Upgrade of the T2K near detector ND280: effect on oscillation and cross-section analysis

NUFACT 2017

M. Lamoureux (CEA, France),
on behalf of the T2K collaboration

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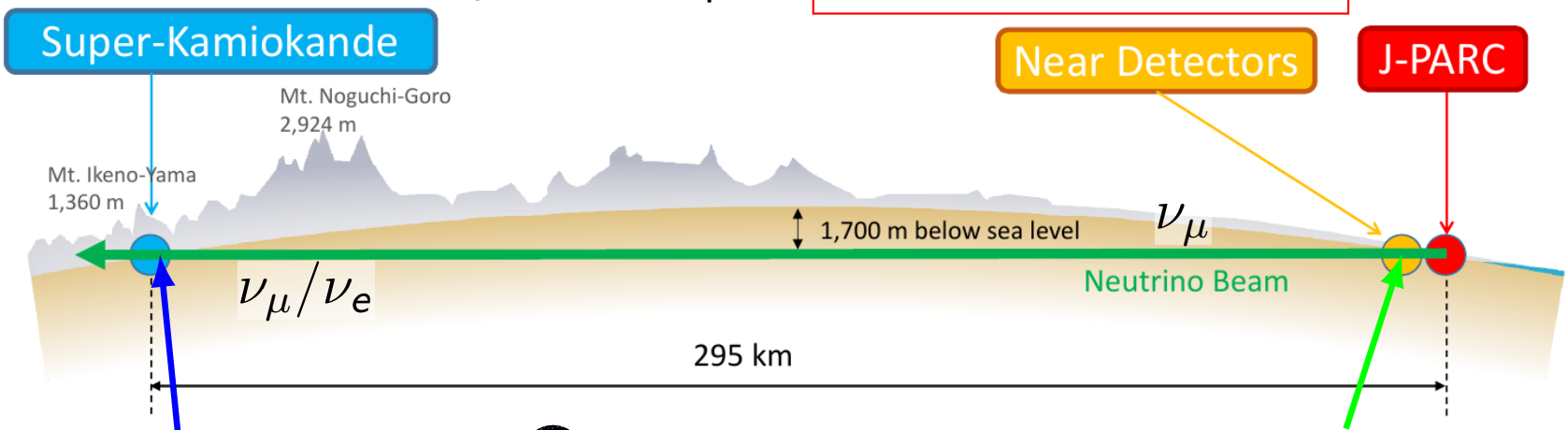
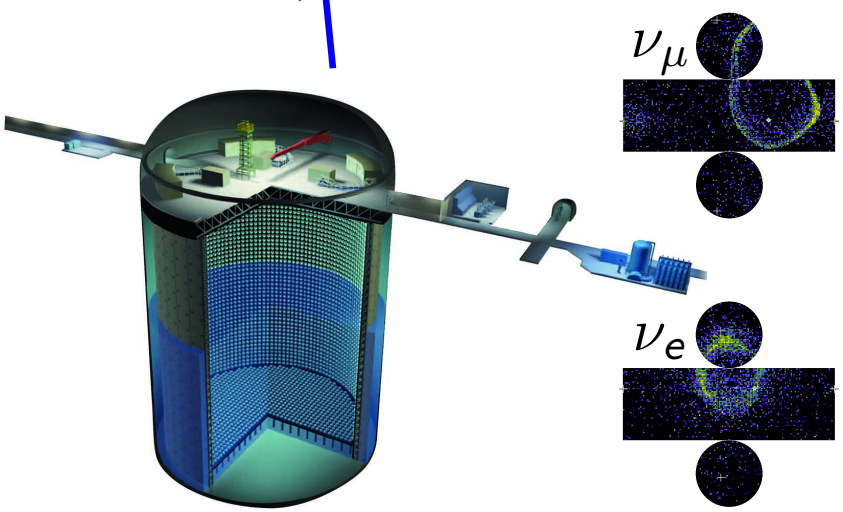
The T2K experiment

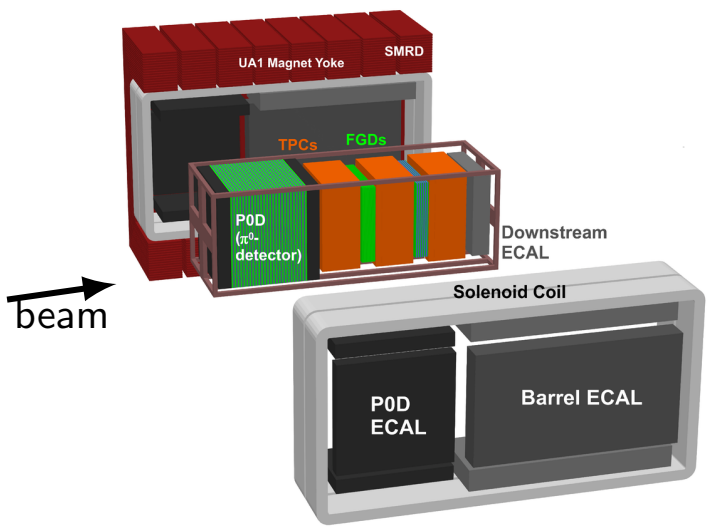
Off-axis beam (2.5°)
Neutrino flux peaks at 0.6 GeV
Less than 1% ν_e under the peak

