Current and future measurements with electron neutrinos and electron anti-neutrinos in the T2K off-axis near detector

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On behalf of the T2K collaboration

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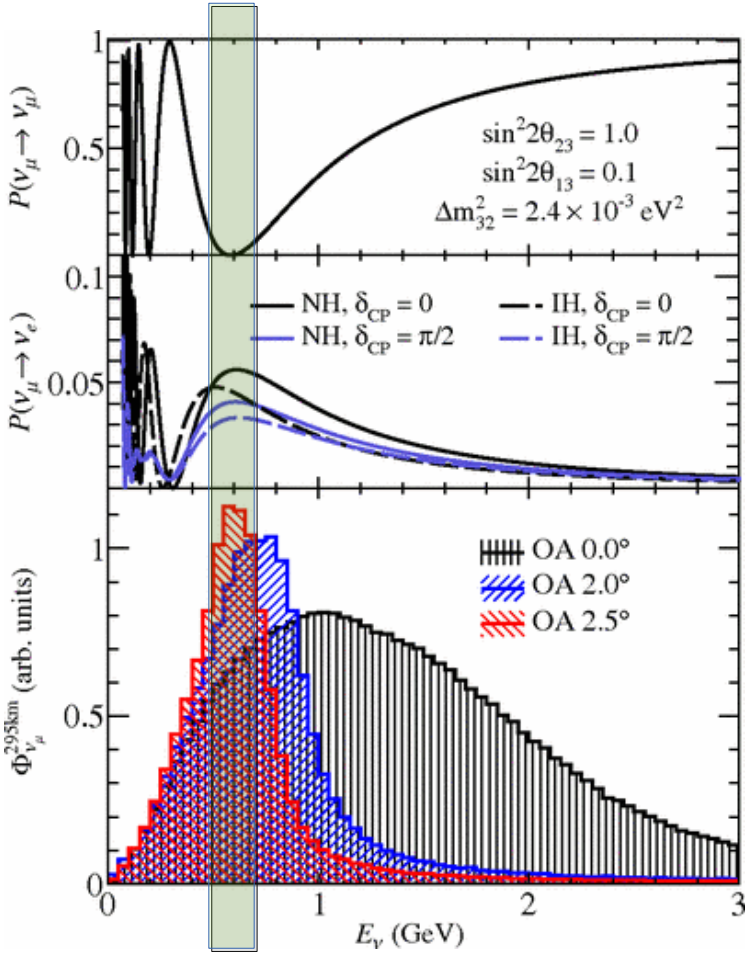
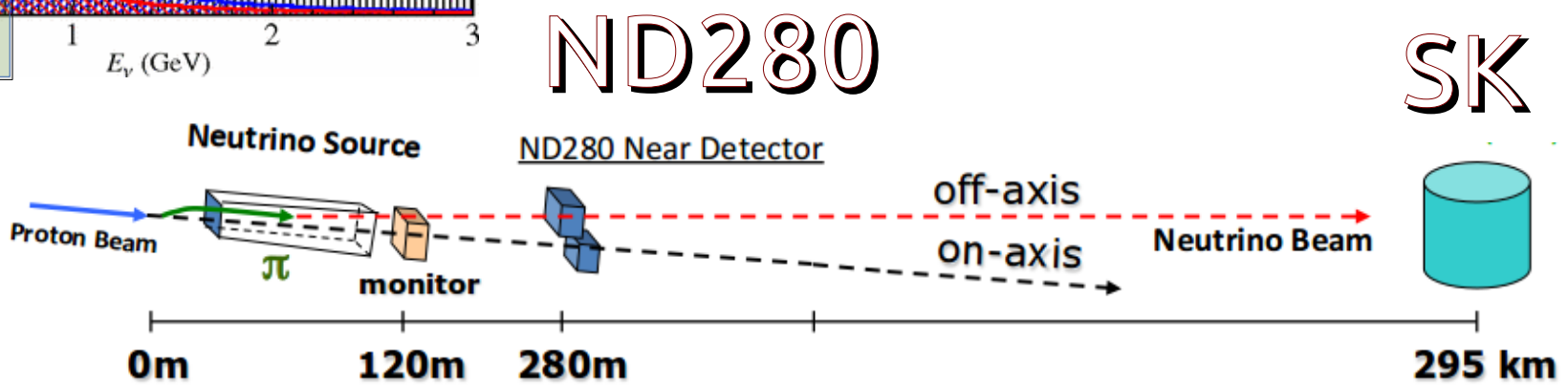
The T2K Experiment



P^+ (30 GeV) → graphite target → hadrons → ν_μ beam



The importance of ν_e measurements for oscillation experiments such as T2K

ν_e are **signal** in **oscillation** ($\nu_\mu \rightarrow \nu_e$) search

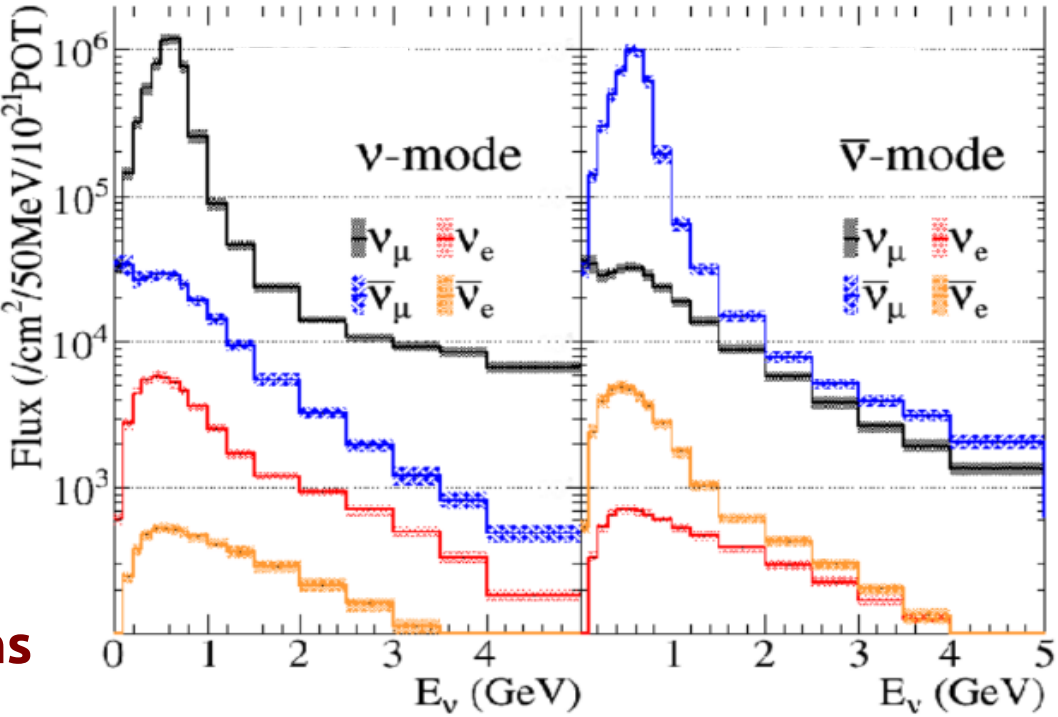
ν_e are largest **background** (**intrinsic ν_e beam component**)

→ need reliable model for cross-section and ν_e flux

Phys. Rev. D86:053003, 2012.

- Theoretical **differences in ν_e and ν_μ cross sections** due to lepton mass
- Many ν_μ cross-section measurements
- Data for ν_e interactions is more scarce
- Sensitivity of neutrino oscillation experiments is increasing

  → Look to future: **ν_e cross-sections** constrained with data



ν_e cross-section measurements

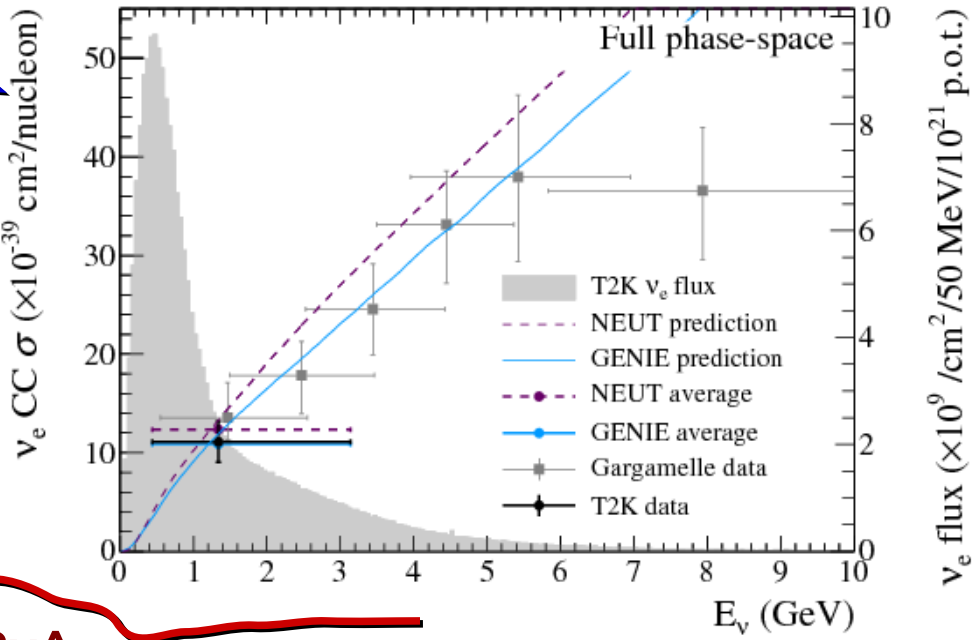
T2K: ν_e CC inclusive cross-section

Phys Rev Lett 113,241803 (2014)

T2K Run **2010-2013** (ν-beam)

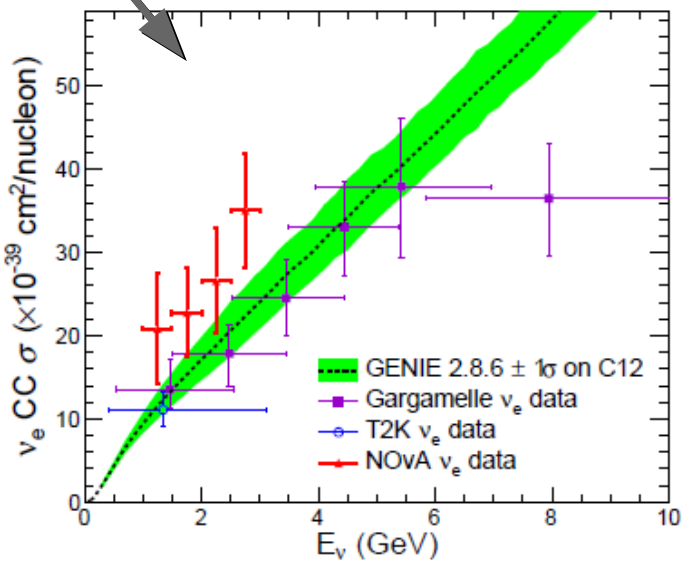
Good quality data collected from

5.9×10^{20} protons on target (POT)



Gargamelle ν_e and $\bar{\nu}_e$ CC inclusive

(included on plots) **Nucl Phys B 133,1978**



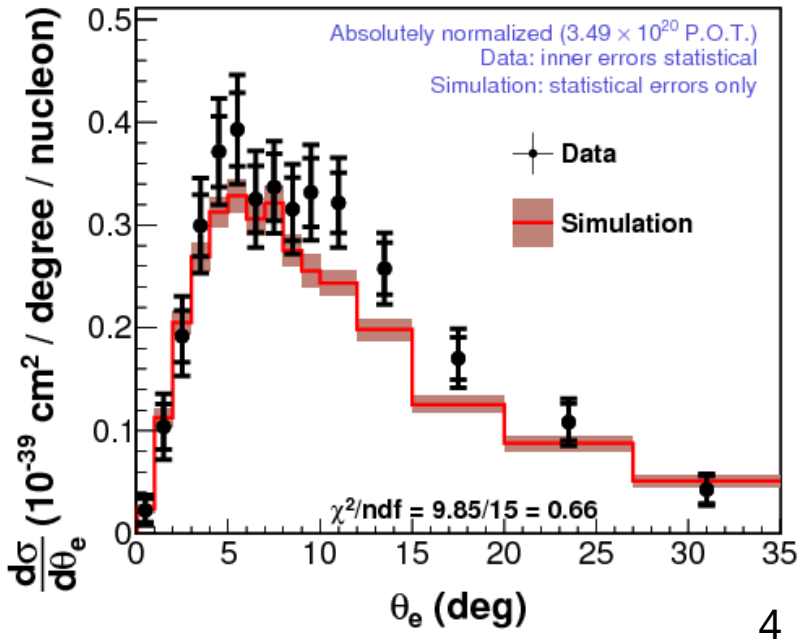
Nova: ν_e CC inclusive

ArXiv:1601.0121 (2016)

MINERvA: ν_e CCQE-like

Phys. Rev. Lett. 116 (2016)

* < Eν >= 3.6 GeV
* Hydrocarbon (similar toT2K & Nova)
* ν_e and $\bar{\nu}_e$ in signal
* 1 GeV cut on E_e



ND280

T2K off-axis near detector

2x **FGDs**

(Fine-Grained scintillator Detectors)

