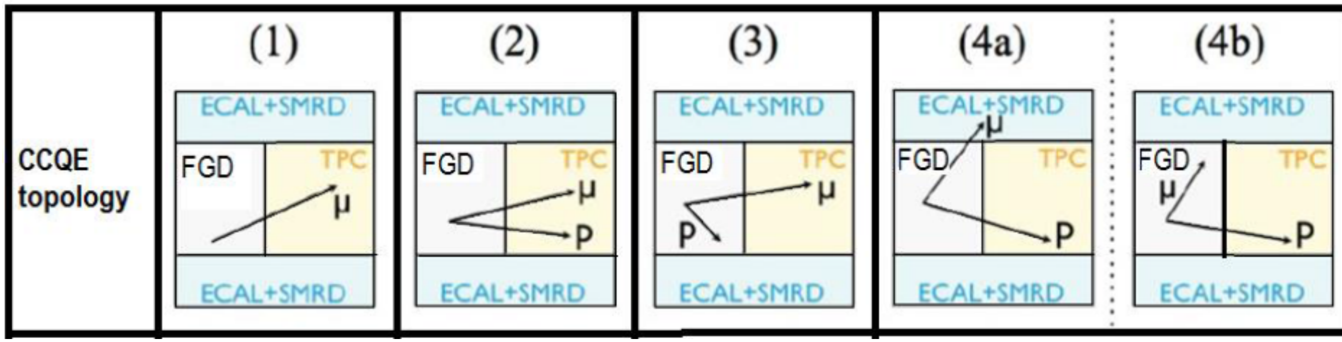
1. Type of neutrino detectors

Cherenkov neutrino detector
- MiniBooNE



- 4π coverage
- not good to measure multi-tracks
- good calorimetric measurement

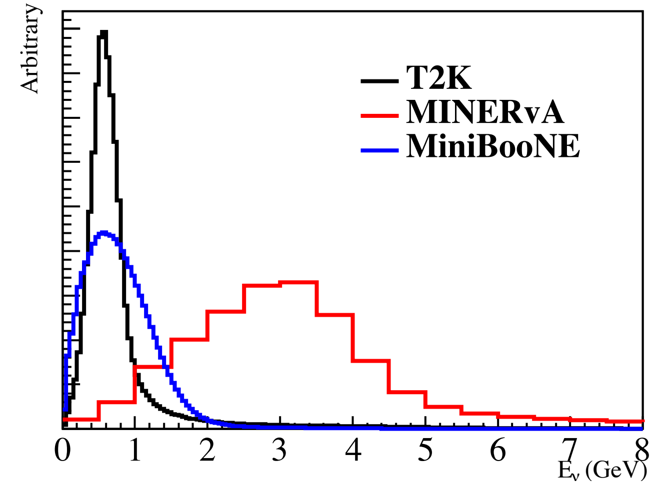
Tracker neutrino detector
- T2K
- MINERvA



- multi-track measurements
- vertex activity measurement (high resolution)
- efficiency depends on topology

Liquid argon TPC neutrino detector
- ArgoNeuT, MicroBooNE
- It claims to have all features
(4π coverage, calorimetric, multi-track, vertex activity)

3. MiniBooNE



Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Highest amount of information of lepton kinematics
- Some calorimetric (scintillation)
- Large normalization error (10.7%)

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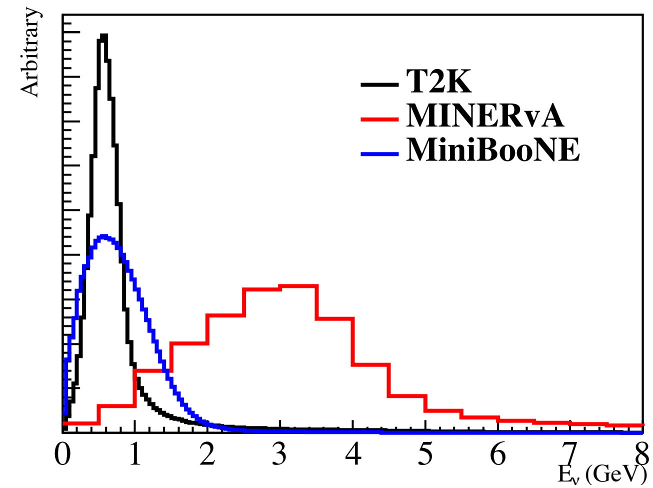
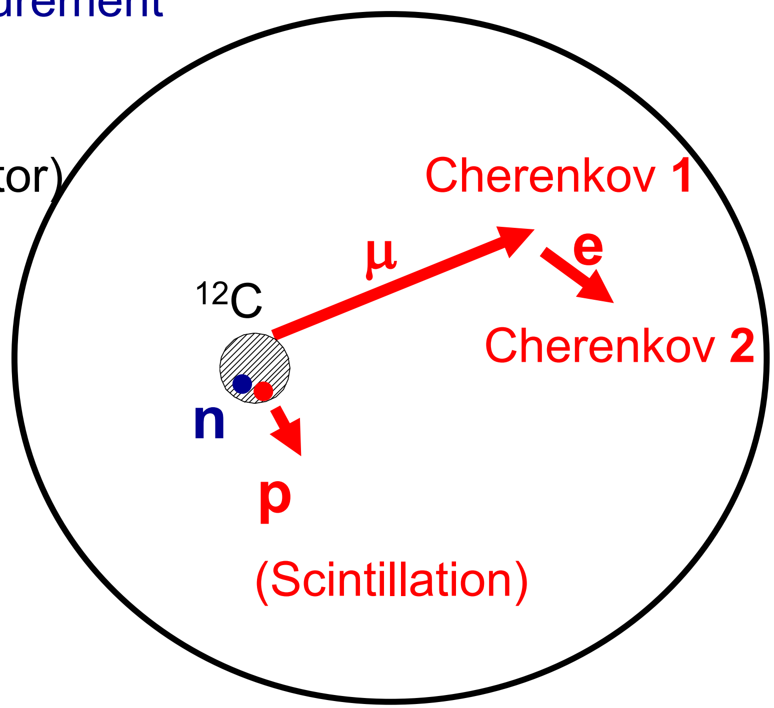
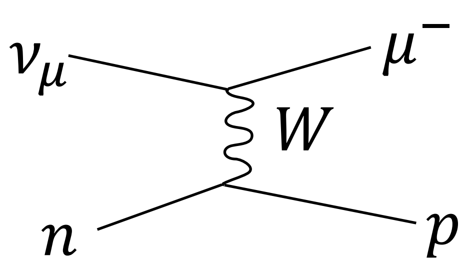


MiniBooNE CCQE measurement

MiniBooNE detector

(spherical Cherenkov detector)





muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

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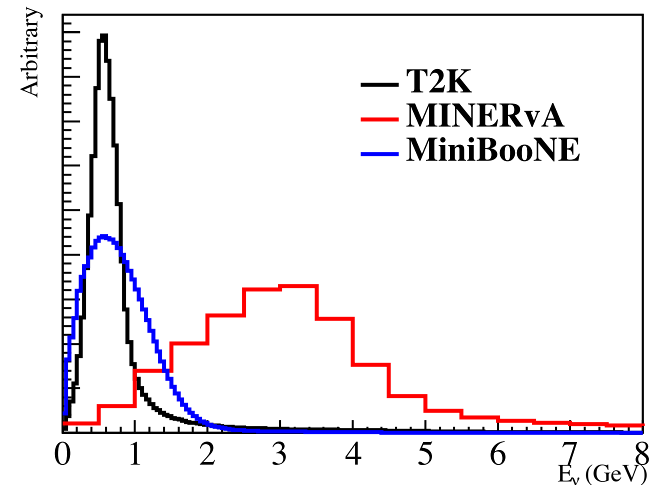
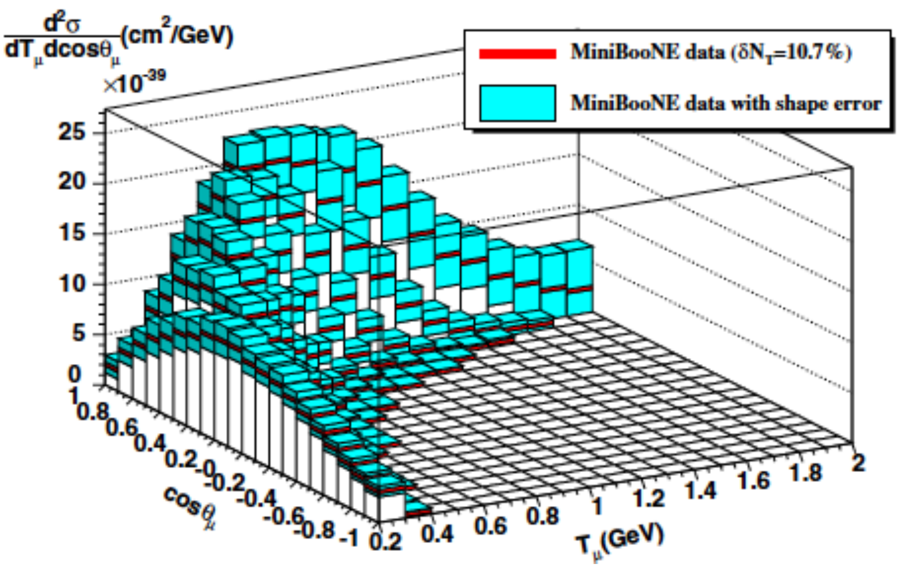
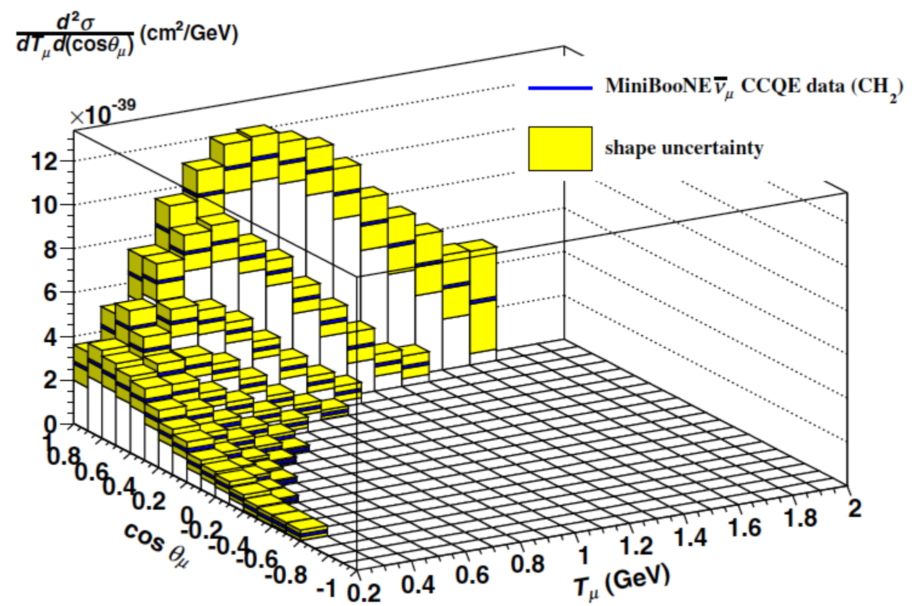


neutrino and anti-neutrino CCQE-like double differential cross sections





Martini et al,PRC80(2009)065501

2. The solution of CCQE puzzle

Presence of 2-body current

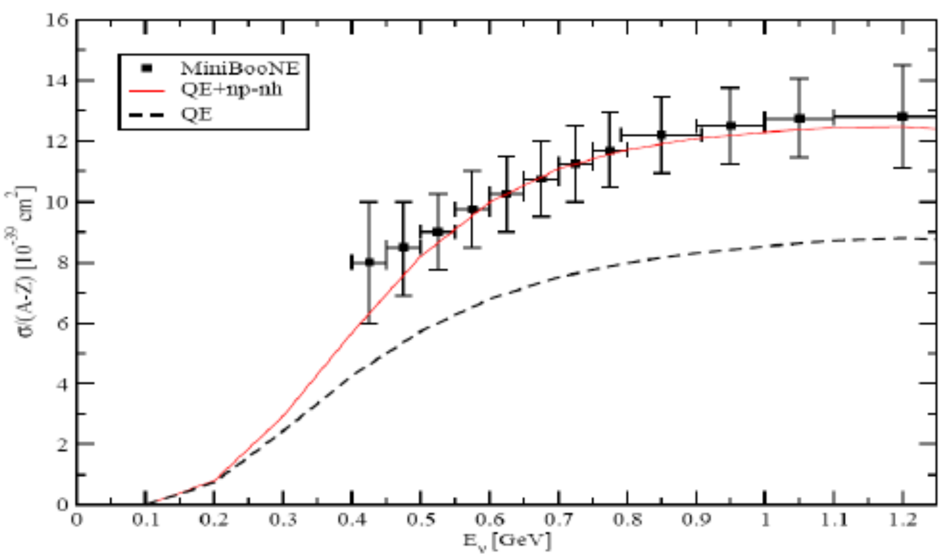
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

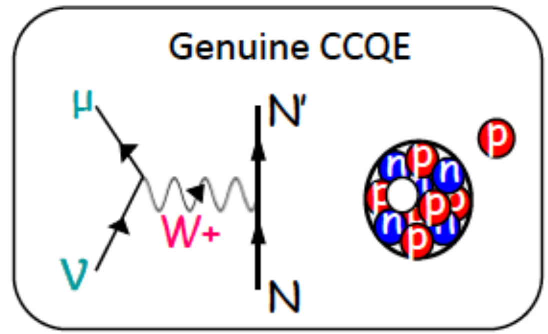
What experimentalists call "CCQE" is not genuine CCQE!

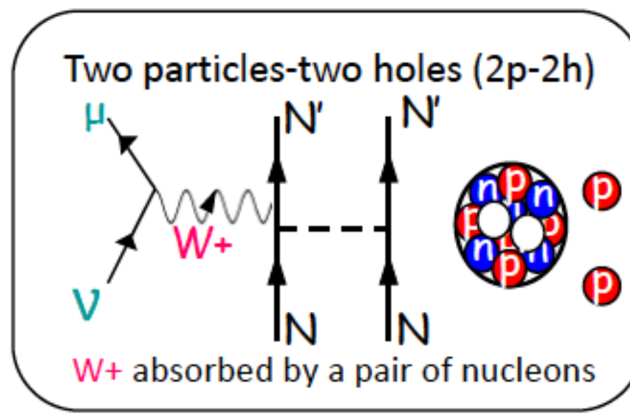
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







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- consistent result is obtained by Nieves et al

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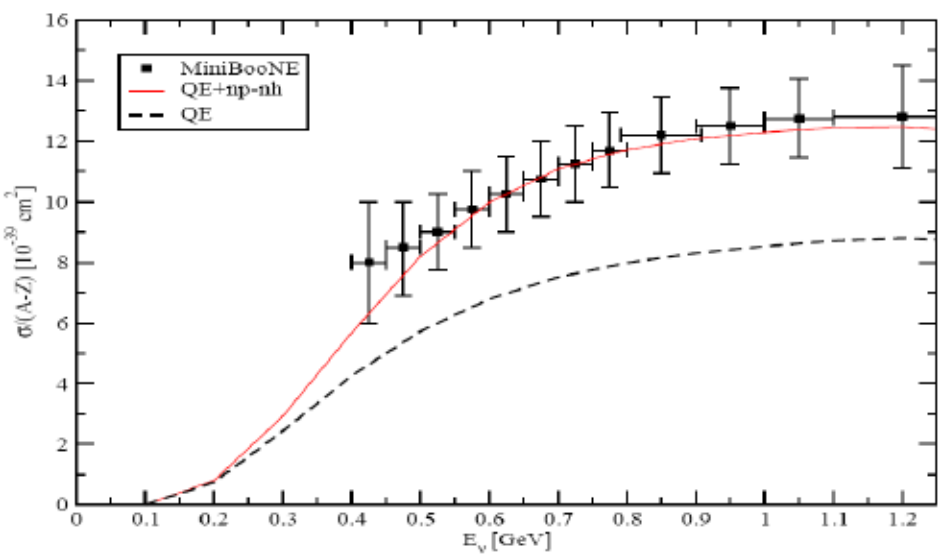
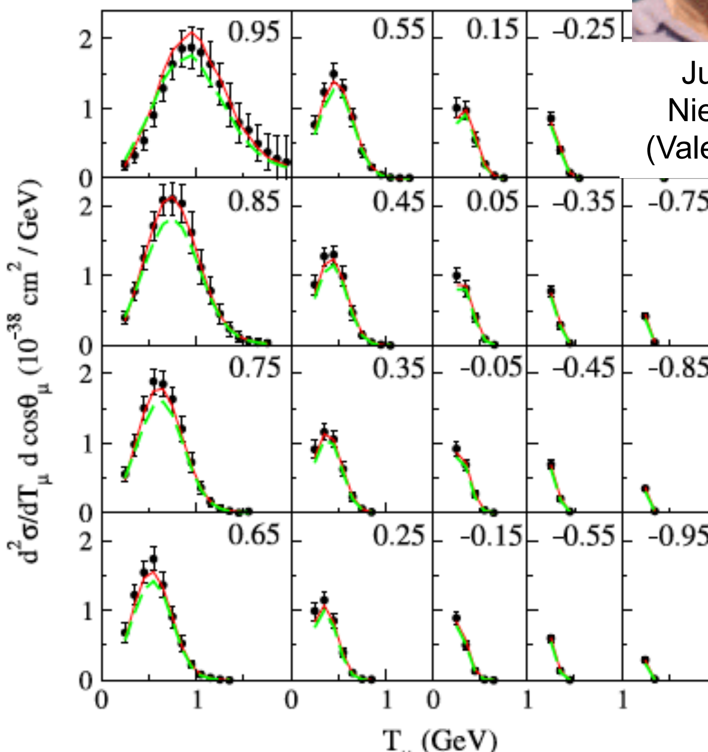


The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)



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

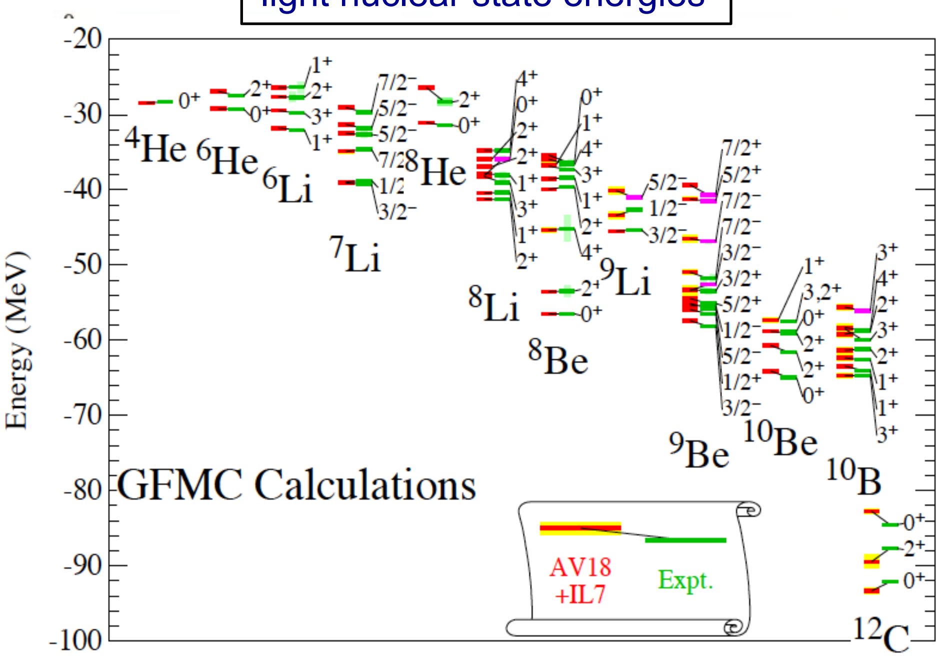
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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

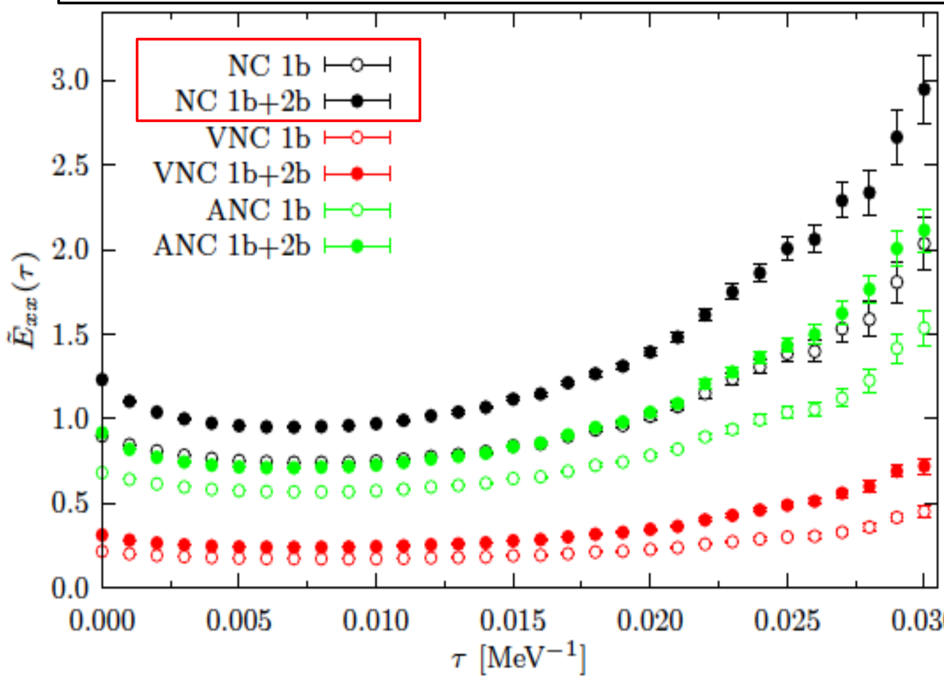
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



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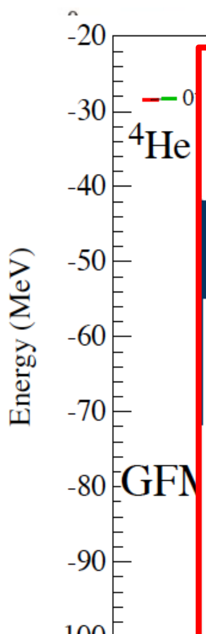
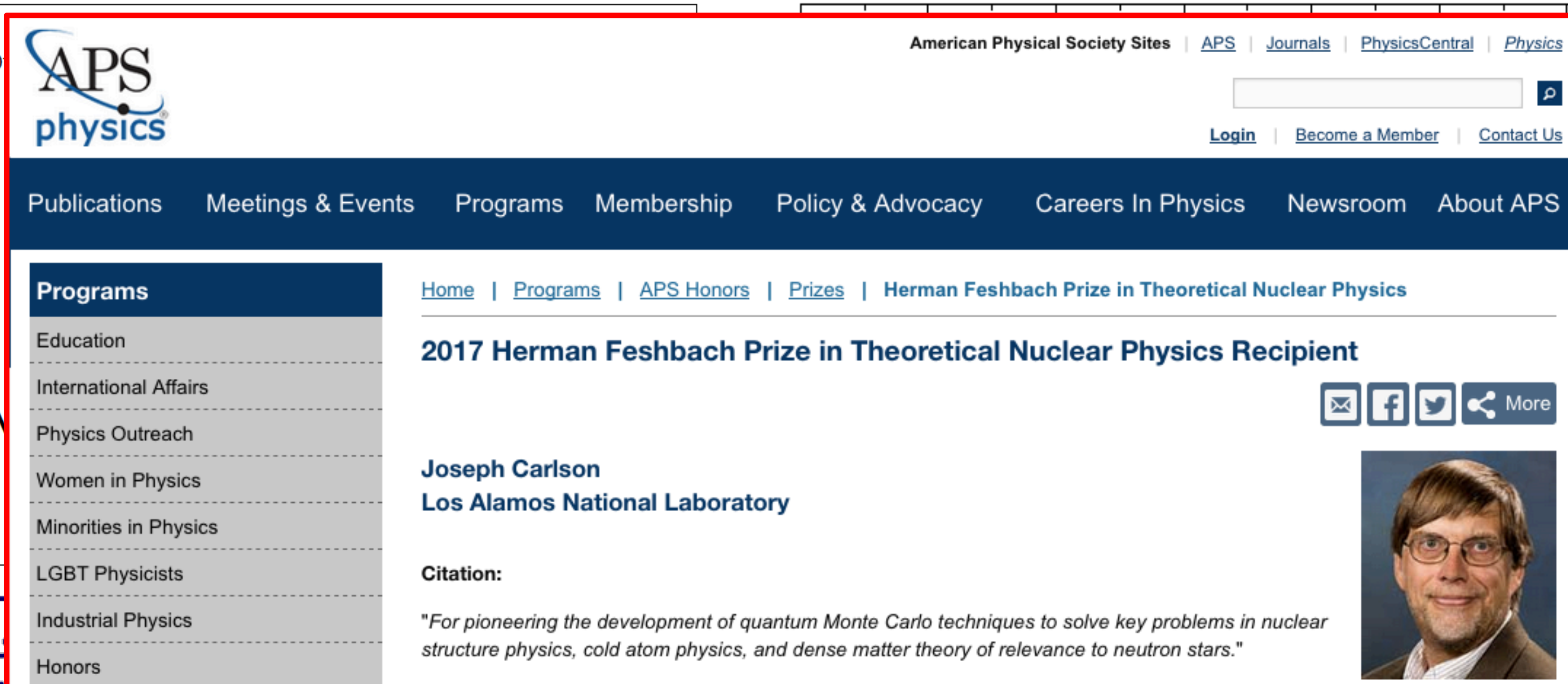
light nuclear state energies

Neutrino NCQE scattering in ^{12}C response function





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2017 Herman Feshbach Prize in Theoretical Nuclear Physics Recipient

More

Joseph Carlson
Los Alamos National Laboratory

Citation:

"For pioneering the development of quantum Monte Carlo techniques to solve key problems in nuclear structure physics, cold atom physics, and dense matter theory of relevance to neutron stars."

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

2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

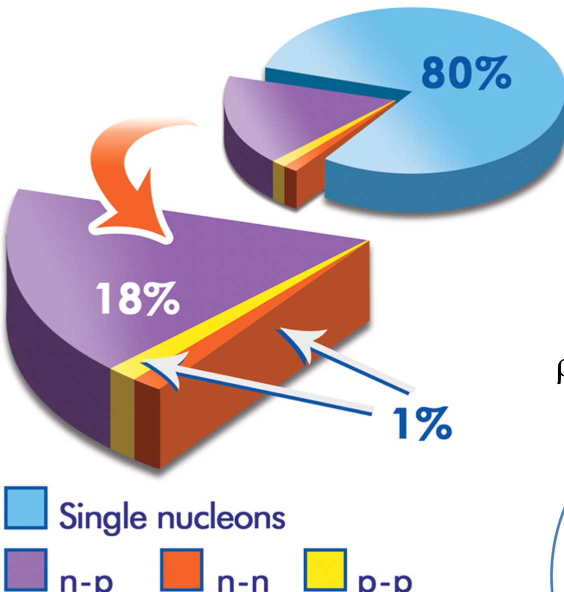
Alessandro Lovato
(Argonne)

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)

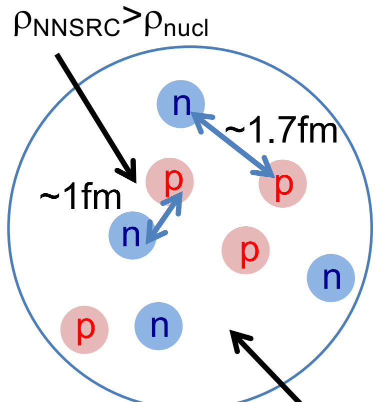
$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1+U_{ij}+\sum_{k\neq i,j}^{A}\tilde{U}_{ijk}^{TNI}\right]|\Psi_J\rangle$$

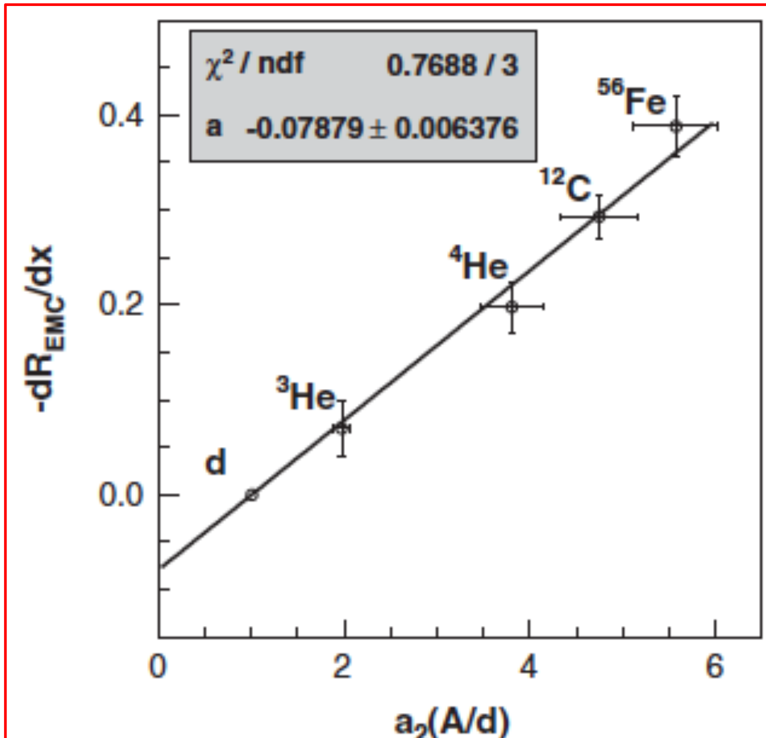
2N potential (Av18) — 3N potential (IL7)



Physics of SRC

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





Nucleon correlation is a very hot topics!

1. Neutrino Interaction Physics

2. MiniBooNE

3. T2K near detector

4. MINERvA

5. LArTPC

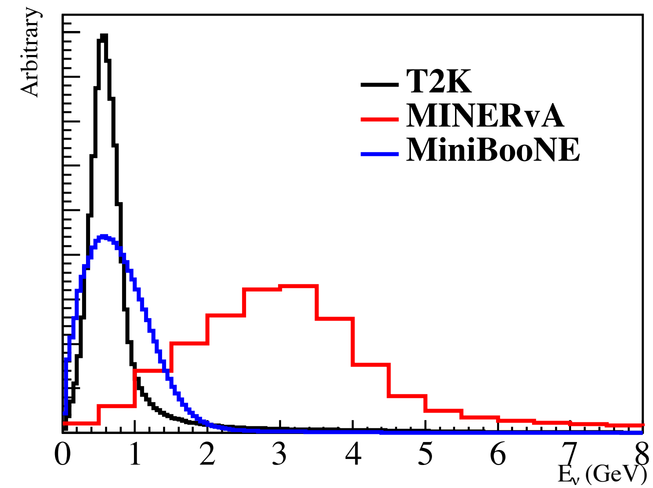
6. Conclusion

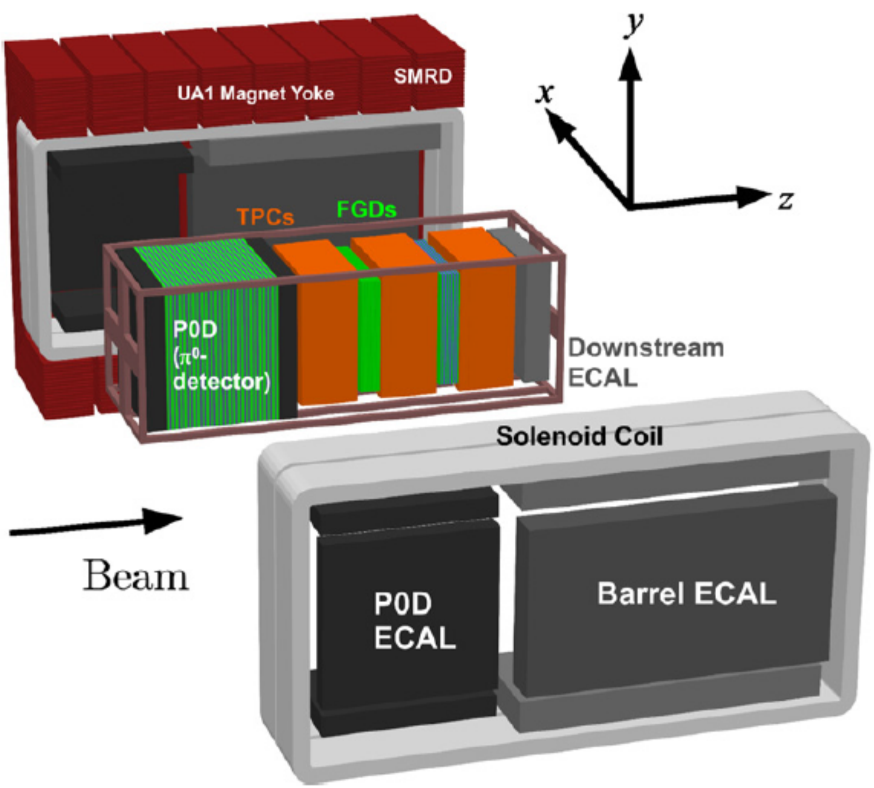
T2K, NIMA659(2011)106

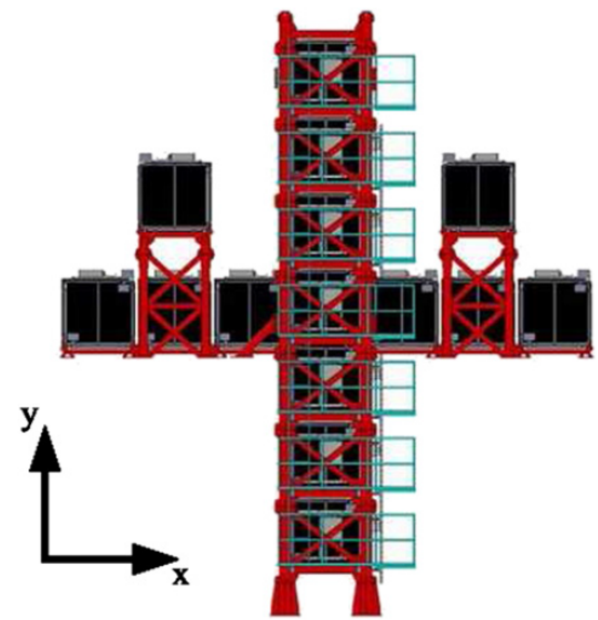
3. T2K near detector

INGRID, FGD, P0D, ECal, TPC, SMRD, Super-K

- Plastic scintillation trackers (except gas TPC)
- 0.2T magnet for momentum measurement
- <E>~600 MeV off-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)







T2K, NIMA659(2011)106

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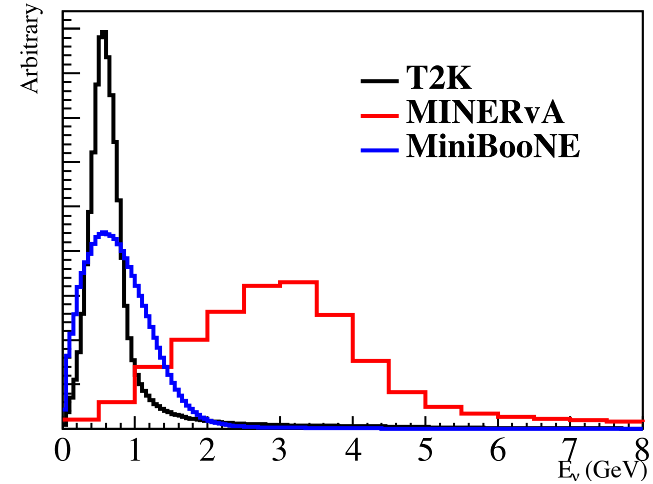
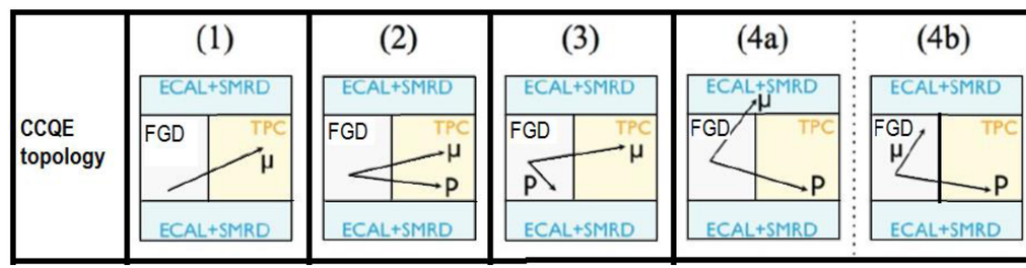
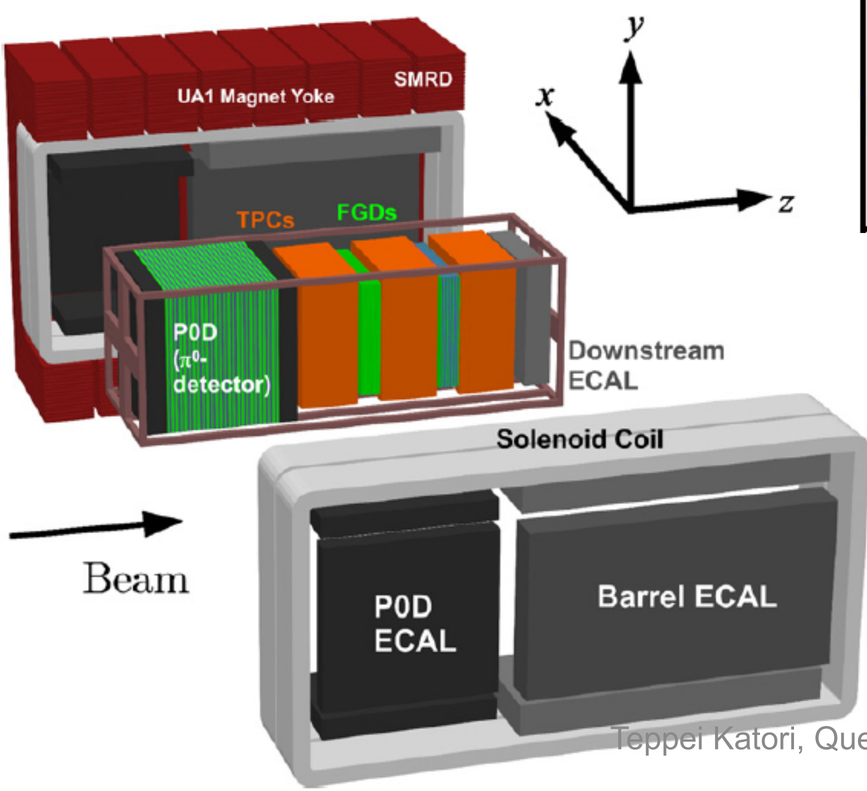
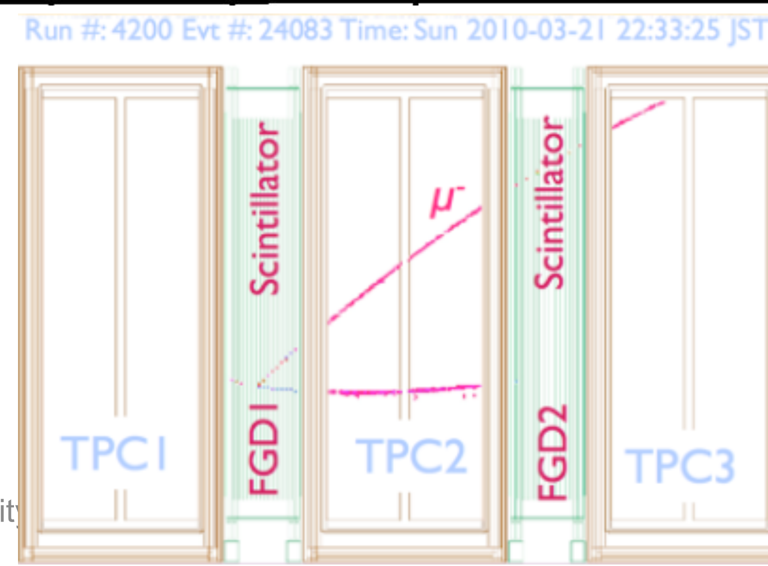


neutrino CC0π double differential cross sections







T2K,PRD93(2016)112012

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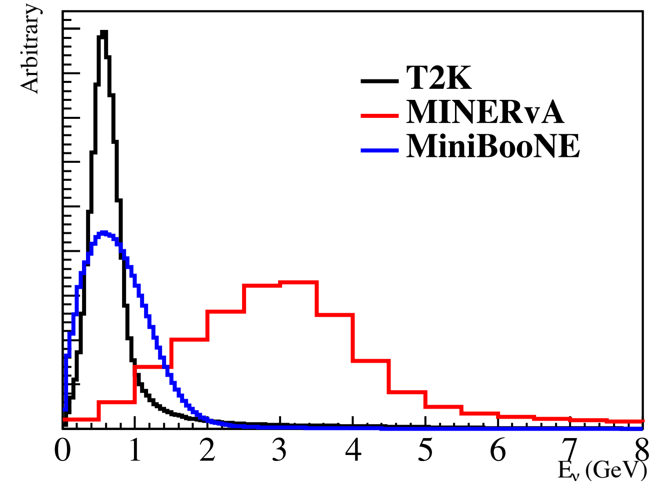