Two production modes:
- Neutrino mode
- Antineutrino mode



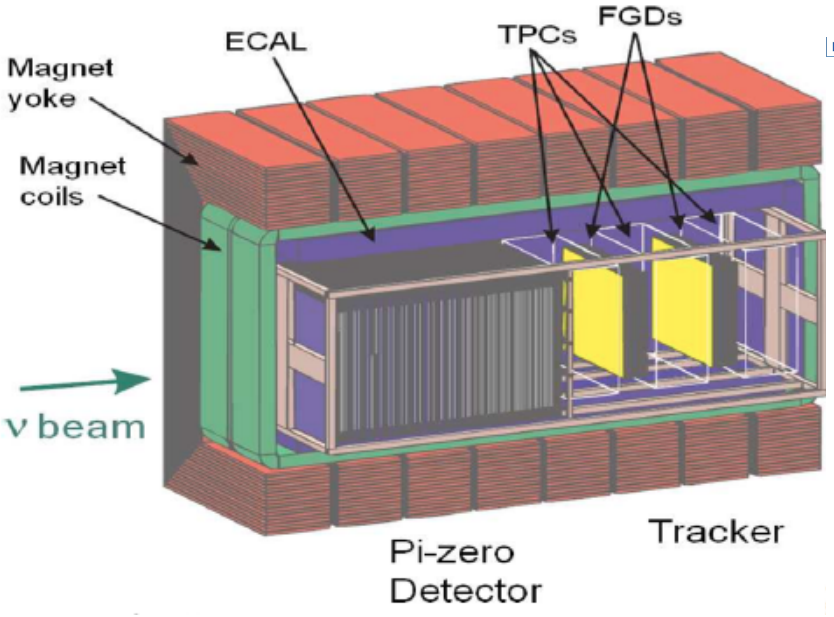


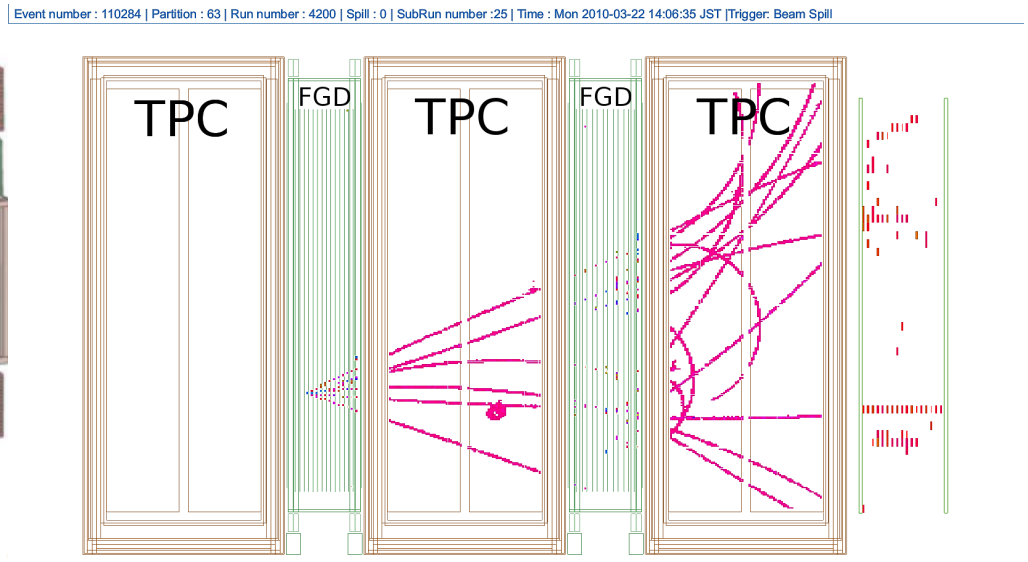
Super-Kamiokande (SK)
50 kt of water



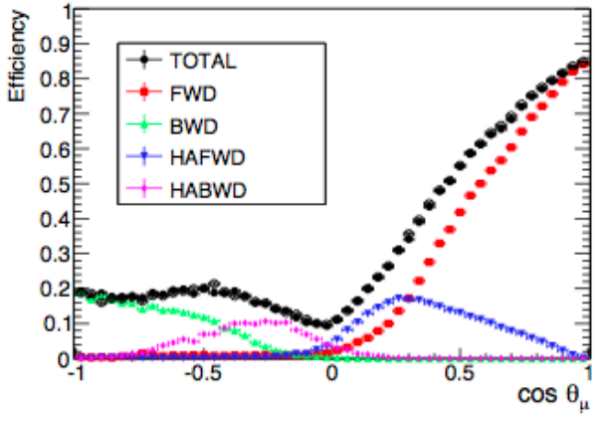
ND280

The T2K off-axis near detector: ND280





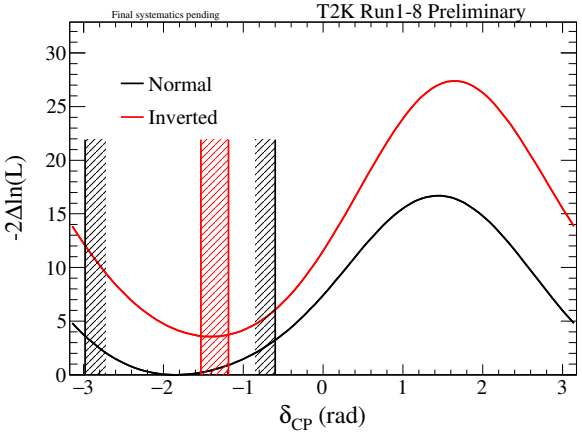
- Inside $0.2\,T$ magnet
- 2 Fine-Grained detectors (FGD) planes of *scintillator bars along XY* (perpendicular to neutrino beam)
- 3 Time Projection Chambers (TPC)
- 1 π^0 detector (P0D)
- Electromagnetic Calorimeter (ECal)



Good acceptance only for forward tracks

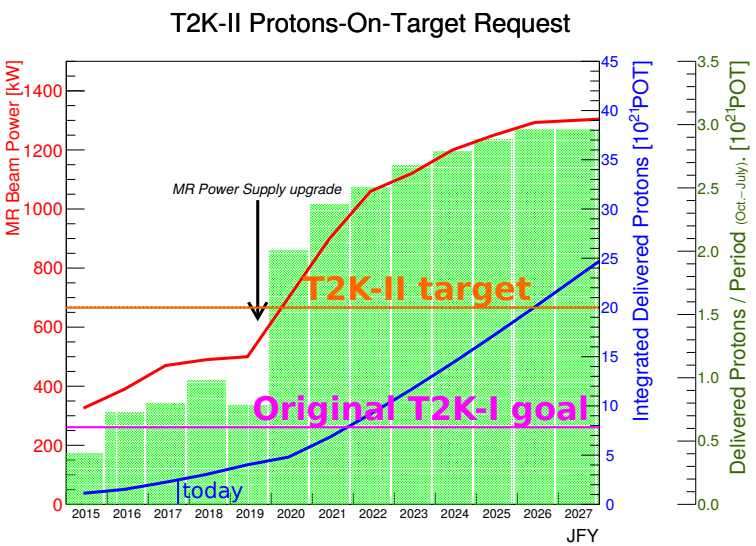
Current results of the experiment and future

