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FACULTÉ DES SCIENCES
Département de physique
nucléaire et corpusculaire

UniGe activities on cross-sections and oscillation analysis

F.Sanchez

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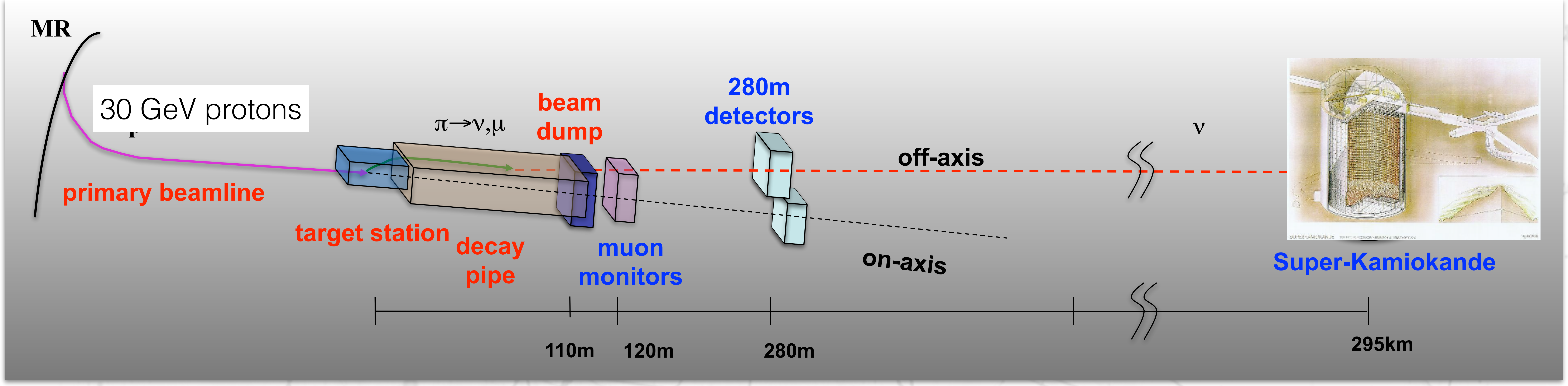
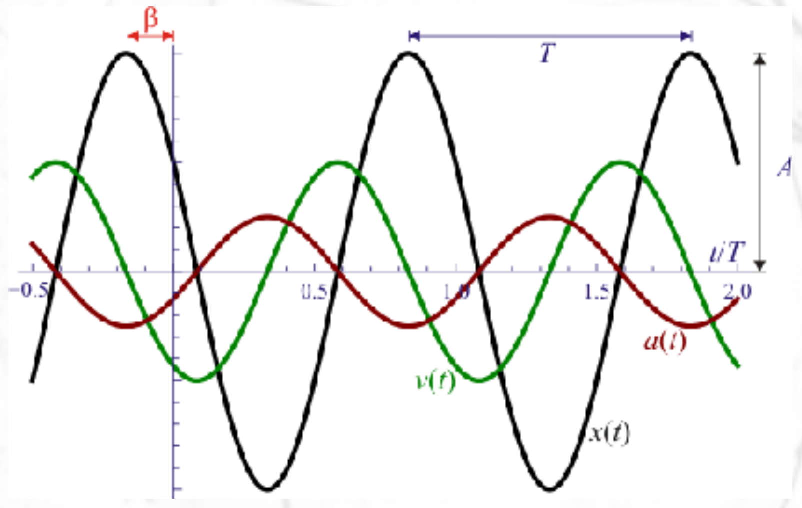
Long Base Line Experiments

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



Neutrino flux meas

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Long base line

- 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 & flux:

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

  - at the far detector

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

- The ratio cancels flux and cross-section:

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

-

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Long base line

- 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.

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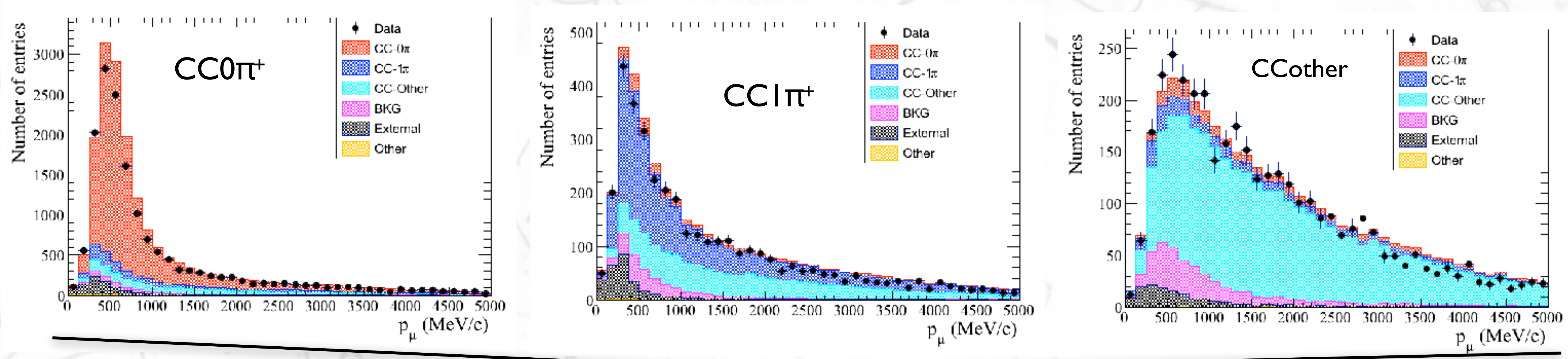
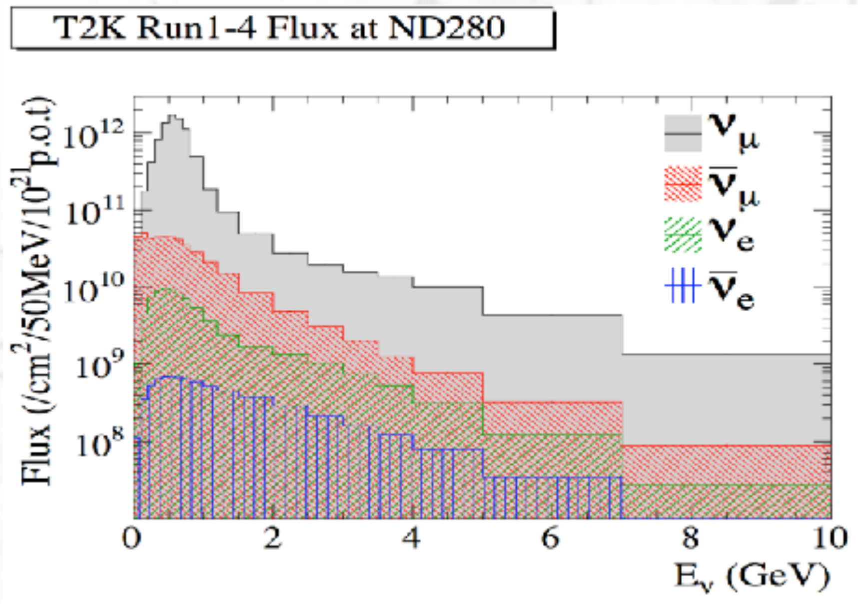
Role of Near detector