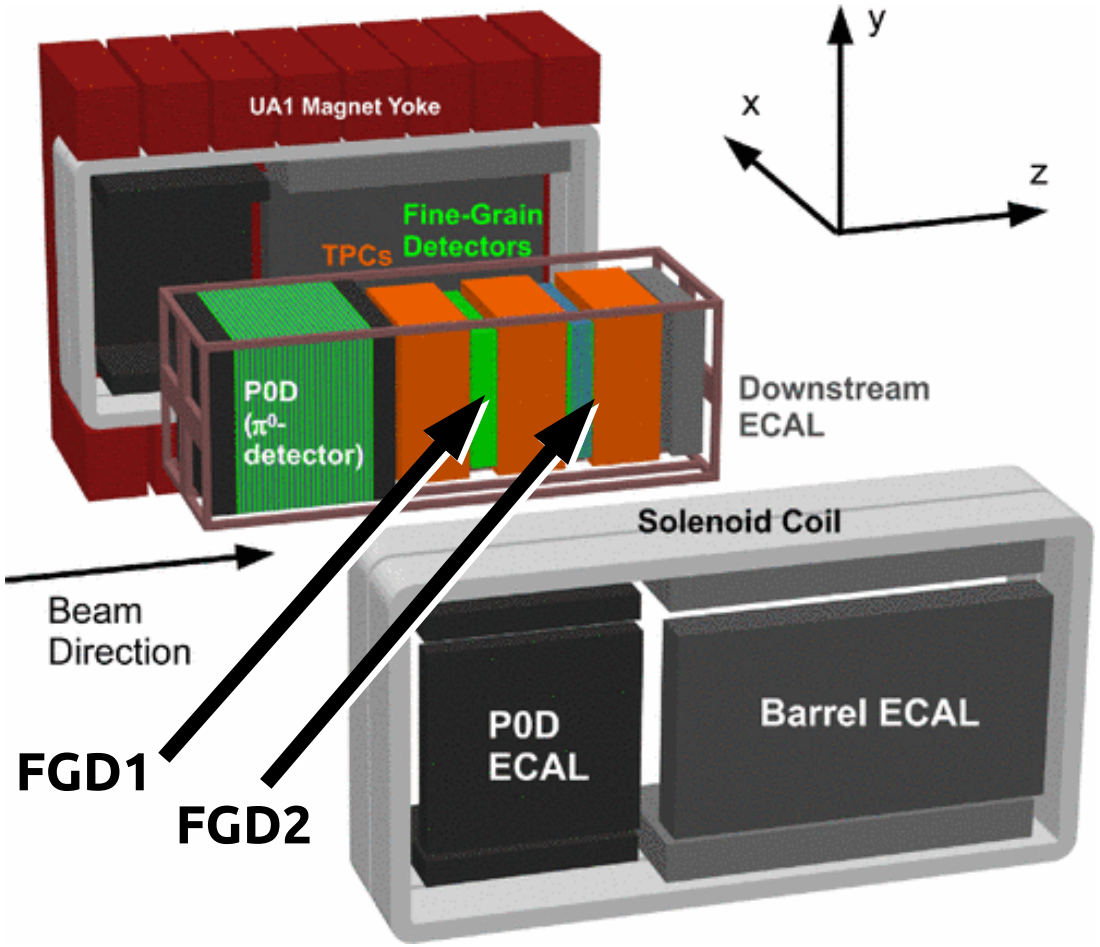
- **target** mass, vertex reconstruction

3x **TPCs**

(Time Projection Chambers)

In an applied magnetic field

- **momentum** reconstruction
- **charge** identification
- **Particle Identification (PID)**



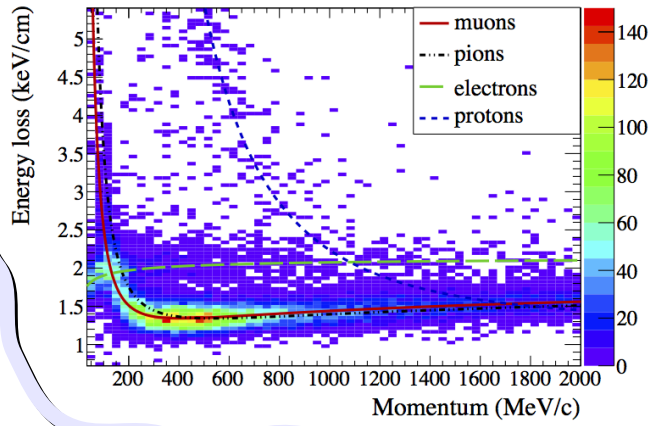
Ecals (Electromagnetic Calorimeters) surrounding the inner sub-detectors

- **energy containment**, more **PID**

Selection: Electron PID

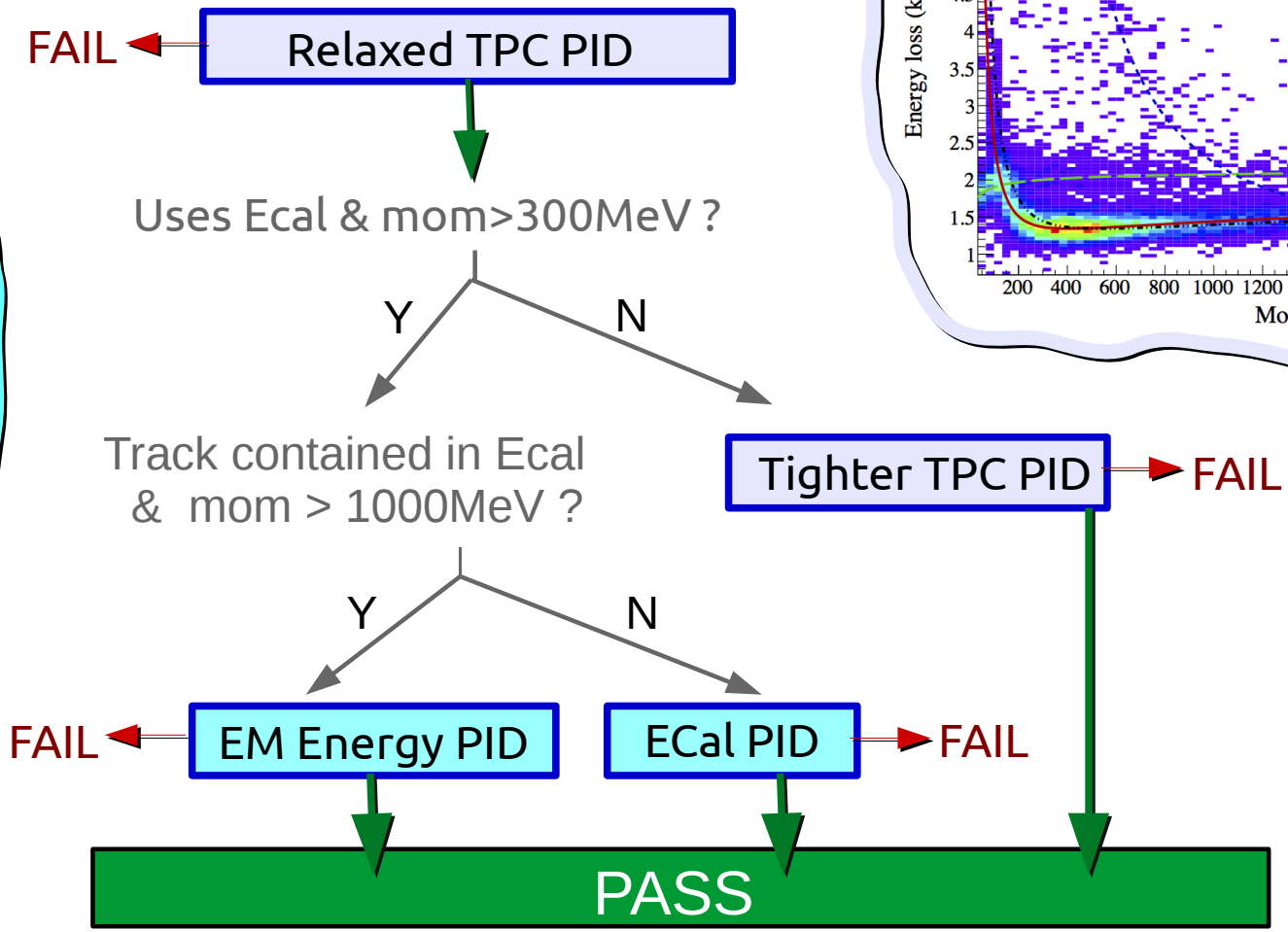
- Select highest momentum **FGD→ TPC track** that starts in the FGD fiducial volume (FV)
- Perform particle identification (PID)

TPC PID
based on energy deposited per distance



EM Energy PID
based on scale of energy deposit

Ecal PID
based on shape of energy deposit



ν_e CC selection

Identify electron candidate: Perform PID using TPC and ECal (previous page)

Reject 'γ-events' : γ → e^+ e^- { predominantly from outside of the fiducial volume (OOFV)

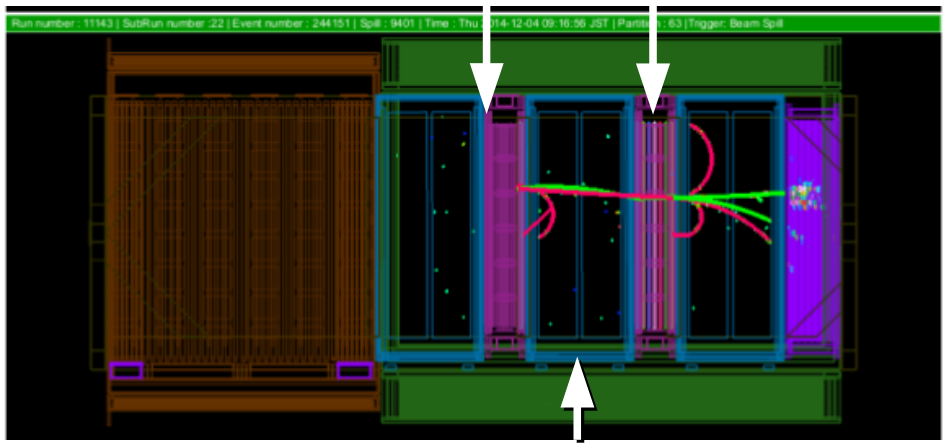
- Veto actvity behind vertex
- Search for paired positron (γ → **e^+** e^-) (see slide 11)
- Require mom > 200 MeV

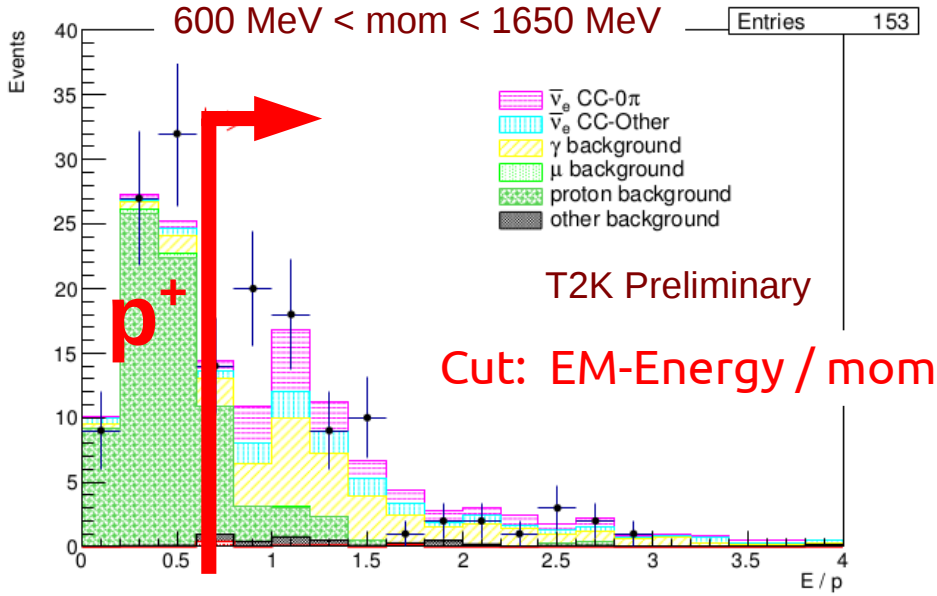
$\bar{\nu}_e$ CC selection

p^+ and e^+ have very similar TPC dE/dx at 1GeV

→ **proton background → need additional cuts**

Tracks showering in FGD2





γ control sample

'γ-events' : γ → e^+ e^- where a photon converts in the FGD

→ largely from NC π^0 interactions → large uncertainties

→ 'γ-sample' control sample with a purity ~ 95%

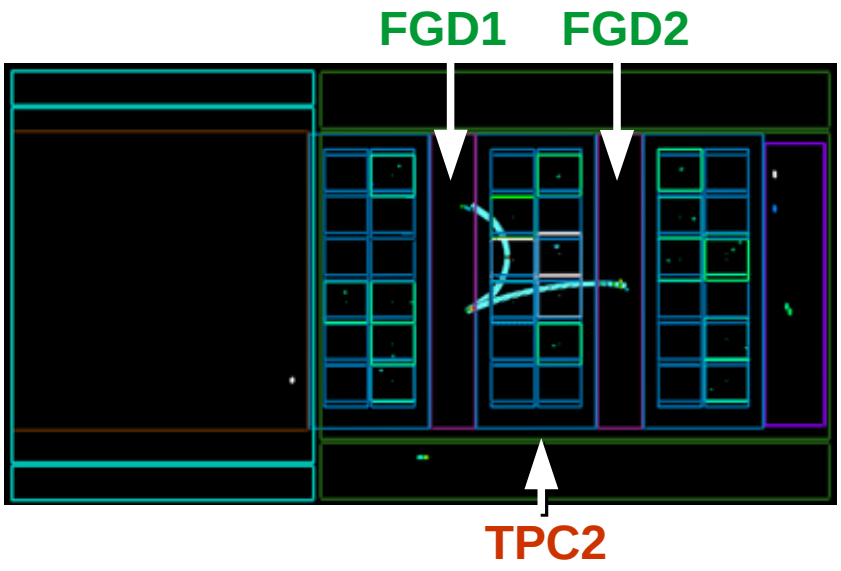
An adapted version of this selection is used to search for NCγ in ND280
→ See poster by Teppei

