Neutrino-nucleus cross-sections Near detectors & TPC's

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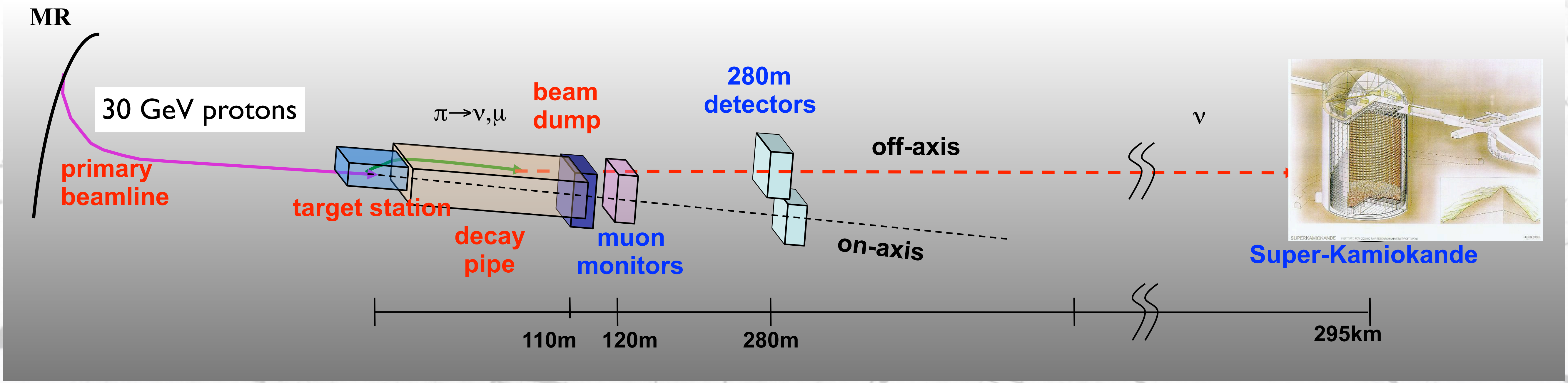
Neutrino oscillations, cross-sections & Near detectors.

Typical Long Base Line experiment layout



Neutrinos produced in a particle accelerators:

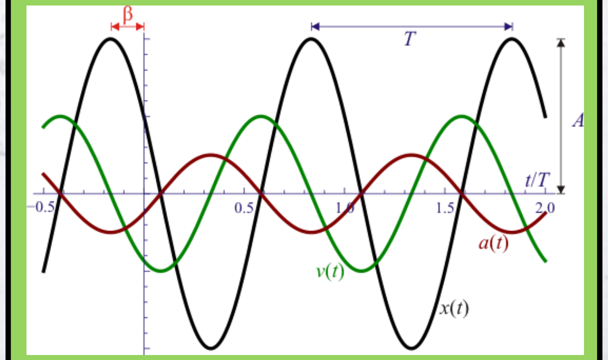
$pA \rightarrow \pi^+ \pi^+ \pi^- \ldots$

$\pi^+ \rightarrow \mu^+ \nu$

$\pi^- \rightarrow \mu^- \bar{\nu}$

Neutrino flux meas

Oscillations



Neutrino flux meas

Neutrino oscillations

- Neutrino oscillation experiments are carried out by comparing neutrino interactions at a near and far sites.
- The number of events depends on the cross-section:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

- This is not so critical if we can determine the energy of the neutrino, since at the far detector

$$N_{events}^{far}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

- and it cancels out in the ratio as function of energy:

$$\frac{N_{events}^{far}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

Neutrino oscillations

- Since the neutrino energy is not monochromatic, we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

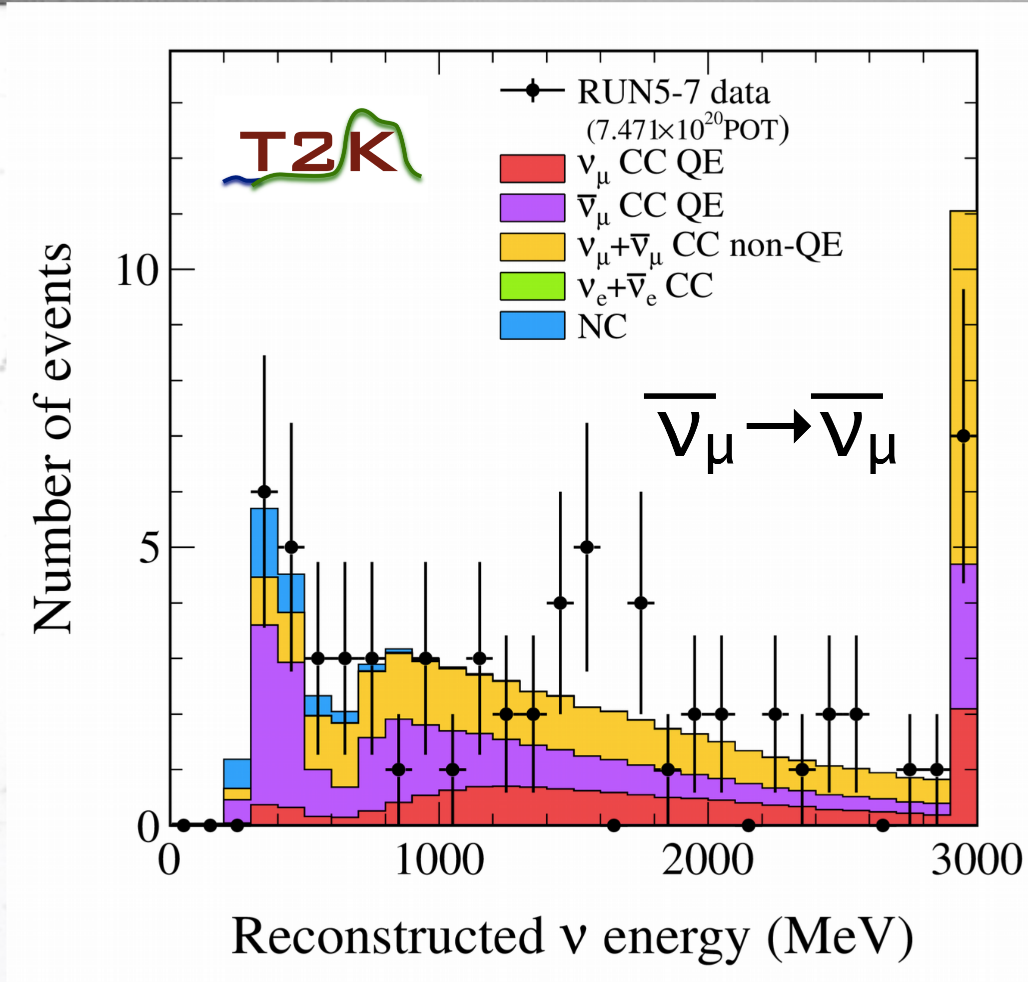
$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

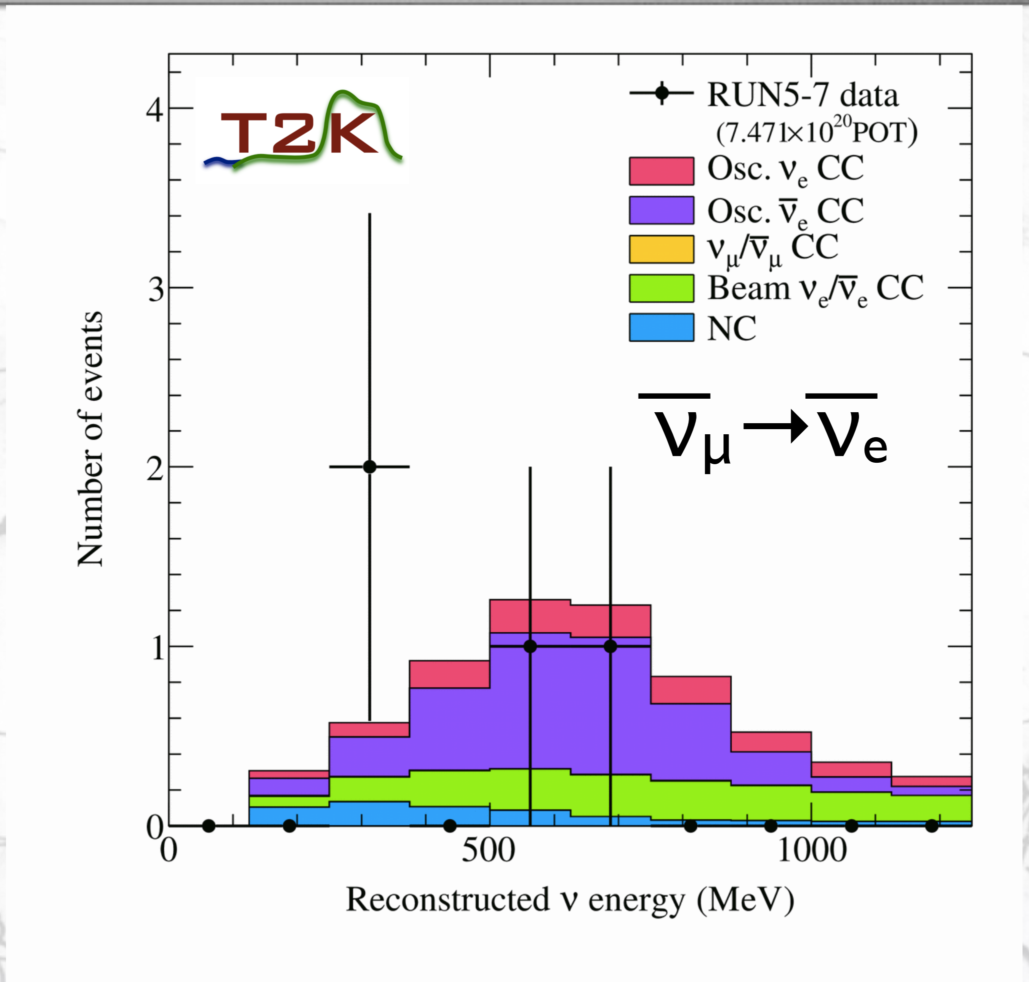
- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

Oscillation experiments require to know $\Phi(E_\nu)$, $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$

$P(E_\nu|E'_\nu)$ is not caused by a mere detector smearing.

Backgrounds

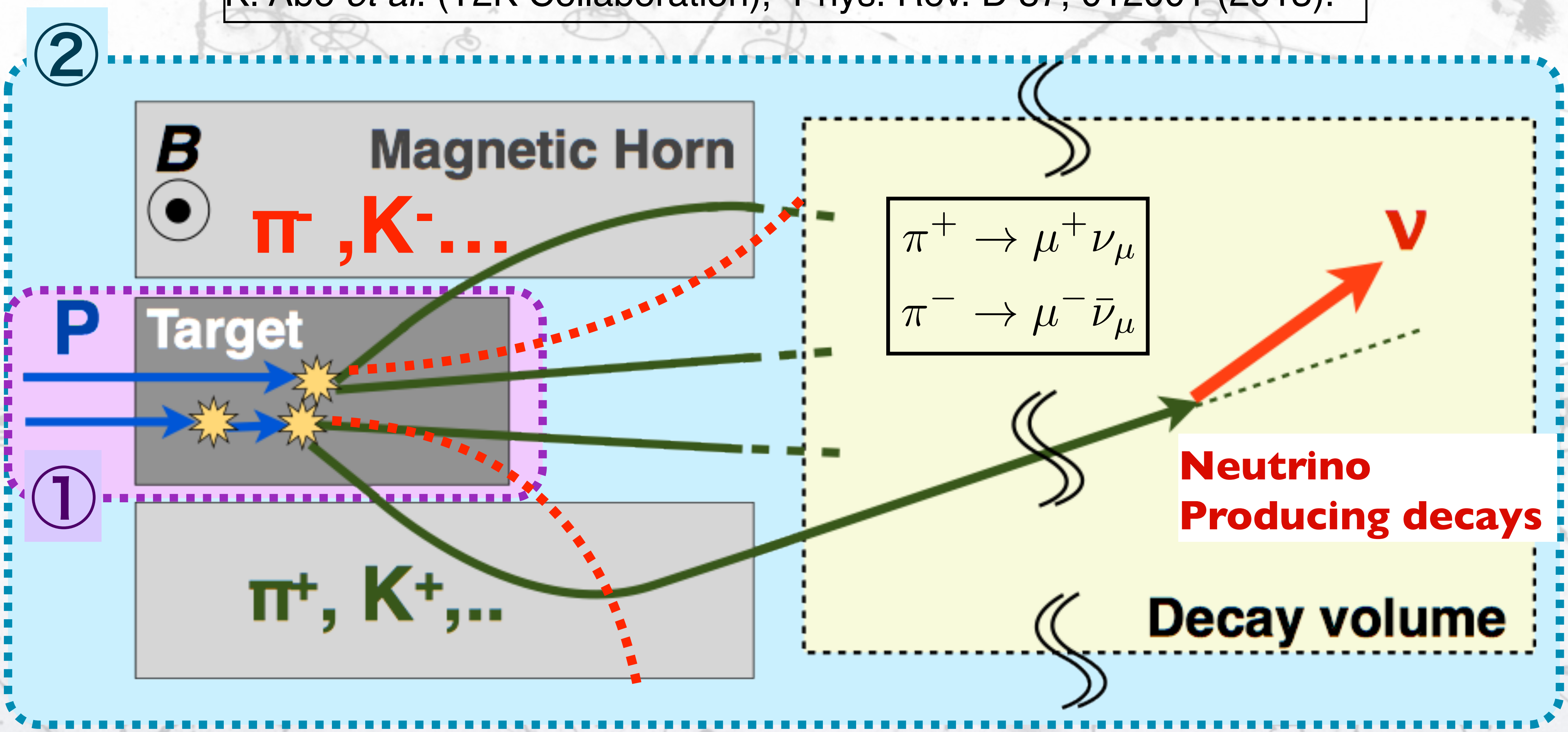




- Far detector also have several sources of backgrounds:
  - wrong sign backgrounds (neutrinos vs. antineutrinos).
  - NC interactions populating low energy bins.
  - Wrong interaction channel leading to biased energies.

Neutrino production

K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).



Other source of neutrinos is the low energy electron antineutrinos from nuclear reactors.

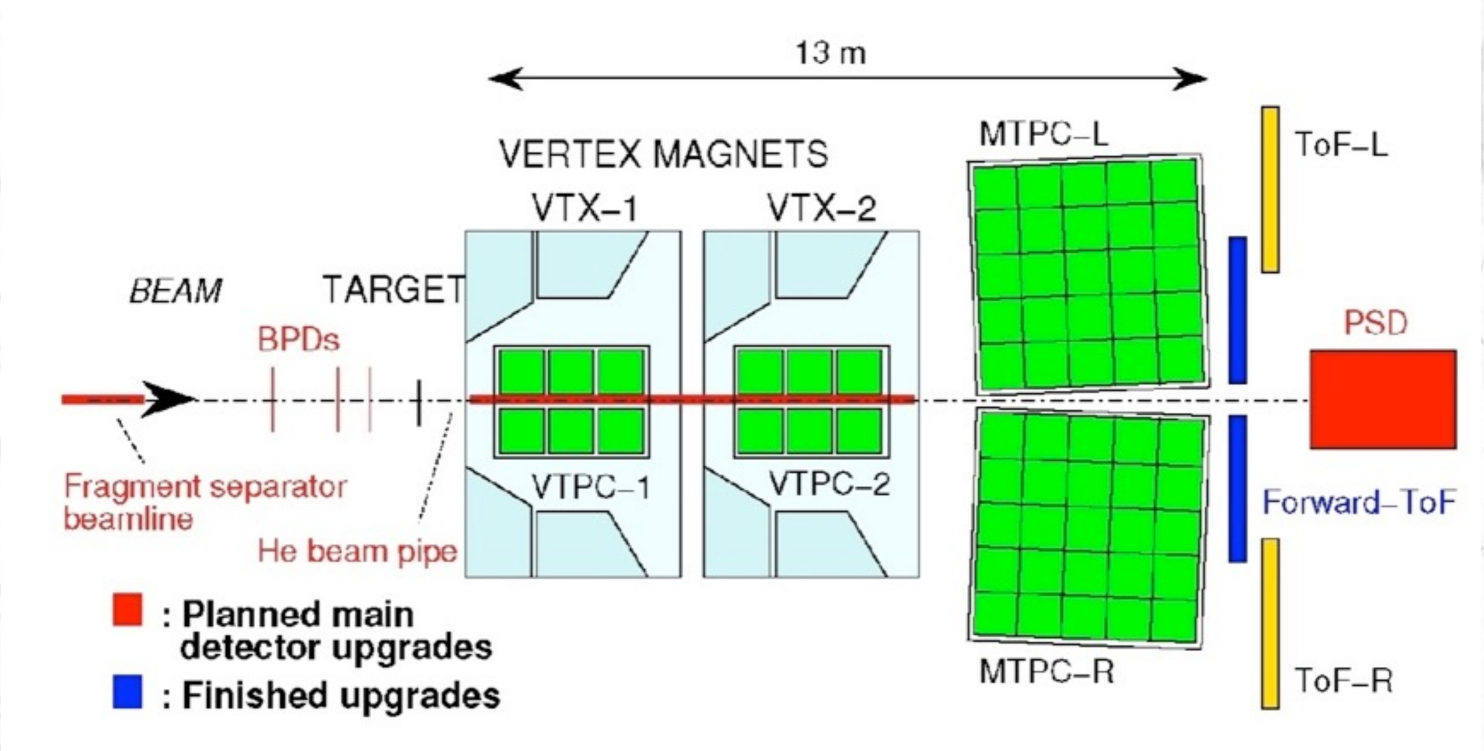
Neutrino Flux

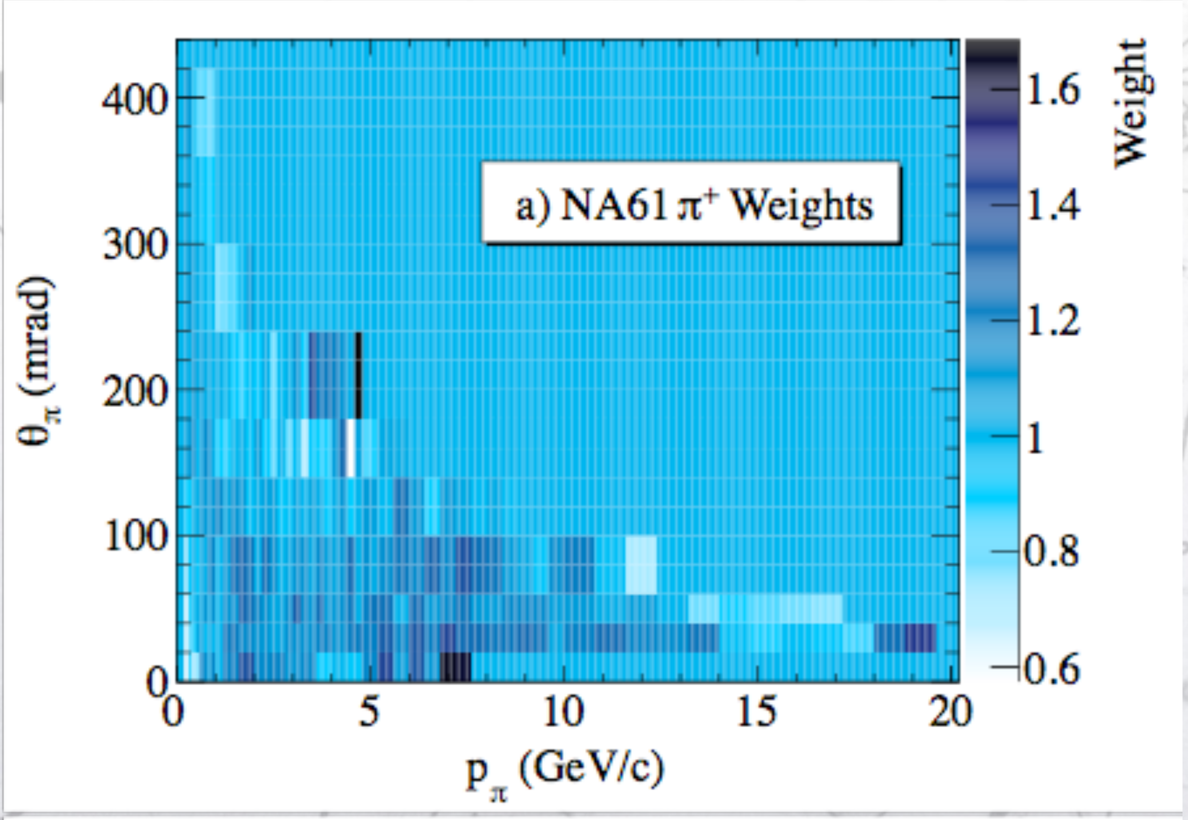
- The neutrino flux has to be obtained from the near detector.
    - Dedicated hadro-production experiments help but not sufficient: target, horn and decay volume description.
    - The only tool we have to calibrate all these parameters is with a near detector using neutrino interactions.
- Cross-sections are the key to the flux problem !
    - But, also the source of most of our problems.
- Other alternatives are possible to complement the measurement (ν e^- scattering). Minerva is exploring this option.

Flux prediction: Shive

$$\pi^+ \to \mu^+ \nu_\mu$$
$$\pi^- \to \mu^- \bar{\nu}_\mu$$

NA61/Shine measures a thin target for absolute production and thick target that is a copy of the ν target and provides also the re-interactions of particles.

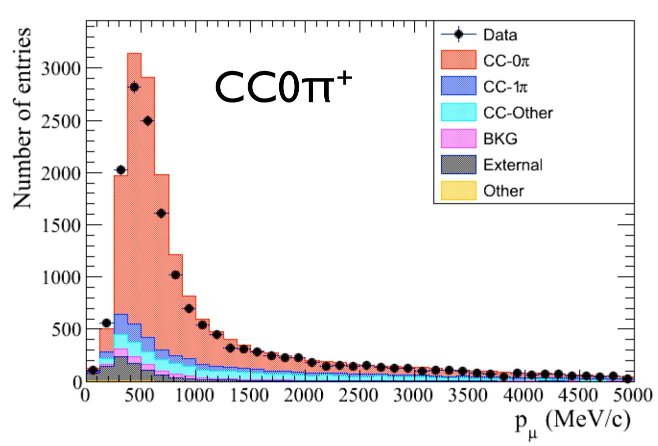


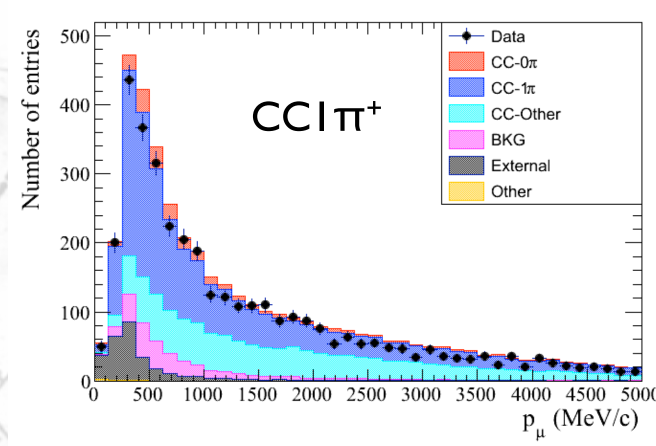


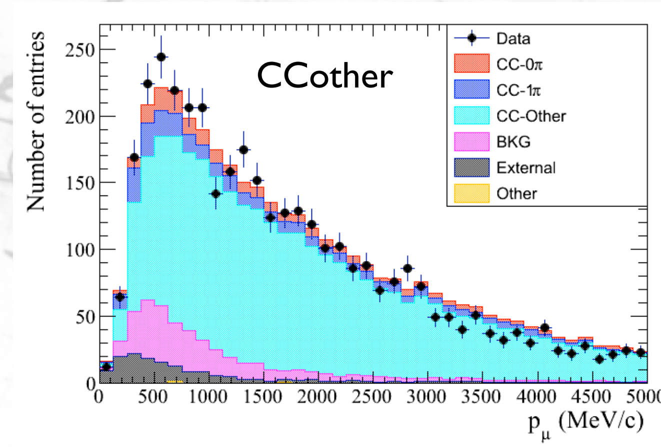
NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

Near detector @ T2K

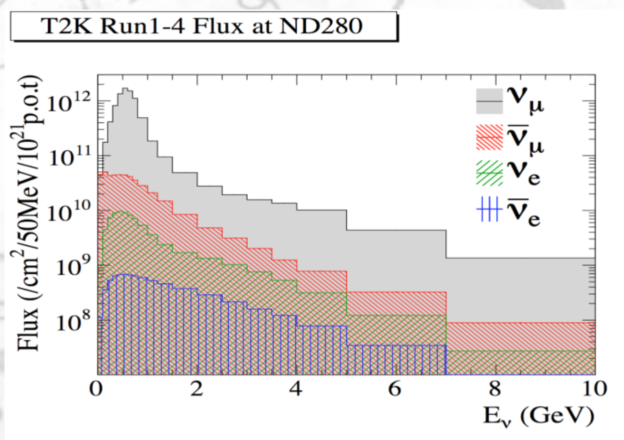
Near detector data



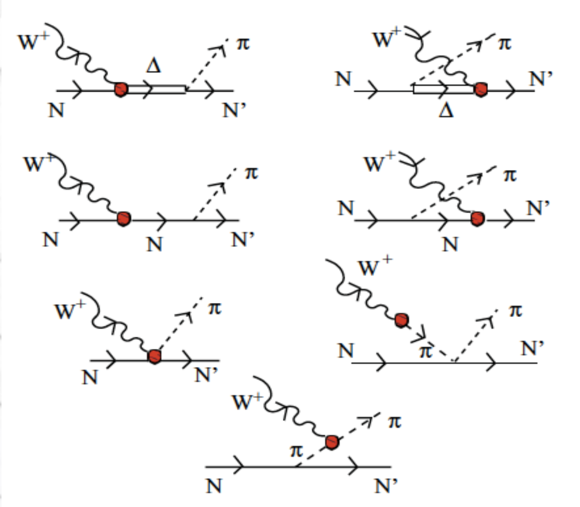




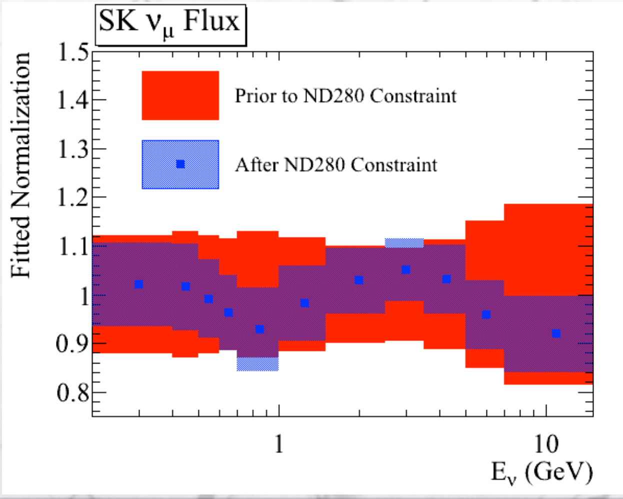
⊕ Hadron production flux prediction



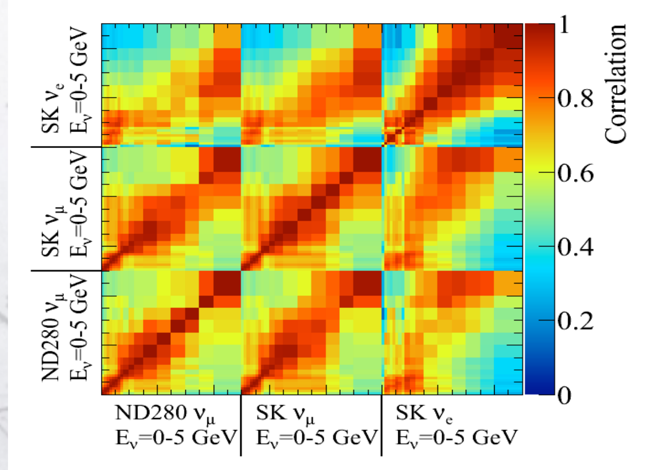
⊕ Cross-section model



= Corrected flux and cross-section model



& correlation



ND for oscillations

How to measure the neutrino energy ? $P(E_\nu|E'_\nu)$

Kinematics

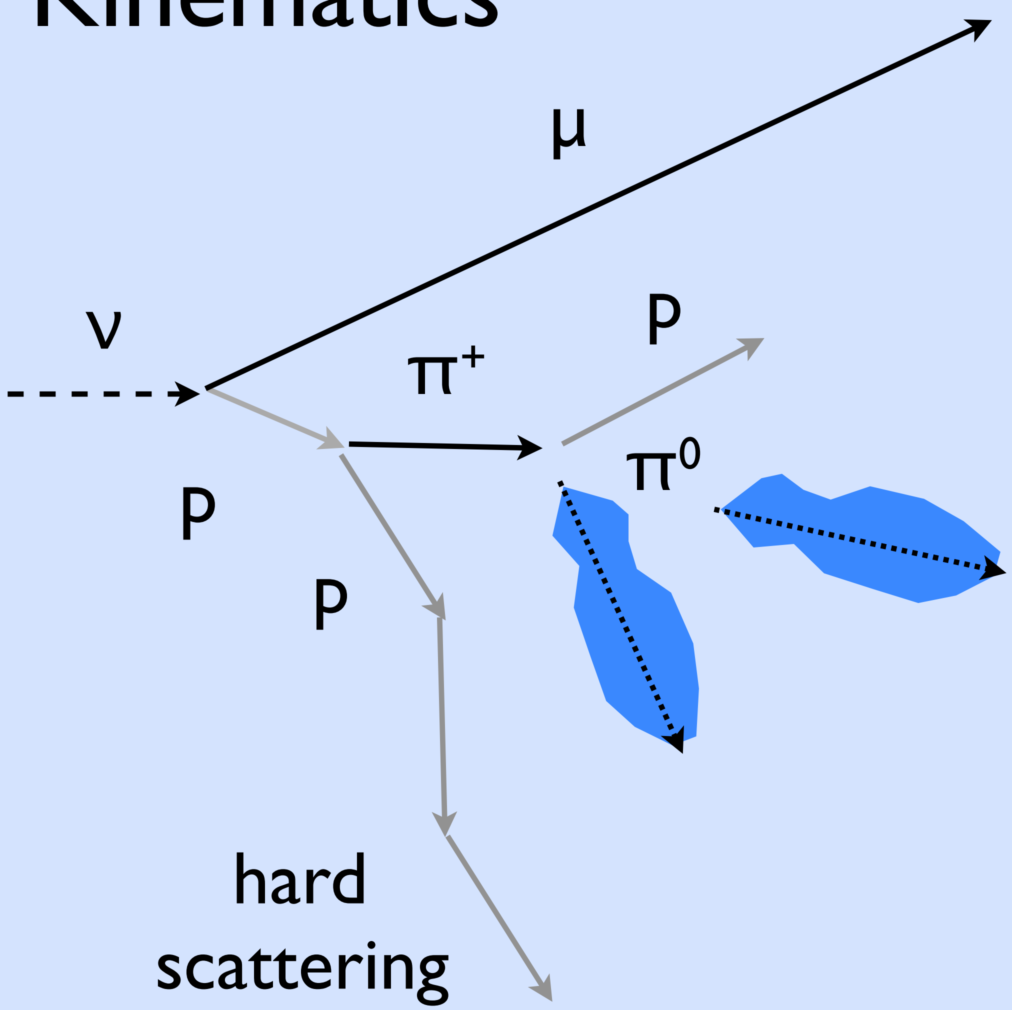
- E_ν relies on the lepton kinematics.
- channel identification is critical:
    - Final State Interactions
    - Hadron kinematics.
- Fermi momentum, Pauli blocking and bound energy are relevant contributions.

