Измерение иерархии масс и фазы CP нарушения в лептонном секторе в нейтринном эксперименте NOvA

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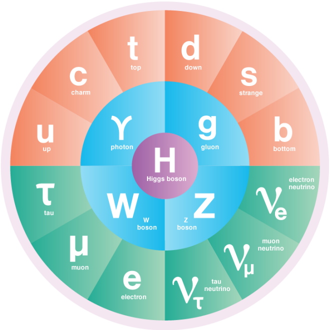
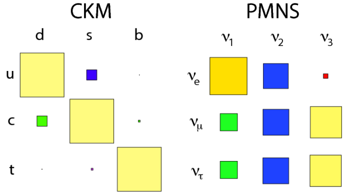
Neutrinos

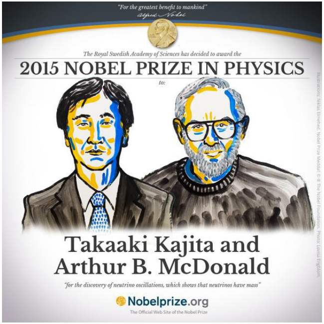




Neutrinos mix like quarks (but mixings are large):

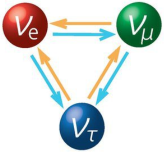
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$i = 1, 2, 3 \quad \alpha = e, \mu, \tau$



Nobel Prize 2015

was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".



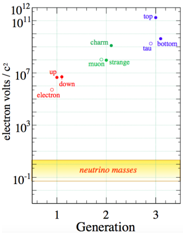
Breakthrough 2016

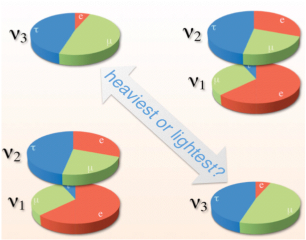
- Daya Bay (China)
- SNO (Canada)
- Super-Kamiokande (Japan)
- KamLAND (Japan)
- K2K/T2K (Japan)

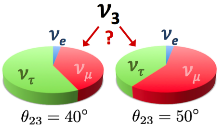
Motivations to study neutrino oscillations

- One of the most wide spread particle in the Universe
- Many open questions:
  - Dirac or Majorana nature
  - Neutrino masses themselves
  - Measurement of θ_{13} (Complete. Reactor experiments result)
  - Mass Hierarchy Problem
  - CP violating phase
  - Precise measurements of oscillation parameters
  - Sterile neutrinos
  - Understanding fundamental principals of all these phenomena
  - ...

NOvA goals (Mass Hierarchy Problem, CP violating phase, Precise measurements of oscillation parameters)







Why is it important?

✳ neutrino mass hierarchy

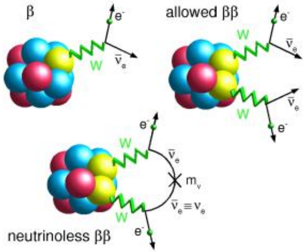
Implications for: $0\nu\beta\beta$ data and Majorana nature of ν; approach to m_β; cosmology; astrophysics; theoretical frameworks for mass generation, quark/lepton unification; Is the lightest charged lepton associated with the heaviest light neutrino?

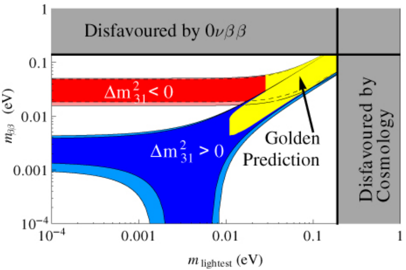
✳ CP violation

baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (is CP respected by leptons?)

✳ ν_3 flavor mixing

Is ν_3 more strongly coupled to μ or τ flavor?; frameworks for mass generation, unification





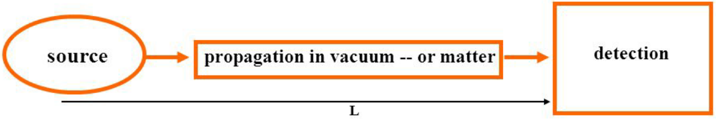
Theory of neutrino oscillations

$\theta_{13} \sim 8.5^\circ$

$$\left| \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \left| \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right\rangle$$

$\lvert\Delta m^2_{32}\rvert = \lvert m^2_3 - m^2_2\rvert$ $\simeq 2.5 \times 10^{-3}$ eV^2	$\Delta m^2_{31} \simeq \Delta m^2_{32}$	$\Delta m^2_{21} = \lvert m^2_2 - m^2_1\rvert$ $\simeq 7.5 \times 10^{-5}$ eV^2
$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$	$\nu_e \to \nu_e$
$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$	$\nu_e \to \nu_\mu, \nu_\tau$
atmospheric and long baseline	reactor and long baseline	solar and reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ, $\lvert\Delta m^2_{13}\rvert$, Δm^2_{12}



Oscillation Probability

ν_μ Disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \underbrace{\sin^2 2\theta_{23}}_{\text{maximal mixing}} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

leading order,
no matter effect,
no CP violation terms ...

ν_e Appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \underbrace{\sin^2 2\theta_{13}}_{\sin^2 2\theta_{13} = 0.084 \pm 0.005} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

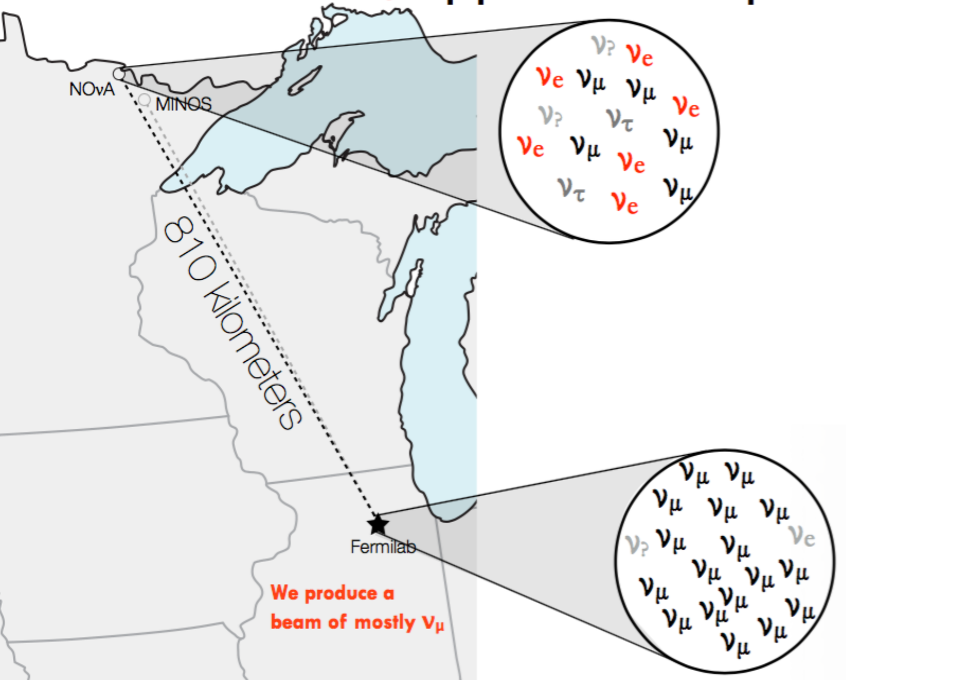
Oscilation Probability in matter (approximate formula):

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$+\alpha\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{32}}, \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}, \quad A \equiv \pm\frac{G_f n_e L}{\sqrt{2}\Delta}$$

NuMI Off-axis ν_e Appearance Experiment



The NuMI Off-Axis ν_e Appearance Experiment. Goals

NOvA experiment goals :

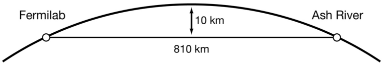
Using $\nu_\mu \to \nu_e$ ($\overline{\nu}_\mu \to \overline{\nu}_e$)

- neutrino mass hierarchy
- CP violating phase

Using $\nu_\mu \to \nu_\mu$ ($\overline{\nu}_\mu \to \overline{\nu}_\mu$)

- precision measurement Δm^2_{32}
- mixing angle θ_{23} octant (more 45° or less).

