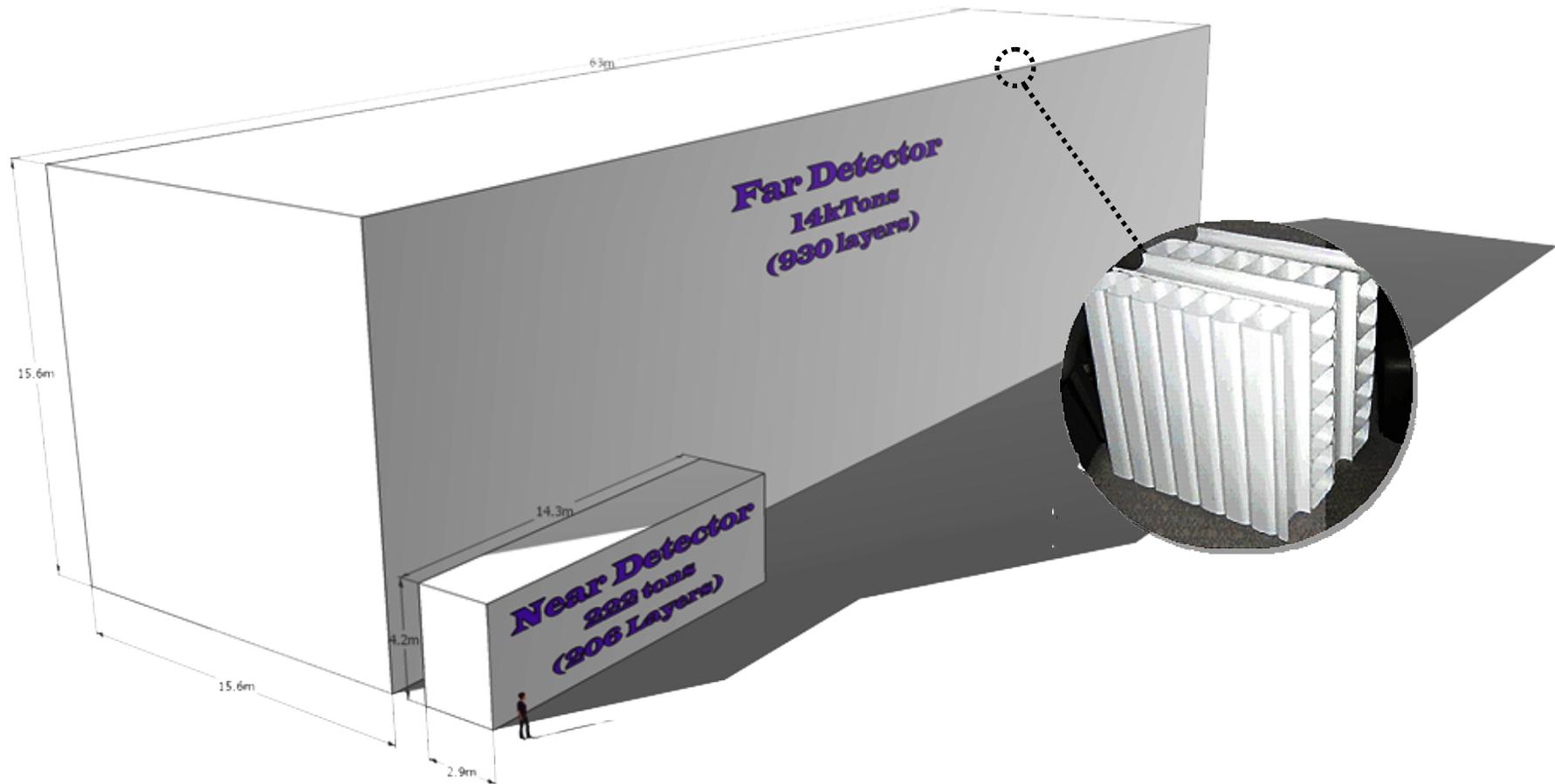


# NuMI Off-axis $\nu_e$ Appearance (NO $\nu$ A)

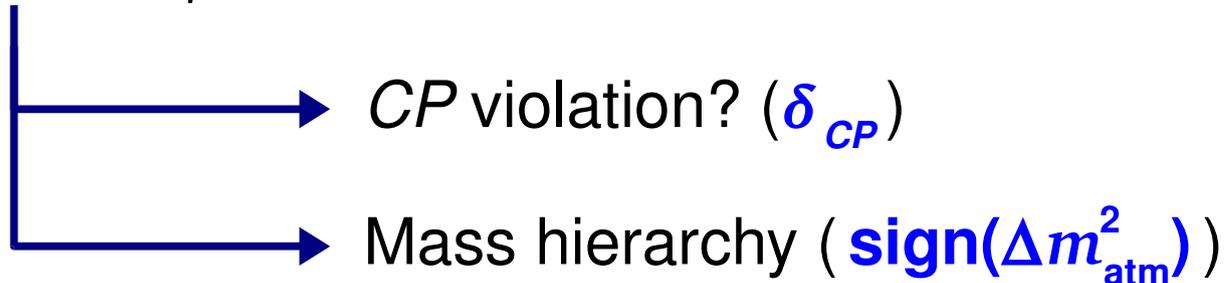


**Ryan Patterson**  
**Caltech**

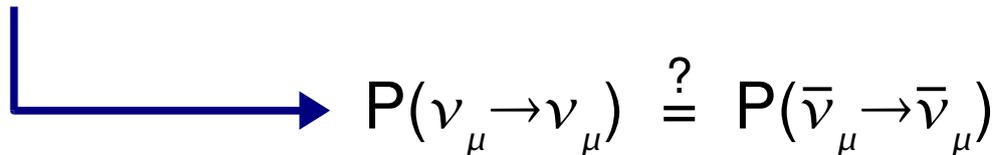
**NNN10, Toyama**  
**December 14, 2010**

# Primary $\text{NO}\nu\text{A}$ Physics Goals

- Precision  $\nu_\mu \rightarrow \nu_e$  **appearance** ( $\theta_{13}$ )



- Precision  $\nu_\mu \rightarrow \nu_\mu$  **disappearance** ( $\theta_{23}$  and  $|\Delta m_{\text{atm}}^2|$ )



- *And:*  $\nu$  **cross sections**, **sterile**  $\nu$  searches, **supernova** signals