Calorimetry

- $E_\nu = E_l + E_{hadrons}$ with $E_{hadrons} << E_l$
- Hadronic energy depends on modelling of DIS and high mass resonances.
- Hadronic energy depends on Final State Interactions and detector response.

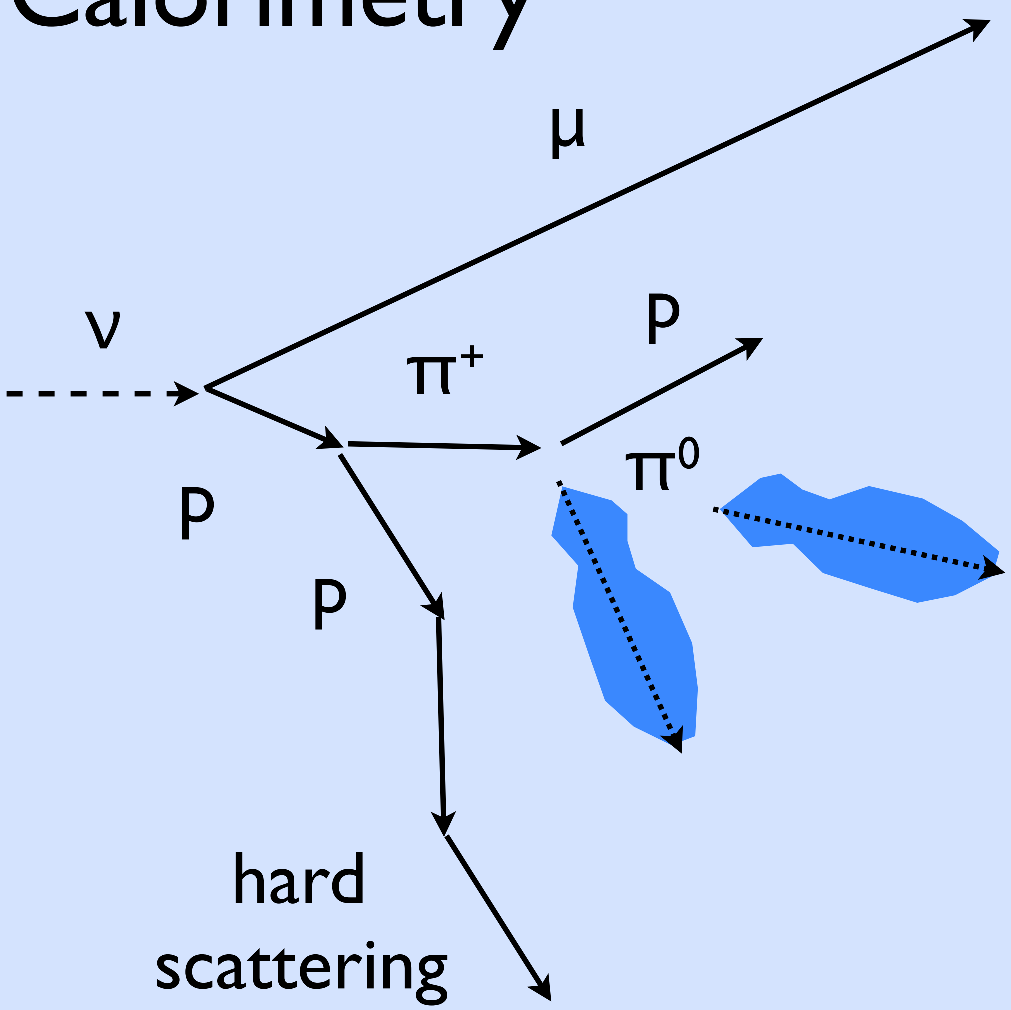
ND for oscillations

Kinematics



- Only a fraction of the energy is visible.
- Rely on channel interaction id.

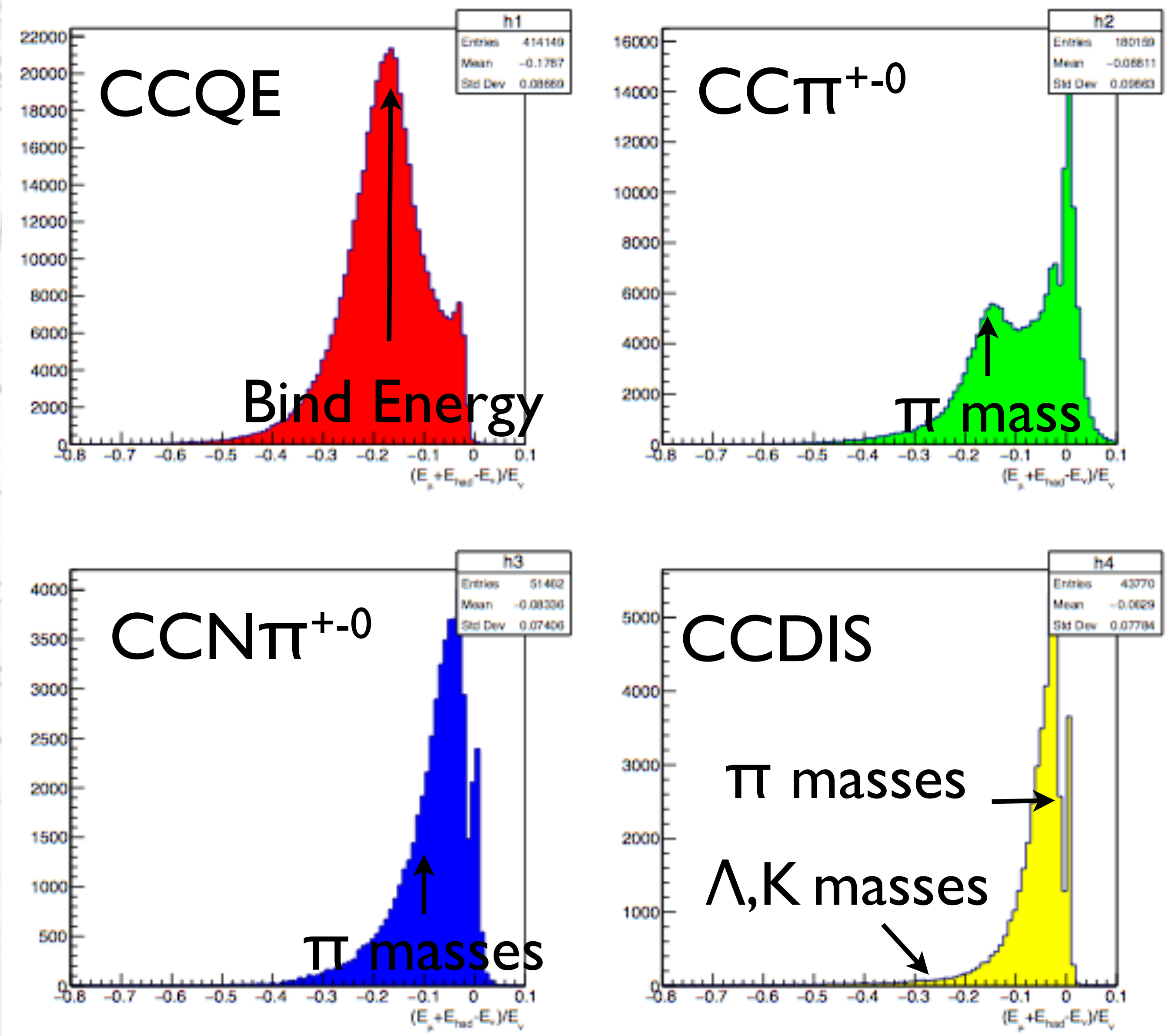
Calorimetry



- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

Calorimetric Approach

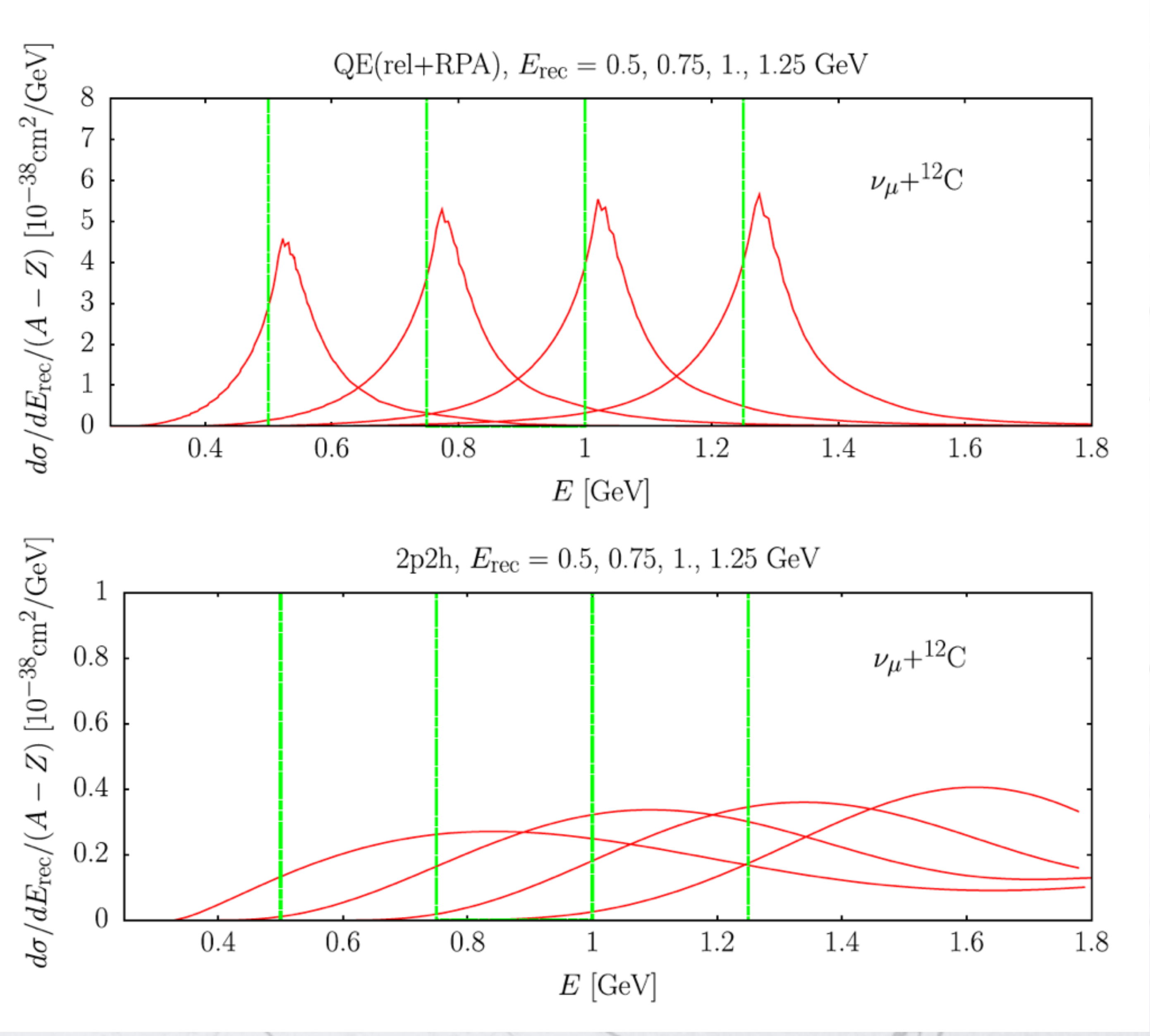
- Simple exercise:
  - Take all particles predicted by Neut MC outside the nucleus and sum the kinetic energy (including neutrons!).
  - Plot the relative energy deviation **$(E_\mu+E_{had}-E_\nu)/E_\nu$** for different channels.
  - The response depends on the channel and the topology of events outside the nucleus.
- This is too simple: **it is not clear that MC includes all possible energy balances** in the equation.
- Part of the pion and kaon mass can be recovered through its decay chain.



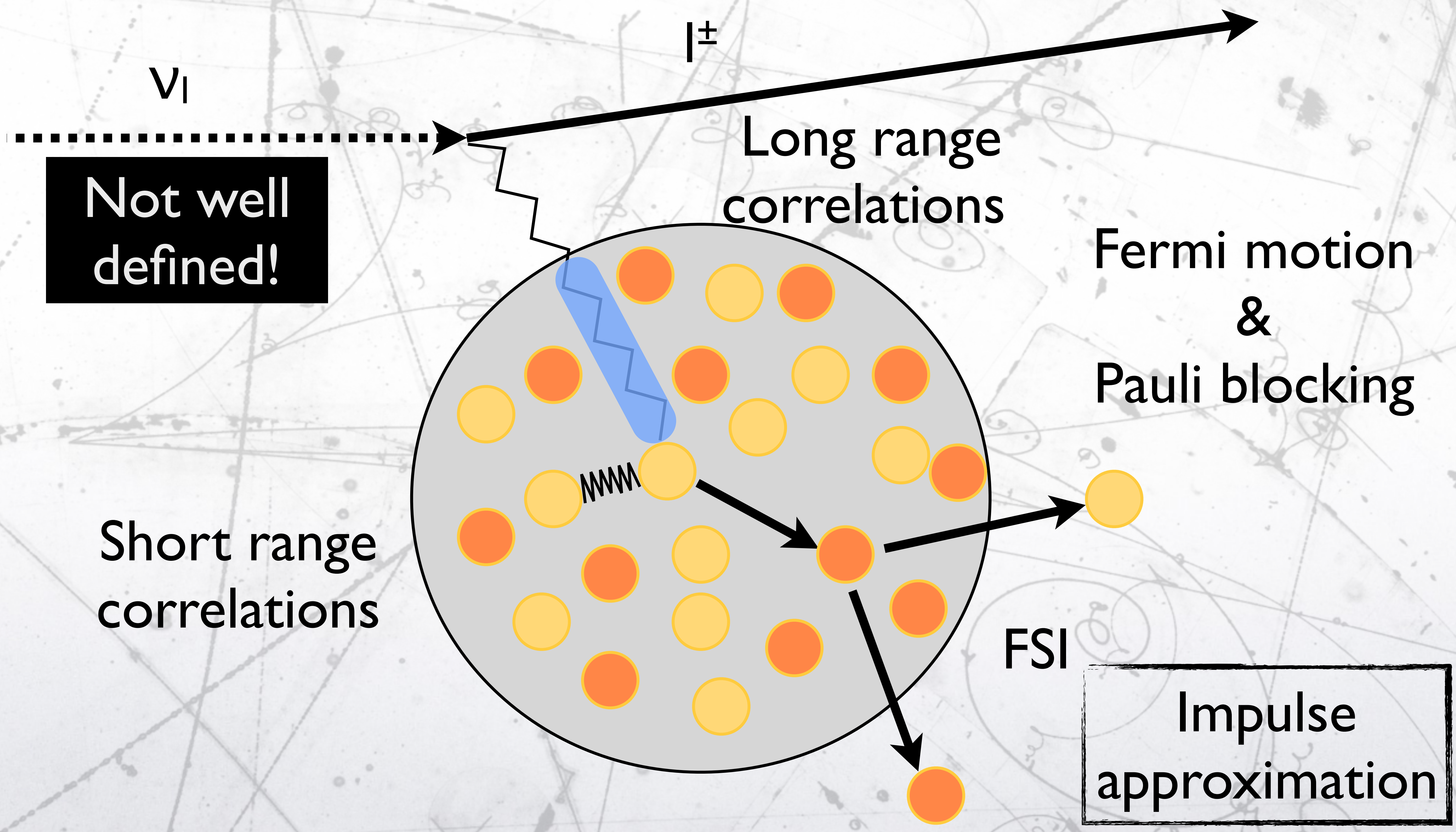
- Are the neutrino interaction models ready for this type of analysis?

Kinematic Approach

- The kinematic approach **relies on the knowledge of the reaction channel at nucleon level.**
- Experimentally we can confuse the channel because:
    - nuclear effects (absorption).
    - detector effects (thresholds).
- If two reactions are confused the energy is wrongly reconstructed.



PHYSICAL REVIEW D **85,** 113008 (2012)

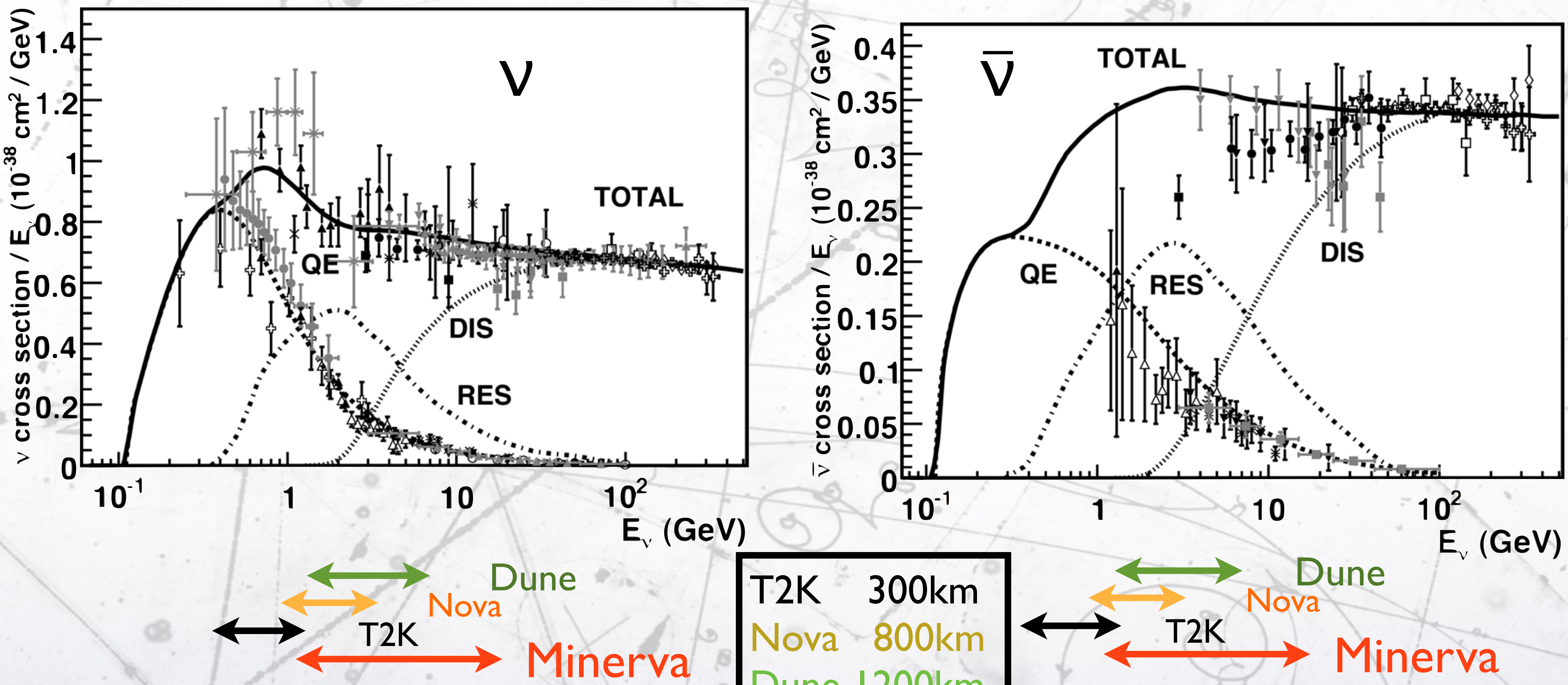

ν_l
$l^{\pm}$
Not well defined!
Long range correlations
Fermi motion & Pauli blocking
Short range correlations
FSI
Impulse approximation

Interactions @ nucleon level !

$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N' \pi\pi \ldots$
$CCDis$	$\nu_\mu N \to \mu^- N' \pi, \pi, \ldots$

The xsec problem

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



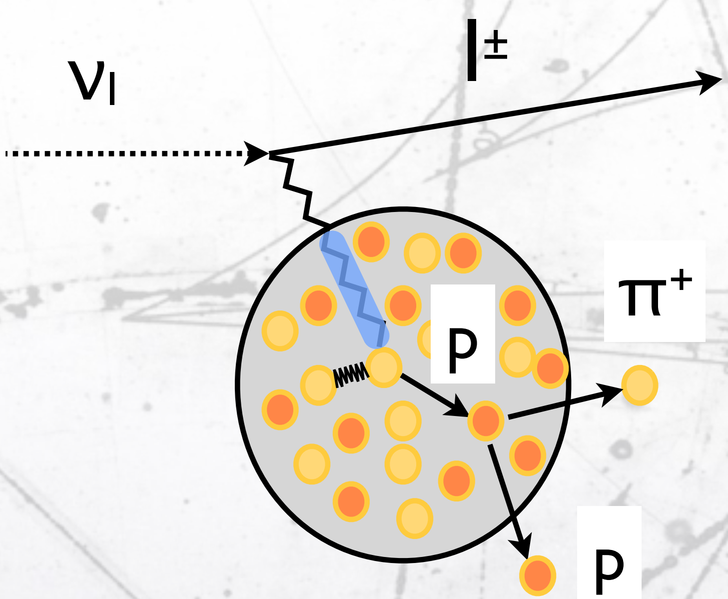
T2K	300km
Nova	800km
Dune	1200km

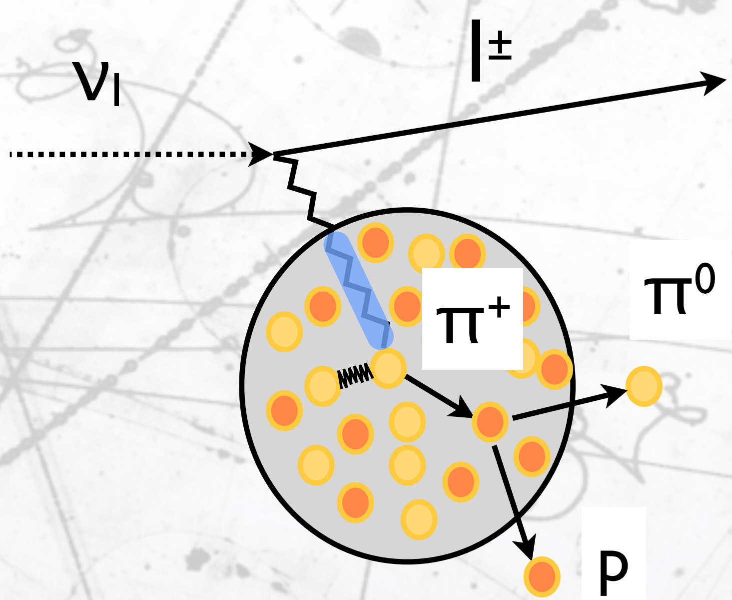
Present and future oscillation experiments cover a complex region full of reaction thresholds and sparse data.

