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Electron scattering for the T2K experiment (e4T2K): a personal view

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Same discussion applies to Hyper-Kamiokande

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Motivation

Neutrino Energy reconstruction

Channel ID
Hadron production
neutrino vs antineutrinos detector response

$\sigma(\nu_e)/\sigma(\nu_\mu)$

ν oscillations

neutrino vs antineutrino

identification

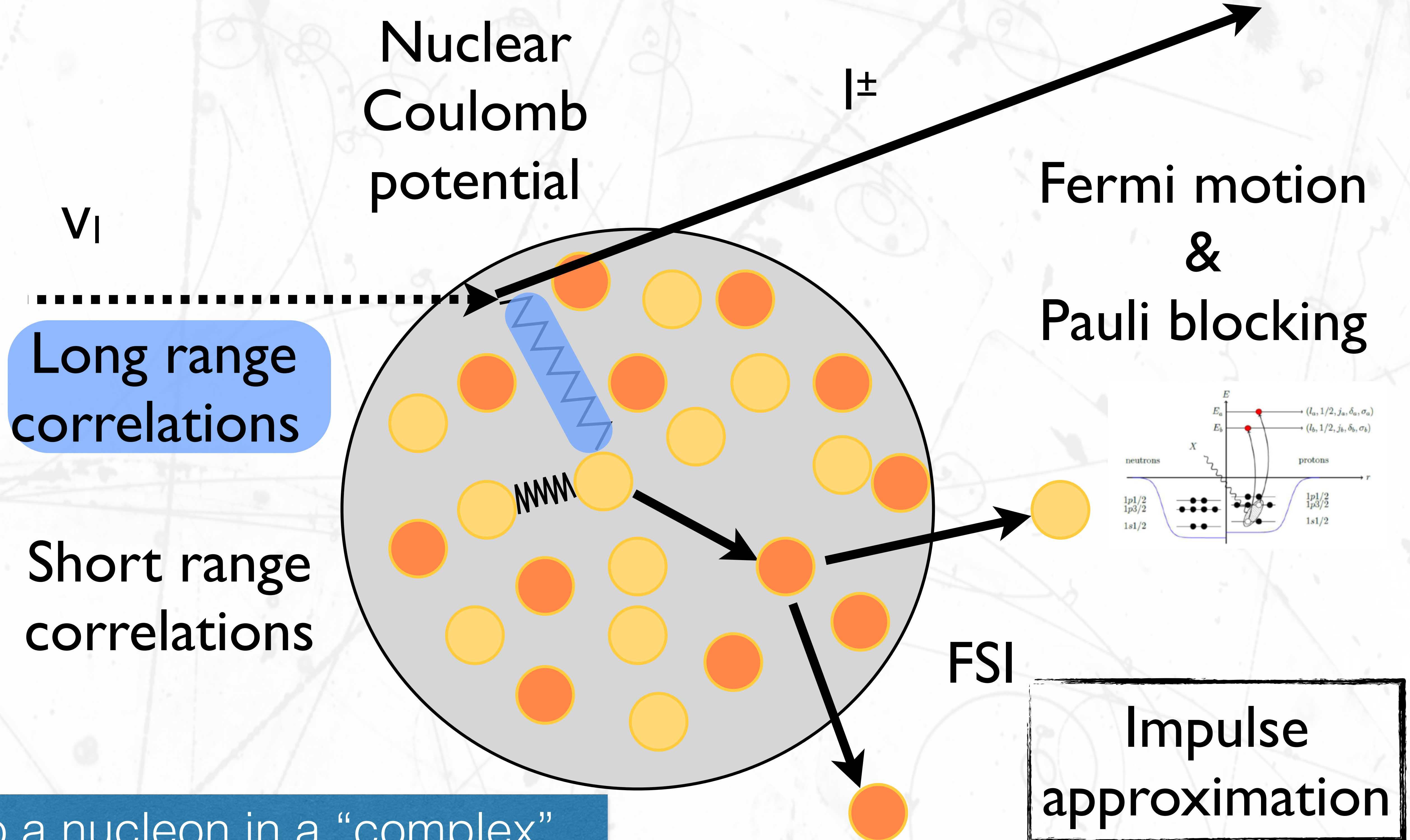
Acceptance corrections
Near vs Far sites

Backgrounds

$NC\pi^{\pm 0}$

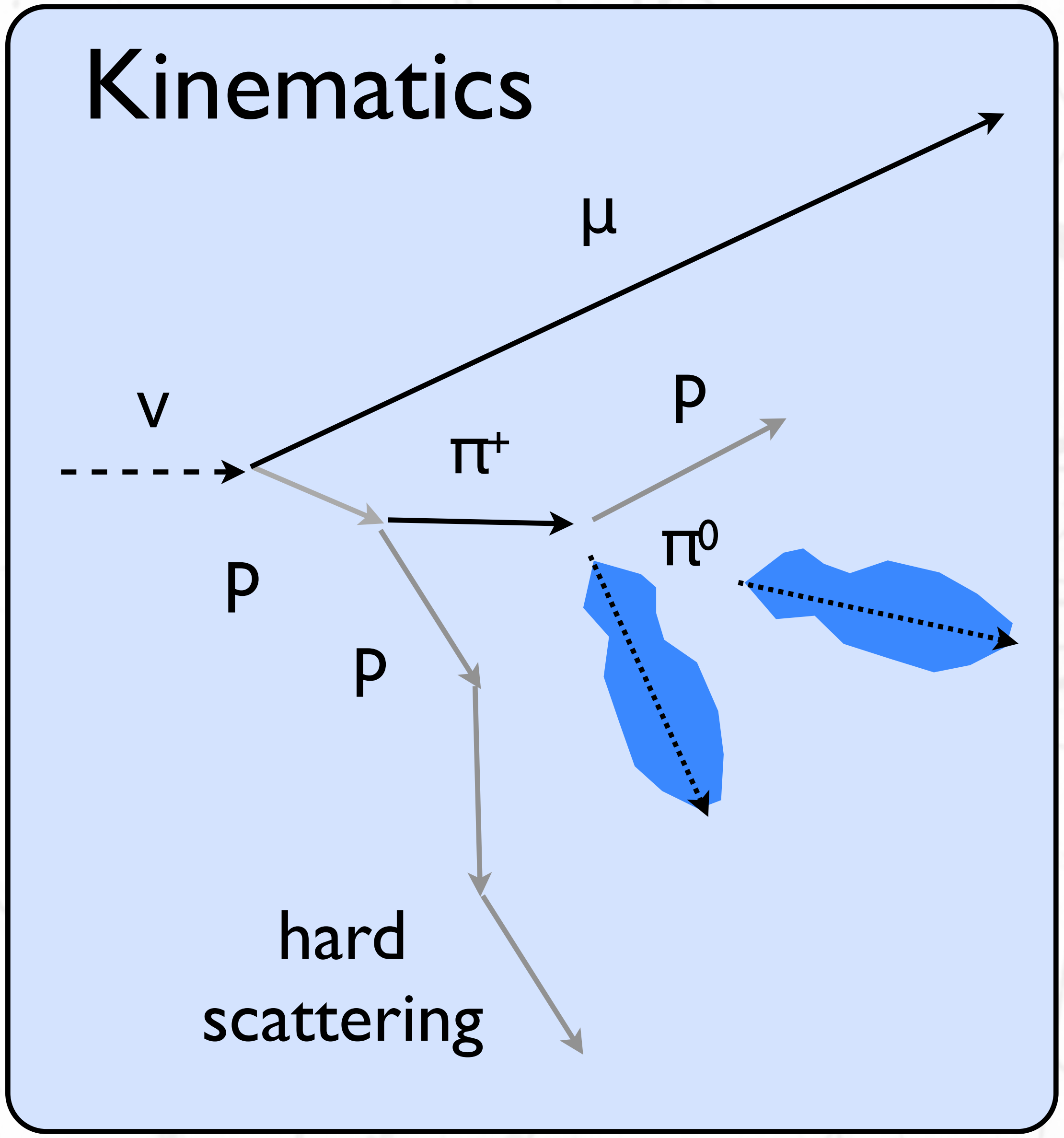
ν cross-sections is the “language” that allows to measure and transport the measurements across detectors and experiments. But, it is imprecise!

Neutrino interactions



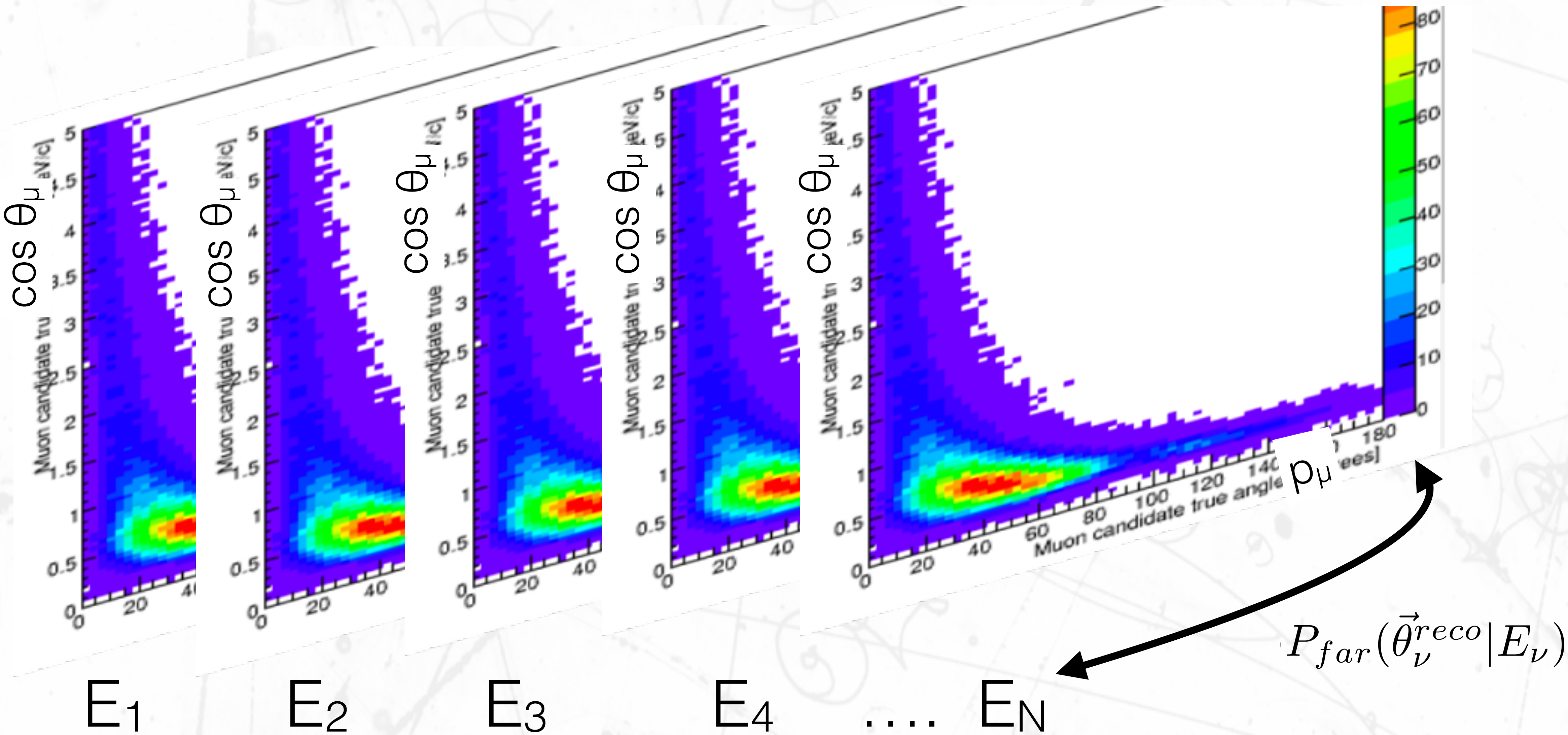
to a nucleon in a “complex” potential well with “toppings”