Also exotics:
sterile neutrino, supernova, neutrino cross section measurements in Near Det., monopoles etc.



NOvA Collaboration

7 countries

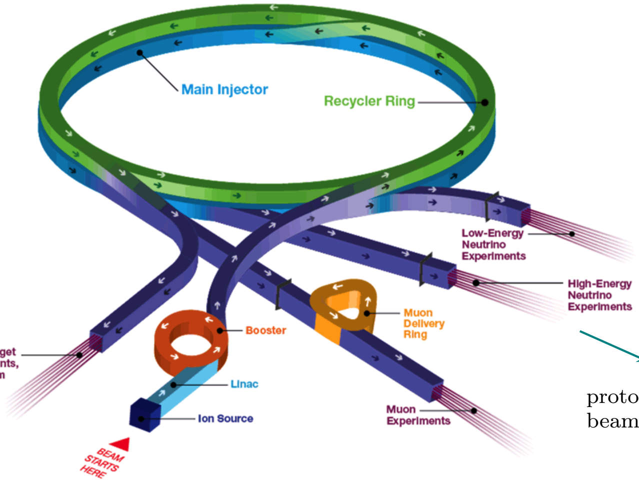
44 insitutes

260 collaborators

FermiLab accelerator complex

Neutrinos at the Main Injector (NuMI)

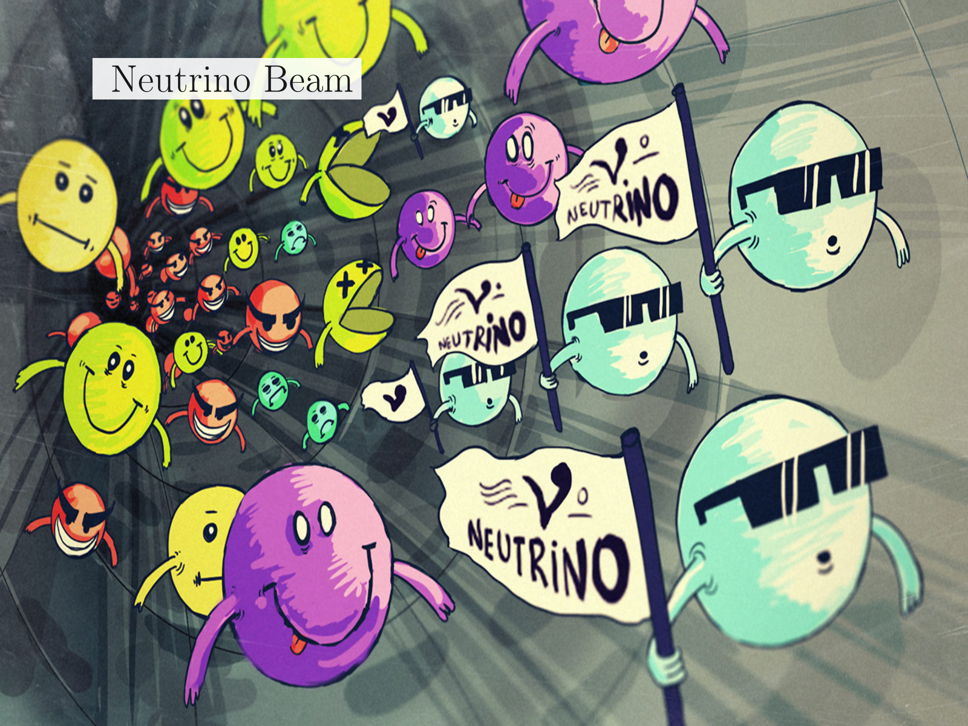
750 keV → 400 MeV → 8 GeV → 120 GeV → to target



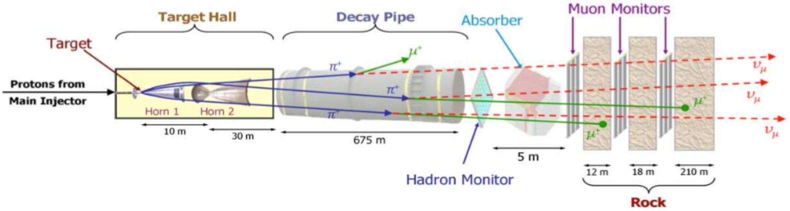
proton 120 GeV beam on target

Fermilab Accelerator Complex 2020

Neutrino Beam



Initial neutrino flux production



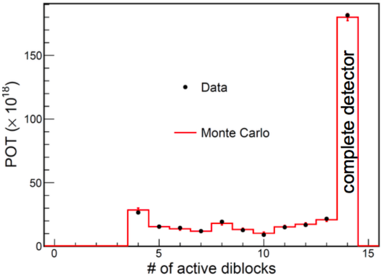
- 120 GeV protons on the carbon target
- NOvA designed power is 700 kW NuMI beam, it is 6×10^{20} POT/year (POT = Proton On Target)
- we are running at 700 kW now!
- horns are pulsed at -200 kA (+200 kA for antineutrinos)
- every 1.3s 6 doubled batches of protons get the target (1 beam spill). 1 spill is 10 us.

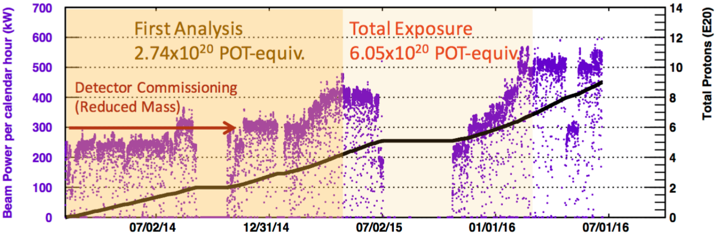
Recorded POT and Far Detector Dataset

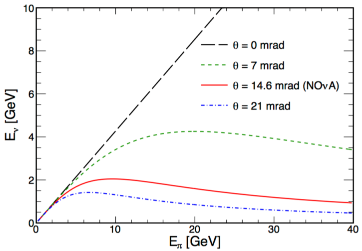
- During the construction era, NOvA began collecting physics data with each Far Detector "diblock" (64 detector planes) as soon as it was fully commissioned and physics-ready
- FD size is not static throughout data set:

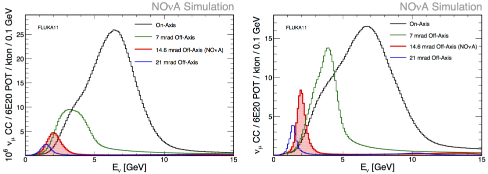
Partial Far Detector during construction (6 diblock example)

Full Far Detector (14 diblocks)









Narrowly peaked ν flux centered at 2 GeV

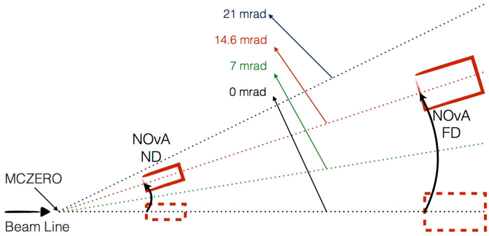
$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1 + \gamma^2 \theta^2}$$

For π decay-in-flight, E_ν dependent on angle π decay and ν interaction.
Off-axis have flat E_π dependence.

