Queen Mary University of London

T2K

Charged current ν_μ and $\bar{\nu}_\mu$ interactions in the T2K off-axis near detector, ND280

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on behalf of the T2K Collaboration

Lake Louise Winter Institute
February 2015

Photo courtesy of Will Kalderon

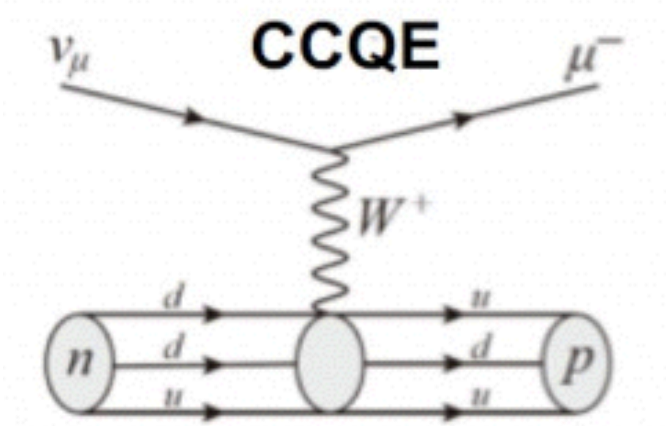
Outline

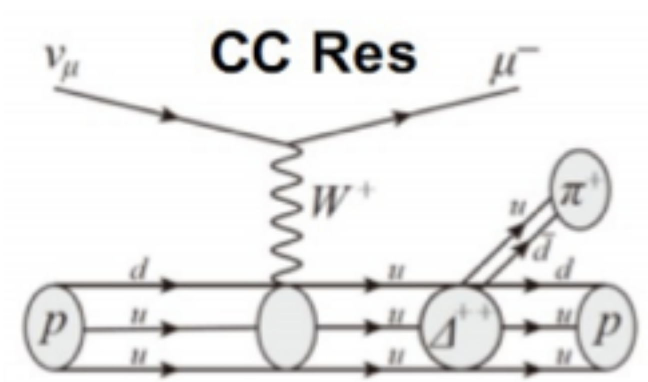
- Brief introduction to the T2K experiment
- ND280 data used to constrain flux and cross-section model parameters
  - **Current** samples: $\boldsymbol{\nu_\mu}$ in $\boldsymbol{\nu_\mu}$ beam
  - **New** samples: $\boldsymbol{\bar{\nu}_\mu}$ in $\boldsymbol{\bar{\nu}_\mu}$ beam
  - **New** samples: $\boldsymbol{\nu_\mu}$ in $\boldsymbol{\bar{\nu}_\mu}$ beam
    (Understanding the $\bar{\nu}_\mu$-mode beam composition)
- Current and future cross-section measurements

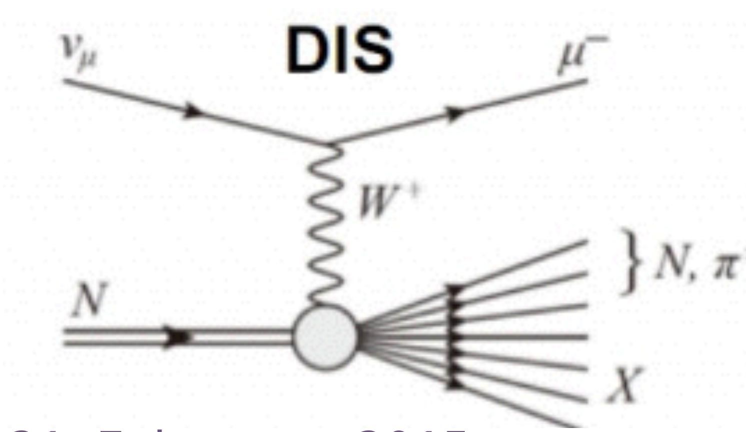
A brief recap of the T2K experiment

T2K Physics Goals

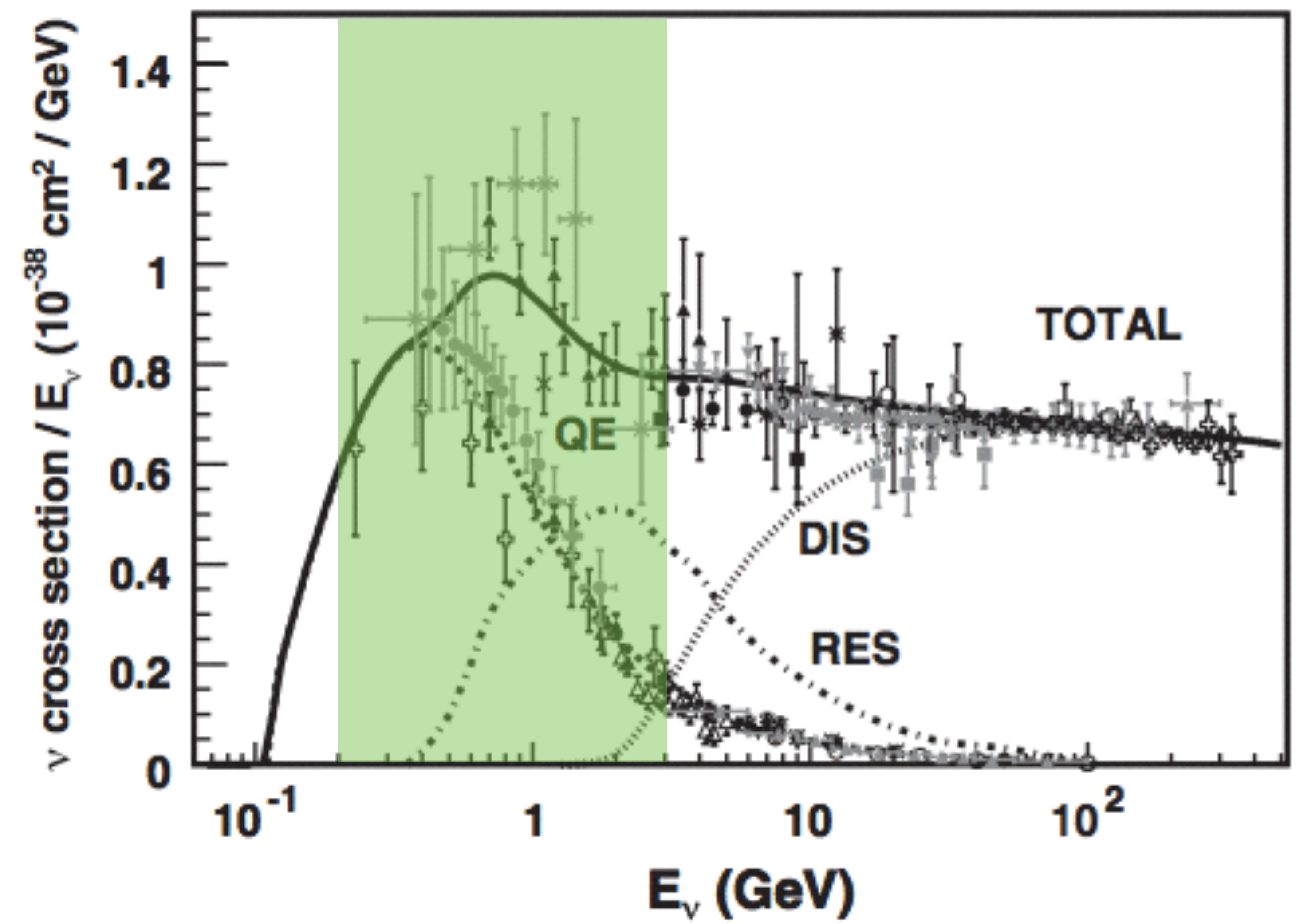
$\nu_\mu \rightarrow \nu_e$ appearance : θ_{13} , δ
$\nu_\mu \rightarrow \nu_\mu$ disappearance : θ_{23} , Δm^2_{23}
ν cross-section measurements







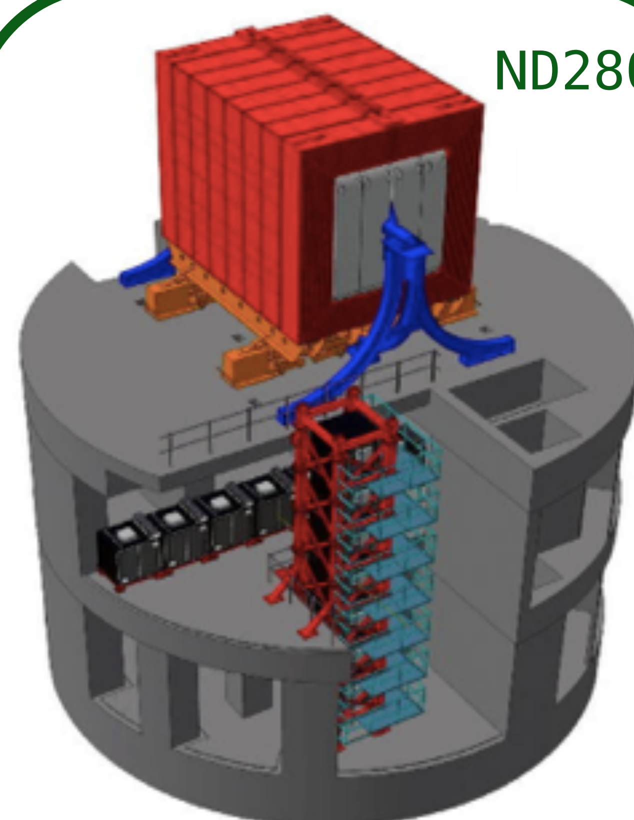
Formaggio Zeller, Rev. Mod. Phys. 84 (2012)



Tokai2Kamioka Experiment

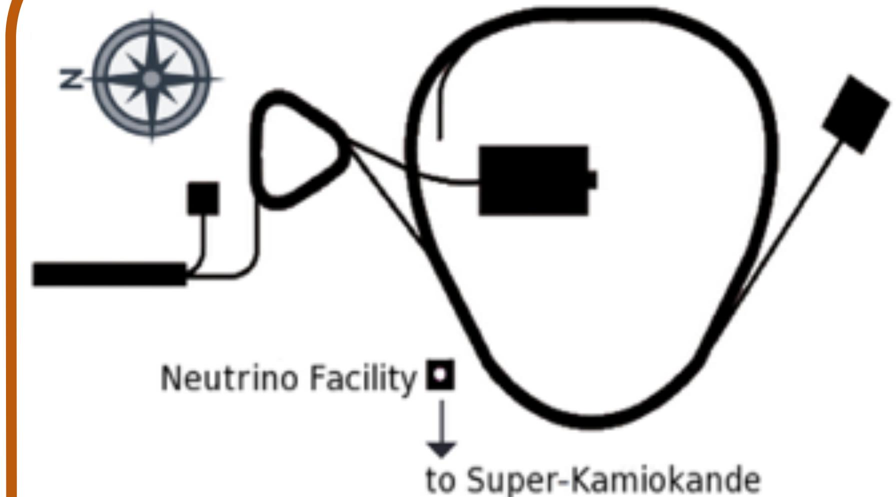
Super−Kamiokande

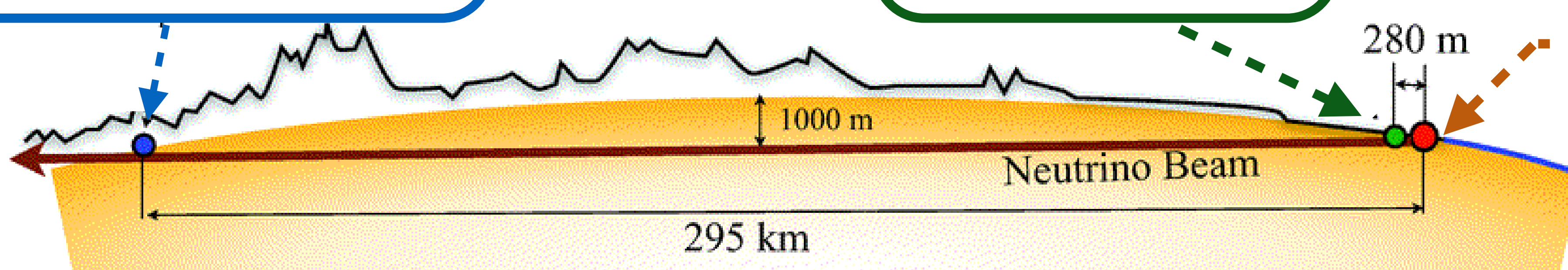
ND280



INGRID

Near Detectors

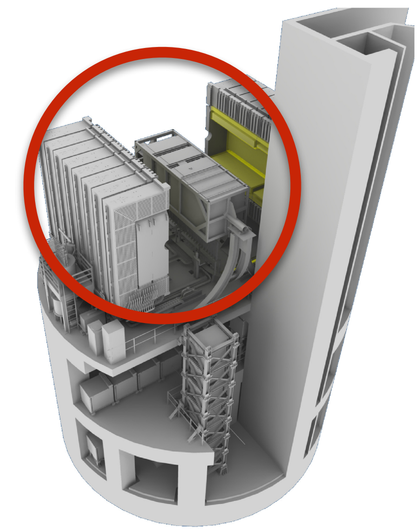


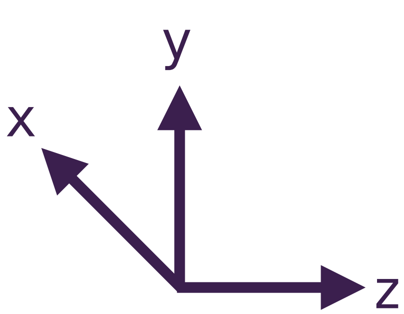


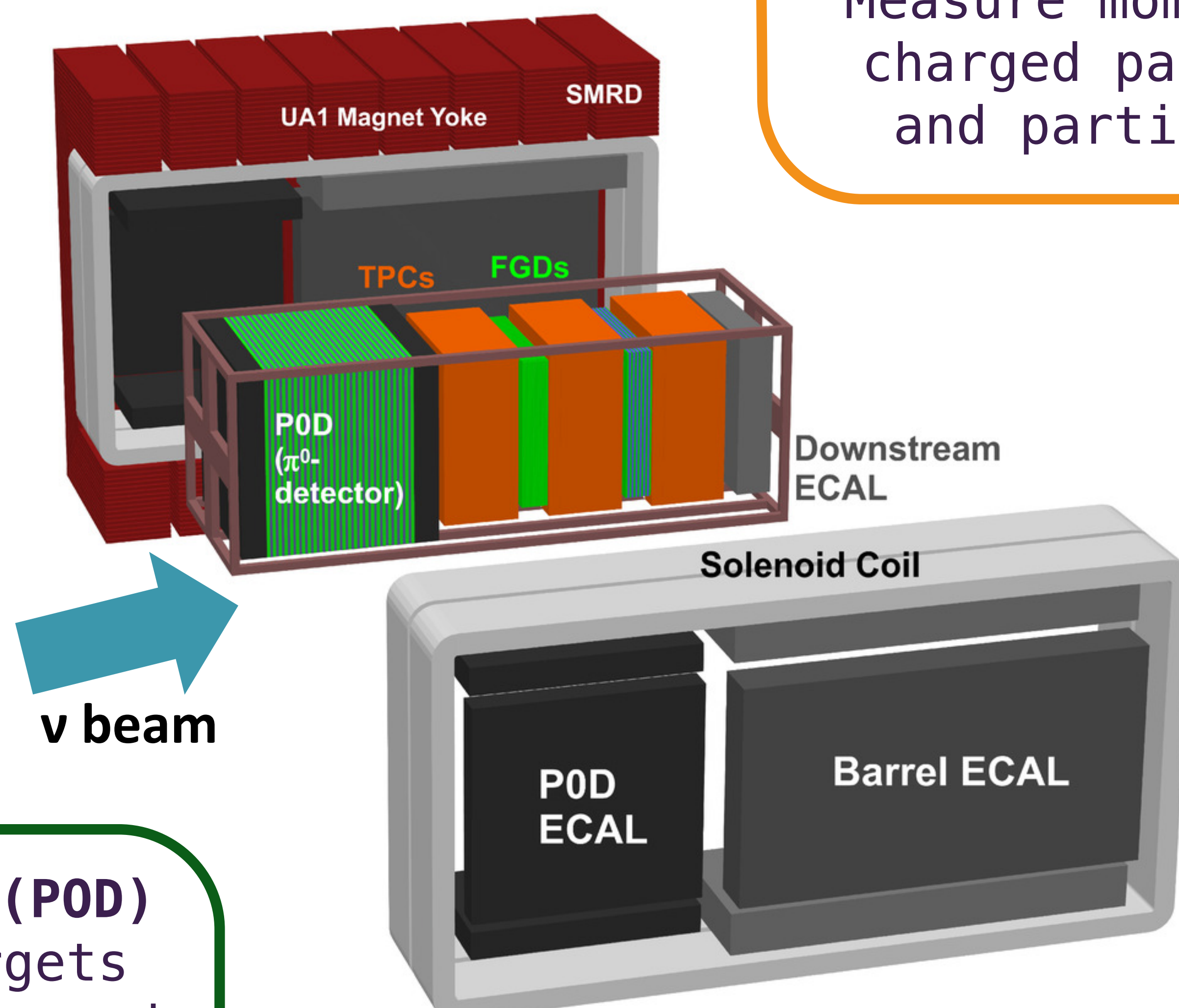
Off-Axis Near Detector: ND280

Fine Grained Detectors (FGDs)
Provide active targets for neutrino interactions
FGD1: carbon
FGD2: carbon + water

