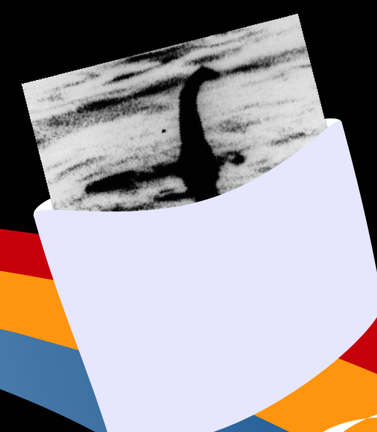
NuFact2014
Short baseline oscillation measurements at T2K

Javier Caravaca-Rodríguez
on behalf of the T2K collaboration



Outline

Short baseline ν_e disappearance at ND280

1. Motivation: Reactor and gallium anomalies
2. ν_e selection at the T2K near detector (ND280)
3. ν_e disappearance at ND280 in the 3+1 model

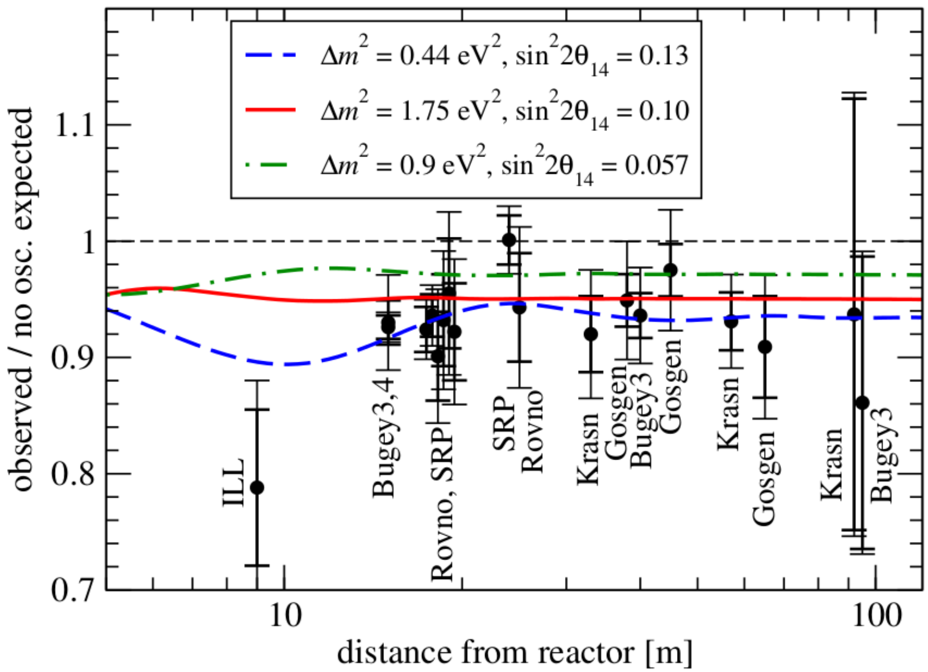
Short baseline ν_e appearance in a ν_μ beam at nuPRISM

Further details of the T2K experiments and oscillation results:
- C. Bronner talk (WG1 Tuesday)
- S. Cartwright talk (WG1+2 Tuesday)

3 Short baseline ν_e disappearance anomalies

Reactor experiments

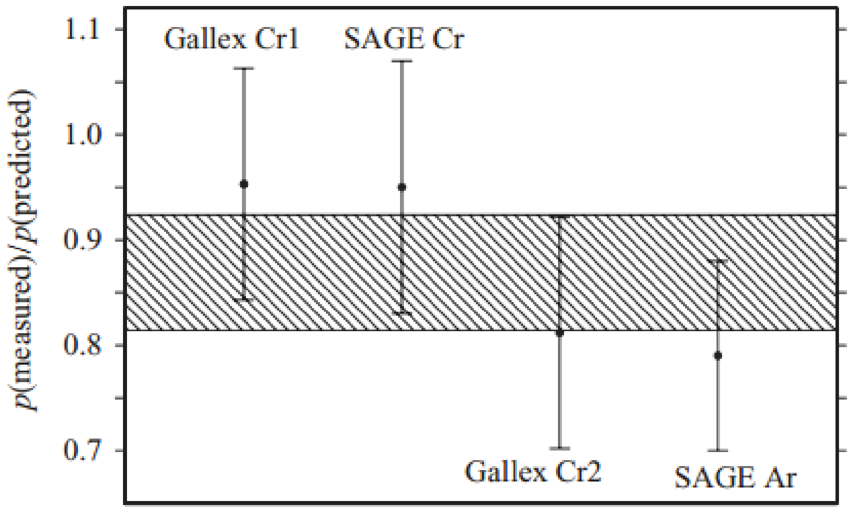
Phys. Rev. D 83, 073006 (2011)



$$R = 0.927 \pm 0.023$$

Experiments with Gallium

Phys. Rev. C 80, 015807 (2009)



$$R = 0.87 \pm 0.05$$

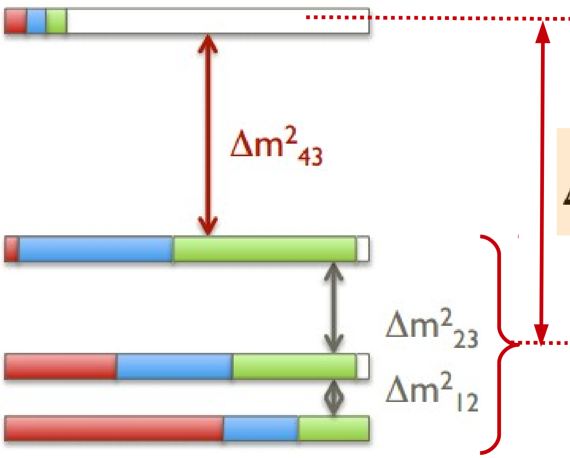
Combined ~3.6σ exclusion of the null hypothesis

Tensions between appearance and disappearance channels → Study anomalies one by one starting from ν_e disappearance

A possible solution: the 3+1 model

Sterile neutrino mixes with active neutrinos enabling active-sterile oscillations

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$



$$\Delta m^2_{41} \gg 10^{-3} eV^2$$

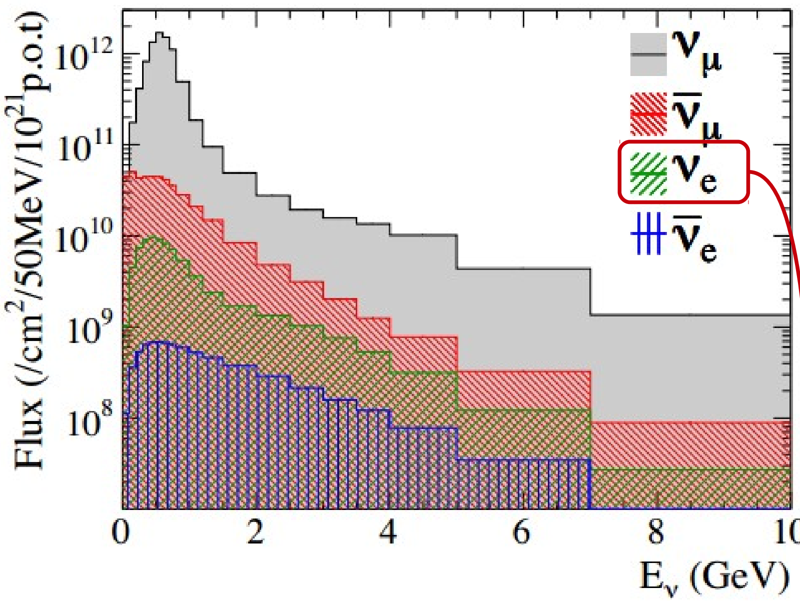
$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

$\nu_e \rightarrow \nu_s$: ν_e disappearance at short baseline

$$P_{ee} = P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{ee})\sin^2\left(1.27\,\Delta m^2_{41}[\mathrm{eV}^2]\frac{\mathrm{L[m]}}{\mathrm{E[MeV]}}\right)$$

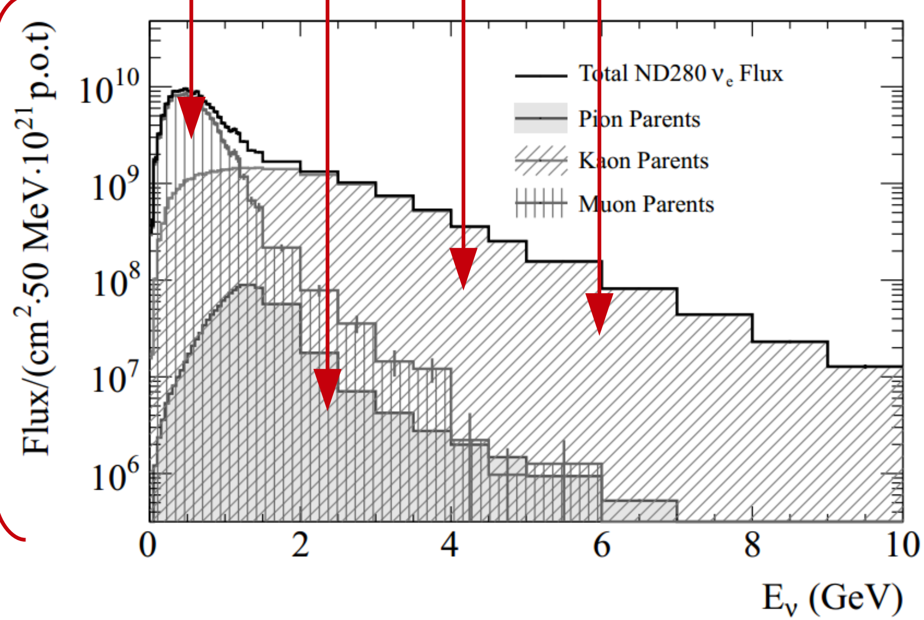
ν_e component of the T2K beam

Flux prediction (Beam MC)



Particle (GeV)	Decay channel	Branching ratio (%)
π^+	$\to \mu^+\nu_\mu$	99.9877
	$\to e^+\nu_e$	1.23×10^{-4}
K^+	$\to \mu^+\nu_\mu$	63.55
	$\to \pi^0\mu^+\nu_\mu$	3.353
	$\to \pi^0 e^+\nu_e$	5.07
K^0_L	$\to \pi^-\mu^+\nu_\mu$	27.04
	$\to \pi^- e^+\nu_e$	40.55

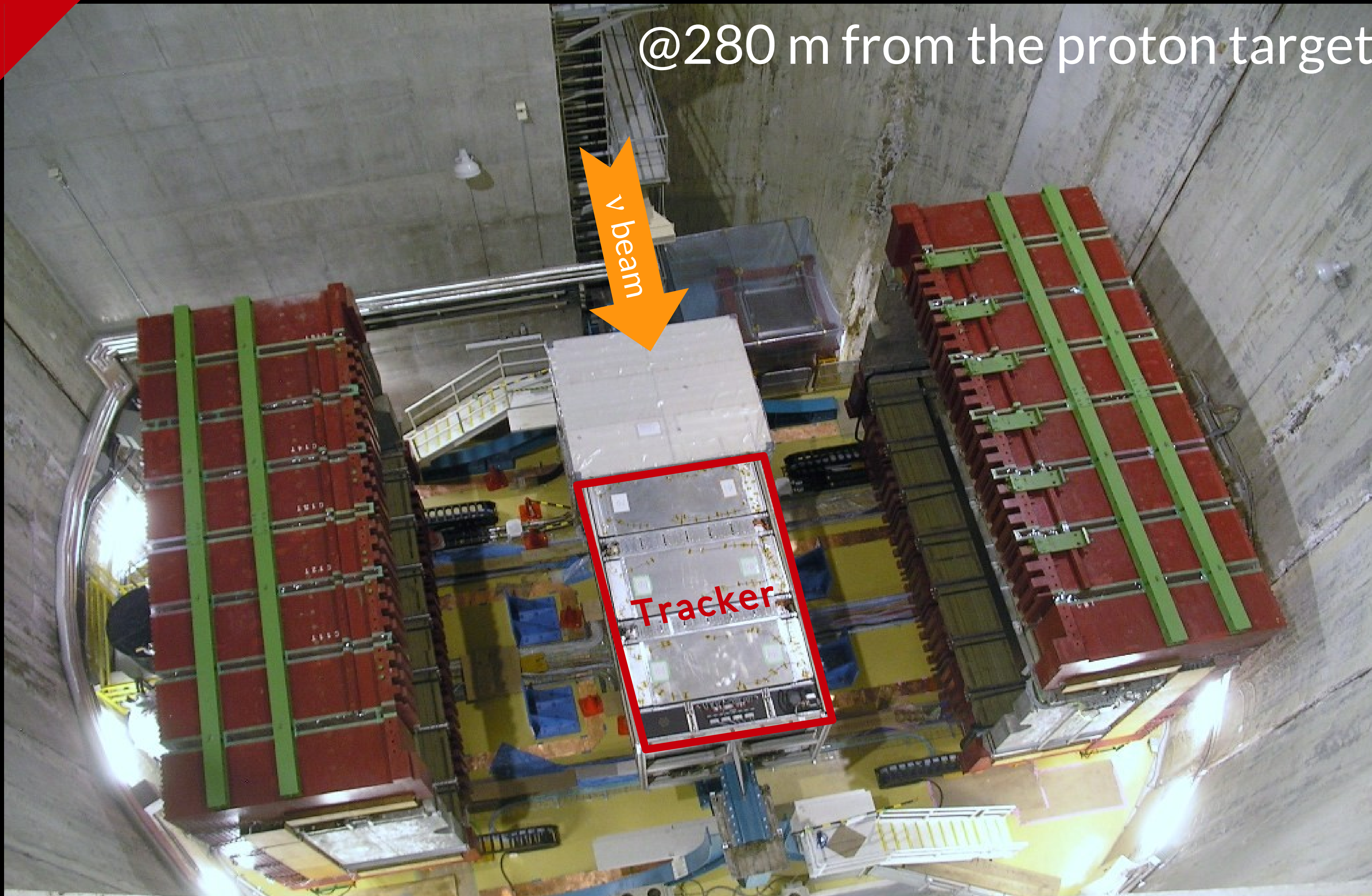
$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$



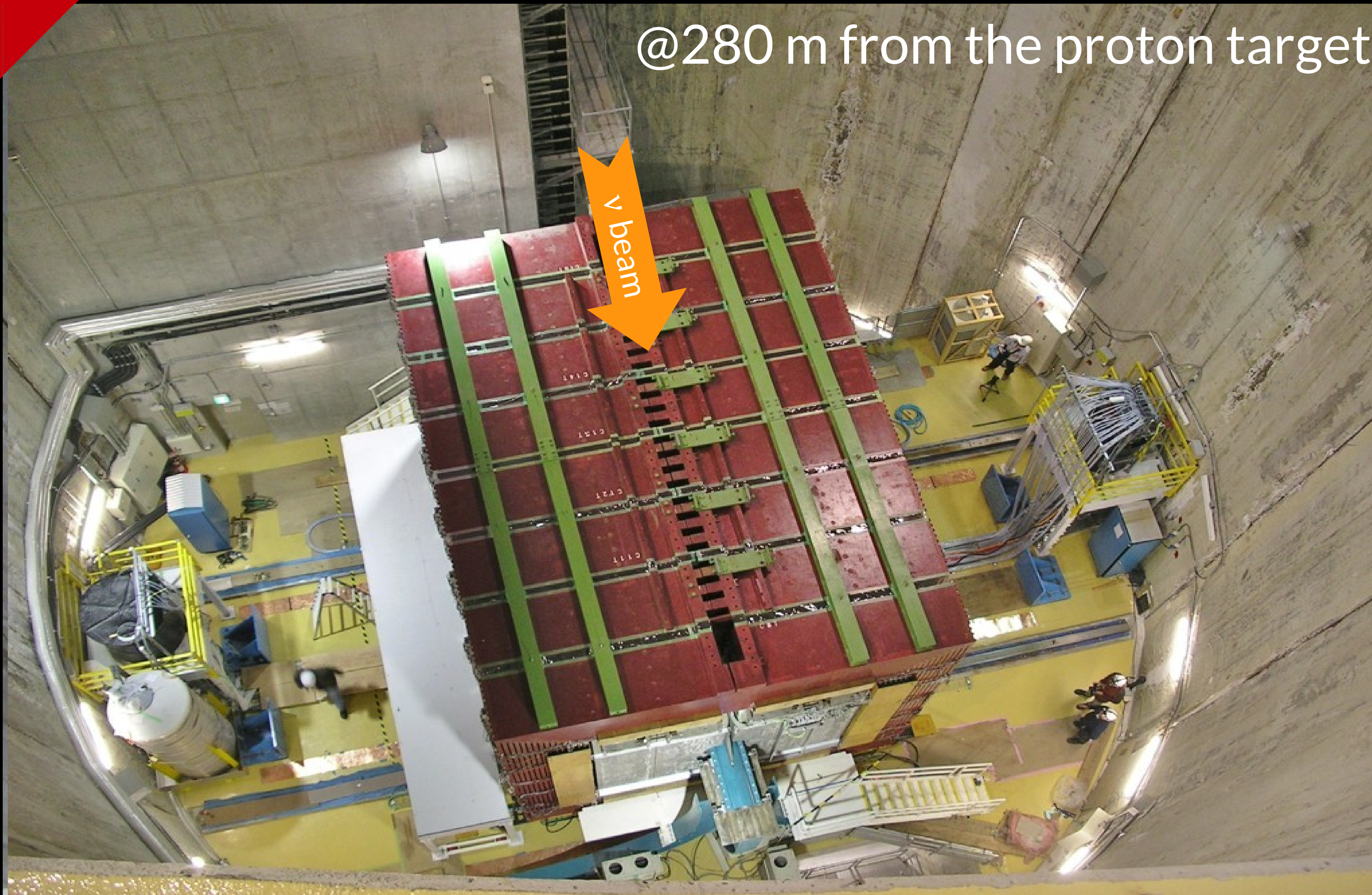
ν_μ ~93% $\overline{\nu}_\mu$ ~6%

ν_e ~1.1% (~0.5% at the peak)

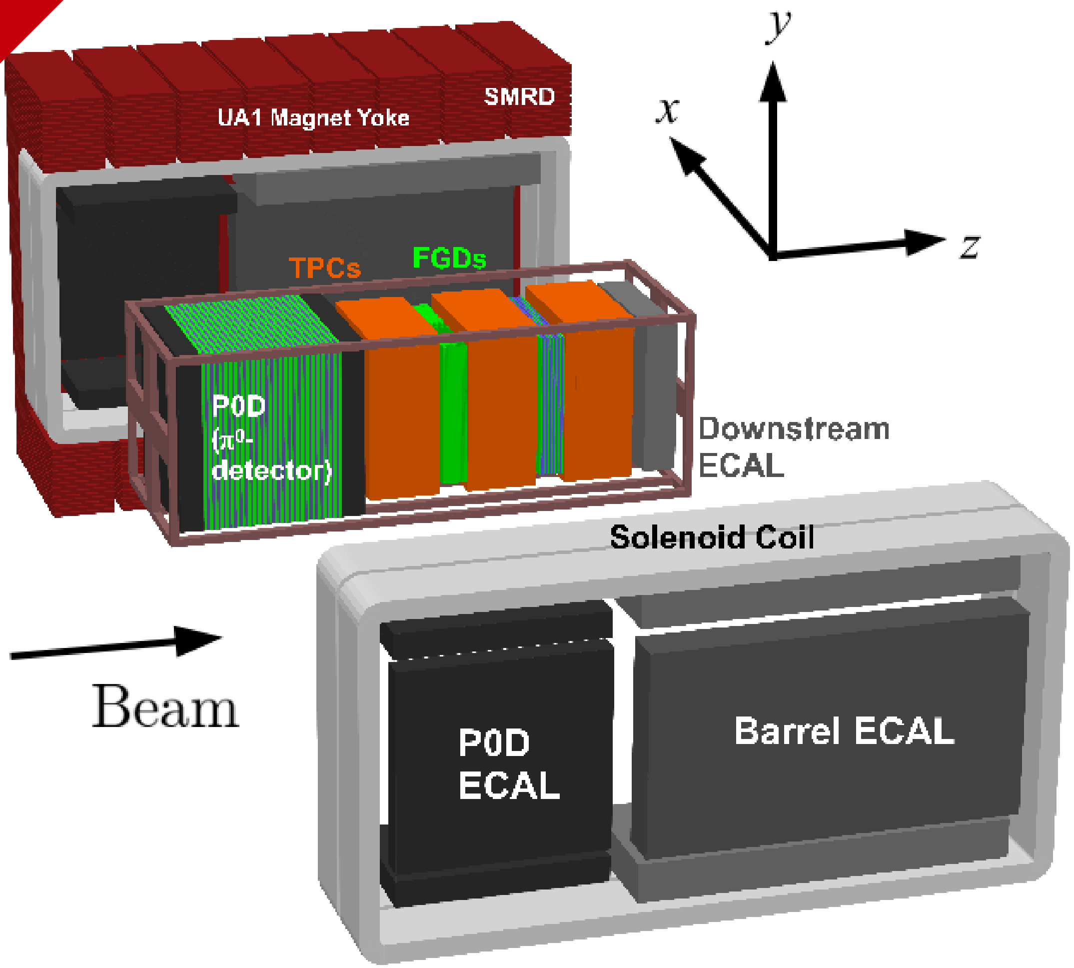
The T2K off-axis near detector: ND280



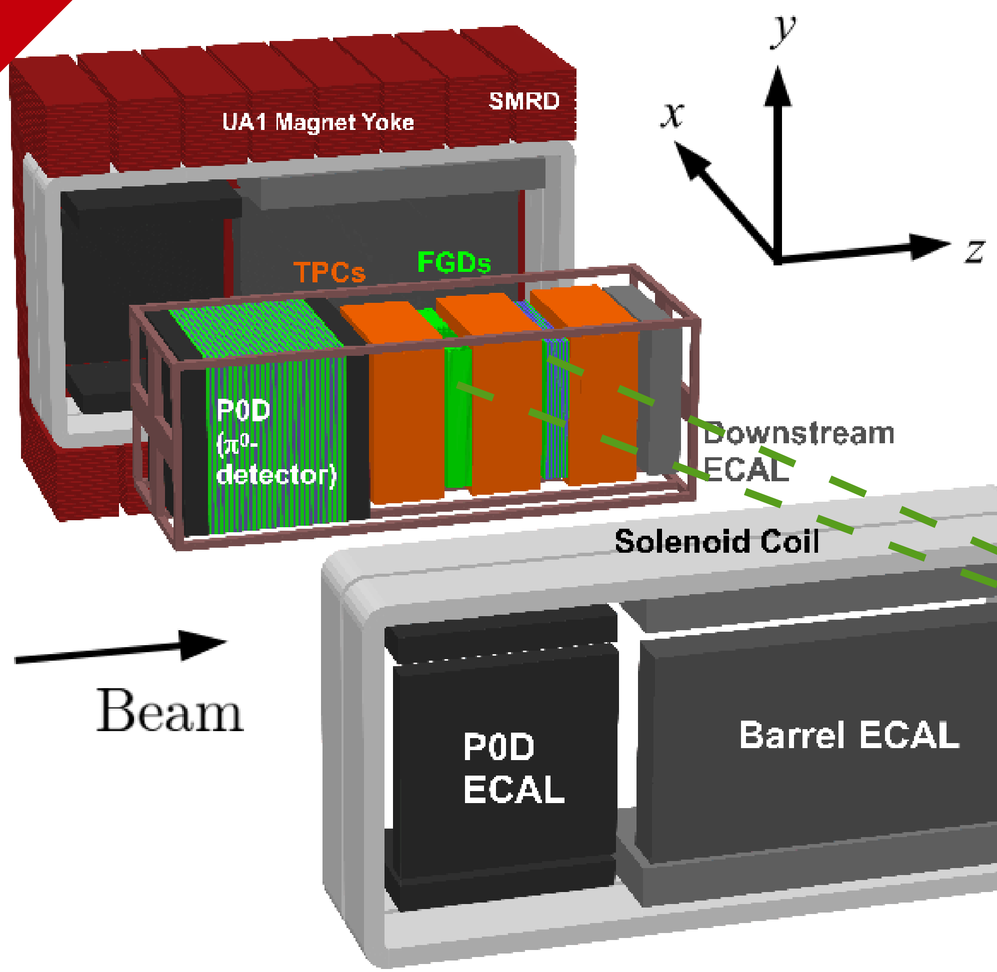
The T2K off-axis near detector: ND280



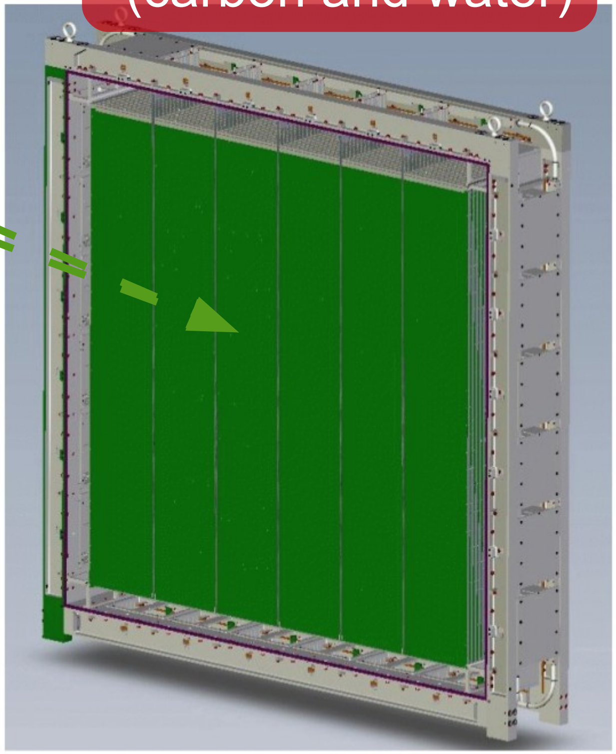
ND280 in parts



ND280 in parts

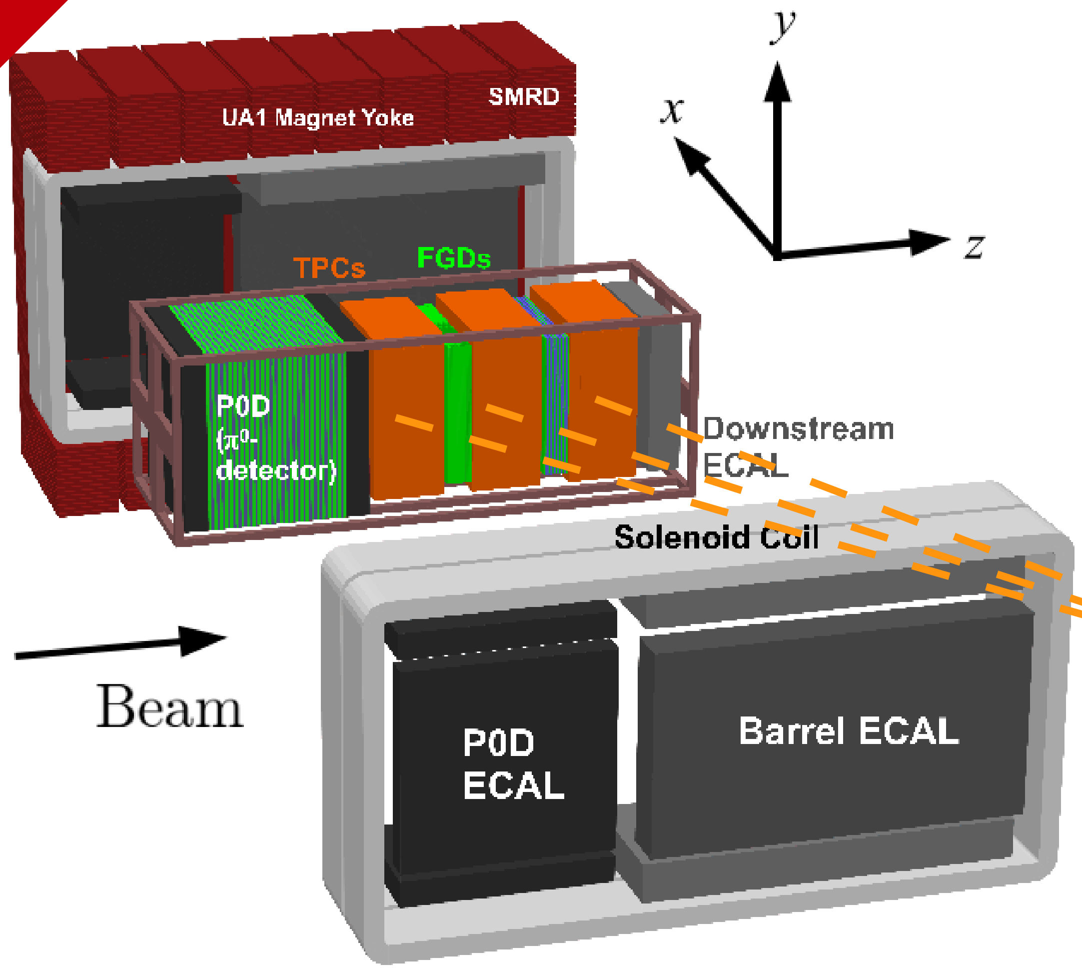


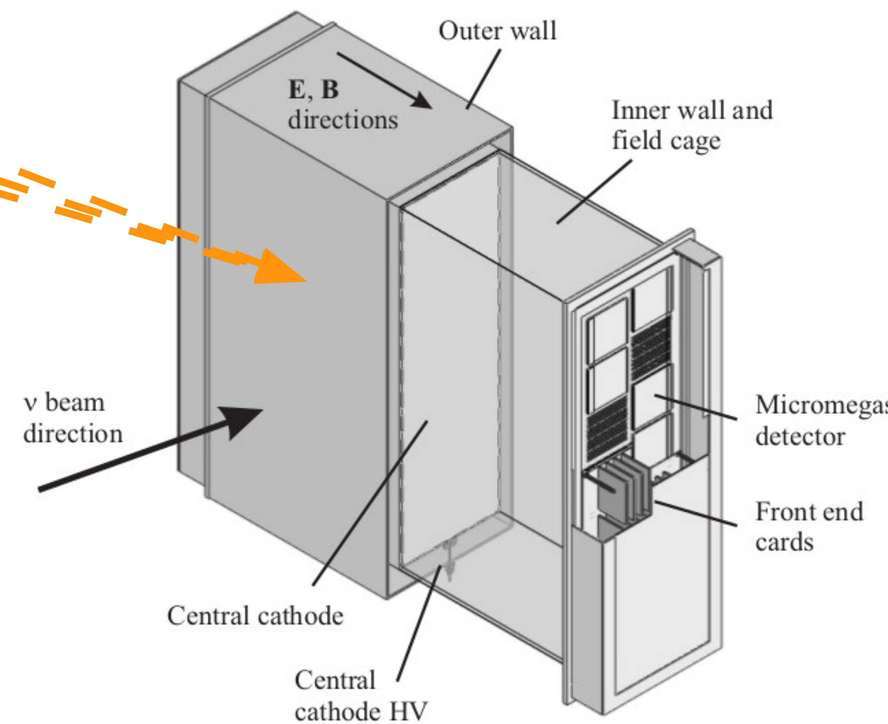
FGDs
Active targets for neutrino interaction (carbon and water)