**A broad program...**

**NO $\nu$ A far detector**  
(MINOS far detector)

# NO $\nu$ A

Minnesota

810 km

Wisconsin

Fermilab

Chicago

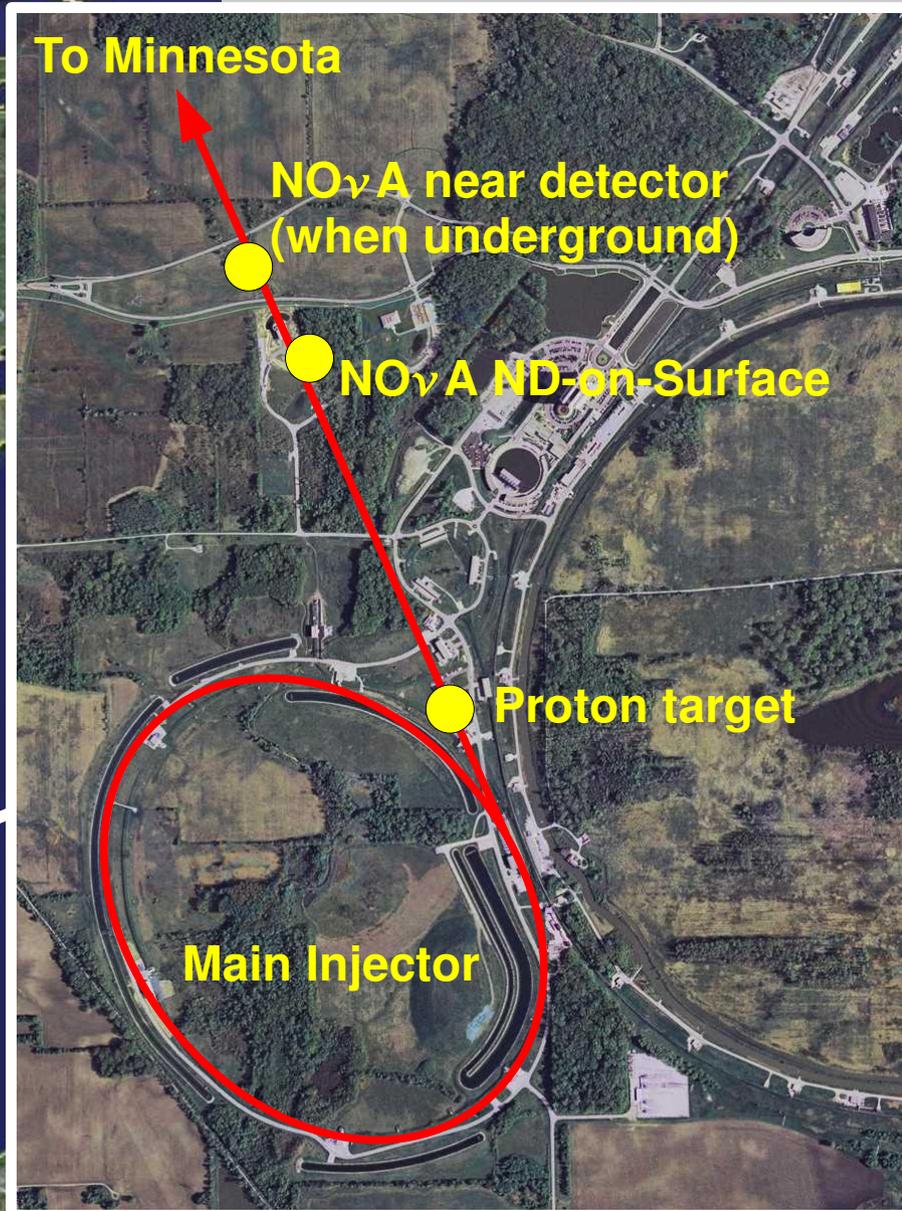
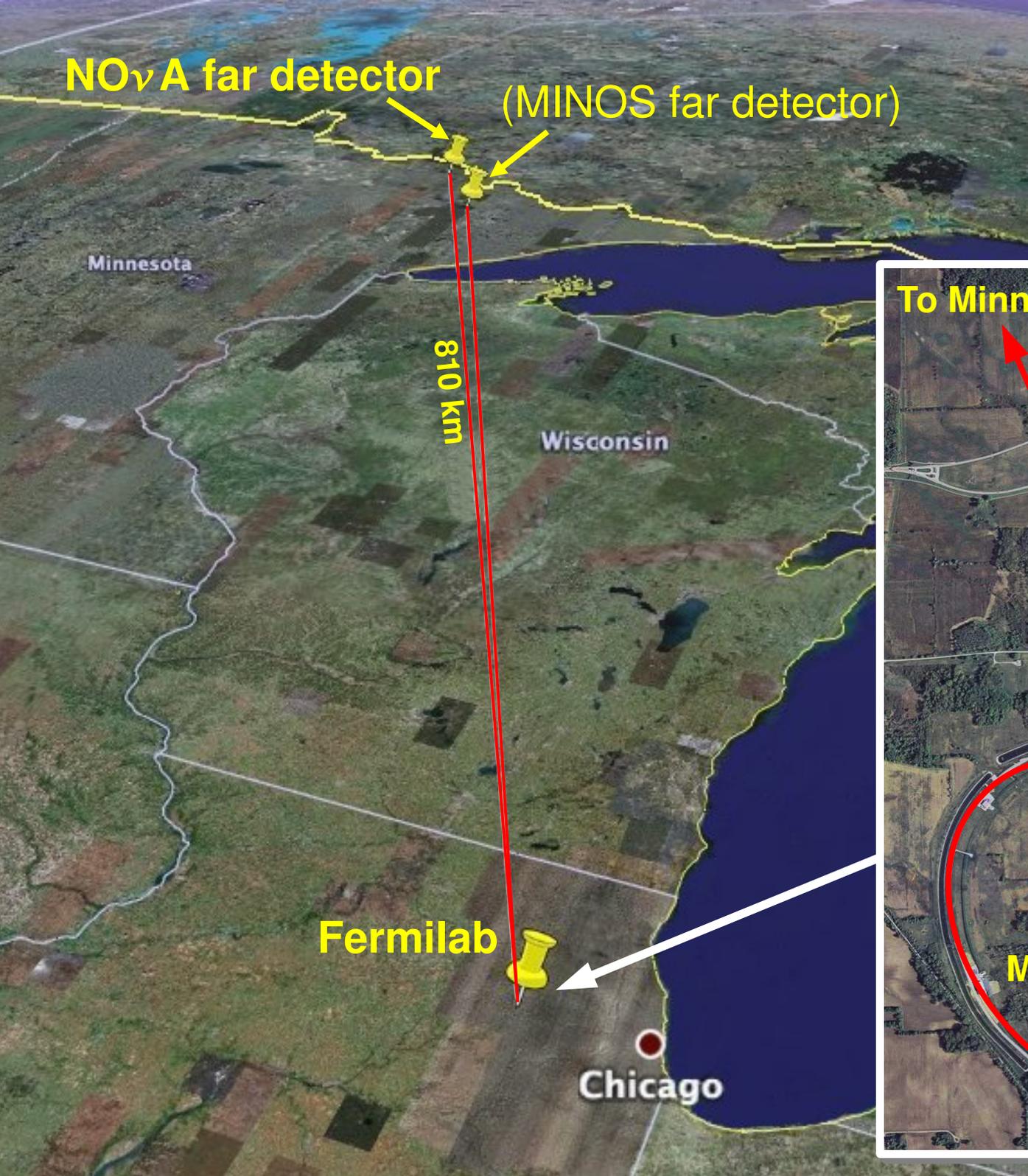
To Minnesota