Energy reconstruction at T2K



- Only a fraction of the energy is visible:
  - The energy reconstruction is obtained guessing the reaction channel:
    - CCQE in the interesting region for T2K.
- Rely on channel interaction id:
  - mainly pion appearance (topologies).
- Rely on the proper modelling of the interactions.

Kinematical approach



$$\frac{N_{evts}^{far}(\vec{\theta}_{\nu}^{reco})}{N_{evts}^{near}(\vec{\theta}_{\nu}^{reco})} = \frac{\int \sigma(E_{\nu})\phi^{far}(E_{\nu})P_{far}(\vec{\theta}_{\nu}^{reco}|E_{\nu})P_{osc}(E_{\nu})dE_{\nu} + Back_{far}(\vec{\theta}^{reco})}{\int \sigma(E_{\nu})\phi^{near}(E_{\nu})P_{near}(\vec{\theta}_{\nu}^{reco}|E_{\nu})dE_{\nu} + Back_{near}(\vec{\theta}^{reco})}$$

In the kinematical case $P_{far}(\vec{\theta}_{\nu}^{reco}|E_{\nu})$ is given by models tuned by experiments.

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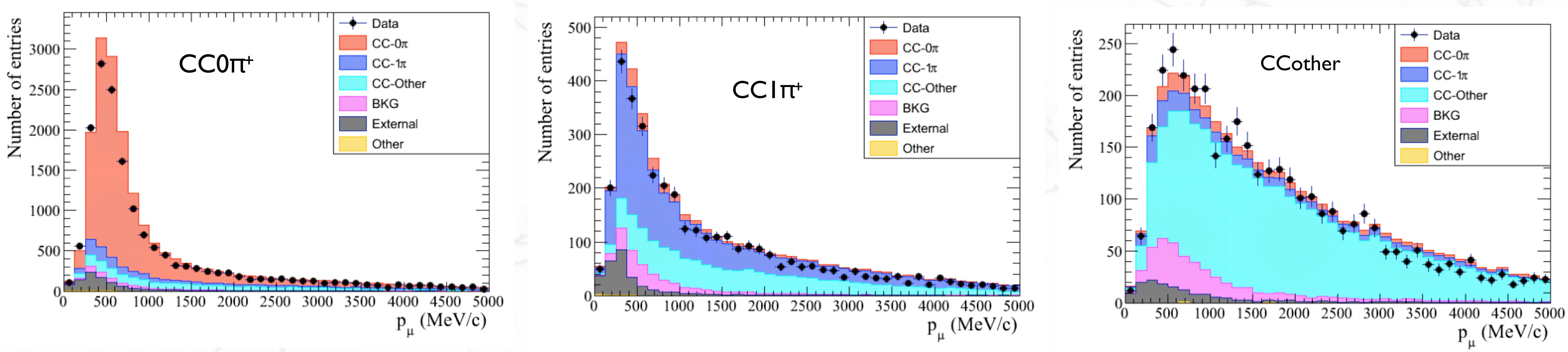
Event topologies



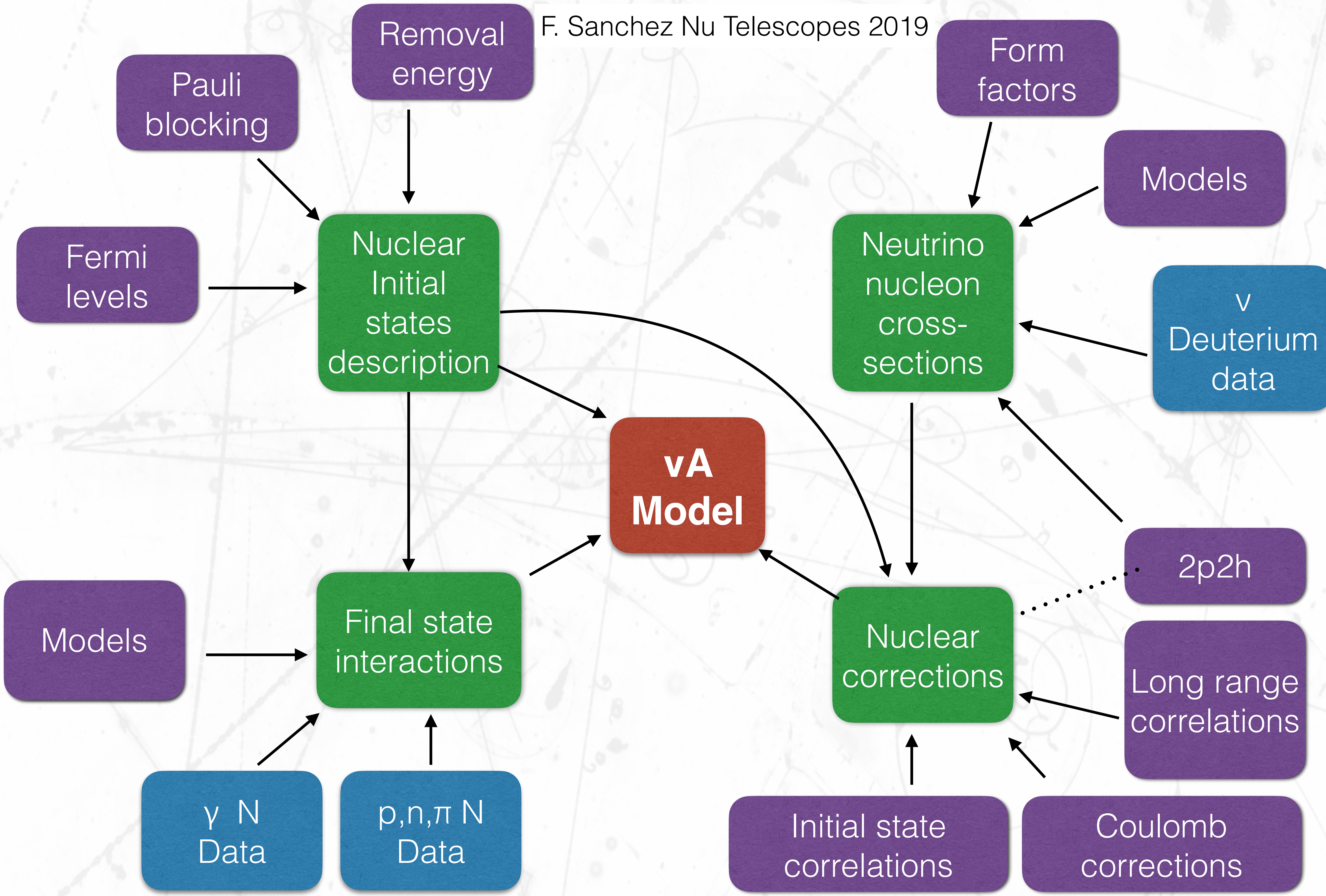
Topologies are used in T2K to identify interactions at the nucleon level for kinematic energy reconstruction.

- Minerva and T2K adopted the idea of the event topologies based on the presence of pions (easy to detect) and or protons in the final state.

This is an excellent way to unify data releases to allow for comparisons.
Do experiments mean the same when talk about CC0π?