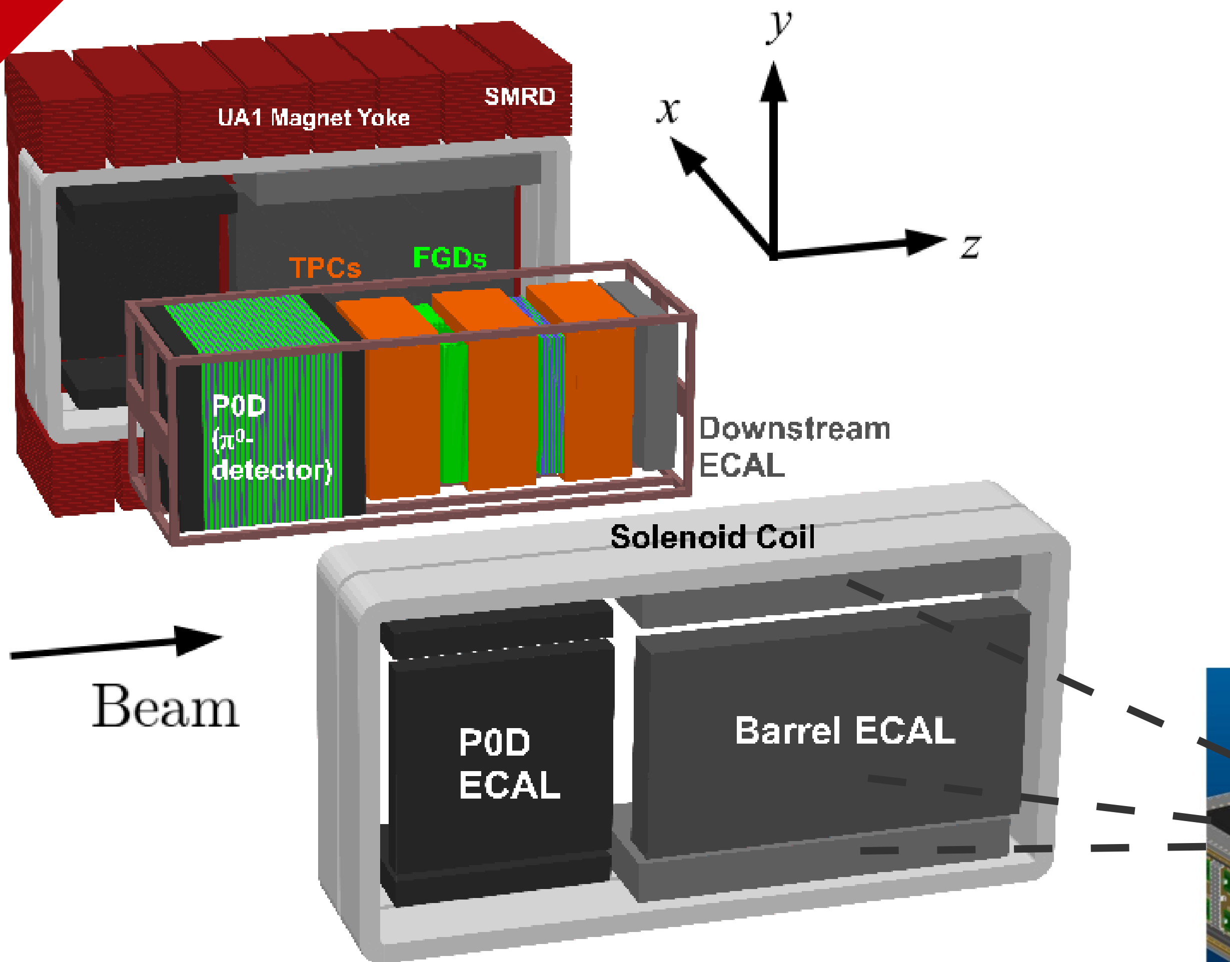
ND280 in parts

TPCs
tracking, momentum measurement and PID capabilities

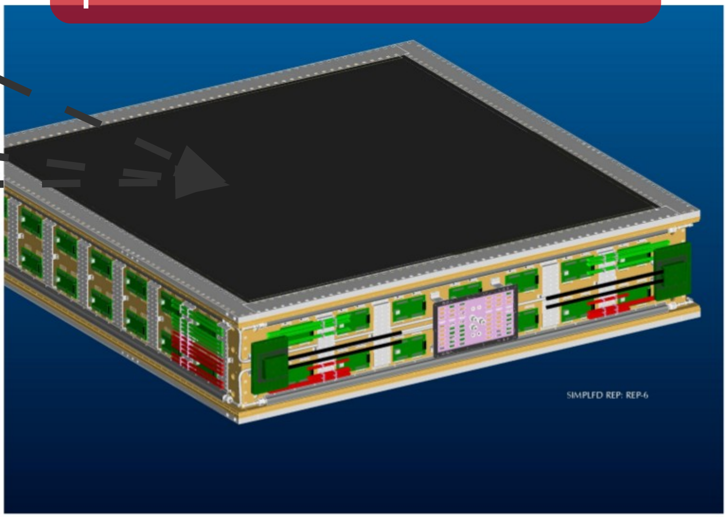




ND280 in parts

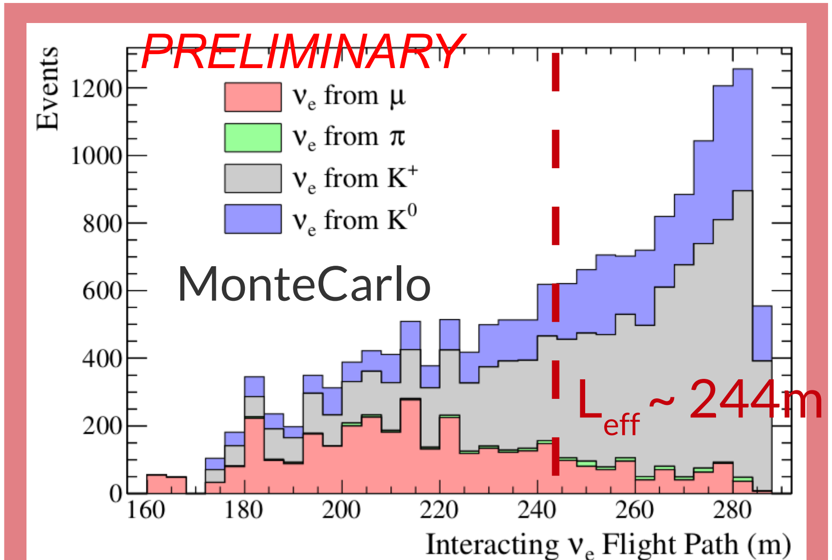


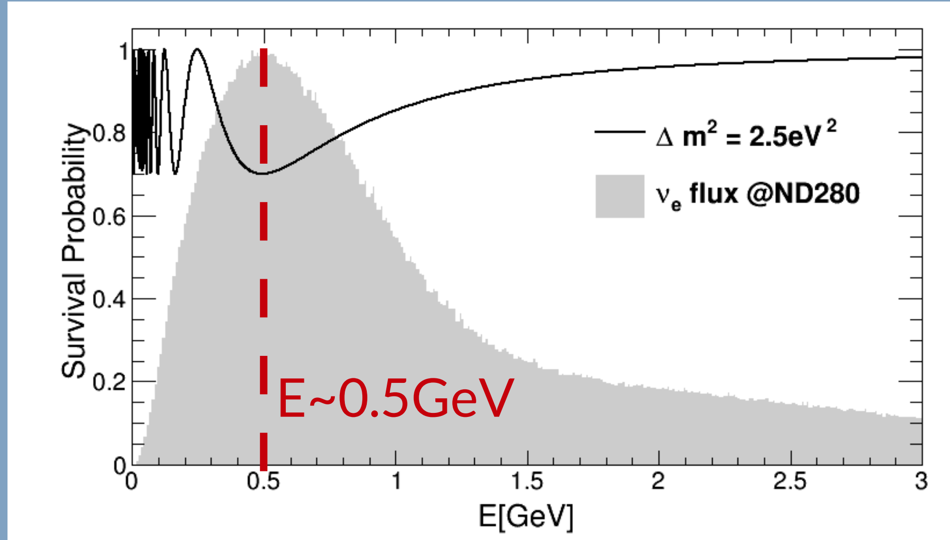
ECals
PID and exiting
particles reconstruction

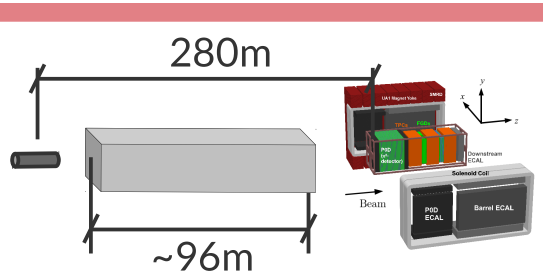


ν_e disappearance at ND280

$$P_{ee} = P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{ee}) \sin^2\left(1.27 \Delta m^2_{41} [\mathrm{eV}^2] \frac{L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$





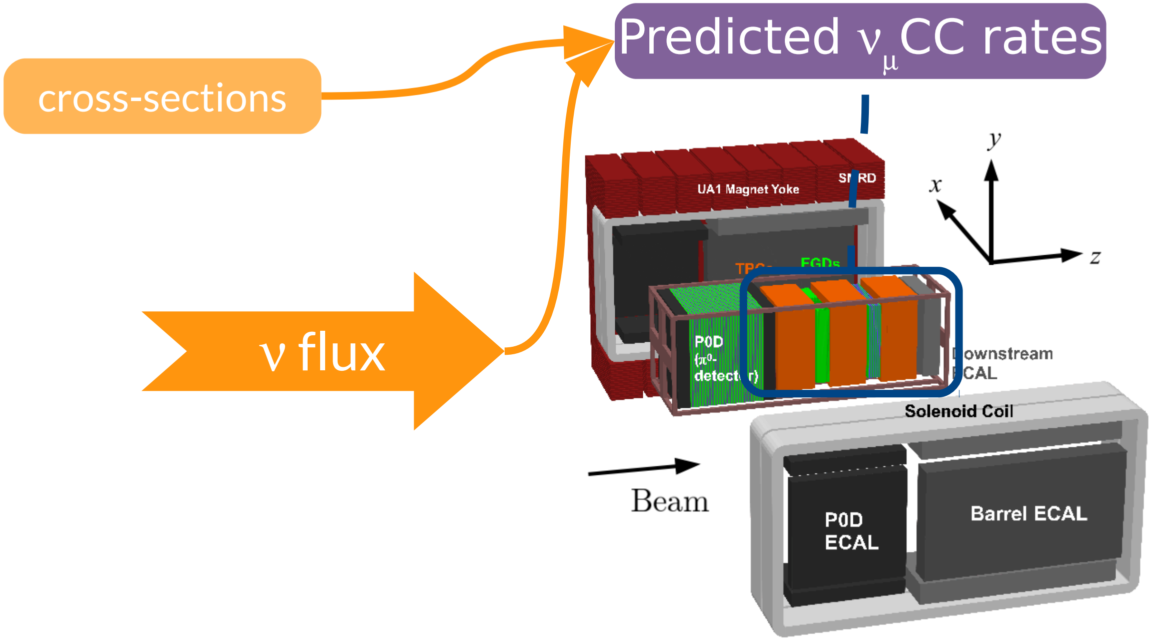


ND280 is sensitive around

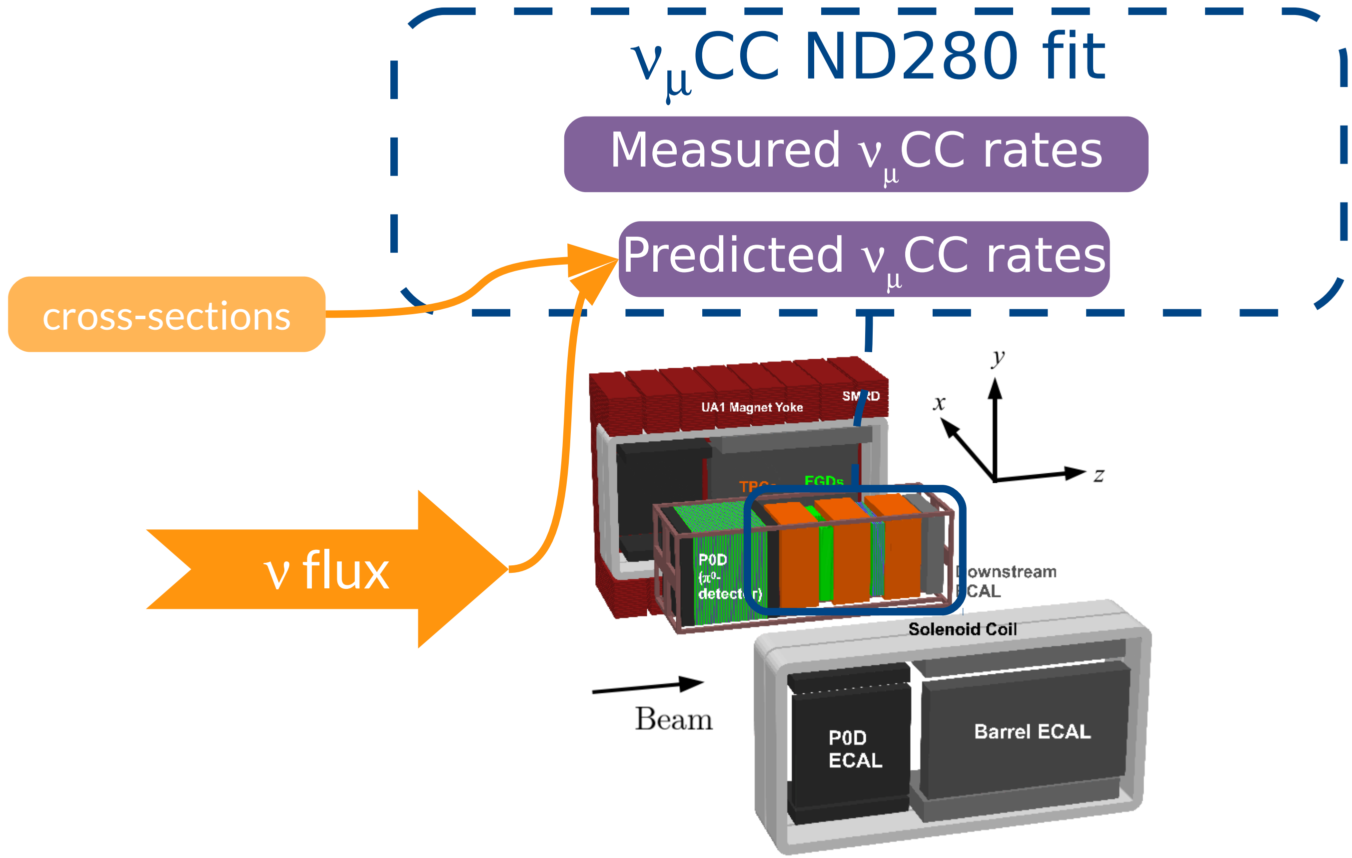
$$\Delta m^2_{41} = \frac{\pi}{2 \times 1.27} \frac{E}{L_{\mathrm{eff}}} \sim 3\,\mathrm{eV}^2$$

Test with ND280 the *reactor and gallium anomalies* in a ~ 1GeV ν_e beam

Analysis overview

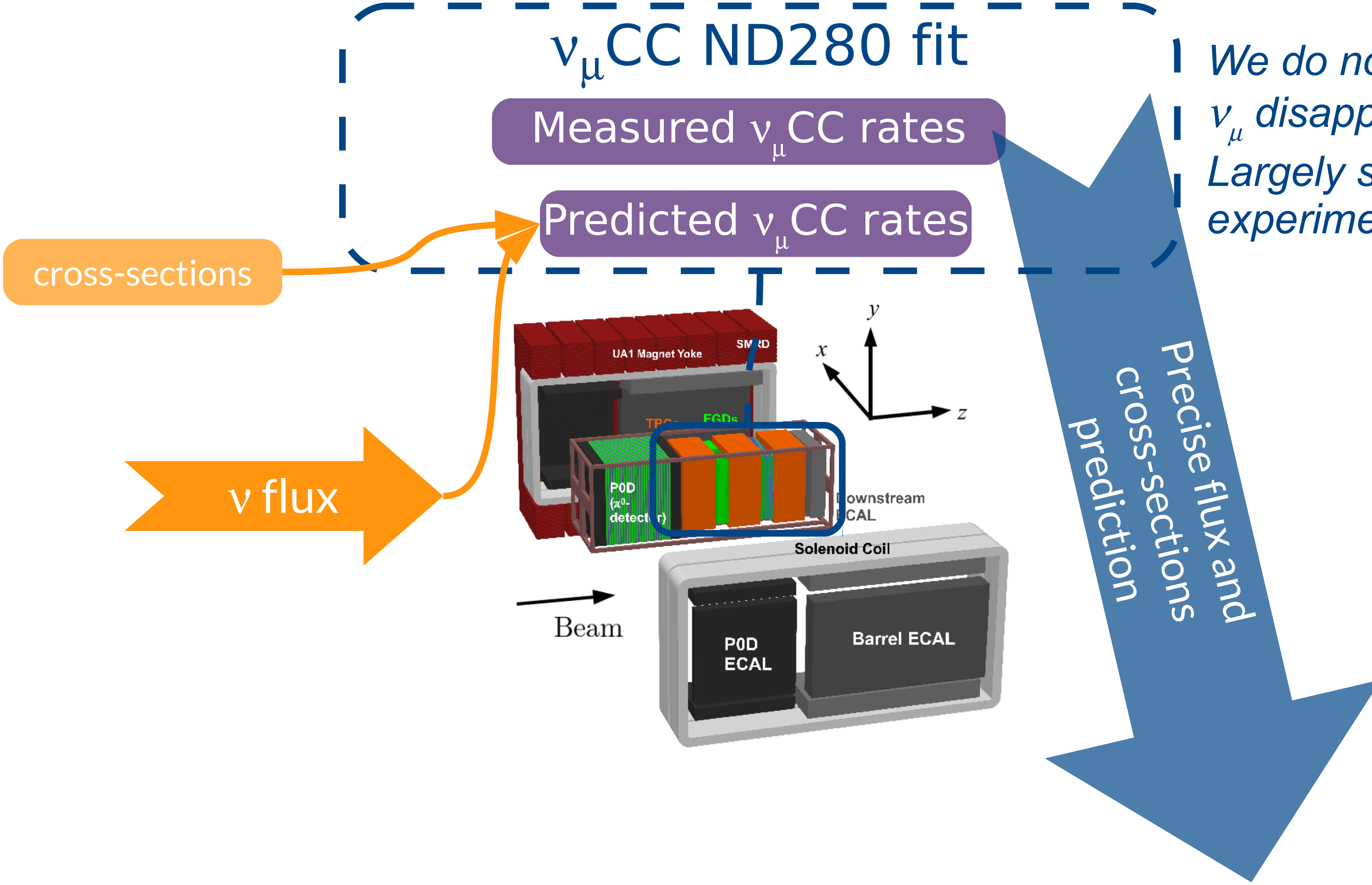


Analysis overview



We do not consider ν_μ disappearance → Largely suppressed by experiments

Analysis overview



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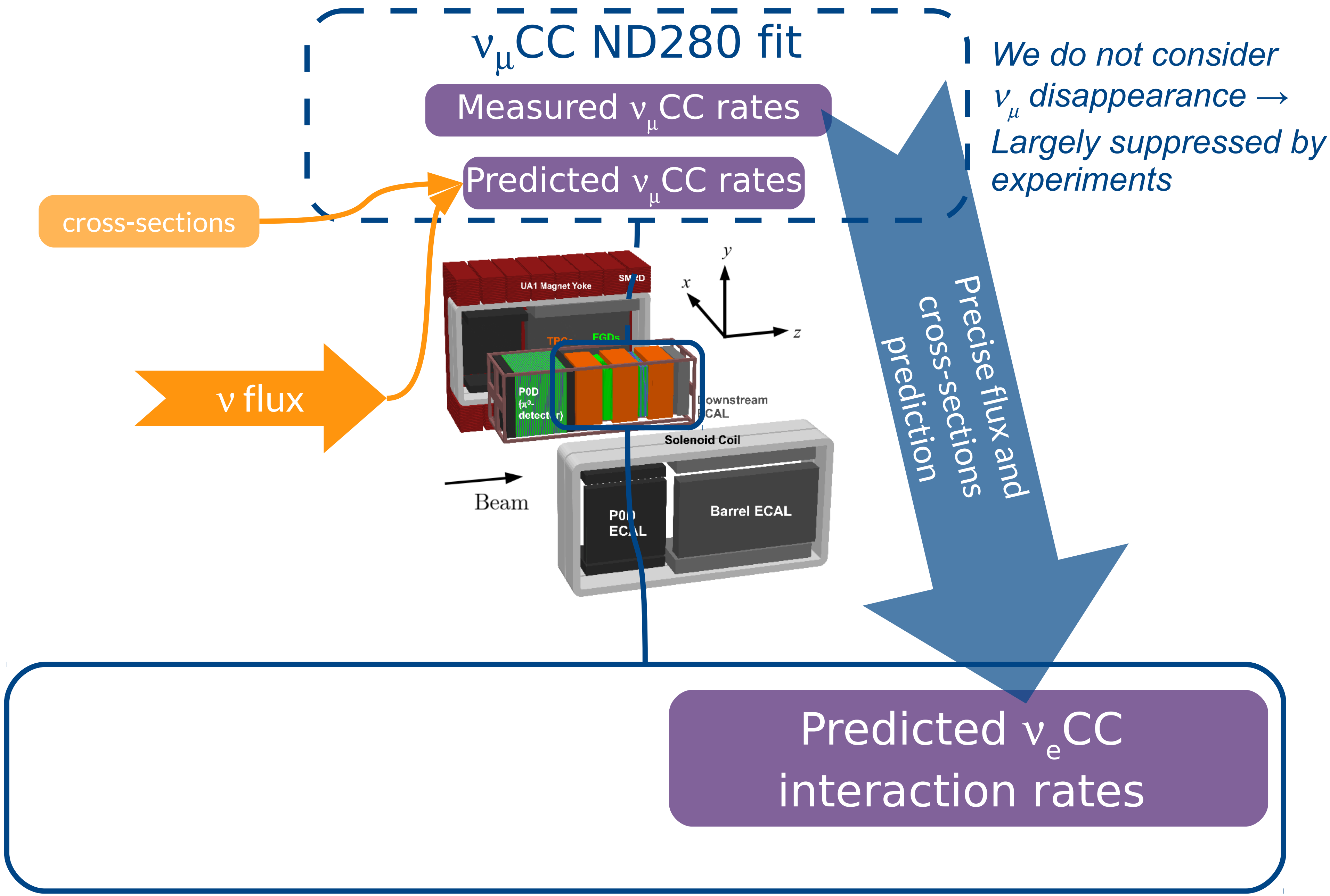
Analysis overview



Analysis overview

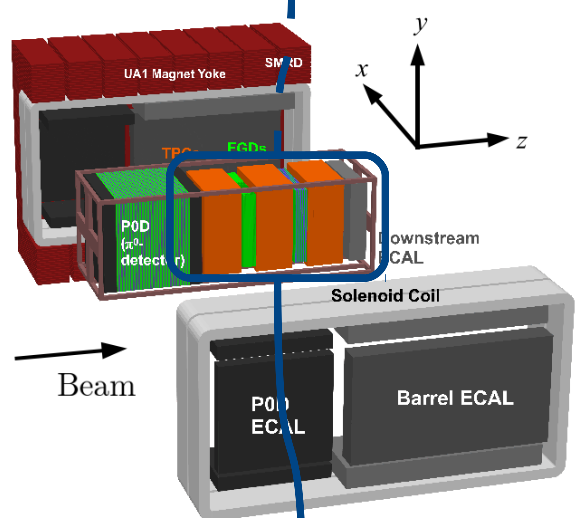
ν_μCC ND280 fit

Measured ν_μCC rates

Predicted ν_μCC rates

cross-sections

ν flux



We do not consider ν_μ disappearance → Largely suppressed by experiments

Precise flux and cross-sections prediction

Measured ν_eCC interaction rates

Predicted ν_eCC interaction rates

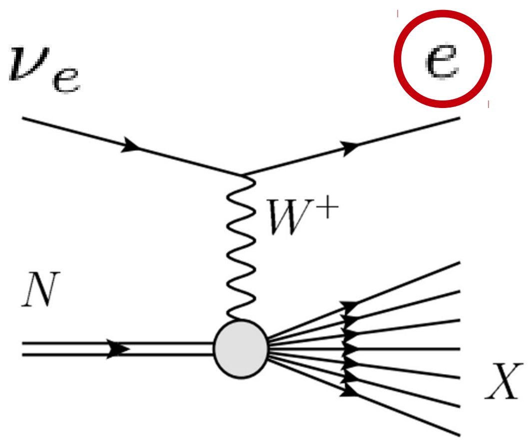
ν_eCC ND280 fit

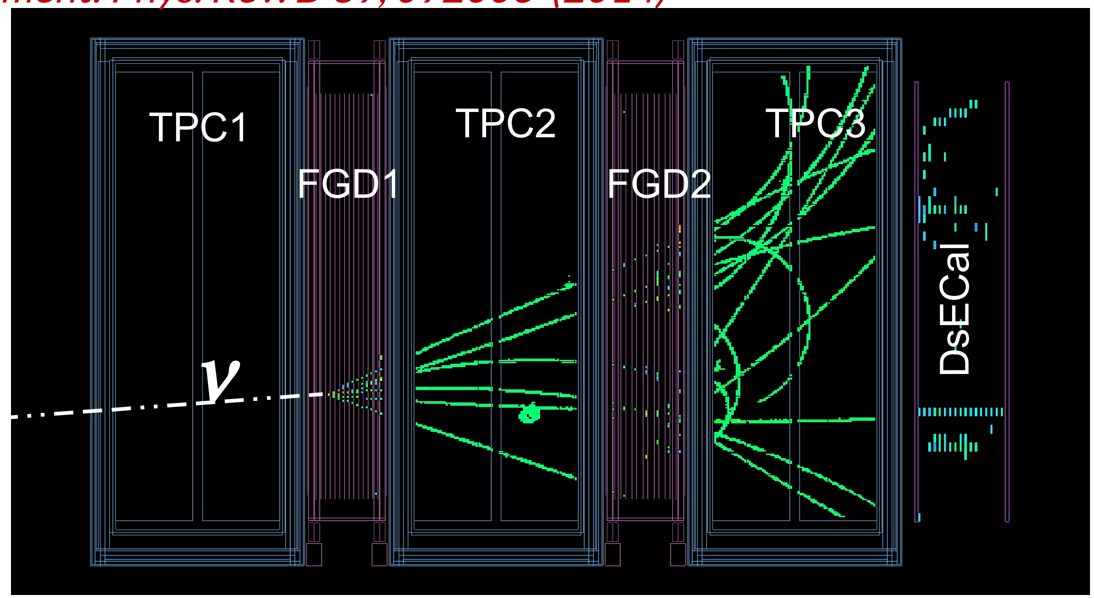
ν_eCC selection: lepton selection

Further details: Luke Southewell poster about ν_e and $\bar{\nu}_e$ analyses

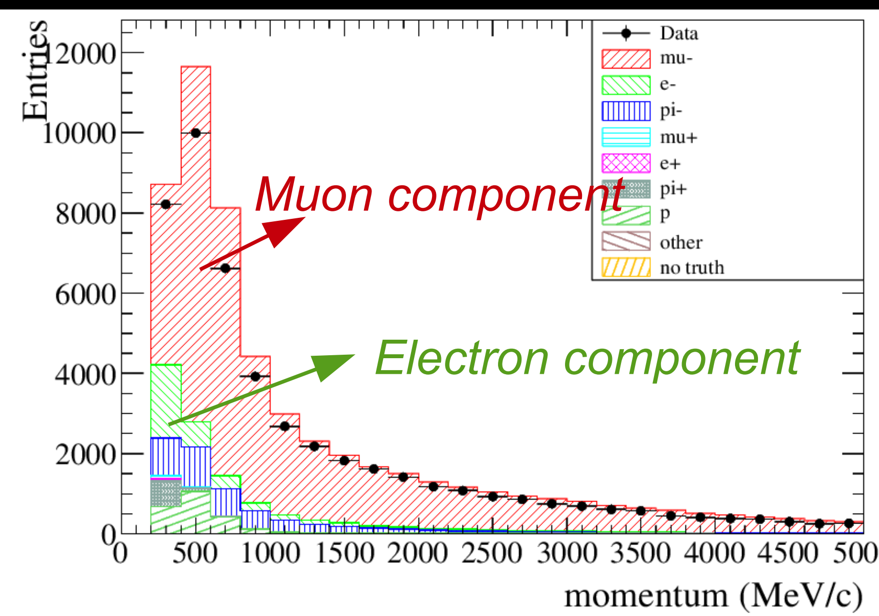
Beam ν_e measurement: Phys. Rev. D 89, 092003 (2014)

