Physics studies for the ND280 upgrade

ND280 Upgrade Workshop
- May 2017 Tokai -

S.Bolognesi (IRFU, CEA), C.Giganti (LPNHE, Paris)

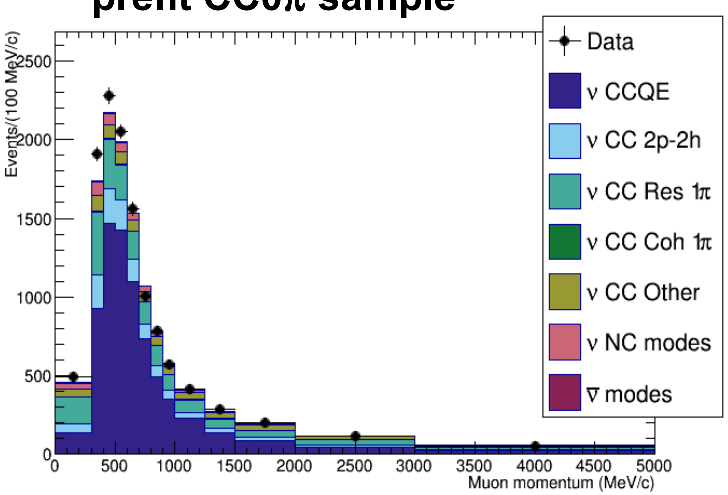
Reproducing the oscillation analysis

- **Well known and quantitative approach** (Simon's talk) 

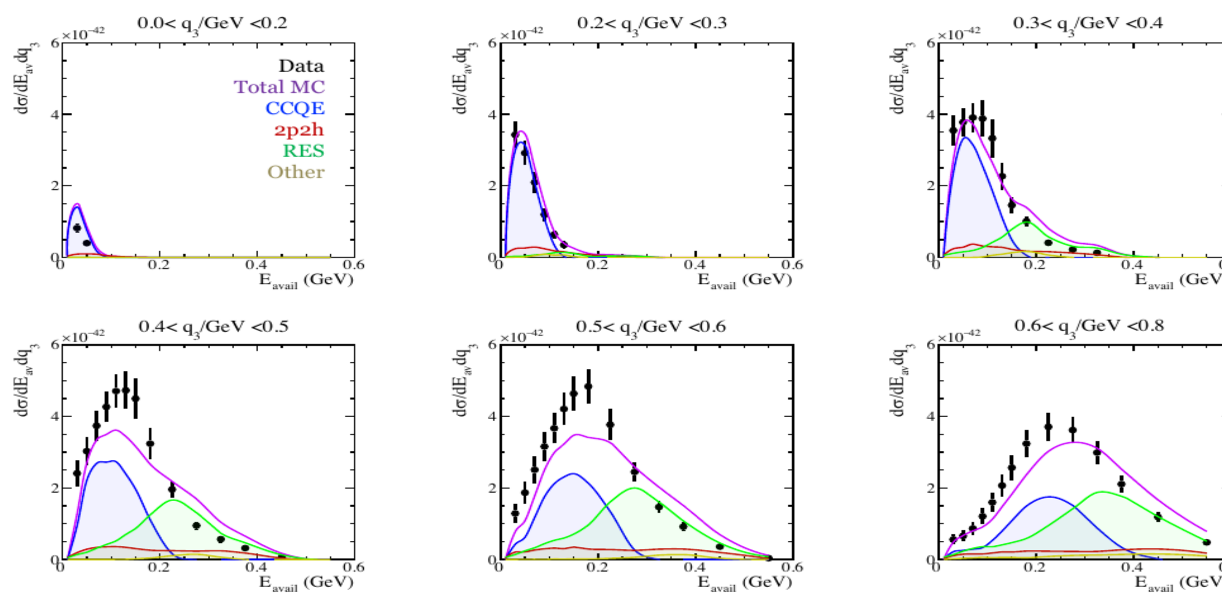
- **Results depend on the xsec model we use...**
(Eg: larger angular acceptance is beneficial proportionally to the size of the Q^2-dependent uncertainty we assume) 

… and we know that our xsec model does not describe our ND280 data (and the external data) well (yet?)

ND280 BANFF 2016 prefit CC0π sample



MINERVA q3,ω measurement



More wide approach

- More basic studies: **how well can we measure a given physical effect in the upgrade?**

  Eg:
  - **C/O** study → is an oxygen target beneficial?
  - ν_e/ν_μ uncertainty → what do we need to measure ν_e well enough to be useful for the oscillation analysis?
  - threshold for low momentum particles (eg: protons) and vertex activity → would a **'more light' target** give us useful information?

- Less model-dependent studies

  but also less straightforward... we are still learning about these issues in T2K:

  - we have not yet the statistics in OA to be limited by these issues but we need to anticipate what will happen at much larger statistics in T2K-2
  - **we don't know yet how to exploit such measurements to improve the model**

- **Not clear if something is feasible in the available timeline of the upgrade studies...** but at least we may use these studies to setup same fake-data studies for the BANFF fits

Oxygen/Carbon

The uncertainties we are including in our OA are relatively small → **will be ever capable of measuring C/O well enough at ND280 upgrade to be useful?**

- The C/O uncertainty is due to different nuclear structure/size → most of the effect at very low transferred energy to the nucleus (ω)

  Typically parametrized as a function of Fermi momentum and binding energy

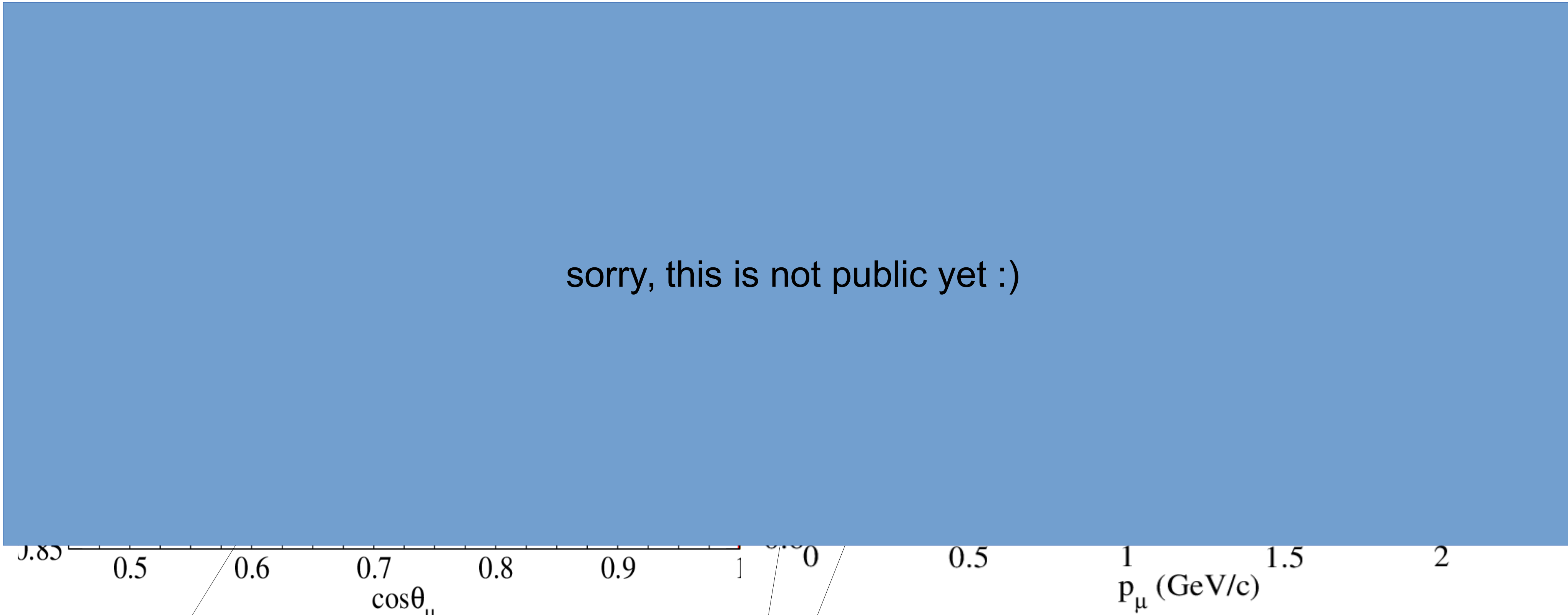
- The best way I found to estimate this uncertainty is to use the latest CCQE+2p2h model from SuSa which tuned the A-dependency from electron scattering data

sorry, this is not public yet :)

T2K uses:
Carbon p_F 223 MeV
Oxygen p_F 225 MeV

Looking into more details

PRIVATE MODEL PREDICTIONS FROM SUSA GROUP (PLEASE, DO NOT CIRCULATE)



- 2p2h and CCQE have opposite C/O behavior! ← 2p2h ~ $A^*p_F^2$, CCQE ~ A/p_F

  Some cancellation: C/O difference 5% goes down to ~1-2%

- Most of the effect in the very low muon momentum region (very difficult to measure muons in water at ~100MeV)

- A large effect also at p_μ~600 GeV but this is due to change in 2p2h/CCQE ratio → quite model dependent effect...

How well can we measure C/O?

Only statistical uncertainty considered!
Compare simplified simulation of ND280 with real analysis (TN305)

$$\frac{\delta R_{O/C}}{R_{O/C}} = \sqrt{\frac{1}{N^{\text{Target 1}}_{\text{events on C}} + N^{\text{Target 2}}_{\text{events on C}}} + \frac{1}{N^{\text{Target 1}}_{\text{events on O}} + N^{\text{Target 2}}_{\text{events on O}}}}$$