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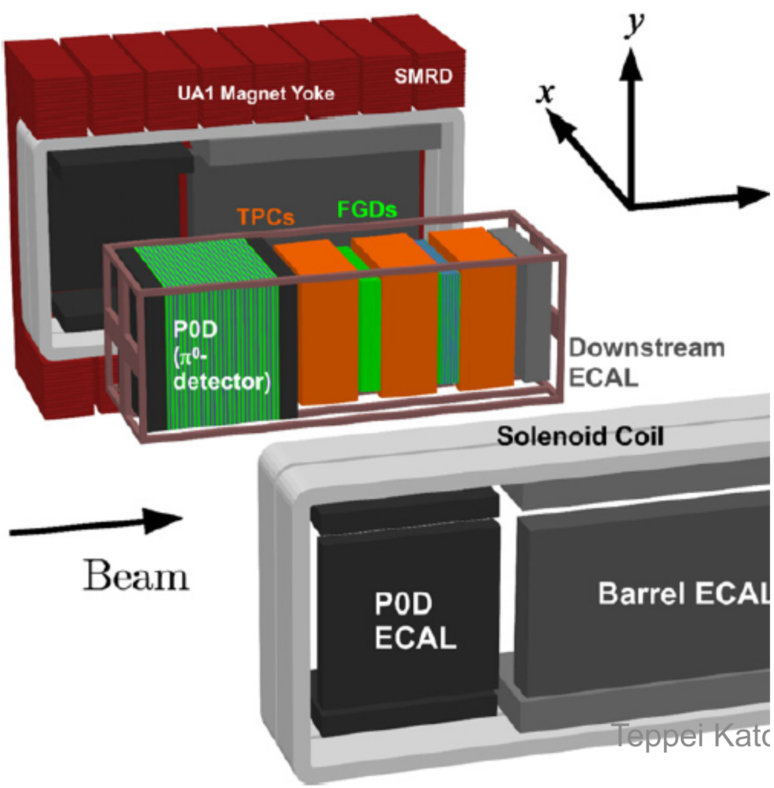
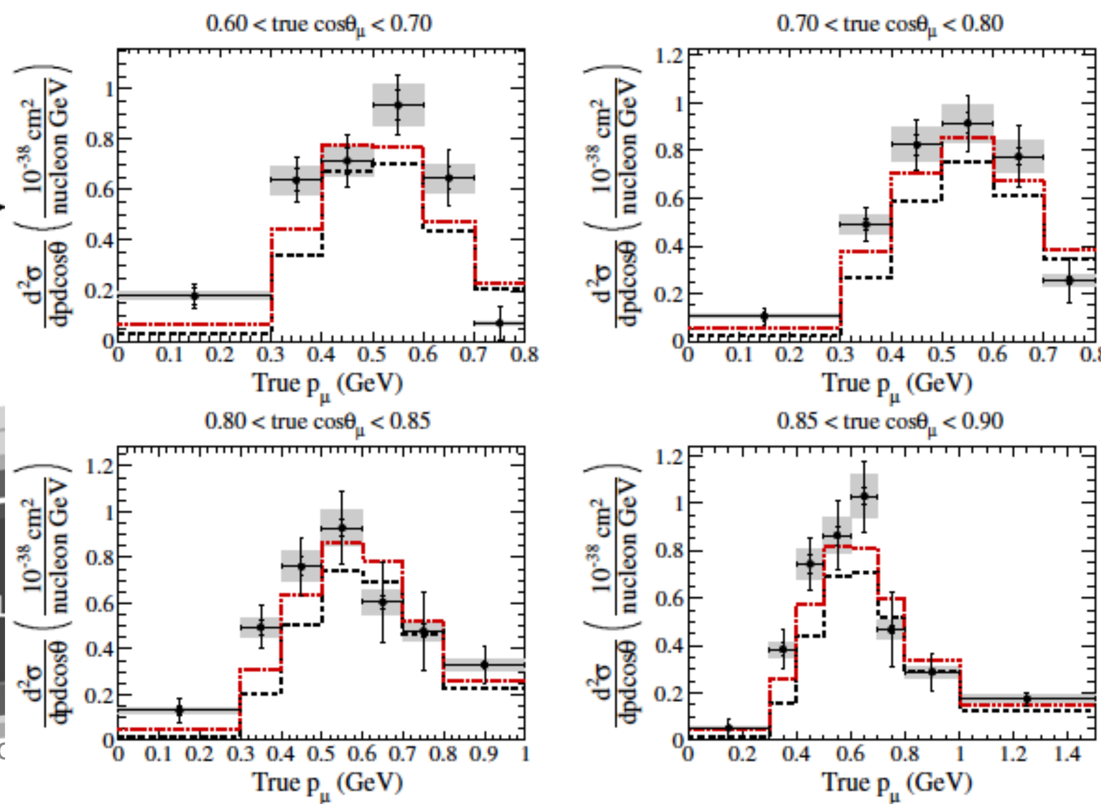
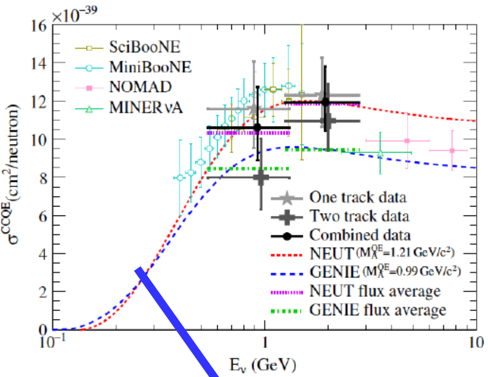


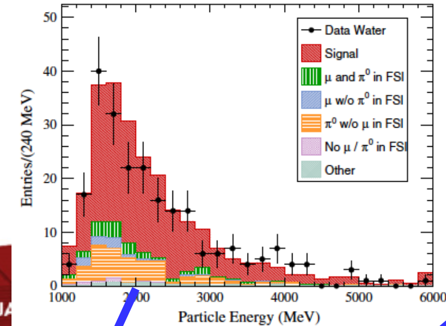


Teppei Katori

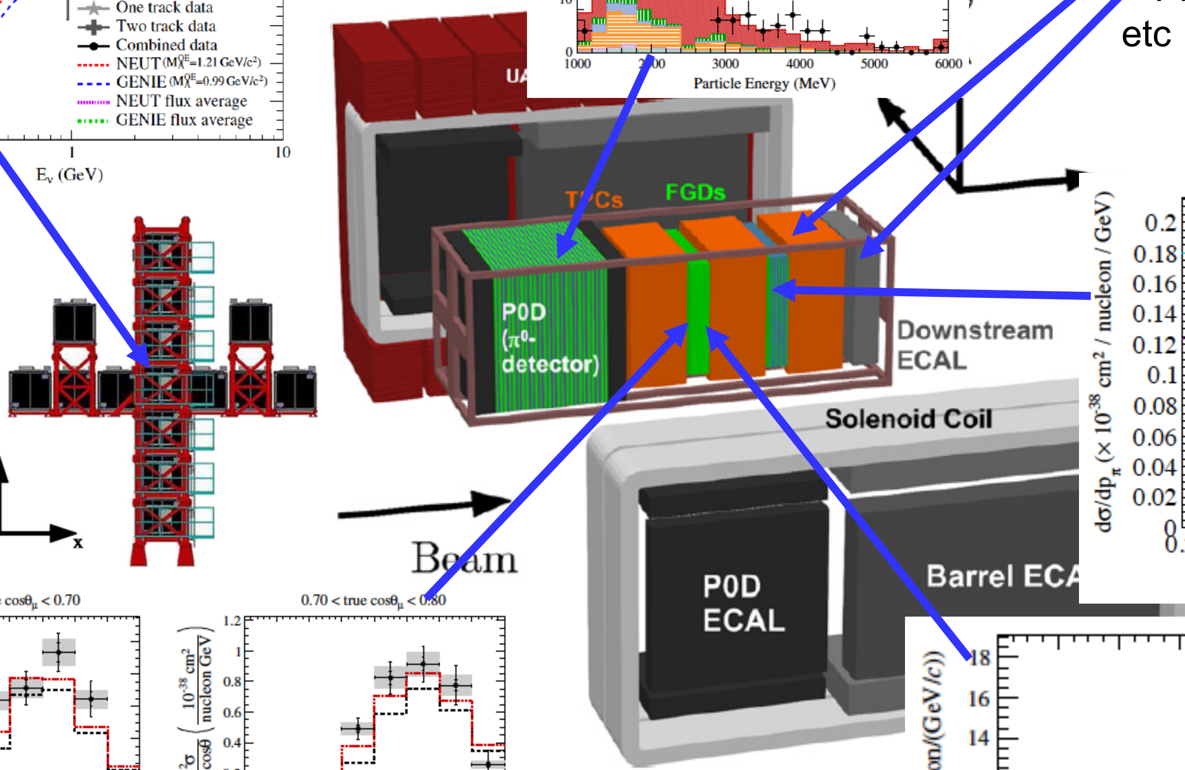
T2K,PRD91(2015)112002;91(2015)112010;93(2016)112012;95(2017)012010
PRL113(2014)241803, Brailsford, PhD thesis (Imperial, 2015), Hamilton, PhD thesis (Imperial, 2016)

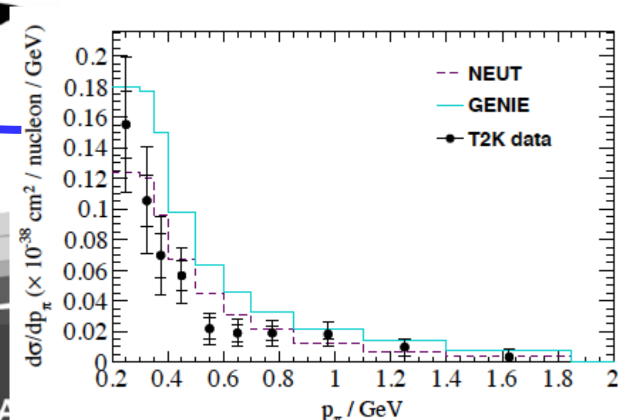
3. T2K near detector

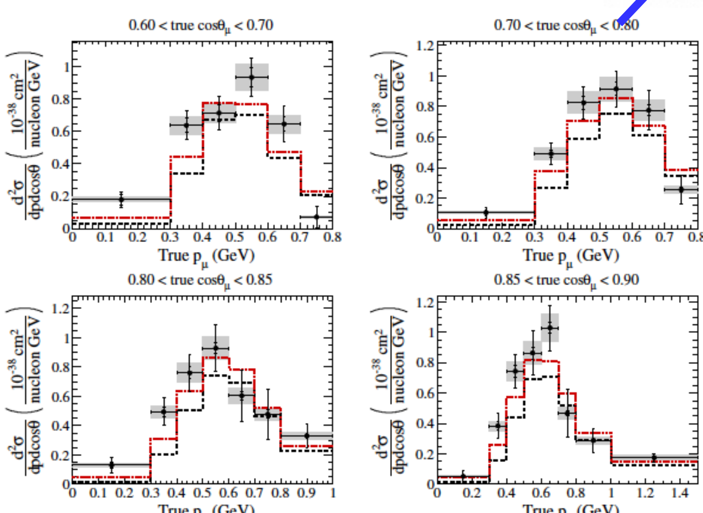


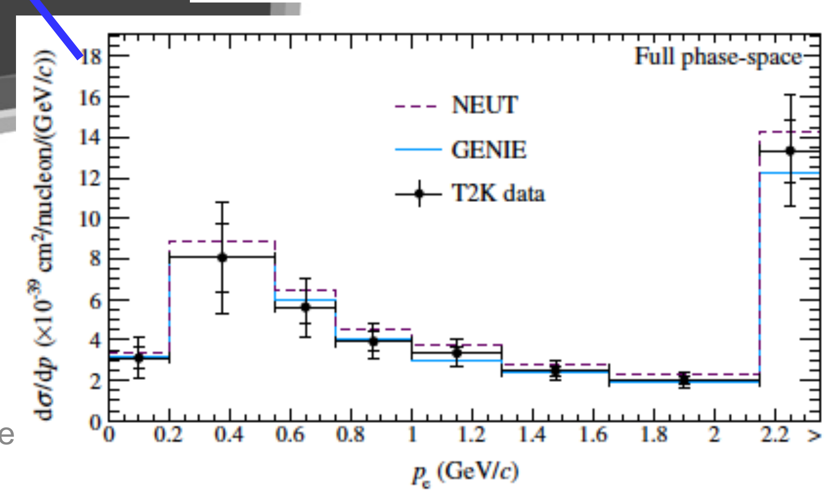


Target dependent measurement
- Ar (TPC gas)
- Pb (ECal)
etc









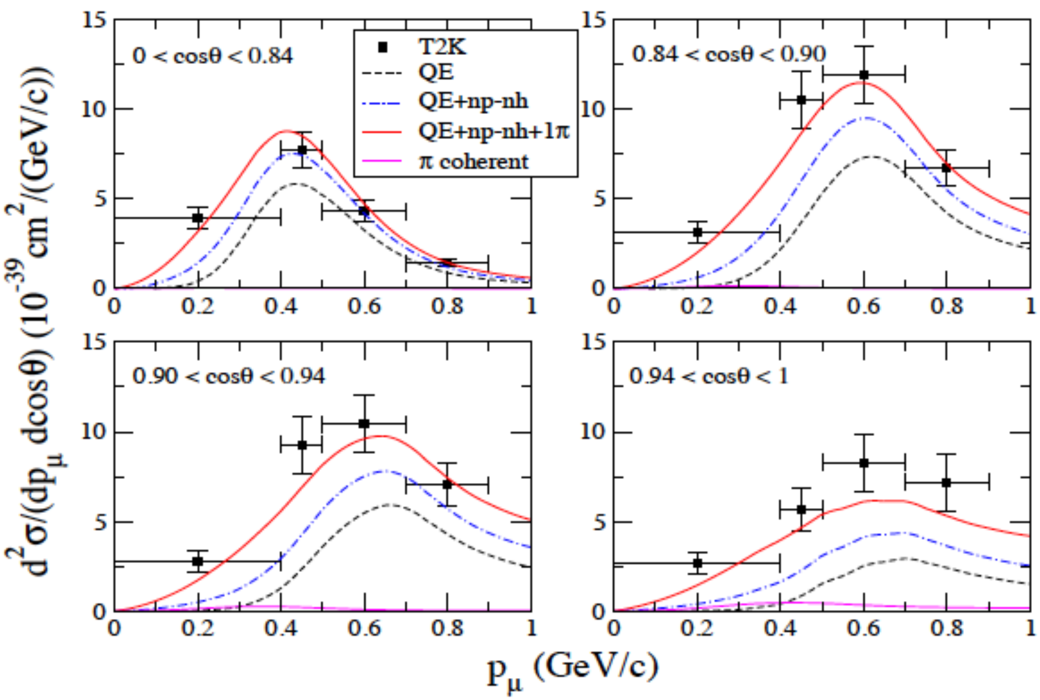
Martini et al,PRC80(2009)065501, PRC90(2014)02550, PRC94(2016)015501
Megias et al.,PRD94(2016)093004

3. The solution of CCQE puzzle

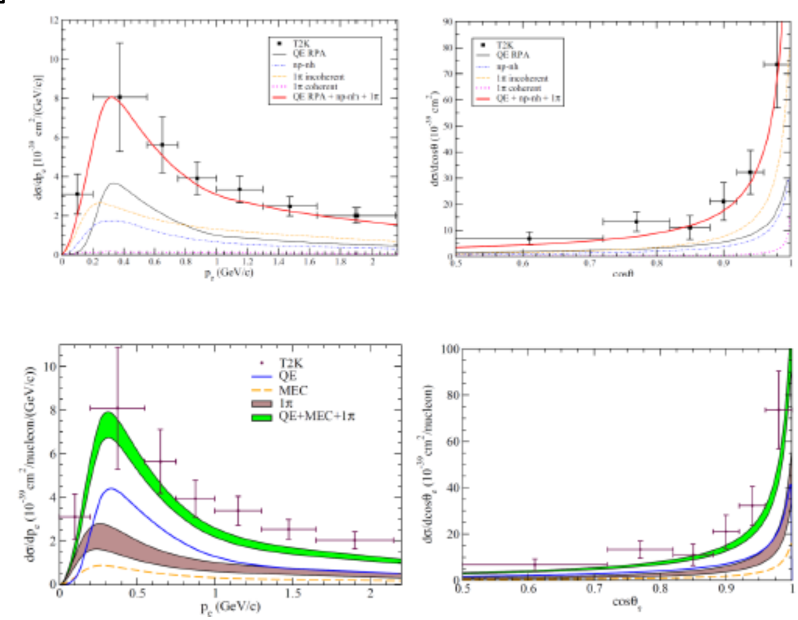
Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K ν_μCC data
- The model also explain T2K ν_eCC data

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



Martini model & SuSAv2MEC vs. T2K electron neutrino CCdifferential cross-section data



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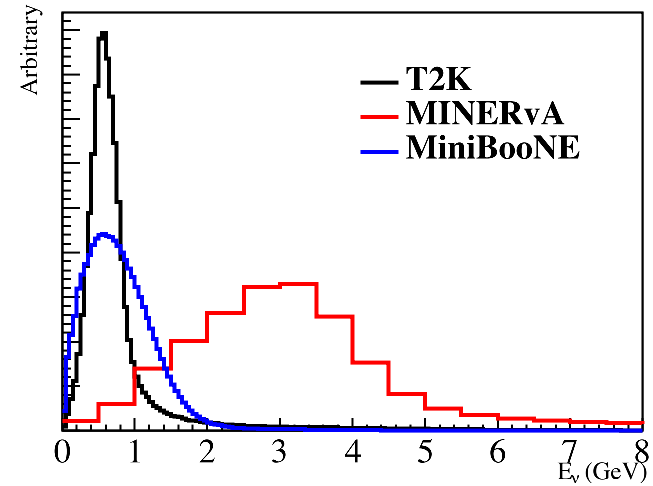
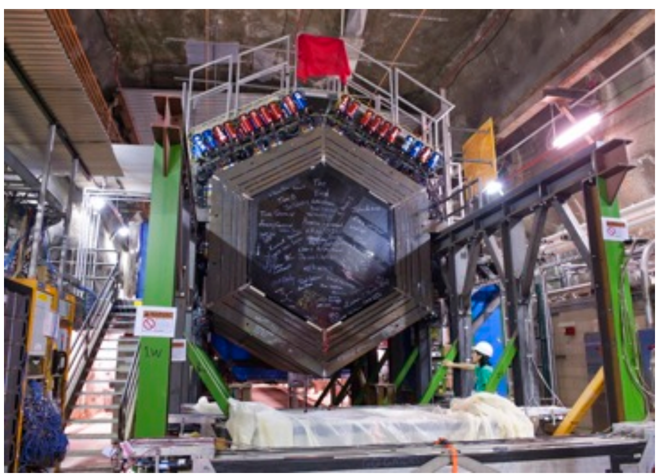
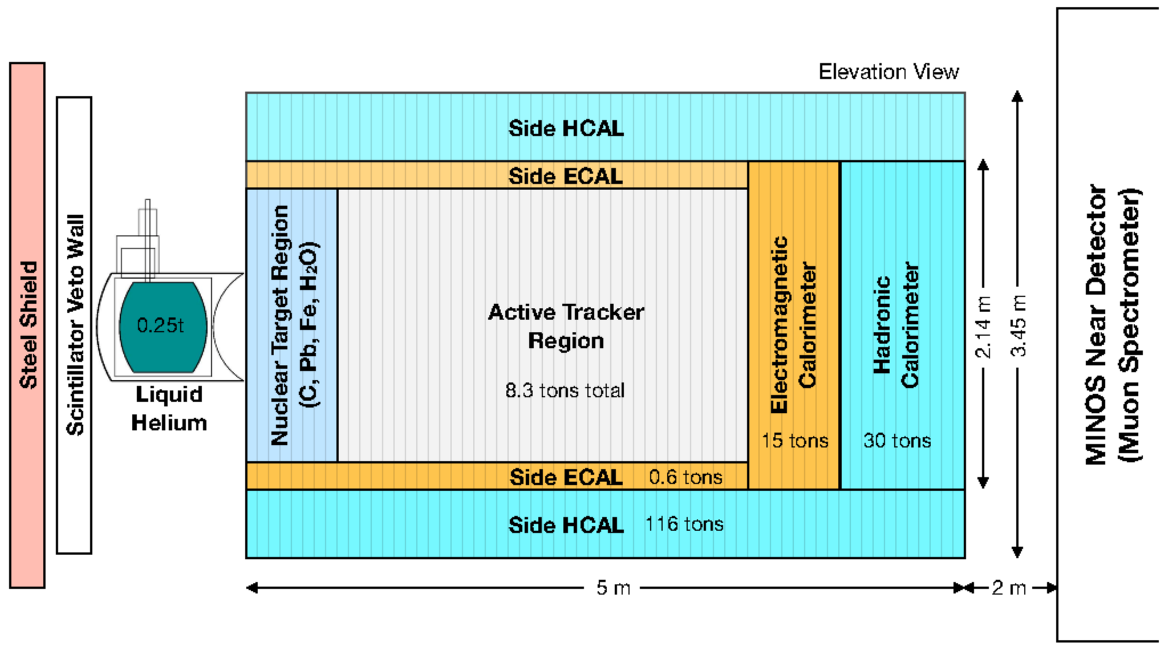


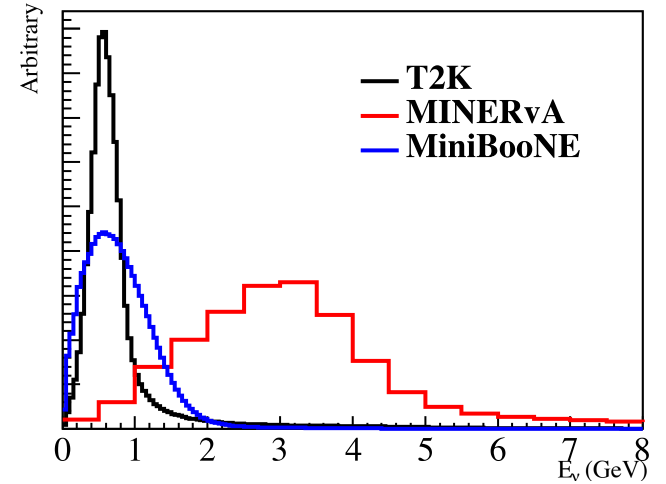
Scintillation tracker

- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)





4. MINERvA



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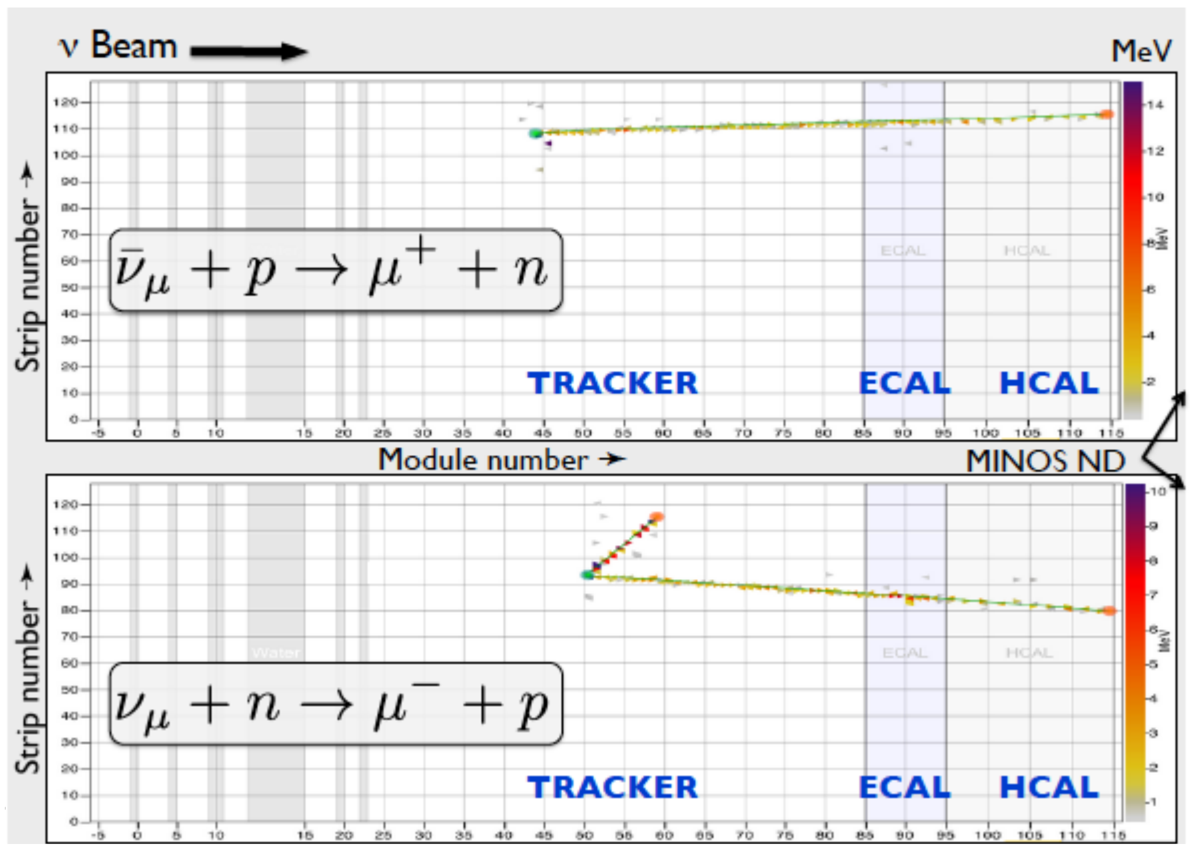

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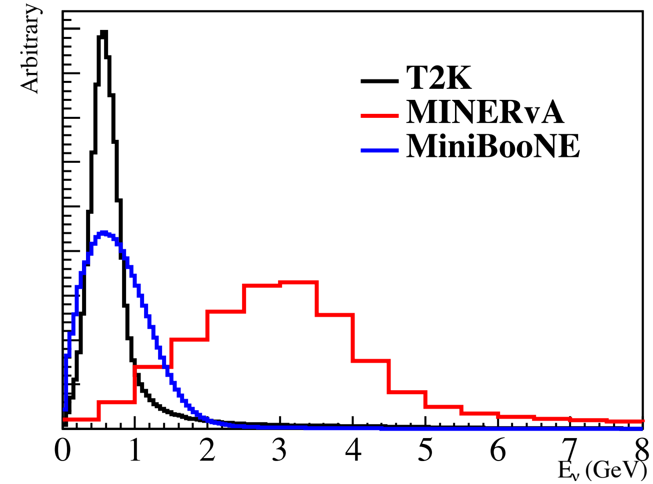
MINERvA, PRL116(2016)071802

4. MINERvA



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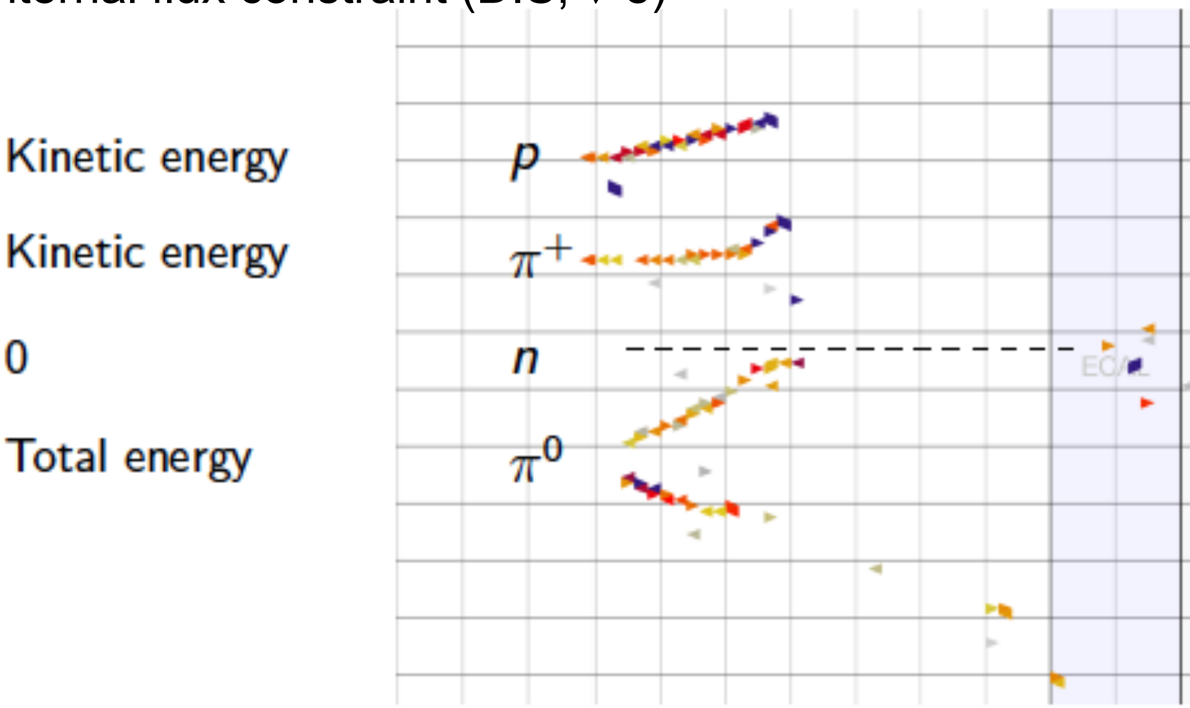


Beam test + better(?) scintillator
→ good hadron measurement
→ kinematics is completely fixed

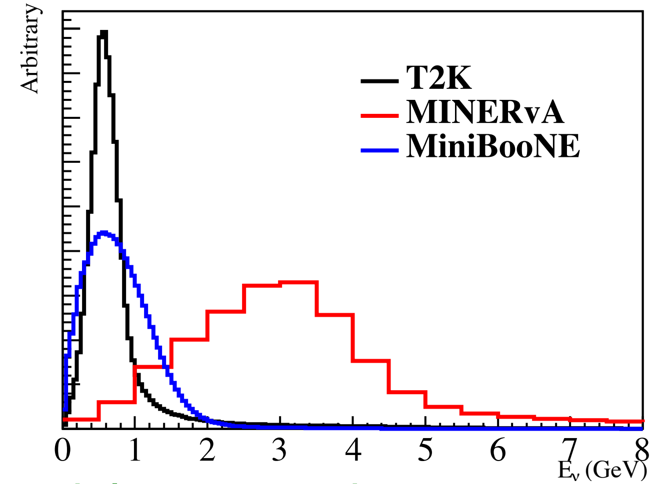
model-dependent

visible hadron energy
↓
total hadron energy
↓
Eν
↓
Q2

On average, we see *available* hadronic energy $E_{\rm avail} \neq q_0$:

$$E_{\rm avail} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

4. MINERvA



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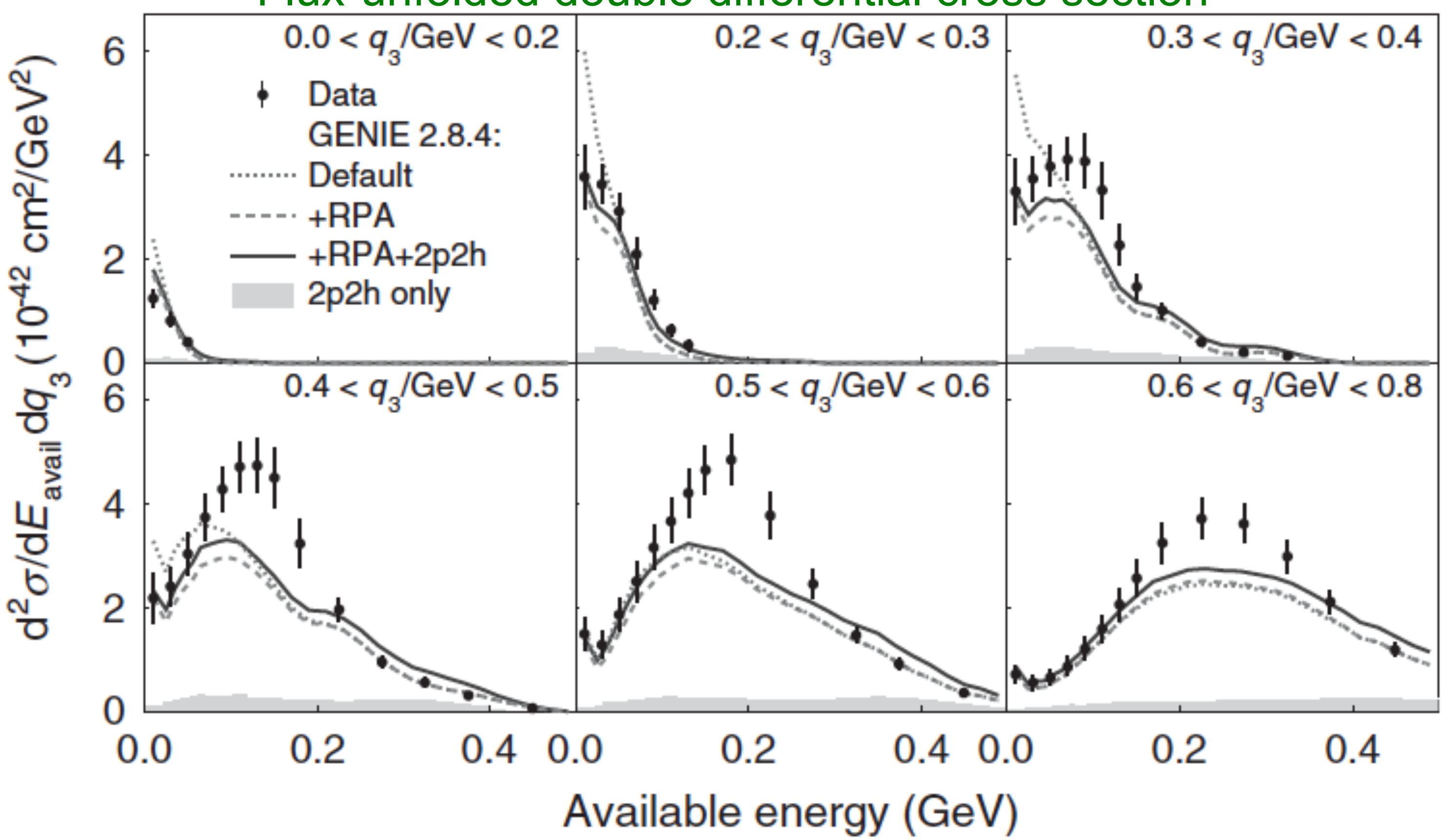
- internal flux constraint (DIS, ν-e)

Flux-unfolded double differential cross section

Directly comparable with nuclear theories



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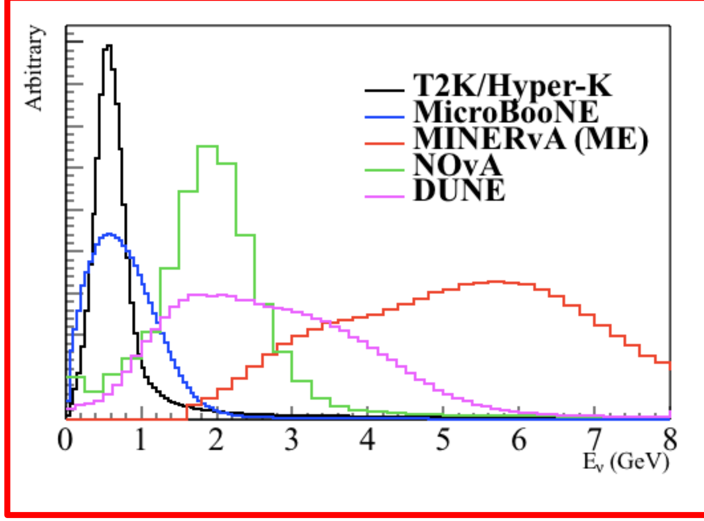
MINERvA,PRD94(2016)052005
Rodrigues et al.,EPJC76(2016)474

4. Pion puzzle

After CCQE puzzle, pion puzzle is the next biggest problem…

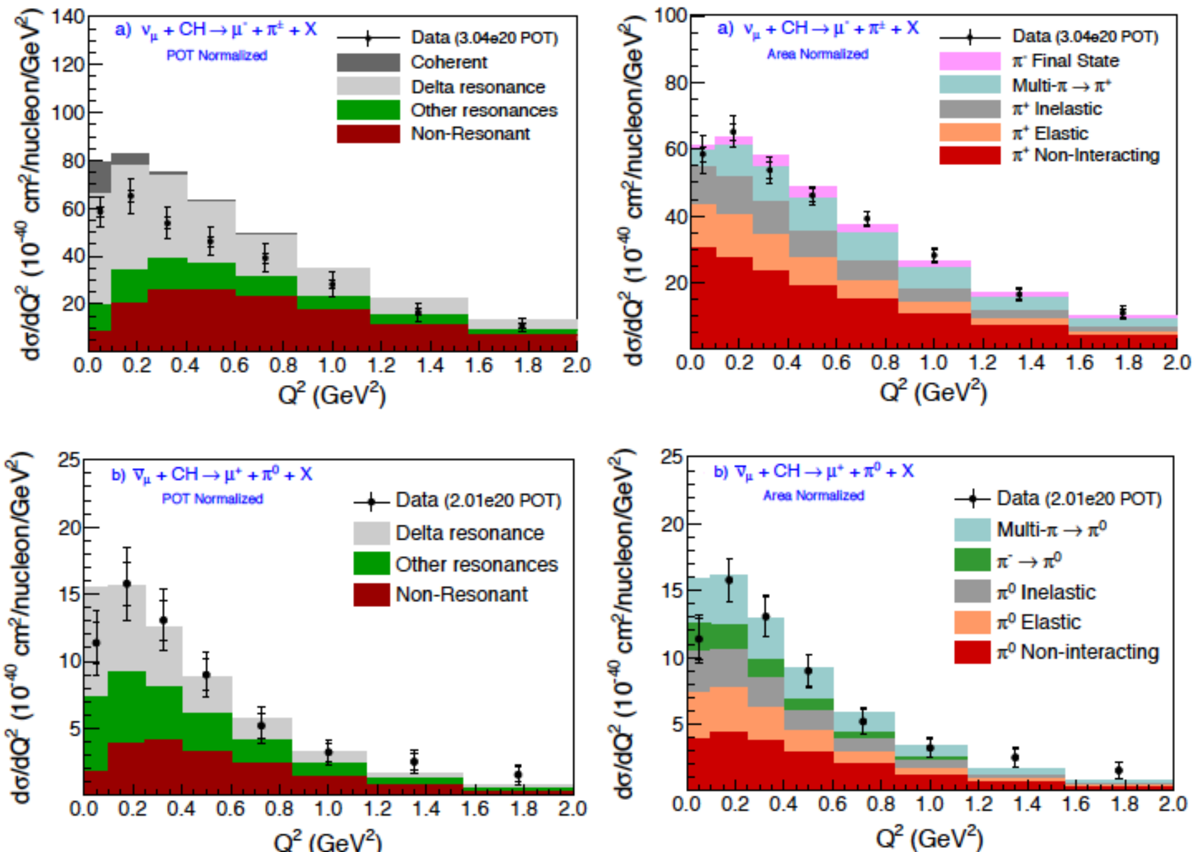


MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu} CC1\pi^o$

- $\nu_\mu CC1\pi^+$ has shape, $\overline{\nu_\mu} CC1\pi^o$ has norm agreement with MC

→ hard to improve data-MC by tuning within GENIE

For future oscillation experiments, we need more sophisticated neutrino baryon resonance (c.f., DDC model by Nakamura et al, next talk).