Achieves near maximal oscillation

Suppresses high energy tail

14 mrad off-axis



Two NOvA detectors - huge tracking calorimeters

Far Detector on the surface

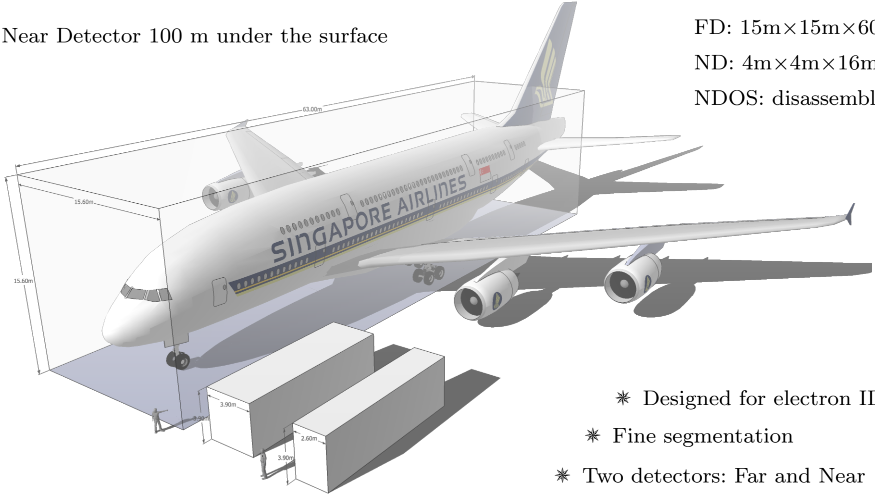
Near Detector 100 m under the surface

Det. size:

FD: 15m×15m×60m

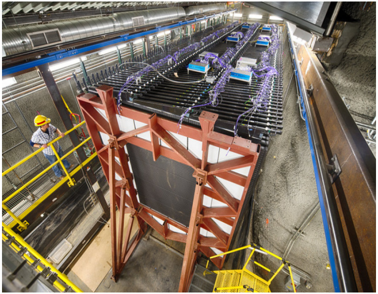
ND: 4m×4m×16m

NDOS: disassembled



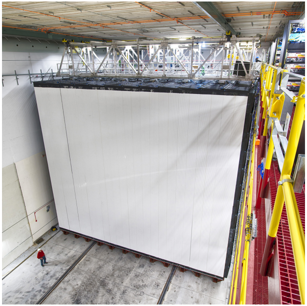
- ✳ Designed for electron ID
- ✳ Fine segmentation
- ✳ Two detectors: Far and Near

Two detector scheme



Near Detector (ND):

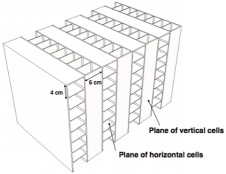
- 1 km after target
- measure flux composition before oscillations
- ND data used for prediction data in FD (extrapolation procedure)

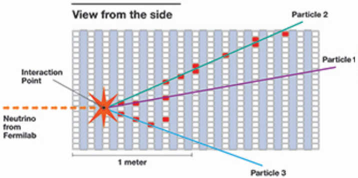


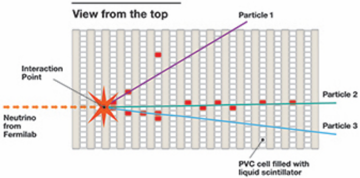
Far Detector (FD):

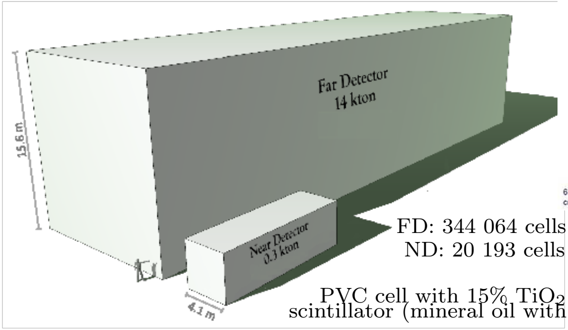
- 810 km after target
- measure neutrino flux after oscillations
- extrapolation cancels most systematics
- FD identical to ND

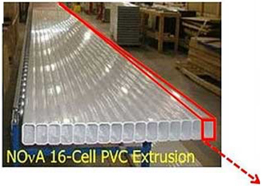
Two NOvA detectors - huge tracking calorimeters