2σ confidence intervals

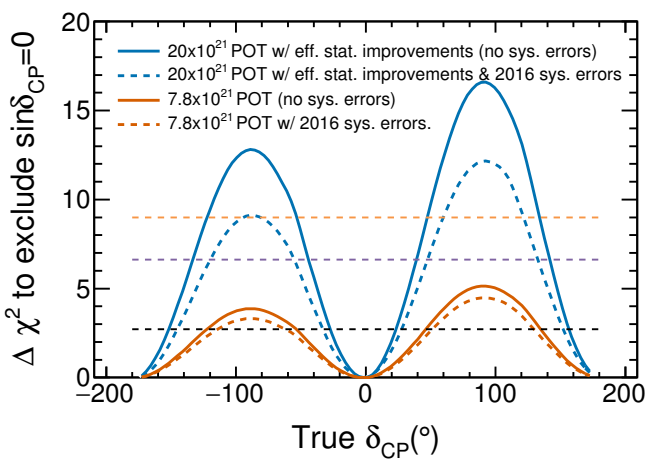


Systematic uncertainty on the predicted event rate of ν_μ and ν_e at the far detector [Phys.Rev.Lett. 118, 151801]

Source [%]	ν_μ	ν_e
ND280-unconstrained cross section	0.7	3.0
Flux and ND280-constrained cross section	**2.8**	**2.9**
SK detector systematics	3.9	2.4
Final or secondary hadron interactions	1.5	2.5
Total	5.0	5.4



ND280 has an important impact on the precision of the Oscillation Analysis. Need to reduce systematics ⇒ **Upgrade of ND280**

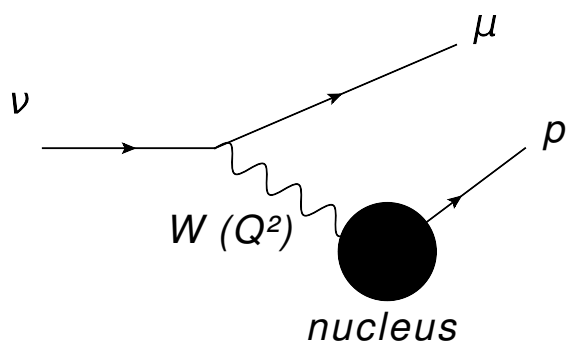


Requirements from physics

We need **good quality experimental data** to :

- test and constrain neutrino interaction models
- to minimize uncertainties propagated to Oscillation Analysis

$$\sigma(\nu - \text{Nucleus}) = \text{Func}\left(\left\{ \begin{array}{l} RFG \\ LFG \\ SF \end{array} \right. , \underbrace{|F(Q^2)|^2}_{\text{Nucleon form factors}}, \sigma_{\text{point-like}}, \underbrace{R(Q^2)}_{\text{Collective nuclear effects (RPA)}}, \text{ FSI} \right)$$



Need to measure the muon in a large phase space (in particular **high-angle** and **backward**) to estimate Q^2-dependence

- Other effects such as 2p2h bias the ν energy reconstruction at SK.
- Differences between ν_e and ν_μ need to be assessed.

*(R/L)FG: Relativistic/Local Fermi Gas, SF: Spectral Function, RPA: Random-Phase Approximation, FSI: Final State Interactions

Limitations with current ND280

- We need a better acceptance for:
  - *high angle tracks:* FGD not efficient for vertical tracks (large systematics), ECal has bad tracking ⇒ need **different geometry**
  - *backward tracks:* need **dedicated system for timing**

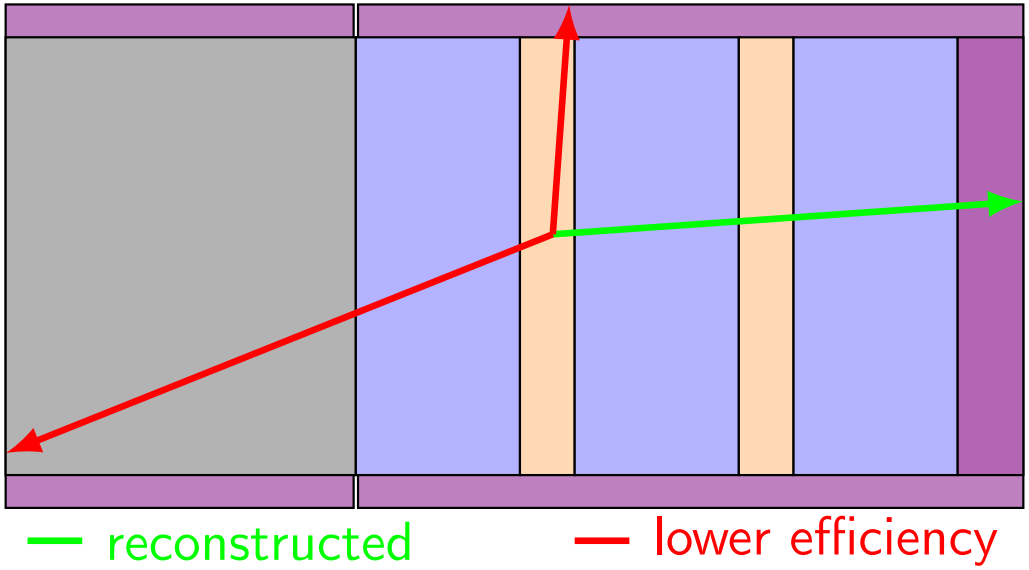


Figure: Schematics of current detector central region, colors: FGD, TPC, P0D, ECal

- Other requirements:
  - High granularity target to study vertex activity and low-momentum tracks (in particular protons)
  - Good separation between electrons and photons

Proposed upgraded ND280

- Keep the current tracker (2 vertical FGDs, 3 vertical TPCs)
- Install a new tracker (1 target, 2 horizontal TPCs)
- Keep the Electromagnetic Calorimeter
- Install Time-of-Flight counters around the new tracker
  - track sense reconstruction and particle identification (e^+-p separation)
  - 2 possible technologies: extruded plastic scint. ($\sim$ 630 ps resolution) or cast plastic scint. ($\sim$ 140 ps resolution)