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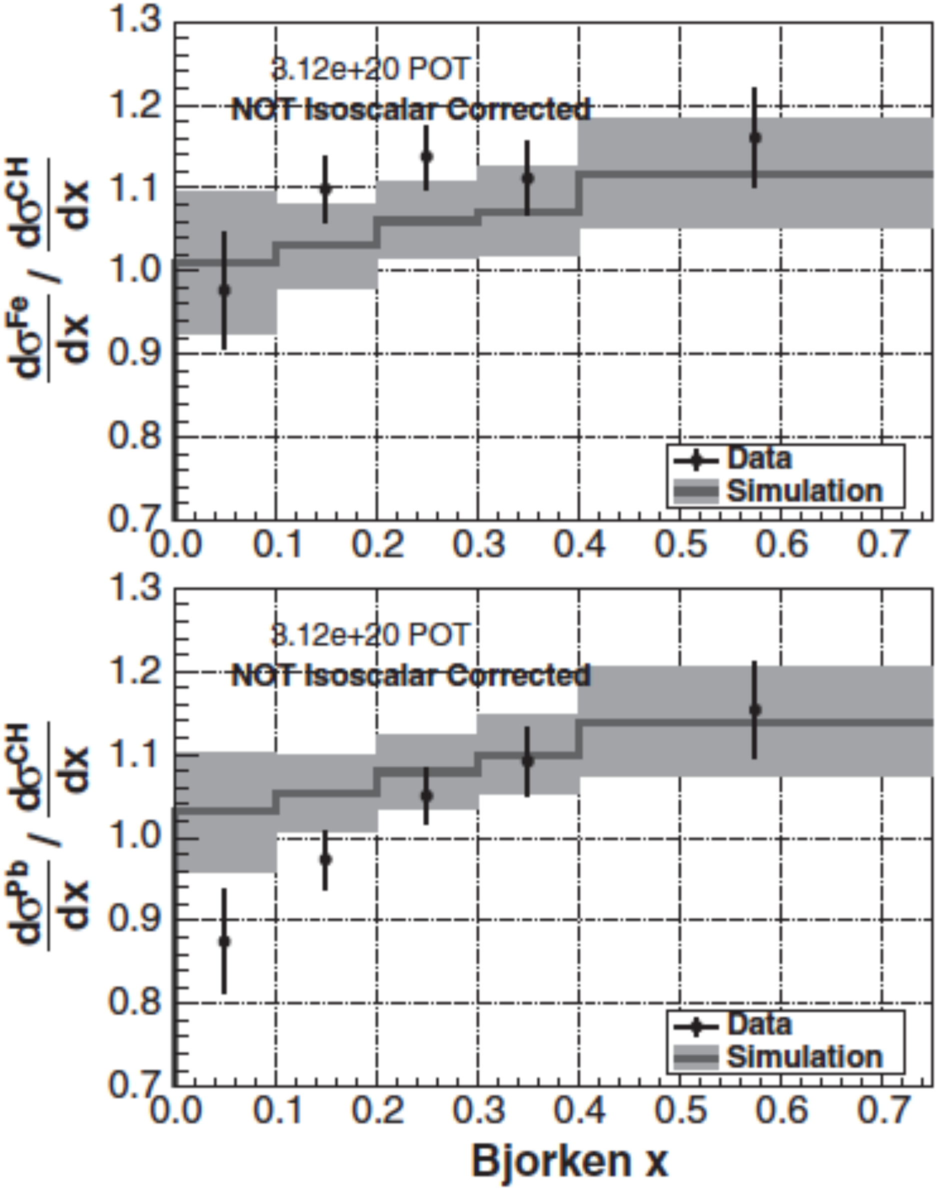
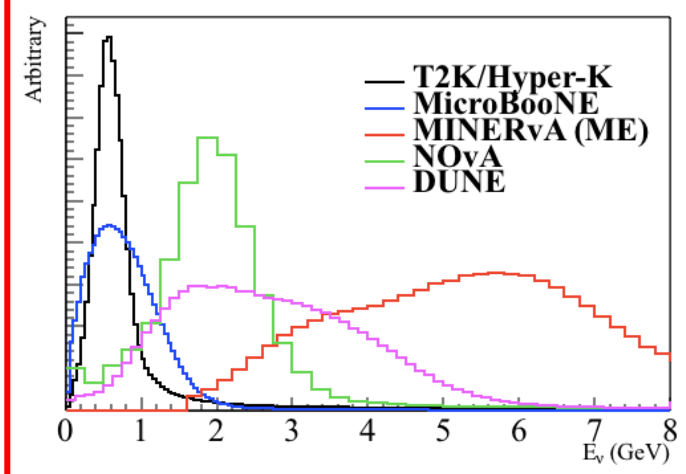
MINERvA,PRD93(2016)071101

4. Nuclear dependent DIS





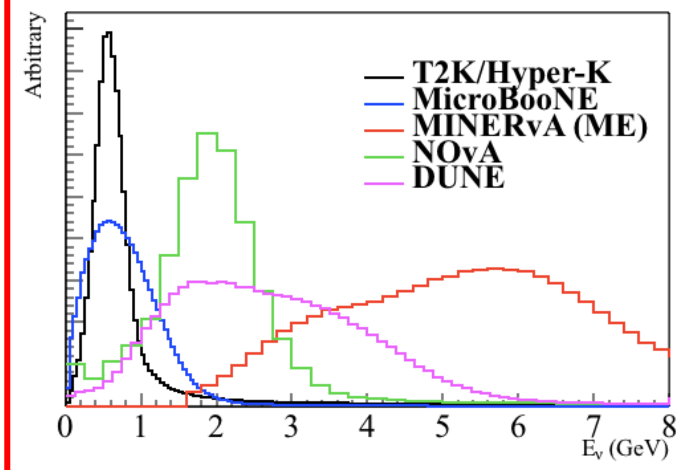
MINERvA DIS target ratio

- DIS event has non-trivial nuclear dependence (nuclear dependent PDF). Currently, neutrino DIS interaction for heavy elements are not predictable

For future oscillation experiments, we need to include nuclear effect on DIS (c.f., Kumano et al, next talk).

AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

4. Shallow Inelastic Scattering (SIS)



Both cross section and hadronization process has transitions

Cross section

$W^2<2.9$ GeV^2 : RES

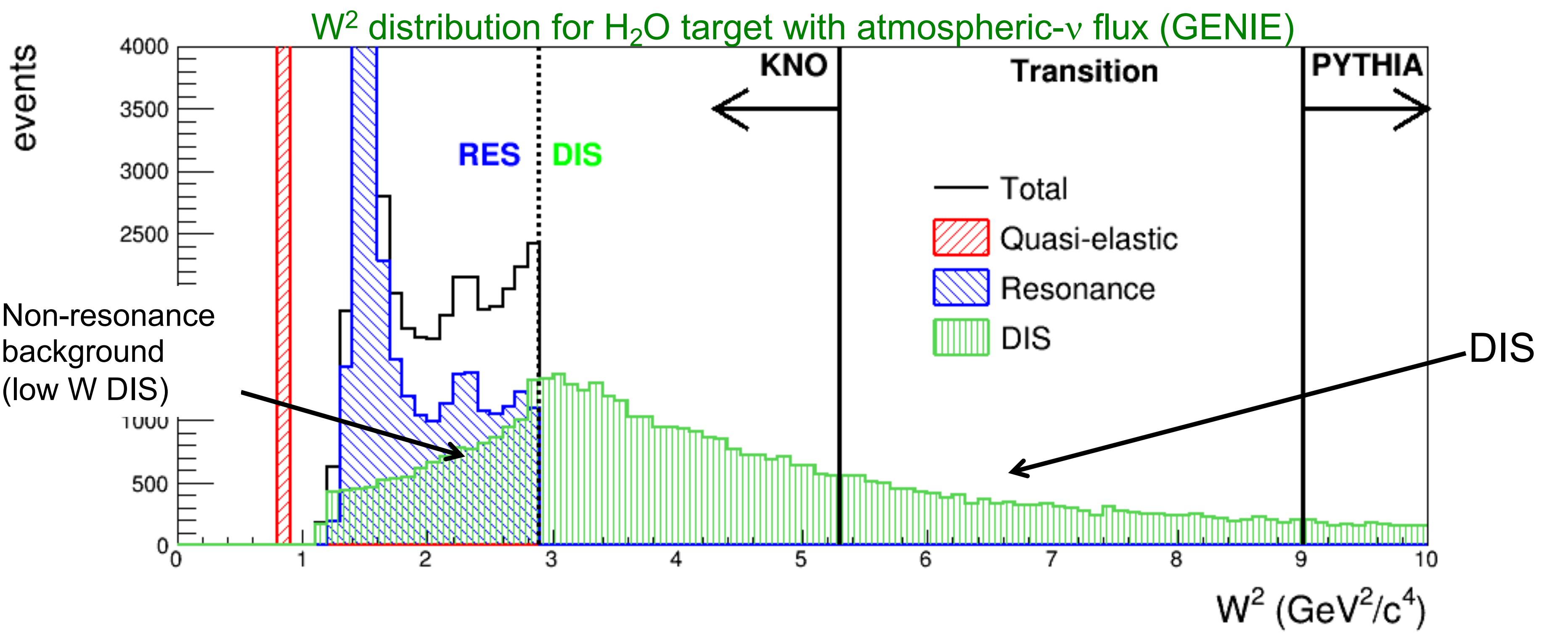
$W^2>2.9$ GeV^2 : DIS

Hadronization (GENIE-AGKY model)

$W^2<5.3$GeV^2 : KNO scaling based model

2.3GeV^2<W^2<9.0GeV^2 : transition

9.0GeV^2<W^2 : PYTHIA6



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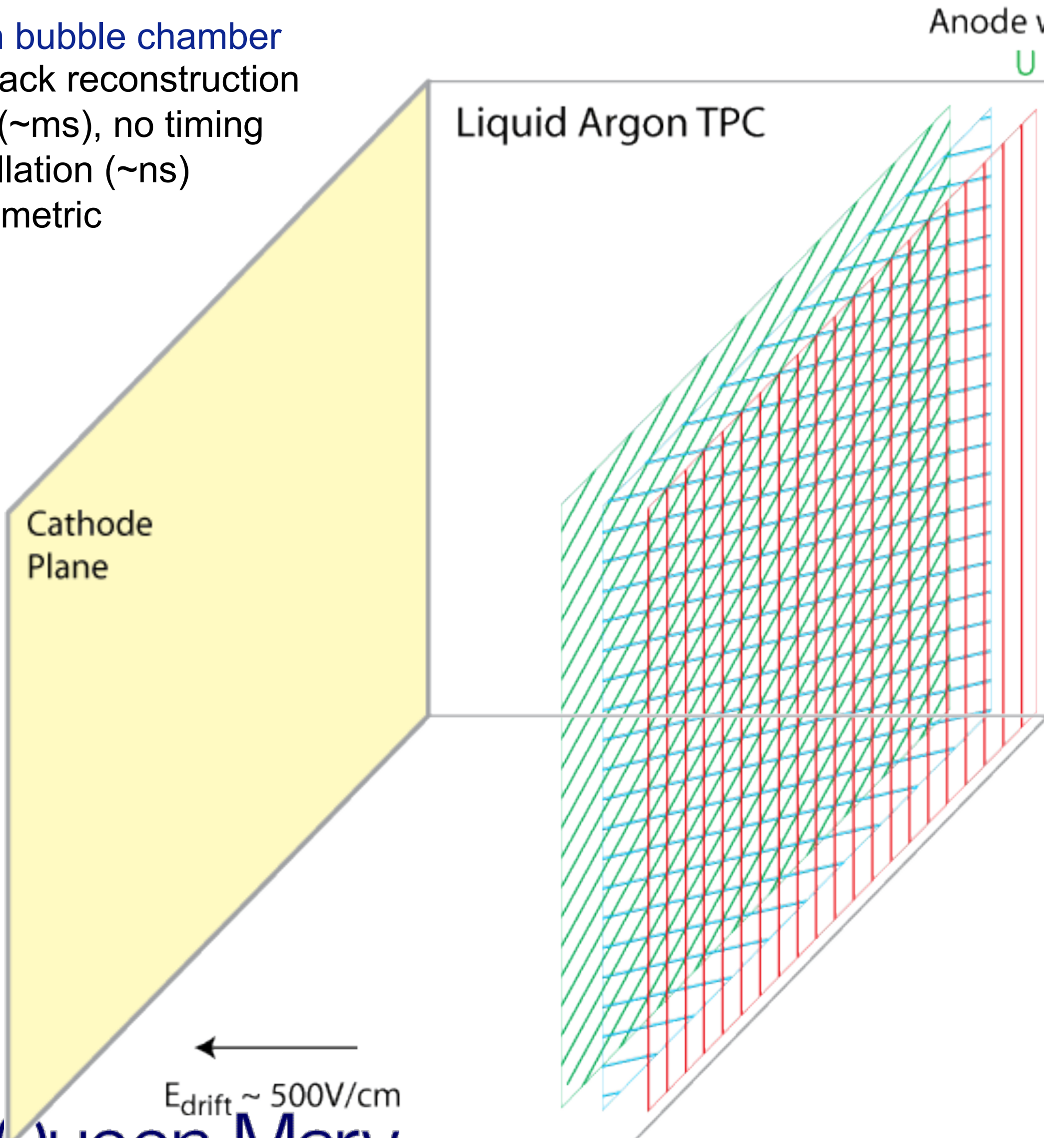
5. LArTPC

Modern bubble chamber

- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric



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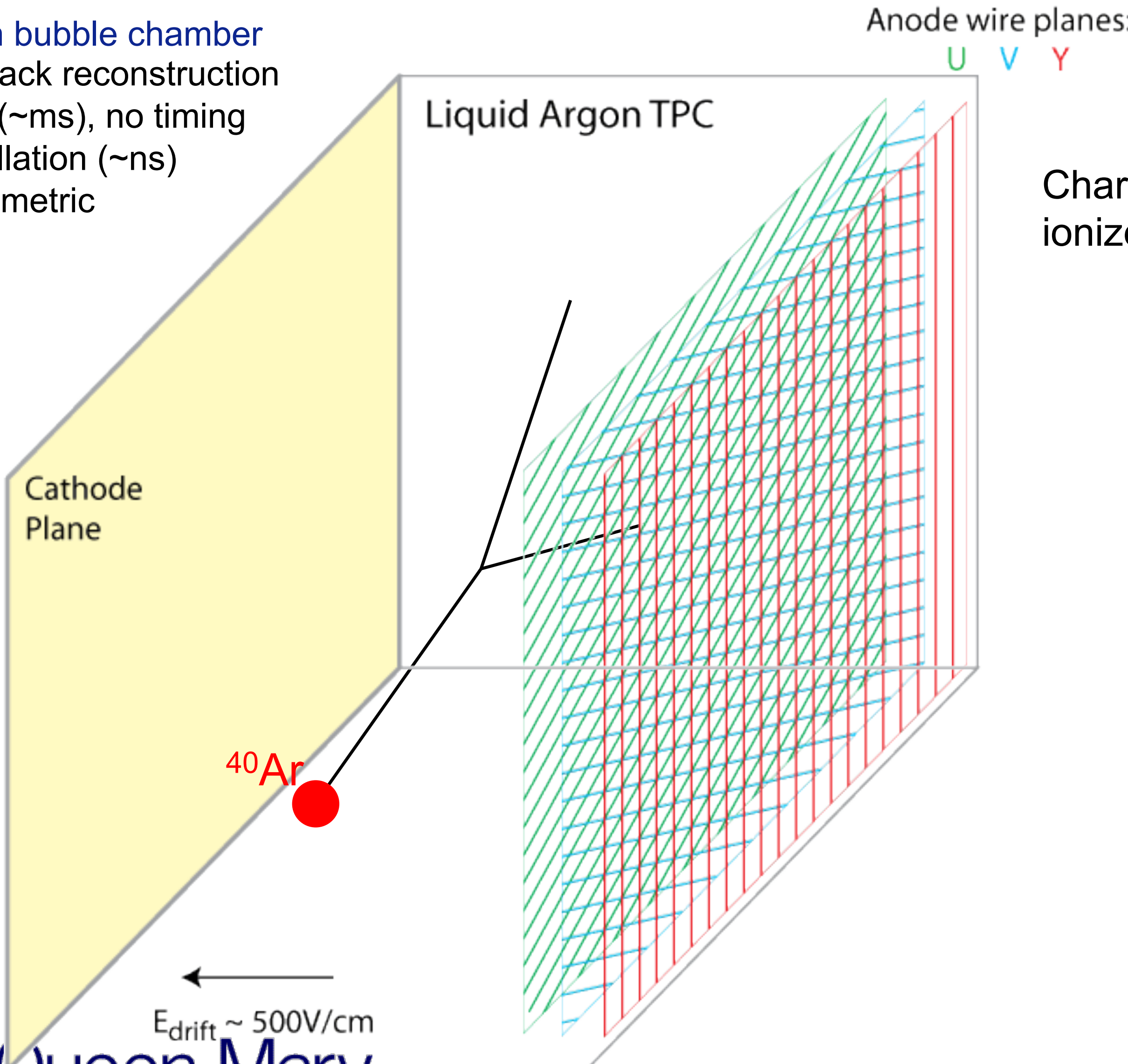

Charged particle tracks ionize Argon atoms

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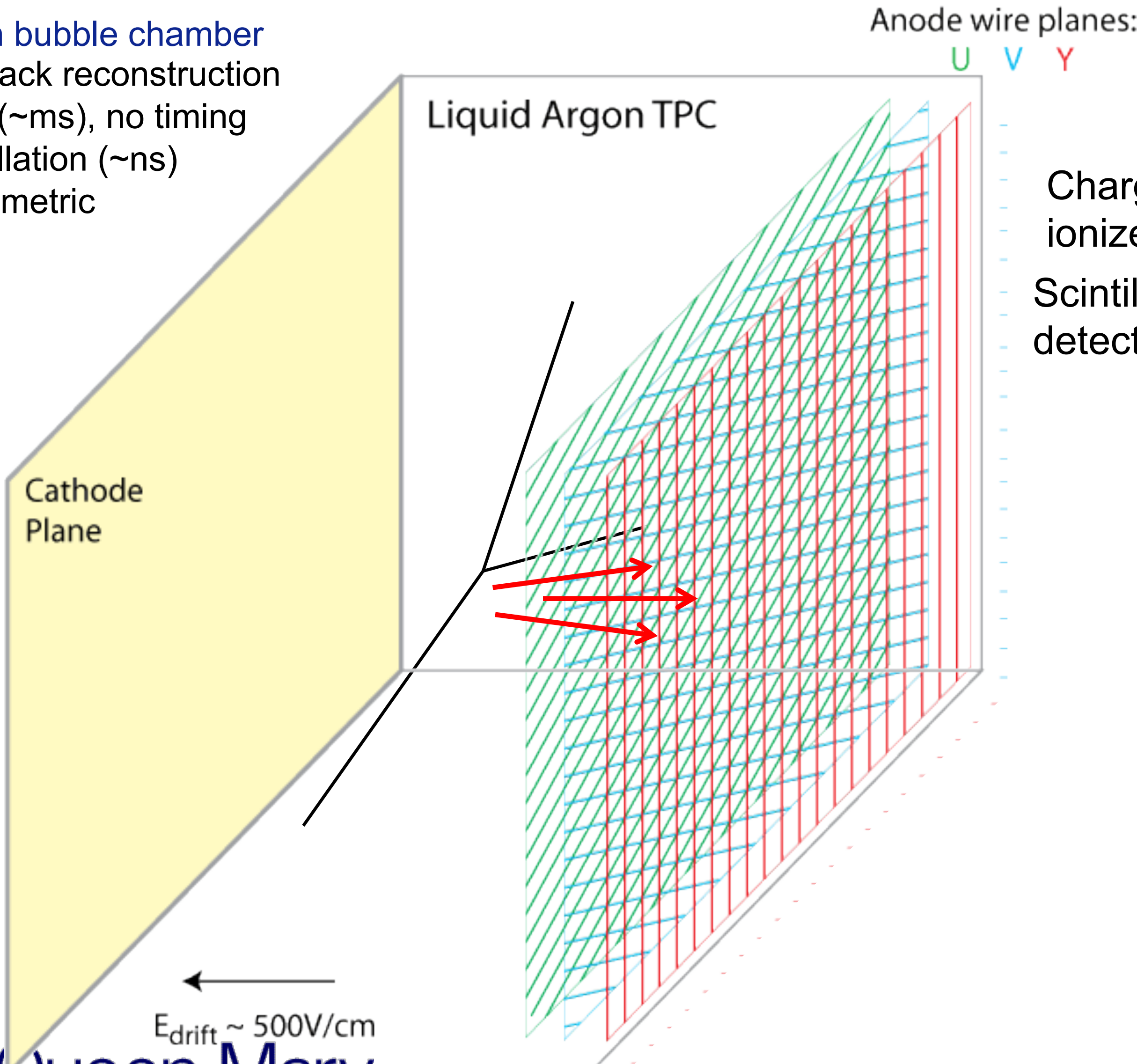
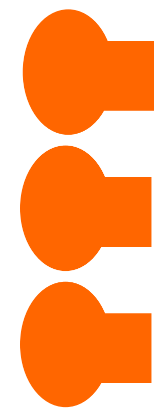


Charged particle tracks ionize Argon atoms

Scintillation light (~ns) is detected by PMTs at same time



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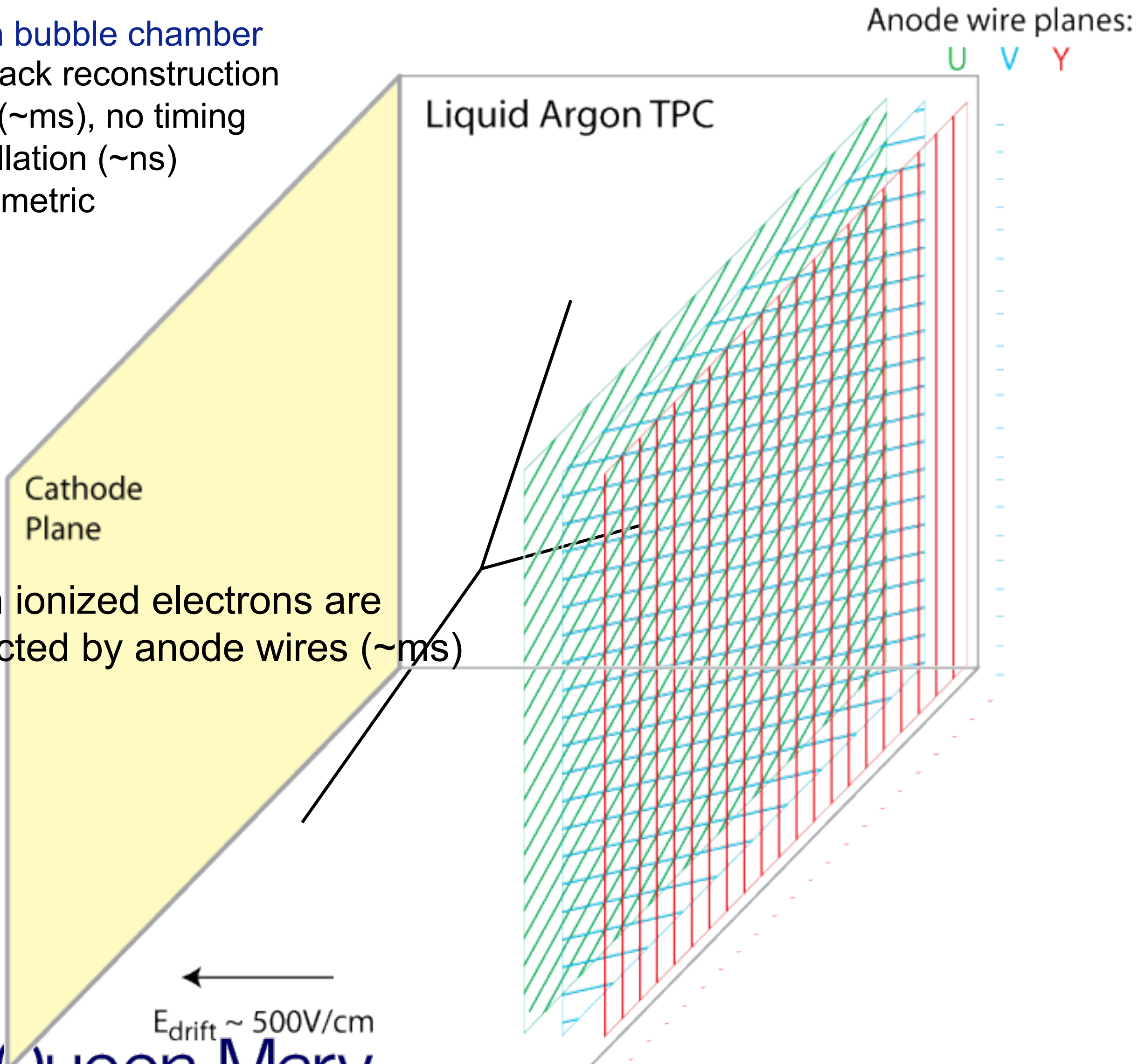


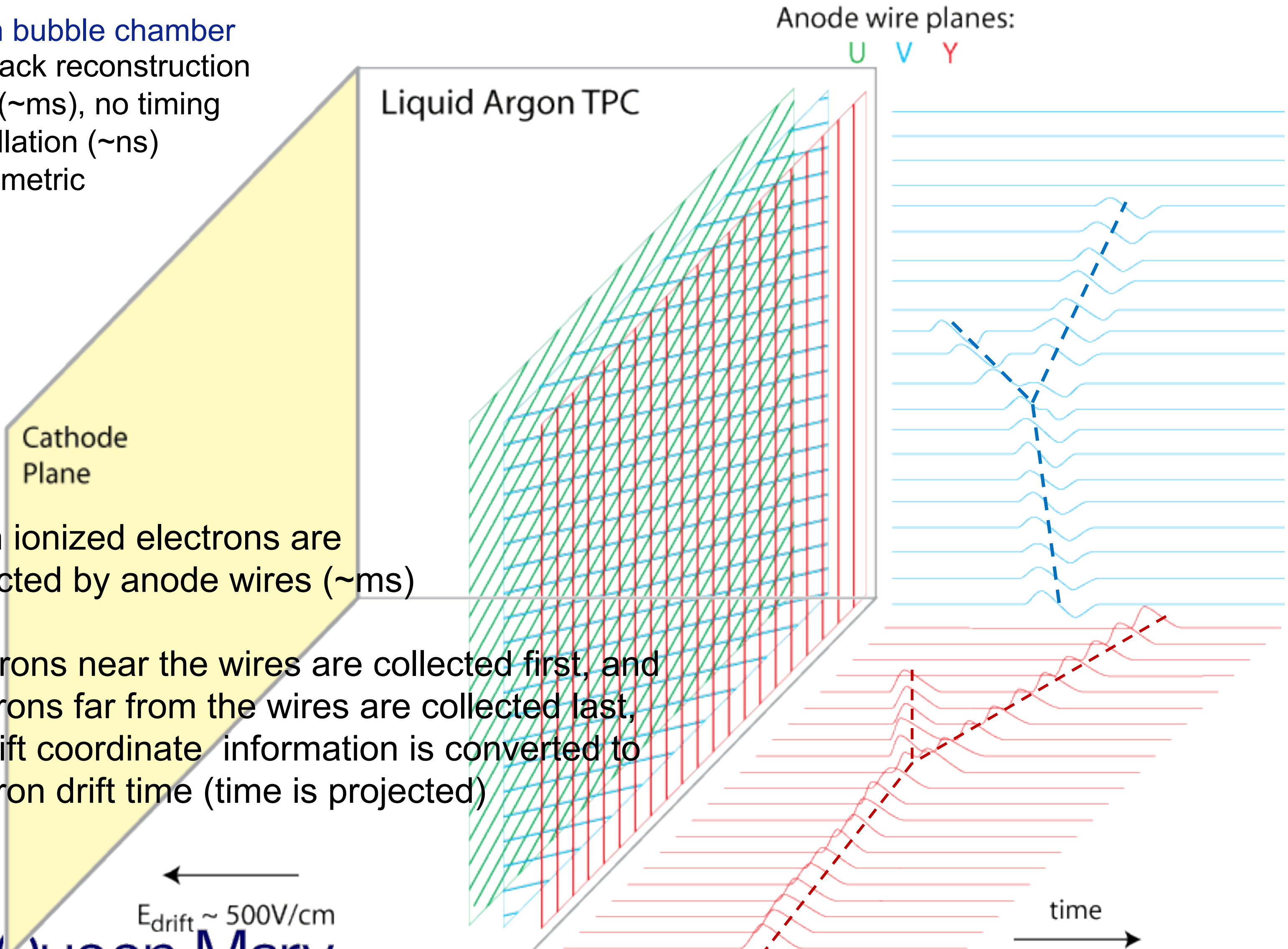
Then ionized electrons are collected by anode wires (~ms)

5. LArTPC

Modern bubble chamber
- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric

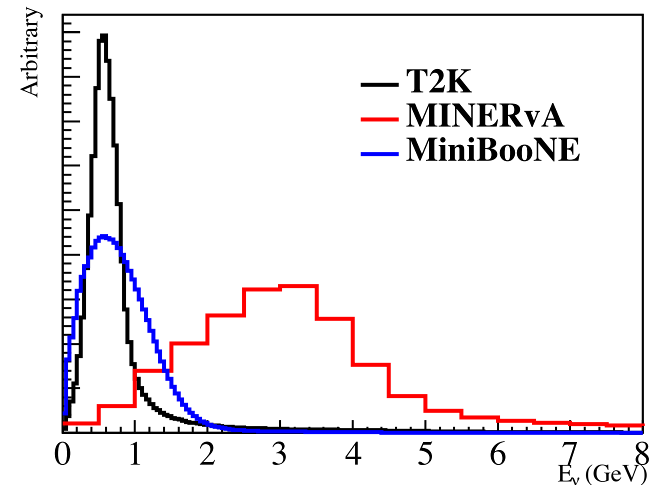
Then ionized electrons are collected by anode wires (~ms)

Electrons near the wires are collected first, and electrons far from the wires are collected last, so drift coordinate information is converted to electron drift time (time is projected)



ArgoNeuT,PRD90(2014)012008

5. ArgoNeuT

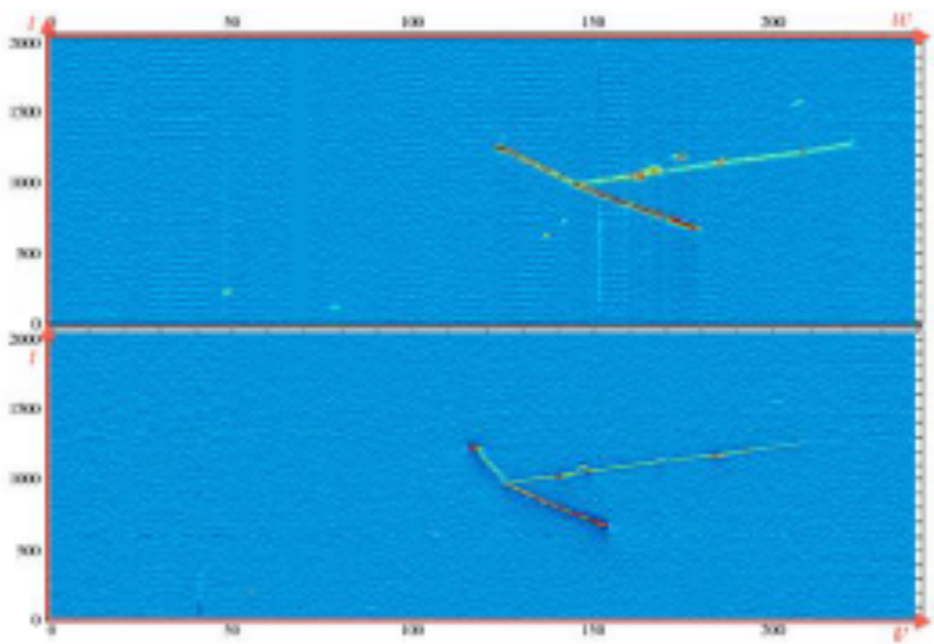


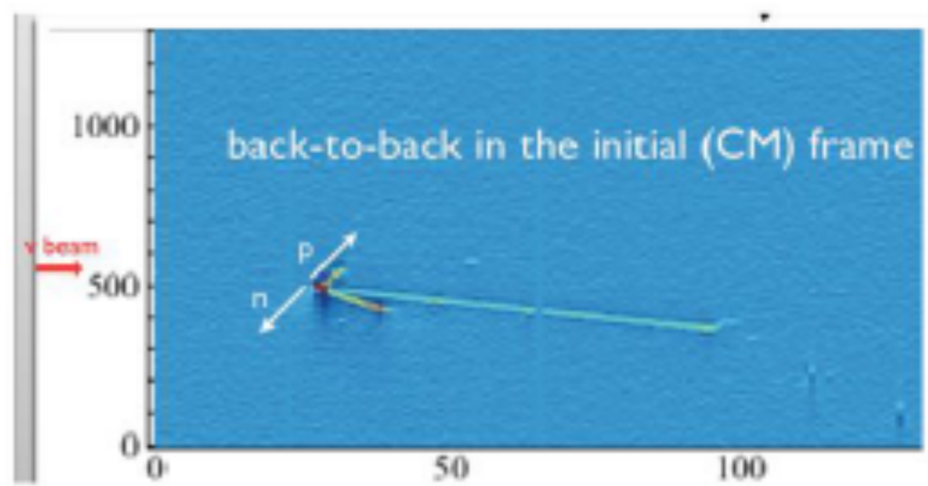
0.25ton LArTPC

- <E>~3.5 GeV NuMI on-axis beam
- Single phase LArTPC, 2-wire-plane reading
- 4mm pitch

ArgoNeuT "hammer" events

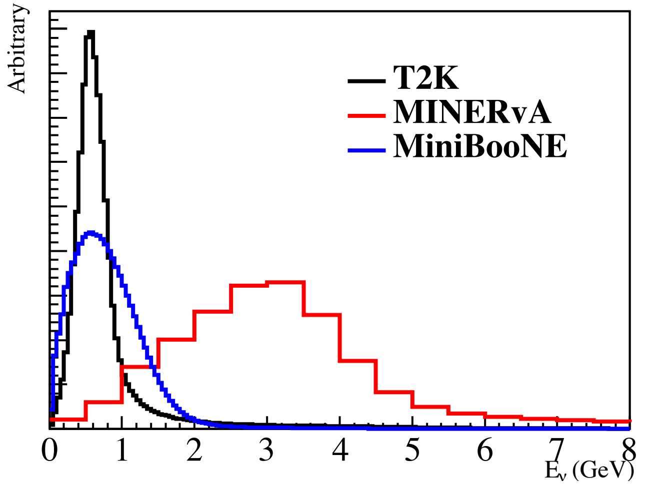
→ candidate topology of NNSRC from ν_μ+(np)→μ+p+p





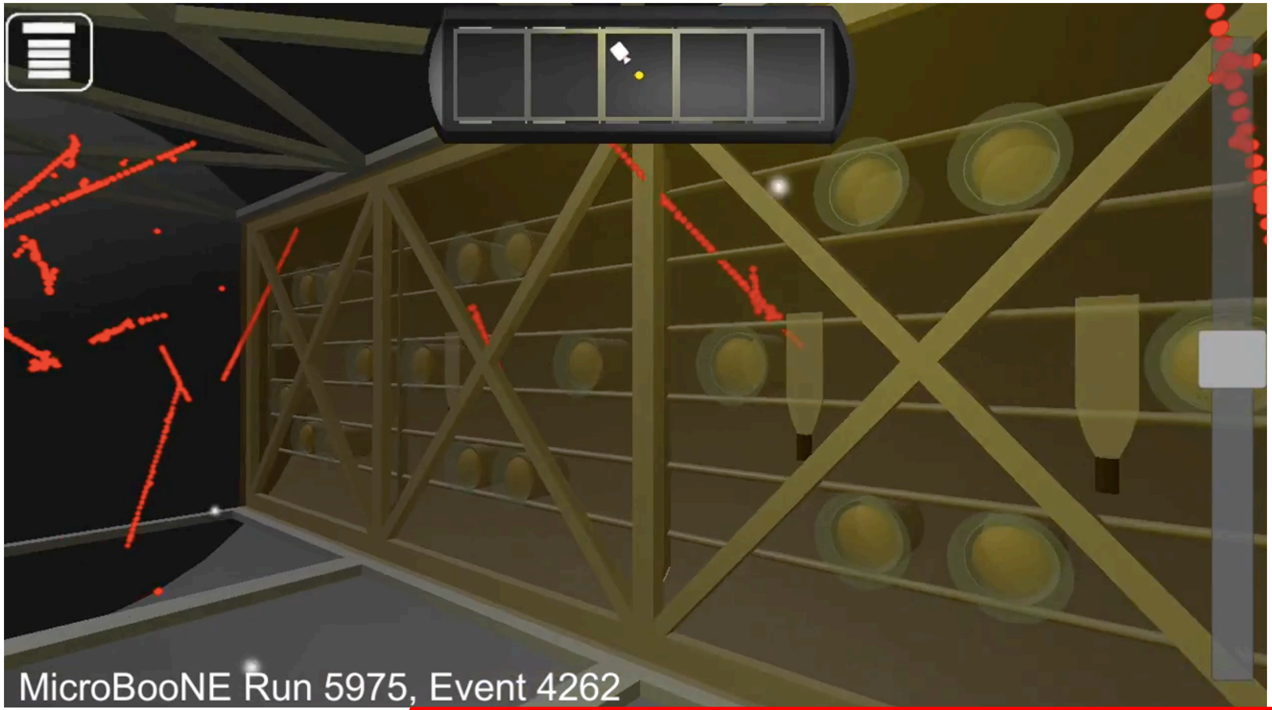
MicroBooNE,arXiv:1612.05824
VENu, http://venu.physics.ox.ac.uk/