Near detector data

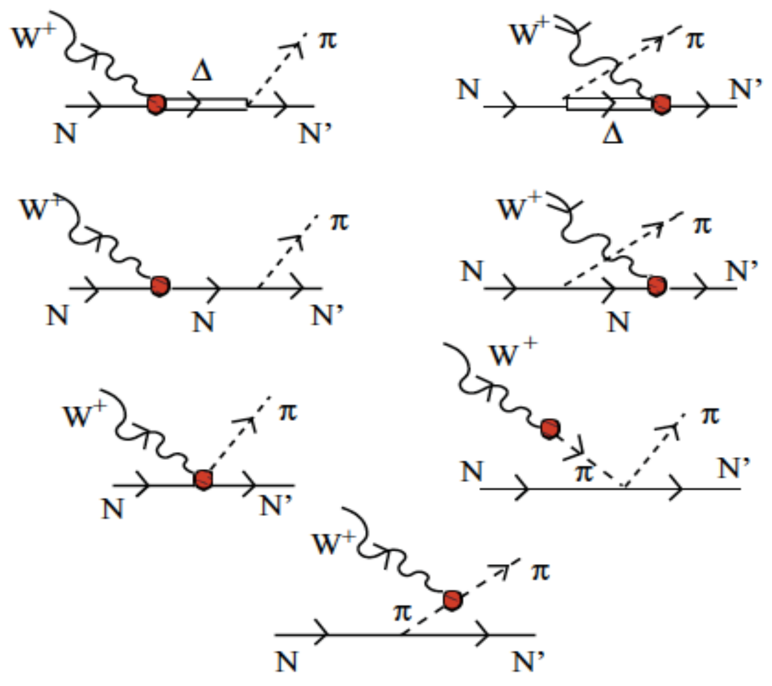


⊕ Hadron production flux prediction

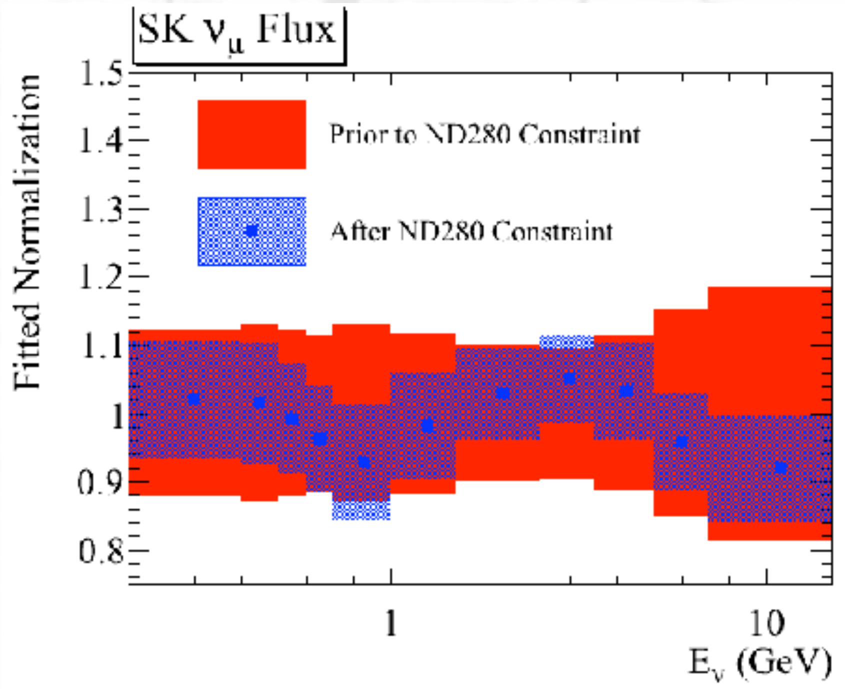


⊕ Feed back

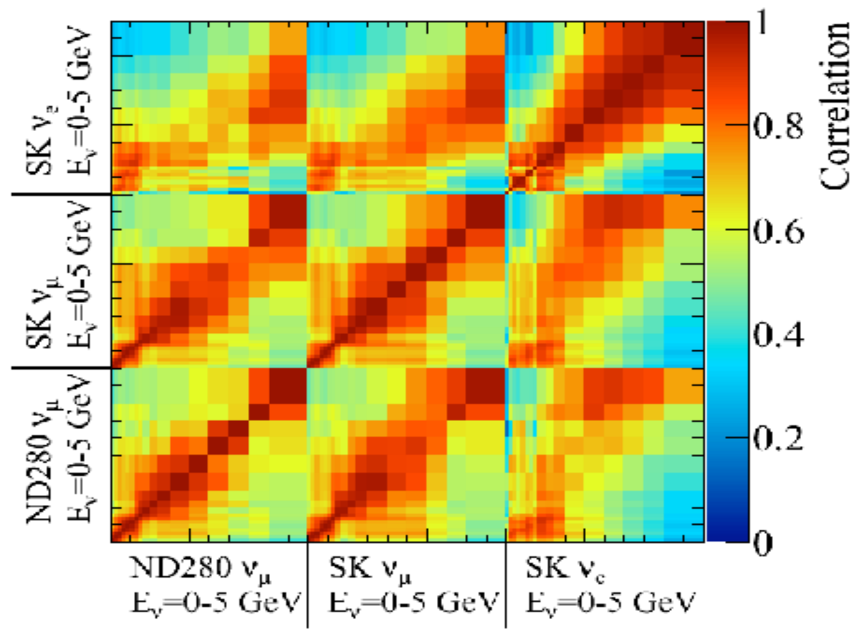
Cross-section model



= Corrected flux and cross-section model

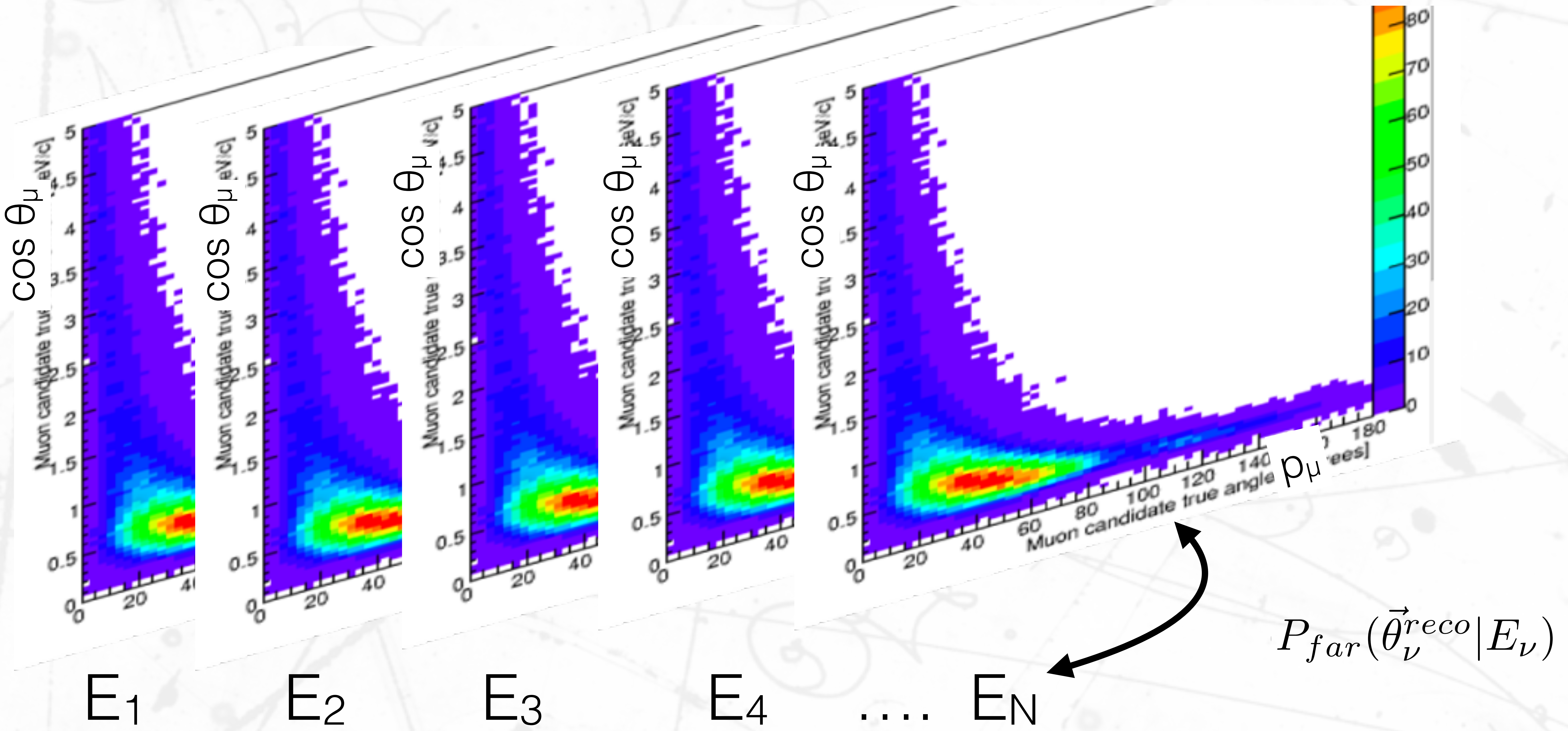


& correlation



Awfully complicated and a limitation nowadays

Kinematical approach



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

$$P_{far}(\vec{\theta}^{reco}_\nu|E_\nu)$$

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UniGe goals

- The group at UniGe concentrates on exploring:
  - ways to improve the oscillation analysis : statistics.
  - consistency check of the procedure: closure tests.
  - Improving the modelling of Neutrino-Nucleus interactions:
    - collaboration theorists-experimentalists (MC and modelling)
    - exploring new experimental observables (Psi’, Phi, S, ….)

Statistics

- The actual oscillation analysis requires > 700 parameter fit.
- Actually in T2K we do not do “parameter” fit but rather estimation of marginalised Probability Density Functions:
  - pseudo-frequentist and Markov-Chain.
- Two main issues in actual models:
  - Markov-Chain : CPU/GPU requirements —> cost and time.
  - Pseudo-frequentist : Gaussian approximations.

Statistics

- In Geneva we have been working with Normalising Flows since long time.
- We have adapted this tool to the generation of PDF without a-priori assumptions:

Isomorphism learned as a Neural Net

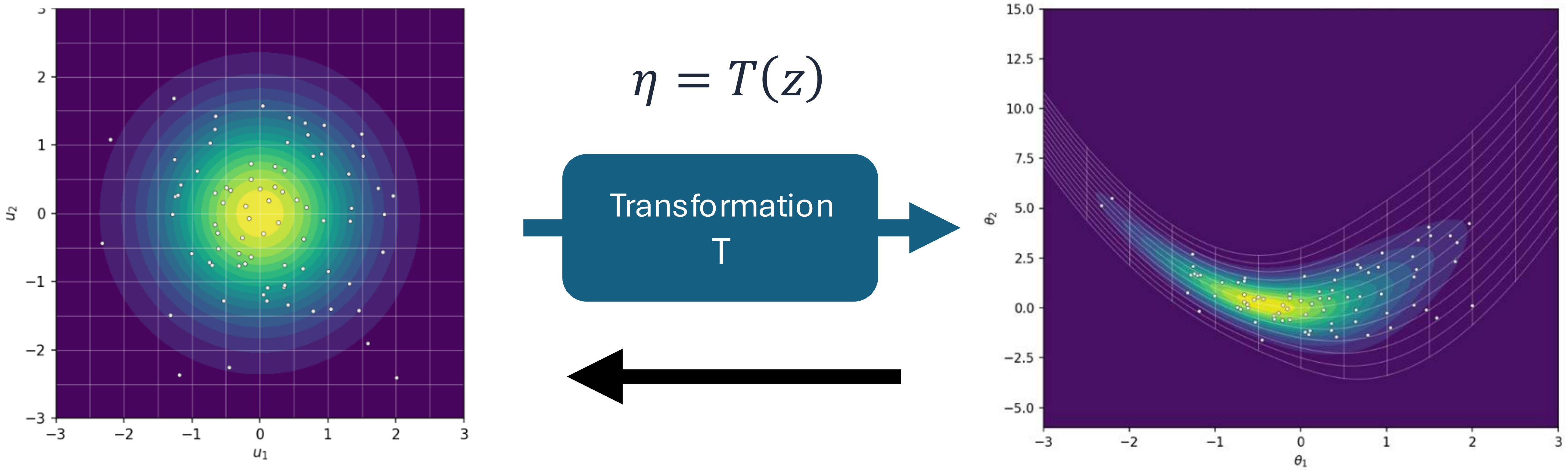
Contiinuous, derivable and invertible

Evaluate with change-of-variable formula:

$$q_{NF}(\eta) = p_z(z)\left|\det\frac{\partial T^{-1}}{\partial \eta}\right|$$

Base distribution (gaussian)

Complex distribution $q_{NF}(\eta)$



N (=dof) independent gaussians

Distribution we are interested!

Statistics: demonstrator

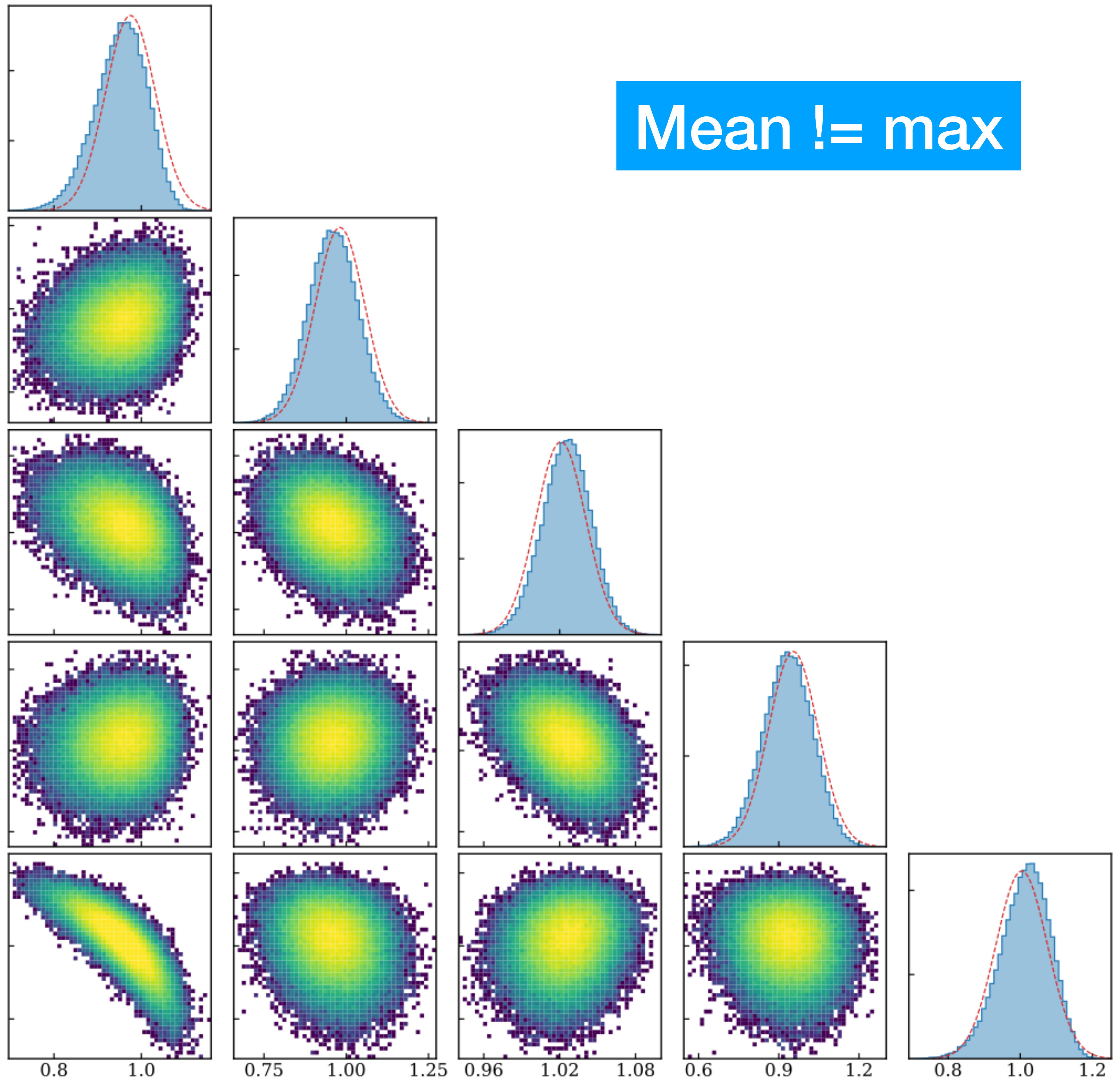
Method demonstrator

1. Non-gaussian correlations between non-linear params arise in NF model
2. NF prediction departs from gaussian - compatible with MCMC

high learning accuracy —> NF ~ true likelihood

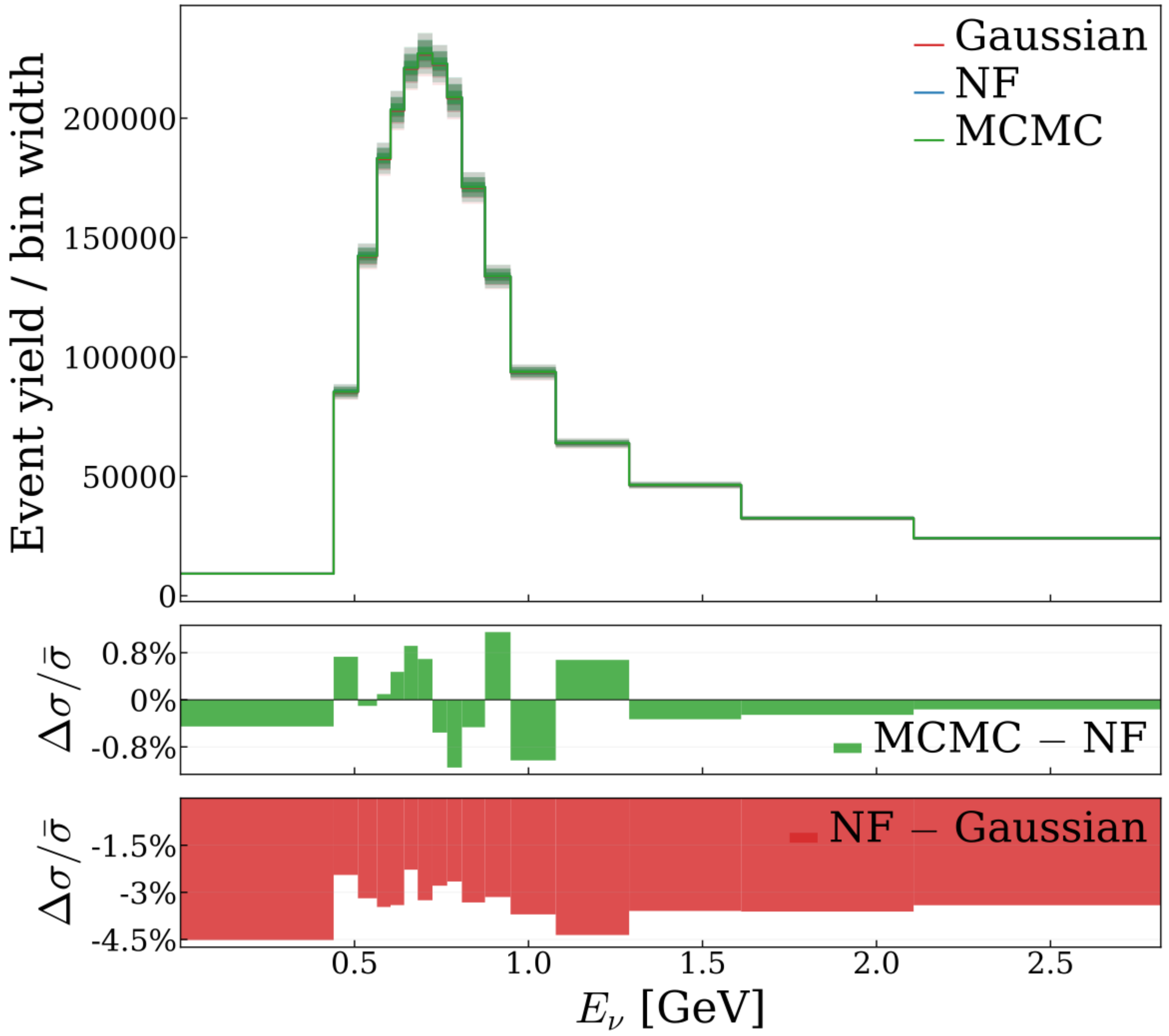
Already testes with realistic T2K conditions

q_{NF} projection onto non-linear parameters



Mean != max

Neutrino flux prediction



Non-gaussian correlations.

