Измерение угла смешивания нейтрино θ_{23} в эксперименте NOvA

Олег Самойлов (ЛЯП ОИЯИ)

Семинар ЛЯП — 03/03/2017

NOvA Collaboration

- 260 scientists from 7 Countries (44 Institutions), are looking for **Neutrino Oscillations**

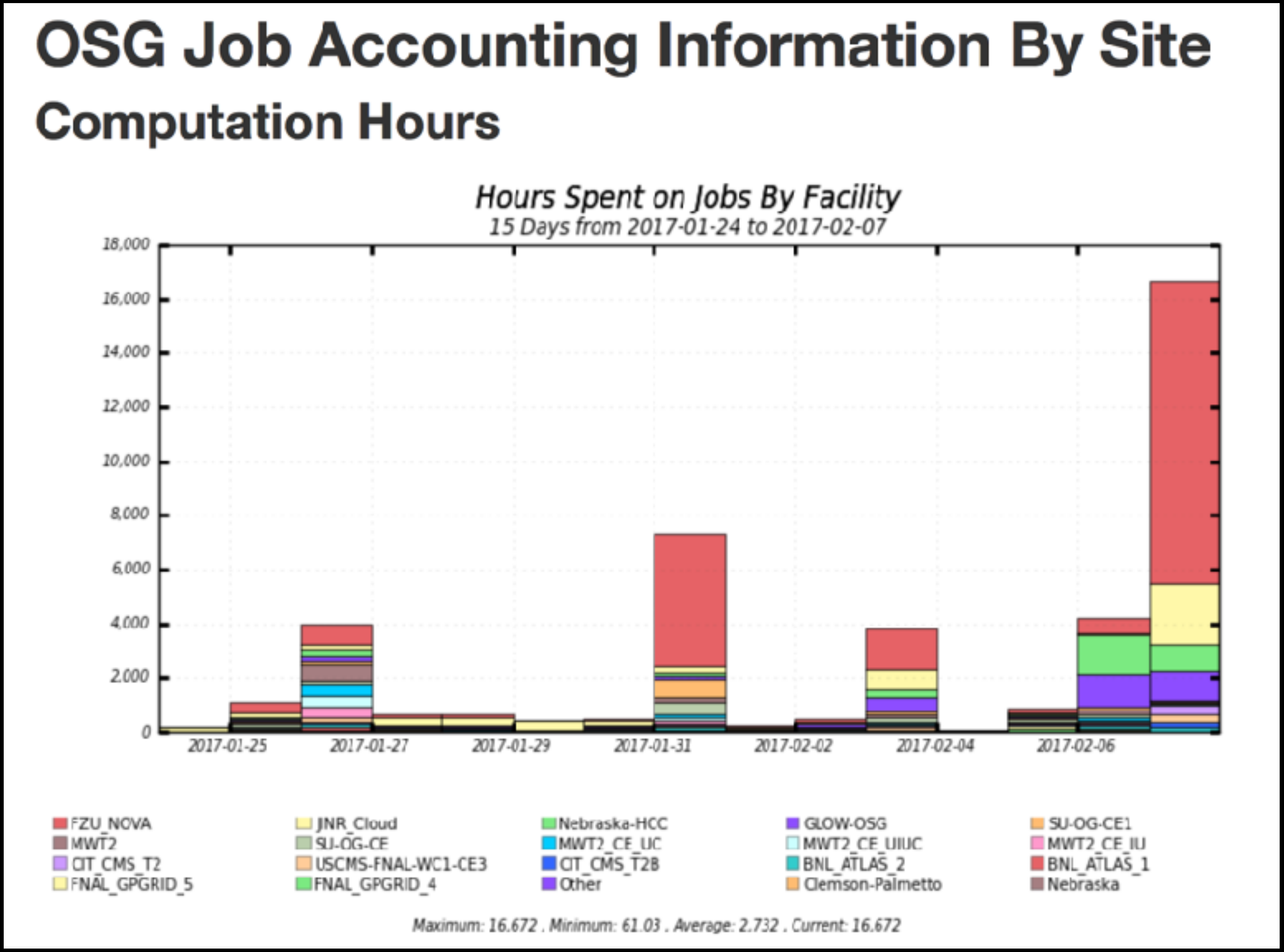
JINR group effort

	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**

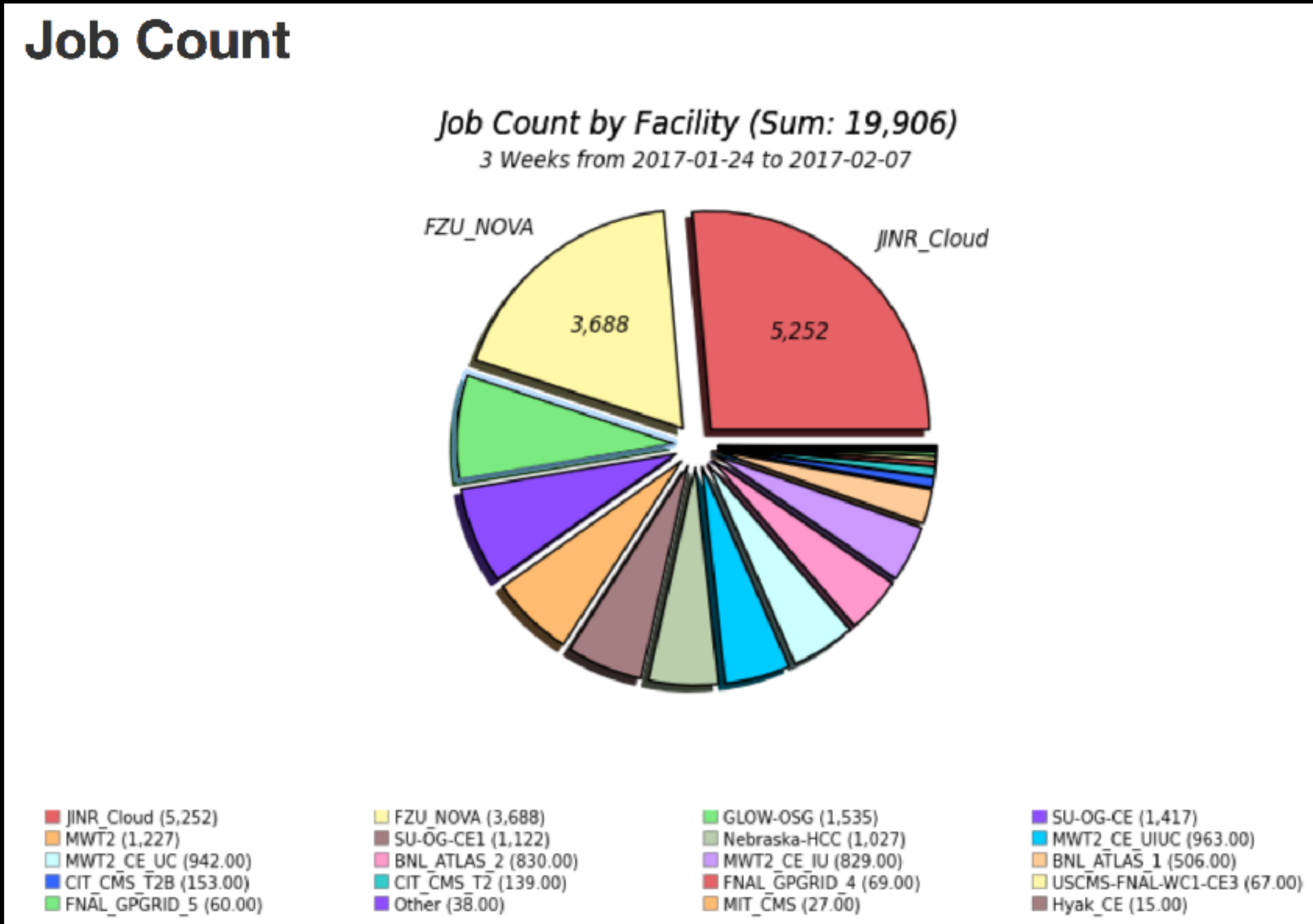
JINR group effort

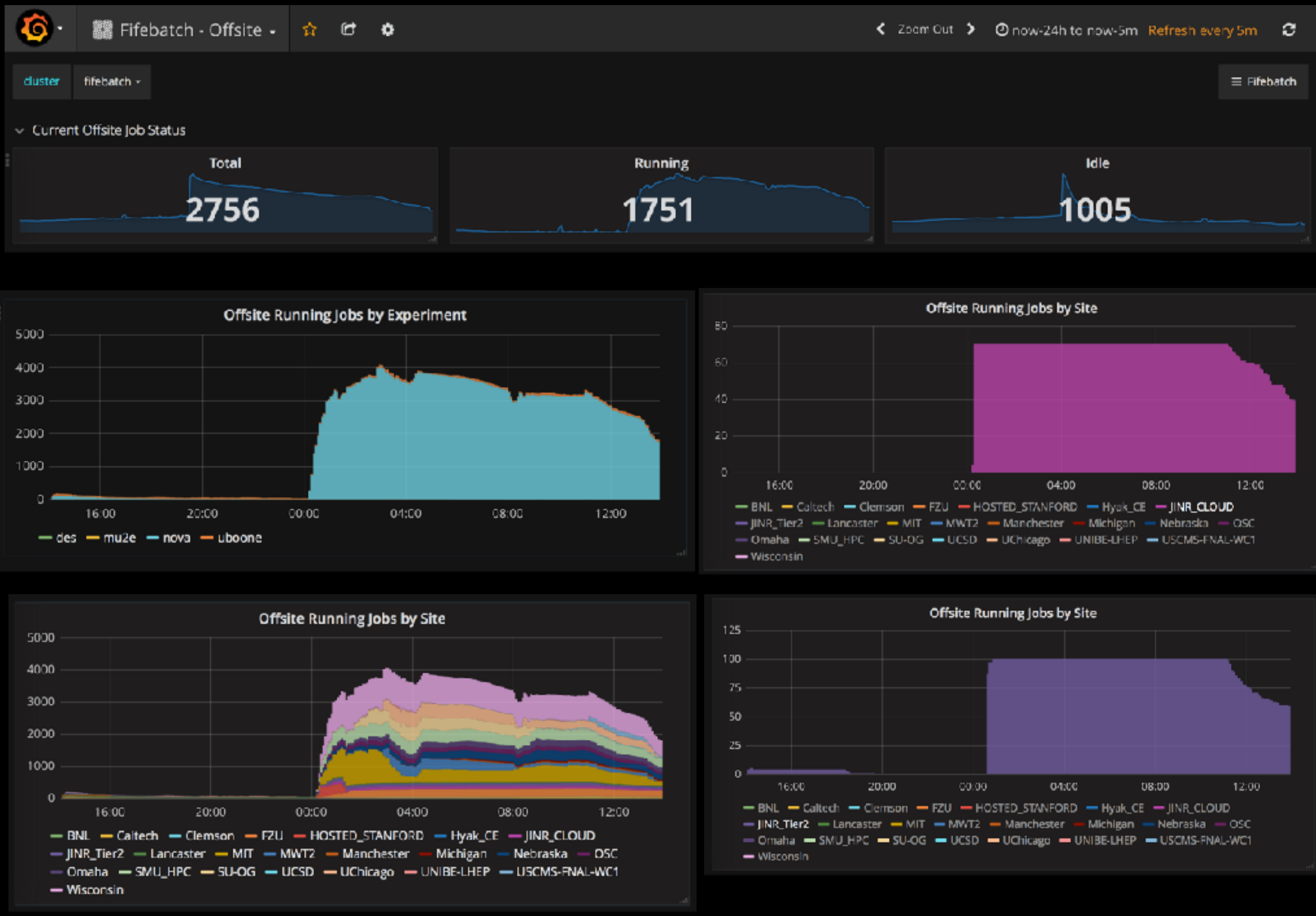
Year, Head (FTE)	2014	2015	2016	2017
Professors	4 (1.2)	4 (1.2)	4 (1.1)	3 (0.9)
PhD degreed	3 (2.3)	3 (2.4)	3 (2.4)	3 (2.1)
Researchers	4 (2.3)	6 (3.3)	7 (4.1)	6 (3.6)
PhD students	0	1 (0.3)	1 (0.3)	1 (0.7)
Master students	1 (0.2)	1 (0.5)	2 (0.8)	2 (1.3)
Bachelor students	3 (0.3)	3 (0.5)	1 (0.2)	3 (0.6)
Engineer	4 (1.3)	5 (1.2)	3 (0.7)	5 (0.7)
Authors (and shift quota)	0 (7)	0 (8)	7 (9)	8 (10)
Average age				35 (35.2)

Fresh news for computing



Fresh news for computing




Fifebatch - Offsite
Zoom Out
now-24h to now-5m
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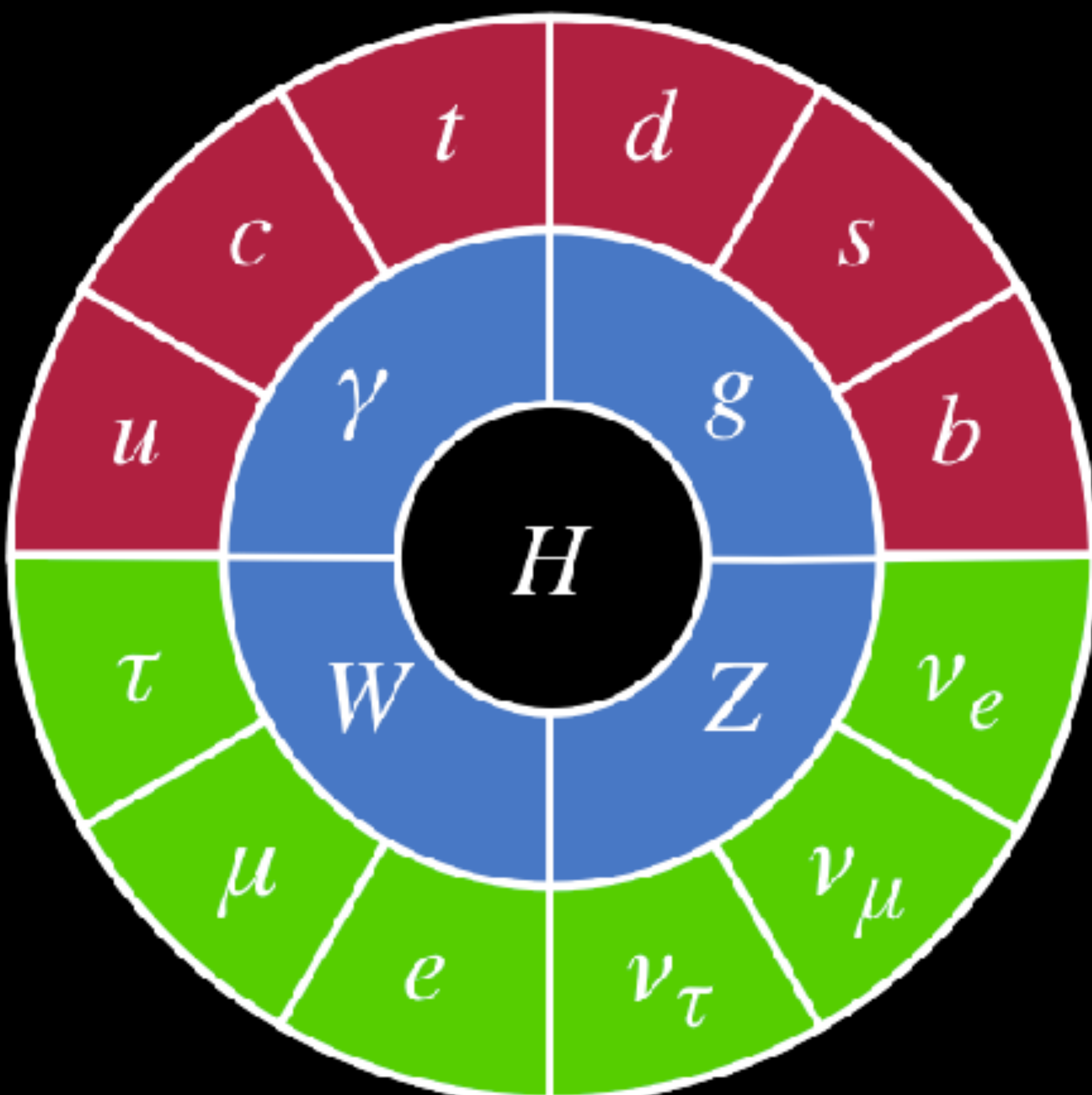
Current Offsite Job Status
Total
2756
Running
1751
Idle
1005
Offsite Running Jobs by Experiment
des
mu2e
nova
uboone
Offsite Running Jobs by Site
BNL
Caltech
Clemson
FZU
HOSTED_STANFORD
Hyak_CE
JINR_CLOUD
JINR_Tier2
Lancaster
MIT
MWT2
Manchester
Michigan
Nebraska
OSC
Omaha
SMU_HPC
SU-OG
UCSD
UChicago
UNIBE-LHEP
USCMS-FNAL-WC1
Wisconsin