* Select e+/e- candidate (PID on slide 7)

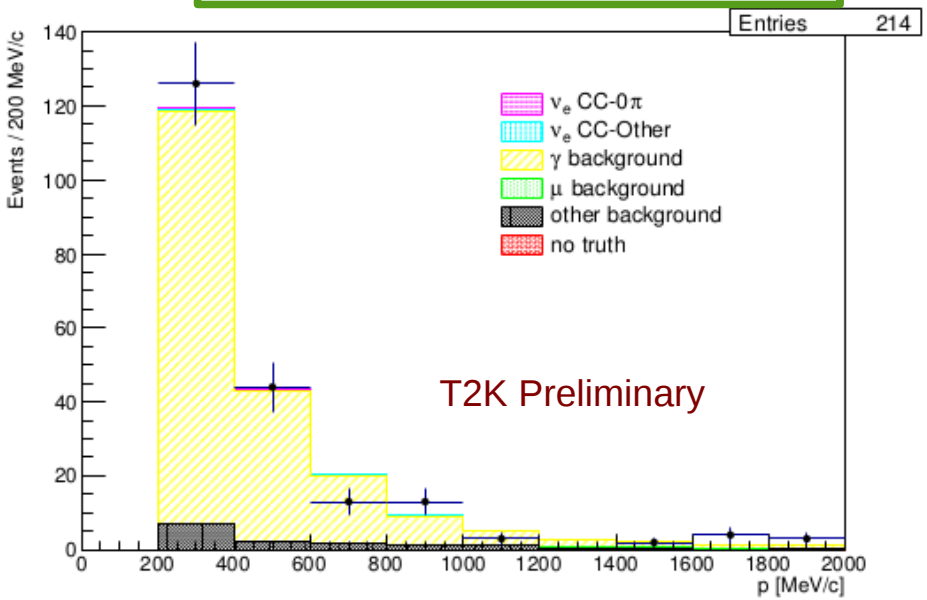
Loop over TPC tracks to search for e+/e- pair. * γ invariant mass: M_{inv}<100MeV where

* opposite charge to first track

* distance between the tracks



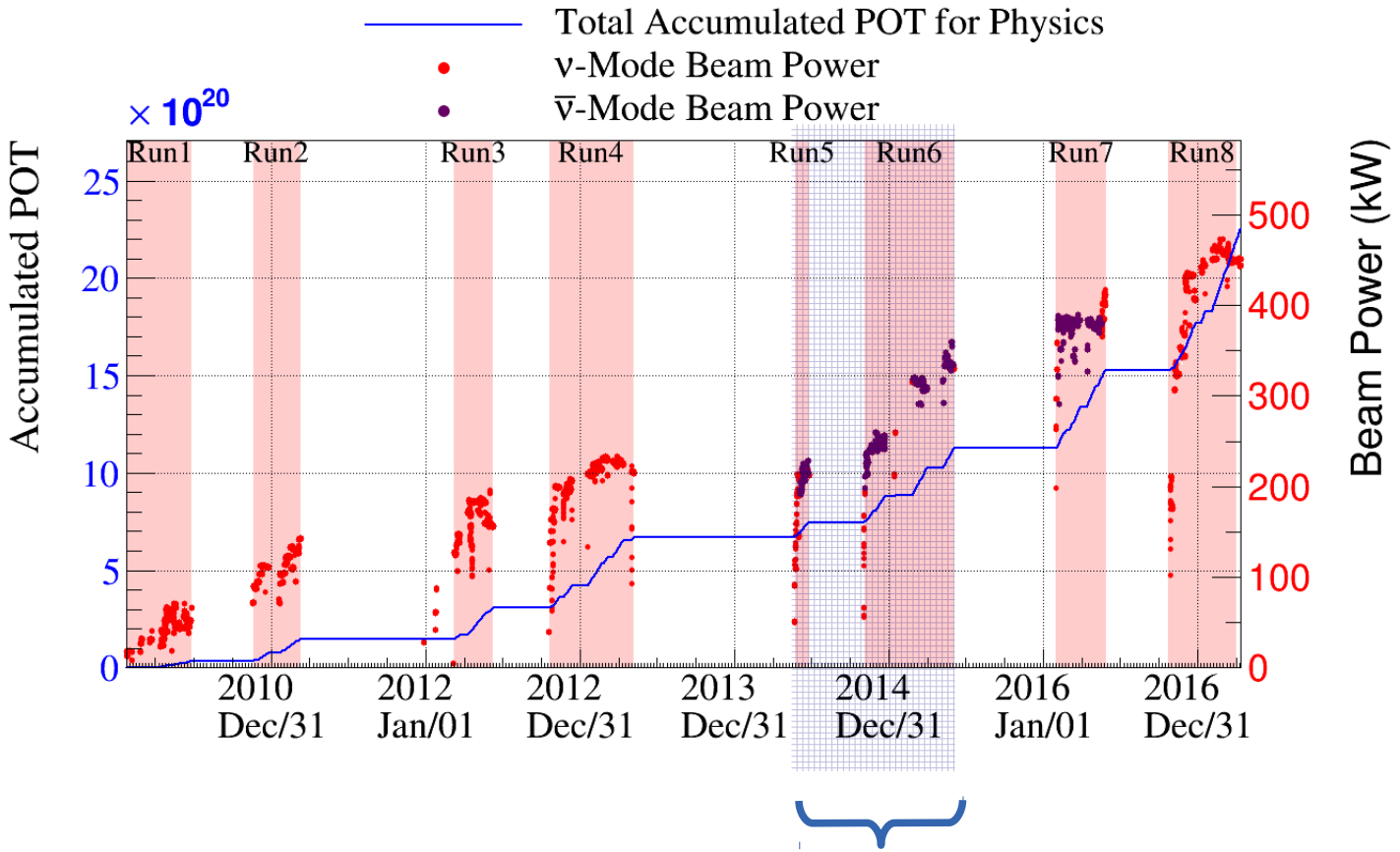
$$M_{inv} = \sqrt{2 \cdot m_e^2 + 2 \cdot (E_1^2 \cdot E_2^2 - P_1^2 \cdot P_2^2)}.$$



Beam component measurement

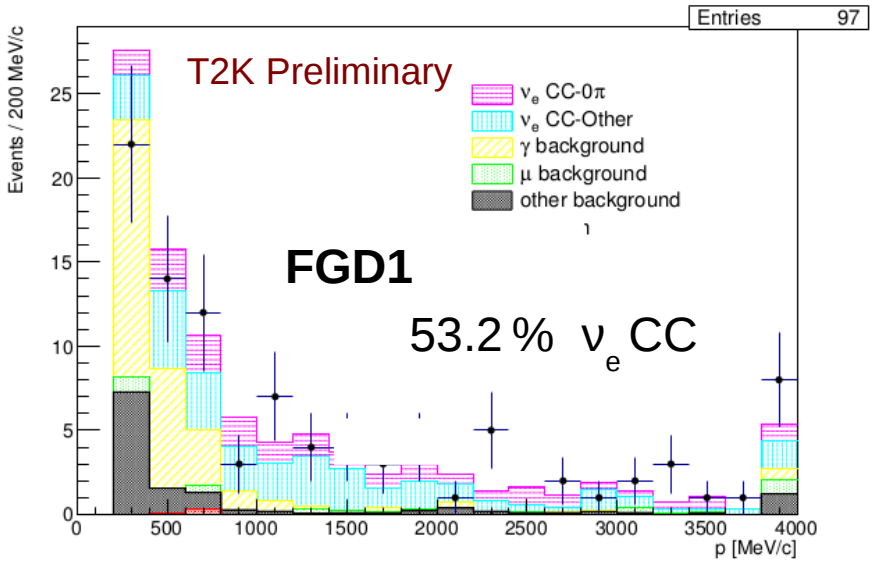
T2K 2014-2015 $\bar{\nu}$**-beam** ~4x10^{20} POT

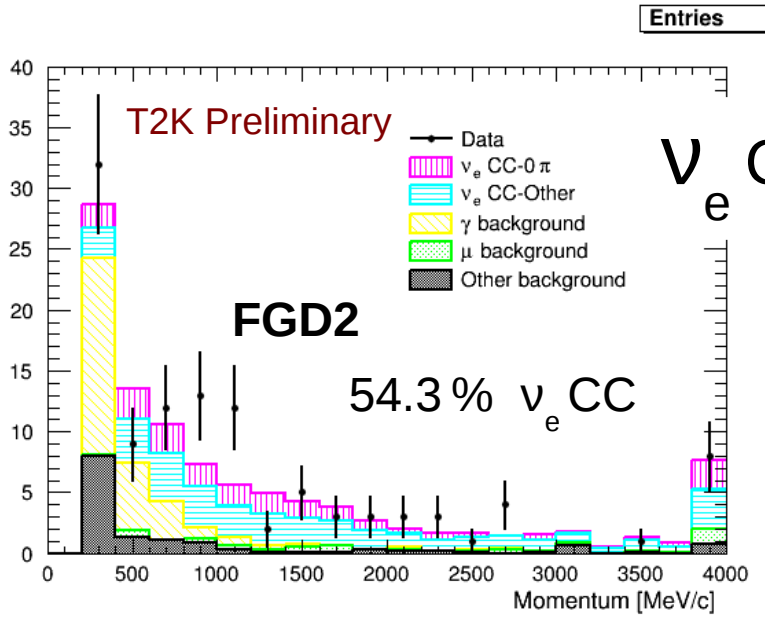
ν_e CC selection and $\bar{\nu}_e$ CC selection



Selections

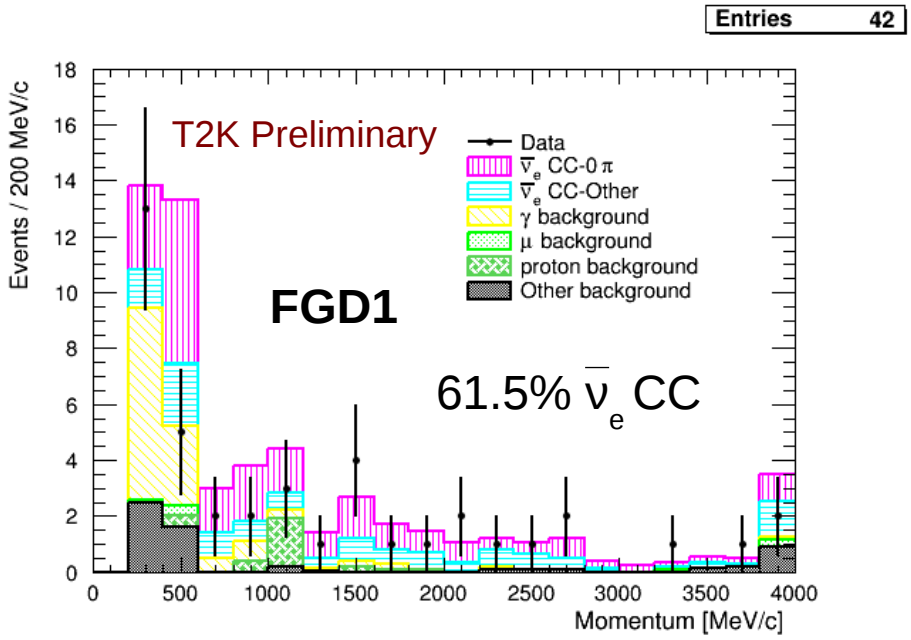
T2K 2014-2015: ~4x10^{20} POT $\bar{\nu}$-beam

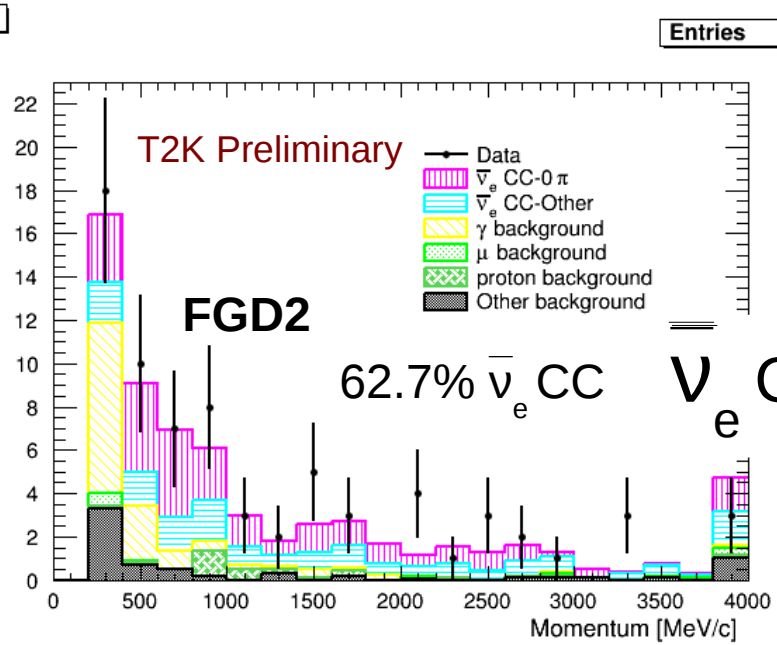




ν_e CC selection

'γ background' → Parent is a γ, selected track is e^+/e^-





'μ background' → Selected track is a muon

ν_e CC selection

Intrinsic ν_e / $\bar{\nu}_e$ component of beam

* T2K Run 2014-2015 ($\bar{\nu}$-beam)

* Performed a fit to extract the ν_e and $\bar{\nu}_e$ components of the beam

* Using ν_e CC and $\bar{\nu}_e$ CC selections in FGD1 and FGD2

* Gamma sample used to constrain the background – scale factor for OOFV γ-background

* Unbinned maximum likelihood – simultaneous fit across 3 samples (ν_e CC, $\bar{\nu}_e$ CC, γ)

T2K Preliminary

Statistics

# Events	FGD1+FGD2	FGD1	FGD2
	ν_e CC		
Data	208	97	111
	$\bar{\nu}_e$ CC		
Data	115	42	73

Scale factor results:

$f(\nu_e) = 1.250 \pm 0.135$ (stats.) ± 0.122 (syst.)