5. MicroBooNE



86ton LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system



VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app to take a look MicroBooNE data

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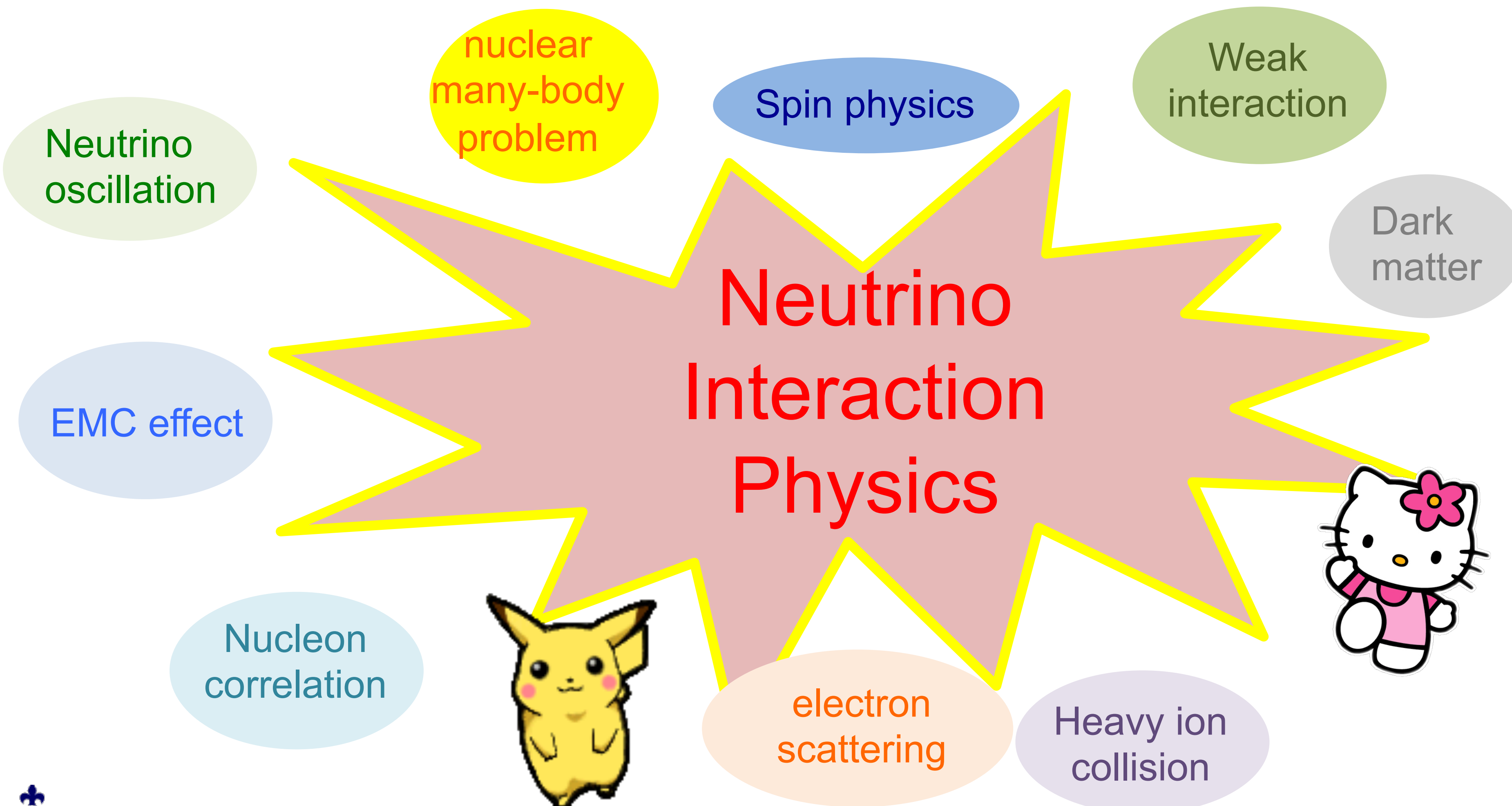
6. Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…



NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

NuSTEC promotes the collaboration and coordinates efforts between
- theorists, to study neutrino interaction problems
- experimentalists, to understand nu-A and e-A scattering problems
- generator builders, to implement, validate, tune, maintain models

The main goal is to improve our understanding of neutrino interactions with nucleons and nuclei

1) NuSTEC Structure

- The Board
  - Present board:
    - » 25 members: experimentalists, theorists and generator developers

Luis Alvarez Ruso (Valencia), Mohammad Athar (Aligarh), Maria Barbaro (Torino), Omar Benhar (Rome), Steven Brice (Fermilab), Daniel Cherdack (Colorado), Steven Dytman (Pittsburgh), Richard Gran (Minnesota), Yoshinari Hayato (Tokyo), Natalie Jachowicz (Gent), Teppei Katori (London), Kendall Mahn (Michigan), Camillo Mariani (Virginia), Marco Martini (Paris), Mark Messier (Indiana), Jorge Morfin (Fermilab), Ornella Palamara (Fermilab), Gabriel Perdue (Fermilab), Roberto Petti (South Carolina), Makoto Sakuda (Okayama), Federico Sanchez (Barcelona), Toru Sato (Osaka), Rocco Schiavilla (JLab), Jan Sobczyk (Wroclaw), Geralyn Zeller (Fermilab)

NuSTEC school

NuSTEC
NuSTEC Training
in Neutrino-Nucleus Scattering Physics
Nov.8-14, 2015, Okayama, Japan

NuSTEC school, Okayama, Japan (Nov. 8-14, 2015)

- NuSTEC school is dedicated for students/postdocs to learn physics of neutrino interactions, both for theorists, and experimentalists

Lecture 1 Introduction to NuSTEC School, Importance of Neutrino Interactions from MeV to GeV energy region
(Electro-magnetic Structure of the nucleus, Electron/Neutrino Nucleus Elastic Scattering)
(M. Sakuda, Okayama U., Japan)

Lecture 2,4,7 (Sakuda) Neutrino Physics and Neutrino Interactions (L. Alvarez-Ruso, IFIC, Spain)

Lecture 3, 5 Basics of Nuclear theory (potential ,current, symmetry etc) (A. Lovato, ANL, USA)

Lecture 8 Nuclear effects in quasi-elastic scattering (S. K. Singh, AMU, India)

Lecture 6, 9 Water Cherenkov Detector and Neutrino Physics (Y. Koshio, Okayama U., Japan)

Lecture 11 Neutrino Oscillation Experiments (TBA)

Lecture 10 ,12 Pion production from nucleons and nuclei & Other Inelastic processes like strange particle production, eta production and associated particle production (M. Sajjad Athar, AMU, India)

Lecture 15 Deep Inelastic Scattering (M Sajjad Athar, AMU, India)

Lecture 13, 16 Liquid Argon Detector and Neutrino Interactions (F. Cavanna, Yale U., USA),

Lecture 14, 17 Generator (TBA)

Lecture 18 Liquid Scintillator Detector and KamLAND [Latest Result] (TBA)

Lecture 19 Reactor Experiment RENO and RENO-50 (S.B.Kim, Seoul Natl. U., South Korea)

Lecture 20 MiNERVA and Neutrino Interactions (J. Morfin,Fermi Lab, USA)

NuInt15, Osaka, Japan (Nov. 16-21, 2015)

Tremendous amount of activities, new data, new theories…

http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt15)

16-21 November 2015 *Icho-Kaikan, Osaka University Suita Campus*

NuInt15, Osaka, Japan (Nov. 16-21, 2015)

Tremendous amount of activities, new data, new theories…
http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

New data
1. MINERvA CC ω-q measurement
2. ν_eCC cross-section measurement from NOvA near detector
3. T2K CC0π double differential cross-sections
4. MINERvA QE-like double differential cross-sections
5. ArgoNeuT CC cross-sections with proton counting
6. Charge exchange and pion absorption cross section
7. CLAS pion production
8. DIS cross-section target ratio by MINERvA

and more…

10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt15)

16-21 November 2015 *Icho-Kaikan, Osaka University Suita Campus*

NuInt17, Toronto, Canada (June 25-30, 2017)

Now registration is open!

https://nuint2017.physics.utoronto.ca/

Conclusion

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Tremendous amount of activities, new data, new theories…
http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

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!

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5. Conclusion

electron scattering

nuclear many-body problem

Weak interaction

Neutrino oscillation

Neutrino Interaction Physics

EMC effect

Nucleon correlation

Spin physics

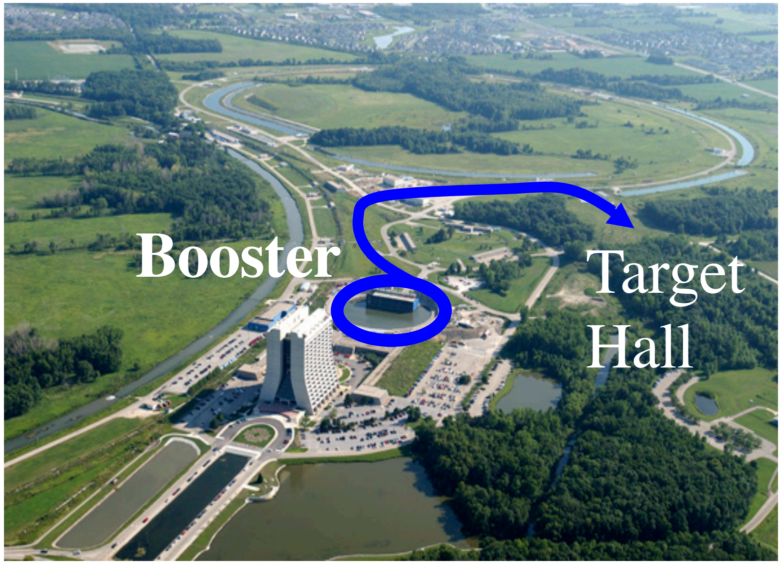
Dark matter

Heavy ion collision

Thank you for your attention!

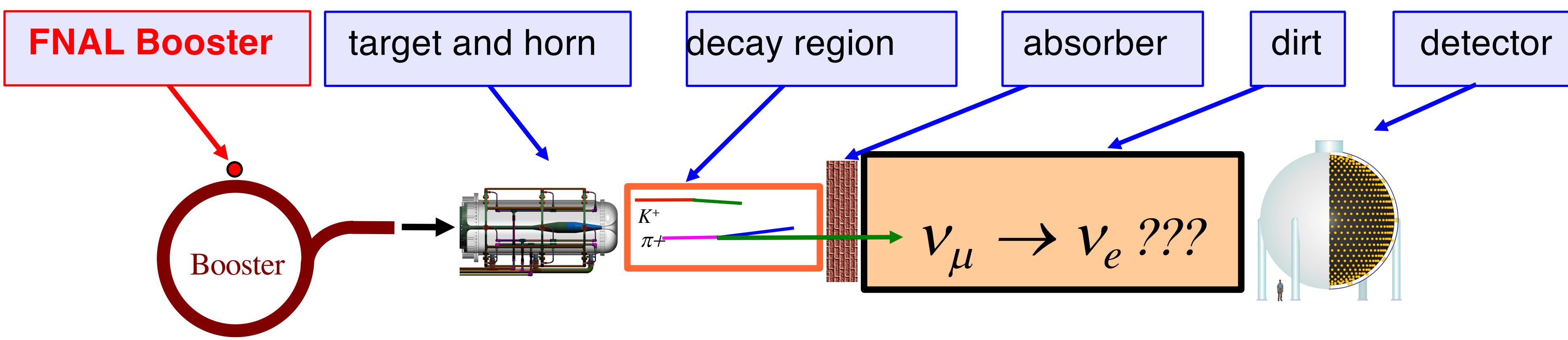
Backup

2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster

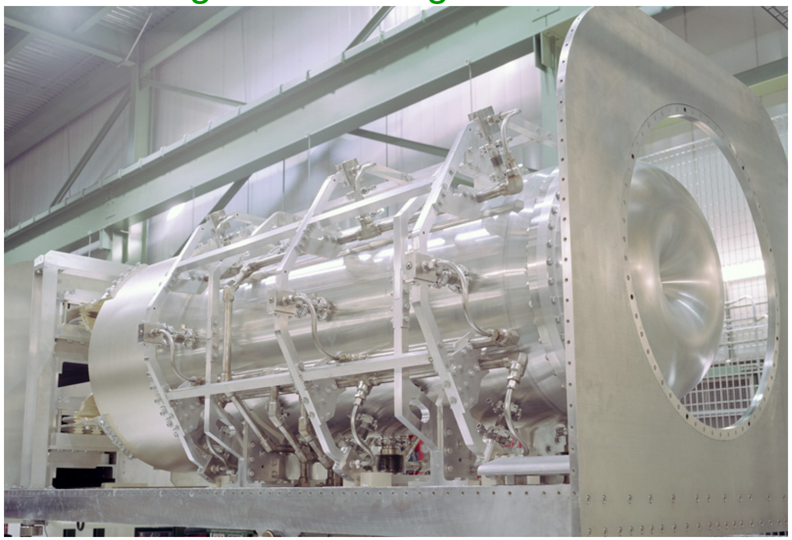
FNAL Booster



primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

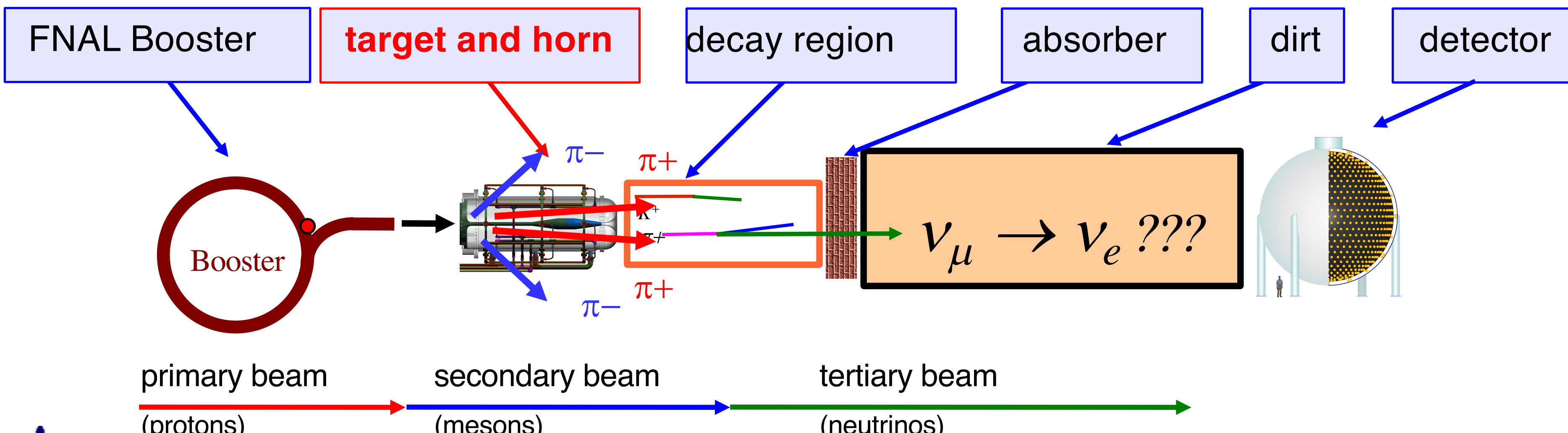
2. Neutrino beam

Magnetic focusing horn



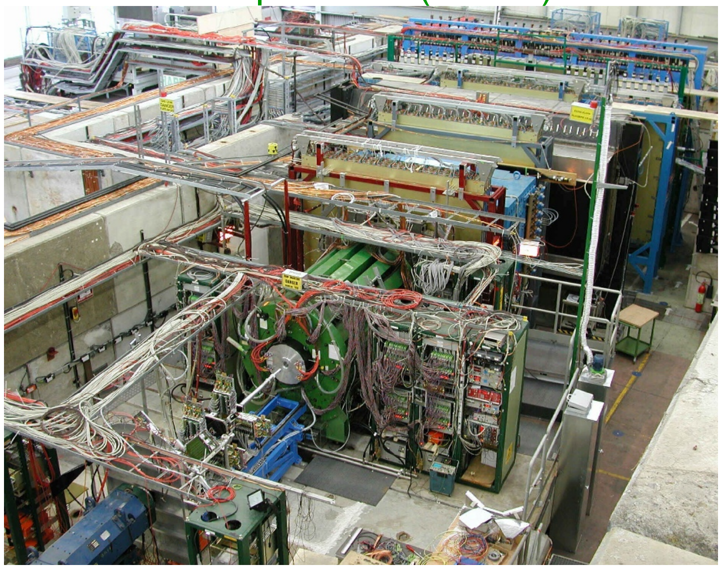
8GeV protons are delivered to a 1.7 λ Be target

within a magnetic horn (2.5 kV, 174 kA) that increases the flux by × 6



2. Neutrino beam

HARP experiment (CERN)

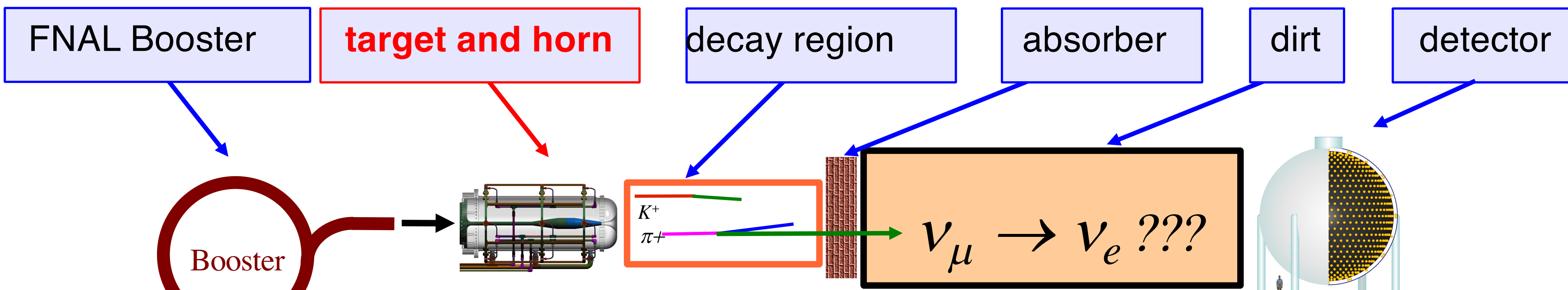


Modeling of meson production is based on the measurement done by HARP collaboration.

HARP collaboration, Eur.Phys.J.C52(2007)29

Thin target
- no re-scattering inside of the target

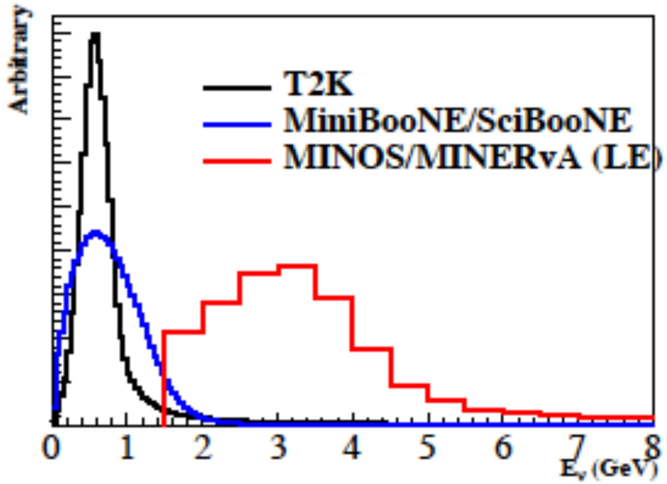
Thick target (replica target)
- data include re-scattering inside of the target

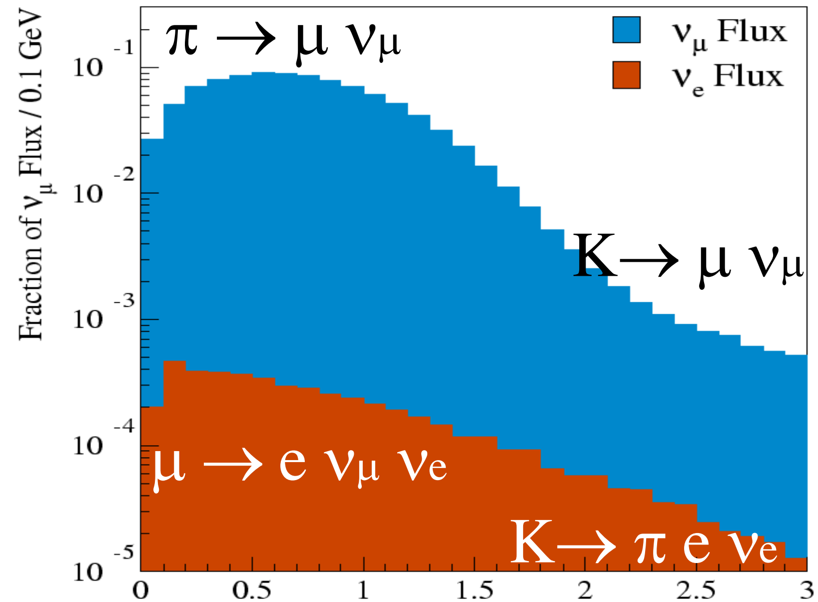


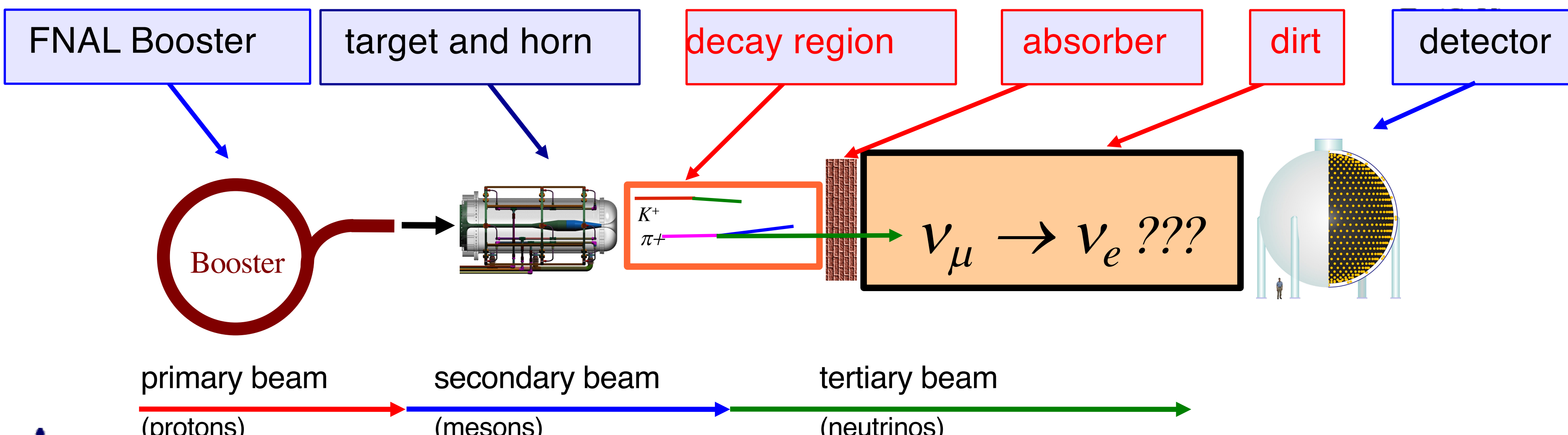
primary beam (protons) → secondary beam (mesons) → tertiary beam (neutrinos)

MiniBooNE, PRD79(2009)072002

2. Neutrino beam





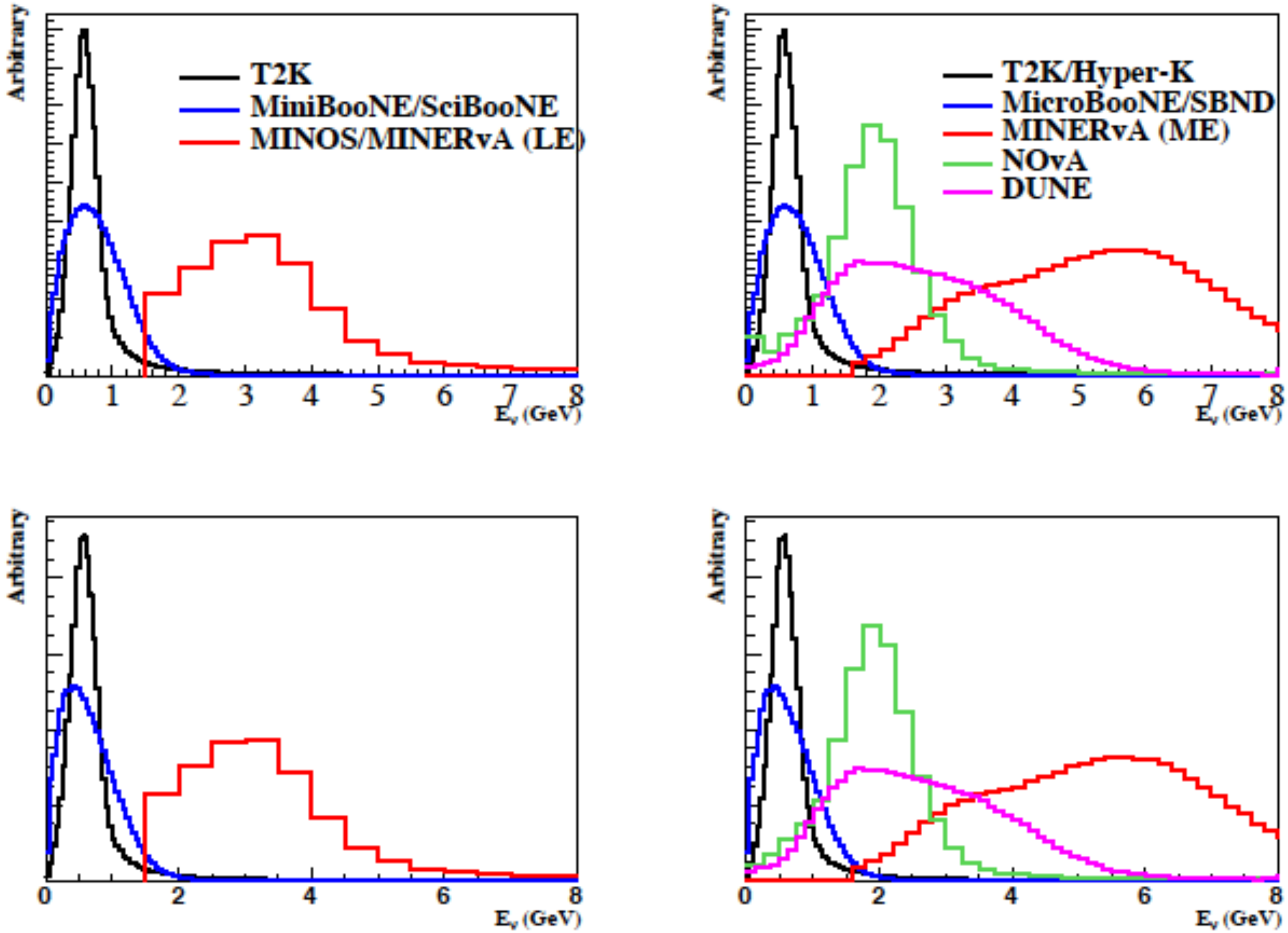


2. Type of neutrino beams

past | present to future

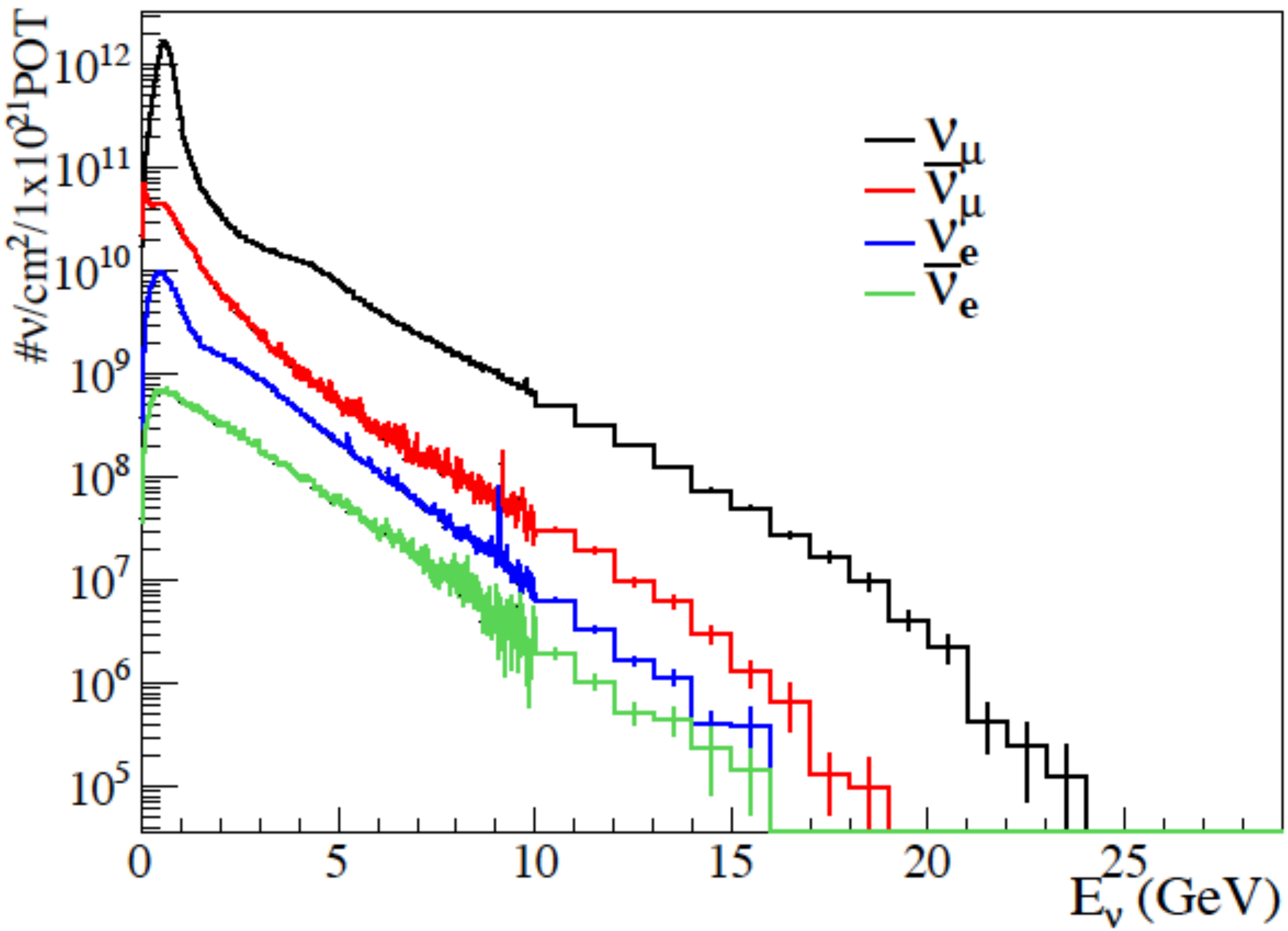
neutrino

anti-neutrino

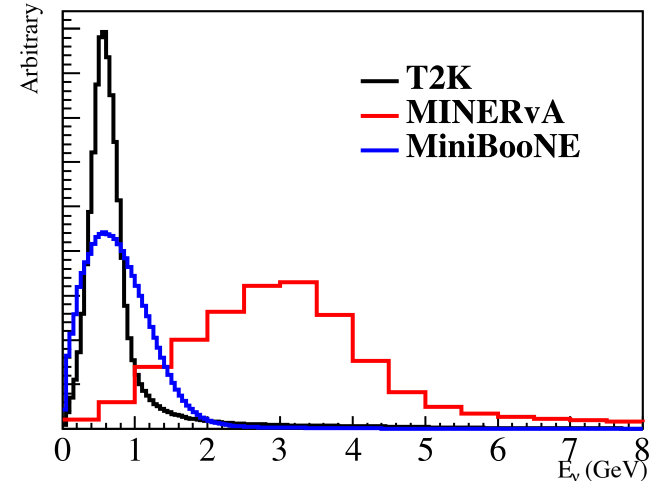


2. Type of neutrino beams

T2K neutrino mode beam



2. MiniBooNE

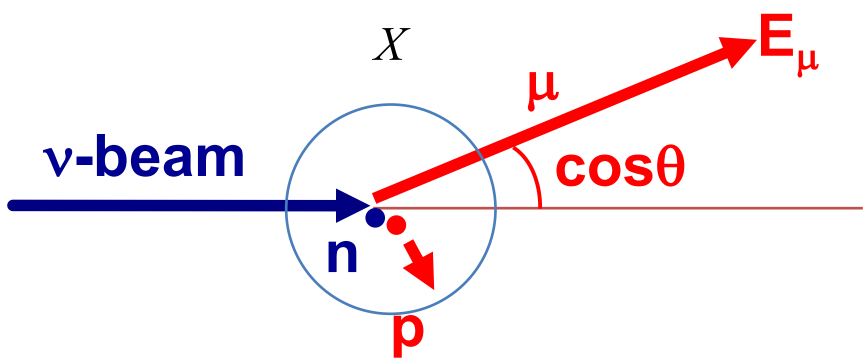


Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Highest amount of information of lepton kinematics
- Some calorimetric (scintillation)
- Large normalization error (10.7%)

MiniBooNE CCQE measurement

- muon energy and direction
- muon kinematics in 4π



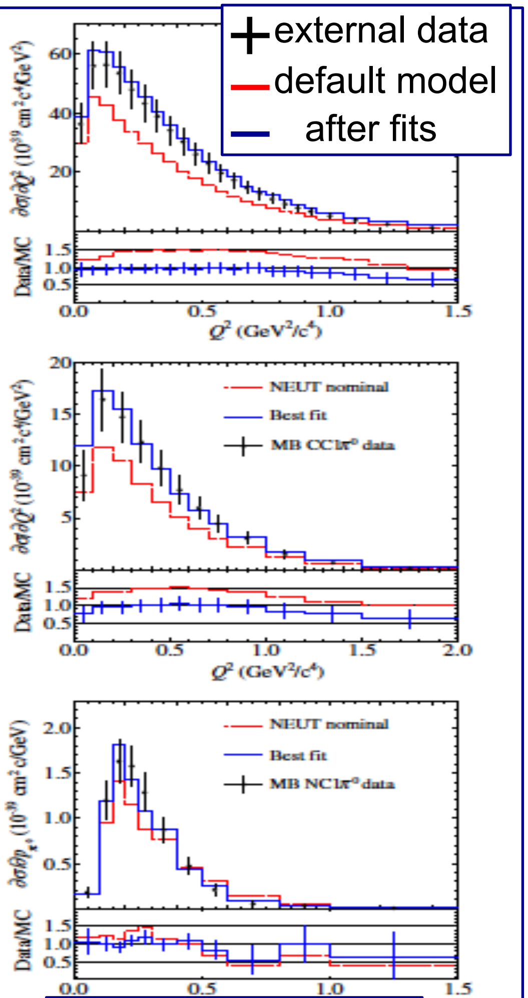
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

CCQE is the single most important channel of neutrino oscillation physics
T2K, NOvA, microBoonE, Hyper-Kamiokande, DUNE (2nd maximum)…etc

1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

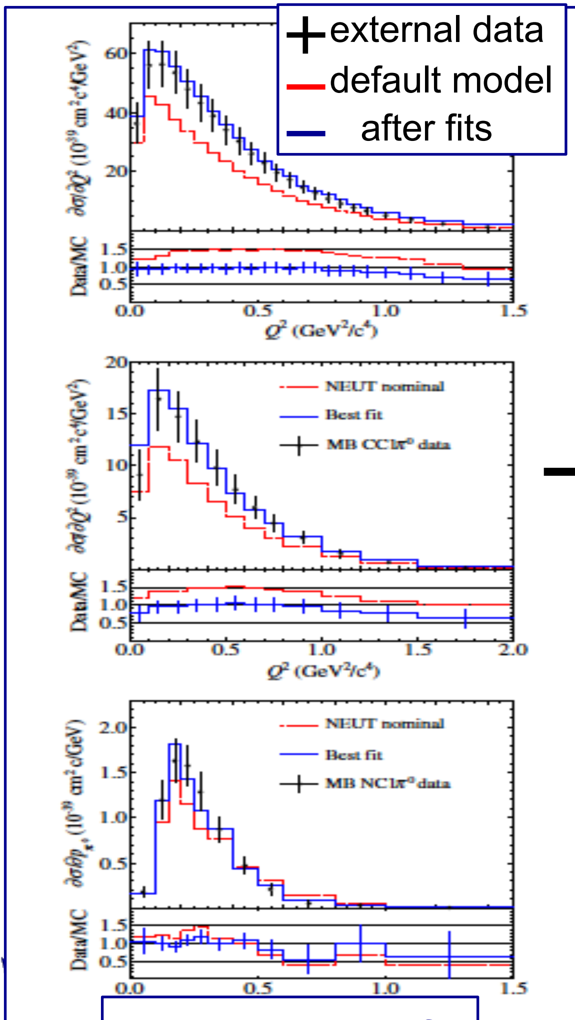
External data give initial guess of cross-section systematics

T2K, PRD88(2013)032002; PRL112(2014)061802

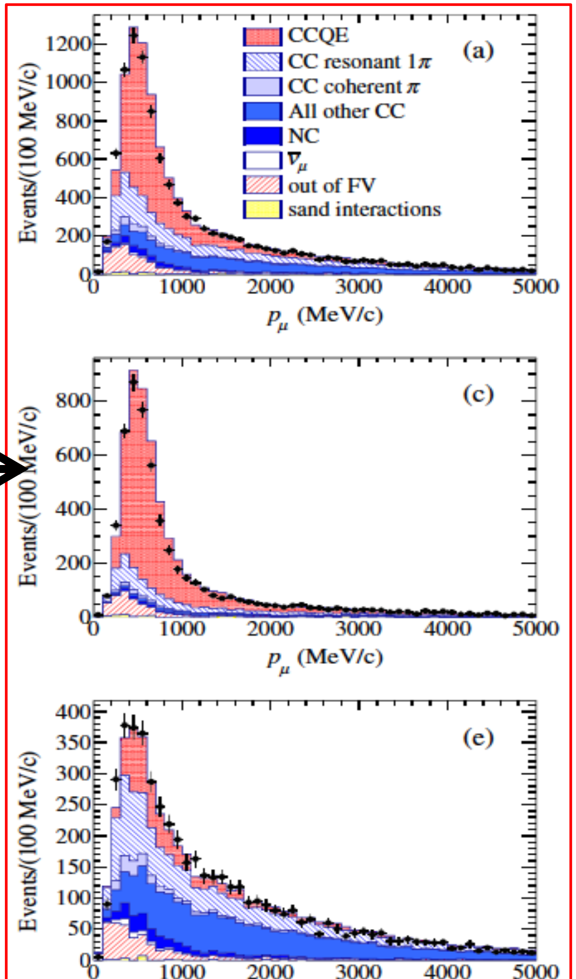
1. e.g.) T2K oscillation experiments

External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint
Near detector
oscillation non-sensitive channels