NO $\nu$ A near detector  
(when underground)

NO $\nu$ A ND-on-Surface

Proton target

Main Injector



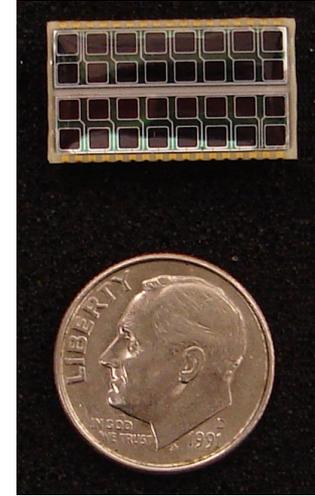
# NO $\nu$ A detectors

Designed for **excellent  $\nu_e$  CC identification**

*Fine-grained readout, low-Z materials, 80% active volume*

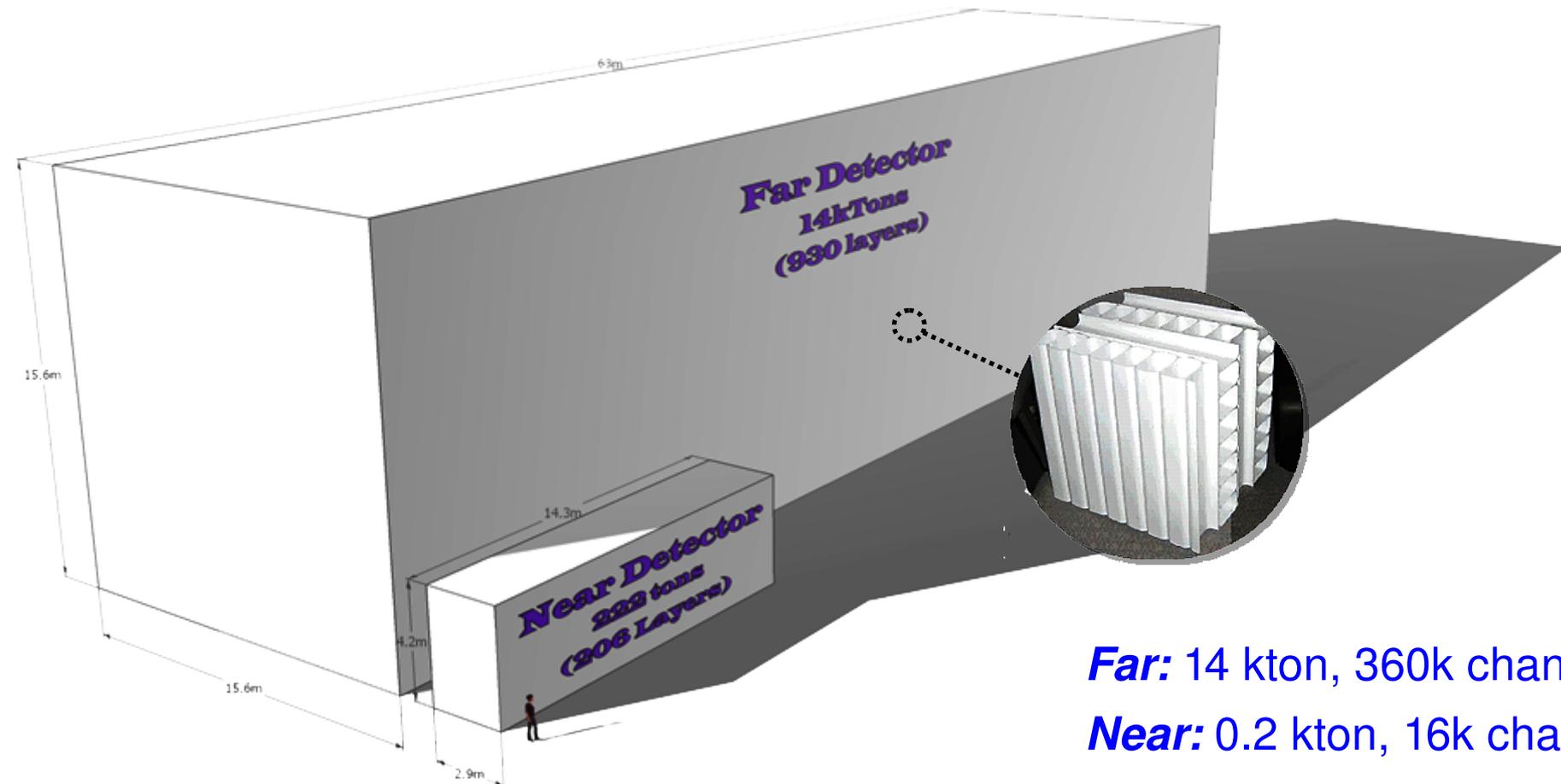
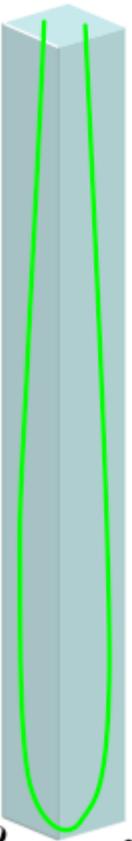
- ▶ planes of **4 cm x 6 cm x 1560 cm** PVC cells
- ▶ cells filled with **liquid scintillator**
- ▶ readout by **WLS fiber / avalanche photodiode**