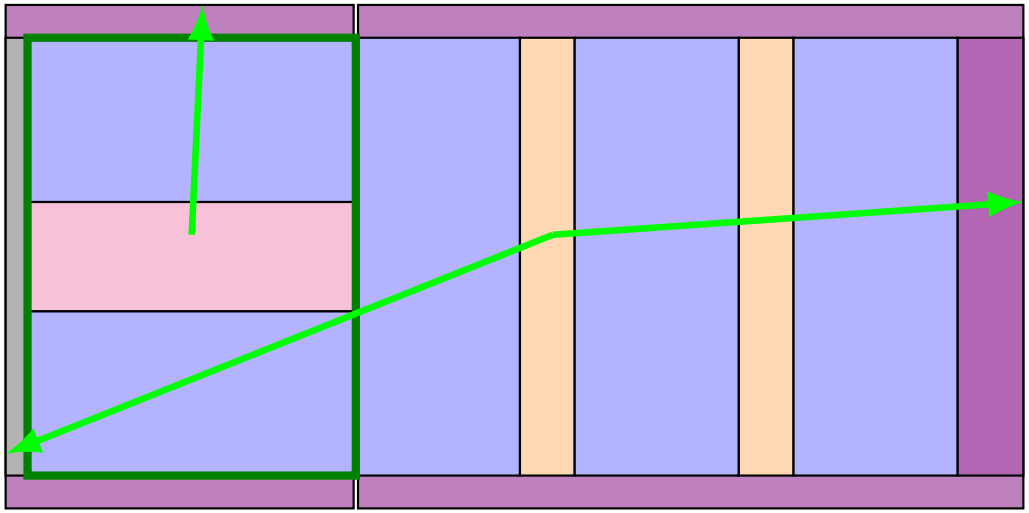


Figure: Schematics of upgrade detector central region, colors: New target, FGD, TPC, ECal, ToF counters

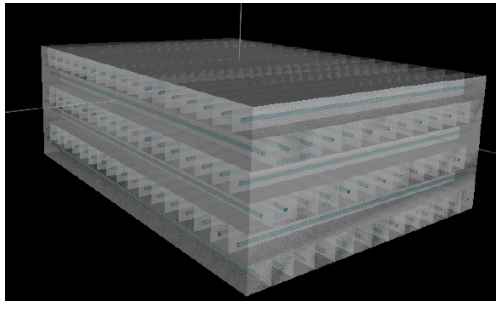
	Current	Upgrade
Total target mass (tons)	2.2	4.3

Different technologies for the target

- New target is $1.8 \times 0.6 \times 2$ m^3, with a mass ~ 2 tons.
- Several options of plastic scintillators are under study.
- Requested performance: 4π acceptance, fine granularity, $e - \gamma$ separation, improved PID and momentum threshold...

Same technology as current target but bars are along X and Z

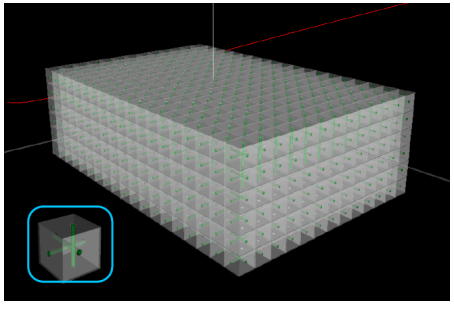
FGD XZ



- known technology
- good acceptance only for vert. tracks

Small cubes of 1 cm^3 with wavelength-shifting (WLS) fibers along X,Y,Z

SuperFGD

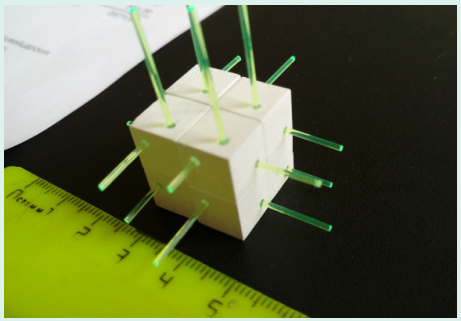


- 3 views per hit

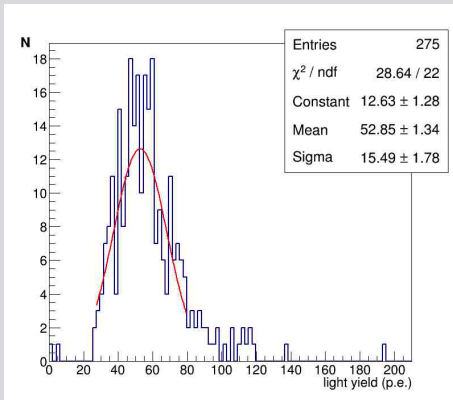
SuperFGD (arXiv:1707.01785)

Setup

Plastic scintillator cubes of $(1cm)^3$ (coated) with 3 WLS fibers

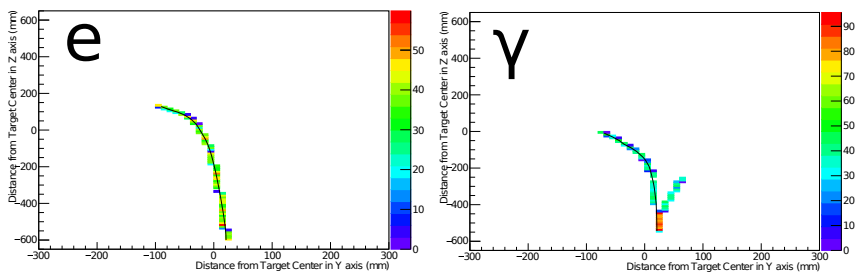


Light-yield



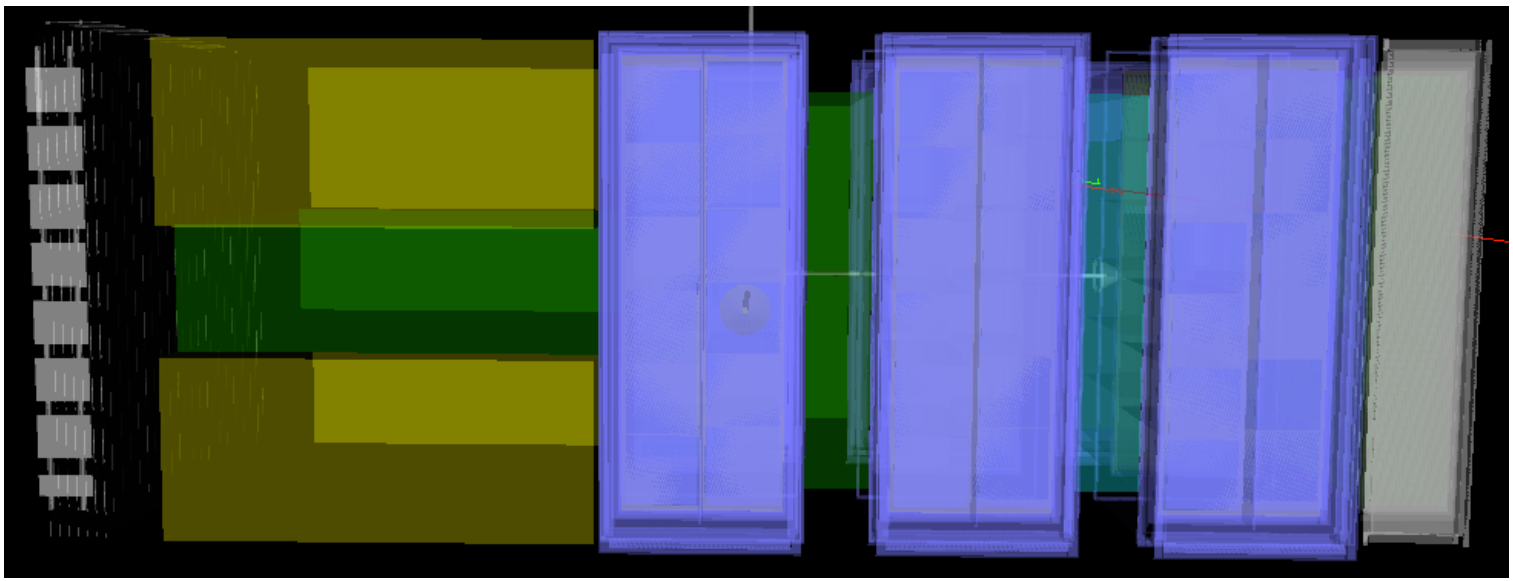
$\sim$ 50 p.e/MIP/fiber, $\sim$ 150 p.e/MIP/hit