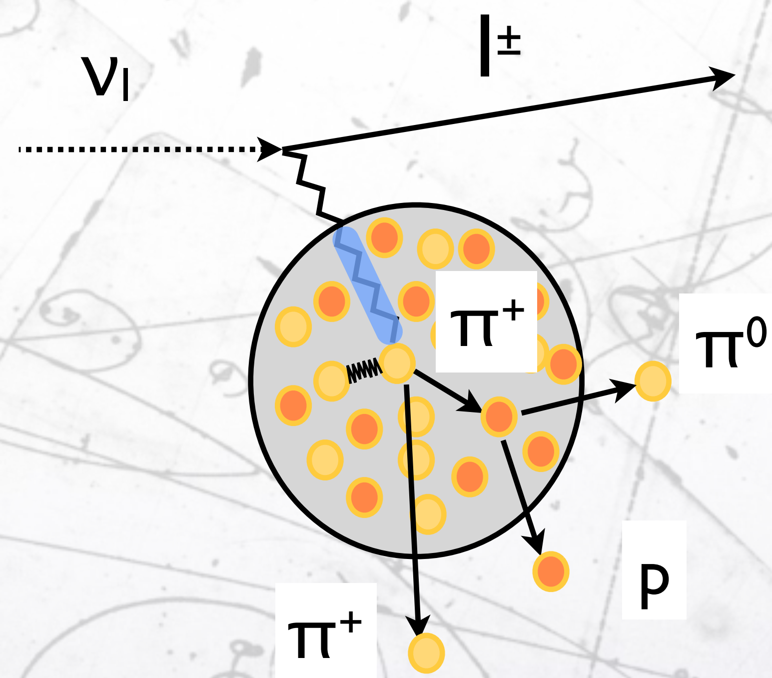
Problem factorisation

Nuclear re-interactions alters the “topology” of the event

Example: events with μ^- & π^+ in final state





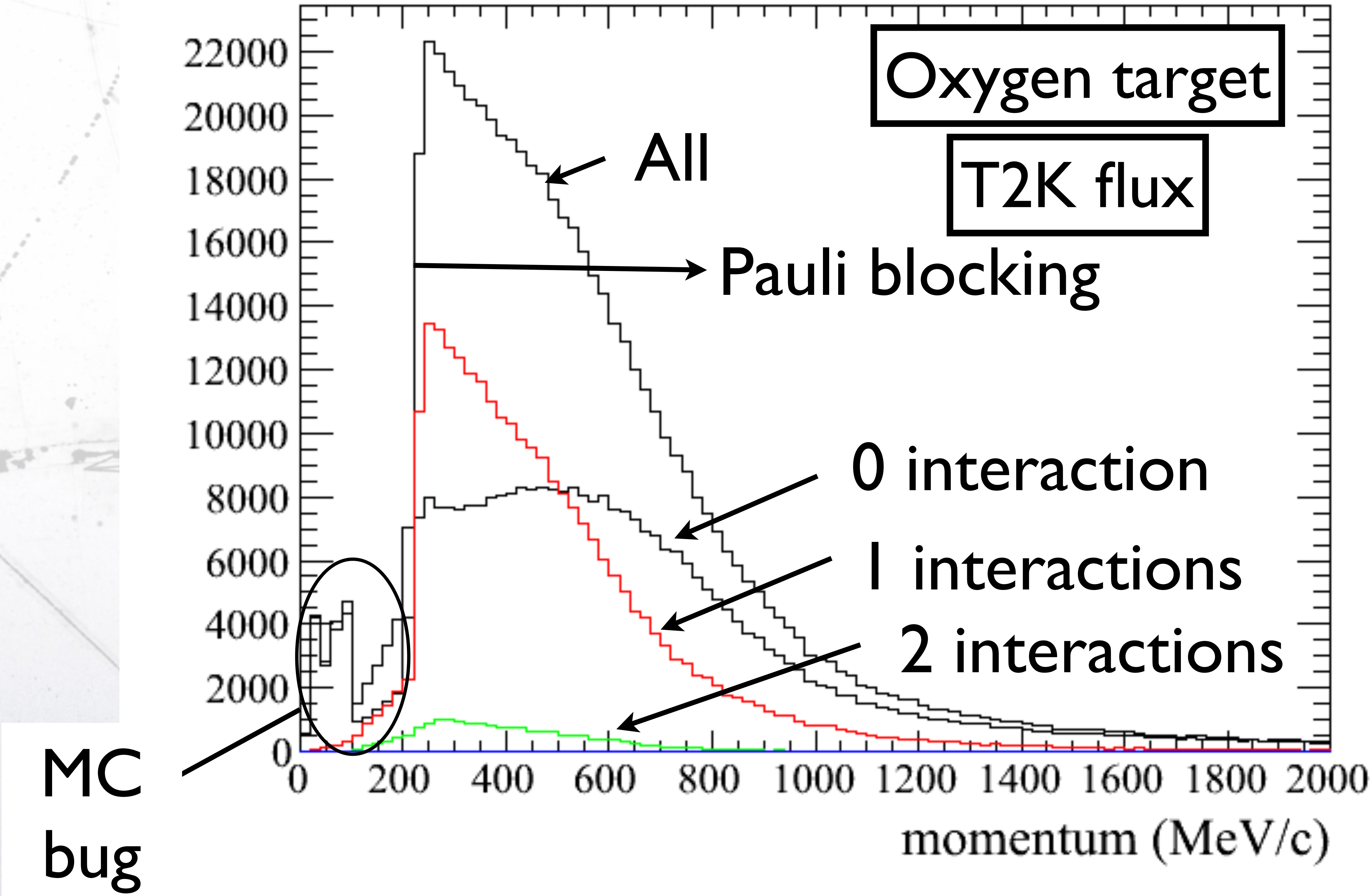


1. CCQE
2. proton in final state
3. p p→p n π^+

1. CC1 π^+
2. π^+ in final state
3. π^+ n → p π^0

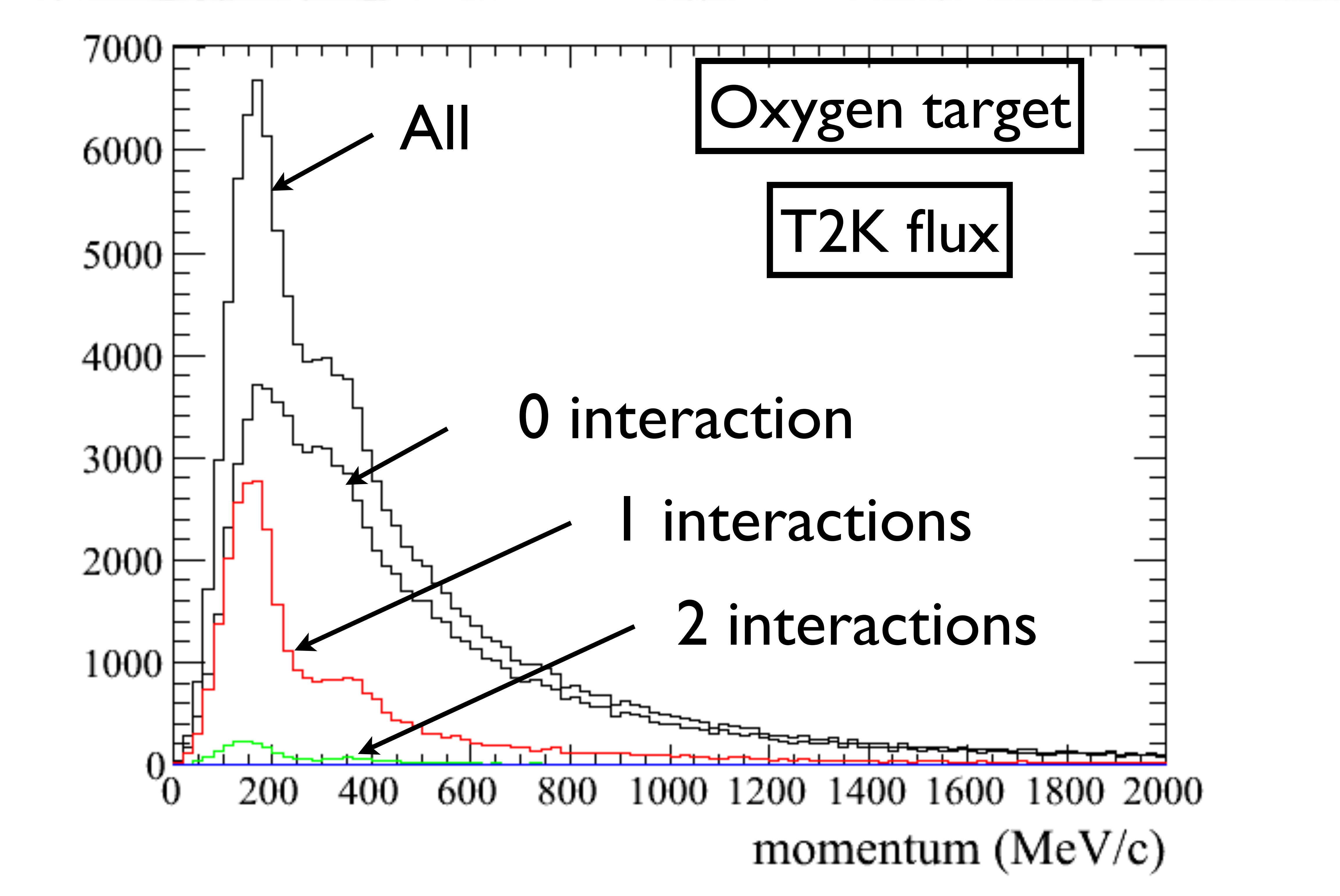
1. CC 2π^+
2. 2π^+ in final state
3. π^+ n → p π^0

Proton momentum



Non-relativistic protons!

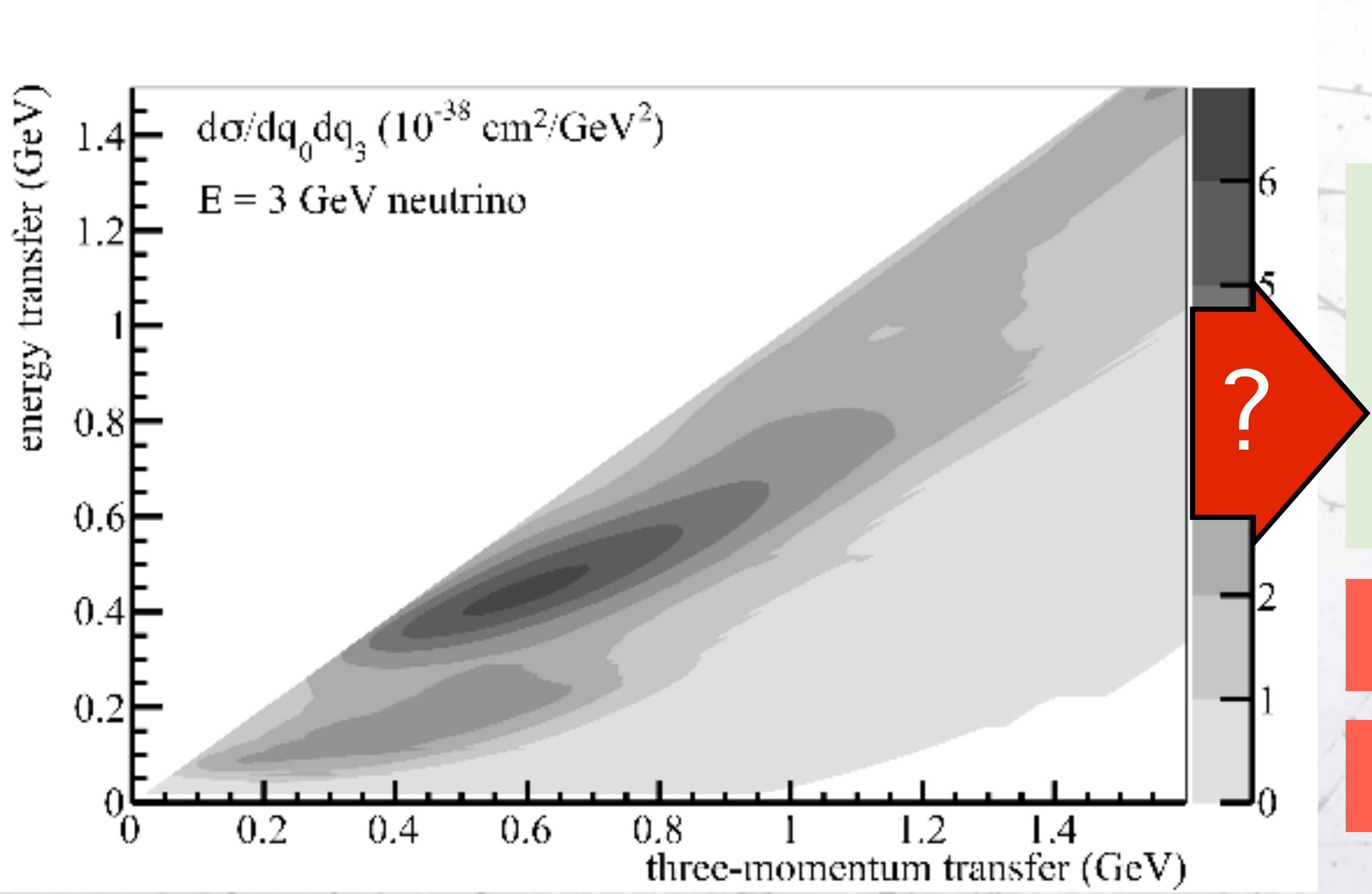
Pion momentum



Sub-GeV pions!

Limits of models

- The main problem with models is that they are valid only in certain regions of the available kinematic space. Nominally, the low q^2 region.
- Extrapolations to the high q^2 region are complex since it implies a different treatment of the nucleus (relativistic, non-relativistic, etc...).
- Agreement with experiments might vary with experiment energy range.



Gran, R. *et al.* Phys.Rev. D88 (2013) 11, 113007

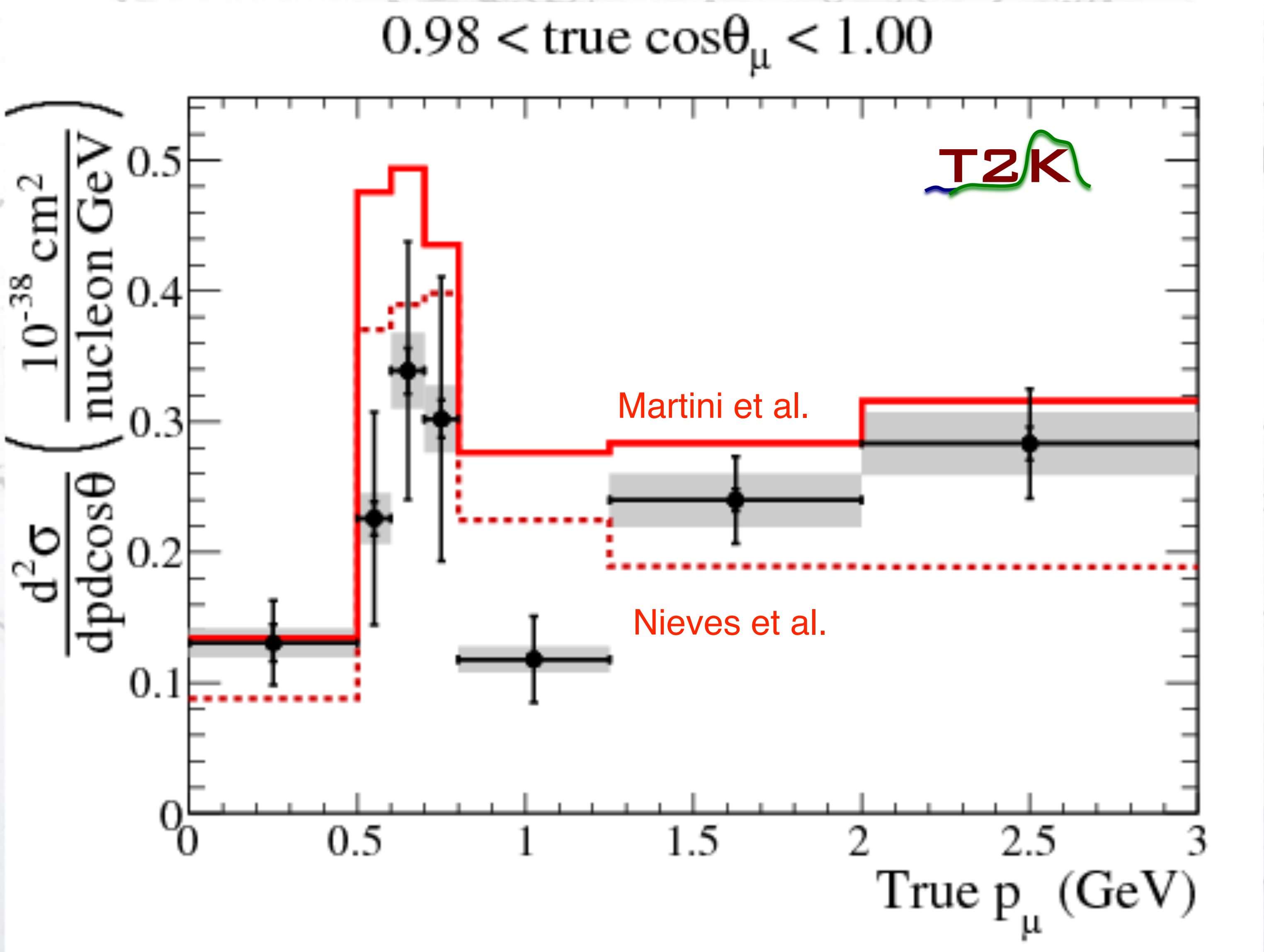
Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

(Nuclear) Theorists needed!

More (better) data needed!

How bad is bad ?

μ momentum distribution in the forward direction



$$Q^2 = -q^2 = 2(E_\nu E_\mu - p_\nu p_\mu \cos\theta_m u) - m_\mu^2$$

- In one bin we get different E_ν (flux) & Q^2 (x-section) contributions.
- The flux is constrained from the hadro-production experiment.
- Adjusting the model to the flux will migrate problems from flux to cross-section and viceversa.

Low and High Q2 contains different level of uncertainties at the nucleon level (form factors) and nuclear level (short and long range correlations)

Nieves et al. and Martini et al. are the best two models in the market. Same physics but two implementations !

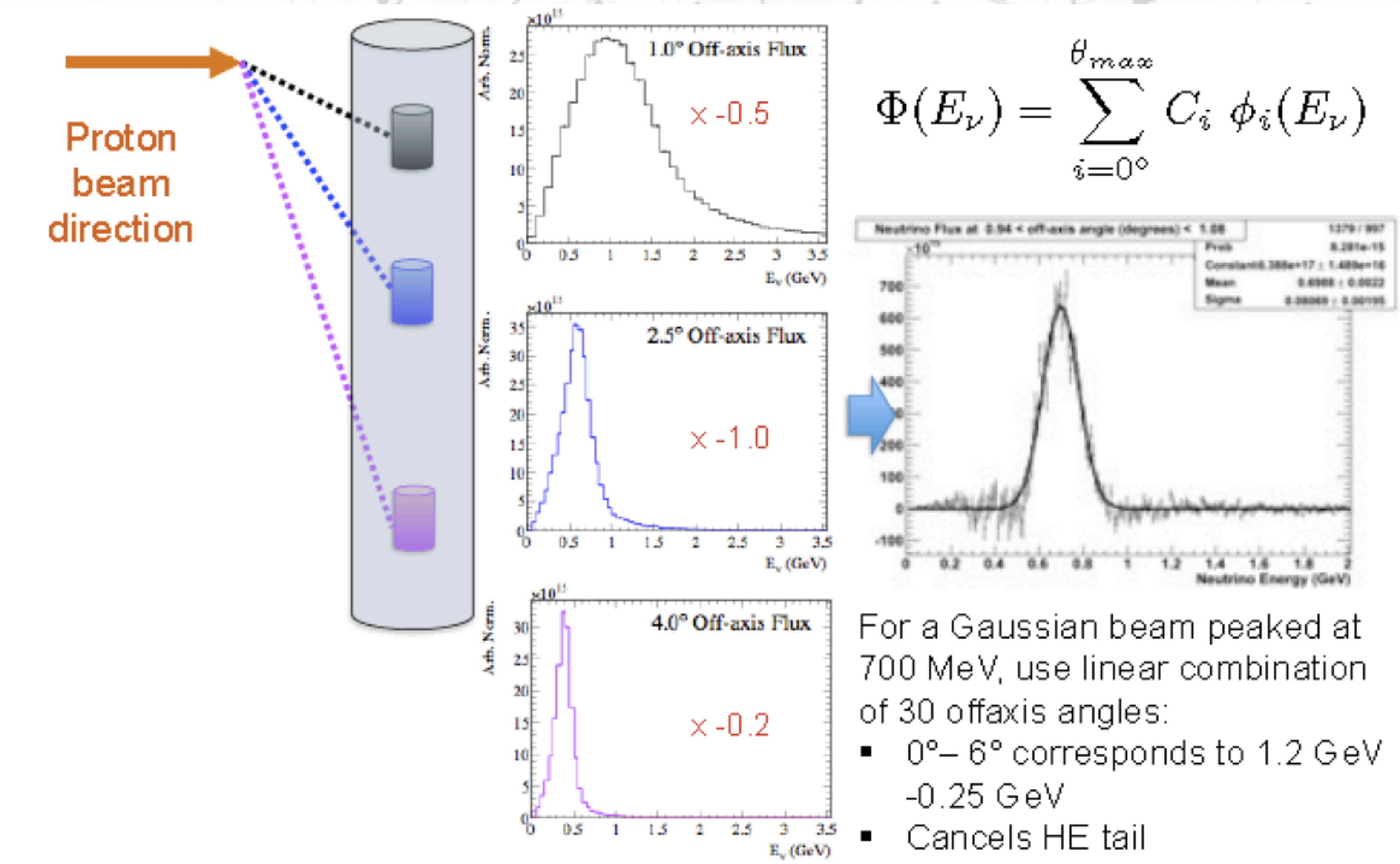
ND for oscillations

- $P(E_\nu|E'_\nu)$ is the critical point on the above formula.
- This reconstruction depends on:
  - BIAS: The validity of the reconstruction assumption for the right topology of the event.
  - BACKGROUND: The error when the formula is applied to the wrong event.
  - ENERGY SCALE AND EXPERIMENTAL BIAS: Difference between the near and the far detector and absolute calibration scale.

Similar near and far detector technology is a plus but it is not always the right solution.

New ideas: NuPrism

- Profit from the **dependency of E$_\nu$ with beam angle**.
- Take linear combination of events in angular slices to build a monochromatic beam.
- Technique **only valid with off-axis** beam like T2K. (True beam is one slice!).
- **Big detector (10 m x 50 m deep!)**



$$\Phi(E_\nu) = \sum_{i=0^\circ}^{\theta_{max}} C_i \, \phi_i(E_\nu)$$

For a Gaussian beam peaked at 700 MeV, use linear combination of 30 offaxis angles:

- 0°– 6° corresponds to 1.2 GeV -0.25 GeV
- Cancels HE tail

Reduces the dependency on cross-section models.

$$P(E_\nu|p_\mu,\theta_\mu) = \sum_{i=0^o}^{\theta_{max}} C_i P(p_\mu,\theta_\mu|\theta_i)$$

Only valid for off-axis beams!

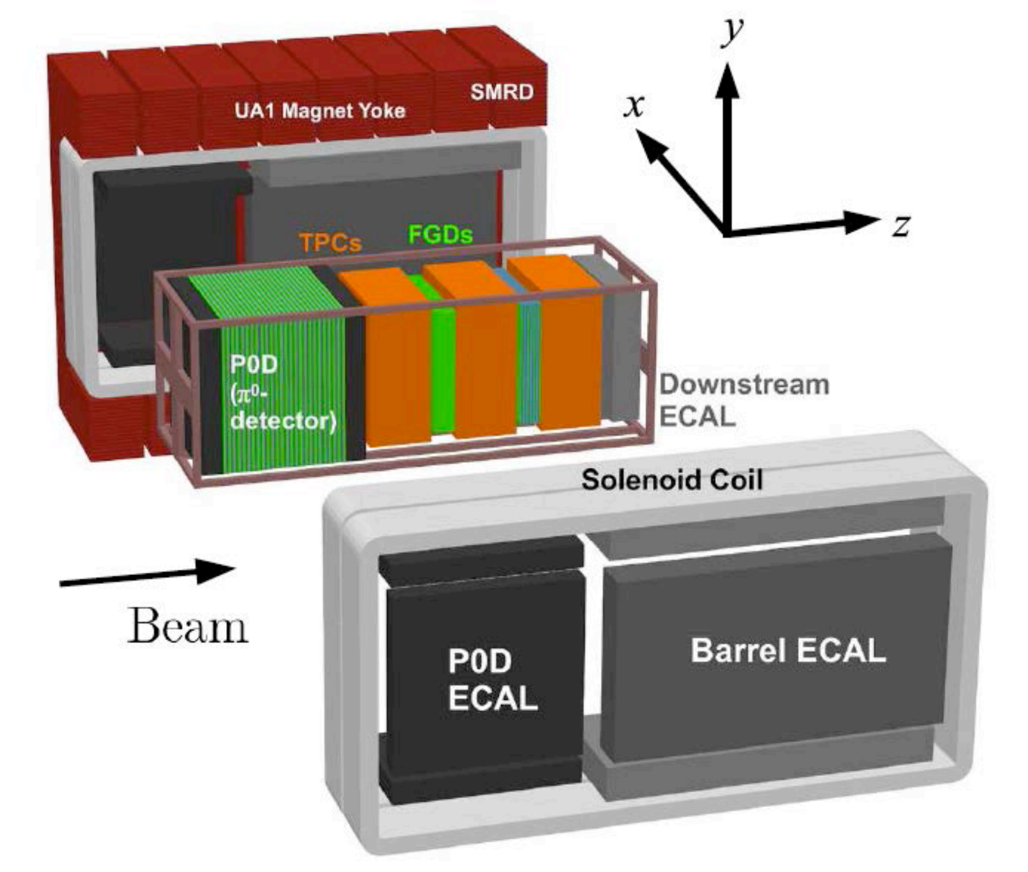
Near detectors (to the help)

T2K: ND280

T2K far detector is a 40 kTon water (mainly oxygen target) Cerenkov detector.

- Off-axis ND280 is a detector complex with tracking calorimeters, time projection chambers and Electromagnetic calorimeters in the **UA1 0.2T magnet**.
  - **ν interaction target polystyrene (CH) and water** (to measure with same far detector target).
    - 1x1cm^2 → proton track threshold around 500 MeV/c
  - **Particle ID by dE/dx and calorimetry for electrons.**
  - **Charge sign by curvature.**
- **Kinetic reconstruction** approach.

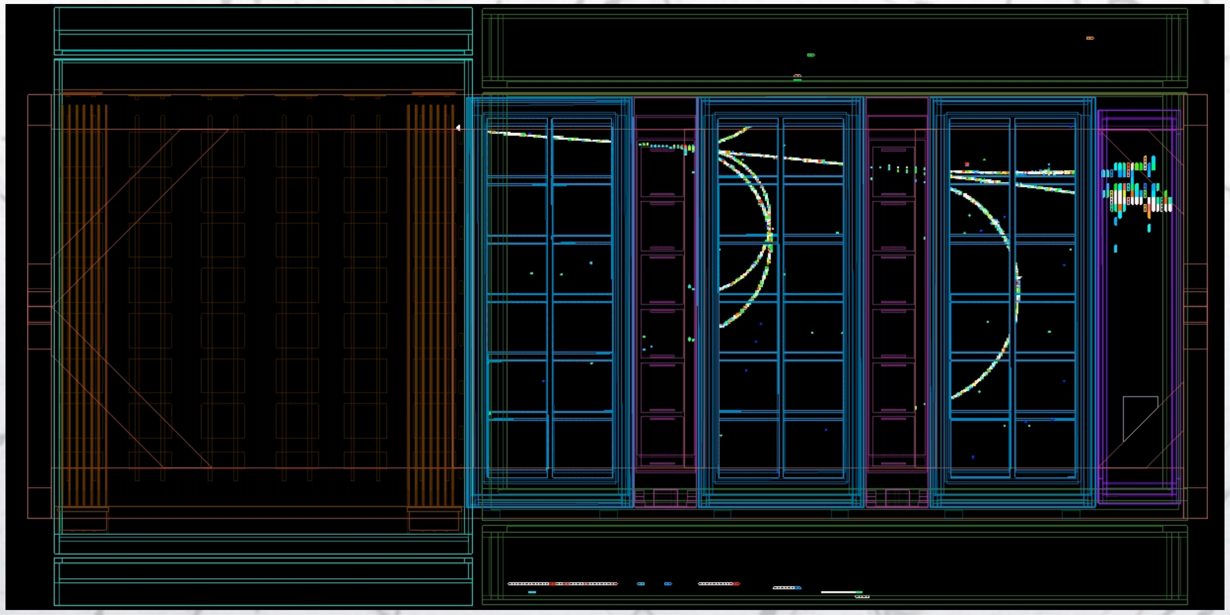
Magnet was granted by CERN

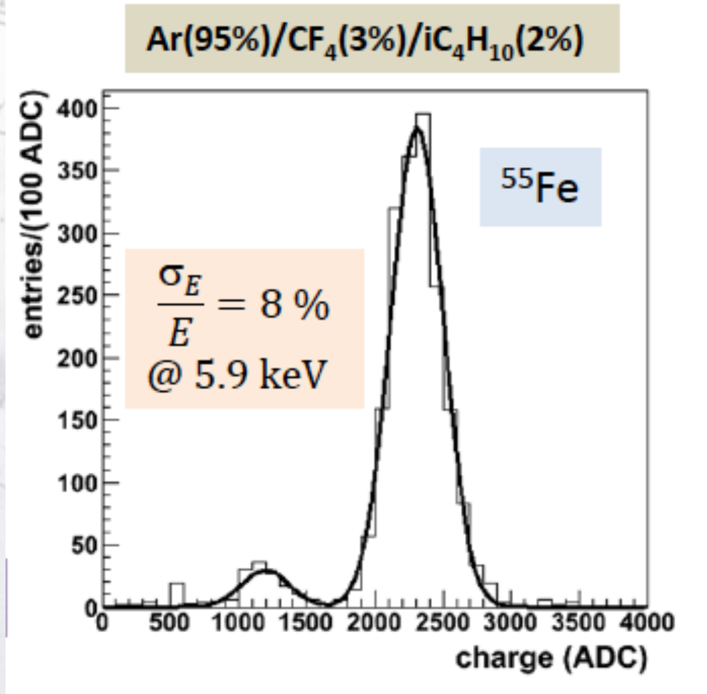



Magnet @ CERN Prévessin

T2K TPC

- First ever MicroMega TPC.
- 359.1 x 349.3 mm^2
- 1726 active pads / MM
- 9.8 x 7.0 mm^2
- 128 µm amplification gap.
- 72 modules for 3 TPC´s.
- 125000 readout pads.

