WG2 summary

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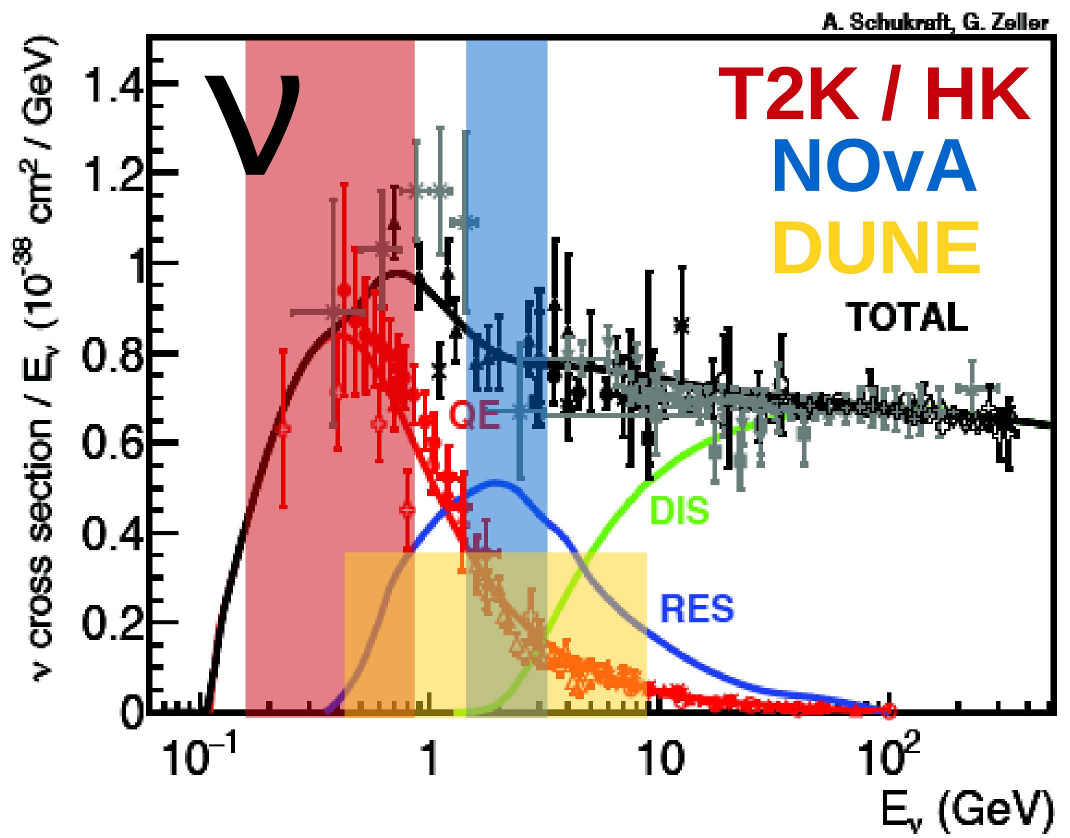
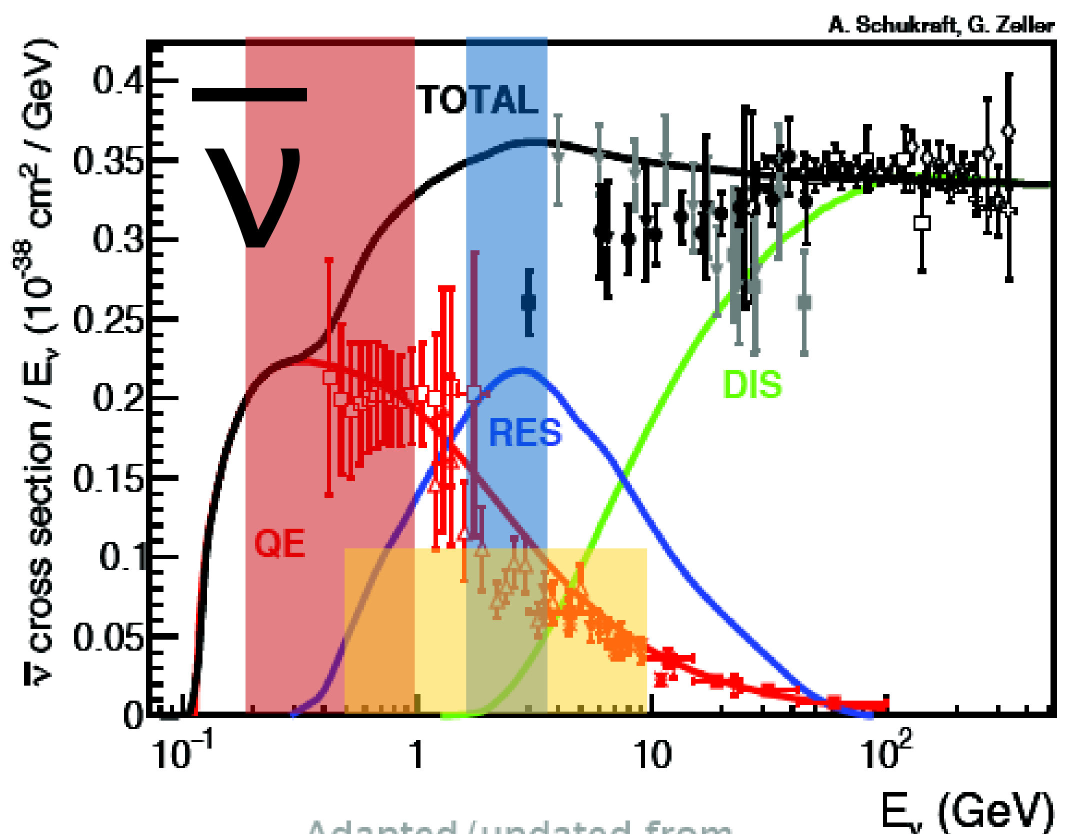
Marco Martini (CEA/Saclay),
Gabriel Perdue (FNAL)

NuFact 2016, August 27, 2016

WG2: ν Scattering Physics

- Present & future ν oscillation meas. have contribution from multiple interaction modes:
  - CCQE-like
    - CCQE, CC-multi nucleon
  - Resonant-π
  - Coherent-π / Diffractive-π
  - Multi-π
  - Deep Inelastic Scattering
- ν osc. measurement requires precise knowledge of each of int. modes
  - Current status on measurements and systematics handling well summarized by Jeff Nelson and Dan Cherdack (Plenary#6)





Adapted/updated from
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

ν-Nucleus interaction

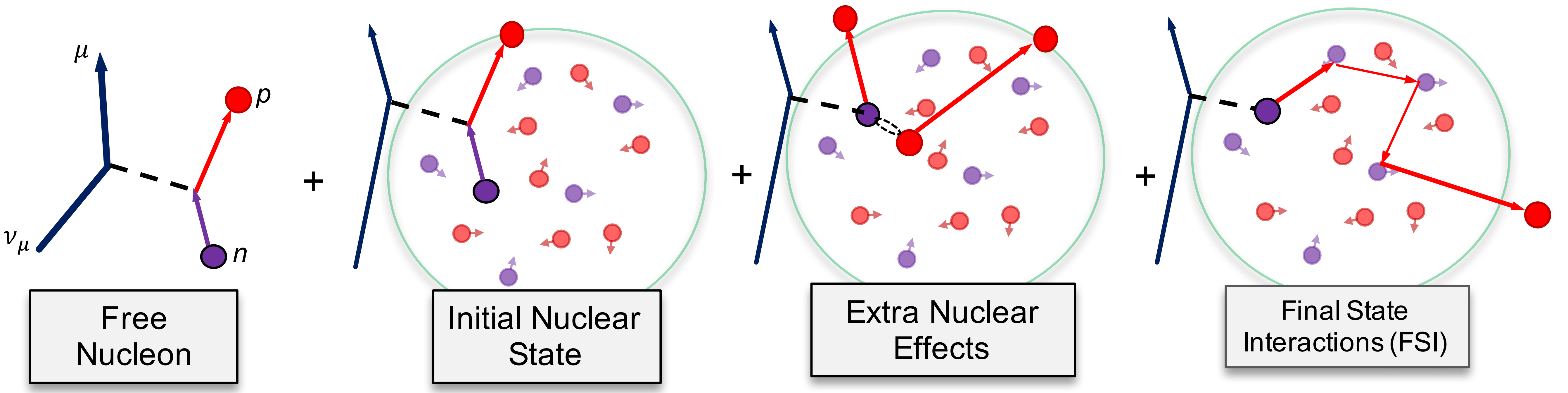


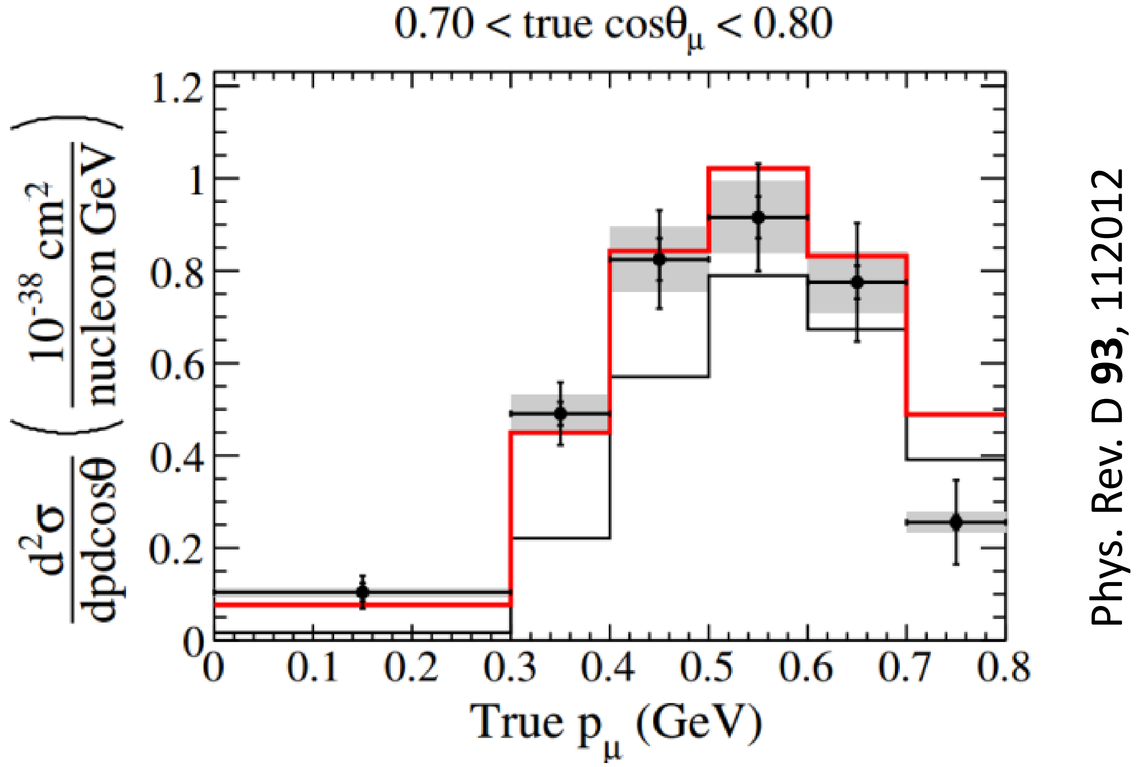
Figure from Patrick Stowell

- ν-A interactions
  - Fundamental reaction cross section (free nucleon)
  - Nuclear model (nucleons are not at rest)
  - Multi-nucleon contributes in the reaction (ex. 2p2h)
  - FSI / nuclear effect in nuclear medium

- In order to reduce ν-A int. systematics, each component needs to understand precisely

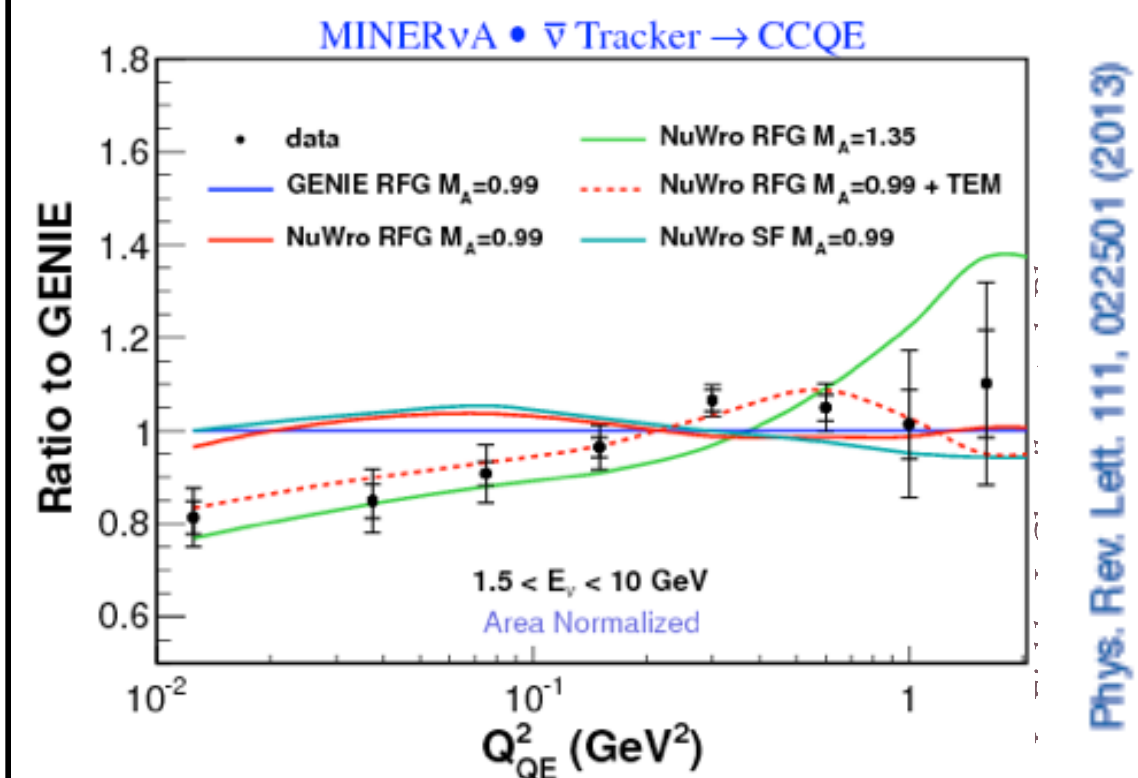
2p2h

T2K: CC0π

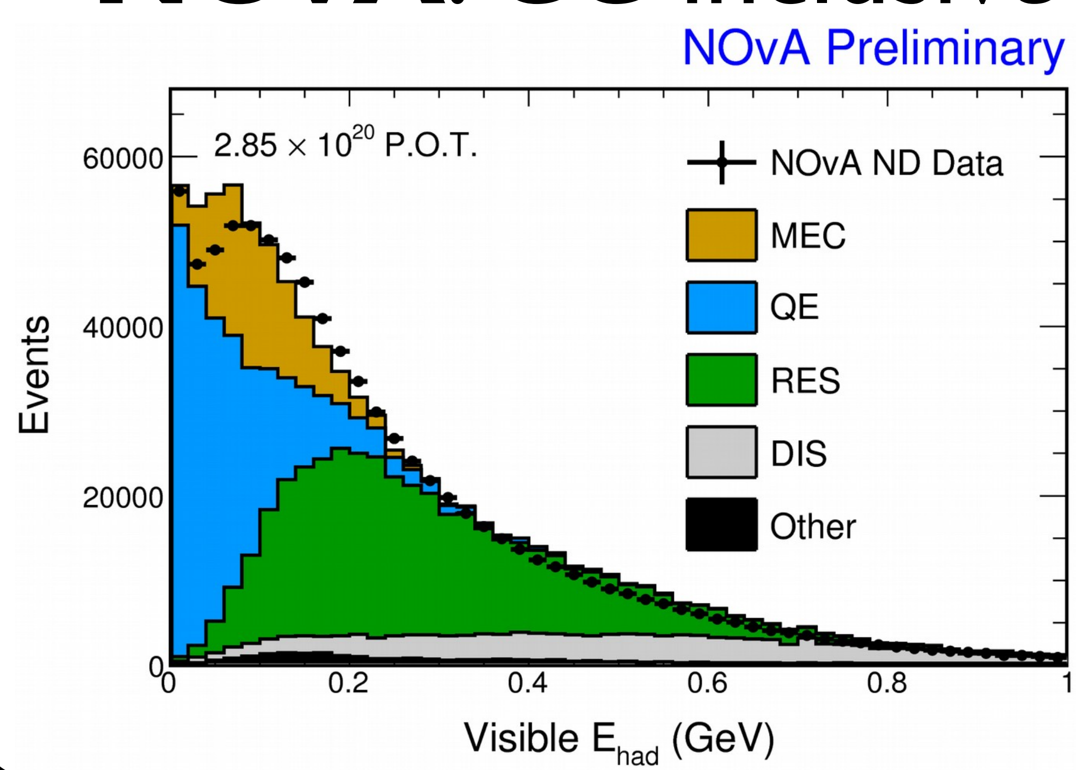


Results compared to Martini *et al.* model **with(red)**/**without(black)** 2p2h

MINERvA: CCQE



NOvA: CC inclusive



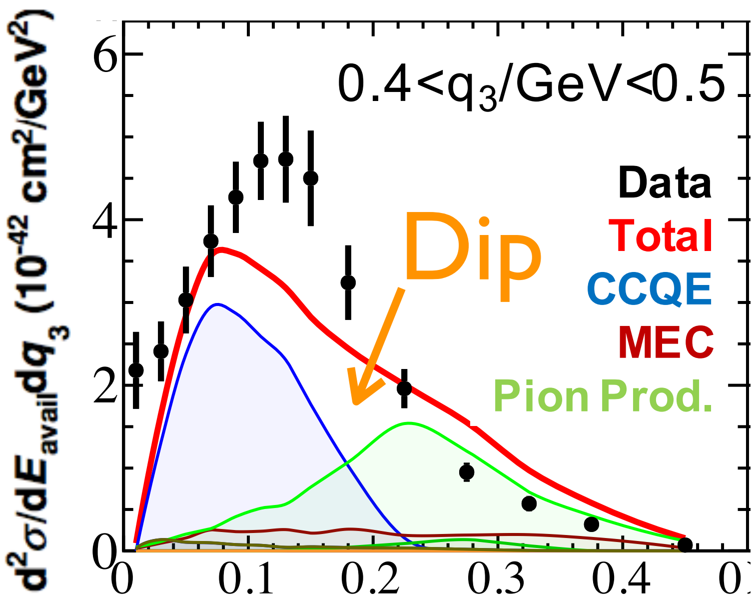
- T2K/MINERvA/NOvA data favors 2p2h contributions

T2K: Stephen Dolan (WG2 parallel#1)
MINERvA: Jeff Nelson (WG2 parallel#1)
NOvA: Jeremy Wolcott (WG2 parallel#1)