$f(\bar{\nu}_e) = 1.142 \pm 0.144$ (stats.) ± 0.132 (syst.)

	Detector syst	Flux + xsec syst
ν_e CC	6.5%	7.5%
$\bar{\nu}_e$ CC	6.5%	9.5%

Planned cross-section measurements with FGD1 selections

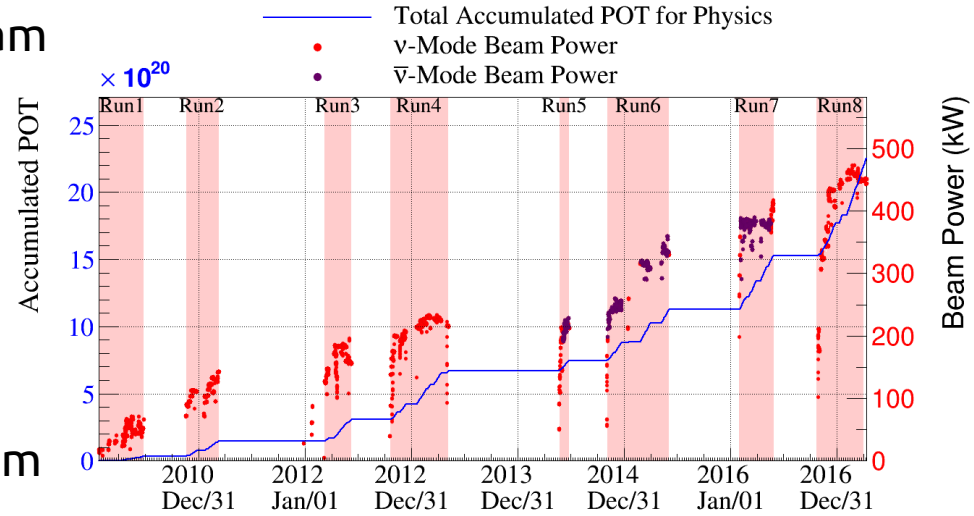
ν_e CC selection and $\bar{\nu}_e$ CC selection

And ν_e CC 0π

T2K Run 2010 – 2013: ~6x10^{20} POT ν – beam
(sample used in plots on next page)

T2K Run 2014-2015: ~4x10^{20} POT $\bar{\nu}$-beam
(sample in previous plots)

T2K Run 2016-: ~3x10^{20} POT $\bar{\nu}$-beam
T2K Run 2016 – 2017: ~4x10^{20} POT ν – beam
(plots not available)

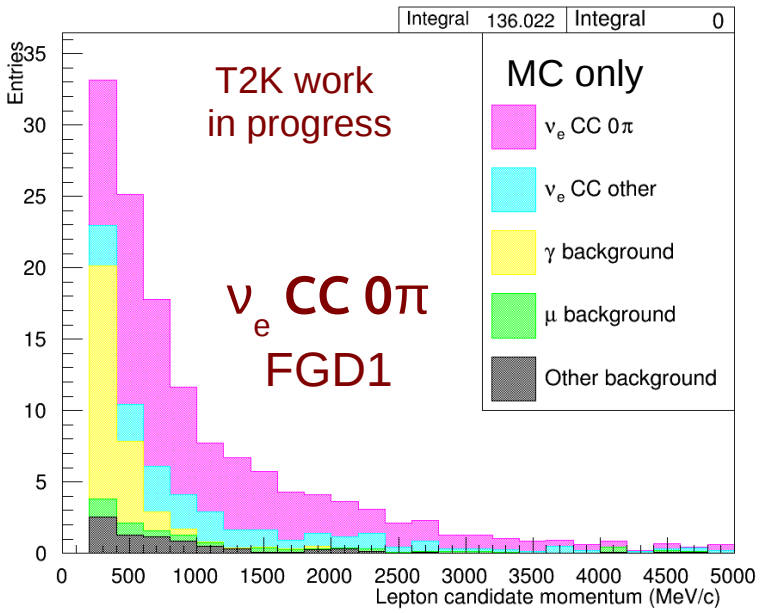


Splitting ν_e CC events into ν_e CC 0π and ν_e CC other sub-samples

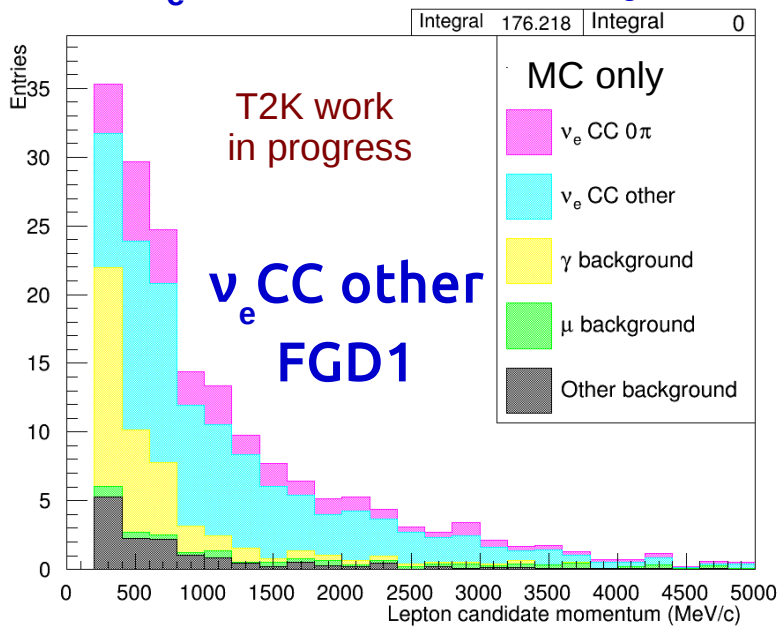
Split ν_e CC sample according to the particles that exit the nucleus (**i.e. after FSI**)

* **Michel/delayed electrons**
* **track multiplicity (+ TPC PID)**

ν_e CC 0π (no mesons exit nucleus)



ν_e CC other (Any ν_e CC that is not CC 0π)



ν – beam selection: T2K Run 2010 – 2013 (~6x10^{20} POT ν – beam)

NOTE: plot does not include recent run period → increased stats for measurement

Summary

Motivation

- Intrinsic ν_e is the biggest background in $\nu_\mu \rightarrow \nu_e$ oscillation
- ν_e cross-section data is scarce, want data-driven constraints in future

Status

- Selections optimised and systematics computed
- Beam component measurements done
- Planned cross-section measurements in FGD1: $\bar{\nu}_e$ CC, ν_eCC, $\bar{\nu}_e$ CC0π

  → Maximum log likelihood fit across signal region and control samples

Selections: $\bar{\nu}_e$ CC ($\bar{\nu}$-beam), ν_eCC (ν-beam and $\bar{\nu}$-beam), $\bar{\nu}_e$ CC0π (ν-beam and $\bar{\nu}$-beam)

Control samples: γ-sample , ν_eCC-other

T2K Rns 2010-2015, good quality POT = ~6×10^{20} POT ν + ~4×10^{20} POT $\bar{\nu}$

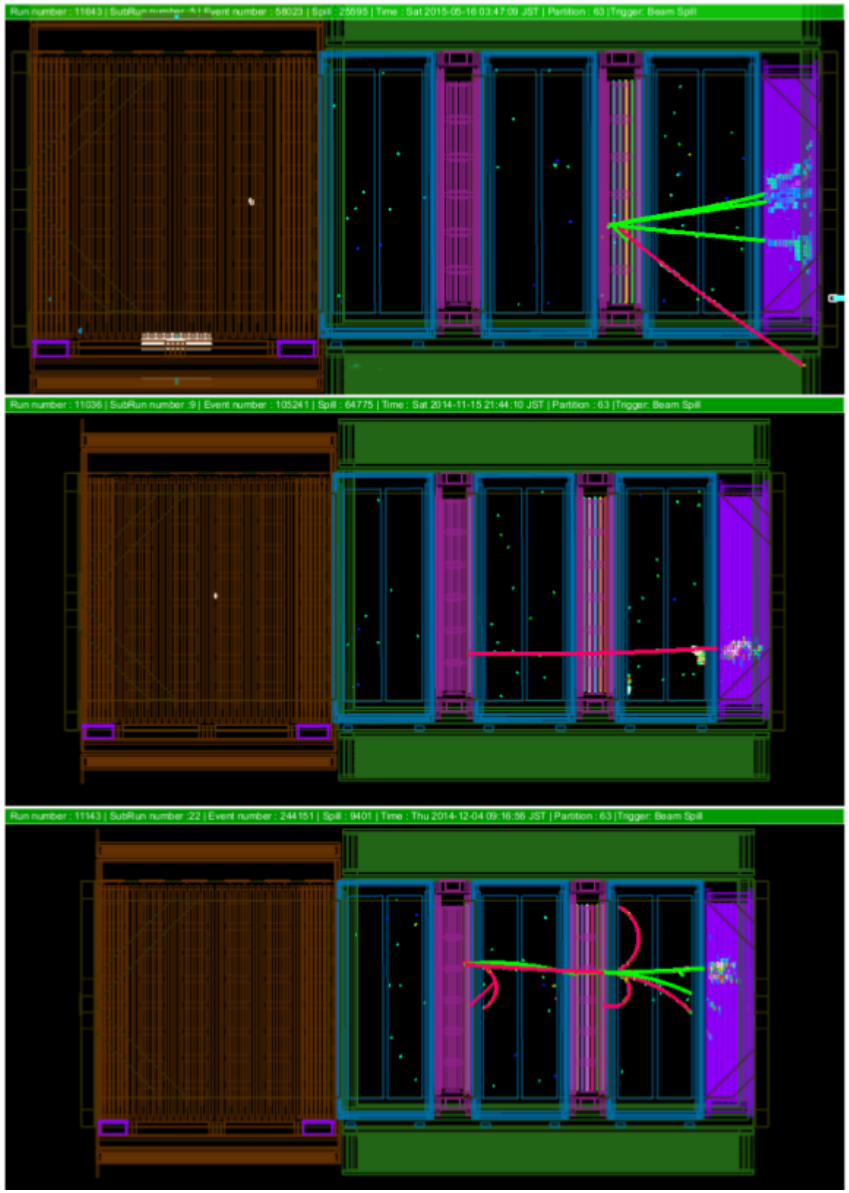
T2K Runs 2010-2017, predicted ood quality POT = ~10×10^{20} POT ν + ~7×10^{20} POT $\bar{\nu}$