32-pixel APD



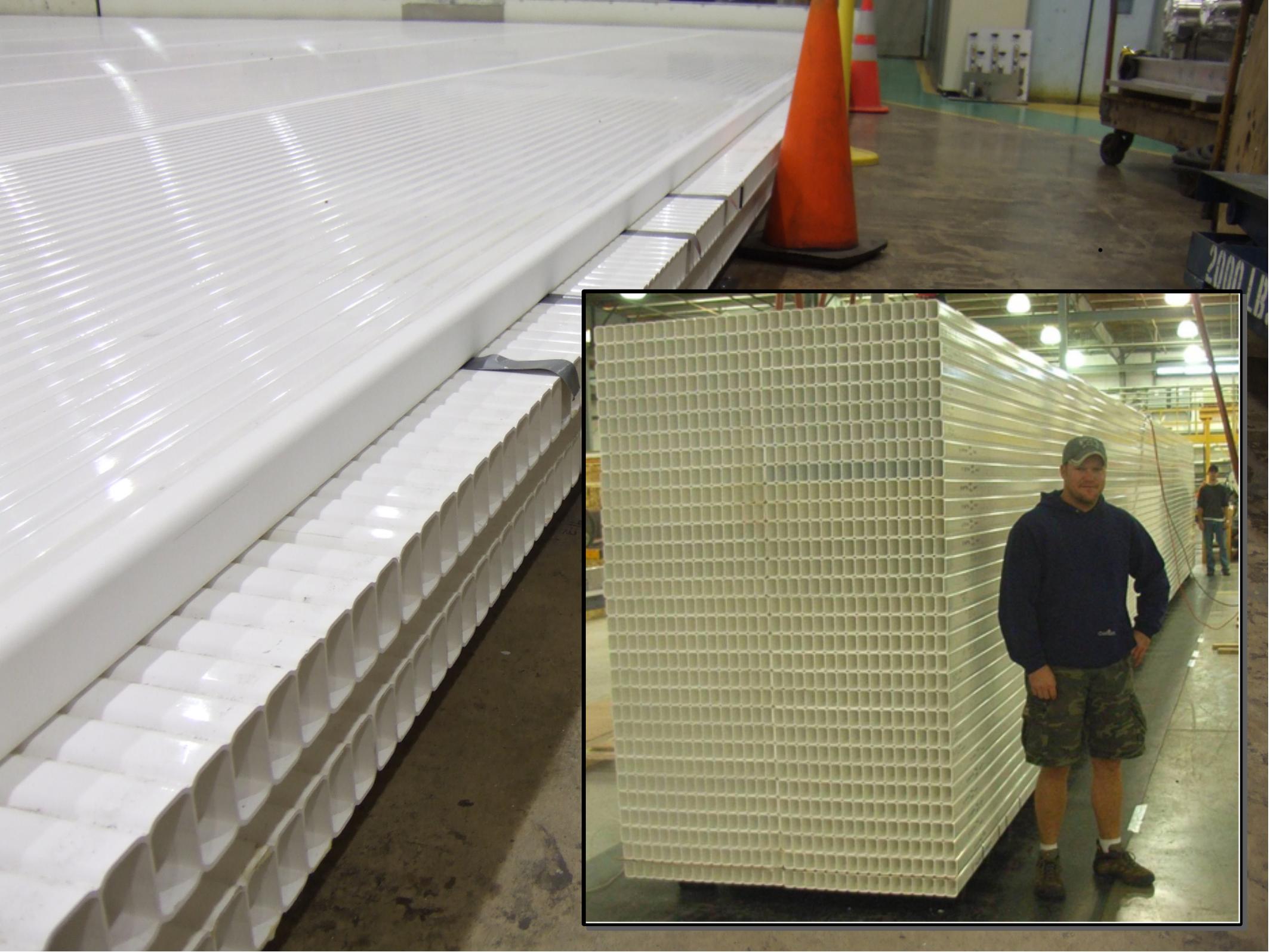
15.6 m