Model ingredients

F. Sanchez Nu Telescopes 2019



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T2K approach

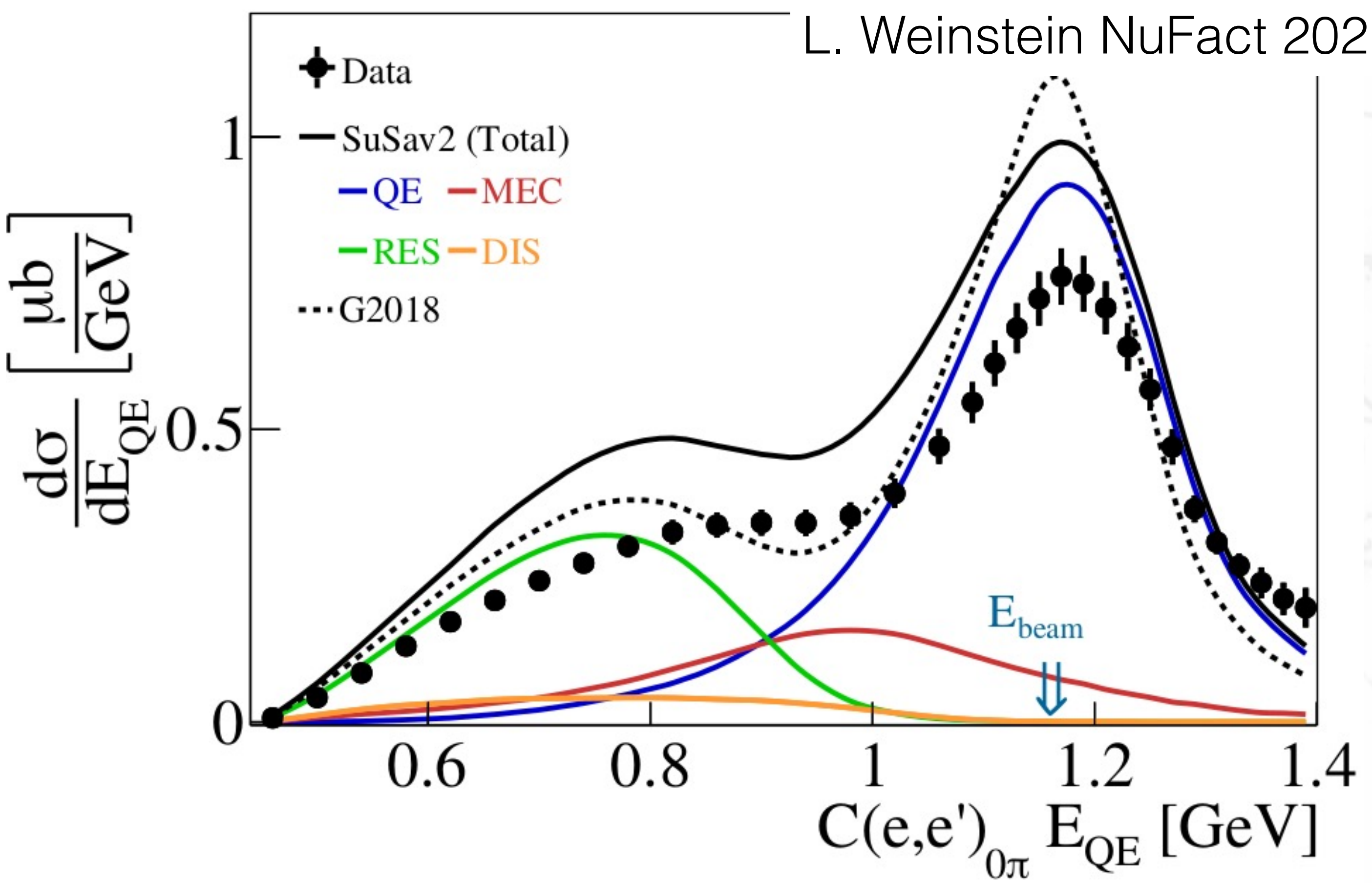
- T2K has a dedicated group "Neutrino Interaction Working group" (NIWG) in charge of:
  - evaluating models to incorporate to the T2K physics analysis.
  - Supervise and evolve the T2K (and SK) neutrino Monte-Carlo: NEUT.
  - define set of uncertainties, based on physics principles as much as possible, to be adjusted to the near detector data for the neutrino oscillation program.
  - Support data analysis on the definition of observables and its relevance.
- This group runs with the support of theorists and a group of experimenters with interest in modelling and Monte Carlo generation.

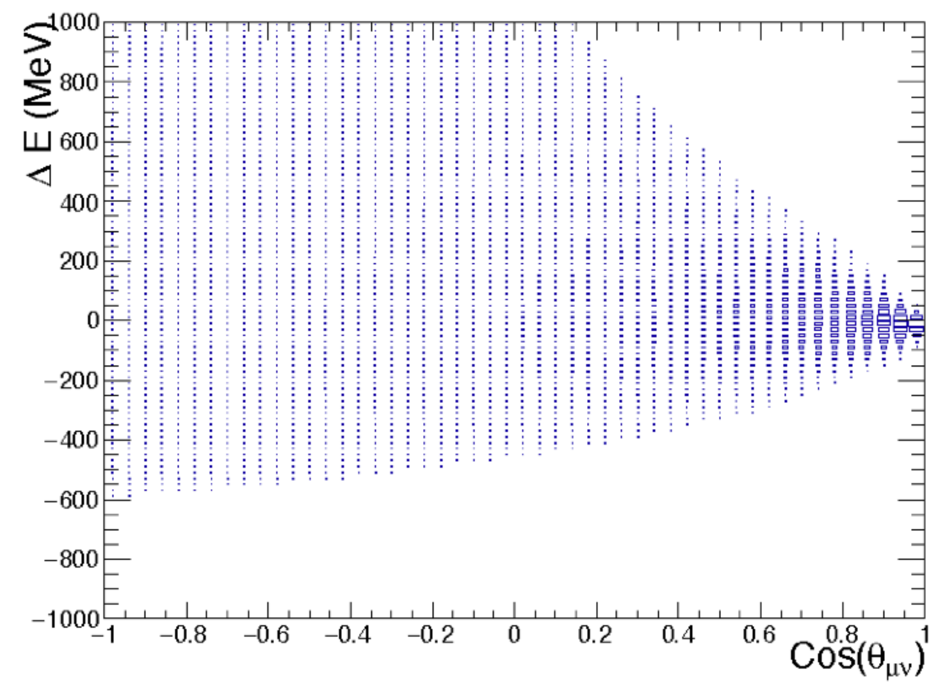
This approach requires plenty of additional experimental measurements.

Energy reconstruction

- Work developed by the e4v collaboration.
- Follow the same recipe that in the v case but with well defined energy electron beam.

L. Weinstein NuFact 2021

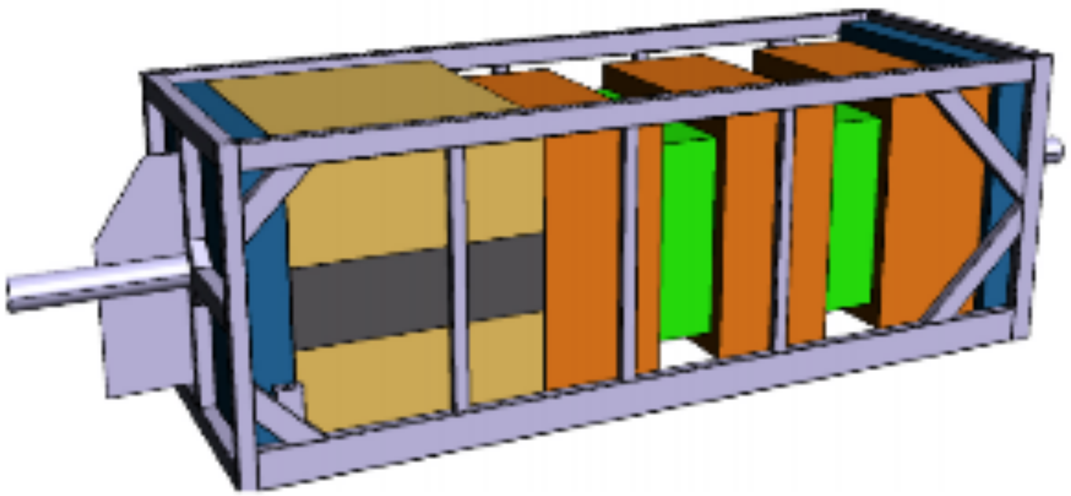


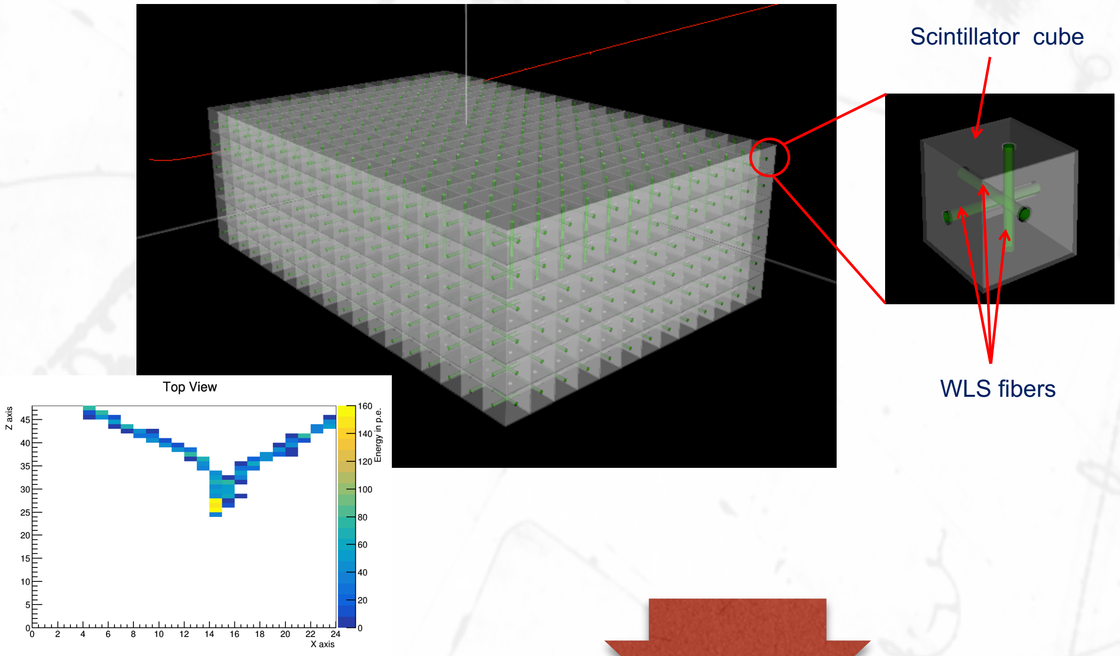


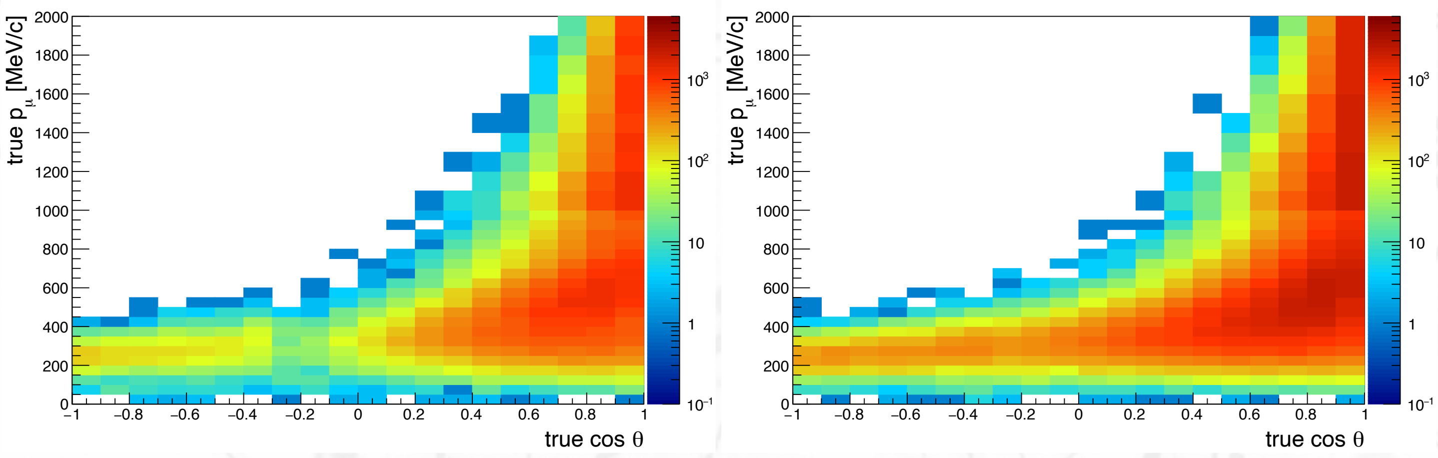
Strong dependency with the final state lepton has to be considered.