50

Possible applications

Near Detector closure tests

- The cross-section parameters are used fitting momentum and direcionof the muon:
  - What happens when using this parameter fit on more complex observables:
    - hadronic energy, Transverse balance, etc…
- This is basically a closure test that indicates possible defects on our cross-section models.

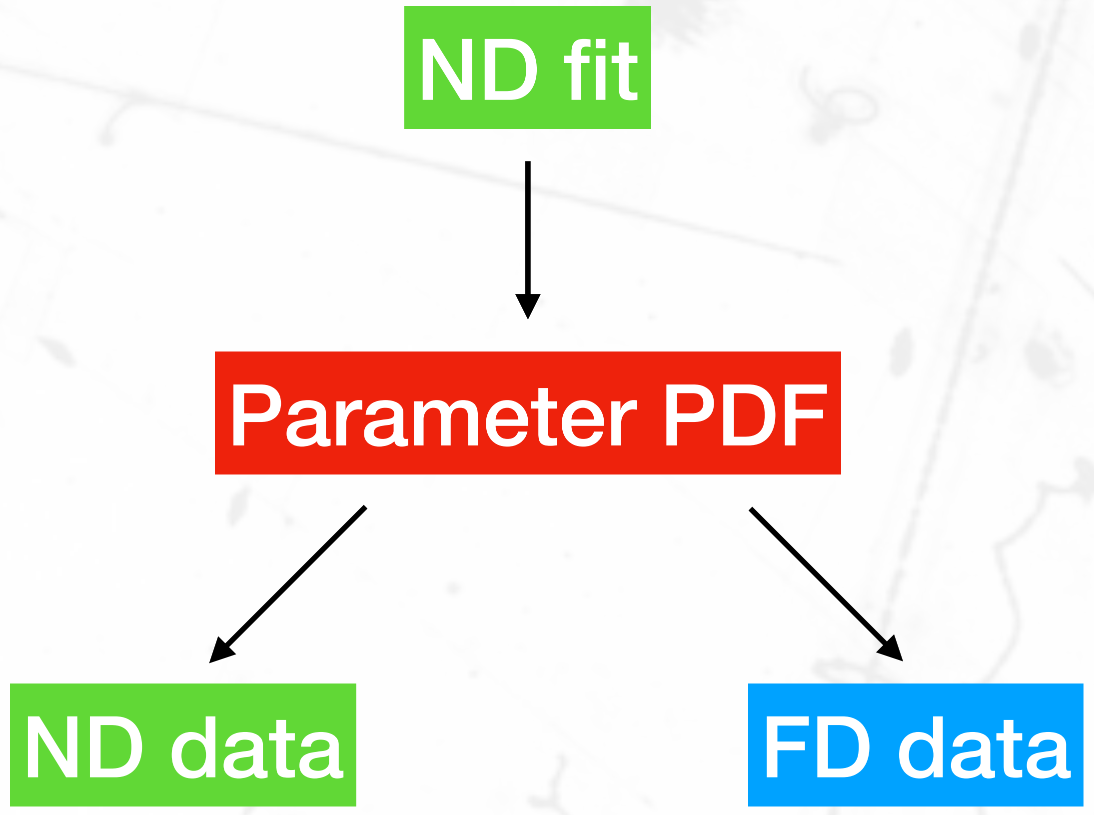
Oscillation fits

- Faster, more robust and more precise (non-gaussian) propagation of parameters allow us to perform oscillation with higher precision and flexibility.

Far Detector closure tests

- A more precise (non-gaussian) propagation of parameters allow us to check basic neutrino interaction parameters in SK. (see later).

Closure tests



- We want to answer the question: after we perform the fit: is the self-consistency of data and model maintained?
- To do this we need to create experimental observables beyond the ones used for the data fit (p_μ,θ_μ).
- Both new and old can help to estimate the validity.

Traditional observables

- Hadronic observables
- Transverse Kinematic observables
- Difficult to relate with “model” assumptions

New potential observables

- ψ' —> Energy reconstruction
- L_1 —> Hadron obeservables with lepton kinematics
- Possibility to address the removal energy

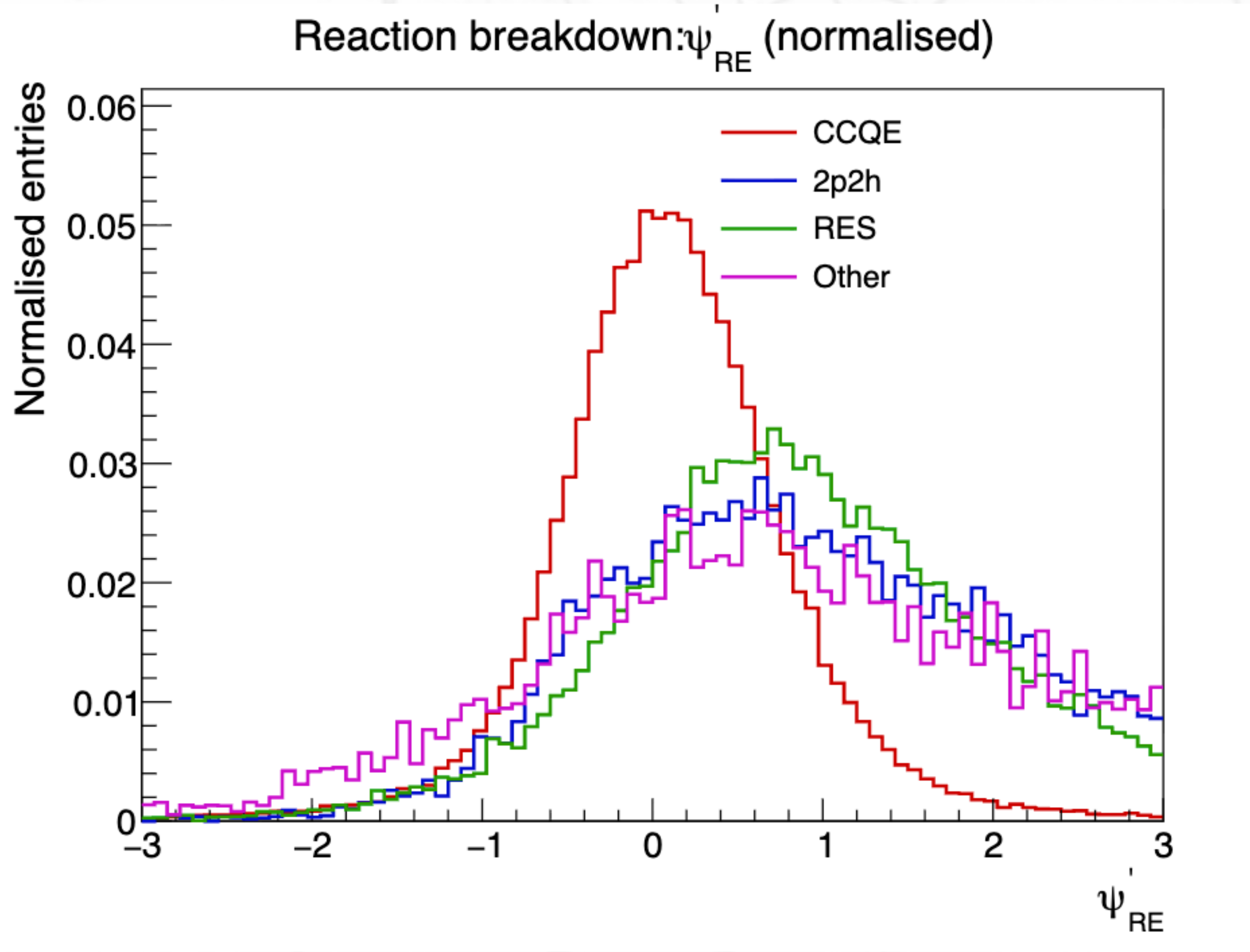
Those observables are rooted on fundamental cross-sections uncertaities.

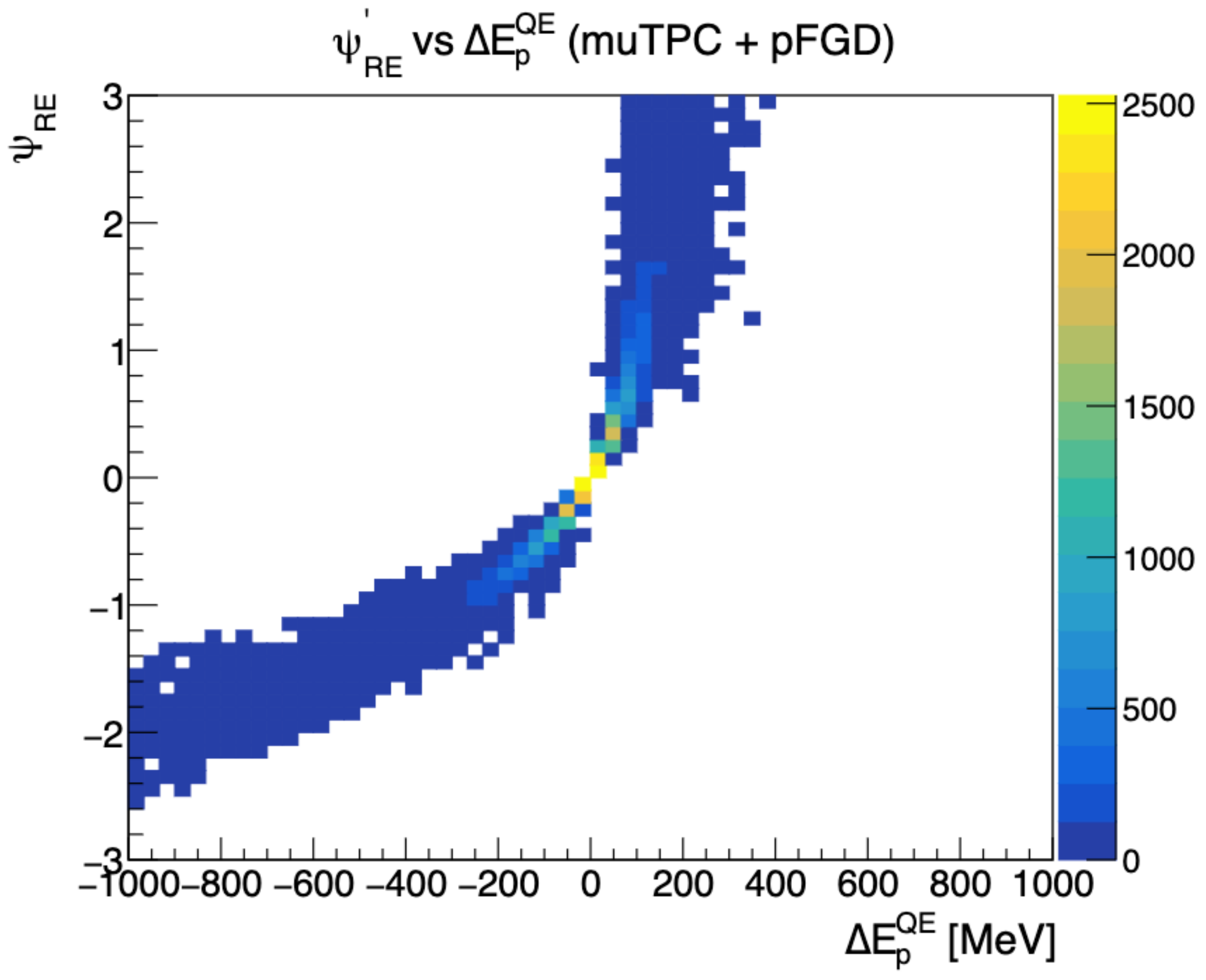
Closure tests

- We can use observables to :
  - explore our bare model —> cross-section model evaluations.
  - applying the fit of the near detector fit and check the variations :
    - If agreement worsens: the fit bias towards non physical results.
    - If agreement is maintained : the fit is not sensitive to basic X-section assumptions —> Change parametrisation in the fit or it was already good (fit is irrelevant).
    - If agreement improves : the fit does a good job obtaining accurate physical results.
- We can repeat this at the far detector to explore if the change in the flux affects the agreement.