Identify ν_eCC interactions searching for *electrons*





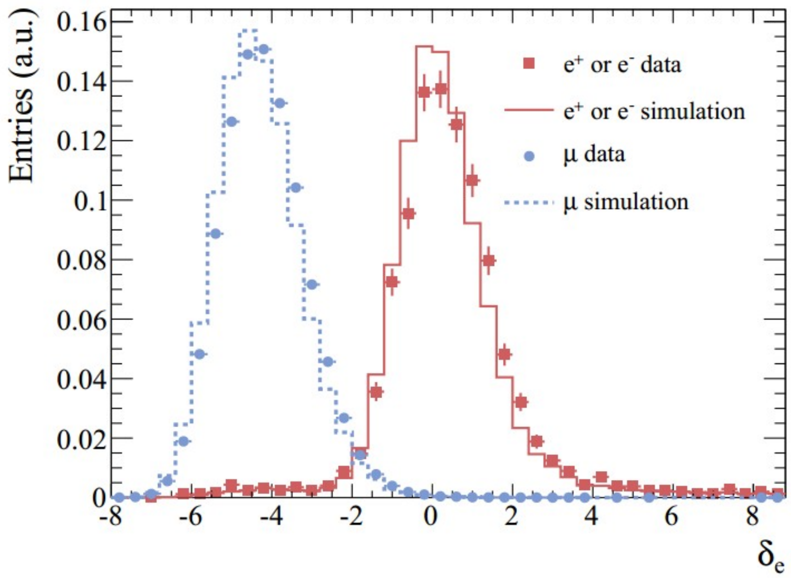
- Select the highest momentum negative track in a fiducial volume
- Look for an electron-like track applying the particle identification



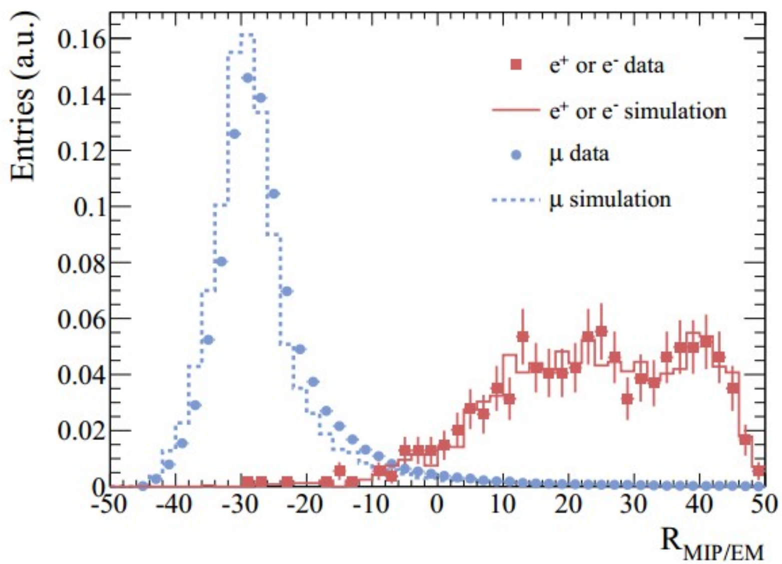
$5.9x10^{20}$pot

ν_eCC selection: electron identification

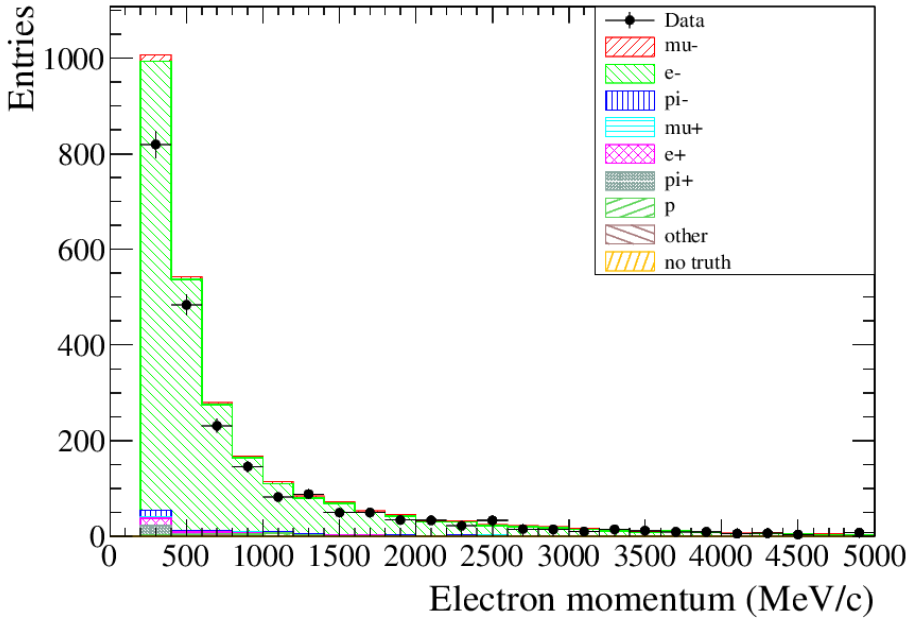
TPC PID



Ecal PID



Muon-electron misidentification for 1GeV <0.5%

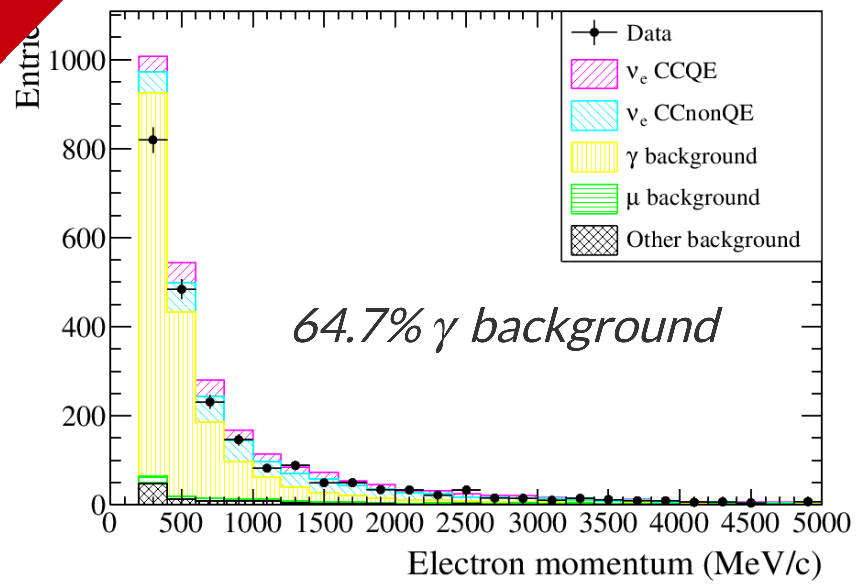


99.8% of the μ rejected

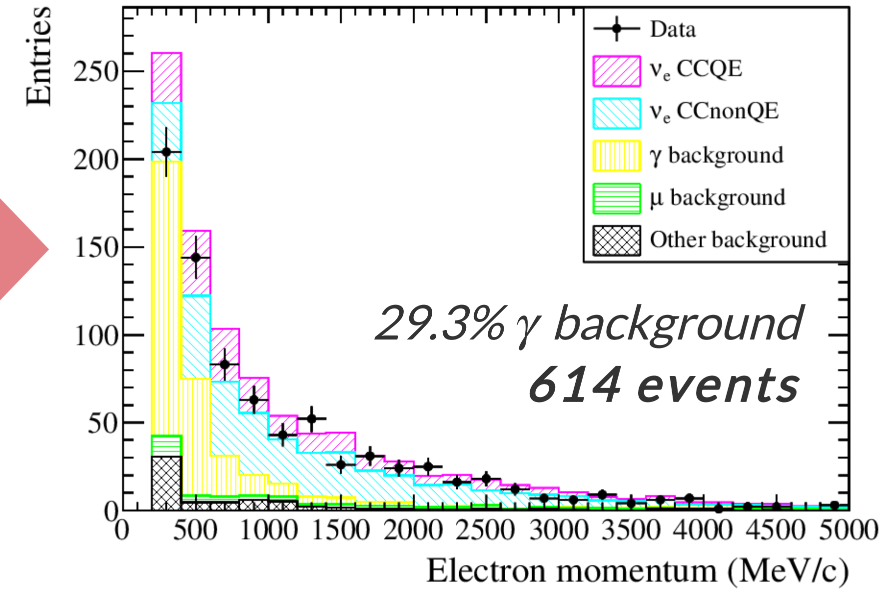
~5% misidentified μ

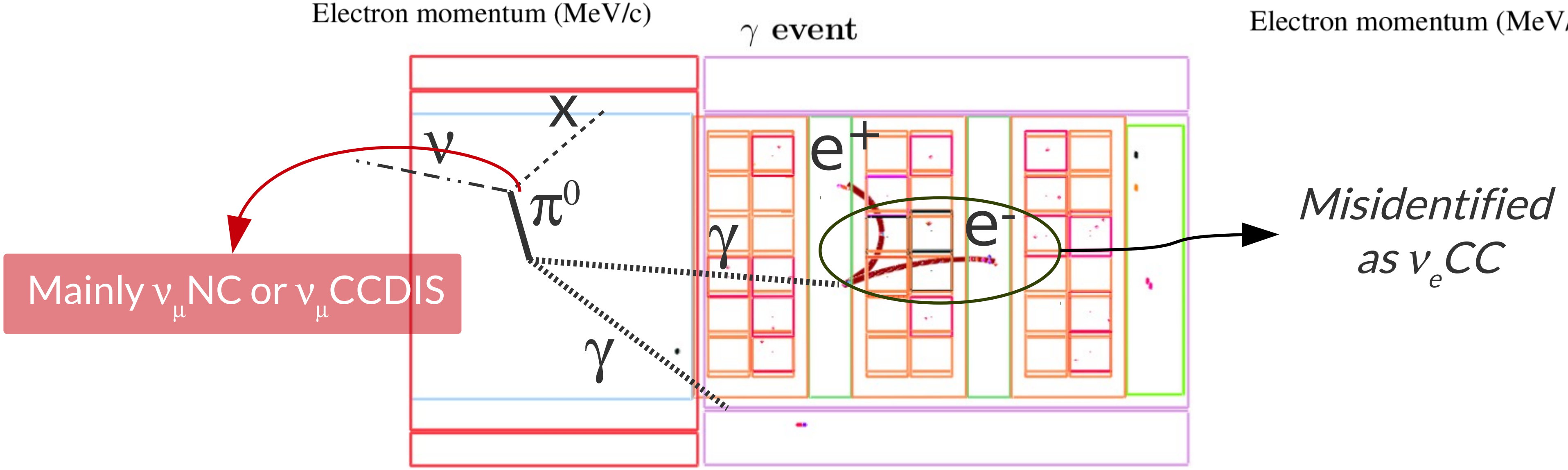
e^- purity of 91,7%
e^- efficiency of 70%

ν_eCC selection: photon background



VETOES





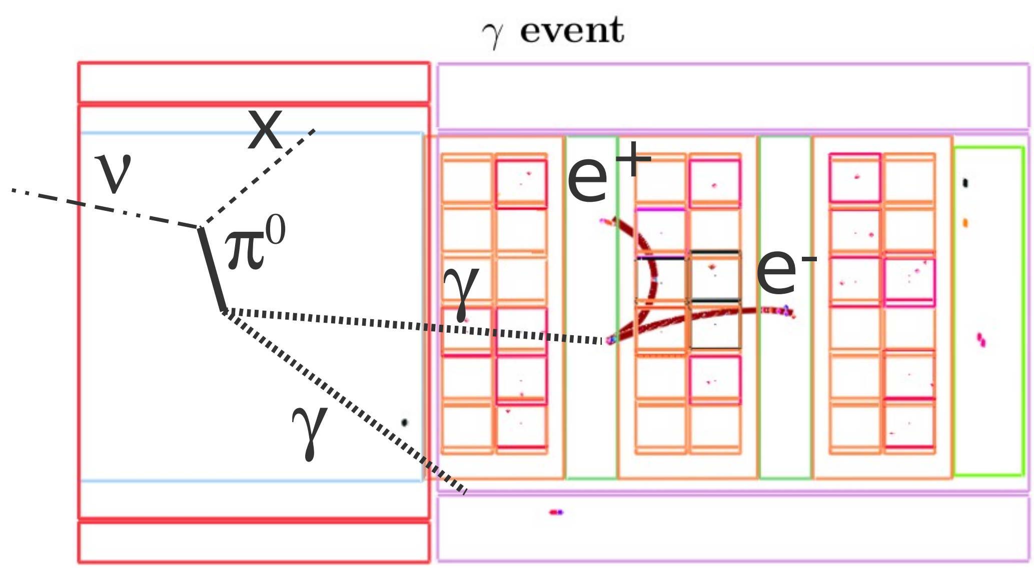
γ background mainly concentrated at low momentum

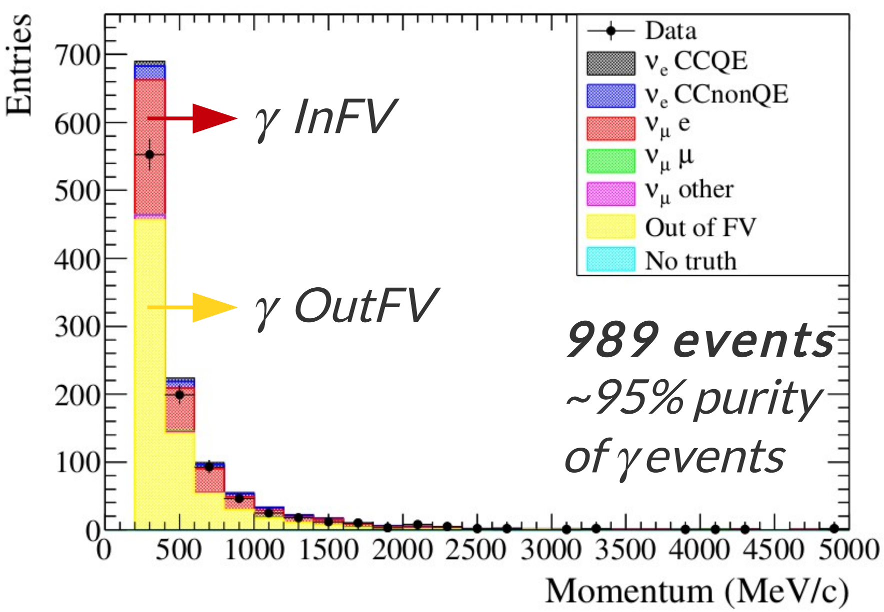
The photon conversion control sample

Develop a pair e+e- selection to control the dominant γ background

Look for close electron-like tracks with opposite charges and invariant mass smaller than 50MeV

$$m_{inv} = \sqrt{2m_e^2 + 2\left(E_+^2 E_-^2 - p_+^2 p_-^2\right)}$$

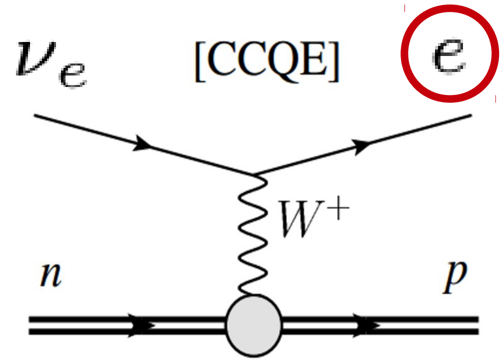




62% come from Out of FV neutrino interactions → Similar break down as ν_e background

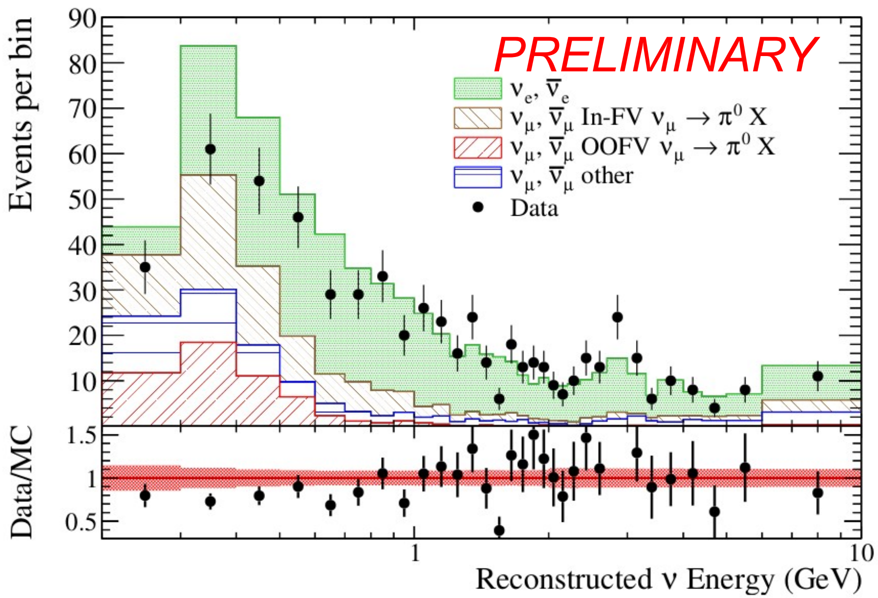
Reconstructed neutrino energy

Reconstruct the neutrino energy in the CCQE hypothesis out of the electron kinematics

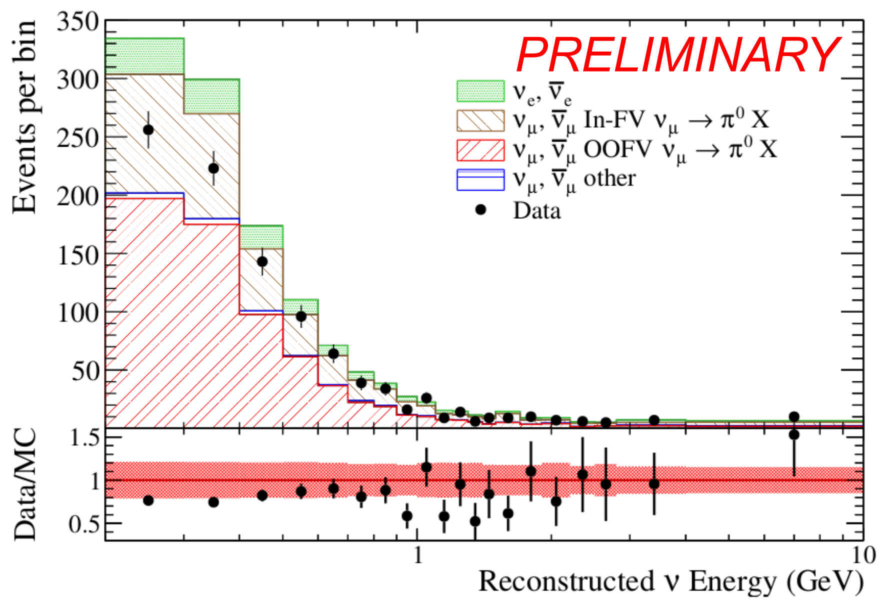


$$E_{Rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

ν_eCC

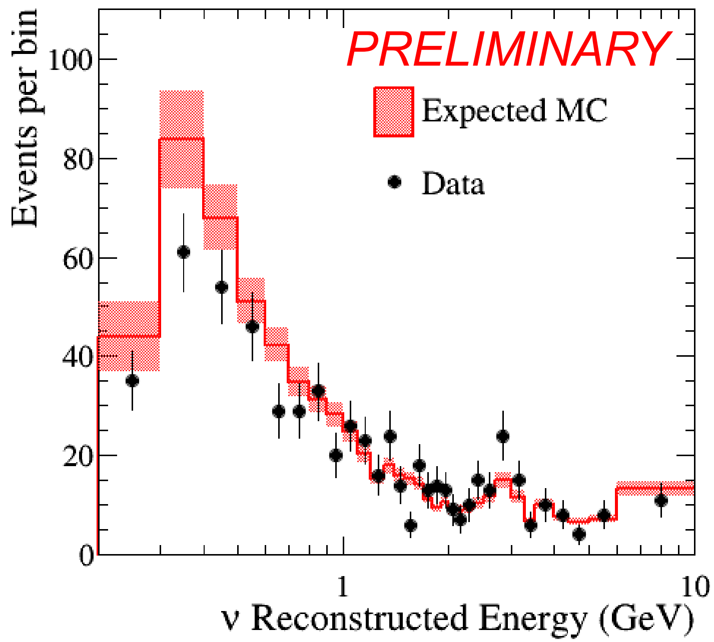


Photon control sample

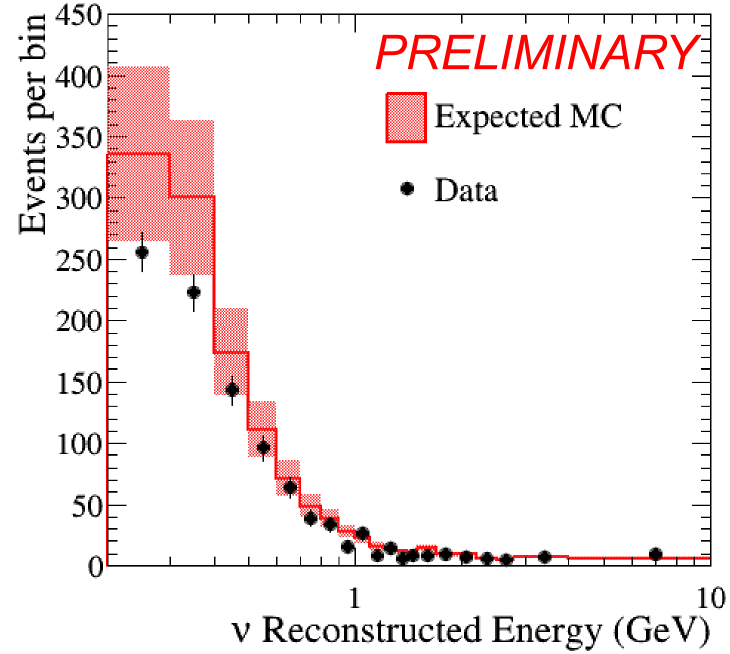


Systematic uncertainties

ν_eCC



Photon control sample



Effect of the systematics in the selections (%)

Error source (# param.)	ν_e sample (sig+bkg)	ν_e sample (sig only)	$\nu_\mu \rightarrow \pi^0 X$ sample
Flux and common (40) cross sections	4.4	5.2	6.7
Not common (5) cross sections	3.7	3.0	17.8
Detector + FSI (10)	5.1	5.5	5.5
Total (55)	7.6	8.1	19.9

Out of fiducial volume systematics are the dominant ones → Calibrated with the γ sample

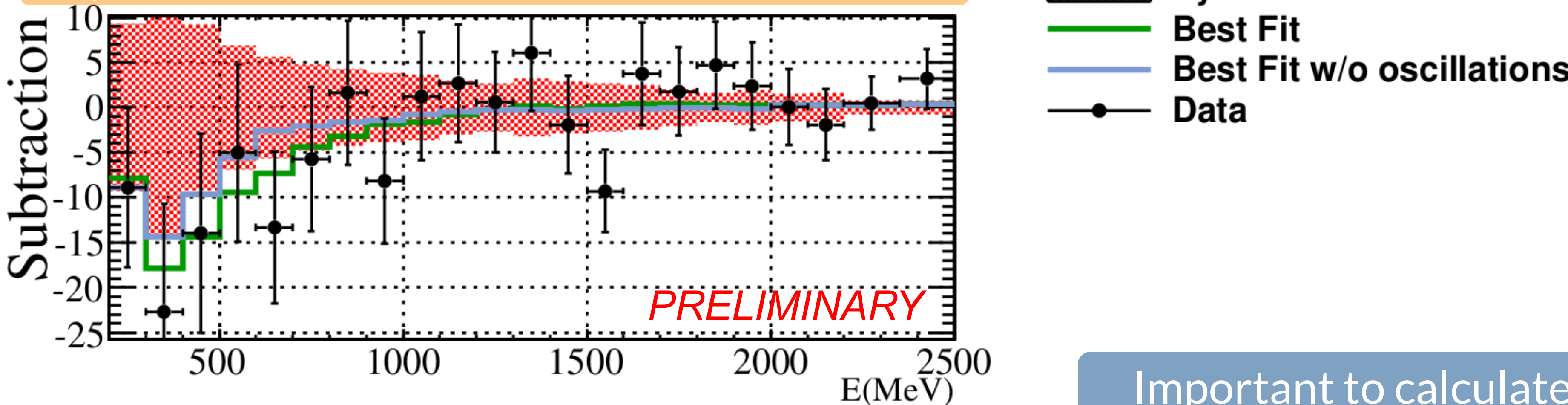
Binned log-likelihood fit

Binned log-likelihood ratio analysis

$$\chi^2 = \chi^2_{\nu_e} + \chi^2_{\gamma} + \textit{penalty term}(\vec{f})$$

Nuisance parameters to model the systematics

ν_eCC: Subtraction to the nominal prediction



Important to calculate the significance

Best fit parameters

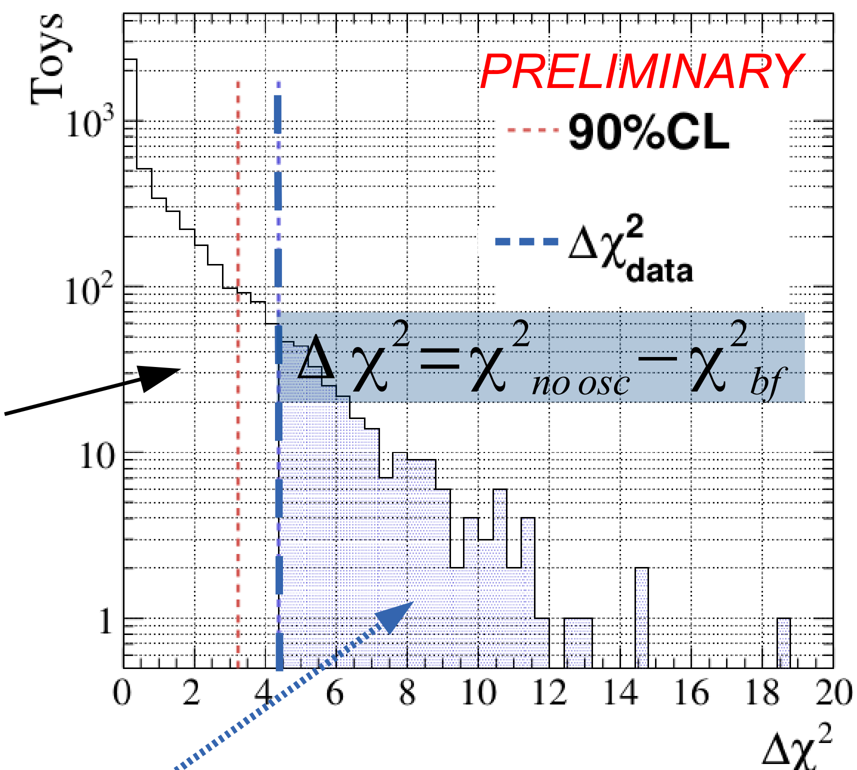
$$\Delta m^2_{41bf} = 2.14\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{ee})_{bf} = 1.00$$