- R&D studies of cubes at INR (Moscow) are ongoing.
- Small prototype (125 cubes) to be exposed on a test beam at CERN in Oct.2017.
- Simulations show that it is promising for the study of protons down to 300 MeV/c (current ND280 500 MeV/c) and the separation of electrons and photons.



Simulation studies

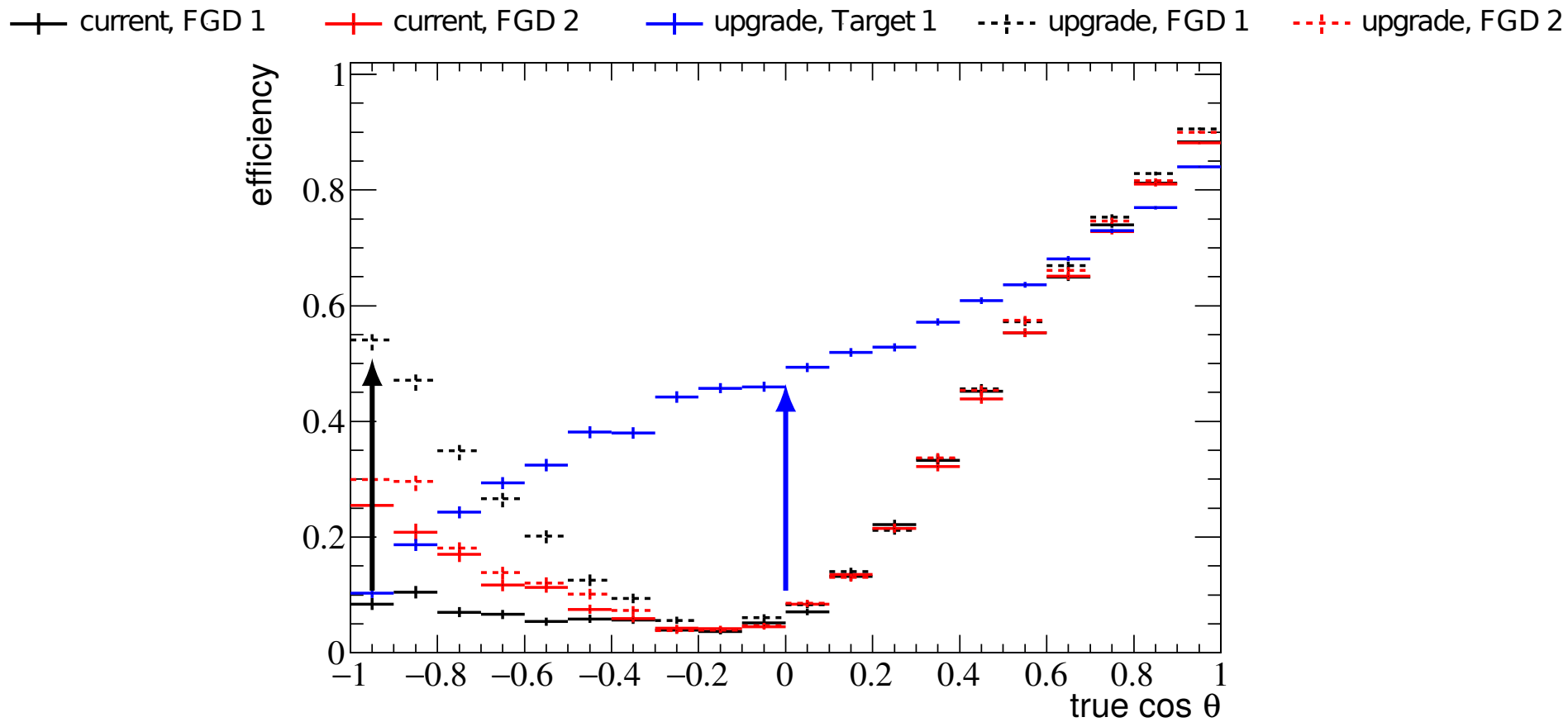
Simulations with GEANT4 for both current and upgraded ND280*, in order to compare performances.



*Target is assumed to be a carbon-based scintillator with uniform density

Selection efficiency

- Selection of muons reconstructed in TPC from a $\nu_\mu(\bar{\nu}_\mu)$CC interaction
- Time-of-Flight is used for track reconstruction



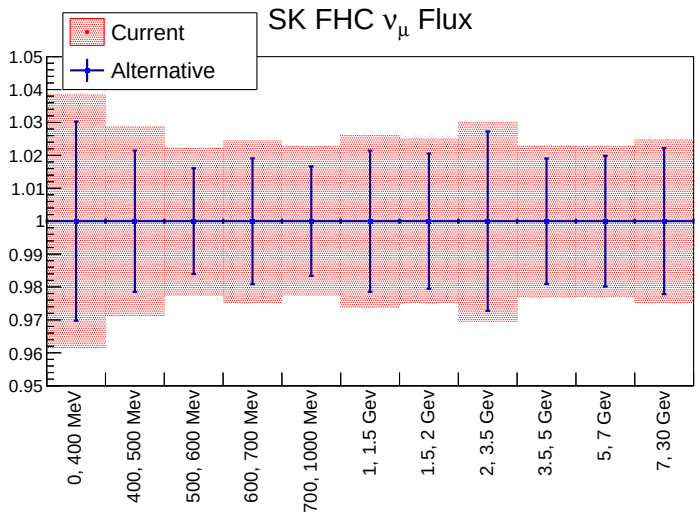
Enlarged phase space with respect to current detector