External data fit



T2K ND280 data fit

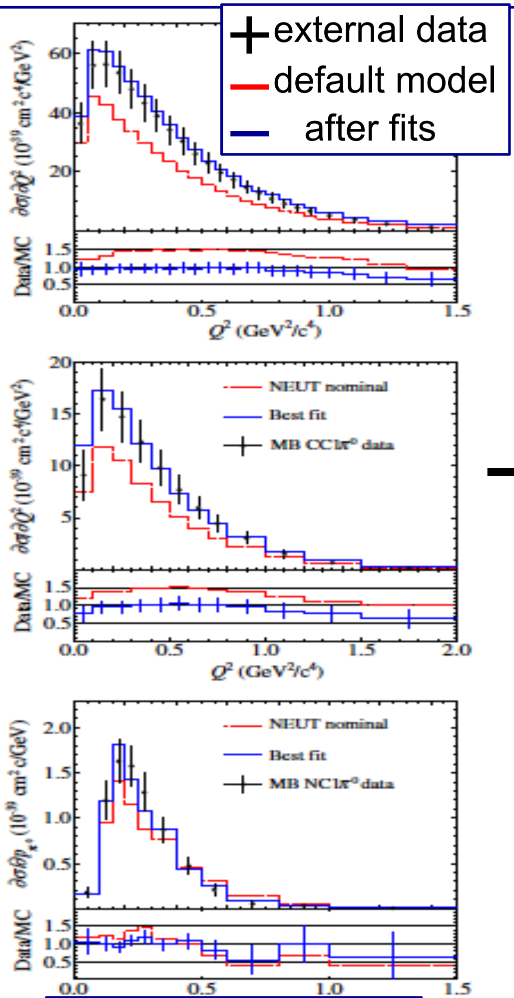
Constraint from internal data find actual size of cross-section errors

1. e.g.) T2K oscillation experiments

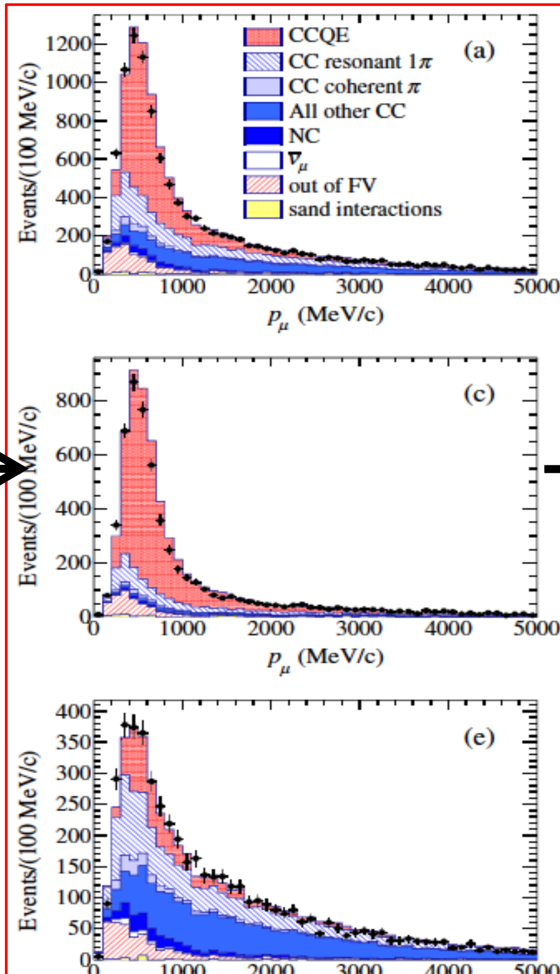
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

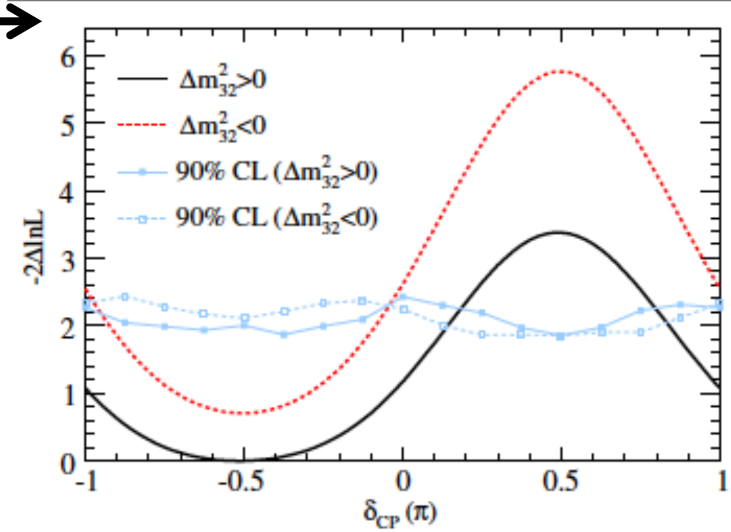


External data fit



T2K ND280 data fit

Error source [%]	$\sin^2 2\theta_{13} = 0.1$
Beam flux and near detector	2.9
(without ND280 constraint)	(25.9)
Uncorrelated ν interaction	7.5
Far detector and FSI + SI + PN	3.5
Total	8.8



oscillation result

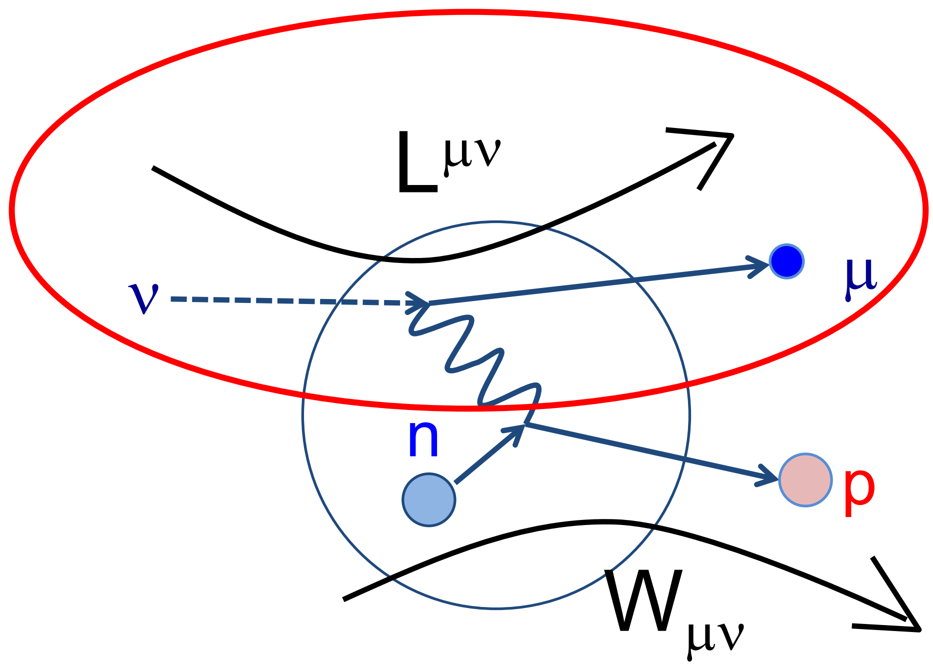
1. Neutrino cross-section formula

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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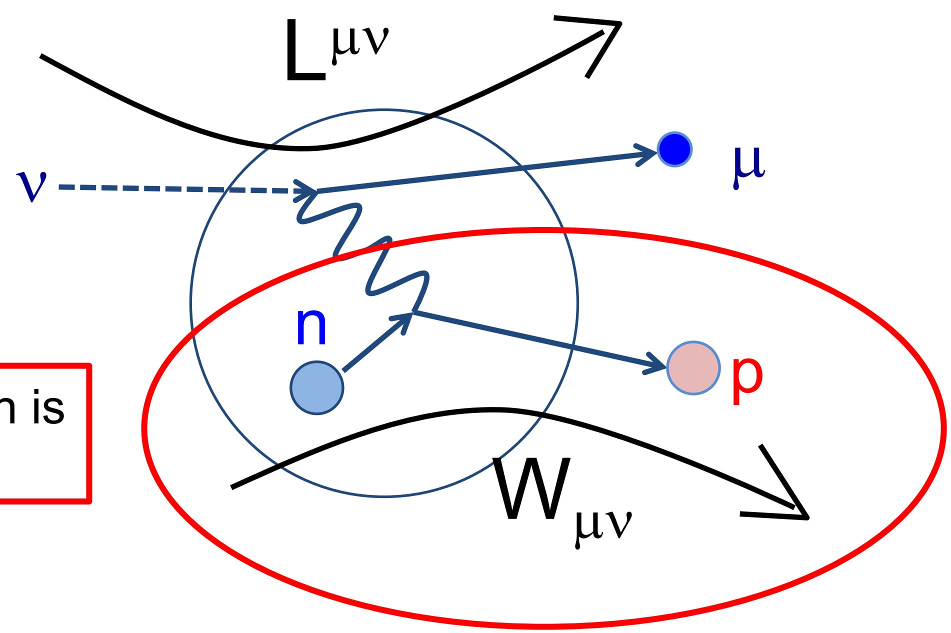
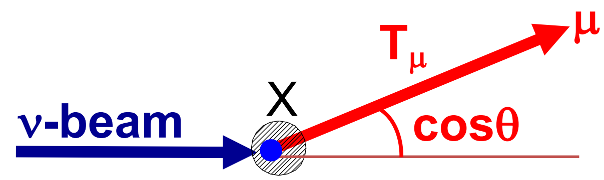


All complication of neutrino cross-section is how to model the hadronic tensor part

2. MiniBooNE phase space



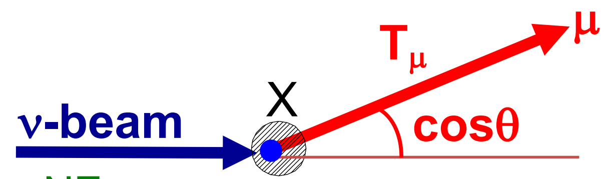
Experiment measure the interaction rate R,

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

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

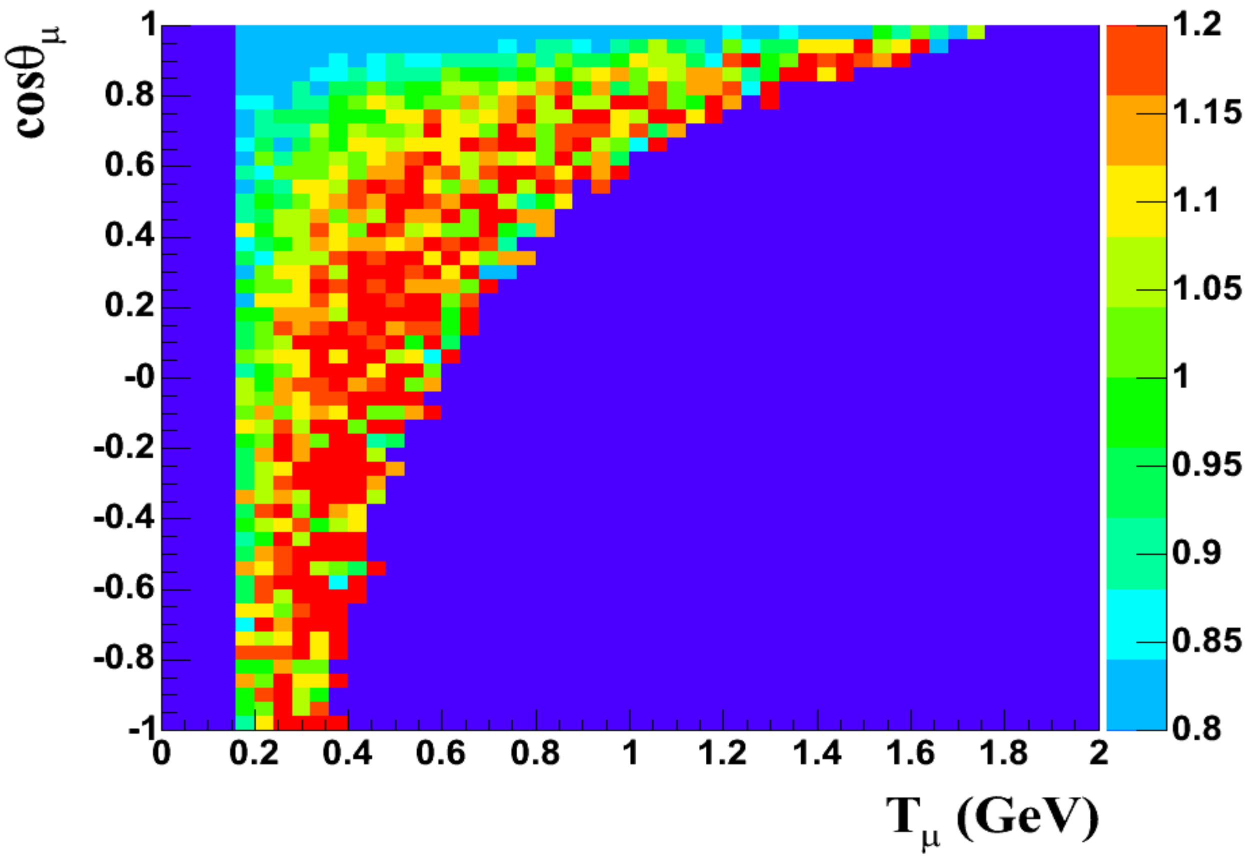
When do you see data-MC disagreement, how to interpret the result?

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.



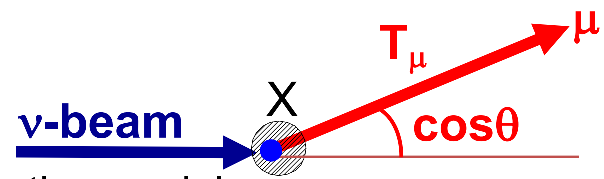
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$

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?

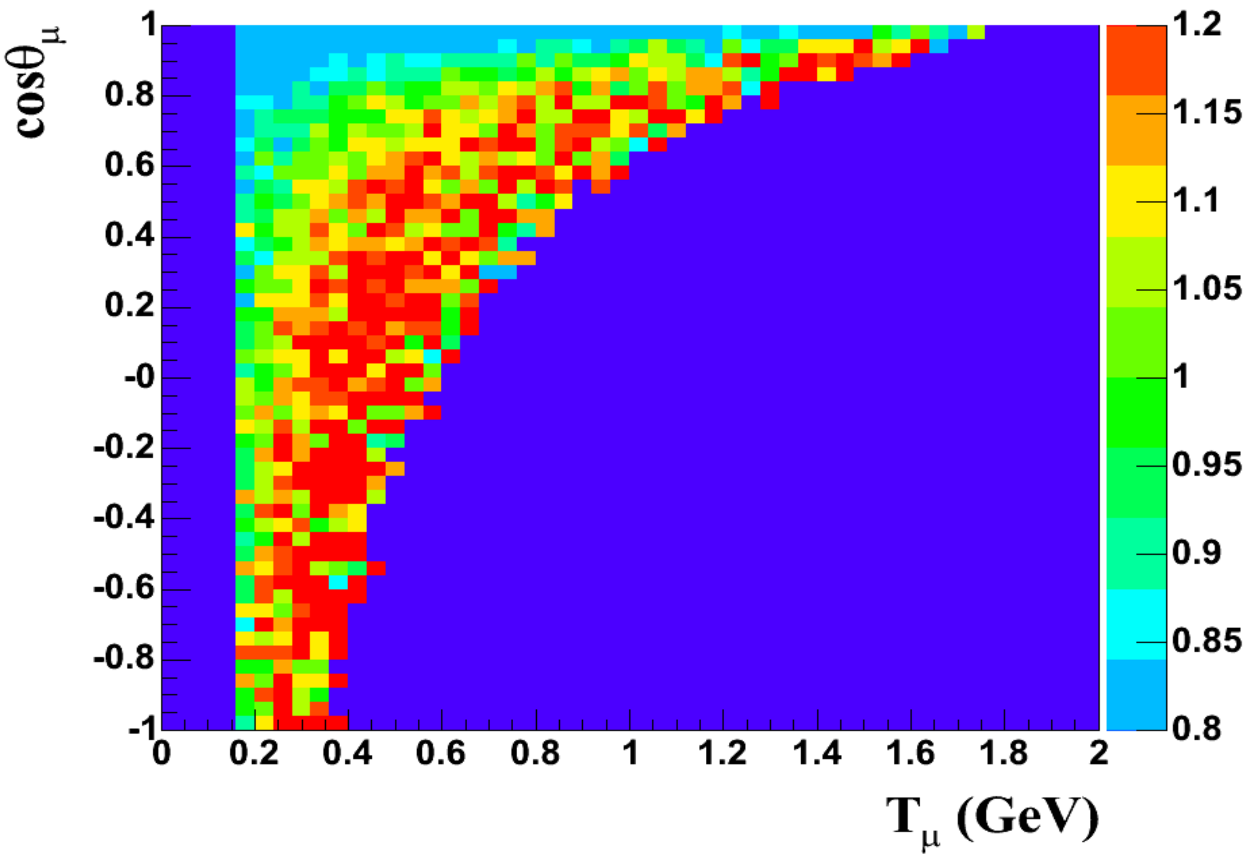
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

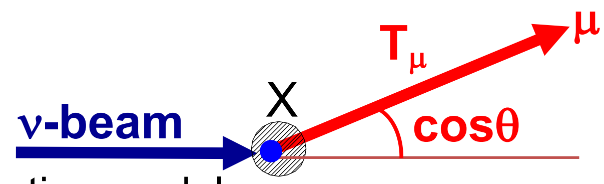
$$R \sim \int \Phi \times \sigma$$

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



MiniBooNE collaboration,PRL.100(2008)032301

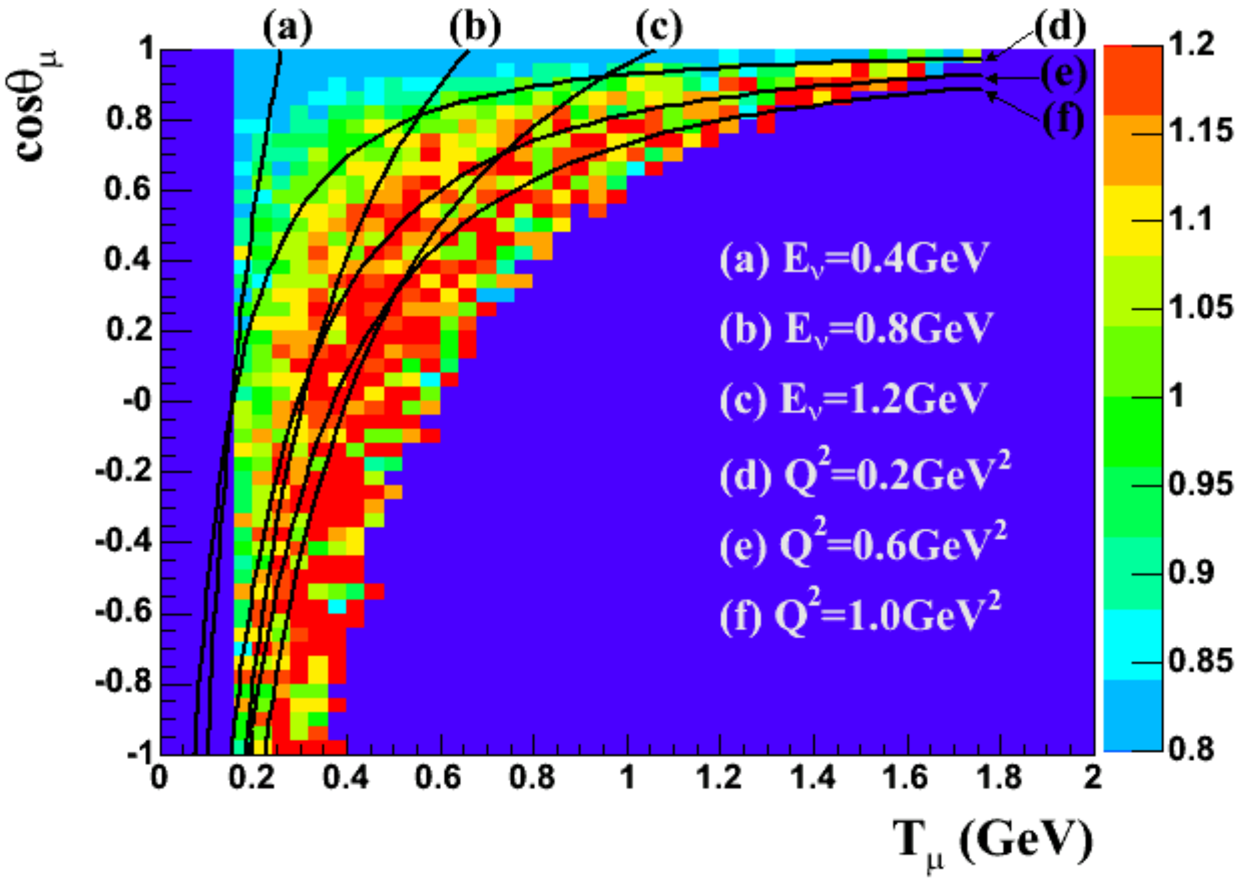
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

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

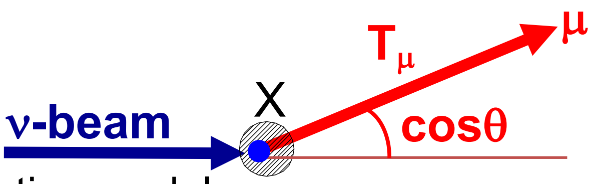
$$\frac{d\sigma^2}{dE d\Omega} \sim \frac{d\sigma^2}{dE d(\cos\vartheta)}$$



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

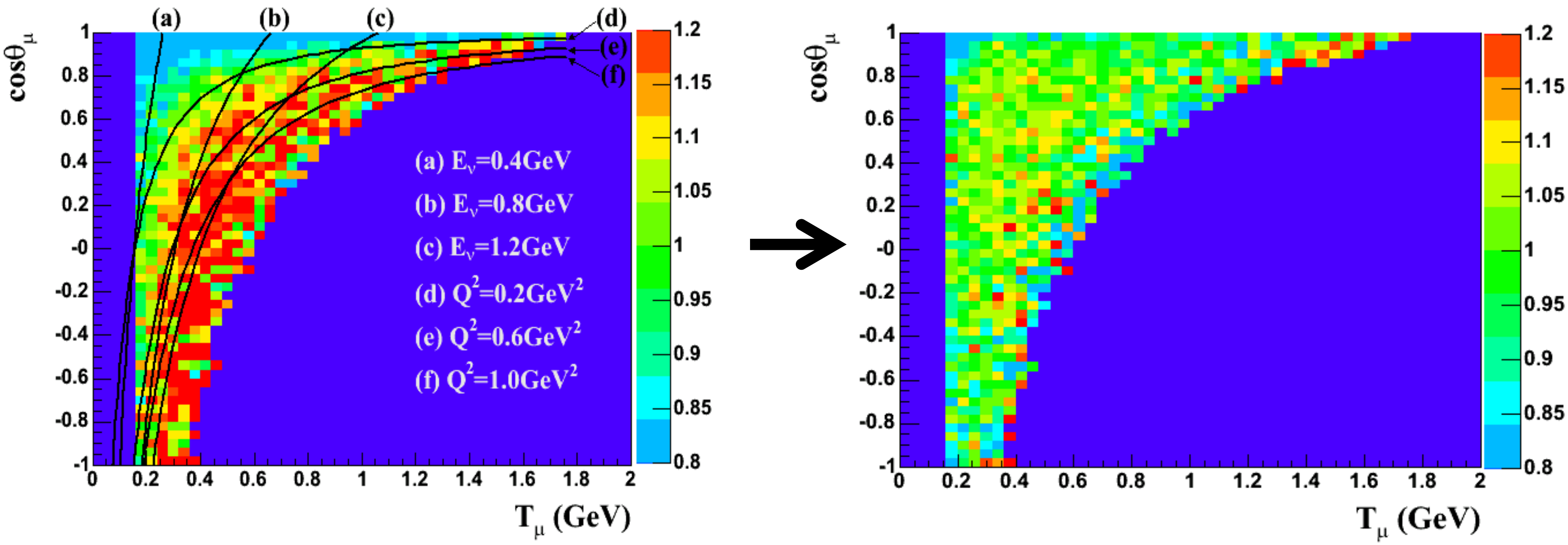


Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



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

2. Smith-Moniz formalism

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

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

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k},\vec{q},w) T_{\mu\nu} dE$$: 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 $=\sqrt{(p_F^2+M^2)}$

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

2. Relativistic Fermi Gas (RFG) model

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

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

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!

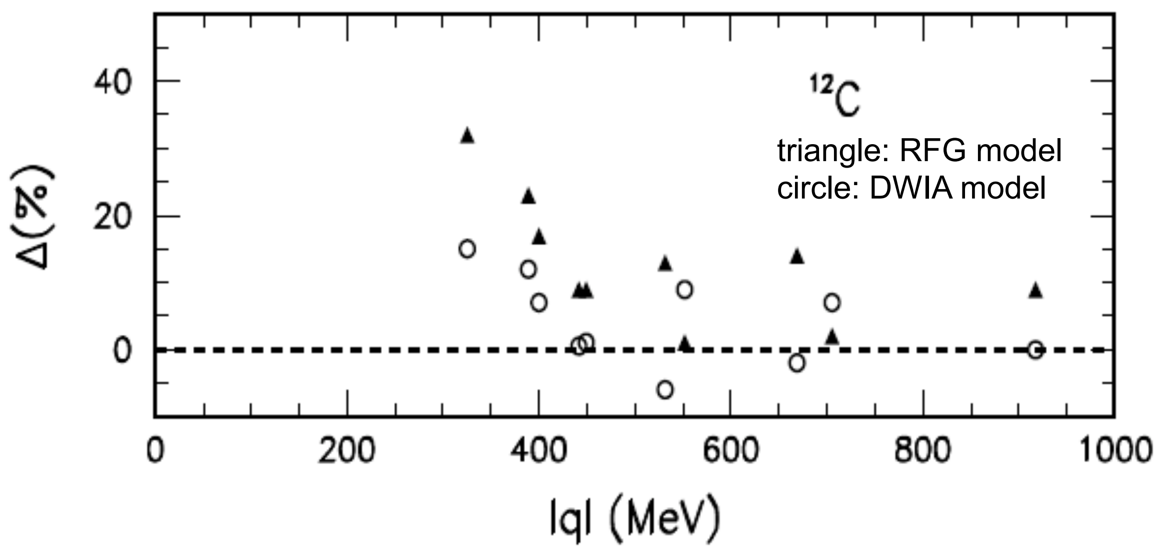
2. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model

Nucleus is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q^2)

Data and predicted xs difference for ^{12}C

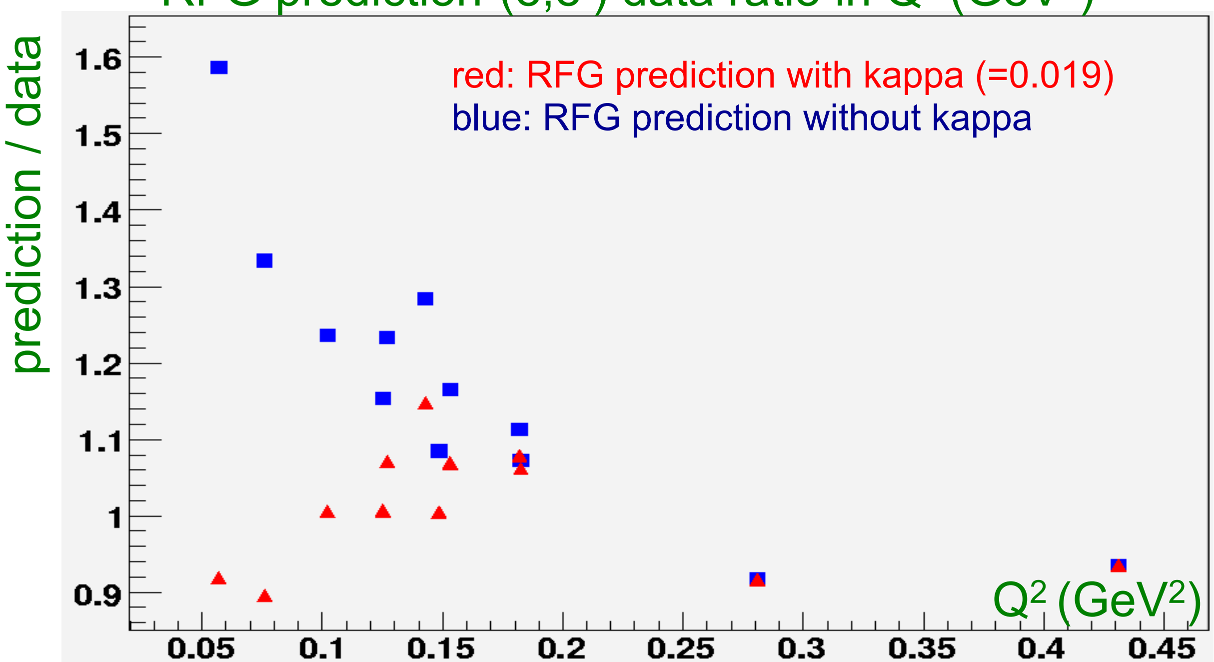


2. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model
Nucleus is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q^2)

RFG prediction-(e,e') data ratio in Q^2 (GeV^2)



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

2. The solution of CCQE puzzle

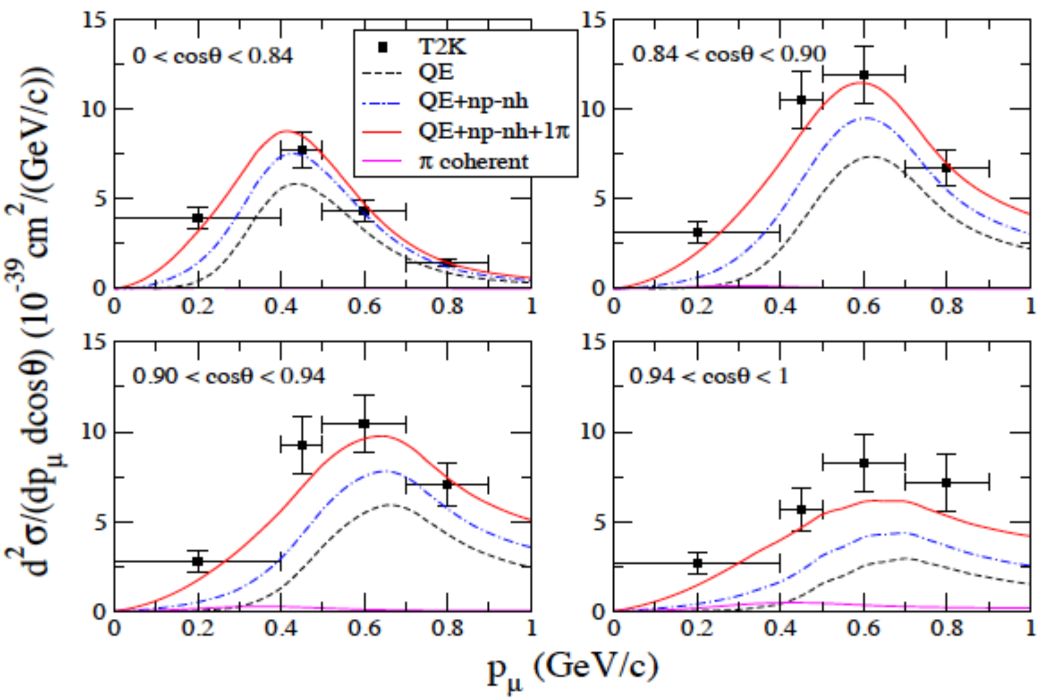
Presence of 2-body current

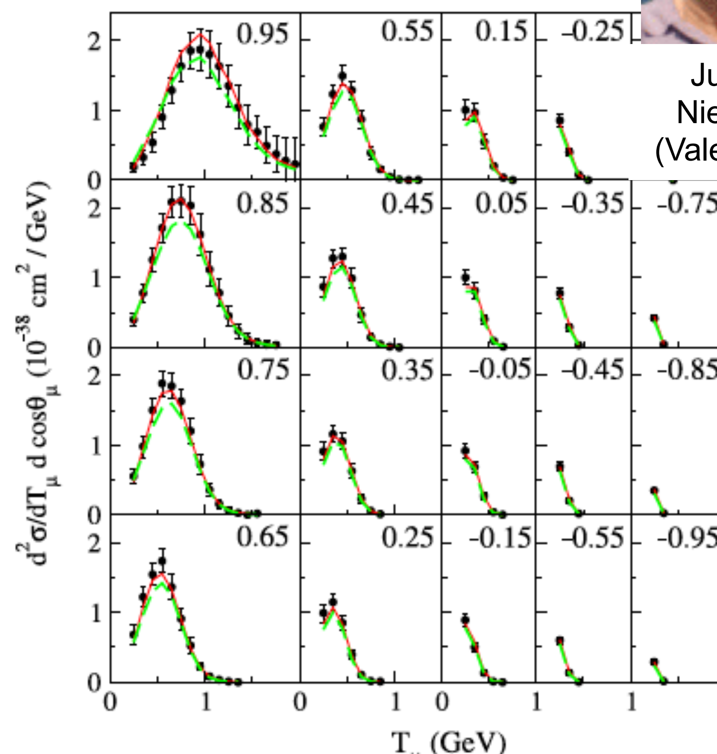
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K ν_μCC data

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

Juan Nieves (Valencia)

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





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

Martini et al,PRC80(2009)065501, PRC90(2014)02550, PRC94(2016)015501
Megias et al.,PRD94(2016)093004

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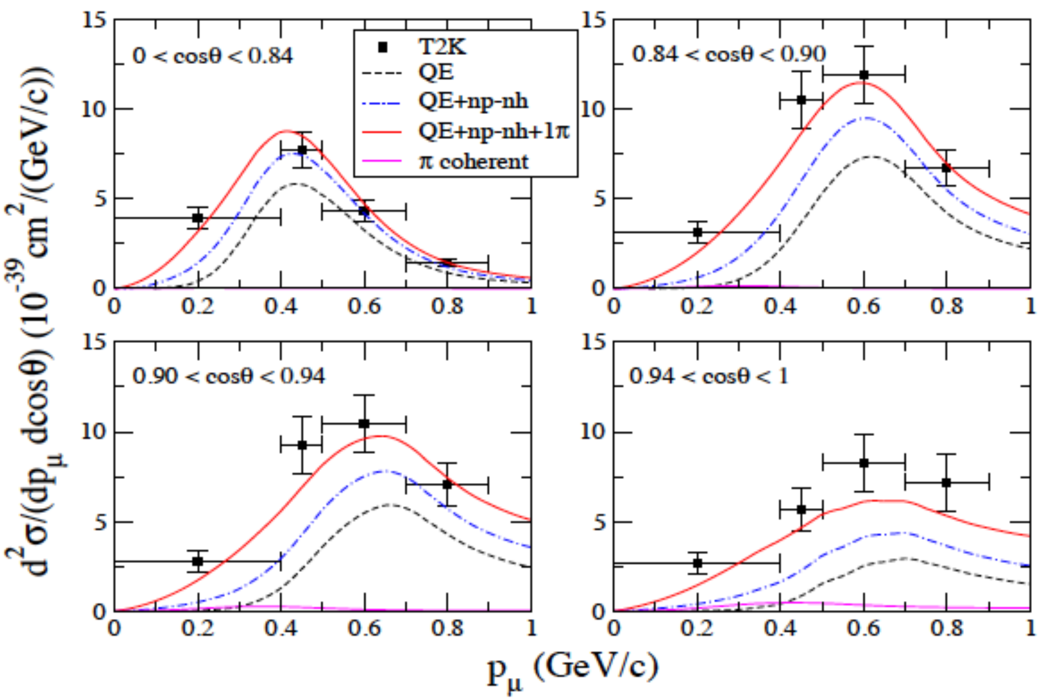
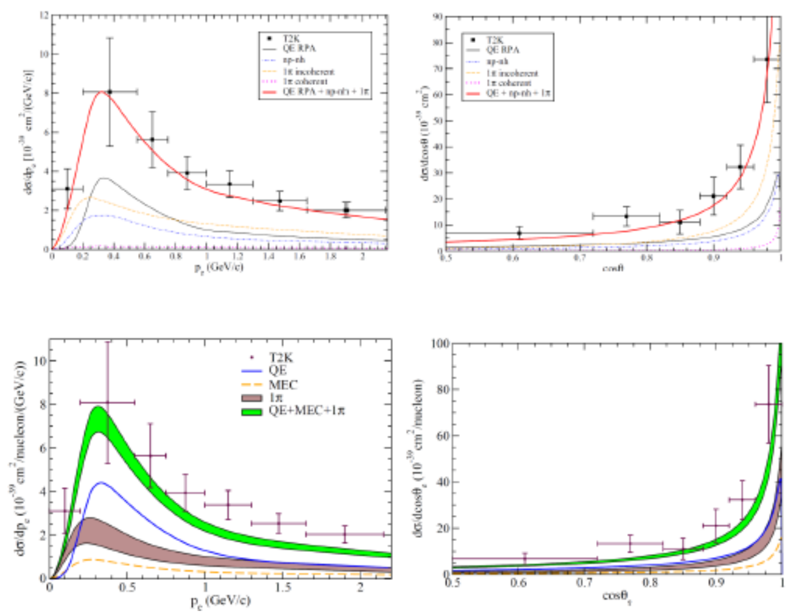
- The model can explain T2K ν_μCC data and ν_eCC data

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



Martini model & SuSAv2MEC vs. T2K electron neutrino CCdifferential cross-section data

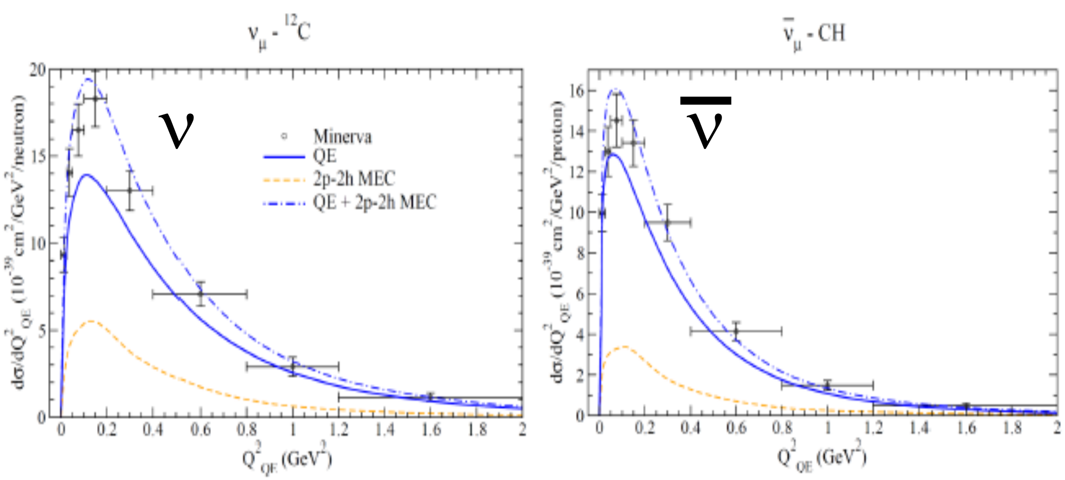


2. The solution of CCQE puzzle

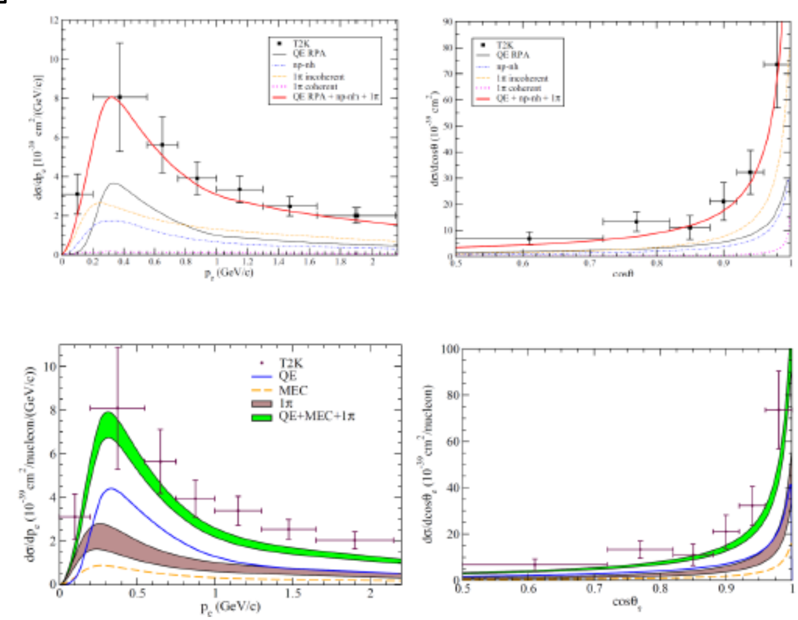
Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K ν_μCC data and ν_eCC data
- Finally, MINERvA data are reproduced

SuSAv2MEC vs. MINERvA CCQE-like differential cross-section data



Martini model & SuSAv2MEC vs. T2K electron neutrino CCdifferential cross-section data



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

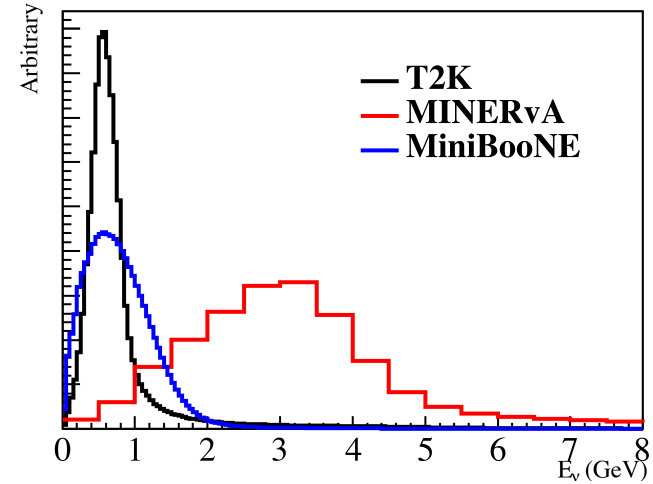
This moment…
Valencia MEC model does not fit T2K (and Super-K) data very well, people are working very hard to understand what is going on

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.