Significance

p-value → estimates the compatibility of the ND280 data with the non-oscillation hypothesis

$\Delta\chi^2_{00}$ distribution for 10,000 toy experiments without oscillations



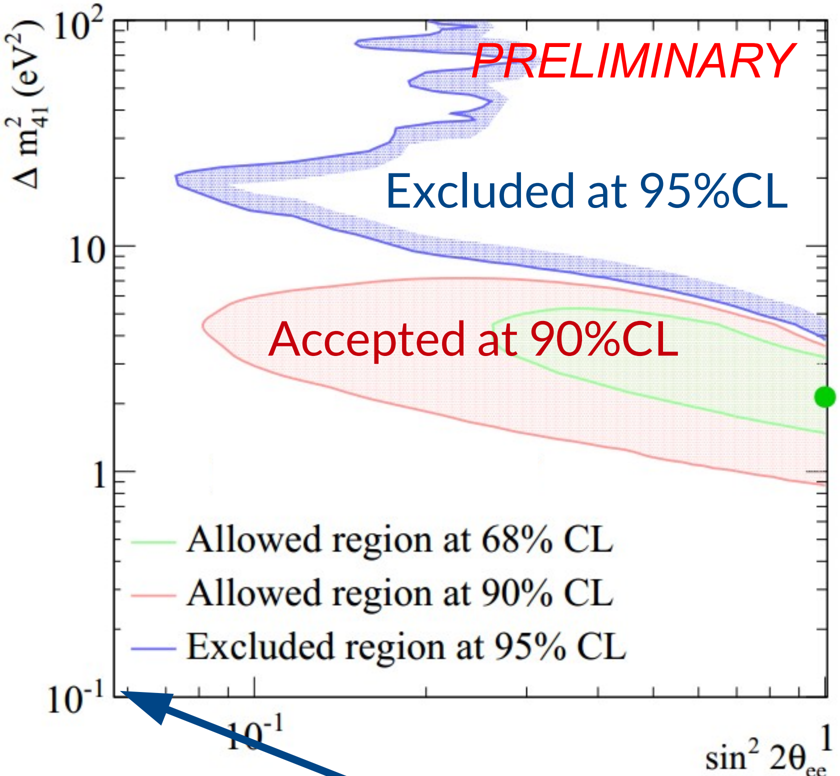
$$p\ value = 0.061$$

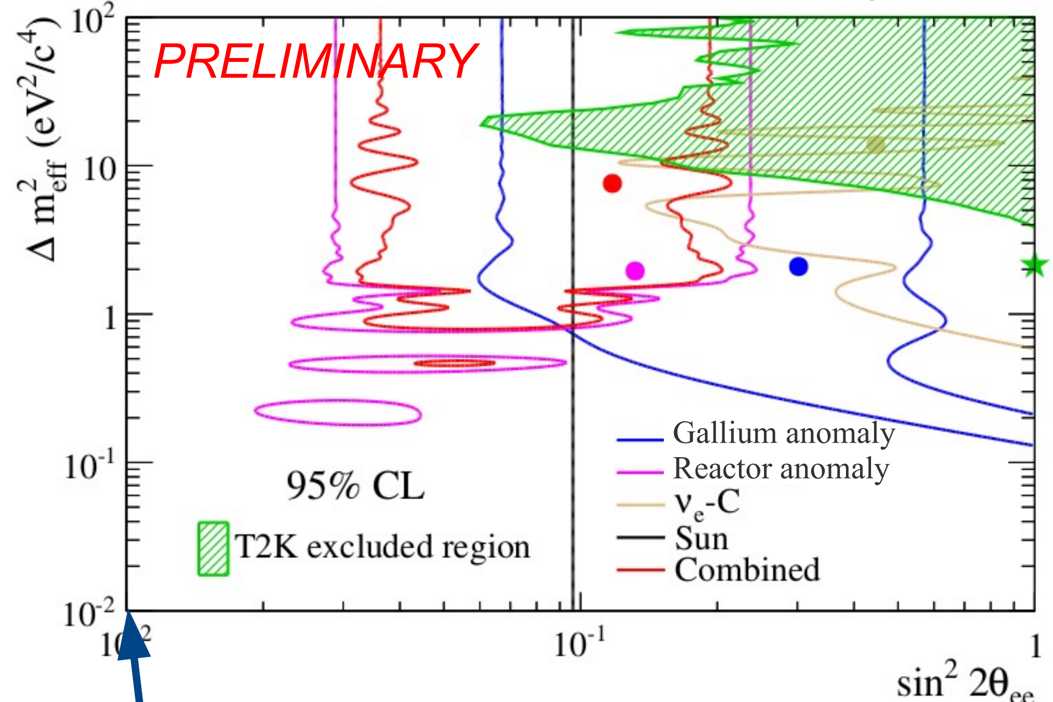
The null hypothesis is accepted at the **~6%**

Confidence intervals

Used the ***Feldman & Cousins*** *method to extract the confidence contours*

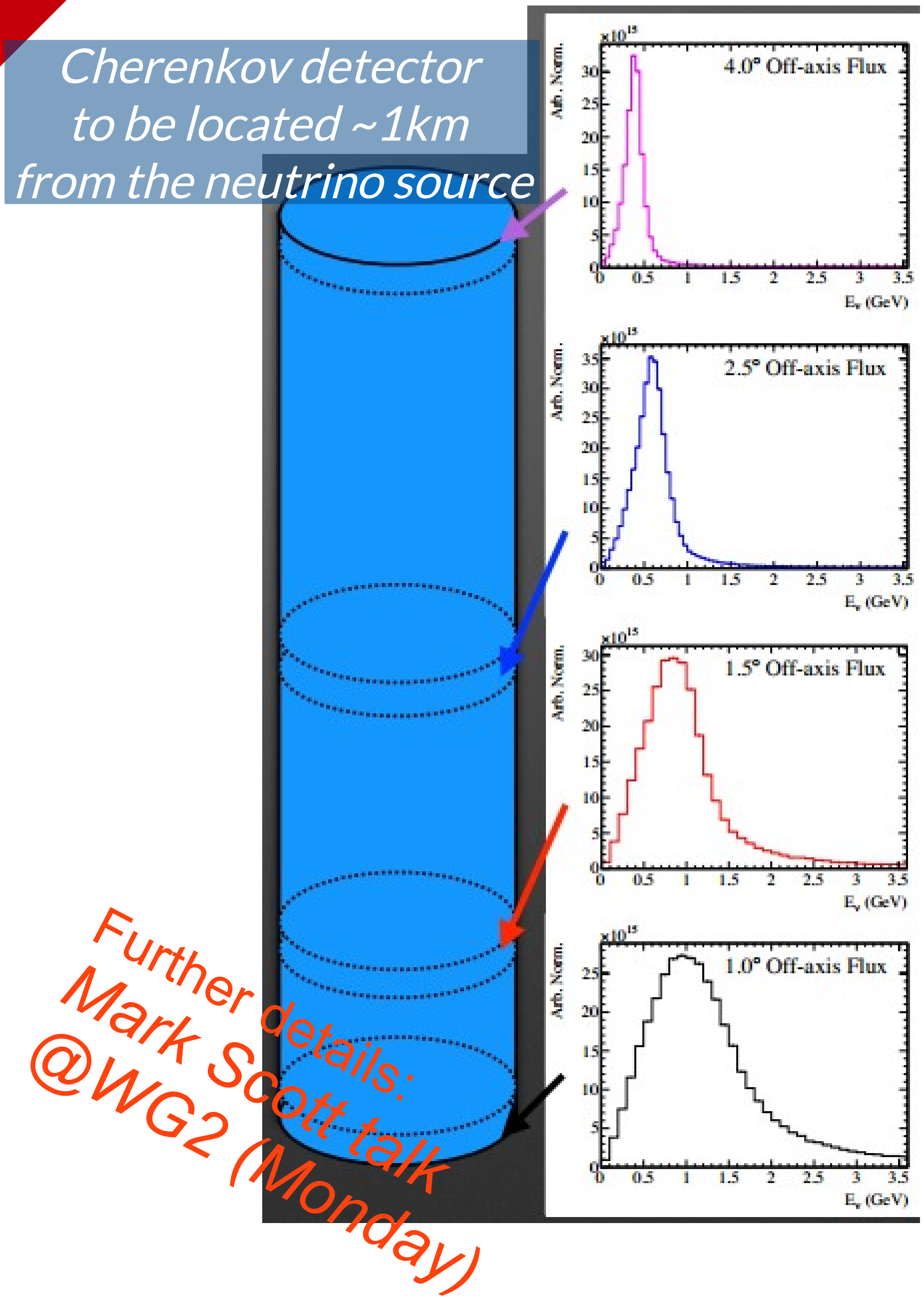
ND280 results



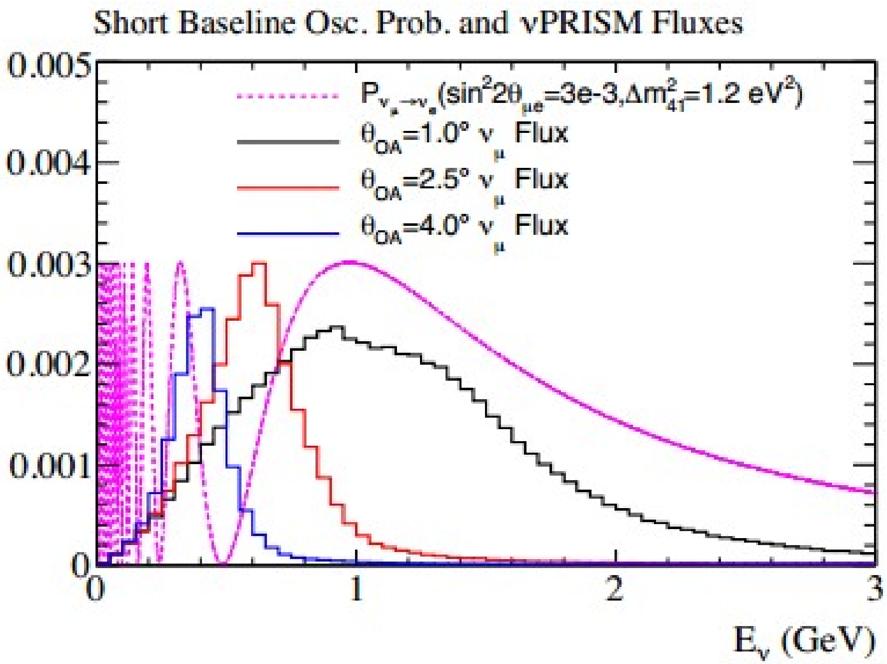


Null hypothesis excluded at ~94%CL

nuPRISM and short baseline ν_e appearance



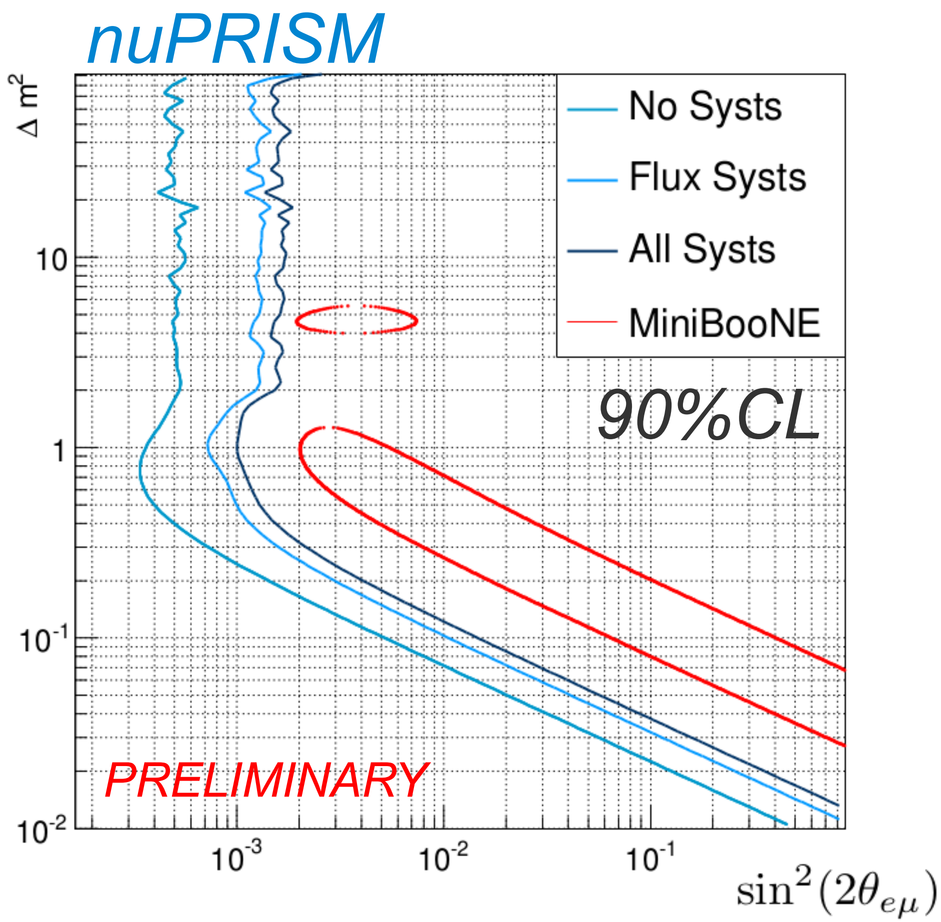
- Proposed new detector in the T2K beamline
- Many neutrino fluxes at different energies for the same flight path → Unique constraint for sterile neutrinos
- It can test the MiniBooNE and LSND ν_e appearance anomalies as a function of the neutrino energy



Preliminary sensitivity

Sensitivity for an analysis in Erec and off-axis angle for the expected T2K exposure after the ~2018 beam upgrade

$$P_{e\mu} \equiv P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{e\mu}) \sin^2\left(1.27\, \Delta m^2_{41} [\mathrm{eV}^2] \frac{\mathrm{L[\,m]}}{\mathrm{E\,MeV}}\right)$$



nuPRISM can test the ν_e appearance anomalies at 90%CL

Large room for improvements

- *HK statistics is x10 larger*
- *ν_e/ν_μ analysis*
- *ND280 has not yet been utilized as a near detector in this analysis*

Summary

ND280 is sensitive to the short baseline ν_e disappearance for $\Delta m^2 \sim 3eV^2$ and above

A clean selection of ν_eCC interactions at ND280 is developed with a good purity

ND280 studies the 3+1 model for an exposure of $5.9x10^{20}$ pot and is able to reject some parameter space allowed by the reactor and gallium anomalies at the 95%CL

The multi off-axis nuPRISM concept provides a promising sensitivity to the ν_e appearance at short baseline, covering the whole MiniBooNE anomaly within 90%CL

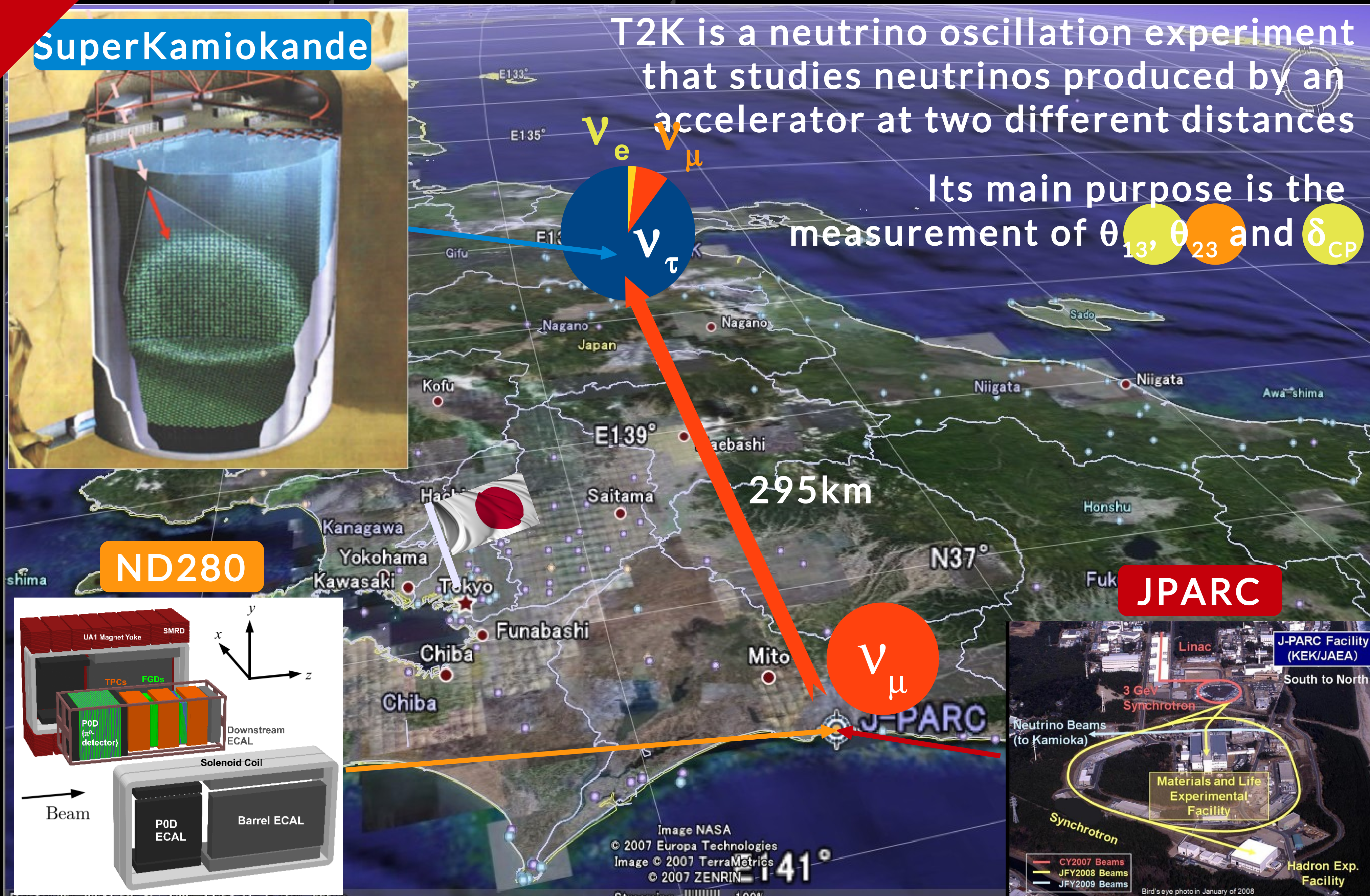
Thanks for your attention!

BACK-UP SLIDES

T2K experimental set-up

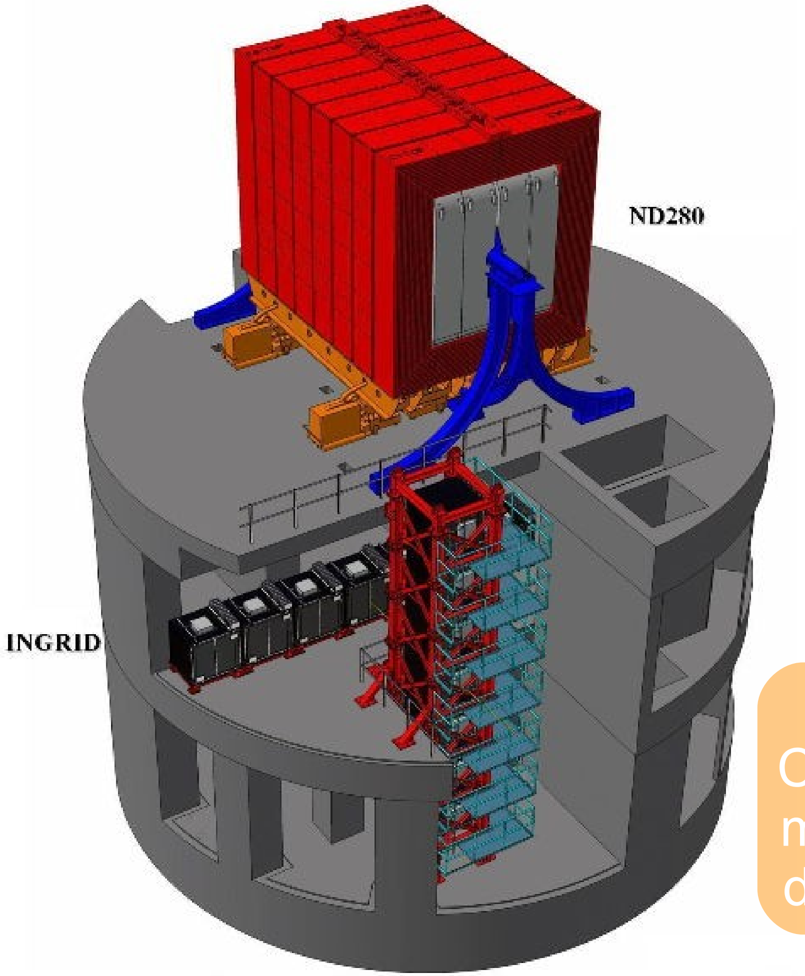
T2K is a neutrino oscillation experiment that studies neutrinos produced by an accelerator at two different distances

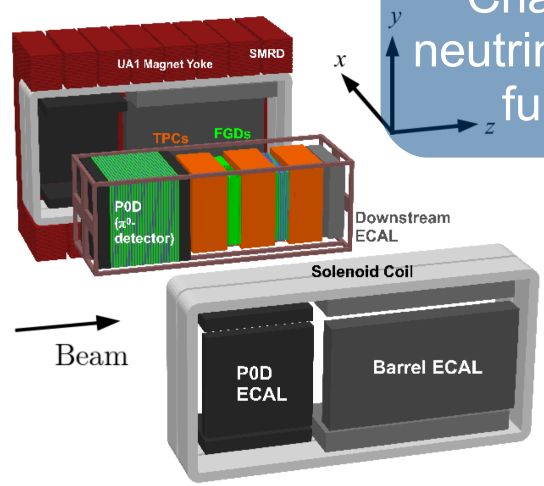
Its main purpose is the measurement of θ_{13}, θ_{23} and δ_{CP}



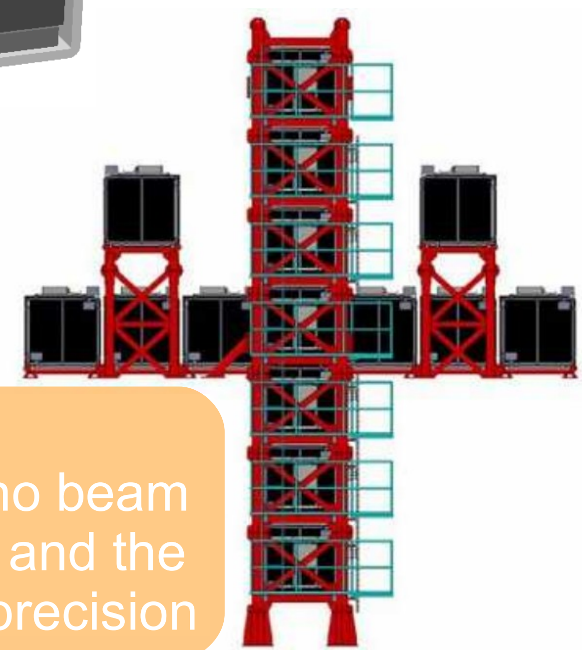
The near detectors

Neutrino monitors at 280 meters from the source → Studies neutrino fluxes *BEFORE* the oscillations





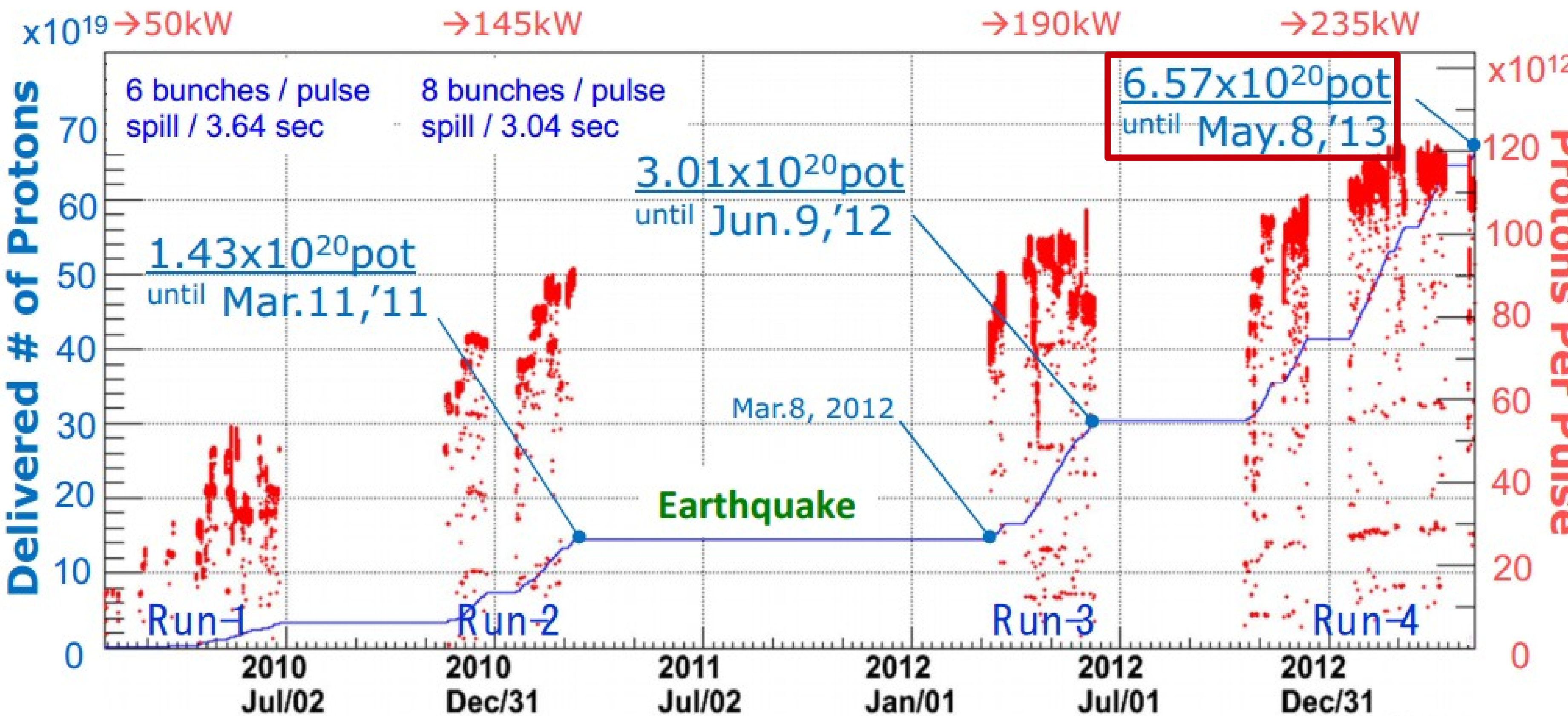
ND280
Characterize the off-axis neutrino beam composition in function of the energy



INGRID
Characterize the neutrino beam measuring the intensity and the direction with 0.4mrad precision