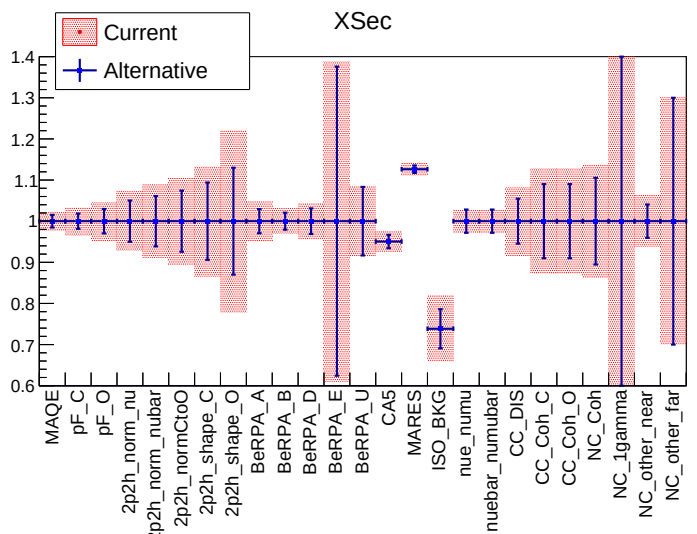
Sensitivity studies

Sensitivity studies (using the same framework as current T2K analysis) are undergoing in order to assess the impact of upgrade on oscillation and physics analysis.

Parameters	Expected improvement on uncertainties
SK flux	$\sim 20\%$
FSI	$\sim 45\%$
CCQE/2p2h	$\sim 25 - 40\%$
Other (Q^2-dependent)	$\sim 25\%$

Results obtained with 8×10^{21} POT



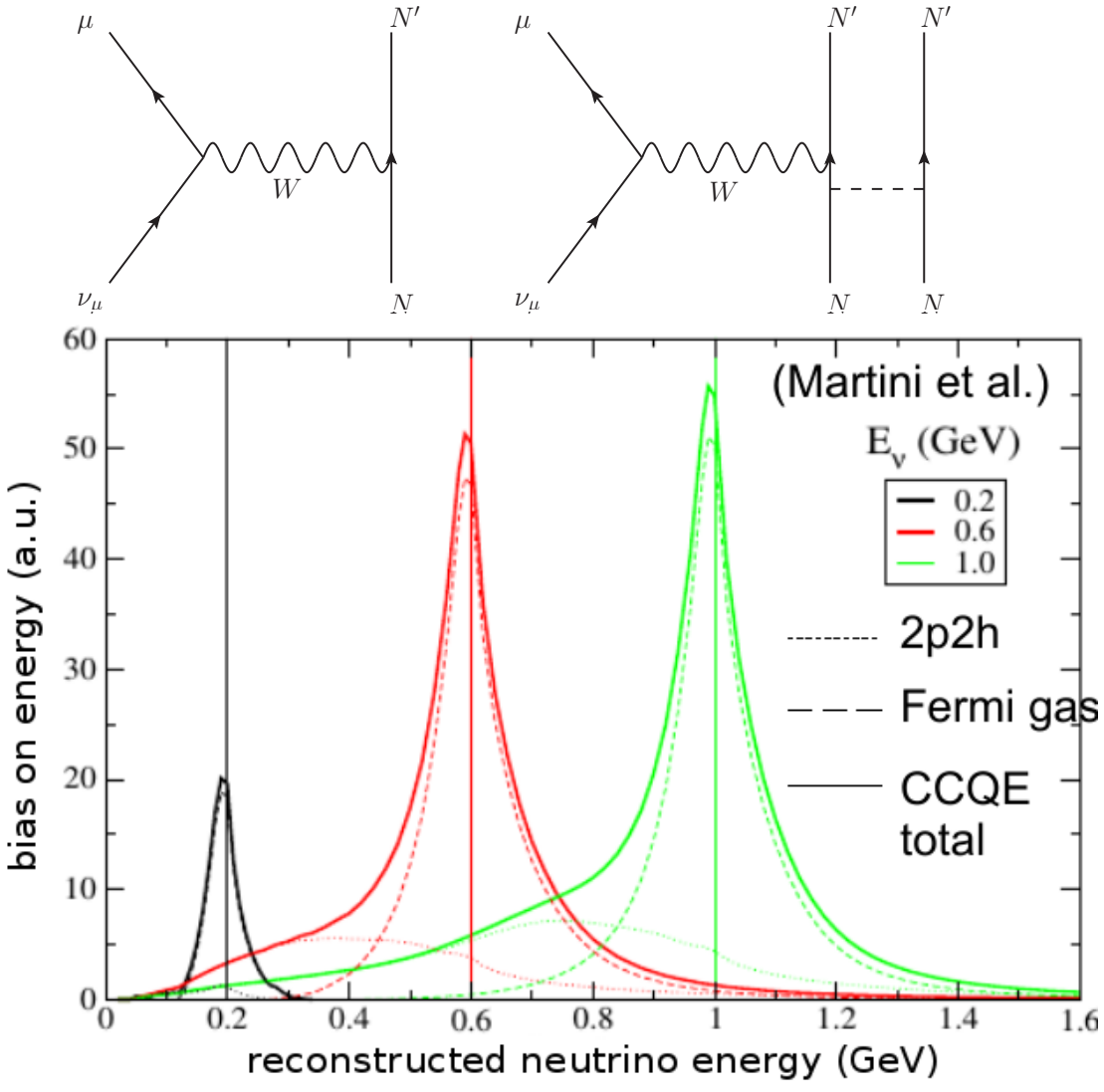


Summary

- T2K proposes to keep taking data up to $\sim$ 2026 and near-detector upgrade seems a necessary step to improve oscillation results.
- An upgrade configuration is proposed:
  - keep current tracker
  - add one *new target* (R&D ongoing) surrounded by additional TPCs and *Time-of-Flight detectors*
- Studies have shown that it is able to cover better *high-angle and backward tracks* $\Rightarrow 4\pi$ acceptance.
- This would allow us to:
  - *better constrain flux and* Q^2*-dependent parameters* in current model parametrization
  - study and test different models (such as 2p2h Martini VS Nieves)