Tracker: FGDs + TPCs
Measure momenta of charged particles and particle ID





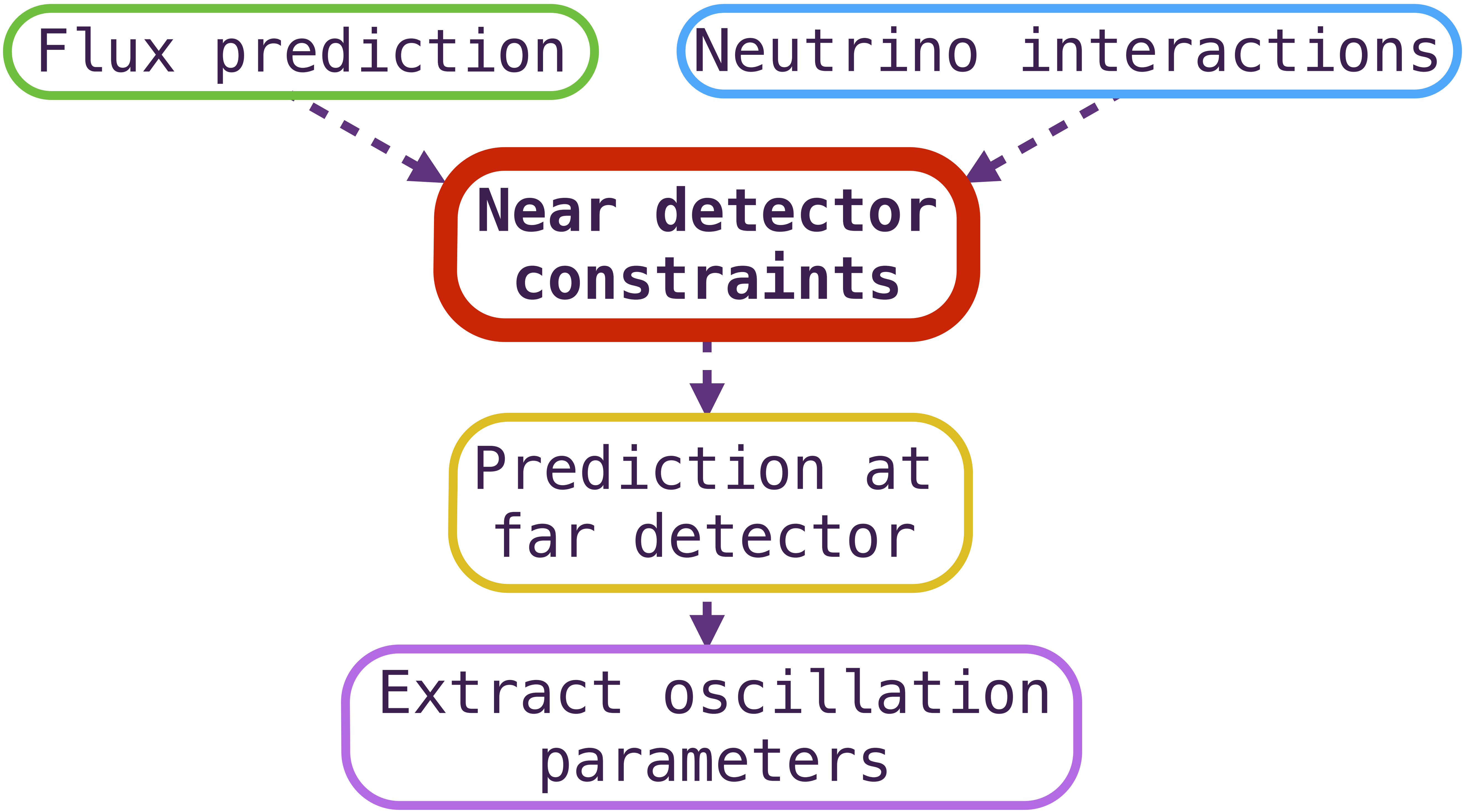


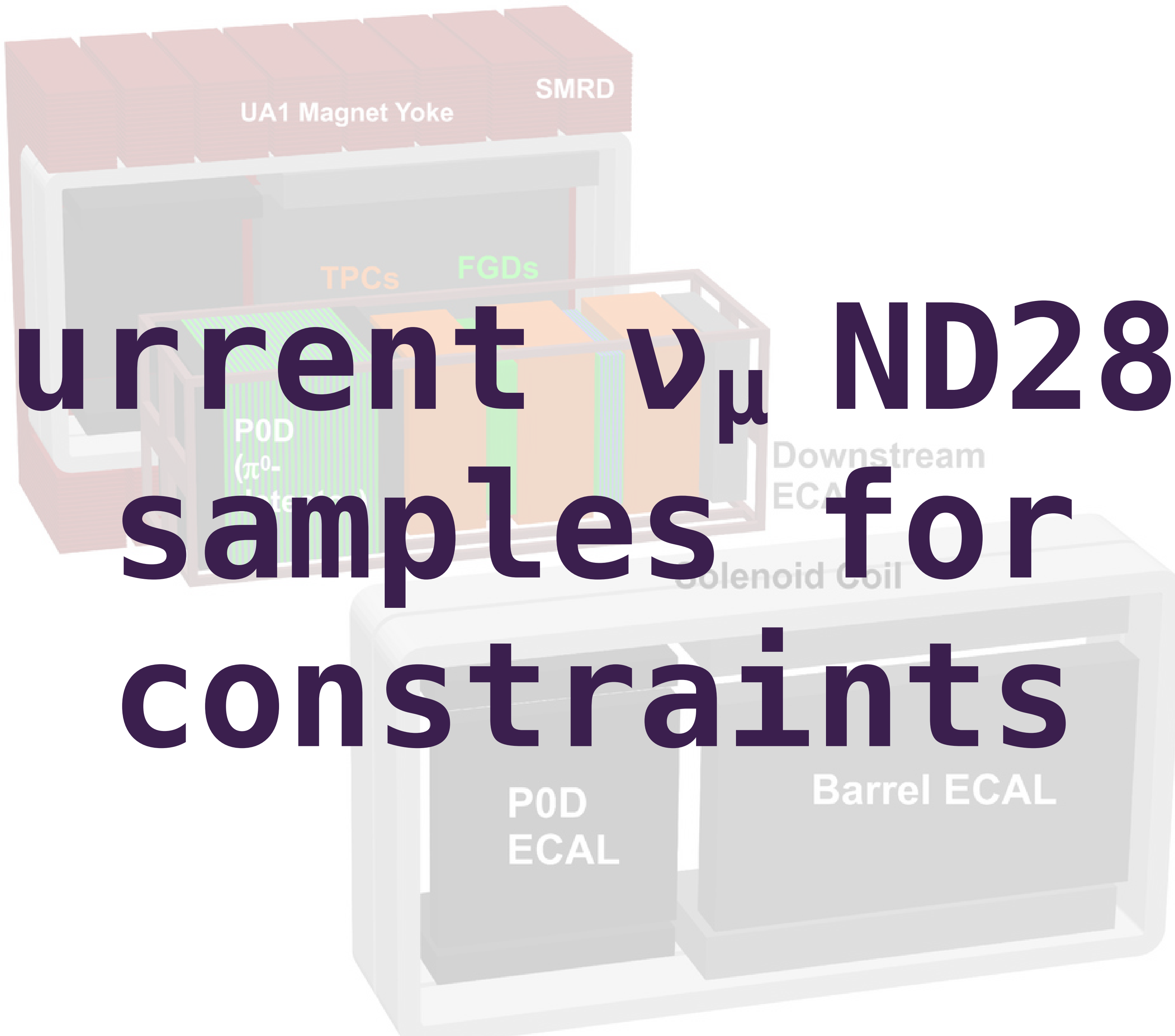
Electromagnetic Calorimeter (ECAL)
Plastic scintillator and lead
Aids in PID and photon reconstruction

Upstream π^0 detector (P0D)
Carbon and water targets interleaved with brass and lead

UA1 magnet: 0.2T magnetic field
SMRD: aids in track reconstruction

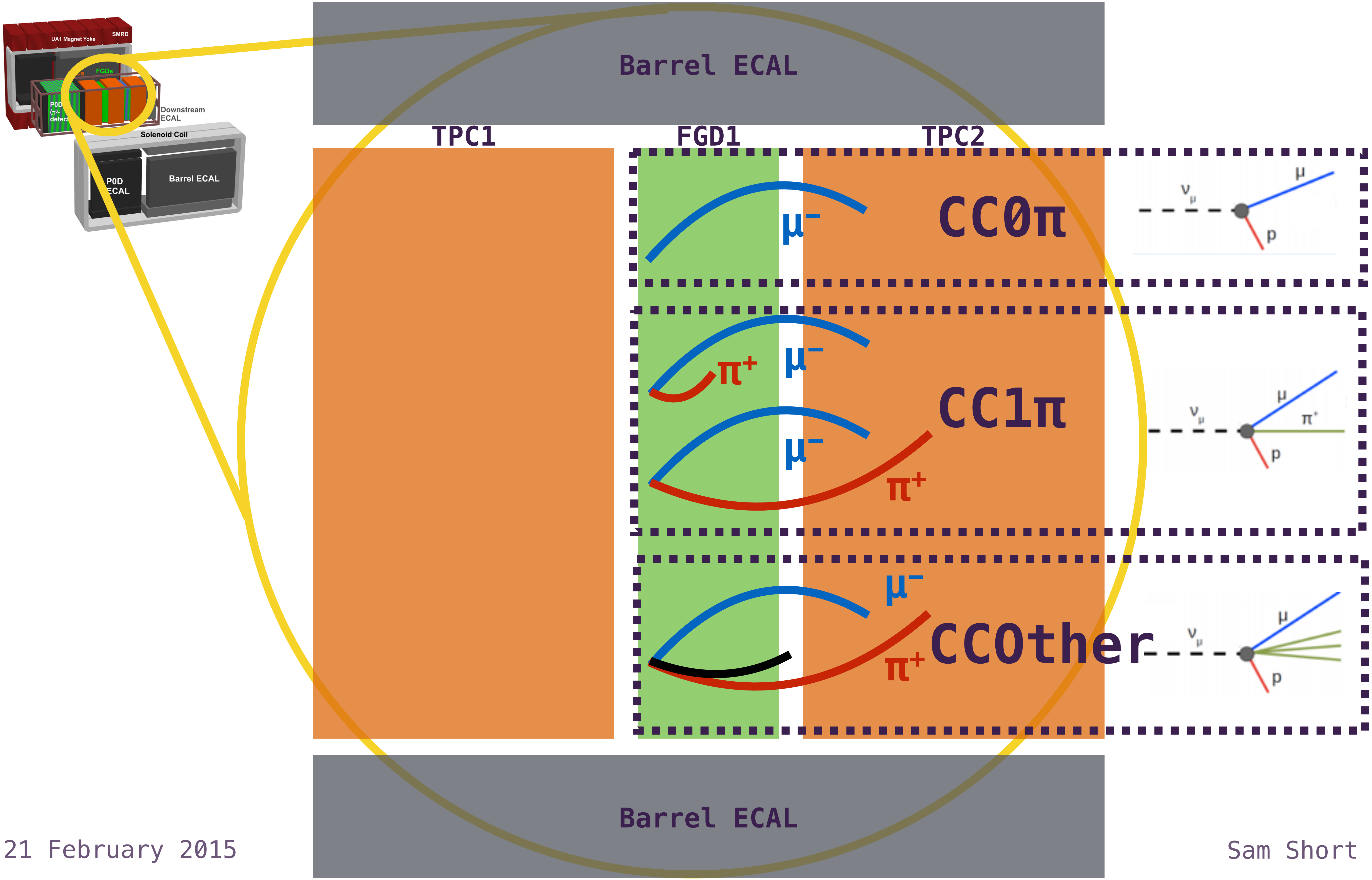
Oscillation Analysis Strategy





Current ν_μ ND280 samples for constraints

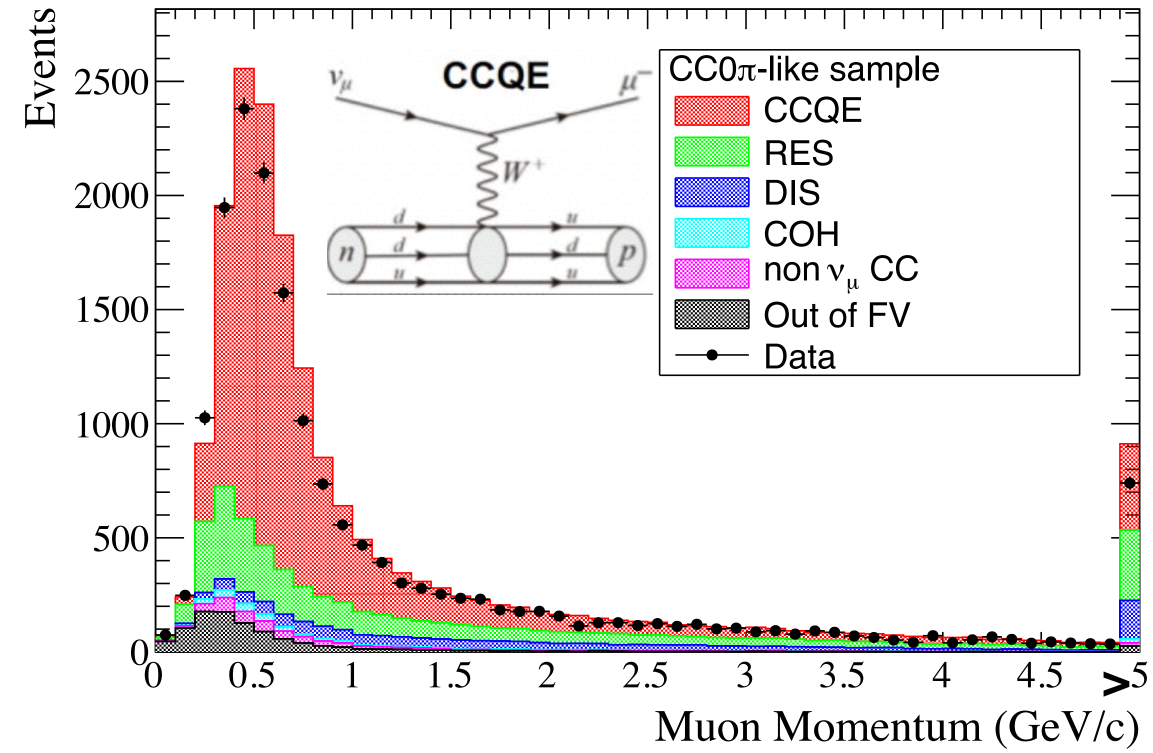
Selecting ν_μ Interactions

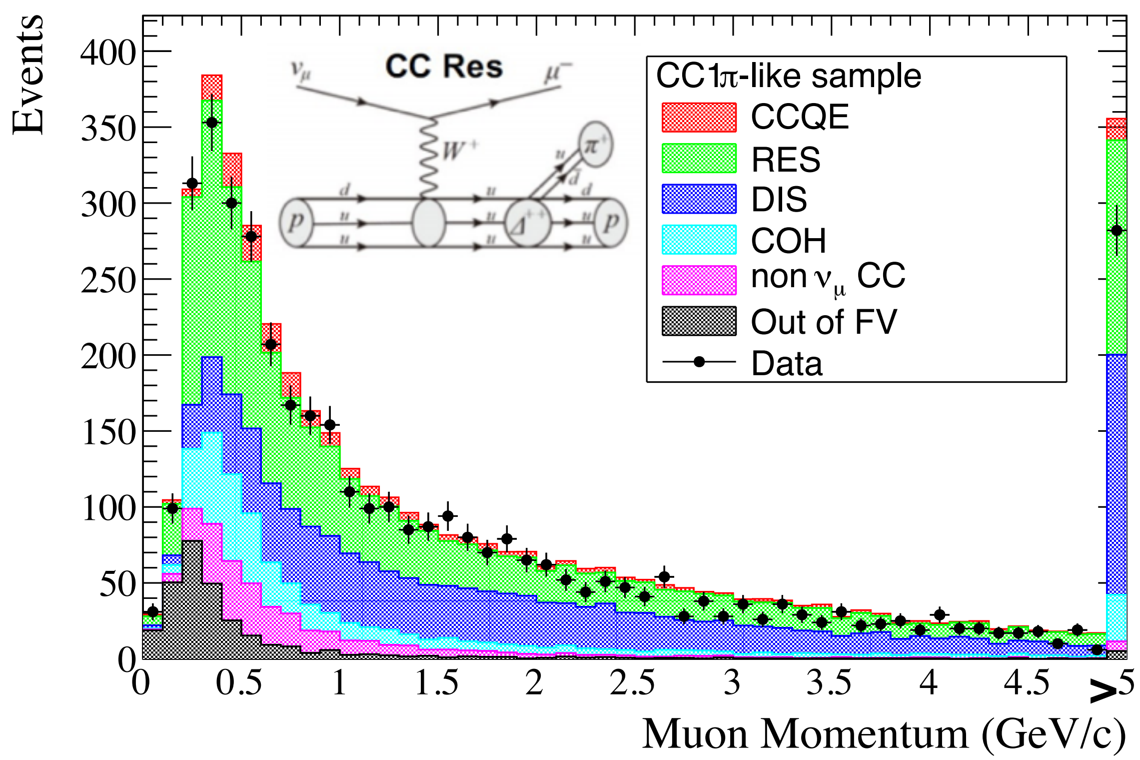


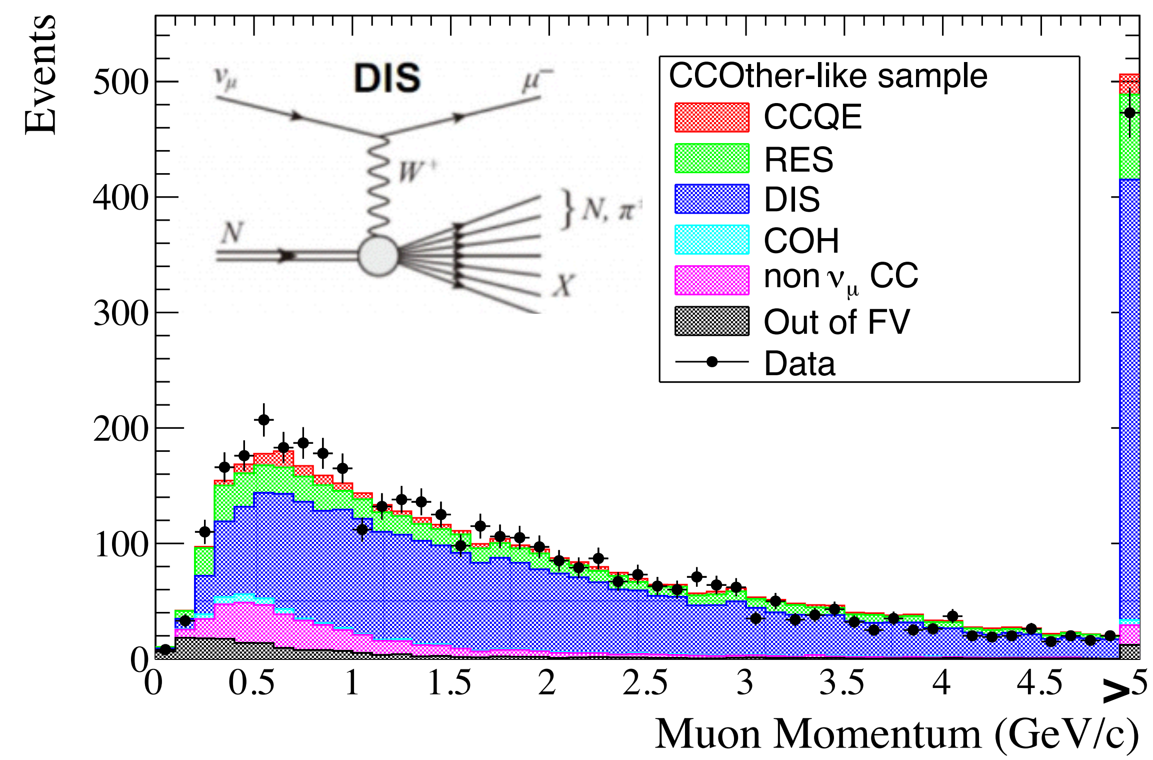
ν_μ Samples for Constraints

For the joint appearance and disappearance oscillation analysis
arXiv:1502.01550v1 [hep-ex]

- $(p,\theta)_\mu$ distributions measured for each sample
- Float cross-section and flux parameters to find best fit
- Reweight NEUT MC at far detector to reflect results of near detector measurements for each sample