Neutrino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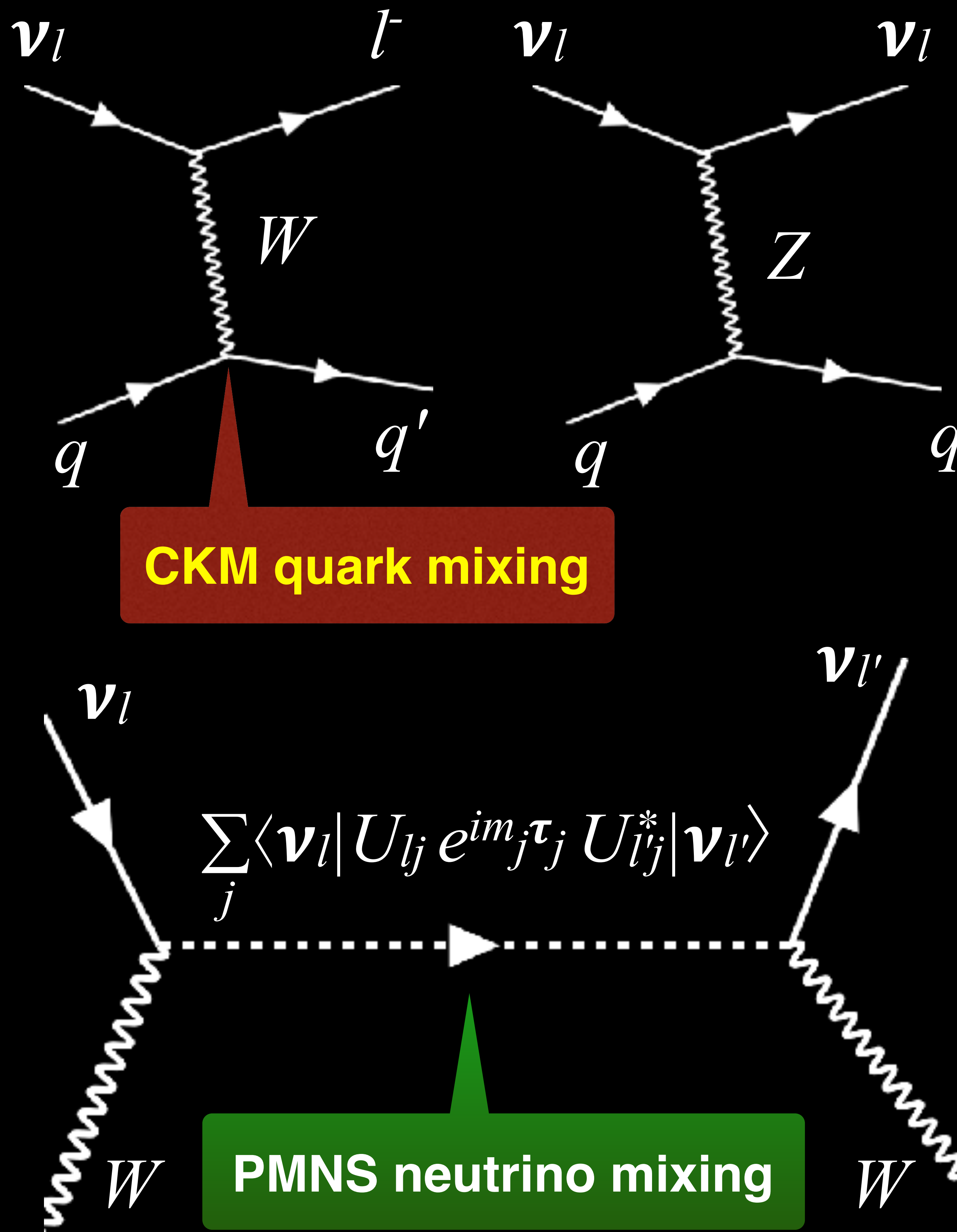
νl
l-
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νl
W
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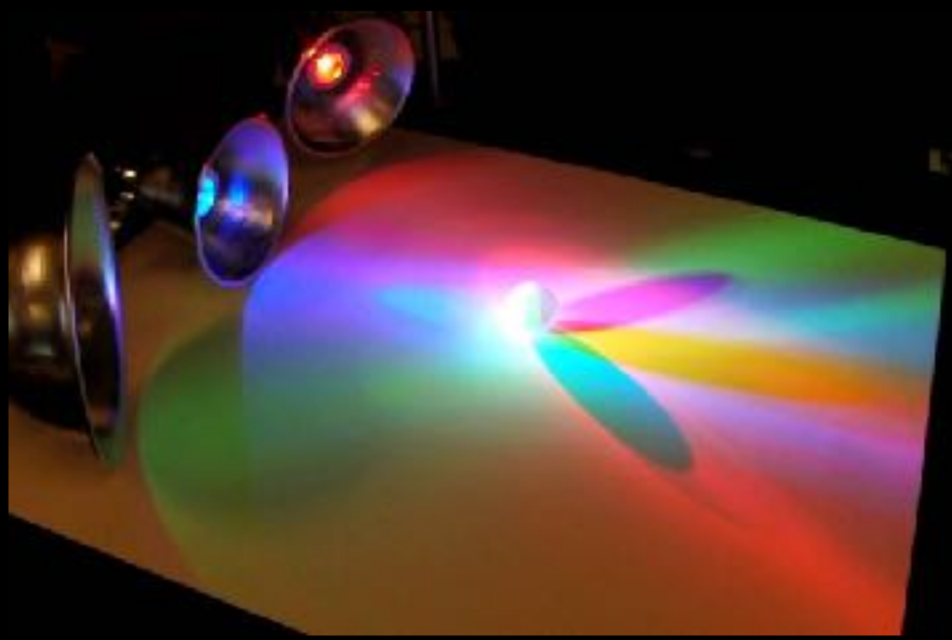
q
q'
q
q
CKM quark mixing
νl
νl'
$\sum_j \langle \boldsymbol{\nu}_l | U_{lj}\, e^{im_j\tau_j}\, U^*_{l'j} | \boldsymbol{\nu}_{l'} \rangle$
W
PMNS neutrino mixing
W

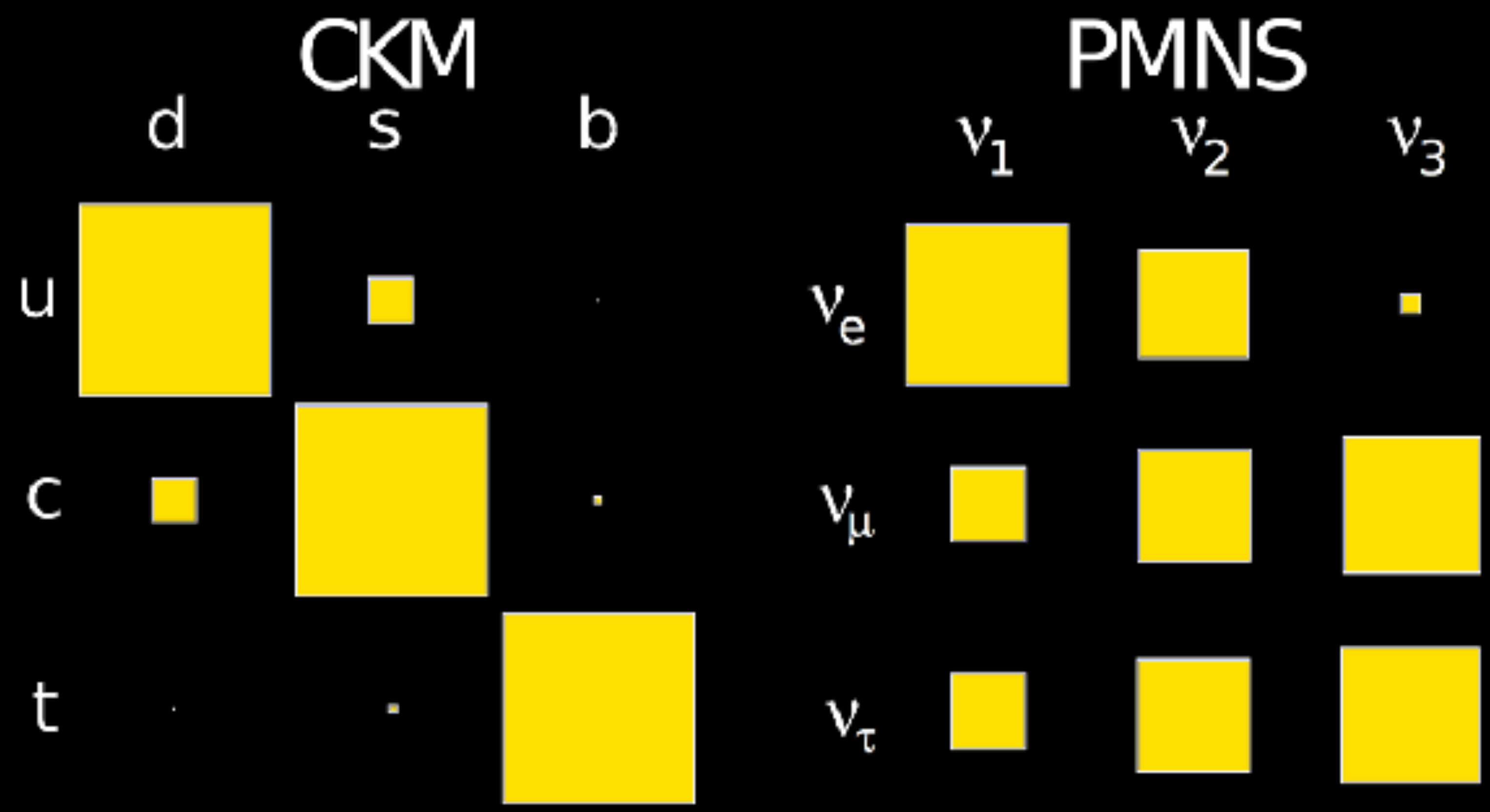
Neutrino

- Neutrinos mix, just like quarks?



$$|\boldsymbol{\nu}_l\rangle = \sum_i U^*_{li}|\boldsymbol{\nu}_i\rangle \quad l=e,\mu,\tau \quad i=1,2,3$$

- PMNS matrix like CKM matrix?
- Unlike the quarks, neutrino mixing are large



Neutrino oscillations

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

Neutrino oscillations

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 1^\circ$ small ? $\theta_{12} \sim 12^\circ$

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$|\Delta m^2_{32}| = |m^2_3 - m^2_2|$
$\simeq 2.5 \times 10^{-3}$ eV^2
$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$

atmospheric and long baseline

$\Delta m^2_{31} \simeq \Delta m^2_{32}$
$\nu_e \to \nu_e$
$\nu_\mu \to \nu_e$

reactor and long baseline

$\Delta m^2_{21} = |m^2_2 - m^2_1|$
$\simeq 7.5 \times 10^{-5}$ eV^2
$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu, \nu_\tau$

solar and reactor

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

Reactor Experiments Provided Breakthrough on θ_{13}

- Daya Bay, RENO and Double Chooz

Neutrino oscillations

$\theta_{23} \sim 45^\circ$ $\qquad$ $\theta_{13} \sim 8.5^\circ$ $\qquad$ $\theta_{12} \sim 12^\circ$

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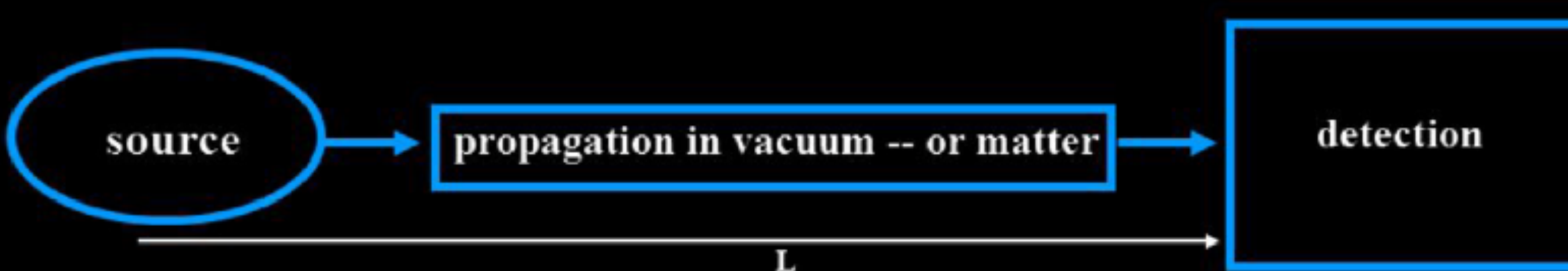

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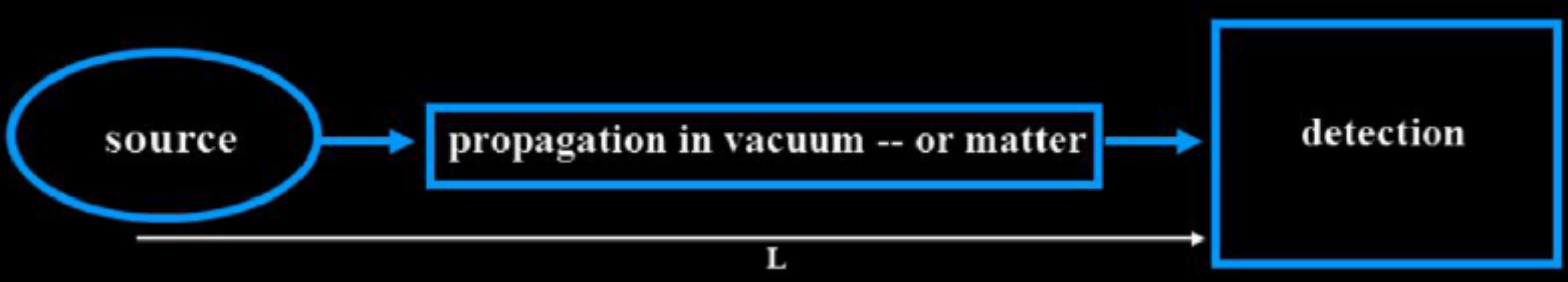

Mixing patterns

- Only a small fraction of ν_e in $|\nu_3\rangle$ (the famous $\mathrm{Sin}^2 2\theta_{13}$)
- The remainder is split about 50/50 ν_μ/ν_τ ($\mathrm{Sin}^2\theta_{23}$)
- Accident? Or a sign of underlying structure?

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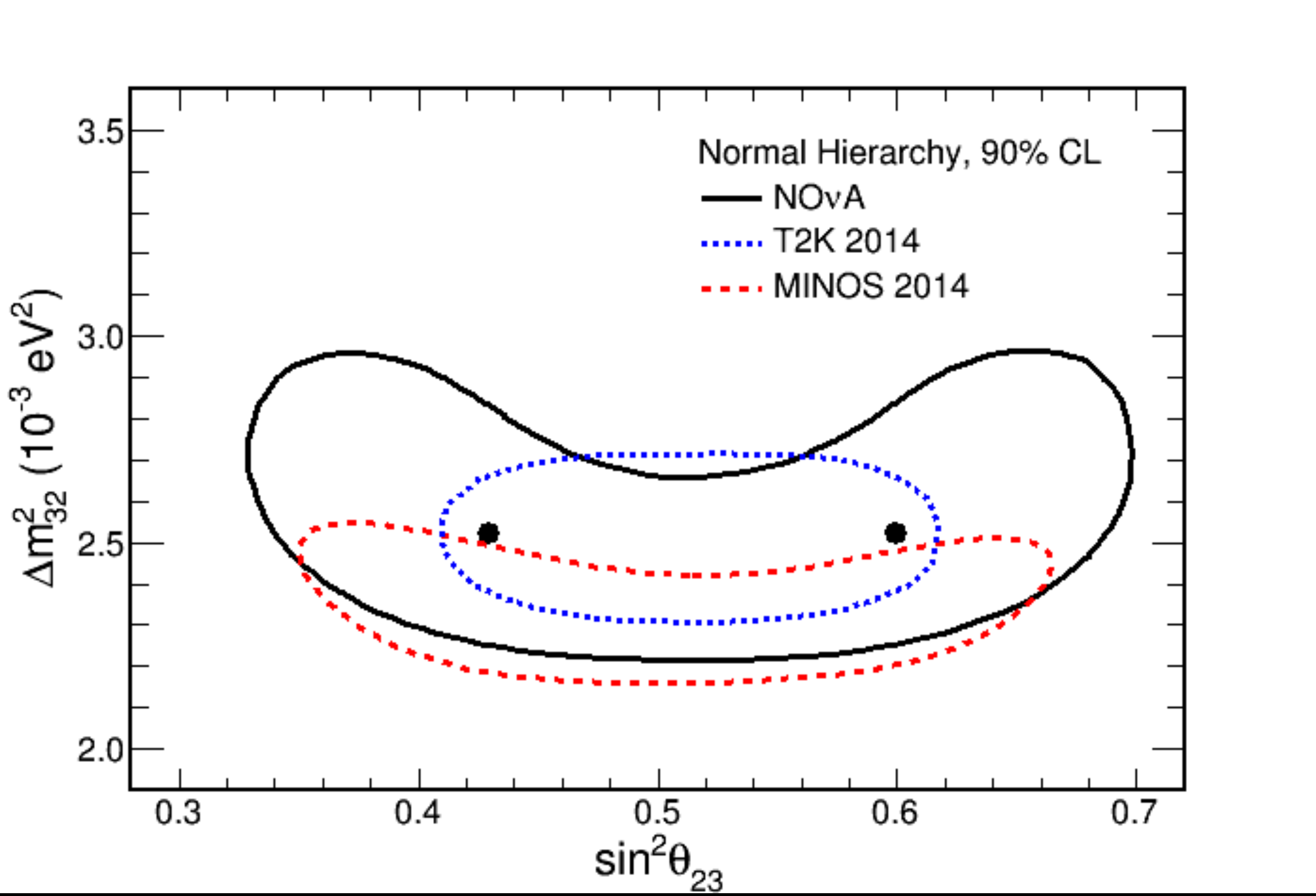
- Accident? Or a sign of underlying structure?

- Is θ_{23} exactly 45°?
- If not, it is

➡ $< 45^\circ$ $|\nu_3\rangle$ more ν_τ, like in quarks

➡ $> 45^\circ$ $|\nu_3\rangle$ more ν_μ, unlike quarks

Previous experimental results including NOvA 2015



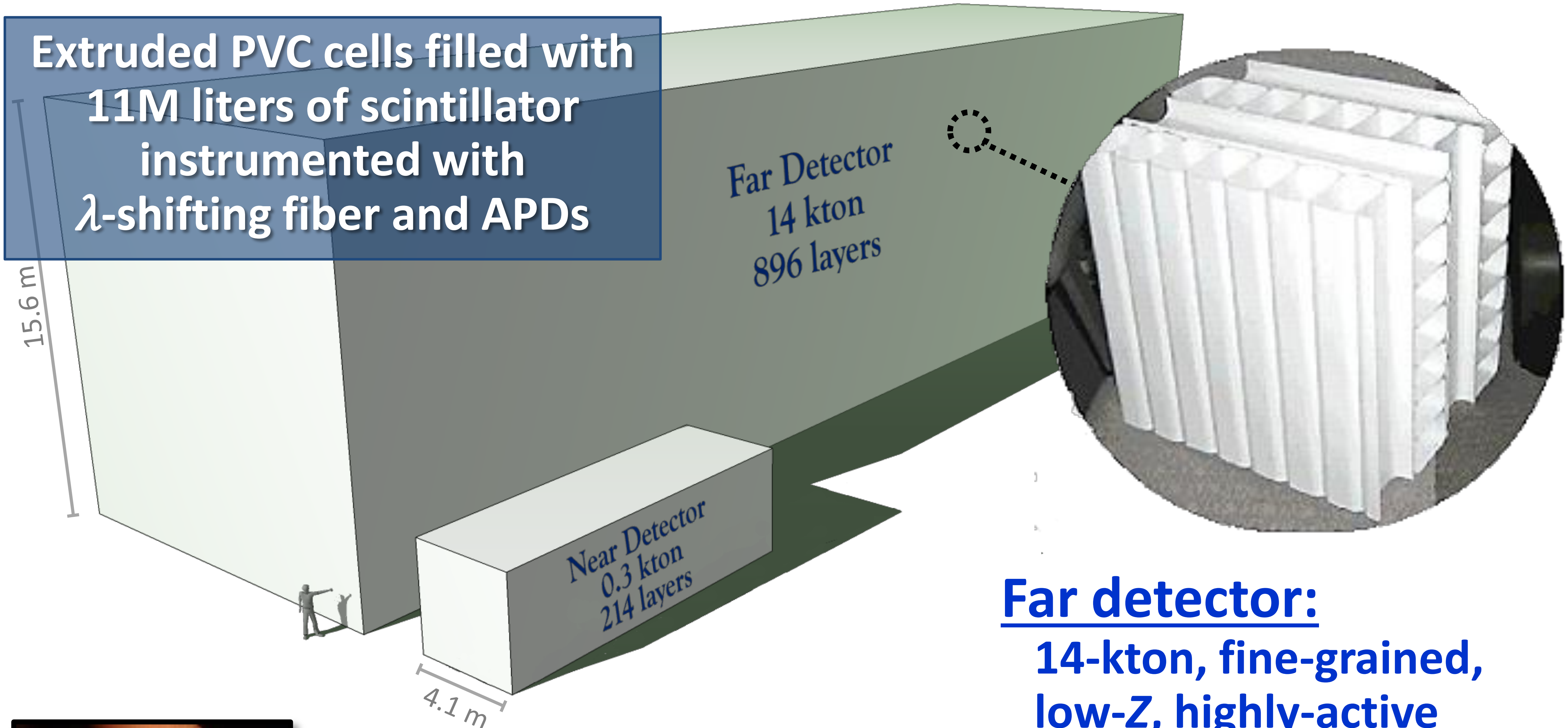
$\theta_{23} \simeq \pi/4$: $\nu_\mu — \nu_\tau$ symmetry ?