2. T2K

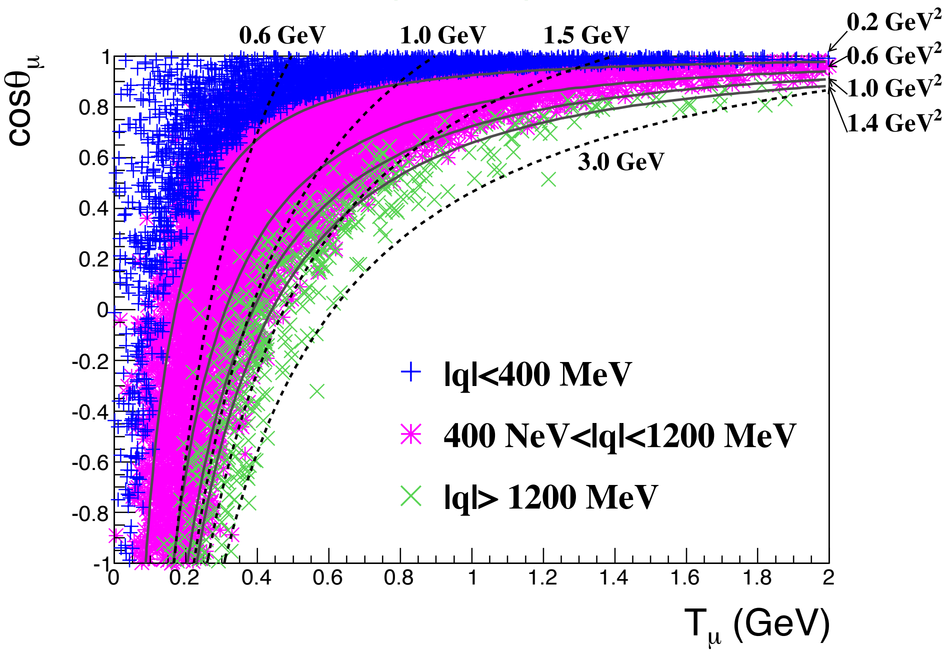


INGRID, FGD, P0D, ECal, TPC, SMRD, Super-K

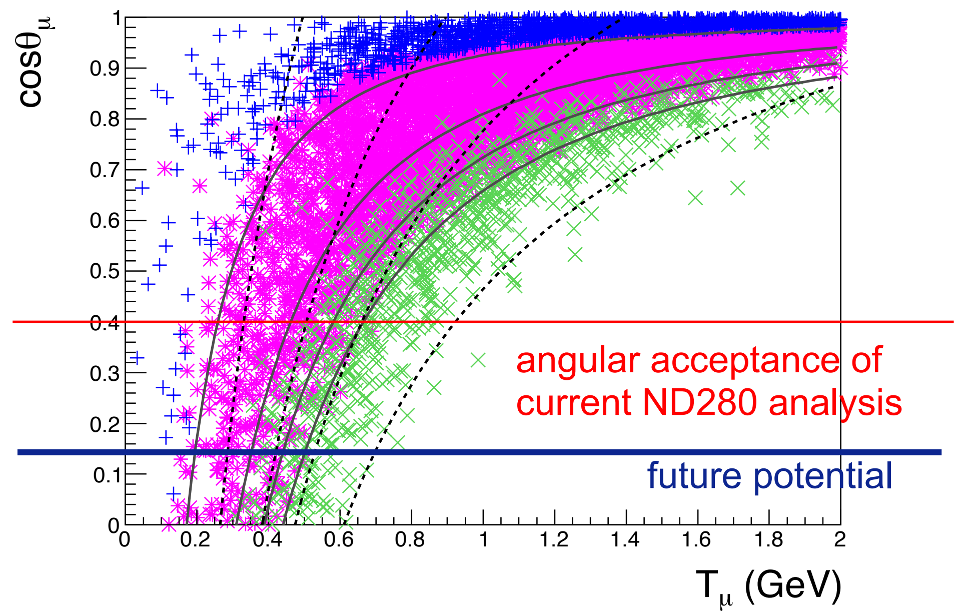
- <E>~600 MeV off-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)

Within the limited coverage, neutrino interactions of MiniBooNE and T2K have similar kinematics

MiniBooNE CCQE phase space

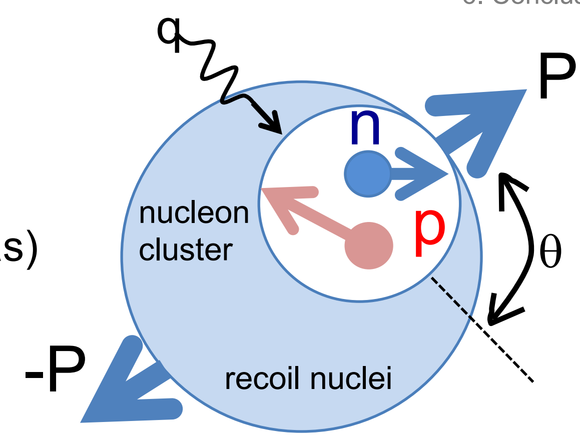


T2K CCQE phase space



Sobczyk, PRD86(2012)015504, TK, arXiv:1304.6014
GENIE, arXiv:1510.05494

2. How to emit 2 nucleons from correlated pair?



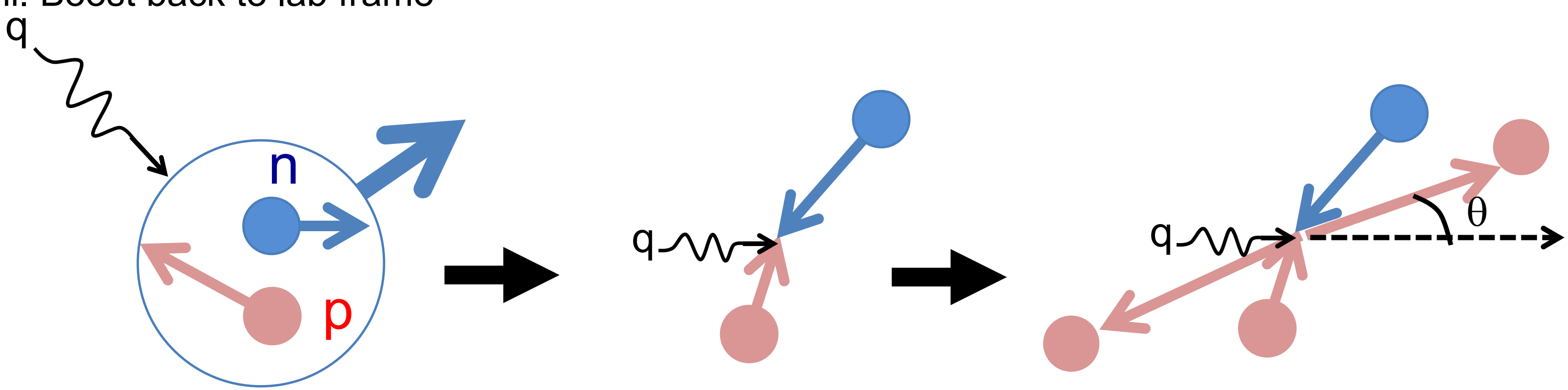
Default model for GENIE, NEUT, NuWro…

For a given Energy-Momentum transfer...

1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)
2. n-n, n-p, p-p pairs are allowed, if interaction is allowed
3. Energy-momentum conservation

Once 2 nucleons from on-shell are choosed

i. ω-q vector and nucleon cluster makes CM system (hadronic system)
ii. Isotropic decay (random θ and ϕ) of hadronic system creates 2 nucleon emission
iii. Boost back to lab frame



Queen Mary University of London

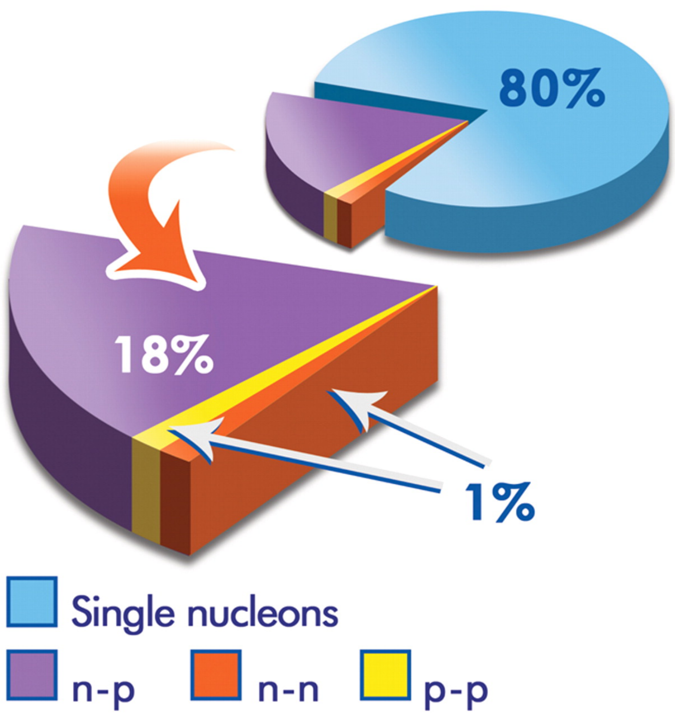
Is there correct way to model 2 nucleon emissions from a correlated nucleon pair?

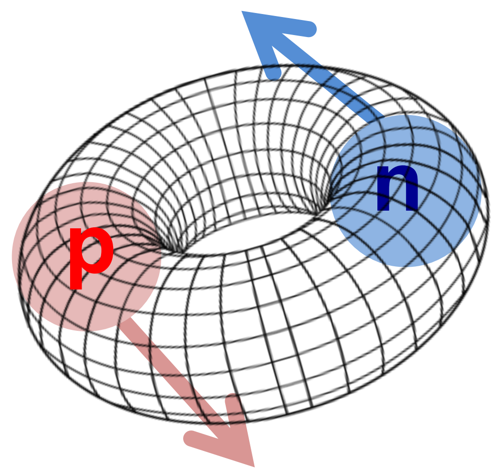
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504
JLab HallA, PRL99(2007)072501, Science320(2008)1476

2. Nucleon correlations

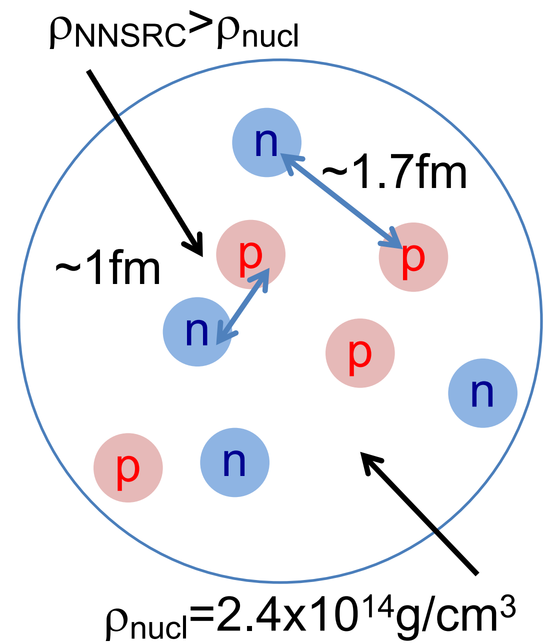
Short Range Correlation (SRC)

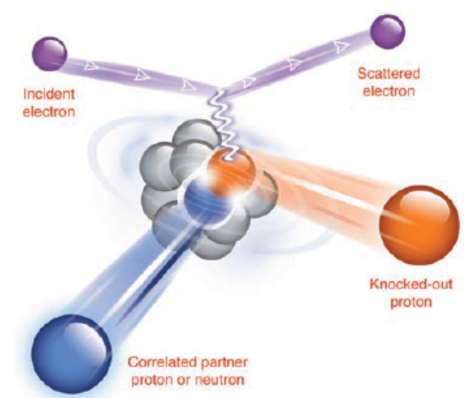
~20% of all nucleons in heavy elements (A>4)
~90% are neutron-proton (n-p) pair
~nucleon pair have back-to-back momentum
~ momentum can be beyond Fermi sea





NNSRC~quasi deuteron





CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504;106(2011)052301
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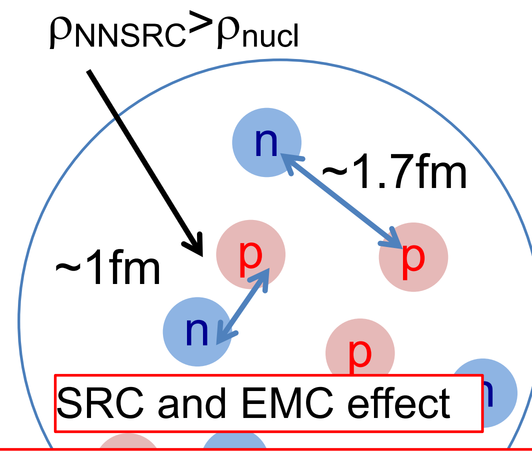
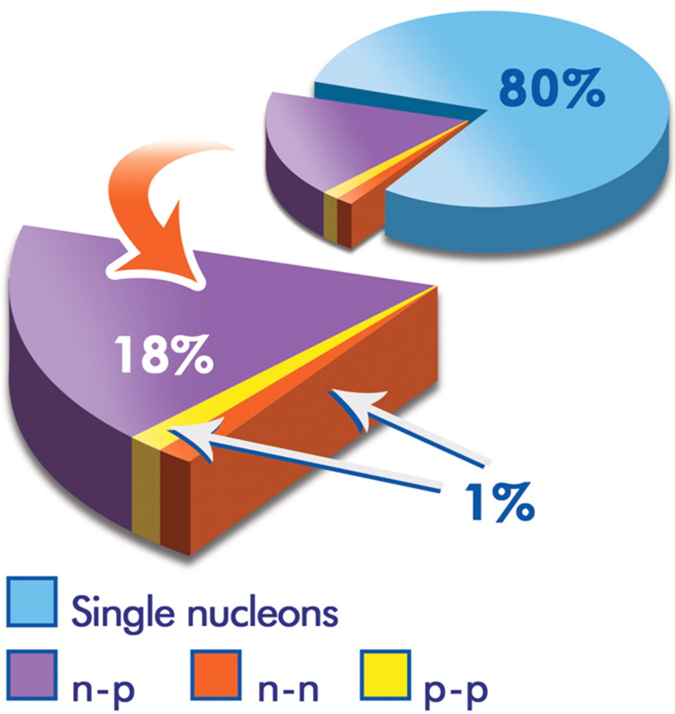
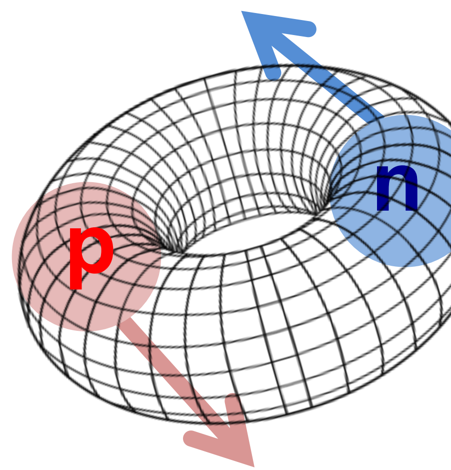
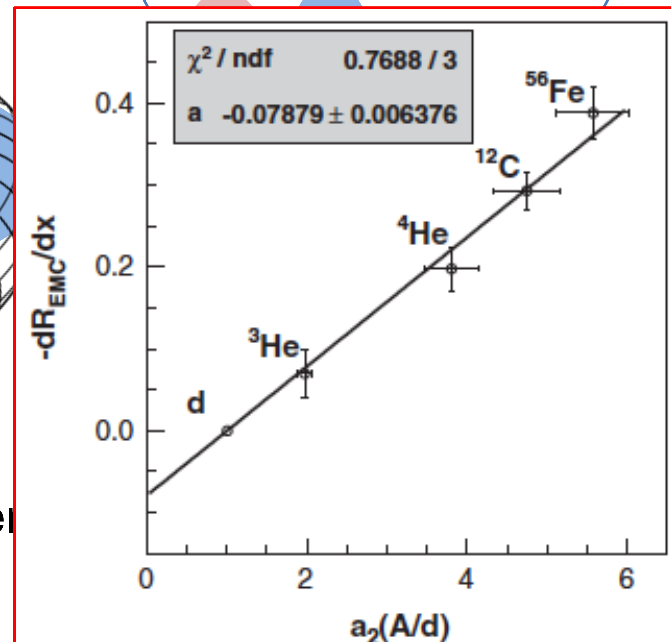






NNSRC~quasi deuter

SRC and EMC effect



Martini et al,PRD85(2012)093012
Nieves et al,PRD85(2012)113008

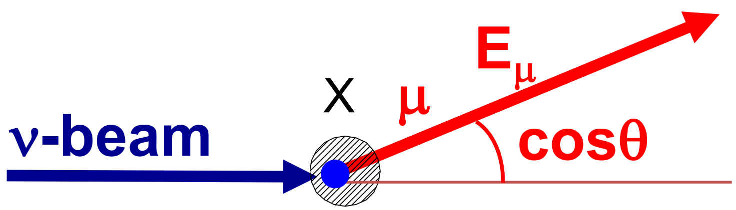
3. Neutrino oscillation experiment

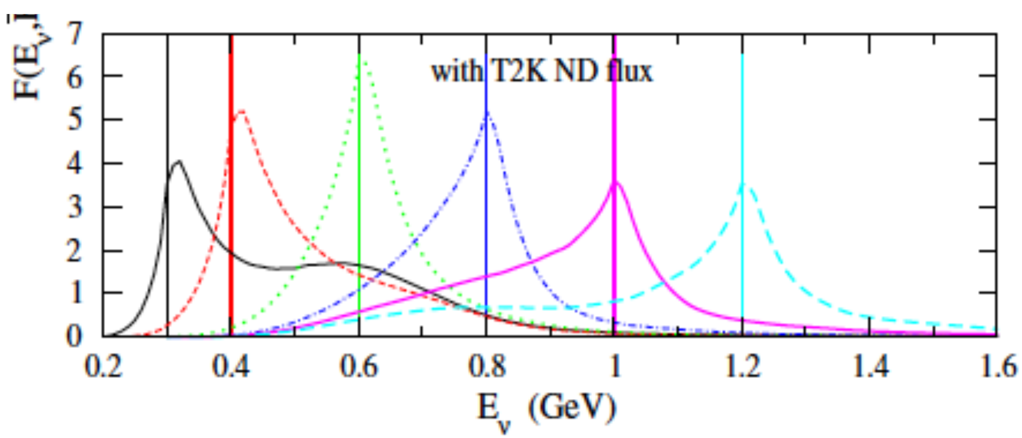
Reconstruction of neutrino energy with QE assumption

- We can reconstruct neutrino energy if we know it is CCQE interaction
  → There is bias because of all "CCQE-like" interactions.

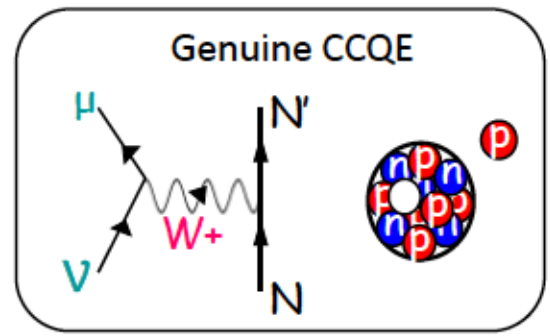
(interaction with 2-nucleons, pion production with pion nuclear absorption)

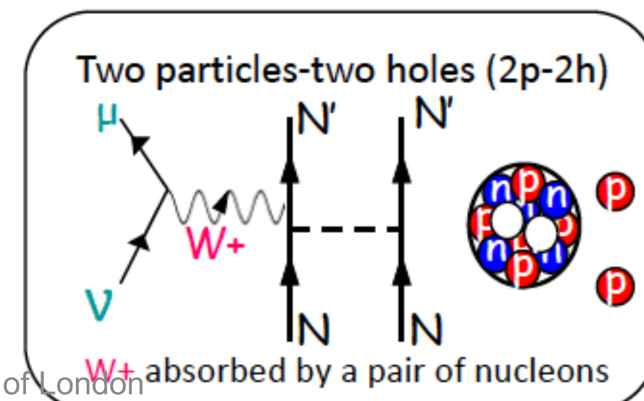
$$\nu_\mu + n \rightarrow p + \mu^- \quad (\nu_\mu + X \rightarrow X' + \mu^-) \qquad E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$





estimated reconstruction due to 2-body current





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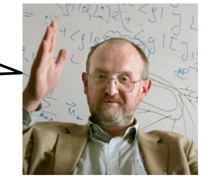

Jan Sobczyk (Wroclaw)

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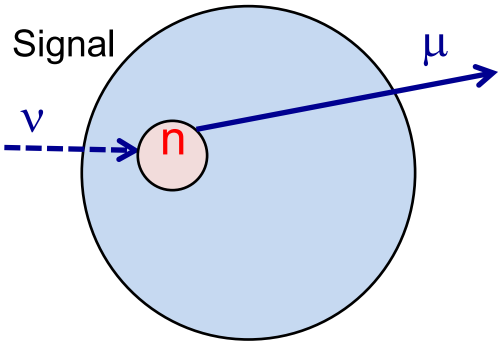
Baryon resonance, pion production by neutrinos

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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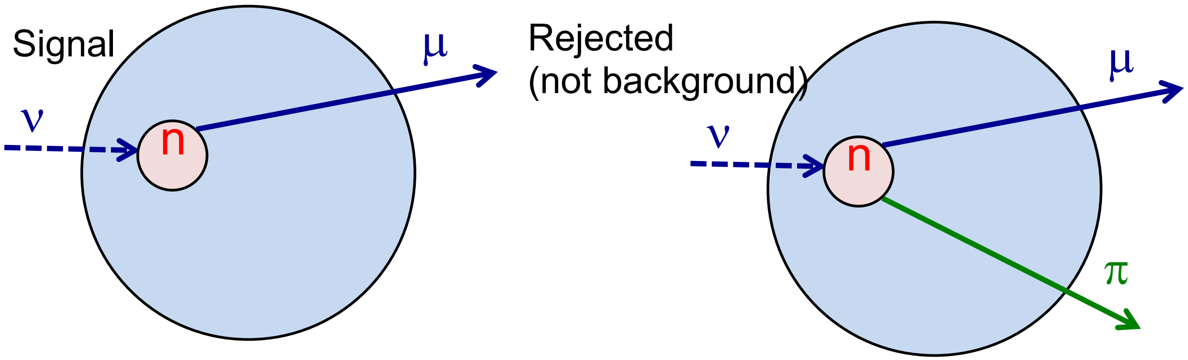

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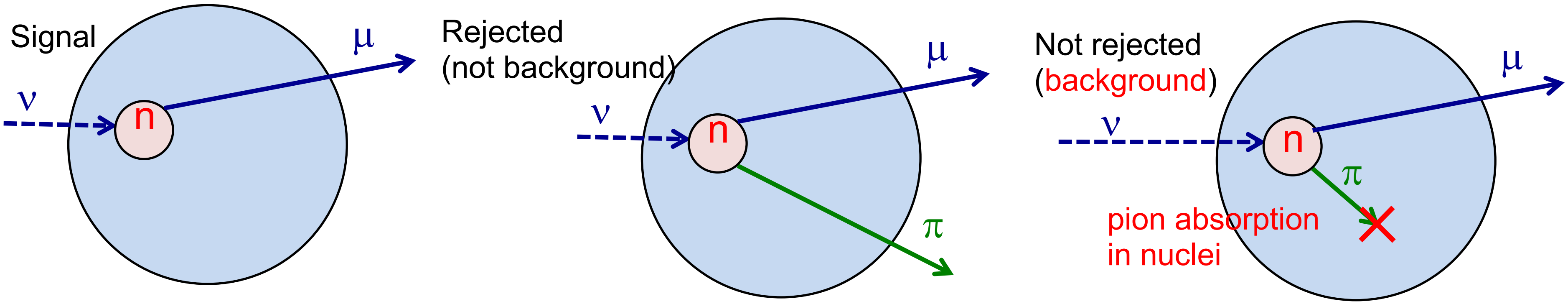

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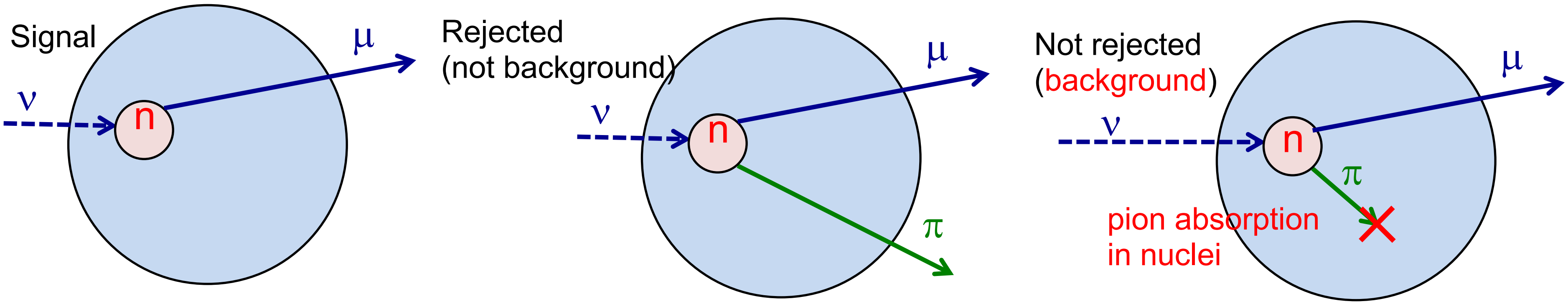
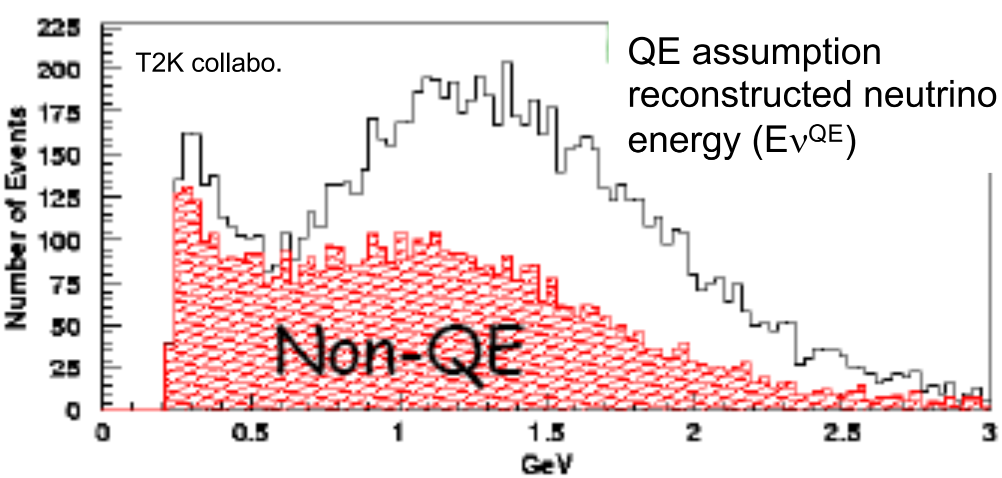
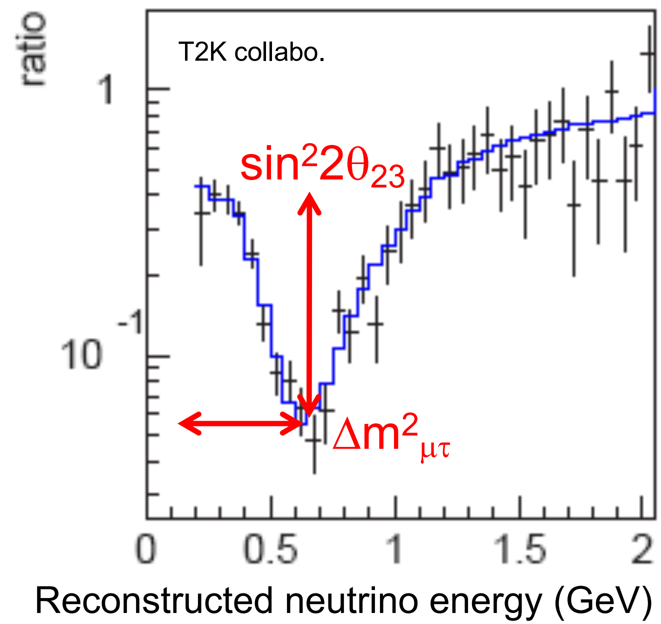




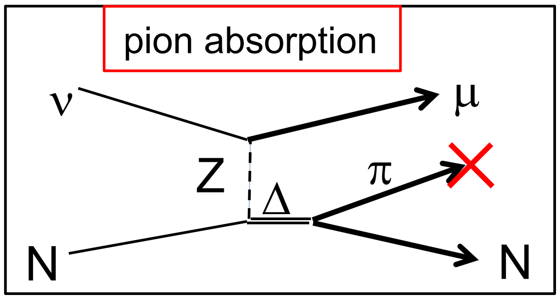


Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

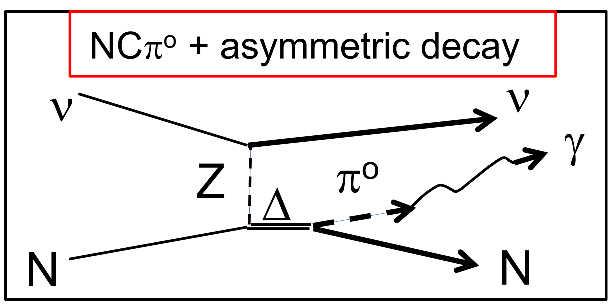
3. non-QE background

Understanding of neutrino pion production is important for oscillation experiments

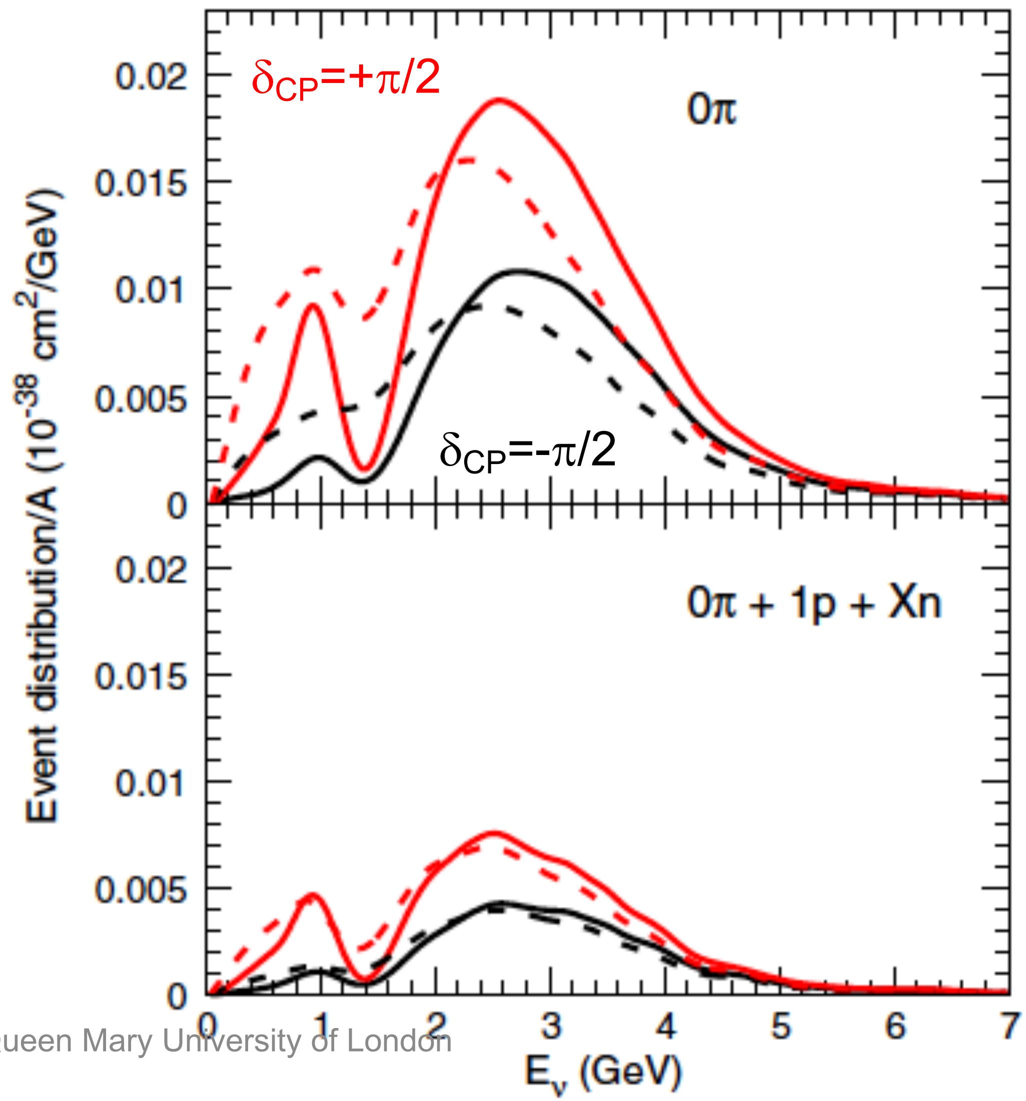
Pion production for ν_μ disappearance search
- Source of mis-reconstruction of neutrino energy



Neutral pion production in ν_e appearance search
- Source of misID of electron



DUNE true vs. reconstructed Eν spectrum



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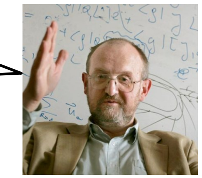

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Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Garvey et al.,Phys.Rept.580 (2015) 1

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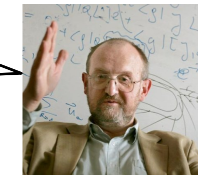

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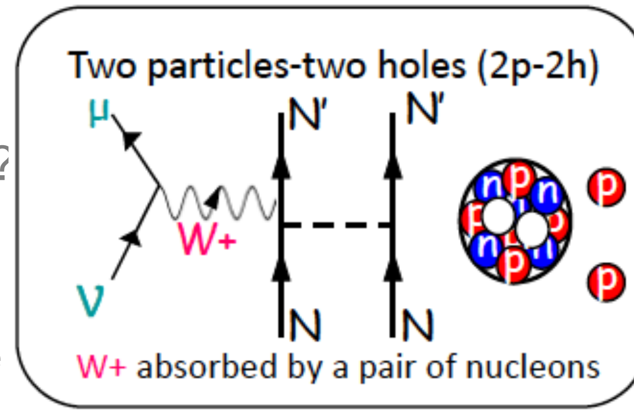

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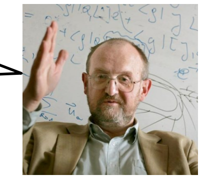

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Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