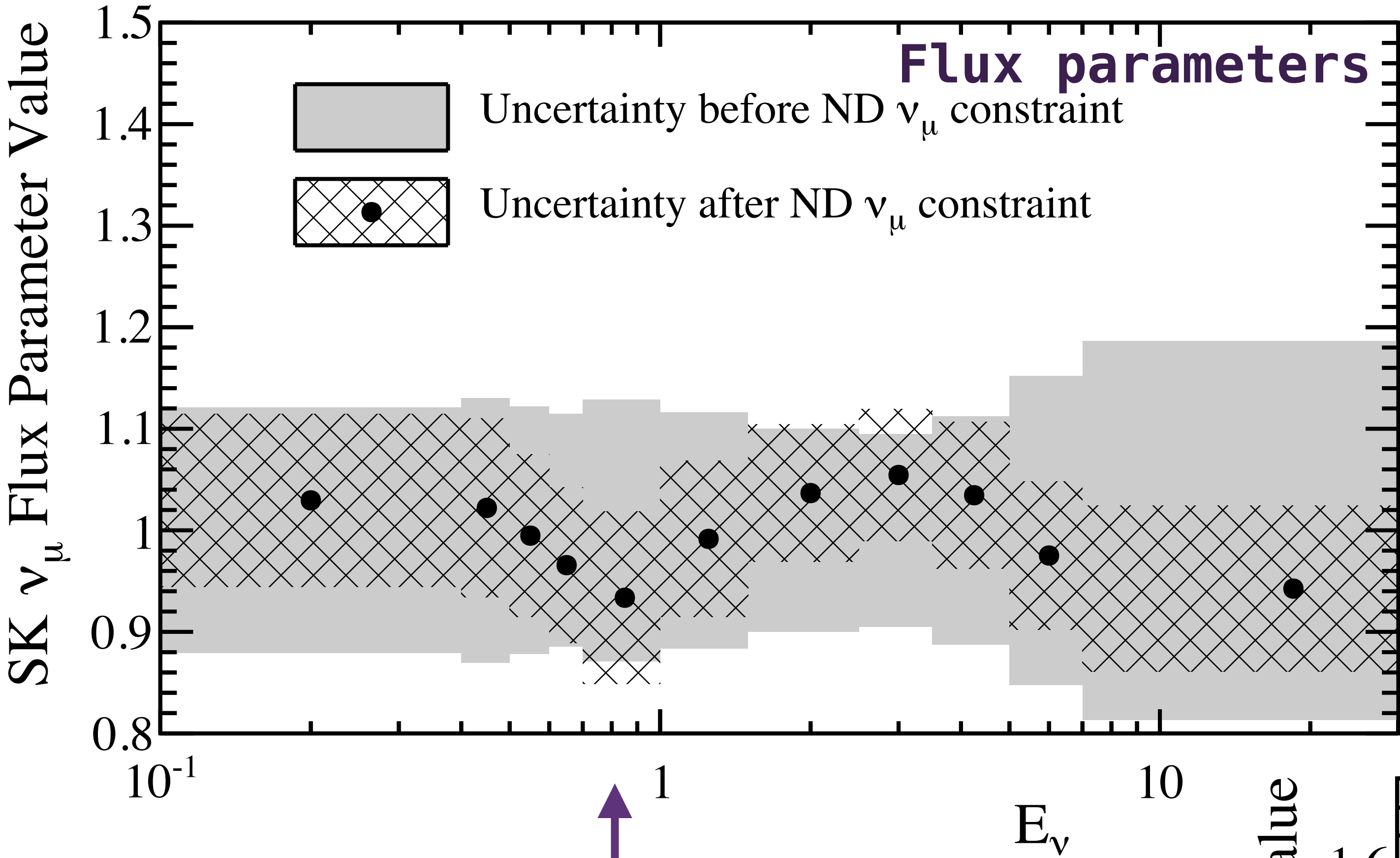






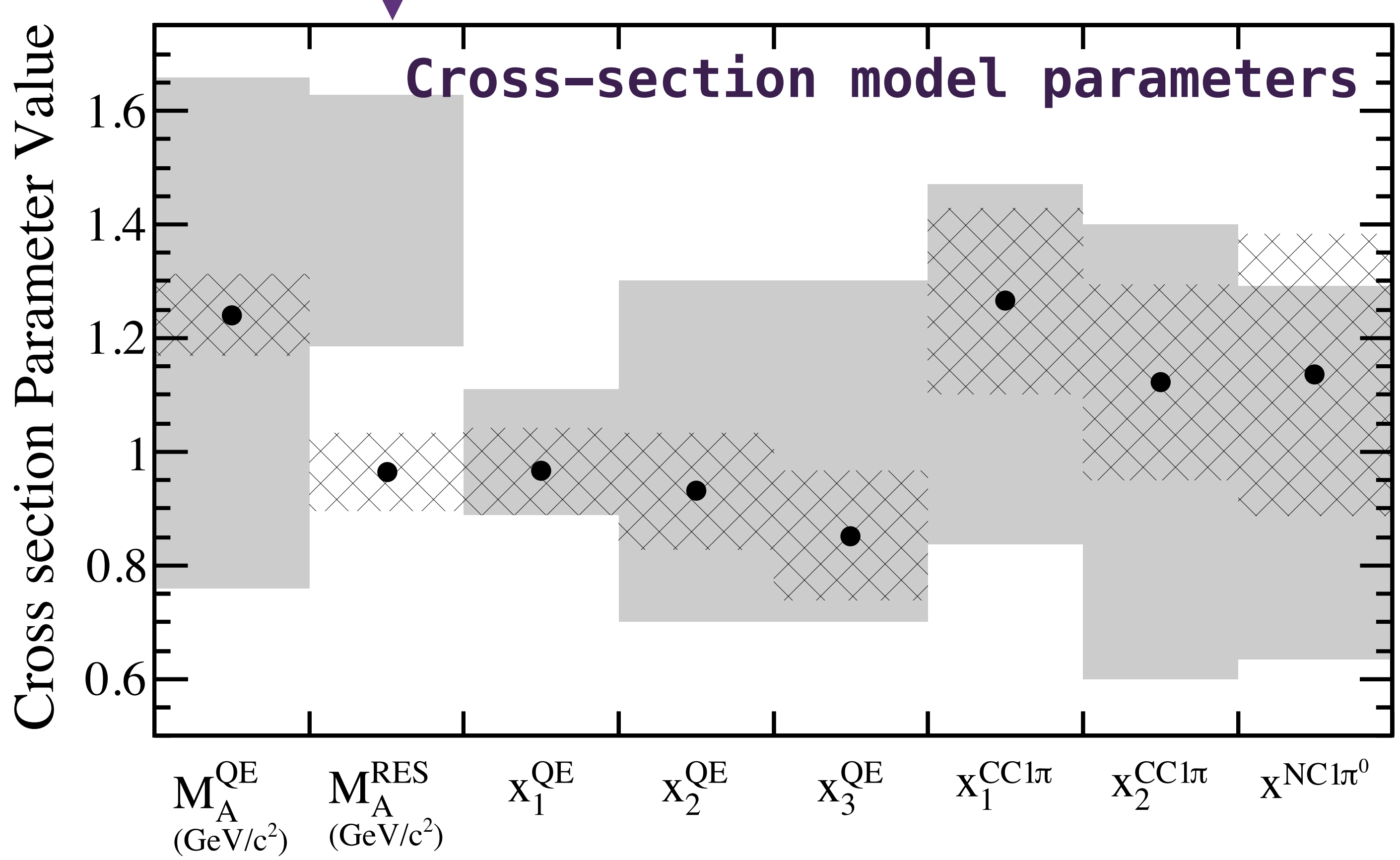
* Data = Runs 1-4 = 5.47×10^{20} protons on target

Impact of ν_μ Constraints



M_A^{RES}:

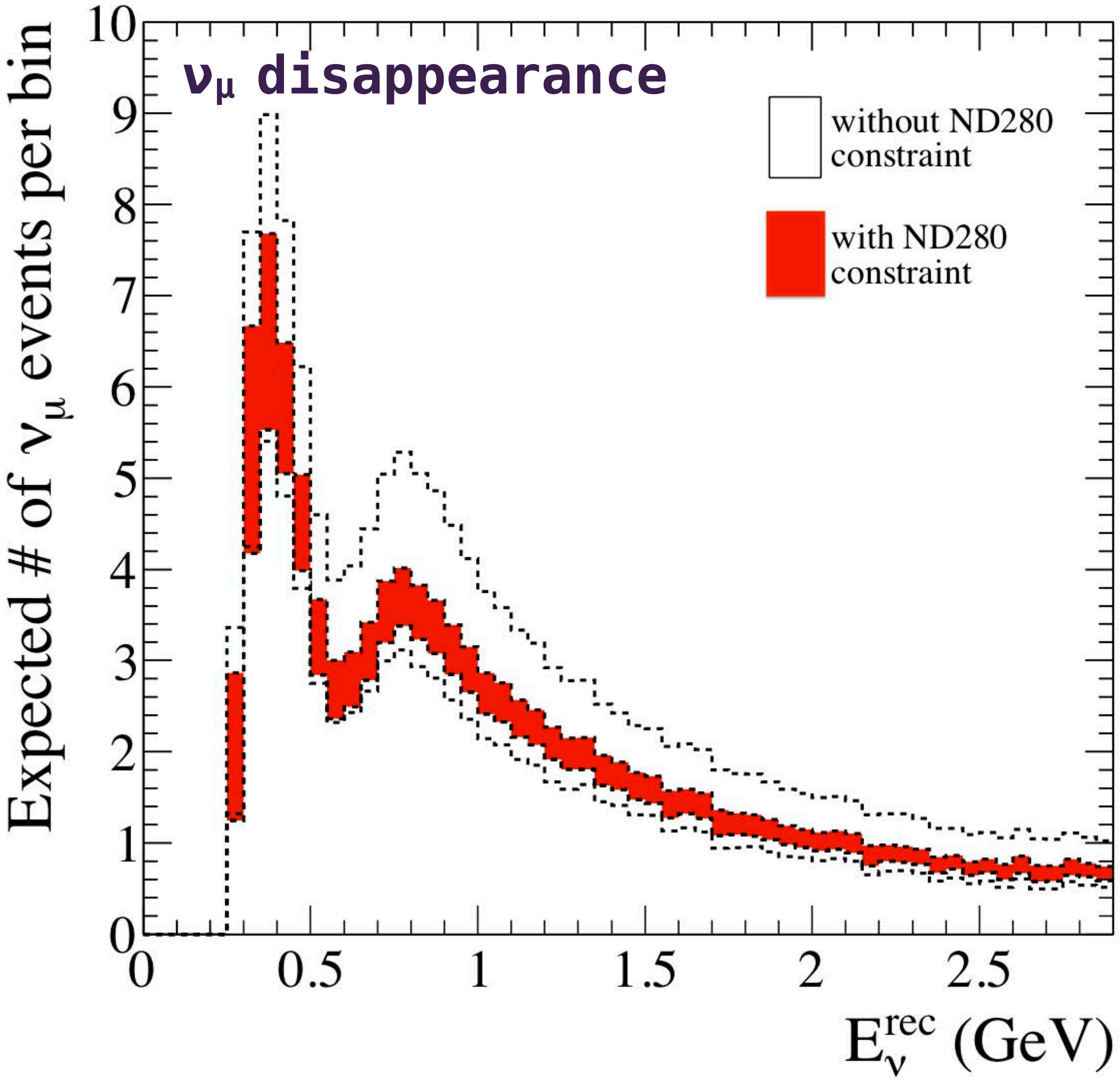
- Much lower value after fit
- Highlights:
  - power of near detector data
  - importance of CC1π-like sample

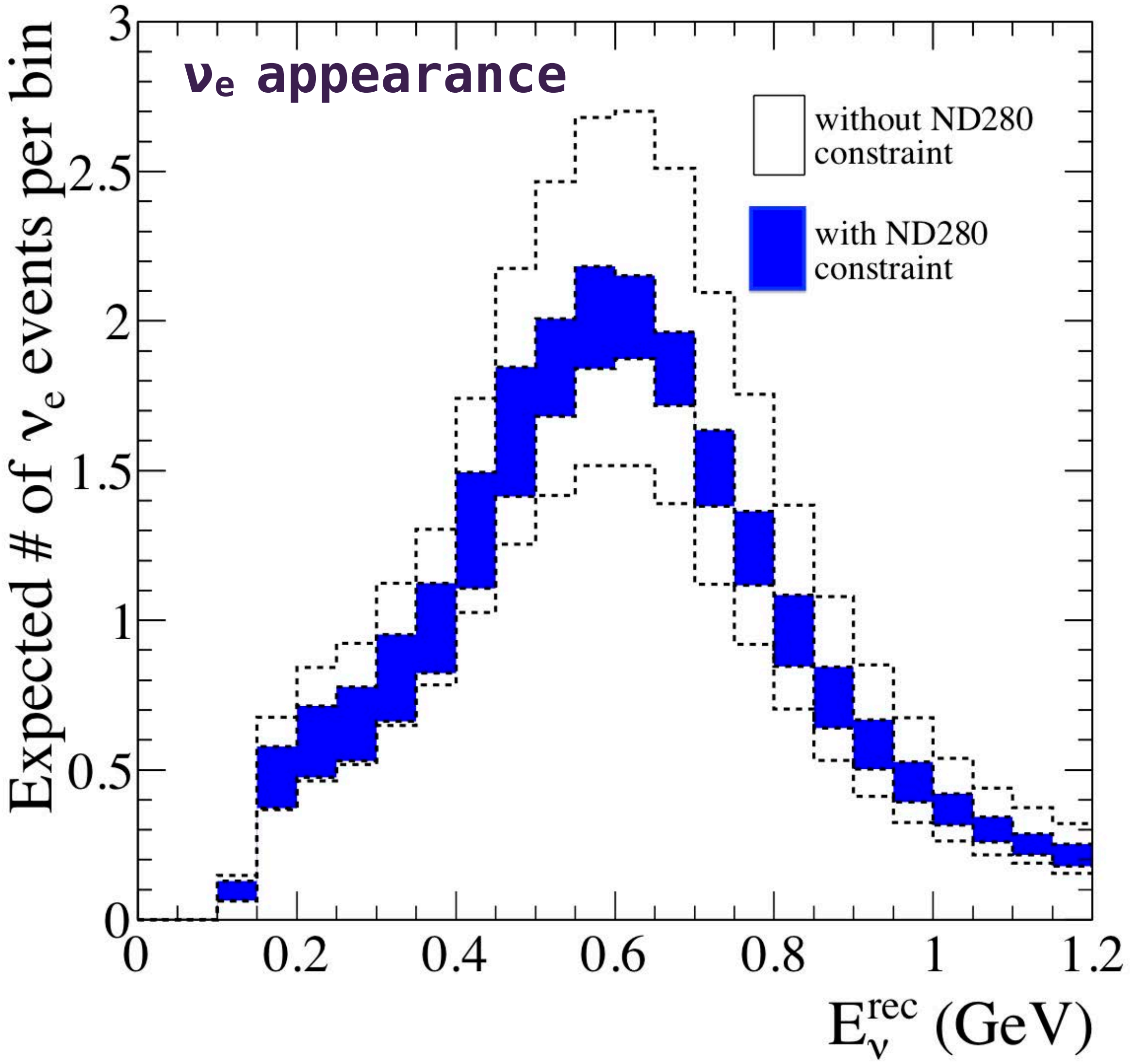


- Dip in flux parameters around 1 GeV (peak of T2K beam flux)
- Region of interest for oscillation analyses
- Incorrect prediction in this region can bias estimates of oscillation parameters

Impact of ν_μ Constraints

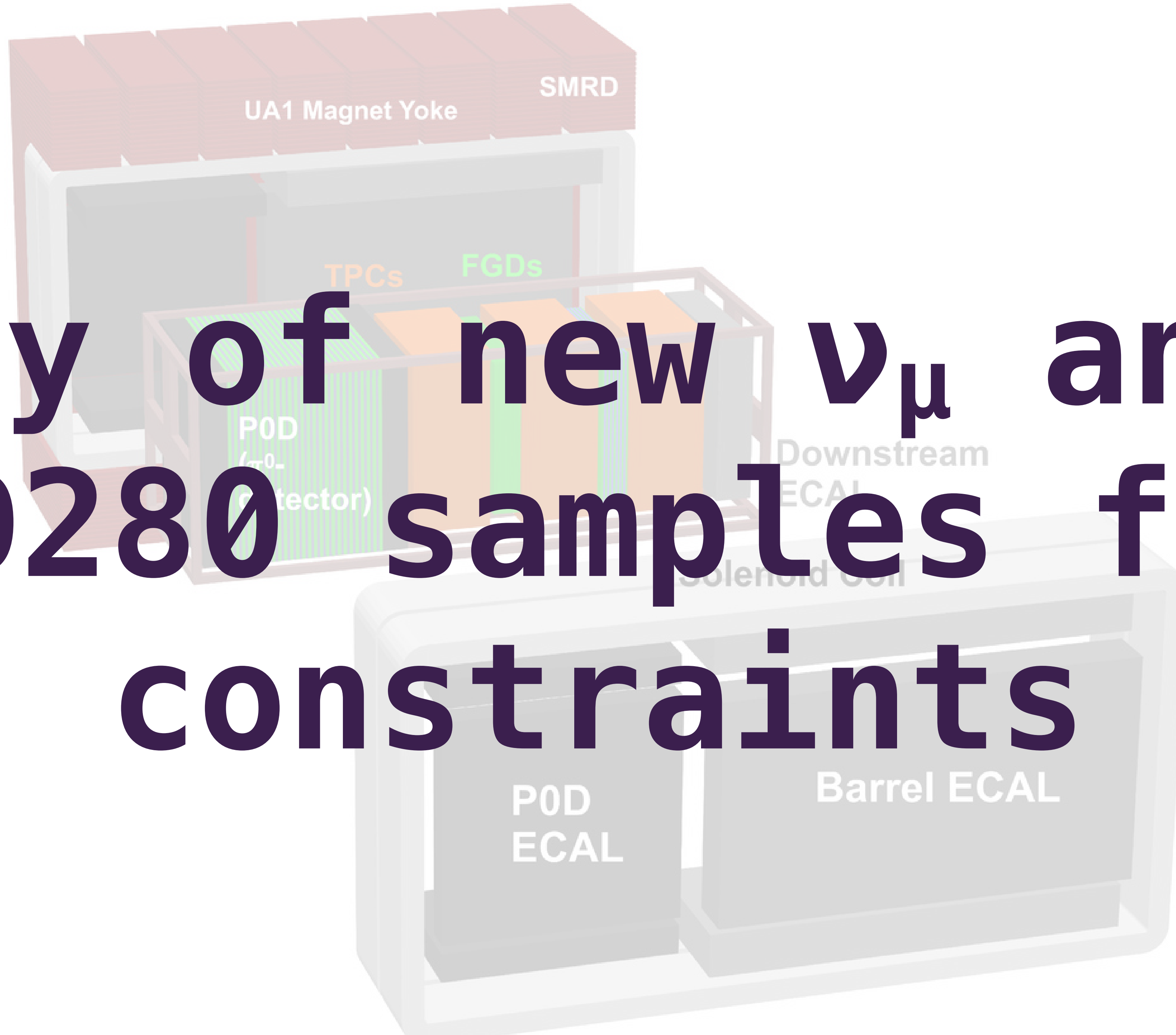
Effect of the near detector constraint on reconstructed neutrino energy at the far detector:



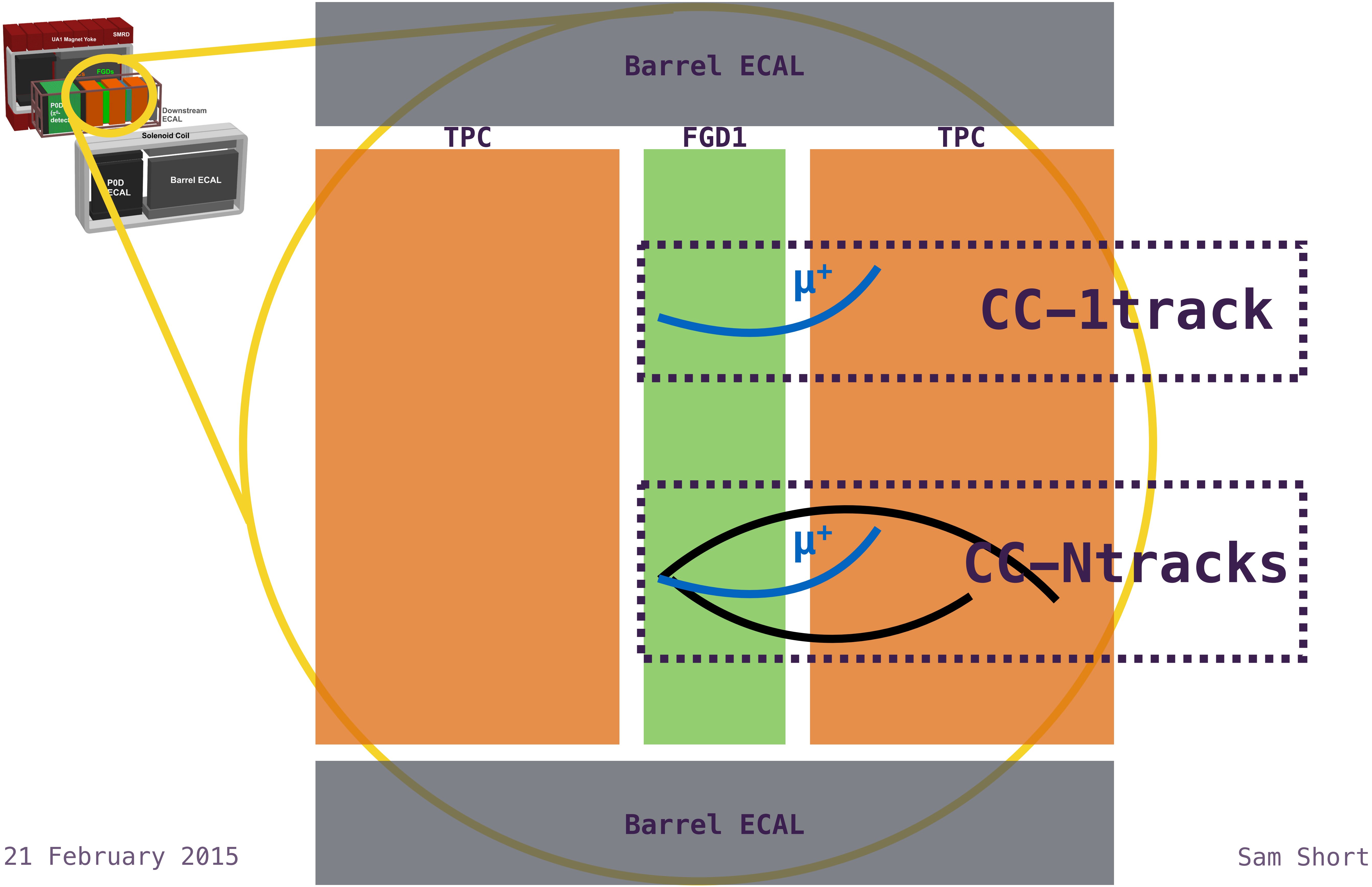


arXiv:1502.01550v1 [hep-ex]

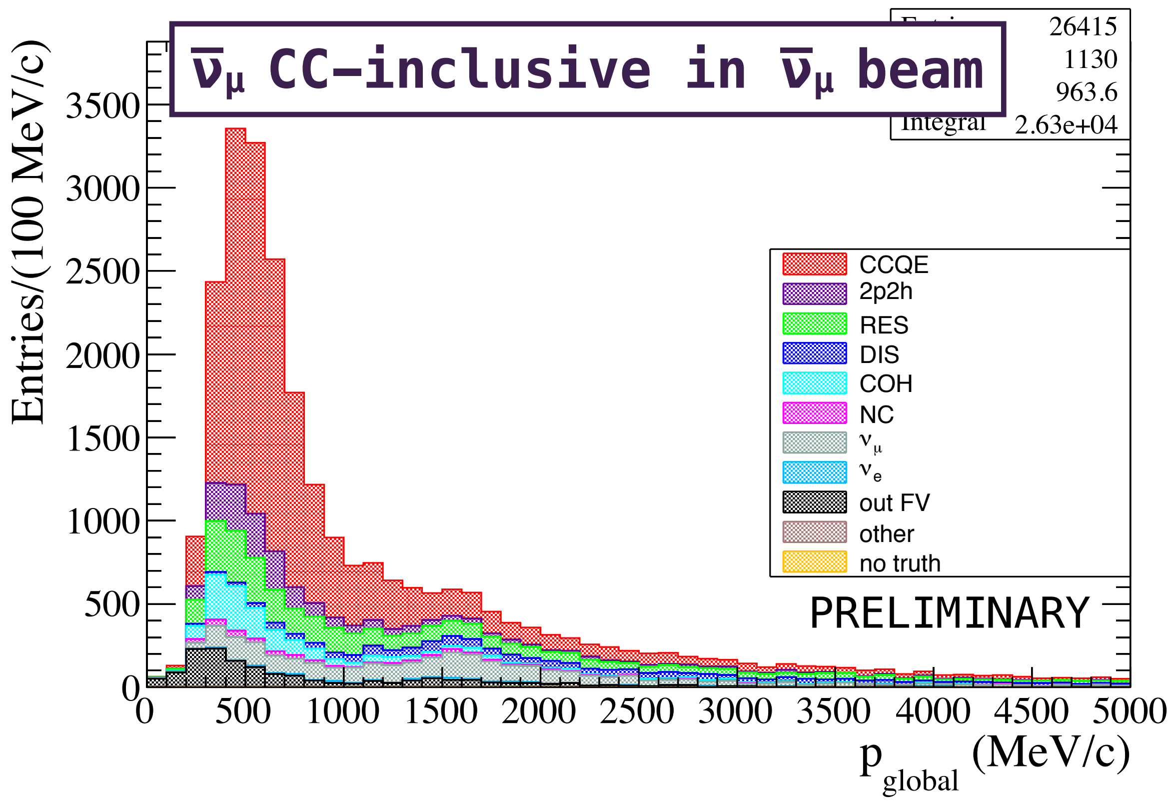
Study of new ν_μ and $\bar{\nu}_\mu$ ND280 samples for constraints



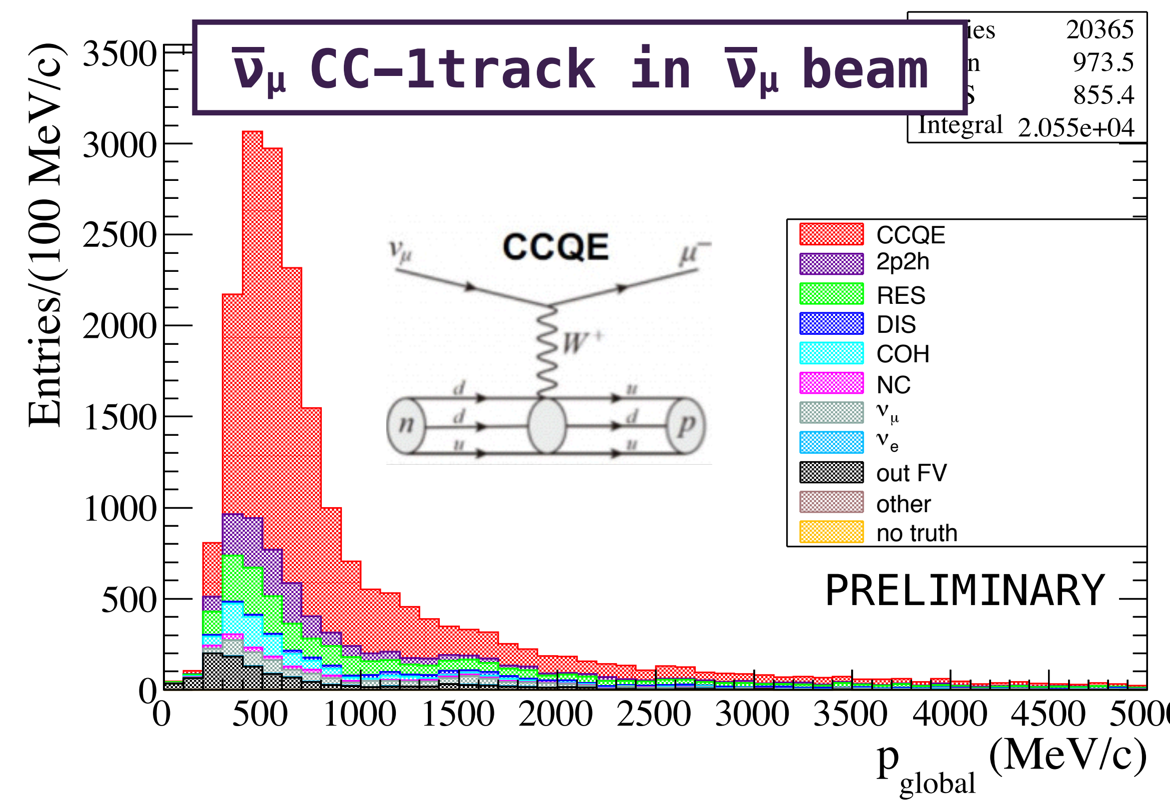
Selecting $\bar{\nu}_\mu$ interactions

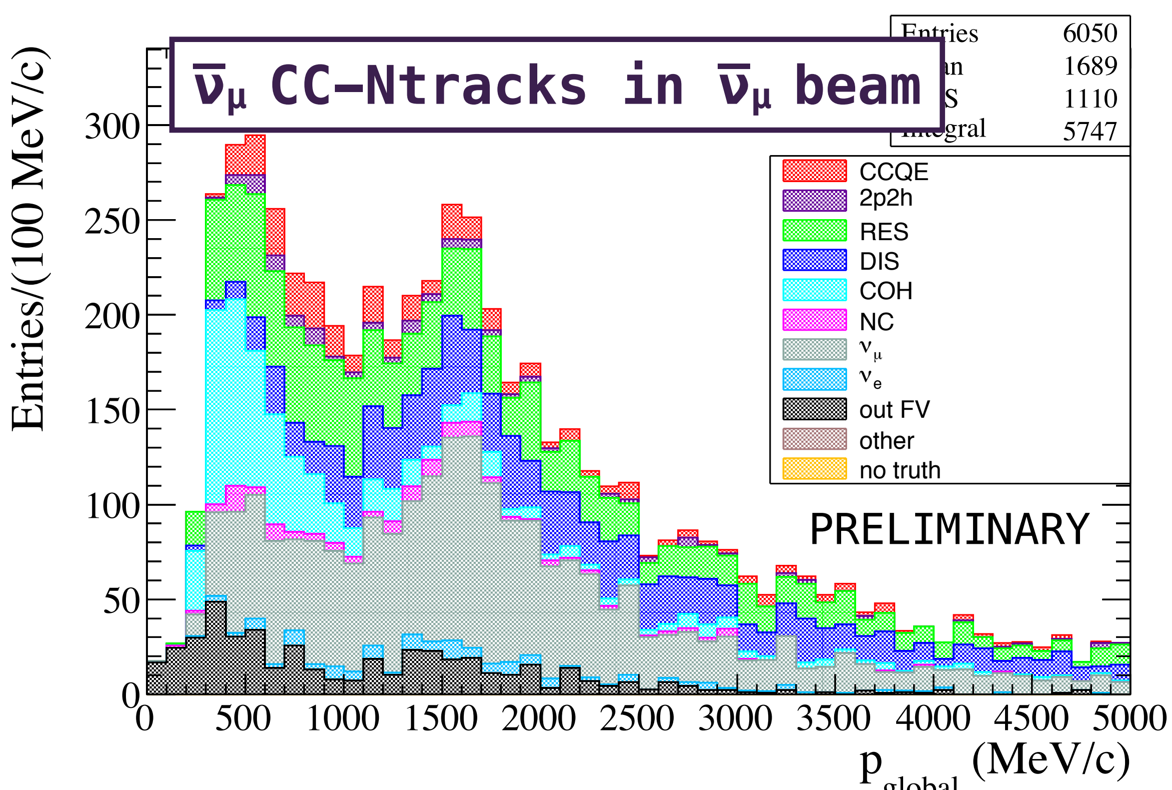


$\bar{\nu}_\mu$ Samples for Constraints



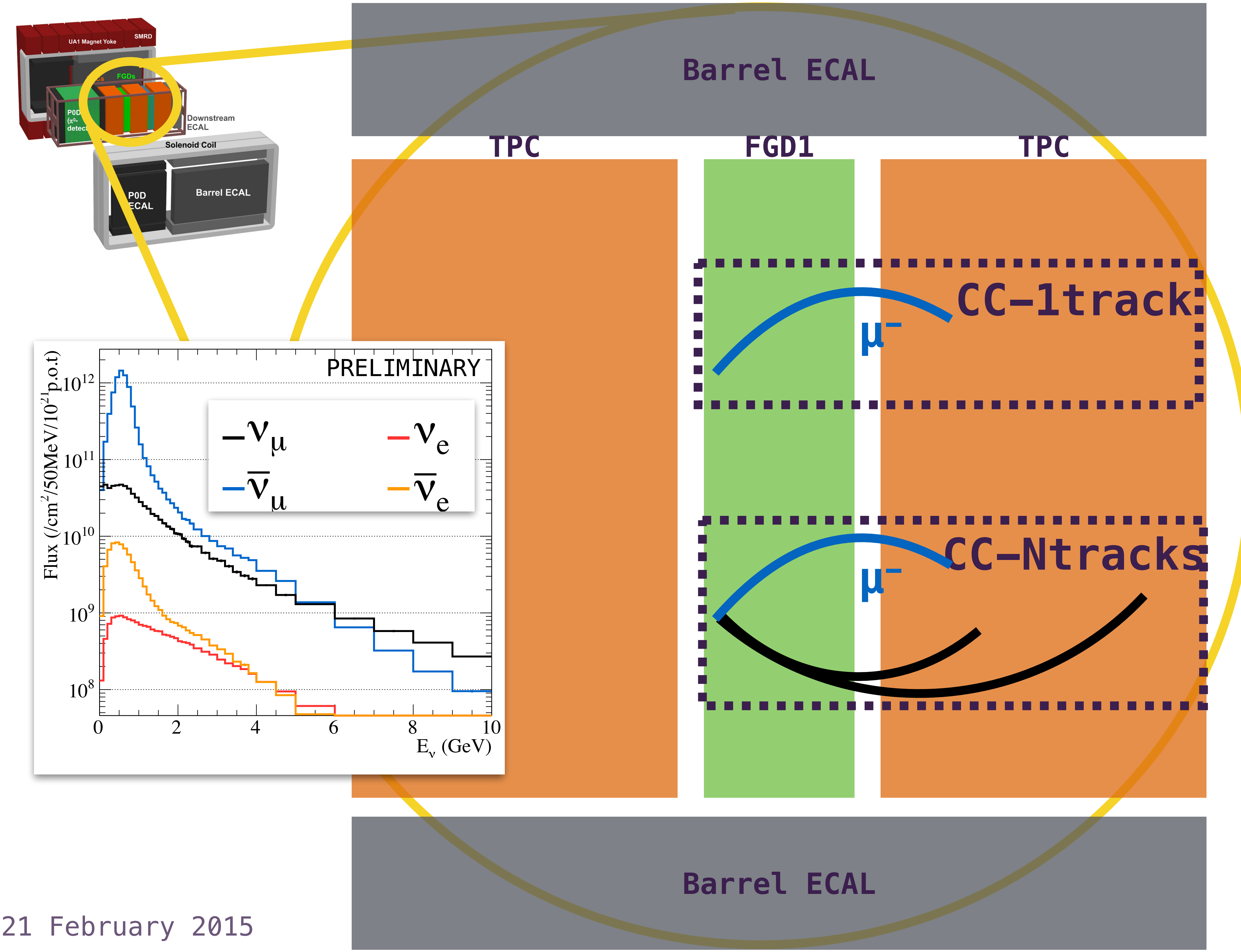
Monte Carlo studies to select $\bar{\nu}_\mu$ charged current interactions in $\bar{\nu}_\mu$ beam (broken down by true interaction type)



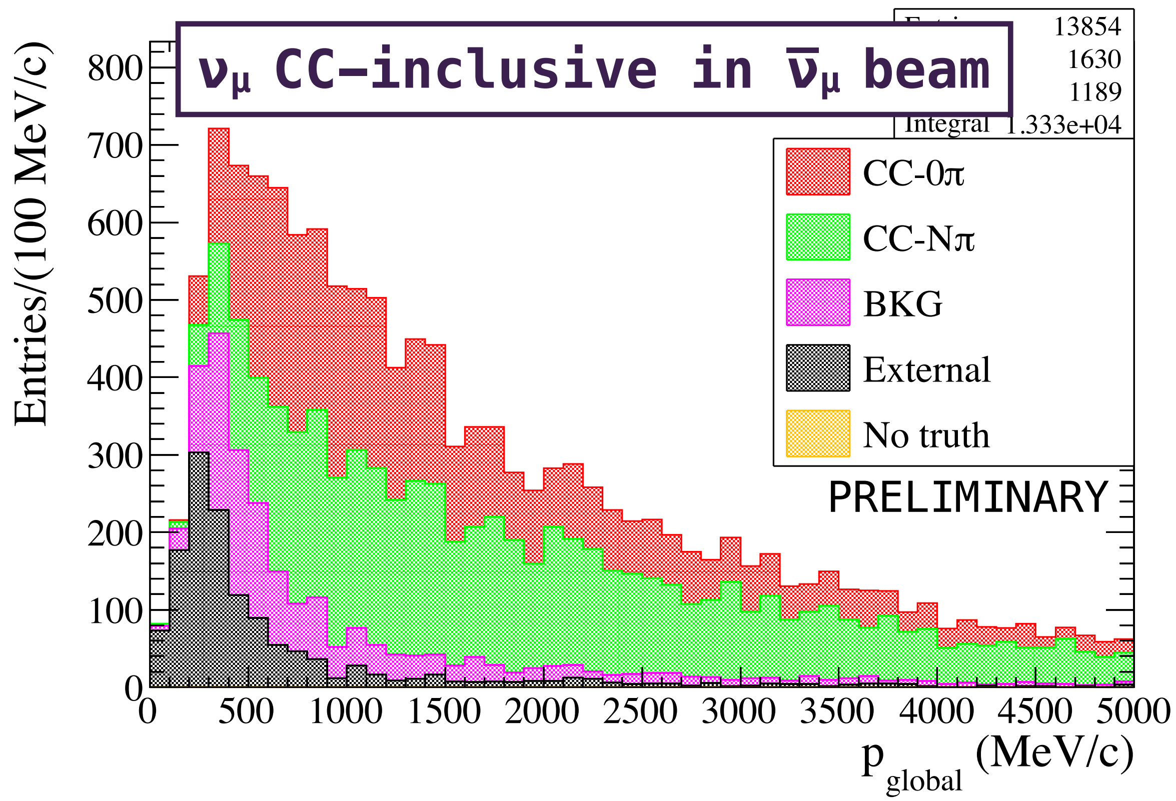


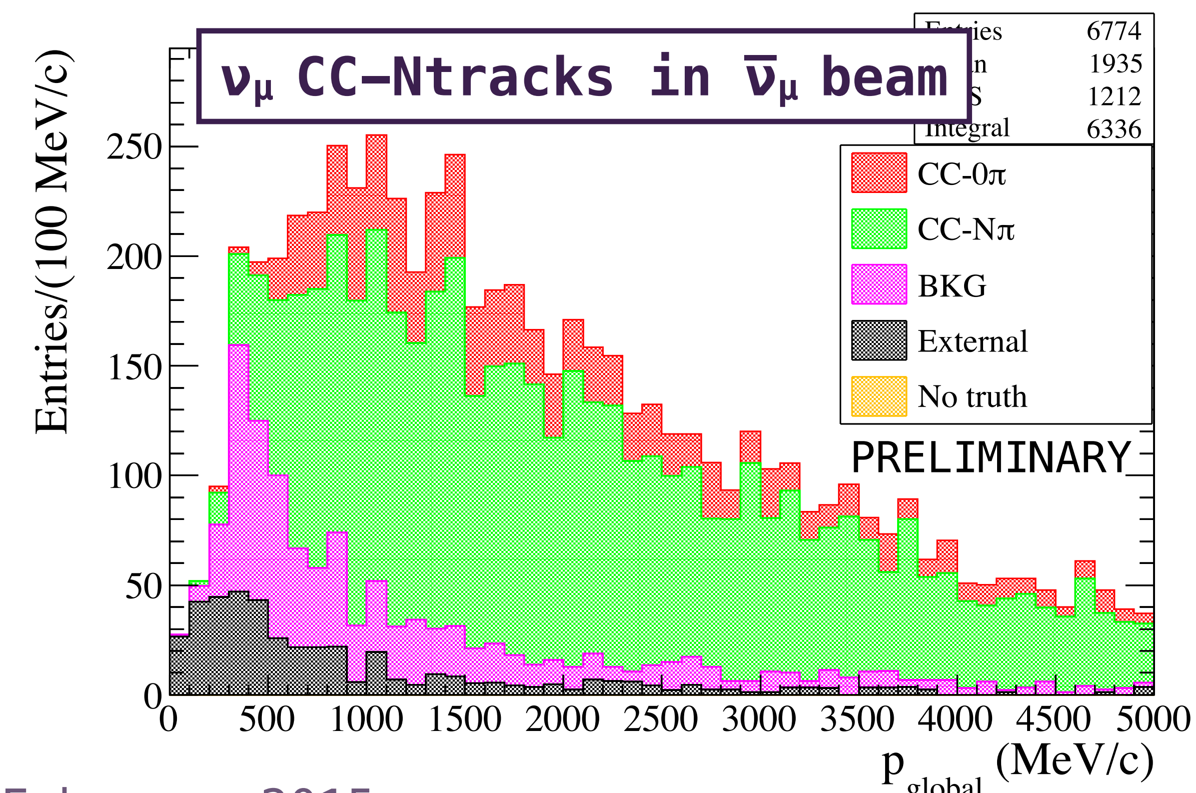
Sample	Efficiency (%)	Purity (%)
CC inclusive	66	82
CC 1track	66	73
CC Ntracks	29	47