Neutrino Oscillation

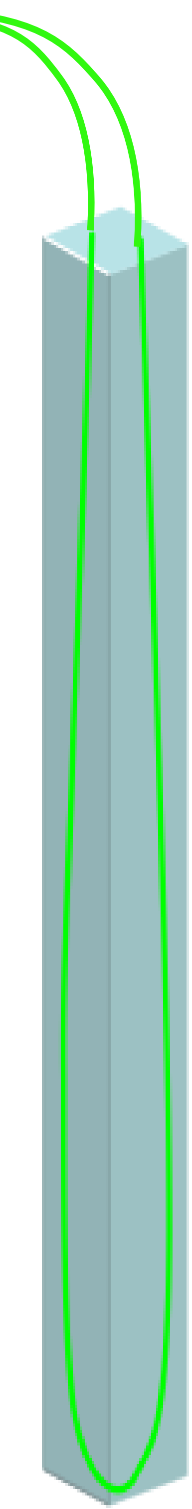
ν_e Appearance

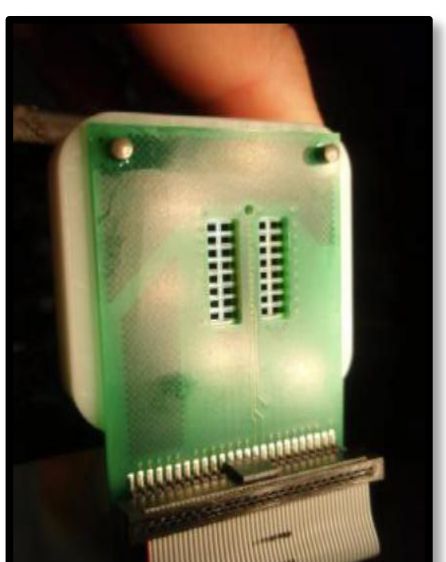
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

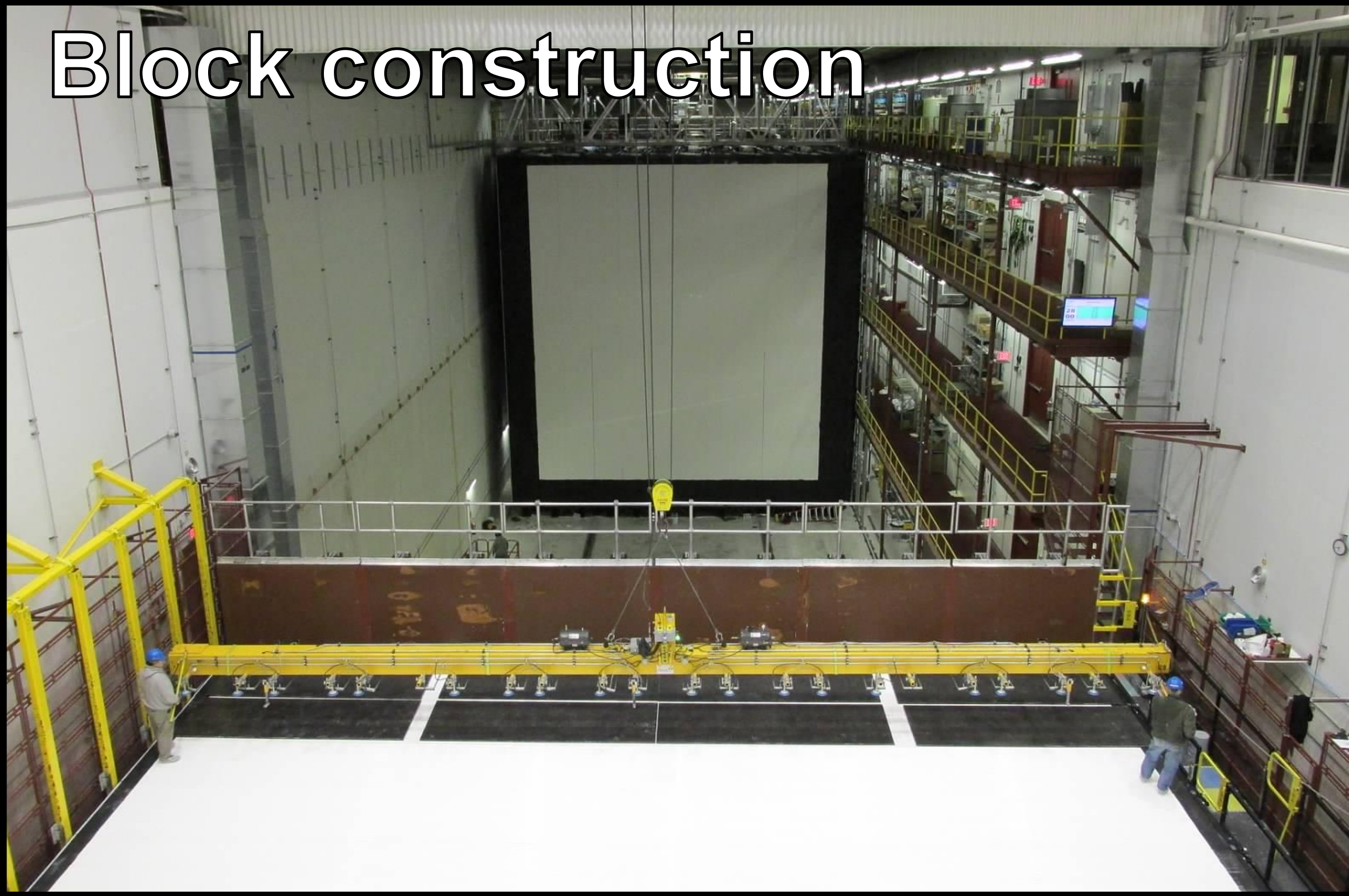
Far detector:

14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:

0.3-kton version of the same
→ *20,000 channels*

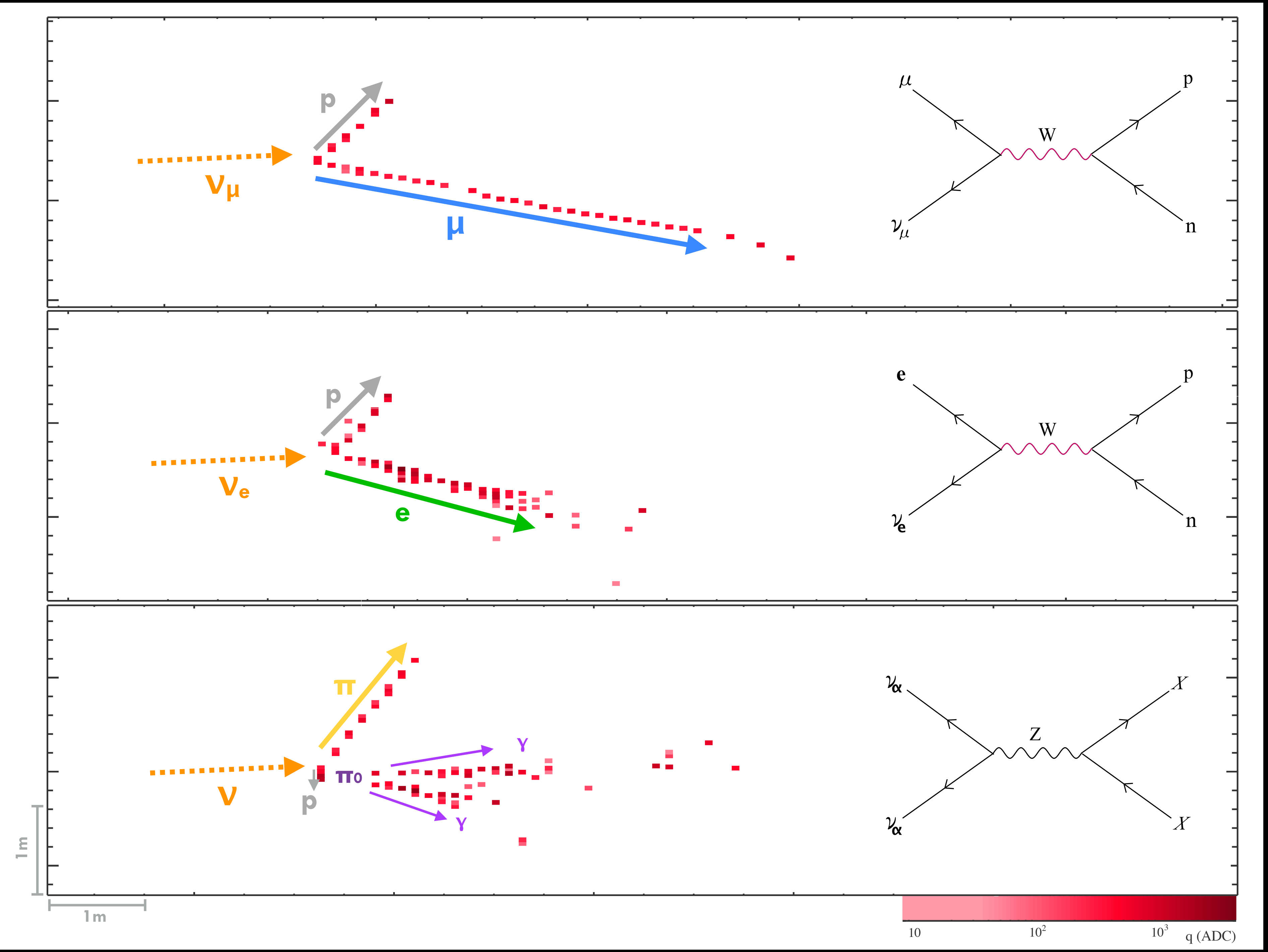

Far Detector site


Block construction


Outfitted Far Detector

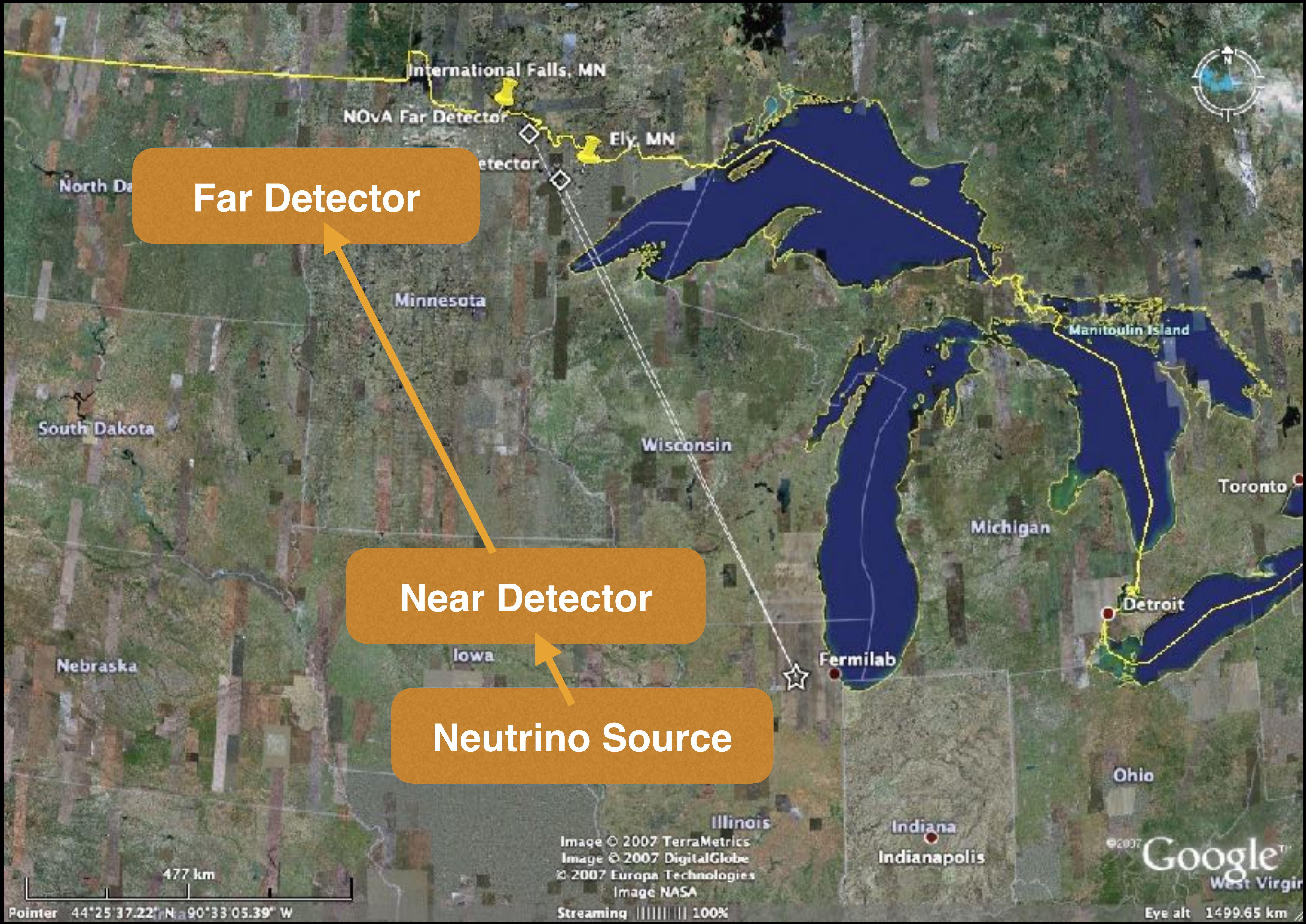

Near Detector

Event topologies



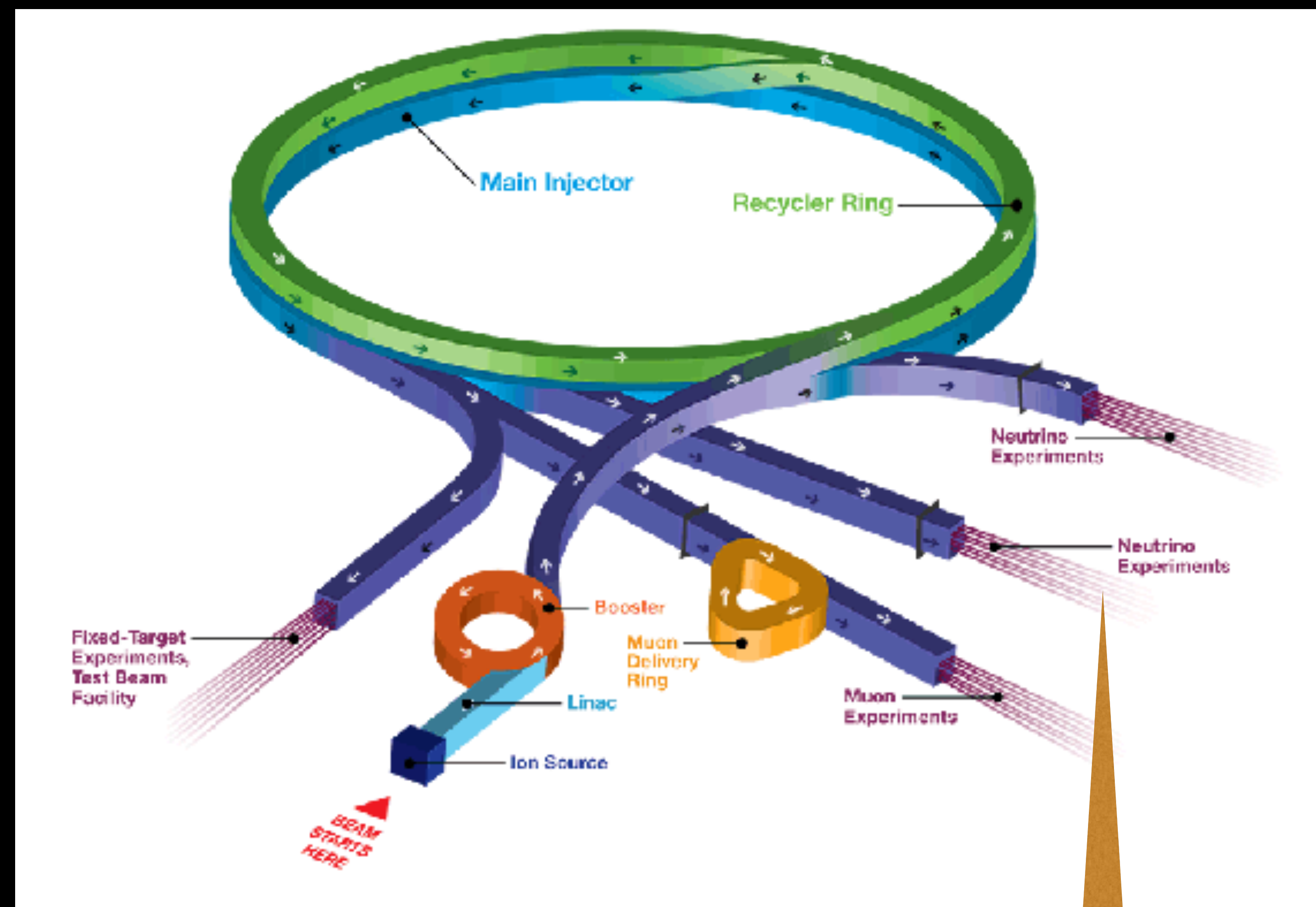
- Very good granularity
- X0 = 38 cm (6 cell depths, 10 cell widths)

NOvA Location - USA, from IL to MN



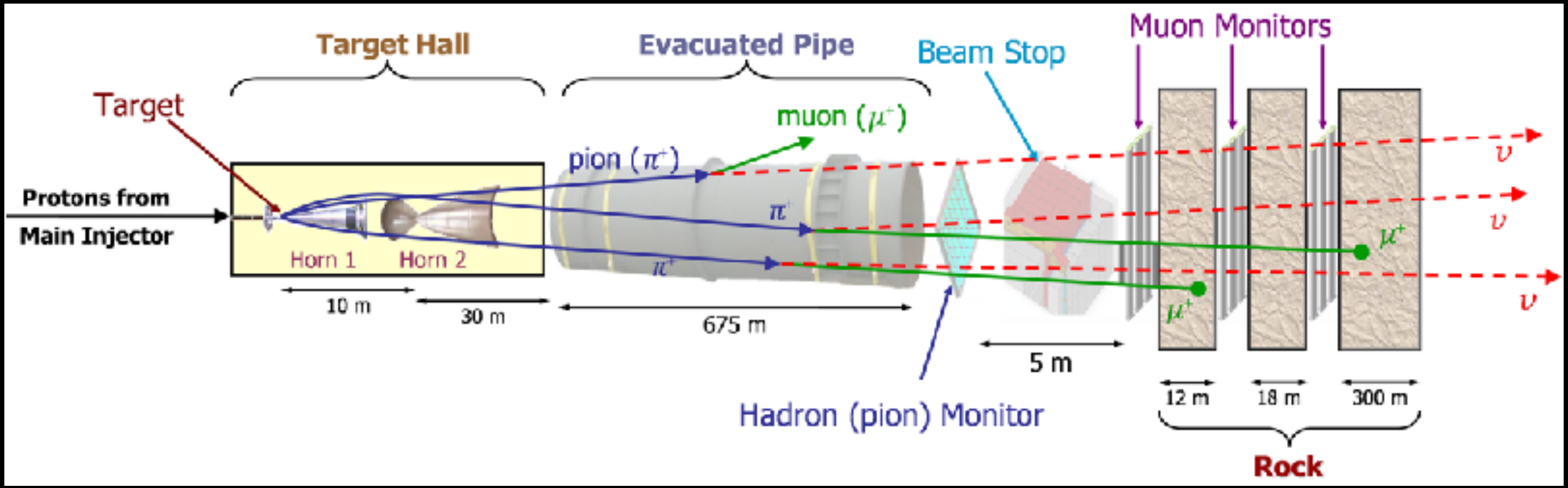
Fermilab accelerator complex

- Neutrinos produced at Main Injector (**NuMI**)
  - ➡ Linac 750 keV
  - ➡ Booster 400 MeV
  - ➡ Recycler 8 GeV
  - ➡ NuMI 120 GeV
  - ➡ to Carbon target