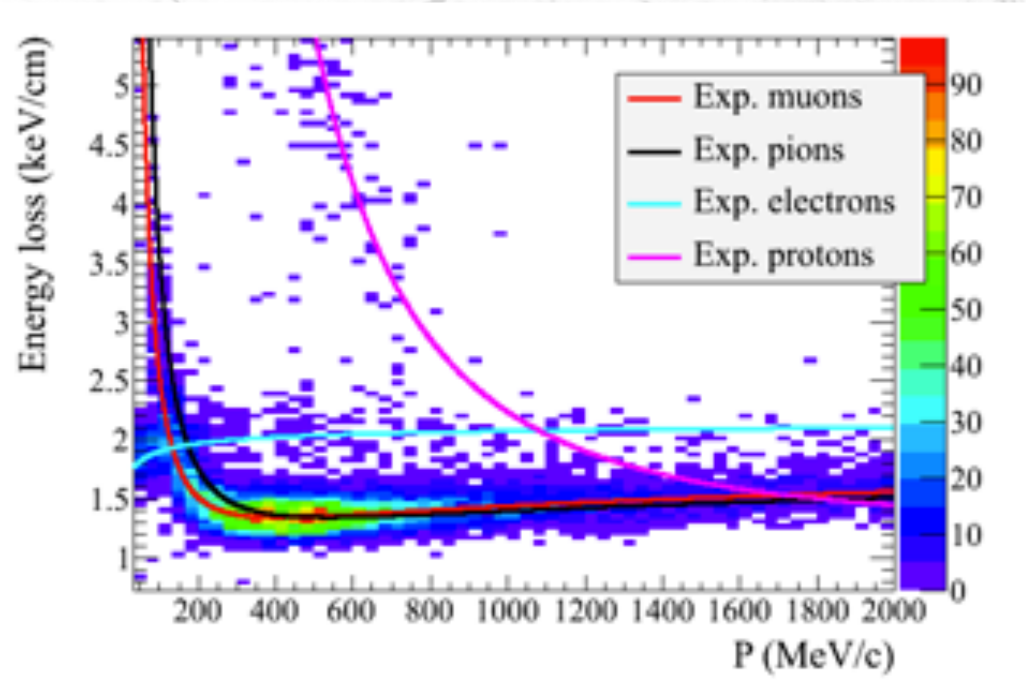


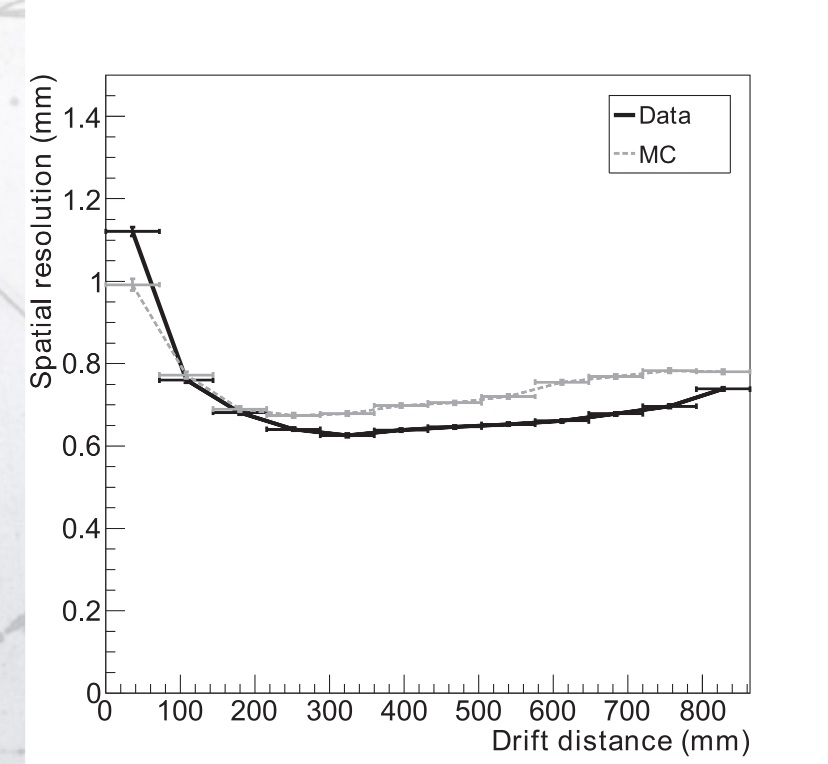


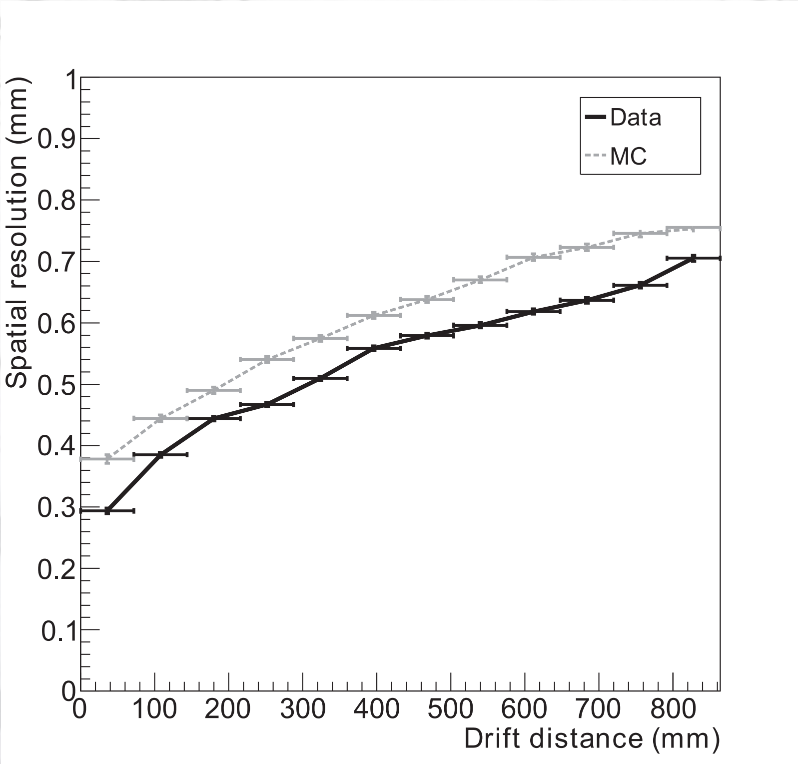
T2K TPC

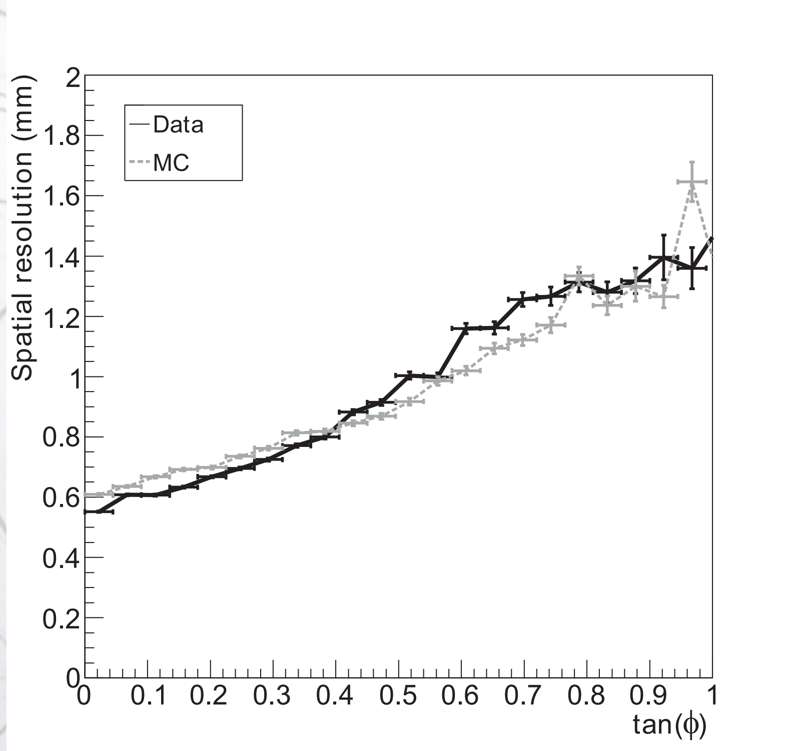
Critical for the T2K physics

- Electron-Muon separation id through pid.
- Charge particle determination (low density).
- Excellent point resolution (~700 um) with ~1 cm² pads (economy of readout channels).



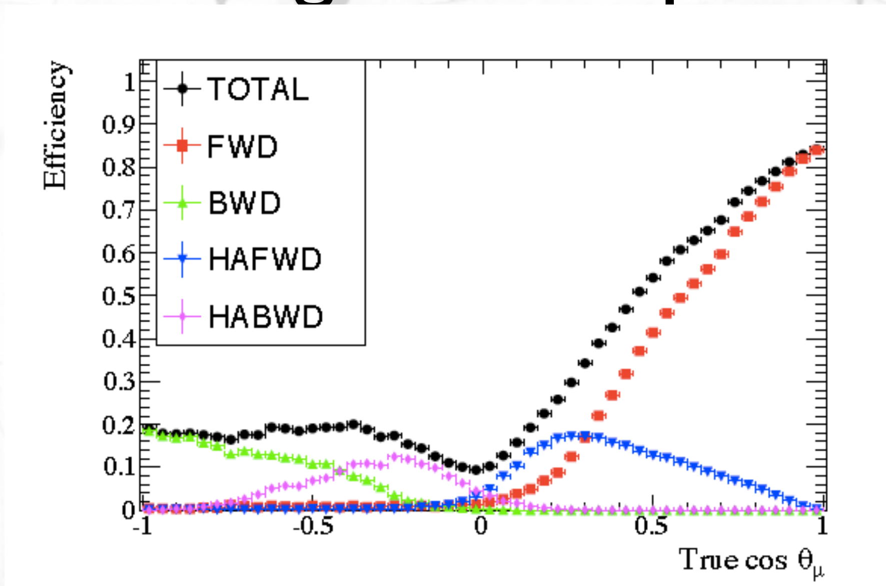


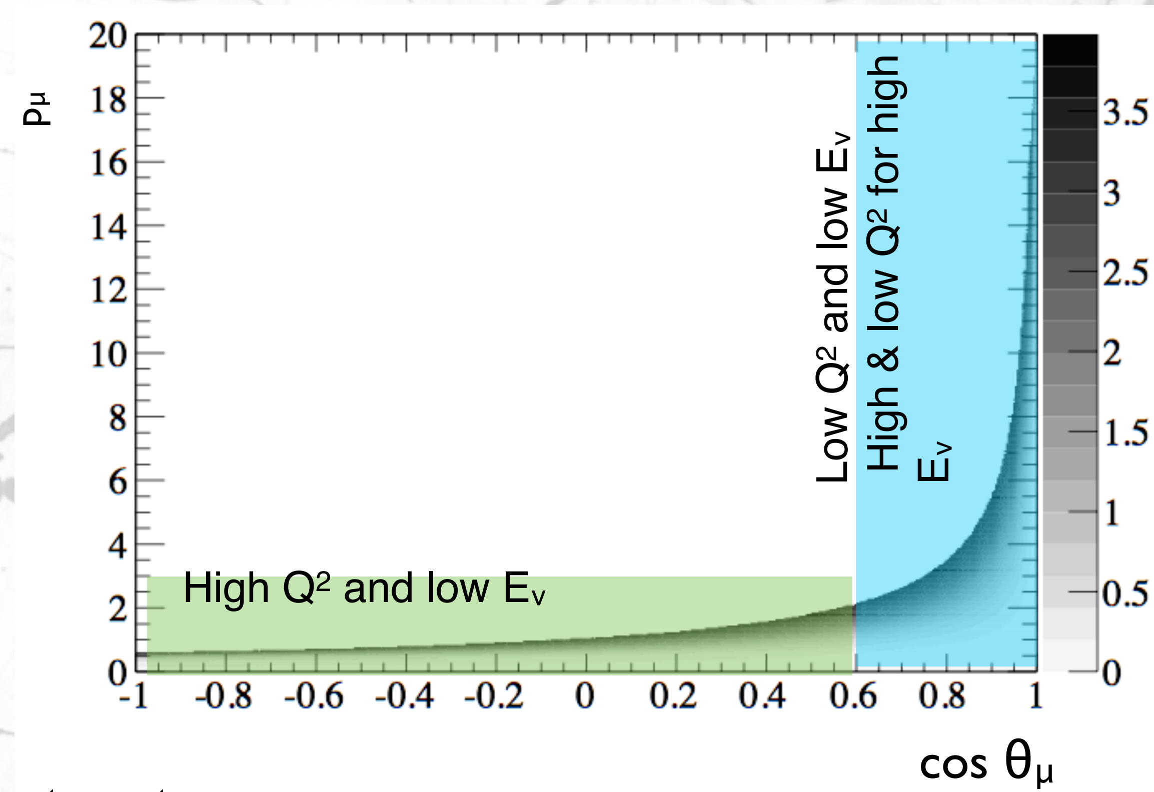




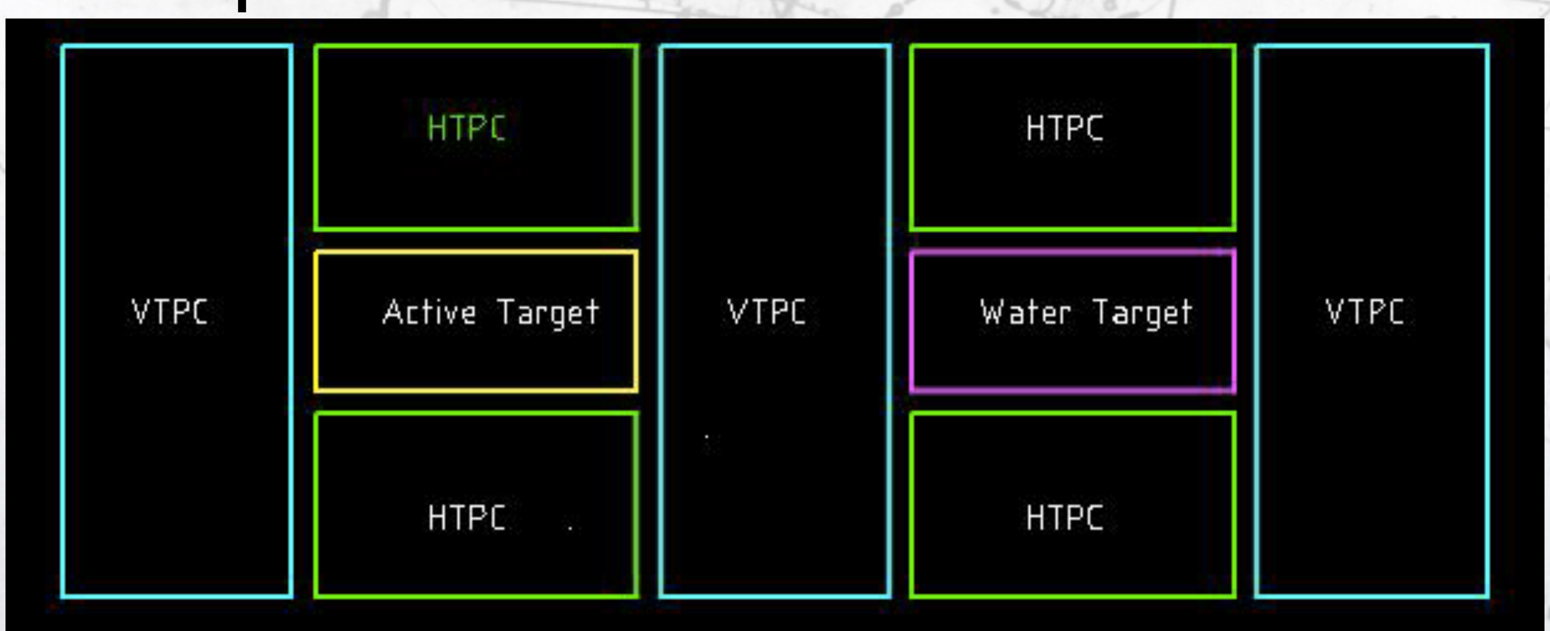
T2K Upgrade

- Actual angular acceptance:





- Proposed modification of the Near Detector.



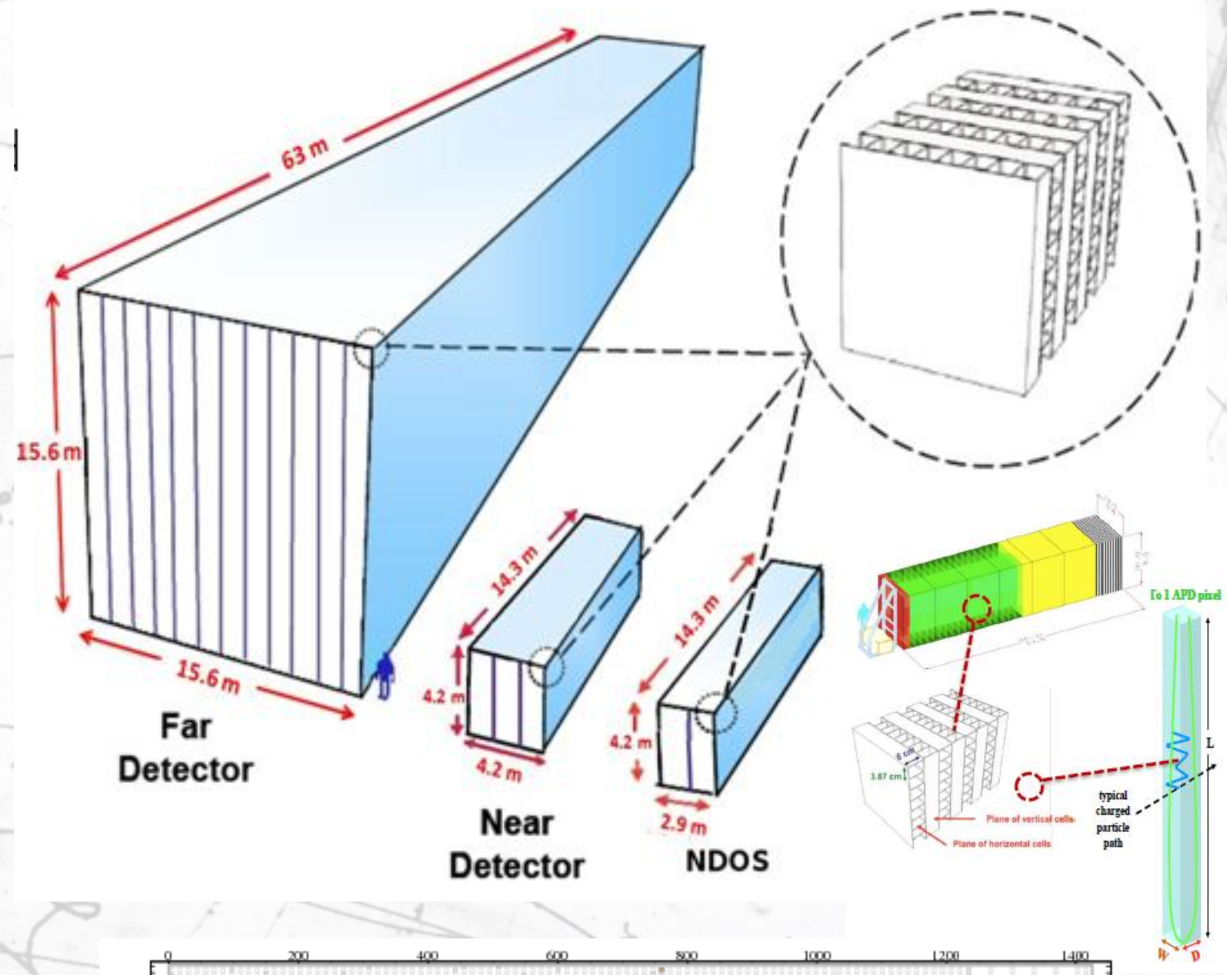
https://indico.cern.ch/event/568177/

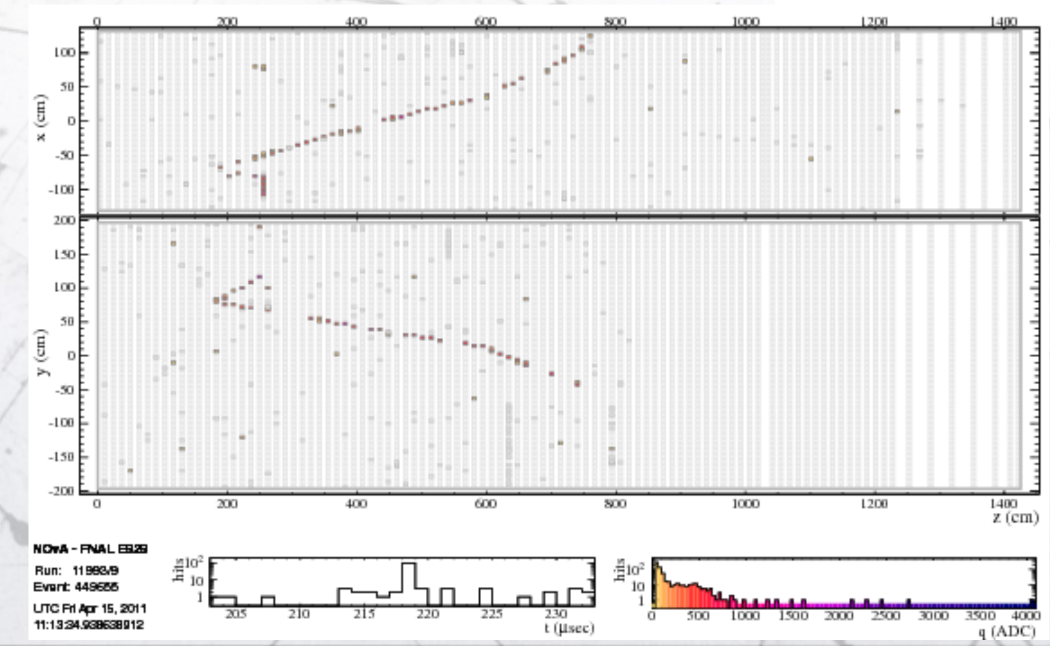
There are large theoretical uncertainties connecting forward (low Q^2) with backward (high Q^2) regions: nuclear form-factors, long and short range correlations,…

T2K-II extension approved!

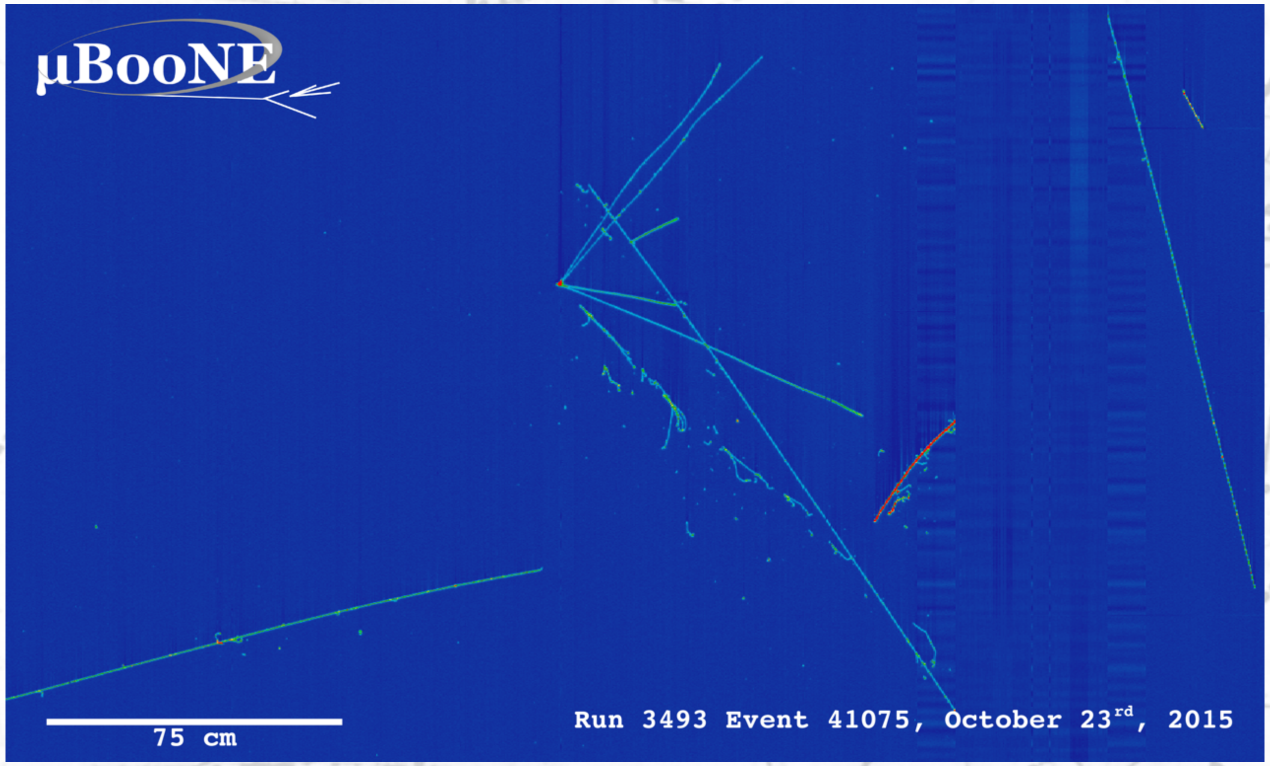
Nova

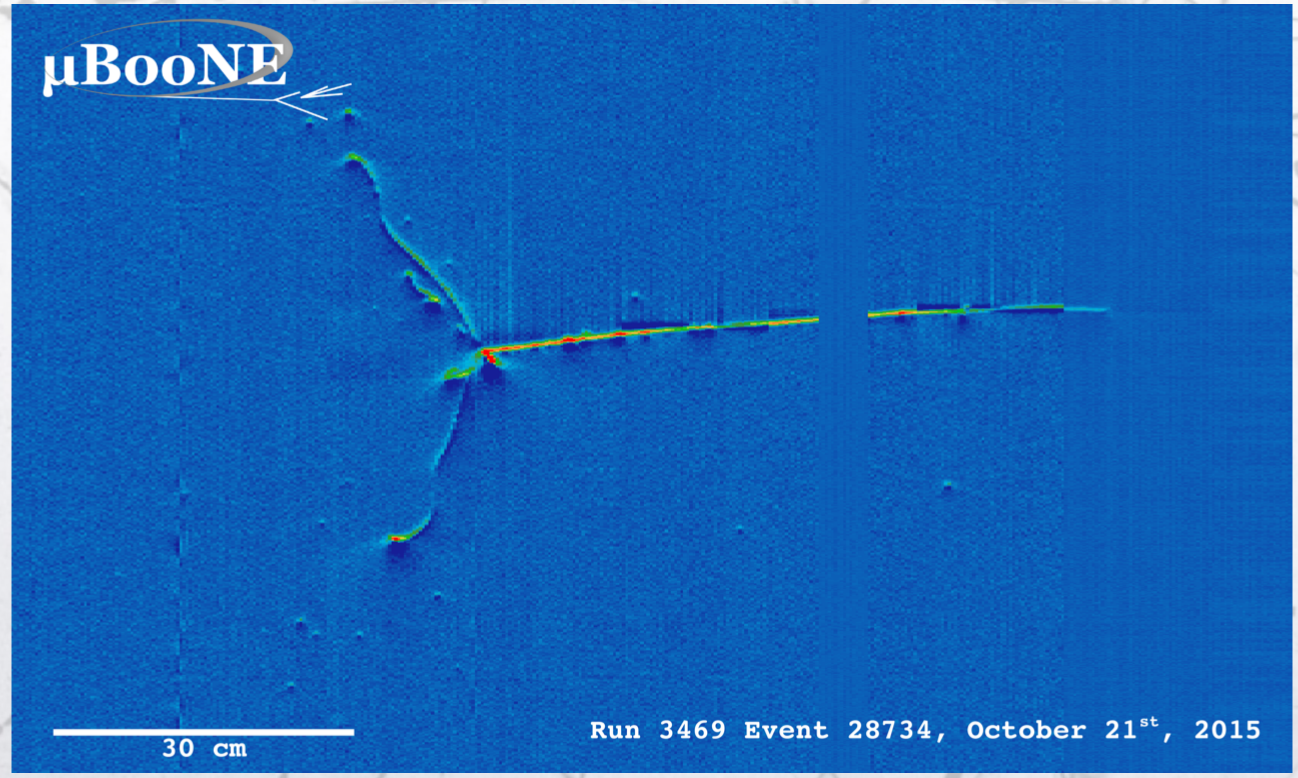
- **Scaled copy of the far detector**.
    - Liquid scintillator poured in extruded plastic bars.
    - Same target, same technology.
- **~200 Tons** of target mass.
    - Monitor and normalisation functionality.
- **Coarse cell** (3.8x5.9cm^2), proton track threshold around 1GeV/c:
    - No topology
- **No charge sign** determination:
    - neutrino vs antineutrino from flux prediction.
- **Calorimetric approach!.**





Future: LiqAr TPC

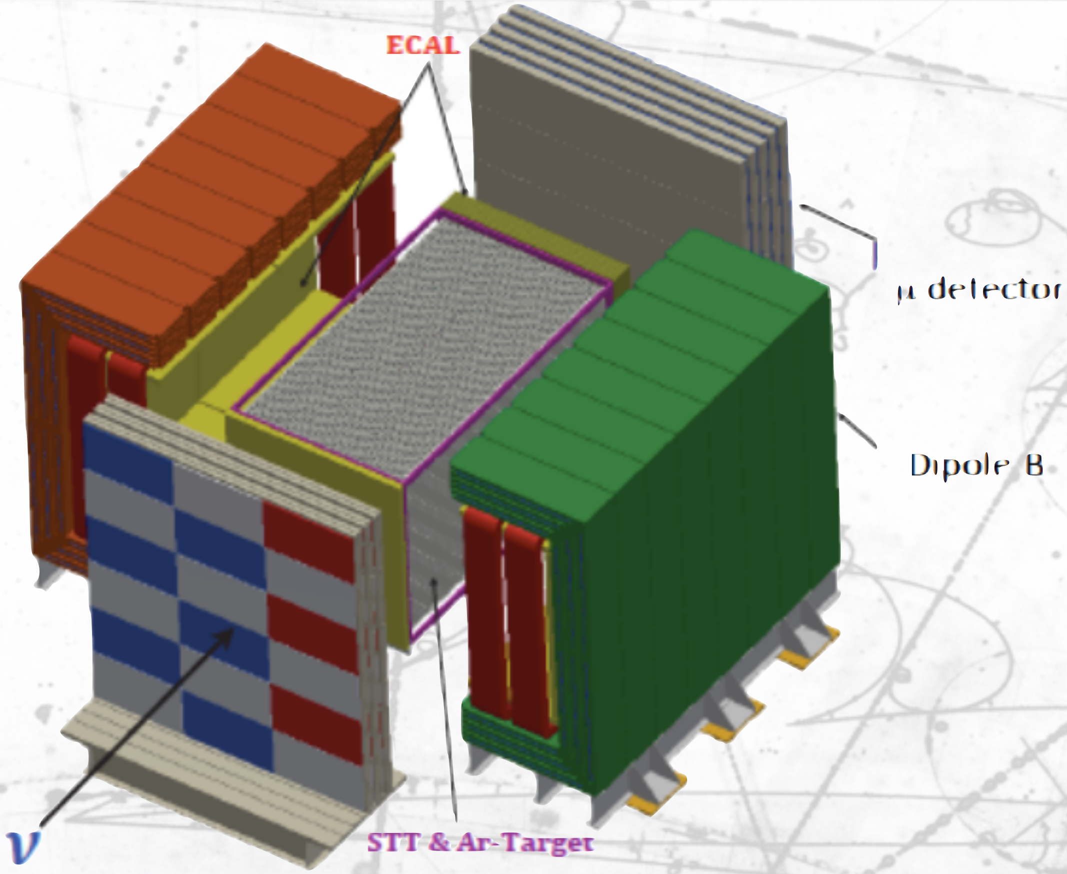


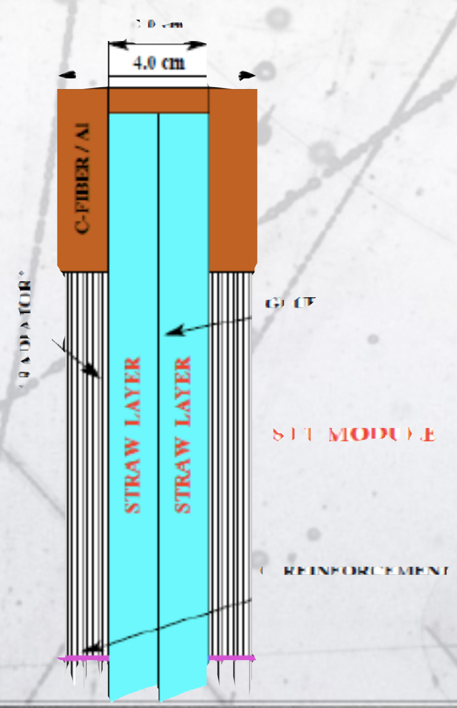


DUNE far detector is made of 4 gigantic LiqArgon detectors 10 kTon fiducial each!.