Selecting ν_μ Component in $\bar{\nu}_\mu$ Beam

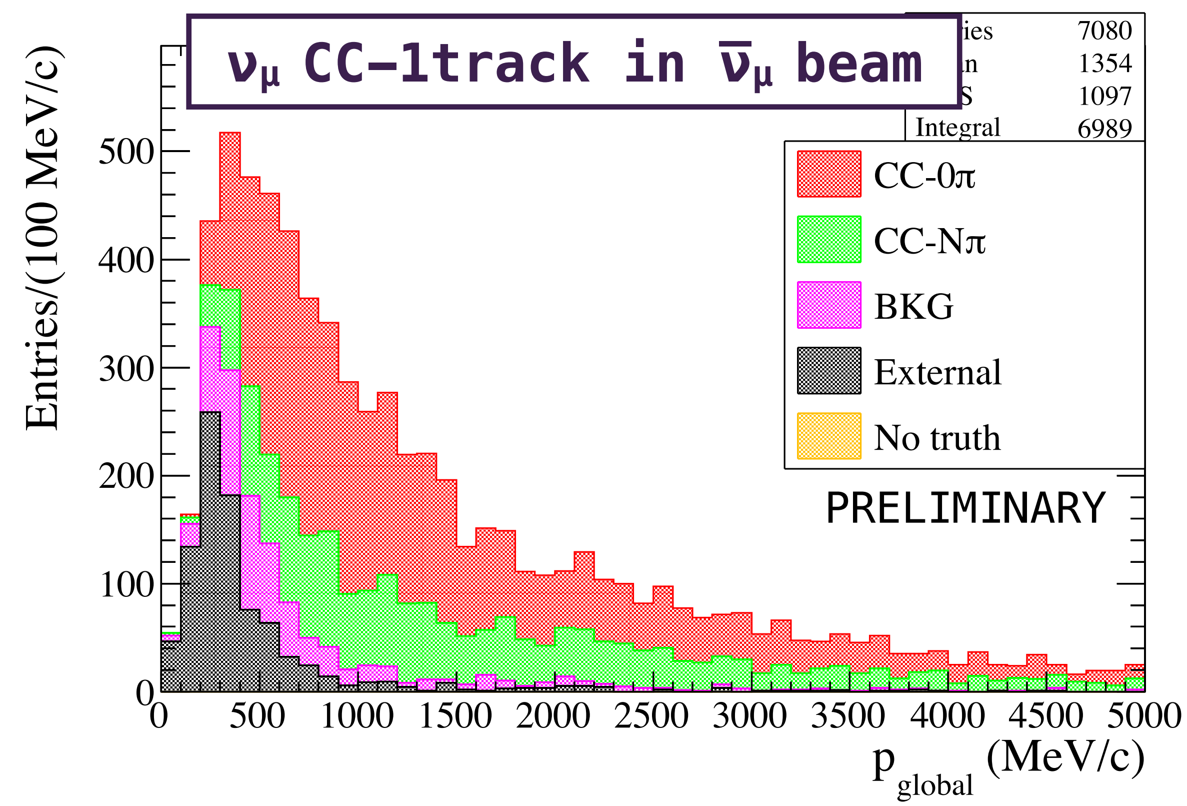


ν_μ Component in $\bar{\nu}_\mu$ Beam



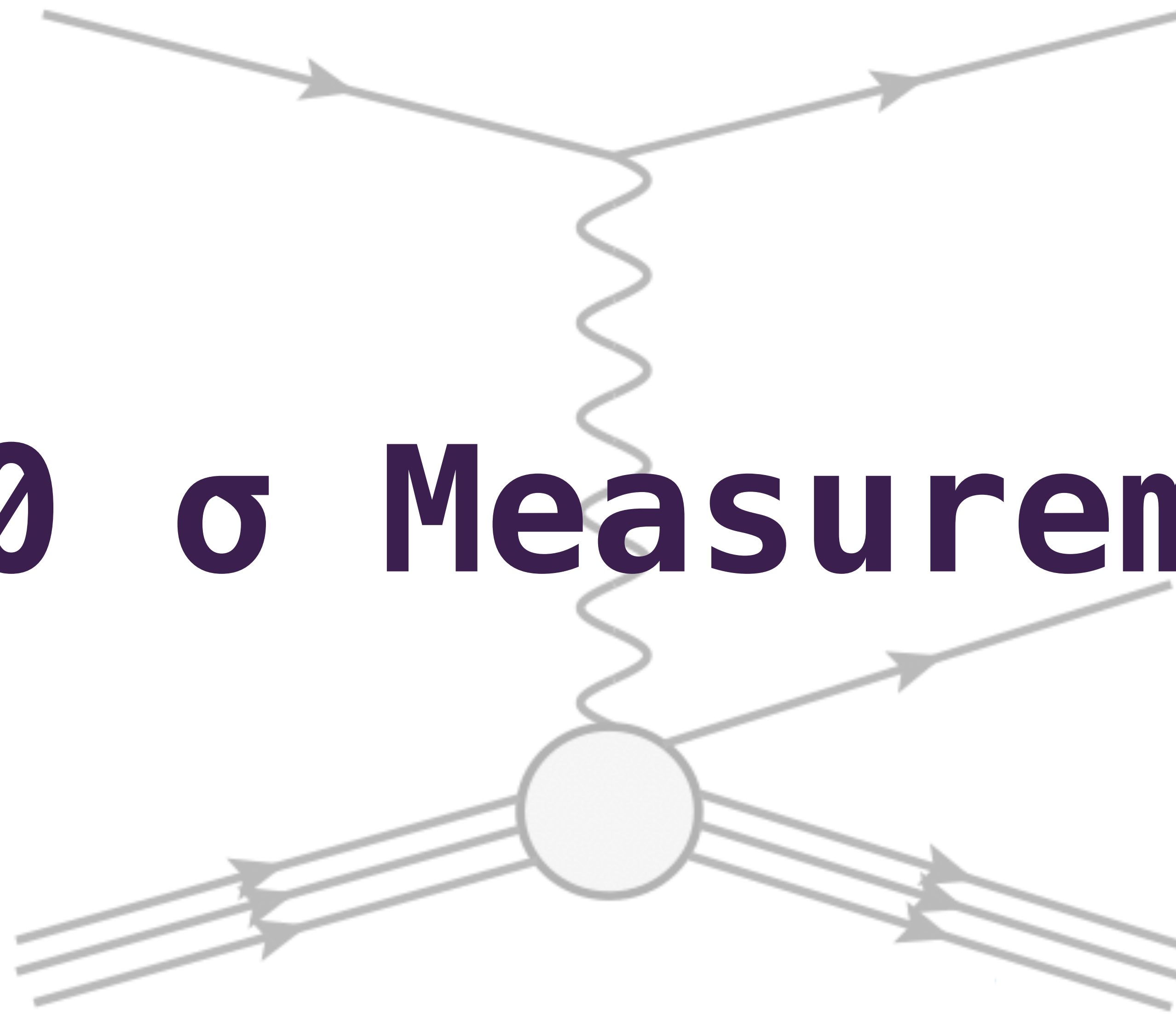


Monte Carlo studies to select ν_μ charged current interactions in $\bar{\nu}_\mu$ (broken down by particle topology leaving the nucleus)



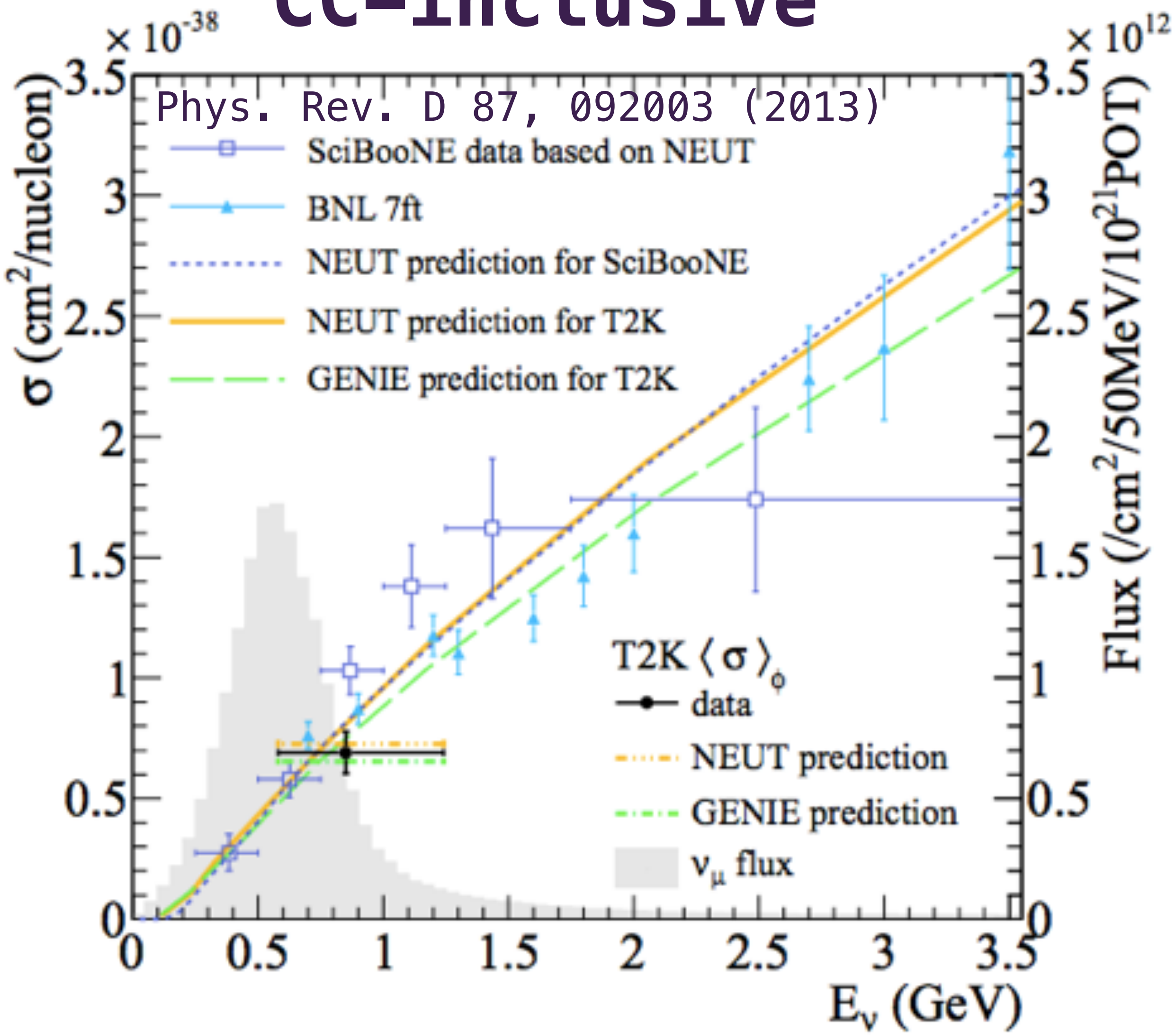
Sample	Efficiency (%)	Purity (%)
CC inclusive	55	80
CC 1track	46	51
CC Ntracks	40	66

ND280 σ Measurements



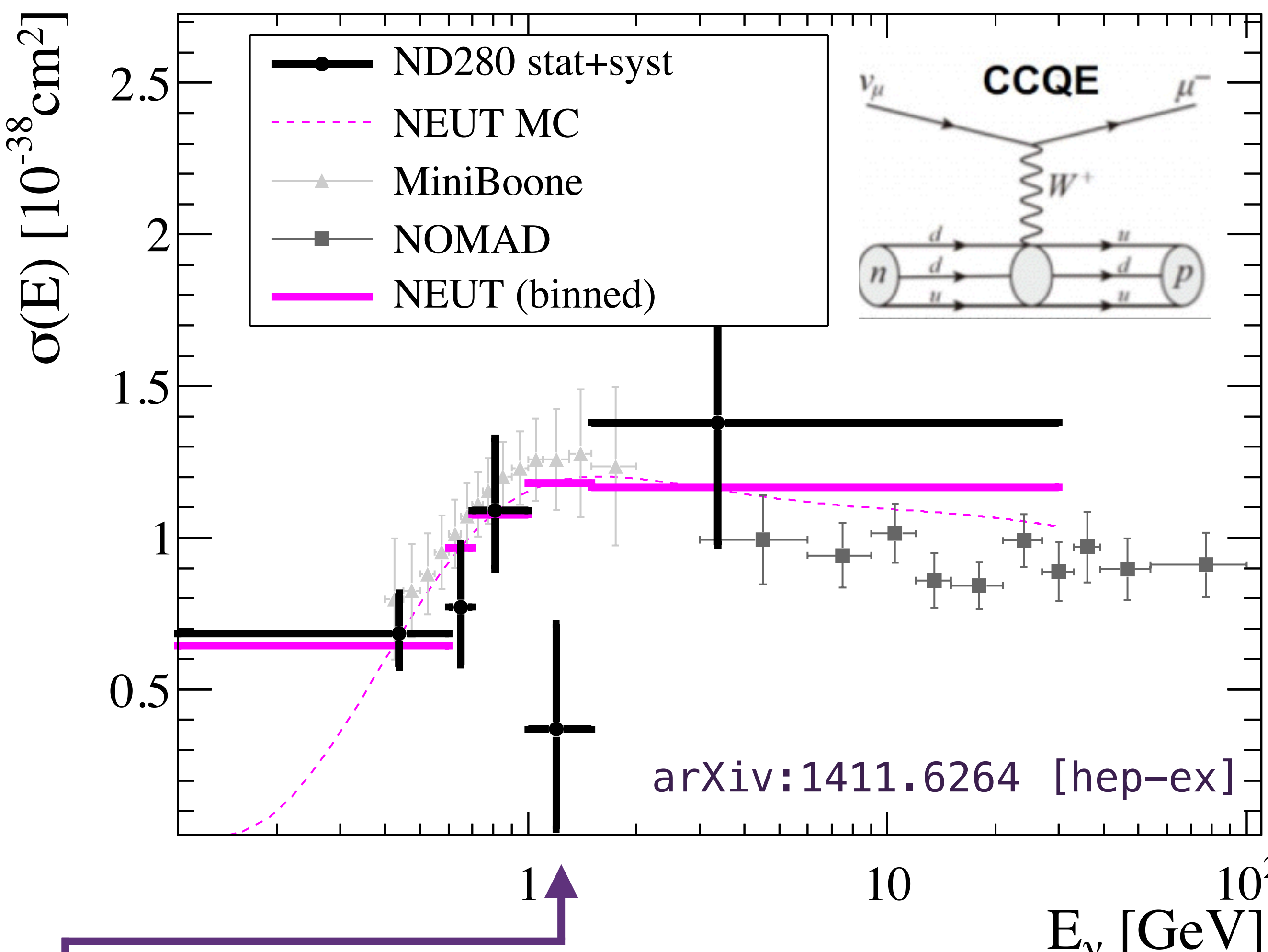
ν_μ σ on Carbon

CC-inclusive



Total flux averaged cross-section:
$\langle\sigma\rangle_\phi = 6.91 \pm 0.13(\text{stat}) \pm 0.84(\text{syst}) \times 10^{-39}\ \text{cm}^2/\text{nucleon}$

CCQE



Flux-integrated CCQE cross section:
$\langle\sigma\rangle = (0.83 \pm 0.12) \times 10^{-38}\ \text{cm}^2$

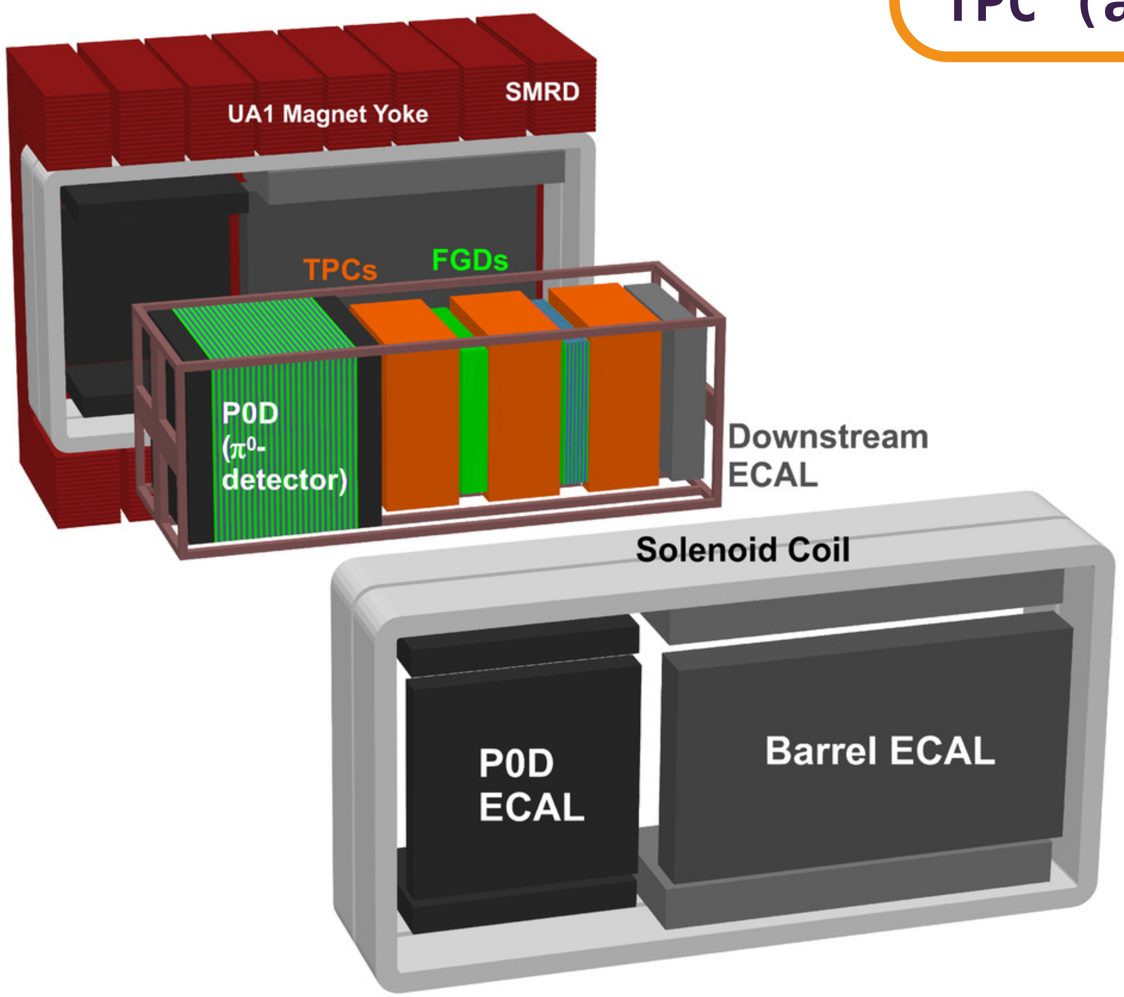
- 2.3σ data/MC discrepancy
- χ^2 test: p-value of 17%
  - agreement between data and σ model