- T2K is interested in this type of analysis for oxygen and carbon for energies from ~400 MeV to ~1200 MeV.

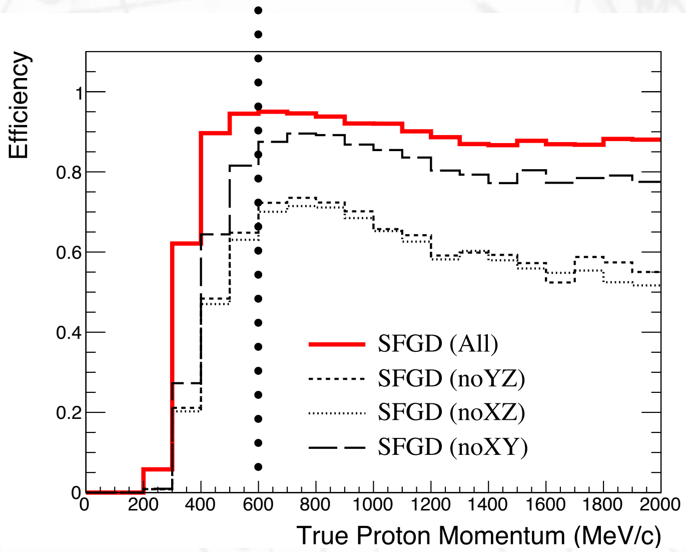
T2K ND280 upgrade







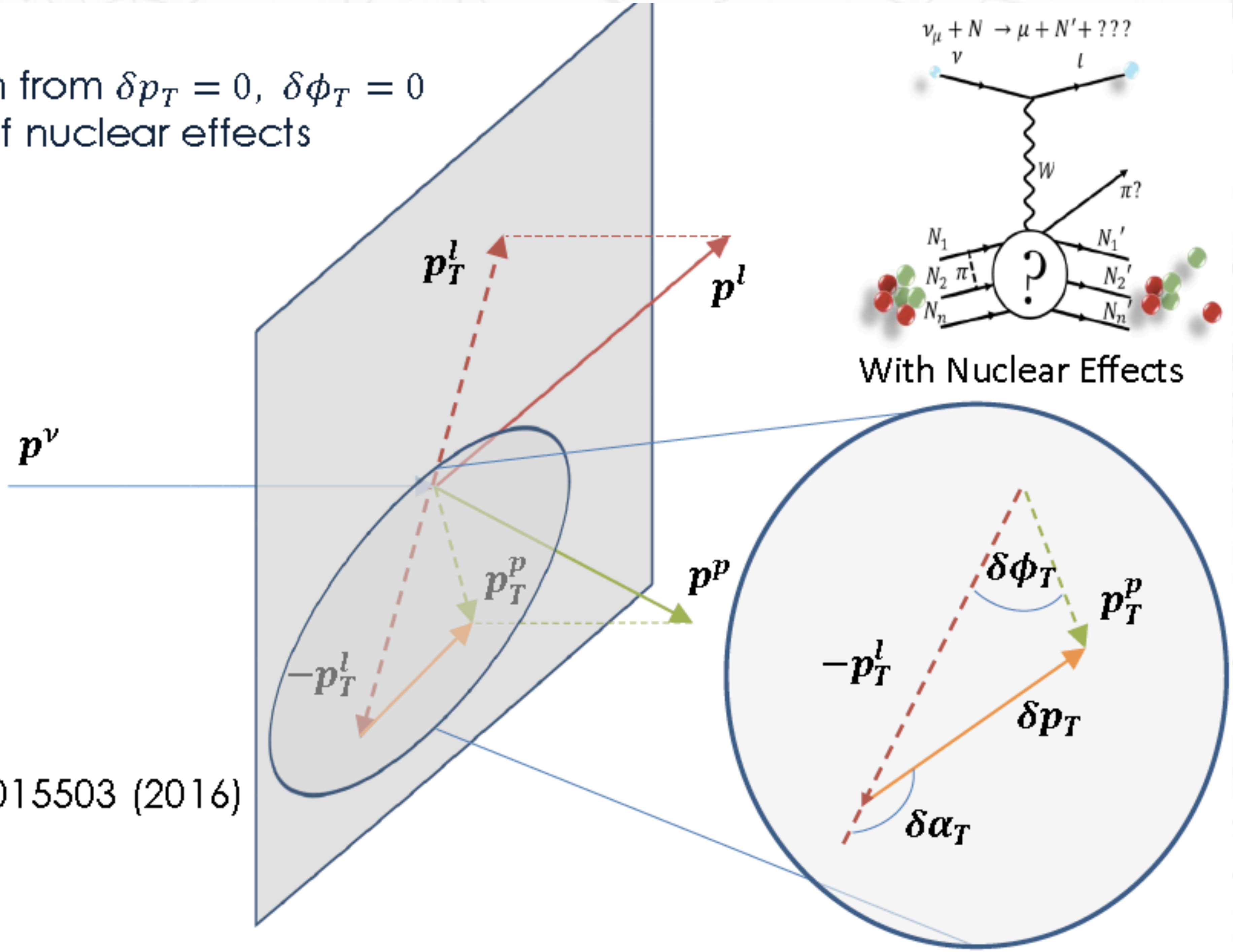
Improved angular acceptance
Better coverage of
high angle/high nuclear effects



Proton threshold from 400 MeV/c
Calorimetric reconstructions

Enhanced transverse variables

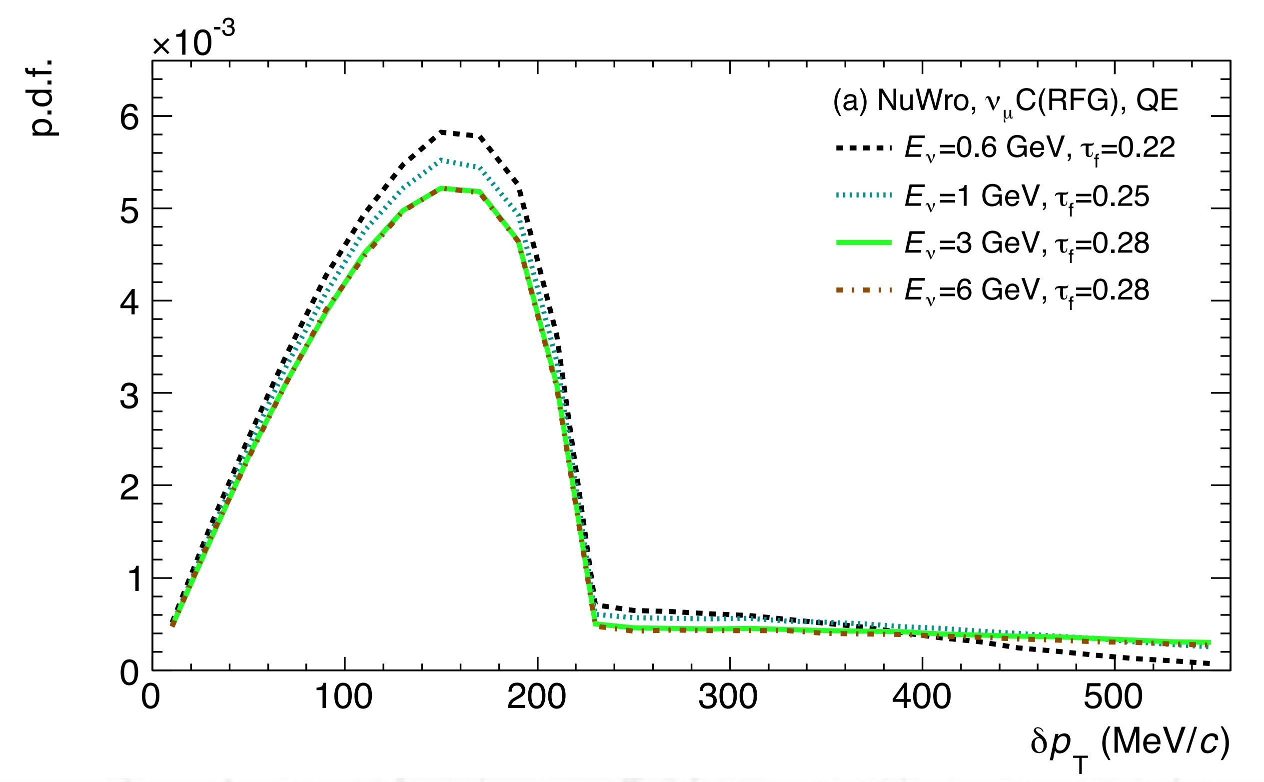
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects