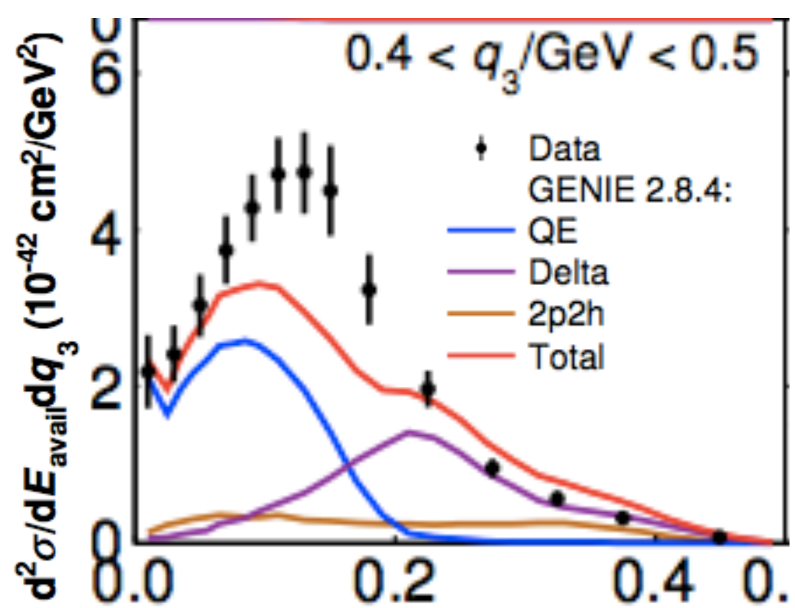
Data/MC comparison

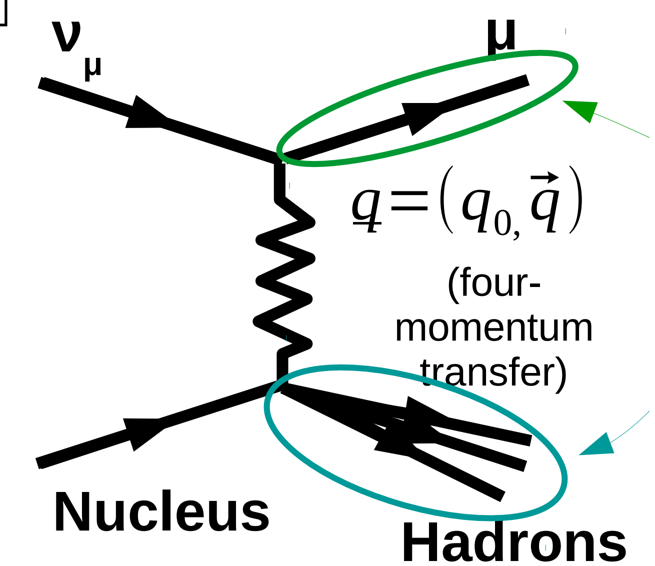
Patrick Stowell (WG2 parallel#4)

NEUT v5.3.6



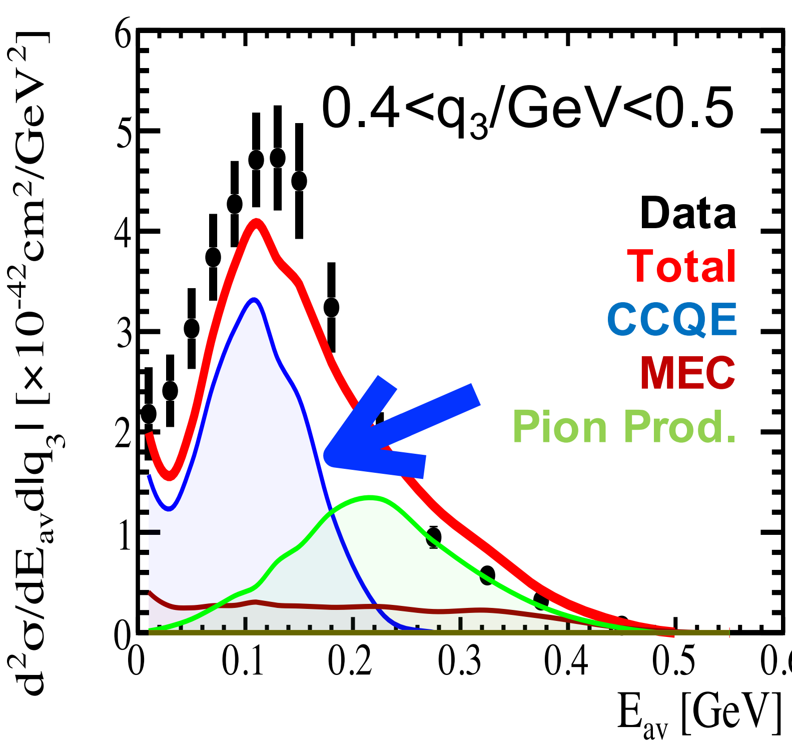
GENIE 2.8.4





$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

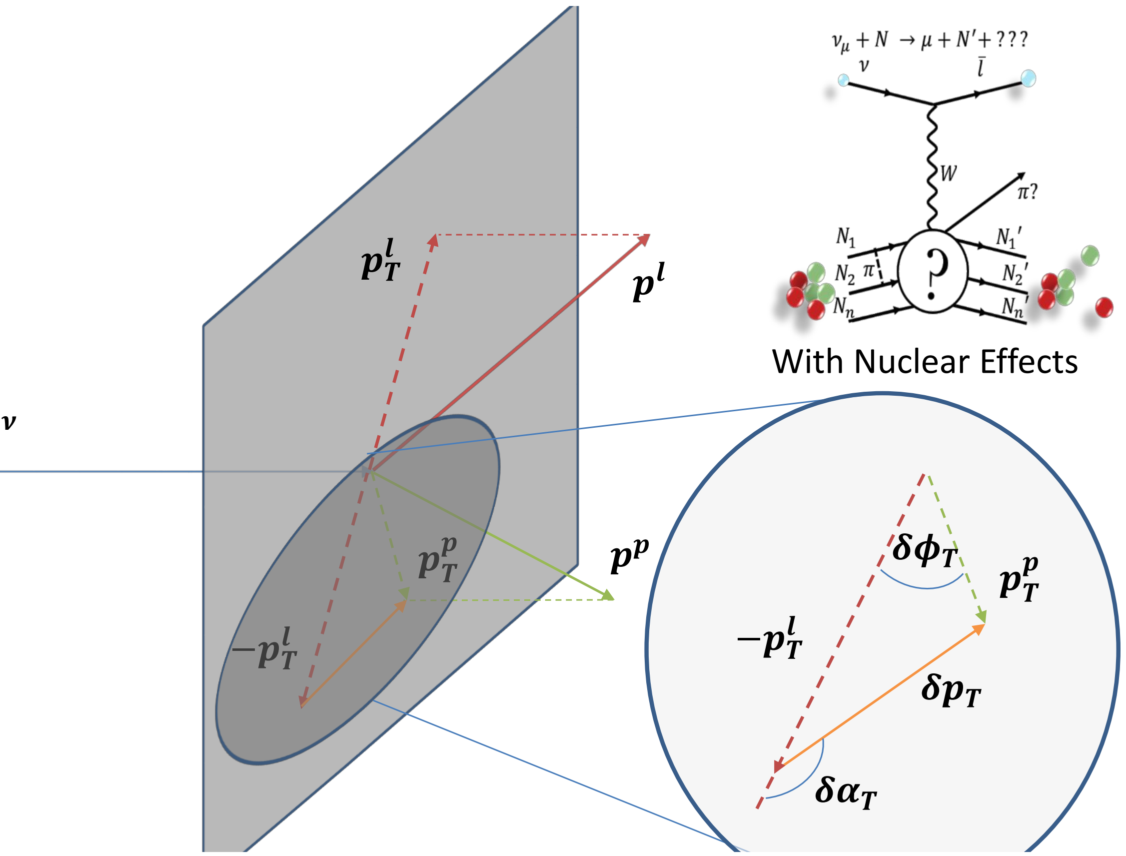
NUWRO v12



- Data: MINERvA CC inclusive 'Available Energy distributions'
  - Sum of final state 'visible' particle energies
- MC generators struggle to explain MINERvA data: "dip disagreement"
- Smaller disagreement for NUWRO comes from CCQE (1p1h) model
  - 1p1h: QE+nuclear model+FSI, ...
- Need to understand 1p1h model as well

T2K: disentangle the effects

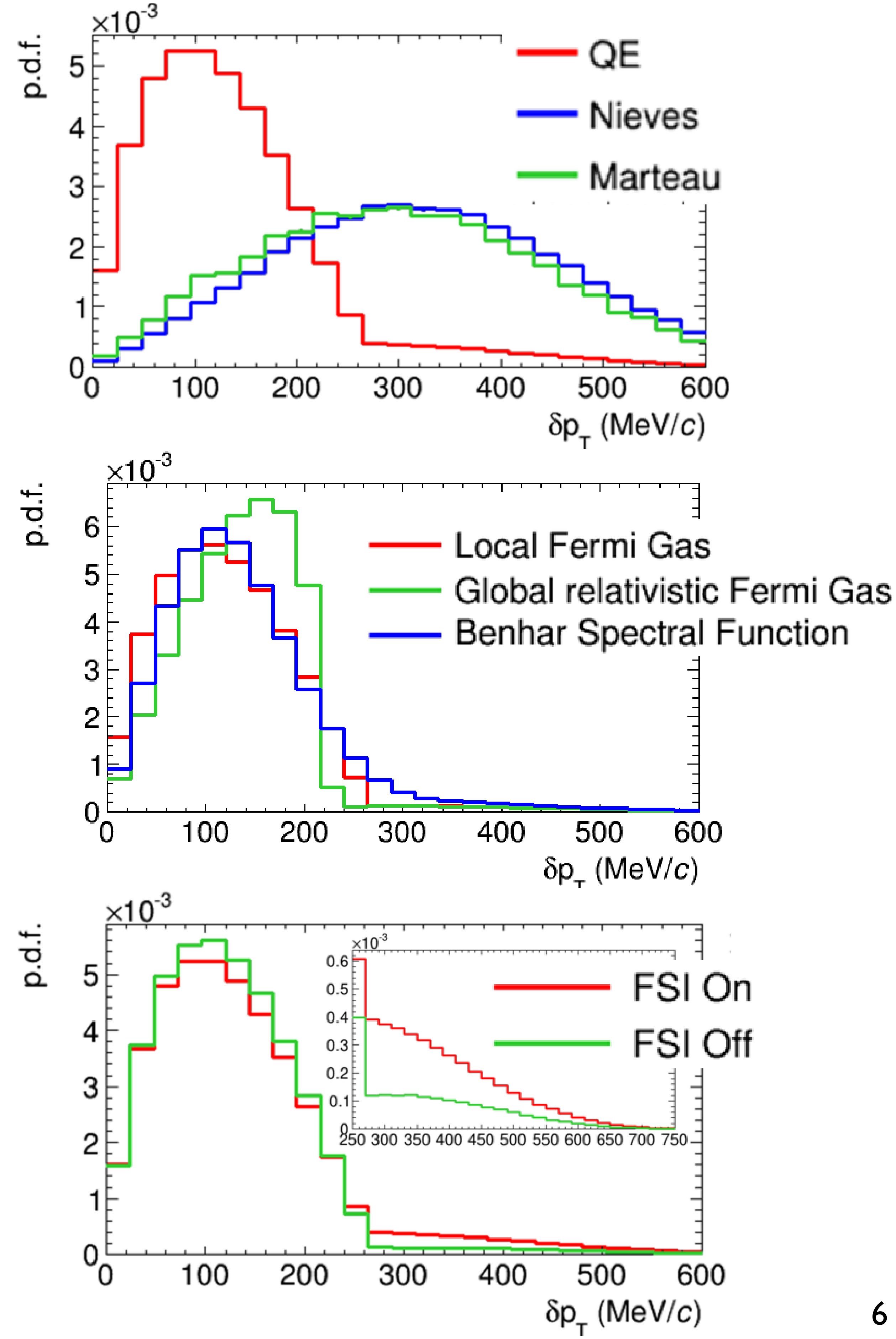
Stephen Dolan (WG2 parallel#1)



3 single transverse variables (STV) characterise imbalance in plane transverse to incoming ν *

For CCQE case any deviation from $\delta p_T = 0$, $\delta\phi_T = 0$ is indicative of nuclear effects

- Lepton/proton 'transverse imbalance' can be a probe to disentangle effects of nuclear model, QE, 2p2h, FSI, ...

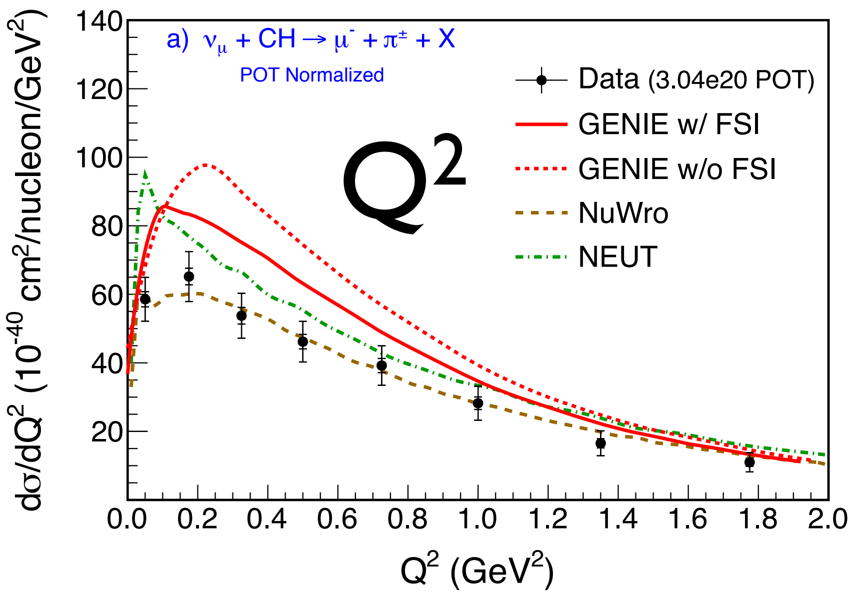


CC1π on CH

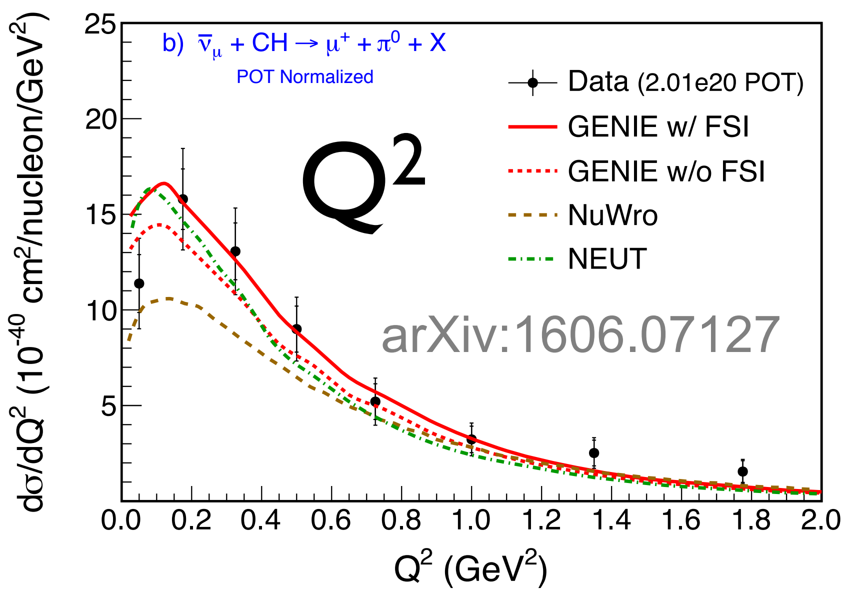
T2K: Erez Reinherz-Aronis (WG2 parallel#8)
MINERvA: Jorge G. Morfin (WG2 parallel#8)