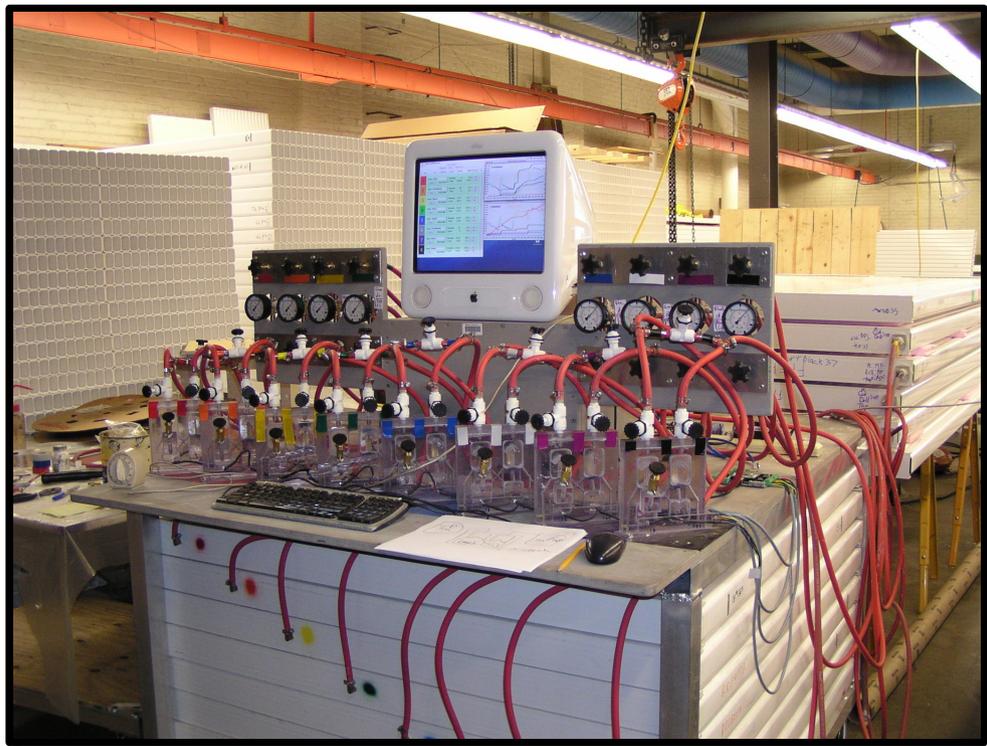
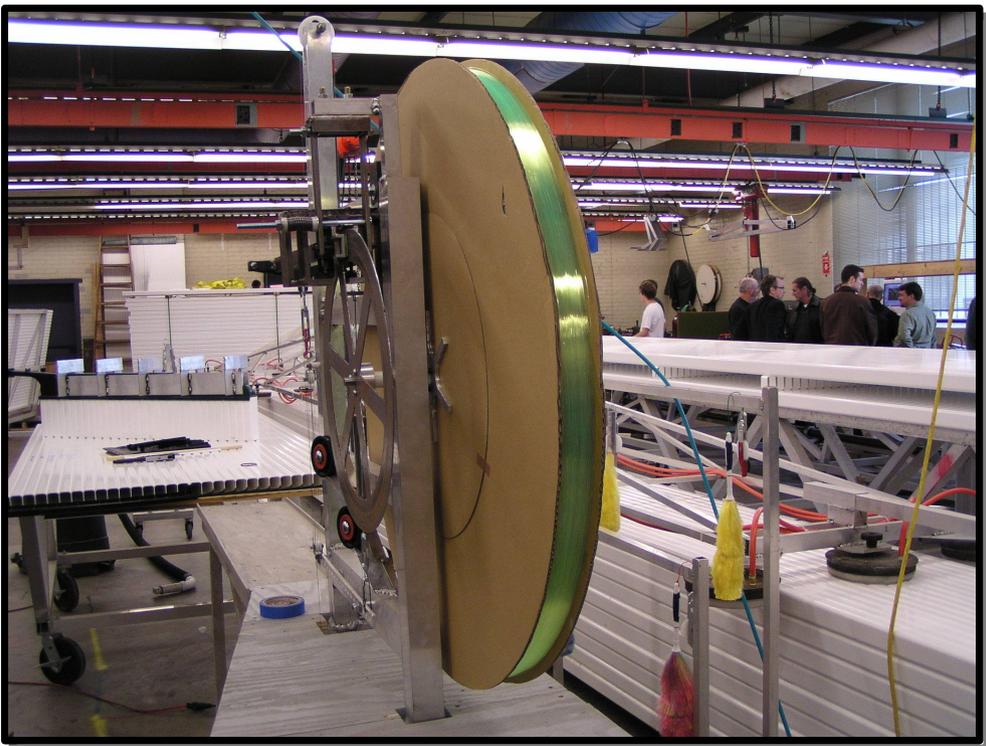