Line to High Energy Neutrino Experiments

The NuMI beam



- 120 GeV protons from MI to Carbon target
- Produce mainly pions and kaons
- Focused by two magnetic horns
- Allow us to select charge sign for (anti)neutrinos
- Neutrinos produced every 1.3 sec in a spill with 6 doubled bunches 10 μs time window
- NuMI designed to provide for NOvA 700kW beam, producing 6×10^{20} POT/year

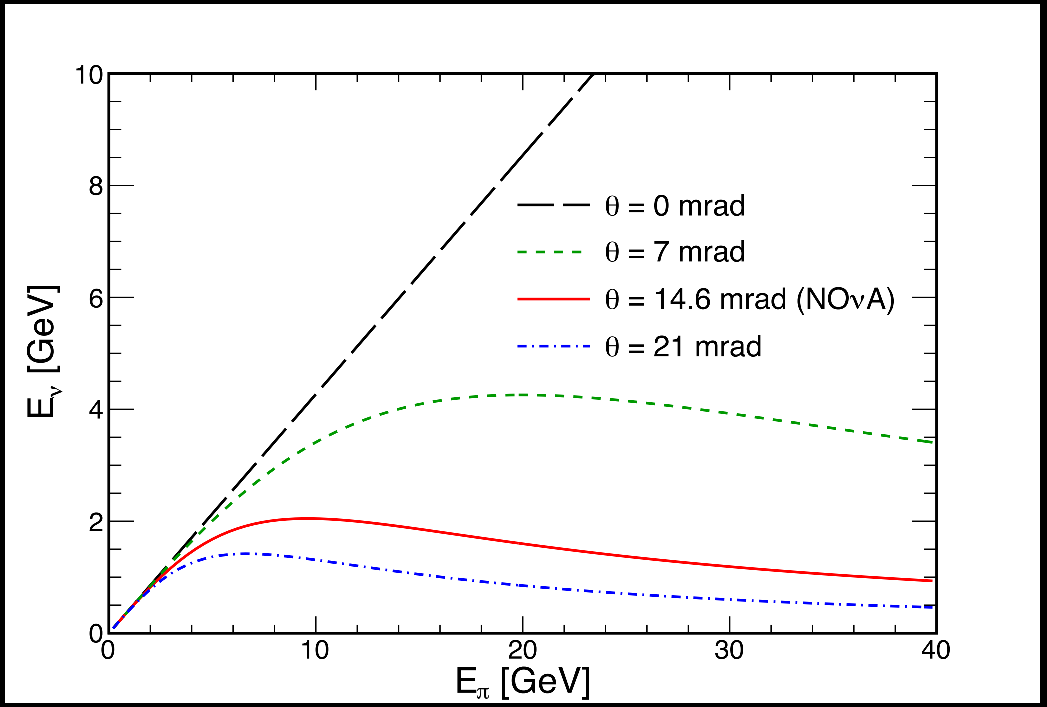
NuMI off-axis beam

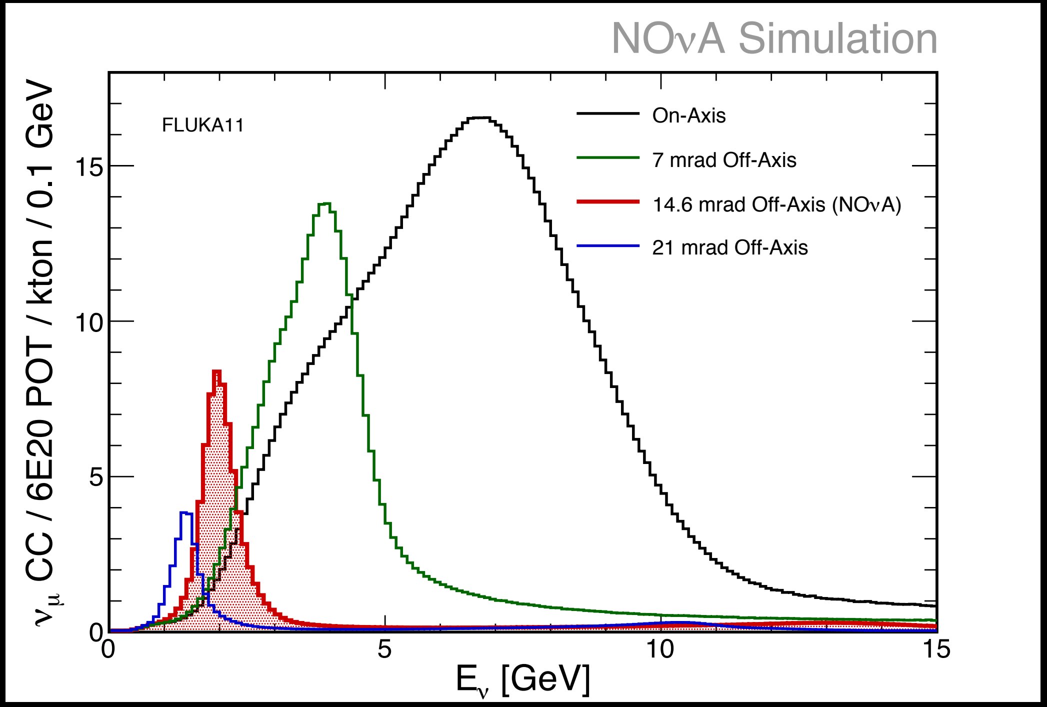
- NOvA detectors are sited **14 mrad** off the NuMI beam axis
- With the **medium-energy NuMI** tune, yields a narrow 2-GeV spectrum at the NOvA detectors

➡ **Reduces NC and ν_e CC backgrounds** in the oscillation analyses while maintaining **high ν_μ flux at 2 GeV**

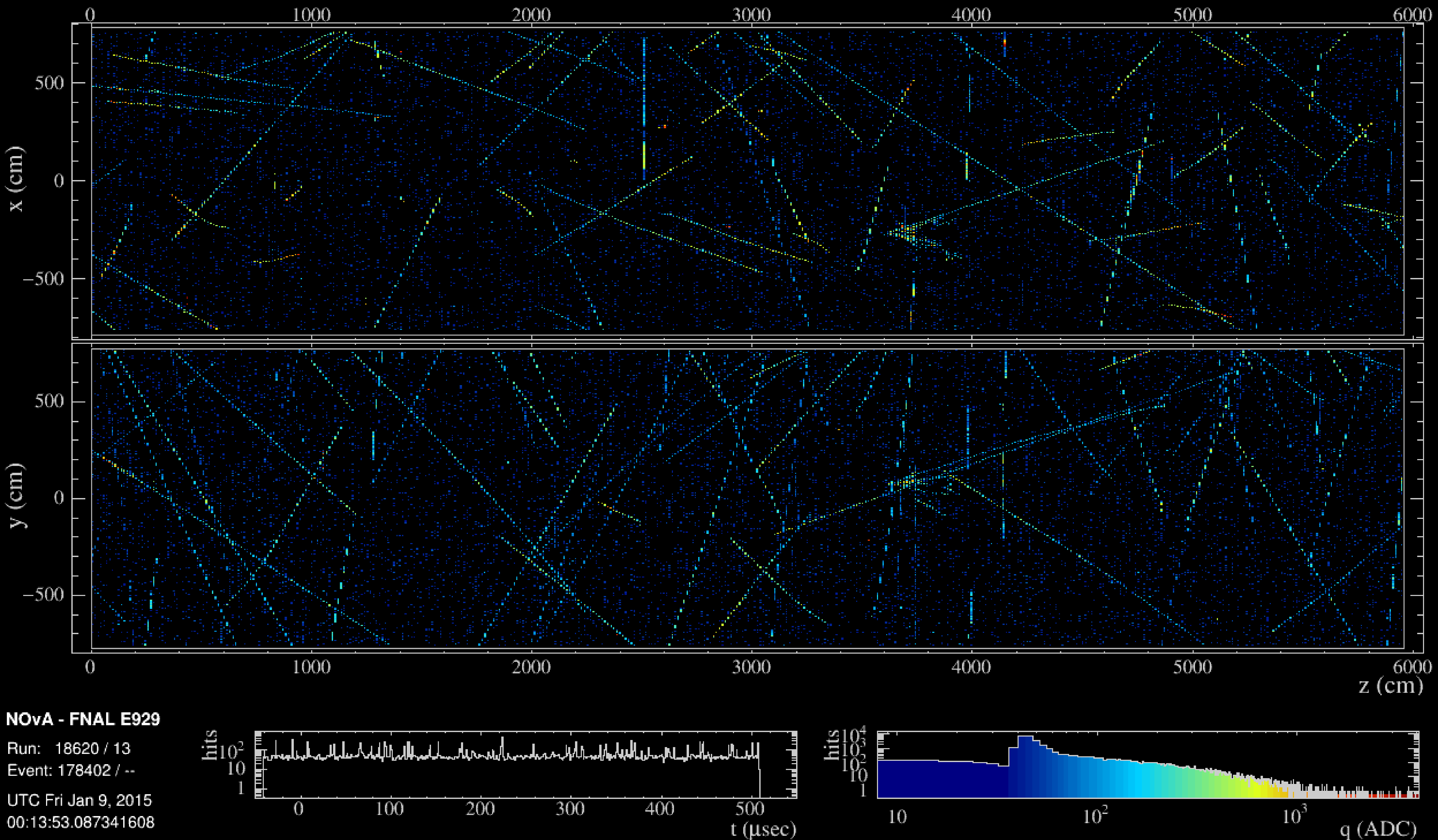
- Flavour composition of beam neutrinos interacting in ND/FD

ν_μ	97,5 %	97,8 %
$\overline{\nu}_\mu$	1,8 %	1,6 %
$\nu_e+\overline{\nu}_e$	0,7 %	0,6 %

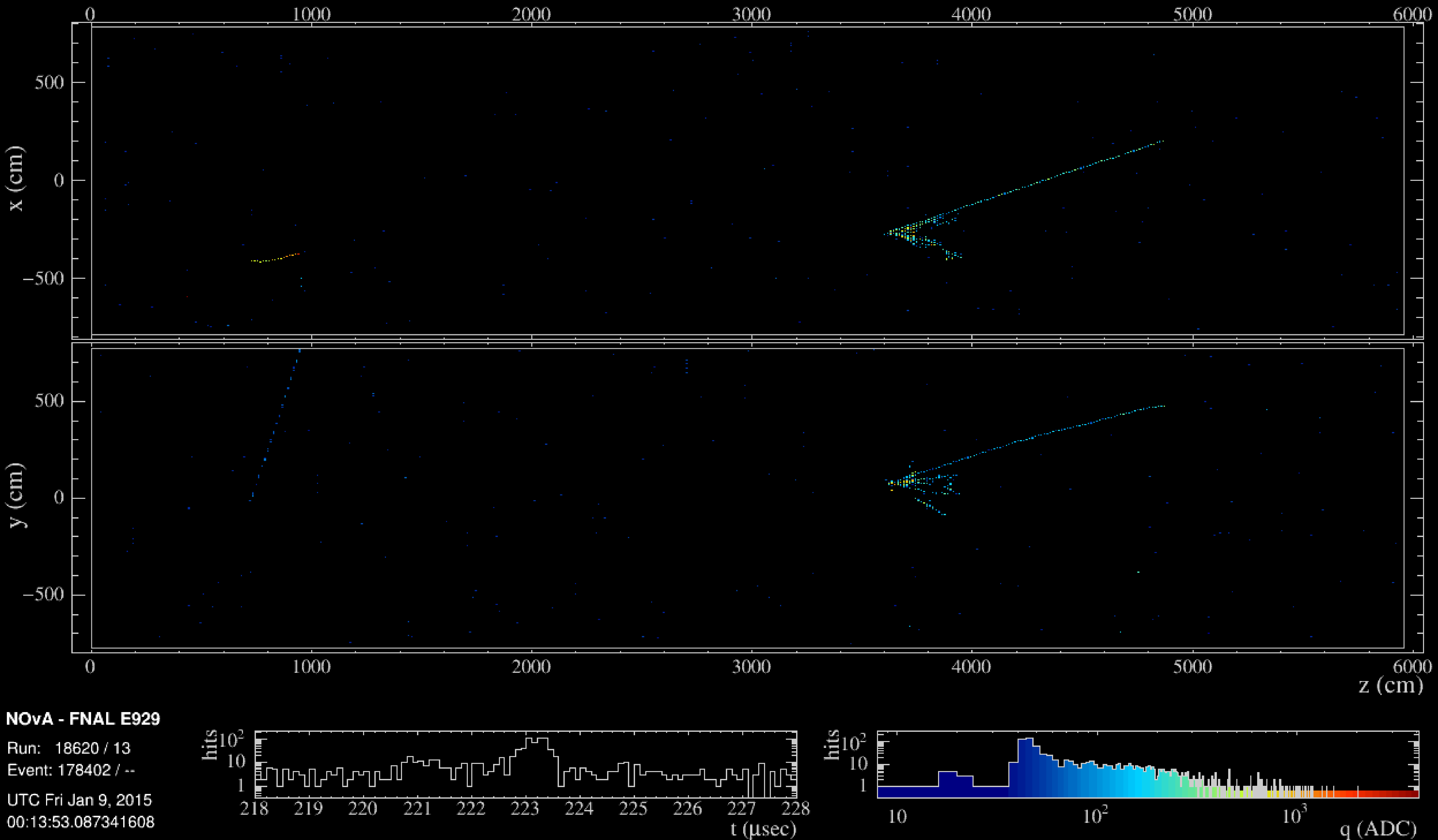




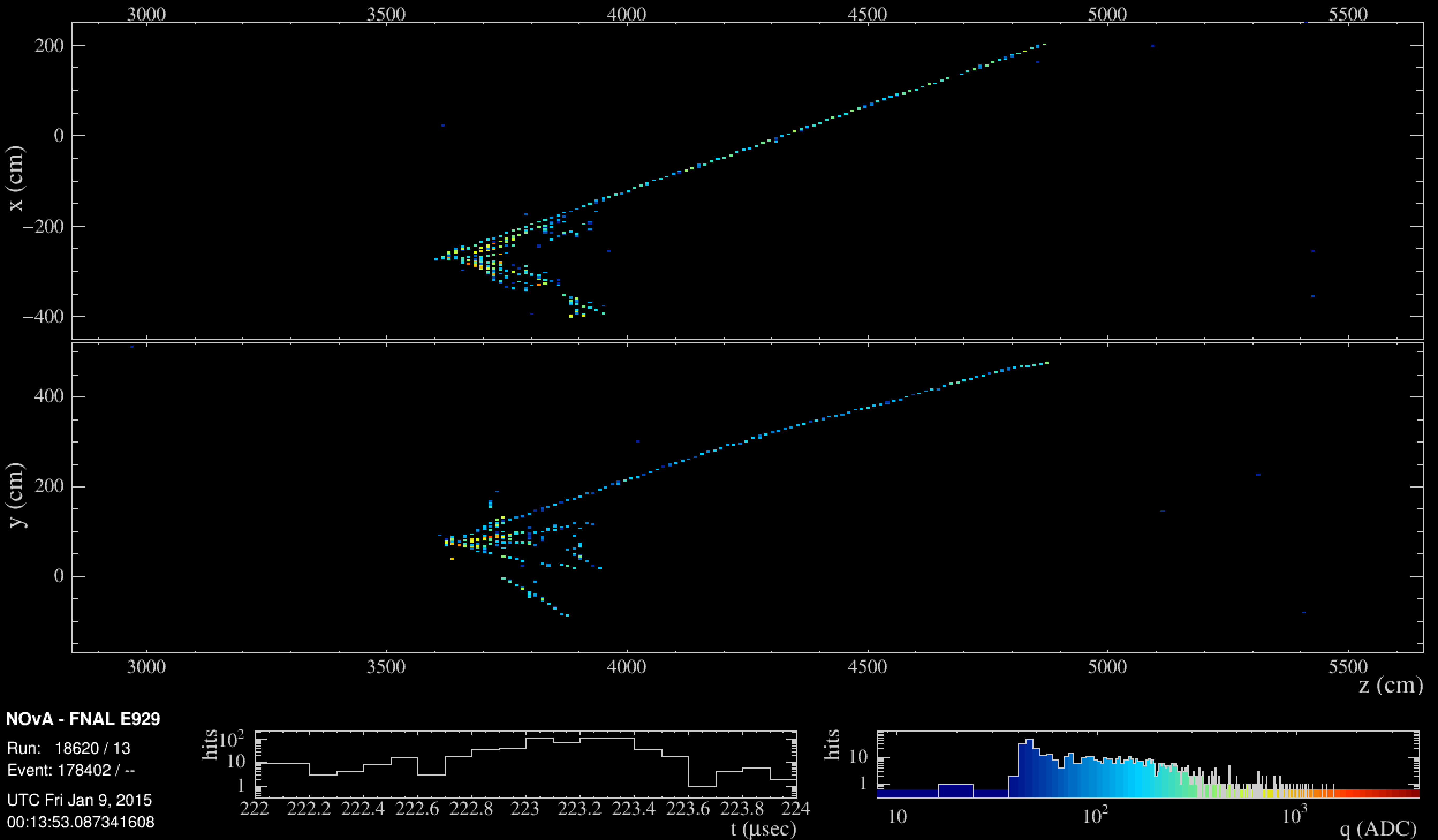
550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