One example: ψ'

Better use observables related to basic theory values like the error in the energy reconstruction





- Clear separation between CCQE and other interactions.
- Relation between the energy reconstruction (ΔE_p) and the ψ'

to check: agreement model-data and potential improvement of agreement after cross-section adjustment to data at ND

Cross-section model

- The neutrino-nucleus interaction is mainly a nuclear problem to describe the initial nuclear state, probability of transitions and final nuclear particle transport.
- Normal assumption: Impulse Approximation:
    - we interact with a single nucleon in the nucleus.
    - We need to describe the “state” of this nucleon prior to the interaction: Relativistic Fermin Gas, Local Fermi Gas, Spectral functions, …
- In reality, we need to describe the nucleus after the interaction: Optical potentials, Pauli Blocking, … Also a proper QM approach includes Antisymmetric WaveForms and interferences.

Traditionally models are done almost classically —> momentum-energy conservation.
New models take into account Quantum Mechanics (Mean Field) which integrate initial and final interaction states.

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Mean Field MC

Geneva is working on facilitating the portage of these models into experimental measurements.

Collaboration with Ghent University and IFIC(Univ. Valencia)

- The main issue on this portability is the time consumed in the calculations:
  - scattering is compute as a sum of plane waves !
- But!, a cross-section is not more than a Probability Density Function:
  - We can use the Normalising flows to "learn" this probability. Two advantages:
    - NF is continuous and derivable and invertible like a PDF, so acwe can "interpolate" calculations to get smooth distribution.
    - Once learned, it is fast to generate events.
    - Because it is invertible, we can compute the probability of any combination of parameters, so we can do important sampling to correct the result or to reweight events with different parameters:

$$W(\theta_i) = \frac{\sigma(\theta_i)}{\sigma_{MC}(\theta_i)}$$

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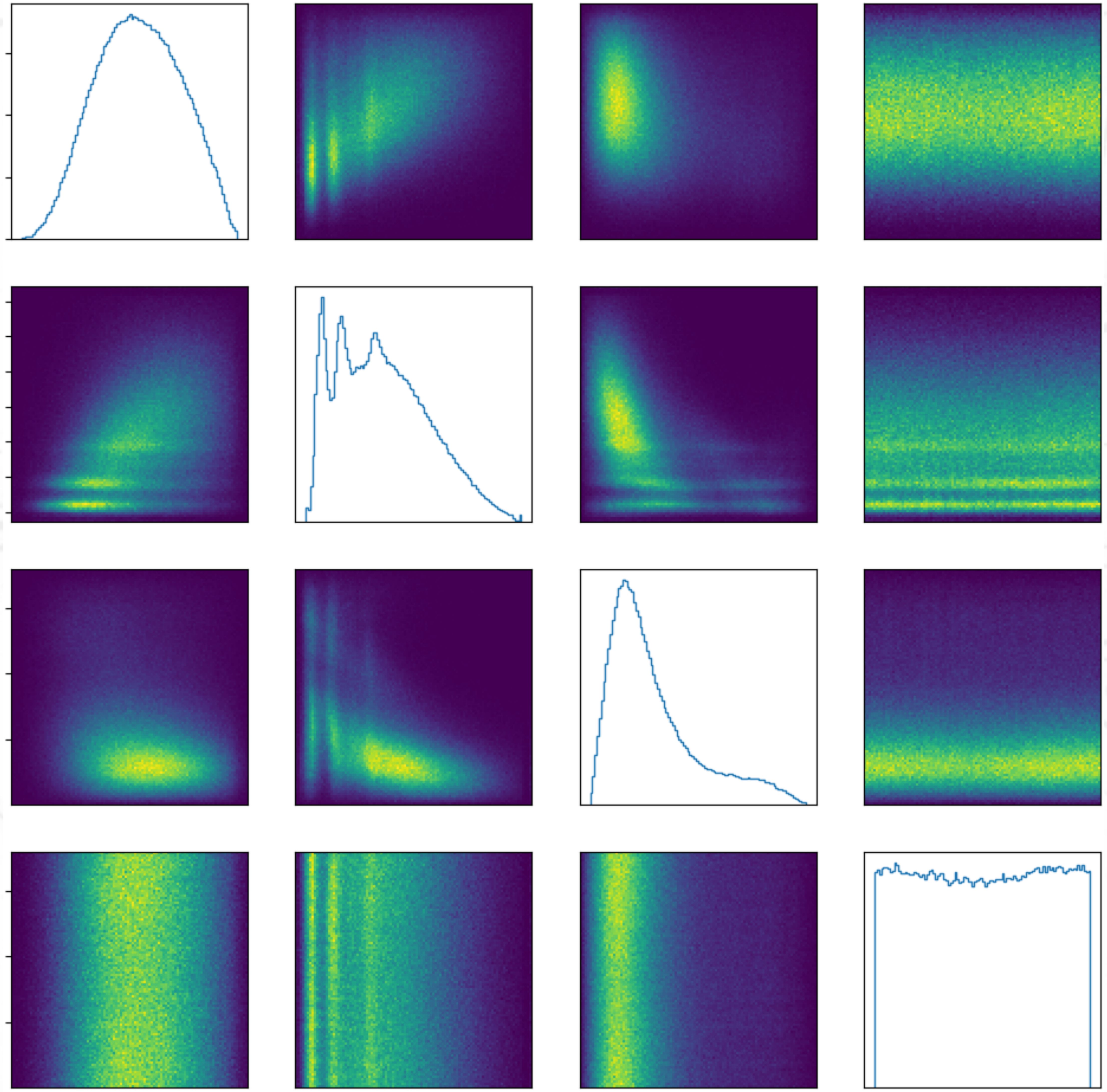
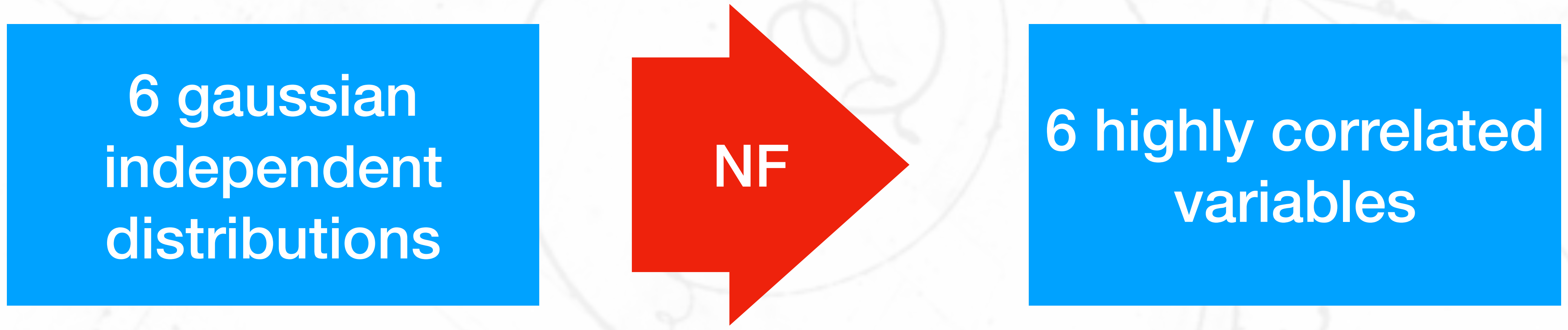
Learning 1p1h



- A cross-section is in fact a probability density function.
- Like in the oscillations, we can learn very complex PDF's using normalising flows including all complex correlations.
- The generation is simple :



