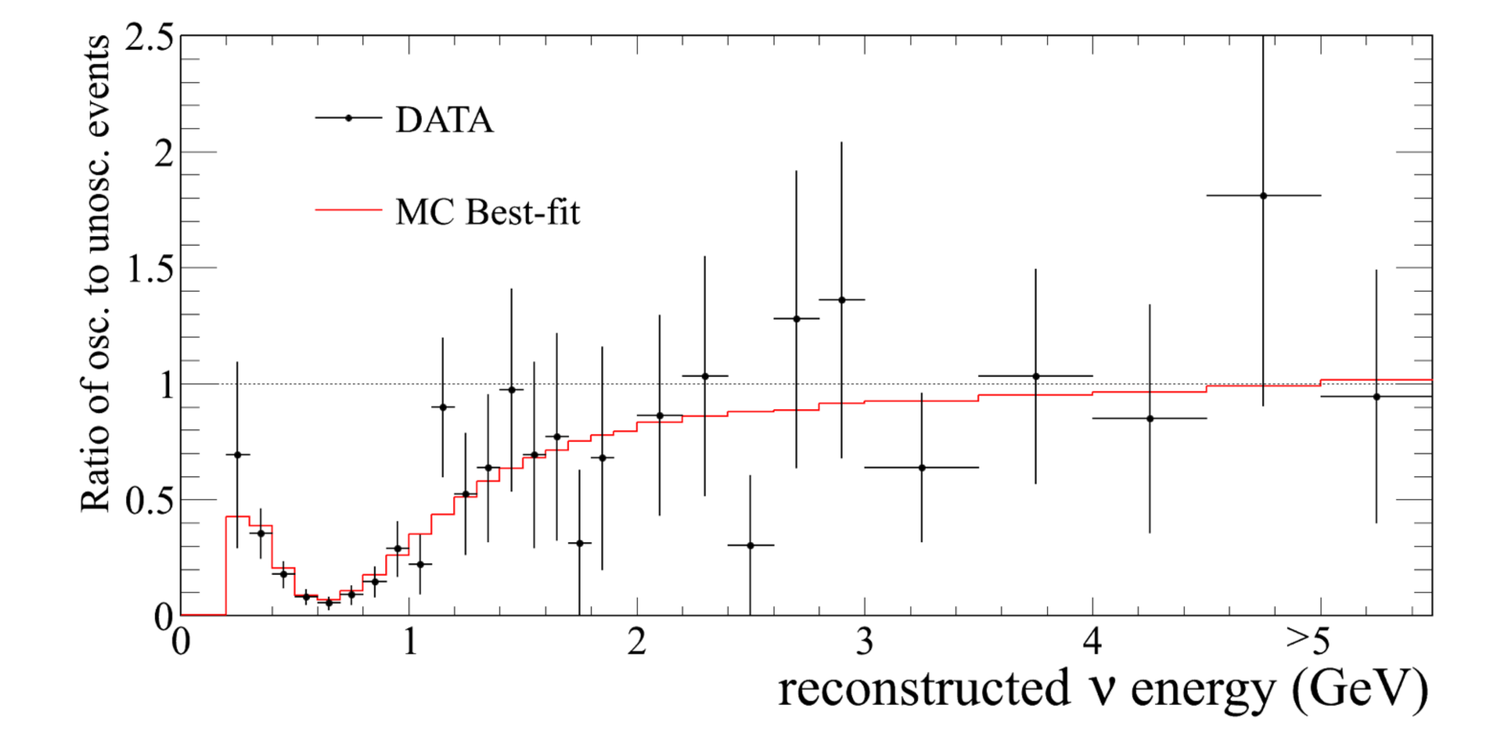
EXCELENCIA SEVERO OCHOA

HPTPC physics motivations

F.Sánchez
IFAE Barcelona

LBL concept

$P_{osc}(E_\nu)$



- The observable is the disappearance/appearance of events as function of the ν energy.
- We have to reconstruct the energy of the neutrinos!!!!!

Cross-section problem

- 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:

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

Cross-section problem

- Since the neutrino energy is not monochromatic, we need to determine event by event the energy of the neutrino.
- This estimation is not perfect, we have the problem that 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 both $\sigma(E_\nu)$ & $P(E_\nu|E'_\nu)$

Both are related to cross-sections !!!!

Cross-section problem

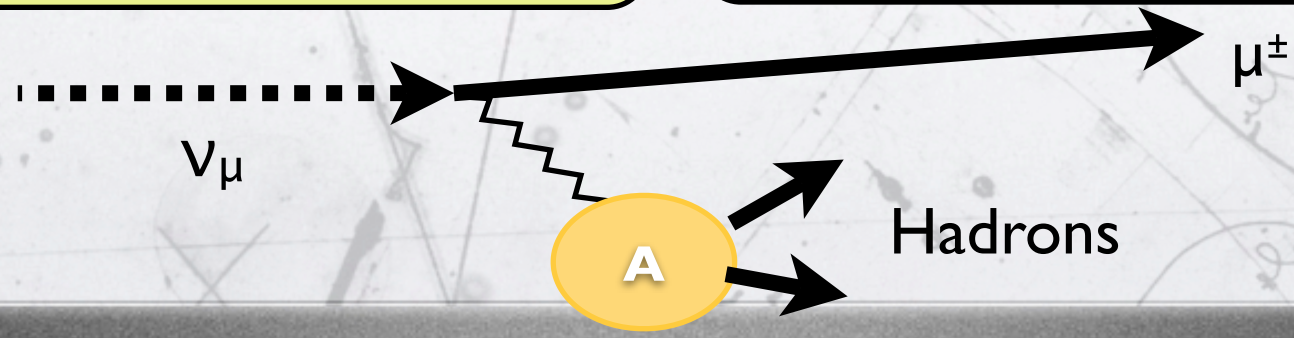
How to measure the neutrino energy ?

Low Energy ν's (≲2GeV)

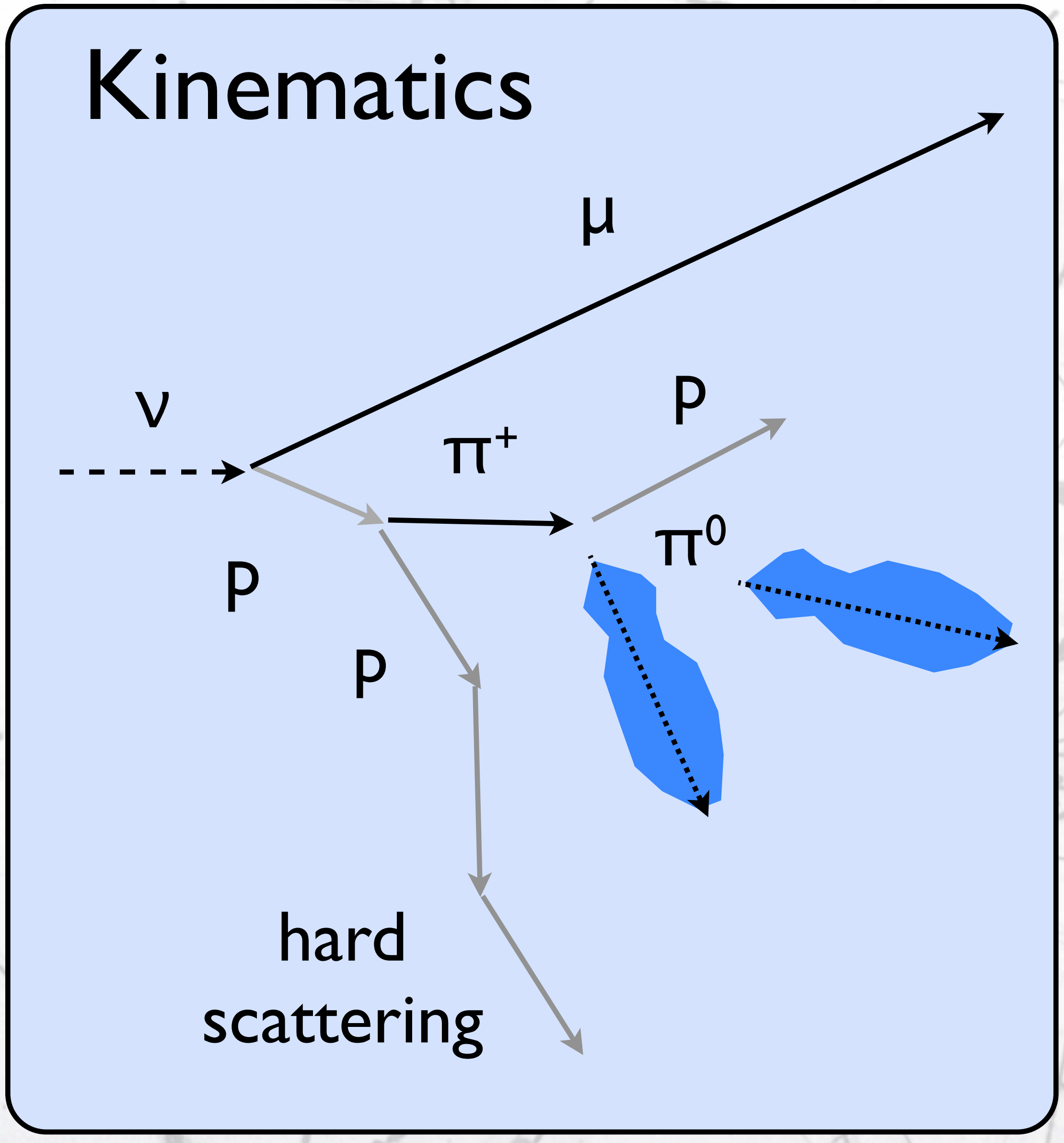
- E_ν relies on the lepton kinematics.
- channel identification is critical:
  - Final State Interactions
  - hadron kinematics.
- Fermi momentum, Pauli blocking and bound energy are relevant contributions.