6×10^{20} POT

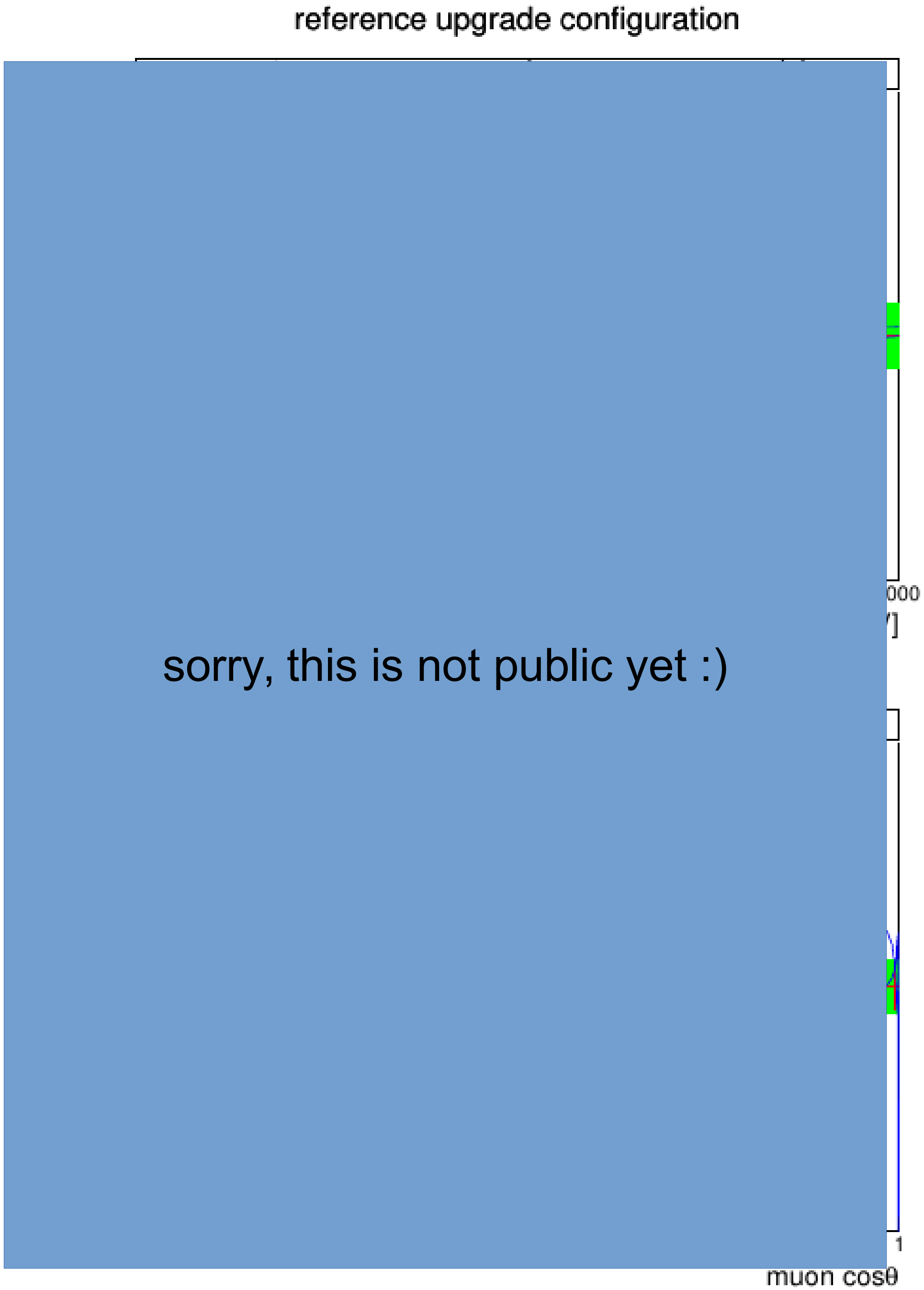
Configuration	N^C_{events}	N^O_{events}	$\delta R/R\|_{inc}$ (%)	$\delta R/R\|_{0\pi}$ (%)
current-like	40842	11756	1.047	1.303
current-like (FGD2)	14333	11748	1.908	2.391
upgrade ref.	22932	25280	0.912	1.109
upgrade alt. Target $\rightarrow$ TPC	58623	51394	0.604	0.746
upgrade alt. TPC $\rightarrow$ Target	58257	48574	0.614	0.754

- The value in blue is to be compared with current ND280 simulation results: $\delta R/R \sim 2.5\%$.
- Current analysis (TN-305) has: $\delta R/R \sim 4.5\%(stat) \oplus 2\%(sys)$ (taking all effects of migration... into account)

M.Lamoureux

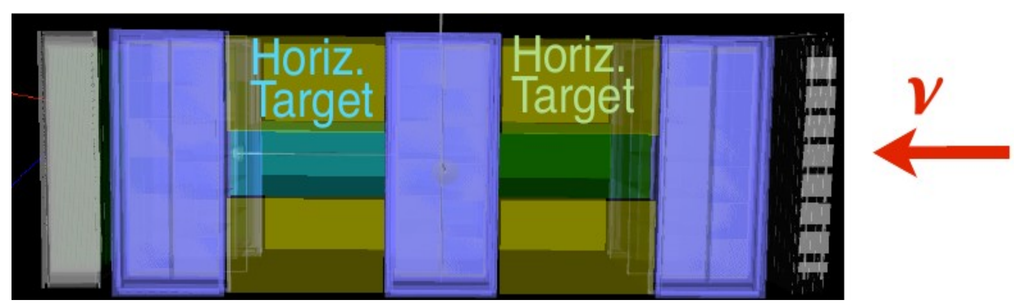
Results for 8×10^{21} POT (upgrade reference)

M.Lamoureux



sorry, this is not public yet :)

Not much gain with respect to ND280 current because of smaller mass of the new targets



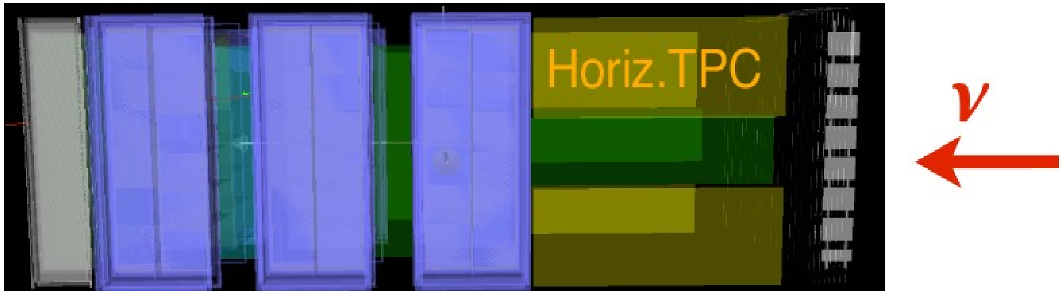
Results for 8×10^{21} POT (upgrade alternative 1)

alt. Target → TPC upgrade configuration

sorry, this is not public yet :)

sorry, this is not public yet :)

- Clear improvements with respect to current ND280
- Still not obvious that we can measure it if we include 2% systematics and in a real analysis ~factor 2 larger statistical error (eg, from background fluctuation)



Results for 8×10^{21} POT (upgrade alternative 2)

alt. TPC → Target upgrade configuration

alt. TPC → Target upgrade configuration

sorry, this is not public yet :)

muon cosθ

Pion FSI in C and O

- We constrain the probability of pion rescattering in the nucleus from π-N scattering data
  → uncertainty from data +
  → large uncertainty extrapolation from nucleus surface to inside the nucleus fully based on (not well known) nuclear physics model

- **The correlation between C and O FSI uncertainty is actually very large (for what we know... see backup)**

  - ND280 fit use fully correlated FSI uncertainty between C and O

- In any case measuring **low momentum pions in water target is not feasible...**

  - not much an issue of ND design, more useful to have external data on π-nucleus scattering measured on O

ν_e/ν_μ

- This is considered the **dominant systematics** for oscillation measurements at very large statistics (eg DUNE and HyperKamiokande)

- Measure of CPV relies on the rate of ν_e and $\bar{\nu}_e$ appearance after oscillation

$$\sin(\delta_{CP}) \approx \frac{(\nu_\mu \rightarrow \nu_e) - (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

→ difference between ν_μ and ν_e / $\bar{\nu}_e$ xsec has a direct impact on δ_{CP}

- In present OA we assume an uncertainty of **2% uncorrelated between ν_e and $\bar{\nu}_e$ + 2% anticorrelated**

$$V_{\nu_e,\bar{\nu}_e} = V_{rad.\,corr.} + V_{SCC} = \begin{pmatrix} \sigma^2_{\nu_e} & \sigma_{\nu_e}\sigma_{\bar{\nu}_e} \\ \sigma_{\bar{\nu}_e}\sigma_{\nu_e} & \sigma^2_{\bar{\nu}_e} \end{pmatrix} = \begin{pmatrix} 2 \times 0.02^2 & -0.02^2 \\ -0.02^2 & 2 \times 0.02^2 \end{pmatrix}$$

(more discussion about where this uncertainty comes from in backup)

ν_e/ν_μ: extrapolating from present status

- **Measurement of intrinsic ν_e component in the flux**

$$R(\nu_e) = 1.01 \pm 0.06(stat.) \pm 0.06(flux \oplus x.sec) \pm 0.05(det. \oplus FSI) = 1.01 \pm 0.10$$

(in Phys.Rev. D89 (2014) 099902, $6\text{x}10^{20}$ POT)

but it assumes same ν_e and ν_μ cross-section model (i.e. measuring the rate knowing the xsec shape from ν_μ)

- A **measurement of ν_e cross-section** give instead:

$$\langle\sigma\rangle_\phi = 1.11 \pm 0.09 \ (\text{stat}) \pm 0.18 \ (\text{syst}) \times 10^{-38} \ \text{cm}^2/\text{nucleon}.$$

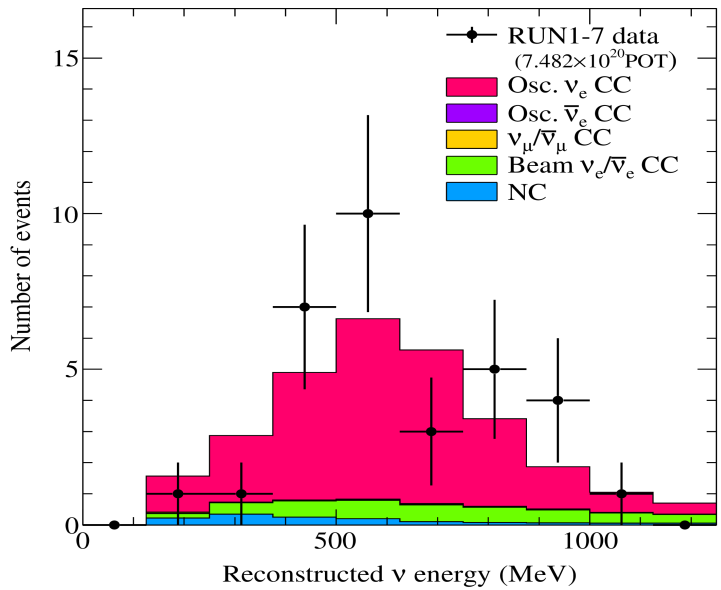
(in Phys.Rev.Lett. 113 (2014) no.24, 241803, $6\text{x}10^{20}$ POT)