Back-up slides

Analysis data set



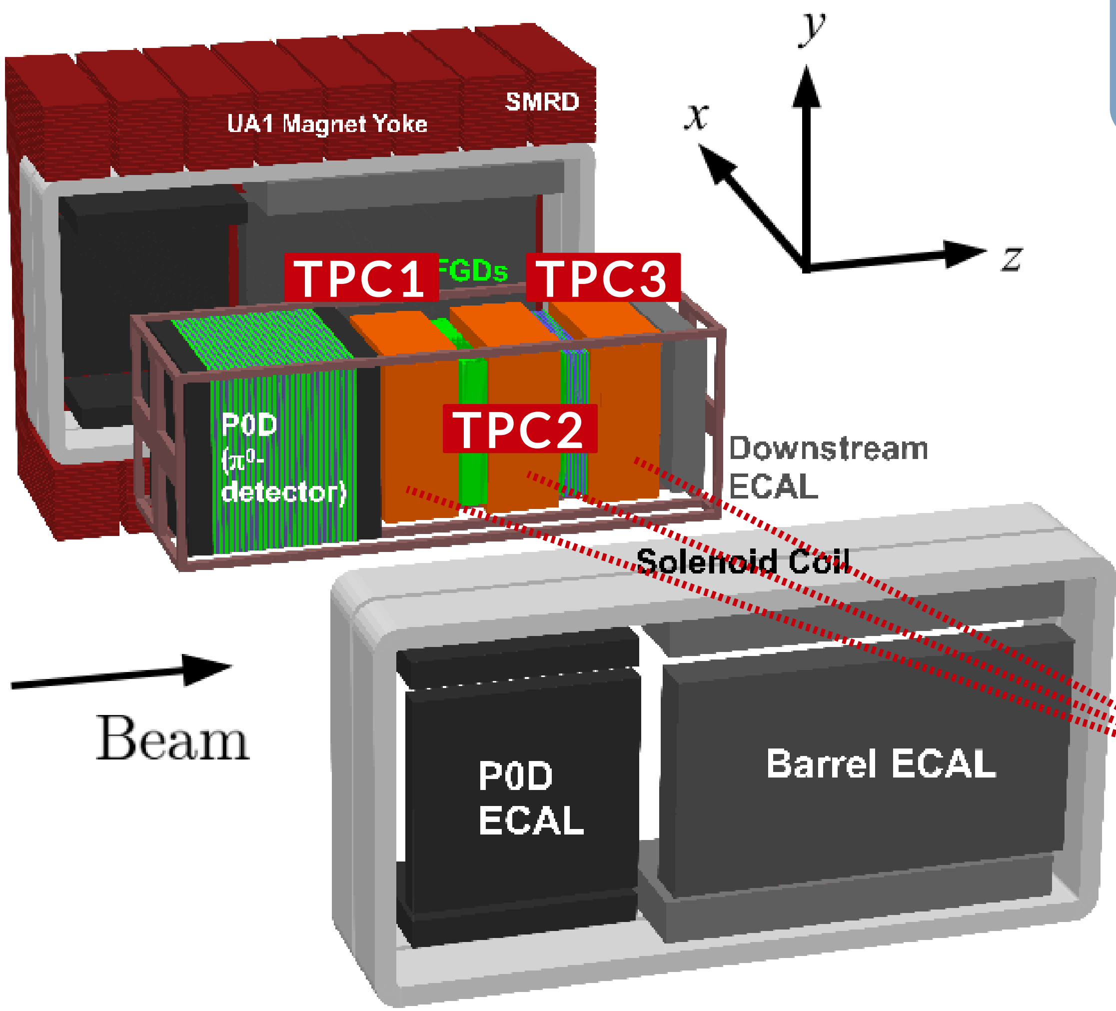
6.57x10^20 protons on target by May 2014
5.9x10^20 with good quality at ND280

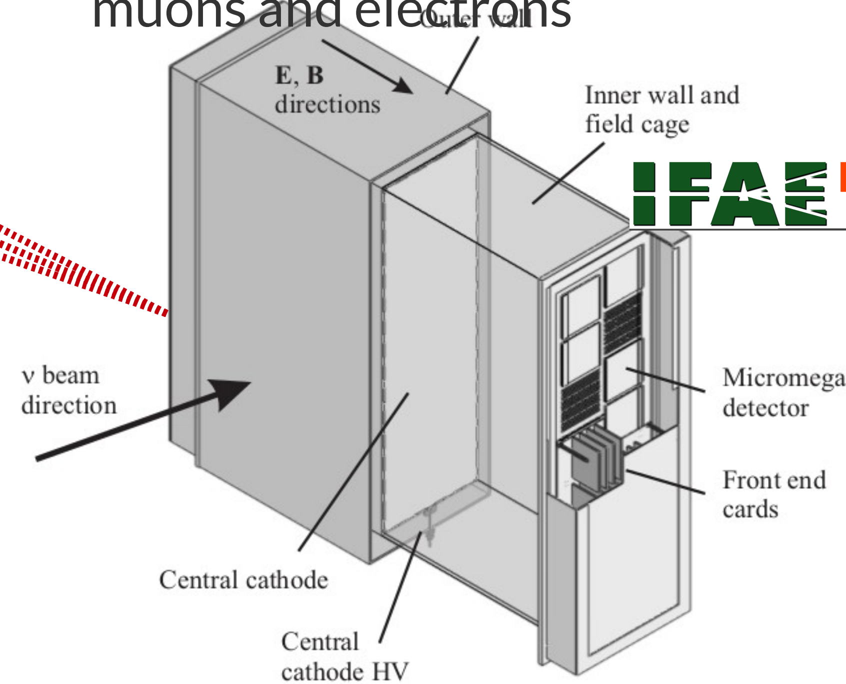
~8% of the total approved pot

Time Projection Chambers (TPCs)

Argon-based gaseous detectors with good tracking and particle identification

- Measure the momentum (10% resolution at 1GeV) and the sign of the charged particles
- Good separation between muons and electrons



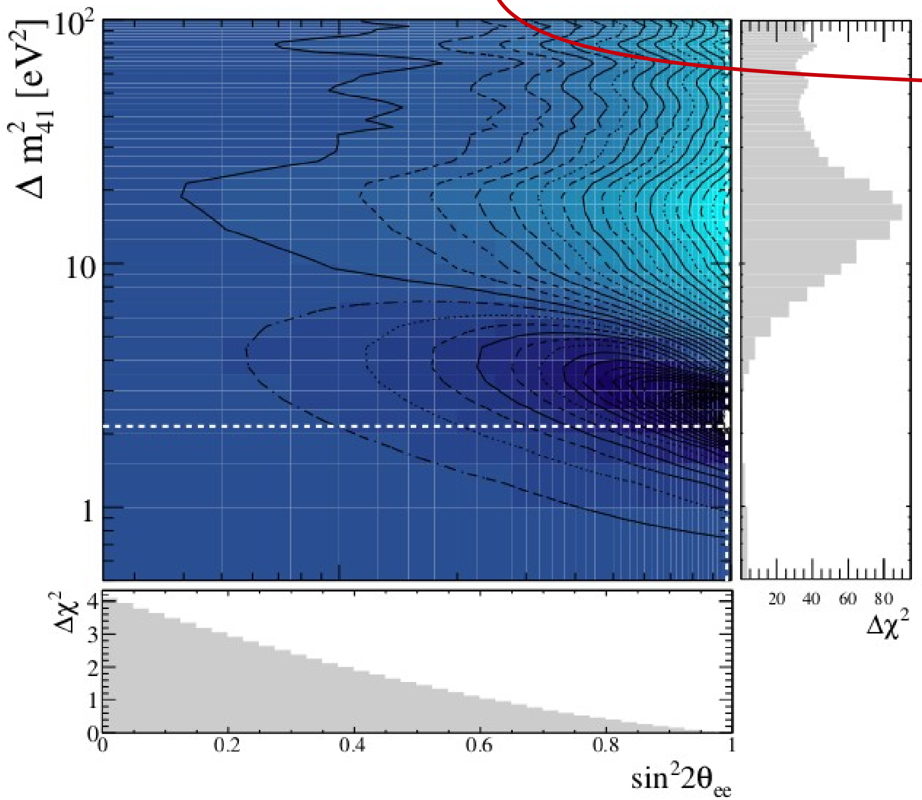


log-likelihood ratio map

Use a log-likelihood ratio as test statistic

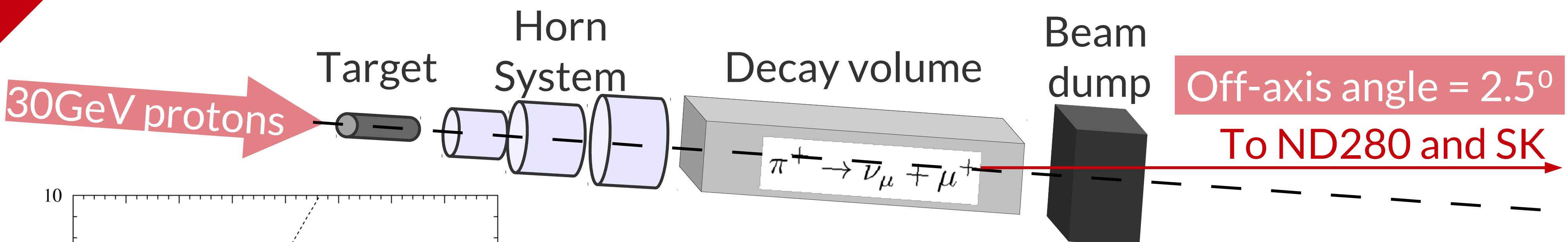
$$\chi^2 \equiv -2\log\mathcal{L} = 2\sum_{l=0}^{31}\left\{n_{exp}^{l,\nu_e} - n_{dt}^{l,\nu_e} + n_{dt}^{l,\nu_e}\times\log\left(\frac{n_{dt}^{l,\nu_e}}{n_{exp}^{l,\nu_e}}\right)\right\} + 2\sum_{i=0}^{20}\left\{n_{exp}^{l,\gamma} - n_{dt}^{l,\gamma} + n_{dt}^{l,\gamma}\times\log\left(\frac{n_{dt}^{l,\gamma}}{n_{exp}^{l,\gamma}}\right)\right\}$$
$$+(\vec{f}-\vec{f}_0)^T V^{-1}(\vec{f}-\vec{f}_0)$$

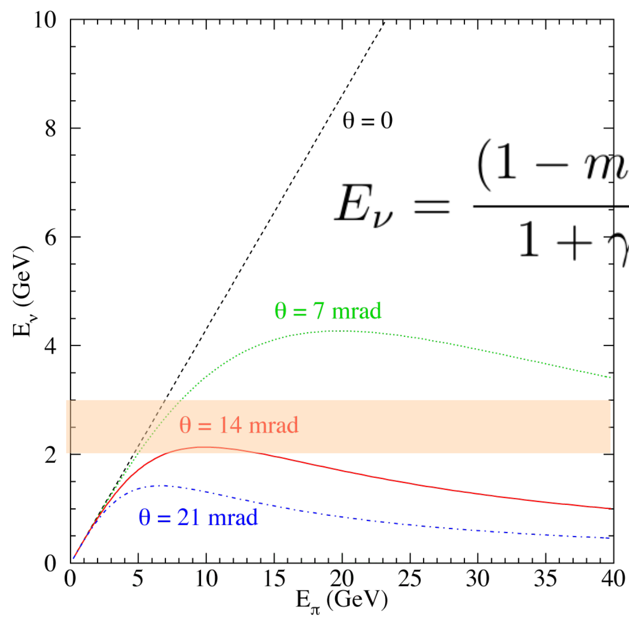
Calculate $\Delta\chi^2_{ij} \equiv -2\log\mathcal{L}^r_{ij} = \chi^2_{ij} - \chi^2_{bf}$ for each point in the parameter space



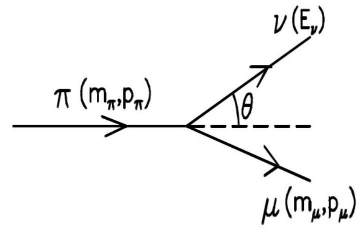
Systematic parameters are treated as *nuisance* parameters and the likelihood is *profiled*

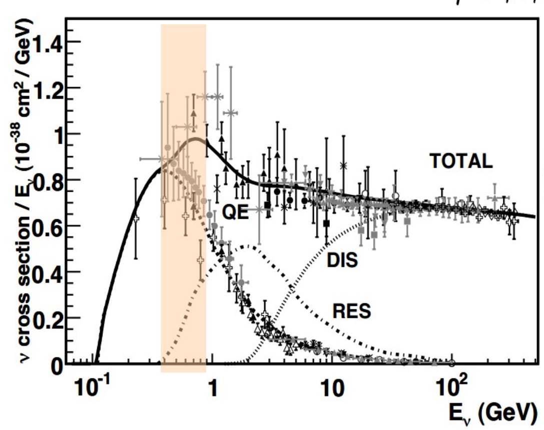
The neutrino beam: Off-axis technique

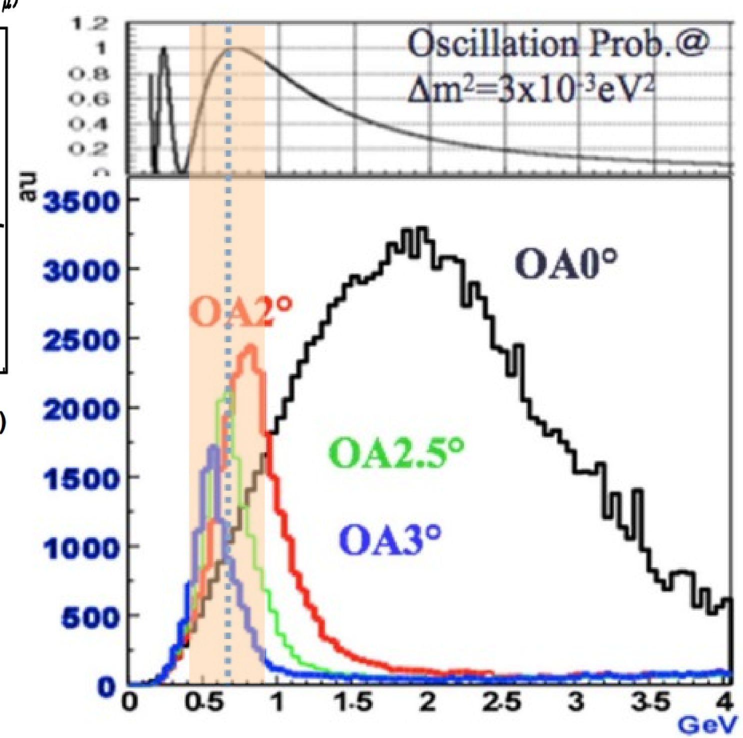




$$E_\nu = \frac{(1 - m_\mu^2/m_\pi^2)E_\pi}{1 + \gamma^2 \tan\theta^2}$$



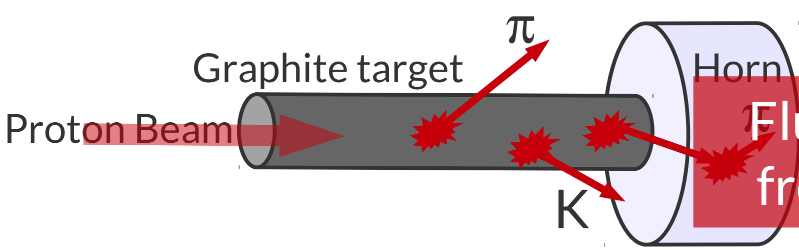




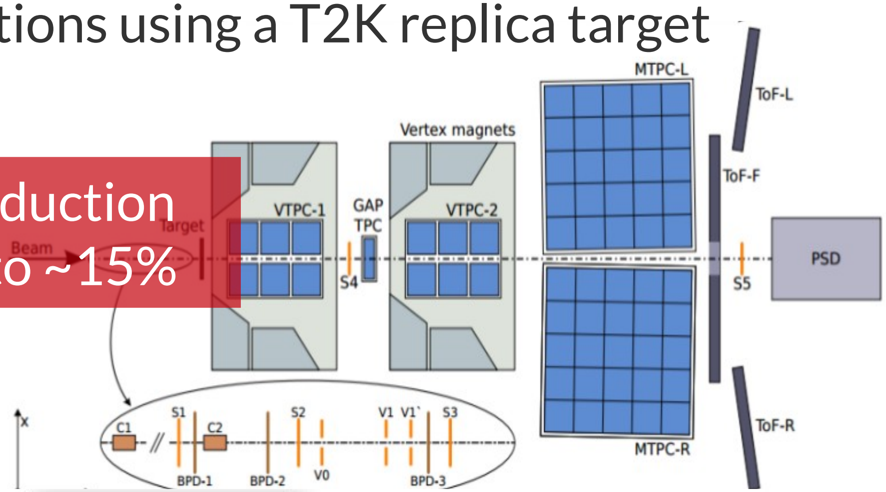
- Enhances neutrino oscillations
- Enhances CCQE interactions
- Reduces ν_e contamination at the peak

The neutrino beam: ν_e flux prediction

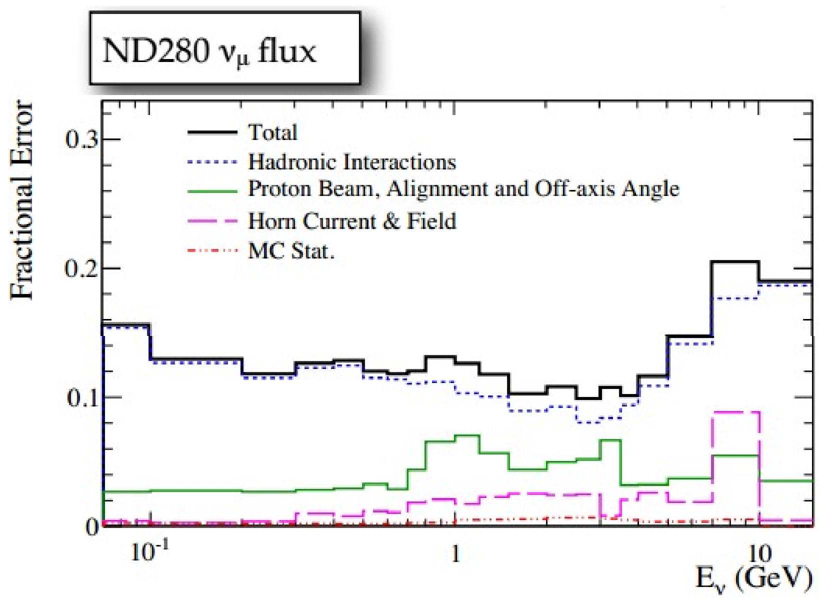
- The flux is predicted from a data-driven simulation → NA61 experiment measures the π and K production cross-sections using a T2K replica target

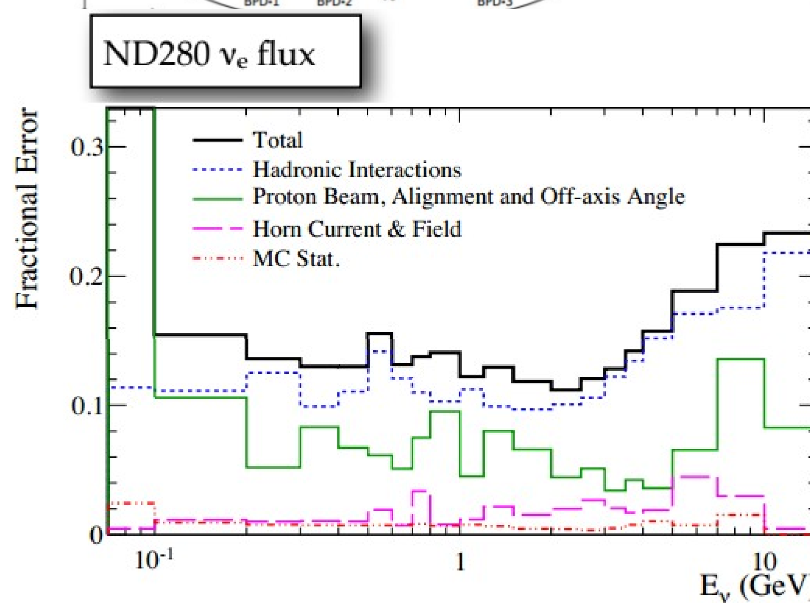


Flux error reduction from ~20% to ~15%



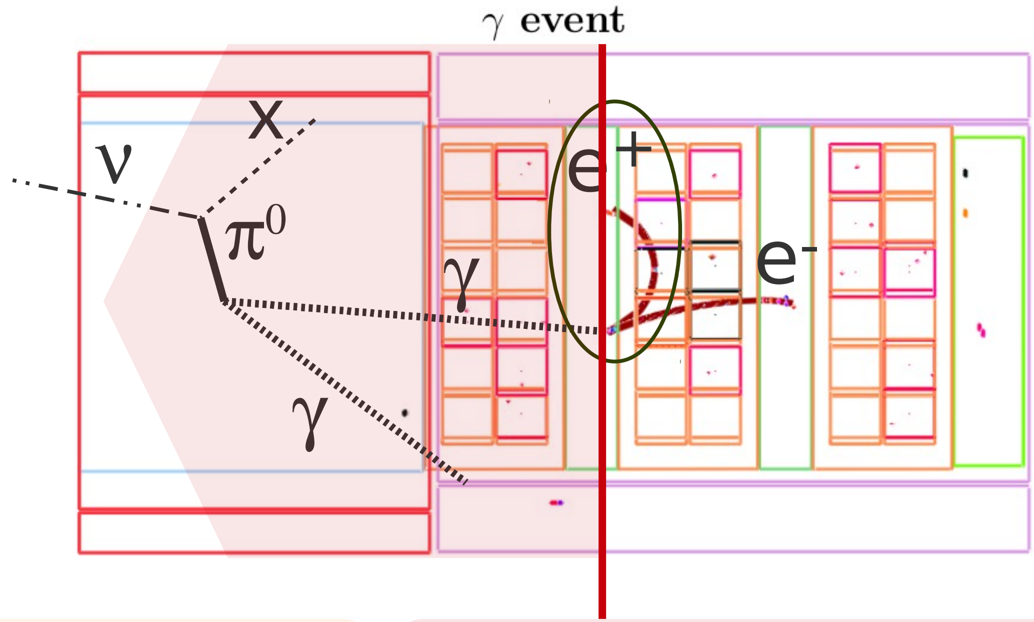
- Beam alignment monitoring provides beam systematics estimations





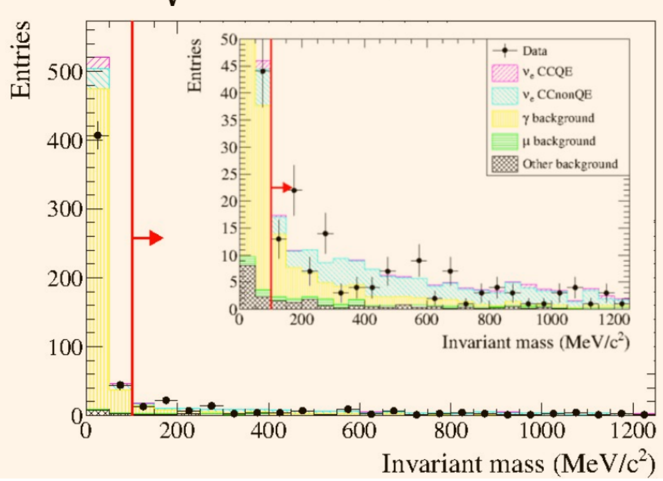
Flux error is further constrain with the ν_μ ND280 analysis from ~15% to <10%

ν_e selection: the photon conversion background



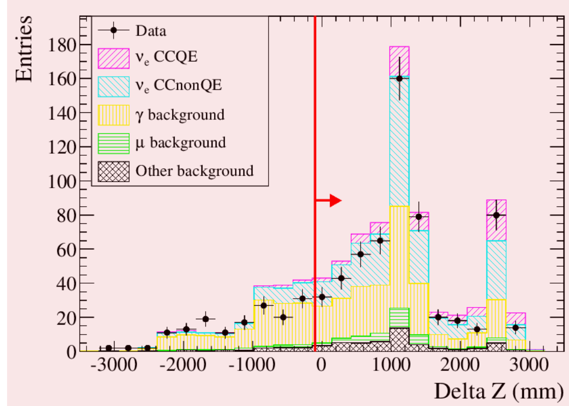
If positron is reconstructed: Calculate invariant mass

$$m_{inv} = \sqrt{2m_e^2 + 2\left(E_+^2 E_-^2 - p_+^2 p_-^2\right)}$$

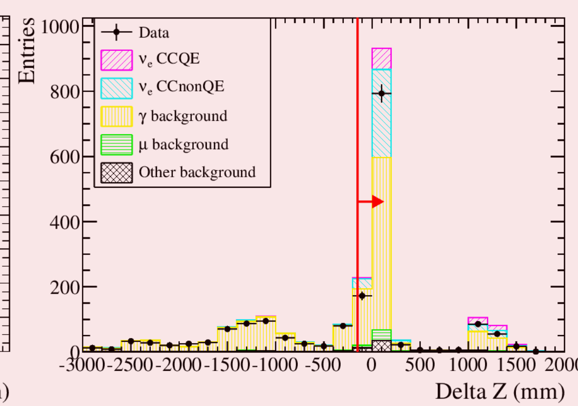


If extra activity exists: Reject events with depositions below the main e⁻ track

ECal Veto



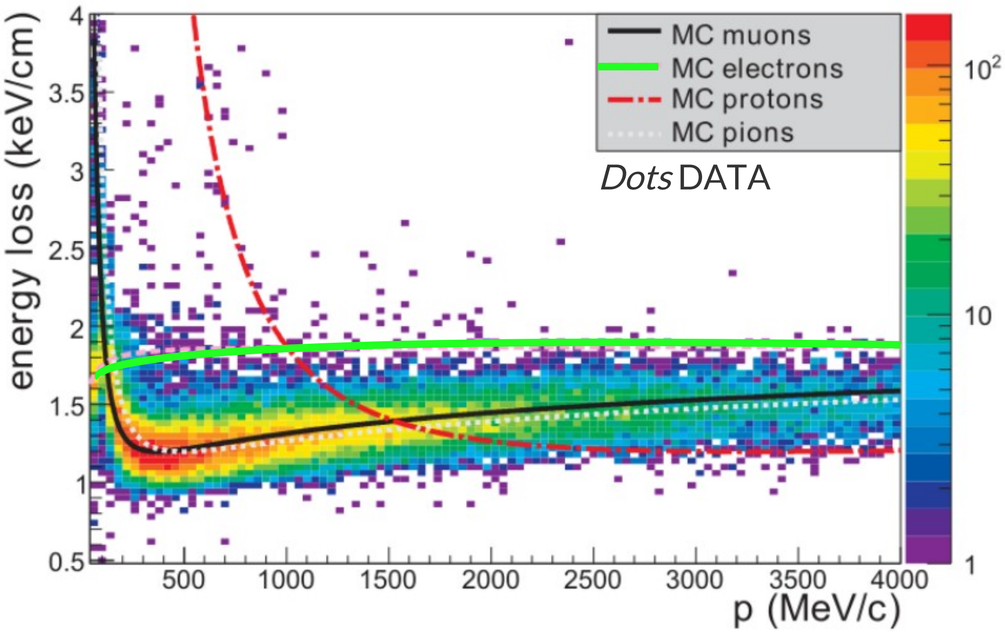
TPC1 Veto



Back-up slides

ν_e selection: TPC PID

Combination of ionization energy (*dE/dx*) and momentum measurement



TPC PULL

C_T measured

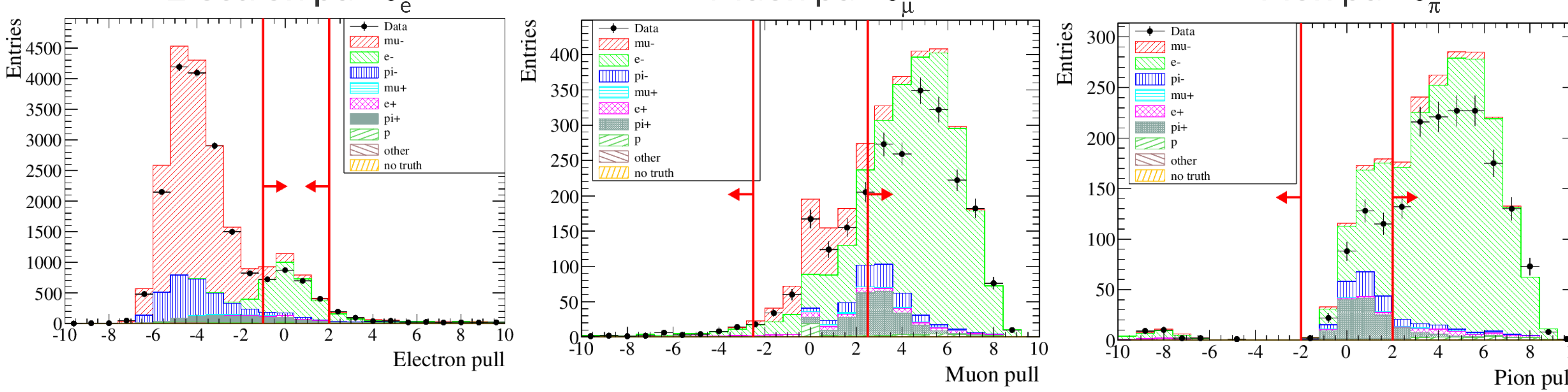
C_T predicted

$$\delta_\alpha = \frac{C_T^{meas} - C_T^{\alpha}}{\sigma^{\alpha}}$$

C_T resolution ~7.8%

C_T = energy loss

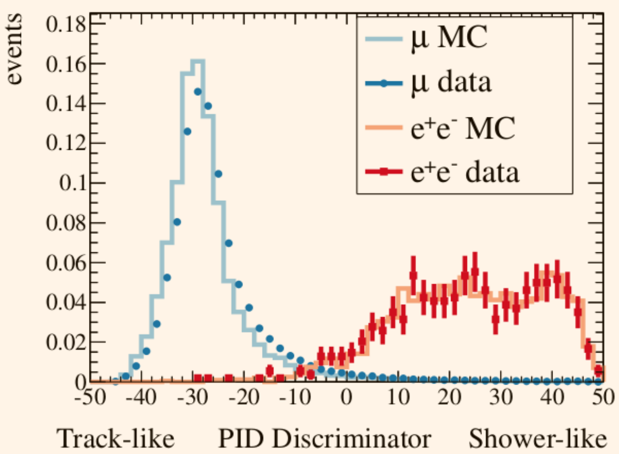
Electron pull δ_e / Muon pull δ_μ / Pion pull δ_π