Future ND280 ν_μ σ Measurements

(a selection)

FGD1 (carbon)
ν CC−inclusive
ν CC−0π
ν CC−1π⁺
ν̄ CC−inclusive

TPC (argon)



FGD2 (water)
ν CC−inclusive
ν CC−1π⁺
ν̄ CC−inclusive

P0D (water)
NC−elastic
NC−1π⁰
ν̄ CC−inclusive

ECAL (Pb)
ν CC−inclusive

Summary

- An exciting time for the T2K experiment
- Using many different samples (ν_μ and $\bar{\nu}_\mu$) to reduce the flux and cross-section uncertainties for the T2K oscillation analyses
  (for specifics stick around for Kikawa-san's talk up next)
- Many different cross-section measurements to be published in the near future

Thanks for listening

Supplementary Slides

Non-Zero θ_{13}

- Prior to 2011 limit set by CHOOZ:
  $\sin^2 2\theta_{13} < 0.17$

- Two ways of measuring θ_{13}:

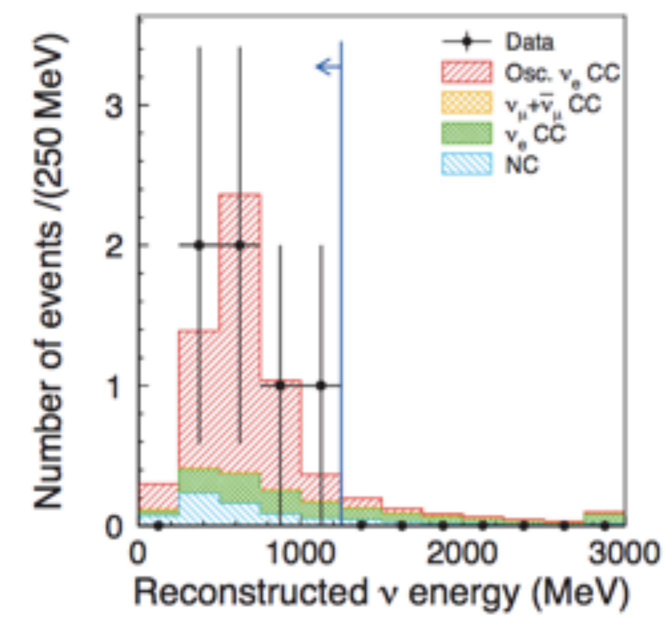
$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{31}^2}{4E} L\right)$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2}{4E} L\right)$$

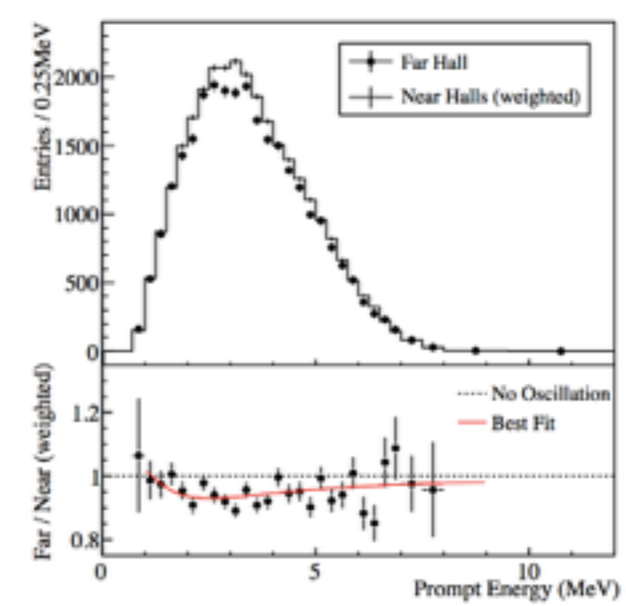
- June 2011: T2K announce an indication of non-zero θ_{13}
  (6 events, 2.5σ)

- In 2012:
  Daya Bay and RENO confirm with over 5σ

T2K 2011



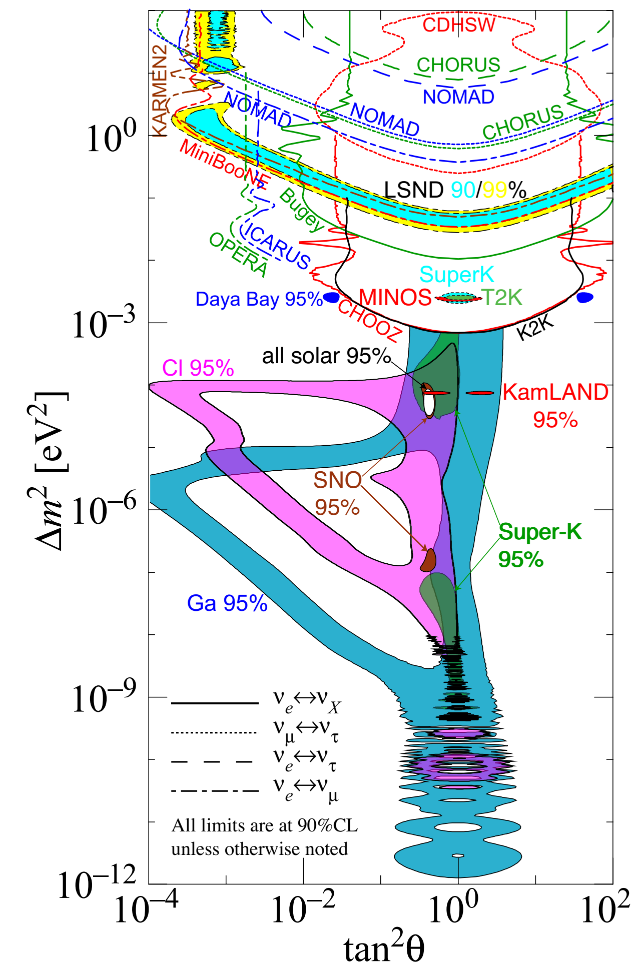
Daya Bay 2012



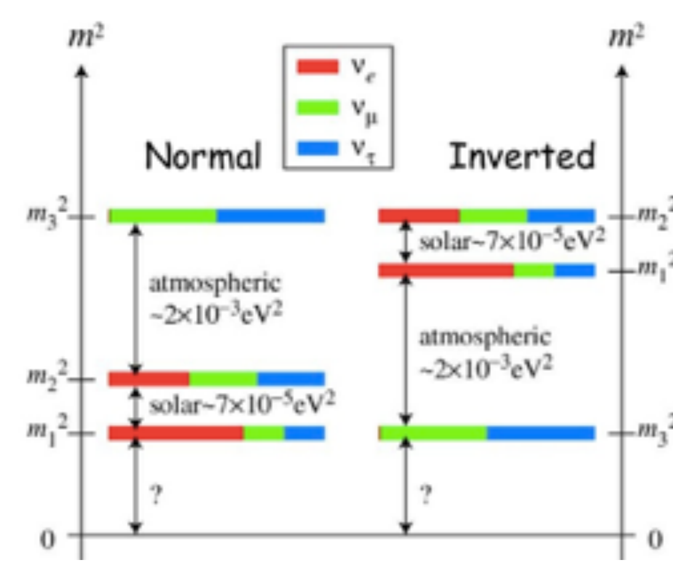
Things We'd Like To Know…

(a non-exhaustive list!)

- Parameters governing neutrino oscillations?
  θ_{12}~34°, θ_{23}~45°, θ_{13}~9°,
  Δm^2_{12}~7.6x10−5 eV^2, $|\Delta m^2_{23}|$~2.4x10−3 eV^2
- CP-violating parameter δ?
- Neutrino mass hierarchy: normal or inverted?
- Sterile neutrinos?



http://hitoshi.berkeley.edu/neutrino



T$_{\text{okai}}$2K$_{\text{amioka}}$ Collaboration

~500 members, 59 institutes, 11 countries

Canada
TRIUMF
U. Alberta
UBC
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN U. Bari
INFN U. Napoli
INFN U. Padova
INFN U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavali IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Met. U.
U. Tokyo

Poland
IFJ Pan Cracow
NCBJ Warsaw
U. Silesia Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

Spain
IFAE Barcelona
IFIC Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial
Lancaster U.
Oxford U.
QMUL
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

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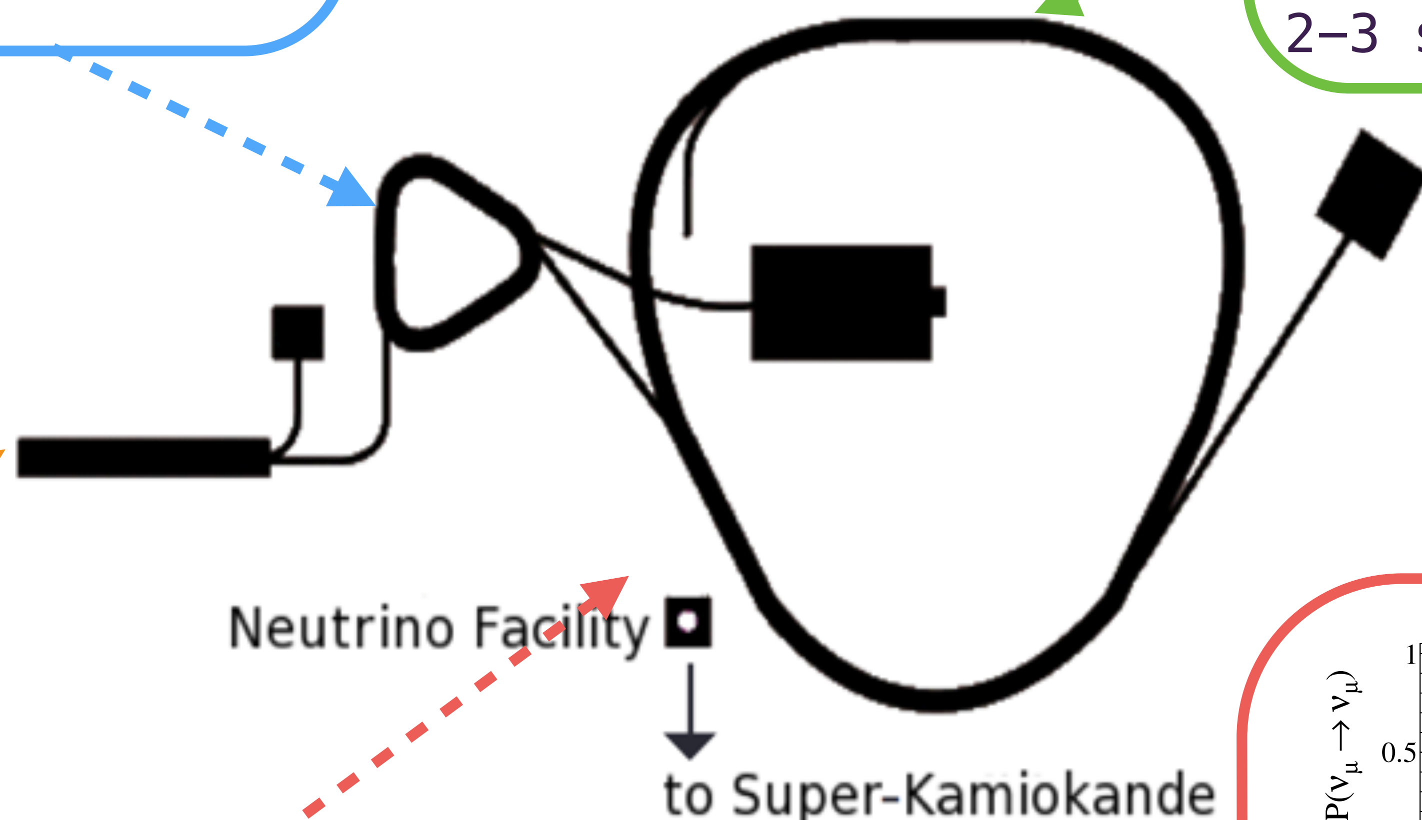
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburg
U. Rochester
U. Washington

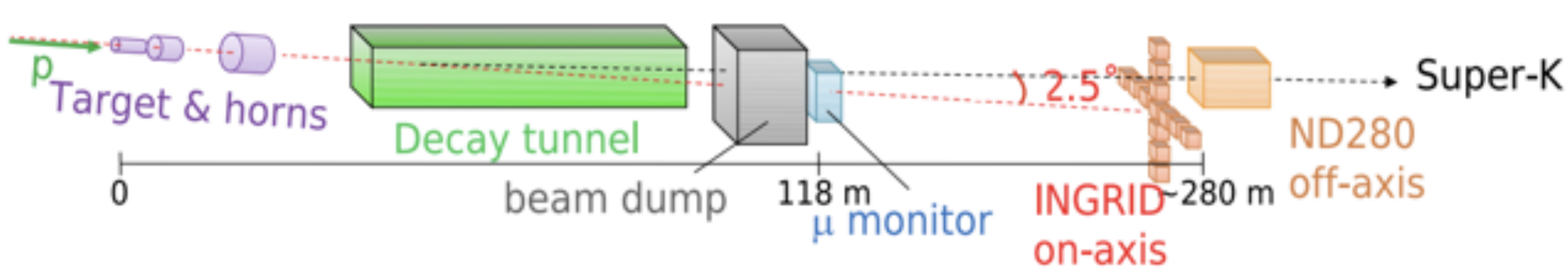
T2K Beamline

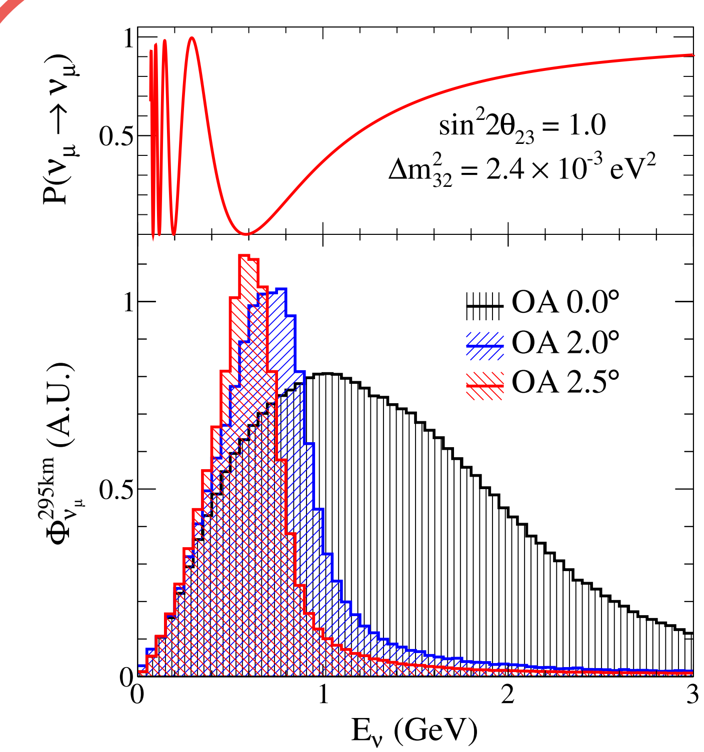
Rapid Cycling Synchrotron:
Accelerate H+ ions to 3 GeV

Main Ring Synchrotron:
30 GeV protons every 2–3 seconds

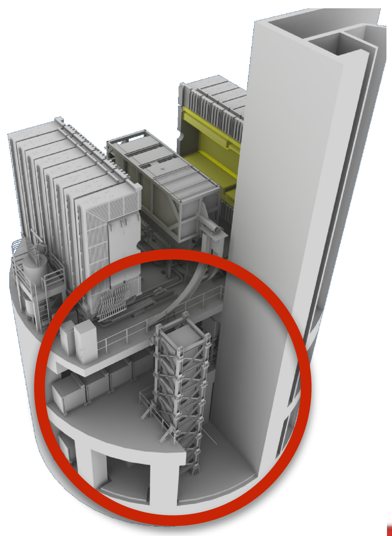
LINAC:
Accelerate H– ions to energy of 400 MeV