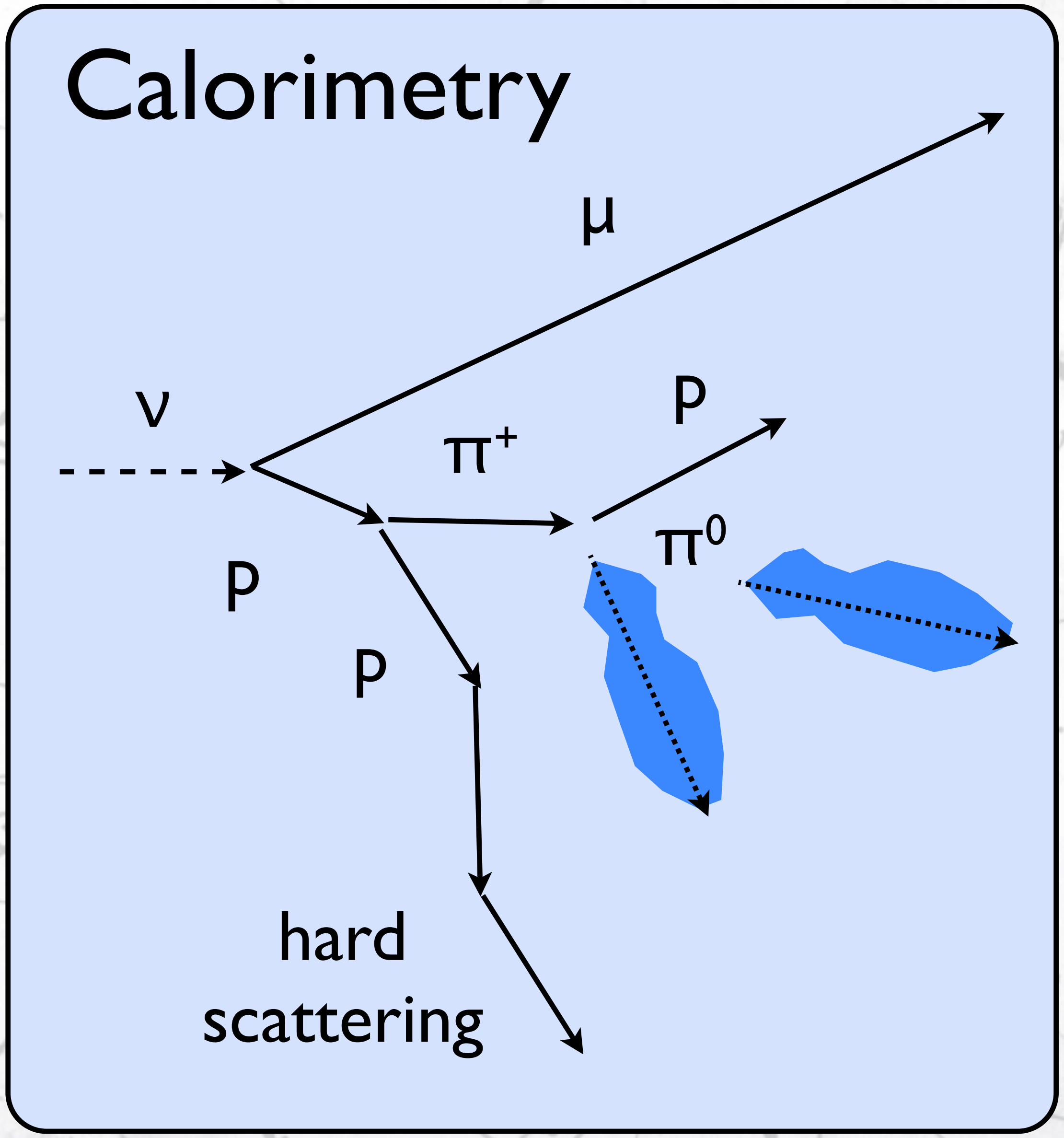
Medium-high Energy ν's (≳ 3GeV)

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



Cross-section problem

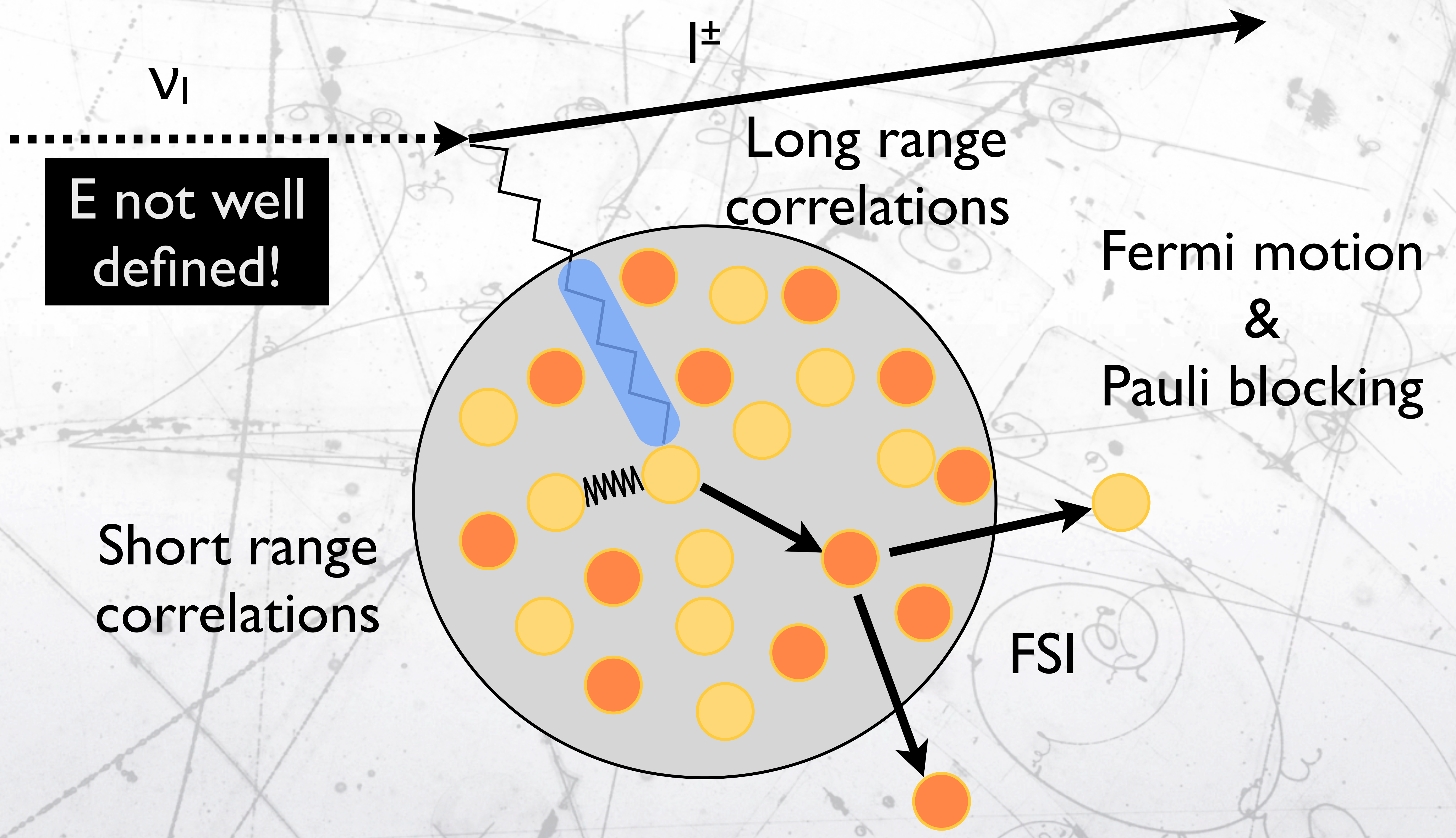




- Only a fraction of the energy is visible.
- Rely on channel interaction id.