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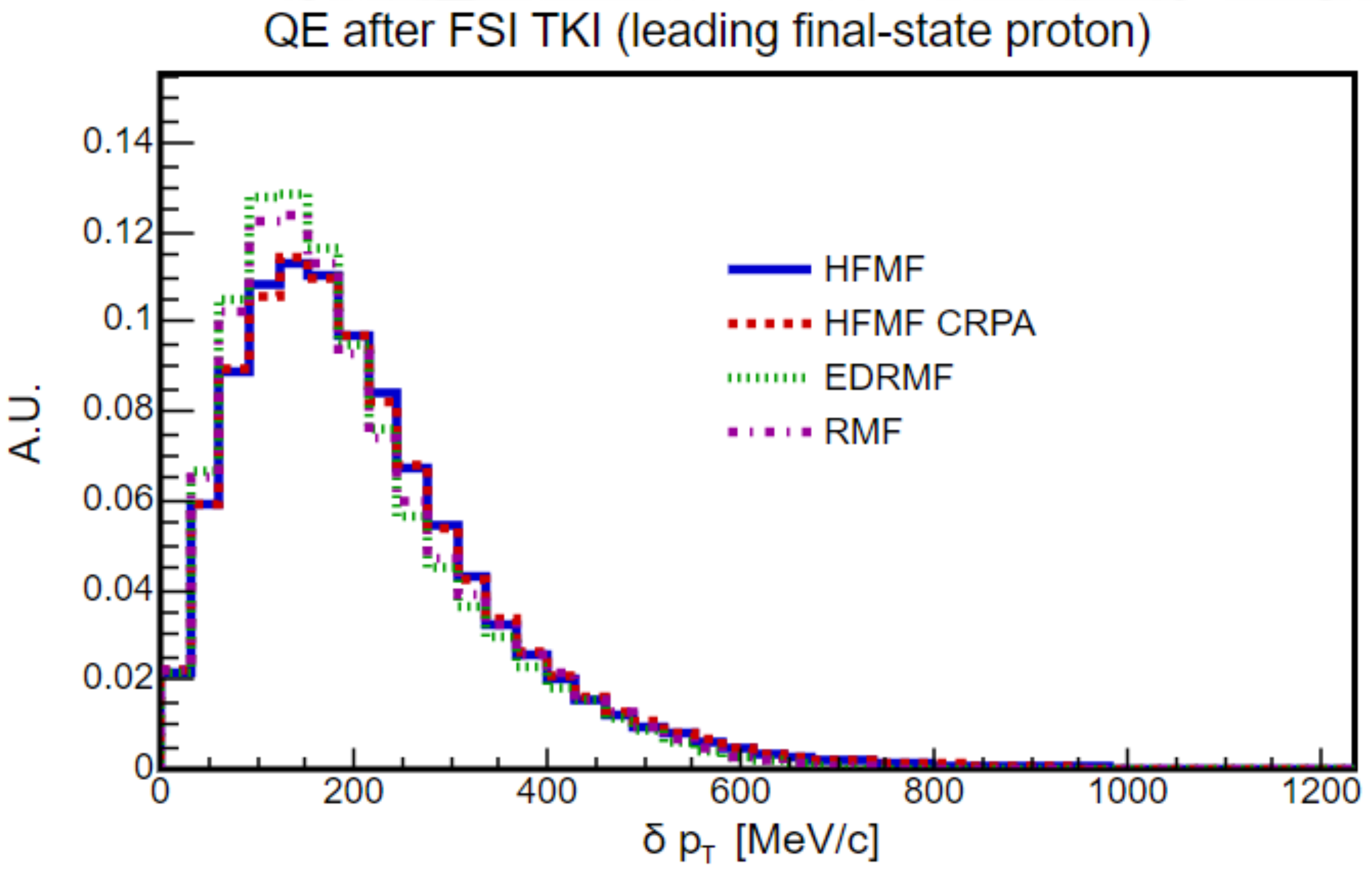
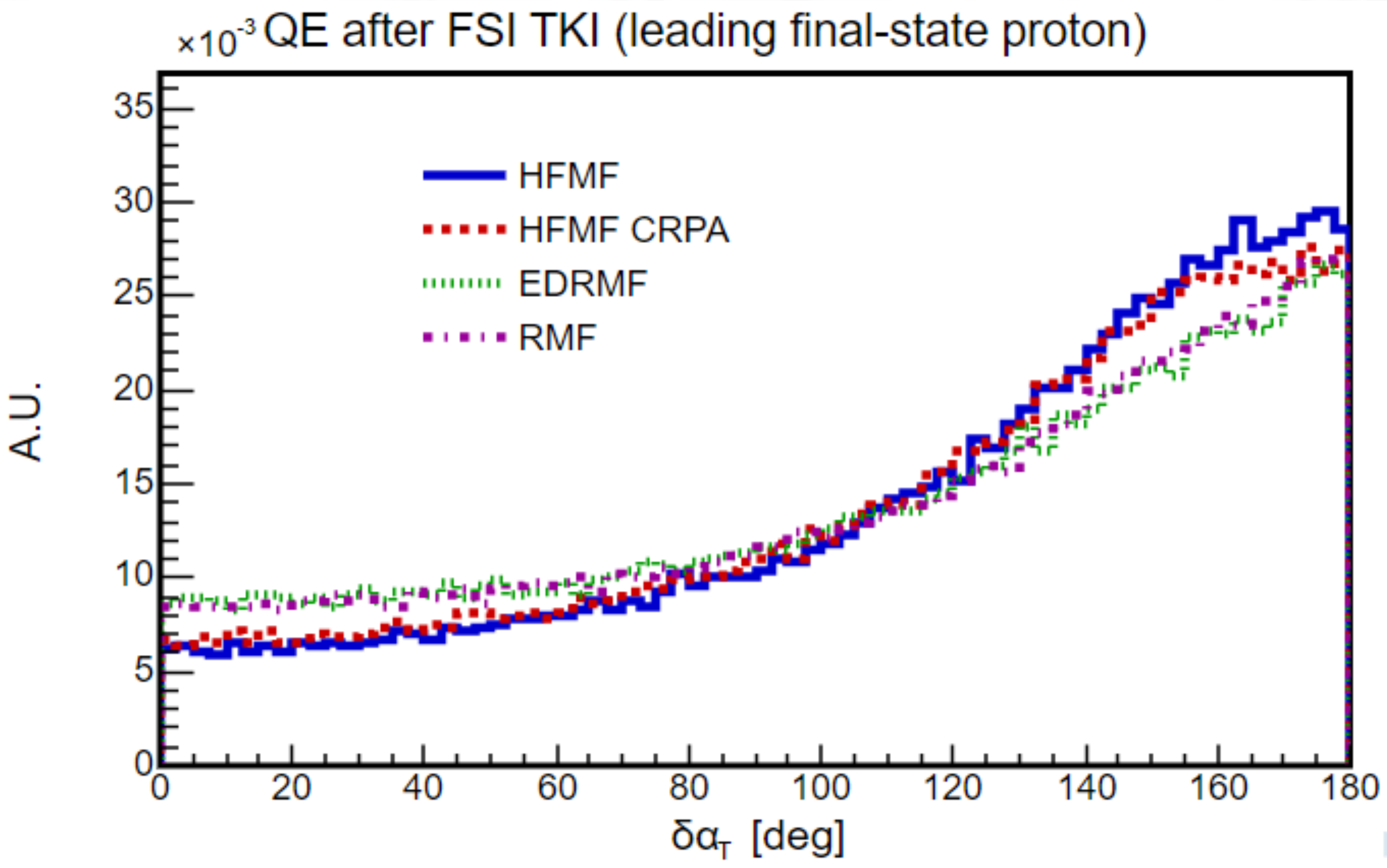
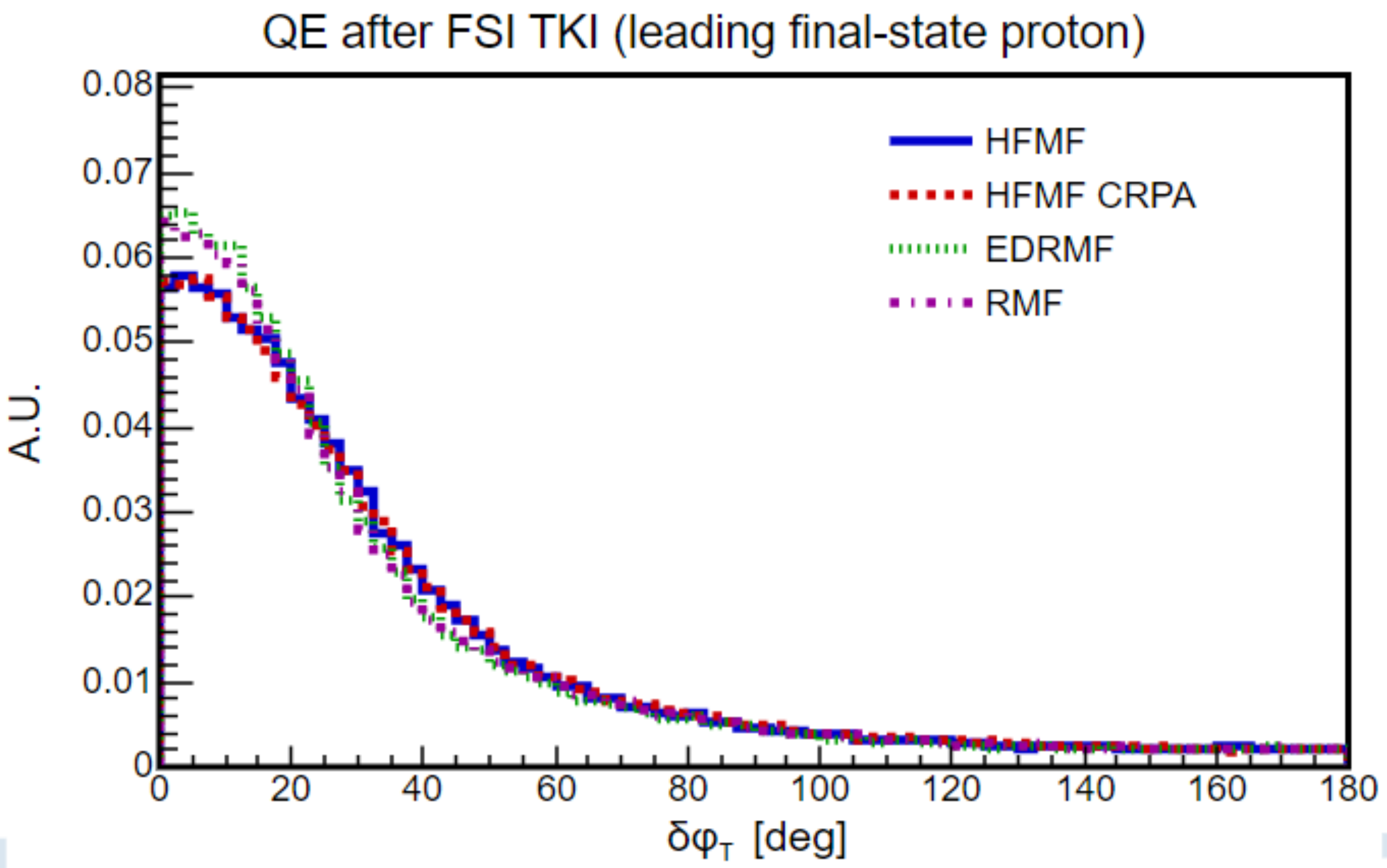
New model on transverse variables







Transverse variable explore the momentum conservation transverse to the neutrino direction.

Small dependency with the Neutrino Energy

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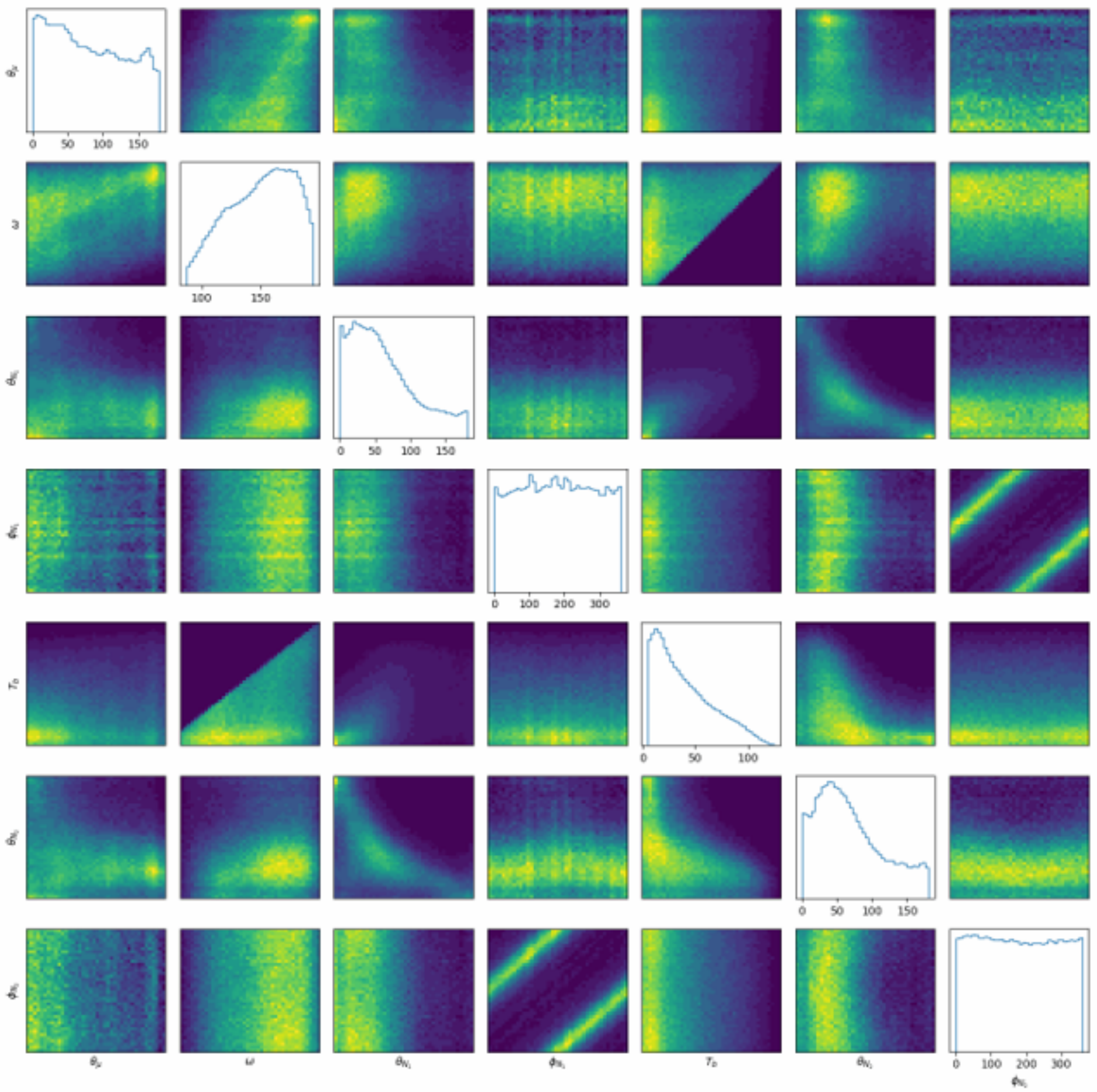
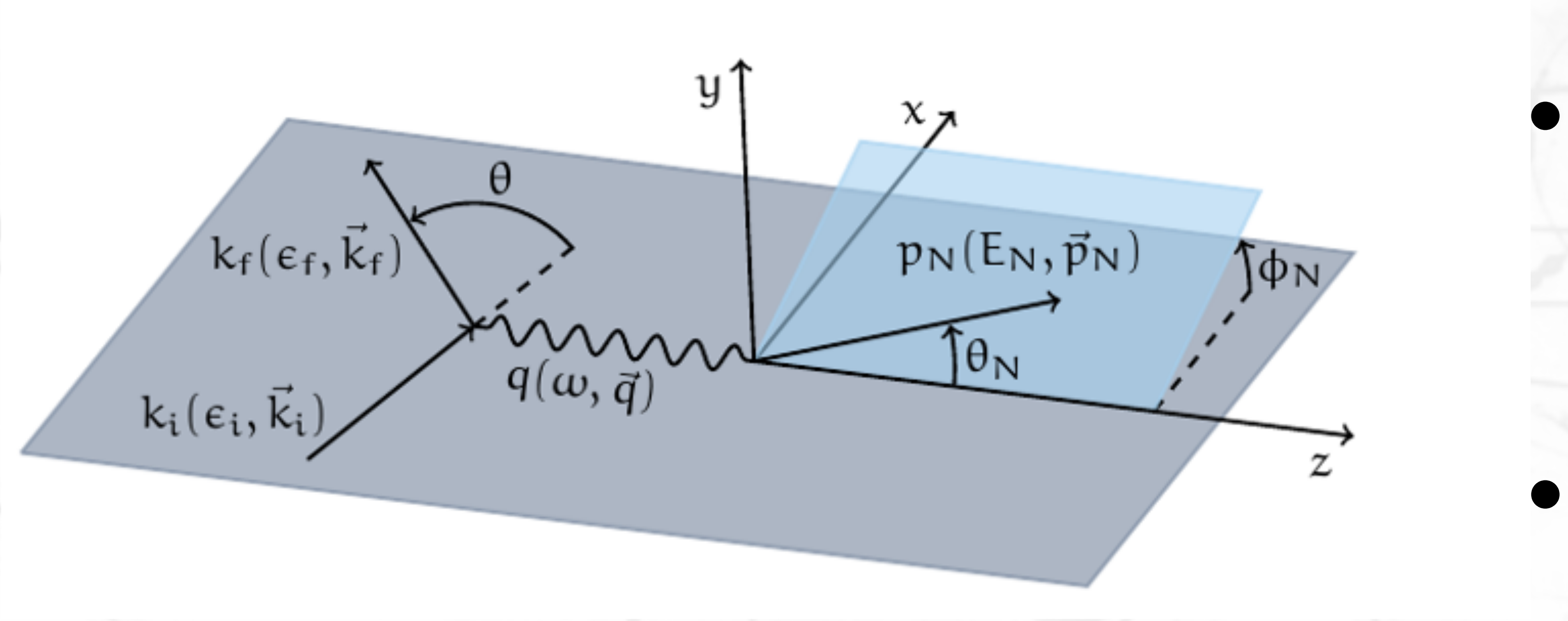
Applied to CC-2p2h



- 2 particle-2hole CC interactions (CC2p2h) has many more degrees of freedom (3 particles vs 2 in CC1p1h).
- The NF is also able to learn it providing the world-first 2p2h fully exclusive montecarlo.
- In the past we did only leptonic MC and hadronic part was generated on a random way conserving E and p.