MINERvA

ν CC1π+X

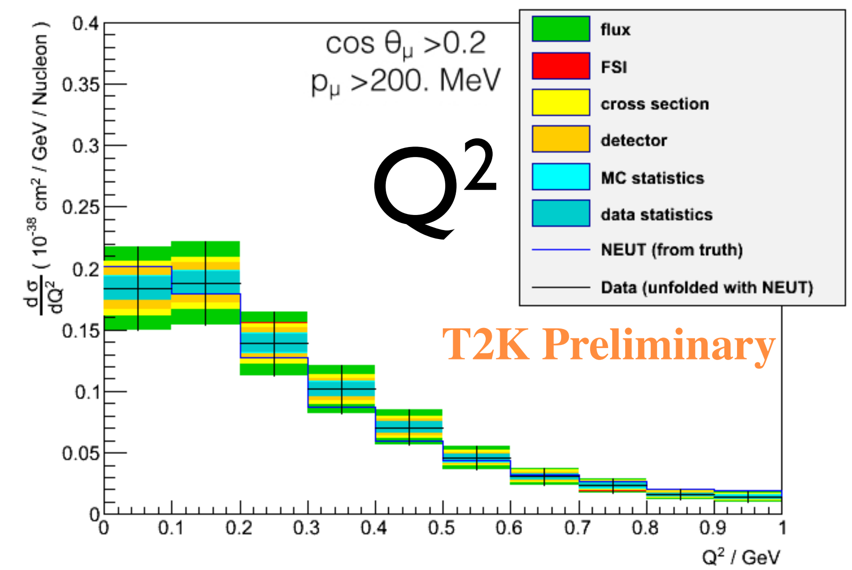


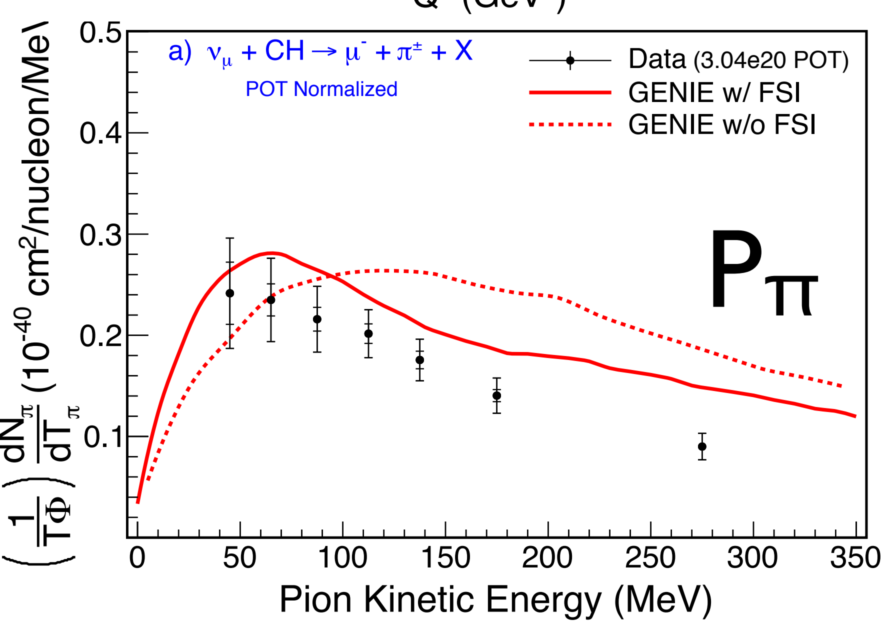
$\bar{\nu}$ CC1π+X

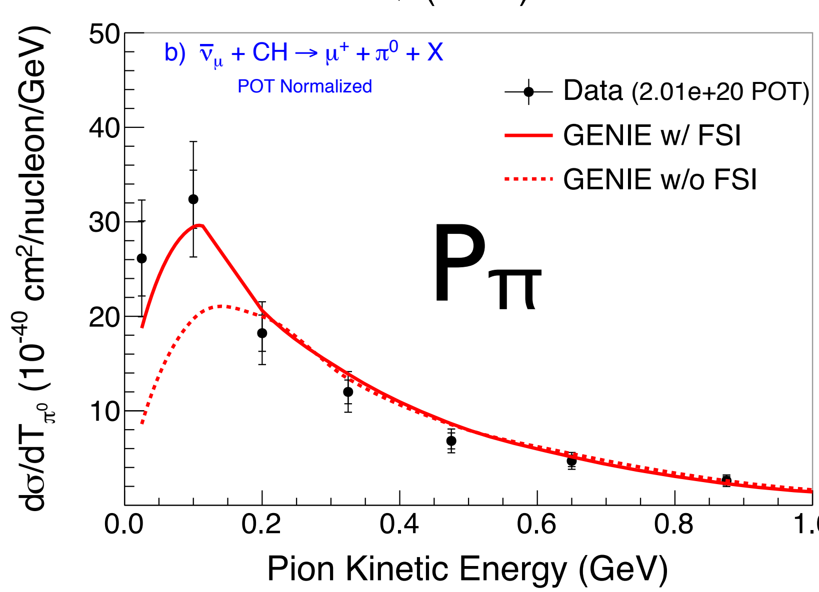


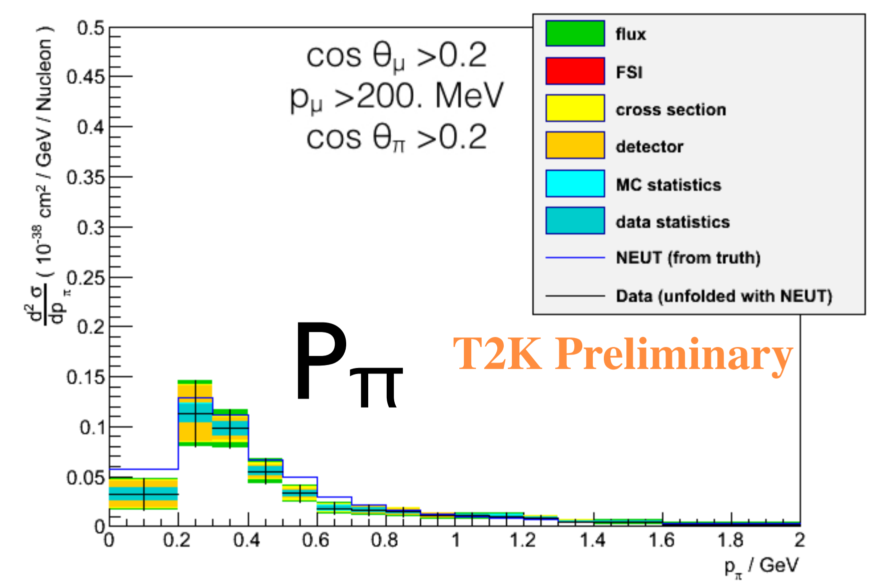
T2K ν CC1π

(cosθ$_{\mu/\pi}$>0.2, P$_{\mu/\pi}$>200MeV)







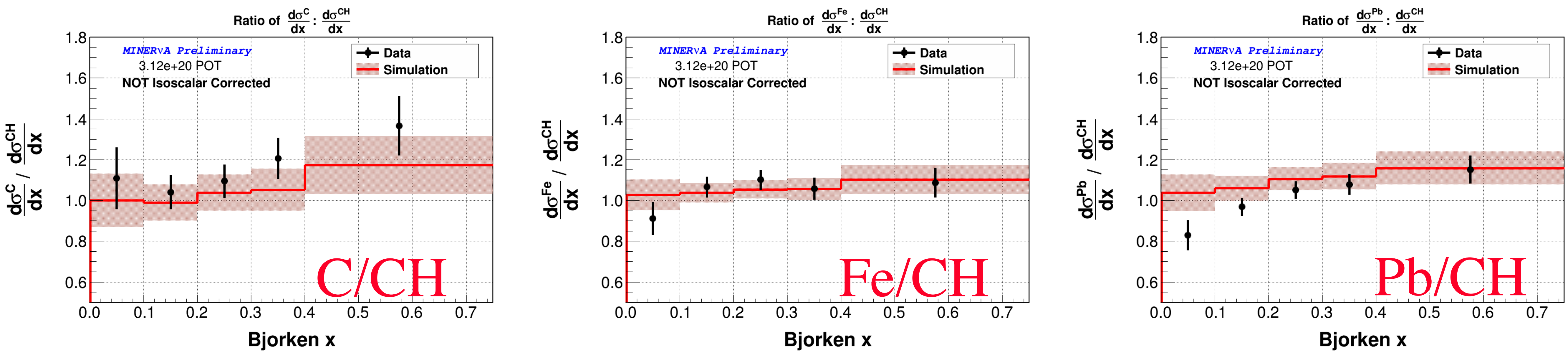


- T2K/MINERvA data indicate FSI contribution
- Note: T2K/MINERvA not an apple-to-apple comparison…

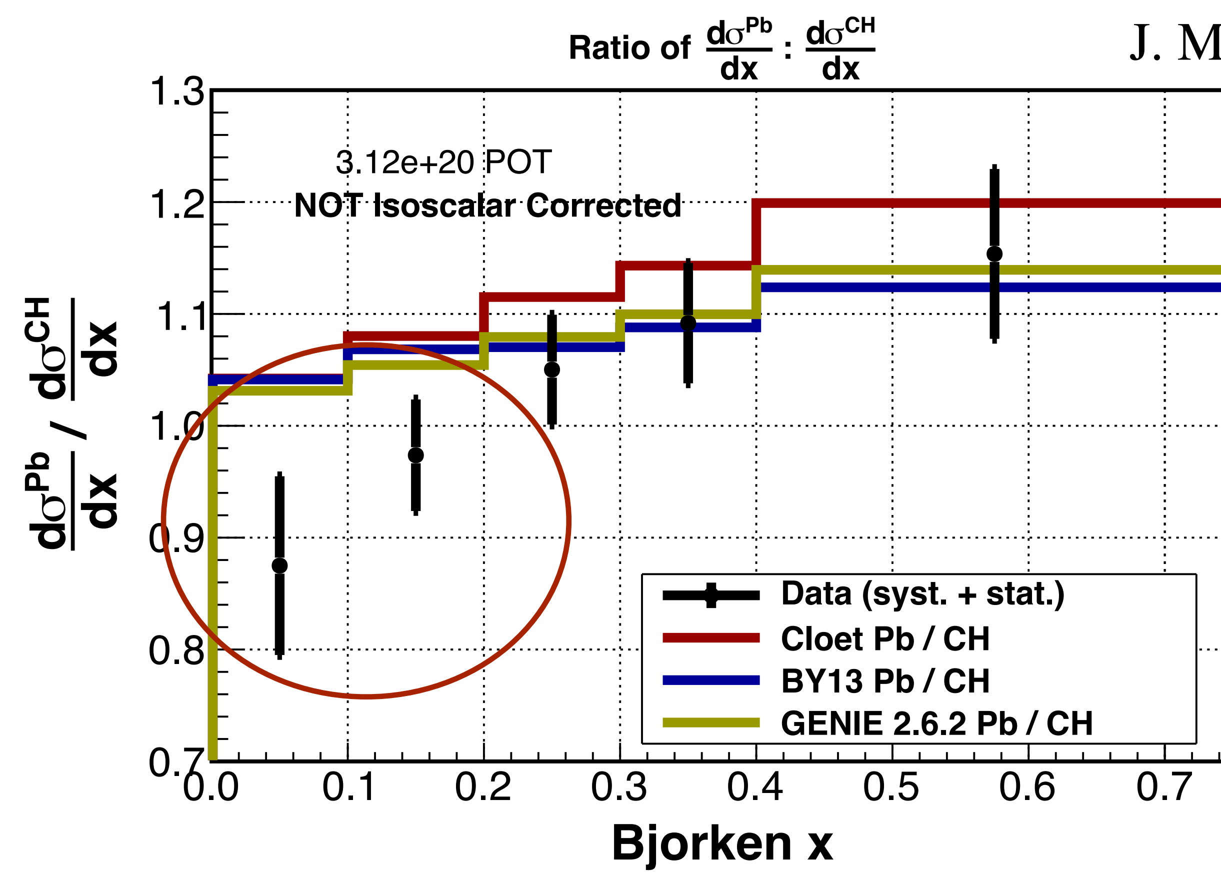
CC inclusive

Phys. Rev. D 93, 071101 (2016)

Jorge G. Morfin (WG2 parallel#8)



J. Mousseau



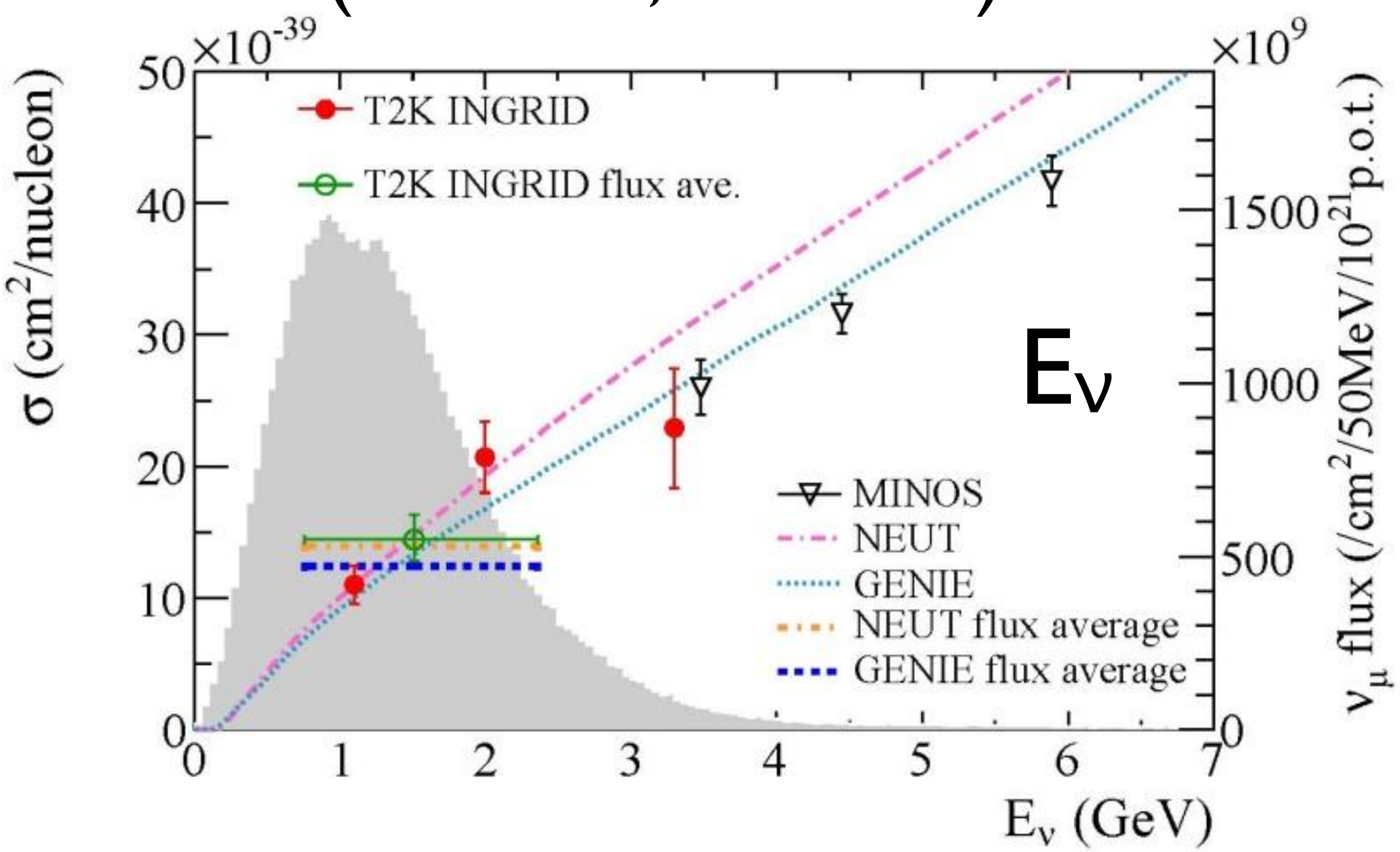
- **MINERvA** CC inclusive
- General agreement between data/MC within stat+syst error
- Lead data hints additional nuclear shadowing at low x_{Bj}

CC inclusive

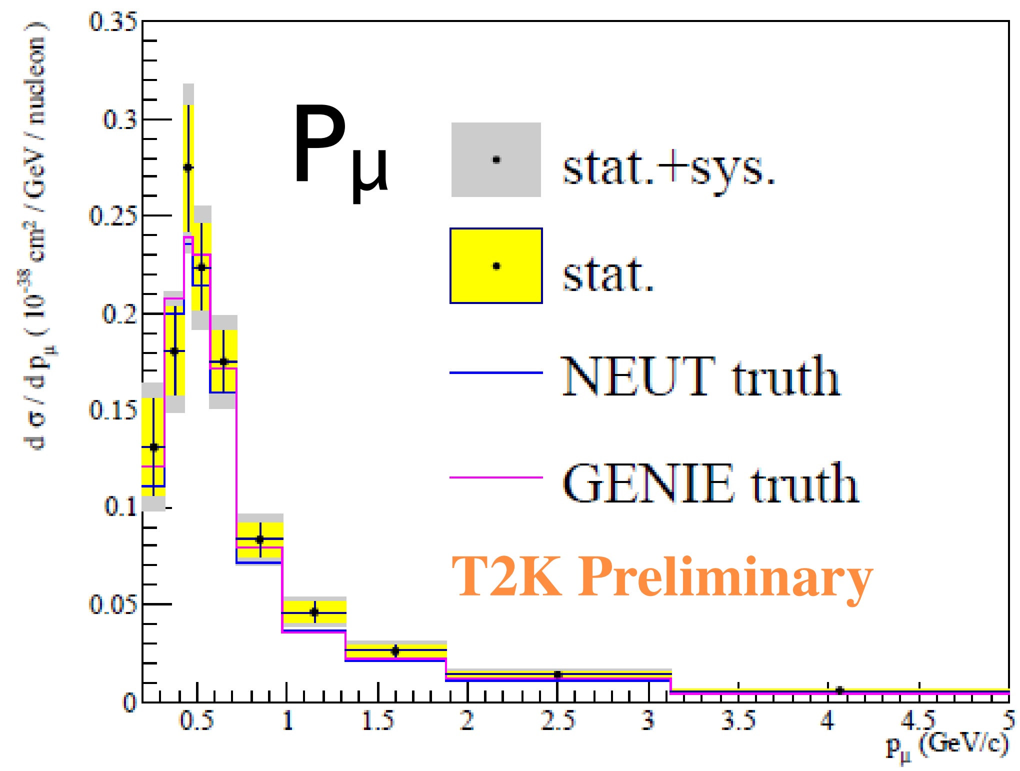
Erez Reinherz-Aronis (WG2 parallel#8)

T2K INGRID & ND280

ν CC Inclusive on Fe
(INGRID; On-Axis)



$\bar{\nu}$ CC inclusive on CH
(ND280; Off-Axis)



CC inclusive

$$\sigma(\bar{\nu}) = (0.91 \pm 0.03(\mathrm{stat}) \pm 0.09(\mathrm{syst})) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{nucleon}$$

$\nu/\bar{\nu}$ ratio
(ND280; Off-Axis)

$$\sigma(\bar{\nu})/\sigma(\nu) = 0.368 \pm 0.011(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

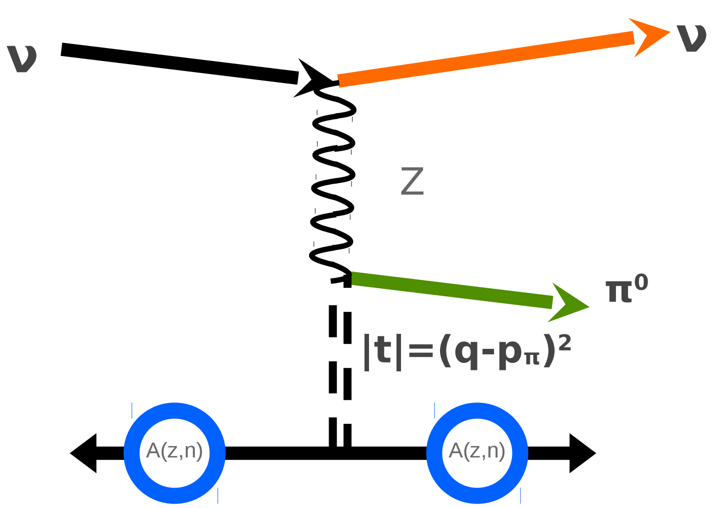
Restricted: $\theta_\mu < 74^o$, $p_\mu > 250$ MeV

NC coherent/diffractive π

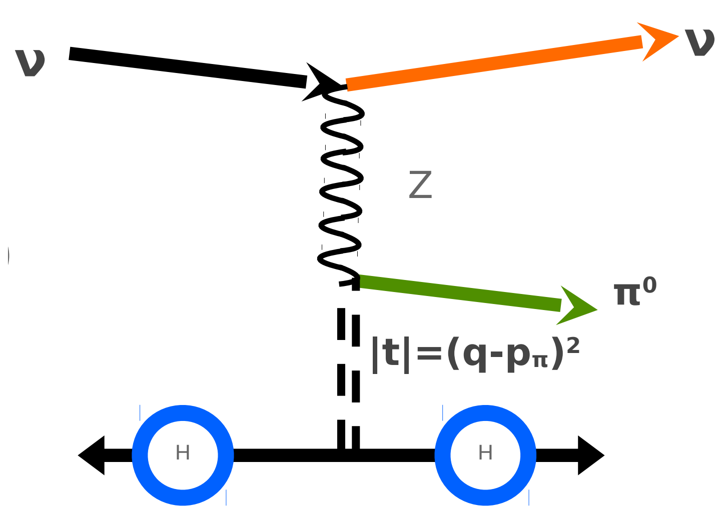
Jorge G. Morfin (WG2 parallel#8)
Hongyue Duyang (WG2 parallel#8)

NC coherent π (scattered off nuclei)

NC diffractive π (scattered off H)