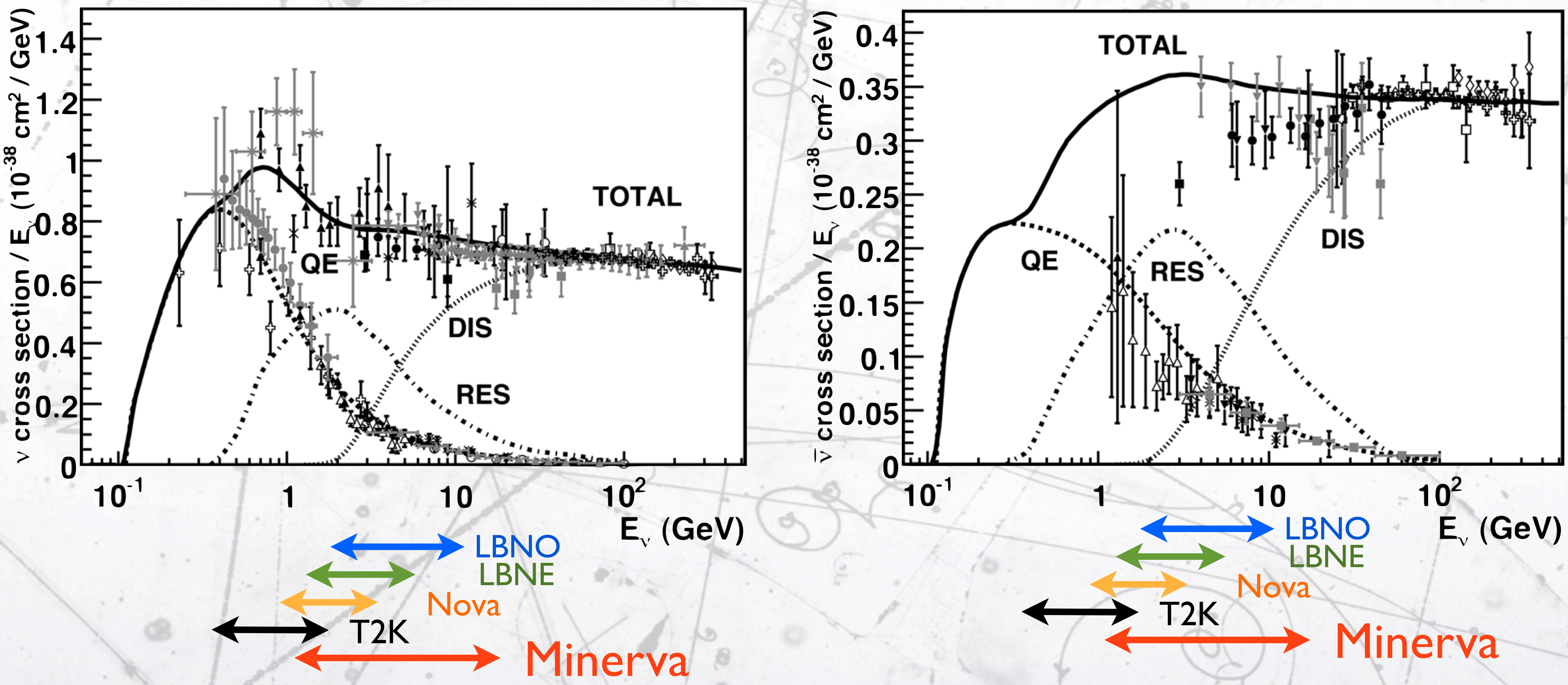
- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

The problem


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

The problem

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

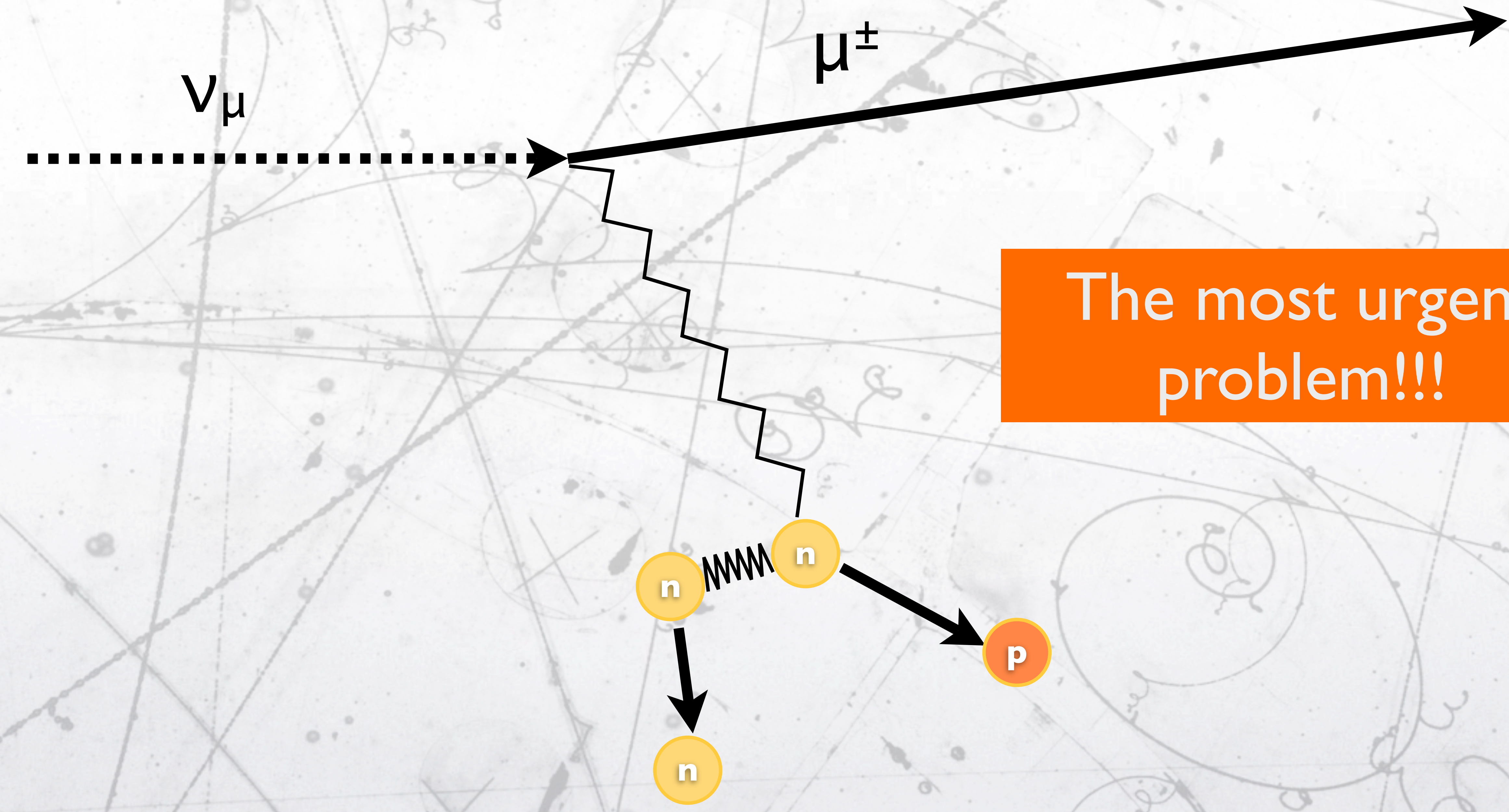


- Present and future oscillation experiments cover a region full of reaction thresholds and sparse data.