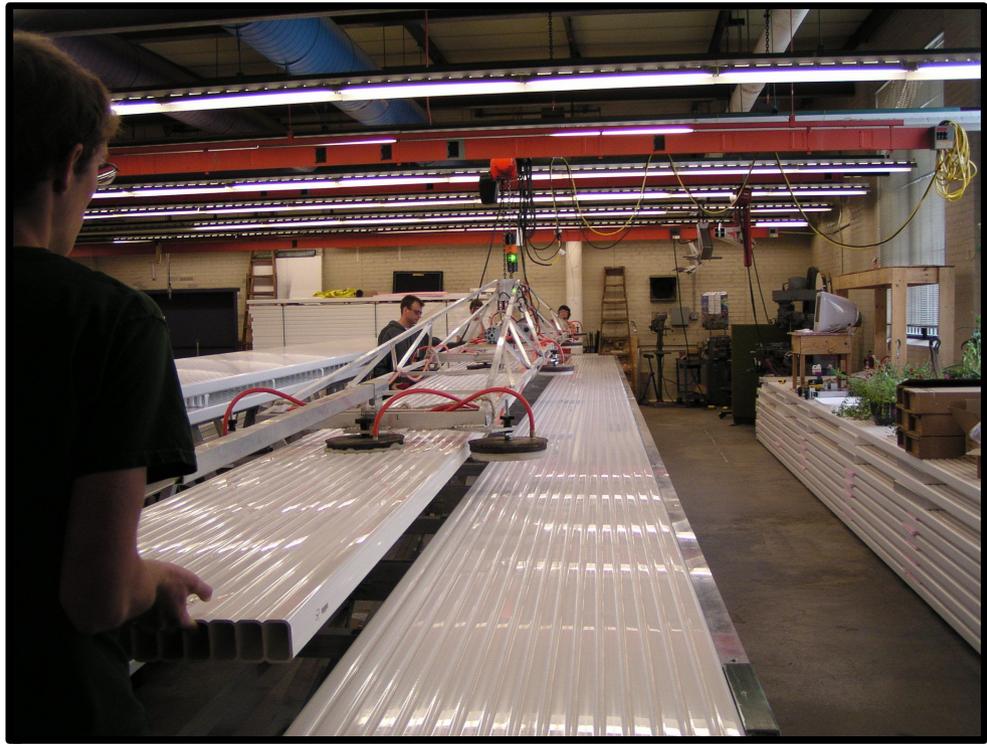
3.9 cm 6 cm