Parity violation with protons in neutrinos



$$\nu_\mu A \to \mu^- p A'$$

- A new observable was discovered by looking into the exclusive CC1p1h interactions.
- The phi angle (proton azimuthal angle with respect to the reaction plane) is not constant !
- In reality it contains information on the nuclear shell the integration took place.
- It also violates parity!

And it is observable experimentally !

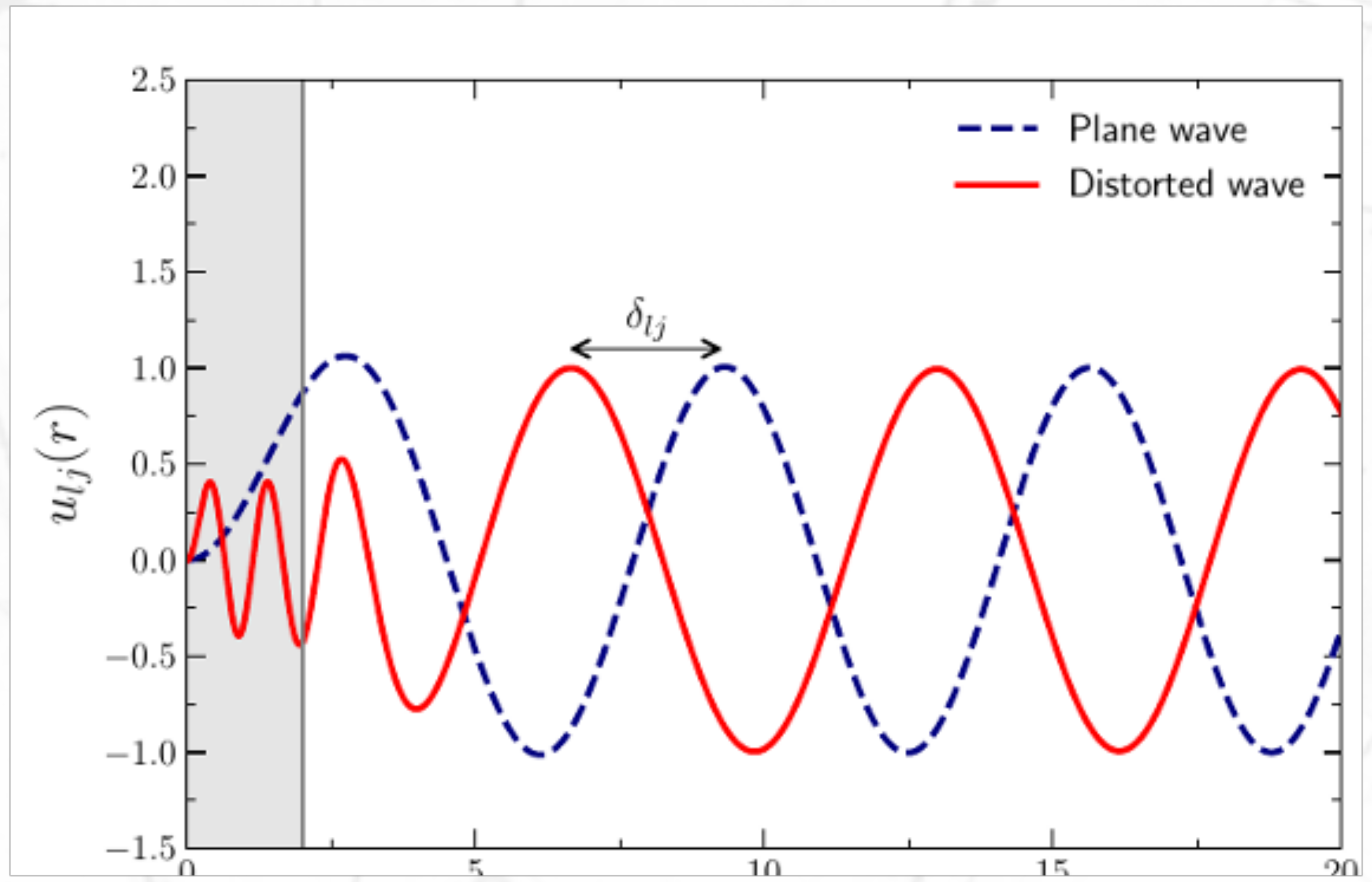
QM origine !

Solve the shrodinger equation for $V_{\mathrm{MF}} = V_C + V_{SO}$ for the ε > 0 continuum (outgoing) nucleon.

$$\left[\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} - \frac{2\eta k}{r} + k^2 - \frac{2m}{\hbar^2}\left(\hat{V}_C(r) + \hat{V}_{SO}(r)\right)\right] u_{lj}(r) = 0$$

Far from the nucleus the radial wave is a Coulomb sine shifted by δ_{lj} relative to the free wave:

$$u_{lj}(r) \sim \sin\left(kr - \eta \ln 2kr - l\tfrac{\pi}{2} + \sigma_l + \delta_{lj}\right)$$

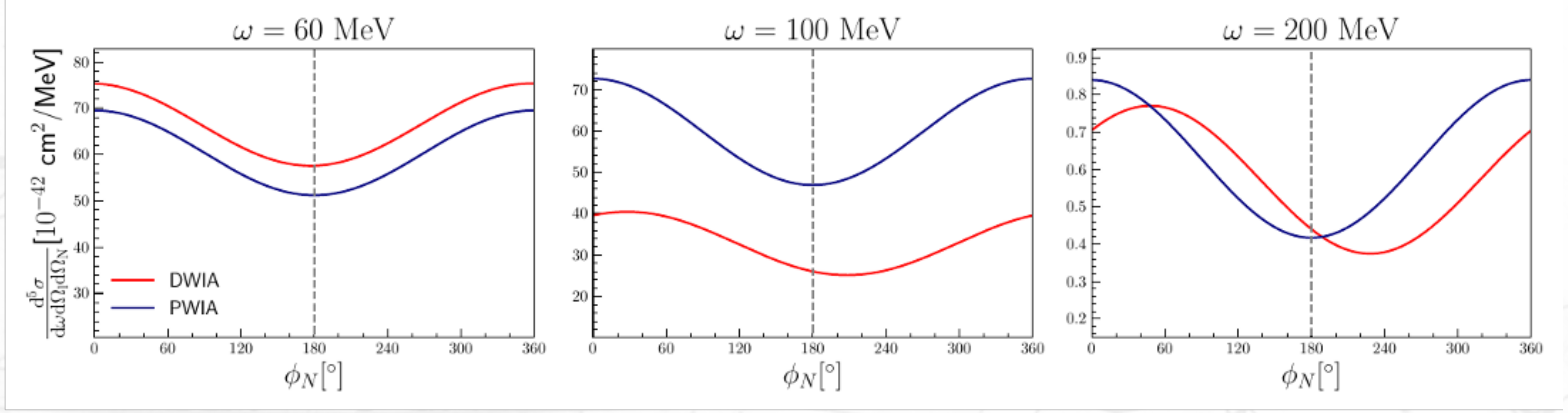


It distinguished C from O & PW from DW

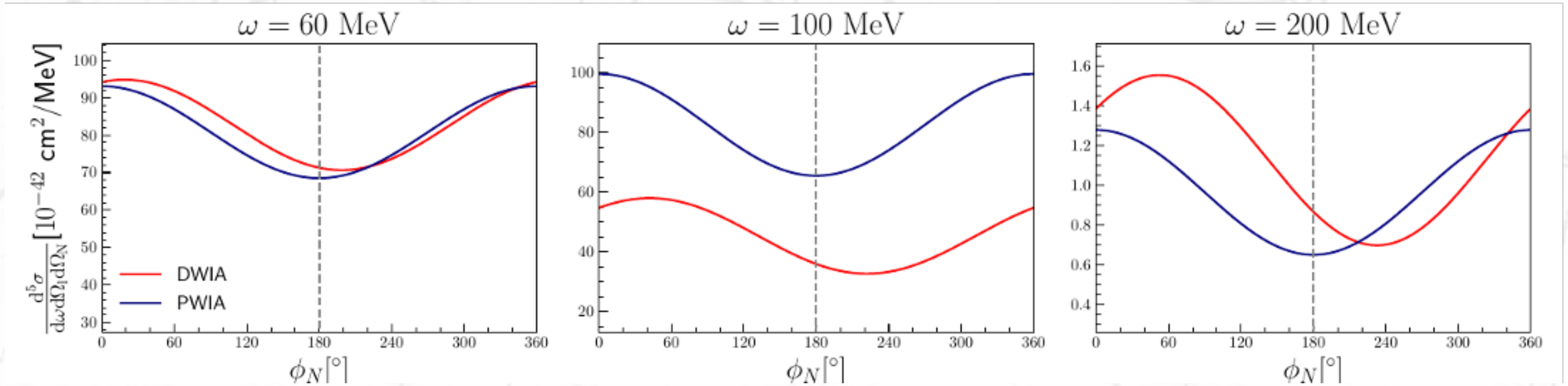
DW = Distorted wave by the nuclear potential after the interaction.

PW = Plane Wave, QM approach without nuclear potential.

CCQE on carbon



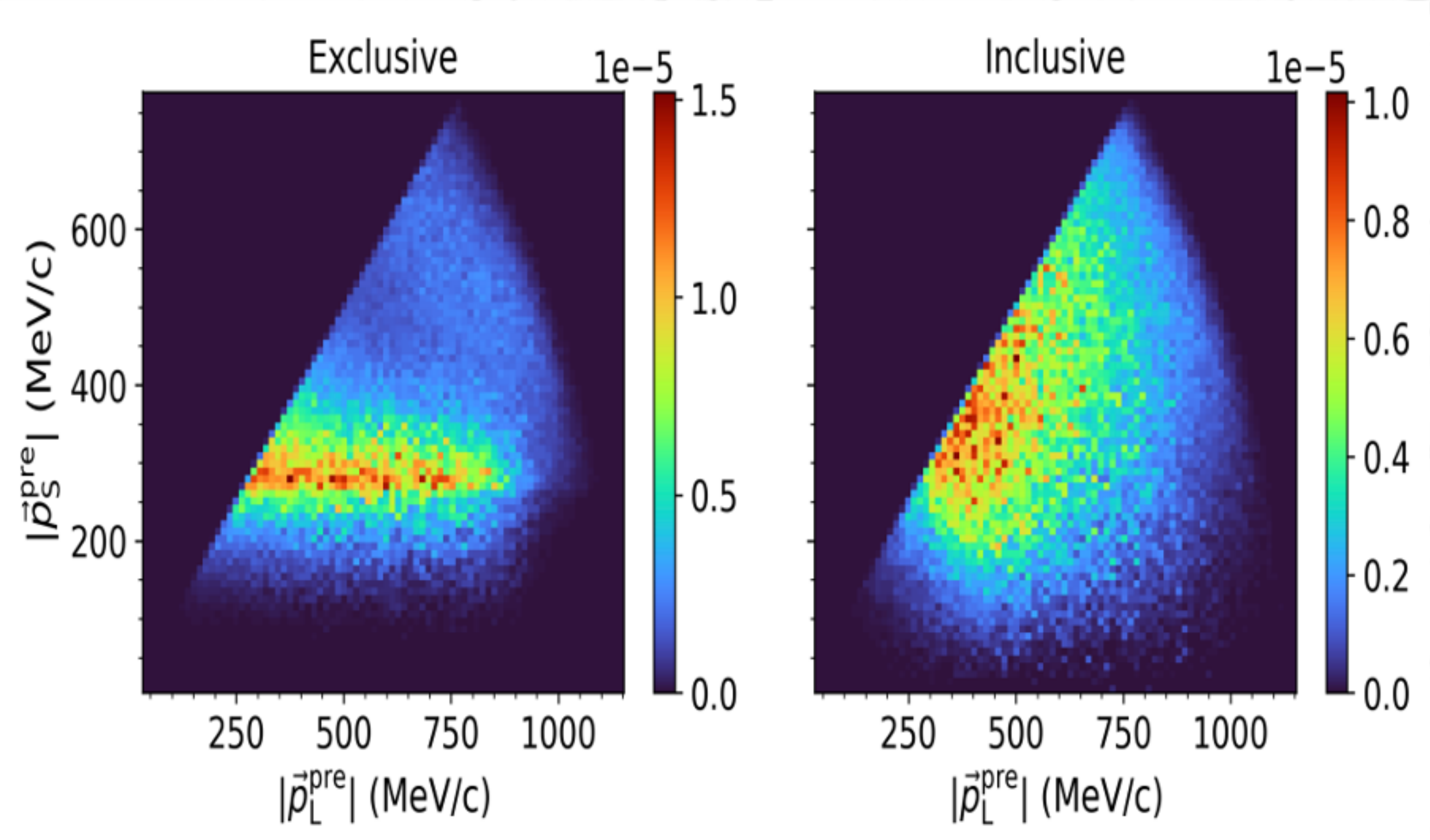
CCQE on oxygen



C vs O is a problem in T2K and HK since Near detectors are based on C and far on O

Exclusive vs Inclusive 2p2h

- Together with the Valencia group we have analysed the relevance of exclusive x-sections.