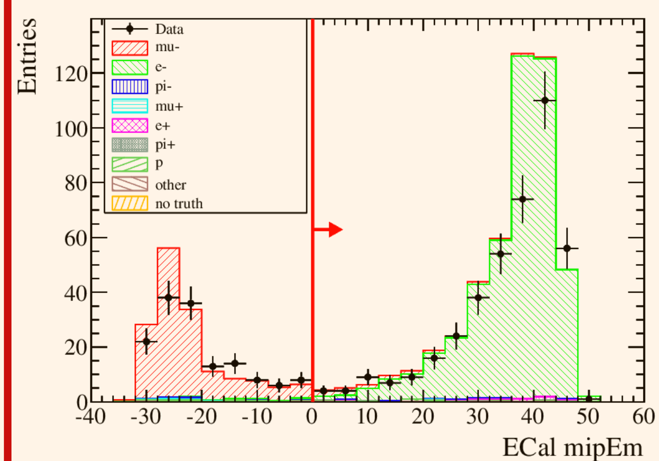
ν_e selection: ECAL PID

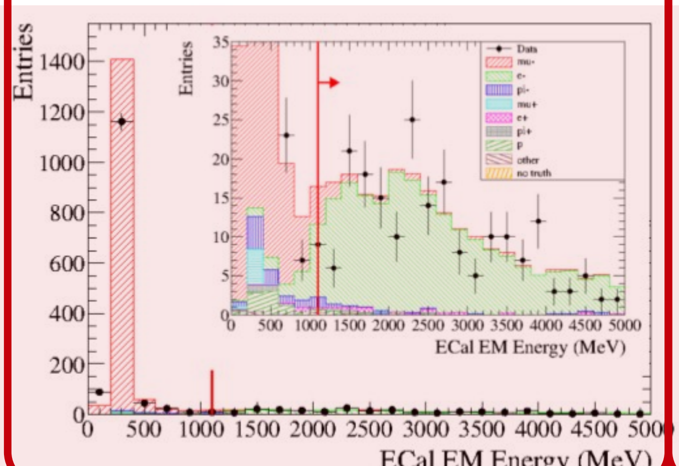
Only used if momentum > 300MeV

Geometry of the cluster

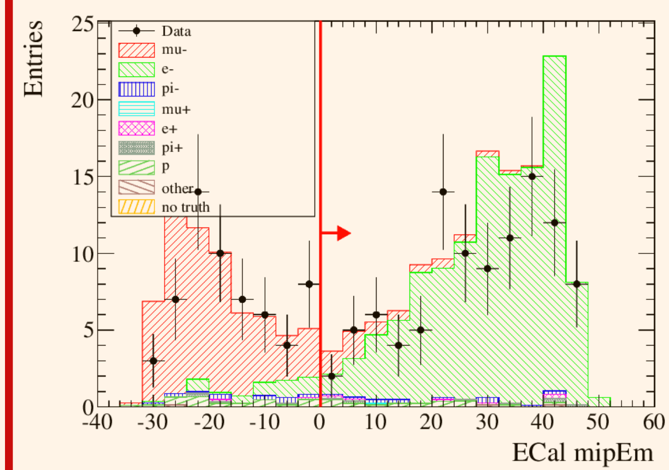


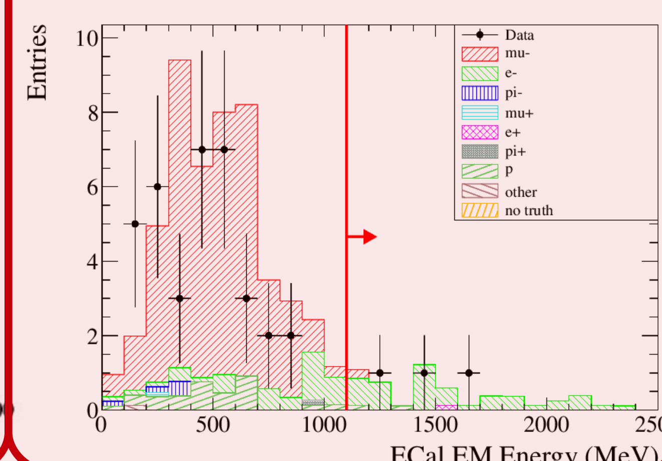
DsECal





BrECal





Ionization energy

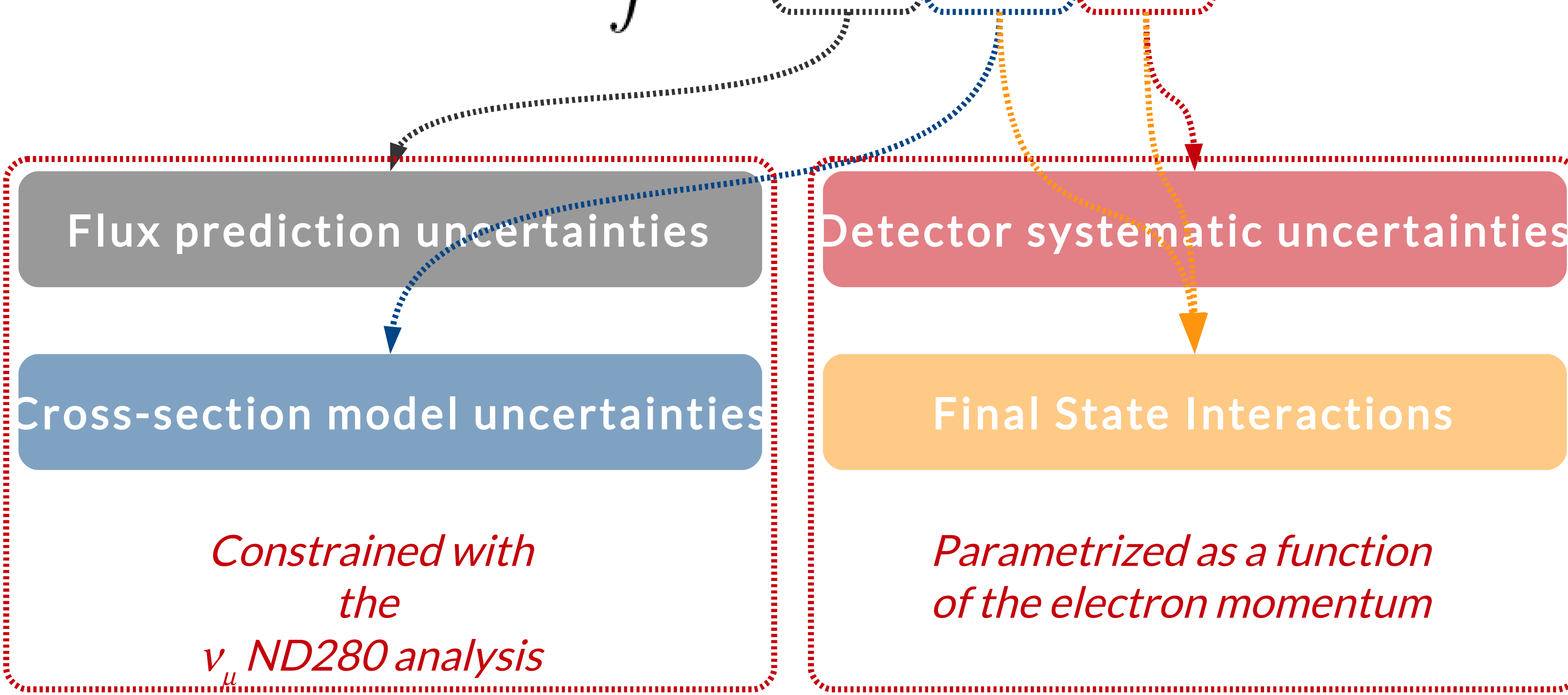
Total deposited energy in the ECal

Only used if momentum>1GeV

Systematic uncertainties: overview

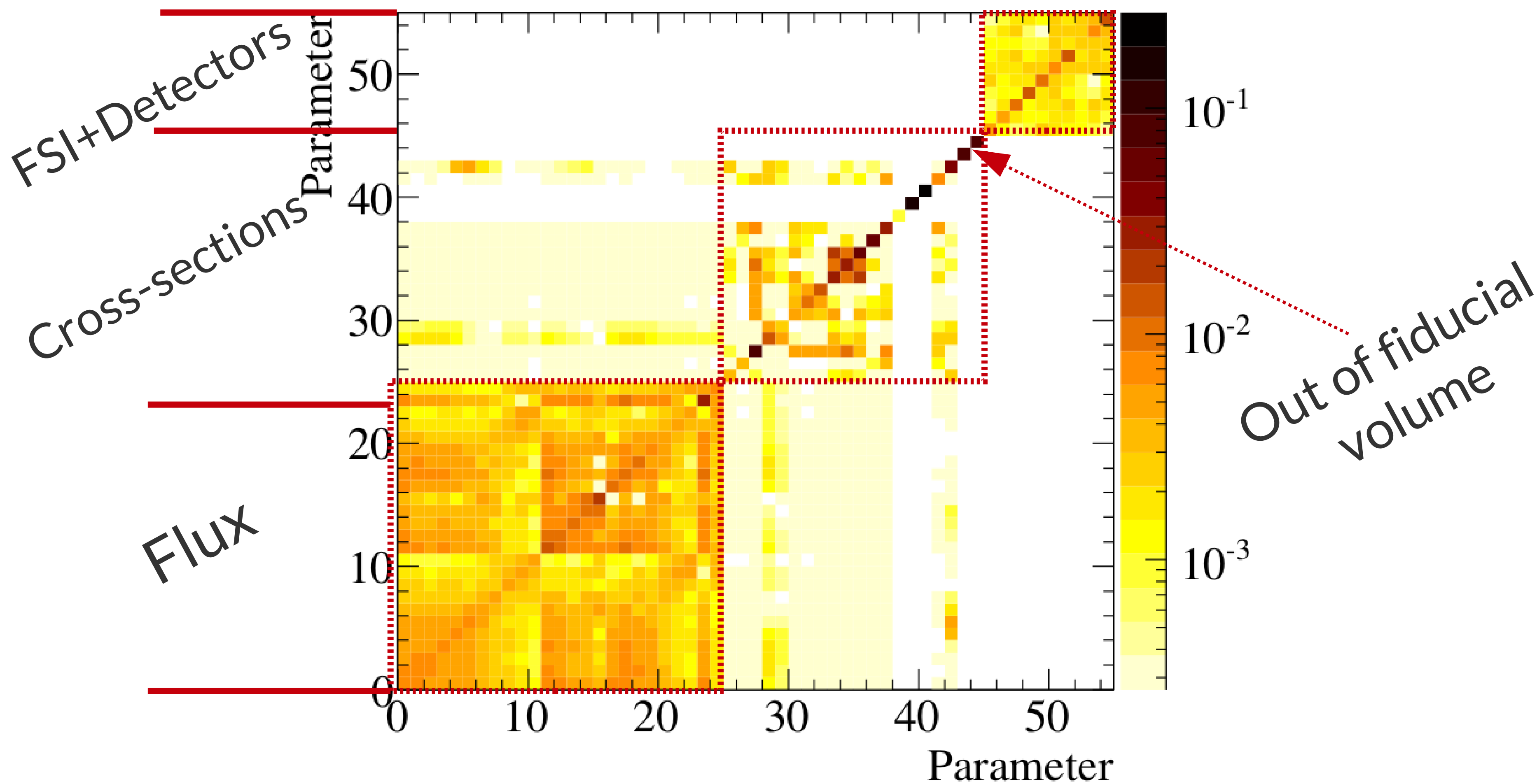
Expected number of electron-neutrino interactions

$$N_{exp} \propto \int dE\, \phi(E) \sigma(E) \epsilon(E)$$



Systematic uncertainties: covariance matrix

Parameters that take into account all the systematic uncertainties sources are treated through a covariance matrix



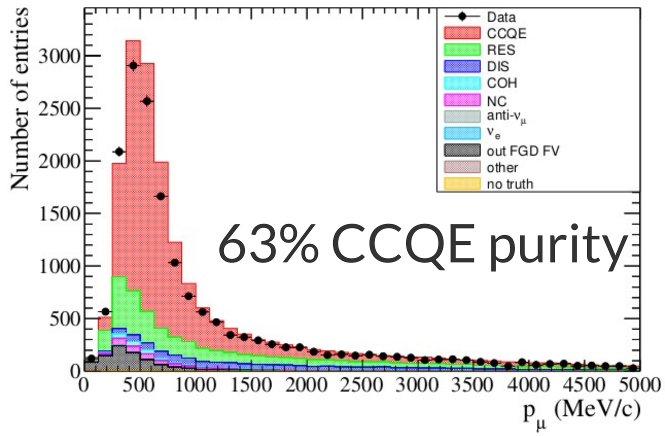
Systematic uncertaintiν_μ ND280 constraints

- Three ν_μCC samples are selected according to the event topology
- The simulation is fit to the data tunning flux and cross-section parameters

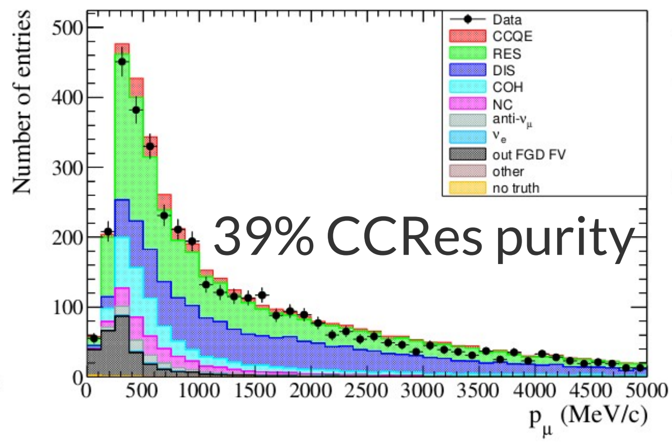
Reduce ν_e flux error due to strong correlations with ν_μ flux

Reduce ν_e cross-section uncertainties due to are similar to ν_μ within the 3%

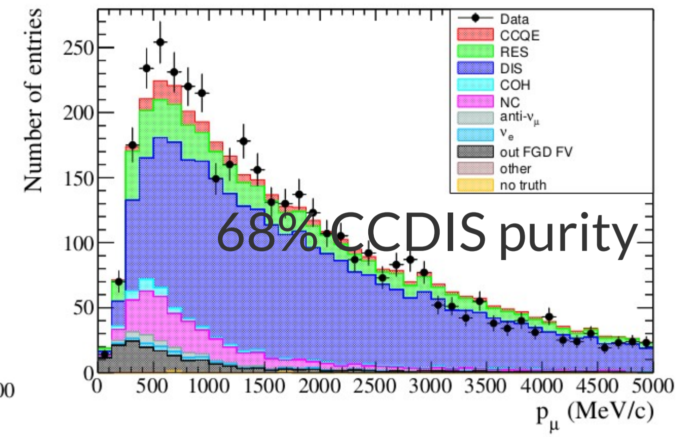
CC-0π

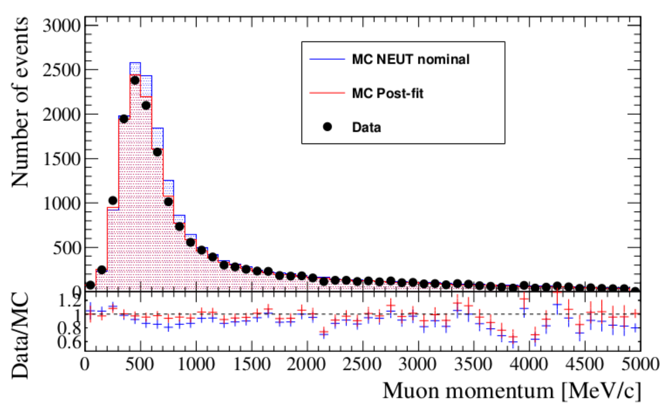


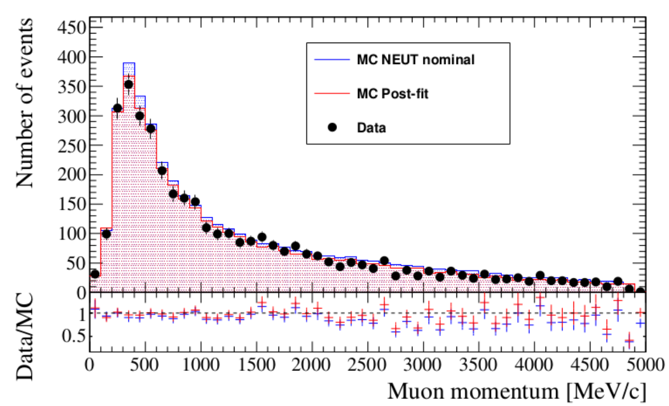
CC-1π+

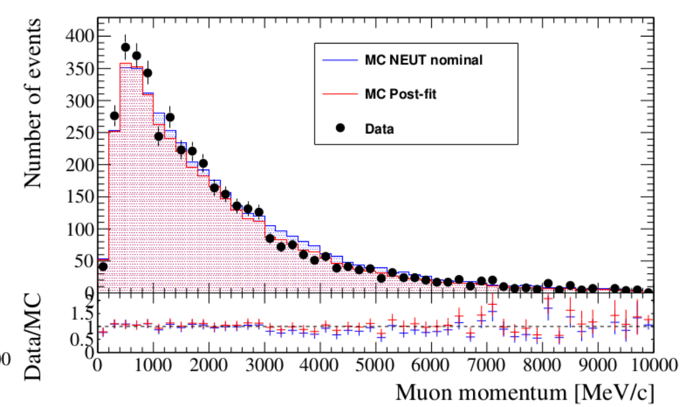


CC-Other







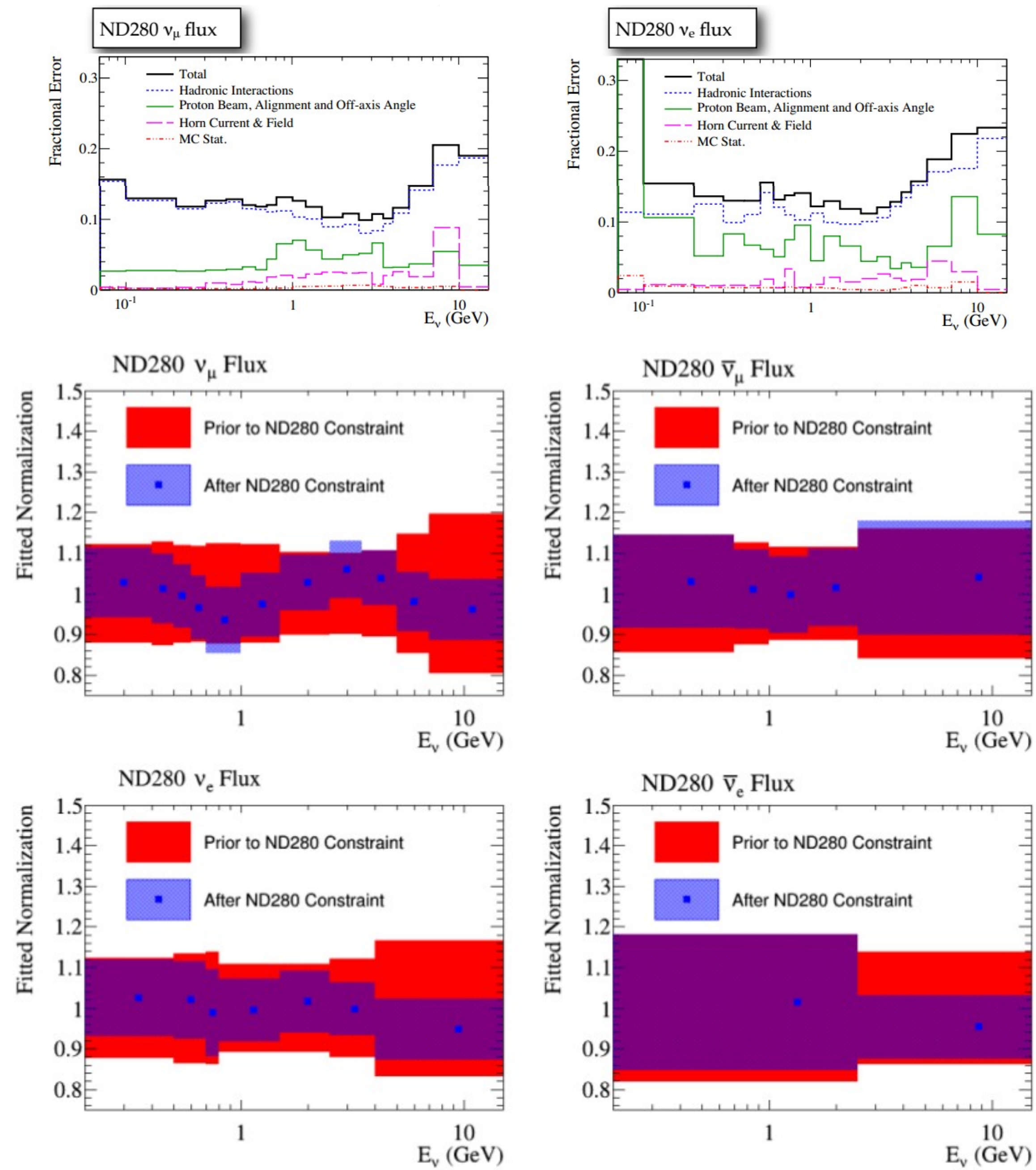


Back-up slides

Systematic uncertainties: Neutrino flux uncertainties

- NA61 reduces flux errors from ~20% to ~15%
- ν flux is parametrized in neutrino energy and flavour with 25 normalization parameters

ND280 ν_μ measurement reduces the errors from ~15% to <10%



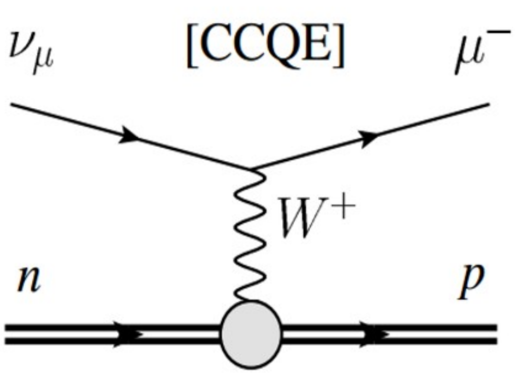
Systematic uncertainties: Neutrino cross-section uncertainties

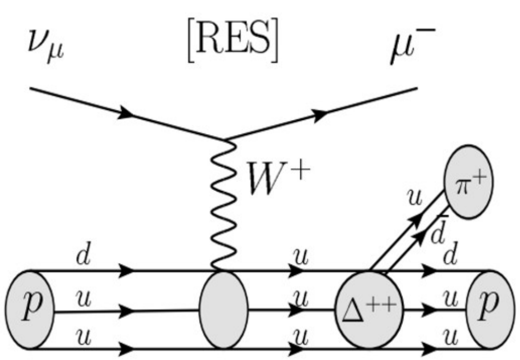
The cross sections are parametrized with a minimal set of parameters (20)

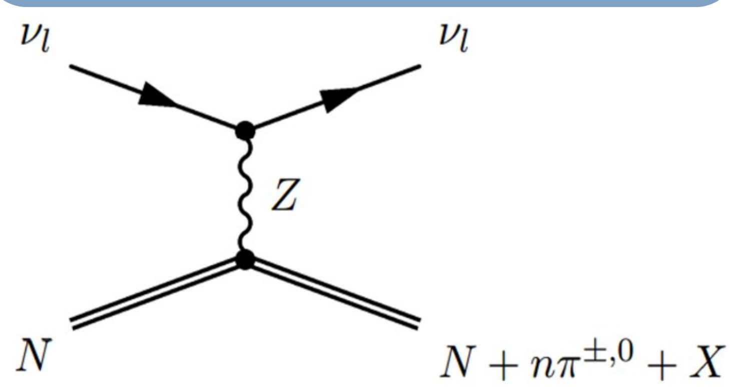
CCQE
- M_A^{QE}
- 3 normalizations

CC1π
- M_A^{RES}
- 2 normalizations

Neutral Currents
- π^0 production → 1 normalization and *W-shape*
- Other NC → 1 normalization

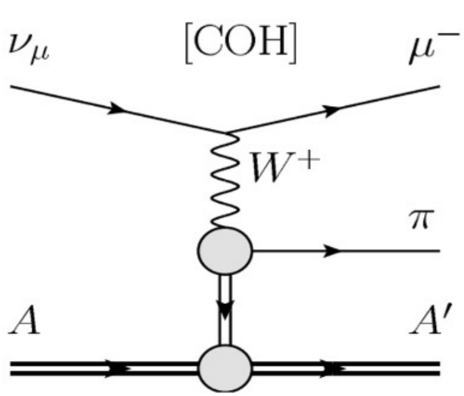






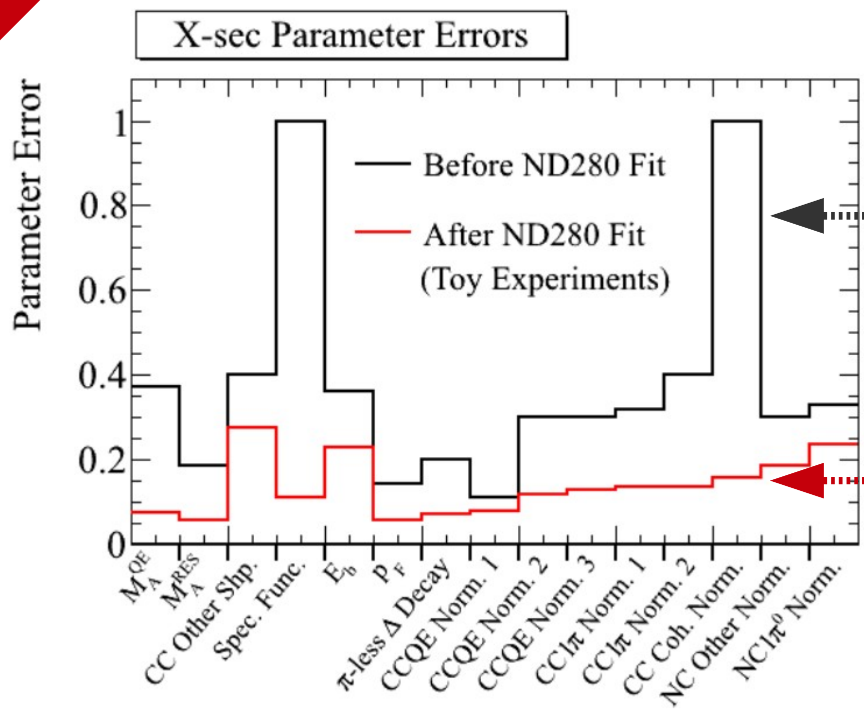
Nuclei models
- Binding energy uncertainty
- Fermi momentum
- Spectral function model