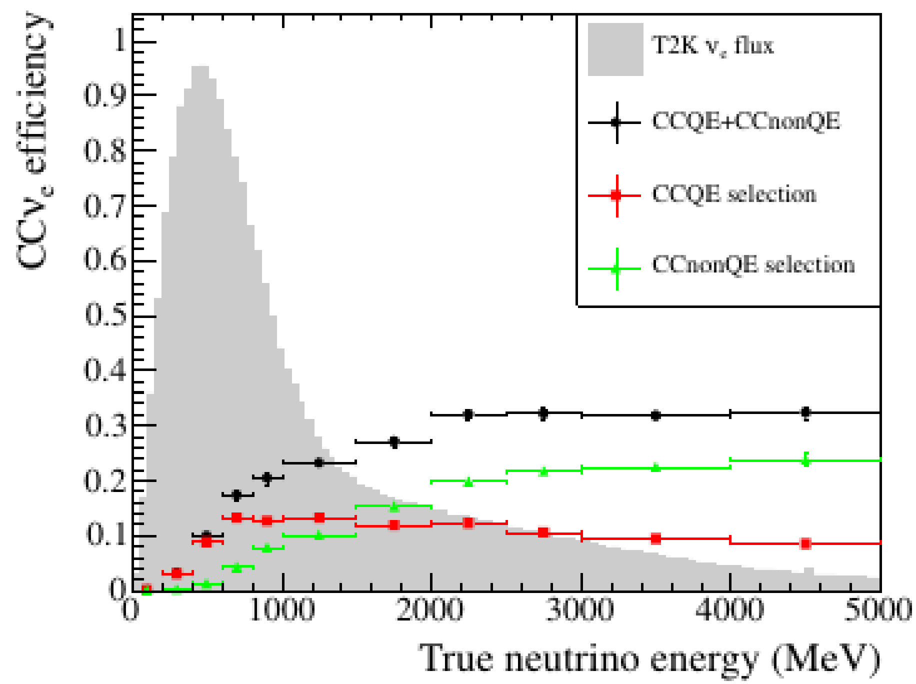
systematics uncertainty: 13% flux, 8% detector (let's optimistically assume to be fully correlated between ν_e and ν_μ) → remaining 6% uncertainty (2% OOFV γ background)

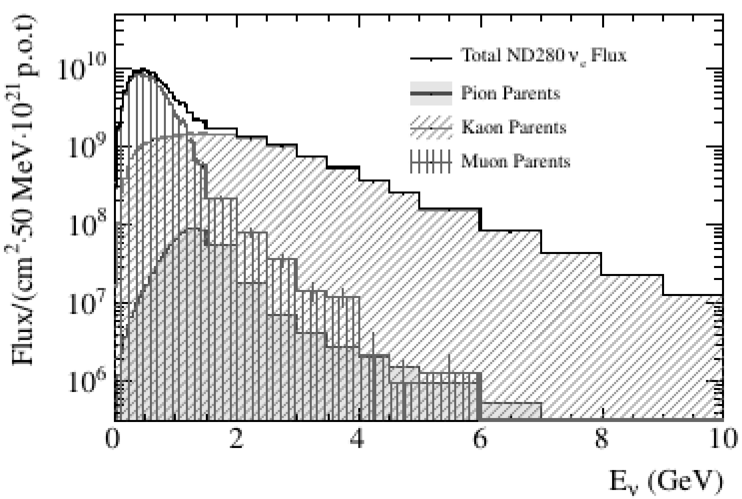
→ **to get to ~2% ν_e/ν_μ measurement we need to gain a factor >3 in systematics**

ν_e statistics at low energy

OA electron events are below 1 GeV but, due to efficiency, ND280 electron events are mostly above 1 GeV







Stat error below 1 GeV (eg from μ decay only) is 4 times larger than total:

$$R(\nu_e(\mu)) = 0.68 \pm 0.24(stat.) \pm 0.11(flux \oplus x.sec) \pm 0.14(det. \oplus FSI) = 0.68 \pm 0.30$$

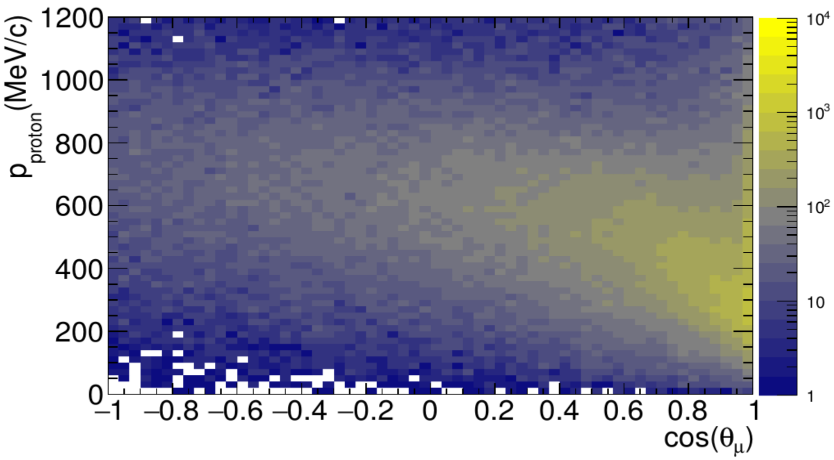
35% → **8% with 10*10²¹ POT**
Need to improve by a factor ~16 the stat (larger mass, better efficiency and purity)

Protons

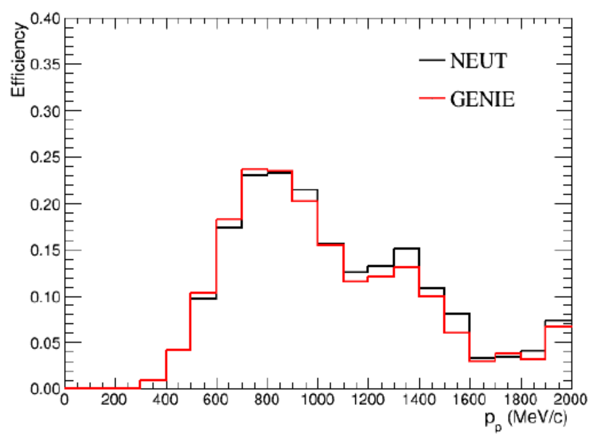
- **Present ND280 proton measurements limited by efficiency**

→ in practice only the protons with momentum > 500 MeV can be reconstructed

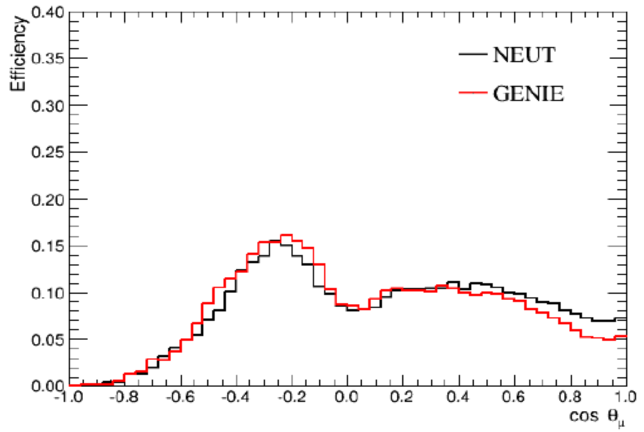
phase space: muon angle vs proton momentum



μ+p efficiency vs proton momentum

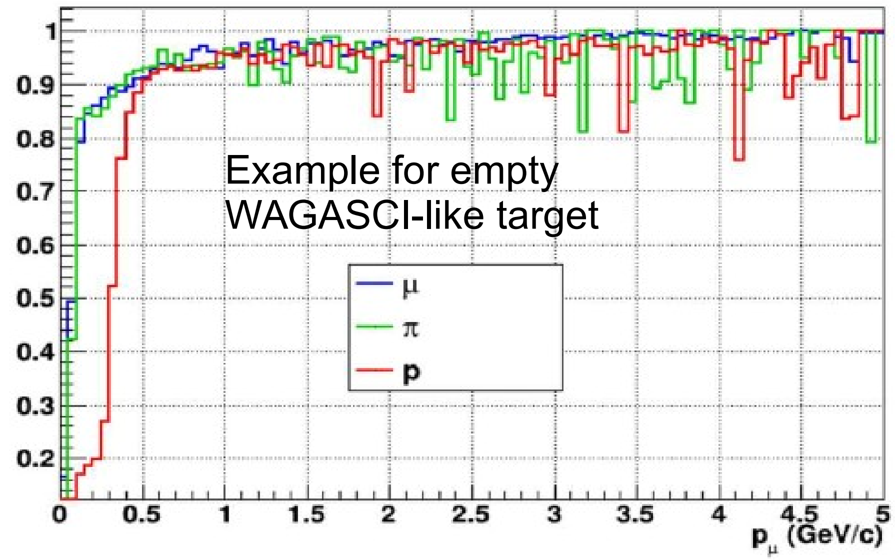


μ+p efficiency vs muon angle



- Interesting **ND280 upgrade:** a much larger angular acceptance on muons (horizontal TPC) coupled with a light CH target for low momentum protons

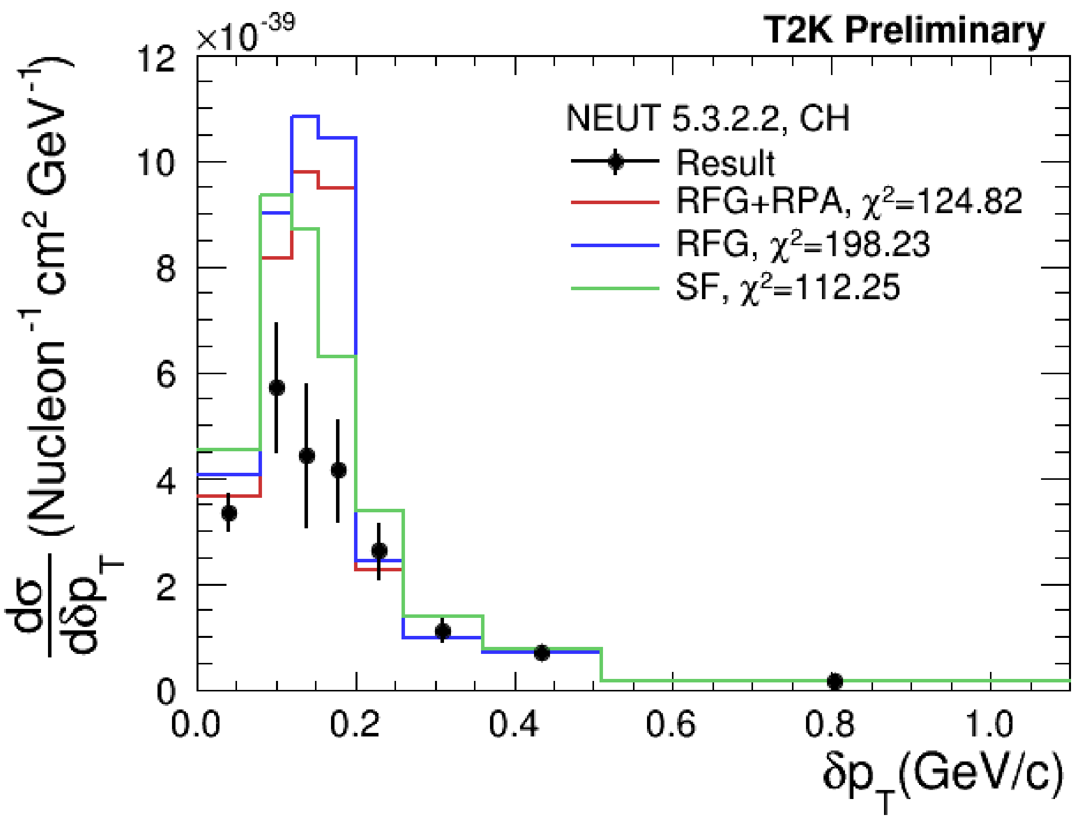
→ **big improvements in muon+proton(s) measurements**