The shopping list

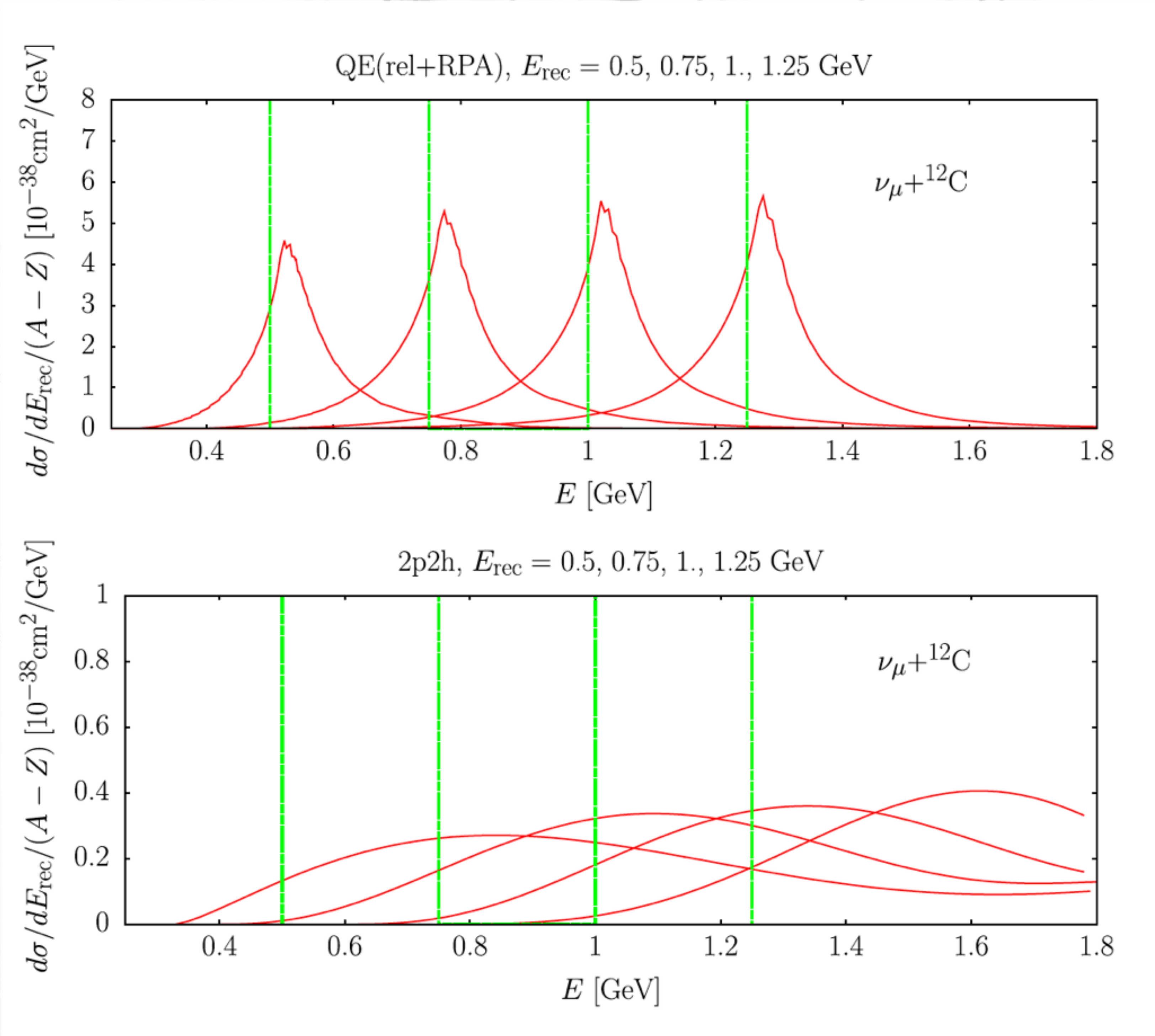
- Future CP violation measurements with Long Base Line neutrino beams require "ideally" the measurement of ν_μ, anti-ν_μ, ν_e and anti-ν_e
  - between ~500 MeV and ~10 GeV,
  - for (at least!) 4 nuclei: C, O, Fe and Ar. (Not all isoscalars!)
  - for ~10 exclusive channels:
    - QE, $1\pi^{0\pm}$, $N\pi^{0\pm}$, DIS both CC and NC.
  - Require a precise determination of the energy of the neutrino for the dominant(s) channel(s) at each energy.

CCQE + 2p2h



The most urgent problem!!!

2p2h and E_ν



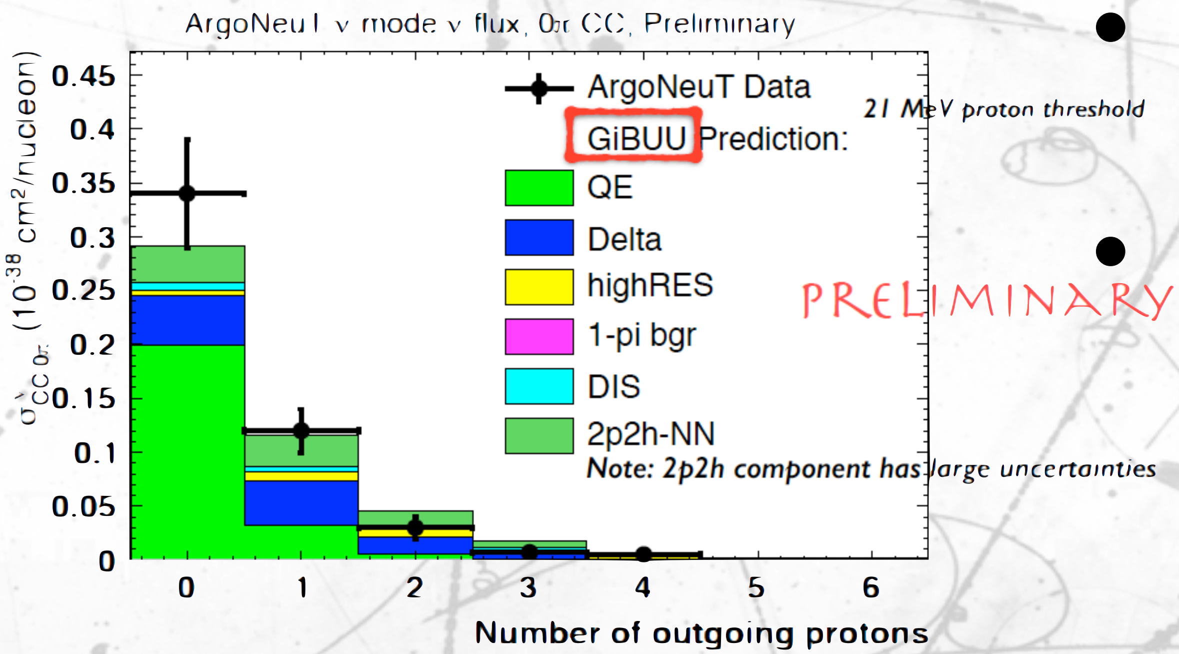
PHYSICAL REVIEW D **85,** 113008 (2012)

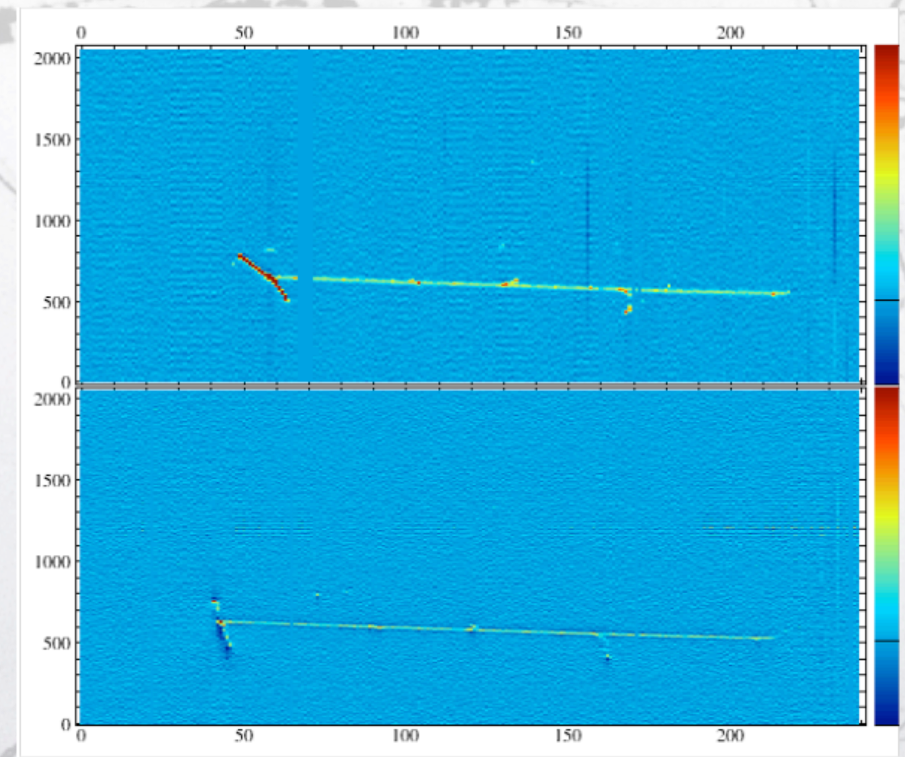
Effect of multi-nucleon (2p2h) interactions in the neutrino energy reconstruction.

- Recon values (E_ν)
- $P(E_\nu|E'_\nu)$

The problem is that the E_ν is wrongly reconstructed.