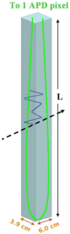






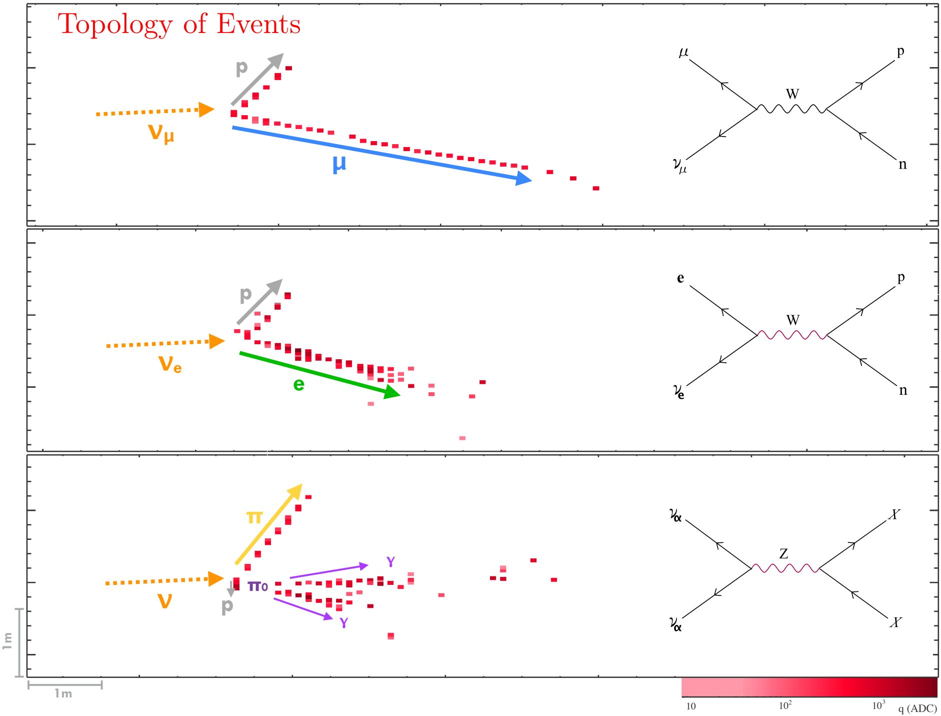






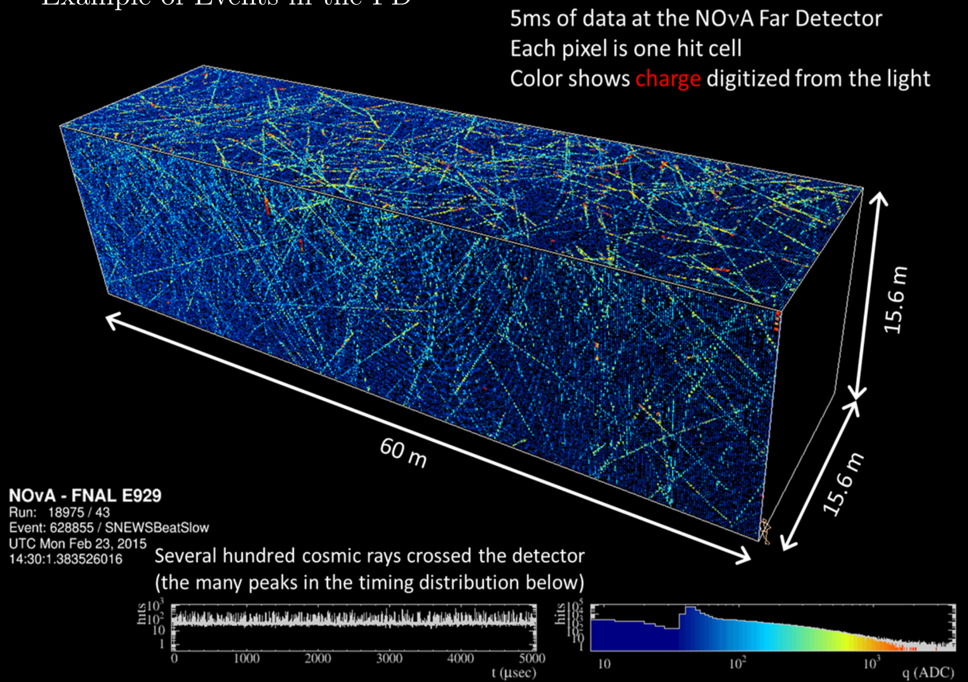
FD: 344 064 cells
ND: 20 193 cells

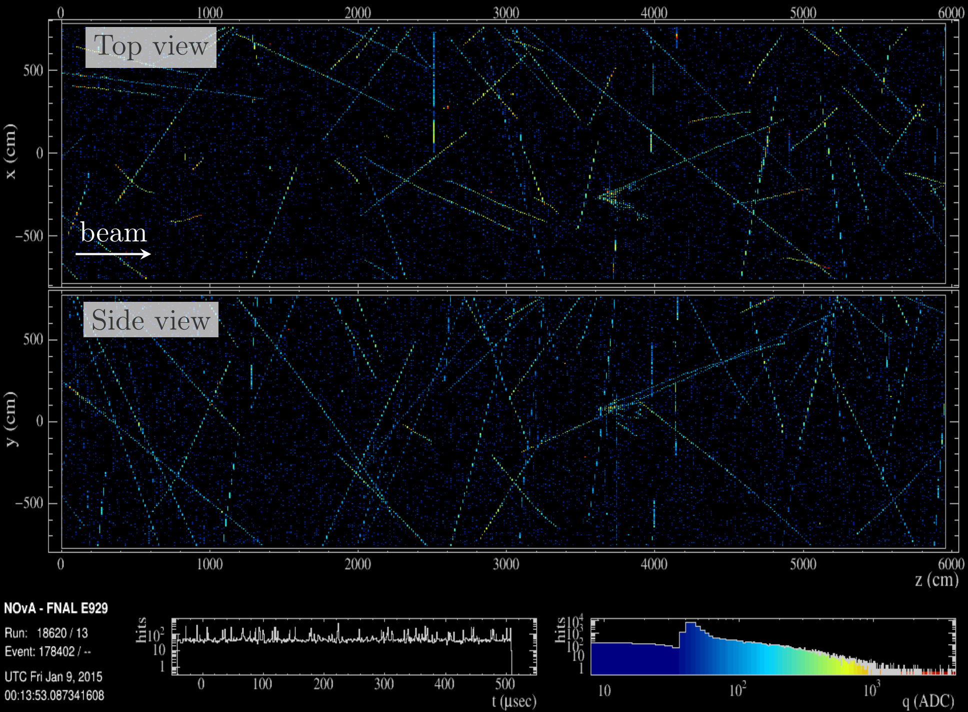
PVC cell with 15% TiO_2 with liquid scintillator (mineral oil with 5% pseudocumene)



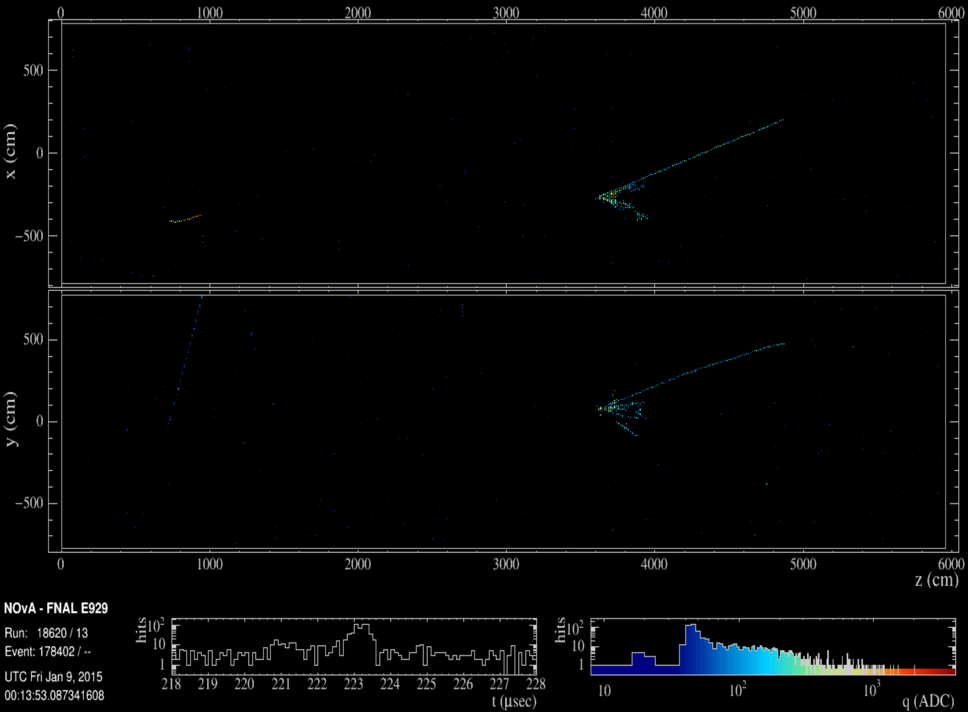
Topology of Events
p
ν_μ
μ
μ
W
p
ν_μ
n
p
ν_e
e
e
W
p
ν_e
n
π
γ
ν
p
π0
γ
ν_α
Z
X
ν_α
X
1m
1m
10
10^2
10^3
q (ADC)