- **Magnetised (?)** LiqAr detector.
- Potentially **same technology as Far Detector.**
- **Large mass & slow detectors** (~ms drift) → event pileup!.
- Balance **pile-up vs. particle range.**
- ECAL and muon range.
- **Low proton threshold:** ~150 MeV/c.
- **Calorimetric** approach.

Future: DUNE

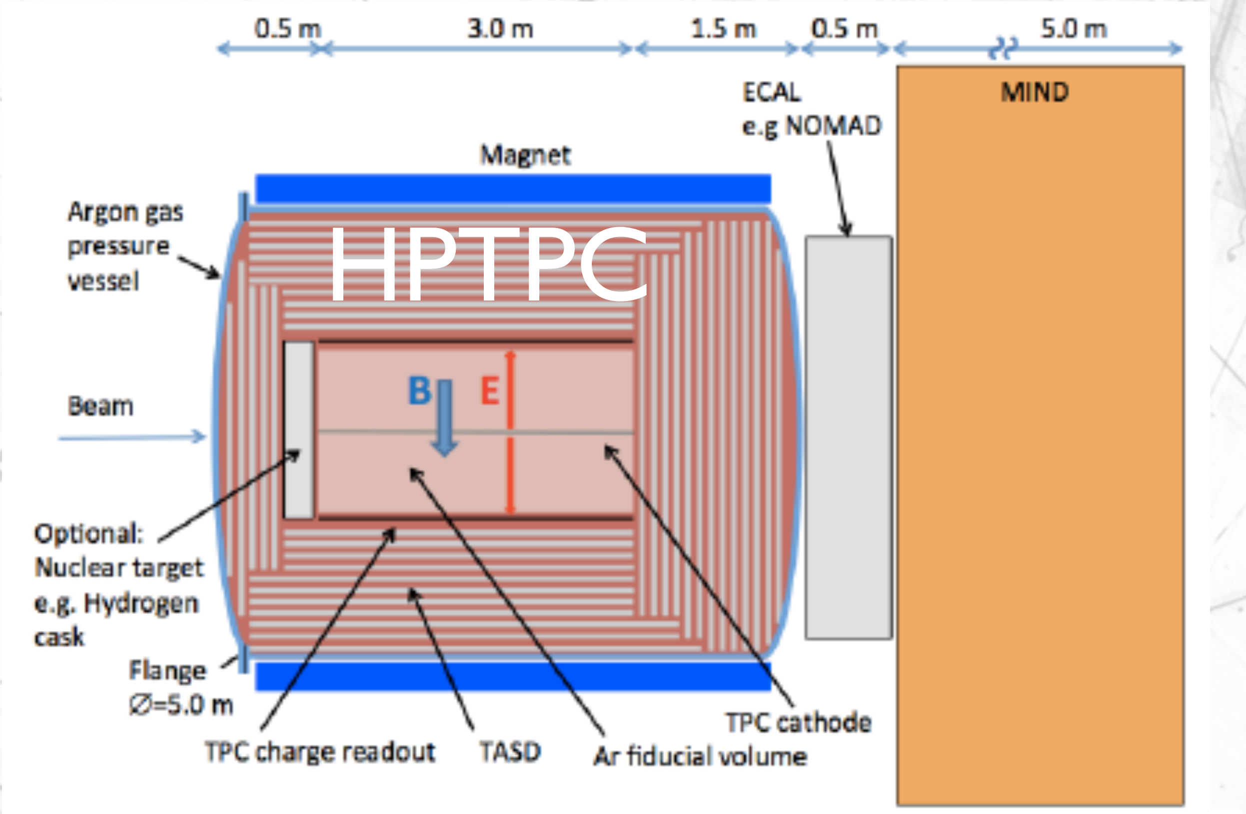


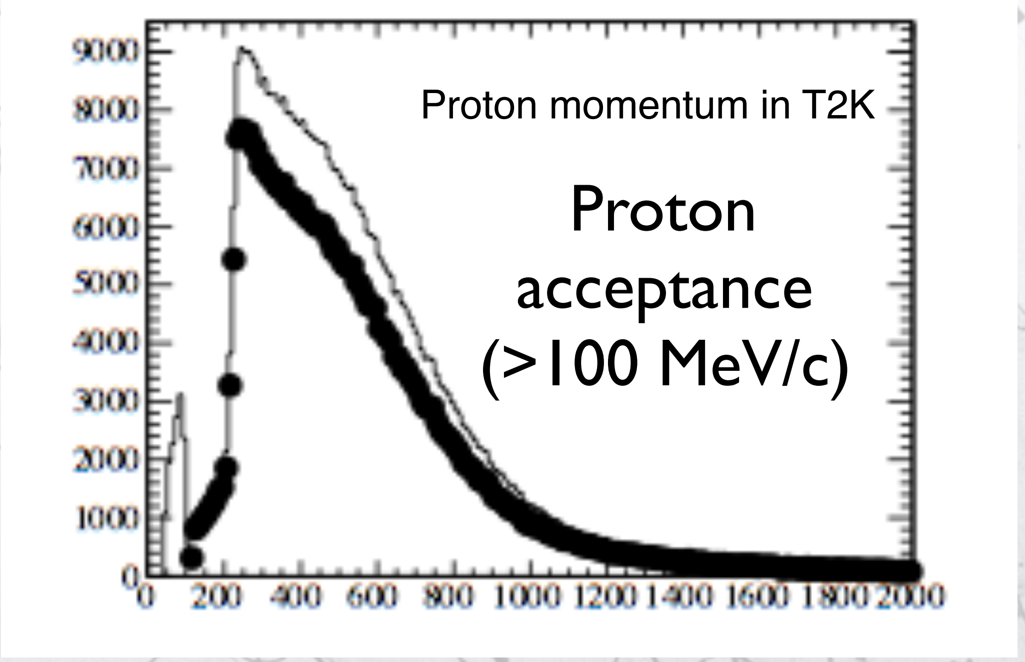


- **Magnetised (0.4T)** high resolution straw tube design with planar geometry (event acceptance non uniform).
- **Mixed target (gas and container):** Target/Nucleus selection by track vertexing.
- **Low average density** for low energy particle detection.
- **ECAL gamma catcher** and muon range detector.
- Mixed **Calorimetric/kinematic** approach.

Future: HPTPC

- **Magnetised gas detector →** excellent momentum reconstruction.
- **Low mass** (~100 kg), moderately fast detector (~100 μs)
  - **No pileup** but **large external background** (magnet,…)
- ECAL for π^0 detection and particle Id.
- **Calorimetric** approach.
- **Lowest proton threshold: ~100 Mev/c.**
- Do we need High Pressure ?





HPTPC: # events

HPTPC allows to change target nuclei to study nuclear effects on ν interactions → ***excellent x-section experiment.***

CC events assuming a $8m^3$ detector & full FV.

Acceptance ~45% for a $2x2x2\ m^3$

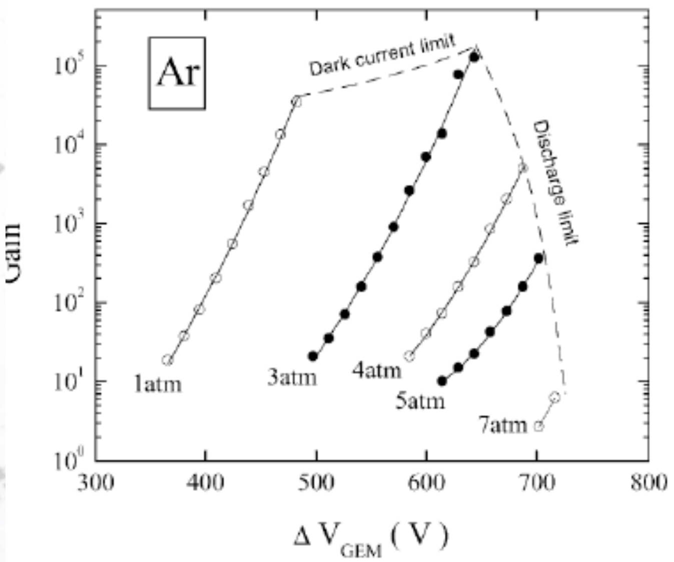
$2x2x2\ m^3$ 20°C	5 bars	10 bars
He	6.65 kg	13.3 kg
	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	32.5 kg	67.1 kg
	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	66.5 kg	133 kg
	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	146.3 kg	293 kg
	11450 evt/10^{21}pot	22893 evt/10^{21}pot

T2K Expected ~1.6 10^{21} pot/year for ~4 years

Gas selection

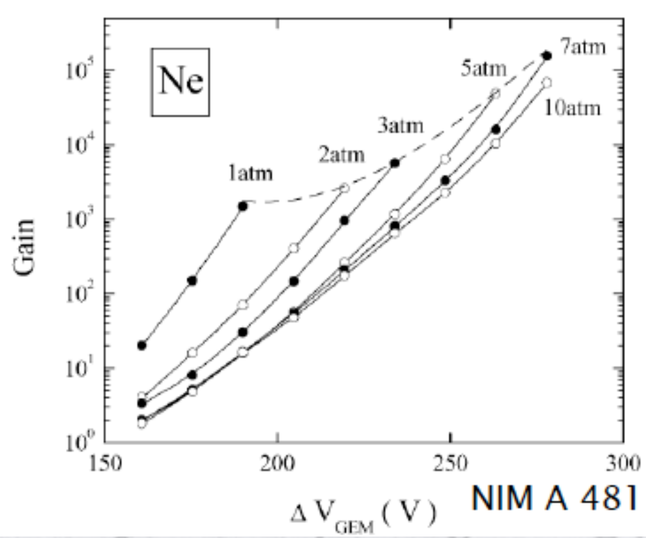
R&D needed.

Gain in Pure Noble Gases:

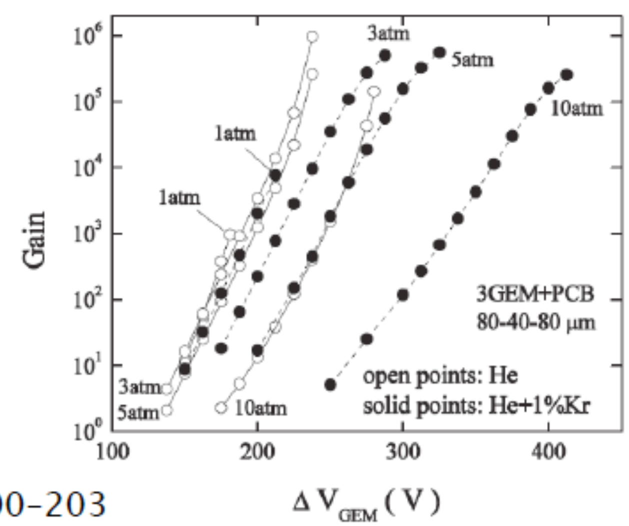


- Measurements performed with GEMs but should be the similar behavior for MM (to be confirmed by R&D studies).
- Maximal gain limited for Argon at high pressures
- Scintillation light in pure noble gases (He,Ne: ~15.5 eV, Ar: 9.7 eV) => Effect on detector material?

NIM A 513 (2003) 256-259



NIM A 481 (2002) 200-203



- Gain is limited on Ar at high pressures:
  - Ar has larger electron yield.
  - Ar can be run at lower pressures.
- OK for He or Ne.
- Need of T_0 and prompt scintillator light readout ?

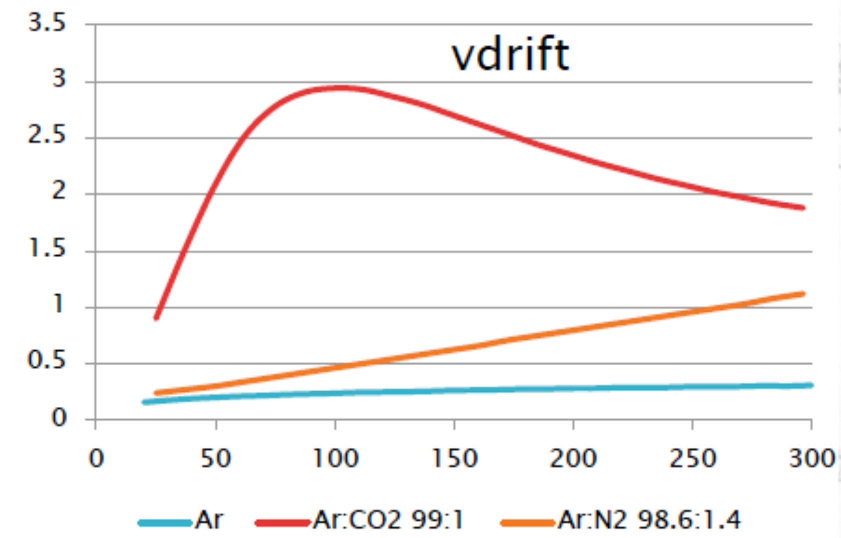
Gas selection

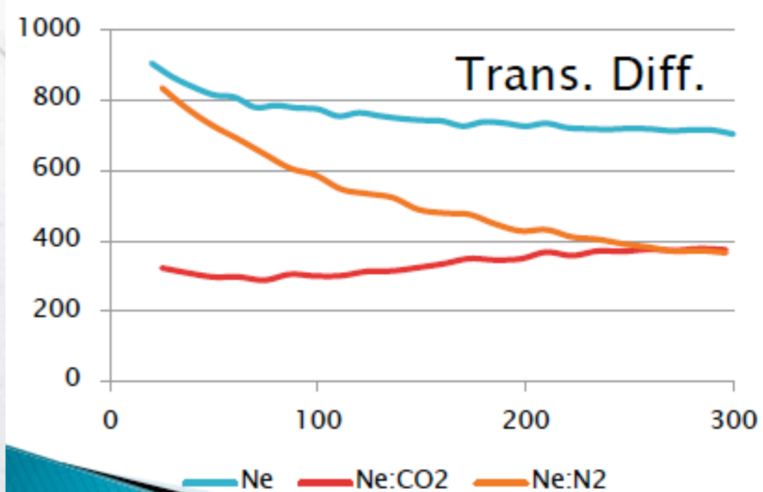
R&D needed.

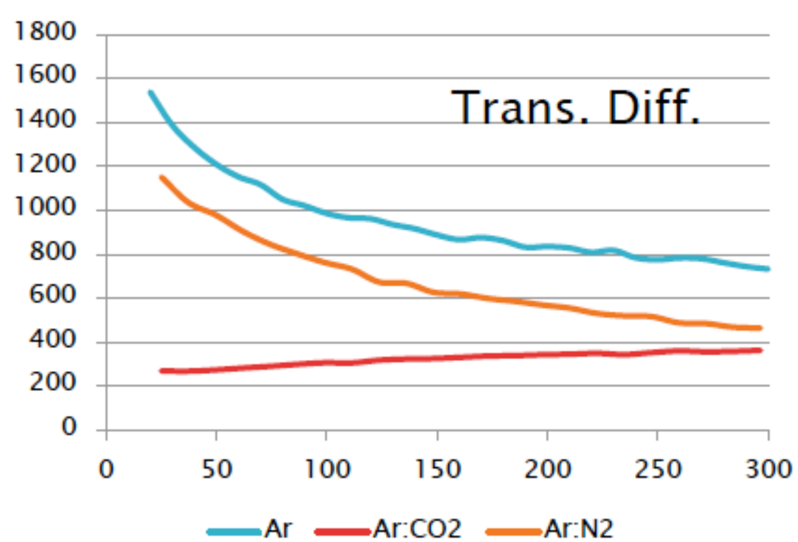
Some Magboltz Simulations:

•1% in mass:

- ➢ He: CO_2=0.1%, N_2=0.15%
- ➢ Ne: CO_2=0.5%, N_2=0.7%
- ➢ Ar: CO_2=1%, N_2=1.4%





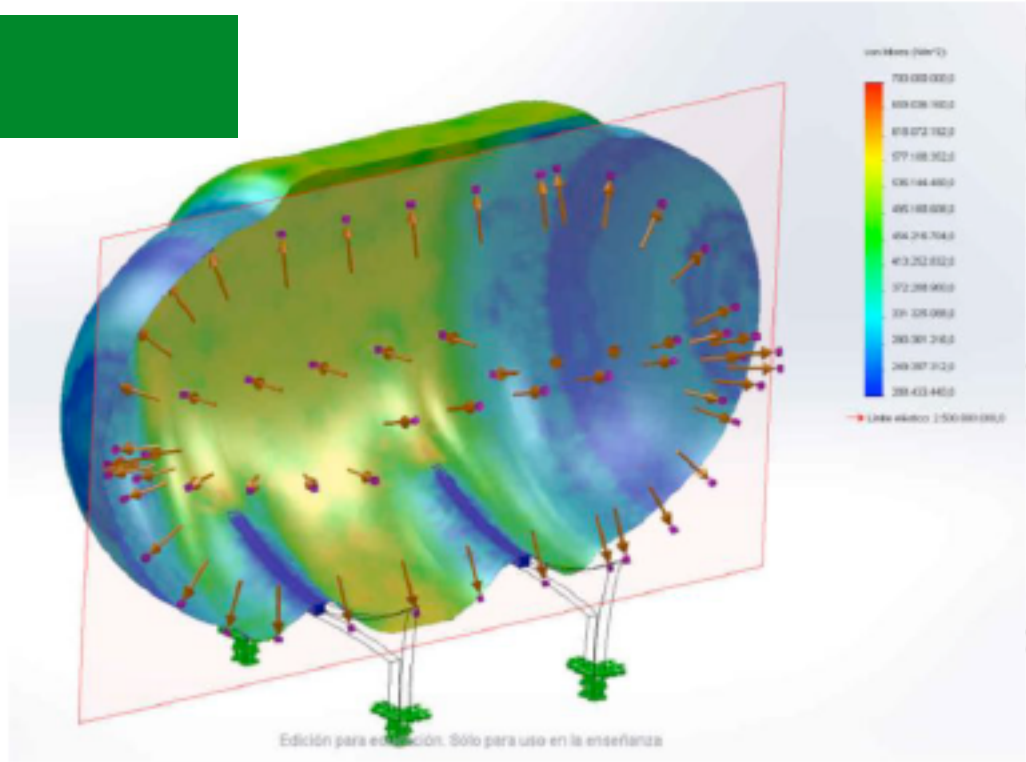


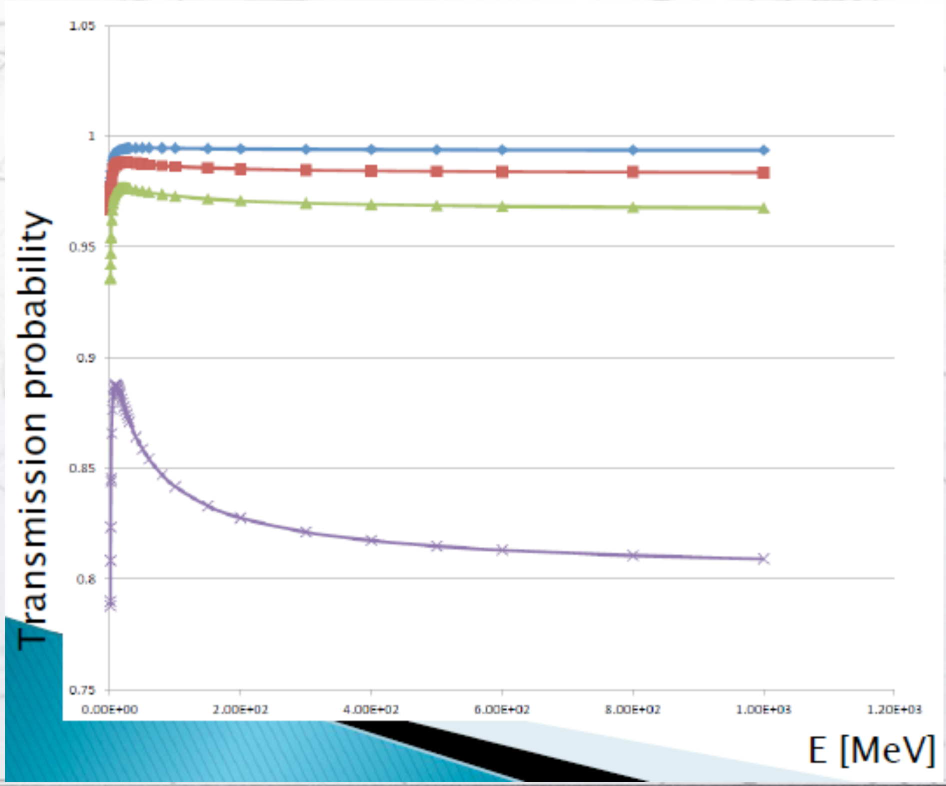
- Small fraction of quencher improves diffusion and speed.
- Quencher < 1% to ensure systematics below 1% in nucleus determination in νA interactions.
- Effect of attachment increases as p^2: low quencher fraction requested!.

Around a HPTPC

R&D needed.

- We would need a magnet and a calorimeter:
  - Low threshold calorimeter needed for photon tagging and hadron/lepton separation.
  - Magnet and ECAL will drive the cost of the detector.
- HPTPC walls design is critical!:
  - Carbon fiber?
  - Integrated Calorimeter in TPC walls ?





(HP)TPC program @ CERN

CERN-SPSC-2017-002 ; SPSC-EOI-015

- Expression of interest submitted in January to CERN. Goals:
  - T2K upgrade (TPC + Fine grained target) for 2020
  - HPTPC for Dune/T2K/X-section experiment beyond 2020.
- Many European (and non-European) countries: GB, France, Switzerland, Germany, Spain, Italy, Poland, Russia, Japan, Sweden, …
- Detailed proposal to be submitted in fall.
- Collaborators welcome!

As conclusions

- ND are fundamental tools for future(and current) neutrino oscillation physics.
- ND requirements are broad:
  - Large mass & low density
  - Similar nuclei as far detector.
  - charge sign determination & particle id
  - momentum from 100 MeV/c protons to few GeV muons.
  - hermeticity for energy determination.
  - 4π acceptance for low energy int.
  - **All at reasonable cost.**

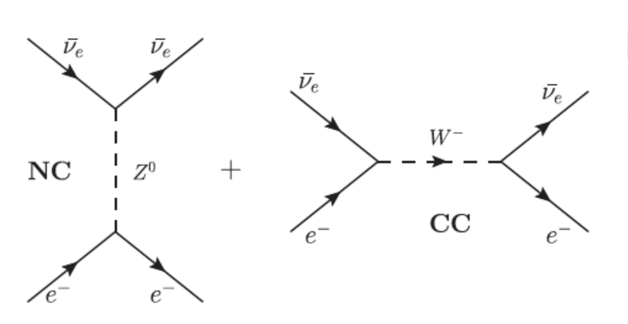
- **Several technologies proposed but not a clear winner.**
- TPC's has been key to the success of T2K experiment.
- T2K-II (and Dune) exploring (HP)TPC for the future.
- New proposal at CERN to develop technology for atmospheric and HPTPC.

Backup slides

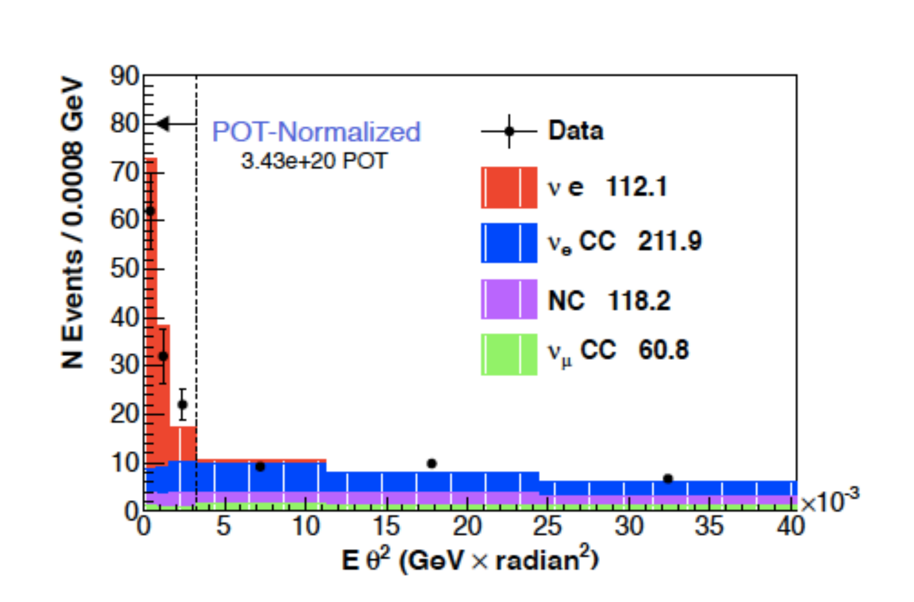
Neutrino flux

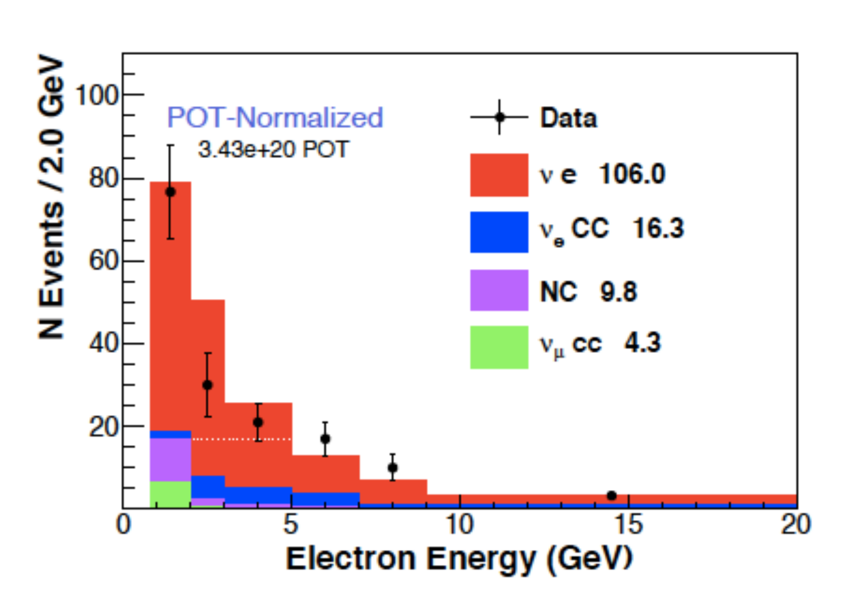
- Constrain the flux using the neutrino-electron scattering:
  - $\overset{(-)}{\nu}_\mu e^- \rightarrow \overset{(-)}{\nu}_\mu e^-$
  - The cross-section is well known:

$$\left[\frac{d\sigma}{dT}(\overset{[-]}{\nu}_\mu e)\right]_{\mathrm{SM}} = \frac{G_F^2 m_e}{2\pi} \cdot \left[(g_V \pm g_A)^2 + (g_V \mp g_A)^2 \times \left(1 - \frac{T}{E_\nu}\right)^2 - (g_V^2 - g_A^2)\frac{m_e T}{E_\nu^2}\right],$$



- The electron energy can constrain both absolute flux and the energy dependency.