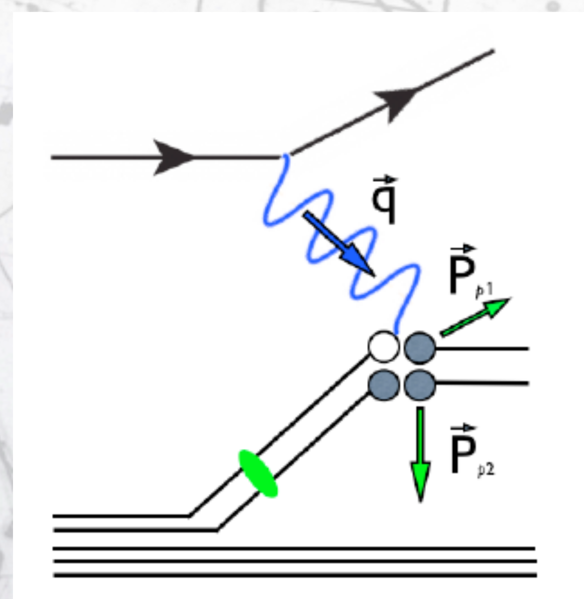
Search for 2 proton

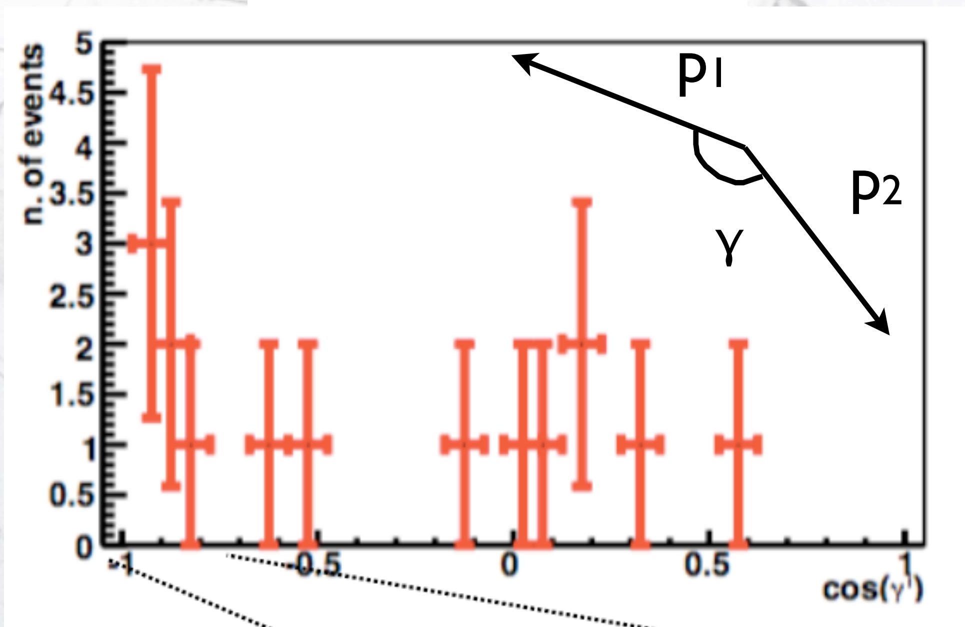




- LiqAr ArgoNeut (FNAL) has bubble chamber imaging capabilities to look into final states.
- It has first indications of correlated final state protons.
  - Spectral functions ? (~Initial state correlations)
  - 2p2h ? (~Final state correlations)
  - Both ?

Low statistics!

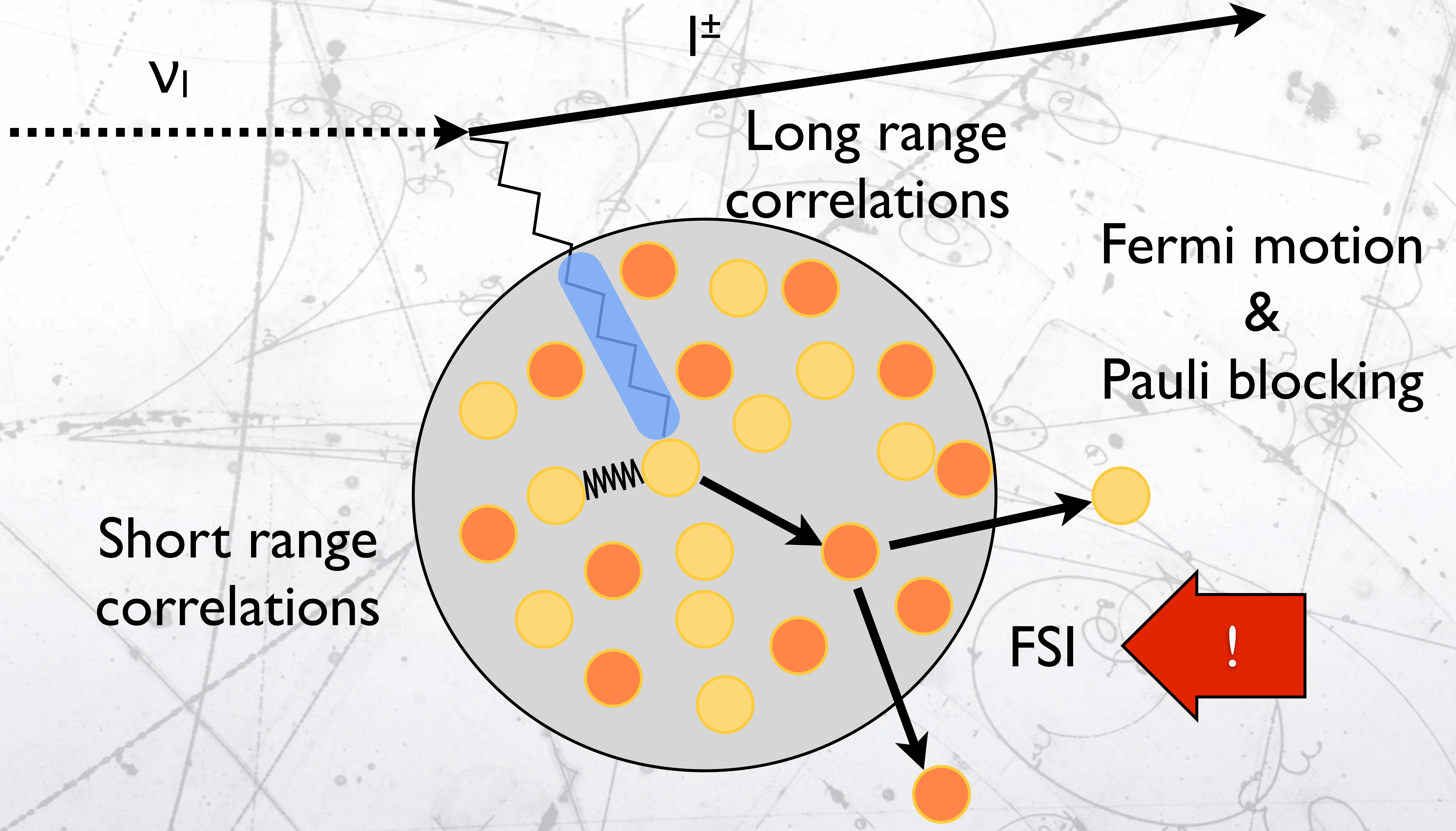




Effect of RPA

- RPA model is based on pion capture by nuclei and NN interactions (both at very low q^2). No process to tune it at higher values of q^2 except electron/neutrino scattering.
- RPA changes the acceptance of the events, reduces the cross-section in forward direction (low q^2) and increases in backward (high q^2).
  - Systematics!
- RPA calls for full acceptance near and far detectors (4π coverage).

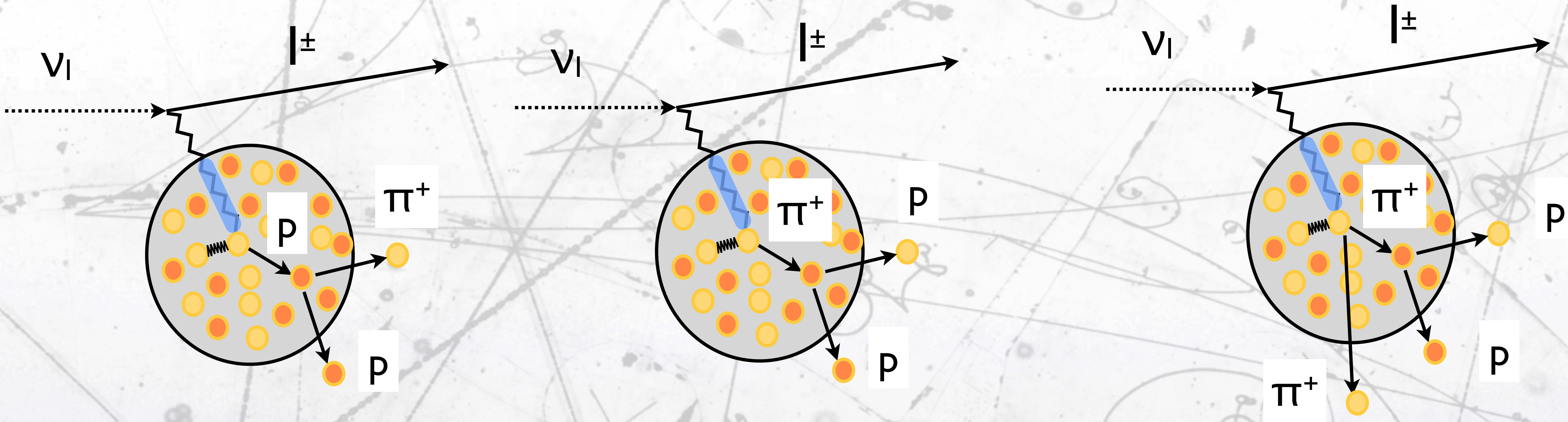
Final state interactions



Problem factorisation

- Example: events with $\mu^-+\pi^+$ in the final state.
- Topology is altered by FSI.