Example of Events in the FD

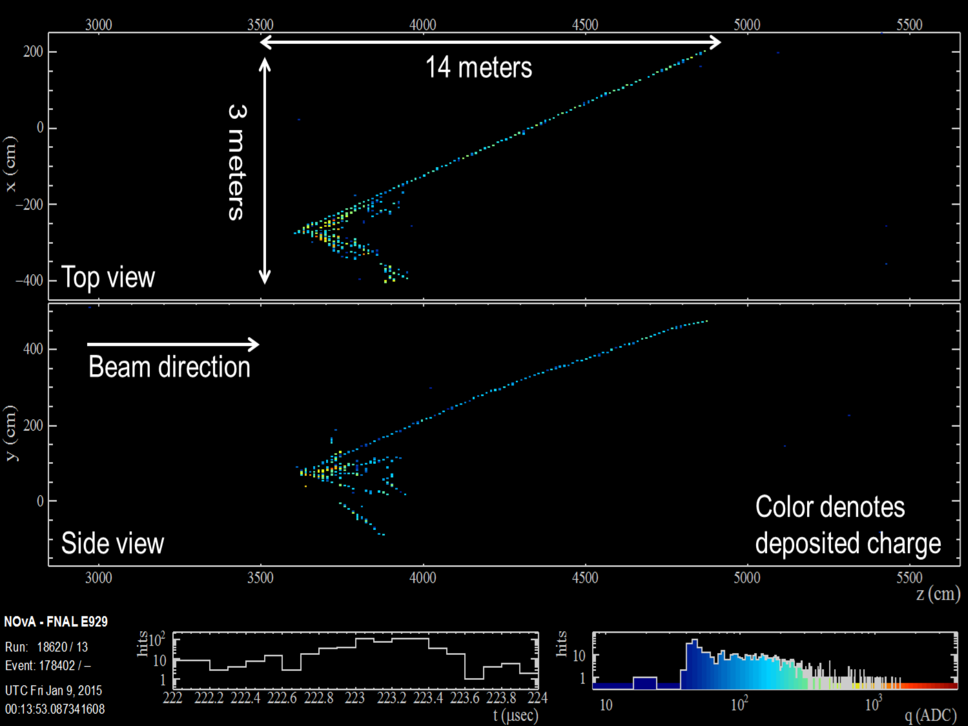




Top view
Side view
beam
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)



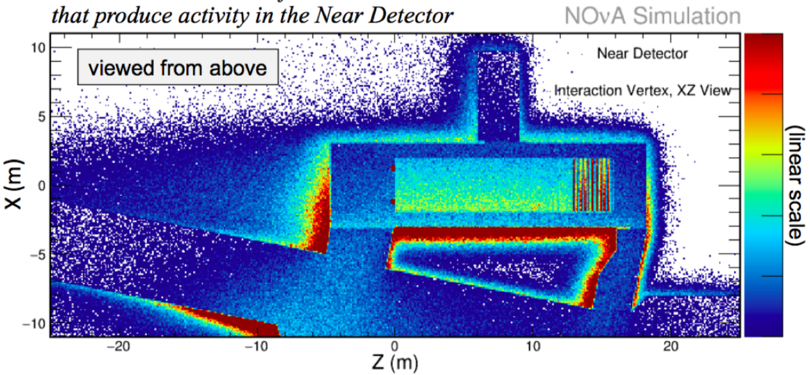
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)


14 meters
3 meters
Top view
Beam direction
Side view
Color denotes deposited charge
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / –
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
t (μsec)
q (ADC)

Simulation

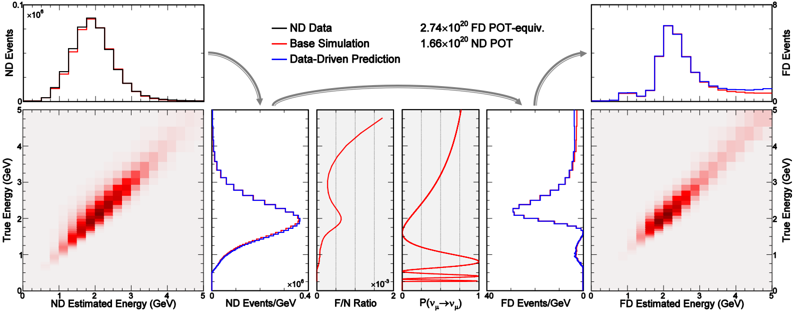
- Beam hadron production, propagation; neutrino flux: FLUKA/FLUGG
- Cosmic ray flux: CRY
- Neutrino interactions and FSI modeling: GENIE
- Detector simulation: GEANT4
- Readout electronics and DAQ: Custom simulation routines

Simulation: Locations of neutrino interactions that produce activity in the Near Detector

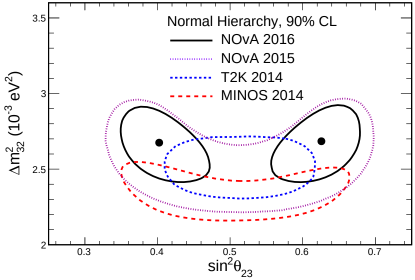


Extrapolation to Far Detector

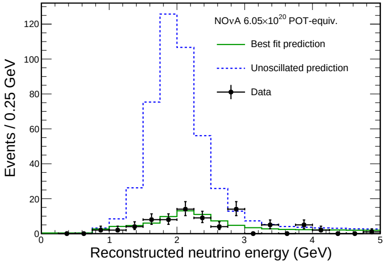
- Estimate true energy distribution of selected Near Detector events
- Multiply by expected Far/Near event ratio and oscillation probability as a function of true energy
- Convert FD true energy distribution into predicted FD reco energy distribution
- Systematic uncertainties assessed by varying all MC-based steps



ν_μ Disappearance. Results. See Oleg Samoylov seminar



- expected without oscillations 473 ± 30 (syst.)
- NOvA observed 78 ν_μ CC candidate events
- background events:
  - 3.4 NC and 2.7 cosmic-ray



Best-fit:

Normal H.:
$$\Delta m^2_{32} = 2.66 \pm 0.11 \times 10^{-3}\ \text{eV}^2$$
$$\sin^2\theta_{23} = 0.403^{+0.030}_{-0.022}, 0.626^{+0.022}_{-0.030}$$
(68% CL)

Inverted H.:
$$\Delta m^2_{32} = -2.70 \pm 0.11 \times 10^{-3}\ \text{eV}^2$$
$$\sin^2\theta_{23} = 0.396^{+0.030}_{-0.022}, 0.618^{+0.022}_{-0.030}$$

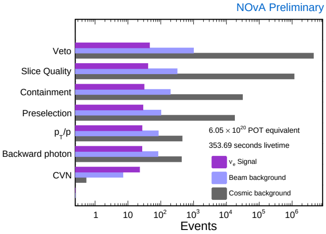
Selecting Electron Neutrinos. Cosmic rejection.

Select ν_e CC events

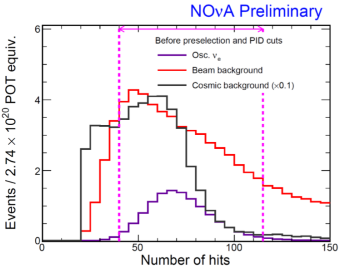
- with electromagnetic showers
- suppress background and cosmic

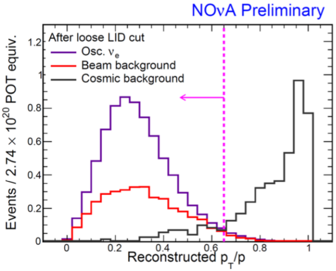
Basic cuts:

- Fiducial and Containment cuts
- Shower length
- Calorimetric energy
- Number of hits
- Reconstructed p_T/p

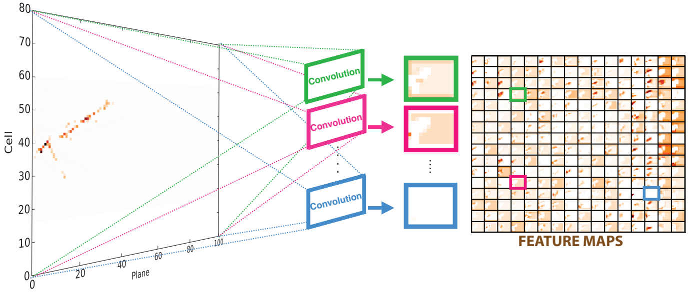


Expected cosmic background: 0.5 events





Selecting Electron Neutrinos



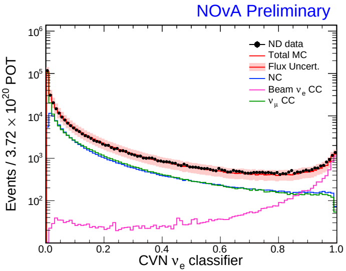
- features a new technique based on ideas from computer vision and deep learning
- "Convolutional Visual Network" (CVN)
- Input: Calibrated hit maps
- Image processing transformations → abstract features
- Network decides important features + correlations
- Output: event classifier