It requires large mass and good discrimination against ν_e backgrounds

No direct distinction between neutrinos and antineutrinos.

arXiv:1512.07699v2

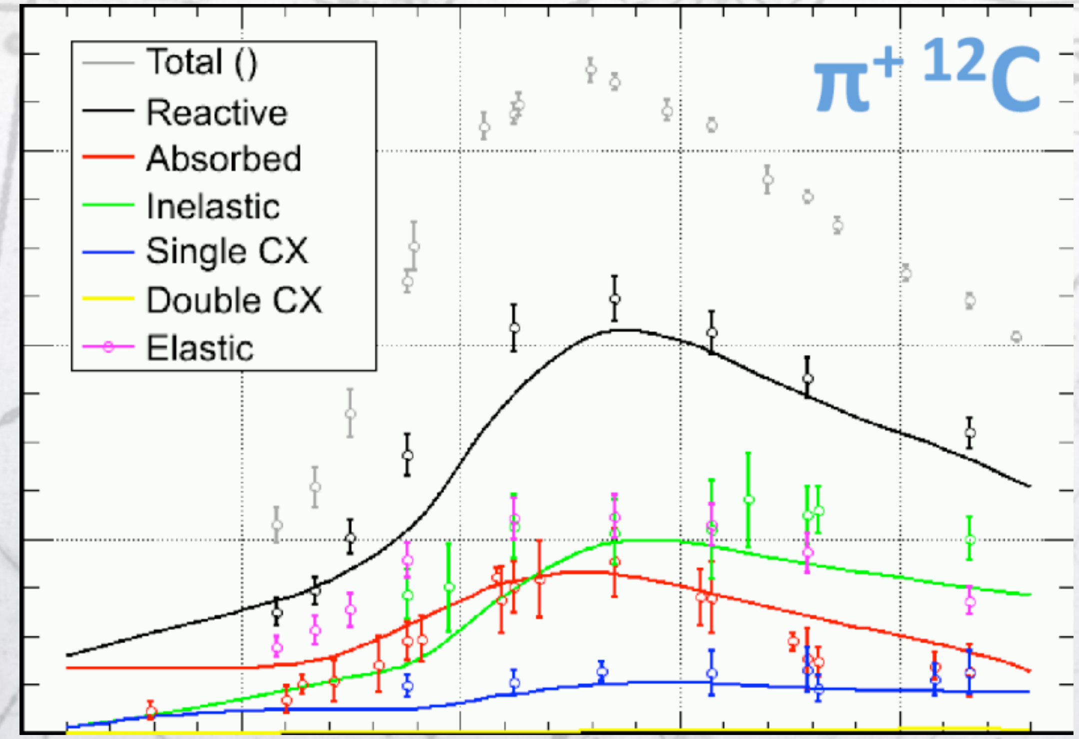
ND for oscillations

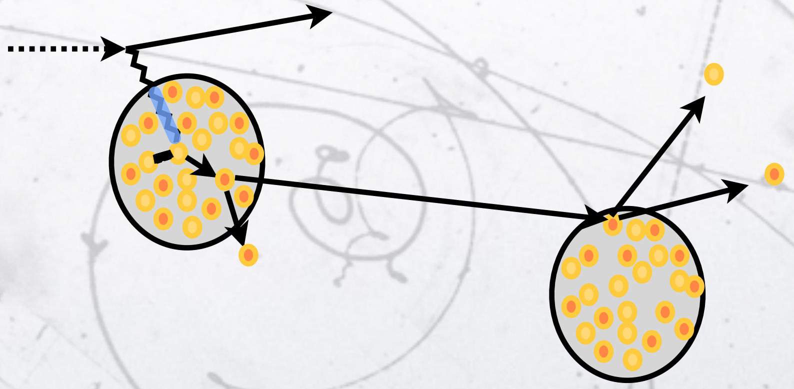
- Obviously, we can't make the ND the same size as the far detector:
  - The hermeticity of the detector will be different for neutrons electrons and gammas.
    - Low energy gamma's from π^0 critical!
  - The momentum of long range particles need to be estimated in different ways:
    - FD: range for muons/pions and energy for electromagnetic energy.
    - ND: range/curvature/energy depending on the particle and the range.
- This will affect the reconstruction criteria and energy reconstruction depending in hadronic secondary interactions.

ND for oscillations

- Secondary interactions are also critical:
  - Hadronic particles leaving the nucleus are affected by hadronic interactions similar to the FSI.
  - Those cross-sections are not well known for low energy (< GeV) pions and nucleons.
  - Data is even more sparse in Argon.

→ ProtoDune





ND for oscillations

- The nuclear target alters the cross-section:
  - Number of nuclei (~A)
  - Fermi momentum change probabilities close to reaction thresholds.
  - Pauli blocking inhibits interactions.
  - Final State Interactions does not have a simple dependency with A.

Model dependent

It is recommended that near and far detector are made of the same nuclei.

Difficult for water (T2K/HK) easy for argon (DUNE)

ND for oscillations

- If ($Acc_{FD} \subseteq Acc_{ND}$), the acceptance is not a problem.
- If ($Acc_{FD} \supseteq Acc_{ND}$), there are two potential issues:
  - The total cross-section extrapolation from the accepted events in the near detector to the far detector is model dependent.
    - And models are poor!!!!
  - For the same topologies, P(E|E´) might depend on the event properties:
    - Large vs small hadronic energy (E_{had})
    - …

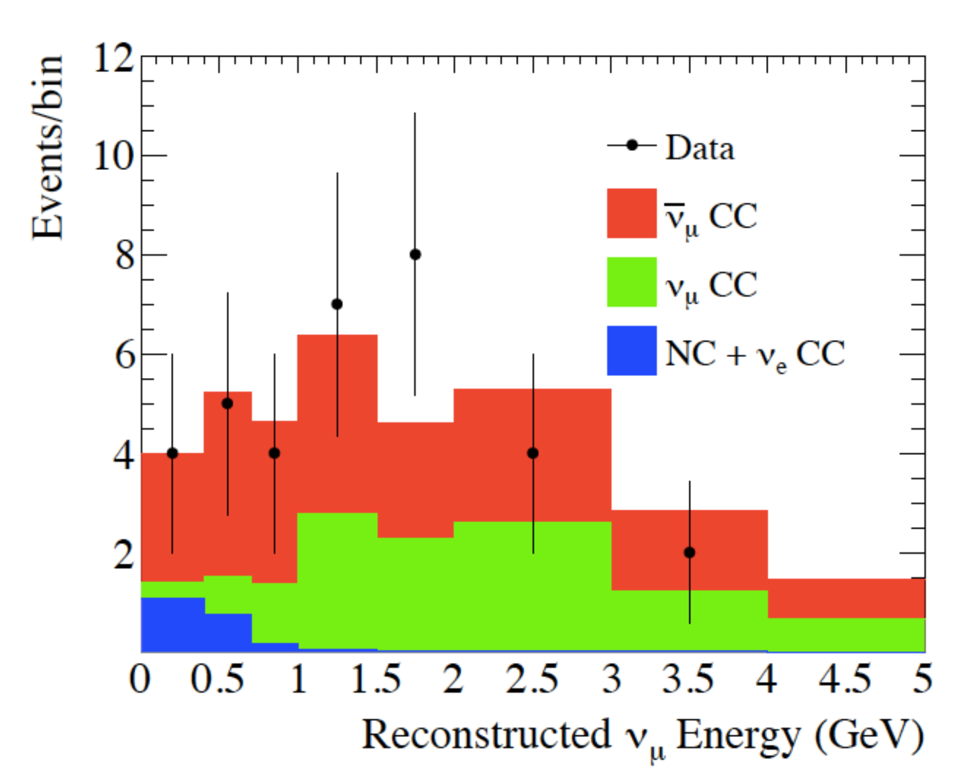
ND for oscillations

- The ν_e appearance has two additional issues:
  - Near $\Phi(E_\nu) x \sigma(E_\nu)$ is computed for ν_μ but far detector is for ν_e. This implies that we need to compute or model:
    - $\sigma_e(E_\nu)/\sigma_\mu(E_\nu)$ for neutrinos and anti-neutrinos.
    - Additional model of $P(E_\nu|E'_\nu)$ and energy scale.
    - Control the π^0 background in the electron sample.
  - There is also the intrinsic beam ν_e background to be constrained.

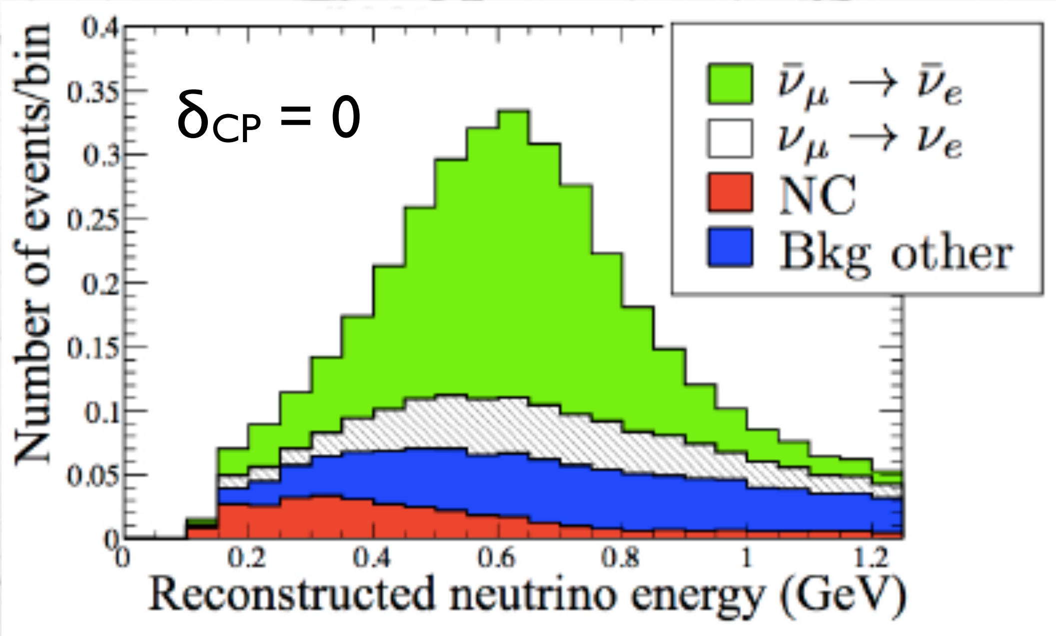
Excellent $e/\mu/\pi^0$ separation.
Large statistics: masive near detector / large flux !
Enhanced electron sample (off-axis ?)

ND for oscillations

- CP violation also requires the separation of neutrinos and antineutrinos.
  - neutrino beam is normally very pure.
  - anti-neutrino beam has large contribution of neutrinos:
    - antineutrino cross-section and production yield is low.
- FD has some capability to distinguish neutrinos from antineutrinos (i.e. neutron production in CCQE).
- ND has to be able to measure the neutrino background in the antineutrino beam → Magnetised detector.



PoS EPS-HEP2015 (2015) 047



Cross-section and flux

- Resolving the three components in $\Phi(E_\nu) \times \sigma(E_\nu) \times P(E_\nu|E'_\nu)$ is complex:
  - Need to improve on cross-section models:
    - dedicated experiment?
    - electron scattering?
    - but also strong theoretical support.
  - Have the possibility of change $\Phi(E_\nu)$ in the experiment or with other experiments.
  - Start with an excellent prediction for $\Phi(E_\nu)$ (external pA experiments like Shine)

Physics requirements

- The perfect ND detector has:

Same/better acceptance as far detector

Same/Similar technology

Same nuclear target

Excellent $e/\mu/\pi^0$ discrimination

Large mass

Good control on external backgrounds

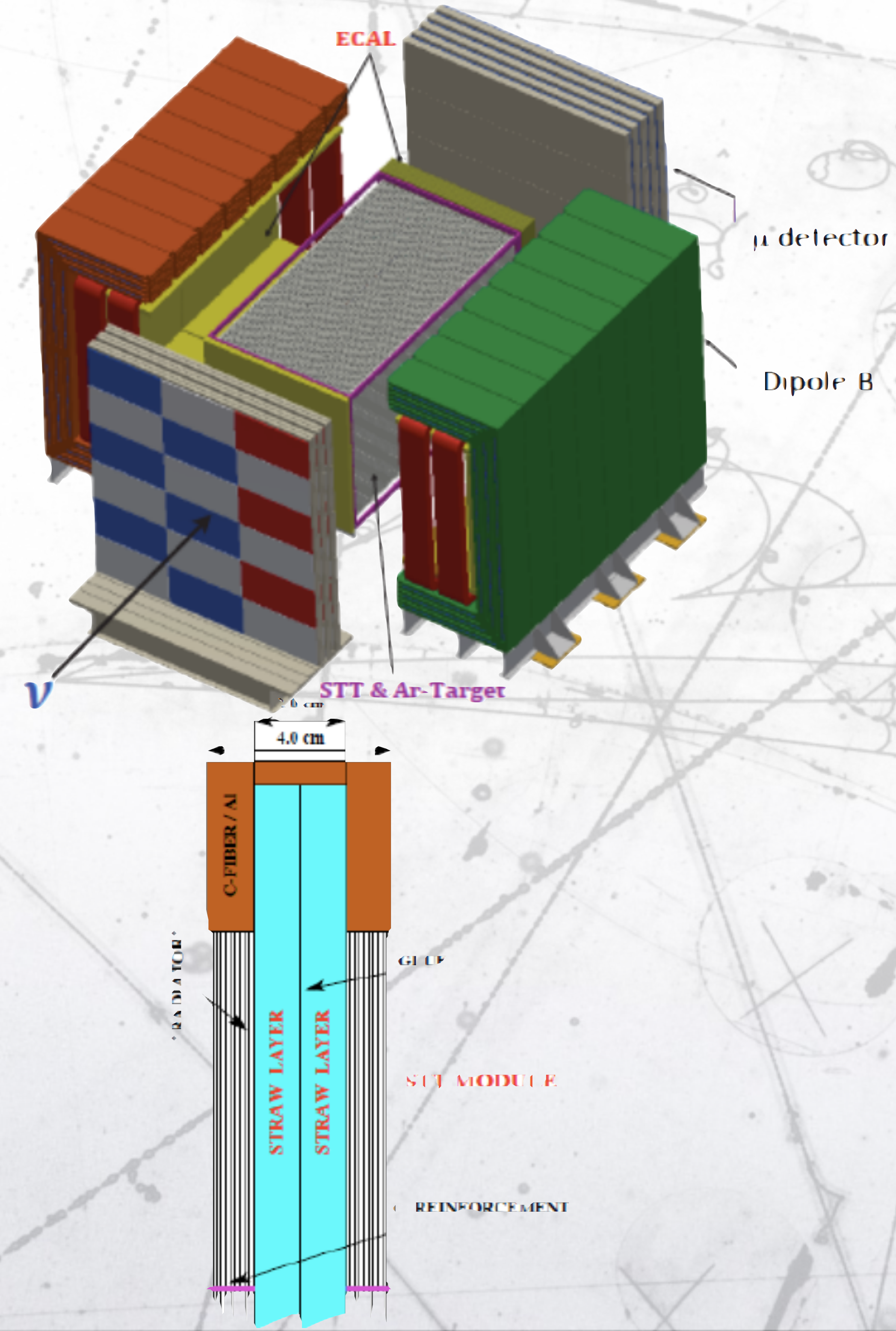
Excellent purity for ν_μ e^- scattering samples

Excellent charge separation for neutrino vs antineutrino

Options

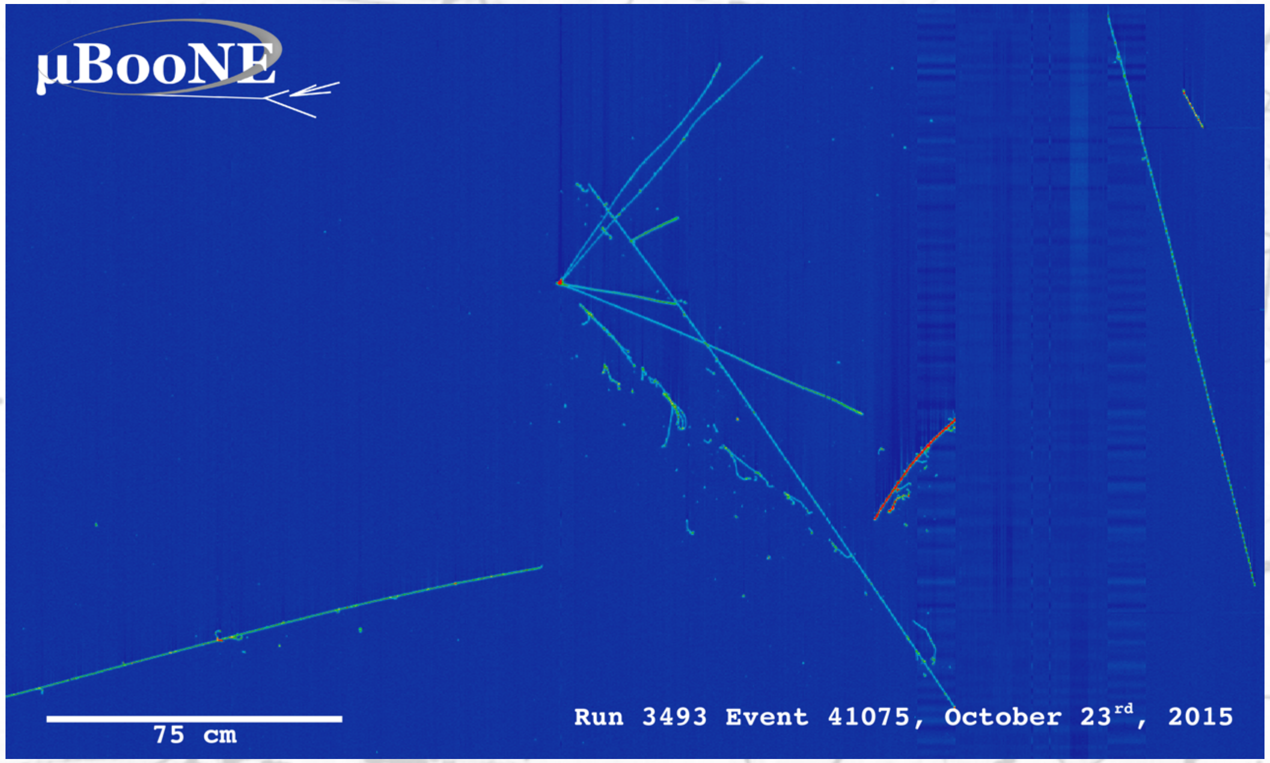
- There are three options for ND:
  - Segmented tracker.
  - LiqAr TPC.
  - HPTPC
- But, there is no reason why there should be only one detector. Neutrino beams are very “democratic”.

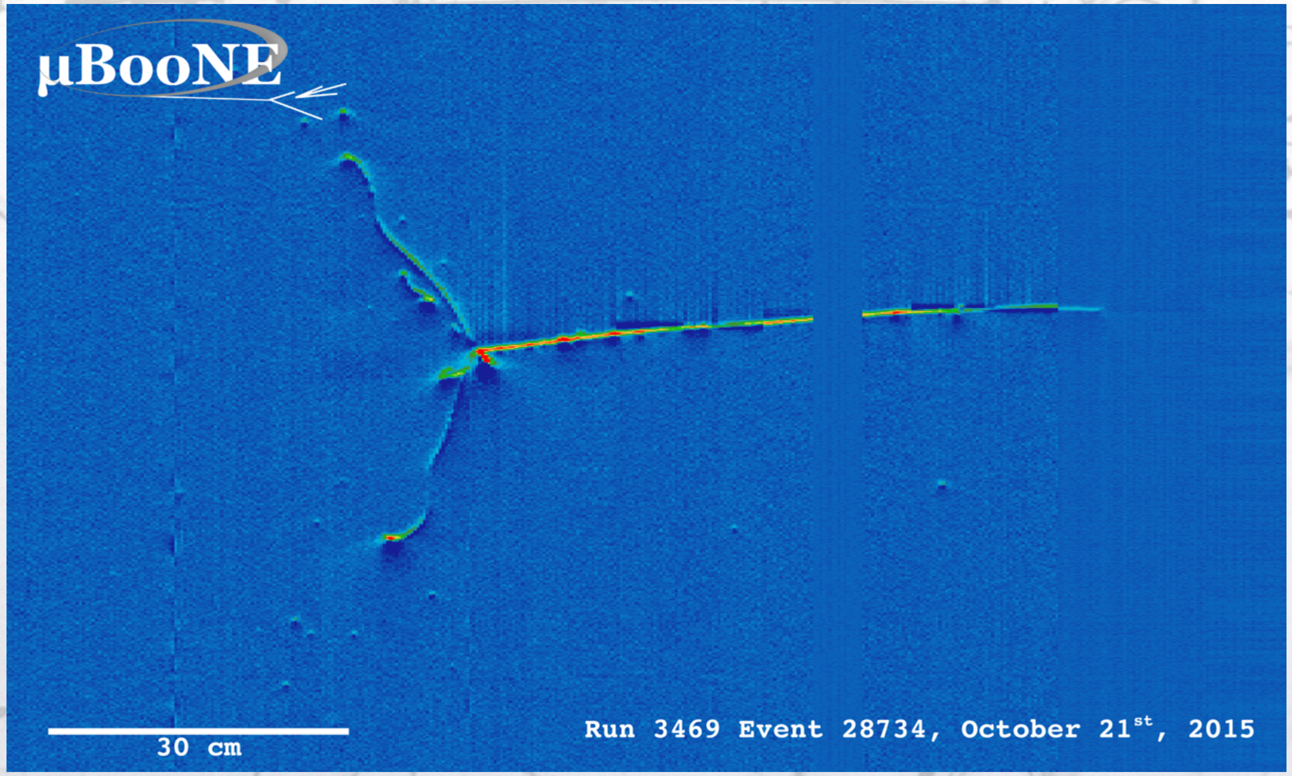
Segmented tracker



- Magnetised (0.4T) high resolution straw tube design “a la” Nomad with plannar geometry.
- Target/Nucleus selection by track vertexing.
- Low density for low E particle detection.
- ECAL gamma catcher and muon range detector.

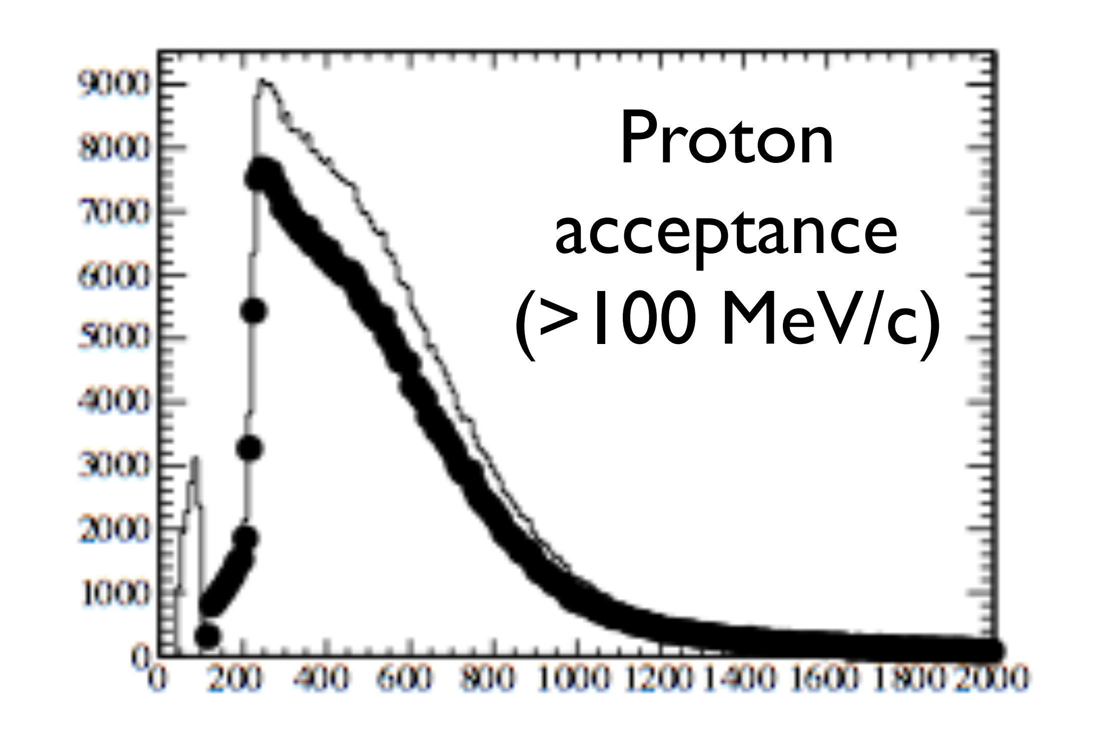
LiqAr TPC

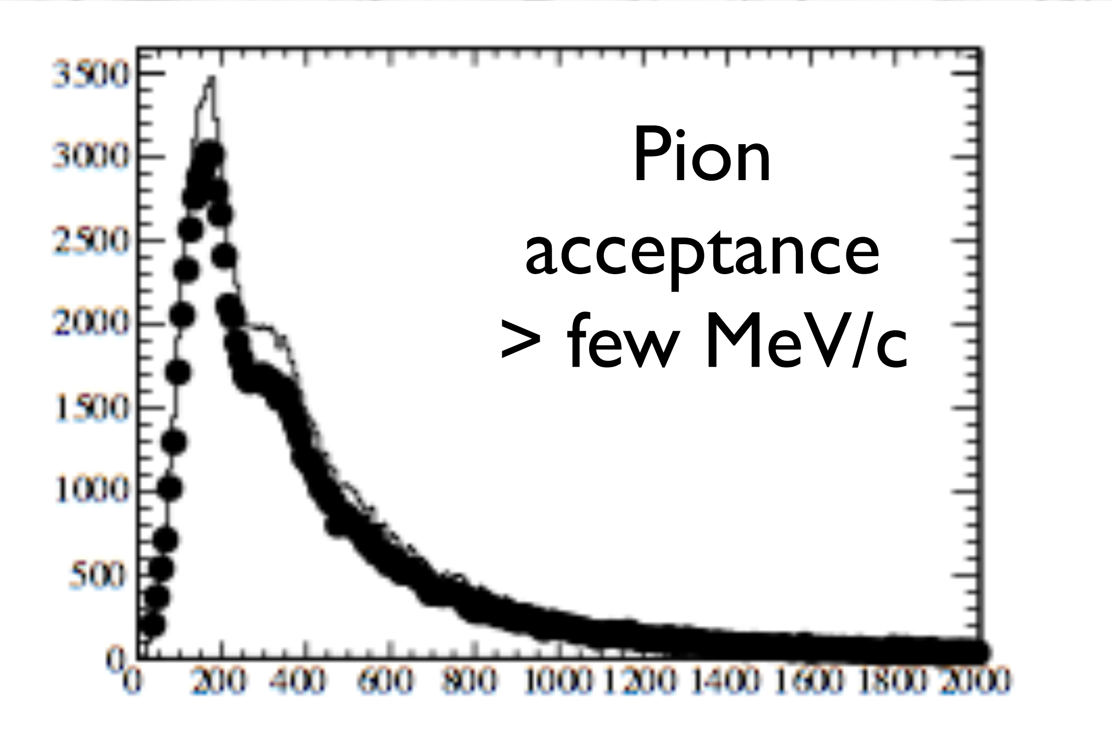




- Magnetised (?) LiqAr detector.
- Same technology as FD.
- Large mass.
- Balance pile-up / range.
- ECAL and muon range.