FSI alters the definition of the event



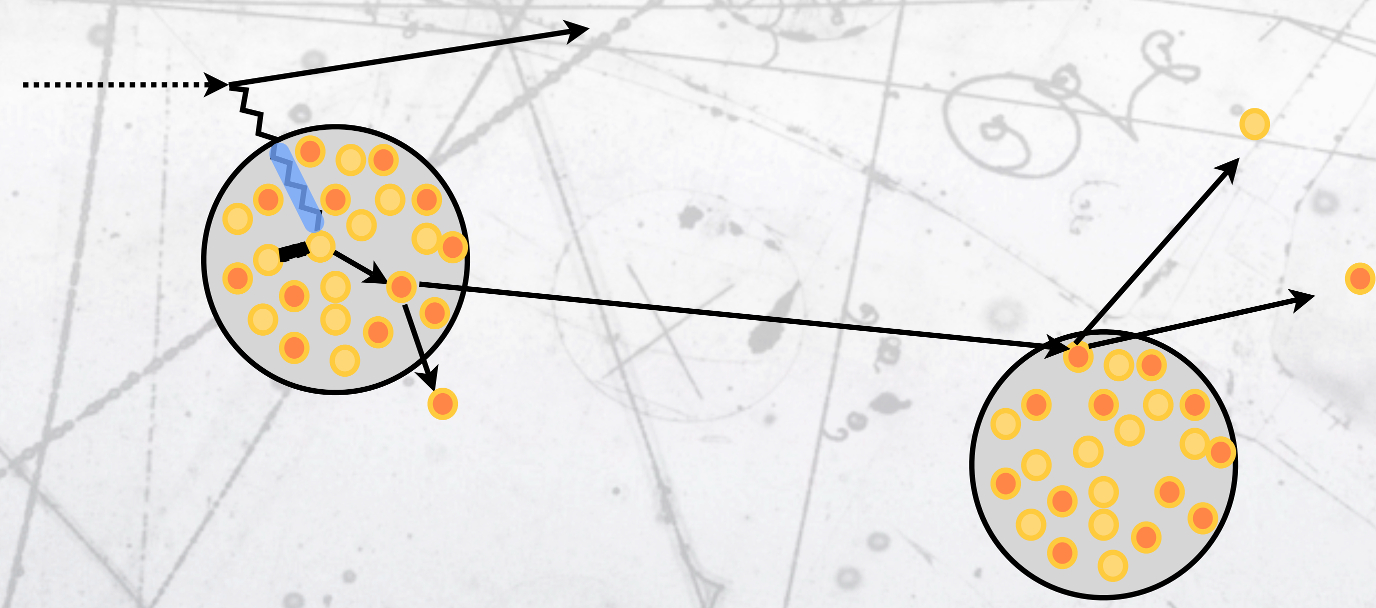
1. CCQE
2. proton in final state
3. p p -> p π^+

1. CC1 π^+
2. π^+ in final state
3. π^+ p -> p p

1. CC 2π^+
2. 2π^+ in final state
3. π^+ p -> p p

More on FSI...

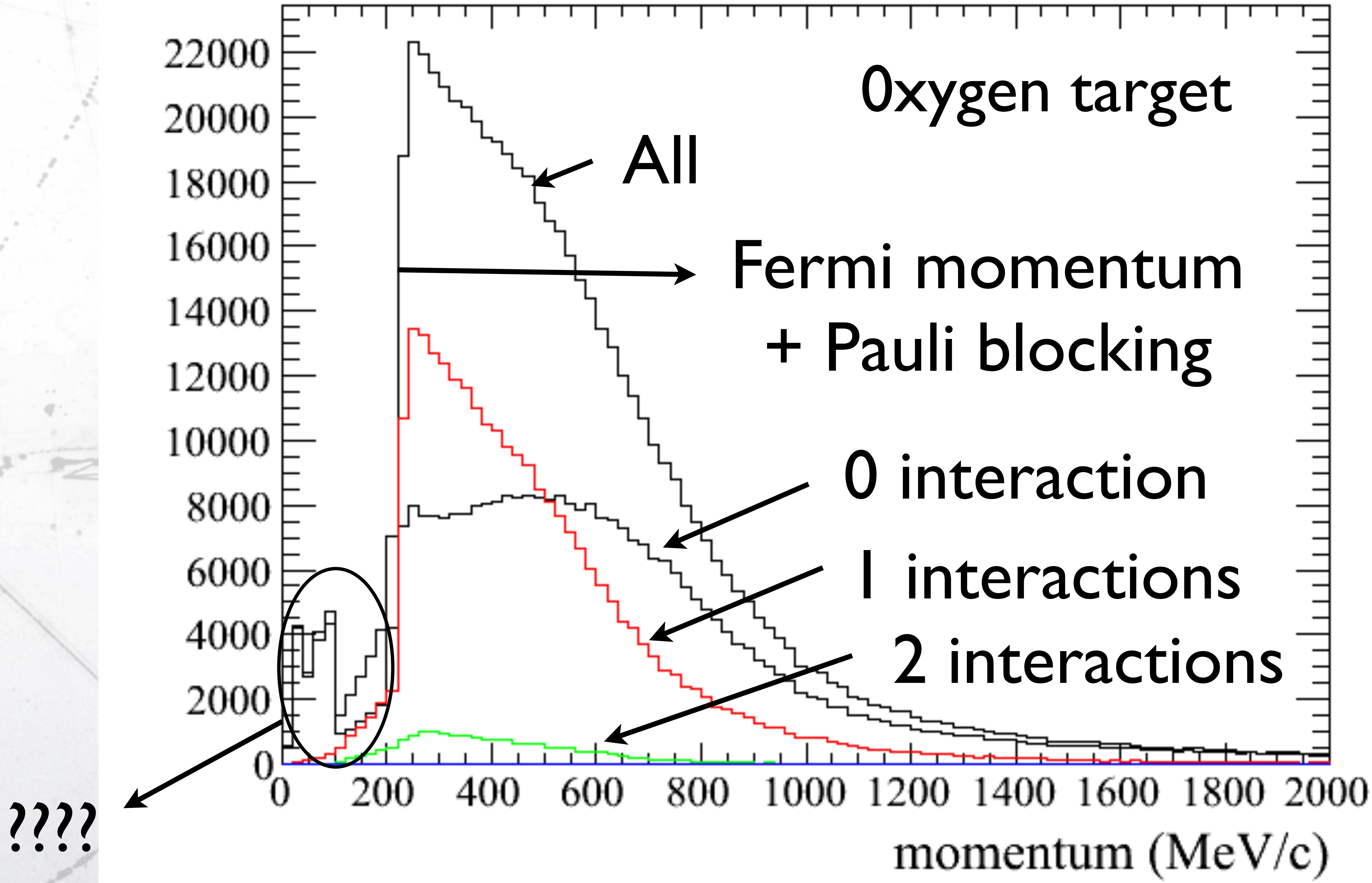
- Hadrons outside the nucleus will keep interacting altering the event topology.
- This is already part of the measurement program of WA105 but we need to measure exclusive channels and not only calorimetry.



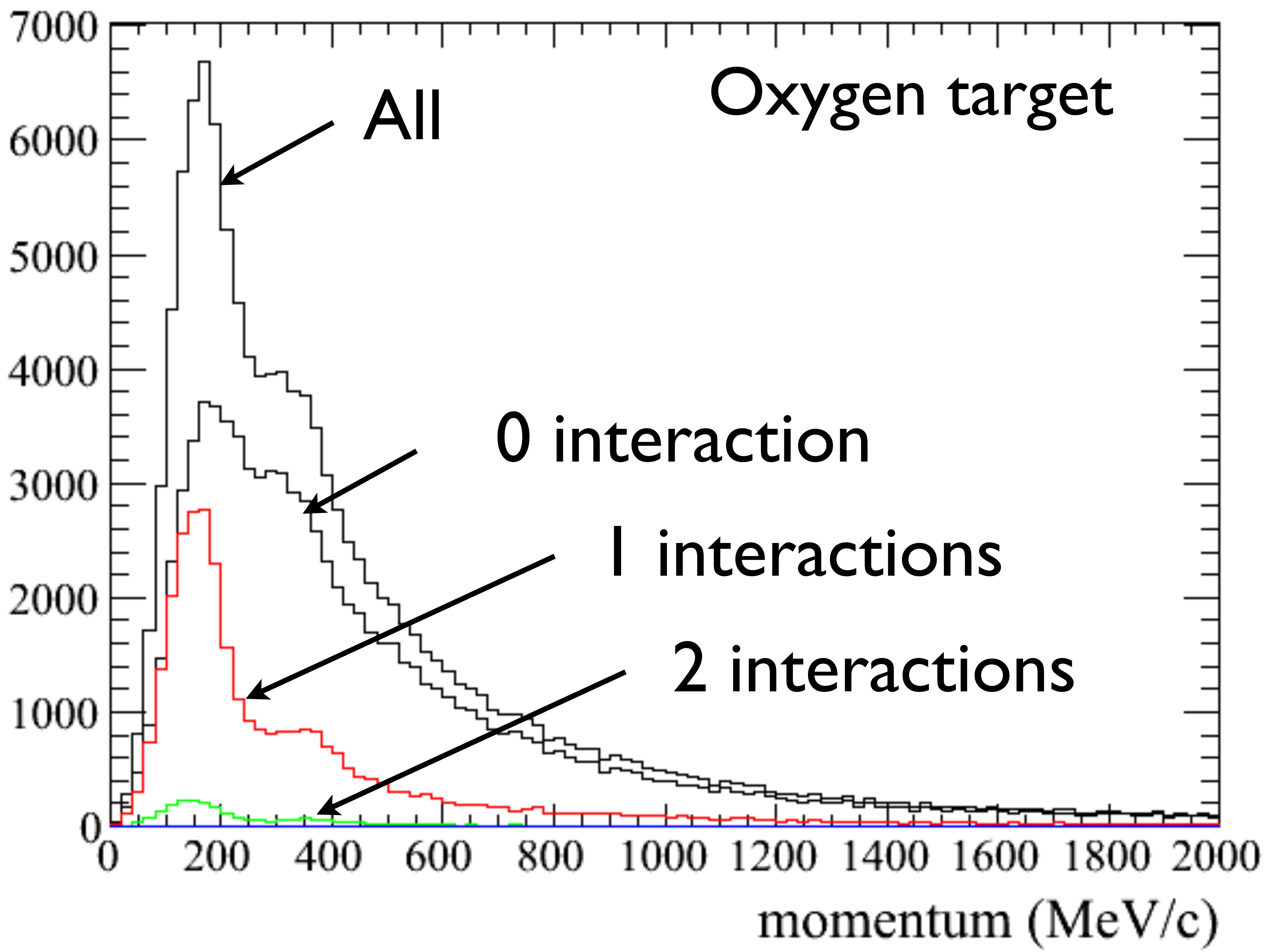
This is already a dominant systematic @T2K

Specific experiment (DUET) is being run to reduce it.