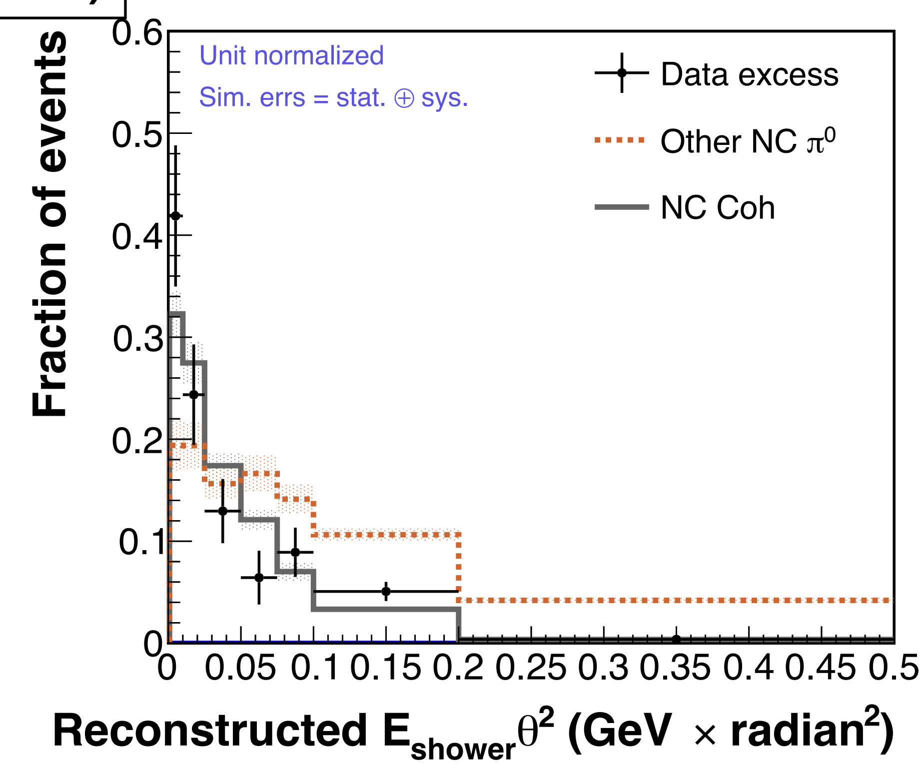


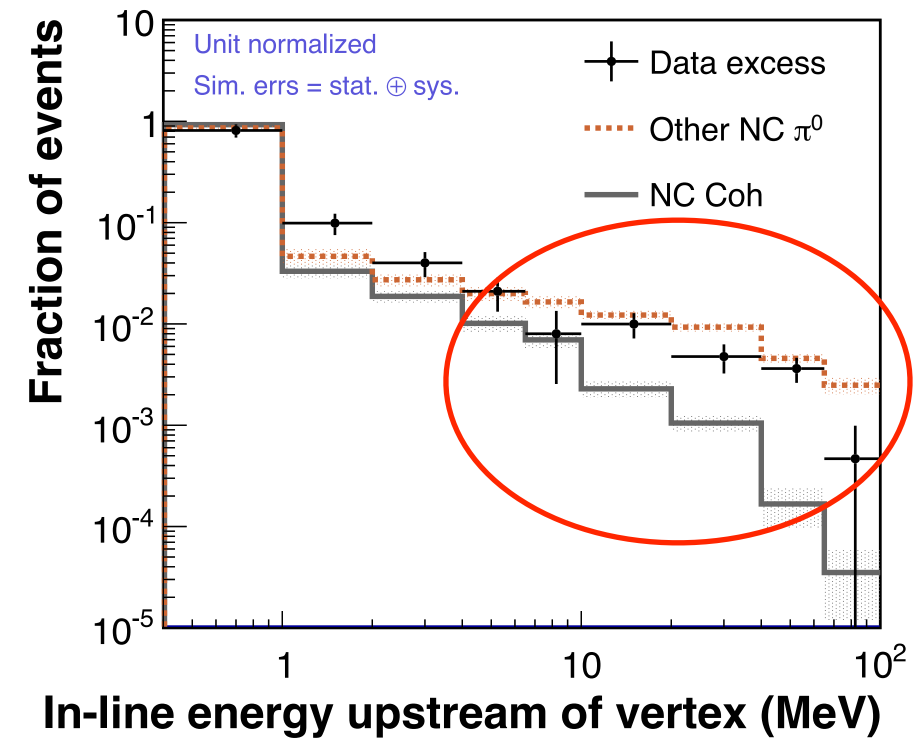
PCAC-based NC coherent production from *nuclei*



PCAC-based NC diffractive production from *H*

MINERvA



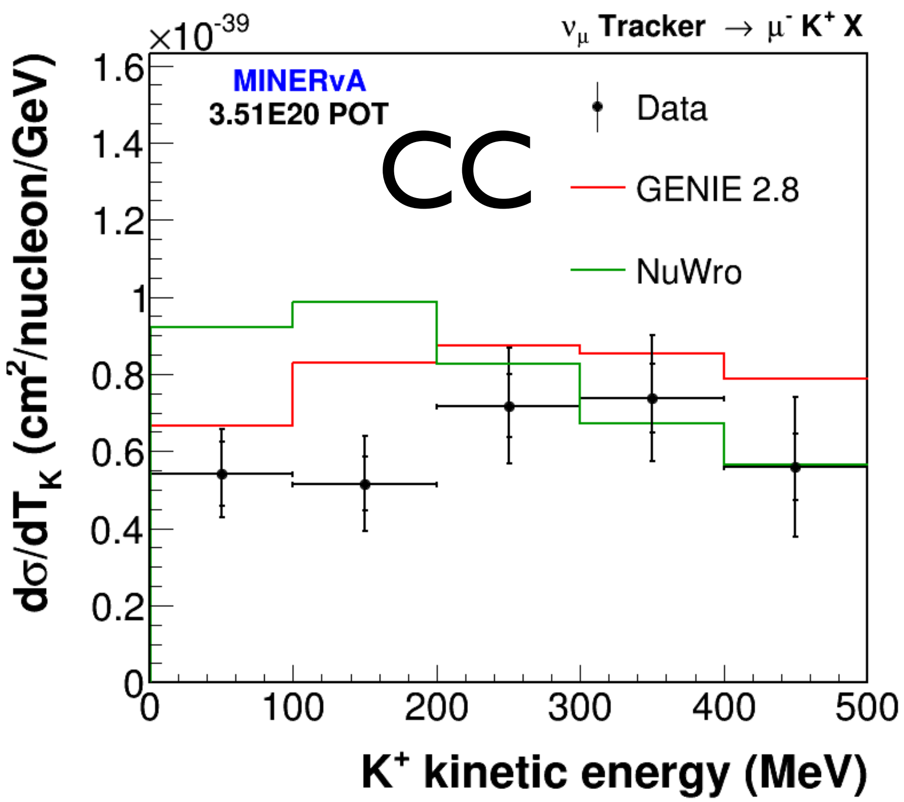


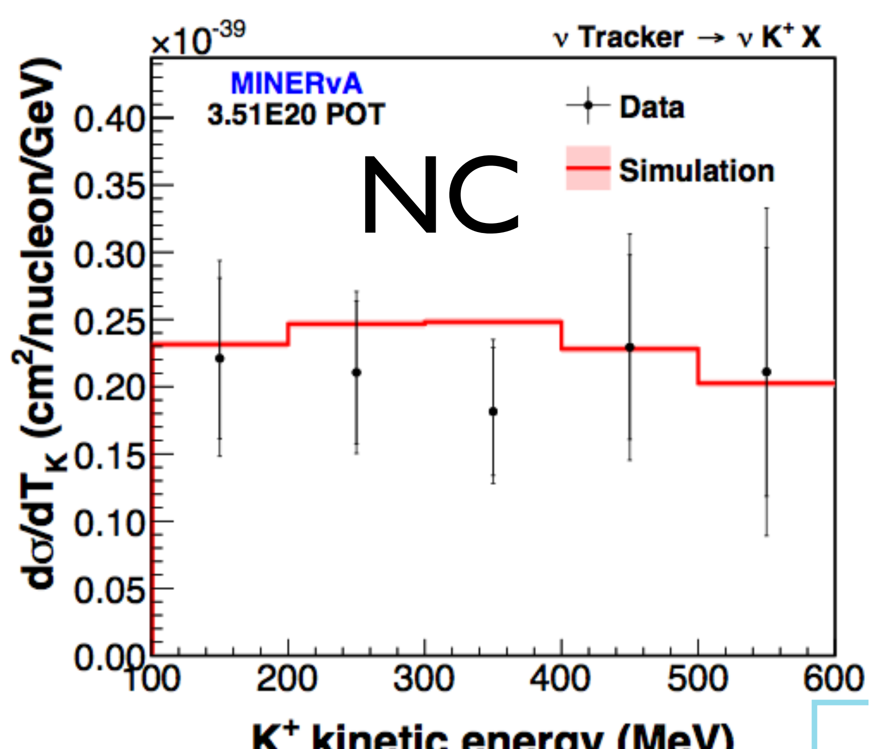
- MINERvA results suggesting a diffractive interaction off a light target (H)
- NOvA NC coherent-π analysis in progress; release results shortly

CC, NC Kaon prod.

Jorge G. Morfin (WG2 parallel#8)
Jeff Nelson (Plenary#6)

Phys. Rev. D 94, 012002 (2016)



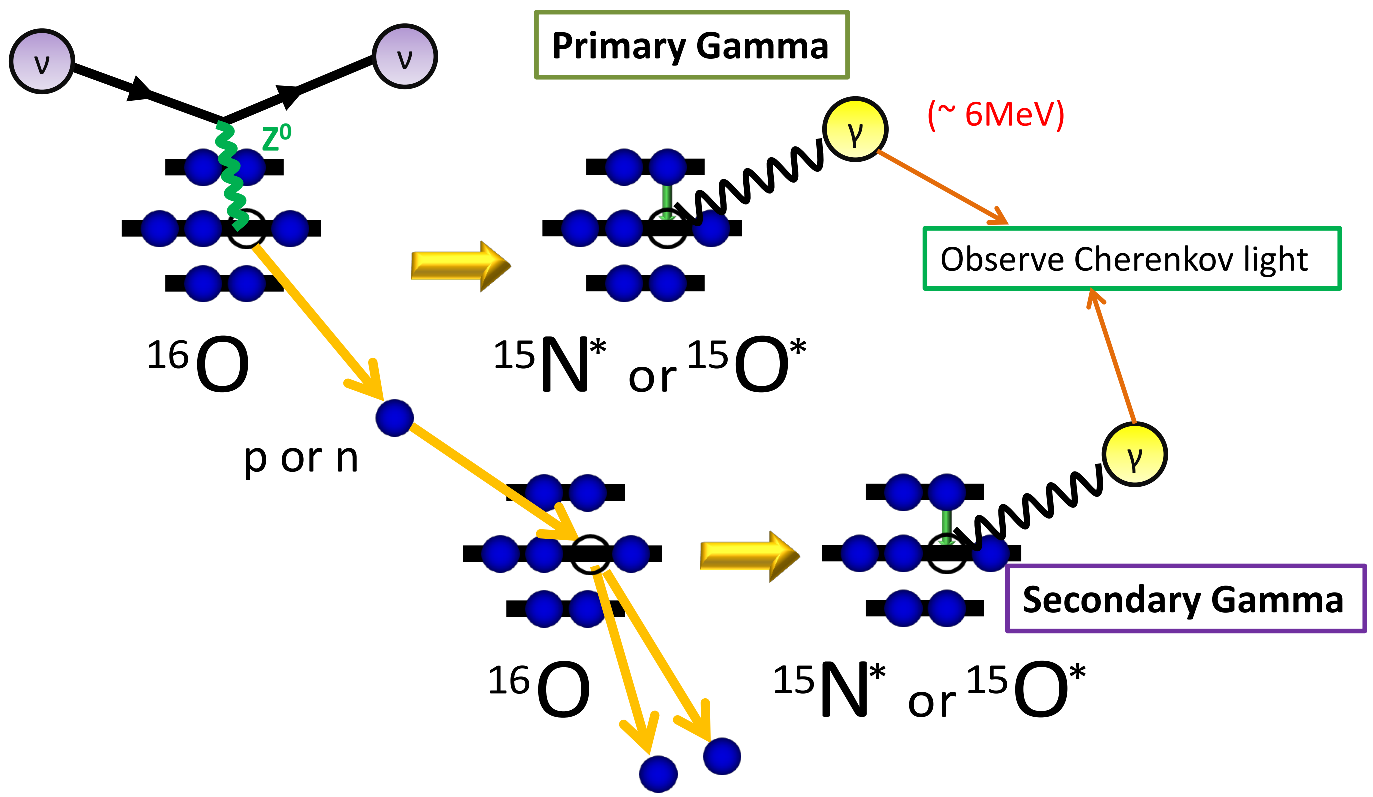


- MINERvA CC and NC kaon production measurements
- GENIE prediction reasonably reproduce data
- Observed CC coherent K+ production at 3σ PRL 117, 061802 (2016)

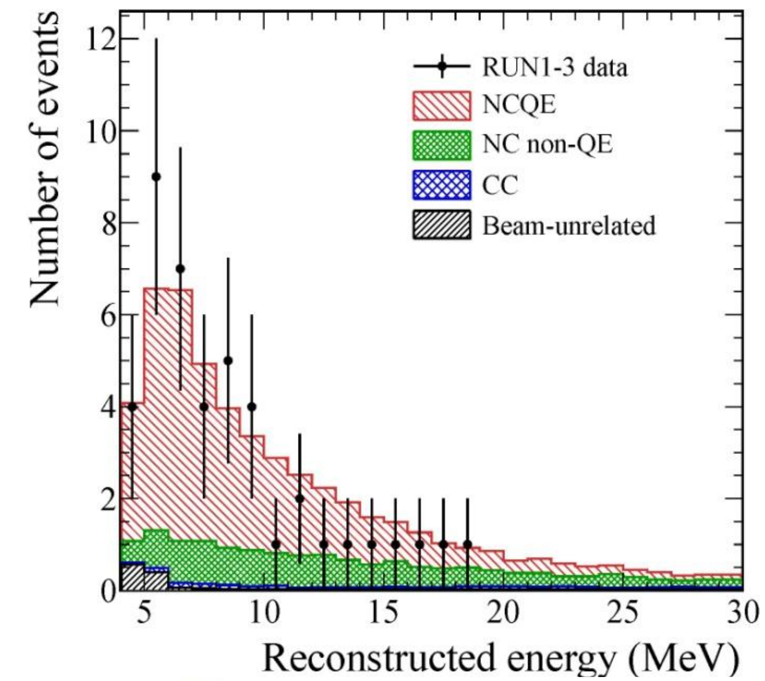
- NC Kaon production is major background for proton decay search $p \rightarrow \bar{\nu} K+$

NC-elastic on O

Erez Reinherz-Aronis (WG2 parallel#8)



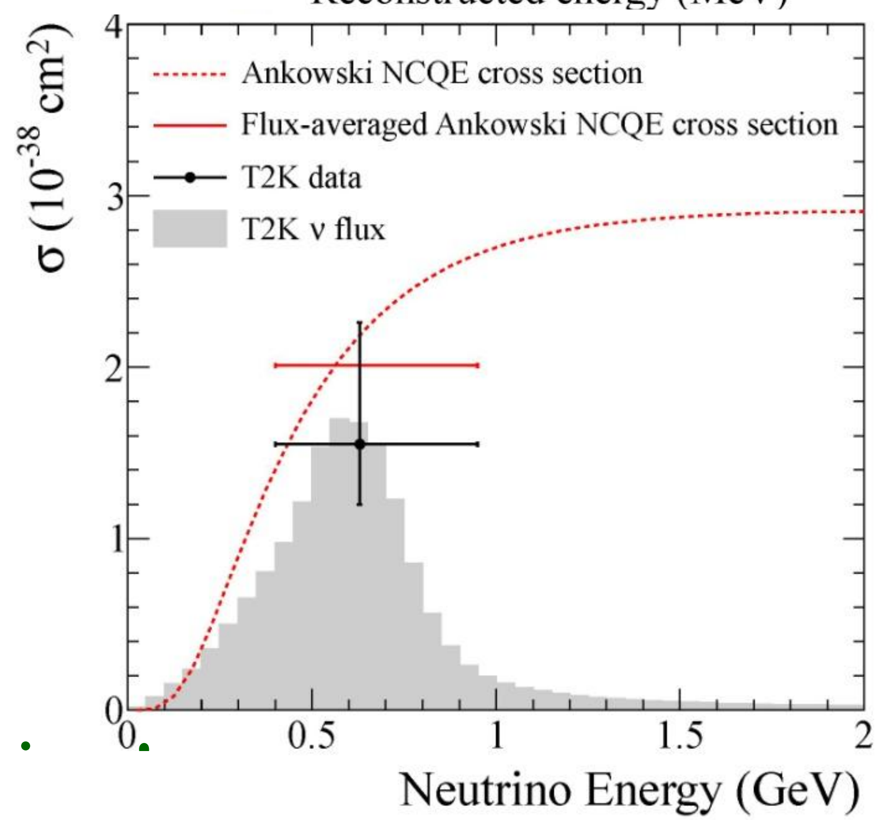
T2K SK



- Look for de-excitation γ's in SK around T2K beam bunch timing
- Observed: 43 e-like events

Flux-averaged ν-Oxygen NCQE

$$\langle \sigma_{NCQE}^{obs} \rangle = 1.55^{+0.71}_{-0.35} \times 10^{-38} \mathrm{cm}^2/\mathrm{nucleus}$$



PRD 90 072012

First measured ν-Oxygen NCQE cross section

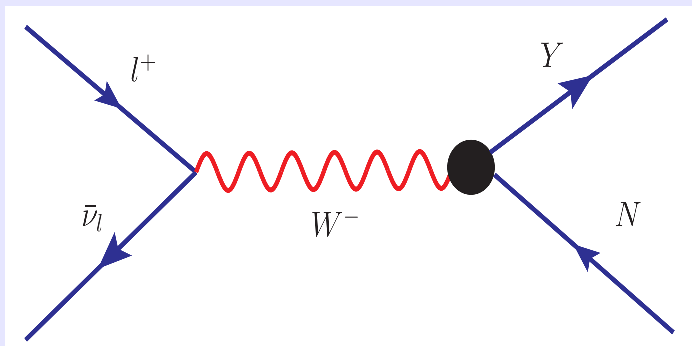
Theoretical developments

Quasi-elastic hyperon prod.