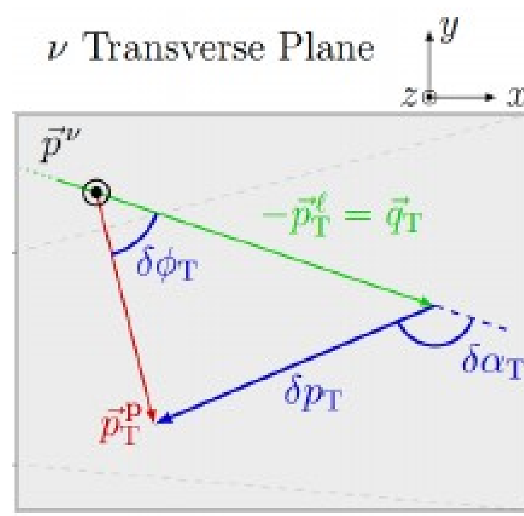


Example: transverse variables

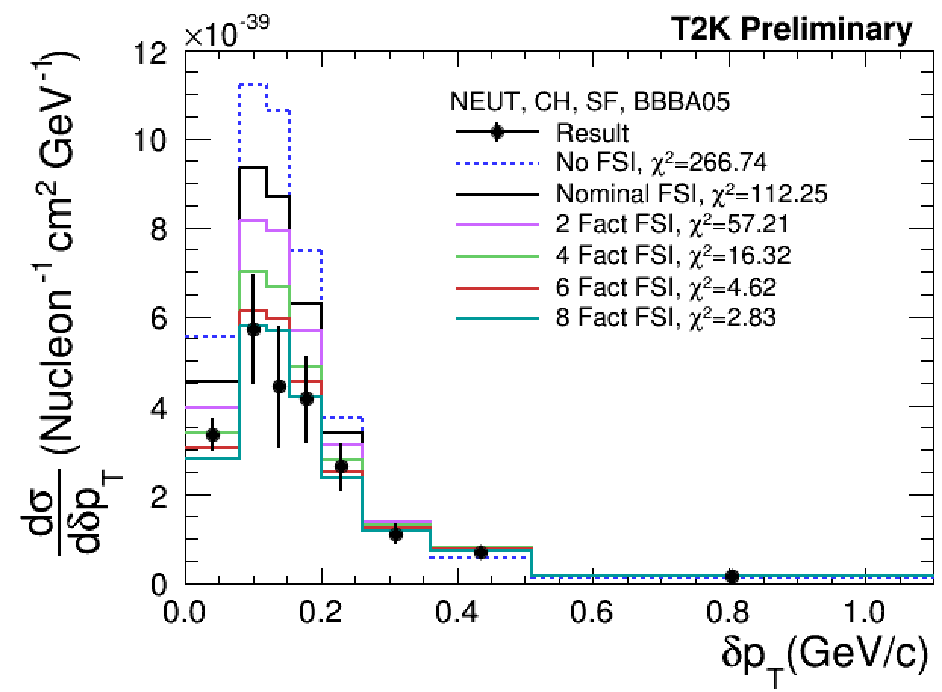
arXiv:1512.05748
arXiv:1610.05077

Official T2K results from TN278 (S.Dolan)





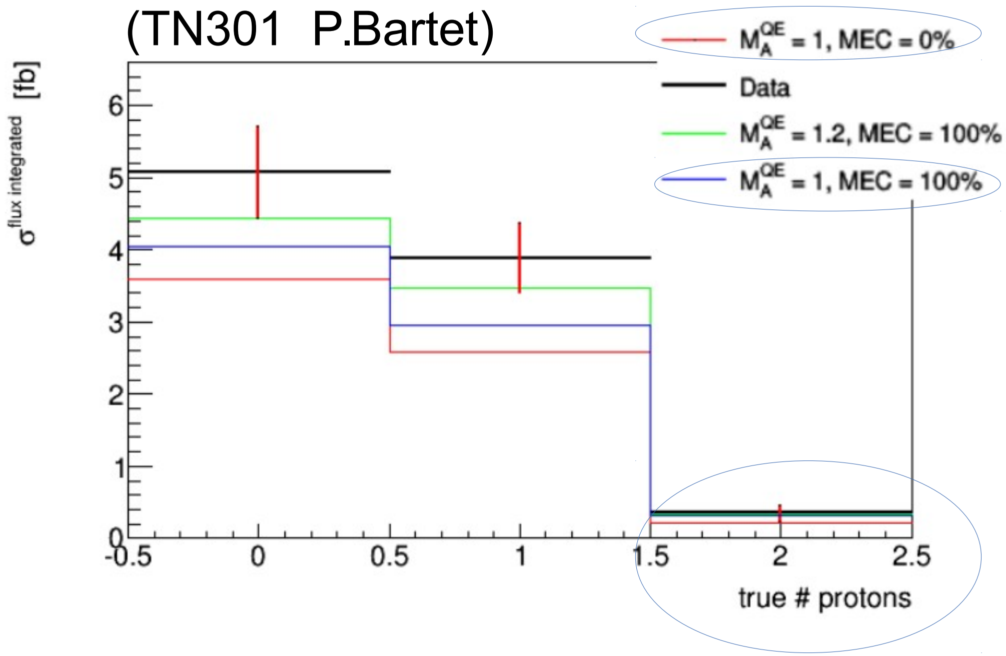
Proton rate dependent on FSI due to p_p>500 MeV cut



→ interpretation of other experiments with lower threshold (Minerva, ArgoNEUT) is not conclusive...

Example: proton multiplicity

(TN301 P.Bartet)



2p2h signature gives 'often' 2 protons but most of the time they are low momentum
→ present multiplicity measurement also limited by high momentum threshold

- We can certainly learn 'a lot' from a light target … can we be more quantitative?

  Is the gain large enough to compensate the lost of mass in the target?

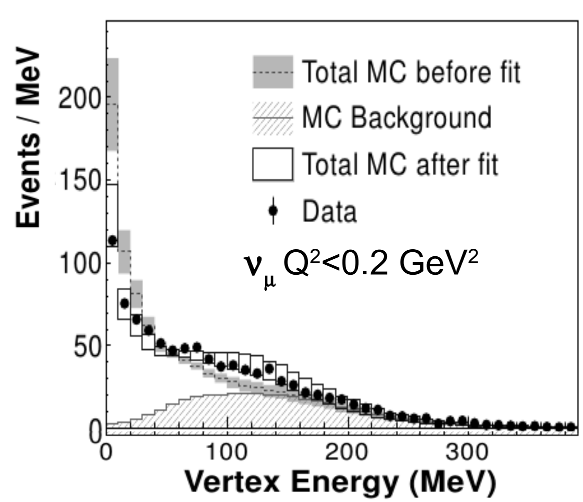
- Difficult to asnwer since even the results from present low-threshold experiments did not produce (yet?) a flourish of theoretical interpretation

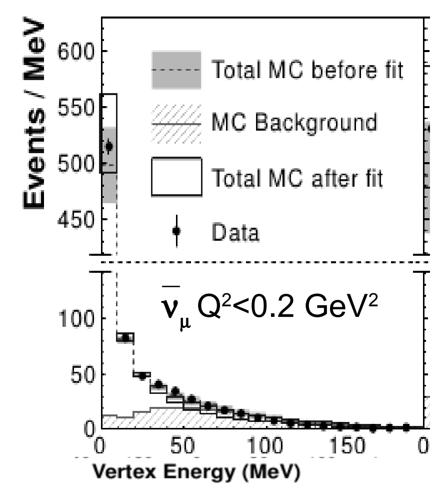
Vertex activity

- A more complete picture is emerging... (much less 'demanding'/difficult variable for the

sorry, this is not public yet :)

- **MINERvA :**
  comparison $\nu - \bar{\nu}$: systematics highly correlated (70%)





possible 2p2h signature:

ν_μ **data** suggest additional proton with E<225MeV in 25 ± 1(stat) ± 9(syst) % of events

$\bar{\nu}_\mu$ **data**: no additional proton (2p2h would produce neutrons)

Conclusions

- We have well-known quantitative assessment of physics gain from the upgrade using the BANFF fits and reproducing the OA results

- Less model-dependent studies are also useful even if difficult to quantify

Need manpower!
Eg, for proton variables and vertex activity, study the gain in sensitivity to separate the models with a new light target with lower threshold

- Need to find the best compromise and/or prioritize between:

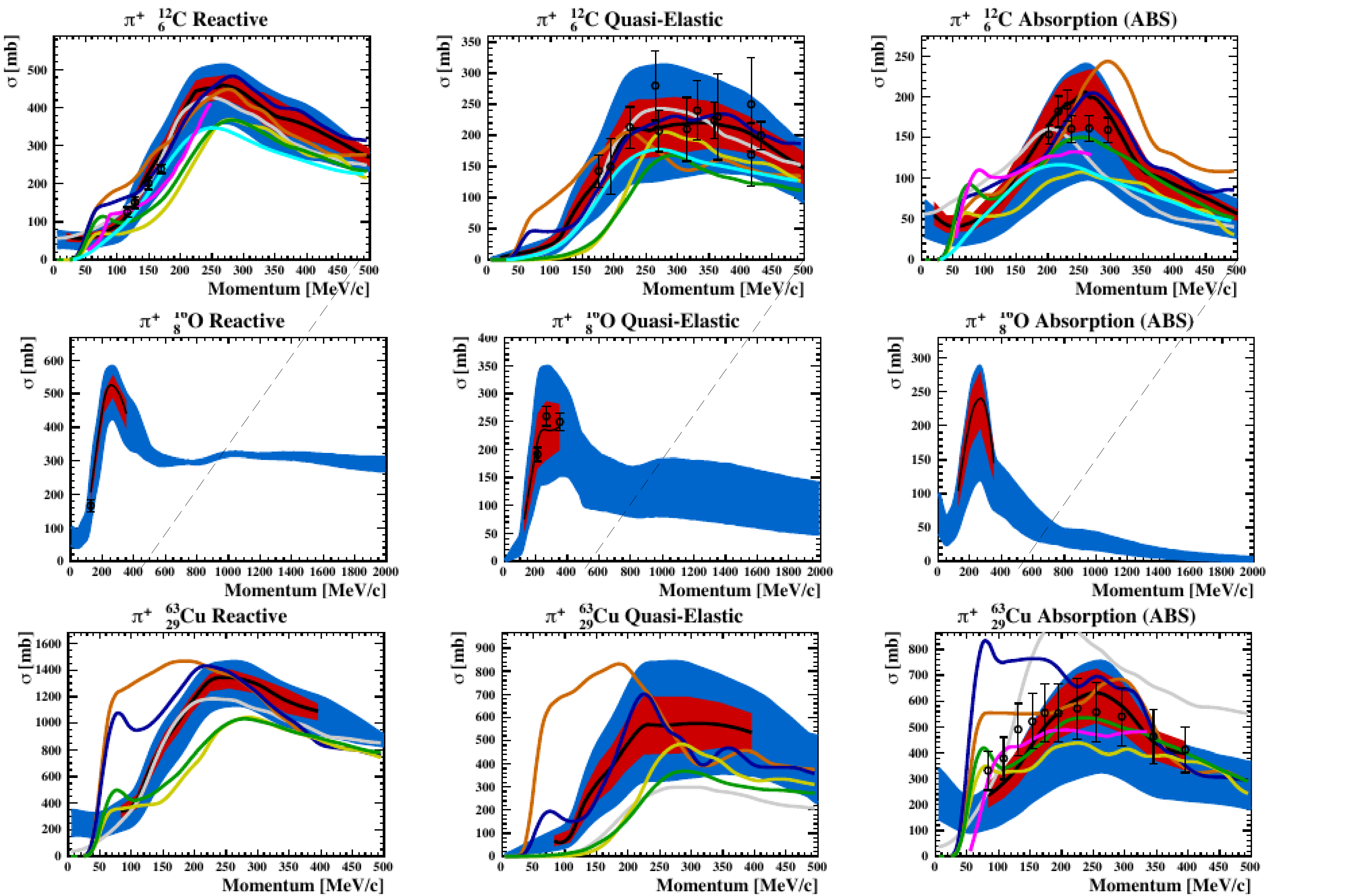
large mass target (beneficial for ν_e) and/or large water target (for C/O)