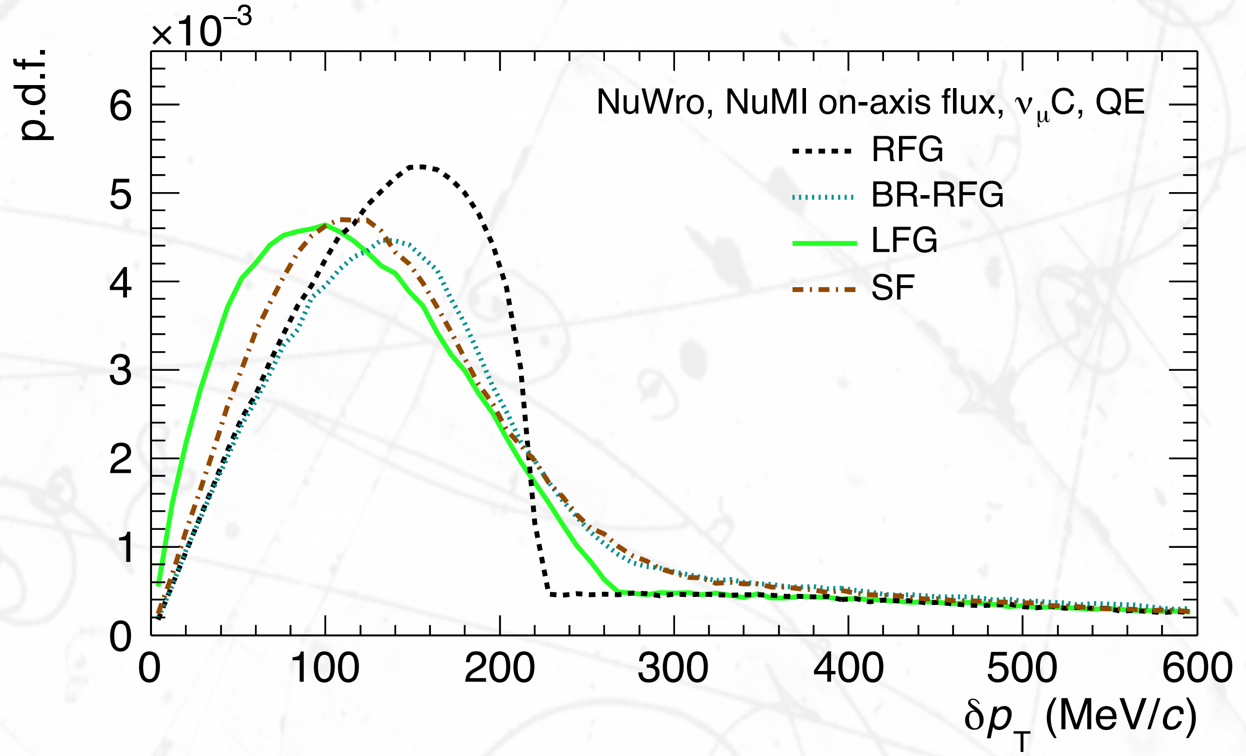
Phys. Rev. C **94**, 015503 (2016)

Transverse variables sensitivities

Insensitive to the ν energy



Sensitive to specific model assumption: nuclear model



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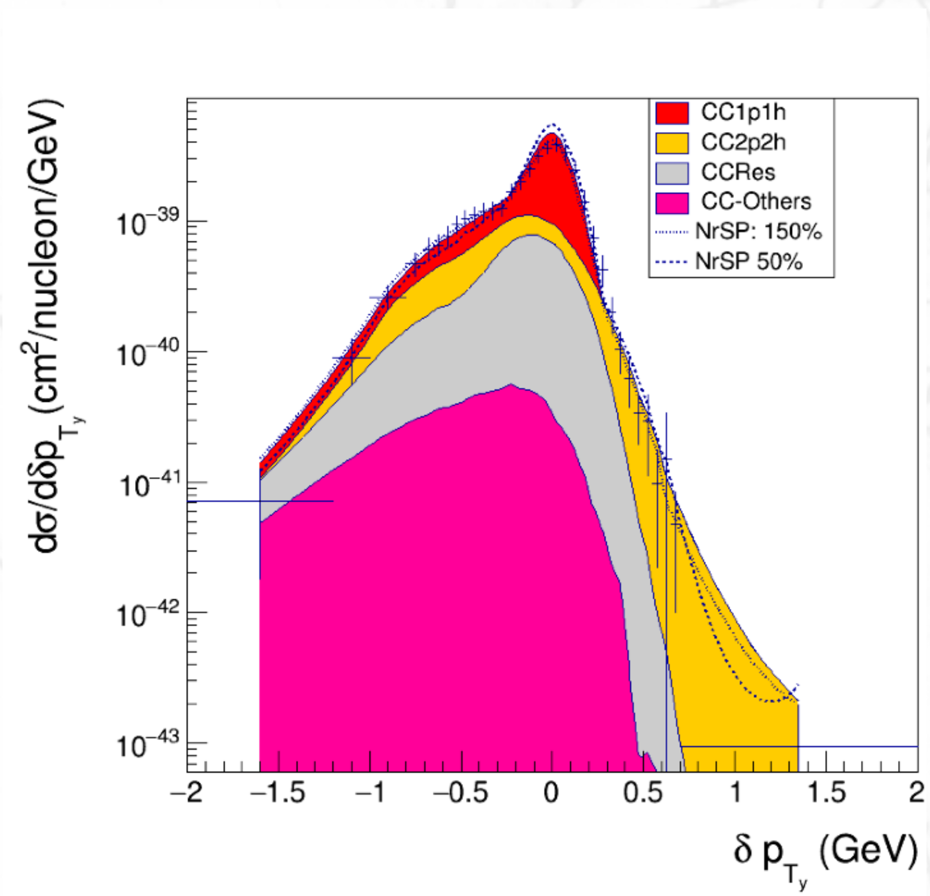
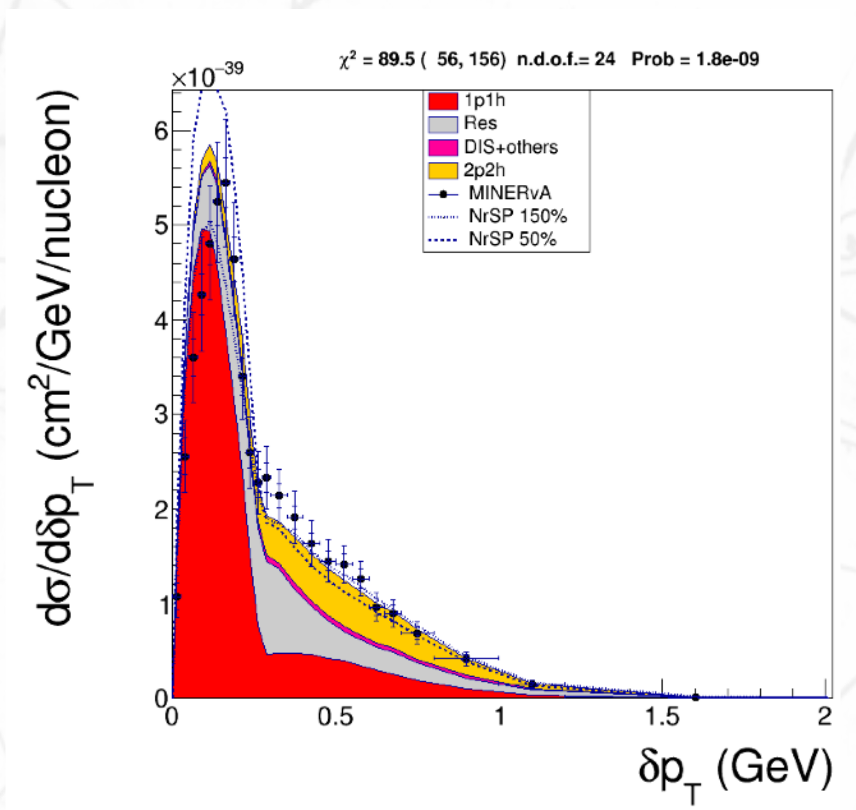
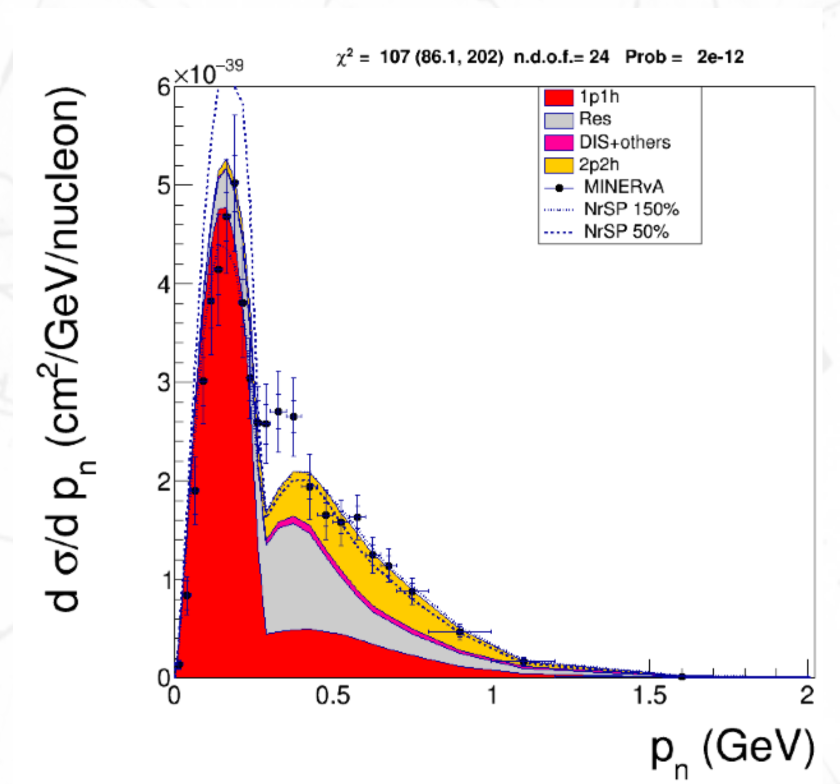
Transverse variables relation to basic model parameters