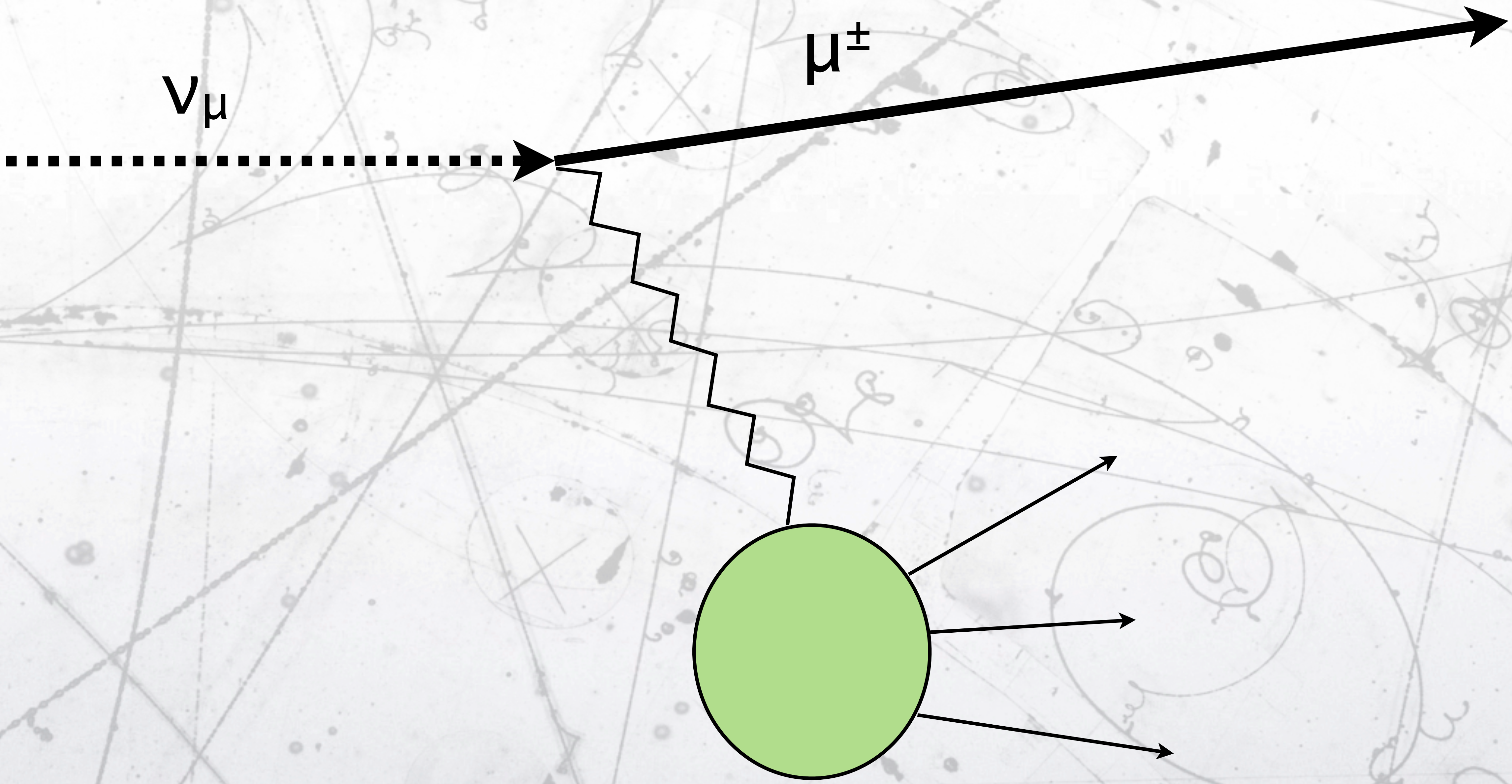
Proton momentum



Pion momentum



Monochromatic beam ?



Monochromatic beam

- Many of the problems in neutrino cross-section and neutrino oscillations comes from the reconstruction of the energy.
- Imaging you know precisely the response function of a detector:

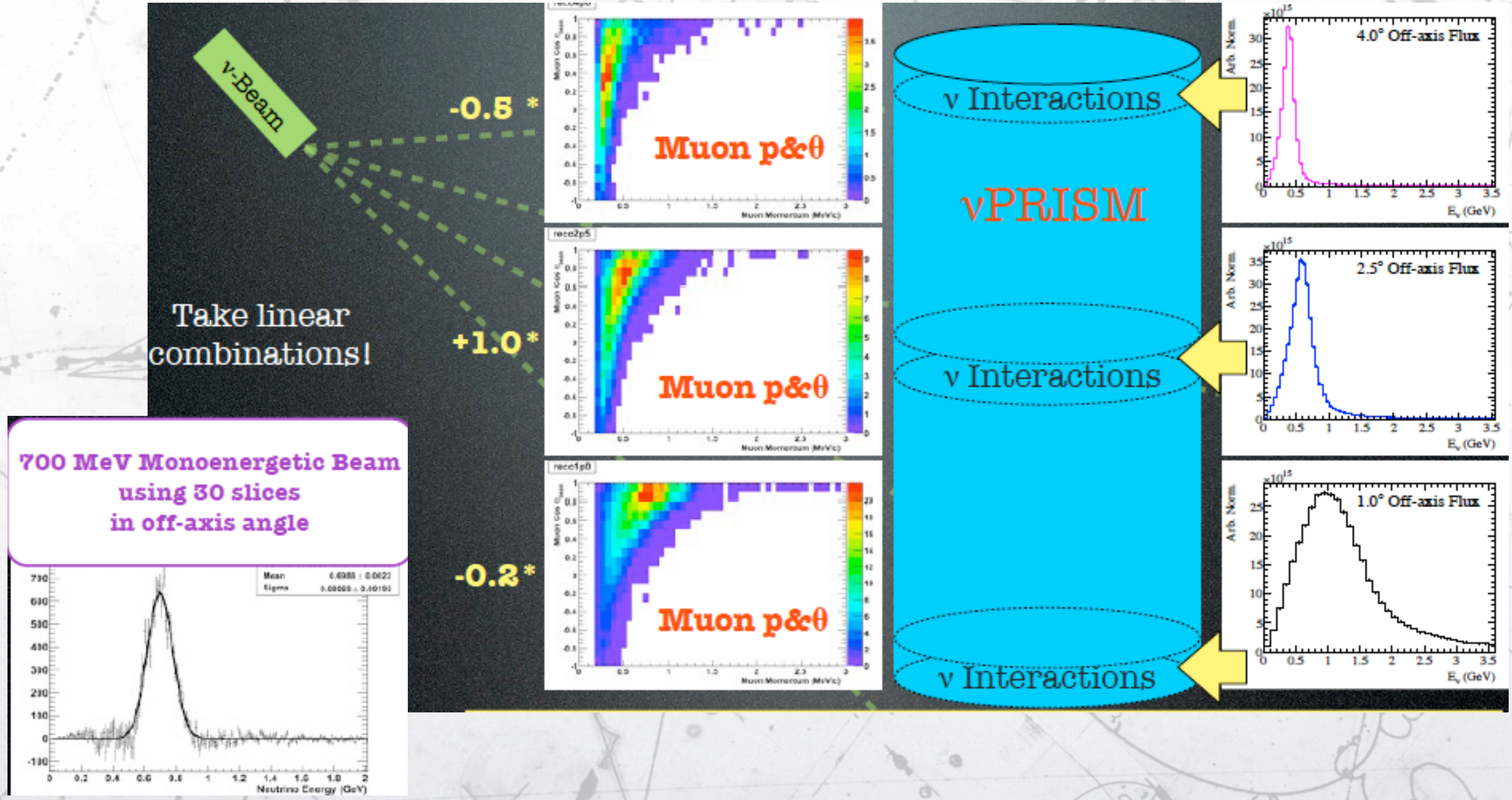
$$P(p_\mu, \theta_\mu | E_\nu)$$

- The oscillation result of the oscillation would be:

$$\int P(p_\mu, \theta_\mu | E_\nu) \times P_{osc}(E_\nu) \times \phi(E_\nu) dE_\nu$$

- and the cross-section problem is reduced/vanished.