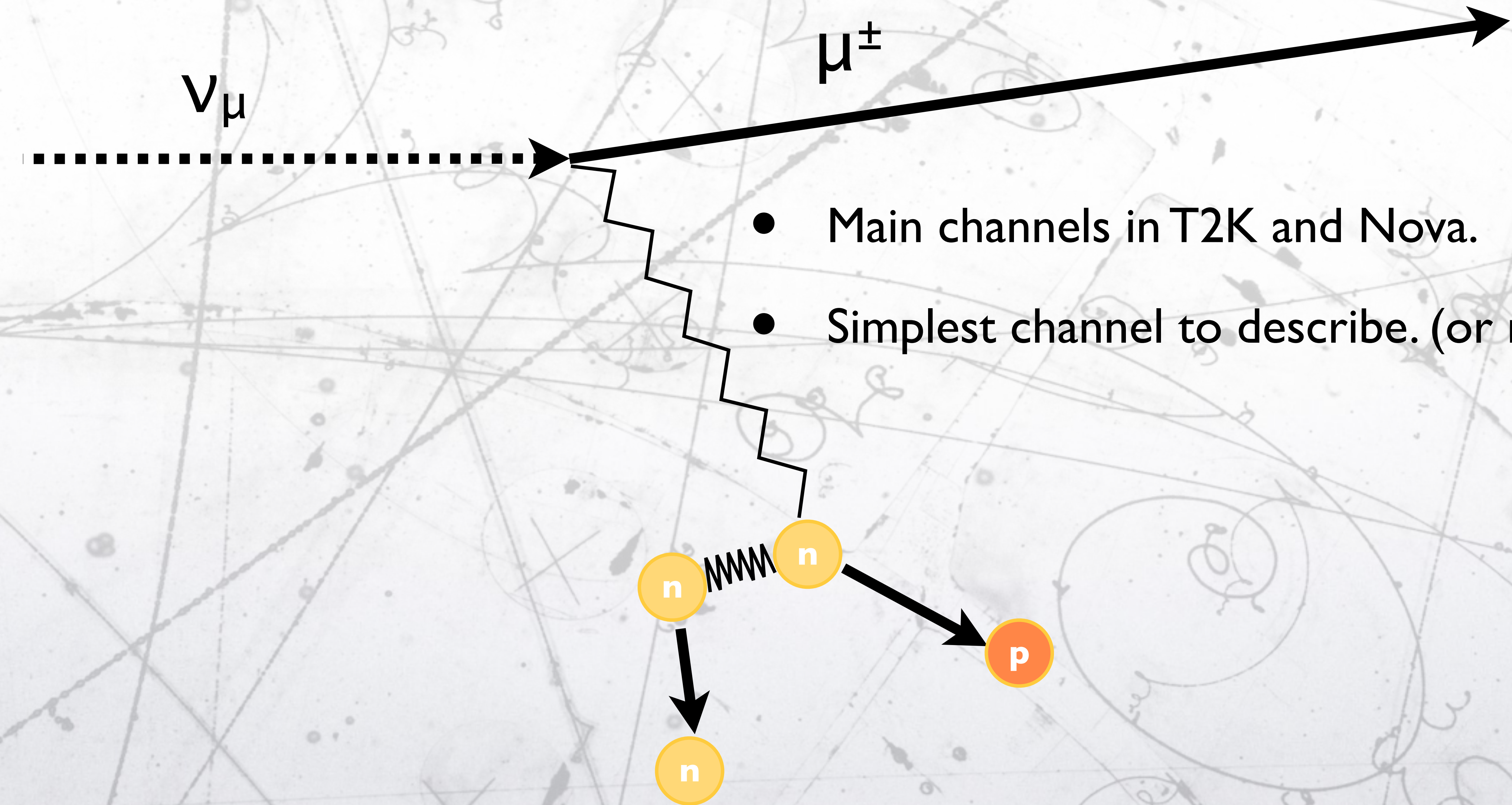
HPTPC





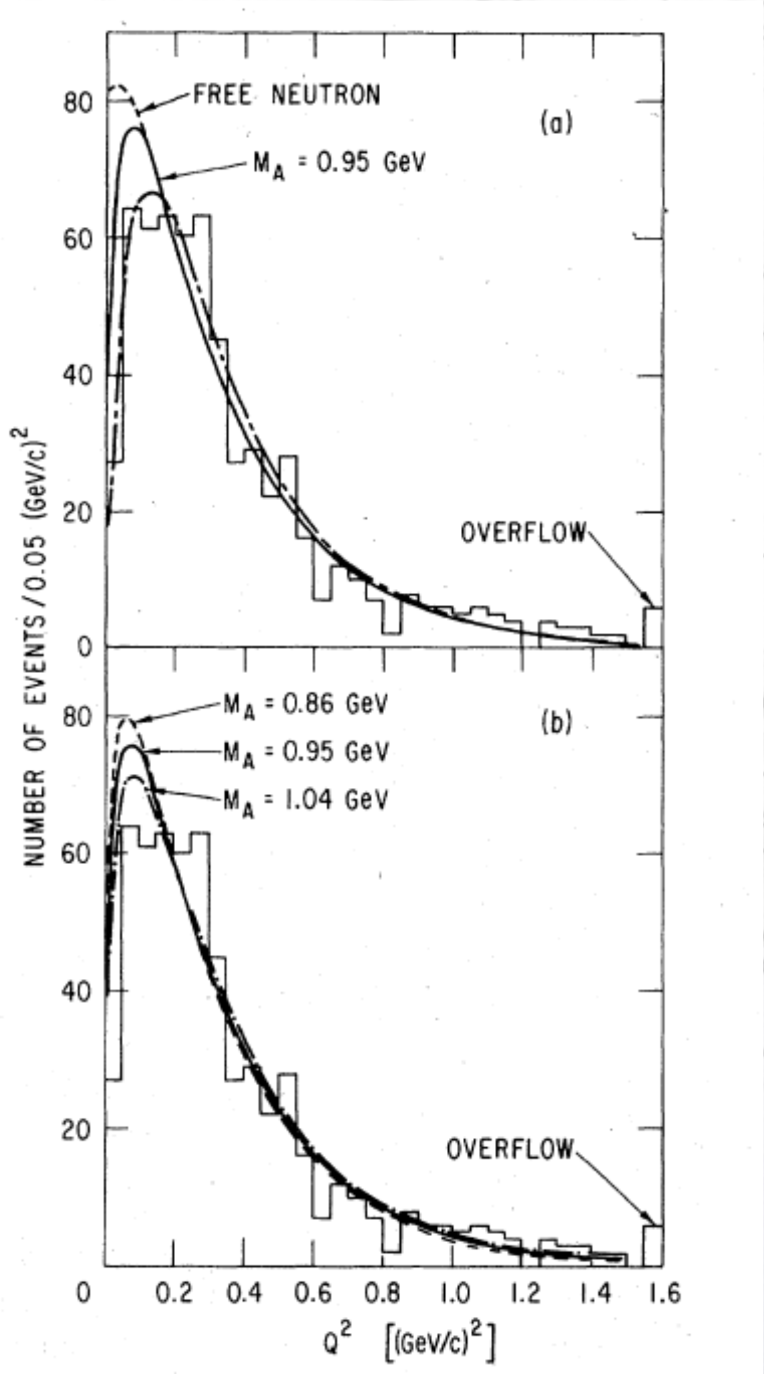
- Magnetised High Pressure TPC.
- Low mass.
- Very low momentum threshold.
- Same target as far detector / similar technology.
- Inner/Outer mass balance.
- ECAL and muon range.

CC 1p1h + 2p2h



- Main channels in T2K and Nova.
- Simplest channel to describe. (or not?)

Single nucleon



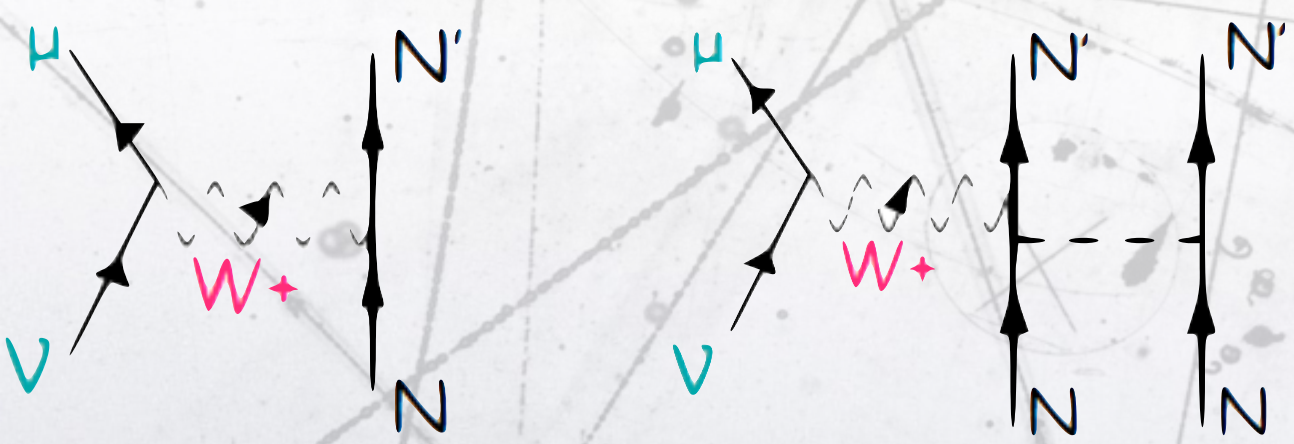
PHYSICAL REVIEW D
VOLUME 16, NUMBER 11
1 DECEMBER 1977

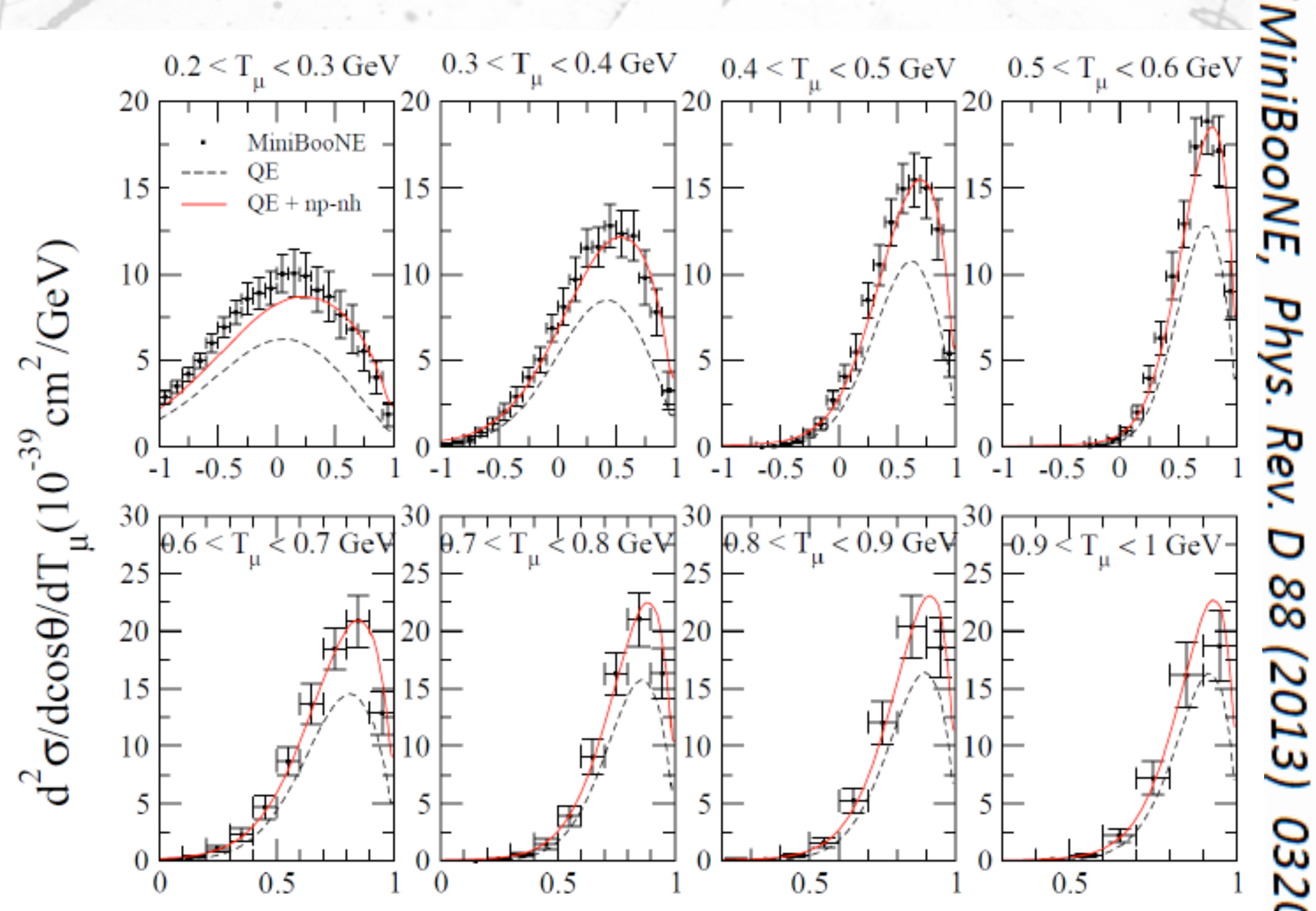
- Free nucleon (H and D) data is very limited.
- Many of the assumptions of the basic cross-section can't be accurately tested with nuclei:
  - Conserved Vector Current
  - Partially Conserved Axial Current.
  - Dipole form factor
  - Vanished scalar and tensor form factors.
- …

1p1h vs 2p2h

- Recently the community has realised the presence of short range correlations, so called 2p2h.
- They are basically interactions with 2 nucleons at the time.
- They alter the energy balance and the neutrino energy reconstructions.

CCQE CC-2p2h





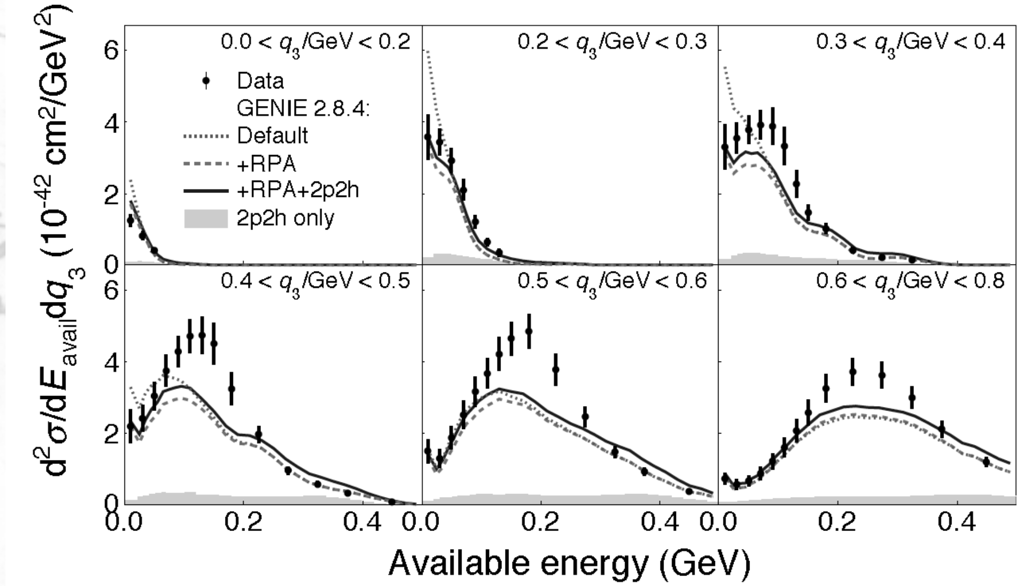
MiniBooNE, Phys. Rev. D 88 (2013) 032001

Martini et al. PRC 84 055502 (2011)

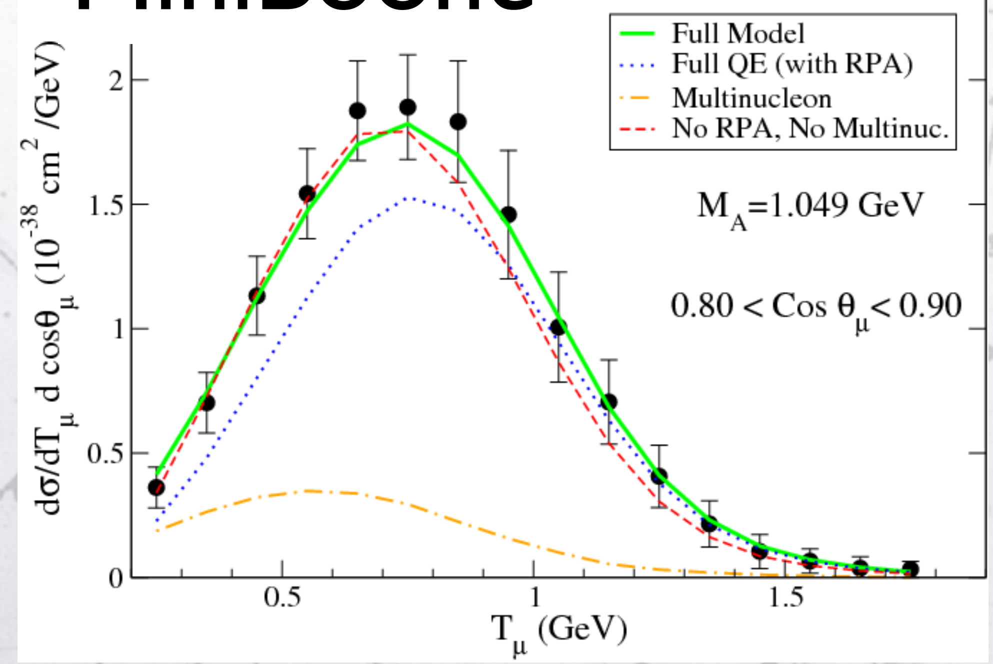
- Models agree with MiniBoone but not with other experiments: Minerva and T2K.
- Models based on same principles do not agree.

This is a large systematic error in T2K & Nova

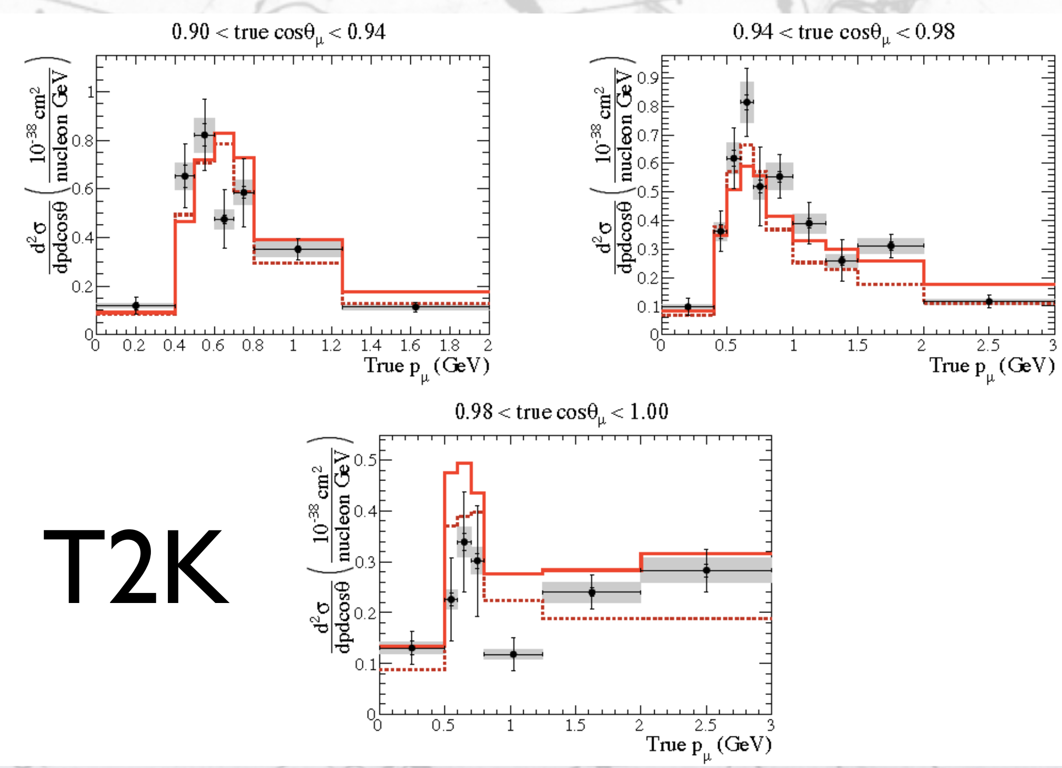
Minerva



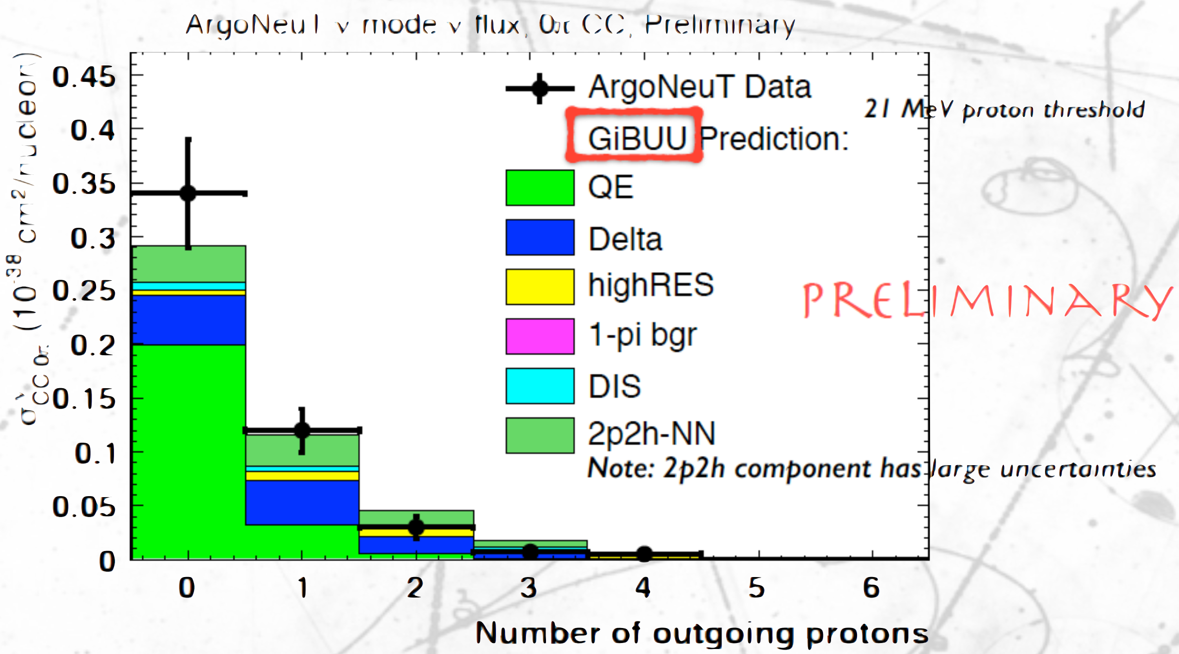
MiniBoone



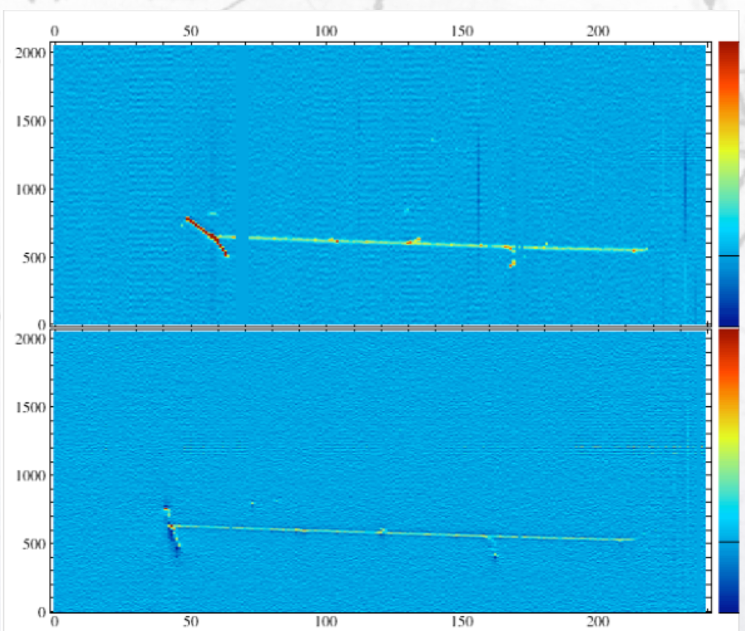
T2K

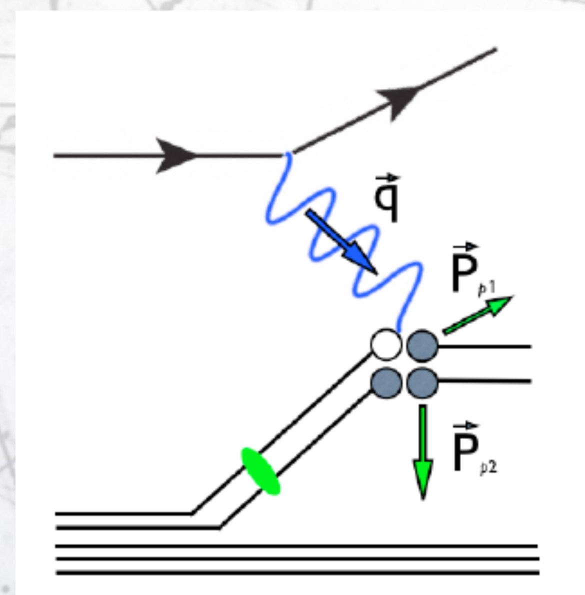


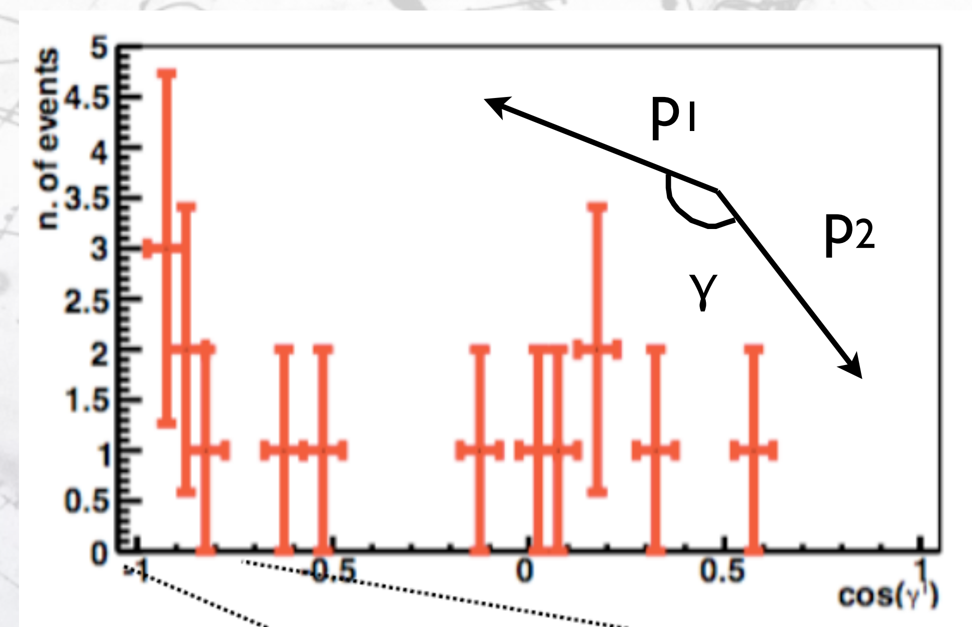
Search for 2p2h



- LiqAr ArgoNeut has bubble chamber imaging capabilities to look into final states.
- It has first indications of correlated final state protons.
  - Spectral functions ?
  - 2p2h ?