Sensitive to specific model assumption:
2p2h and others through pion absorption



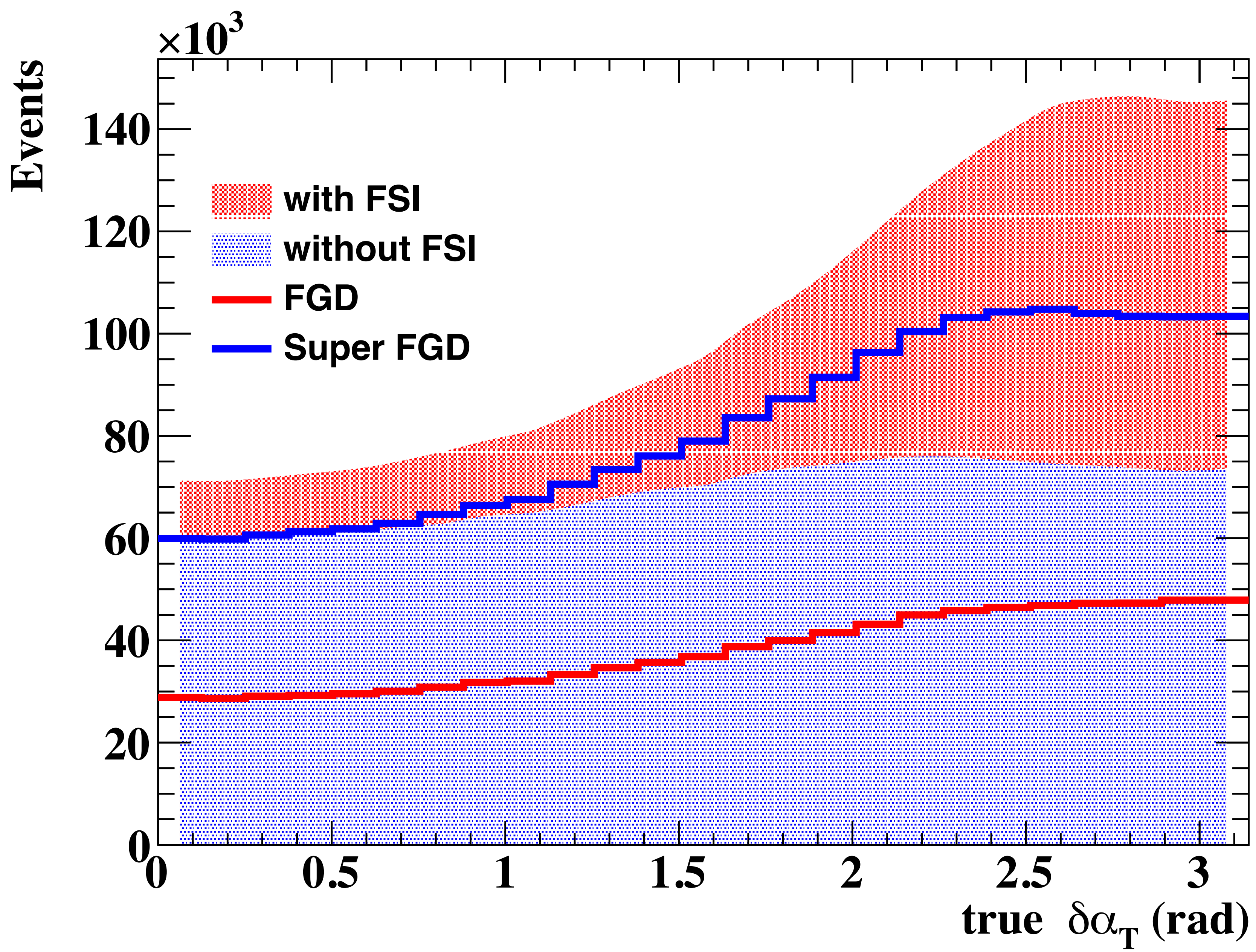




JHEP 04 (2021) 004

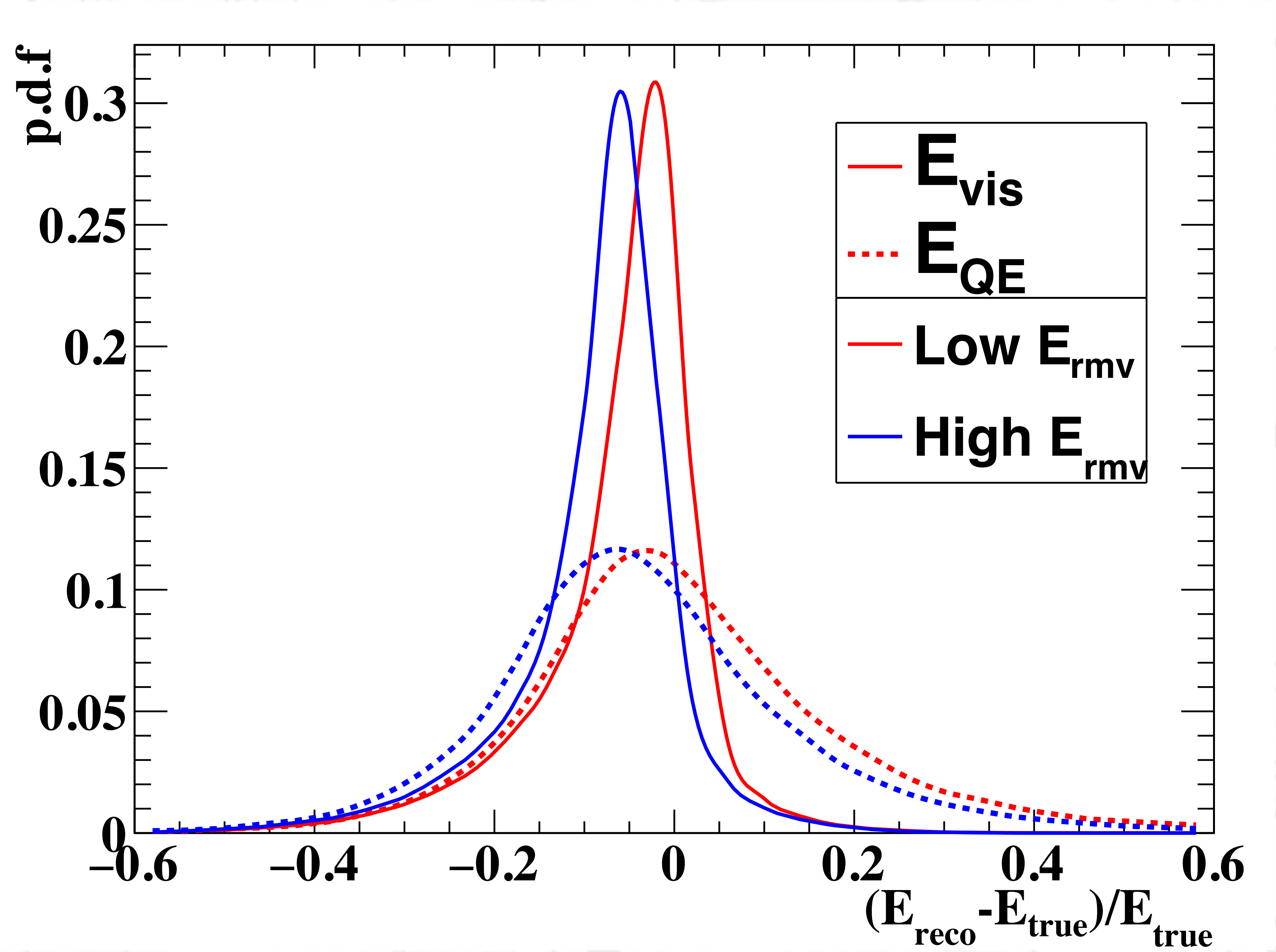
Transverse variables relation to basic model parameters