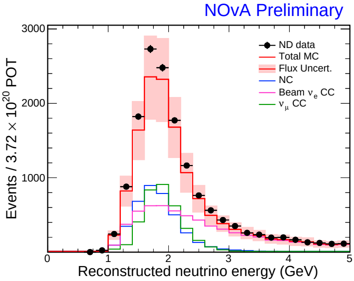
ν_e Appearance. CVN and Near Detector Data

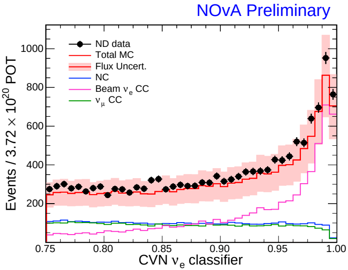
ND: select 3 components: beam ν_e CC, ν_μ CC,NC

Correspond to 3 FD backgrounds

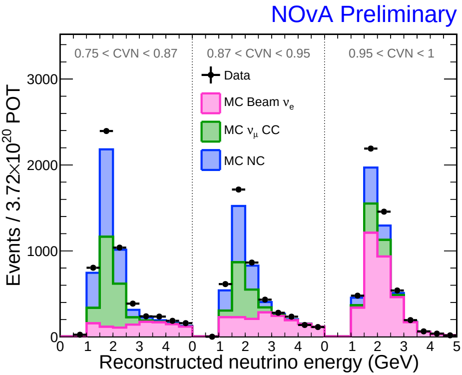
Translate ND data to a FD bkgd. expectation in energy x PID bins using Far/Near ratios from simulation







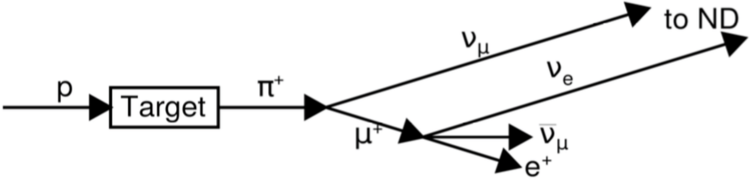
Data driven background prediction. Near Detector.



- $\sim$ 10% excess of data over MC
- beam composition in the ND: ν_μ CC, ν_e CC and NC - source of bkg in FD
- each component oscillates independently

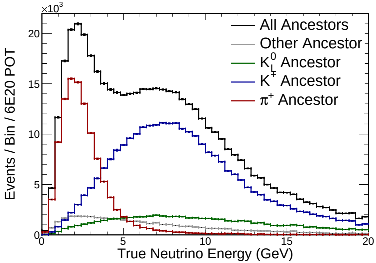
Solution in SA: 2 decomposition techniques

ν_e CC component.



- ν_e CC - from muon decay (from K^+ or π^+)
- π^+ - low E, K^+ - high E
- correct pion and kaon yields in MC
- output weights :
  Kaon yield is higher by 17%
  Pion yield lower by 3%

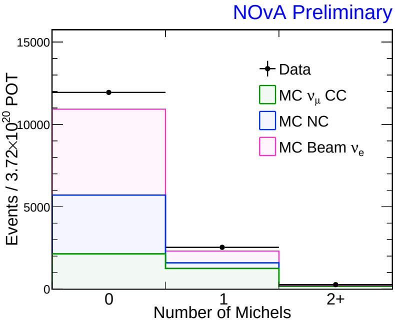
Cause +1% increase in ν_e CC



and ν_μ CC and NC background.

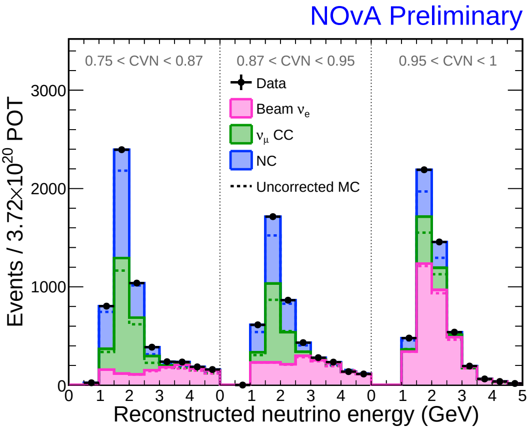
- look for Michel electrons associated with interactions
- ν_μ CC should have $+1$ additional ME than ν_e CC and NC
- fit analysis bins with fixed ν_e CC from the previous page

Cause increase of 17.4% in ν_μ CC and 10.4% in NC



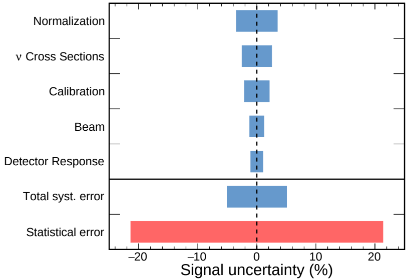
Result in the Near Detector.

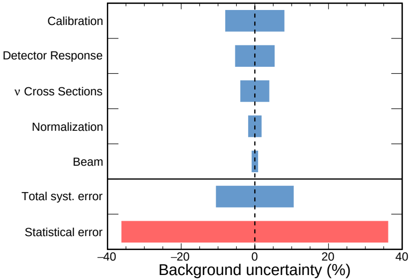
Both these techniques give :



So we have near detector beam composition now.

ν_e Appearance. Systematic Uncertainties and Background





- Considered multiple possible sources of systematic error
- Propagate shifts through to update FD prediction
- Total 5% error on signal, 10 % on bkg.
- Dominated by statistical error

Far Detector Signal and Background Expectations

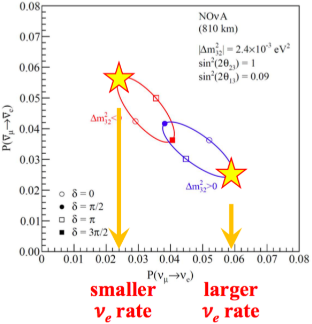
Signal prediction:

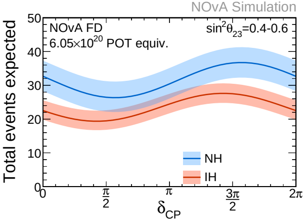
- Signal depends on oscillation parameters