against

light target for low momentum protons (and pions)

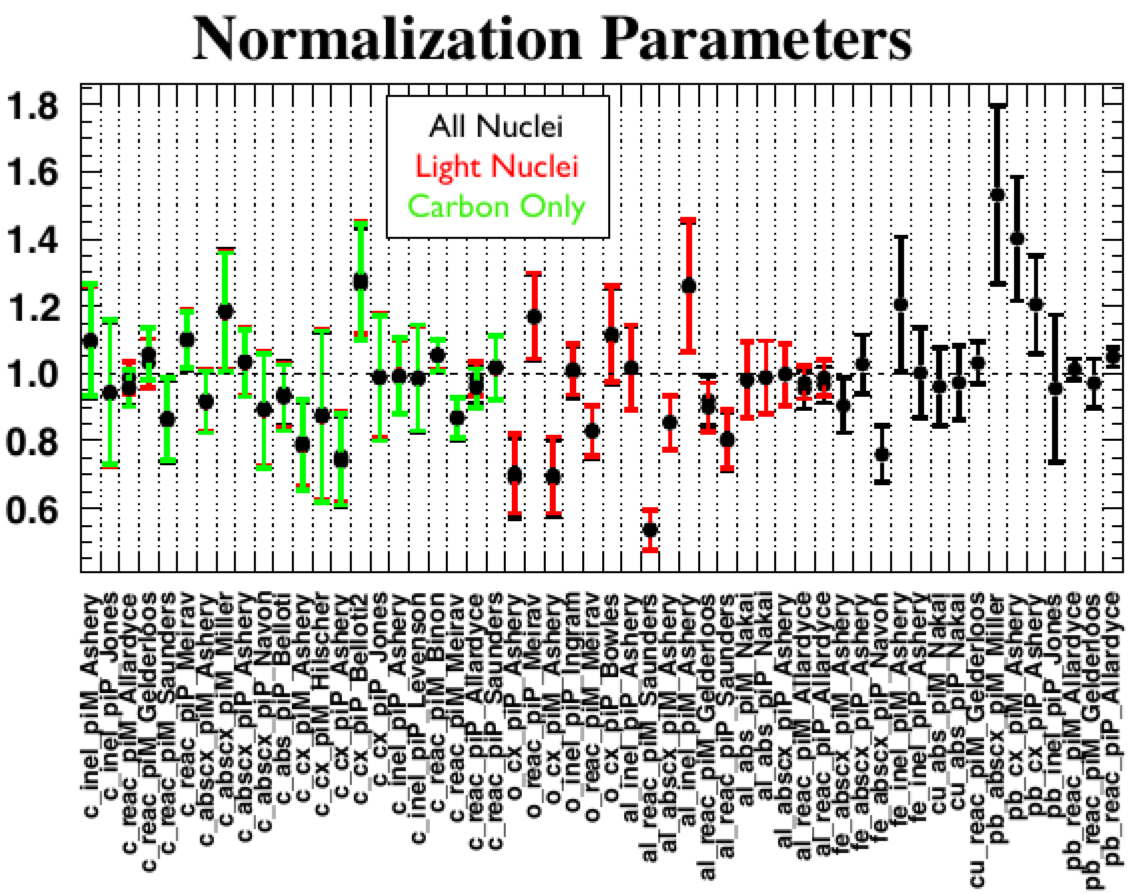
Elder Pinzon

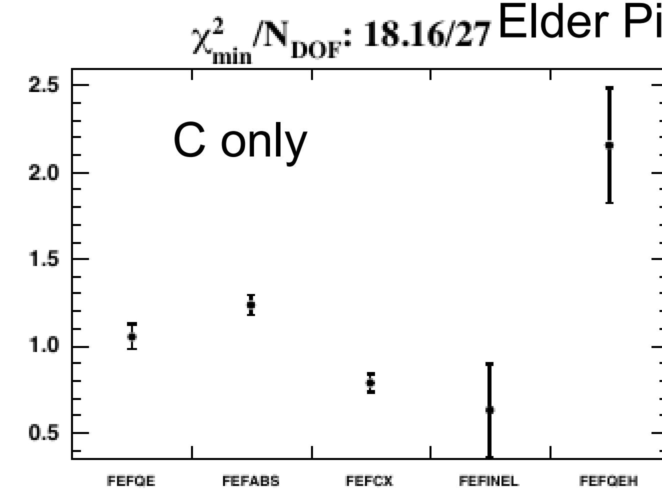
Pion scattering on C,O, Cu

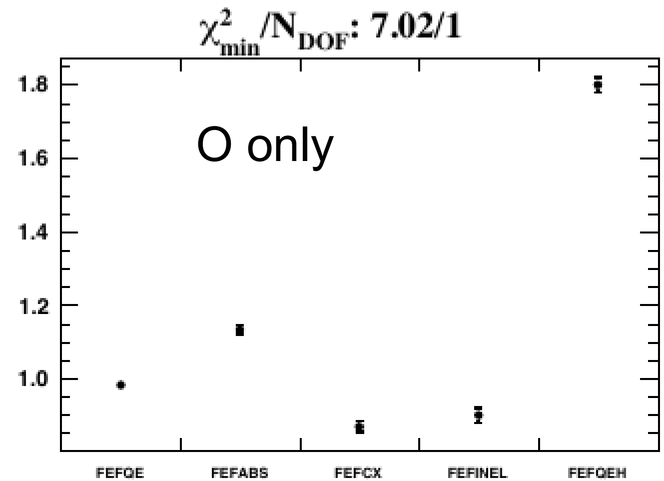


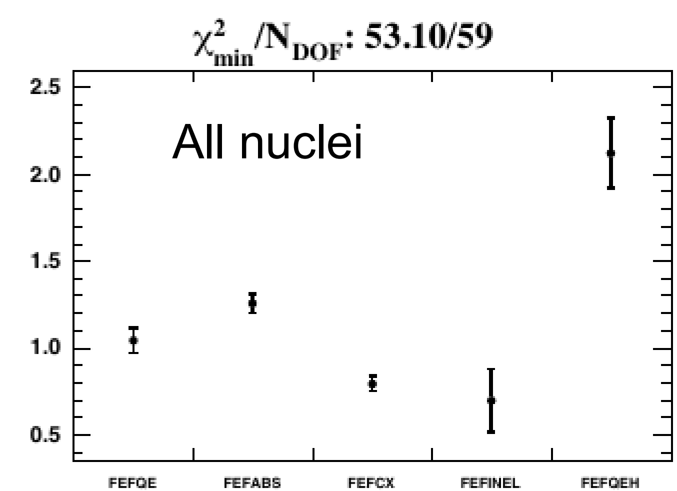
Elder Pinzon

Pion FSI fit results









δ_{CP} and $\nu_e/\bar{\nu}_e$ xsec

- Measure of CPV relies on the rate of ν_e and $\bar{\nu}_e$ appearance after oscillation

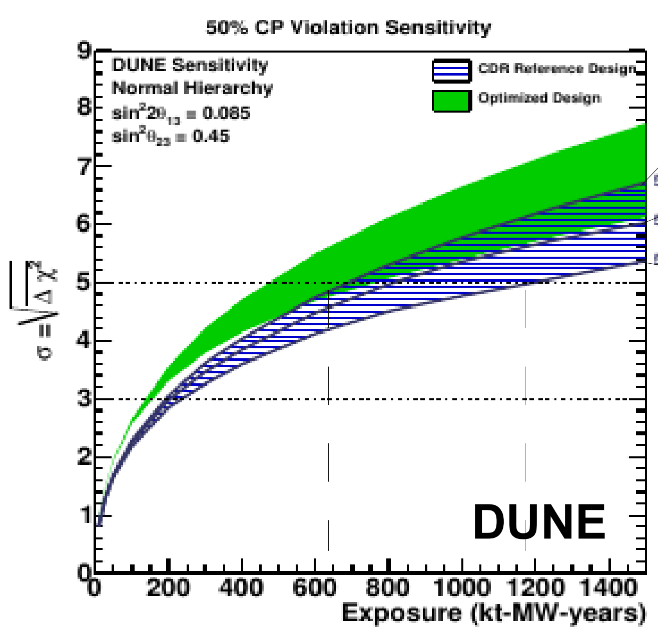
$$\sin(\delta_{CP}) \approx \frac{(\nu_\mu \rightarrow \nu_e) - (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

→ difference between ν_μ and ν_e / $\bar{\nu}_e$ xsec has a direct impact on δ_{CP}

- Very low statistics of ν_e in 'standard' beam → cannot be constrained at ND

ν_e / $\bar{\nu}_e$ largest systematics for DUNE and HyperKamiokande

- For future long baselines what matter are the uncorrelated uncertainty between different neutrino flavors and 'charge':