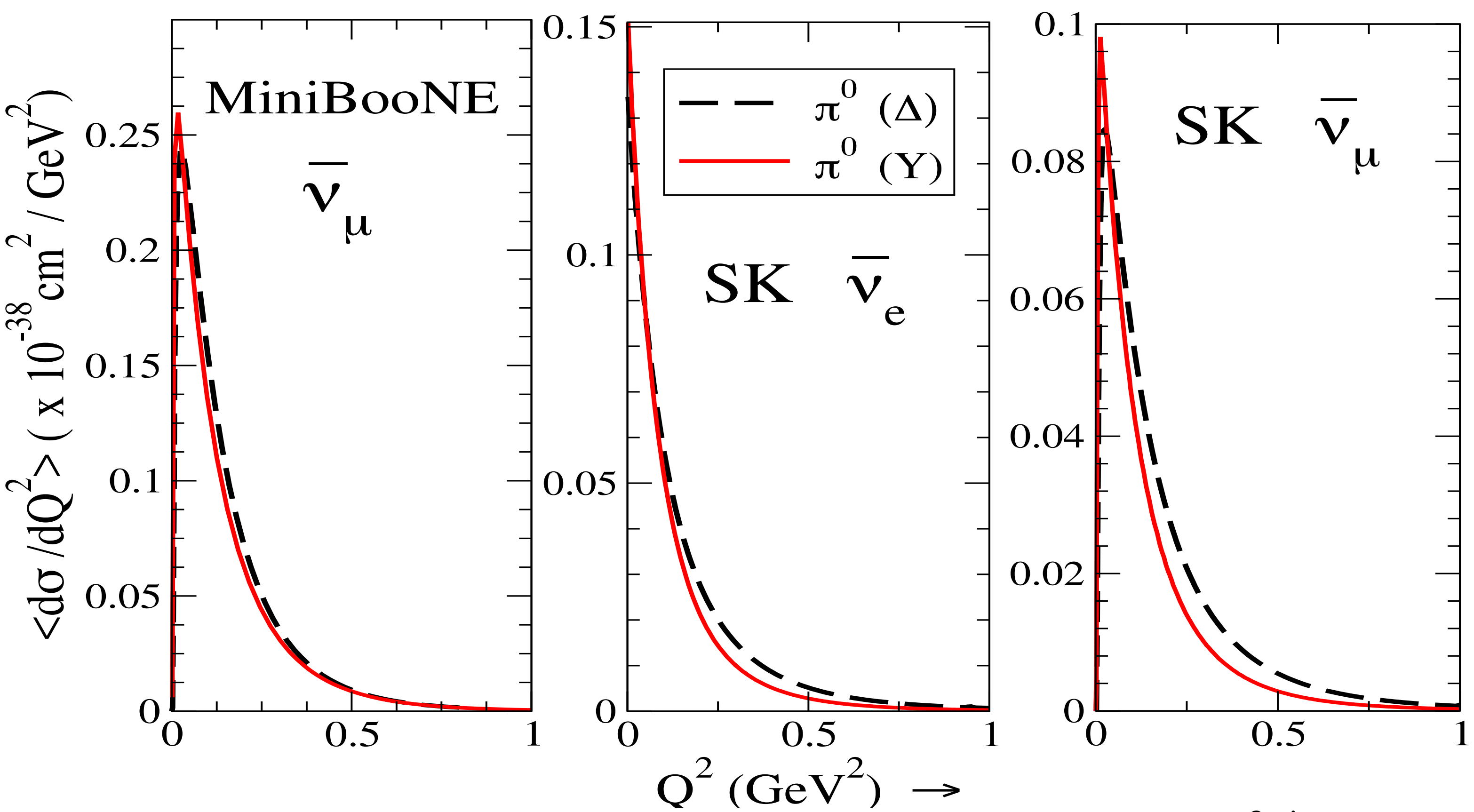
Mohammad Sajjad Athar (WG2 parallel#2)

Antineutrino induced Single Hyperon Production

$$\bar{\nu}_l(k) + p(p) \rightarrow l^+(k') + \Lambda(p')$$
$$\bar{\nu}_l(k) + p(p) \rightarrow l^+(k') + \Sigma^0(p')$$
$$\bar{\nu}_l(k) + n(p) \rightarrow l^+(k') + \Sigma^-(p')$$



These processes are Cabibbo suppressed as compared to the $\Delta S = 0$ associated production of hyperons.



scaled by a factor of 1.3 i.e $\sim 30\%$

Phys. Rev. D **88**, 077301 (2013)

- $|\Delta S|=1$ processes
  - Cabibbo suppressed by $\tan^2\theta_C=0.054$
- In $\bar{\nu}$-A reaction, π prod. from hyperons can be enhanced
  - ~30-40%
- Need to compare w/ data

Antineutrino induced Single Hyperon Production

$$\bar{\nu}_l(k) + p(p) \rightarrow l^+(k') + \Lambda(p')$$
$$\bar{\nu}_l(k) + p(p) \rightarrow l^+(k') + \Sigma^0(p')$$

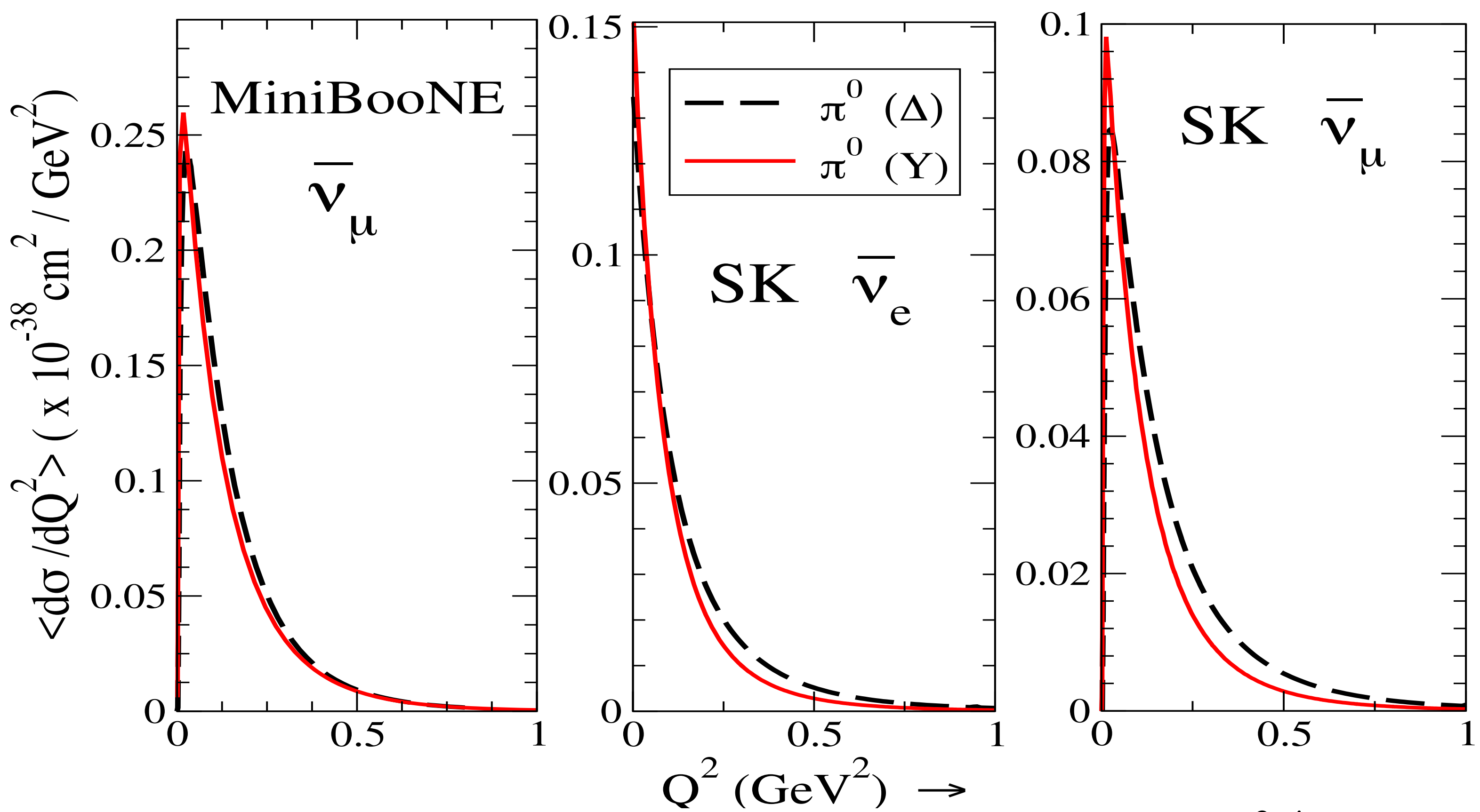
Quasi-elastic hyperon prod.

Hyperon giving rise to pions

As the decay modes of hyperons to pions are highly suppressed in the nuclear medium, making them live long enough to pass through the nucleus and decay outside the nuclear medium.

Therefore, the produced pions are less affected by the strong interaction of nuclear field, and their FSI have not been taken into account.

by $\tan^2\theta_C$=0.054



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Phys. Rev. D **88**, 077301 (2013)

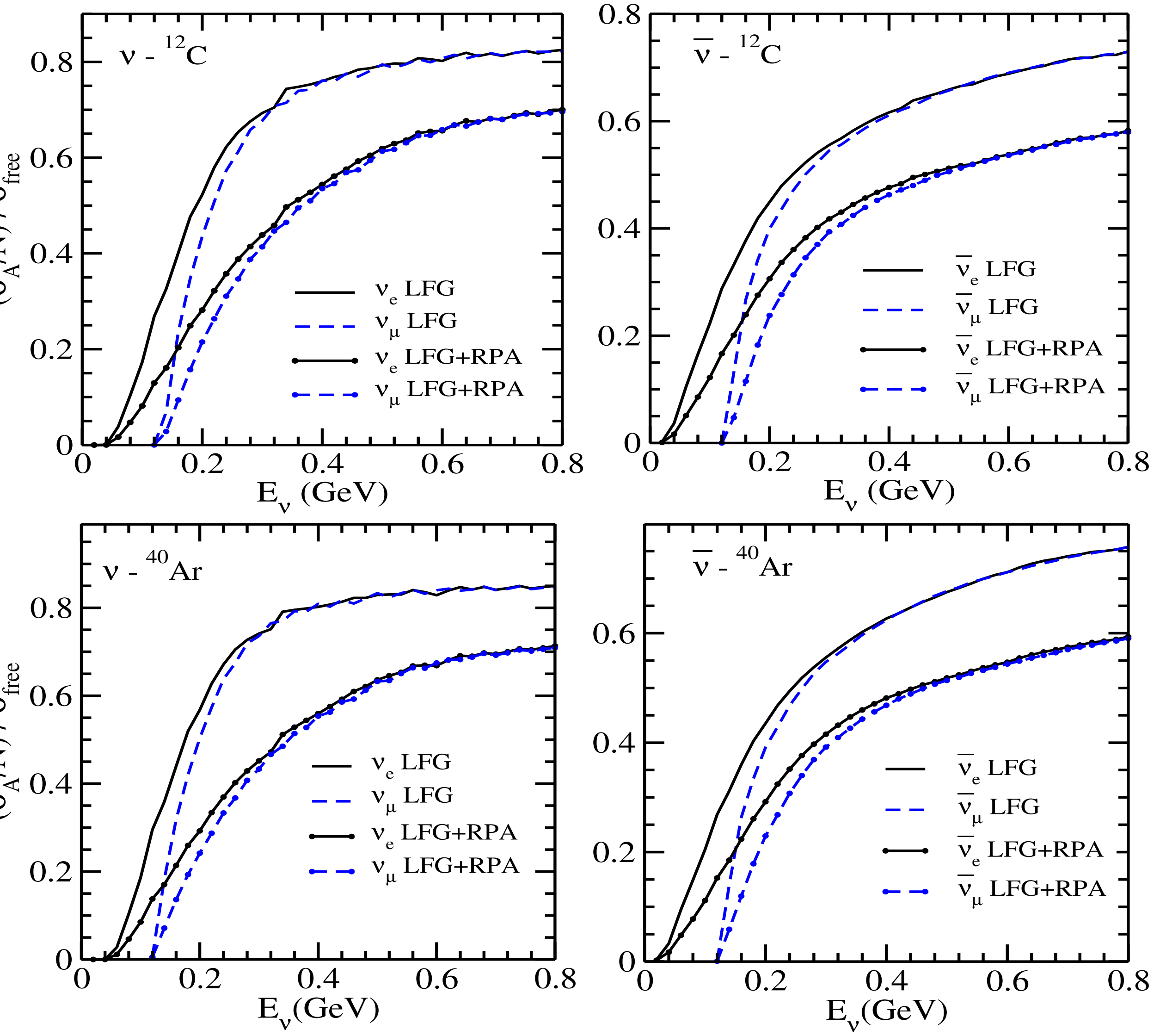
- In $\bar{\nu}$-A reaction, π prod. from hyperons can be enhanced
  - ~30-40%
- Need to compare w/ data

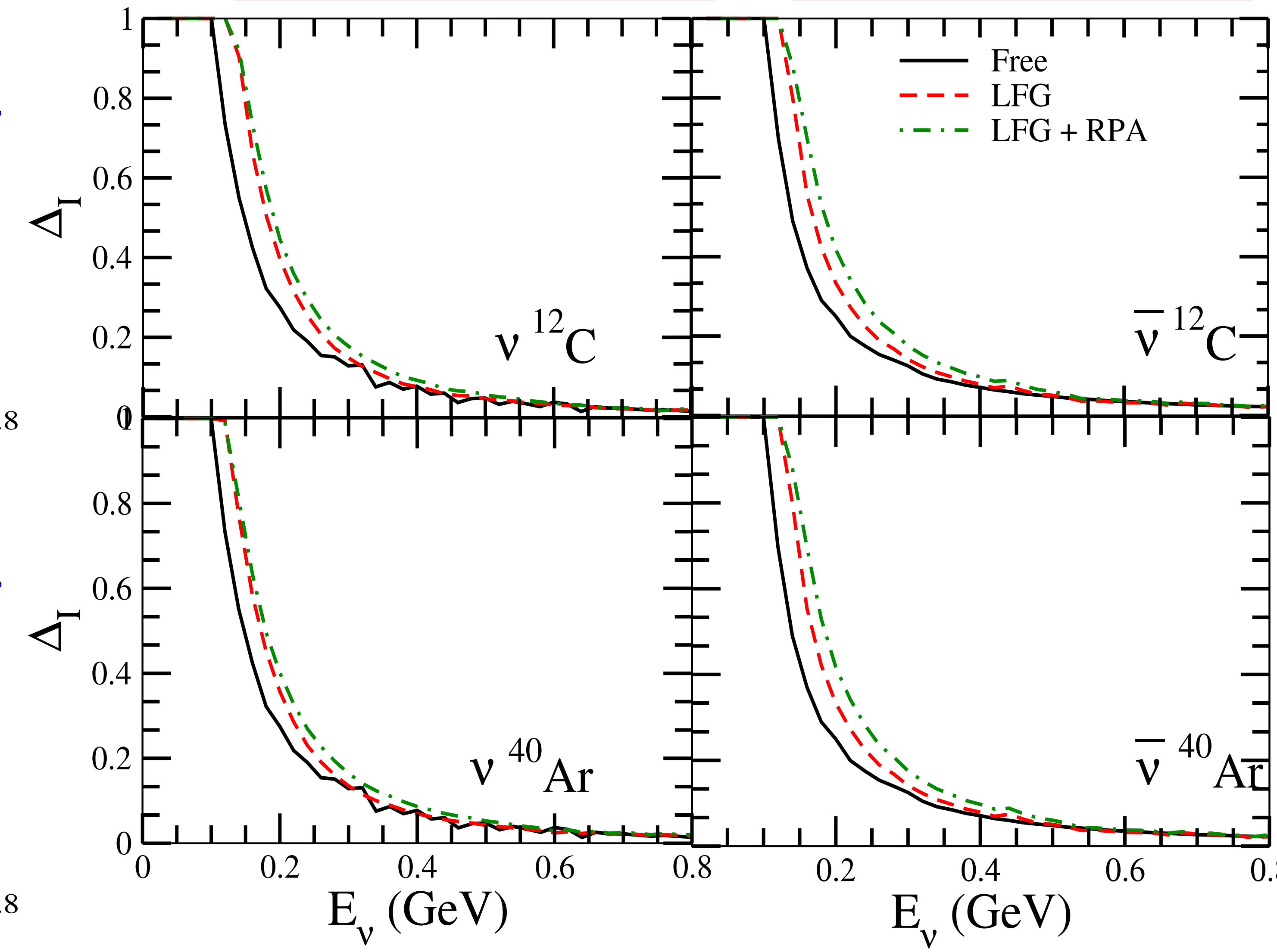
CC quasi-elastic $\nu/\bar{\nu}$-A scattering

Mohammad Sajjad Athar
(WG2 parallel#4)

$$\Delta_I = \frac{\sigma_{\nu_e} - \sigma_{\nu_\mu}}{\sigma_{\nu_e}}$$

$$\Delta_I = \frac{\sigma_{\bar{\nu}_e} - \sigma_{\bar{\nu}_\mu}}{\sigma_{\bar{\nu}_e}}$$





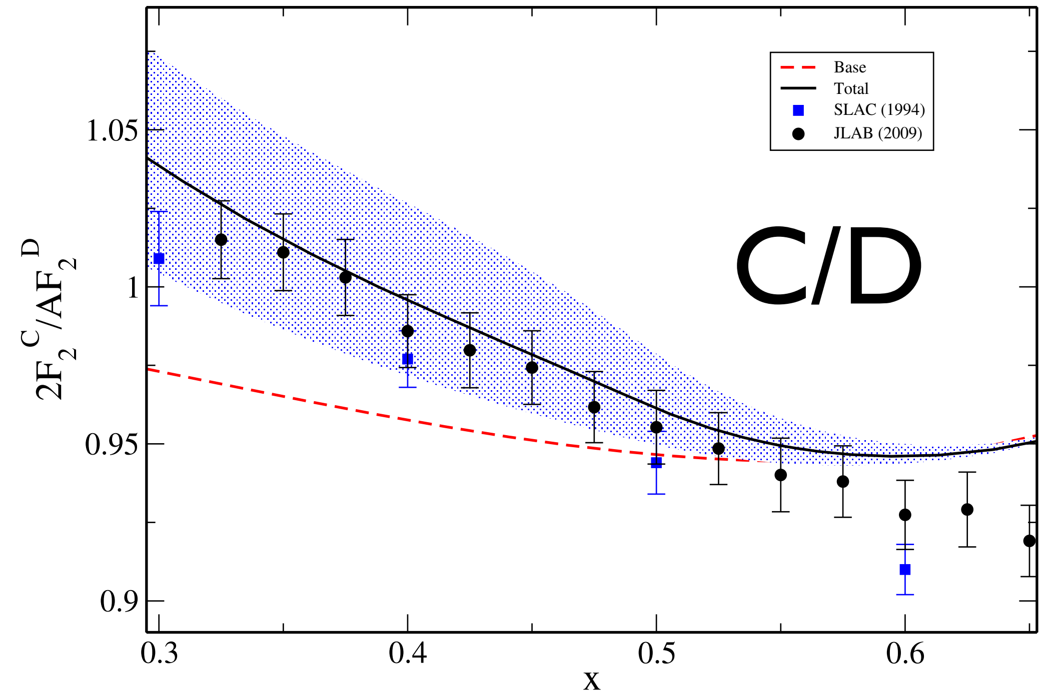
- At low energies $E_{\nu/\bar{\nu}} < 0.5\ GeV$ there is appreciable nuclear model dependence on $\nu/\bar{\nu} - A$ cross sections for both flavors of $\nu/\bar{\nu}$.
- The suppression due to NME is larger in the LFG as compared to the Fermi gas model of Llewellyn Smith.