Sensitive to specific model assumption:
Final state interactions



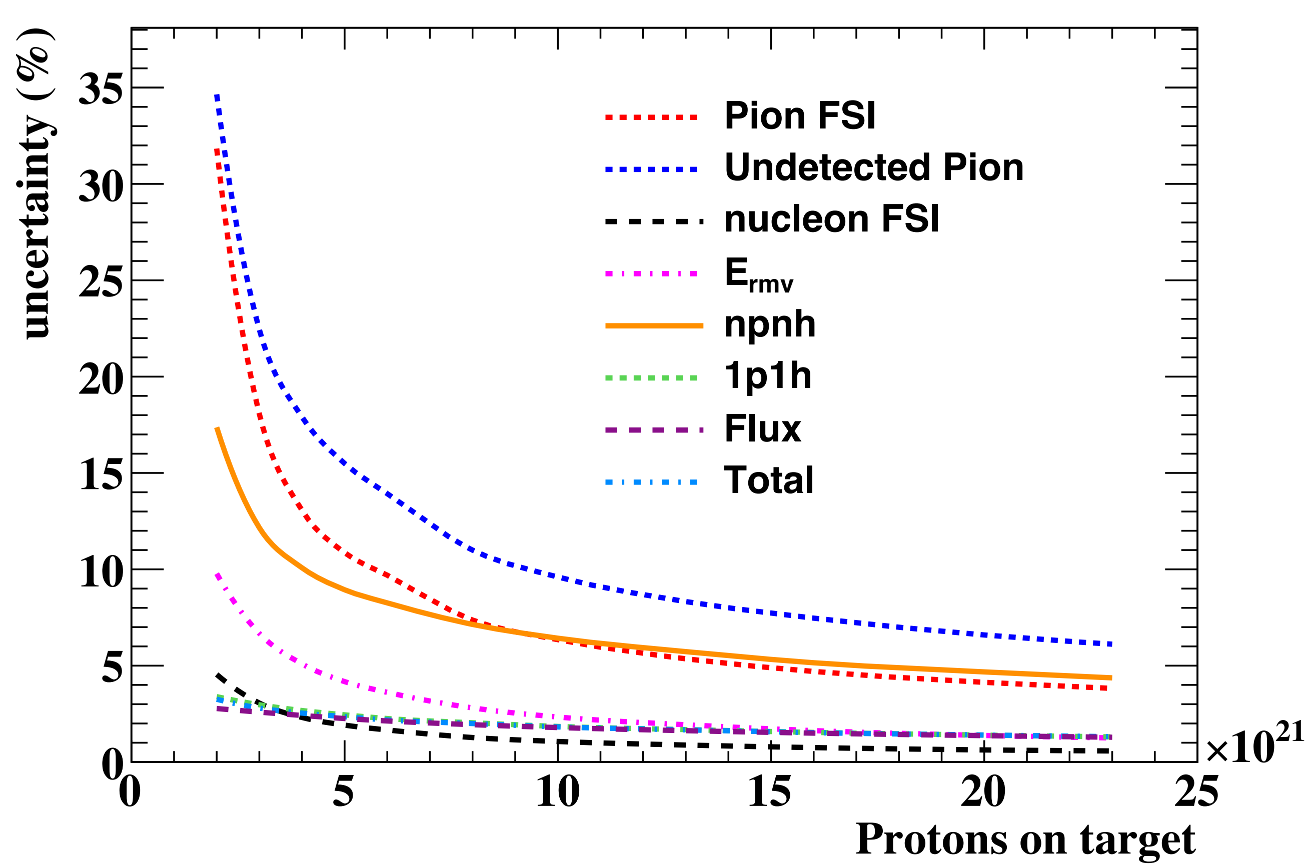
T2K & full kinematics

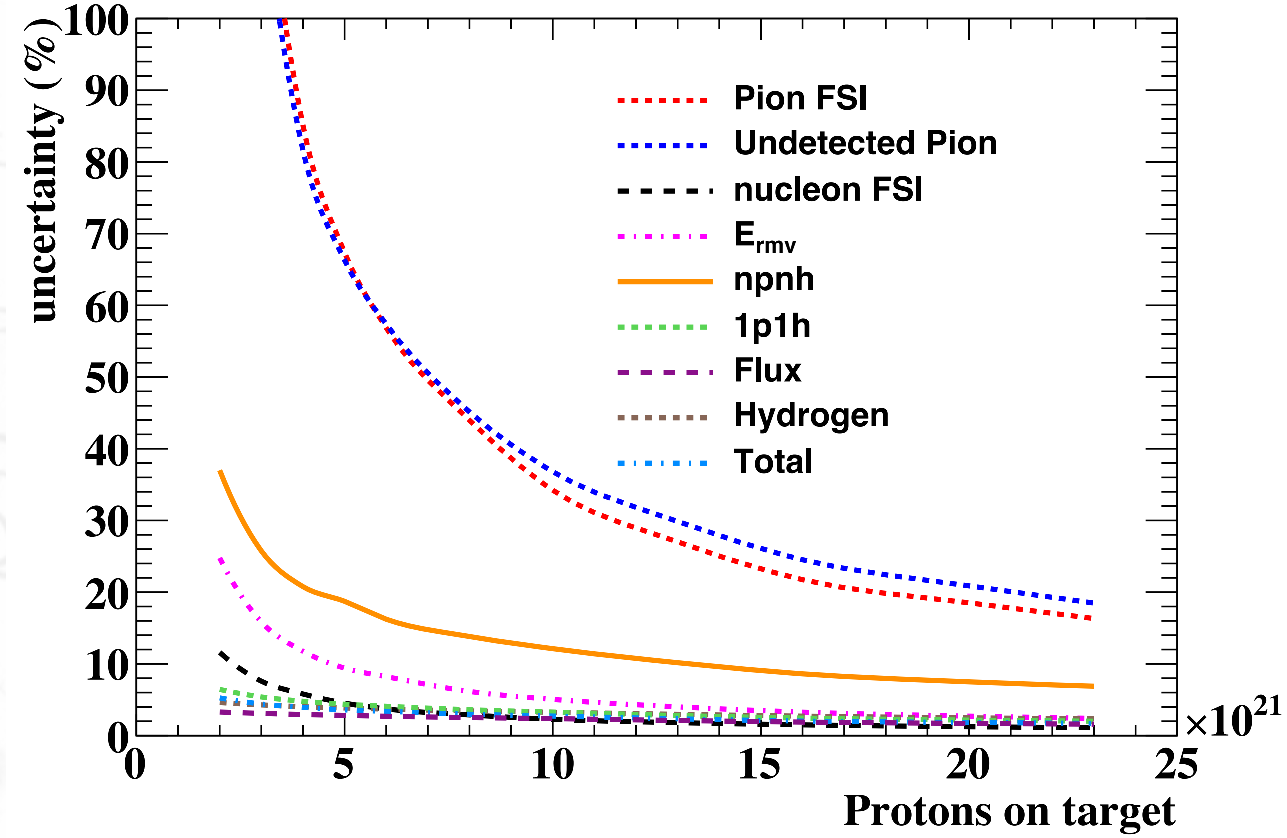
- Energy reconstruction from calorimetry



Phys.Rev.D 105 (2022) 3, 032010

T2K & full kinematics





Phys.Rev.D 105 (2022) 3, 032010

e4T2K

- T2K can exploit similar approach from electron scattering:
  - full acceptance and kinematics.
  - transverse variables.
- This approach will allow us to compare “degree of freedom” to “degree of freedom” in the model and not model to model.
- CLAS data can help to explore these concepts.

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Possible experiment beyond CLAS

- **Trade acceptance by resolution:**
  - give up on high precision trackers.
  - have high acceptance:
    - low energy pions and protons. (neutrons?)
    - close to 4π acceptance.
  - Possibility to exchange nuclei.
- Develop detectors that can be used both in electron scattering and neutrino interactions.

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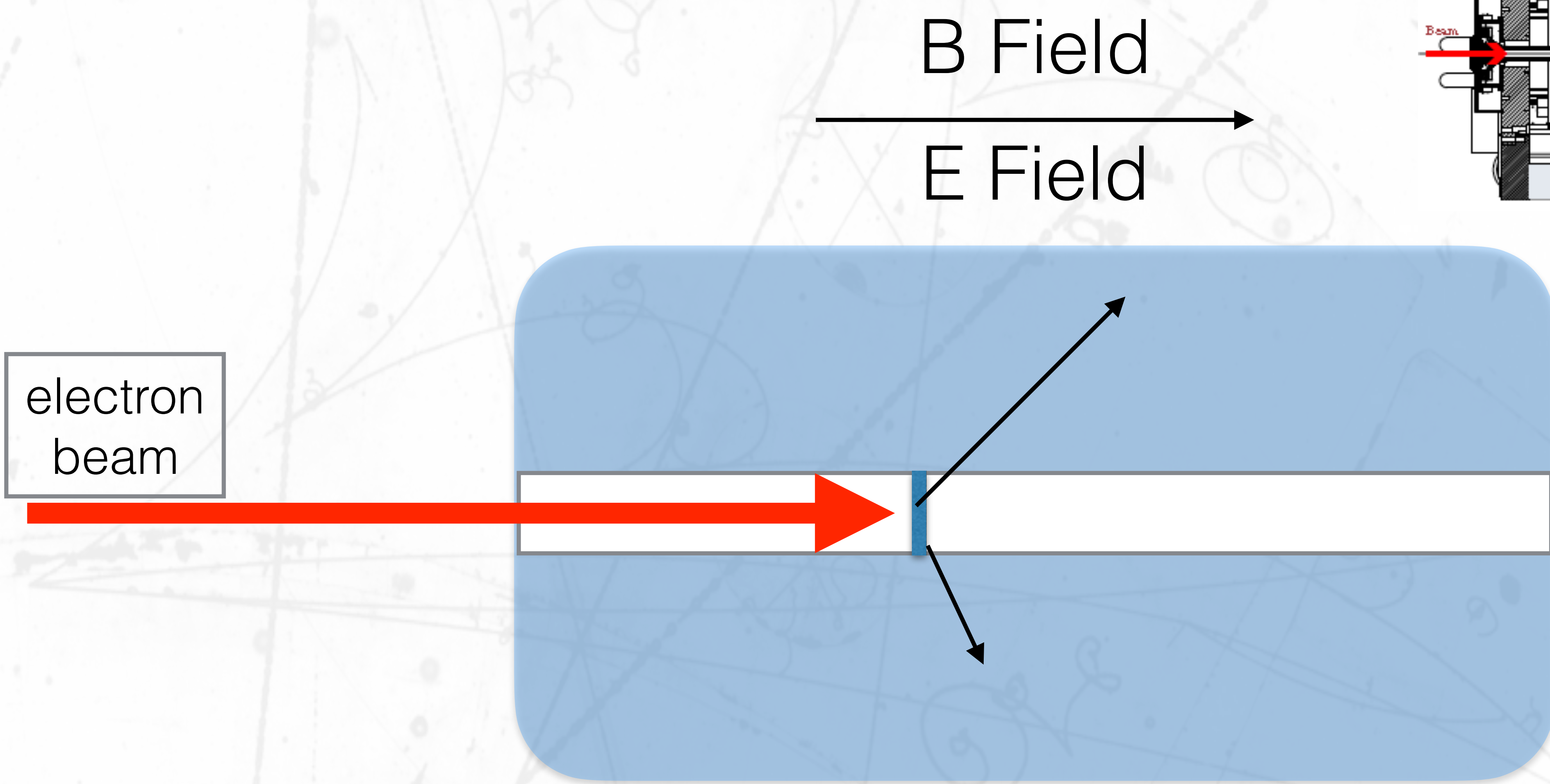
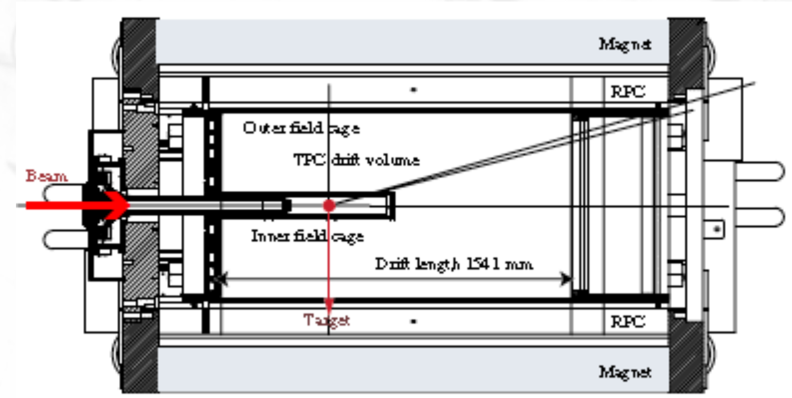
TPC detector