Out of Fiducial Volume
- OOFV e+e-
- OOFV Other



Other interactions
- Coherent π production in CC
- Multi-π production
- π-less Δ decay
- Differences in $\sigma(\nu_e)$ and $\sigma(\nu_\mu)$
- Differences in $\sigma(\nu)$ and $\sigma(\bar{\nu})$

Systematic uncertainties: Neutrino cross-section uncertainties



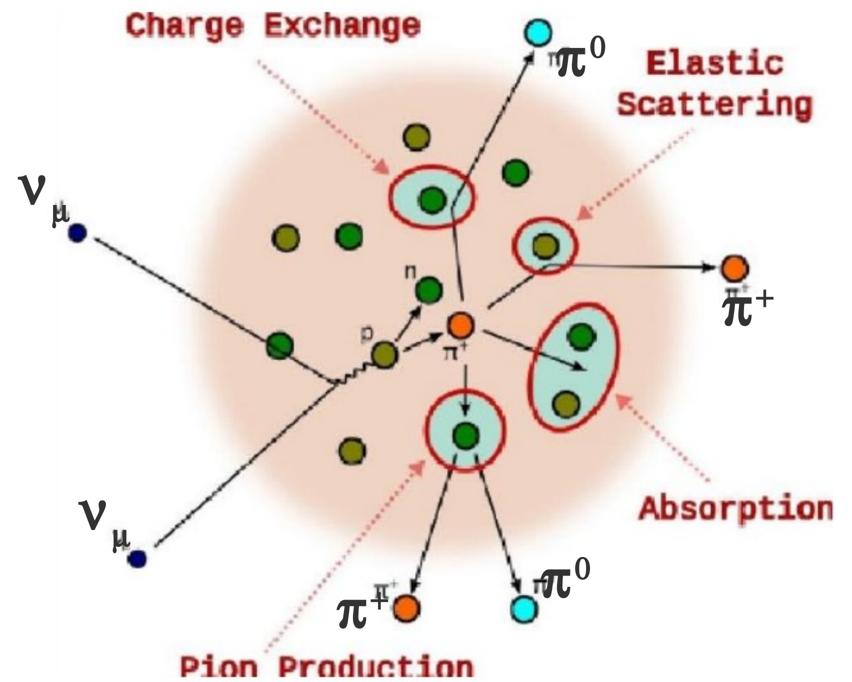
Before ν_μ fit: errors are estimated fitting external data (e.g. MiniBooNE) with NEUT and using *the difference as uncertainty*

After ν_μ fit: 15 parameters are further constrained from ~40% to <20%

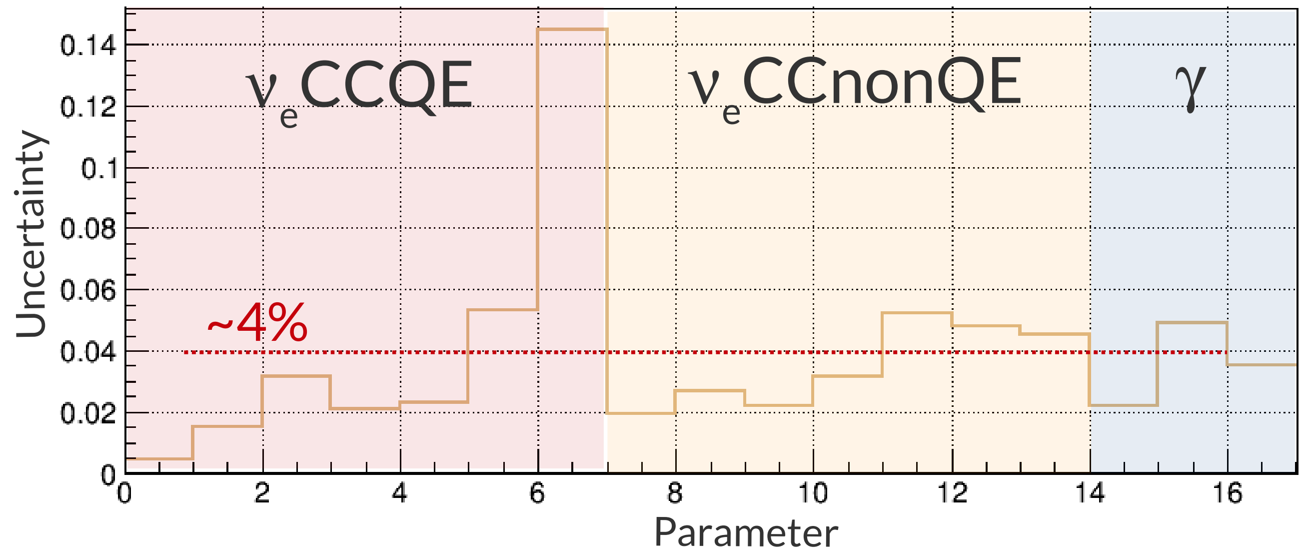
Unconstrained by ND280 ν_μ

- W-shape → 52%
- $\sigma(\nu_e)/\sigma(\nu_\mu)$→ 3%
- $\sigma(\nu)/\sigma(\bar{\nu})$ → 40%
- OOFVe+e- → 30%
- OOFVOther → 30%

Systematic uncertainties: Final State Interactions (FSI)



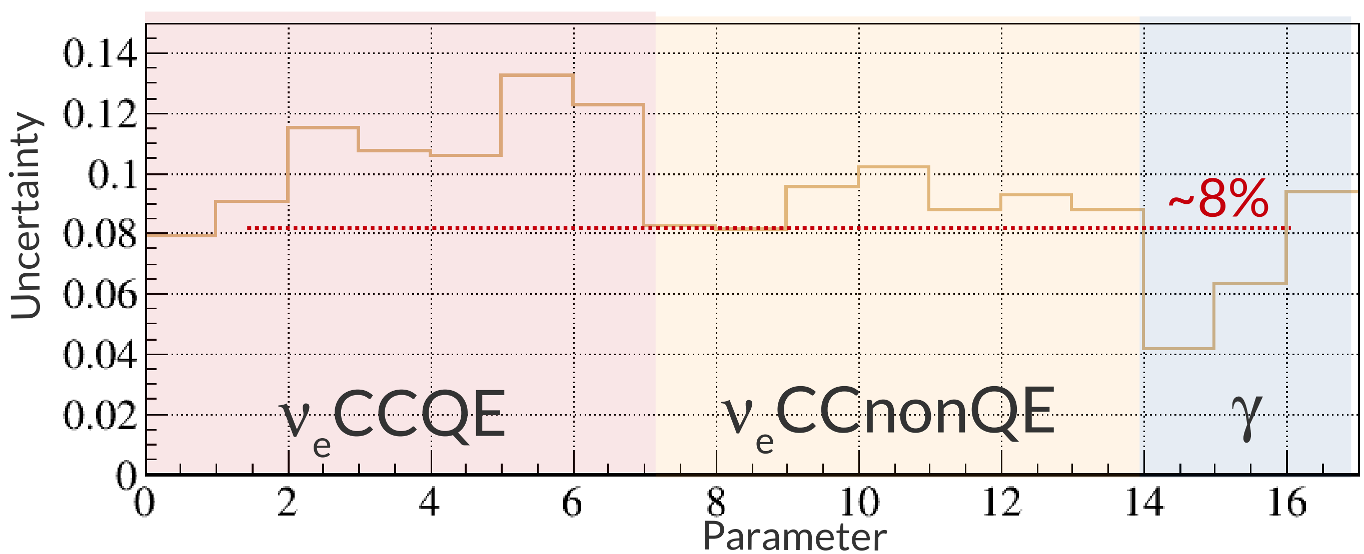
We rather treat the FSI through effective parameters that parametrize the number of events along the analysis variable



Systematic uncertainties: Detector

- Detector systematic uncertainties are calculated using control samples
- A total of 24 systematic sources are considered → TPC momentum resolution is the dominant one
- They are parametrized and propagated using low-level parameters
- The simulation is corrected by the estimated detector systematics

We treat them in the same way than that FSI



Detector and FSI uncertainties are added and treated together

Detector systematic uncertainties

Systematic	Type	Applied to
B-field distortion	Migration	All
FGD mass uncertainty	Weight	All
FGD track efficiency	Weight	Not used for γ
Michel electron eff.	Weight	Not used for γ
Pile-up (TPC1)	Weight	Not used for γ
Pion secondary interactions	Weight	All
TPC-FGD matching eff.	Weight	All
TPC charge confusion	Weight	All
TPC momentum scale	Migration	All
TPC momentum resolution	Migration	All
TPC track eff.	Weight	All
TPC track quality	Weight	All
TPC PID scale ($e^{\pm}$)	Migration	All
TPC PID bias ($e^{\pm}$)	Migration	All
TPC PID scale ($\mu^{\pm}$ and $\pi^{\pm}$)	Migration	All
TPC PID bias ($\mu^{\pm}$ and $\pi^{\pm}$)	Migration	All
TPC PID scale (p)	Migration	All
TPC PID bias (p)	Migration	All
ECal energy resolution	Migration	All
ECal energy scale	Migration	All
ECal PID	Migration	All
Pile-up (P0D)	Weight	Not used for γ
Pile-up (ECal)	Weight	Only for ν_eCCQE
Pile-up (Upstream ECal)	Weight	Only for ν_eCCnonQE
TPC-ECal matching eff.	Migration	All

Binned log-likelihood fit

Binned log-likelihood ratio definition

$$\chi^2 \equiv -2\log\mathcal{L} = 2\sum_{l=0}^{31}\left\{n_{exp}^{l,\nu_e} - n_{dt}^{l,\nu_e} + n_{dt}^{l,\nu_e}\times\log\left(\frac{n_{dt}^{l,\nu_e}}{n_{exp}^{l,\nu_e}}\right)\right\}$$
$$+2\sum_{i=0}^{20}\left\{n_{exp}^{l,\gamma} - n_{dt}^{l,\gamma} + n_{dt}^{l,\gamma}\times\log\left(\frac{n_{dt}^{l,\gamma}}{n_{exp}^{l,\gamma}}\right)\right\}$$
$$+(\vec{f}-\vec{f}_0)^T V^{-1}(\vec{f}-\vec{f}_0)$$

Nuisance parameters

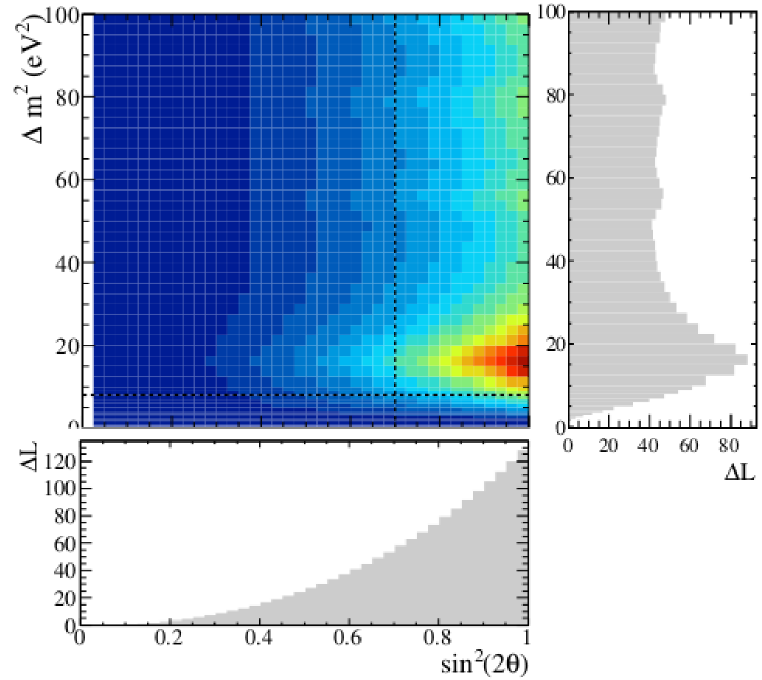
Systematics covariance matrix

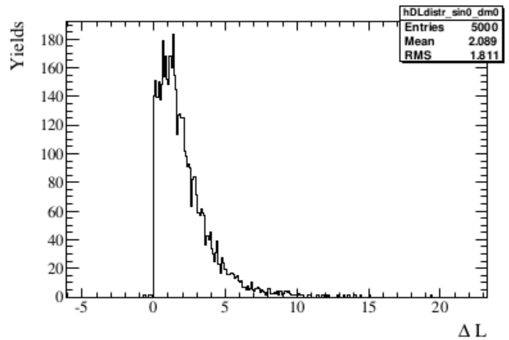
Penalty term

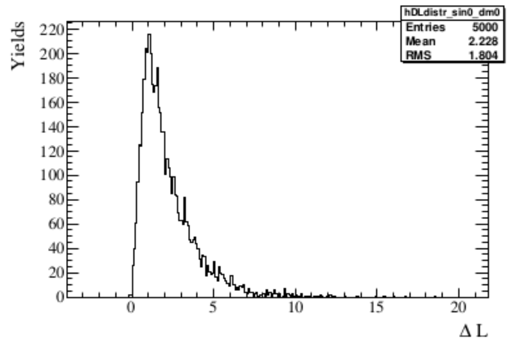
Back-up slides

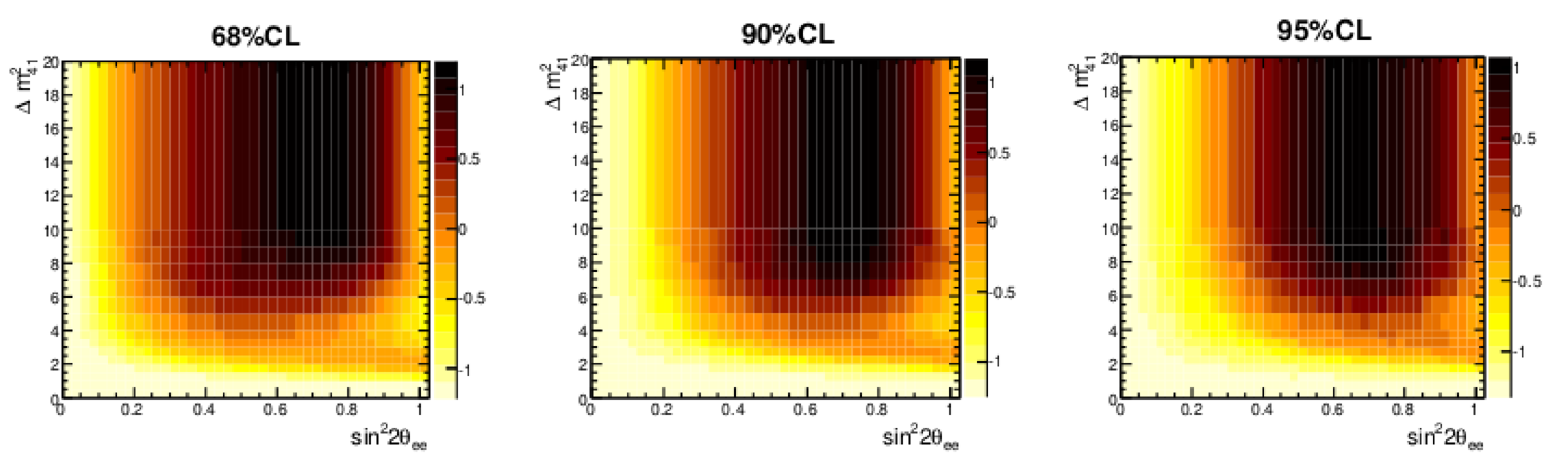
Feldman & Cousins method

- Generate and fit many toysMC in one point of the parameter space grid
- Calculate the $\Delta\chi^2$ distributions and from there the critical values
- Repeat for various grid points to scan the whole space



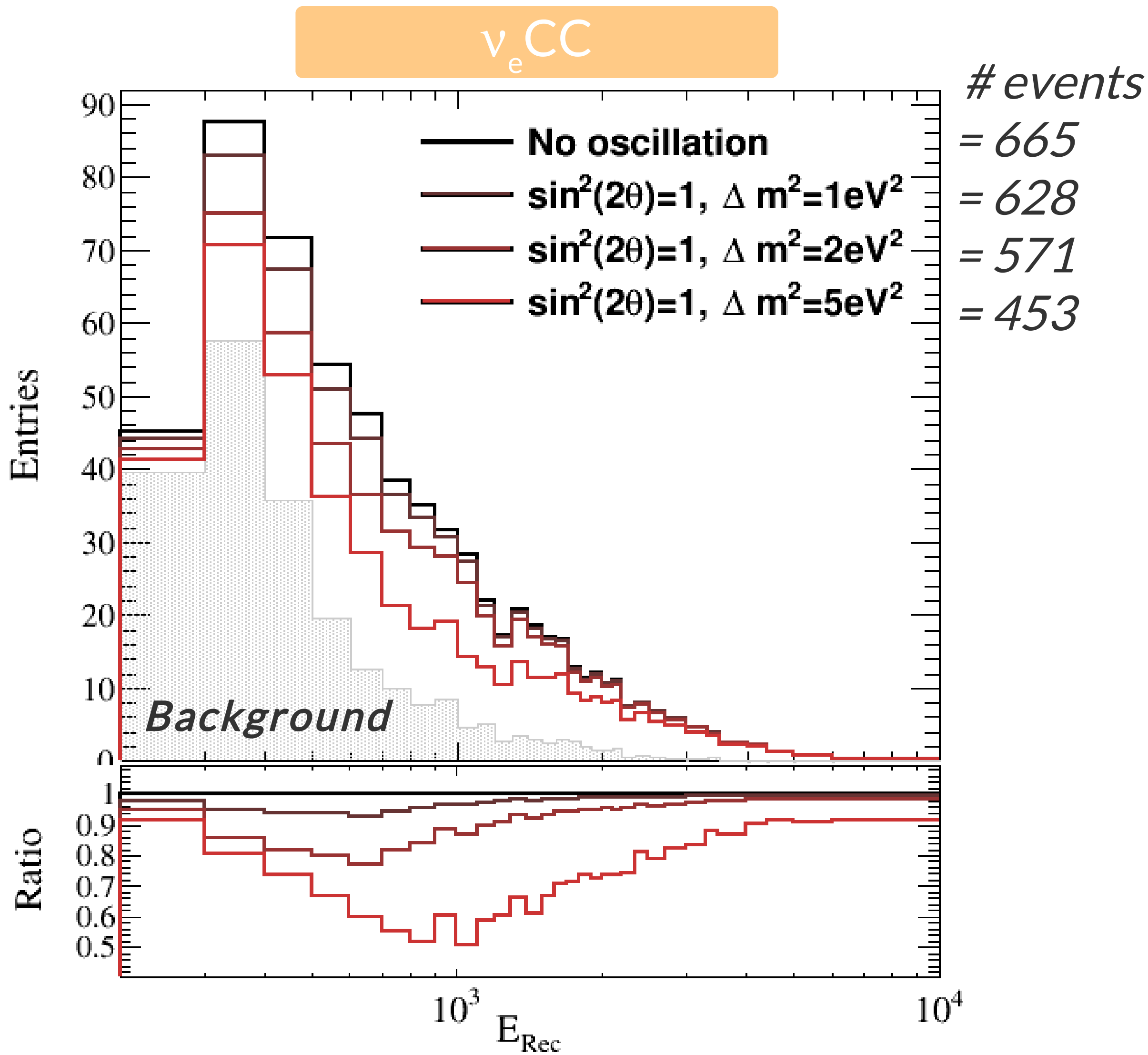






Effect of the oscillations

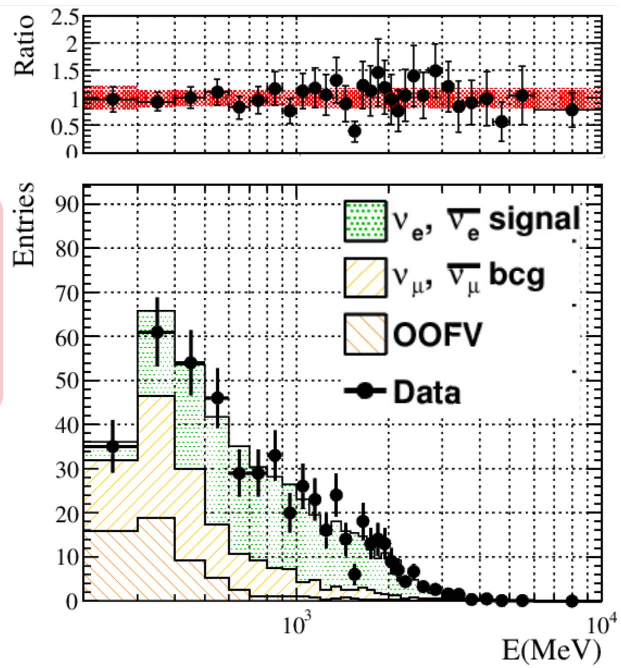
Calculated in an *event-by-event* basis so the energy and flight path are treated exactly

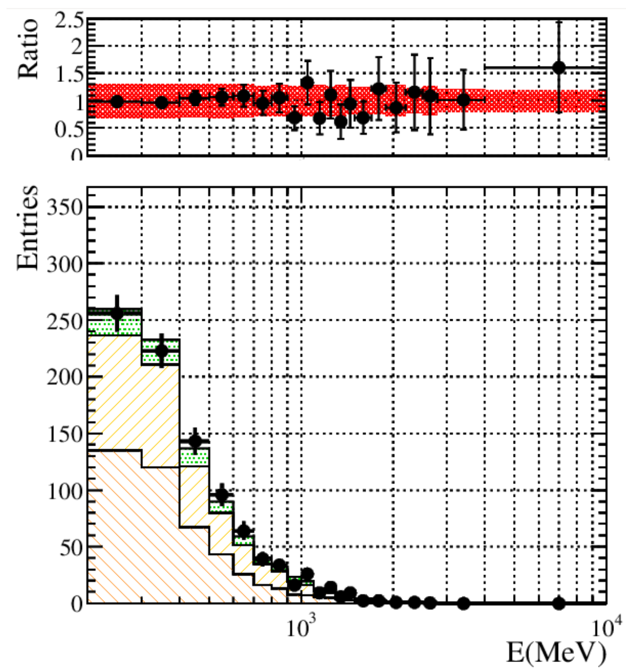


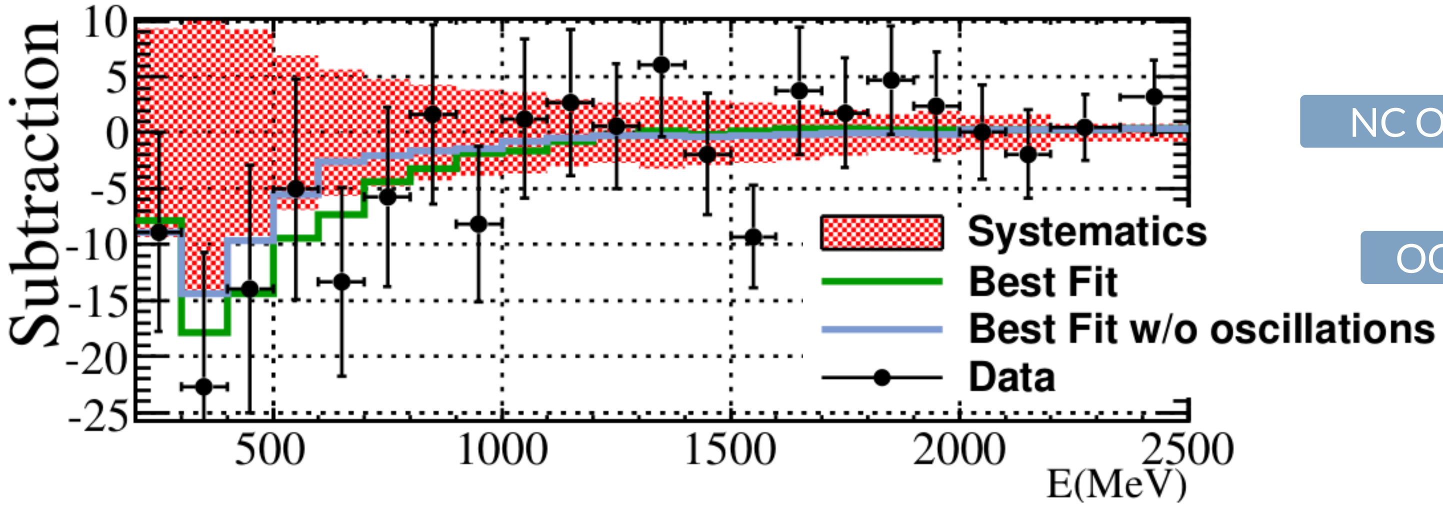
Results on the data: best fit parameters

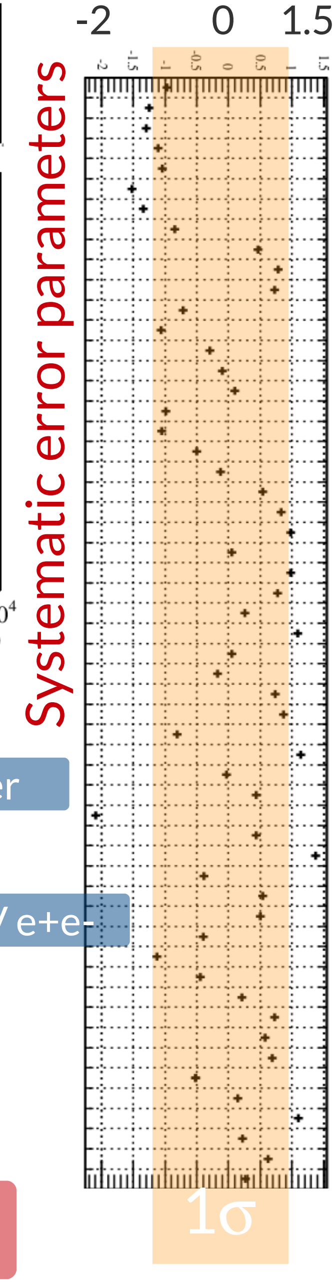
$$\sin^2(2\theta_{ee})_{bf} = 1.00$$

$$\Delta m^2_{41\,bf} = 2.14$$







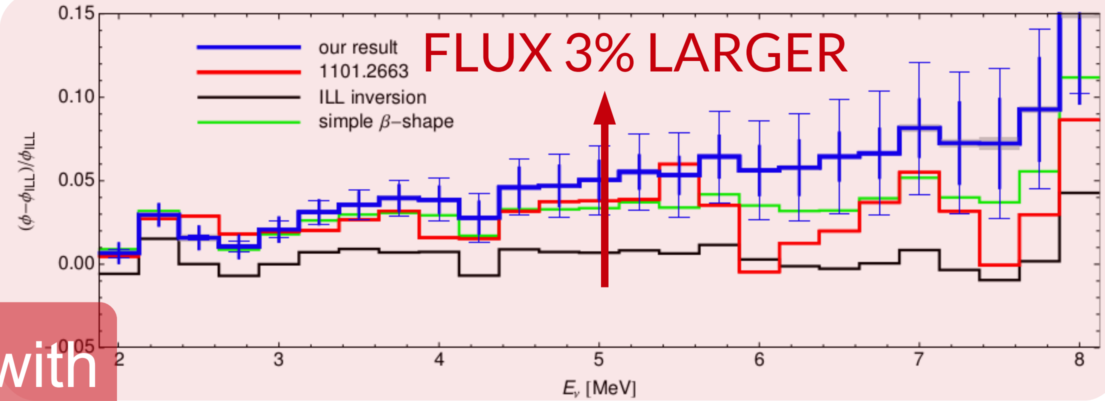


Small deficit that is better fit taking into account $\nu_e \rightarrow \nu_s$ oscillations