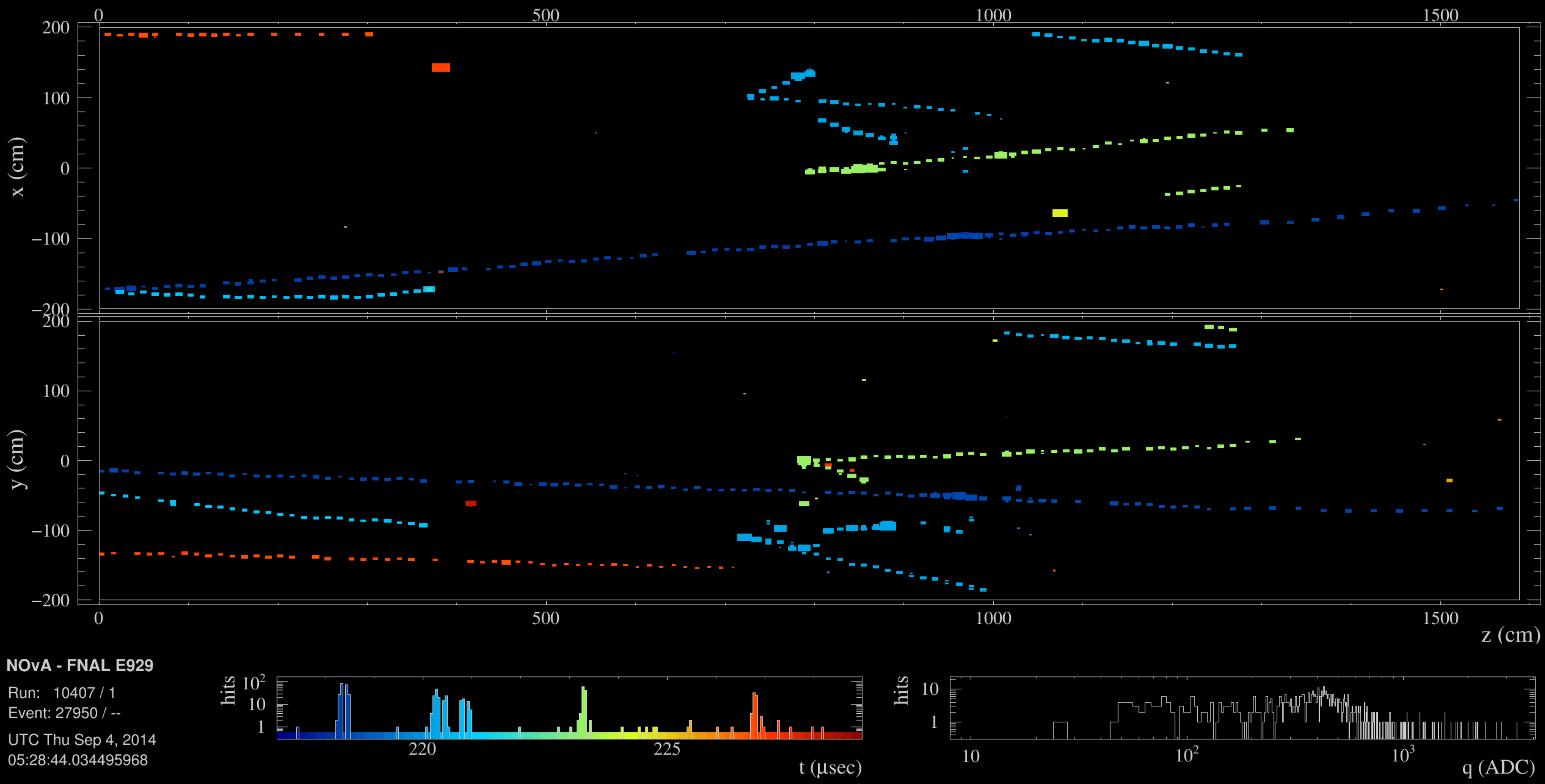


Close-up of neutrino interaction in the Far Detector



Near Detector: 10 μs of readout during NuMI beam pulse

(color ⇒ time of hit)



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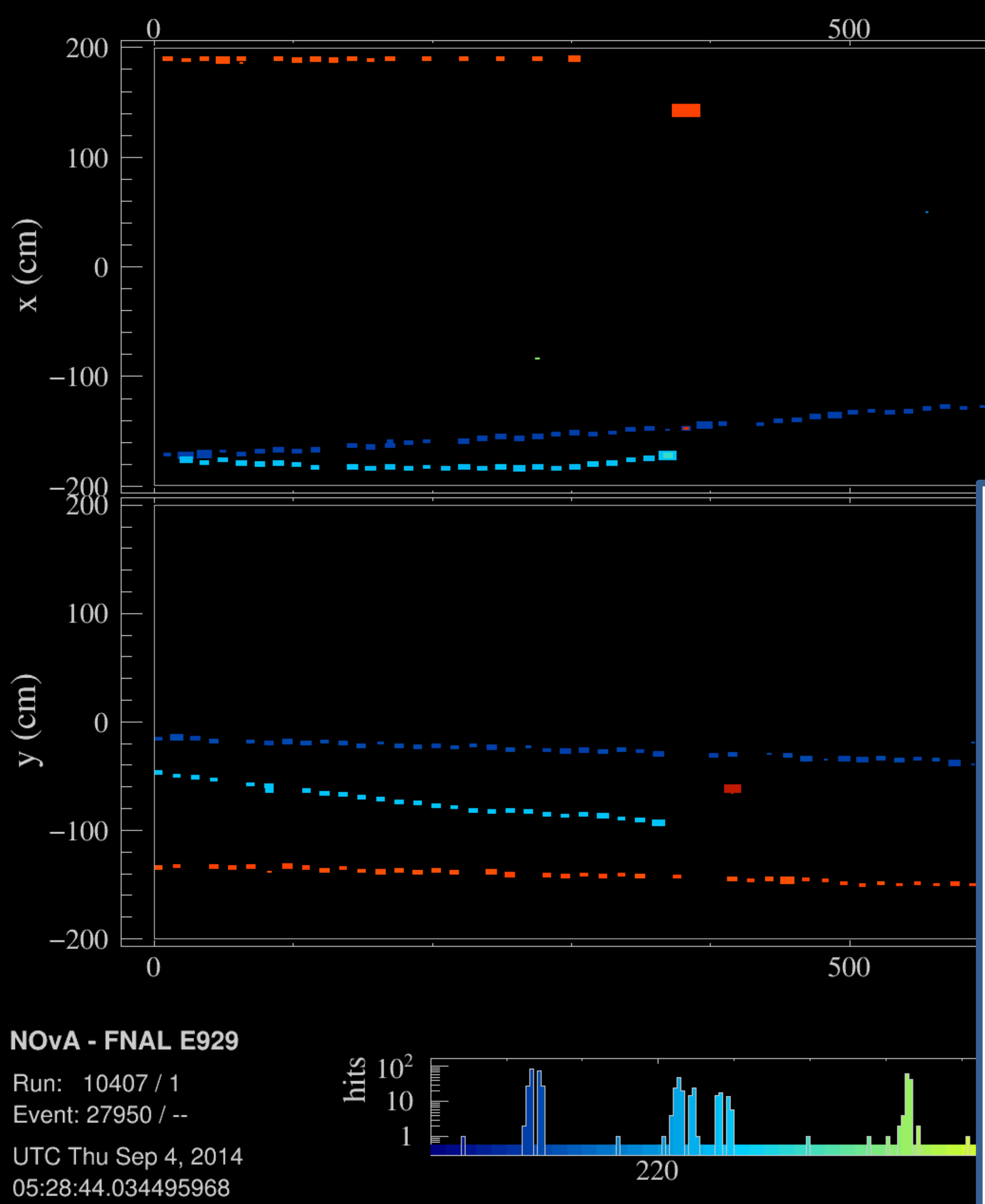
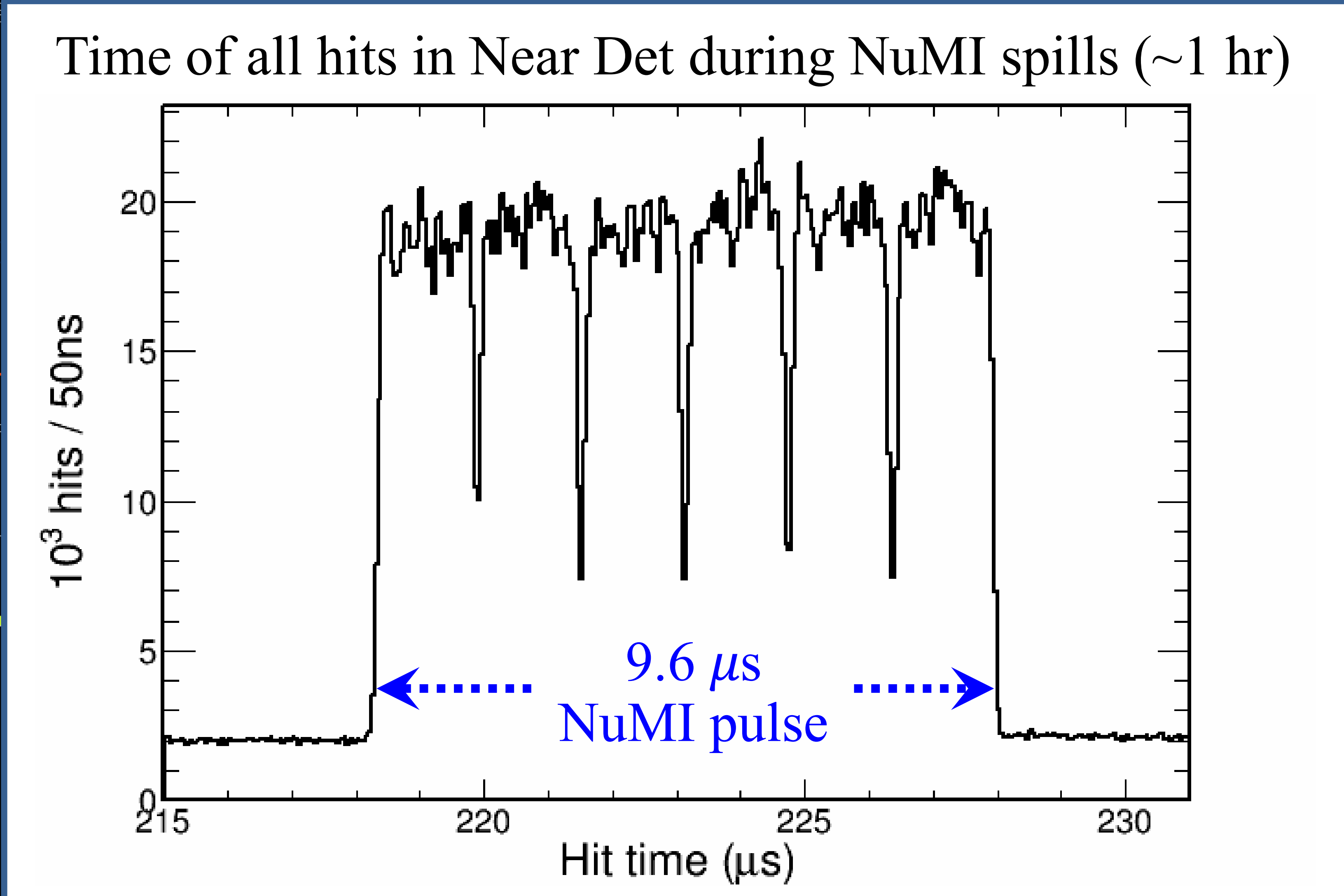
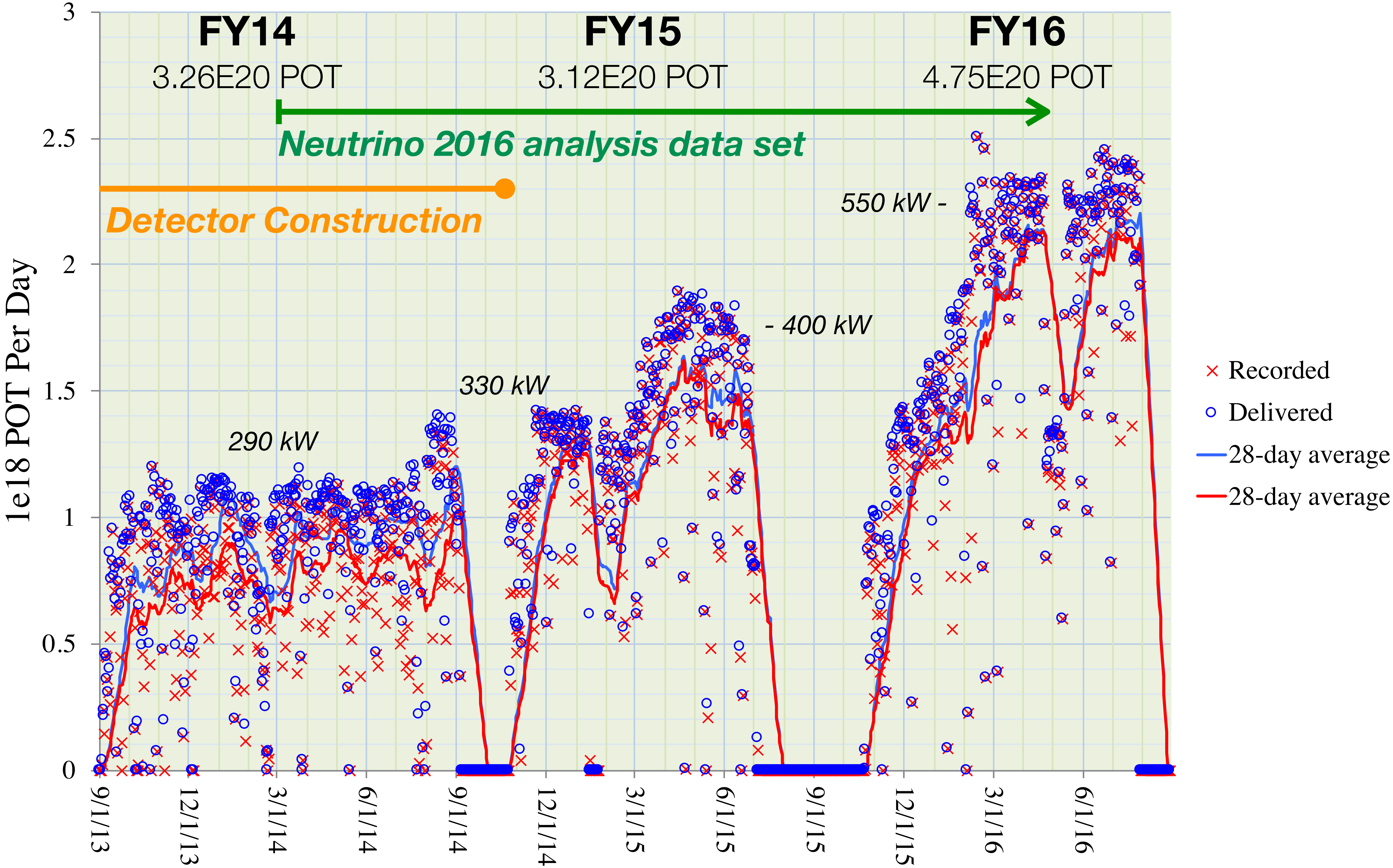






Beam Performance

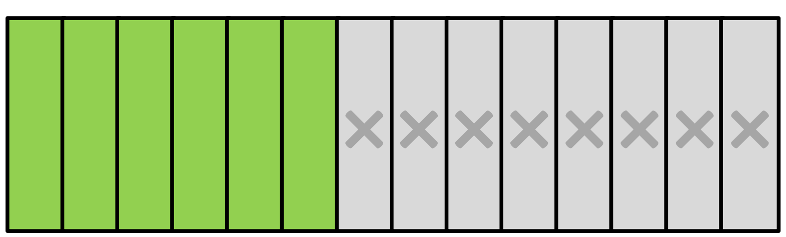
- Last year saw routine delivery at 550 kW of proton power.
- Peak of 700 kW demonstrated last year.
- Expect routine operations at 630 kW (700 kW-10%) in early calendar 2017

Far Detector data set

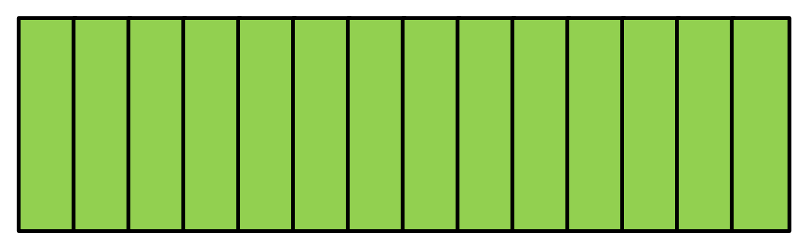
In the First Analysis

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

Protons-on-target in data set:	3.45×10^{20} POT
Fraction of detector operational:	79.4% (POT-weighted average)
Full-detector-equivalent exposure:	**2.74×10^{20} POT-equiv**



Partial Far Detector during construction
(6 diblock example)



Full Far Detector
(14 diblocks)