NEW EXCLUSIVE **OLD INCLUSIVE**

- The exclusive shows one final proton with higher energy thattheother.
- The inclusive shows a more “democratic” sharing of the energy.
- This difference makes large impact on the visibility of the proton and on the energy detection at the detector.

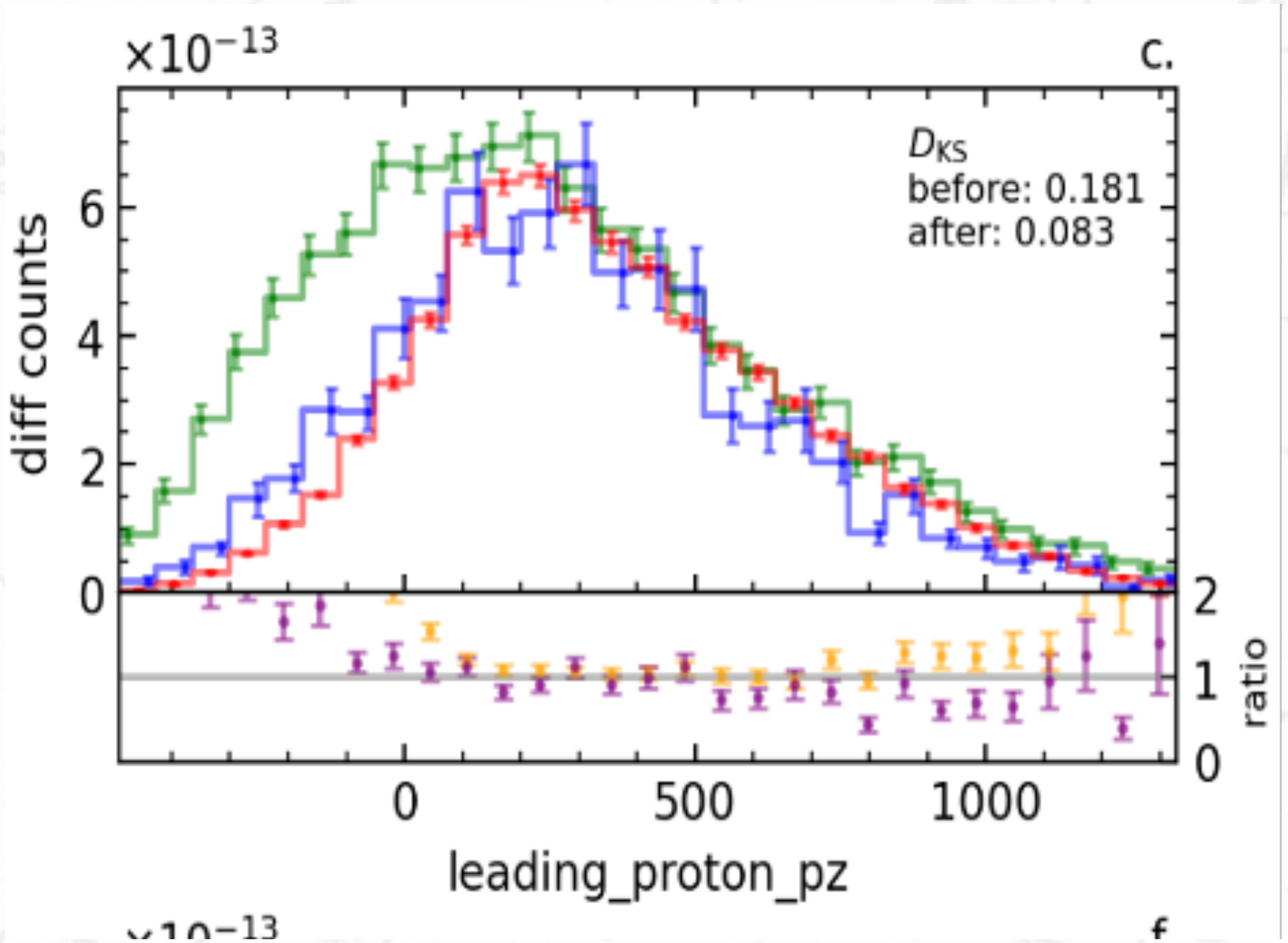
IMPORTANT TO INCLUDE THIS ON OUR MC’s

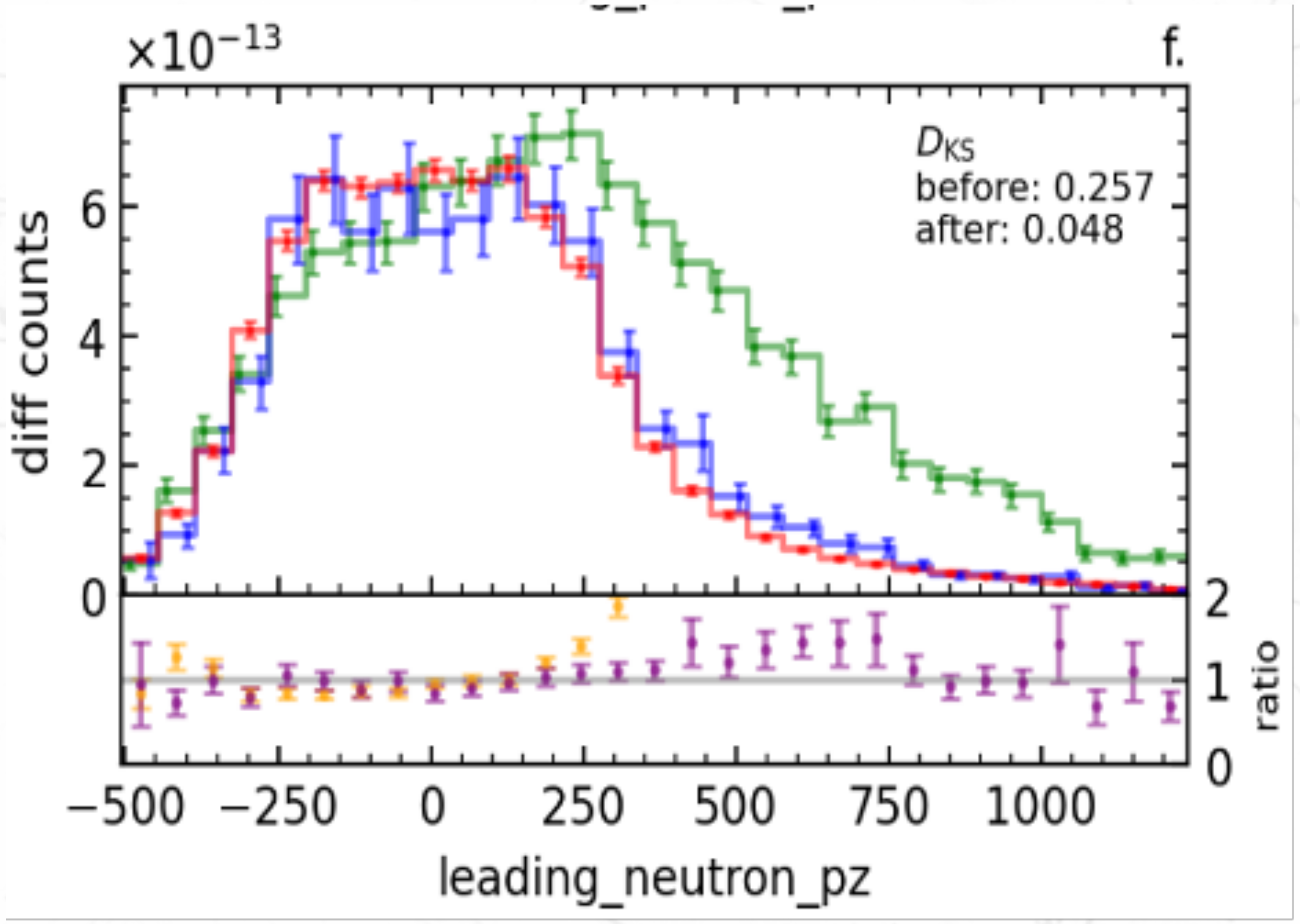
Exclusive Valencia 2p2h in MC

- We will provide a NF model in the future but at the moment we collaborate with Rochester Univ. to **BDT reweight inclusive events to show exclusive behaviour**.

- Standard method in MINERvA and T2K but limiting: intermediate “FAST” solution.

Inclusive source , Exclusive target, Reweighted inclusive

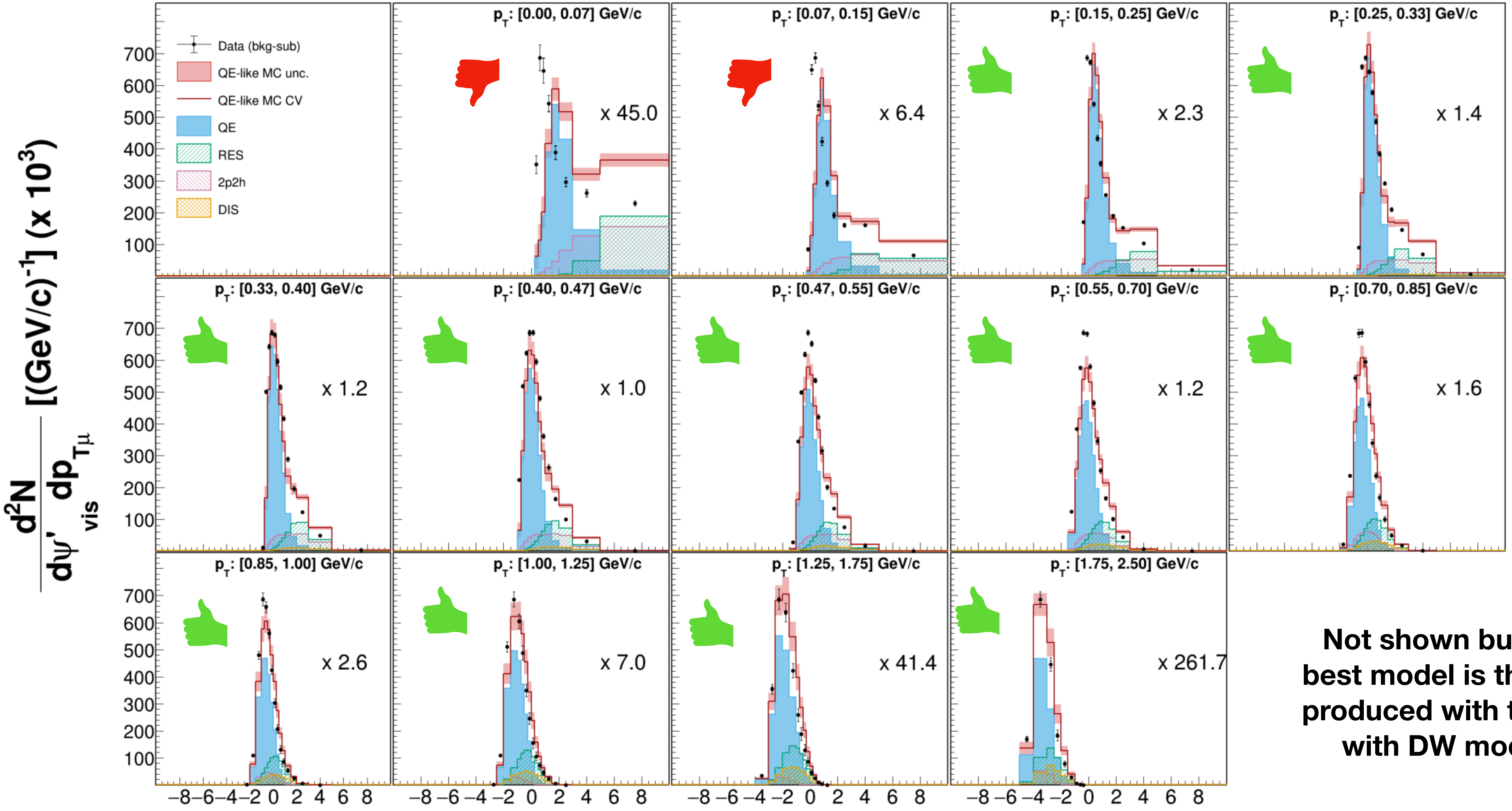




Measuring ψ'

- We use Minerva experiment date and exploit its large statistics to measure ψ' (see Lounes talk)
- ψ' is a variable that:
  - is universal for all nucleus, energies for the CCQE. (condense information).
  - It is directly related to the energy reconstruction of the neutrino.
  - Contains information about the interaction model.
- Existing for electron scattering we have recovered the concept and made it availlable for neutrinos for the first time.