Nuclear medium effect in DIS

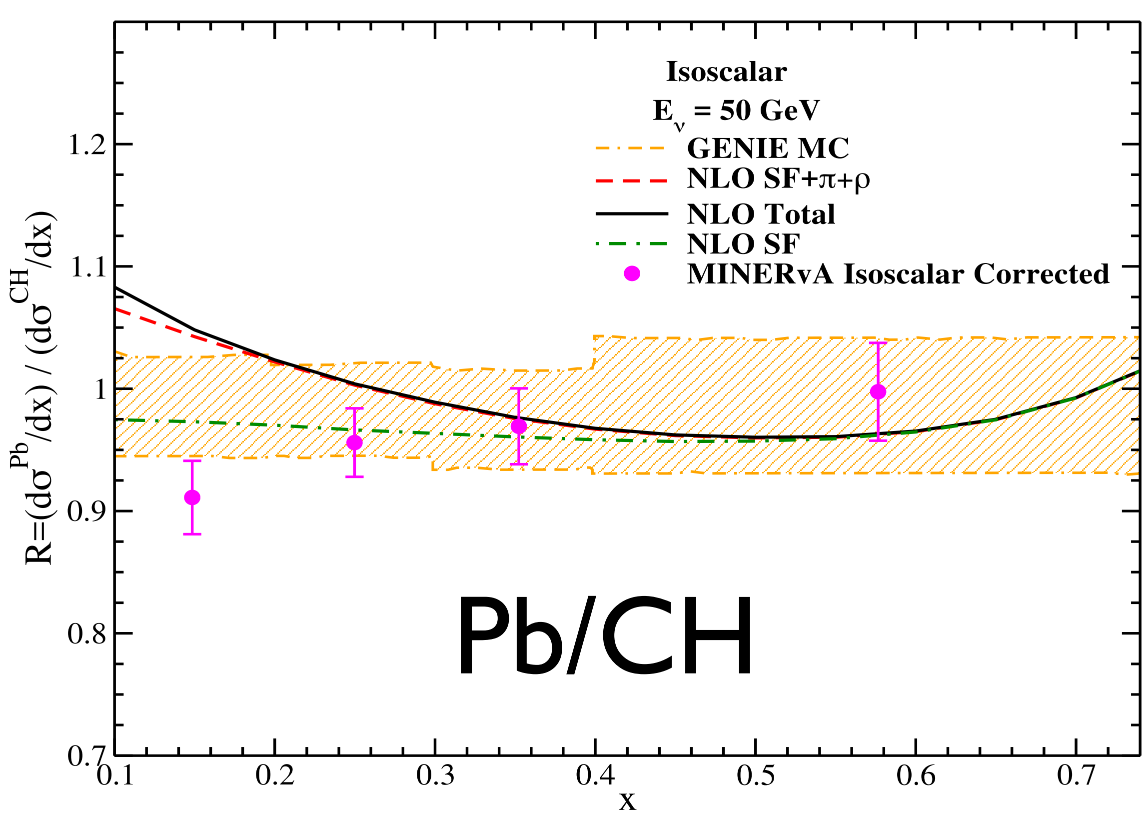
Huma Haider (WG2 parallel#2)

- The model reproduces EM data
- Compare with MINERvA CC inclusive results: Pb/CH
  - Seems not well reproduce at xBj≤0.1 ('shadowing' region)
  - Improvement on-going

Compare w/ EM data



Compare w/ MINERvA data

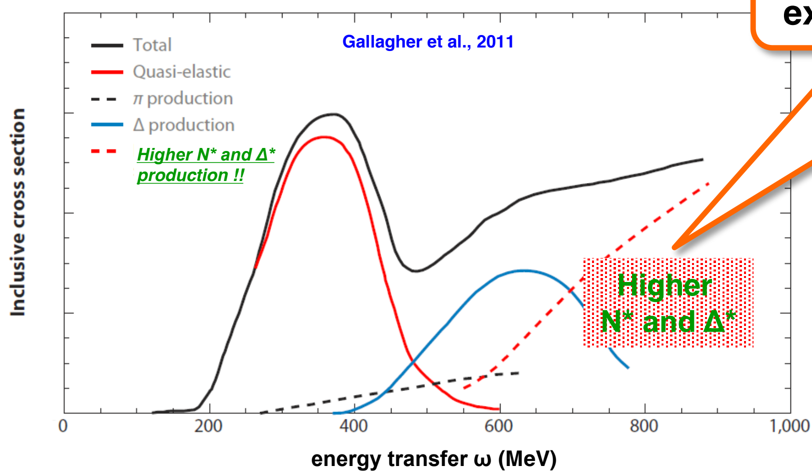


Neutrino induced π production

Dynamical coupled channel (DCC) model

Satoshi Nakamura (Plenary#6)
Hiroyuki Kamano (WG2 parallel#2)

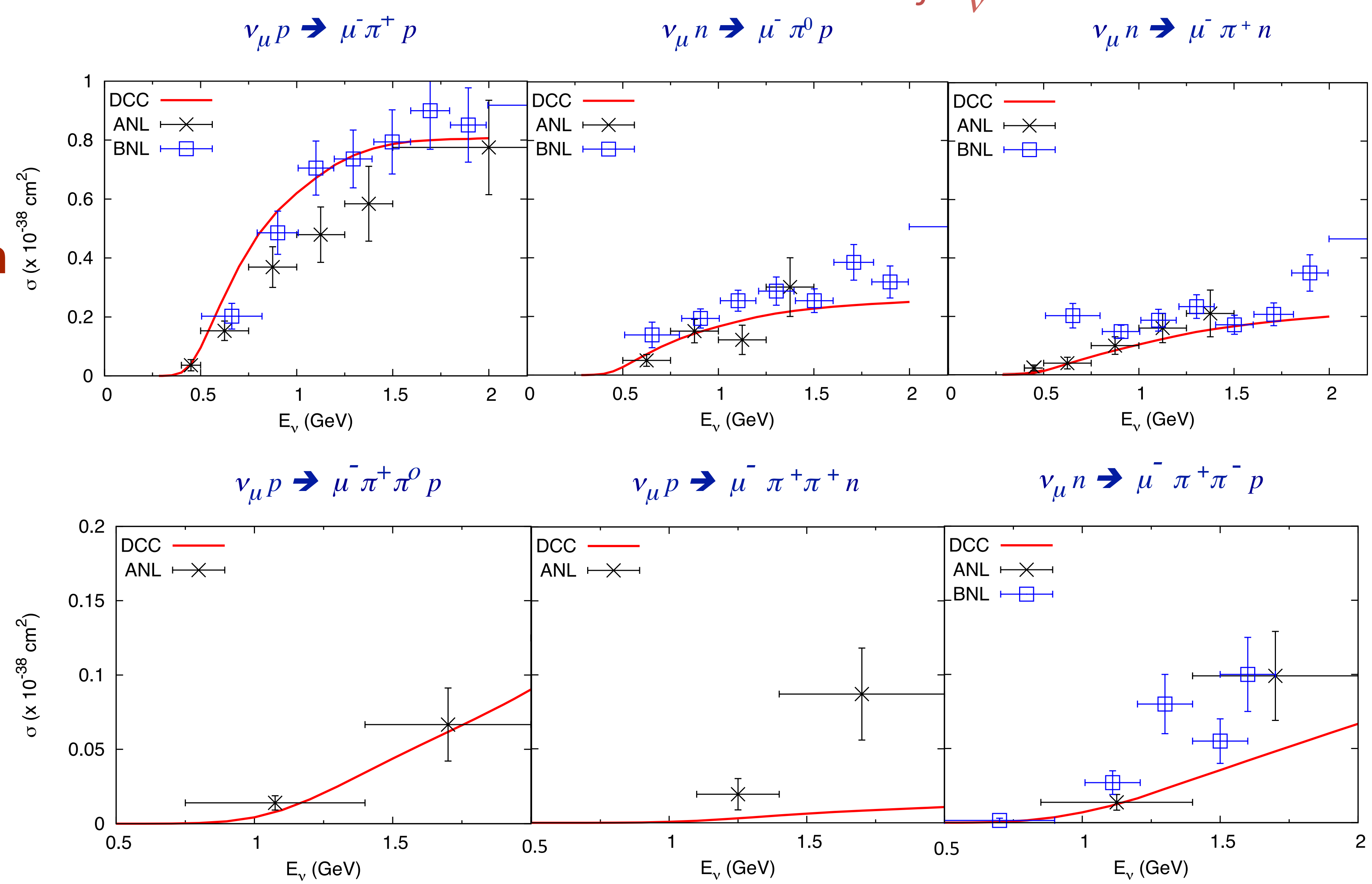
In reality, ~ 50 N* and Δ* baryons exist up to ω ~ 2 - 3 GeV !!



Higher N* and Δ* productions result in various (multi-)meson productions:

X = πN, ππN, ηN, KΛ, KΣ, ωN, …

DCC vector currents has been tested by data for whole kinematical region relevant to neutrino interactions of $E_\nu \lesssim 2$ GeV



DCC model prediction consistent with 1π data (BNL, ANL)

Fairly good DCC prediction of 2π prod.

SXN, Kamano, Sato, Lee, PRD 92, 074024 (2015)

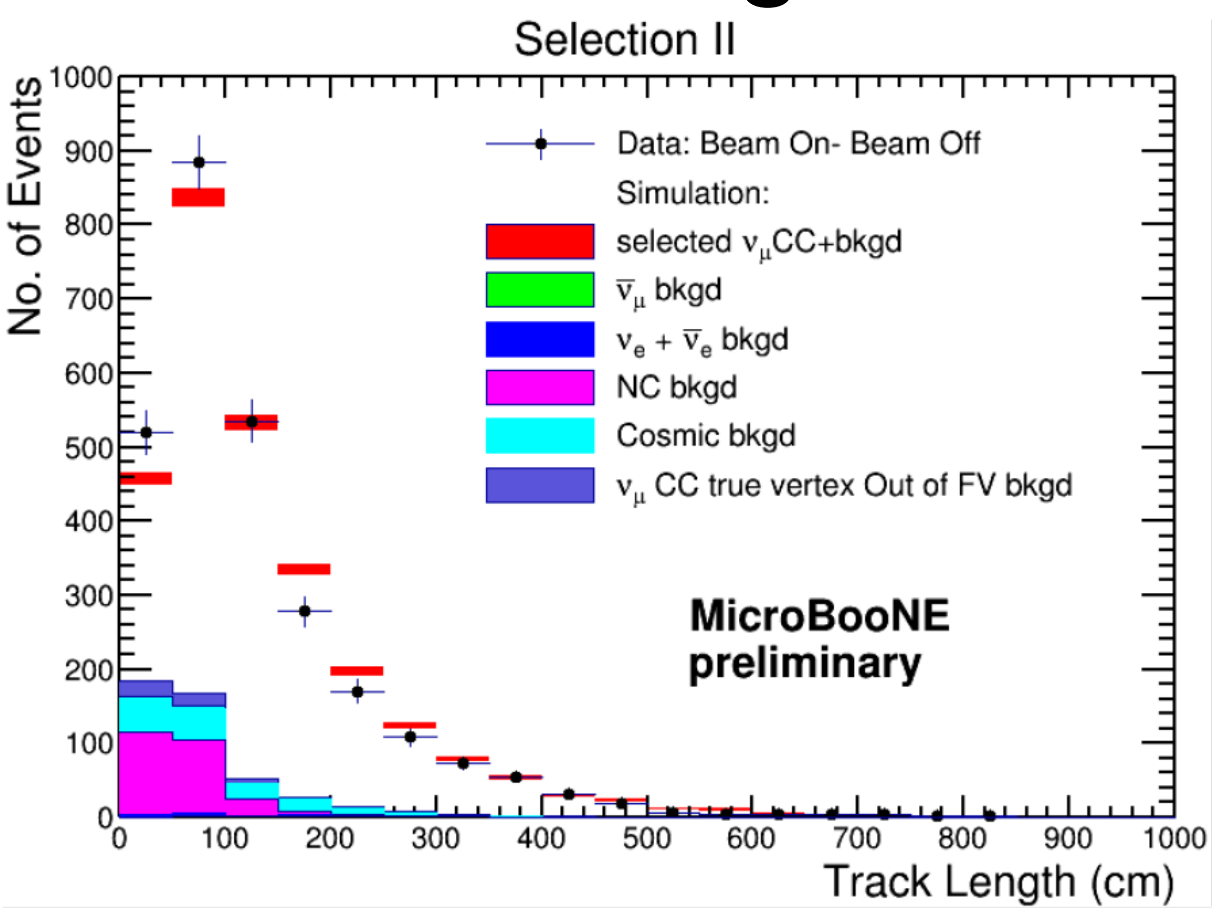
New results from LAr experiments

MicroBooNE first results

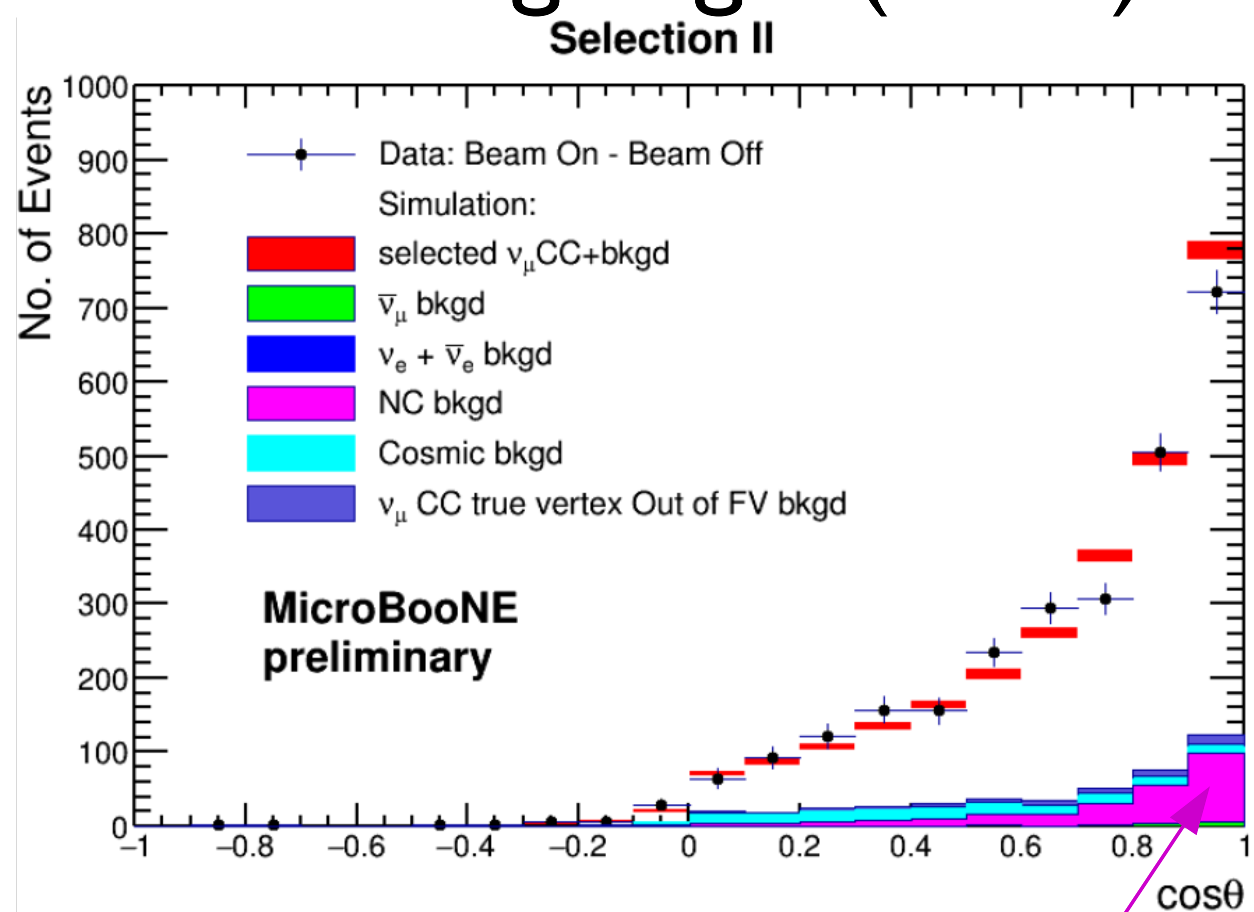
Philip Hamilton (WG2 parallel#3)

$\nu\mu$ CC distributions

Track length



Scattering angle (cosθ)



NC interactions form dominant background

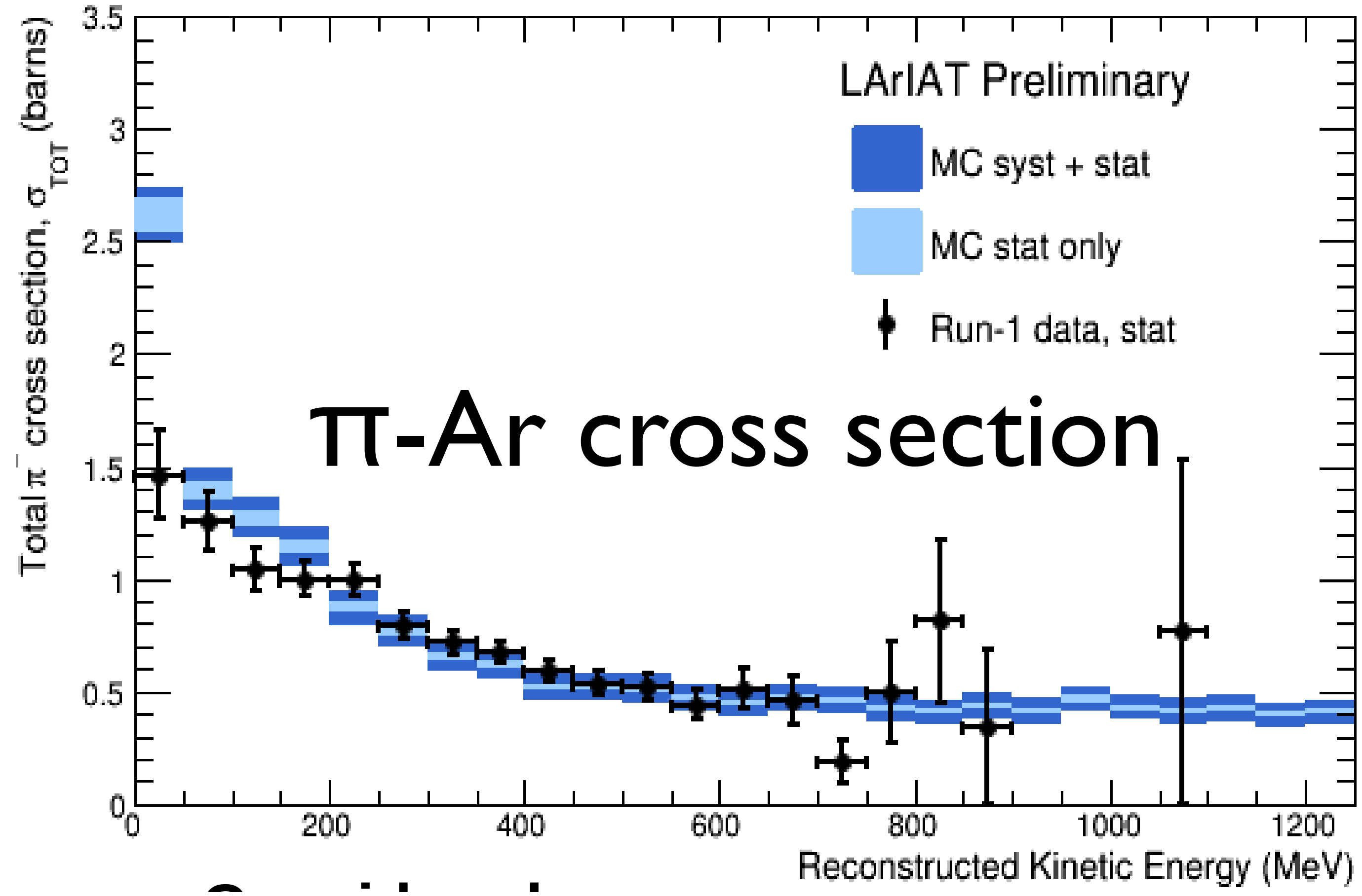
- Error bars in the plots only statistics
  - Systematics not fully addressed yet
- CC-inclusive corss section will follow soon