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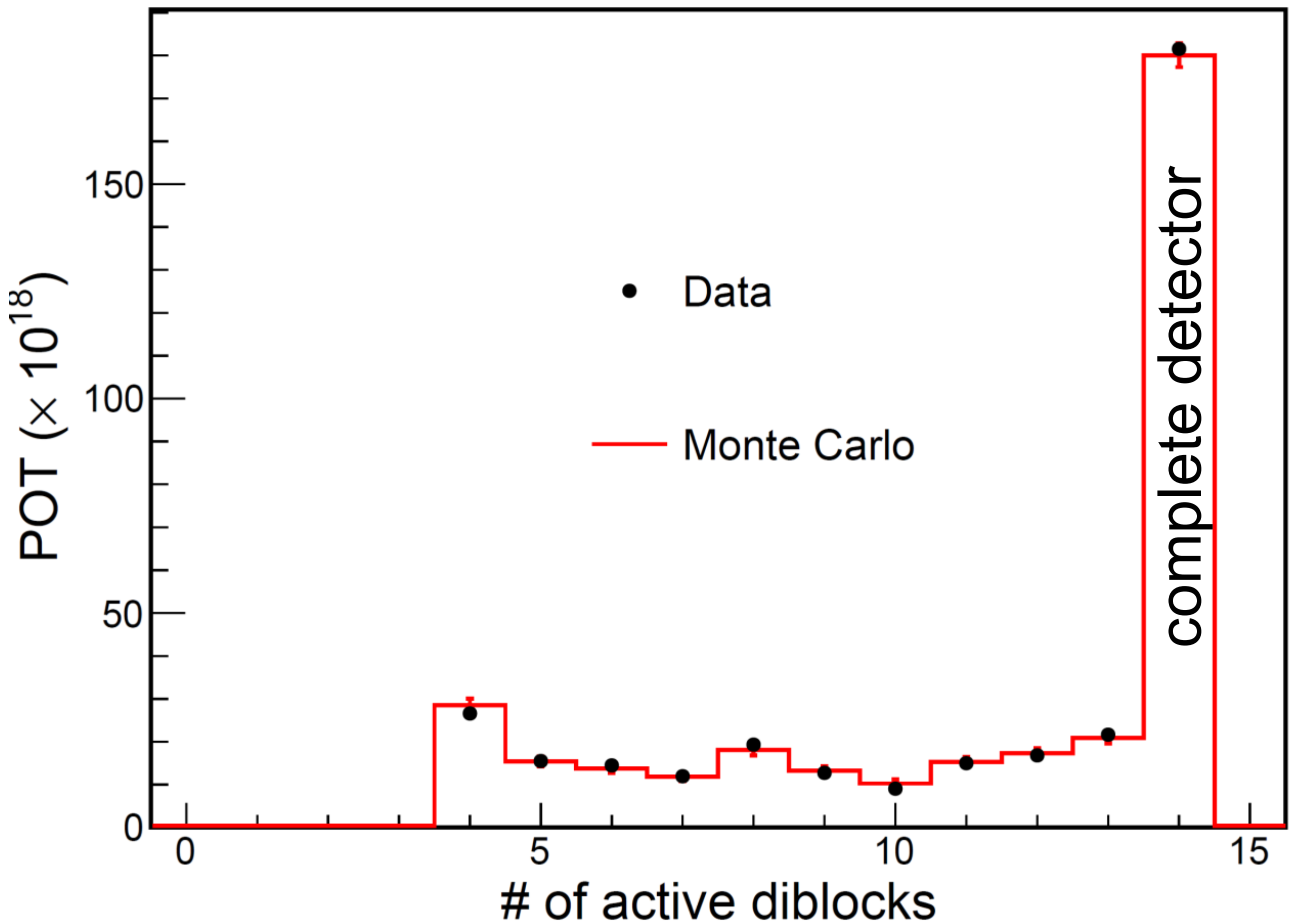
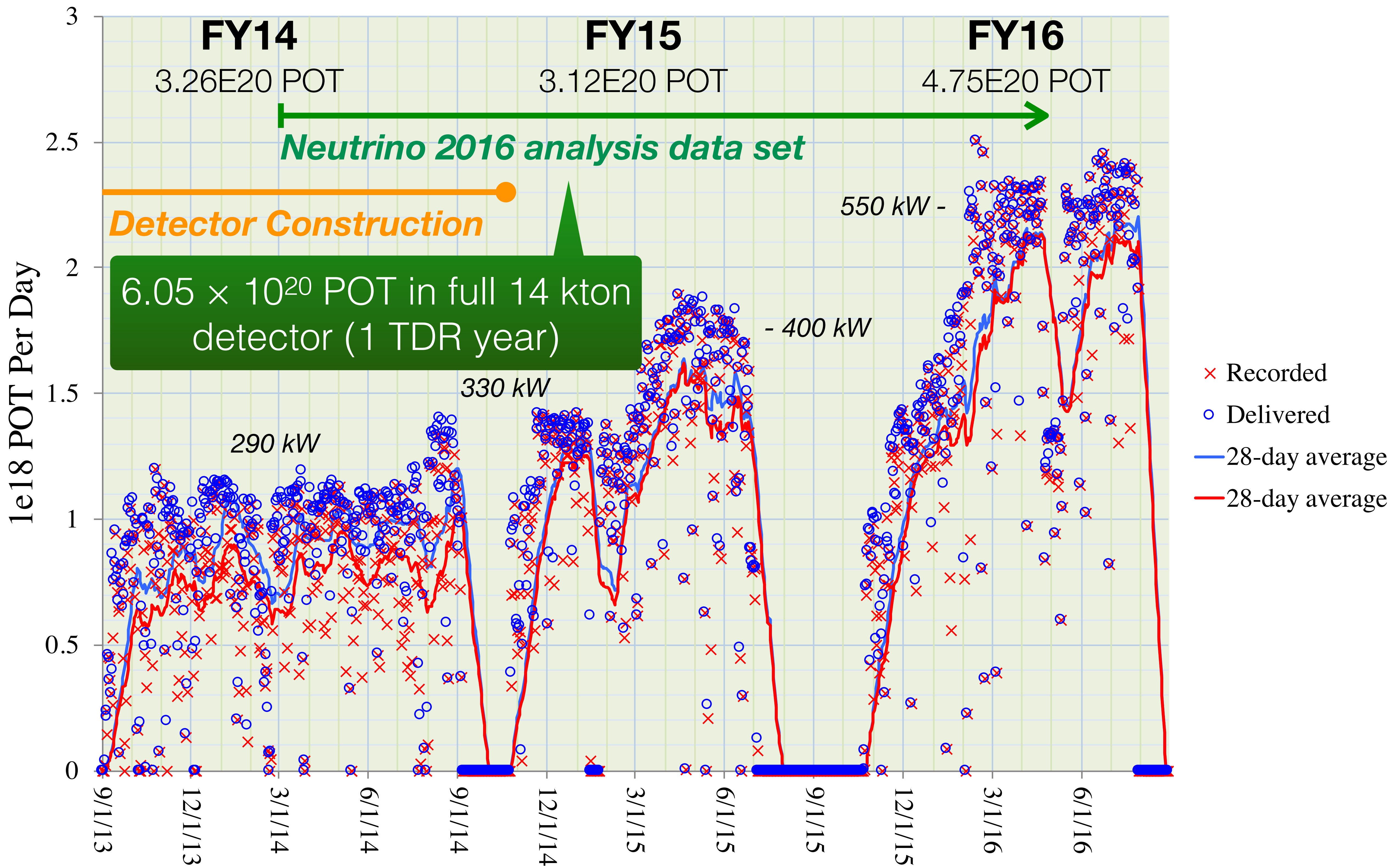
- *Aside:* We simulate the full suite of FD configurations in our analyses





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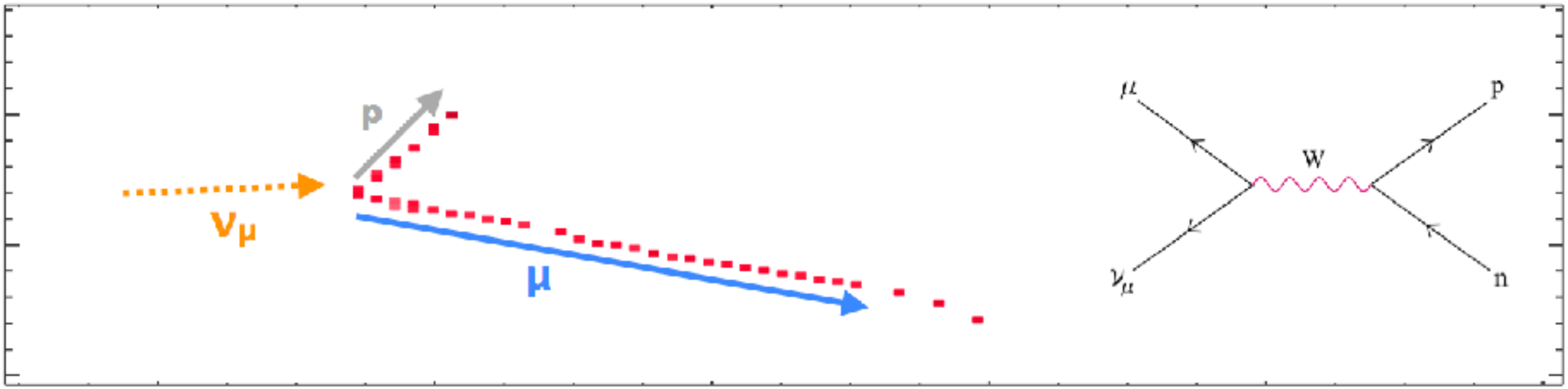
- Expect routine operations at 630 kW (700 kW-10%) in early calendar 2017

Muon Neutrino by Chris Backhouse

Principle of the ν_μ measurement

- Separate ν_μ CC interactions from backgrounds
  - Long muon track with distinctive dE/dx easy to spot

- Extrapolate observed ND spectrum to make FD unosc. prediction
- Measure shape of ν_μ deficit in the FD



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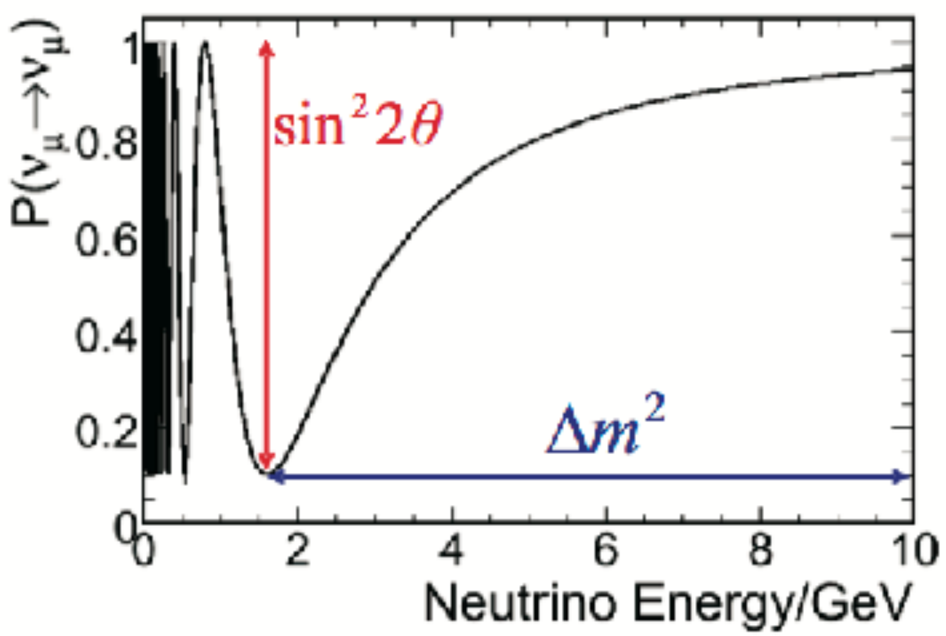
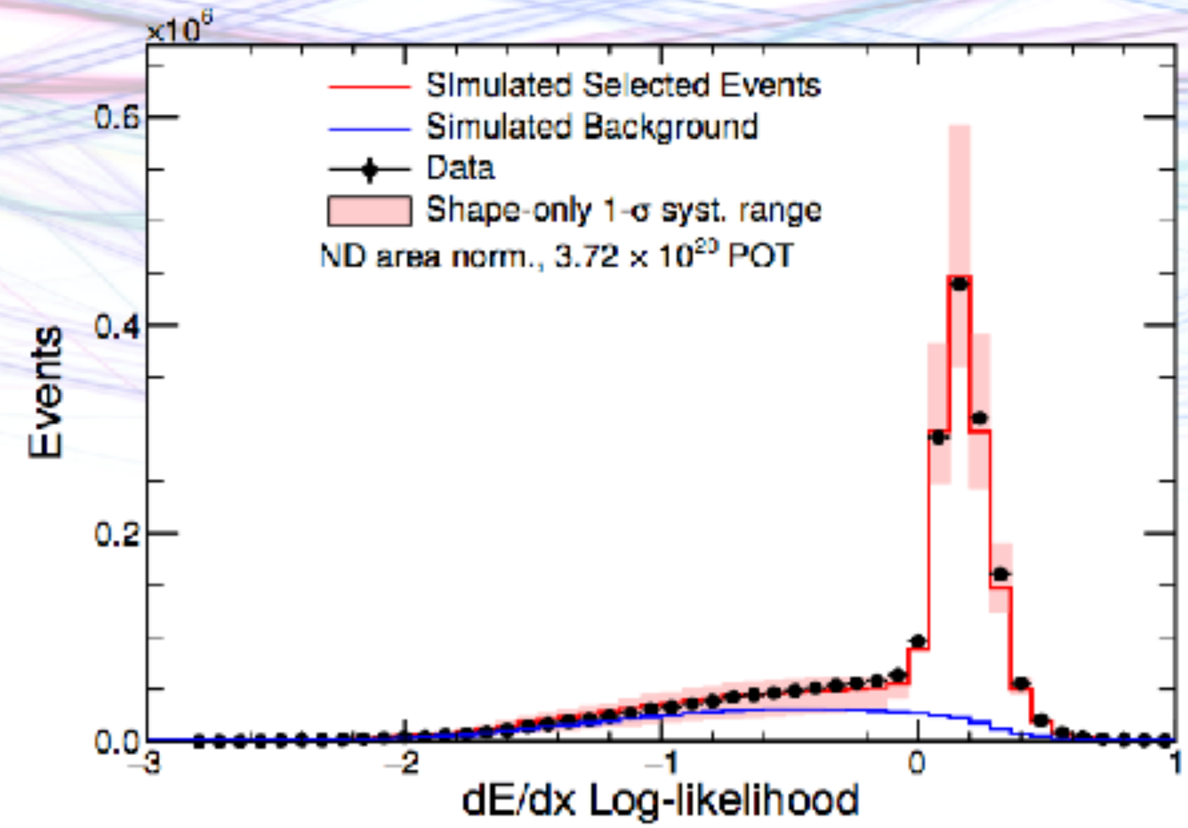
- Two flavor approx. works well here
- $P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$
- $\theta_{23} \approx 45^\circ \rightarrow$ almost all ν_μ expected to disappear at oscillation max.

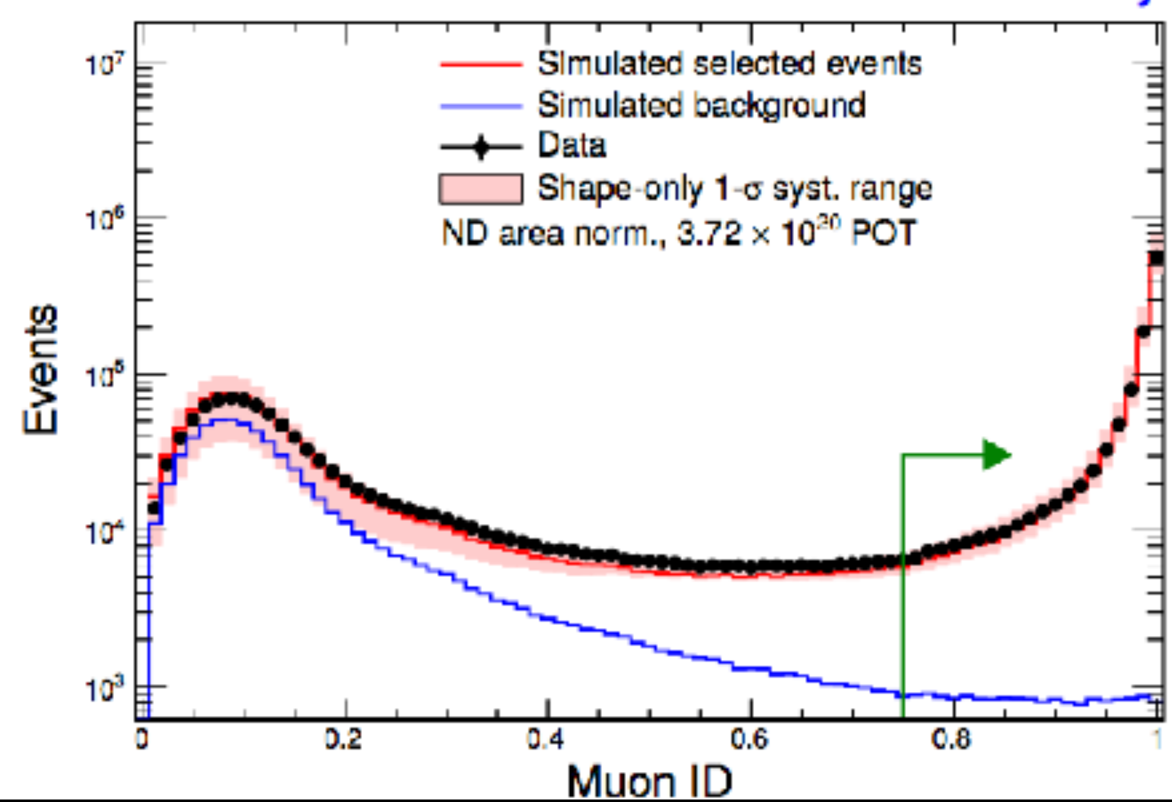


Selecting muon neutrinos

- Basic containment cuts requiring no activity close to detector walls
- kNN-based ν_μ classifier using 4 inputs
  - Track length
  - dE/dx
  - Scattering
  - Fraction of planes that have track-only
- Selection 81% efficient for ν_μ signal, 95% pure