→ Upcoming Xsec measurements using FGD1 as target, with 2010-2017 data

Backup

Data event displays

T2K Preliminary

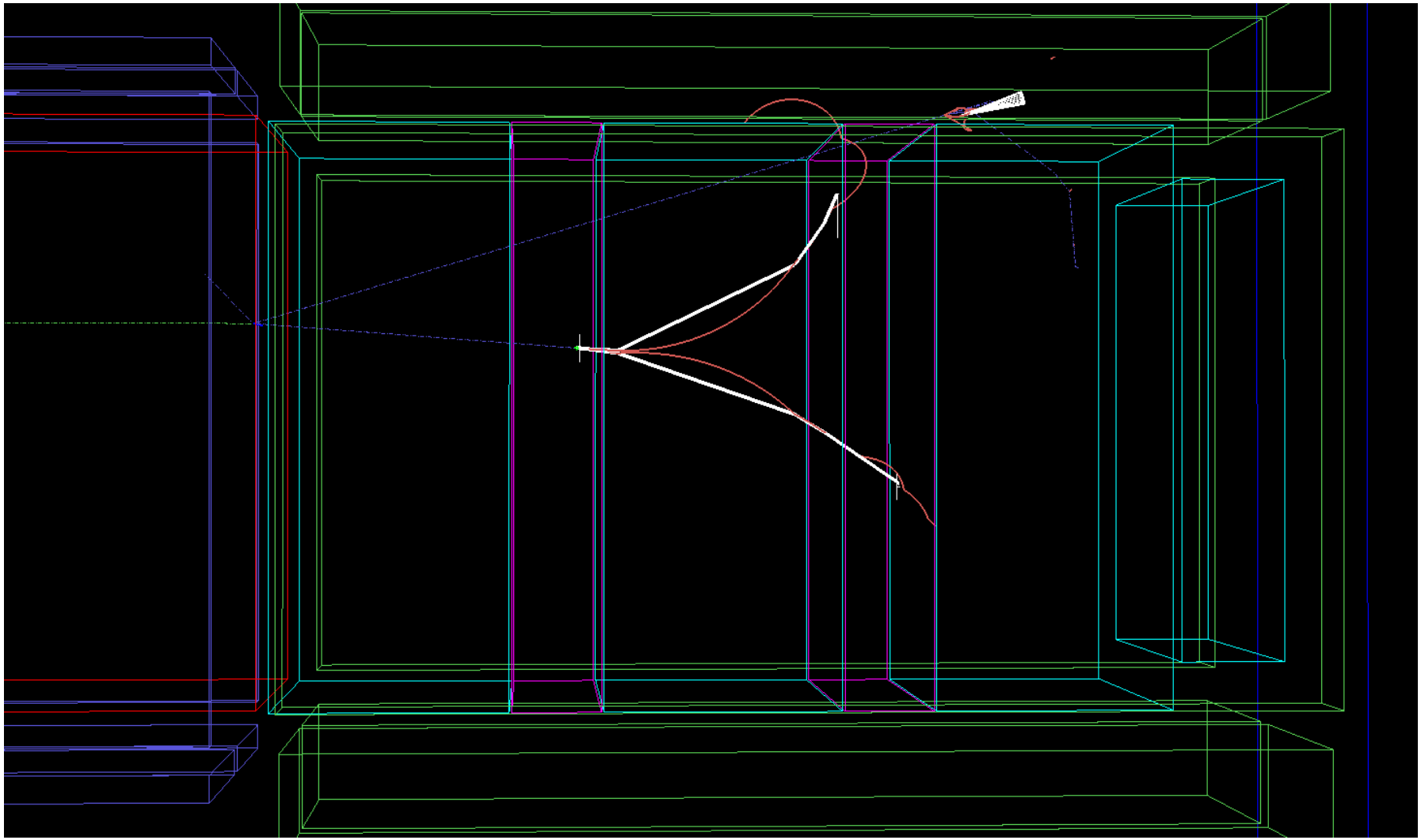


FGD2 ν_e CC candidate

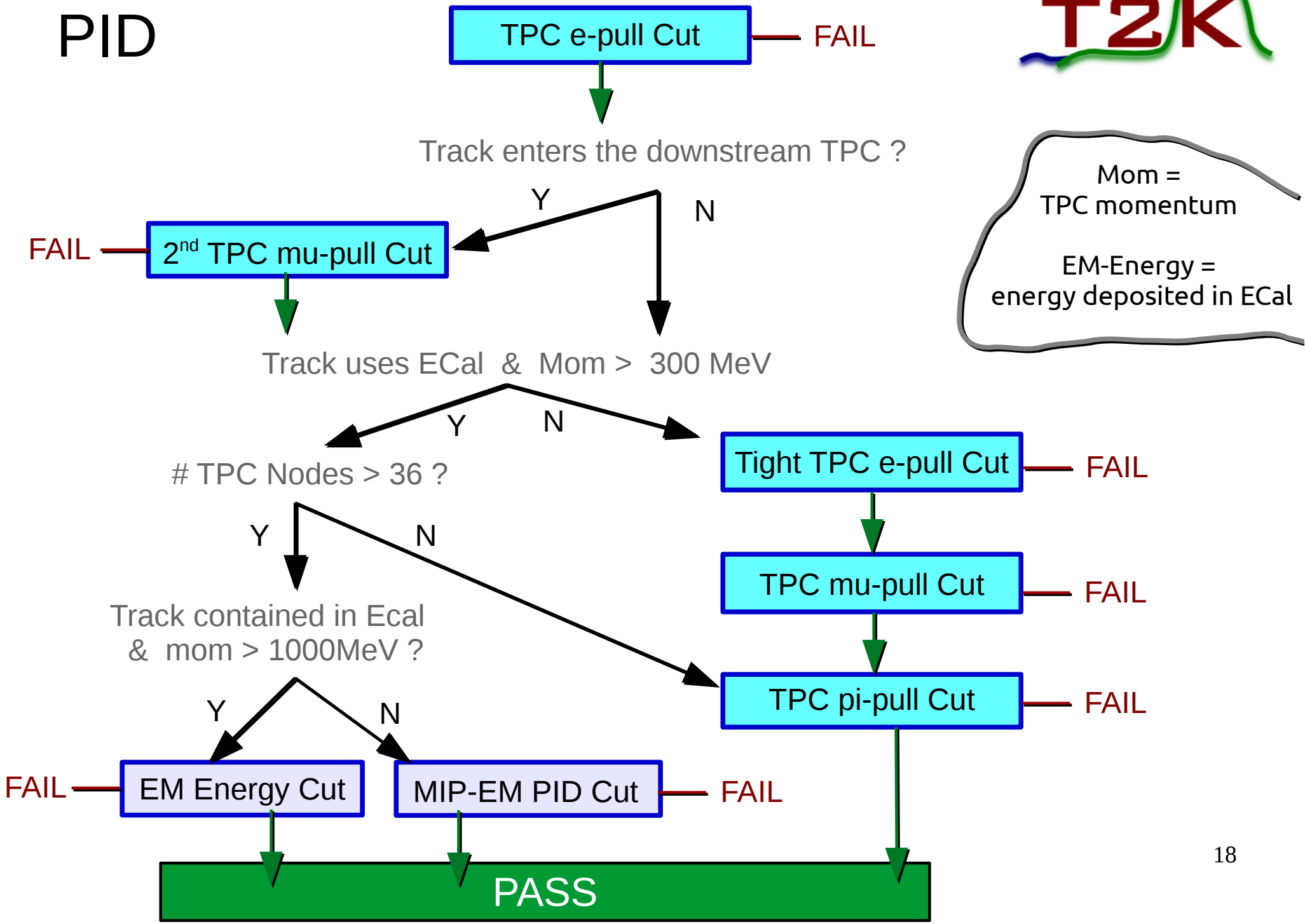
FGD1 $\bar{\nu}_e$ CC candidate
→ FGD1 event
→ track goes through FGD2 to ECal

FGD1 $\bar{\nu}_e$ CC candidate
→ FGD1 event
→ track showers in FGD2

MC π^0 event display



PID


TPC e-pull Cut
FAIL
Track enters the downstream TPC ?
Y
N
FAIL
2nd TPC mu-pull Cut
Track uses ECal & Mom > 300 MeV
Y
N
TPC Nodes > 36 ?
Y
N
Track contained in Ecal
& mom > 1000MeV ?
Y
N
FAIL
EM Energy Cut
MIP-EM PID Cut
FAIL
Tight TPC e-pull Cut
FAIL
TPC mu-pull Cut
FAIL
TPC pi-pull Cut
FAIL
PASS
Mom =
TPC momentum
EM-Energy =
energy deposited in ECal

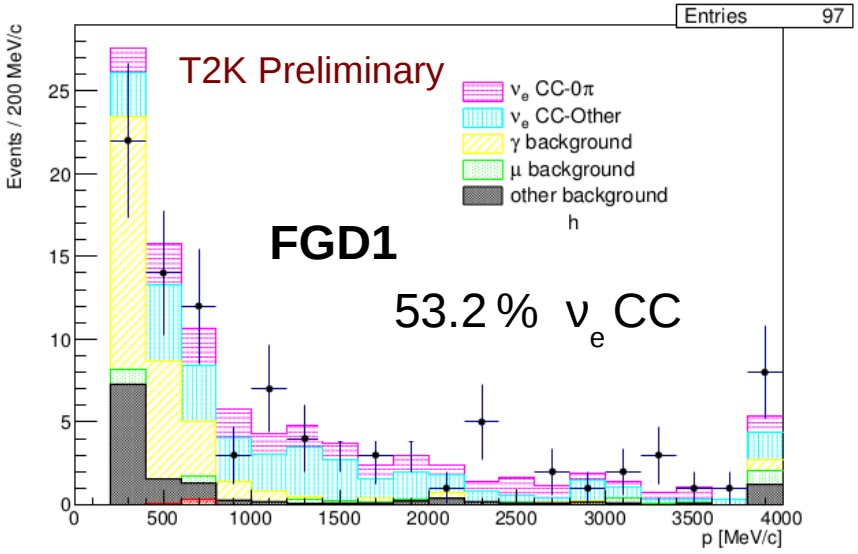
ν_e CC selection

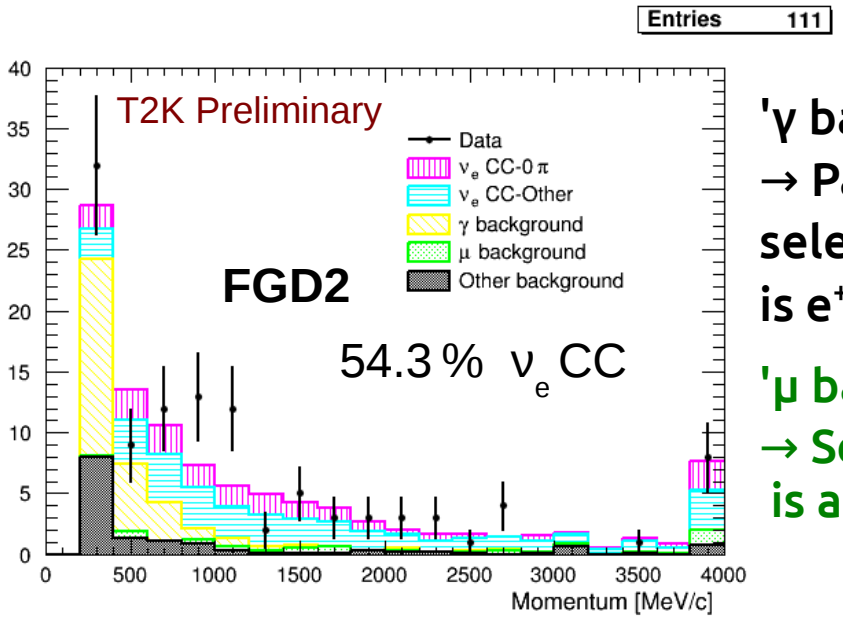
Identify electron candidate

- Select highest momentum **FGD→ TPC track** starting in the FGD fiducial volume (FV)
- Perform PID using TPC and ECal (previous page)

Reject 'γ-events' : γ → e^+ e^- { predominantly from outside of the fiducial volume (OOFV)

- Time of flight between FGD1 and Ecal or FGD2 → removes OOFV tracks
- Veto upstream activity in ECal, TPC, P0D → reject out of fiducial volume (OOFV)
- Search for paired positron (γ → **e^+** e^-) (see slide 11)
- Require mom > 200 MeV





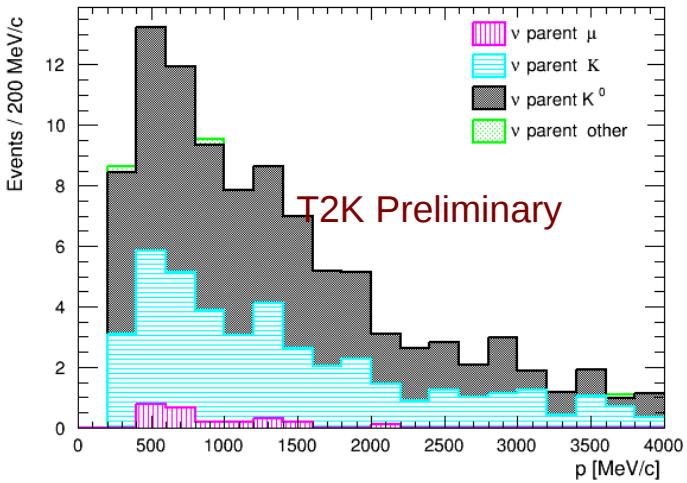
'γ background' → Parent is a γ, selected track is e^+/e^-

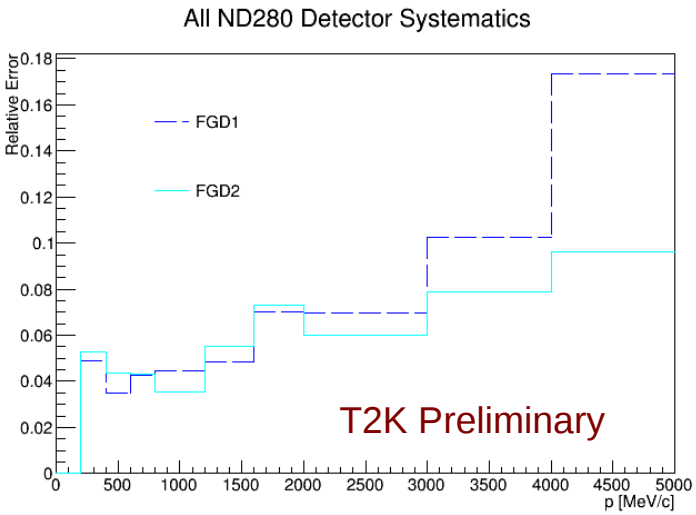
'μ background' → Selected track is a muon

ν_e CC in T2K Run 2014-2015 ($\bar{\nu}$-beam)