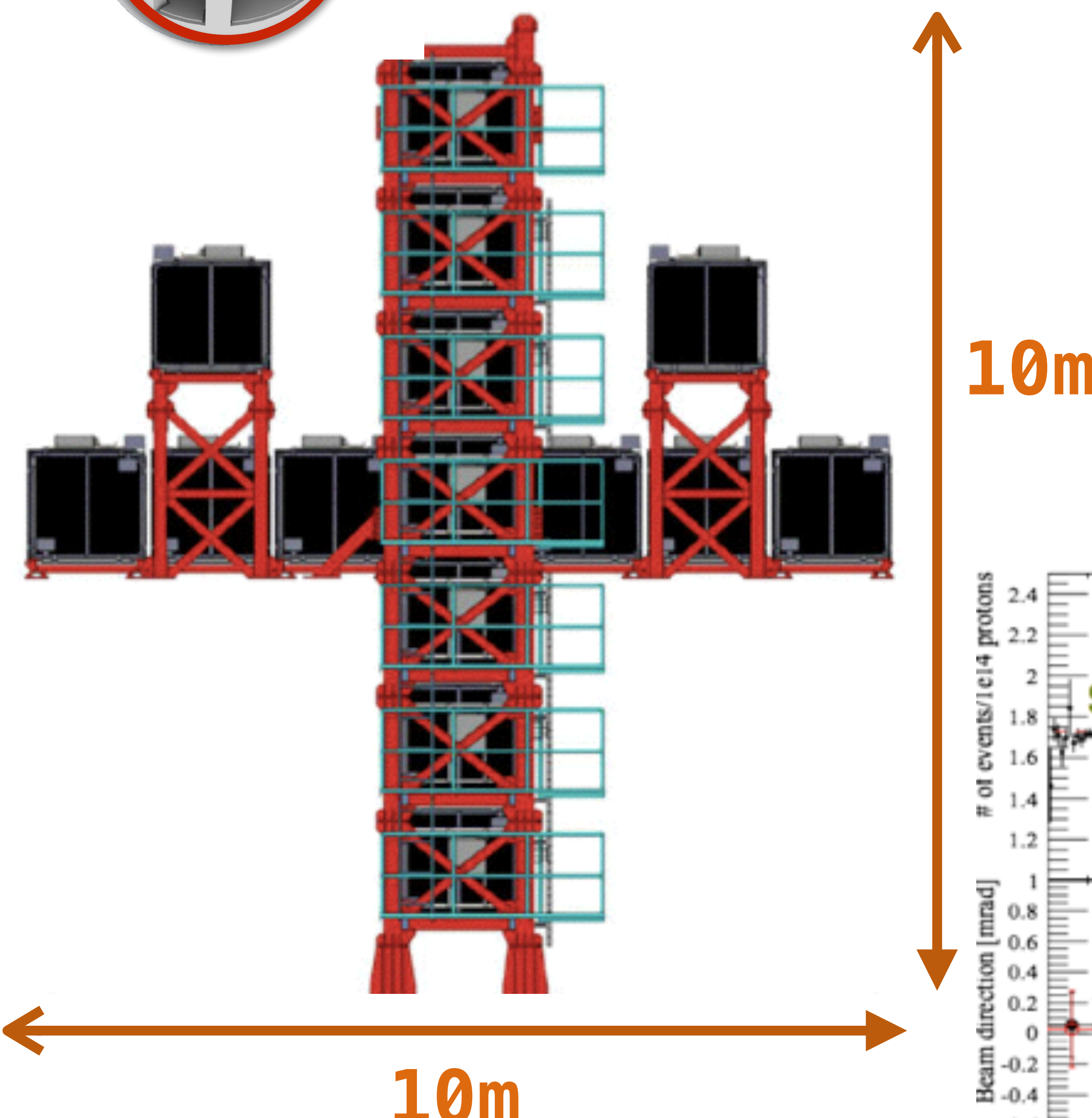






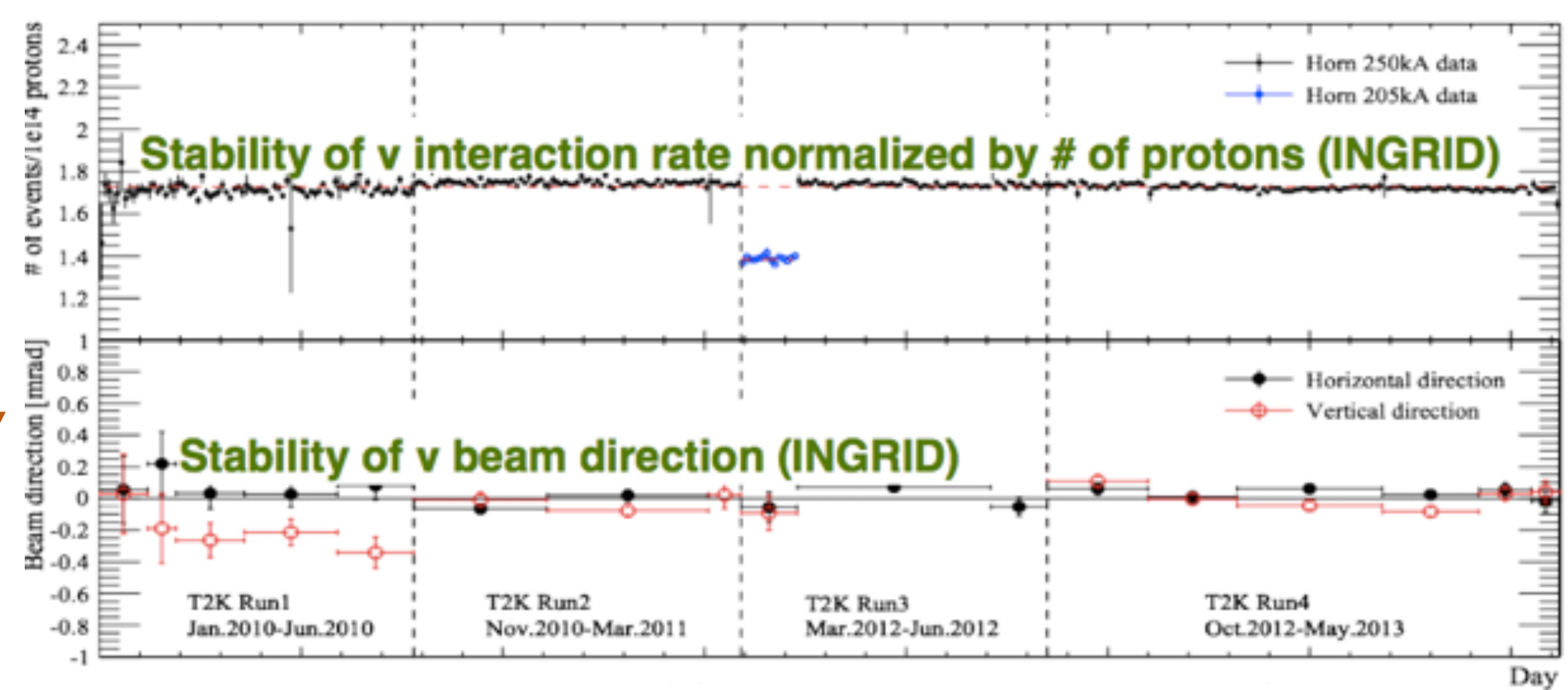
On-Axis Near Detector: INGRID





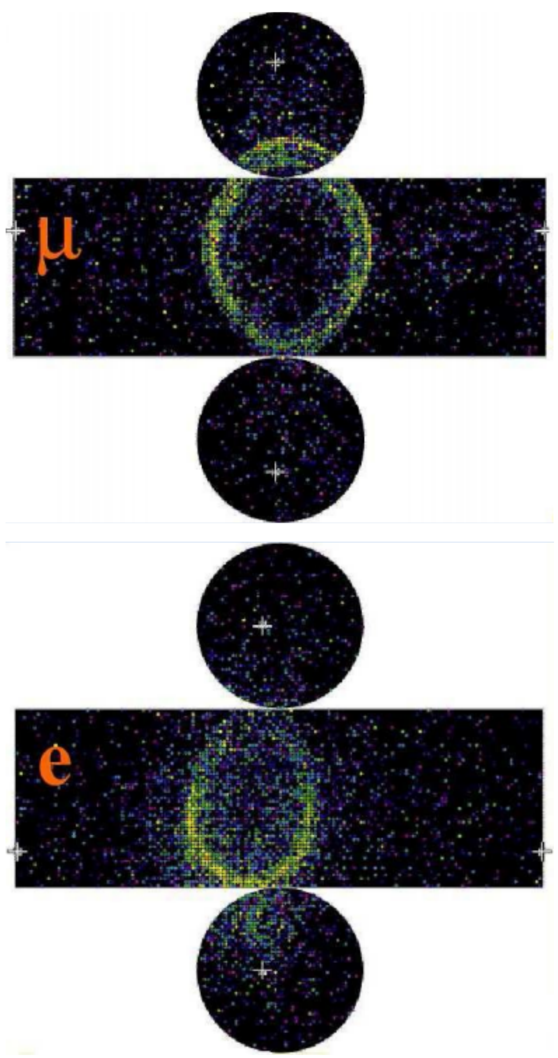
Interactive Neutrino GRID:

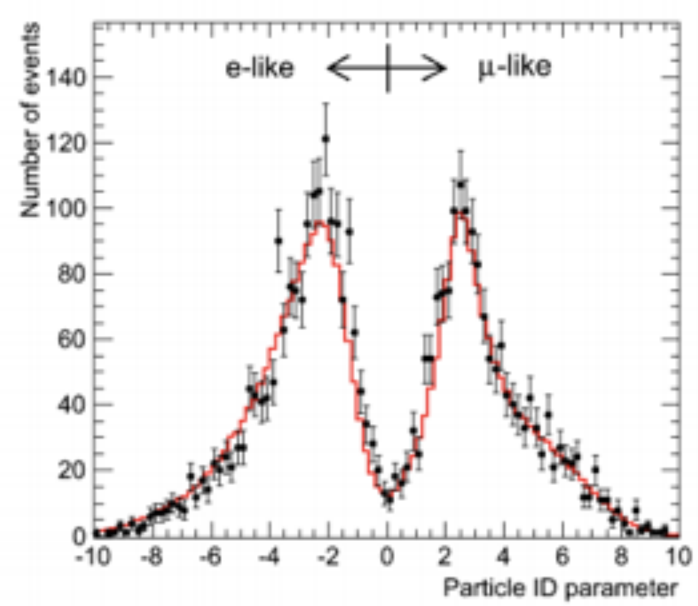
- 280m from target on beam axis
- 16 iron/scintillator module
- 1 scintillator tracking module
- Monitors beam centre, profile and neutrino flux

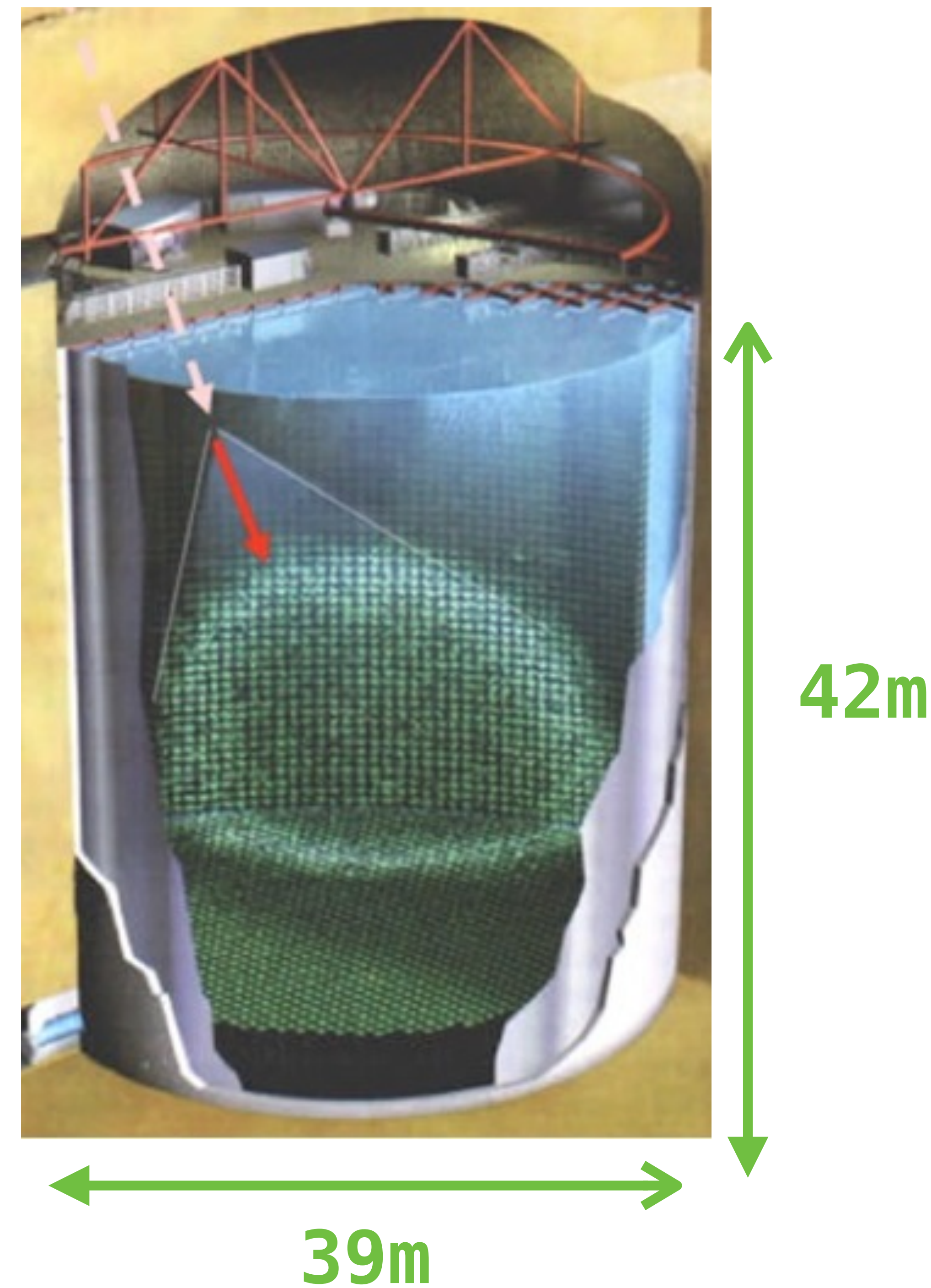


Far Detector: Super–K

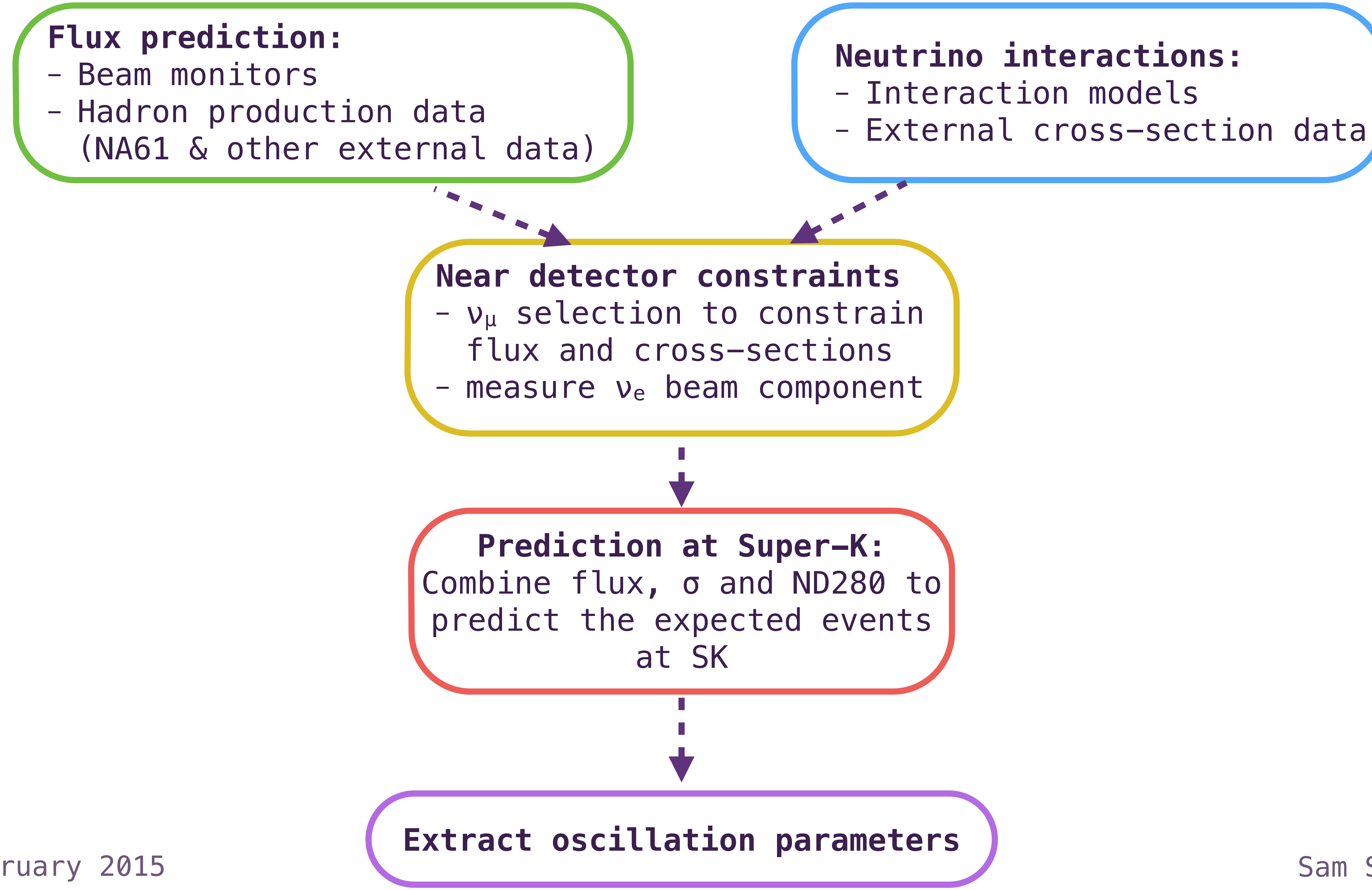
- 50kton water Cherenkov detector (22.5 kton fiducial volume)
- Inner detector: ~11,000 20inch PMTs
- Outer detector: ~2,000 8inch PMTs





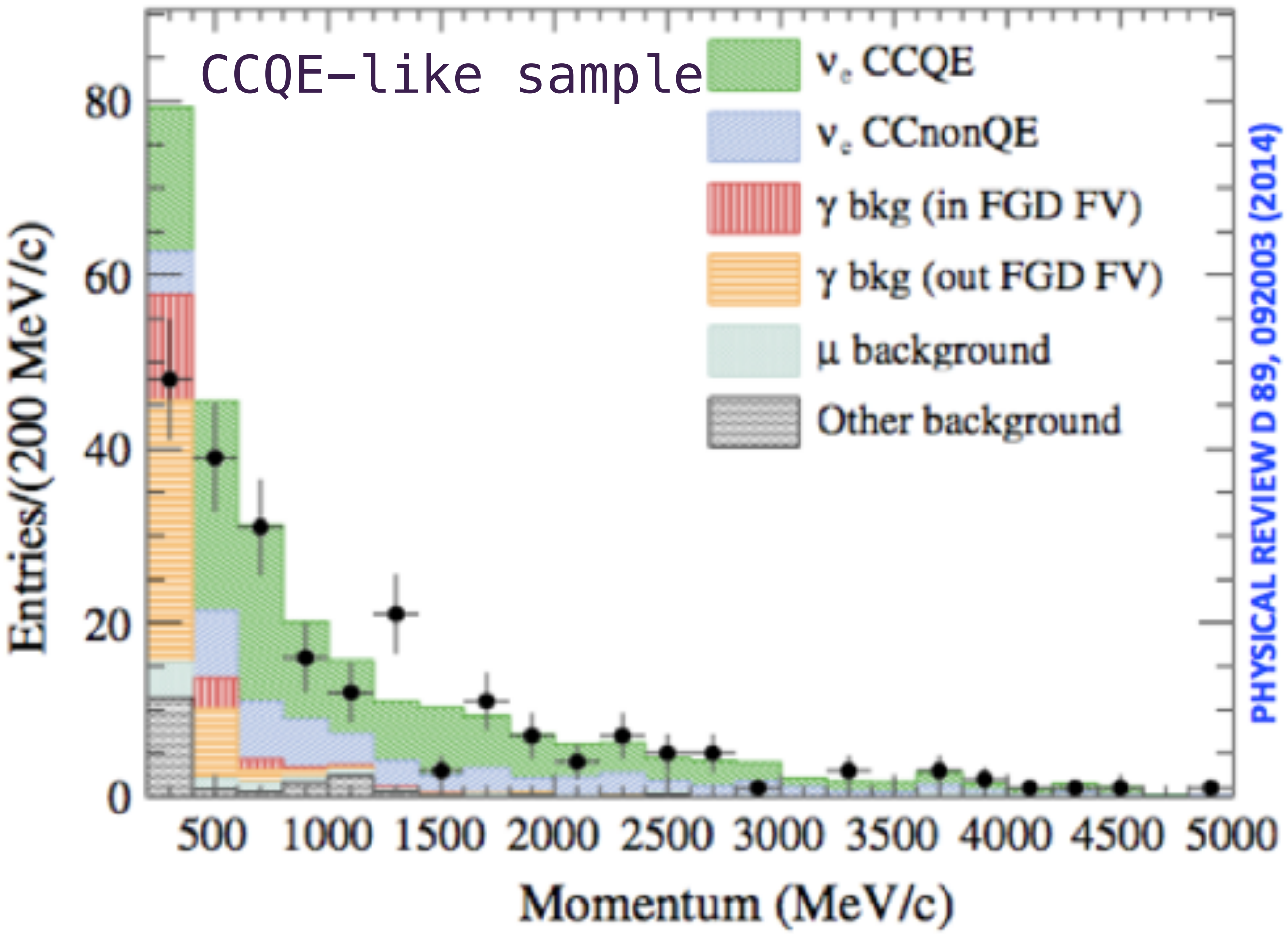


Oscillation Analysis Strategy



ν_e Near Detector Constraints

- Measure intrinsic ν_e component of the beam
- Important background to ν_e appearance
- **Expect:** 1.2% contamination of ν_e (from MC)
- **Measure:** $N\nu_e(\text{data}) / N\nu_e(\text{MC}) = 1.01 \pm 0.10$