5% ± 1%

5% ± 2%

5% ± 3%

5% $\nu_\mu - \bar{\nu}_\mu$ + uncorrelated ν_e - $\bar{\nu}_e$ 1-3%

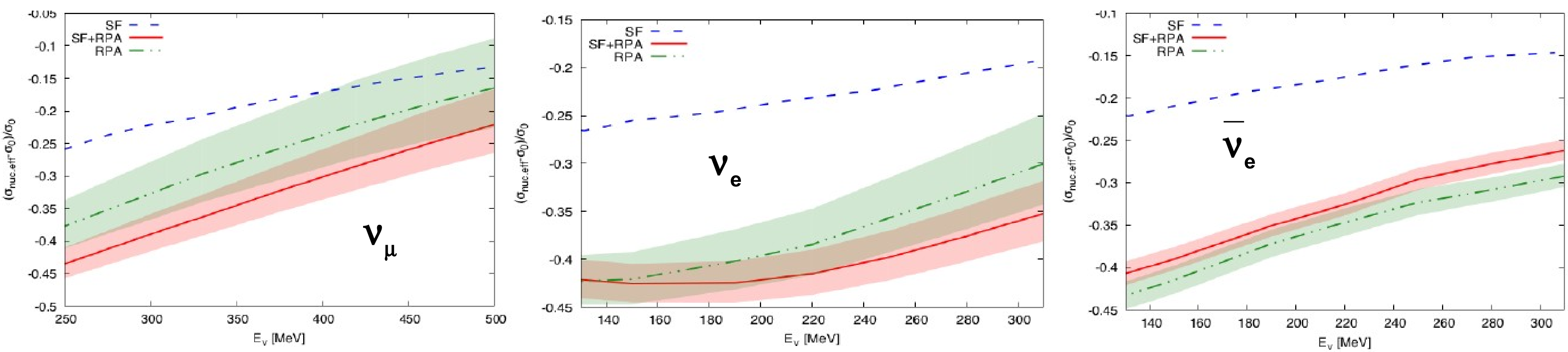
→ equivalent to factor 2 in exposure!

$\nu_e/\bar{\nu}_e$ xsec

- In principle, **if ν_μ xsec is perfectly known, the model can be easily used to extrapolate to $\bar{\nu}_\mu$ and ν_e** (lepton universality and CP symmetry hold in neutrino interactions)

In practice, large uncertainty on ν_μ due to nuclear effects, may affect differently ν_μ, $\bar{\nu}_\mu$ and ν_e
→ **Uncorrelated uncertainty between ν_μ, $\bar{\nu}_\mu$ and ν_e are just a product of our limited knowledge on ν_μ interactions**

Correction to the CC inclusive cross-section due to nuclear effects for different model with theoretical uncertainty band:

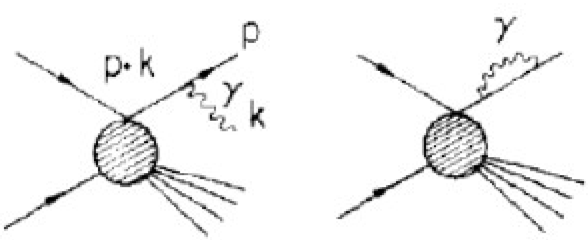


- **Need to control ν_μ *very* precisely** (or find a way to produce a high stat beam of ν_e)

An important missing piece for ν_e

Different radiative corrections for $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$ (because of different lepton mass)

- The only approximated calculation available is:



Nuclear Physics B154 (1979) 394–426

RADIATIVE CORRECTIONS TO HIGH-ENERGY NEUTRINO SCATTERING

A. DE RÚJULA * and R. PETRONZIO **
CERN, Geneva, Switzerland

A. SAVOY-NAVARRO
DPhPE, CEN, Saclay, France

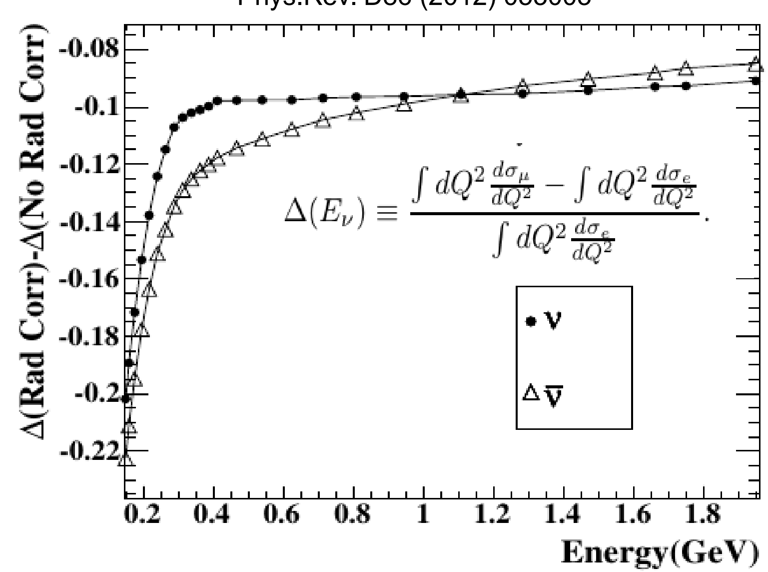
Received 19 January 1979

- That formalism has been recently applied to QE cross-section computation:

  ~10% effect on the difference between ν_μ and ν_e cross-section !

  → **need less approximated calculation?**

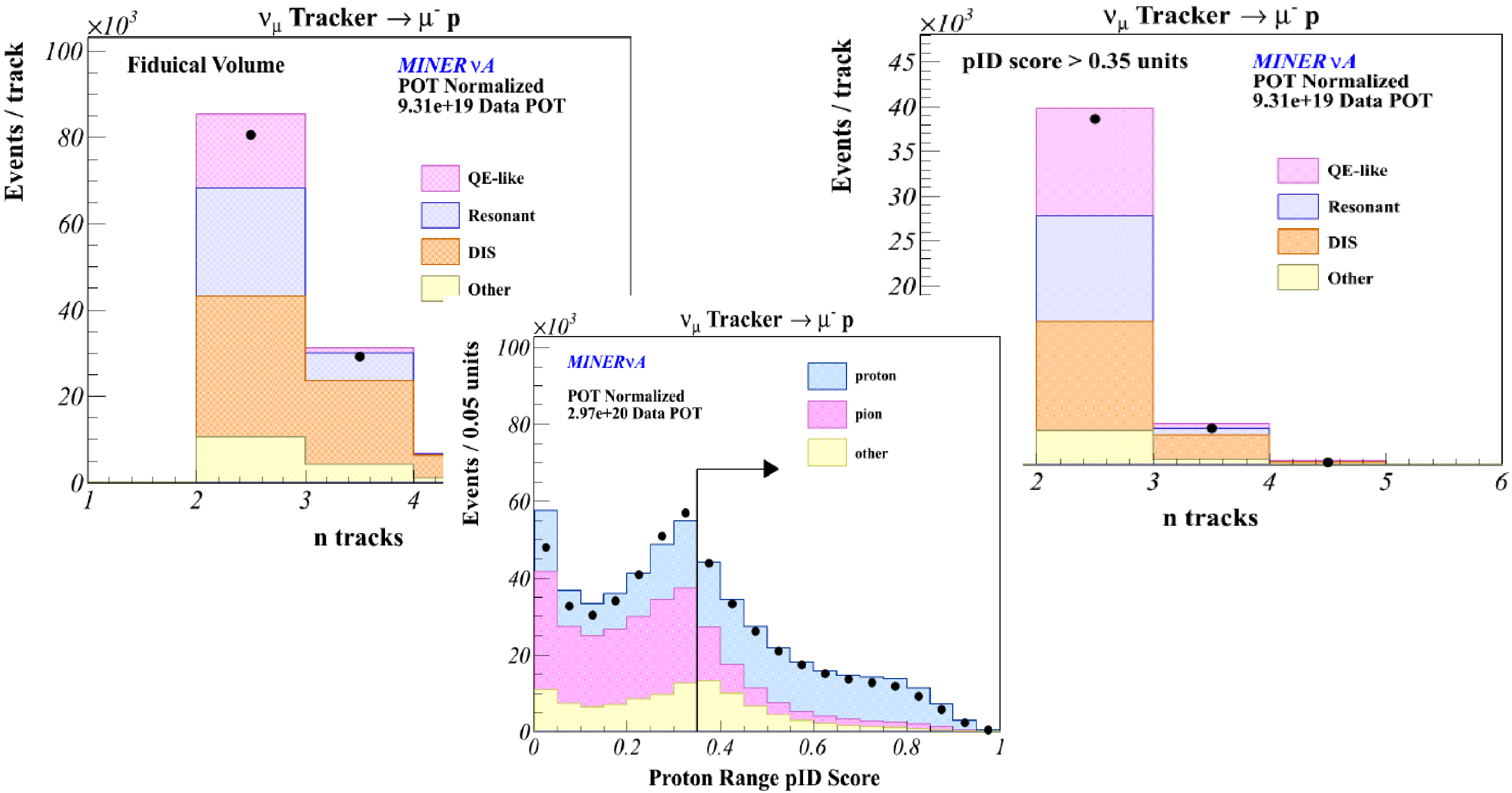
Phys.Rev. D86 (2012) 053003



Protons in Minerva (1)

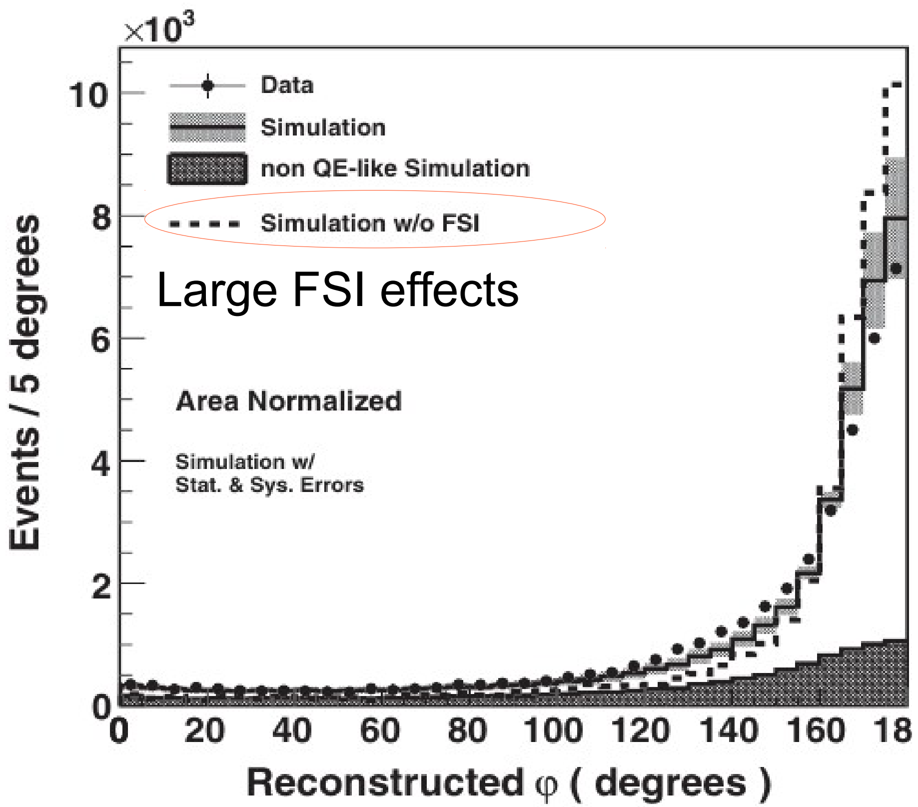
- Track in scintillator with dE/dx compatible with proton: **threshold E^{kin}_{p}>110 MeV with ~ 50% efficiency**