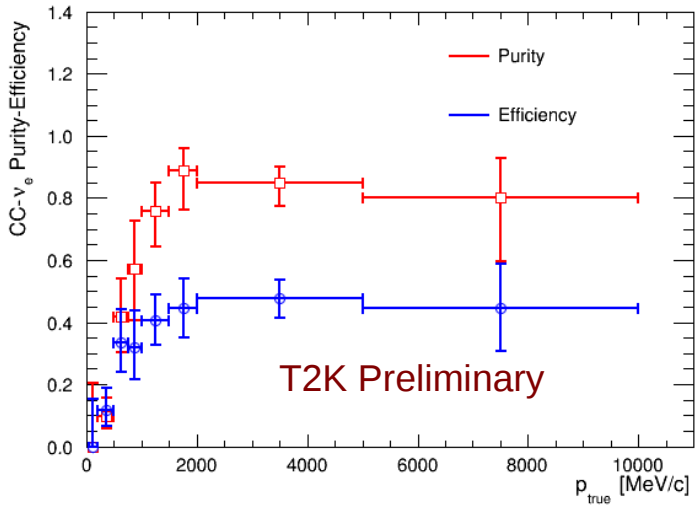
ν_e CC events

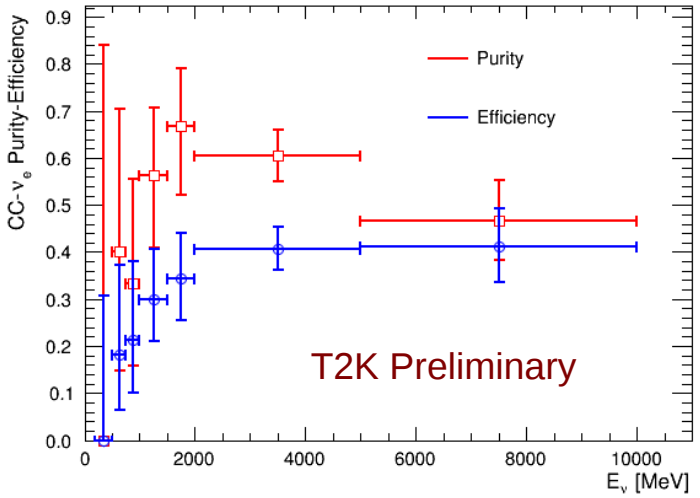
T2K 2014-2015 ($\bar{\nu}$-beam)





Selection	FGD1-FGD2(%)	FGD1(%)	FGD2(%)
CC-0π	20.0	20.1	19.9
CC-Other	33.2	31.9	34.4
Gamma	28.6	30.4	27.0
Muon	4.0	3.4	4.6
Other	14.1	14.2	14.0





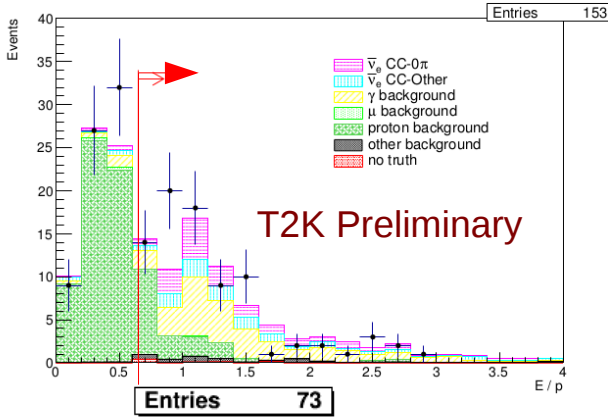
$\bar{\nu}_e$ CC selection

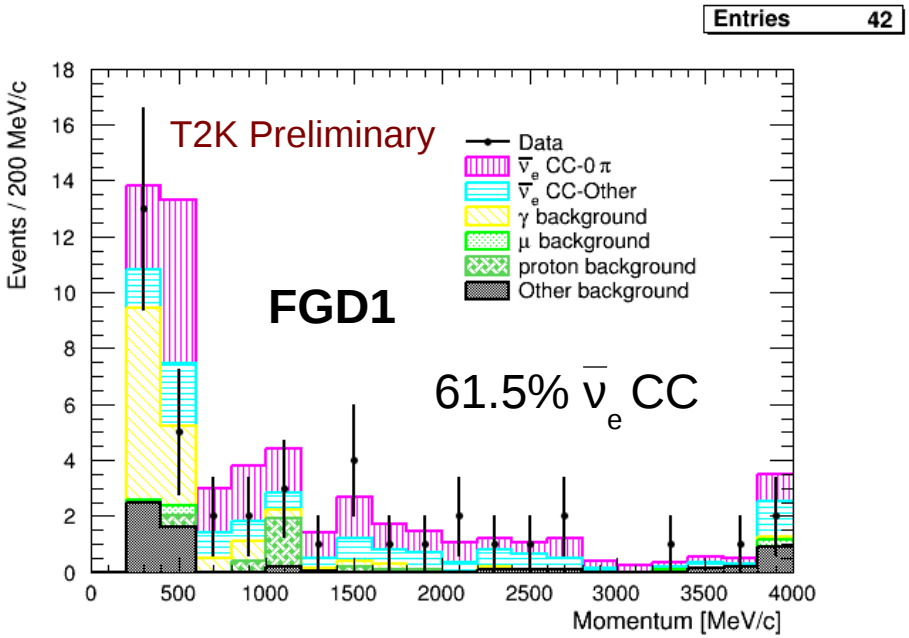
Searching for a positron instead of electron

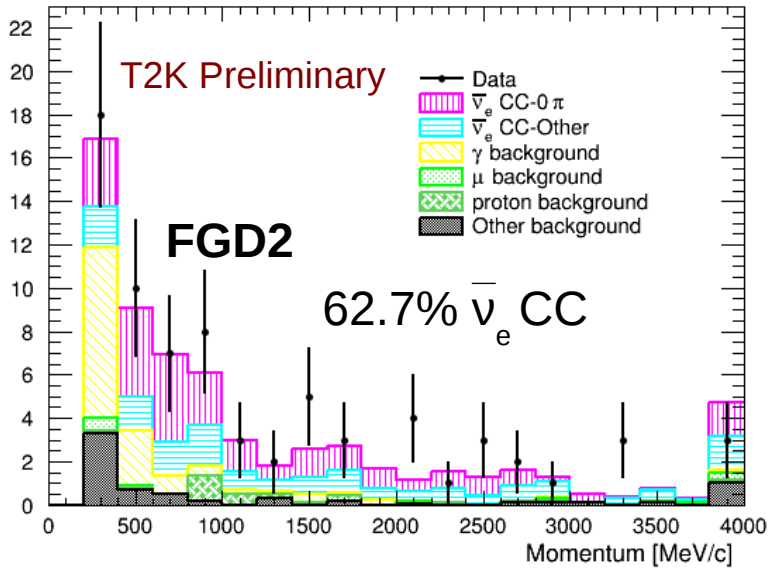
Proton and positron/electron have very similar dE/dx in the TPC around 1GeV
→ **protons form a background** to positron selection → **need additional cuts**

- Select highest momentum track, if negative then remove event (instead of highest positive → p^+ often 2nd highest mom)
- Additional ECal PID - separate EM showers from hadronic
- Cut on ratio: EM-Energy / mom
- Search for tracks showering in FGD2

600 MeV < mom < 1650 MeV







$\bar{\nu}_e$ CC events in T2K 2014-2015 ($\bar{\nu}$-beam)

E/P cut

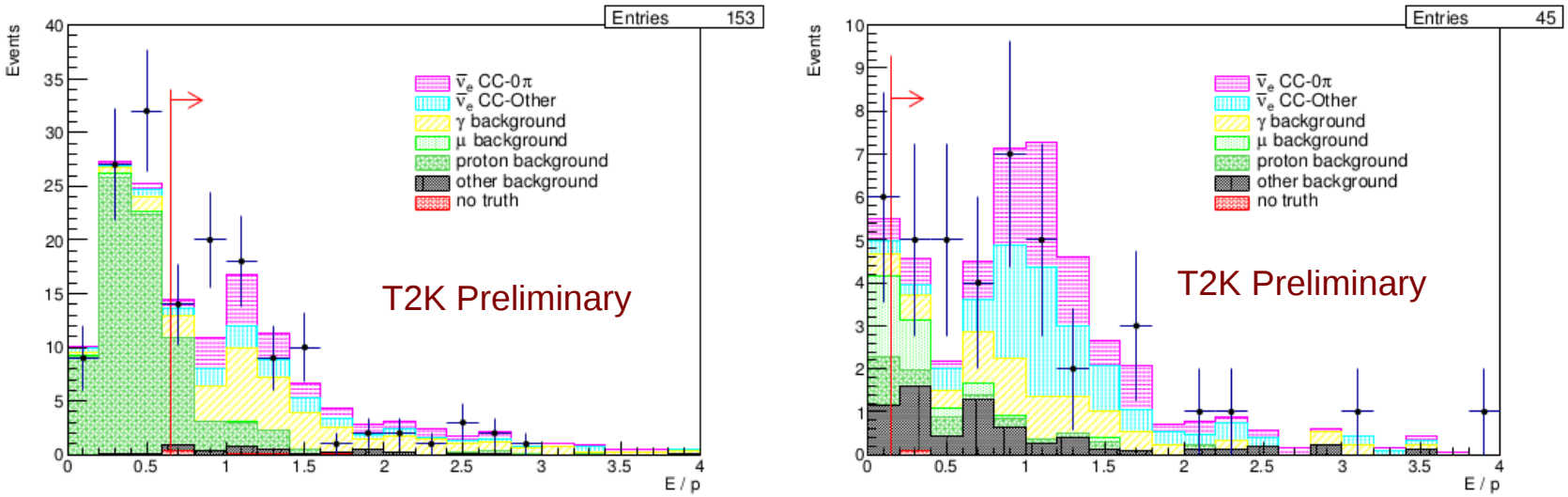
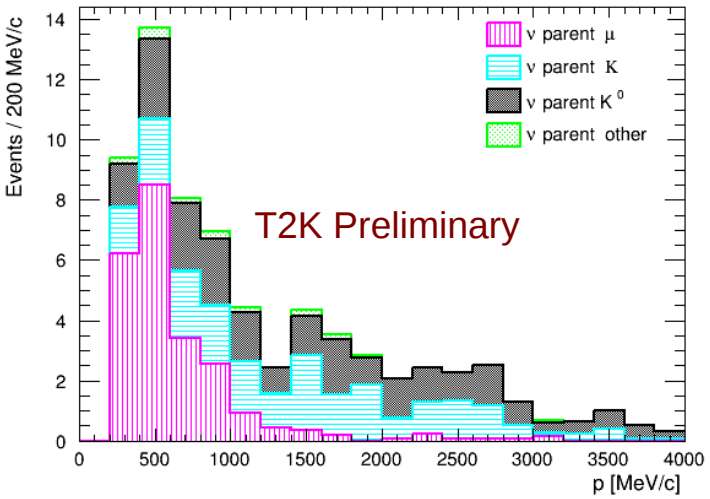
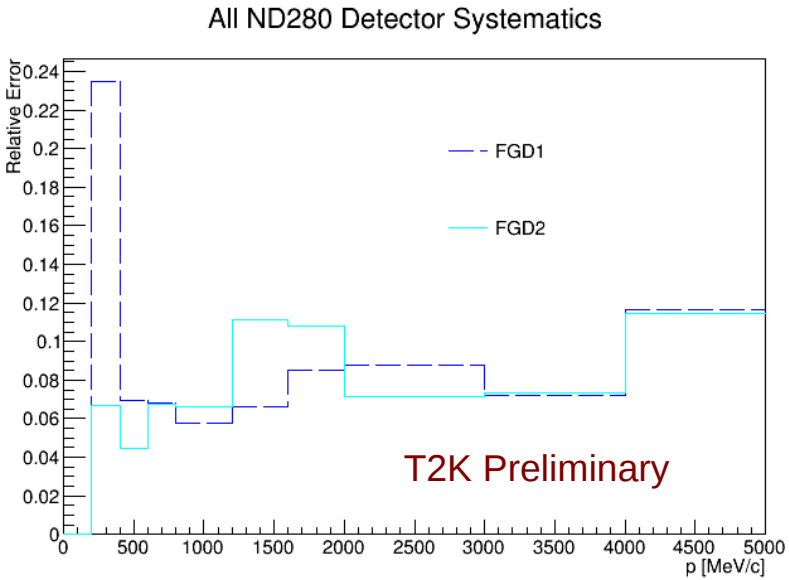


Figure 11: E/P for tracks with 600 MeV/c < p < 1650 MeV/c (left) and with $p \geq 1650$ MeV/c (right) for the $\bar{\nu}_e$ selection.