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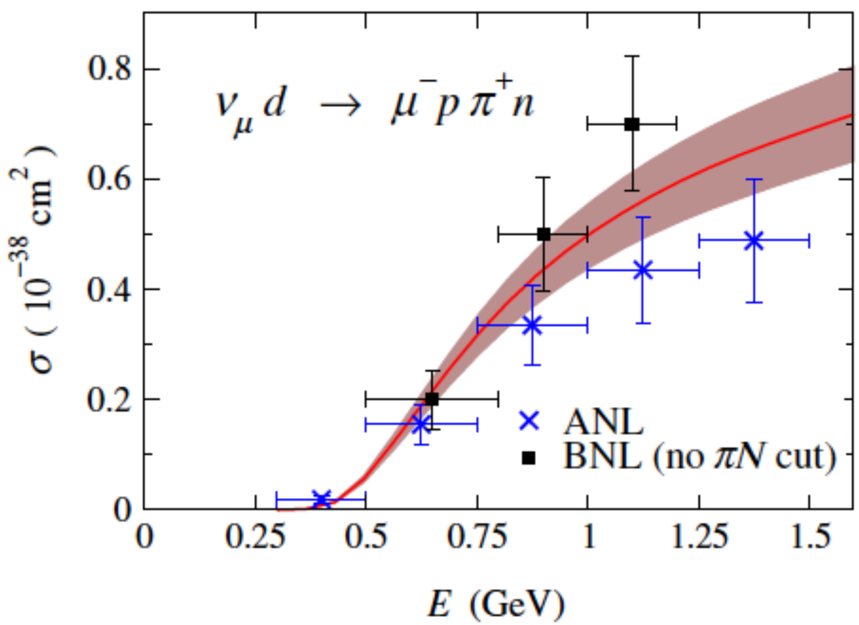
Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

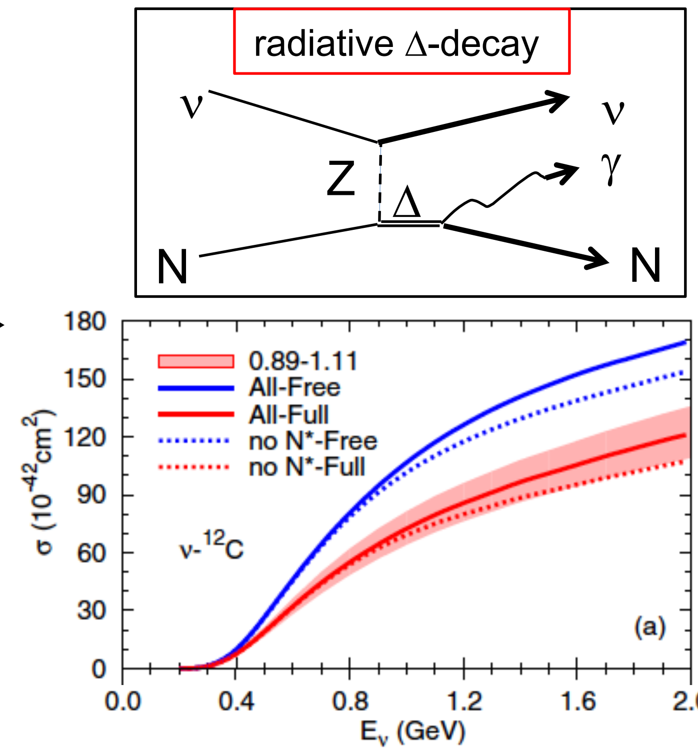
→ this propagates to every interactions with baryon resonance

ANL vs. BNL



→

e.g.) NCγ production model



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

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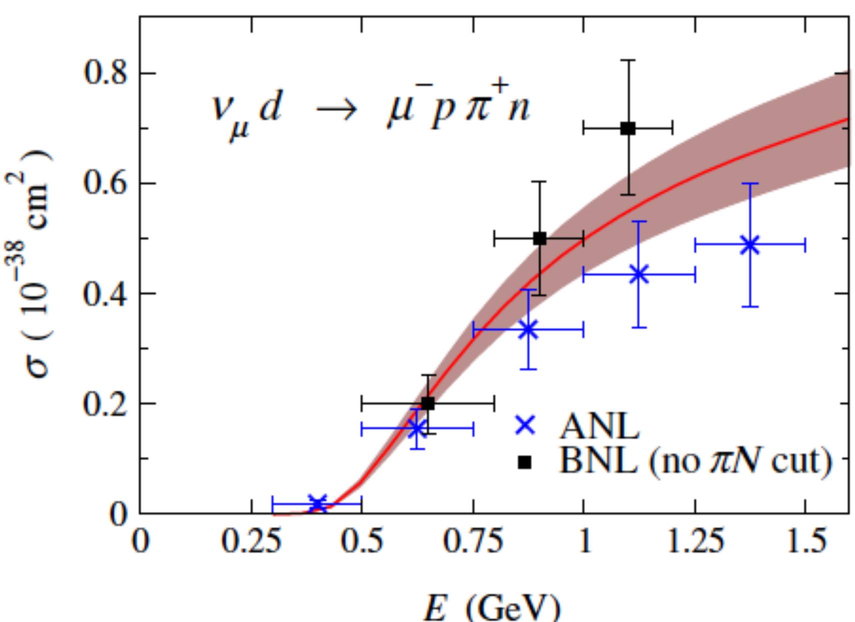
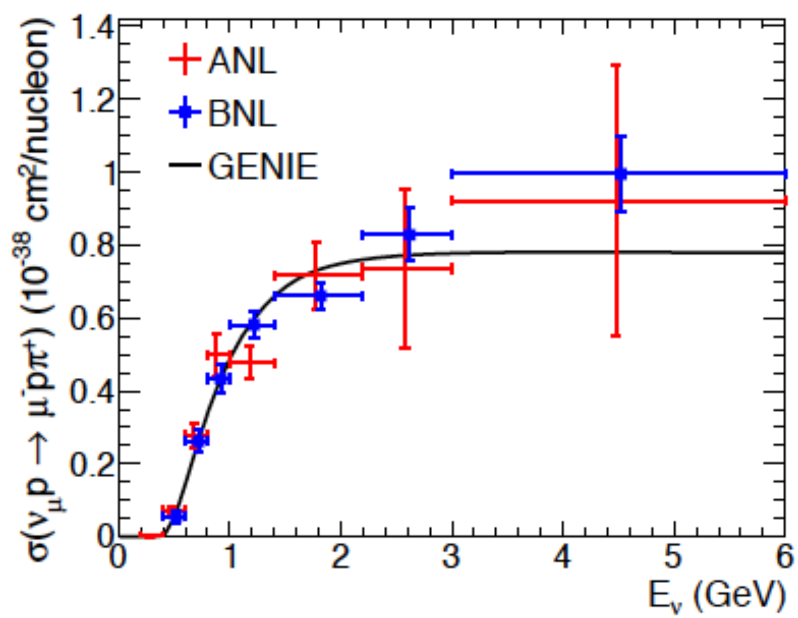


→



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

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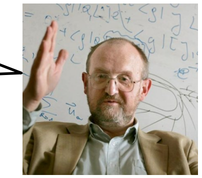

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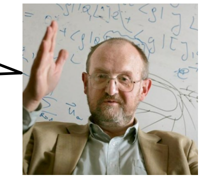

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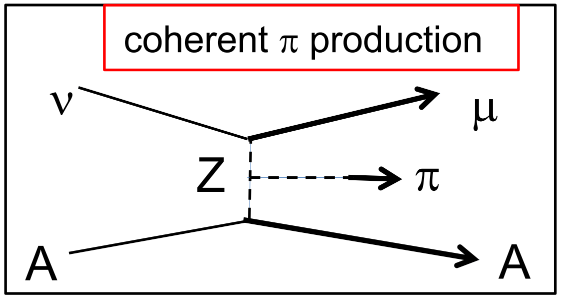
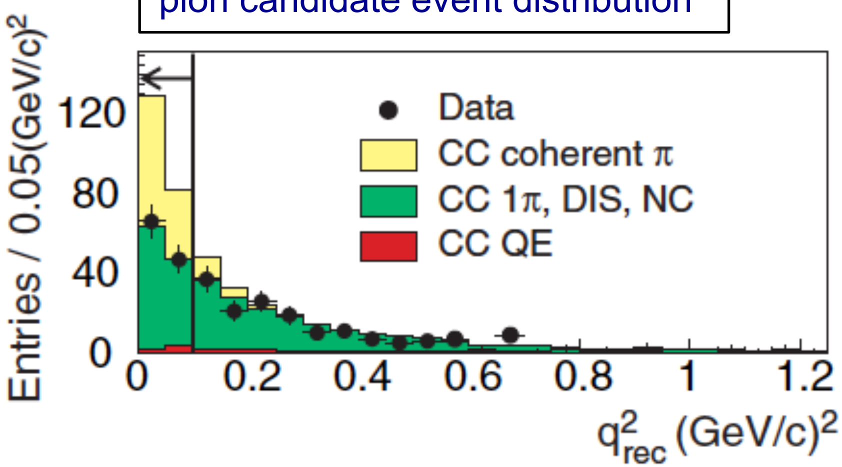
K2K and SciBooNE data show CC coherent pion production is consistent with zero.



K2K muon neutrino CC coherent pion candidate event distribution



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K2K and SciBooNE data show CC coherent pion production is consistent with zero.

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

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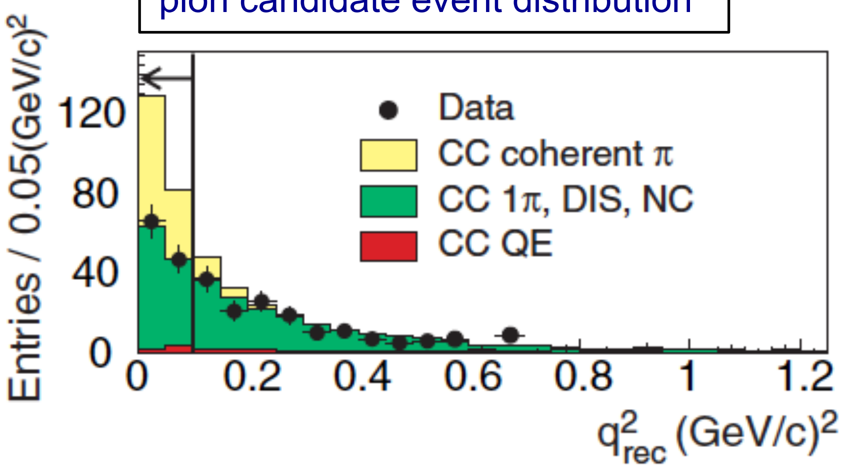
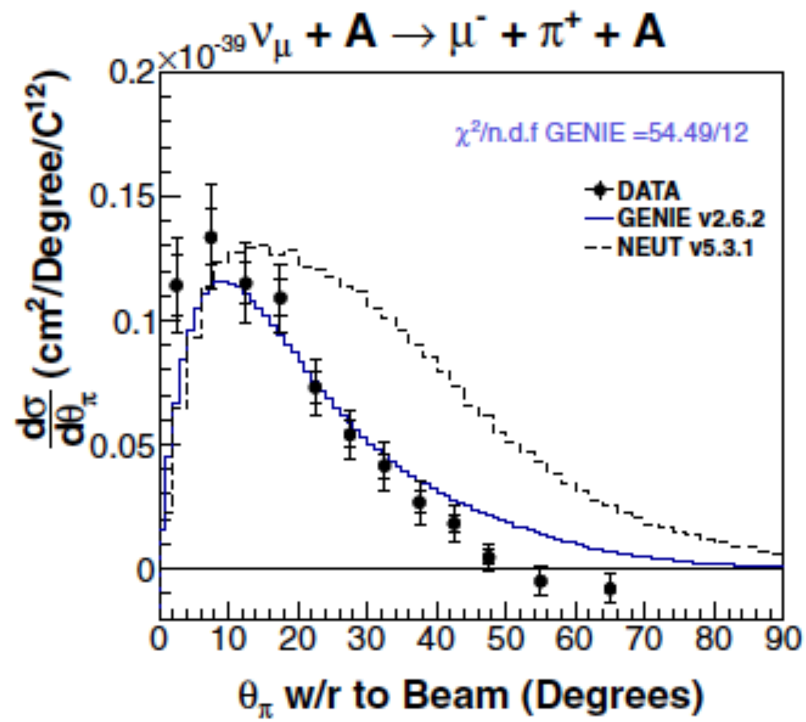


MINERvA muon neutrino CC coherent pion production differential cross-section



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

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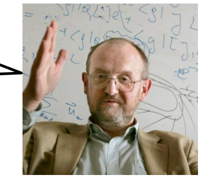

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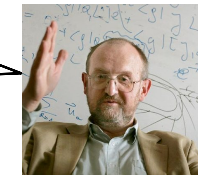

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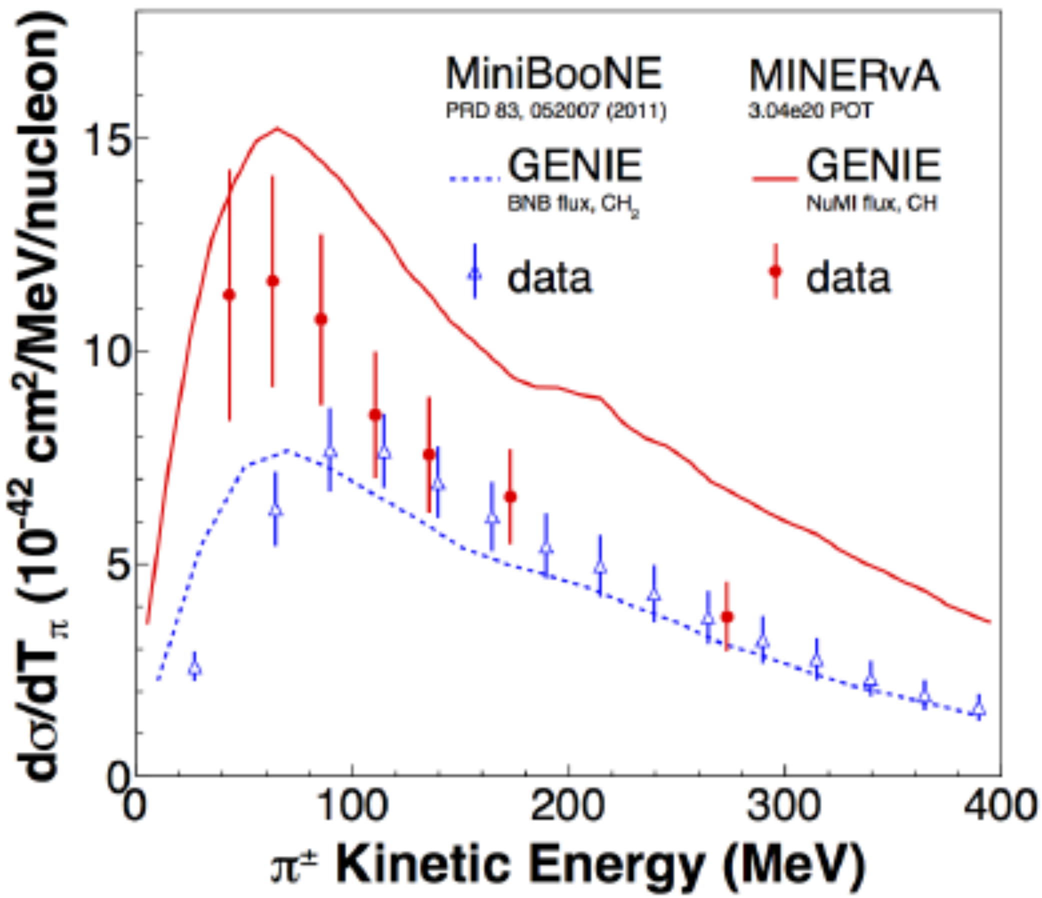
Data from MiniBooNE and MINERvA and simulation are all incompatible

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…



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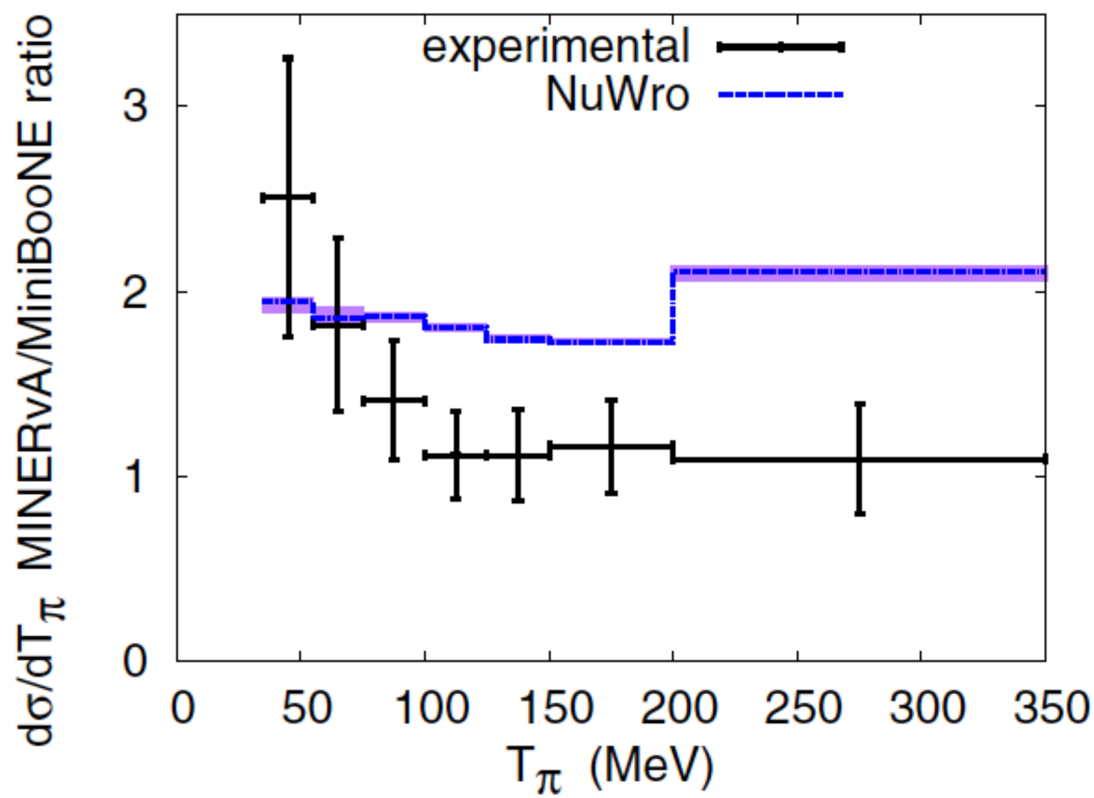


MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

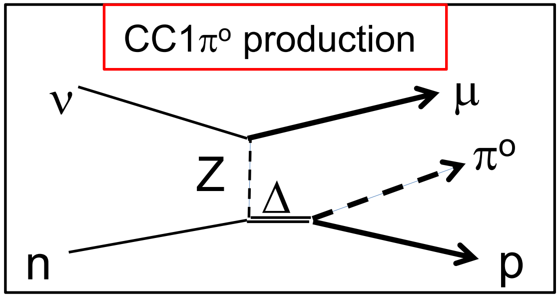
3. Pion puzzle

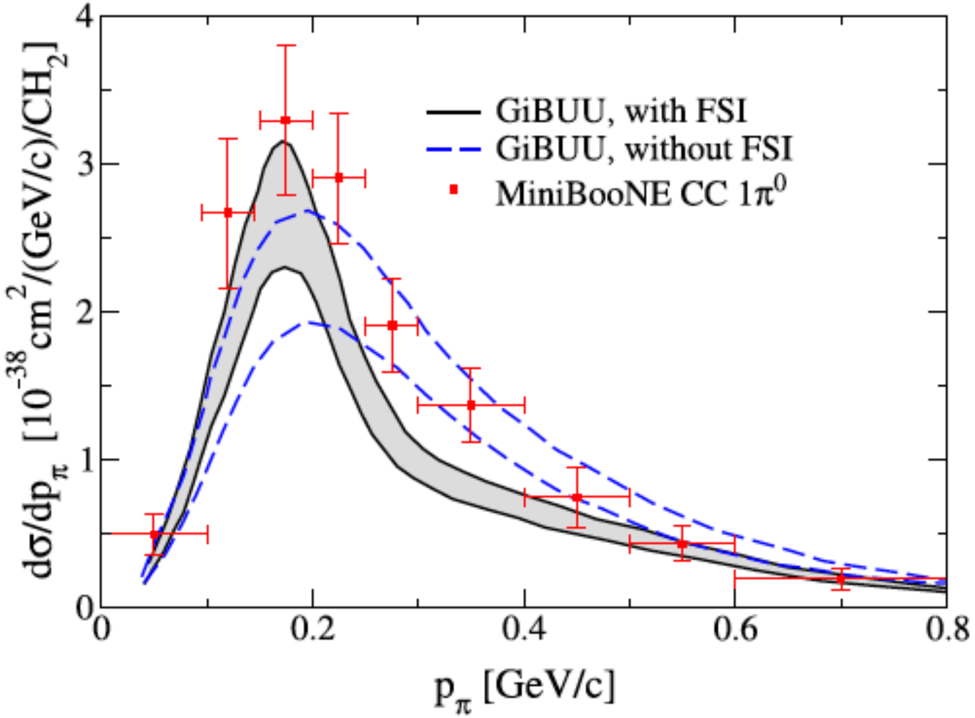
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

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

MiniBooNE,PRD83(2011)052009
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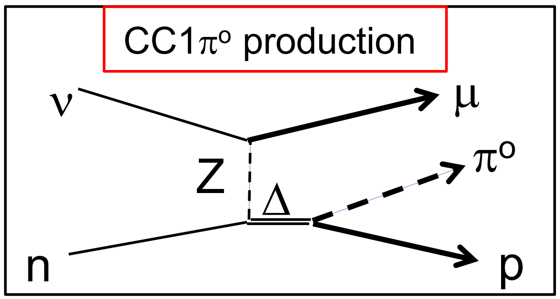

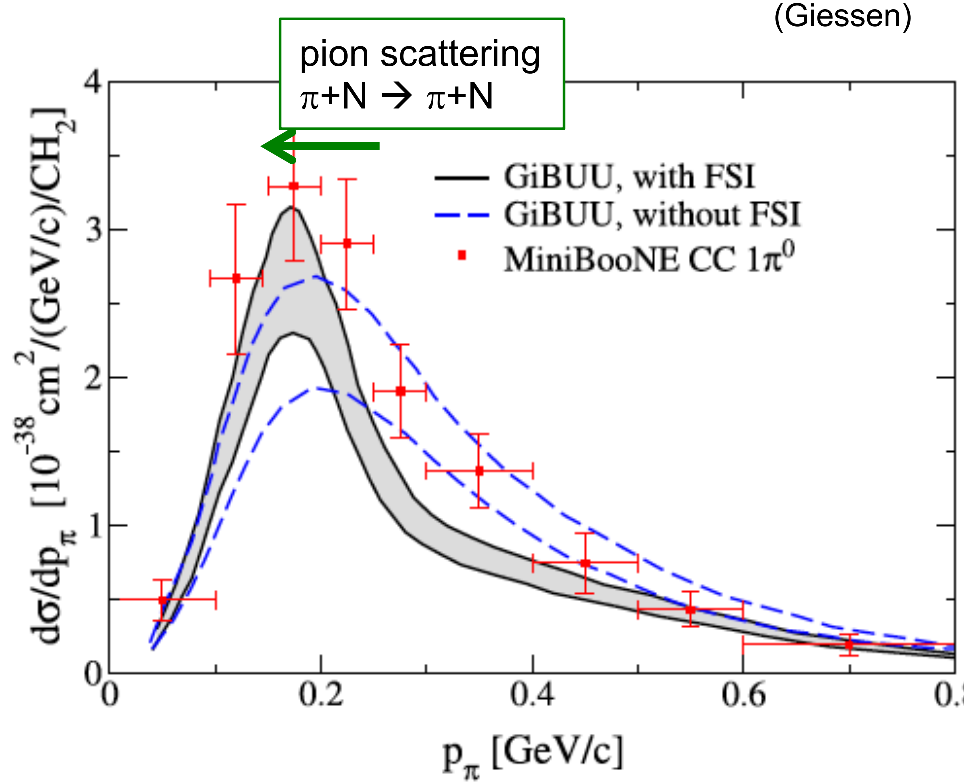

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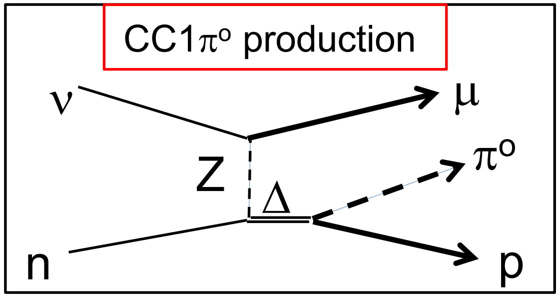

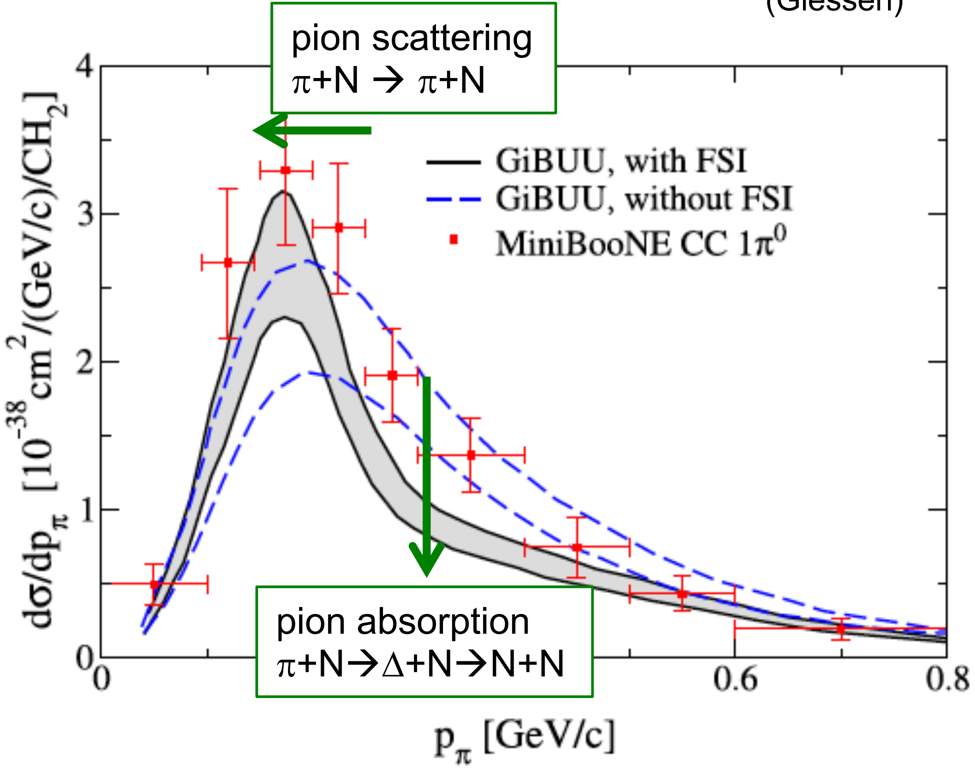

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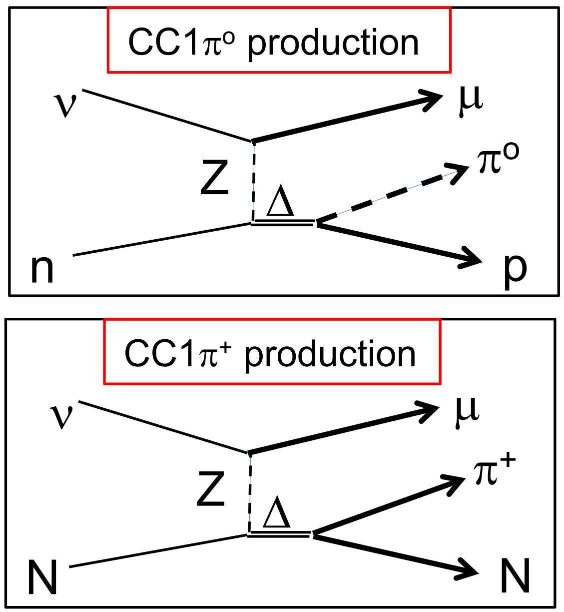
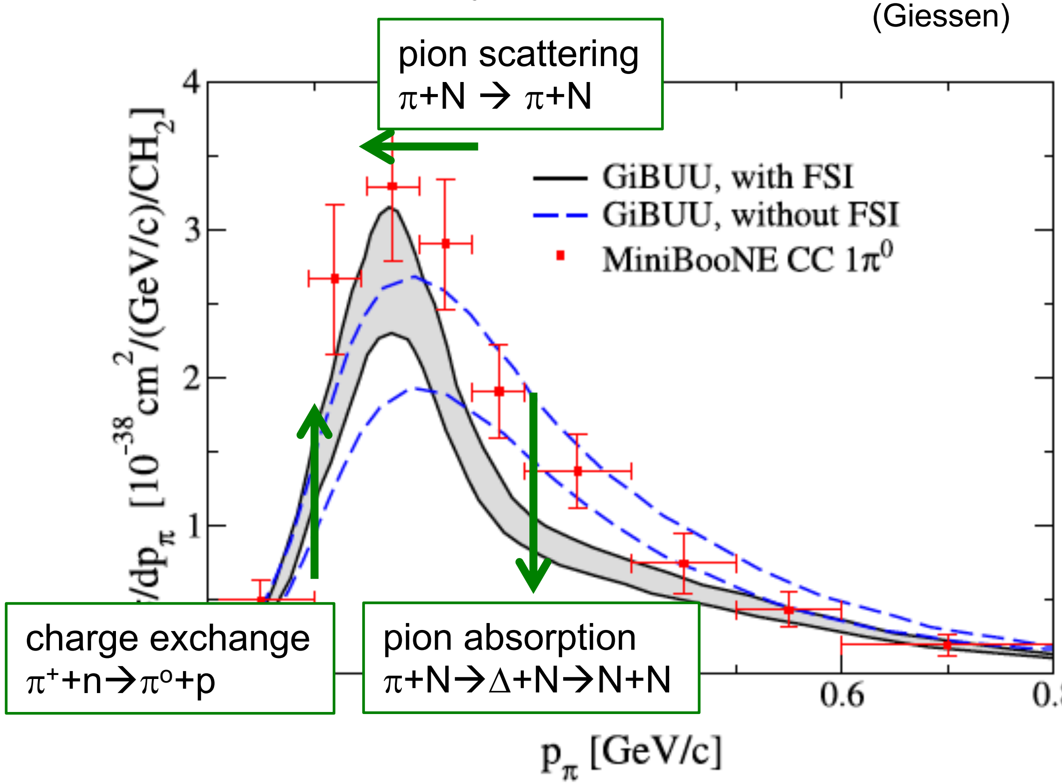


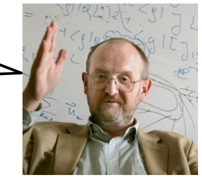


You need to be right for all
1. neutrino flux prediction
2. pion production model
3. final state interaction

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

→ ???

3. MINERvA pion results

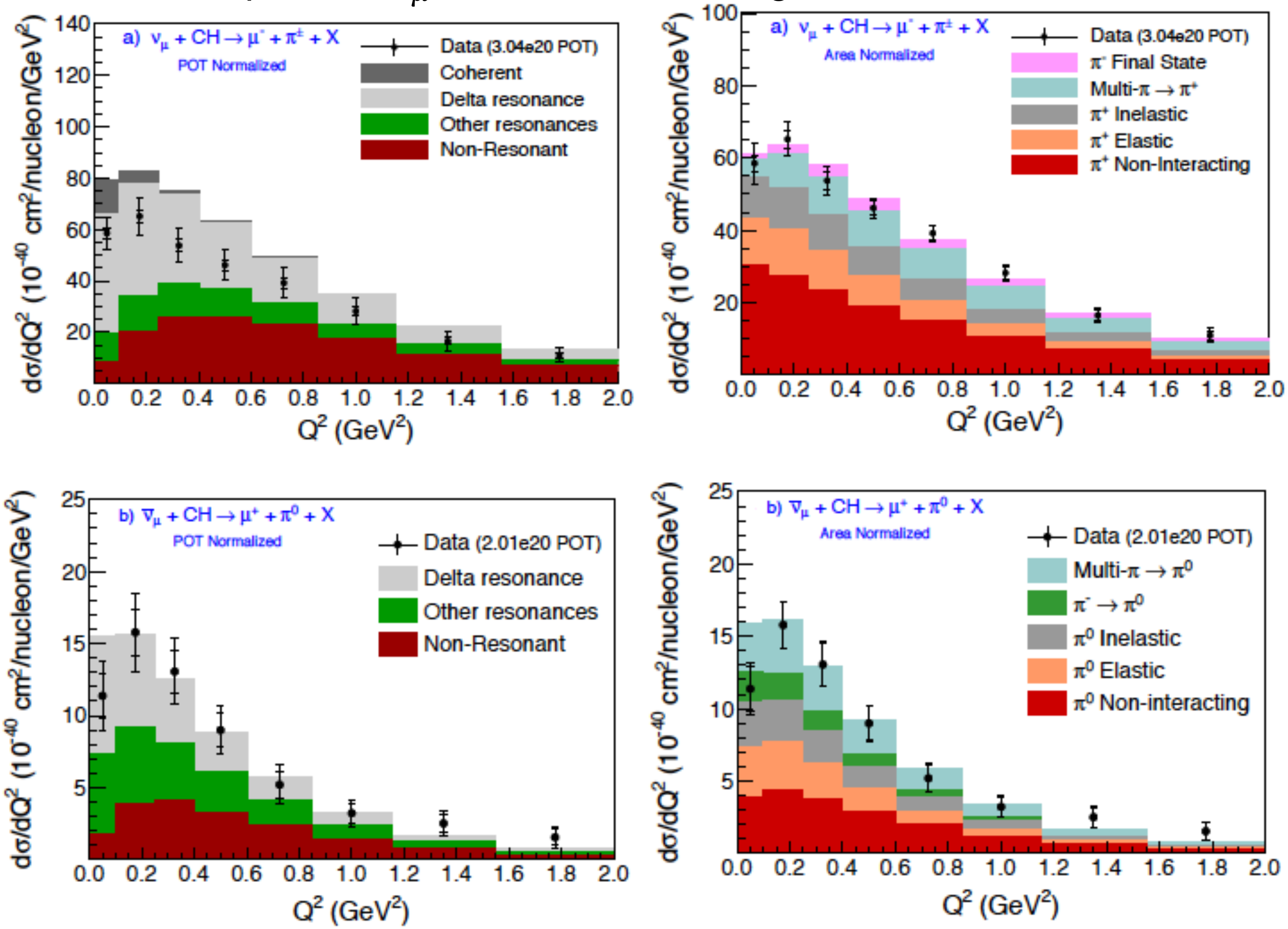
MINERvA ν_μCC1π^+ vs. $\overline{\nu_\mu}$CC1π^o

- In general, ν_μCC1π^+ has shape, and $\overline{\nu_\mu}$CC1π^o has norm agreement with simulation

It's hard to improve data-MC by tuning FSIs within GENIE.

Reduce non-resonant background.

Add RPA correction to fix low Q²?



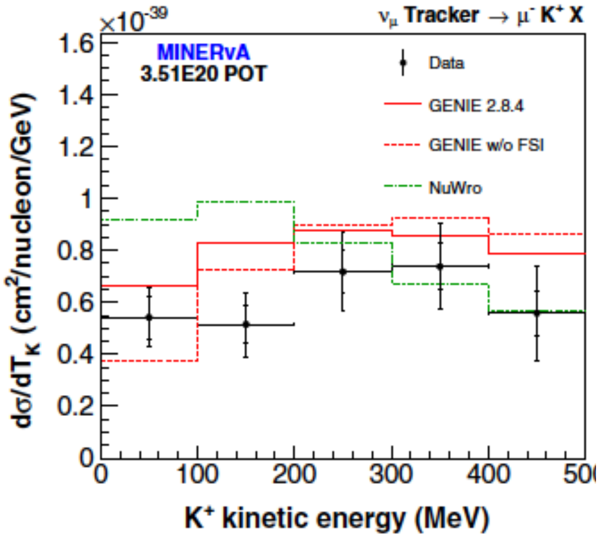
Queen
University of Lo

3. Other new MINERvA data (now)

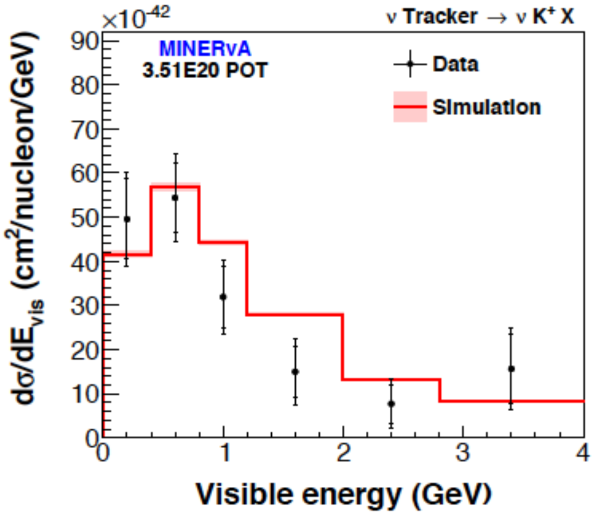
Chris Marshall (kaon main analyzer), a.k.a "MC Truth"
- Notorious nucleus (rap)
https://www.youtube.com/watch?v=jSQusza4VqA#t=3m42s

Kaon bombs

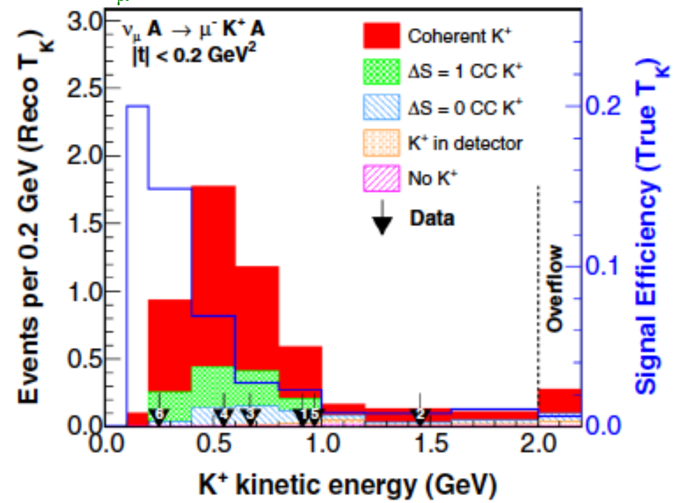
ν_μCC K^+ production



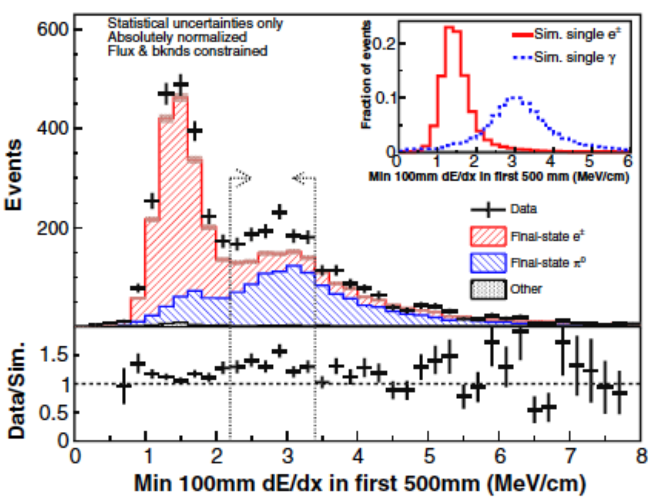
$\nu(\bar{\nu})$NC K^+ production



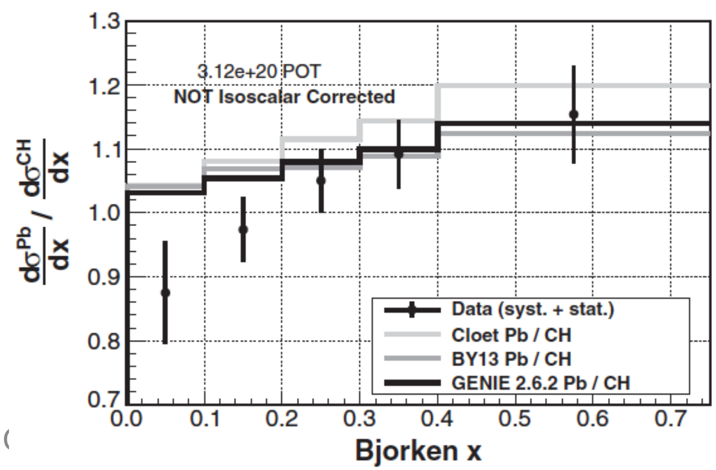
ν_μCC coherent K^+ production



Diffractive pion production



DIS target ratio



Dytman, Fermilab neutrino seminar (2015)

3. GENIE update

Many new neutrino pion production data are available from T2K and MINERvA, but theories are not successful to reproduce them. For GENIE, having correct pion production model and FSI (final state interaction) is an urgent issue (for DUNE, NOvA, T2K, etc)

Updates to GENIE

- v2.6.2 – used in all Minerva results shown today
- v2.8.6 – present production release
  - Improved FSI
  - Will be used for Minerva ME results
- v2.10.0 – imminent – same default (new alternate models)
  - Effective spectral function
  - Improved pion production form factors
  - Improved FSI (better A dependence)
- v2.12.0 – in progress
  - Spectral function nuclear model
  - Valencia MEC
  - Oset-Salcedo FSI model
  - Nieves QE/ local Fermi Gas nuclear model

46 FNAL Seminar 1 October, 2015

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%.