CC0pi analysis: effect of proton ID cut:

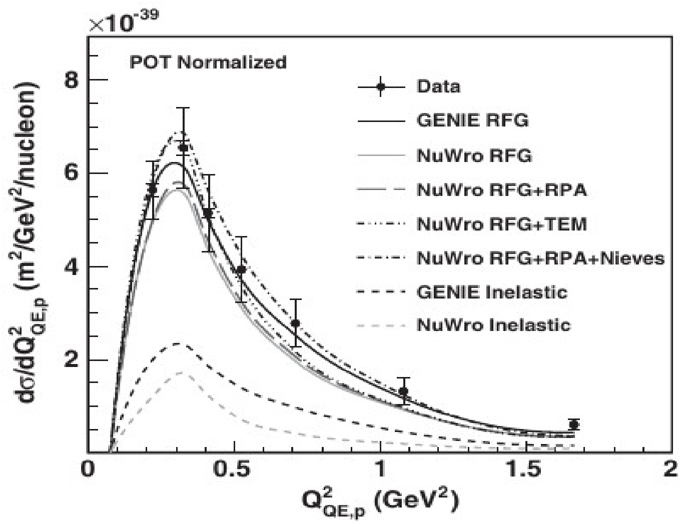


Proton-muon correlations

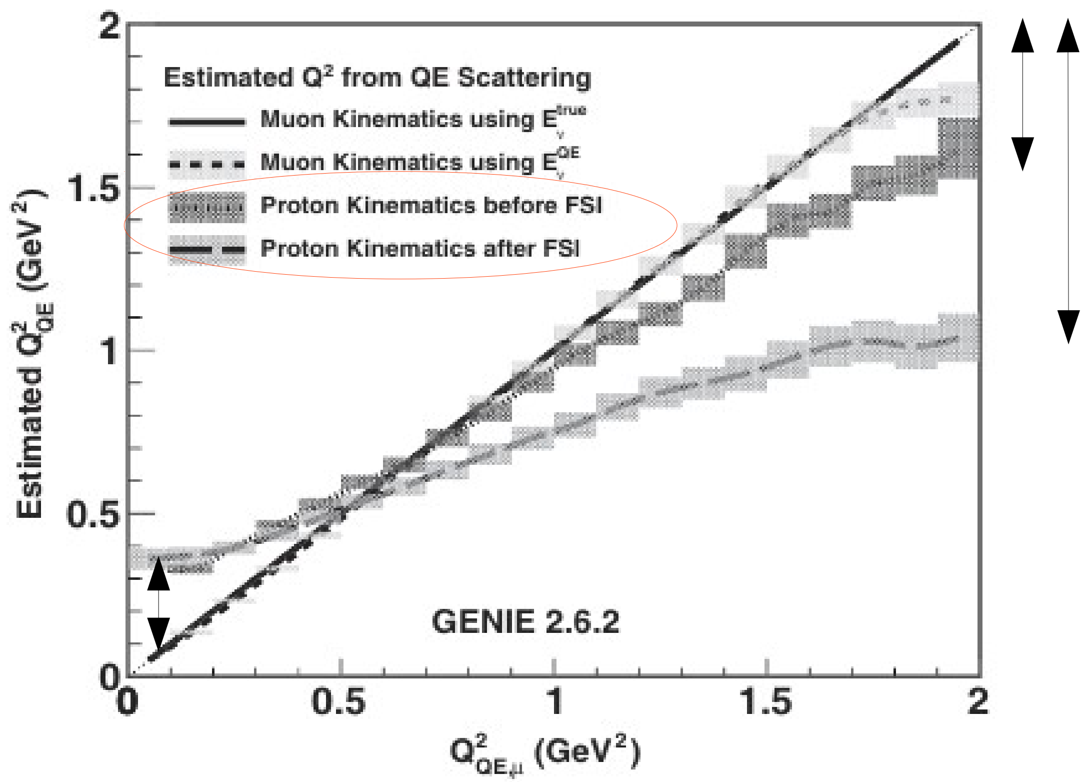
Angle between ν-μ and ν-p planes



Q^2 from proton kinematics



Q^2 estimated with muons or with protons

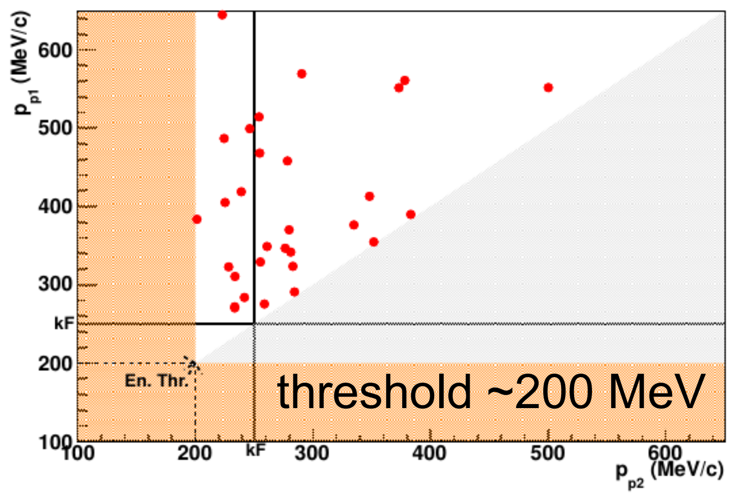


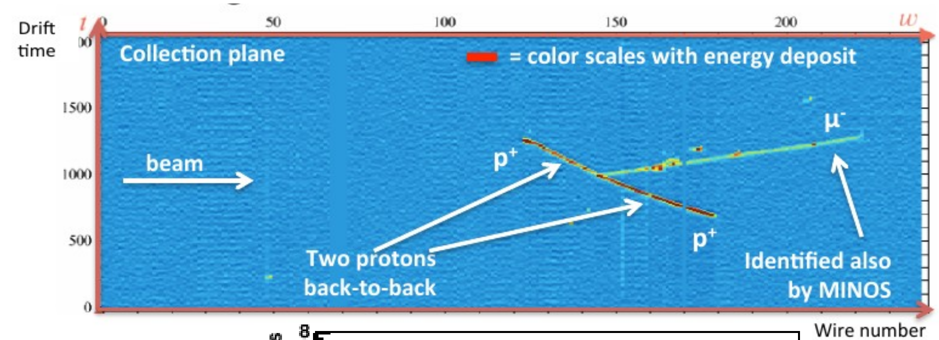
Q^2 estimation affected by:

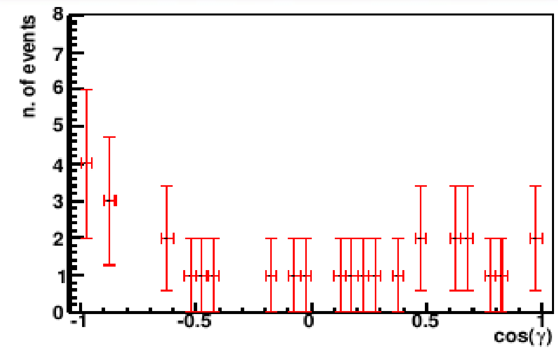
- proton threshold
- initial nucleon momentum
- large FSI effects

Protons in LAr

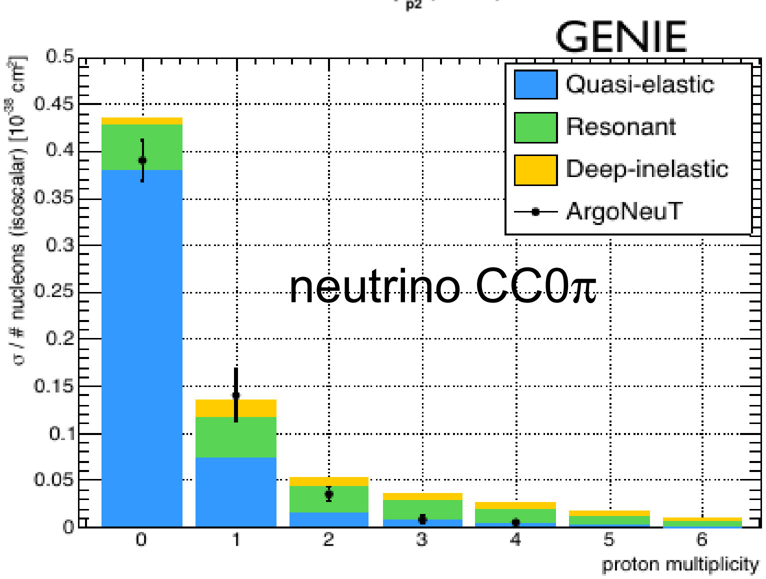
- **ArgoNEUT**: small statistics but powerful Ar technology → waiting for MicroBooNE!
  - 30 events with 2 protons: some of them back-to-back in LAB frame ('hammer events')