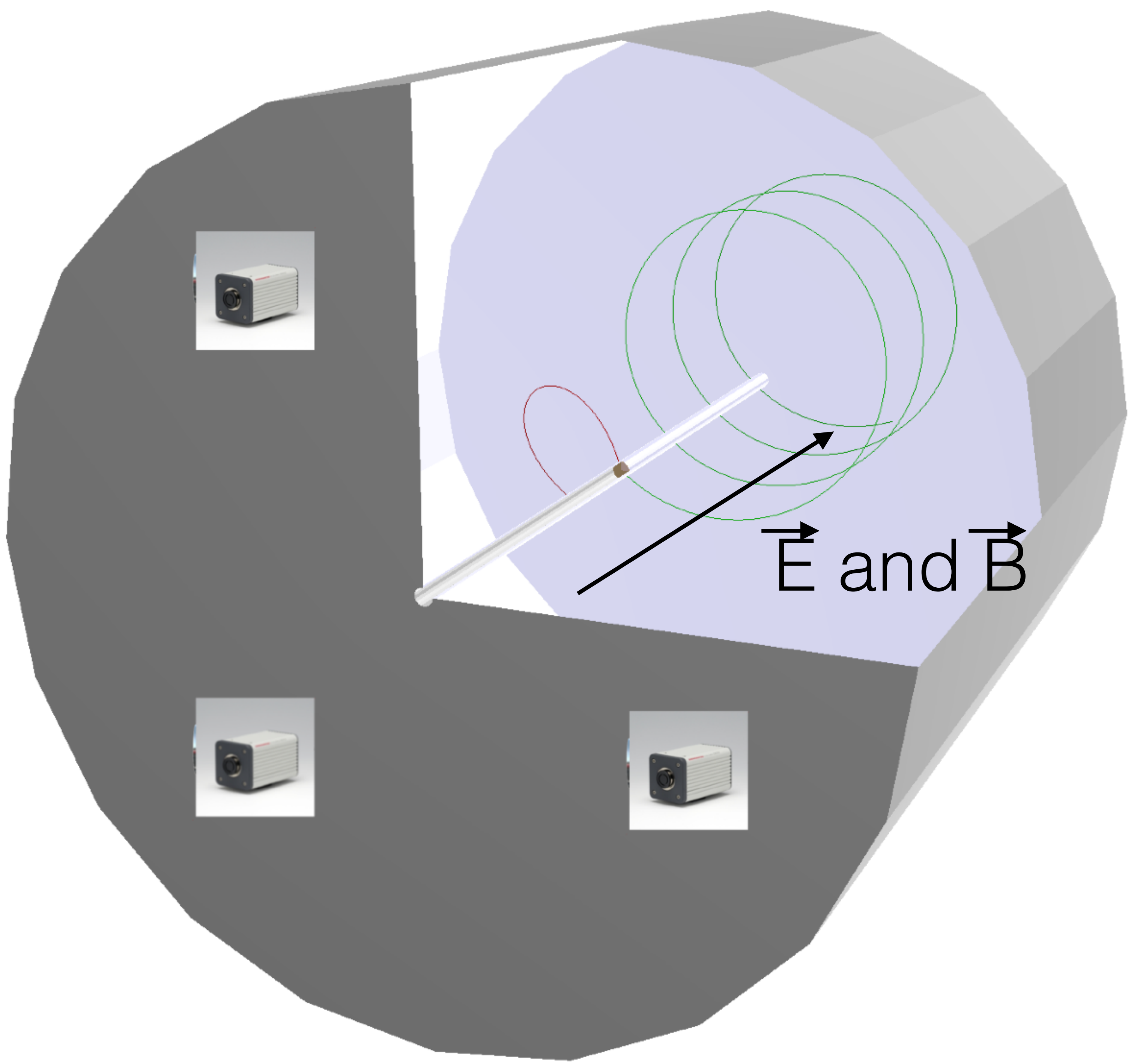
Similar to HARP

arXiv:2203.06853

Plus
No ion feed-back from electrons
Easy to replace the target
Uniform acceptance (same interaction point)

Minus
Not a full acceptance in p and angle
Complex field cage design.

A visual concept.



arXiv:2203.06853

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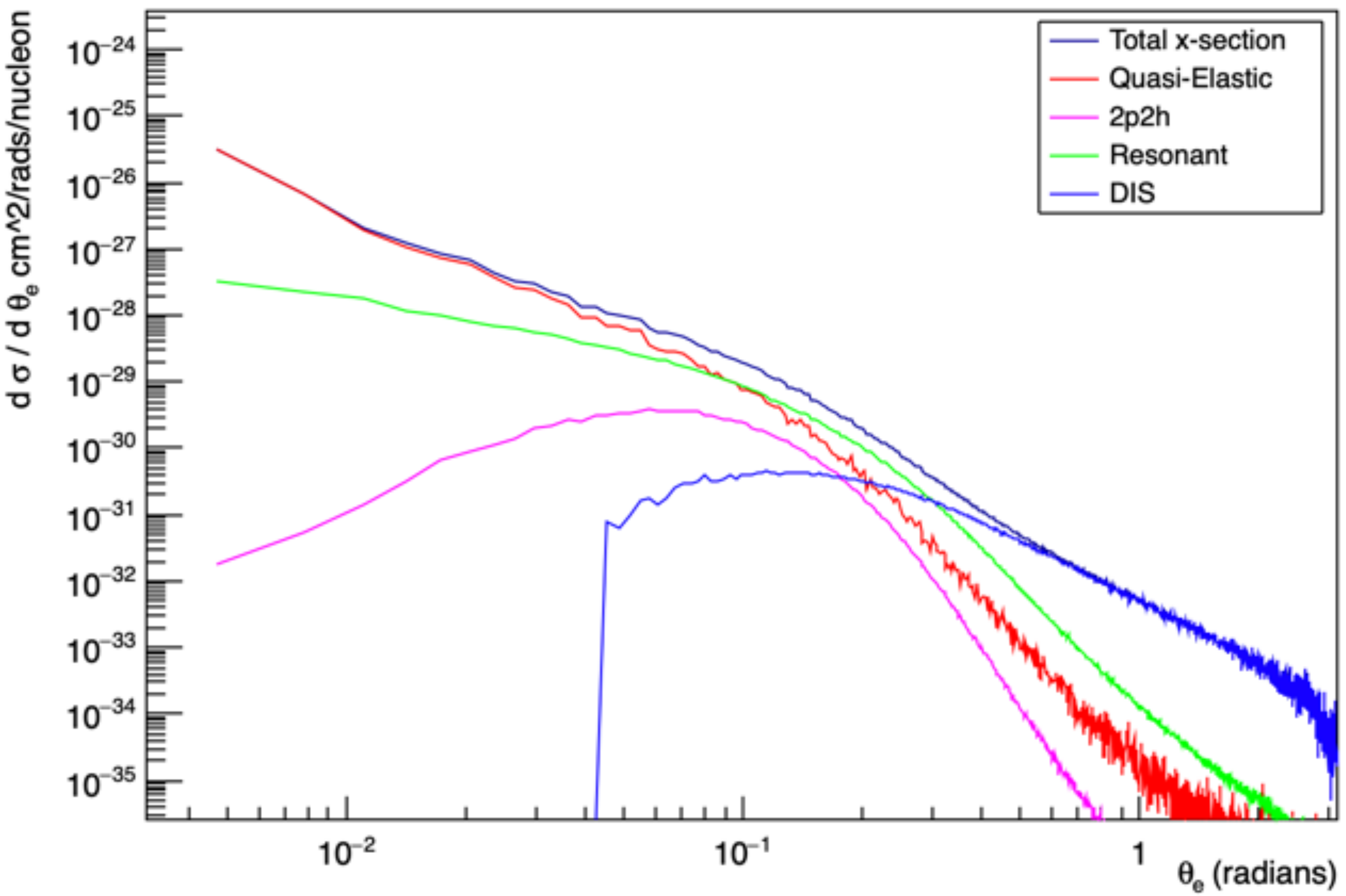
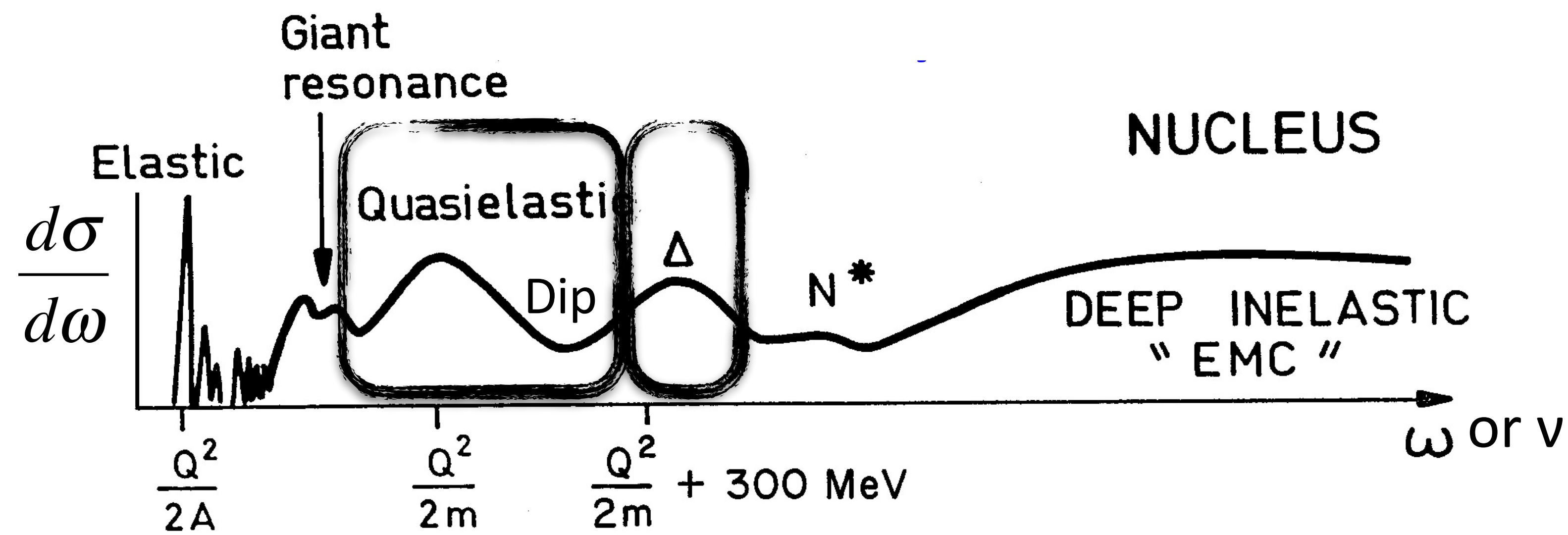
Angular dependency according to GiBuu



arXiv:2203.06853

e4nu and topologies

- Topology is a fundamental concept for the T2K experiment since it defines the wrong-energy background.
- Electron scattering experiments can help to study concepts such as pion transparency and pion multiplicity.



Select dominant Δ production with e kinematics and explore event topologies.

Similar for proton scattering by defining difference from expected to observed: $\Delta\theta_p$ Δp_p.

Issues on the ee'p experimental results

- The very forward region ($q^2 \sim 0$) is difficult to cover with electron scattering:
  - in this region we see plenty of anomalies and expect nuclear contributions.
- How do we translate from electron to neutrinos:
  - Modelling:
    - special attention to the information to be obtained.
    - Exploring each of the ingredients of the model might help: enough?

Facilities

Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	E_e = 2.222 GeV $15.5^\circ \leq \theta_e \leq 21.5^\circ$ $-50.0^\circ \leq \theta_p \leq -39.0^\circ$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	E_e = 1, 2, 4, 6 GeV $\theta_e > 5^\circ$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	E_e = 4.0, 8.0 GeV $\theta_e < 40^\circ$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\leq E_e \leq 1.5$ GeV $7^\circ \leq \theta_e \leq 160^\circ$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')

Table 5: Current and planned electron scattering experiments.

arXiv:2203.06853

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Personal conclusions

- T2K will profit from electron scattering experiments adapted to its needs and experimental approach.
    - light nuclei.
    - access to transverse and full kinematics.
    - reduced energy.
- New generation of T2K will use calorimetry and TKI at the near detector to control systematics:
    - electron scattering is capable of similar measurements that will be very useful for modelling and model comparisons.
- T2K is very much model driven, we need also theoretical work to be developed to understand the connection between e and ν models.

Many of these concepts require proper studies.
I am open to collaborate on exploring them.