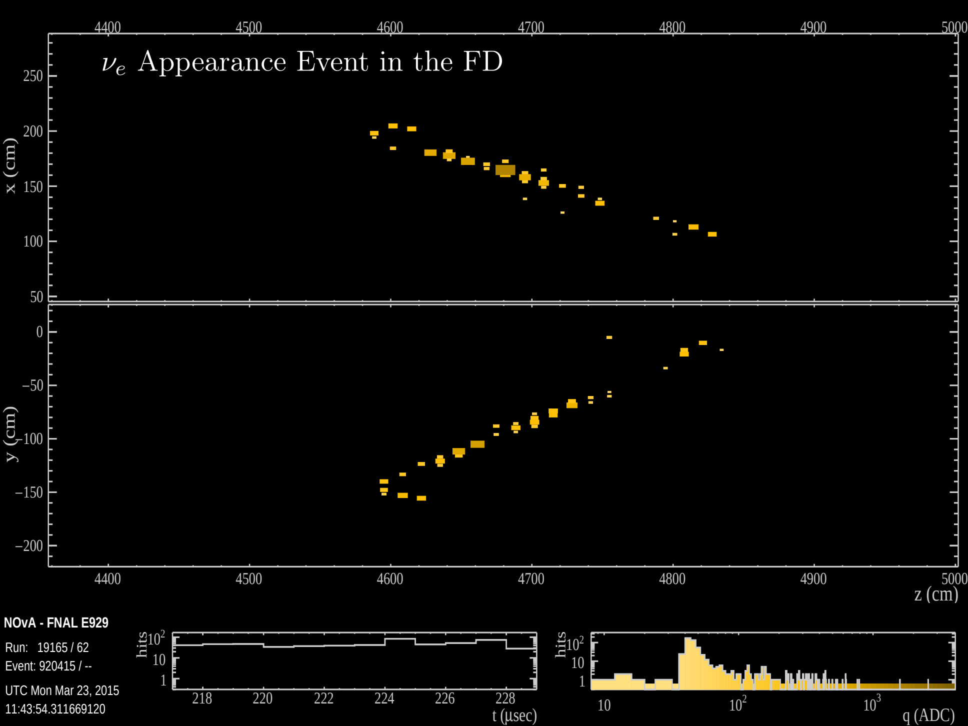
IH, $\delta_{CP} = \pi/2$	NH, $\delta_{CP} = 3\pi/2$
19.4	36.4

- Expect about 8.2 background event
- Backgrounds dominated by Beam ν_e and NC events
- Background has small variation with oscillation parameters

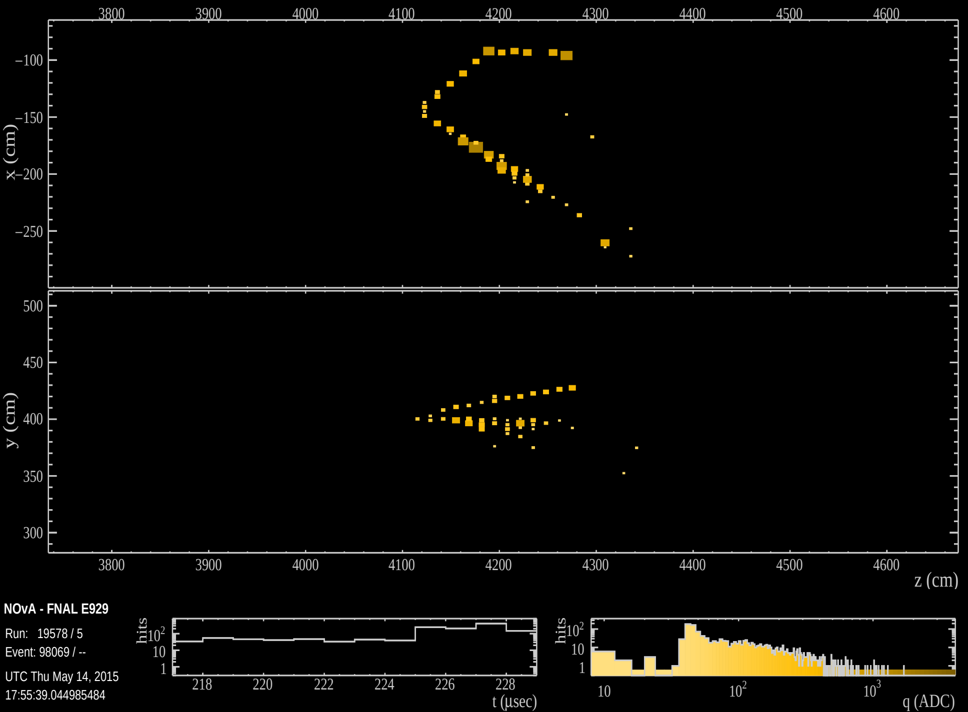
Total bkg.	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
8.2	3.1	3.7	0.7	0.1	0.5



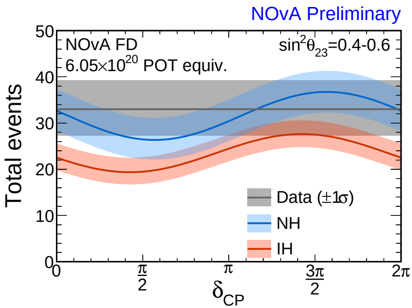


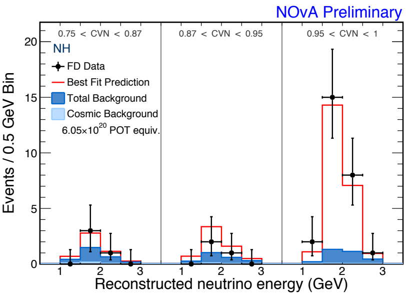


ν_e Appearance Event in the FD
x (cm)
y (cm)
z (cm)
4400
4500
4600
4700
4800
4900
5000
250
200
150
100
50
0
−50
−100
−150
−200
NOvA - FNAL E929
Run: 19165 / 62
Event: 920415 / --
UTC Mon Mar 23, 2015
11:43:54.311669120
hits
10^2
10
1
218
220
222
224
226
228
t (μsec)
10^2
10^3
q (ADC)


3800
3900
4000
4100
4200
4300
4400
4500
4600
−100
−150
−200
−250
x (cm)
500
450
400
350
300
y (cm)
z (cm)
NOvA - FNAL E929
Run: 19578 / 5
Event: 98069 / --
UTC Thu May 14, 2015
17:55:39.044985484
hits
218
220
222
224
226
228
t (μsec)
q (ADC)

ν_e Appearance Results. Selected Events.

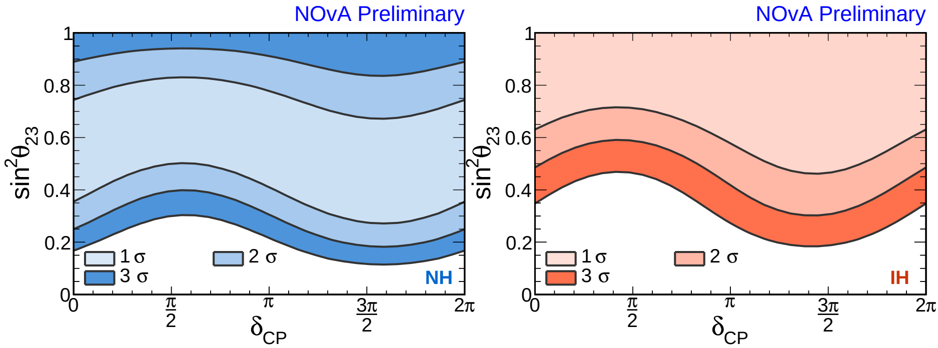




(8.2 expected background)

- Observe 33 events passing ν_e selection
- Towards the higher end of expectations

ν_e Appearance Result. Fit.