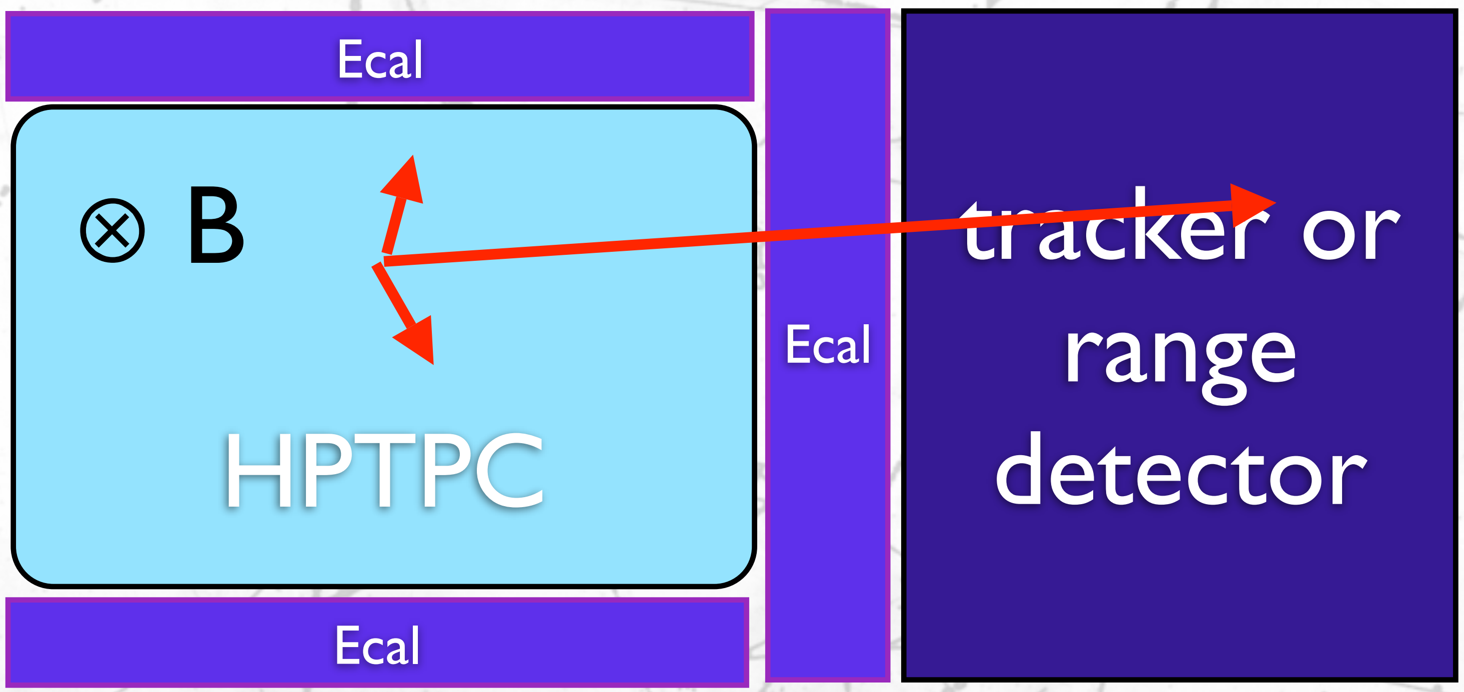
NuPrism


ν-Beam
-0.5 *
+1.0*
-0.2*
Take linear combinations!
Muon p&θ
Muon p&θ
Muon p&θ
ν Interactions
νPRISM
ν Interactions
ν Interactions
4.0° Off-axis Flux
2.5° Off-axis Flux
1.0° Off-axis Flux
Arb. Norm.
E_ν (GeV)
700 MeV Monoenergetic Beam
using 30 slices
in off-axis angle
Neutrino Energy (GeV)

Ideal xsect experiment

- Design of a perfect neutrino cross-section detector:
  - 4π coverage
  - very low energy hadrons and mesons thresholds and excellent PID for muon/proton/electron separation.
  - Charge separation to separate neutrinos from antineutrinos. (B field)
  - Variable target A including hydrogen.
  - Reduced external background (reduced mass around active target)
  - Excellent control of beam systematics and variable beam spectra.
- In addition:
  - Improved theory to be able to extract the information from data.
  - Electron scattering hadron production.

HPTPC experiment

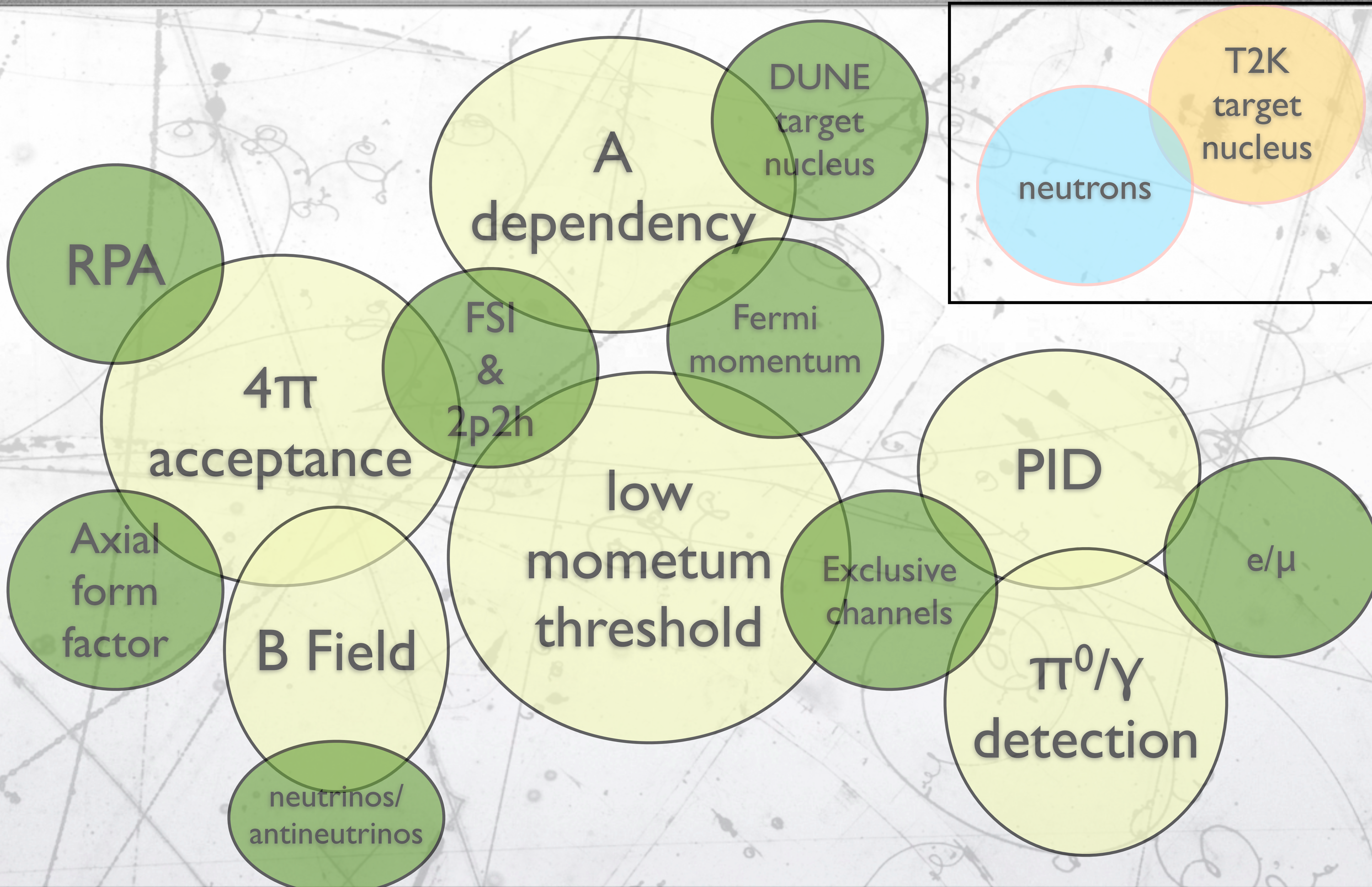


A moving detector ("a la NuPrism") or tuneable beam will help to reduce systematics.

A dream (?): a HPTPC filled with hydrogen and deuterium.

- TPC imaging capabilities.
- Interactions in the same gas (no passive material).
- Low momentum detected inside the TPC. Large momentum done with tracker chambers or range detector.
- High pressure (~10 bars) to increase particle containment and # interactions.
- It requires additional calorimeter for neutral energy containment.

HPTPC



A dependency
DUNE target nucleus
T2K target nucleus
neutrons
RPA
4π acceptance
FSI & 2p2h
Fermi momentum
low mometum threshold
PID
e/μ
Axial form factor
B Field
Exclusive channels
π0/γ detection
neutrinos/ antineutrinos