Backups

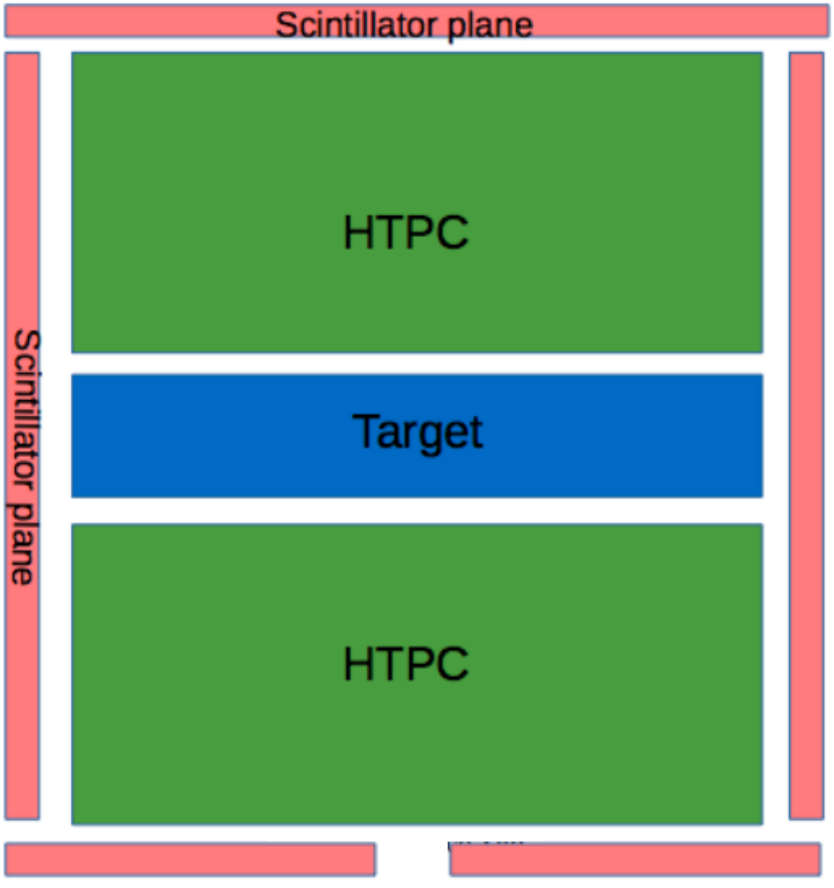
2p2h effect on Oscillation Analysis



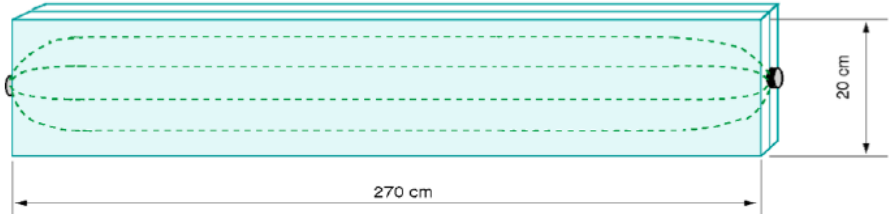
Introducing 2p2h modify the bias on reconstructed neutrino energy

Time-of-Flight counters

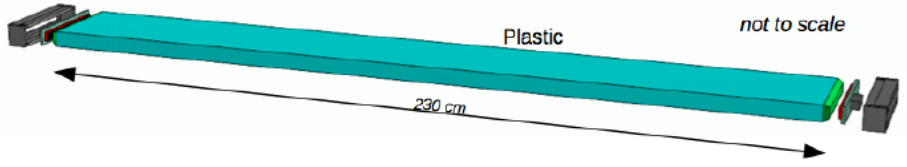
- Determine the sense of the tracks
- Improve particle identification, e^-/μ^- and e^+/p



- **Extruded plastic scintillator:**
  Time resolution of 630-650 ps
  R&D studies at INR (Moscow)



- **Cast plastic scintillator:**
  Time resolution of 120-140 ps
  R&D studies at Geneva (for SHiP)