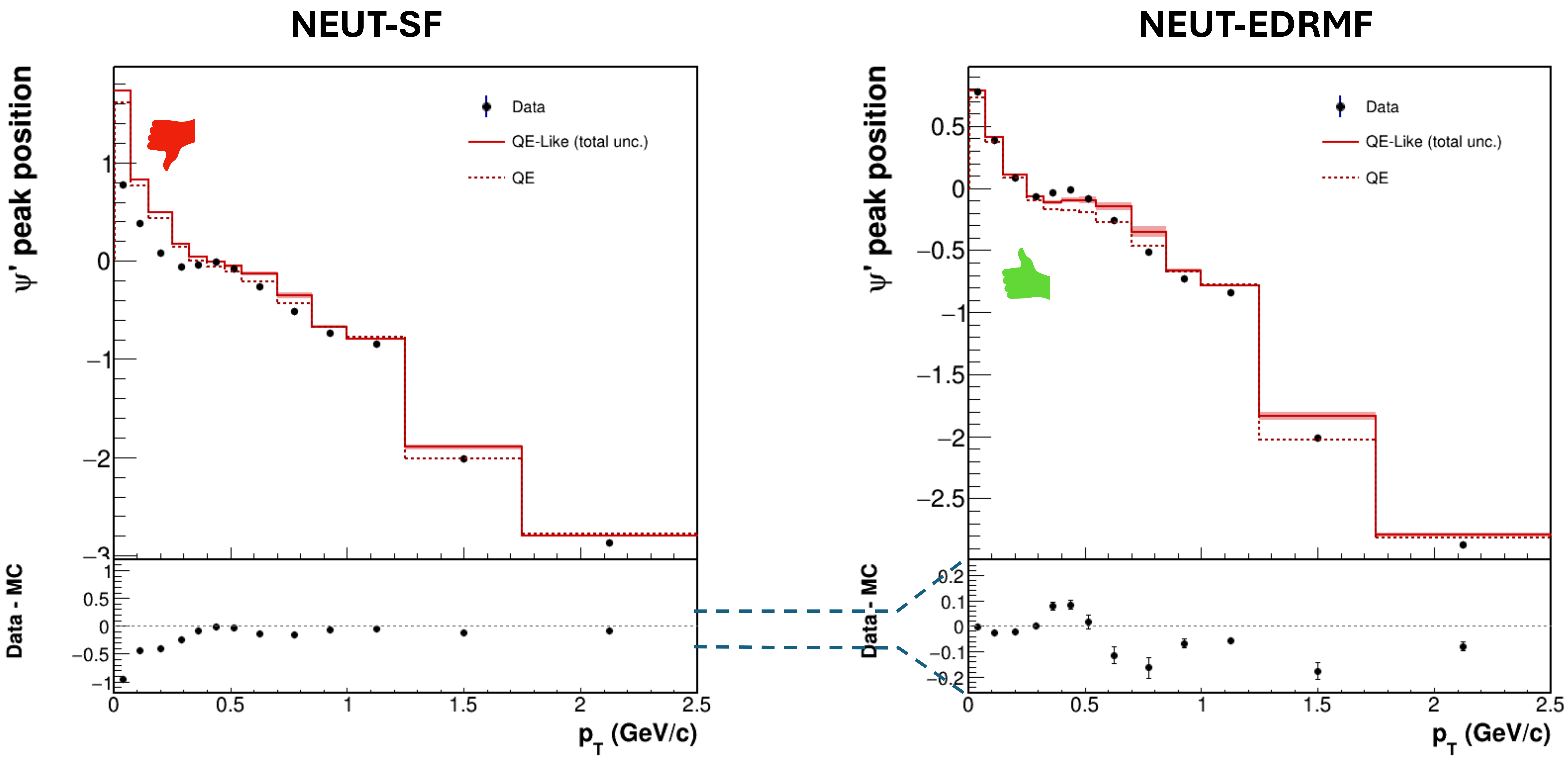
Measuring ψ’ as function of muon p_t



Not shown but our best model is the one produced with the NF with DW model.

Peak position

Peak position is a good estimator of the energy reconstruction



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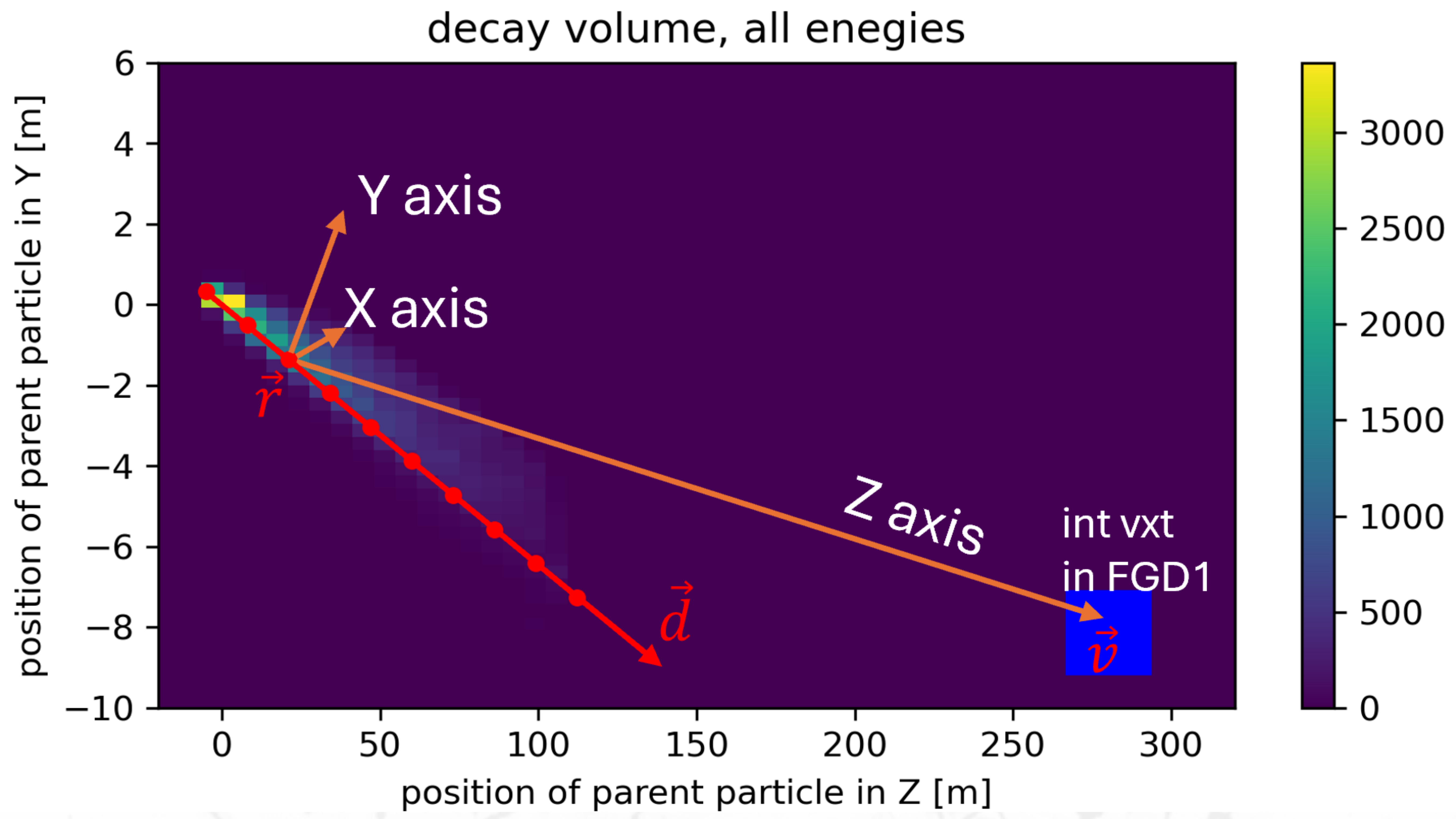
Beam

- Beam is one of the least studies elements of T2K at the near detector.
- We have always assumed that only the energy spectra was possible.
- In GVA we have developed a new observable that is sensitive to the distribution of neutrino production points in the decay volume.
- It is also sensitive to the kaon contributions!

Beam



- Idea:
  - reconstruct the direction of the neutrino as muon+proton.
  - This direction would be uniformly distributed around the direction that connects the direction of the neutrino (line from production to interaction).
  - Explore the angular distribution by changing this line.

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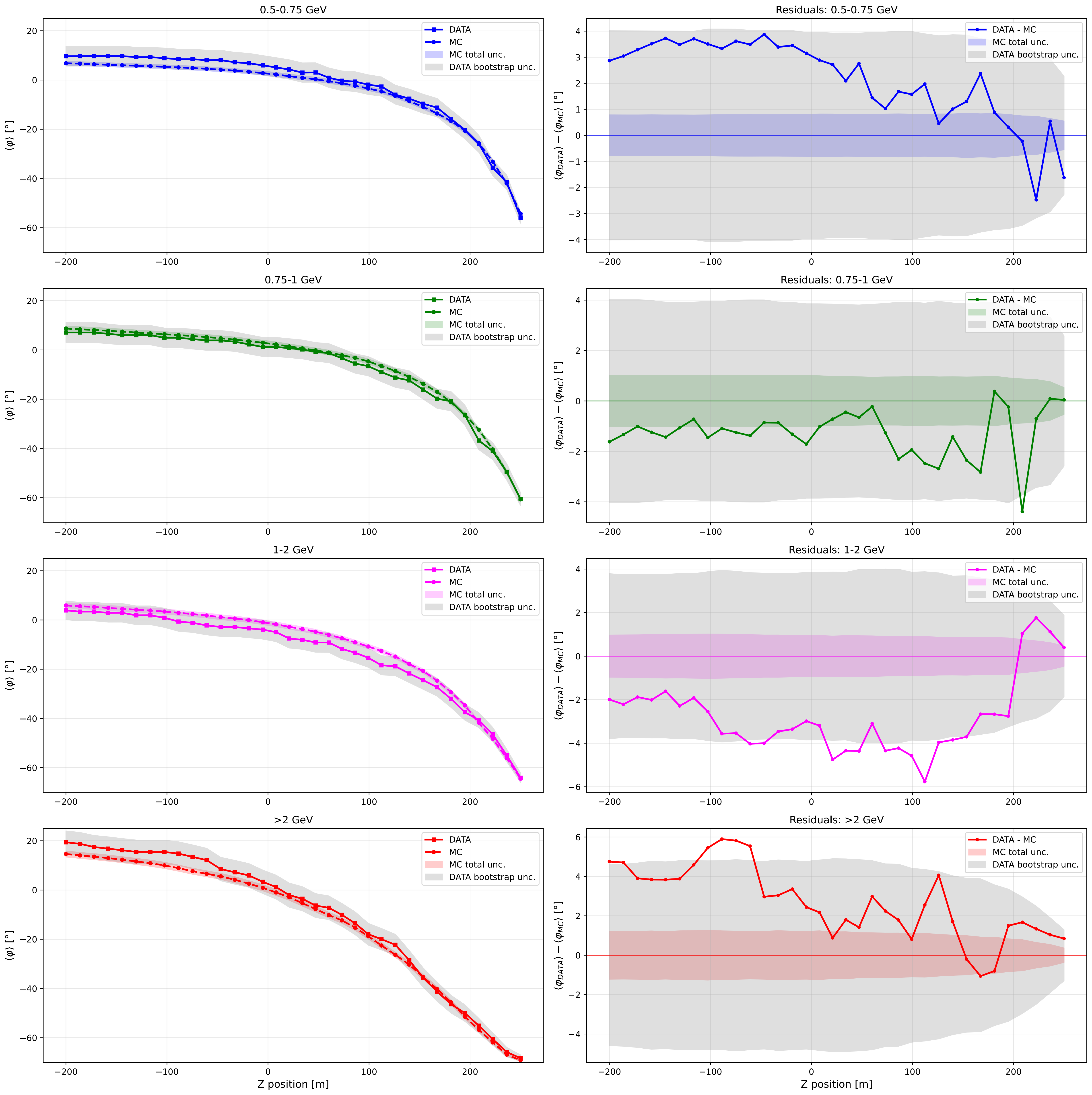
Beam

- Do this for different neutrino energies
- For different neutrino directions.
- Compute the asymmetry <ϕ>.
- <ϕ> ~ 0 approximately at the average point of neutrino disintegration.
- Compare with predictions!

First measurement of the neutrino production point and a nice check of our beam model.



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Summary

- Univ Geneva is concentrated in improving the knowledge on the systematics affecting oscillations from three points of view:
  - Co-developing advanced theoretical models.
  - Developing physics-sensitive observables.
  - Improve on statistical treatment of oscillations.
  - Check the validity of the systematic error assumptions
  - Checking systematically all components potentially affecting the measurement: Beam,…