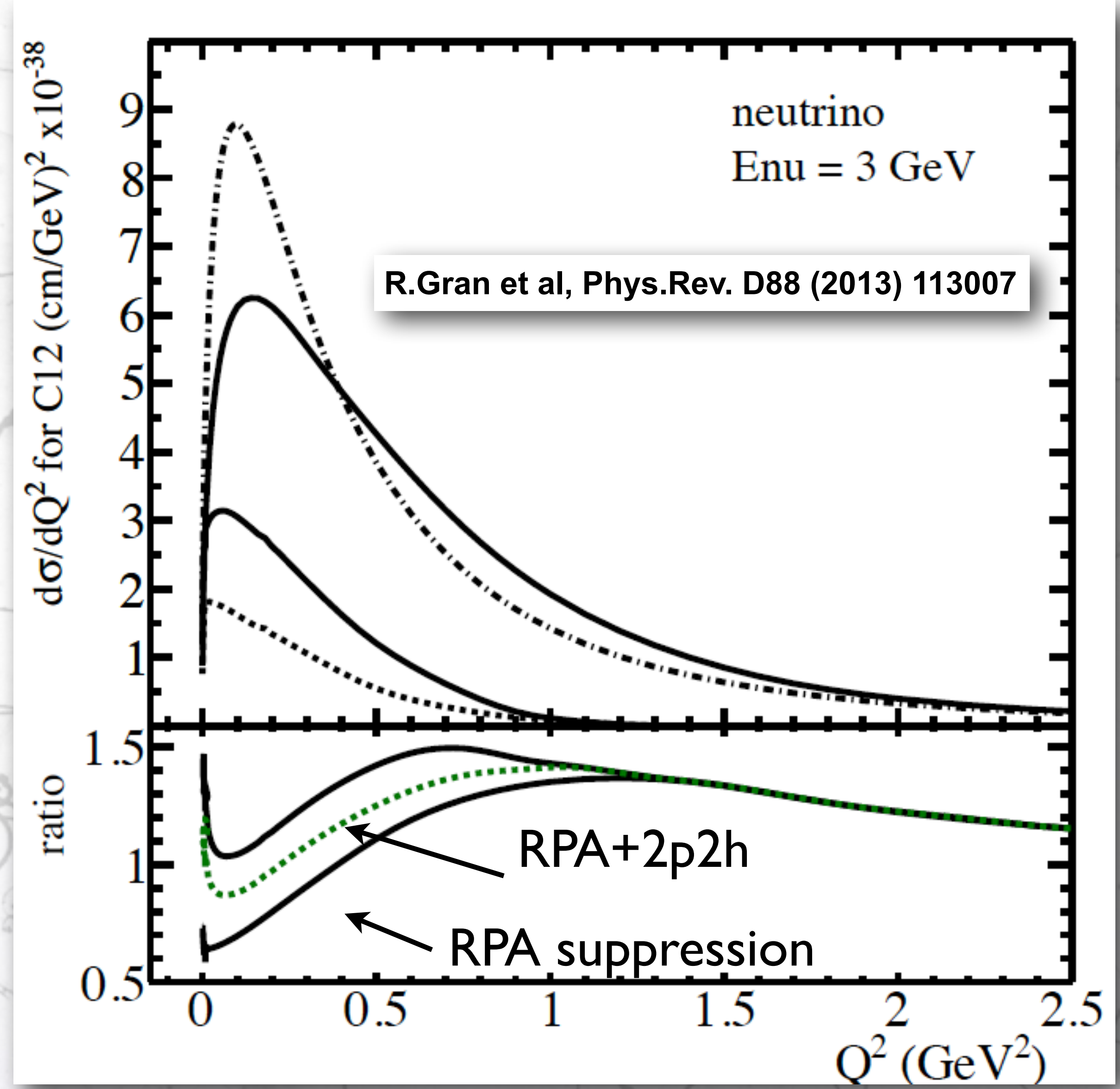




Strength of new generation of low threshold detectors

1p1h

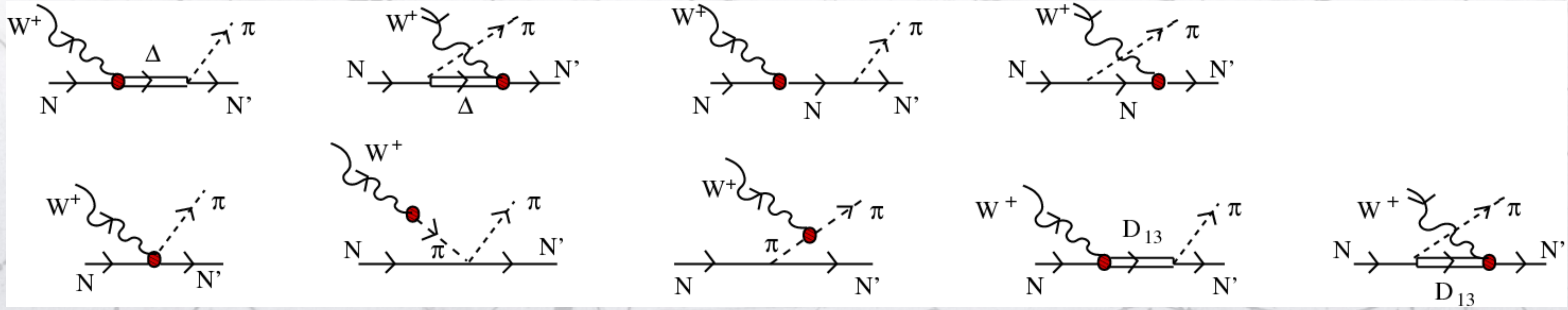
- Actually one of the problems is that the basic nucleus is probably not well described:
  - bind energy !
  - Fermi momentum description: RFG, LFG, Spectral functions.
  - Final State interactions.
  - Large Range correlation appearing as low q^2 quench of the reaction.



Sometimes the different models are degenerate and it is difficult to resolve them. Need different experimental conditions.

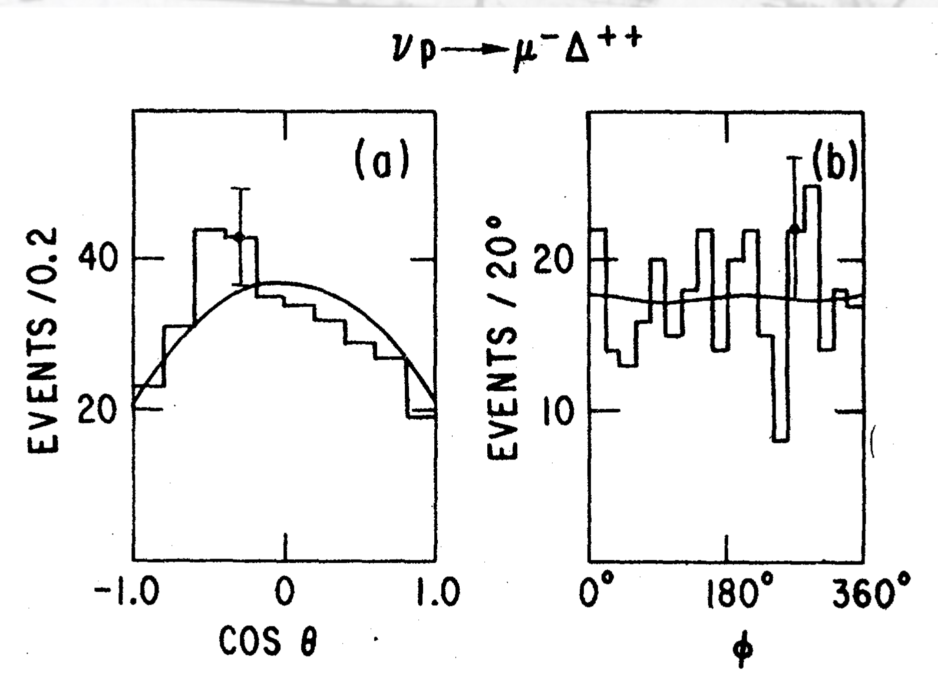
Single pion production

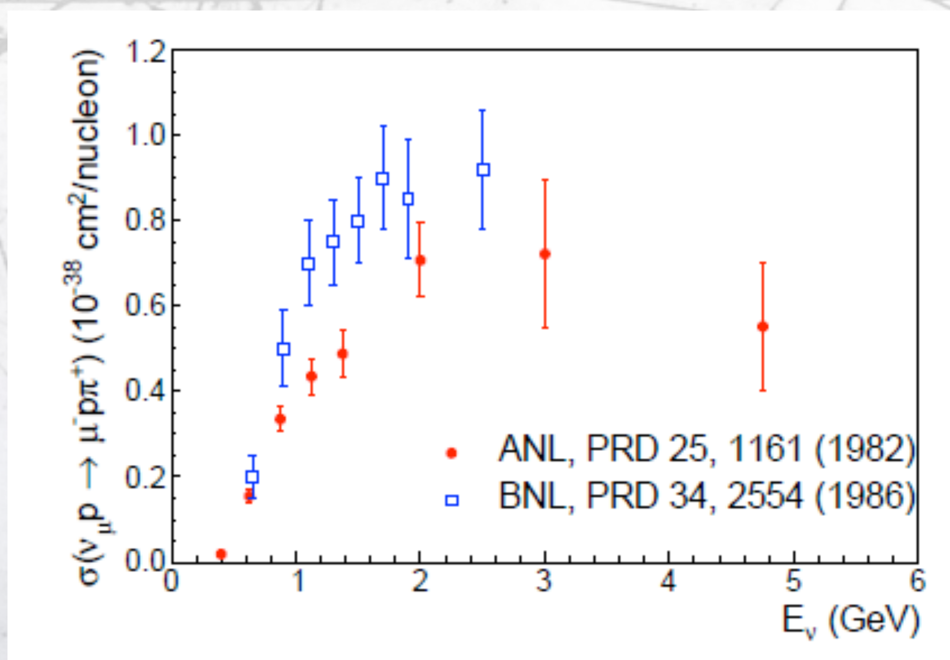
- Second most relevant cross-section in oscillation experiments.
- All set of long and short rage correlation effects in CC1π are ignored in actual pion production models.
    - models are still uncertain on its implementation to CCQE.
- Complex modelling with many intermediate resonances and non-resonant contributions.

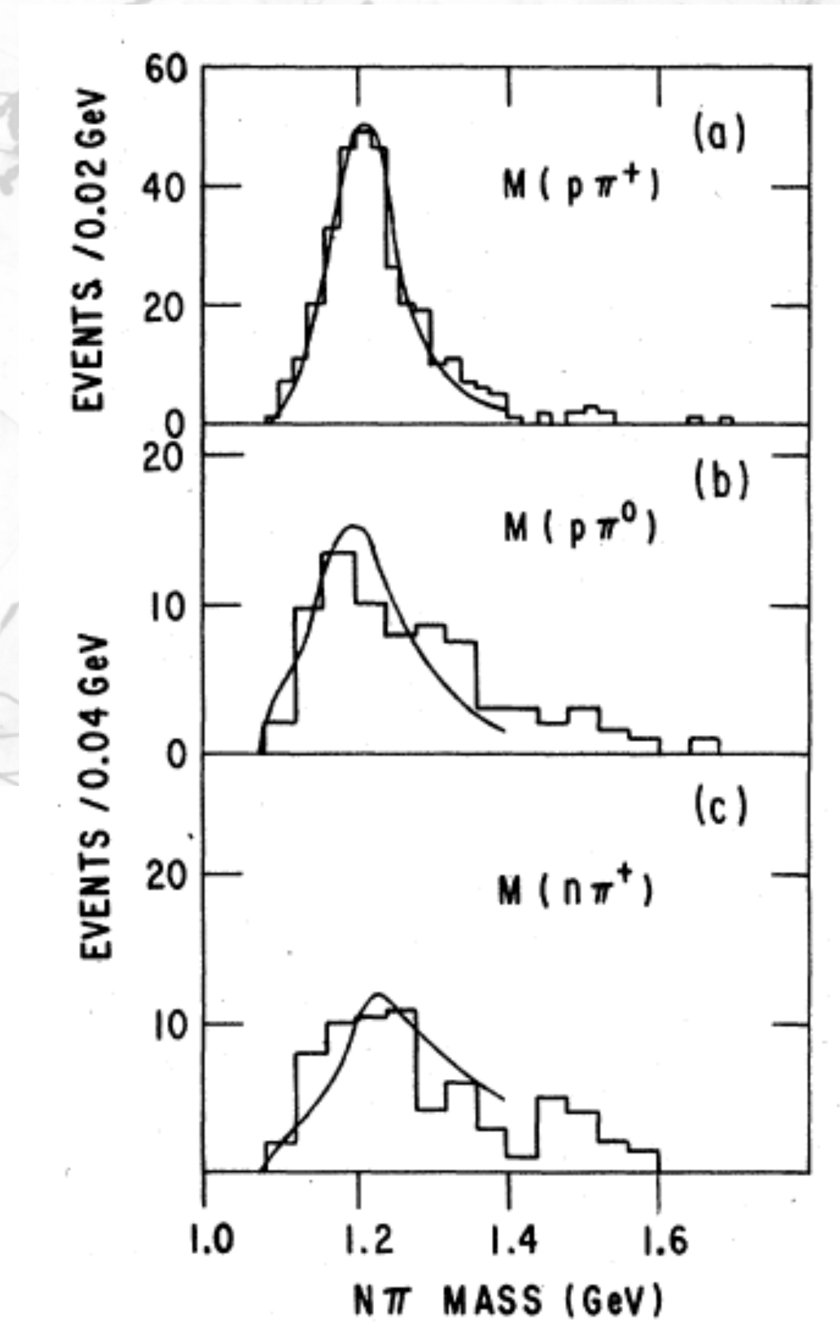


Single pion production

- Poor knowledge at nucleon level both theory and experiment:
    - Mixture between resonant and non-resonant interactions.
    - many resonances and spin amplitudes.
    - poor data.

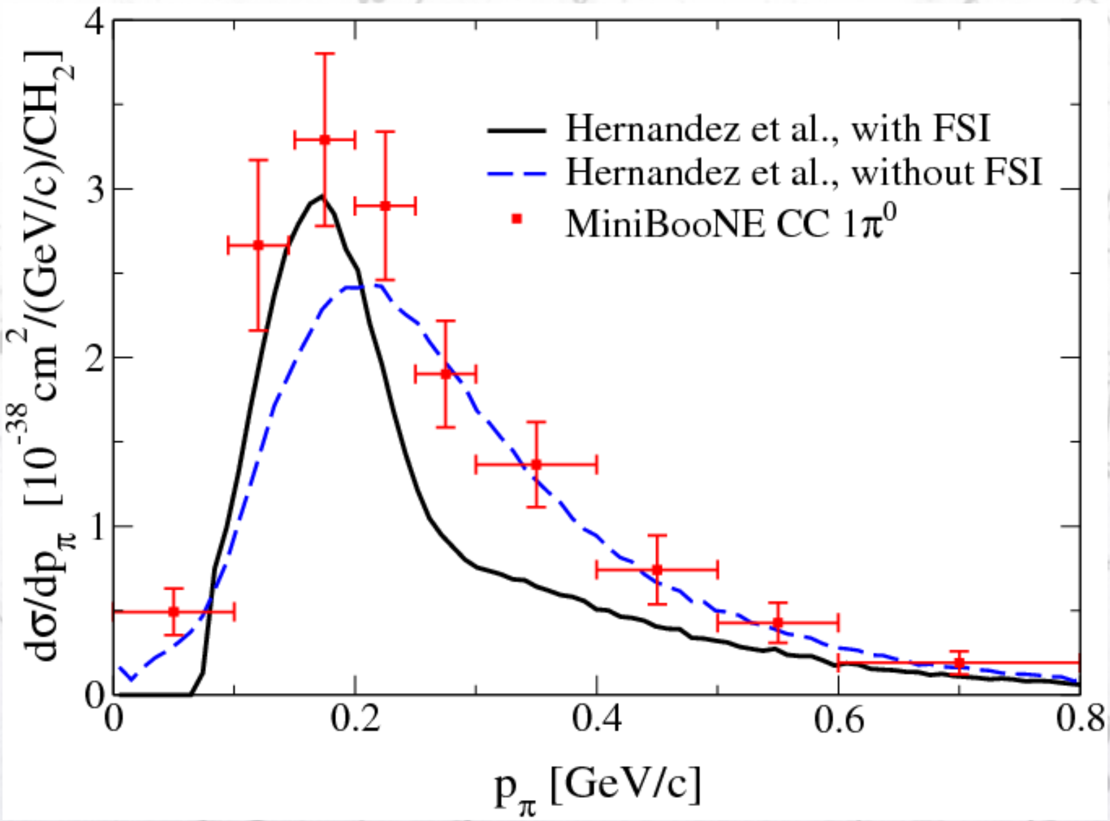


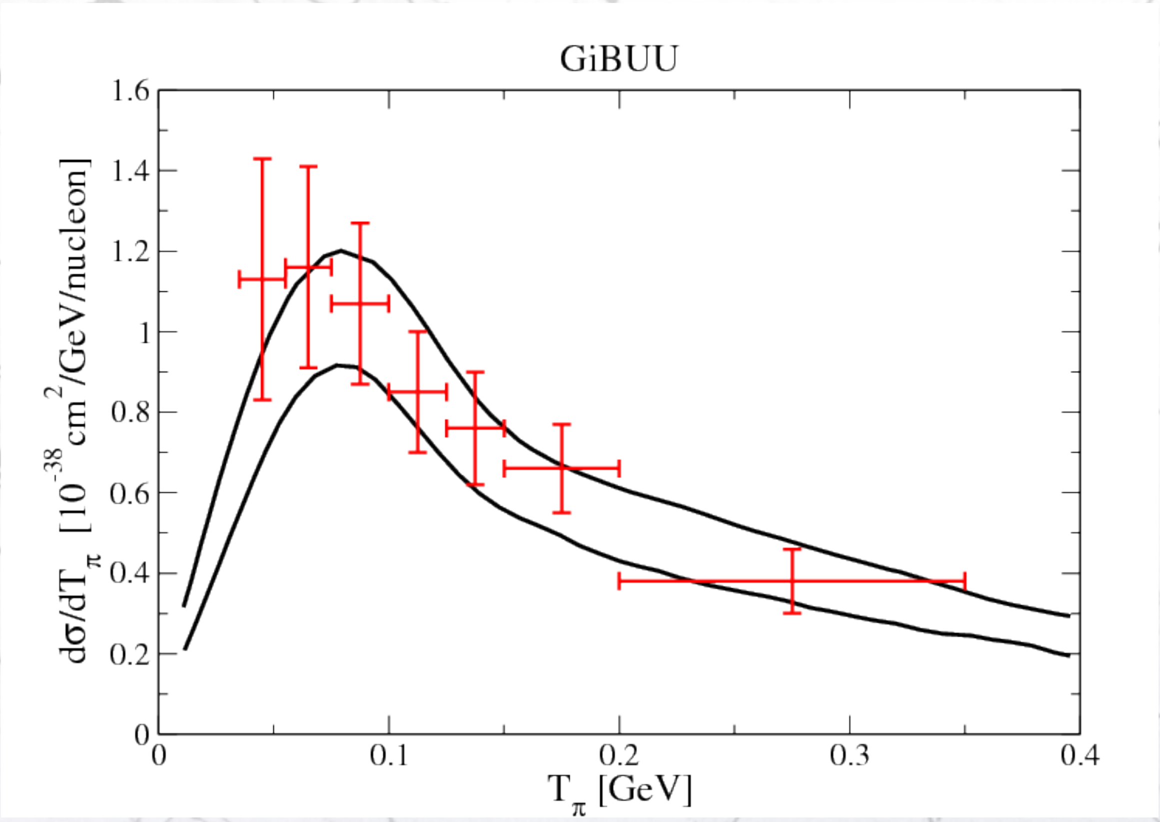




π modern data

- The nucleus distorts severely the distributions.
- Experiments normally define "topological" signal based on the particles emitted by the nucleus and not at the nucleon level.

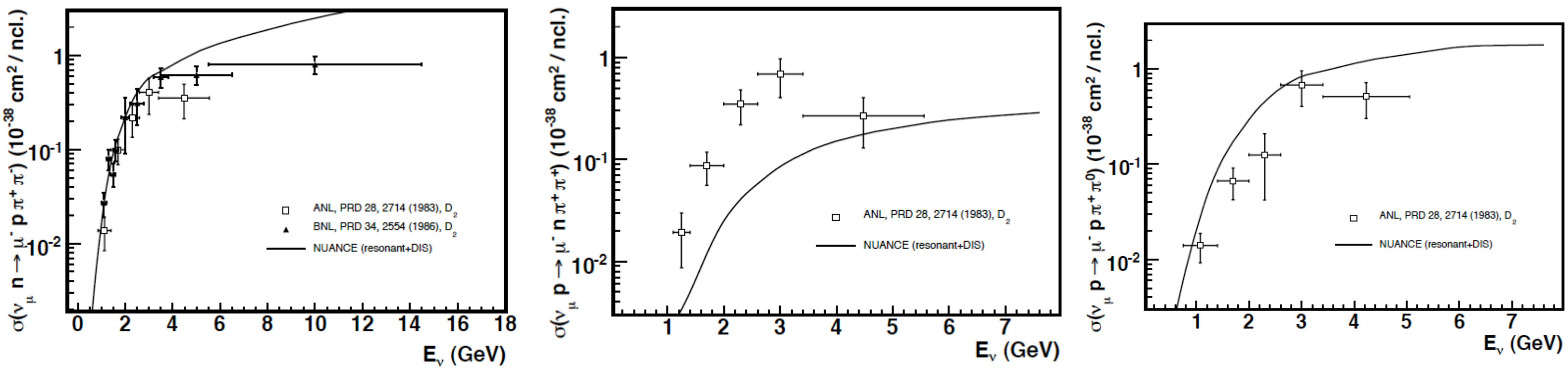




- Experimental errors or faulty models ?

Nπ to DIS

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



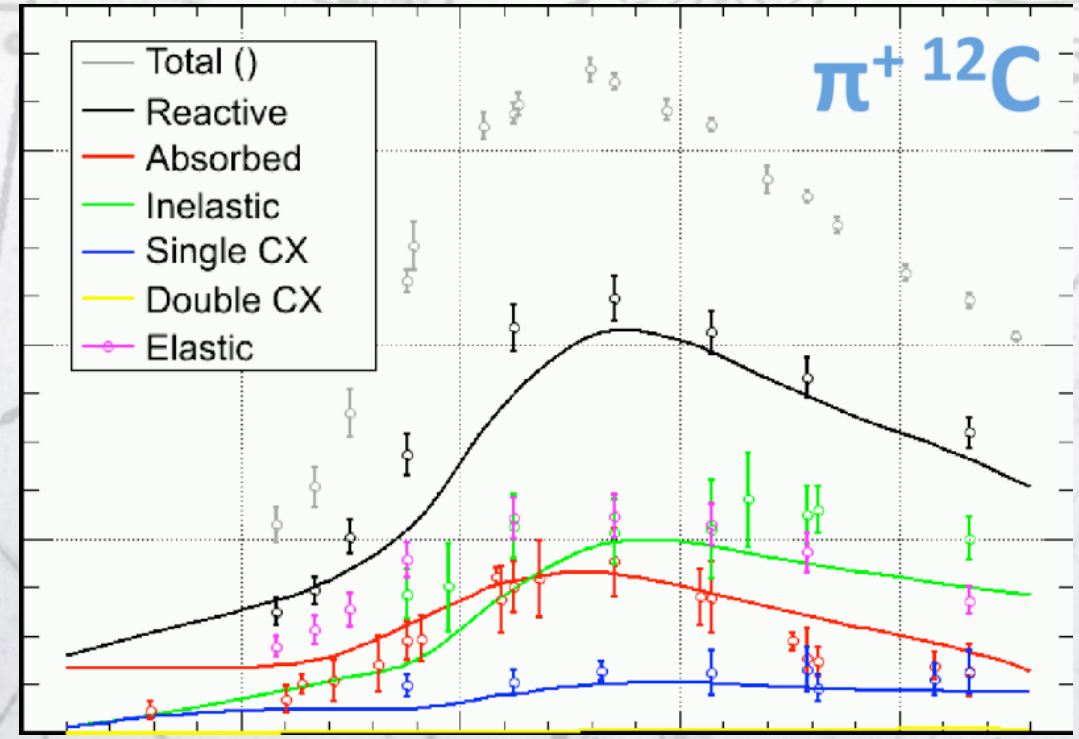
- Complex region with contributions from high mass Δ resonances and low ω DIS. Mixture of models from Pythia to add-hoc pion production.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for Dune!.

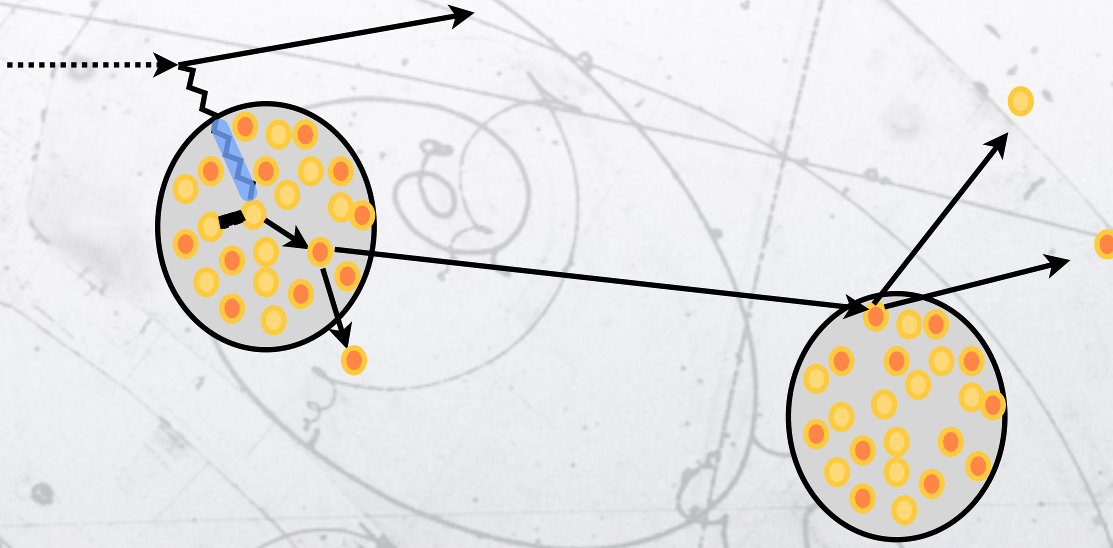
No data for NC potential background

Secondary interactions

- Interactions outside ther nucleus are also critical:
  - Hadronic particles leaving the nucleus are affected by hadronic interactions similar to the FSI.
  - Those cross-sections are not well known for low energy (< GeV) pions and nucleons.
  - Data is even more sparse in Argon.

➜ Test beams like the ones at the CERN neutrino platform.





How to ?

- Near detectors perform most of the cross-section studies.
- This does not be to be ideal since many parameters are static:
  - target nuclei
  - flux
- How to address the problem ?

- New experiments ? : NuStorm, dedicated cross-section experiments…
- New detectors with low detection threshold: modern bubble chambers.
- New ideas? : electron scattering, NuPrism, …
- We are accumulating a lot of data but we struggle with THEORY !

Conclusions

- The dominant errors in the oscillation analysis depends on the knowledge of the flux and neutrino conclusions.
- ND has a broad program of physics beyond oscillation physics related to neutrino-nucleus cross-sections.
- The ND is the place to reduce these systematics to the minimum:
  - the "battle" of precision will take place at ND if mass and power is available.
- The requirements on the ND design are very stringent.
  - Proper degin of the ND is clue for the success of the DUNE program.

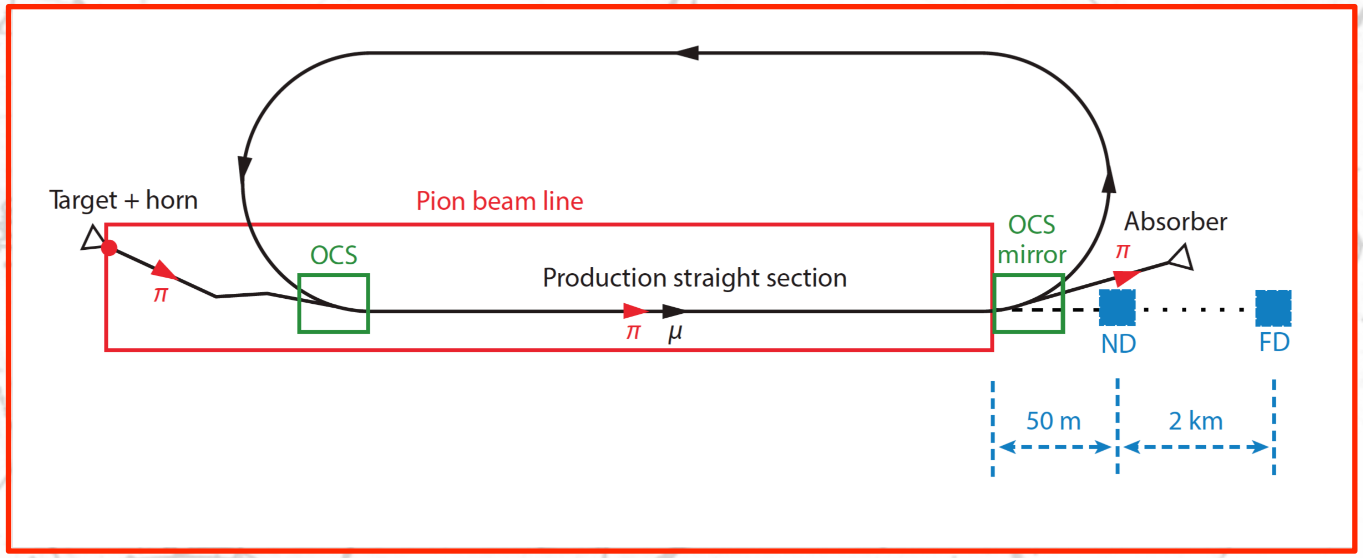
Conclusions

- The language to describe the ND to FD flux extrapolation and analyse the FD data is neutrino interactions. We need to speak it properly not be "lost in translation".

- It is likely that the ND program needs to be complemented by external experiments (electron scattering, hadroproduction,dedicated cross-sections), test-beams and giving strong support to the nuclear theory community.

- The three proposed options have pros and cons (I did not enter into the discussion) but we need to keep in mind that the right answer might be to have two detectors and not only one.

NuStorm



- A ~4GeV muon storage ring NuStorm is probably the best facility to study cross-sections.
- The number of events is sufficient with a 100 Ton LiqAr @ 50 m.

μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\overline{\nu}_\mu$ NC	1,174,710	$\overline{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\overline{\nu}_\mu$ CC	3,030,510	$\overline{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	$\overline{\nu}_\mu$ CC	6,060,580
π^+ Channel	N_{evts}	π^- Channel	N_{evts}
ν_μ NC	14,384,192	$\overline{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\overline{\nu}_\mu$ CC	19,939,704

NuStorm

- NuStorm has two main potential contributions to neutrino-nucleus scattering:
  - large ν_e fraction even below 1 GeV.
  - Precise flux prediction for precise ν_μ cross-section.
- NuStorm can provide the equivalent errors in ν_e and ν_μ cross-sections.