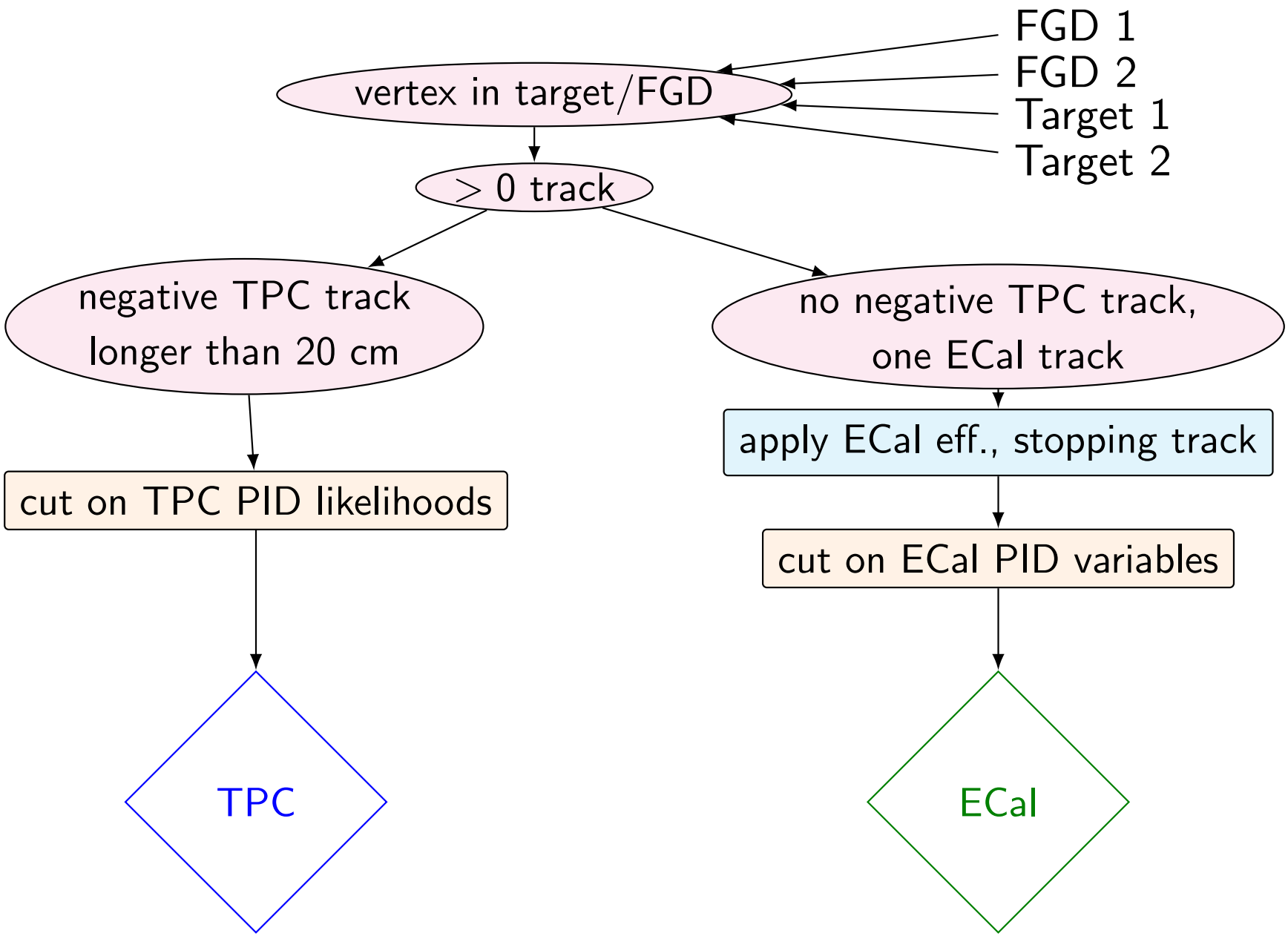


Pseudo-reconstruction

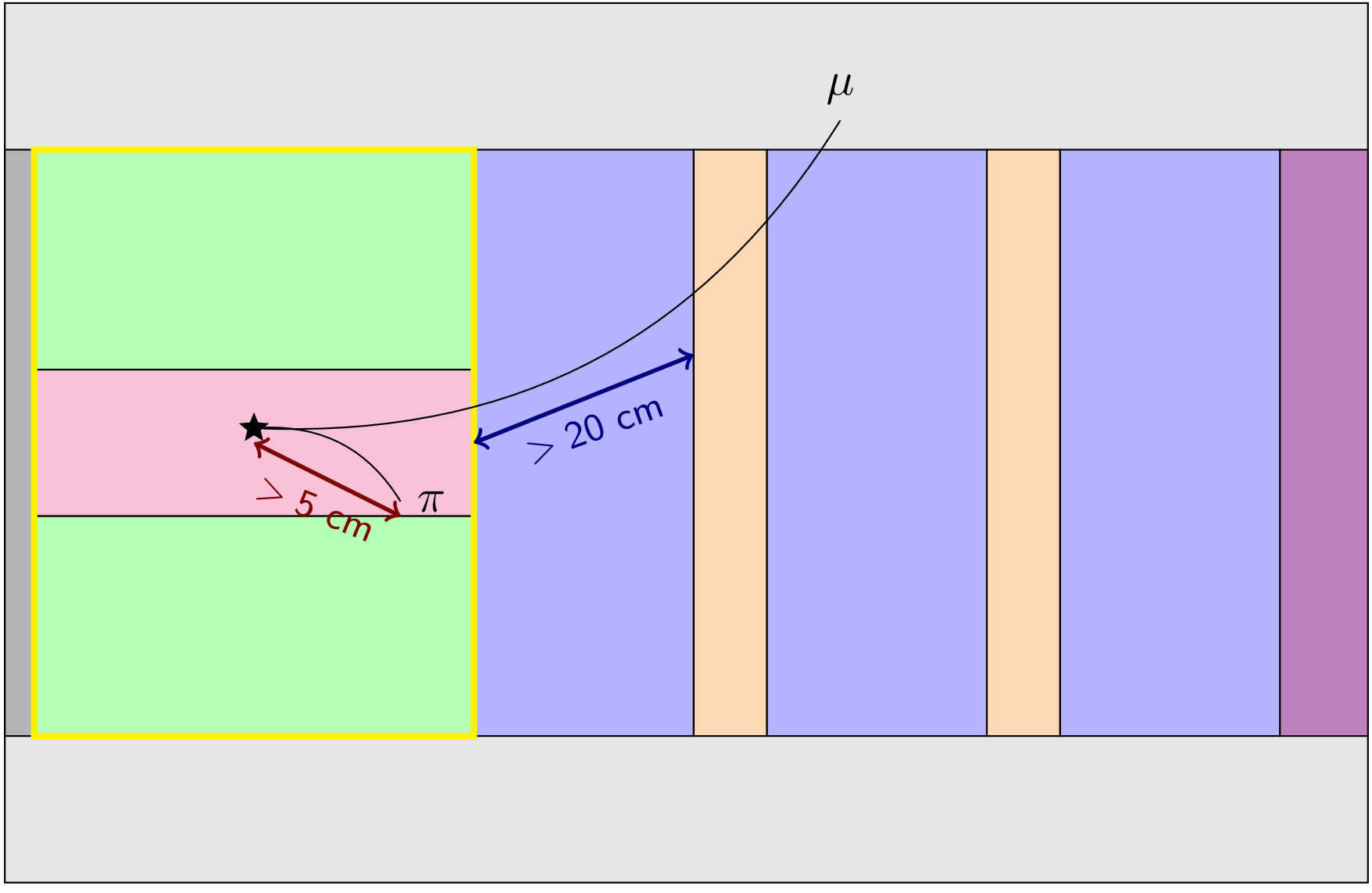
We apply some criteria on true information to mimic reco. effects.

- **TPC tracks:** $L_{TPC} > 20$ cm, momentum is smeared with expected TPC resolution, dE/dx is smeared, charge mis-identification is parametrized.
- **FGD-only tracks:** $L_{FGD} > 7$ cm, cross 4 FGD modules and $|\cos\theta| > 0.3$. PID is parametrized.
- **Target-only tracks:** $L_{\text{Target}} > 5$ cm. PID is parametrized.
- **ECal:** reco/matching efficiencies are parametrized
- **Time:** smeared in each detector giving timing ($3/\sqrt{N_{hits}} \oplus 0.6$ ns in FGD/Target, 5 ns in ECal, 600 or 150 ps in ToF counters)
- **Track sense:** all tracks assumed forward except if two detectors giving sufficient timing to flip the track

$\nu_\mu CC$ selection



Selection in a picture



Impact of the upgrade