LArIAT

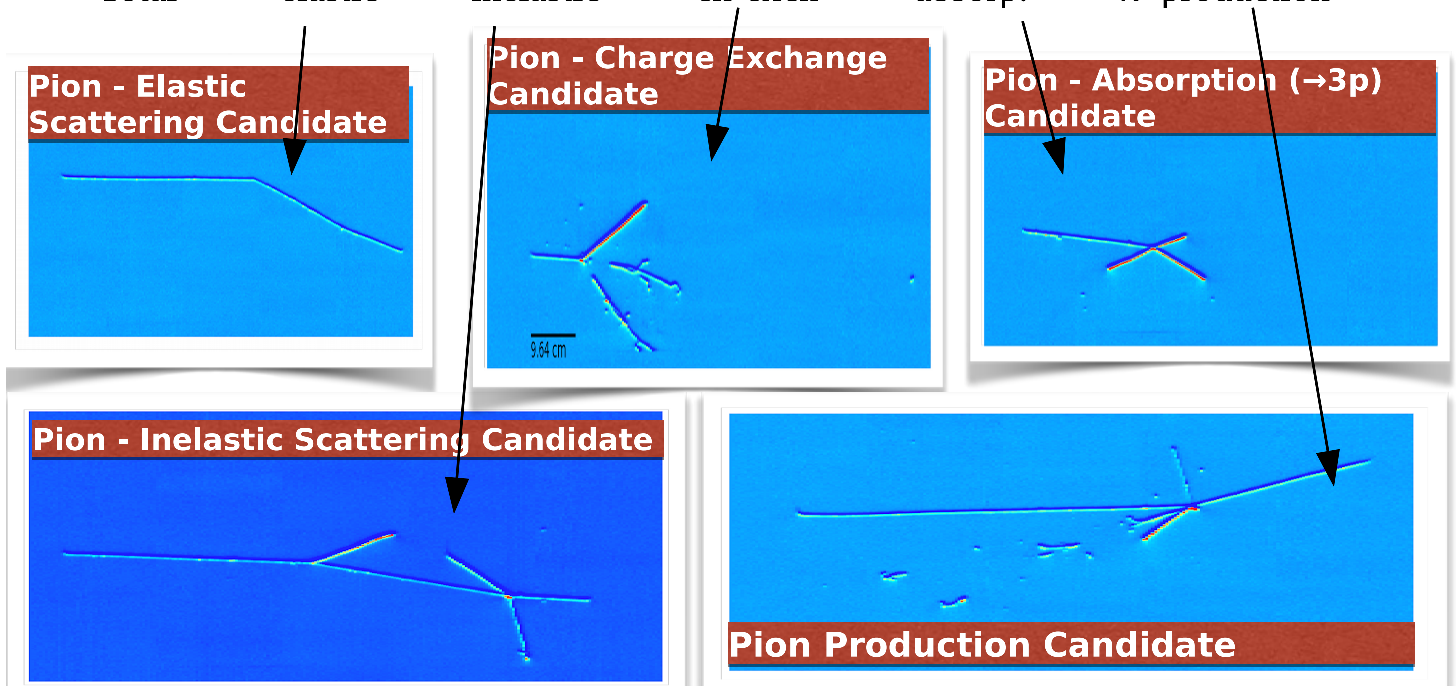
Philip Hamilton (WG2 parallel#3)

Liquid Argon In A Test Beam

World's first π-Ar Xsec results



$$\sigma_{\text{Total}} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{ch-exch}} + \sigma_{\text{absorp.}} + \sigma_{\pi\text{-production}}$$



- LArIAT uses the refurbished ArgoNEUT TPC to take data in the Fermilab test beam.

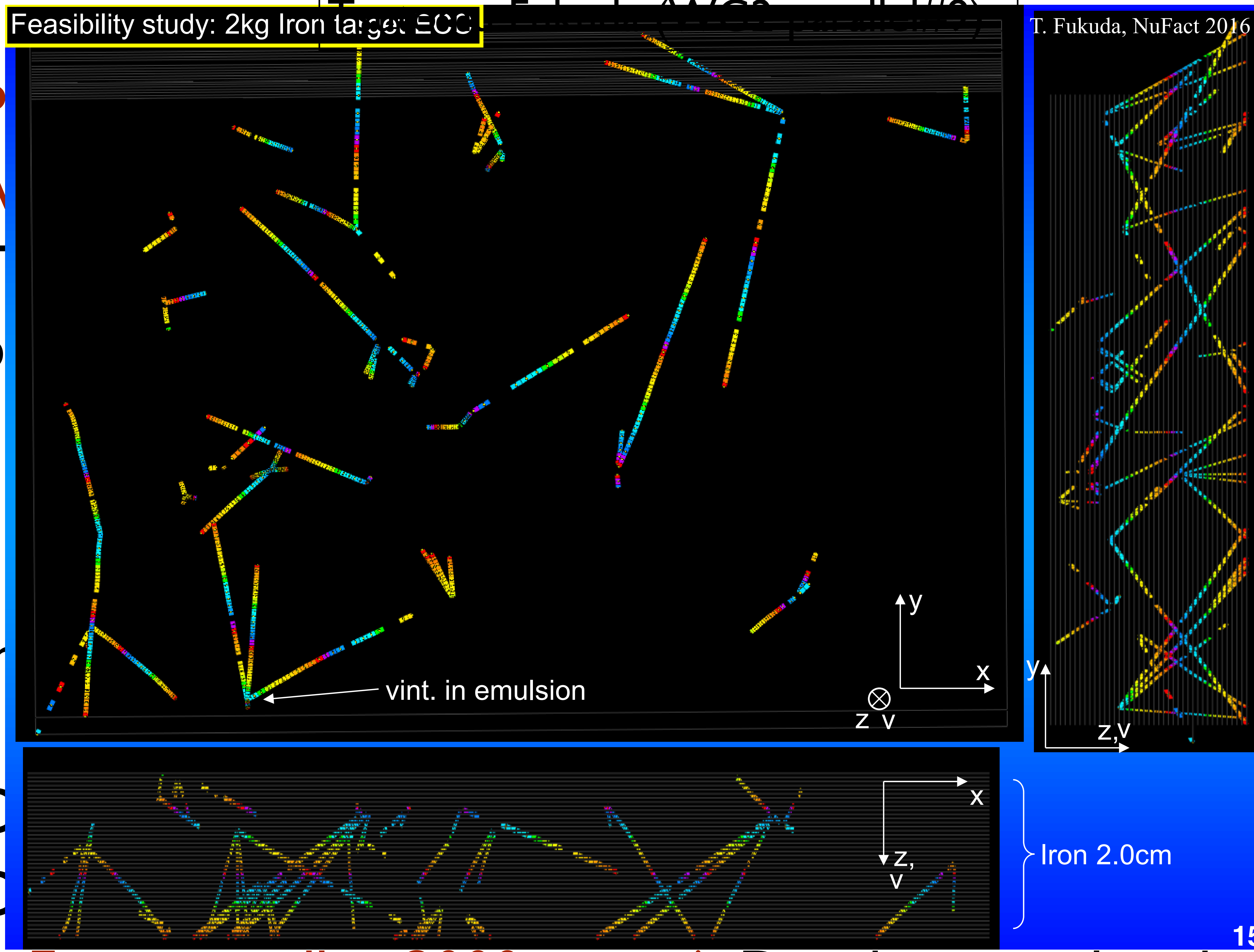
On-going experiments

J-PARC T60

Tsutomu Fukuda (WG2 parallel#9)

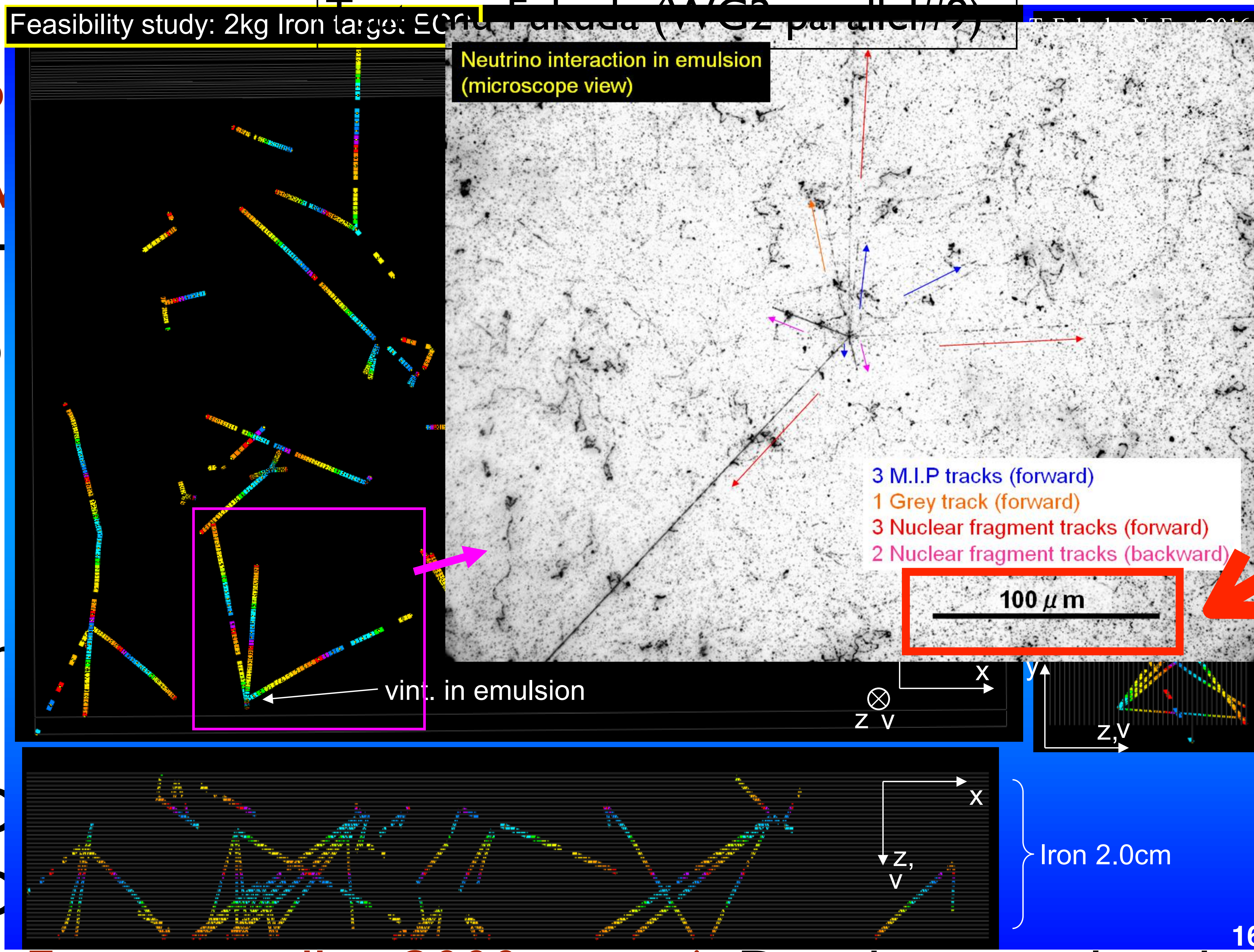
- Precise measurement of neutrino-nucleus interaction with Nuclear Emulsion at J-PARC
- The emulsion technique can measure all the final state particles with very low energy/tracking threshold
  - Tracking threshold: ~200μm
  - Provide essential input for multi-nucleon int. modeling
  - νe cross section with electron/gamma separation capability
- Installed emulsion in front of T2K INGRID detector
  - Time-stamp technique: Emulsion-INGRID track matching
- Data taking began in 2014~
- Data collected 60kg iron data in 2016
  - Expect totally >3000 events! Data being analyzed

J-PARC T60



- P … action
  w
- T … l state
  p … d
  - …
  - … ng
  - … pability
- Ir … ctor
  - … ching
- D
- D
  - Expect totally >3000 events! Data being analyzed

J-PARC T60



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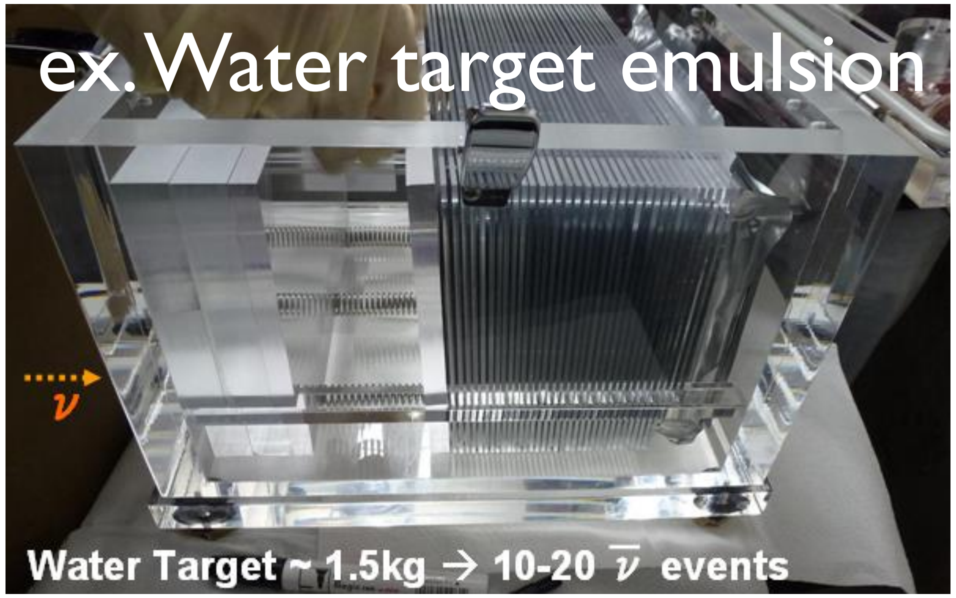
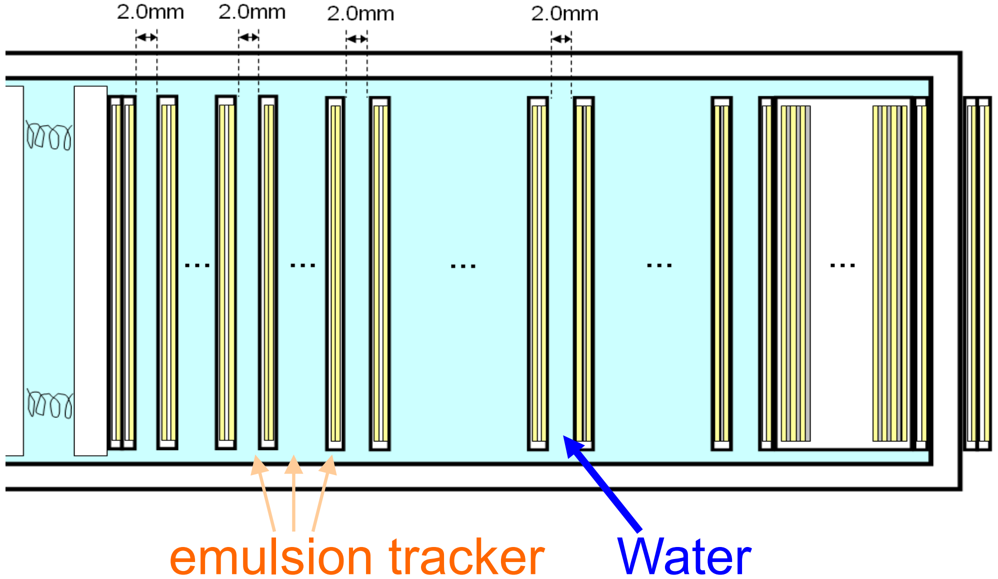
J-PARC T60

Tsutomu Fukuda
(WG2 parallel#9)

Able to employ different nuclear targets

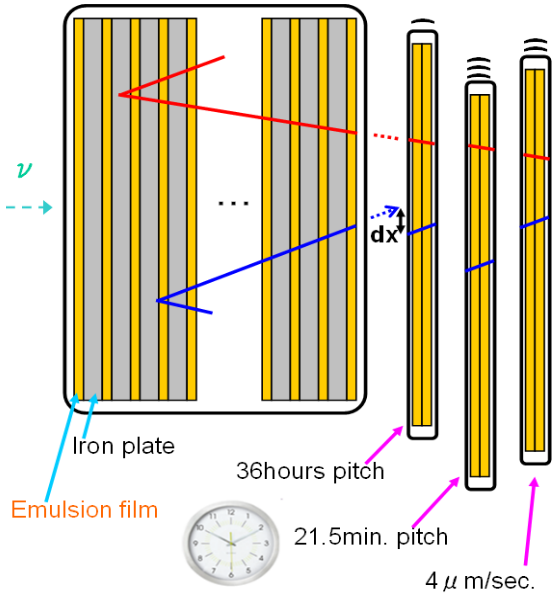




Fe, water targets data collected so far

Emulsion+INGRID hybrid analysis

(Thanks to the *time-stamp* technique)