Impact of ν_μ Constraints

ν_μ disappearance

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

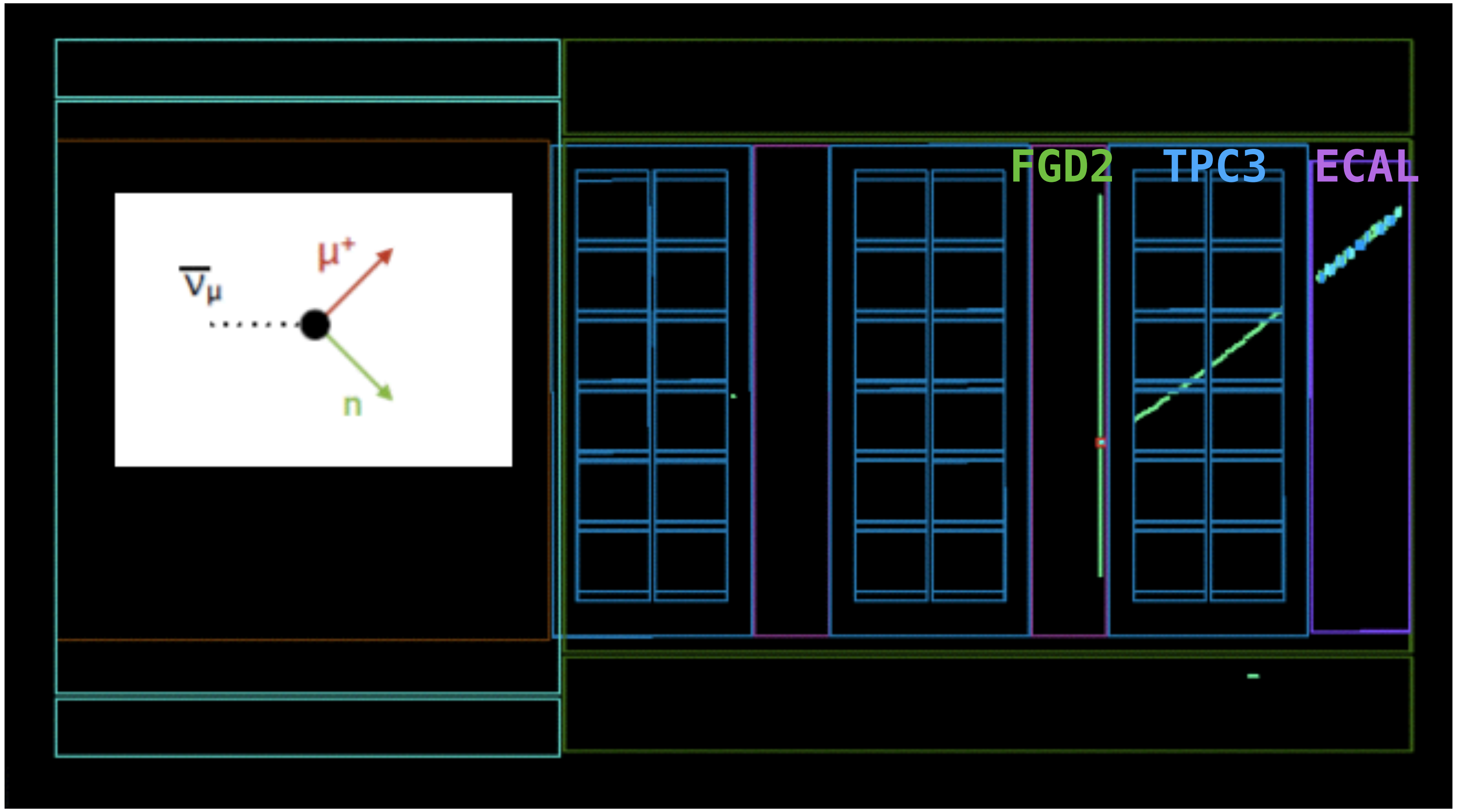
ν_e appearance

Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm.*	1.00 ± 0.11	0.966 ± 0.076
CC1π Norm.**	1.15 ± 0.32	1.26 ± 0.16
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

*For E_ν<1.5 GeV **For E_ν<2.5 GeV

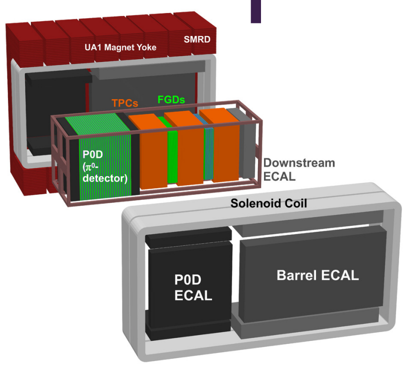
Antineutrino Event @ ND280

Interaction in FGD2 producing a +ve muon

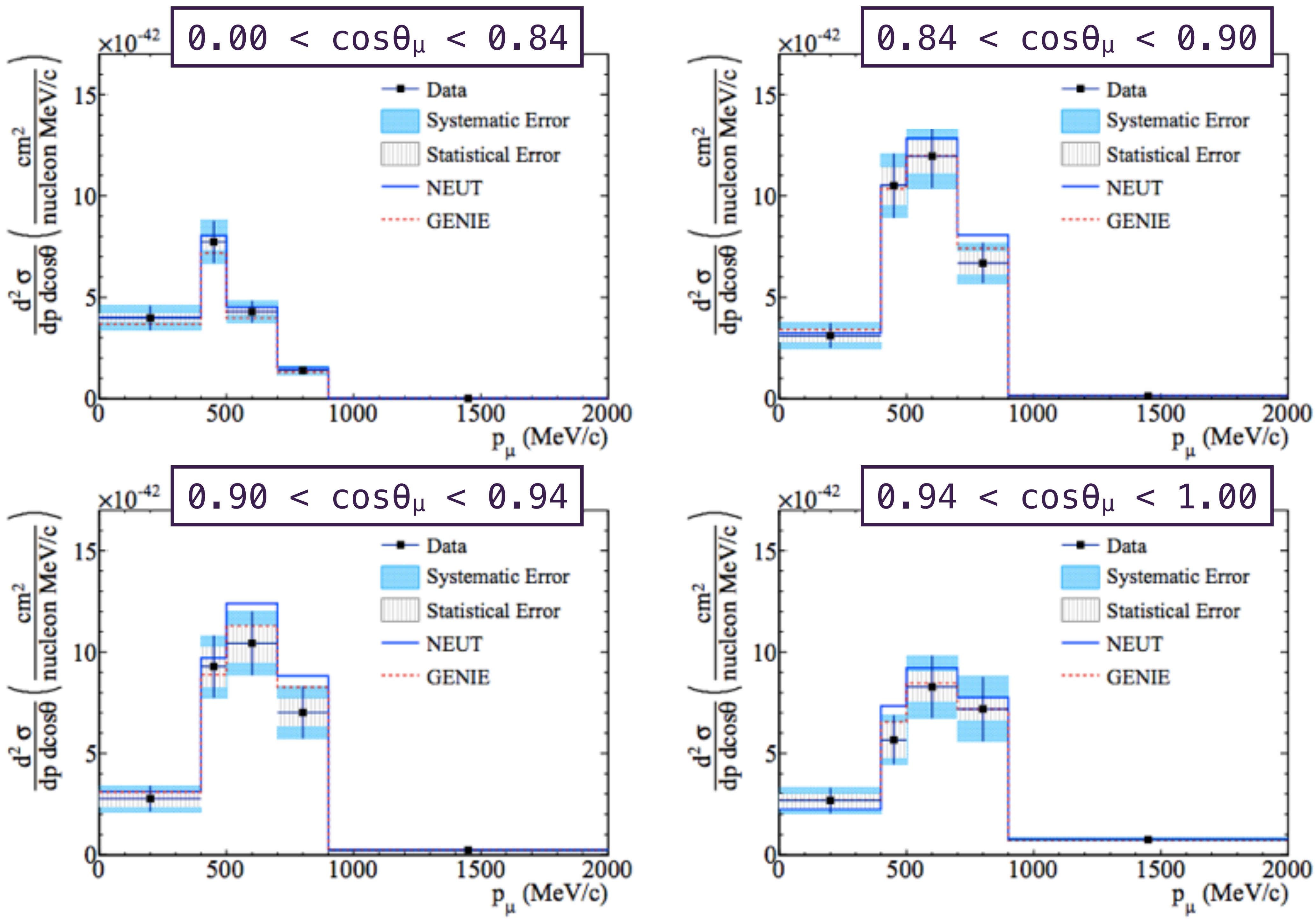


ν_μ CC–inclusive σ on C

Phys. Rev. D 87, 092003 (2013)



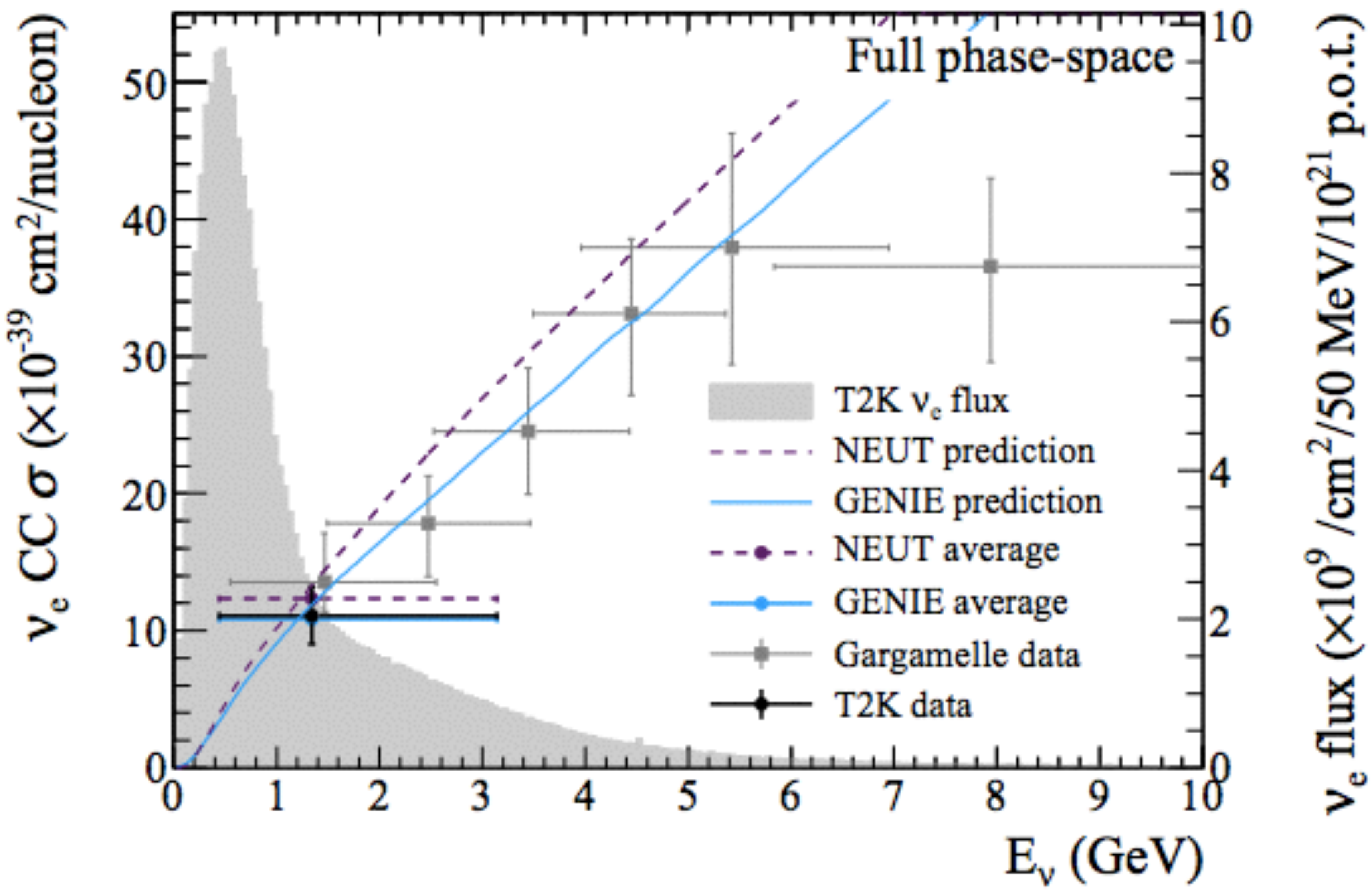
- Select muon–like events in ND280
- Use Bayesian unfolding method
- Fit $(p,\theta)_\mu$ for events

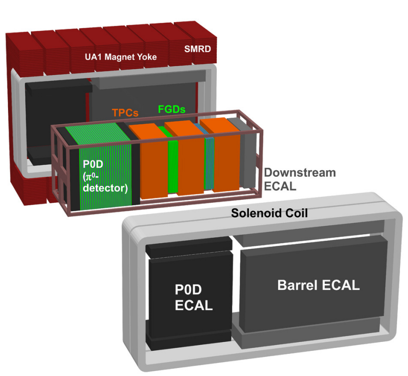


ν_e CC–inclusive σ on C

Total flux averaged cross-section:

$\langle\sigma\rangle_\phi = 1.11 \pm 0.09(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38}\ \text{cm}^2/\text{nucleon}$

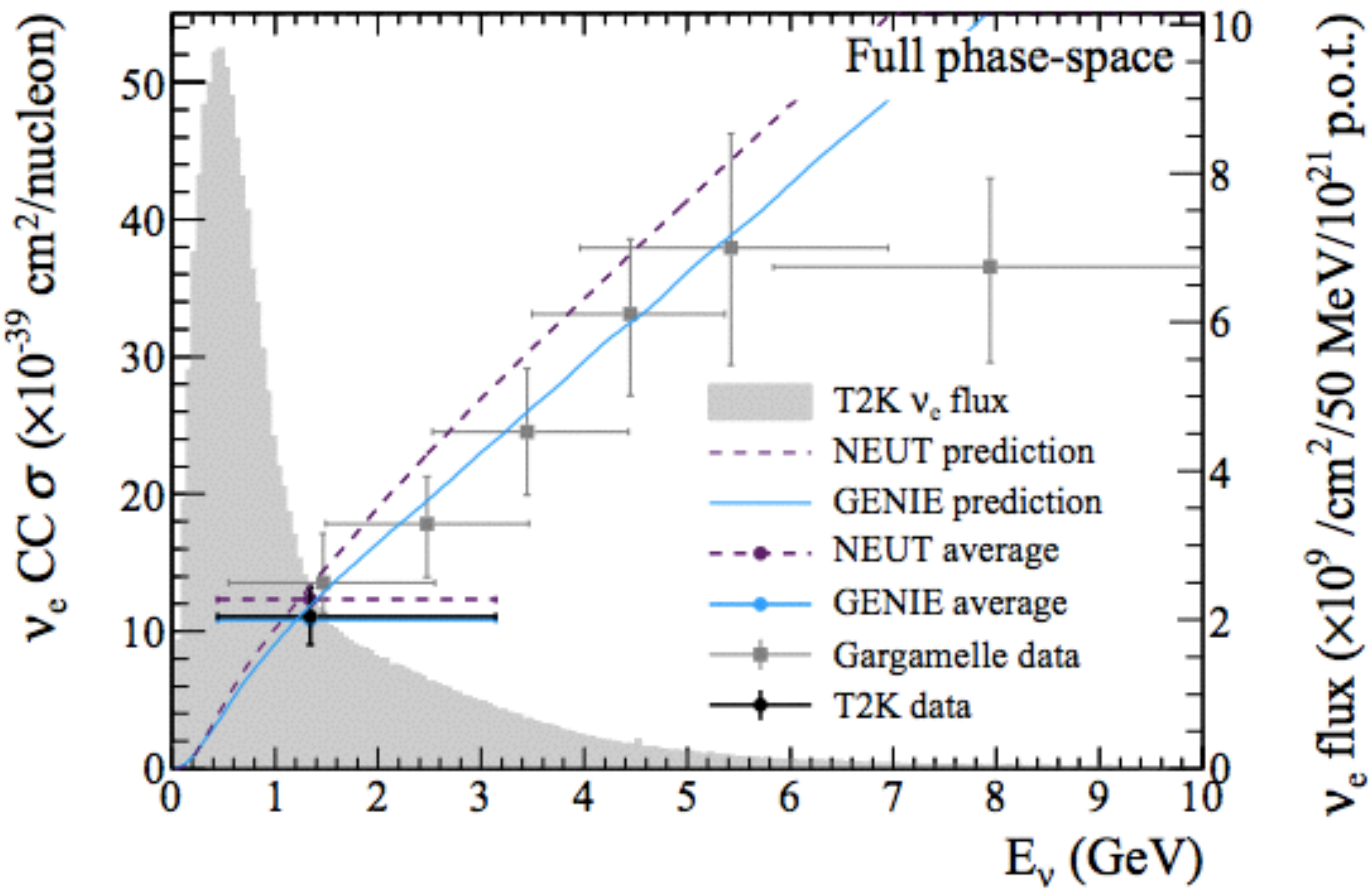


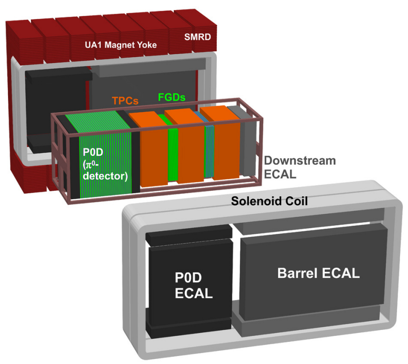


ν_e CC-inclusive σ on C

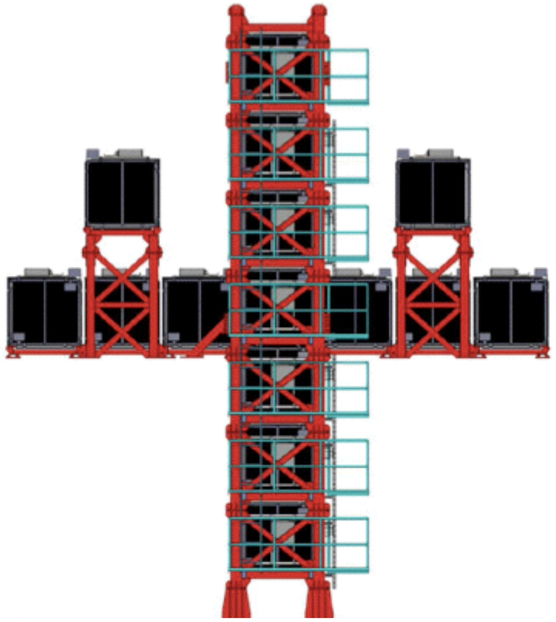
Total flux averaged cross-section:

$\langle\sigma\rangle_\phi = 1.11 \pm 0.09(\text{stat}) \pm 0.18(\text{syst}) \times 10^{-38}$ cm²/nucleon





INGRID σ on C & Fe



$$\sigma_{CC}^{Fe} = (1.444 \pm 0.002(stat.)^{+0.189}_{-0.157}(syst.)) \times 10^{-38}\text{cm}^2/\text{nucleon},$$

$$\sigma_{CC}^{CH} = (1.379 \pm 0.009(stat.)^{+0.178}_{-0.147}(syst.)) \times 10^{-38}\text{cm}^2/\text{nucleon, and}$$

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007(stat.) \pm 0.035(syst.),$$

- INGRID standard module → Fe
- INGRID proton module → CH
- Measure cross-section on different targets