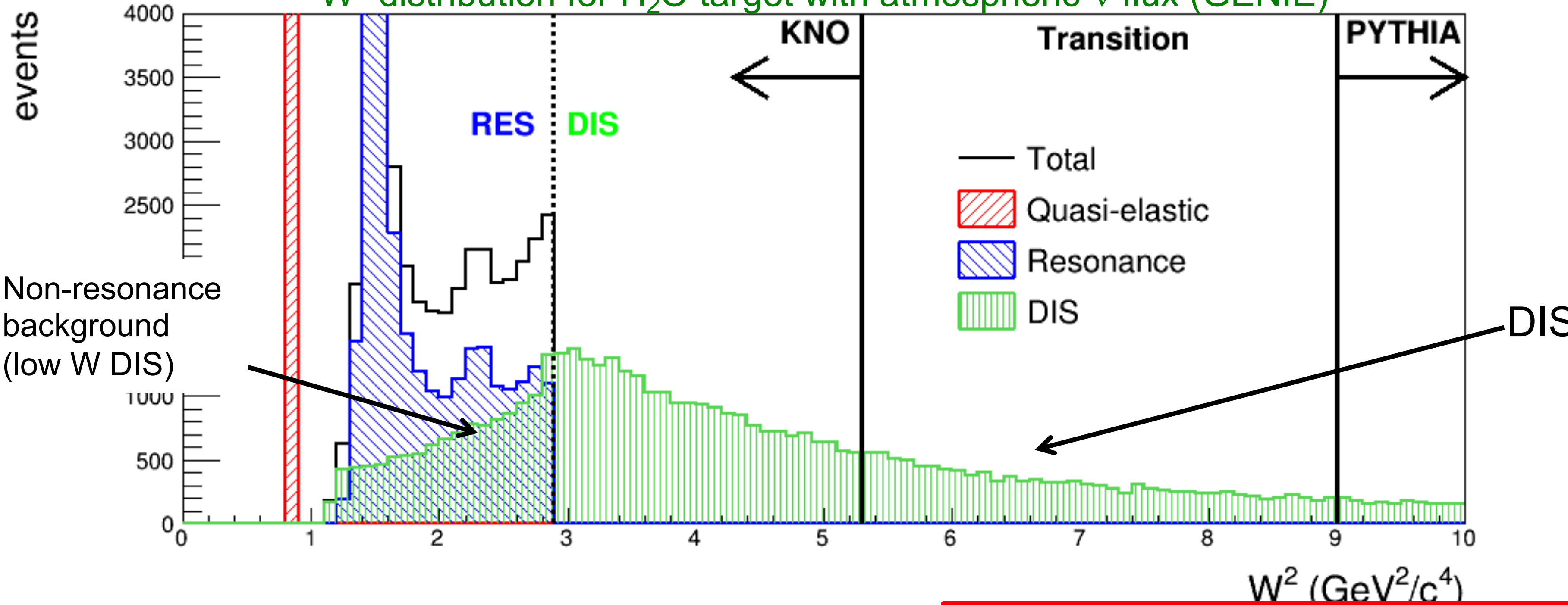
4. Shallow Inelastic Scattering (SIS) region

Cross section
W^2<2.9 GeV^2 : RES
W^2>2.9 GeV^2 : DIS
Hadronization (GENIE-AGKY model)
W^2<5.3GeV^2 : KNO scaling based model
2.3GeV^2<W^2<9.0GeV^2 : transition
9.0GeV^2<W^2 : PYTHIA6

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

Very important energy region for NOvA, PINGU, ORCA, Hyper-K, DUNE

W^2 distribution for H_2O target with atmospheric-ν flux (GENIE)



Typical "Frankenstein" style model!

AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

4. Shallow Inelastic Scattering (SIS) region

Cross section
$W^2 < 2.9\ GeV^2$: RES
$W^2 > 2.9\ GeV^2$: DIS
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$W^2 < 5.3 GeV^2$: KNO scaling based model
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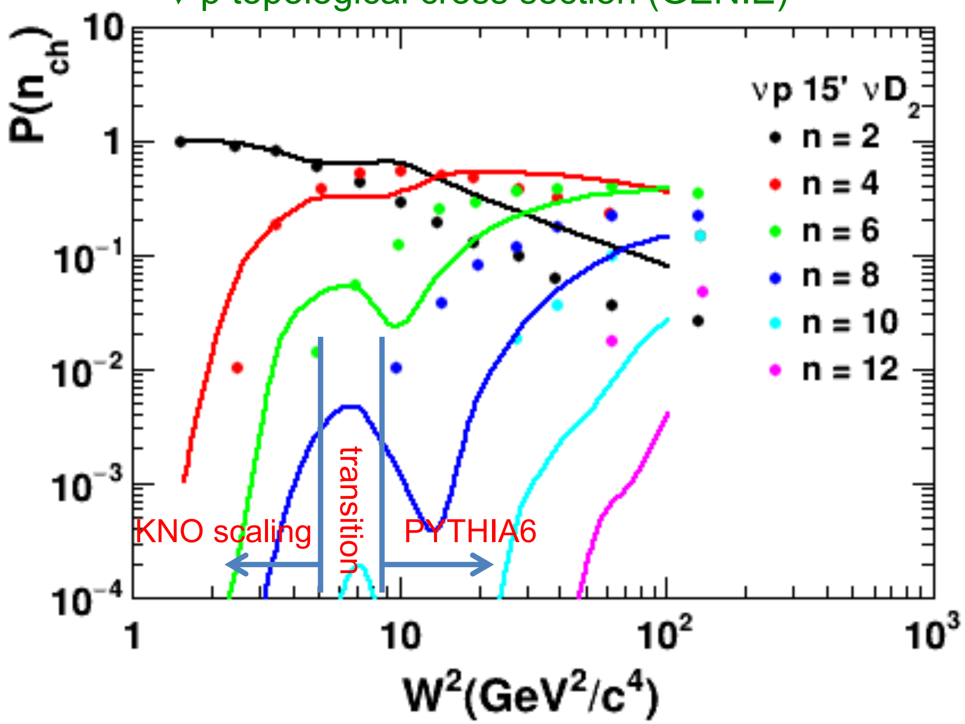
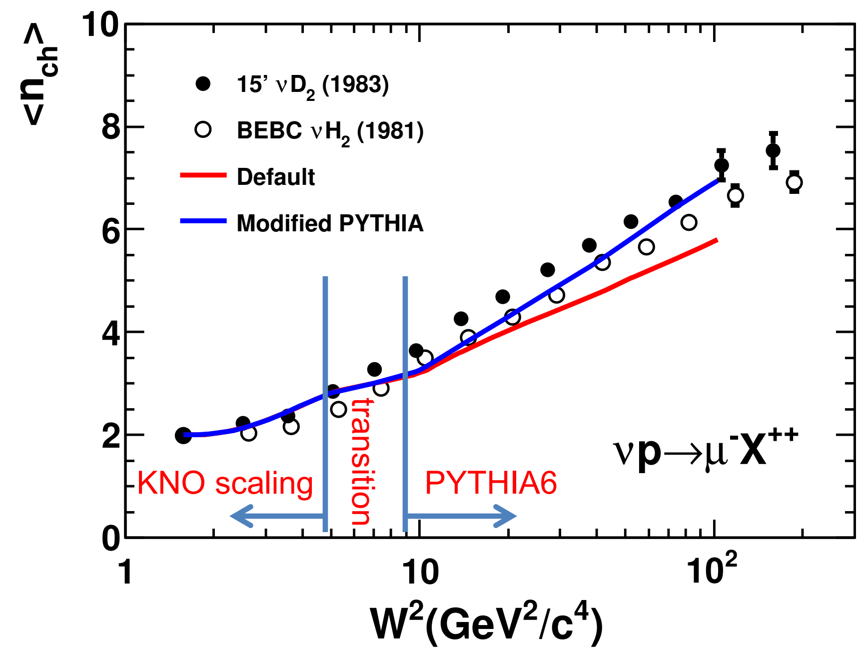
There are 2 kind of “transitions” in SIS region
- cross-section
- hadronization

Very important energy region for NOvA, PINGU, ORCA, Hyper-K, DUNE

ν-p topological cross section (GENIE)



ν-p averaged charged hadron multiplicity (GENIE)



Typical “Frankenstein” style model!

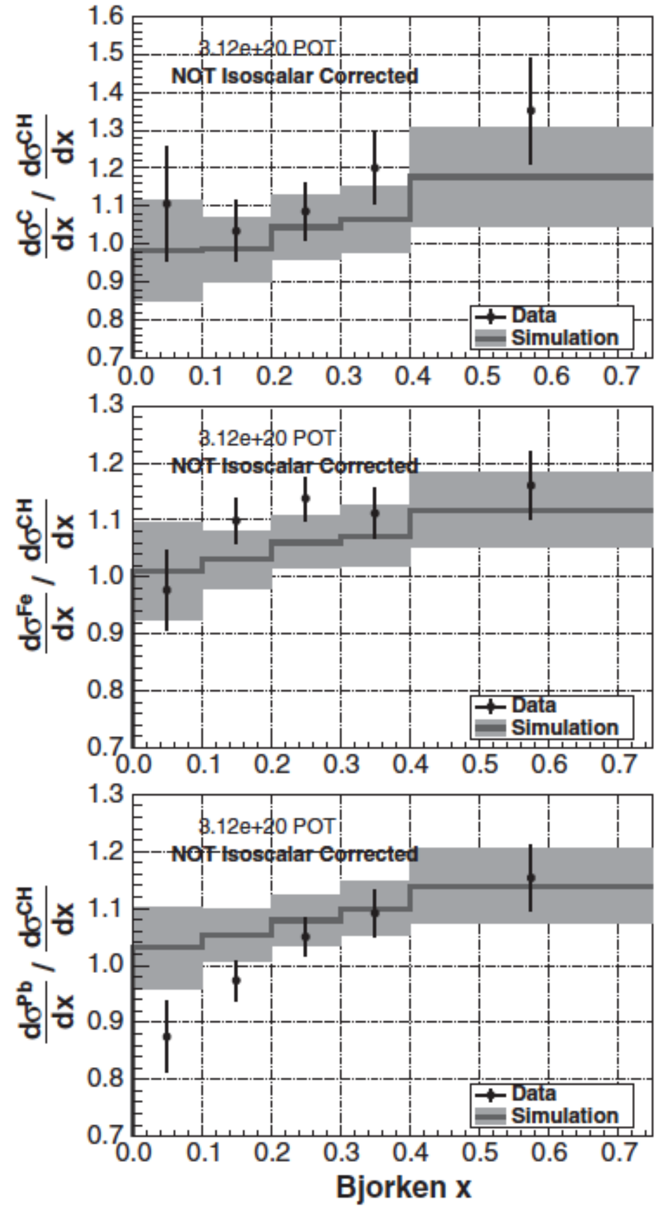
4. Shallow Inelastic Scattering (SIS) region

MINERvA DIS target ratio

- DIS event has non-trivial nuclear dependent (nuclear dependent PDF)

Since neutrinos interact with everything (neutrino beam ~ shower), MC needs to simulate neutrino interactions (and particle propagations) for all inactive materials.

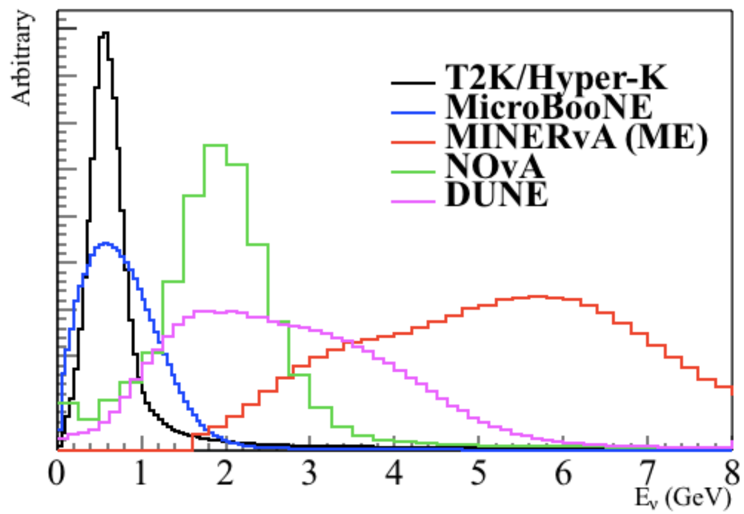
However, community is still using GRV98 LO PDF with Bodek-Yang correction…



4. Summary of SIS, DIS, and hadronization

DIS and hadronization processes have been ignored for oscillation experiments

DIS errors and hadronization errors are not considered seriously
→ Problem for future PINGU, ORCA, DUNE



SIS are 3 times wrong
- no good low Q^2 DIS model
- no good neutrino hadronization model
- no realistic SIS model (resonance→DIS)

5. Conclusion remarks from INT workshop 2013

"ν-A Interactions for Current and Next Generation Neutrino Oscillation Experiments", Institute of Nuclear Theory (Univ. Washington), Dec. 3-13, 2013

Toward better neutrino interaction models…

To experimentalists

- The data must be reproducible by nuclear theorists
- State what is exactly measured (cf. CCQE → 1muon + 0 pion + N nucleons)
- Better understanding of neutrino flux prediction

To theorists

- Understand the structure of 2-body current seen in electron scattering
- Relativistic model which can be extended to higher energy neutrinos
- Models should be able to use in neutrino interaction generator (cf. GENIE)
- Precise prediction of exclusive hadronic final state

4. Differential cross-section measurements for New physics

Differential cross-section measurement itself is often new physics search
→ model-independent rate measurements

Two tantalizing examples

1. Neutral Current gamma production (NCγ) and MiniBooNE low energy excess
2. Neutral Current Quasi-Elastic (NCQE) scattering and dark matter particle search

MiniBooNE,PRL110(2013)161801
TK, arXiv:1107.5112

4. MiniBooNE low energy excess

MiniBooNE observed oscillation candidate event excess
→ but MiniBooNE cannot distinguish e and γ

signal

$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \rightarrow p + e^-$$

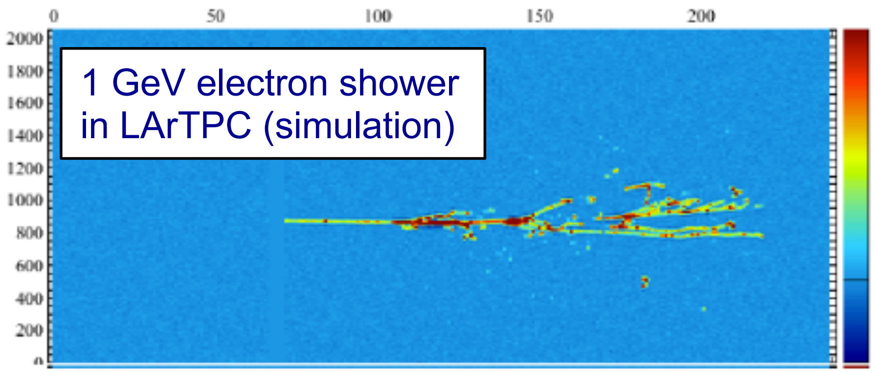
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow n + e^+$$

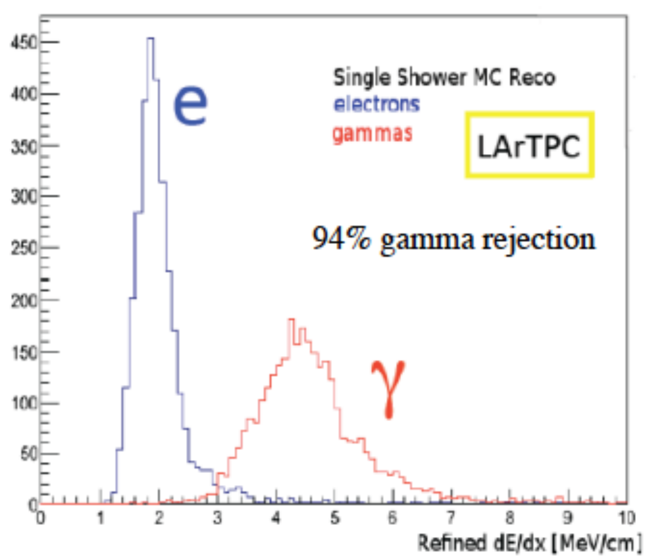
background

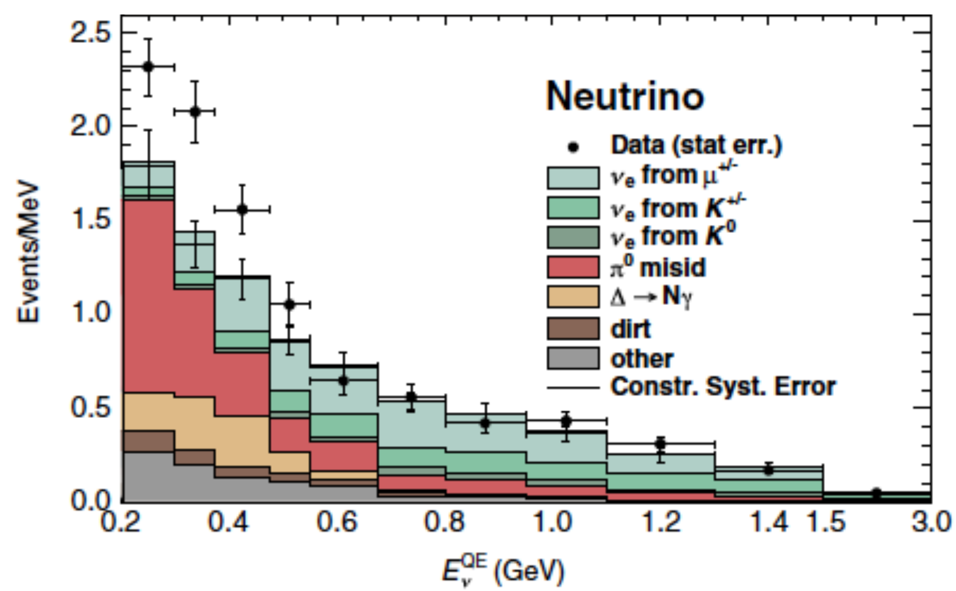
$$\nu_\mu + X \rightarrow \nu_\mu + X' + \pi^o \rightarrow \gamma + \gamma$$

$$\nu_\mu + X \rightarrow \nu_\mu + X' + \gamma$$

Can new NCγ model explain this excess?







Alvarez-Ruso,Nieves,Wang, arXiv:1311.2151, Zhang,Serot, PLB719(2013)409
Hill, PRD81(2010)013008, Gninenko, PRL103(2009)241802

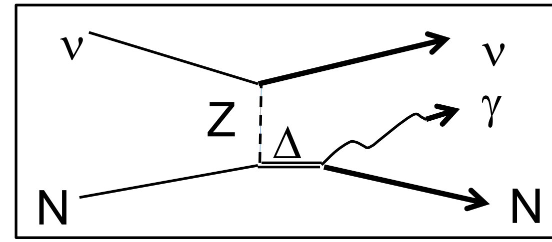
4. MiniBooNE low energy excess

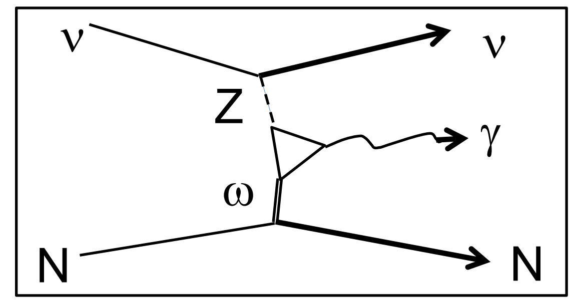
MiniBooNE observed oscillation candidate event excess
→ but MiniBooNE cannot distinguish e and γ

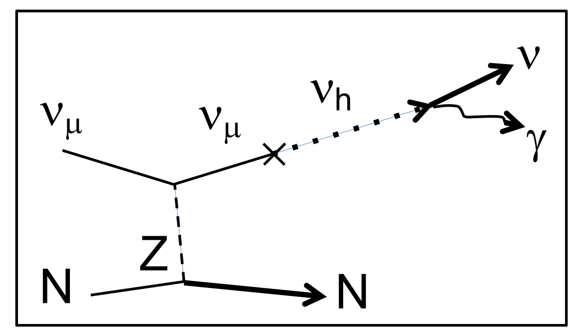
Can new NCγ model explain this excess?

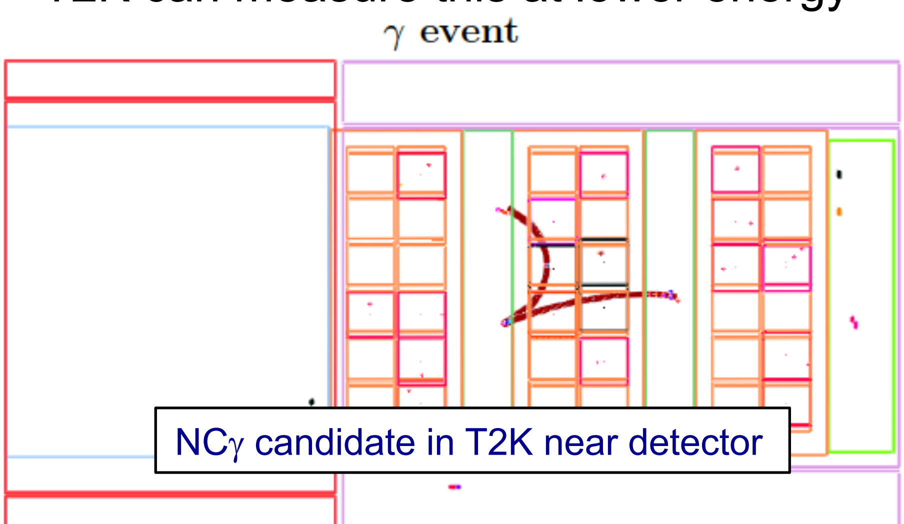
1. New nuclear models
2. New mechanism but within the SM
3. Beyond the SM but not sterile neutrino oscillation

NOMAD measured at <E>~25GeV
T2K can measure this at lower energy









NCγ candidate in T2K near detector

Differential cross-section measurement can test, nuclear physics, new diagram, and BSM physics simultaneously!

4. Neutral Current Quasi-Elastic (NCQE) scattering

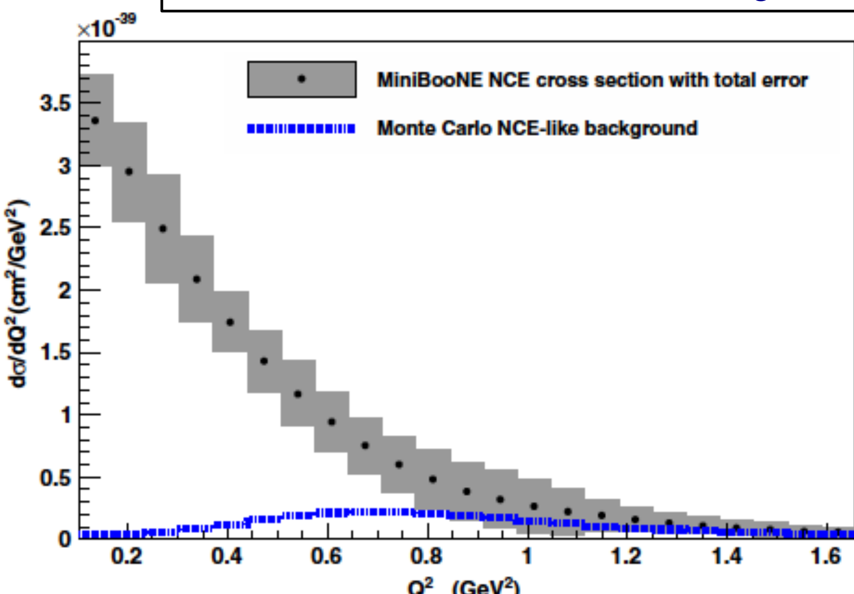
This channel has so many topics

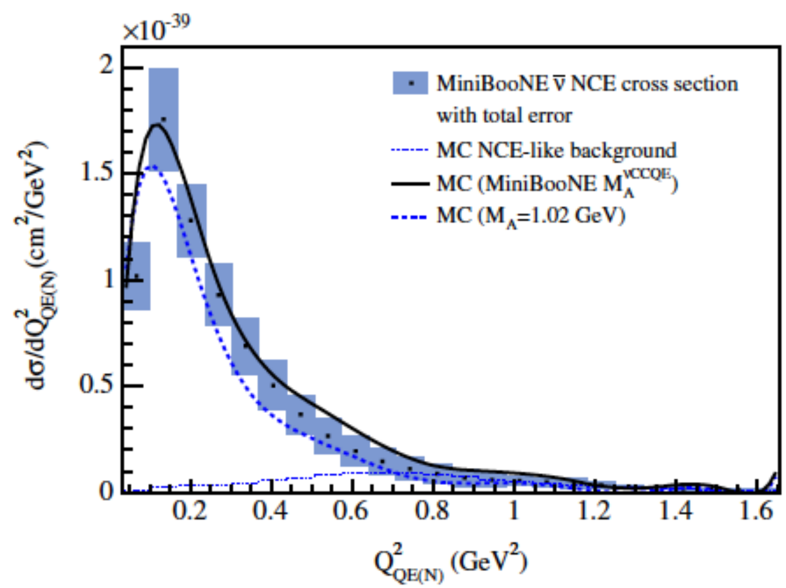
1. Spin physics
2. Sterile neutrino oscillation
3. Light dark matter particle

$$\nu_\mu + p \rightarrow \nu_\mu + p \quad (\nu_\mu + X \rightarrow \nu_\mu + p + X')$$

$$\nu_\mu + n \rightarrow \nu_\mu + n \quad (\nu_\mu + X \rightarrow \nu_\mu + n + X')$$

Neutrino and anti-neutrino flux-integrated NCQE differential cross-section on CH_2





Garvey et al,PRC48(1993)761, Pate et al,PRC78(2008)015207
HERMES,PLB666(2008)446,

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"proton spin crisis"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

quark longitudinal polarization
ΔΣ=Δu+Δd+**Δs** ~ 0.25

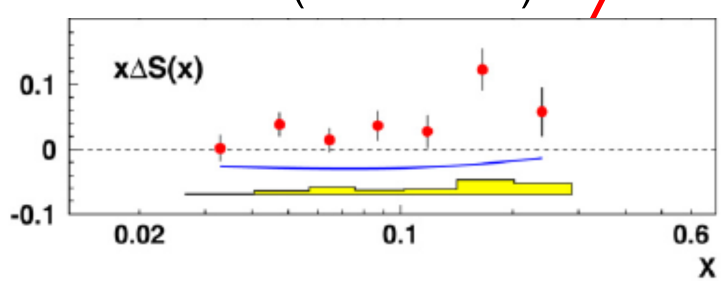
gluon longitudinal polarization ~ 0.2

quark and gluon orbital angular momentum ~?

NC is a unique source of axial-vector isoscalar form factor → strange quark spin components (Δs)

$$\int_0^1 dx\Delta s(x) \equiv \Delta s \equiv G_A^s(Q^2 = 0)$$

HERMES SIDIS
~0 (0.02<x<0.6)



ν_μNCQE+
PV e-scattering
~ -0.1

Garvey et al,PRC48(1993)761, Pate et al,PRC78(2008)015207
HERMES,PLB666(2008)446, Butkevich et al,PRC84(2011)015501

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quark longitudinal polarization
$\Delta\Sigma=\Delta u+\Delta d+\Delta s$ ~ 0.25

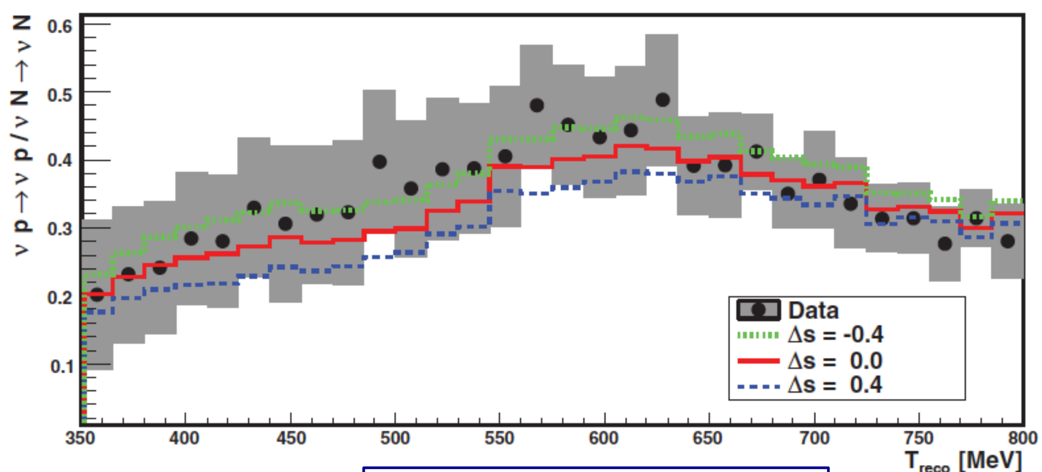
gluon longitudinal polarization ~ 0.2

quark and gluon orbital angular momentum ~?

NC is a unique source of axial-vector isoscalar form factor → strange quark spin components (Δs)

The latest fit is consistent with Δs~0

Problem: separation of νp→νp and νn→νn scattering is very hard



Δs fit on νp→νp/νN→νN data

Wilkinson et al,JHEP01(2014)064

4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

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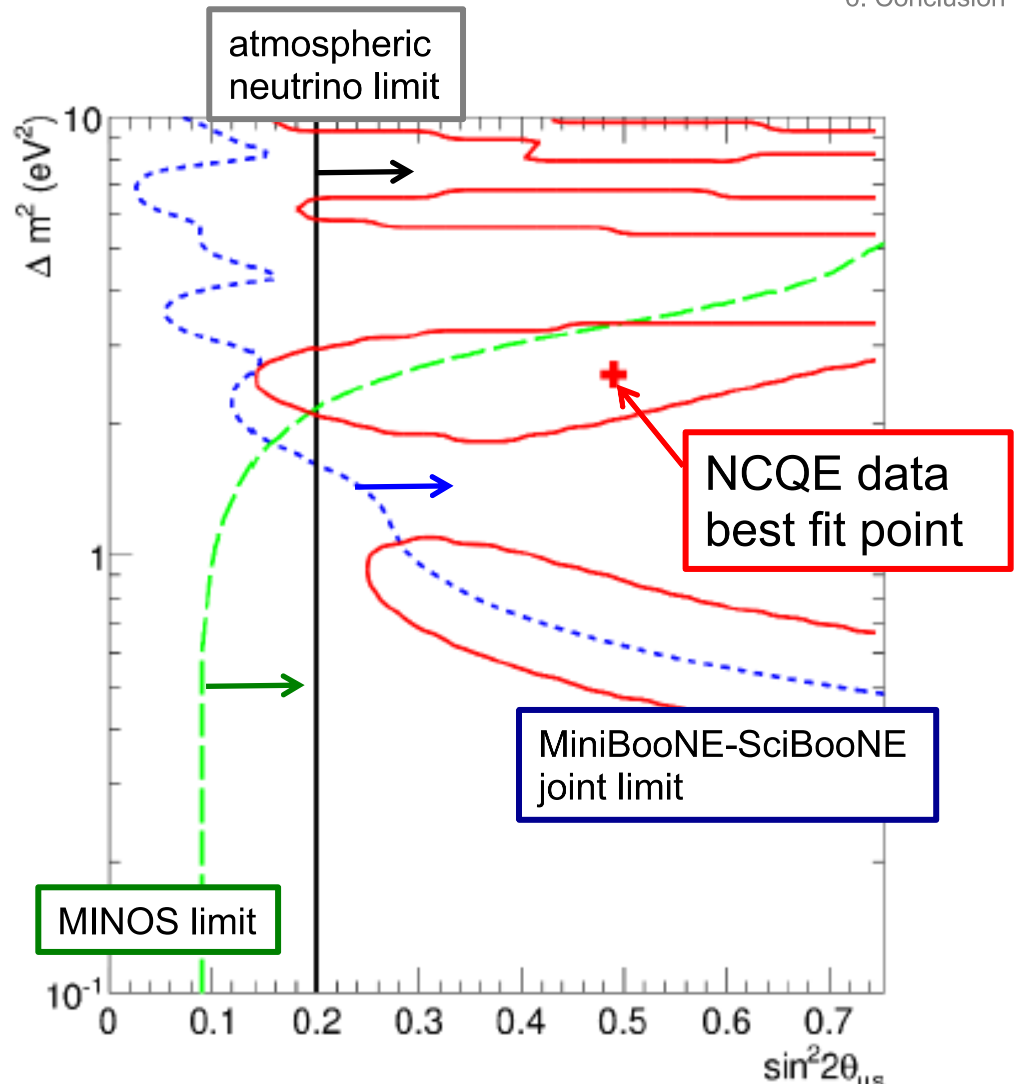
2. Sterile neutrino oscillation
3. Light dark matter particle

NC data can test sterile neutrino hypothesis independently
- different event topology

Problem: large cross-section error
→ simultaneous fit of sterile neutrino parameters and neutrino interaction parameters.



TK et al, AHEP(2015)362971
deNiverville et al,PRD84(2011)075020, Batell et al,PRD90(2014)115014

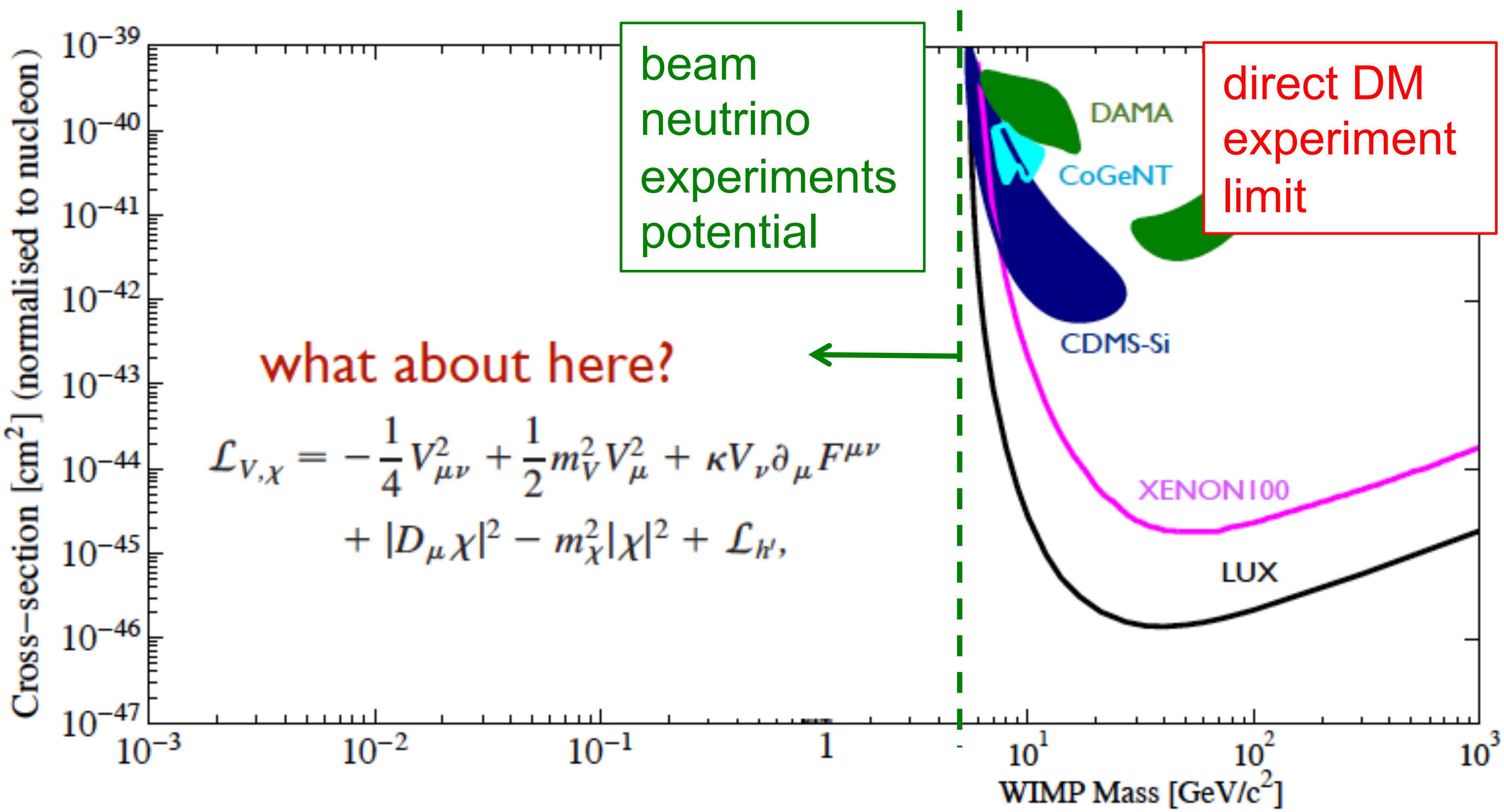
4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

1. Spin physics
2. Sterile neutrino oscillation
3. Light dark matter particle

Experiment sensitive to NCQE are sensitive to all invisible-type particles (cf dark matter particles)

→ NCQE is a large background. Understanding of NCQE is important.



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Both measurements and predictions of hadron final states need to be improved

- nucleon correlation
- baryon resonance
- final state interactions
- hadronization

There is a huge potential of discovery physics!