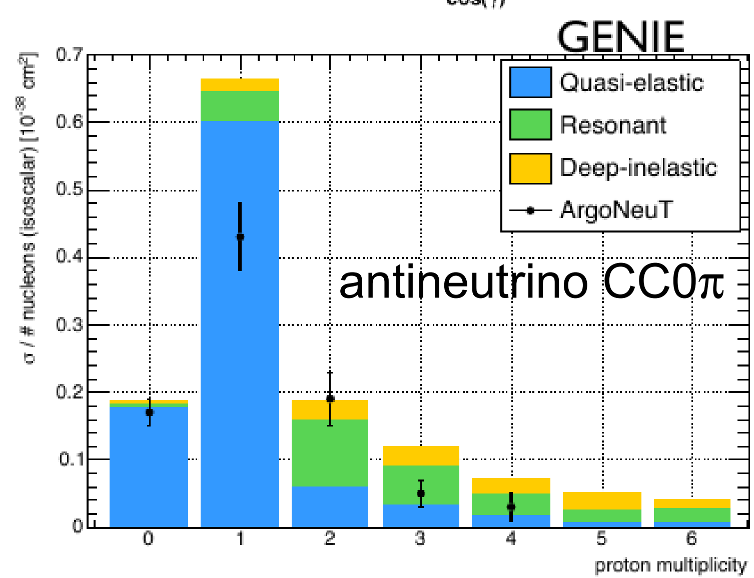






- significative measurement of proton multiplicity

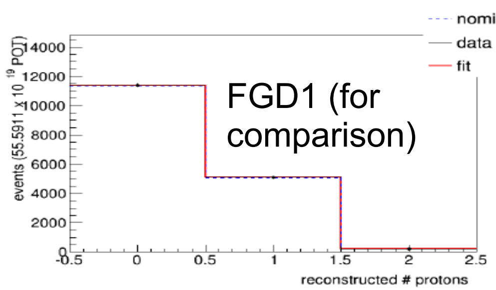


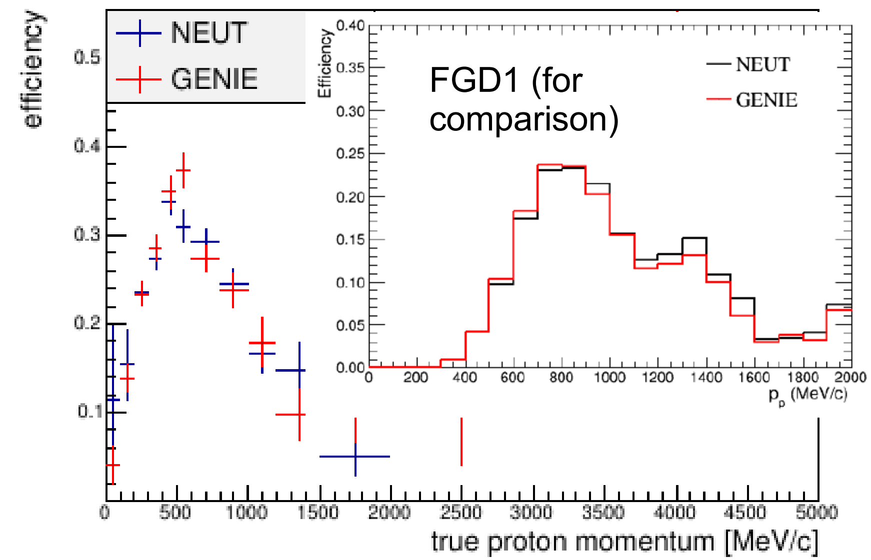


Future prospects

- **ND280 interactions on TPC cathode**
(very low proton threshold)

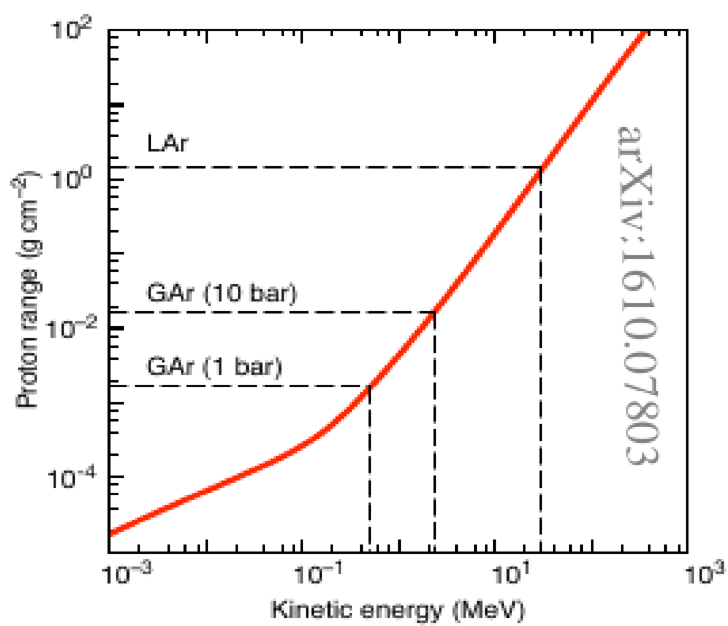
(M.Lamoureux)





- **High Pressure TPC**

Threshold kinetic energy to have 1cm track in Ar TPC



Momentum threshold

Atm pression: ~30 MeV

10 bar: ~70 MeV

Liquid Ar : ~200 MeV

Are we able to interpret the results?

What do we learn from the kinematics of such low energy protons?

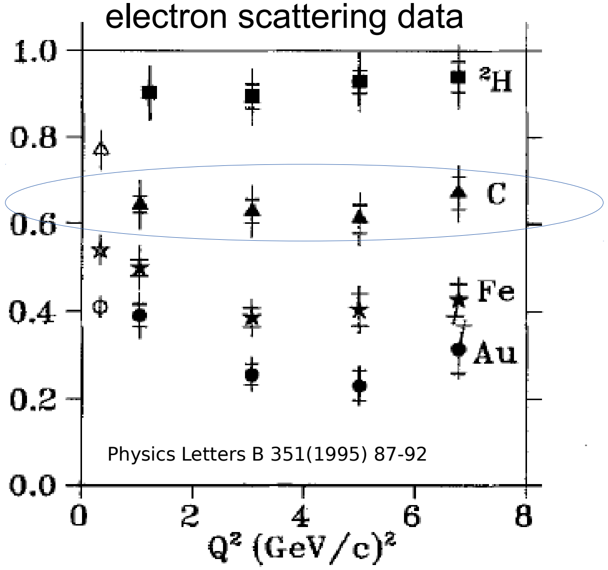
- Limited predictivity on outgoing nucleon(s) kinematics of the most advanced models (eg proton kinematics in 2p2h ?)
  Outgoing nucleons are strongly affected by **initial nucleons kinematics in the target nucleus (exclusive measurements in electron scattering may help)**

- Main problem: **measured protons depend on the convolution of nuclear effects in the interactions and Final State Interaction**

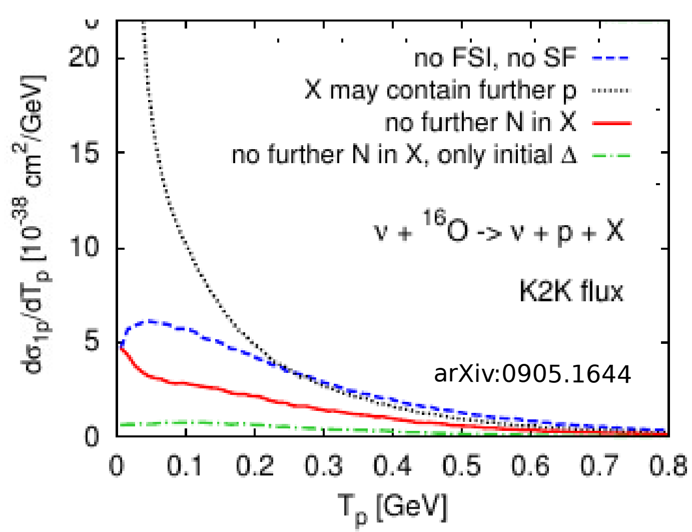
  Need to measure proton scattering and improve proton FSI modeling!

~40% of protons undergo FSI

Nuclear transparency in electron scattering data

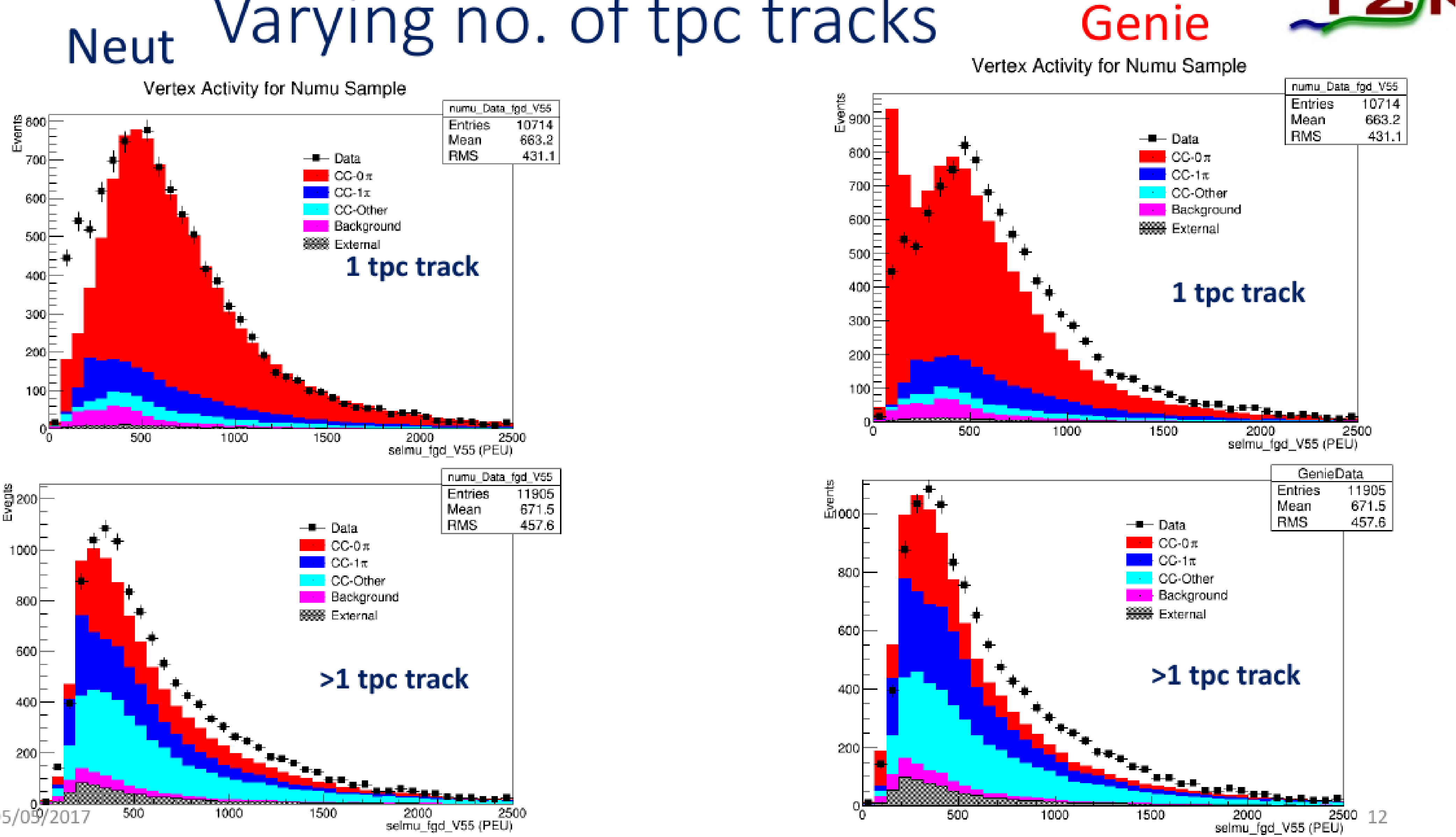


Cross-section for proton knock-out in GiBUU



FSI effects change the outgoing proton kinematics

Varying no. of tpc tracks



Pratiksha Paudyal