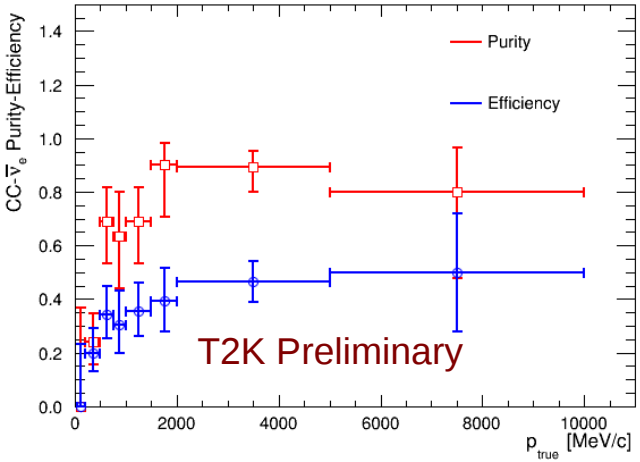
$\bar{\nu}_e$ CC

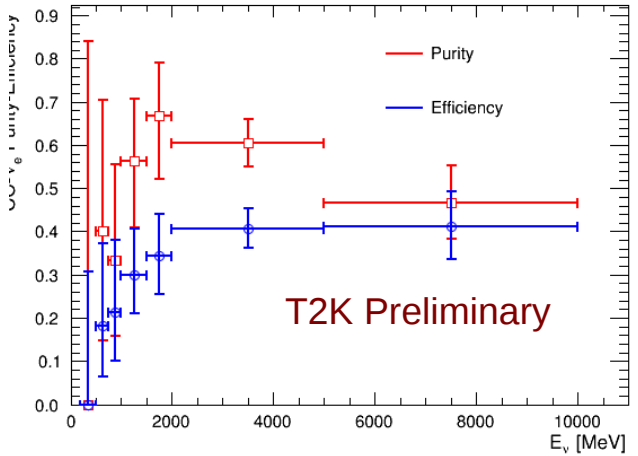
T2K 2014-2015 ($\bar{\nu}$-beam)





Selection	FGD1-FGD2(%)	FGD1(%)	FGD2(%)
CC-0π	38.8	40.1	37.7
CC-Other	23.4	21.4	25.0
Gamma	20.8	21.3	20.4
Muon	1.8	1.5	2.1
Proton	4.7	5.2	4.3
Other	10.4	10.5	10.4





Selection improvements since beam component measurement

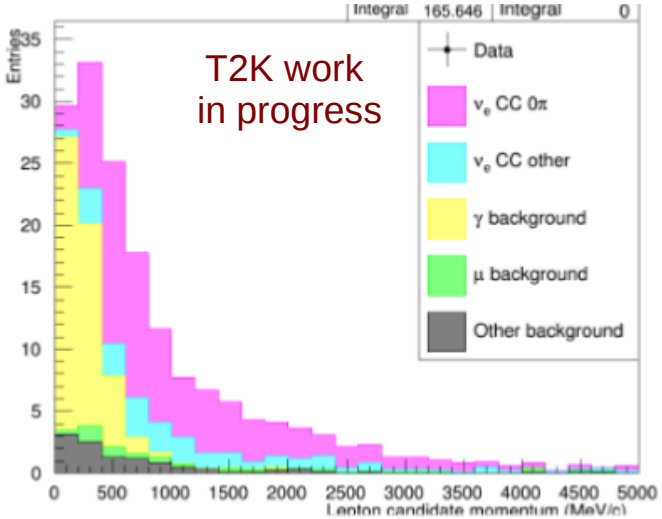
ν_e CC / $\bar{\nu}_e$ CC selection

- Requie mom > 200 MeV (dominated by γ-events below this)
  → unless time of flight information is available

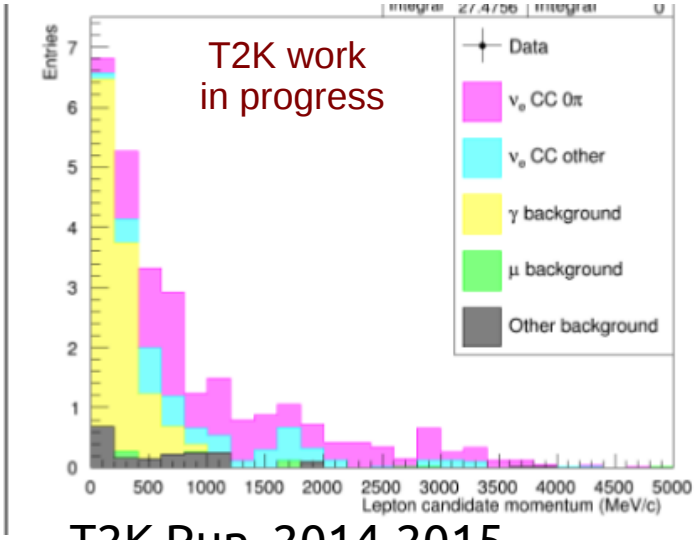
$\bar{\nu}_e$ CC selection

- **For tracks that stop in FGD2, apply FGD PID (reject proton background)**

$\bar{\nu}_e$ CC0π selection



T2K Run 2010-2013
ν-beam (~6x10^{20} POT)

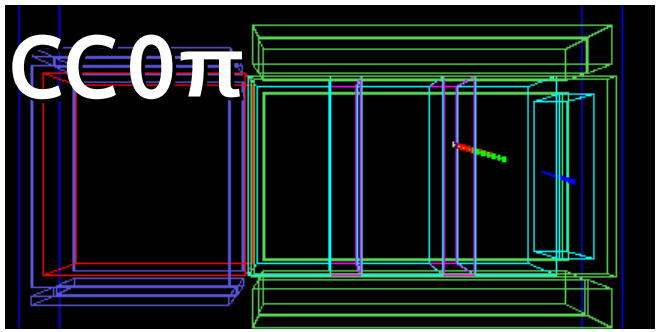


T2K Run 2014-2015
$\bar{\nu}$-beam (~4x10^{20} POT)

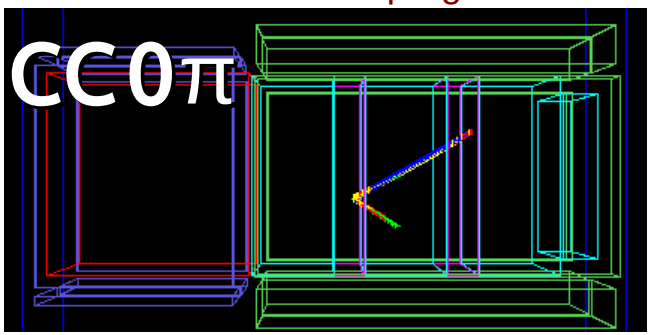
T2K Rns 2010-2015, good quality POT = ~6x10^{20} POT ν + ~4x10^{20} POT $\bar{\nu}$

T2K Runs 2010-2017, predicted ood quality POT = ~10x10^{20} POT ν + ~7x10^{20} POT $\bar{\nu}$

T2K work in progress



T2K work in progress



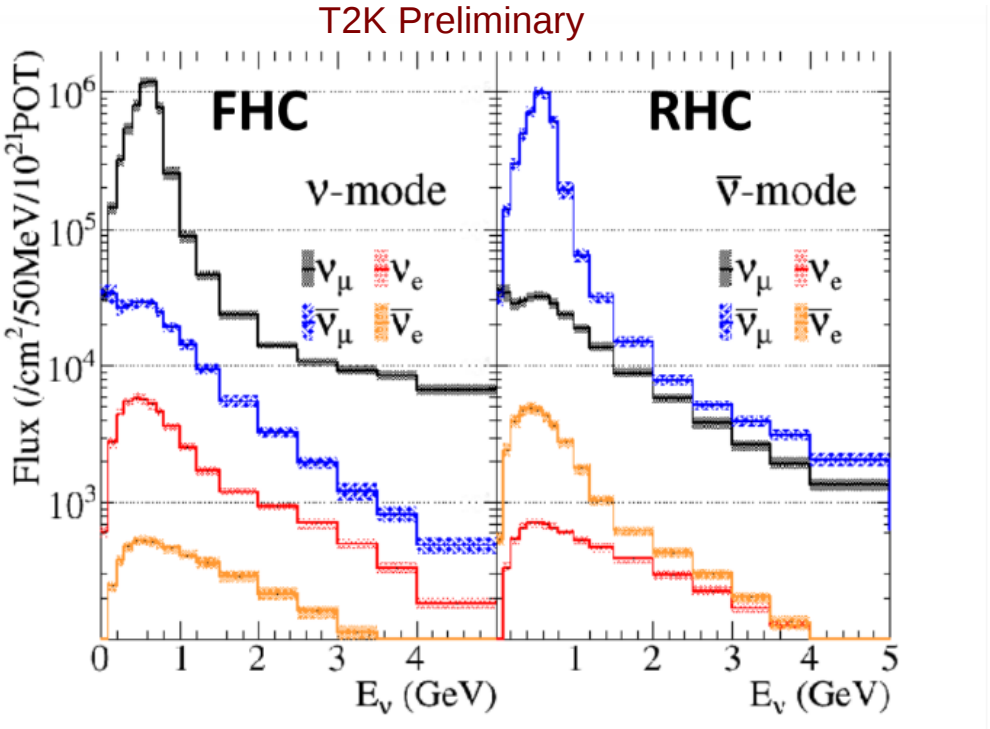
Intrinsic ν_e in the Beam

$$K^{\pm} \rightarrow \pi^0 + e^{\pm} + \nu_e(\bar{\nu}_e)$$
$$K^0_L \rightarrow \pi^{\pm} + e^{\pm} + \nu_e(\bar{\nu}_e)$$