Light sterile neutrinos: The reactor anti-neutrino anomaly

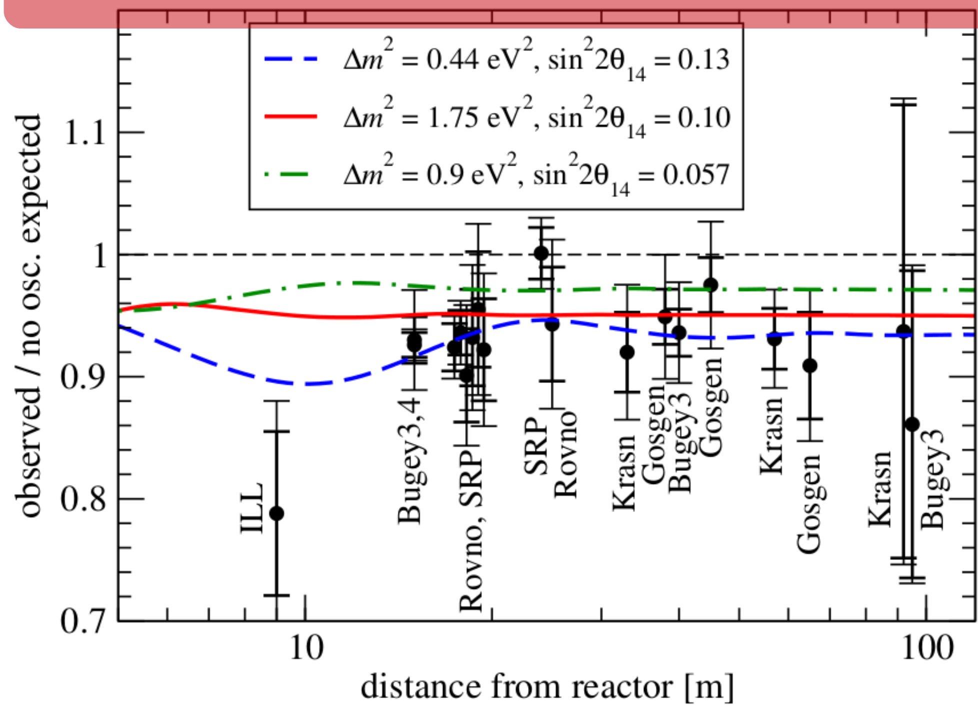
Number of observed *IBD* events:

$$N_{IBD} \propto \phi(E)\sigma(E)$$



FLUX 3% LARGER

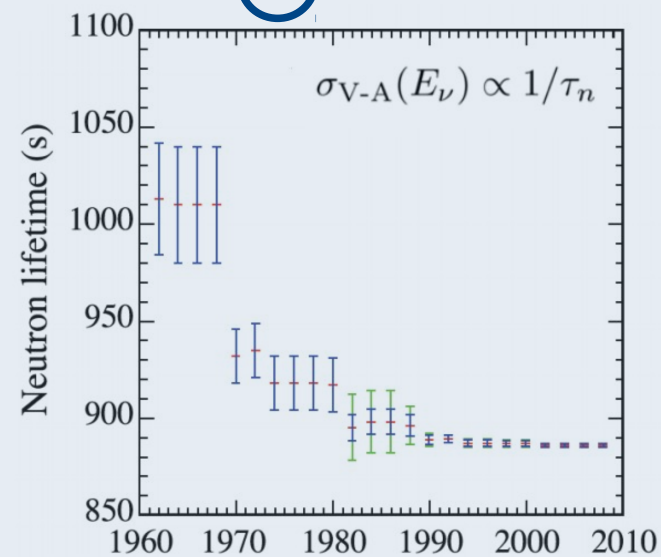
Predicted *IBD* rates increased with new recalculation in 2010



6% deficit → 3σ effect

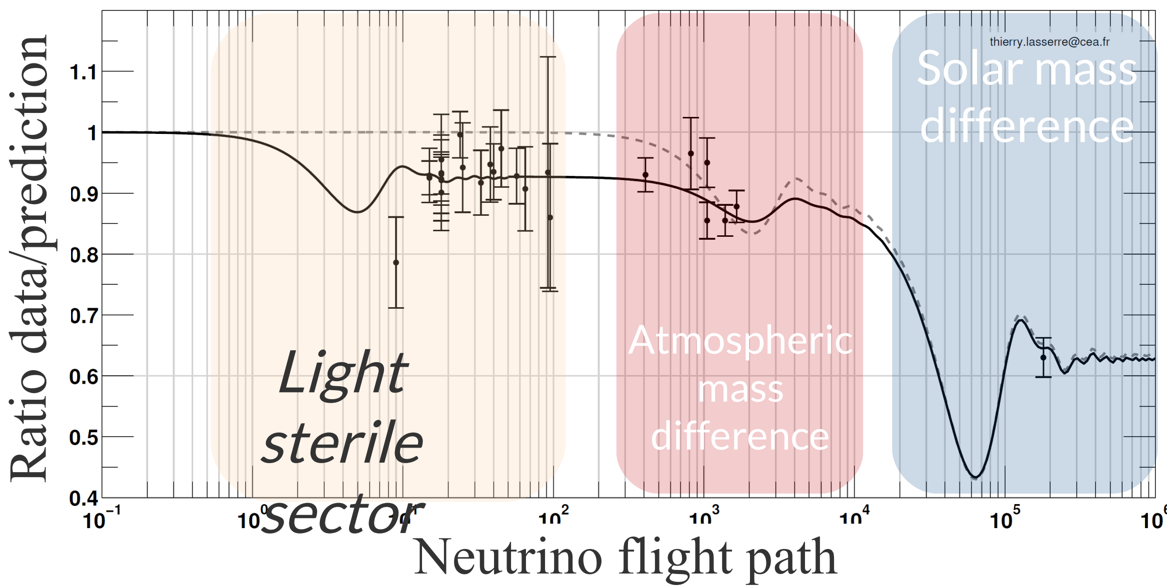
CROSS-SECTION 1% LARGER

$$\sigma = \frac{2\pi^2}{m_e^5 f_{p.s.} \tau_n} E_e p_e \times 10^{-42}\,\mathrm{cm}^2$$



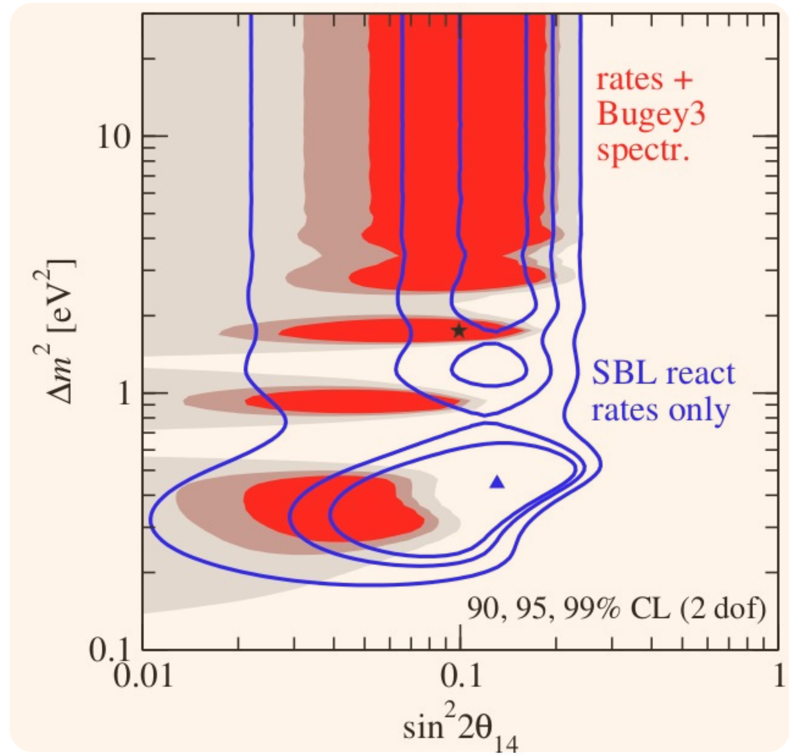
Light sterile neutrinos: The reactor anti-neutrino anomaly

$$P_{ee} = P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{ee}) \sin^2\left(1.27\, \Delta m^2_{41}\,[\mathrm{eV}^2] \frac{\mathrm{L[m]}}{\mathrm{E[\,MeV]}}\right)$$



Standard oscillations

3+1 model



Deficit explainable by ν_e disappearance with parameters

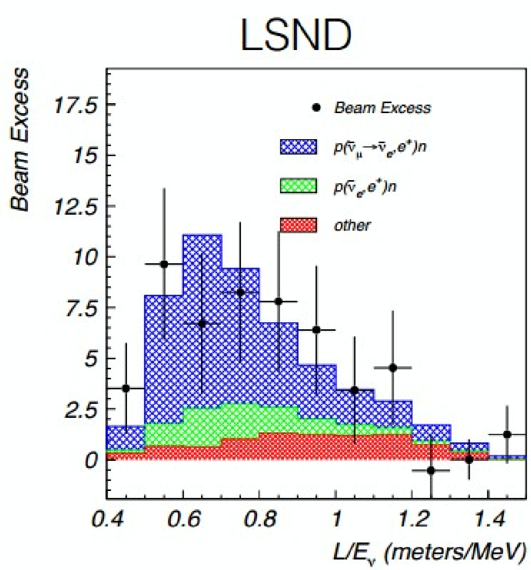
$$|\,\Delta m^2_{41}\,| = 1.75\,\mathrm{eV}^2 \text{ and } \sin^2(2\theta_{ee}) = 0.10$$

Non-oscillation hypothesis rejected by 3σ

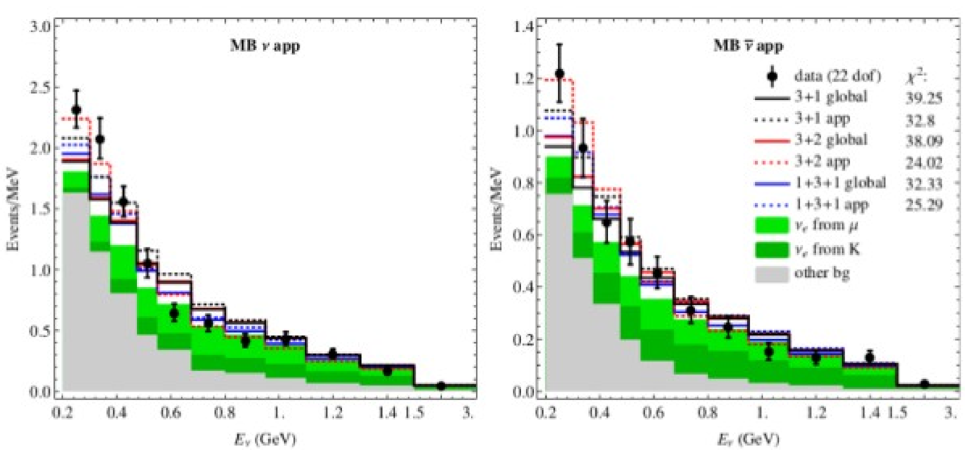
$\nu_\mu \rightarrow \nu_e$ short baseline appearance

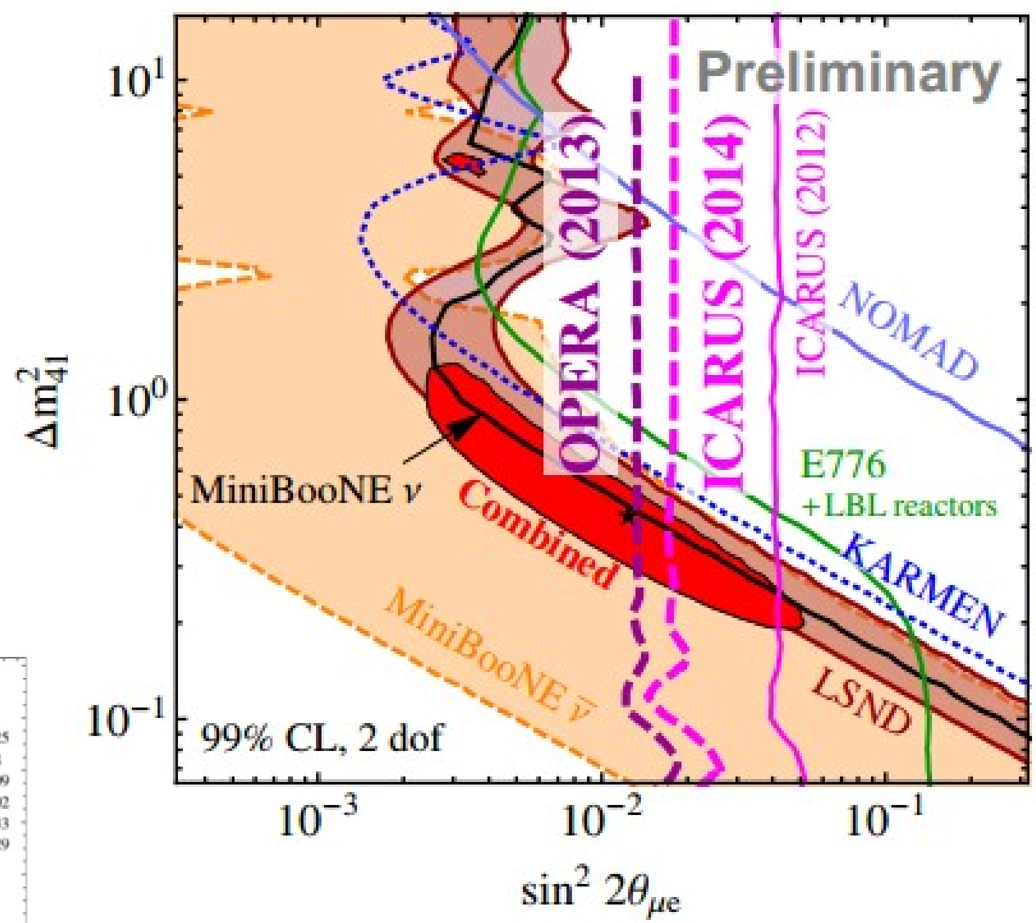
$$P_{e\mu} \equiv P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(1.27\,\Delta m^2_{41}[\,\mathrm{eV}^2]\frac{\mathrm{L}[\,\mathrm{m}]}{\mathrm{E\,MeV}}\right)$$

LSND



MiniBooNE



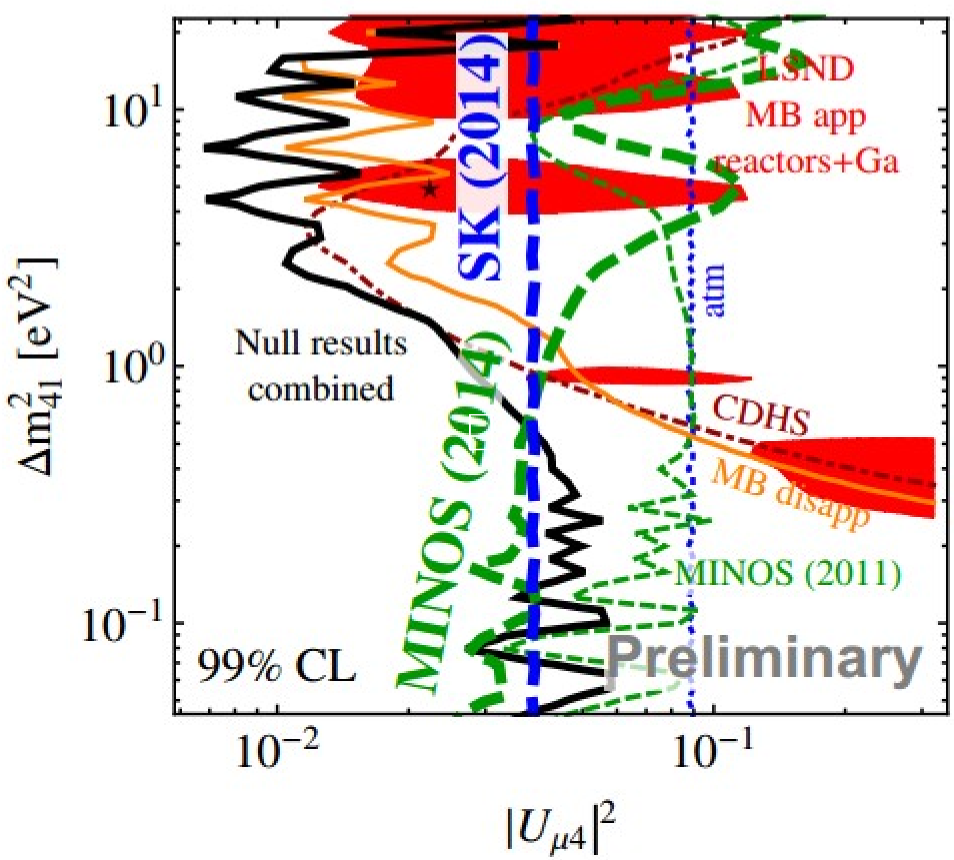


$$\sin^2(2\theta_{e\mu}) \approx \frac{1}{4}\sin^2(2\theta_{ee})\sin^2(2\theta_{\mu\mu})$$

$\nu_\mu \rightarrow \nu_\mu$ short bas$\nu_\mu$ine appearance

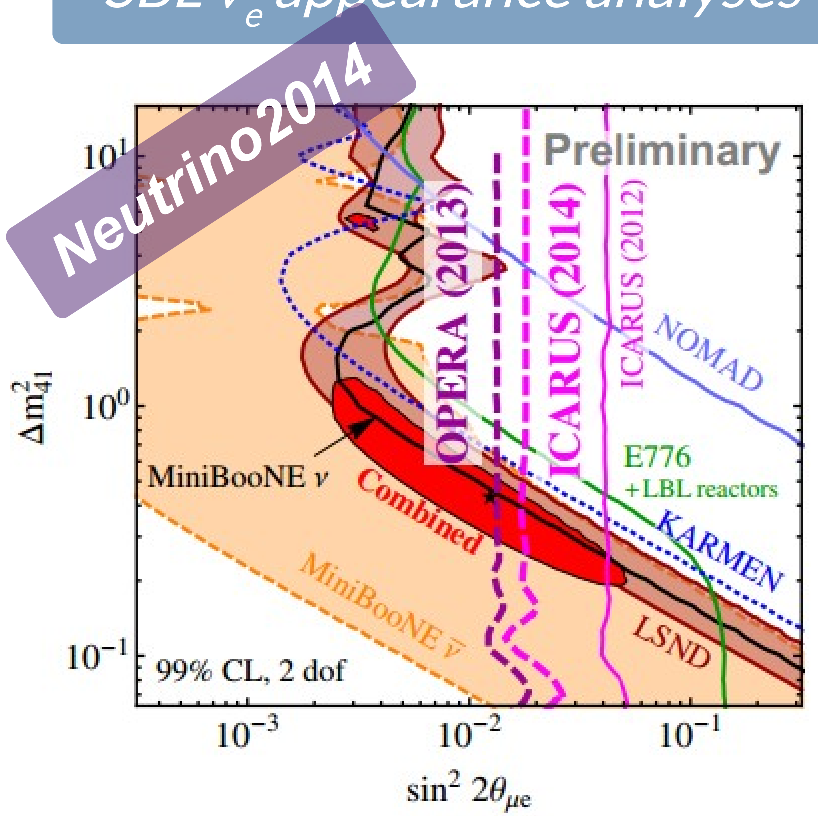
$$P_{\mu\mu} \equiv P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)\sin^2\left(1.27\,\Delta m^2_{41}[\,eV^2]\frac{L[\,m]}{E\,MeV}\right)$$

$$\sin^2(2\theta_{\mu\mu}) = 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$



Preliminary sensitivity

SBL ν_e appearance analyses



Light sterile neutrinos: Summary

$P(\nu_e \to \nu_e)$

ν_e disappearance:

- Reactor anomaly ✔
- Gallium anomaly ✔
- Solar and KamLAND ✗
- Long base-line reactors ✗
- LSND+KARMEN cross-section measurements ✗

$P(\nu_\mu \to \nu_e)$

ν_e appearance

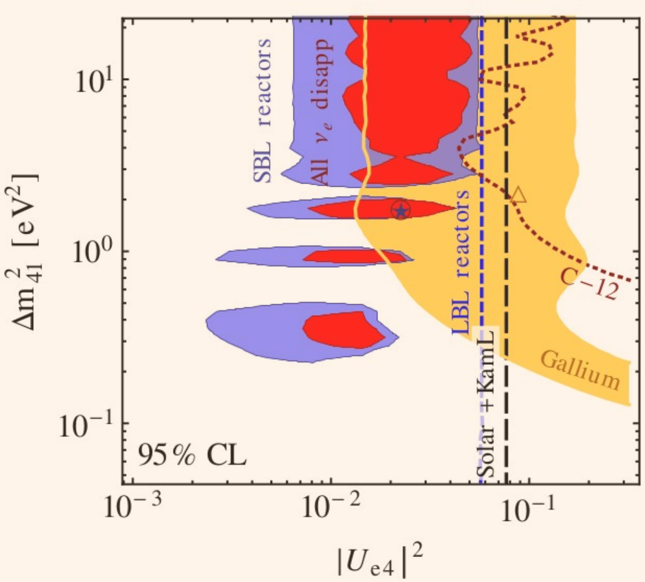
- LSND ✔
- MiniBooNE ✔
- KARMEN ✗
- Others ✗

$P(\nu_\mu \to \nu_\mu)$

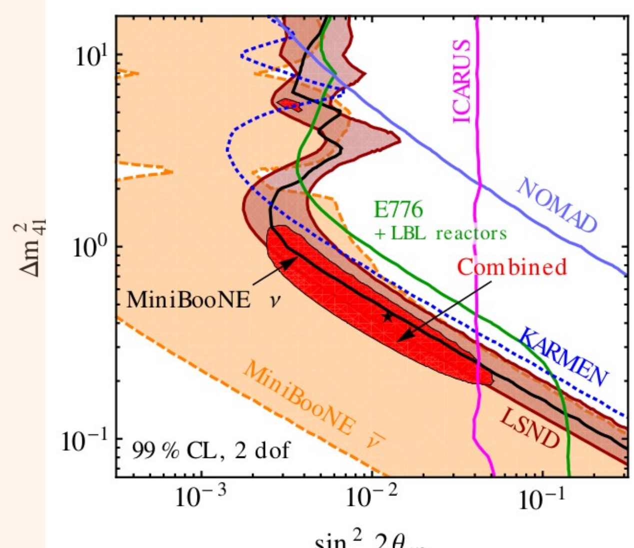
ν_μ disappearance

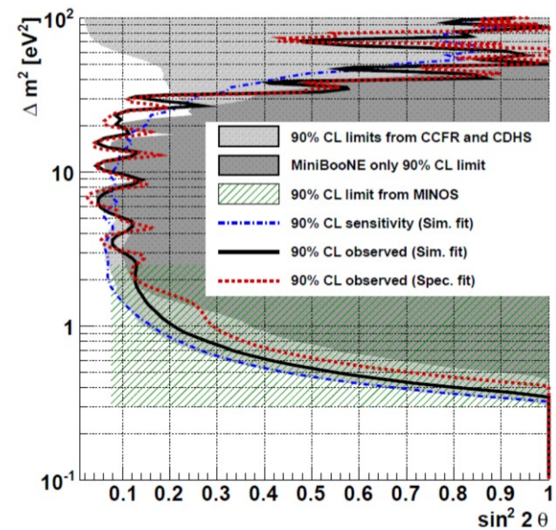
- MINOS ✗
- Sciboone+MiniBooNE ✗
- CDHSW ✗
- CCFR ✗

✔ Anomaly
✗ Standard



Global fit → 99.8%CL





Light sterile neutrinos: The 3+1 model

$$\sin^2(2\theta_{ee}) = 4|U_{e4}|^2(1-|U_{e4}|^2)$$

$$\sin^2(2\theta_{\mu\mu}) = 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)$$

$$\sin^2(2\theta_{e\mu}) = 4|U_{e4}|^2|U_{\mu4}|^2$$

Neutrino flavour disappearance

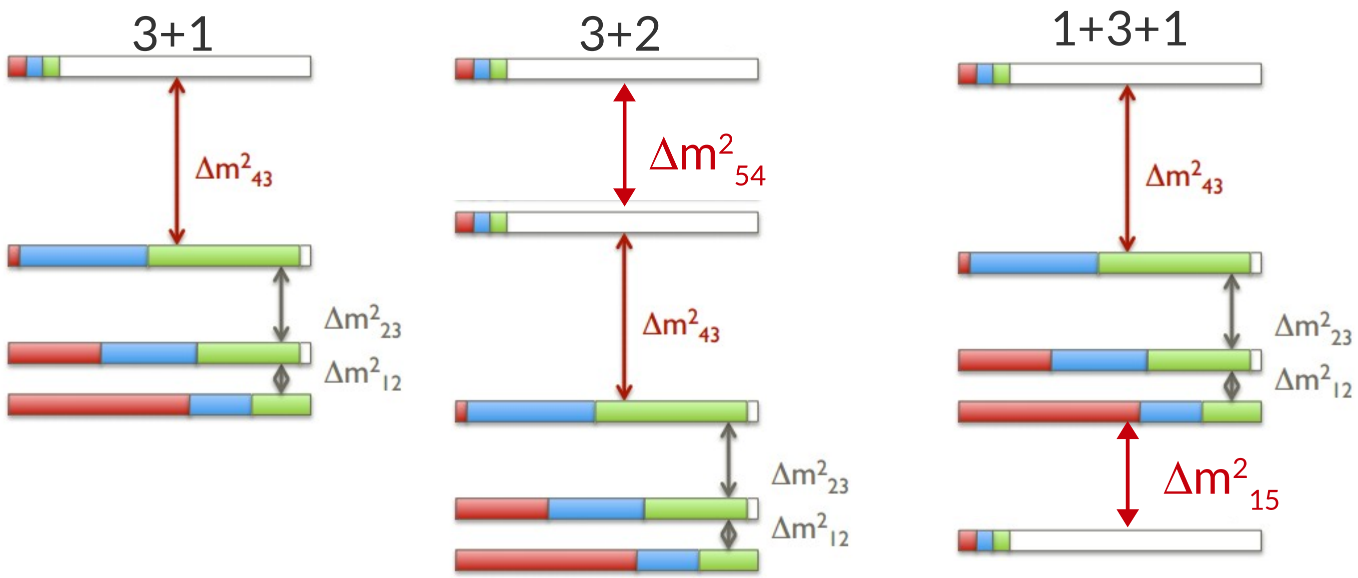
$$P_{ee} \equiv P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\left(1.27\,\Delta \mathrm{m}^2_{41}[\,\mathrm{eV}^2]\frac{\mathrm{L}[\,\mathrm{m}]}{\mathrm{E}[\,\mathrm{MeV}]}\right)$$

$$P_{\mu\mu} \equiv P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\left(1.27\,\Delta \mathrm{m}^2_{41}[\,\mathrm{eV}^2]\frac{\mathrm{L}[\,\mathrm{m}]}{\mathrm{E\,MeV}}\right)$$

Neutrino flavour appearance

$$P_{e\mu} \equiv P(\nu_\mu \to \nu_e) = P(\nu_e \to \nu_\mu) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\left(1.27\,\Delta \mathrm{m}^2_{41}[\,\mathrm{eV}^2]\frac{\mathrm{L}[\,\mathrm{m}]}{\mathrm{E\,MeV}}\right)$$

Light sterile neutrinos: 3+2 and 1+3+1 models



Appearance:

$$P^{\mathrm{SBL},3+2}_{\nu_\alpha\to\nu_\beta} = 4\,|U_{\alpha4}|^2|U_{\beta4}|^2\,\sin^2\phi_{41} + 4\,|U_{\alpha5}|^2|U_{\beta5}|^2\,\sin^2\phi_{51} + 8\,|U_{\alpha4}U_{\beta4}U_{\alpha5}U_{\beta5}|\,\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54} - \gamma_{\alpha\beta})$$

Allows SBL CPV

Disappearance (survival):

$$P^{\mathrm{SBL},3+2}_{\nu_\alpha\to\nu_\alpha} = 1 - 4\left(1 - \sum_{i=4,5}|U_{\alpha i}|^2\right)\sum_{i=4,5}|U_{\alpha i}|^2\,\sin^2\phi_{i1} - 4\,|U_{\alpha4}|^2|U_{\alpha5}|^2\,\sin^2\phi_{54}$$

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}\,, \qquad \gamma_{\alpha\beta} \equiv \arg\left(I_{\alpha\beta54}\right)\,, \qquad I_{\alpha\beta ij} \equiv U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}$$

Light sterile neutrinos: the global picture

$P(\nu_\mu \to \nu_e)$ Sensitive to $\sin^2(2\theta_{e\mu})$

$P(\nu_e \to \nu_e)$ Sensitive to $\sin^2(2\theta_{ee})$

$P(\nu_\mu \to \nu_\mu)$ Sensitive to $\sin^2(2\theta_{\mu\mu})$

Model	χ^2	*Goodness-of-fit*
3+1	712/(689-9)	1.2×10^{-4}
3+2	701/(689-14)	0.34×10^{-4}
1+3+1	694/(689-14)	21.0×10^{-4}

$$\chi^2_{\rm PG} \equiv \chi^2_{\rm min,glob} - \chi^2_{\rm min,app} - \chi^2_{\rm min,dis}$$

$$\sin^2(2\theta_{e\mu}) \approx \frac{1}{4}\sin^2(2\theta_{ee})\sin^2(2\theta_{\mu\mu})$$

- Disappearance experiments are sensitive to appearance parameters
- A global fit to all the available data indicates there are tensions between both sectors
- Tension driven by the negative signal in the $\nu_\mu \to \nu_s$ searches