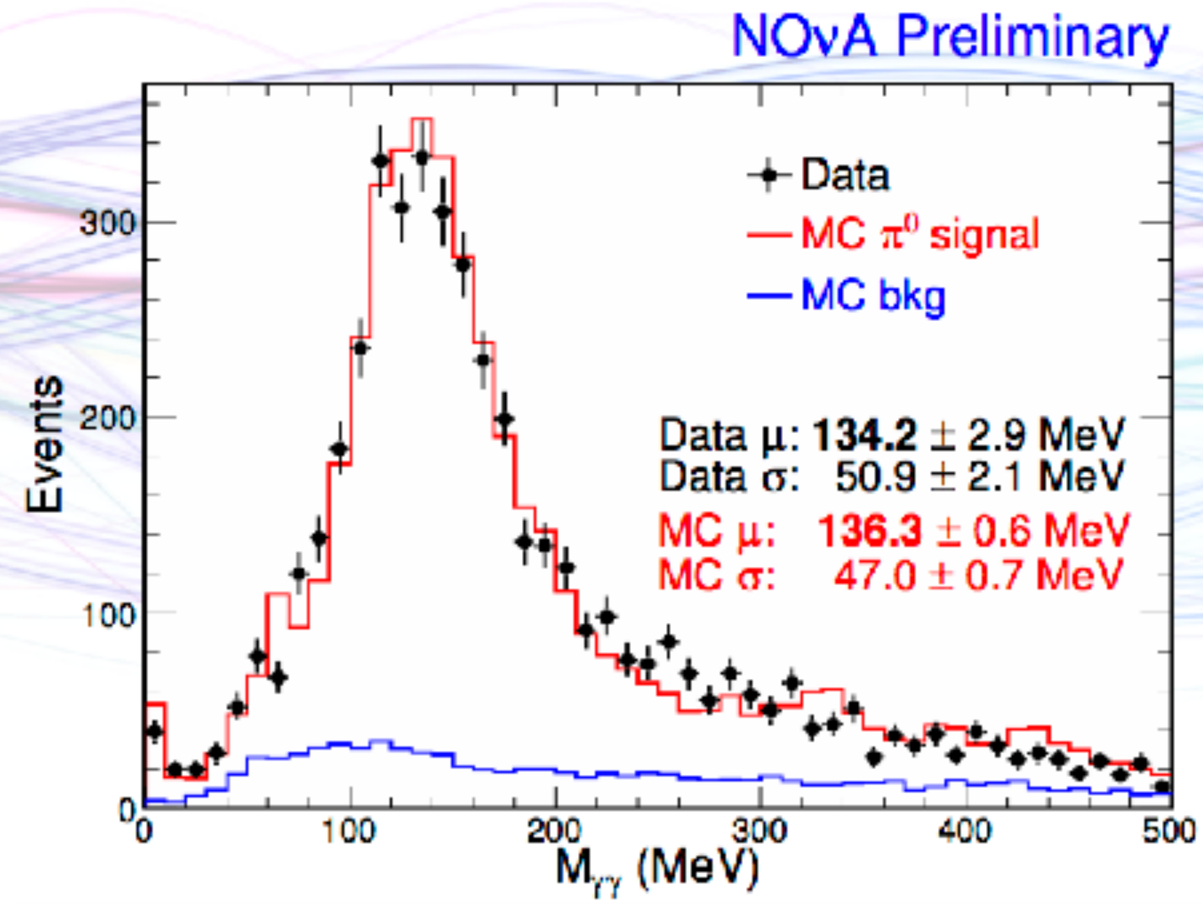


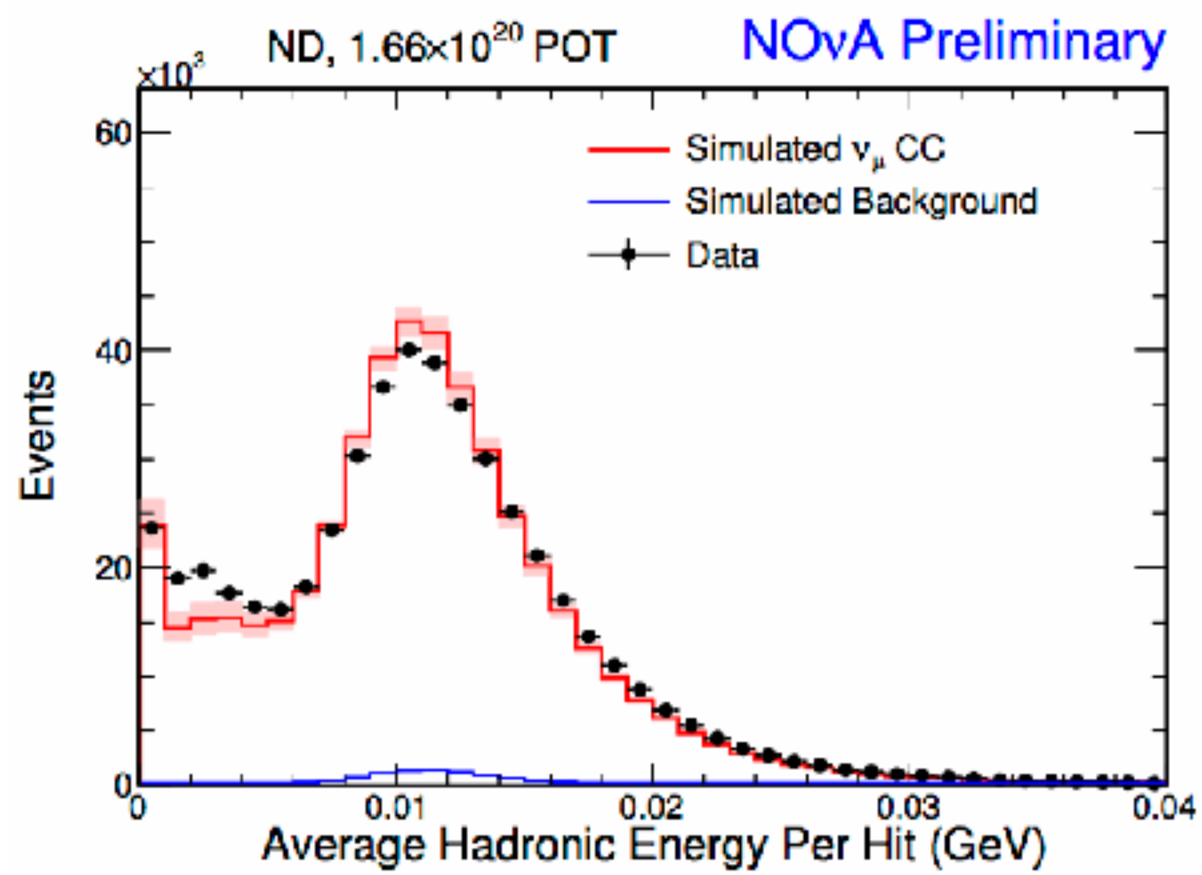
NOvA Preliminary



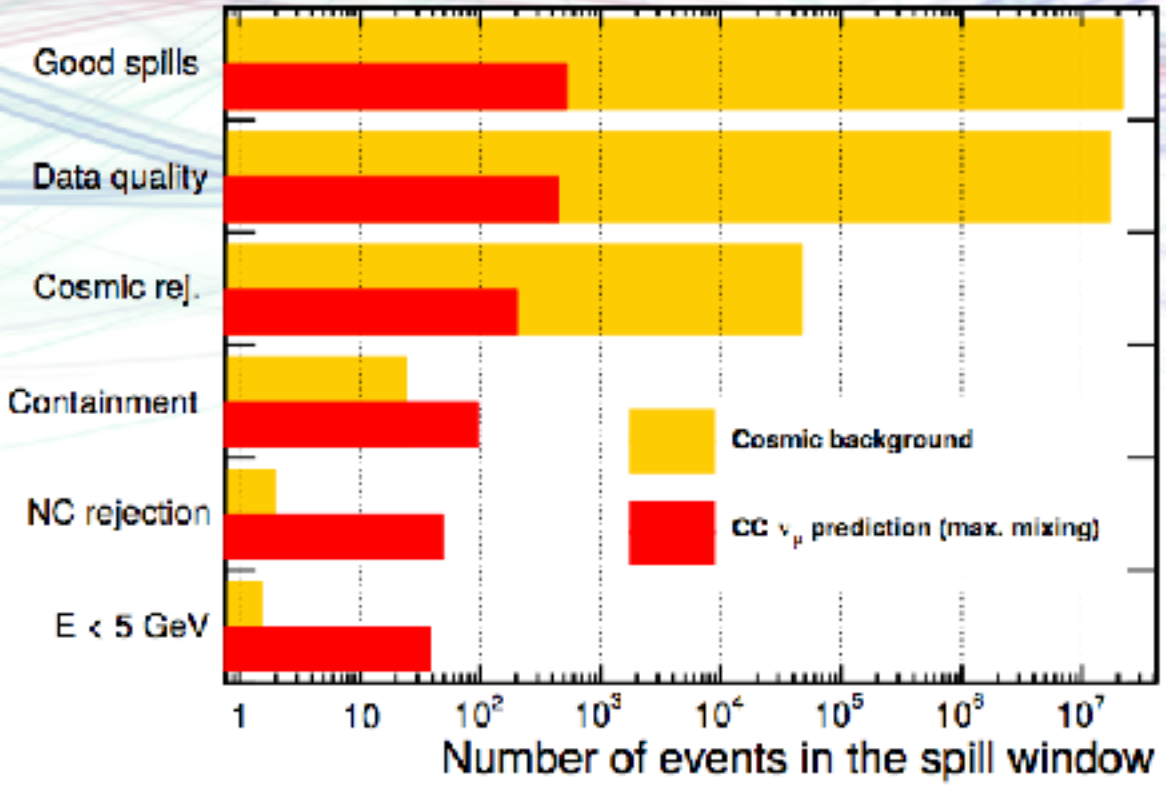
Calibration and energy scale

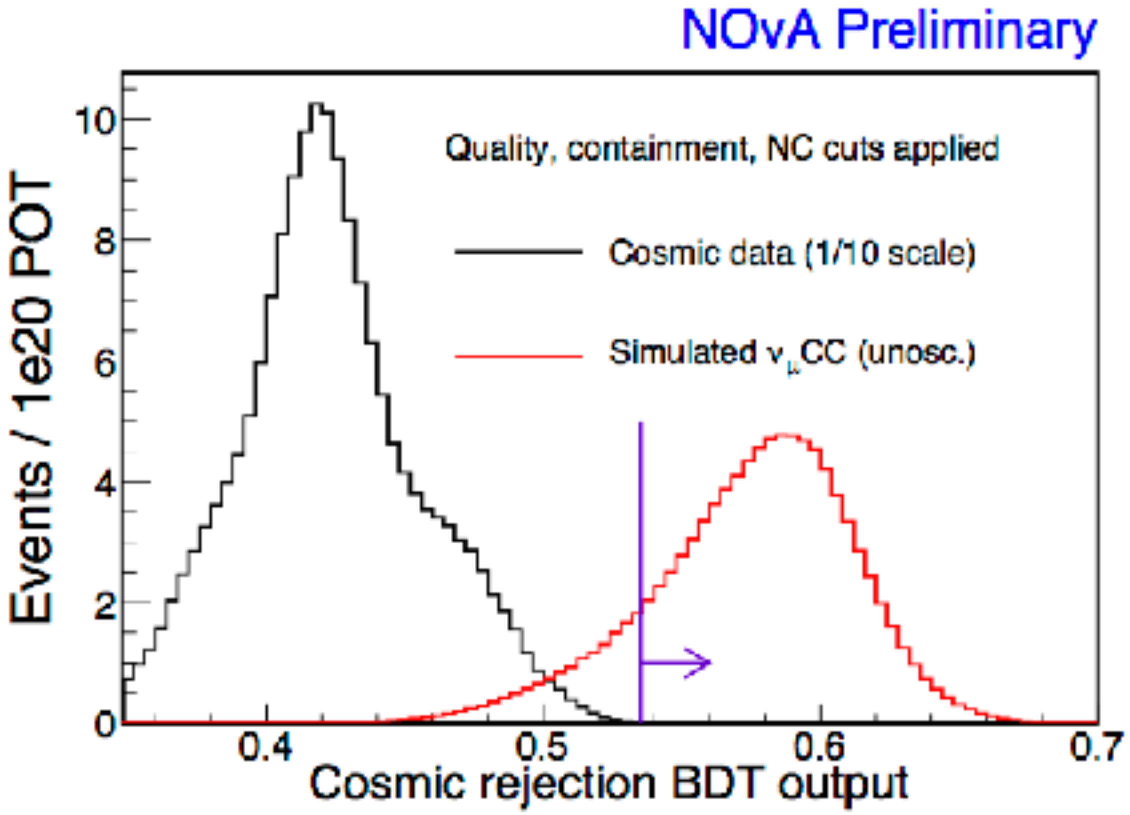
- Response varies substantially along cell due to light atten.
- Use cosmic ray muons as a standard candle to calibrate every channel individually
- Use dE/dx near the end of stopping muon to set abs. scale
- Multiple calibration x-checks
  - Beam muon dE/dx
  - Michel energy spectrum
  - π^0 mass peak
  - Hadronic energy/hit
- Take 5% abs. and rel. errors on energy scale





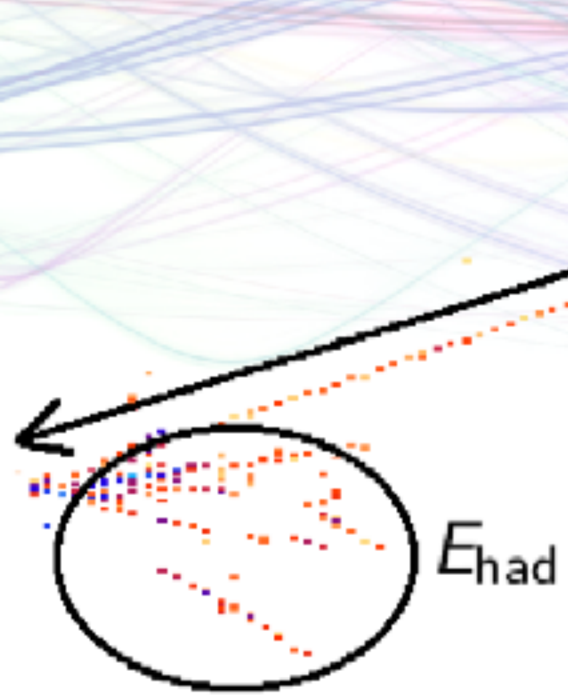
Cosmic rejection for ν_μ analysis





- $10\mu s$ spill window at $\sim$ 1Hz gives 10^5 rejection
- Cosmic background rate measured from data adjacent in time to the beam spill window
- Additional factor 10^7 from event topology plus boosted decision tree based on
  - Track direction
  - Track start and end points
  - Track length
  - Energy
  - Number of hits

Muon neutrino energy reconstruction

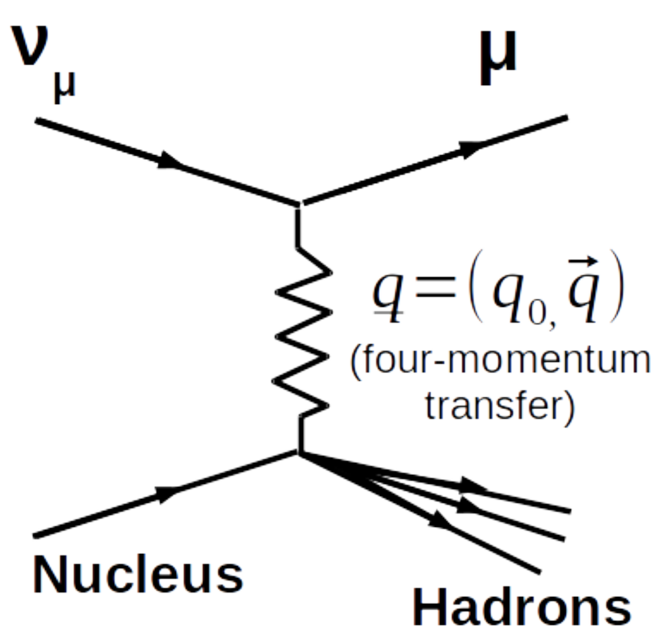


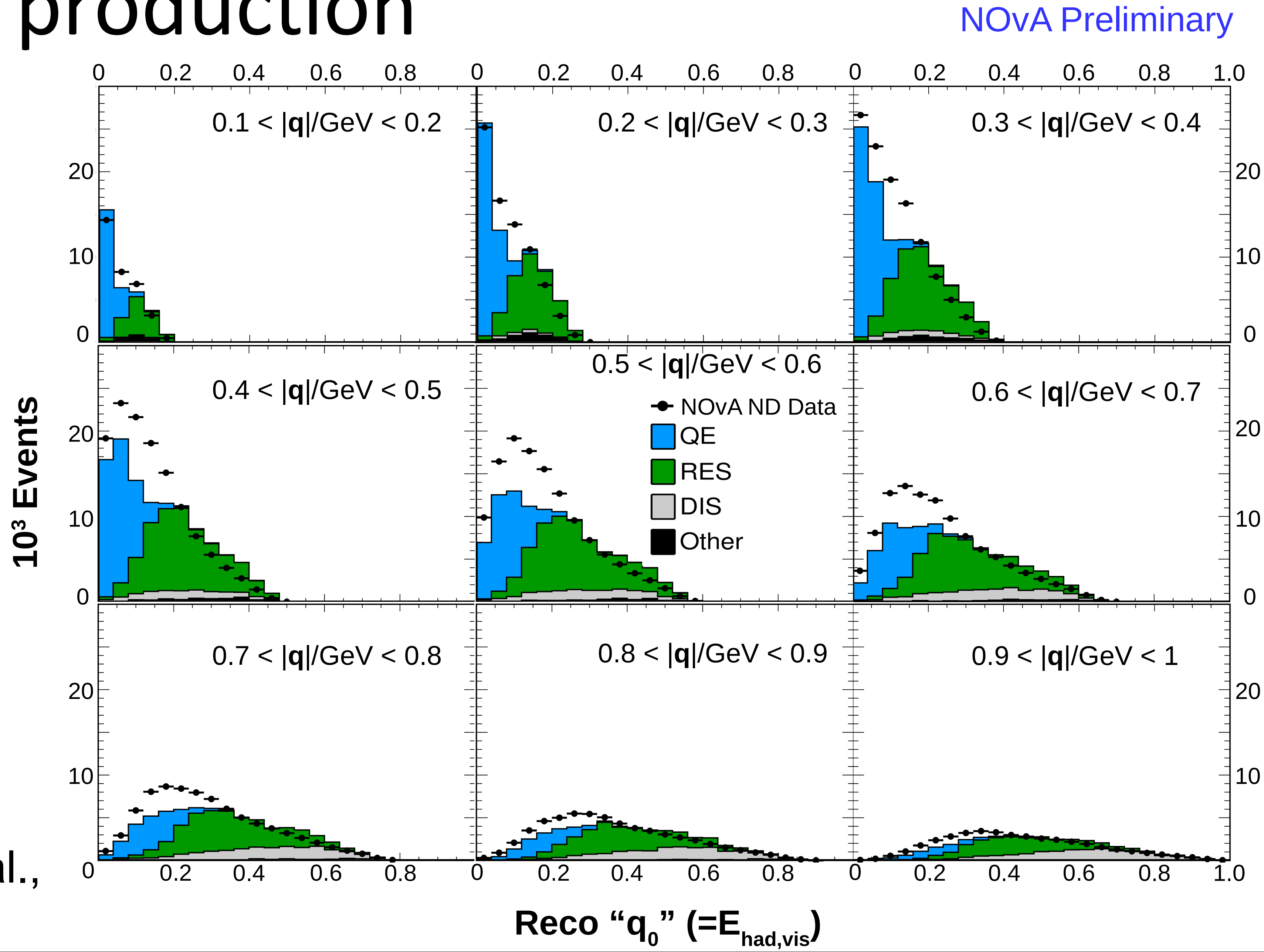
- Estimate energy of selected events to trace out oscillation structure
- Known muon dE/dx $\rightarrow E_\mu = f(L_{trk}) \sim k \times L_{trk}$
- Hadronic part of the event estimated calorimetrically