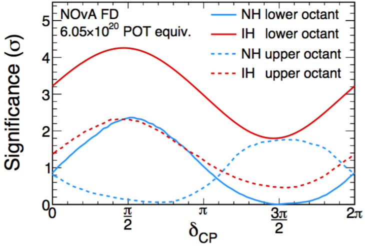


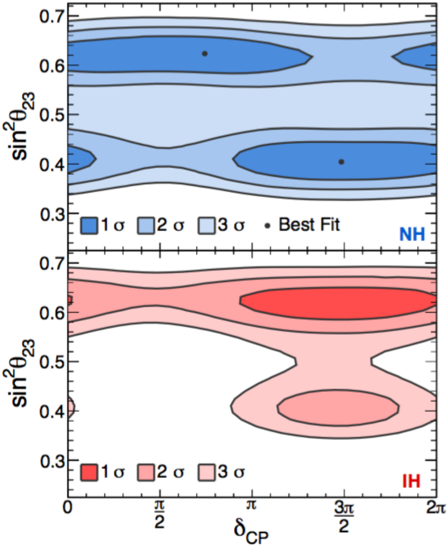
- Fit ν_e only spectra

Not very informative yet

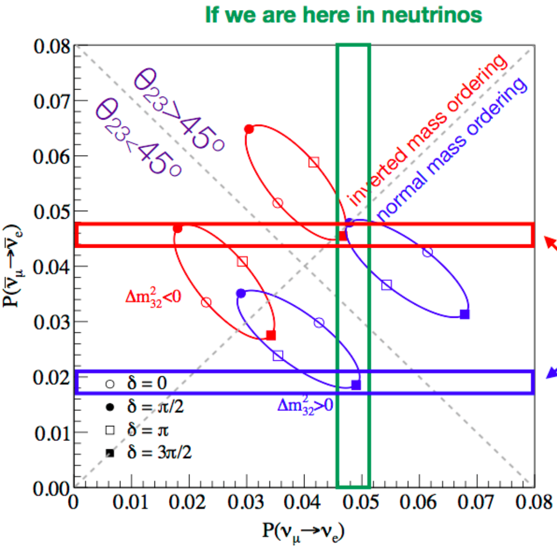
ν_e Appearance Result. Joint Fit.

- Joint fit $\nu_e + \nu_\mu$ spectra, FC corrections applied
- two degenerate points in NH:
  $\sin^2\theta_{23} = 0.404 \quad \delta_{CP} = 1.48\pi$
  $\sin^2\theta_{23} = 0.623 \quad \delta_{CP} = 0.74\pi$
- prefer NH, not statistically significant $\Delta\chi^2 = 0.46$
- exclude region in IH, lower octant, around $\delta_{CP} = \pi/2$ at 3σ
- exclude IH at LO at greater than 93% C.L. for all values of δ_{CP}





Where we now



we need antineutrinos to know if we are here or here

NOvA analysis papers

First Analysis Epoch (2015 year):

- First measurement of electron neutrino appearance in NOvA (arXiv:1601.05022)
- First measurement of muon-neutrino disappearance in NOvA (arXiv:1601.05037)

Second Analysis Epoch (2016 year):

- Measurement of the neutrino mixing angle θ_{23} in NOvA (arXiv:1701.05891)
- Constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in NOvA (arXiv:1703.03328)
- NC result paper — very soon

Third Analysis - this summer

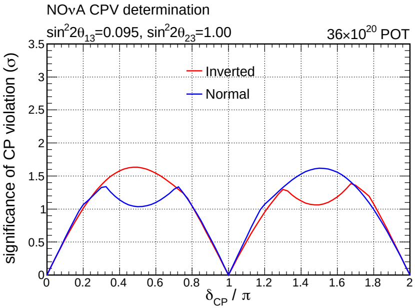
JINR participation in NOvA

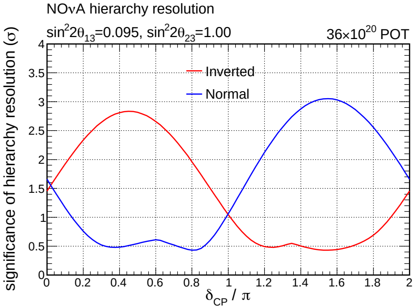
	Tasks	FTE		Tasks	FTE
Allakhverdian, A.	ND Physics	0.4	Kuzmin, K.	DetSim, theory	0.1
Amvrosov, V.	Numu osc, learning	0.1	Kuznetsov, E.	Computing, hardware	0.1
Anfimov, N.	DetOps, test stand	0.3	Morozova, A.	Exotics, CR muons	0.3
Antoshkin, A.	DetOps, test stand	0.3	Naumov, V.	DetSim, theory	0.3
	Exotics, slow monopole	0.3	Olshevskiy, A.	CollManagement, IB-rep	0.5
	DetControl, ROC-liaison	0.1	Petrova, O.	Exotics, CR muons	0.7
Balashov, N.	Computing	0.3		DetSim, theory calculation	0.3
Baranov, A.	Computing, cloud	0.1	Samoylov, O.	DetSim, co-convener	0.5
Bolshakova, A.	Reco, proton ID	0.5		DetControl, ROC-manager	0.3
	DetSim, ADC thresholds	0.5		JINR analyses coordination	0.1
Bilenky, S.	Osc., theory	0.1		CollManag, deputy at JINR	0.1
Dolbilov, A.	Computing, emergency	0.1	Sheshukov, A.	DAQ, software and support	0.3
Kakorin, I.	DetSim, GENIE	0.5		DDT, SN trigger	0.3
Klimov, O.	Reco, proton ID	0.6		Exotics, SN detection	0.3
Kolupaeva, L.	Nue osc analysis	0.8		DetControl, ROC software	0.1
	Software, release manager	0.2	Sotnikov, A.	DetOps, test stand	0.1
Krumstein, Z.	DetOps, supervision	0.1	Velikanova, D.	DetOps, test stand	0.1
Kullenberg, C.	ND Physics, coh pions	0.6	**TOT 22 people**		**10.3**

22 heroes in all essential parts of the experiment

Future

NOvA proposed sensitivity (2014 year):
3 years neutrino and 3 years antineutrino run, totaly $36 \cdot 10^{20}$ POT

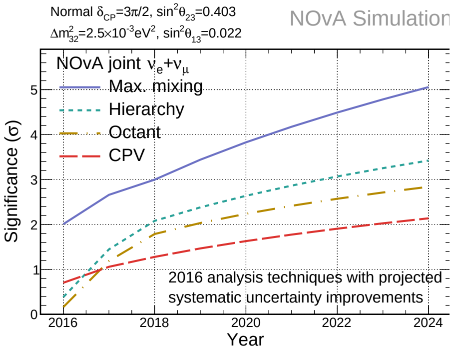


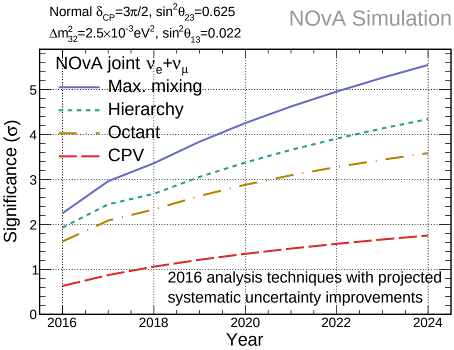


So $< 2\sigma$ for CPV and $\sim 3\sigma$ for mass hierarchy for some values of δ_{CP} ($\pi/2$ and $3\pi/2$)

Future

And now we estimate our sensitivity in the next way:
assume running till 2024 with 54e20 POT





Competition with other experiments:
MH: JUNO 2σ in 2021 and ORCA 3σ in 2022
CP: T2K 2σ in 2021 and 3σ in 2024

Summary

- Analysis with $6.05 \cdot 10^{20}$ POT, 33 ν_e CC events in FD
- First joint fit of NOvA appearance and disappearance data (paper already in arxiv)
- Weak preference for normal hierarchy
- Inverted hierarchy, lower octant is disfavoured at $> 93\%$ C.L.
- NOvA run in antineutrino mode
- Stay tuned!

The next talk devoted to NOvA:

Andrey Sheshukov

“Экзотические анализы в эксперименте NOvA”

5 April 2017

Preliminary program:

- Нейтрино от сверхновых
- Магнитные монополи
- Темная материя
- Атмосферные мюоны
- и многое другое...