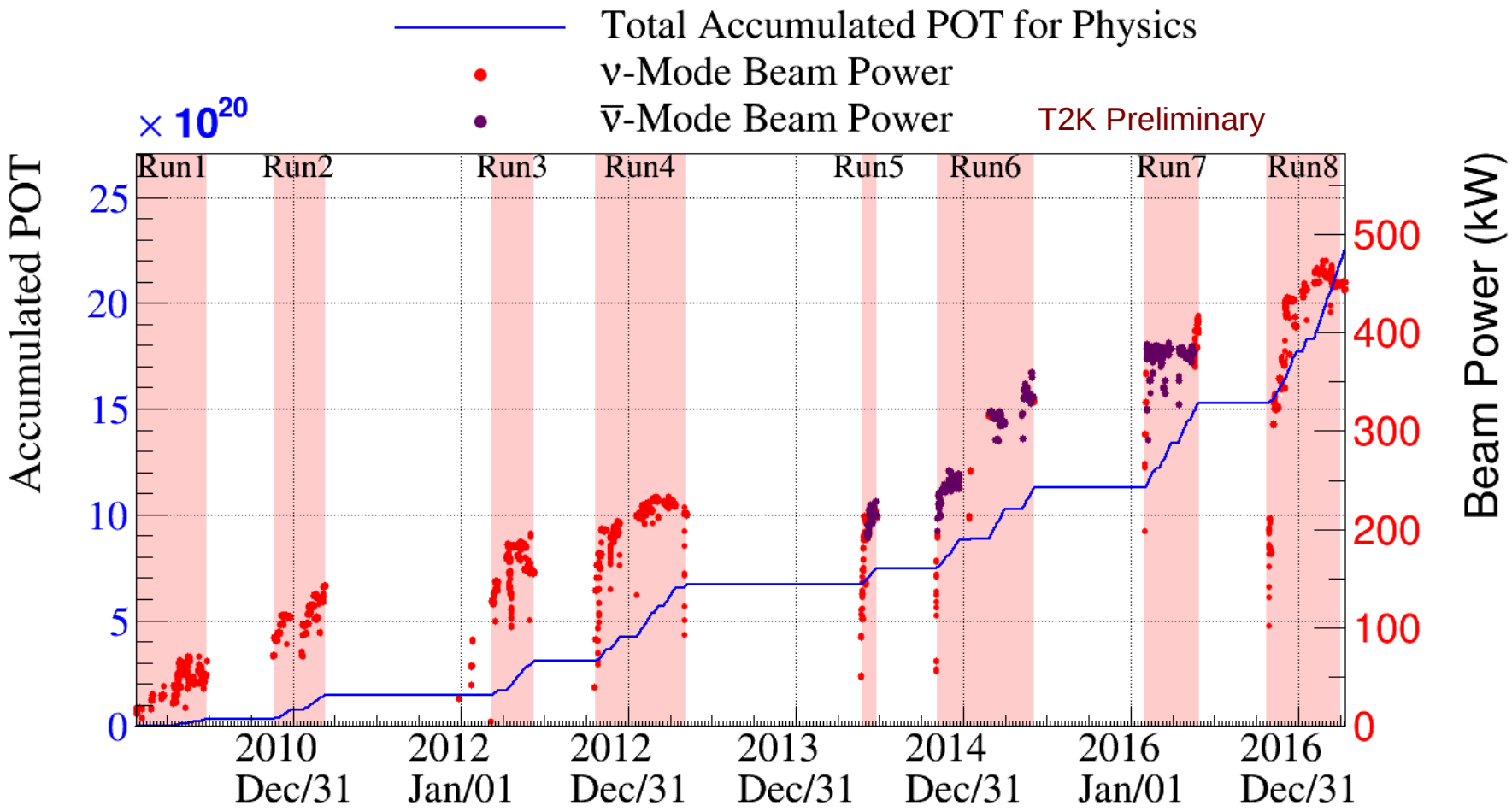
Higer energy

$$\mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$

Lower energy

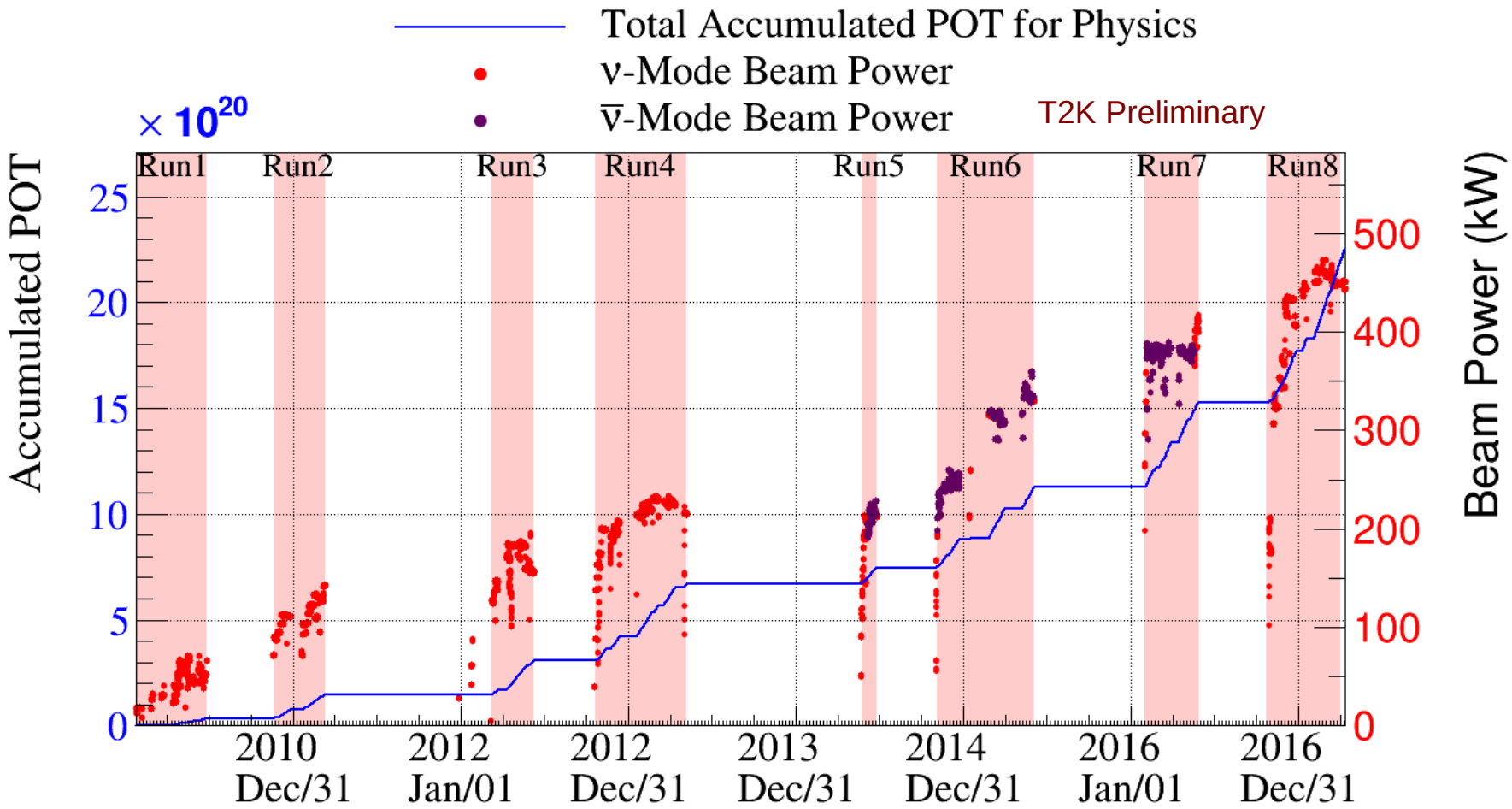


T2K data: Run1-8



Max beam power 495kW
23 January 2010 – 12 April 2017
Nu mode: ~15e20 POT
Antinu-nu made: ~8e20 POT

T2K data: Run1-6

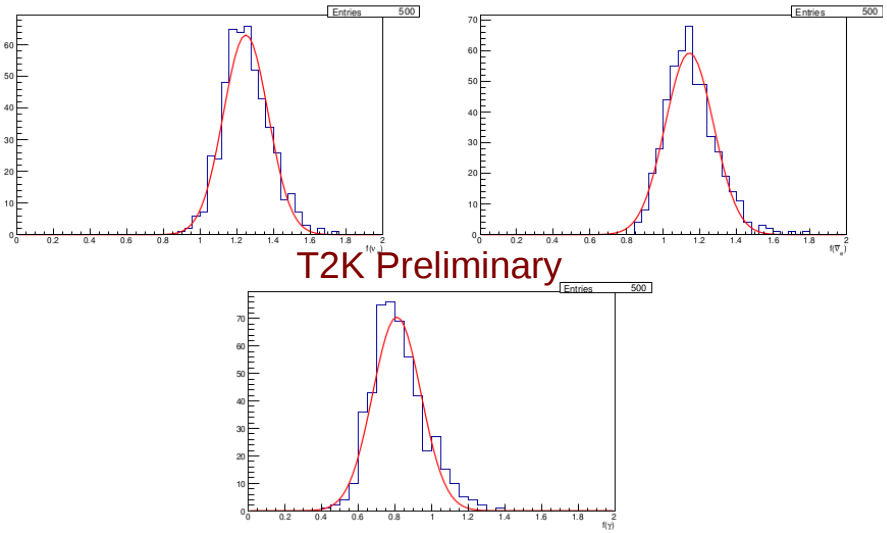


Max beam power 371kW
23 January 2010 – 03 June 2015
Nu mode: ~7e20 POT
Antinu-nu made: ~4e20 POT

More on ν_e / $\bar{\nu}_e$ beam component

Results using constraints from ND280 data

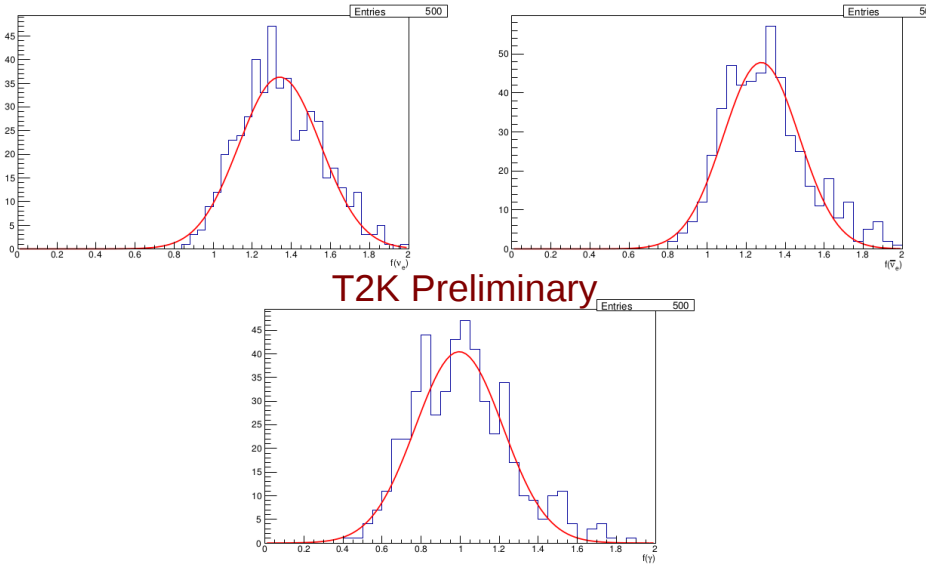
Note: Constraints not implemented on selection plots



$f(\nu_e) = 1.250 \pm 0.135\ (\text{stats.}) \pm 0.122\ (\text{syst.})$
$f(\bar{\nu}_e) = 1.142 \pm 0.144\ (\text{stats.}) \pm 0.132\ (\text{syst.})$
$f(\gamma) = 0.810 \pm 0.063\ (\text{stats.}) \pm 0.142\ (\text{syst.})$

Results without constraints from ND280 data

Note: This corresponds to what is seen on plots



$f(\nu_e) = 1.341 \pm 0.143\ (\text{stats.}) \pm 0.209\ (\text{syst.})$
$f(\bar{\nu}_e) = 1.277 \pm 0.157\ (\text{stats.}) \pm 0.194\ (\text{syst.})$
$f(\gamma) = 0.995 \pm 0.072\ (\text{stats.}) \pm 0.243\ (\text{syst.})$

Cross-section likelihood fitter

Plan to measure cross-sections: ν_e CC, $\bar{\nu}_e$ CC, ν_e CC0pi

Maximum log liklihood fit across signal region and control samples

→ fit performed in reconstructed variables
→ fitting the signal component in each true bin
→ some background constrained by control samples, other background fixed

→ signal split into true regions/bins which are constructed of recon bins
→ background in recon bins
→ PDFs built in reco bins → KDE to smooth PDFs

* Detector systematics treated as nuisance parameters in the fit
    → detector covariance for signal and control samples provided in neccessary bins

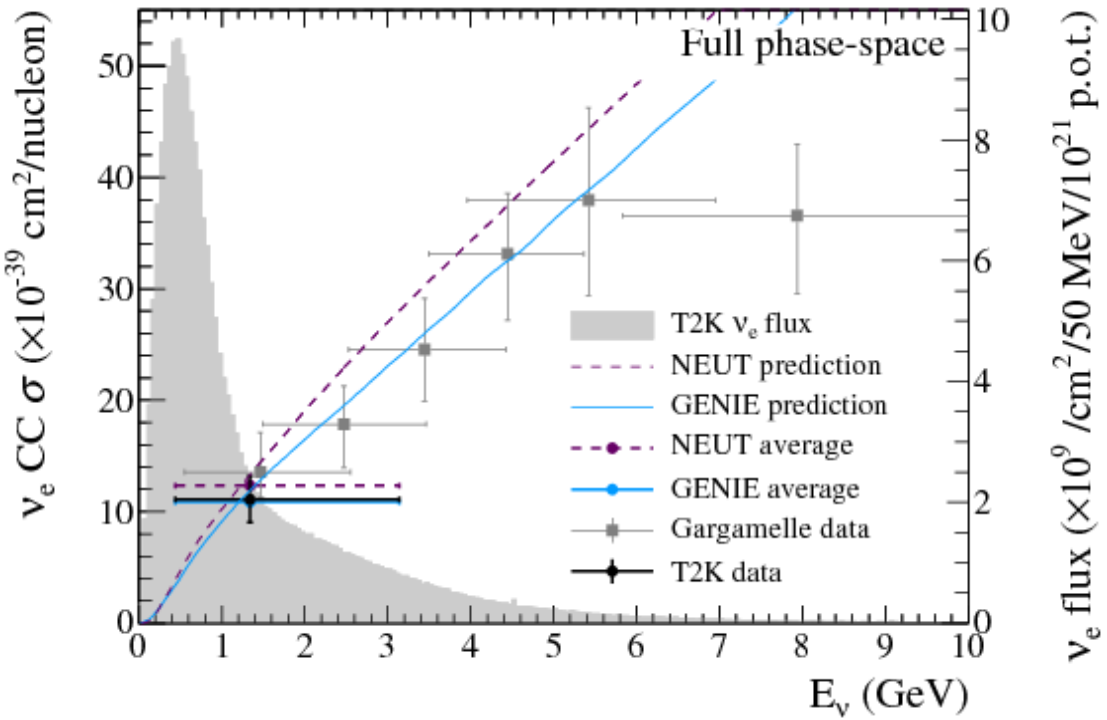
* Flux and interaction systematics computed by generating large number of ‘throws’
    → covariance matrix used to vary model parameters
    → effect propagating using event weights
    → fit redone for each `throw’, then all throws used to compute covariance

* Statistical `throws’ generating by varying bins according to poisson statistics

2014 T2K ν_e CC measurement

T2K: ν_e CC inclusive cross-section

Phys Rev Lett 113,241803 (2014)



Gargamelle ν_e and $\bar{\nu}_e$ CC inclusive

(included on plot) **Nucl Phys B 133,1978**

T2K Run 2010-2013 (ν-beam)

Good quality data collected from 5.9×10^{20} protons on target (POT)

Predicted # signal evts: 245

Predicted Purity: 65%

Predicted Efficiency: 27%

Bayesian unfolding + bkg subtraction

Photon conversion ('γ') control sample → constrain interactions outside fiducial volume → 95% pure

Flux-av. σ = [1.11 ± 0.09 (stat) ± 0.18 (syst)] $\times 10^{-38}$ cm^2/nucleon

→ agrees with Gargamelle result, as well as both the NEUT and GENIE predictions

Systematic error at SK

TABLE II. Systematic uncertainty on the predicted event rate at the far detector.

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

Predicted event rate at SK

TABLE XIX: Predicted number of ν_μ CC candidates and ν_e CC candidates for an exposure of 6.57 $\times 10^{20}$ POT with and without oscillations and with oscillations using the typical parameter values: $\sin^2\theta_{12} = 0.306$, $\Delta m^2_{21} = 7.5 \times 10^{-5}\,\mathrm{eV}^2/c^4$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{32} = 2.4 \times 10^{-3}\,\mathrm{eV}^2/c^4$, $\sin^2\theta_{13} = 0.0243$, $\delta_{CP} = 0$ and normal mass hierarchy. The total numbers are broken down into the intrinsic beam components (those without an arrow) and oscillated components.

	ν_μ CC		ν_e CC	
	Osc.	No osc.	Osc.	No osc.
ν_μ	116.46	431.77	0.94	1.38
$\nu_e \to \nu_\mu$	0.16	0	0.00	0
$\bar{\nu}_\mu$	7.81	13.92	0.05	0.06
ν_e	0.26	0.27	3.13	3.38
$\nu_\mu \to \nu_e$	0.26	0	16.55	0
$\bar{\nu}_e$	0.02	0.02	0.15	0.16
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.00	0	0.22	0
Total	124.98	445.98	21.06	4.97