- $E_\nu = f(L_{trk}) + E_{had}$
- Achieve 7% energy resolution

Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production



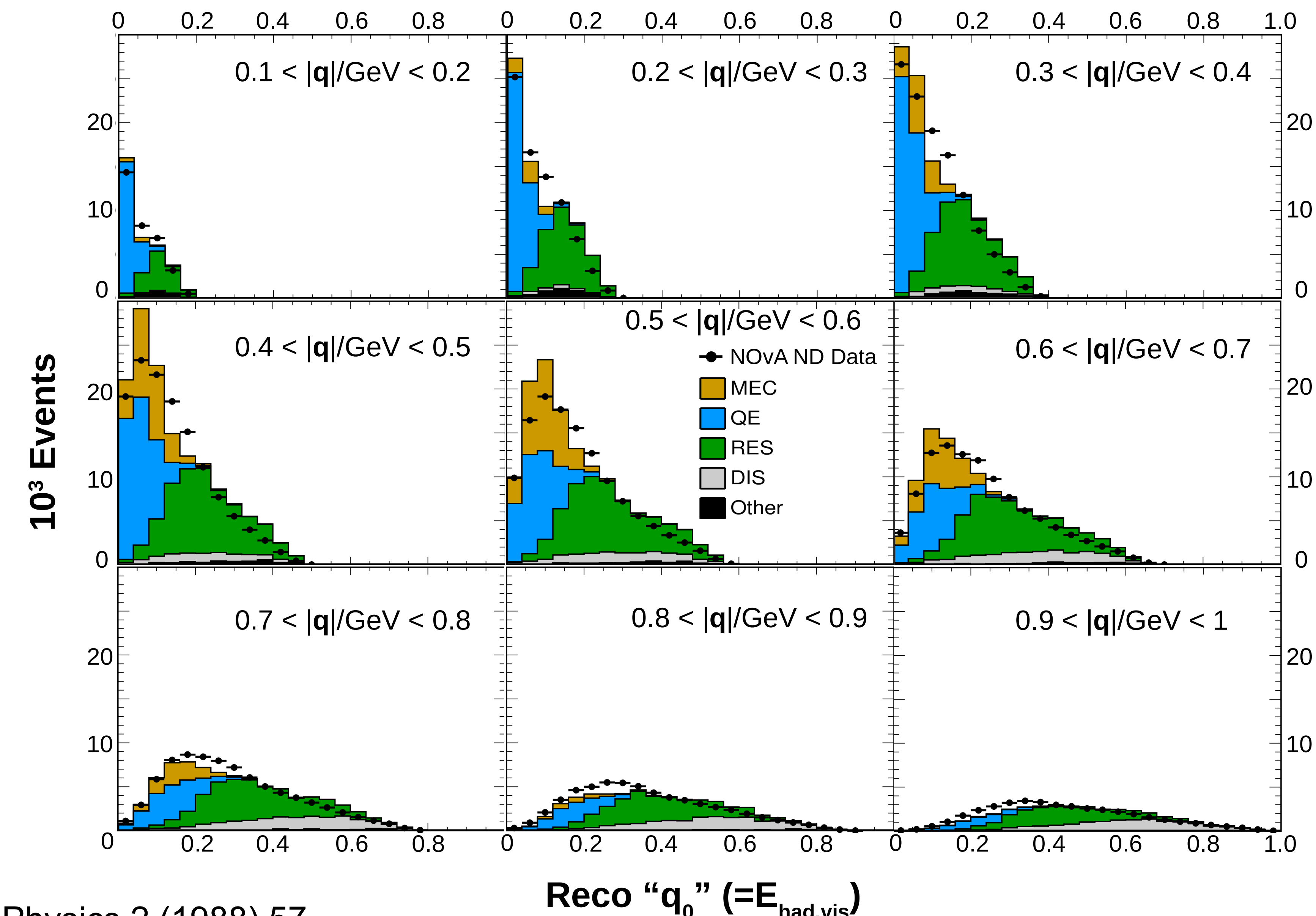


Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802

Scattering in a Nuclear Environment

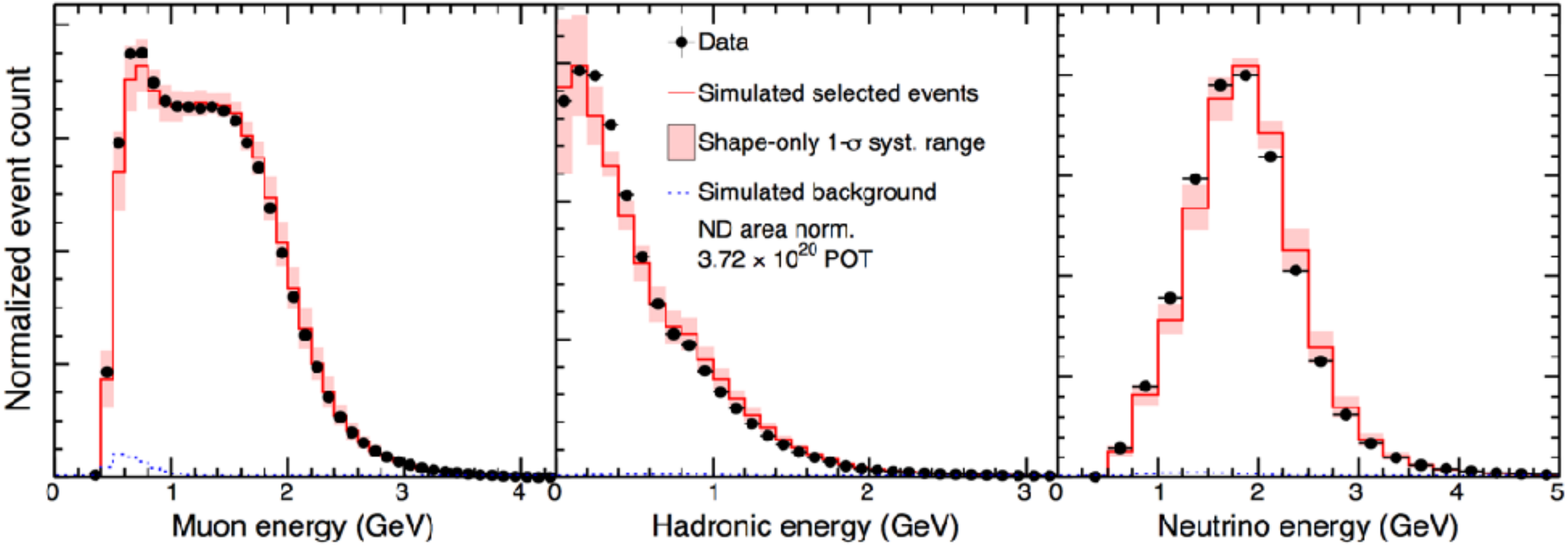
- Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer

- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50% (P.A. Rodrigues et al, arXiv:1601.01888.)



MEC model by S. Dytman, inspired by
J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

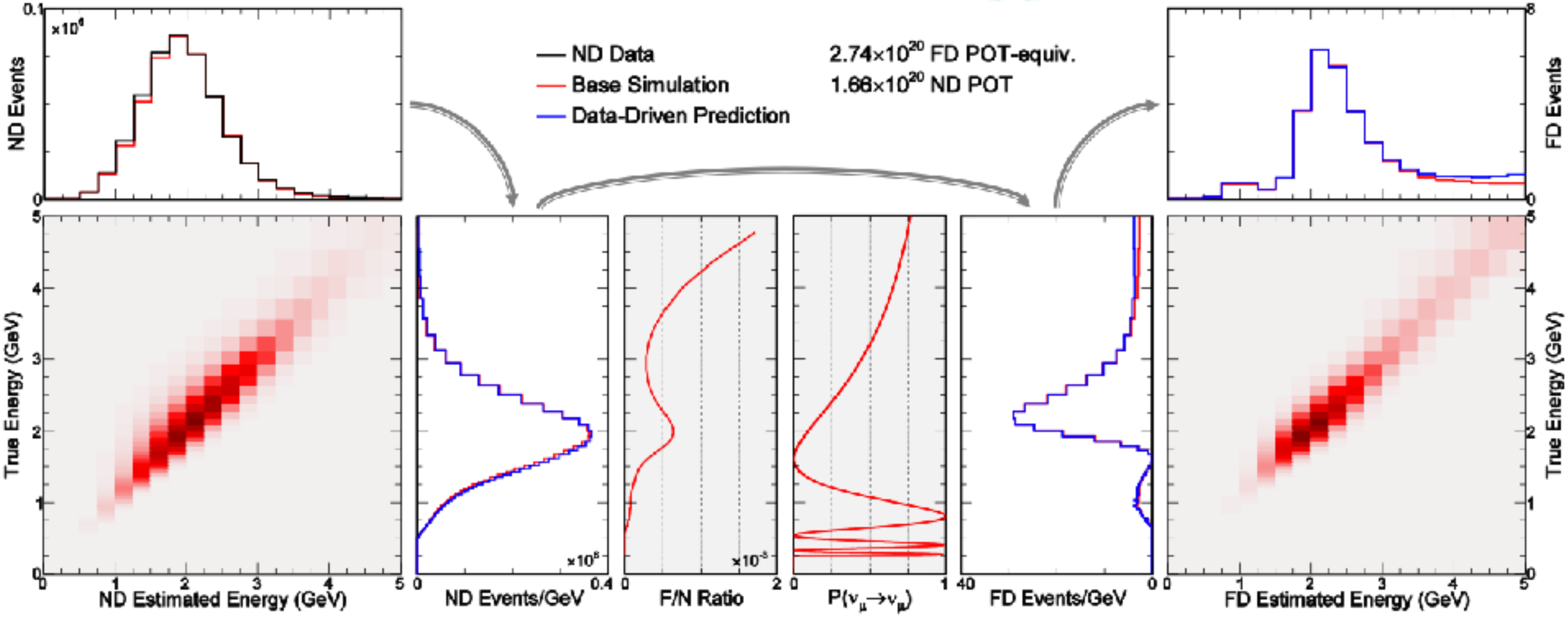
Muon neutrino energy reconstruction



- Good data/MC agreement for muon neutrino selected events
- Hadronic energy scale uncertainty improved to 5%
- Use ND data to predict FD neutrino spectrum

Extrapolation procedure

- Translate ND observations to true energy
- Transport to far detector and oscillate
- Smear back to reco energy

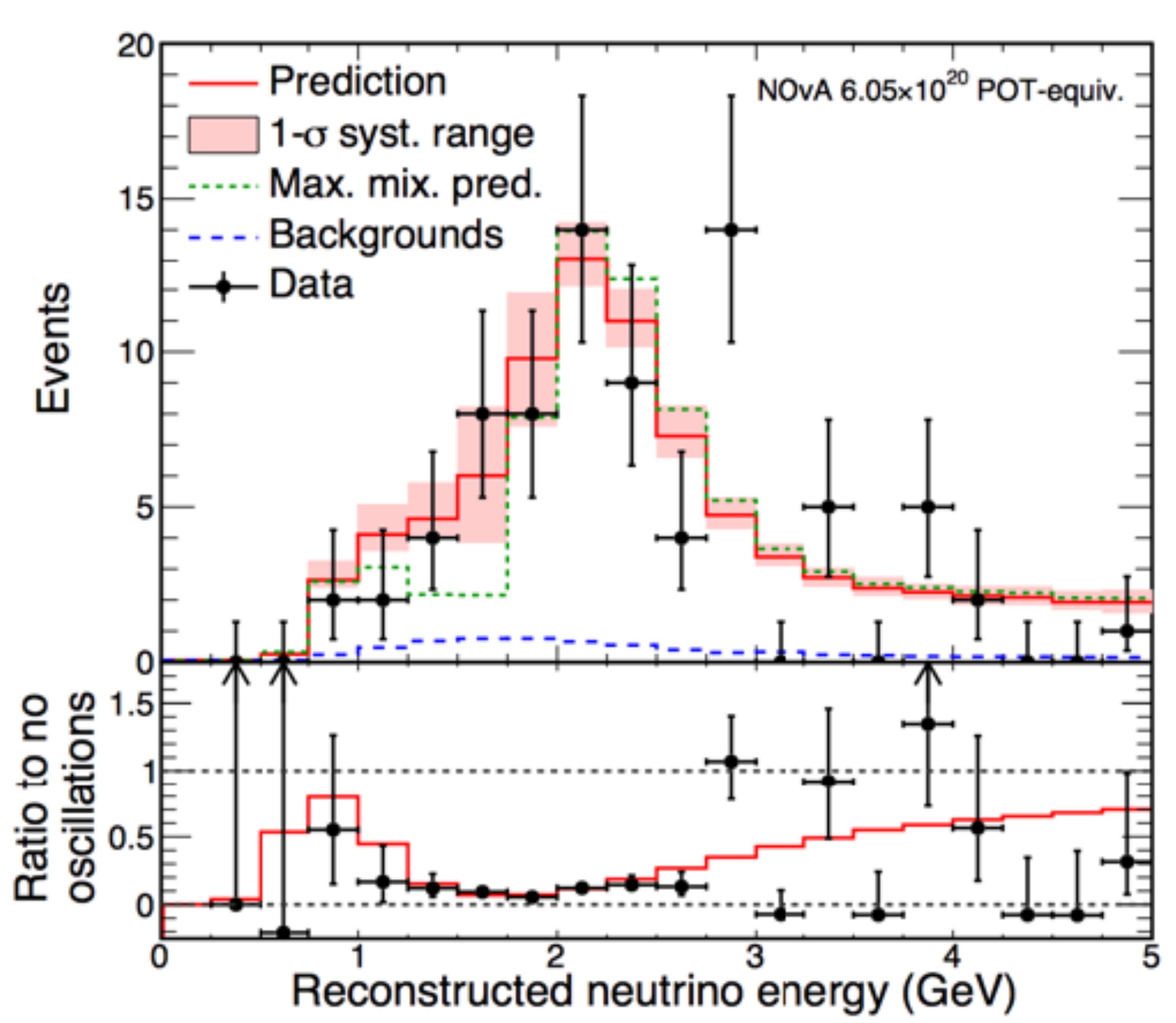


Systematic uncertainties

Source of uncertainty	Uncertainty in $\sin^2\theta_{23} (\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0 - 2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

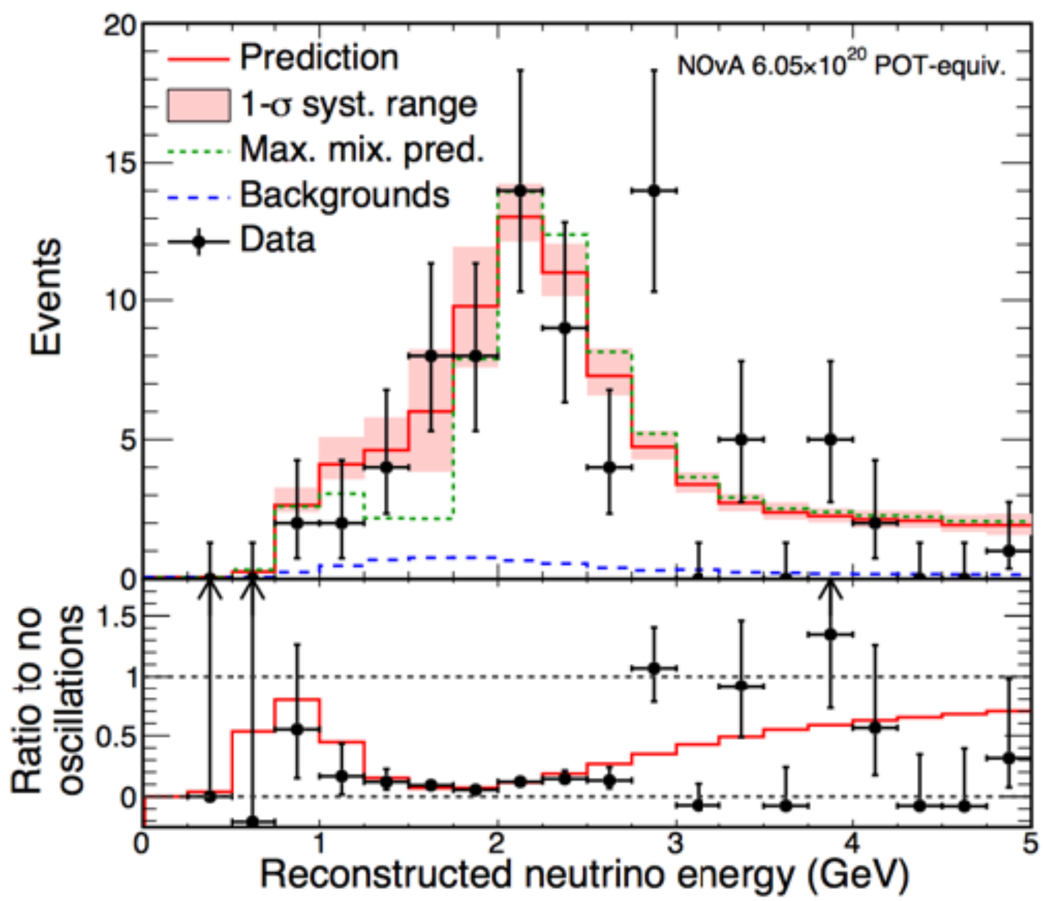
- Consider multiple possible sources of systematic error
- Propagate effect of each through extrapolation
- Include as pull terms in fit
- Quoting increase (in quadrature) of measurement error

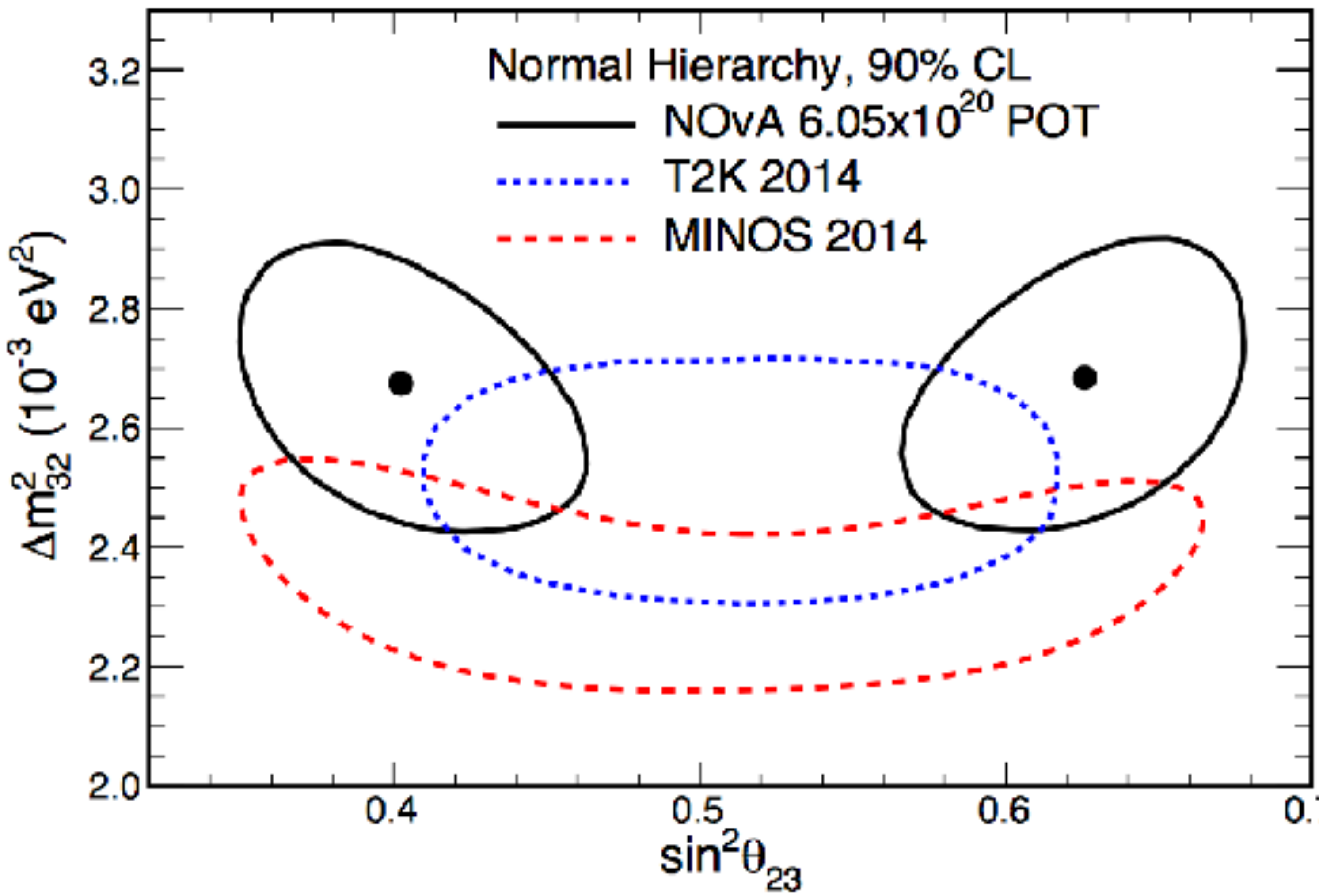
ν_μ disappearance results



- Expect 473 ± 30 events in the FD (no oscillation)
- Observe 78 (bkg 3.4 NC, 0.23 ν_e-CC, 0.27 ν_τ-CC, 2.7 cosmic rays induced events)

ν_μ disappearance results





- Best fit 82.4 events

$$\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.404\,^{+0.030}_{-0.022} \text{ and } 0.624\,^{+0.022}_{-0.030}$$

- Maximal mixing excluded at 2.6 σ

Conclusion

- Second NOvA analysis based on 6.05×10^{20} POT (correspond to 1 year planned and 2.2 times more that used in our previous analysis)
- Observed 78 events in the Far Detector (out of 473 ± 30 no oscillation)
- Best fit for the Normal Hierarchy

$$\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.404\,^{+0.030}_{-0.022} \text{ and } 0.624\,^{+0.022}_{-0.030}$$

- Maximal mixing excluded at 2.6 σ
- Looking forward for our new results

Measurement of the neutrino mixing angle θ_{23} in NOvA

This Letter reports new results on muon neutrino disappearance from NOvA, using a 14 kton detector equivalent exposure of 6.05×10^{20} protons-on-target from the NuMI beam at the Fermi National Accelerator Laboratory. The measurement probes the muon-tau symmetry hypothesis that requires maximal θ_{23} mixing ($\theta_{23} = \pi/4$). Assuming the normal mass hierarchy, we find $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\,\text{eV}^2$ and $\sin^2\theta_{23}$ at the two statistically degenerate values $0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{-0.030}$, both at the 68% confidence level. Our data disfavor the maximal mixing scenario with $2.6\,\sigma$ significance.

arXiv:1701.05891v1 [hep-ex] 20 Jan 2017

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Скоро будет опубликована еще одна статья:

Constraints on oscillation parameters
from ν_e appearance and ν_μ disappearance
in NOvA

Следите за объявлениями семинаров ЛЯП, докладчик Л.Колупаева,
через 2-3 недели