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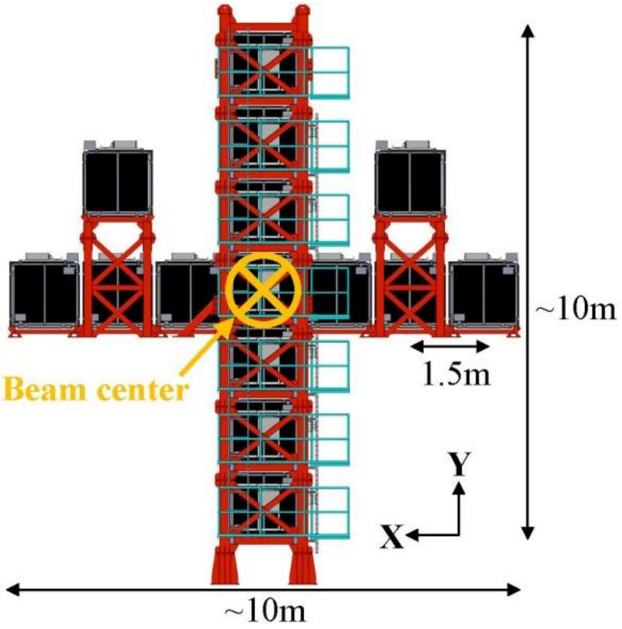
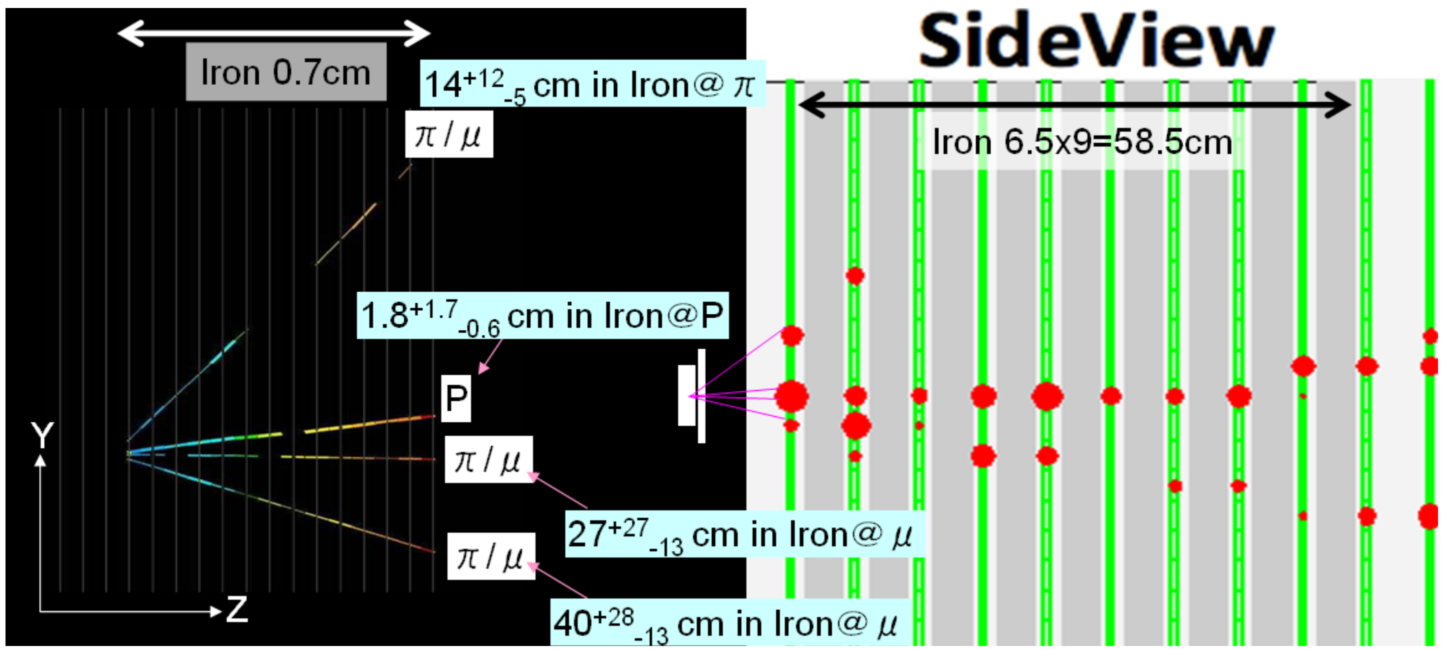
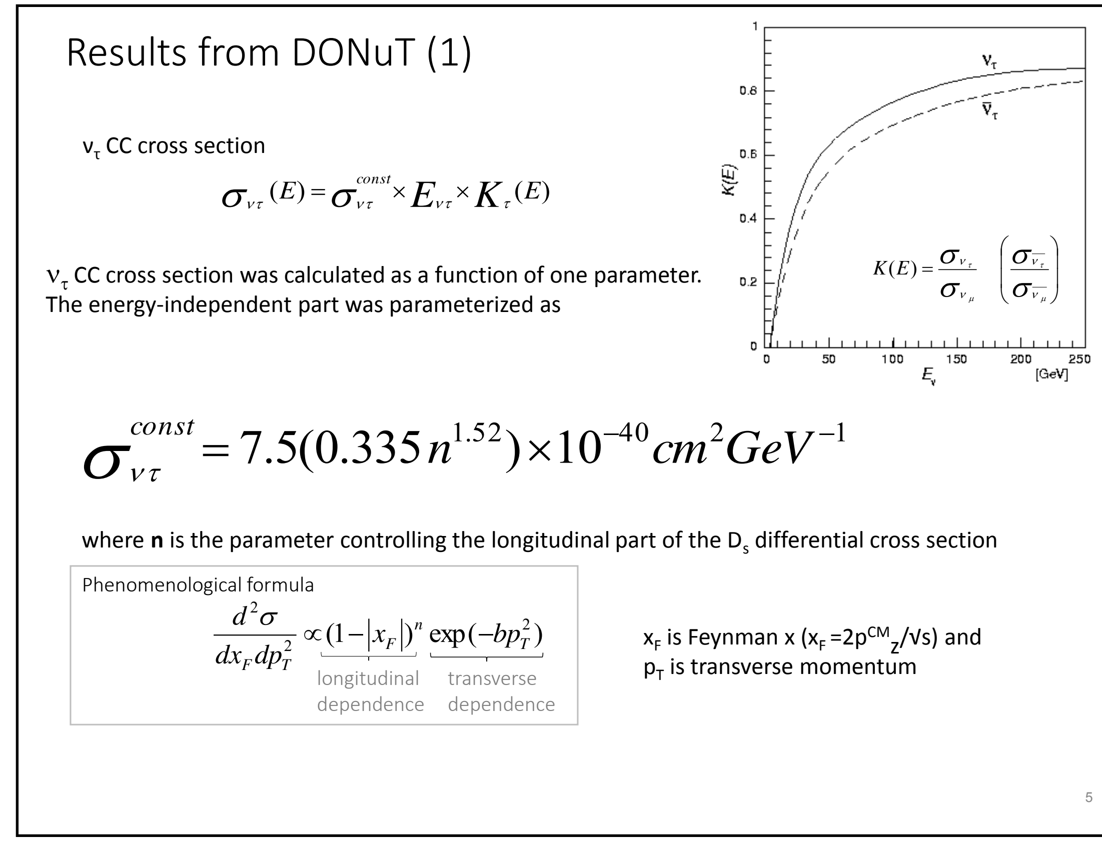


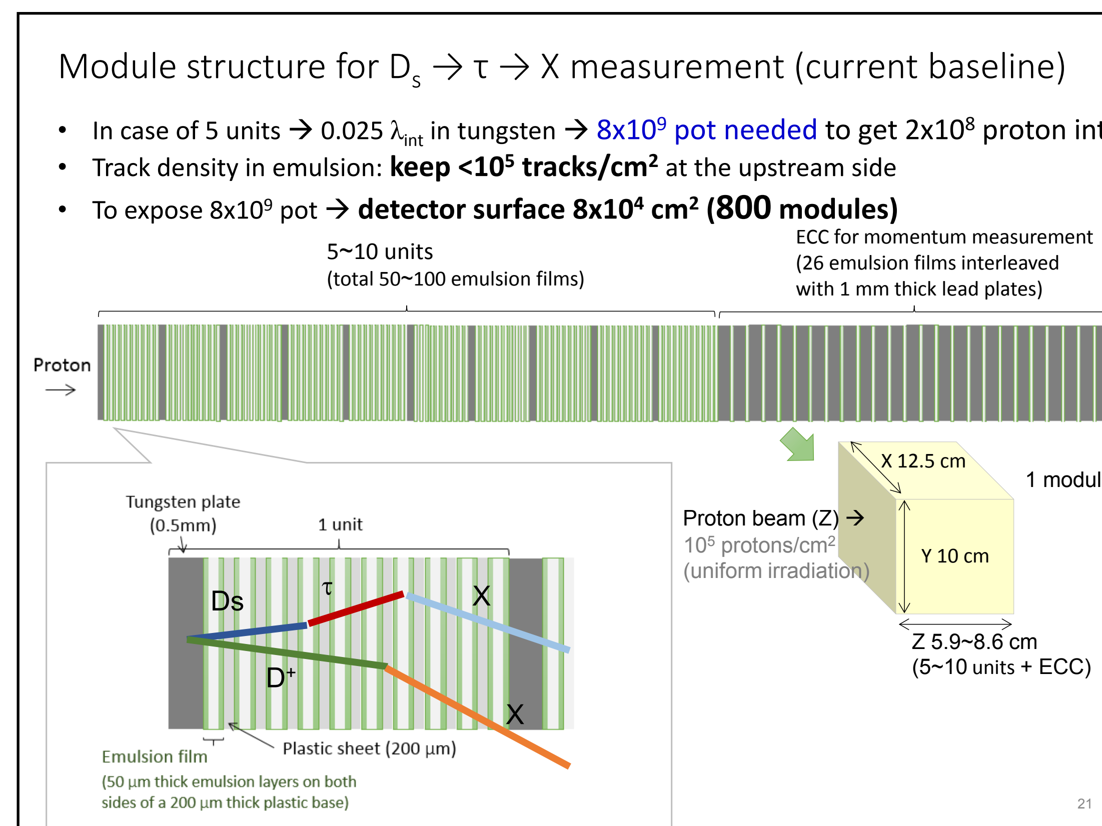


ν_τ CC cross section

Osamu Sato (WG2 parallel#9)

- ν_τ CC cross section measured by only DONuT experiment
  - 9 $\nu\tau$ events observed
  - Large systematics (50%)
    - Main syst. come from uncertainties of Ds production at beam source
- ν_τ CC cross section uncertainty is one of major systematic sources in Super-K atmospheric ν MH measurements
- DsTau project
  - Ds→τ→X precision measurement in high energy proton interactions using Nuclear Emulsion
    - Aim to collect data with 1000 Ds→τ→X events
  - LoI submitted to CERN SPSC
    - CERN-SPSC-2016-013; SPSC-I-245

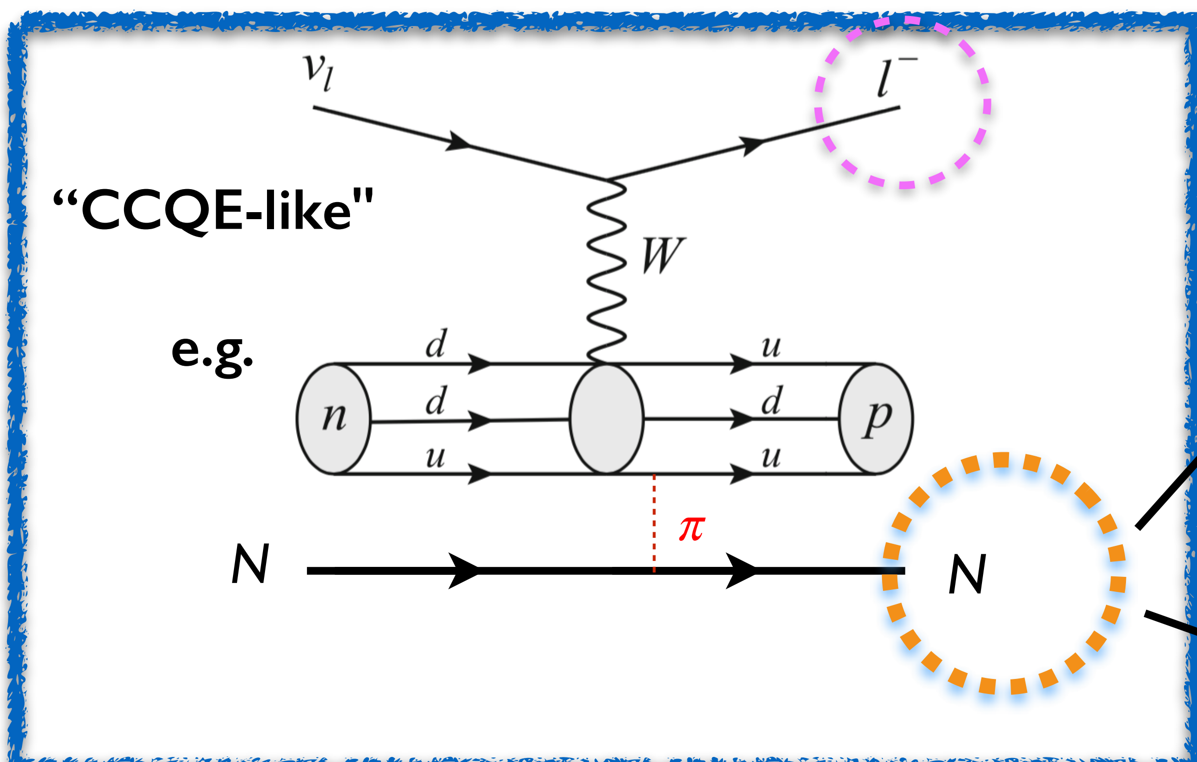




ANNIE

Frank Krennrich (WG2 parallel#9)

- Gadolinium doped water cherenkov detector at BNB
- Measure the abundance of final state neutron from neutrino interactions in water 0.5~3GeV
- Provide important input for modeling of multi-nucleon contribution



neutron(s):
neutron capture in Gd-doped water produces delayed signal (30 us)

proton multiplicity:
liquid-argon technique

ANNIE

Frank Krennrich (WG2 parallel#9)

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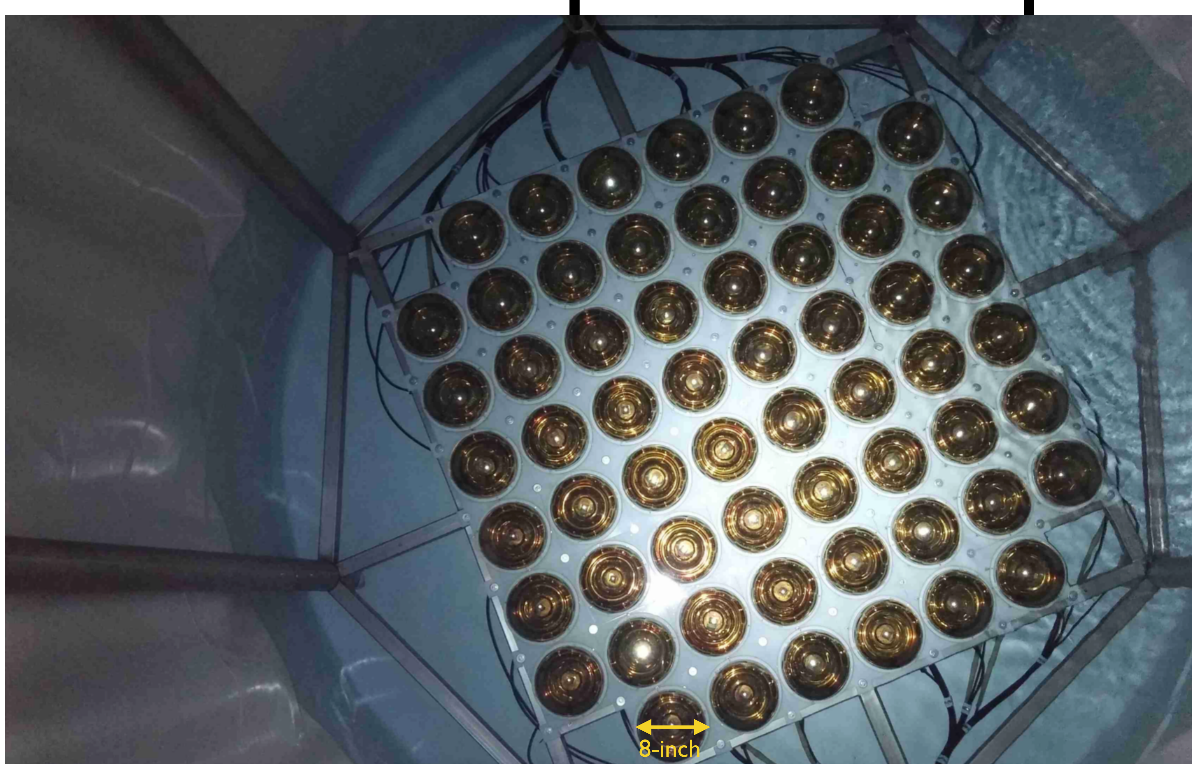

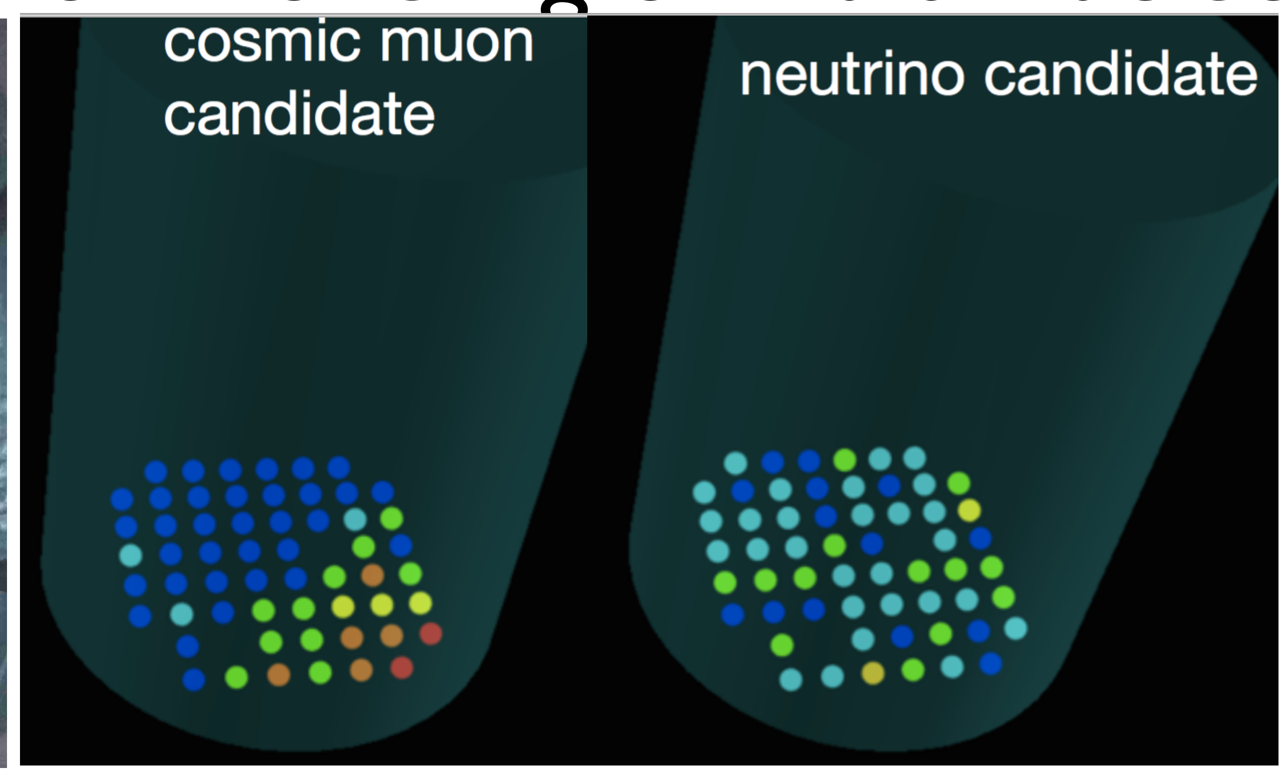

- **Operation of ANNIE Phase-I is underway**, data analysis has started to evaluate beam-correlated neutron background.
- ANNIE Phase-II (2017 - 2021) with the deployment of LAPPDs is in the planning stages.

Near Detector constraint

- T2K/NOvA Near Detector constrain flux and ν-int. cross section uncertainties successfully
  - with hadron production measurement
    - Parallel#5 Katarzyna Kowalik
  - T2K and NOvA employ different techniques
  - Total systematic uncertainties (ν_e app.): $\geq$10% → ~6% so far
  - Expect further improvement
    - Parallel#6: Leila Haegel (T2K), Gregory Pawloski (NOvA)
- Next generation experiments, Hyper-K, DUNE, target ~1% level systematic uncertainties on ν-int.
  - ND designs adopted the same ν targets in ND/Far, and adapted new technique, ex. Gd-water Č
    - WG1+2 parallel: Mark Rayner (Hyper-K), Hongyue Duyang (DUNE)
  - New techniques being tested by on-going exps. and/or in R&D stage

Summary

- Many new developments/results from Theory and Experiments
  - There are many other new results that cannot be covered in this talk
    - Please take a look at slides in WG2 sessions
- But still outstanding issues need to be solved
  - ex. Nuclear modeling, multi-nucleon contribution, final state interaction, etc
- Present/on-going experiments with new approaches & new apparatus can make significant contributions to improve the models
- Close communication & collaboration between theorists and experimentalists are indispensable