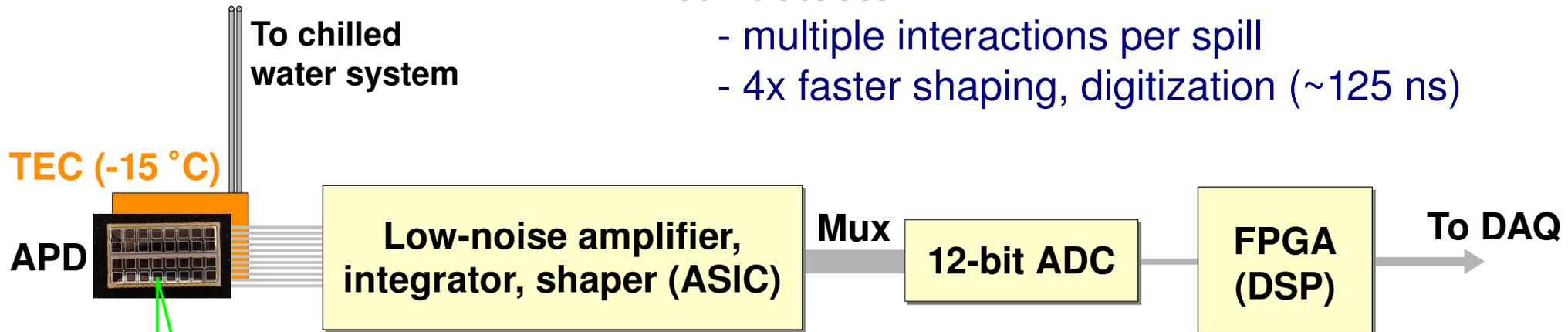
**Far:** 14 kton, 360k channels

**Near:** 0.2 kton, 16k channels





# Cell readout



## Far detector:

- lower light levels (~25 PE from far end of cell)

## Near detector:

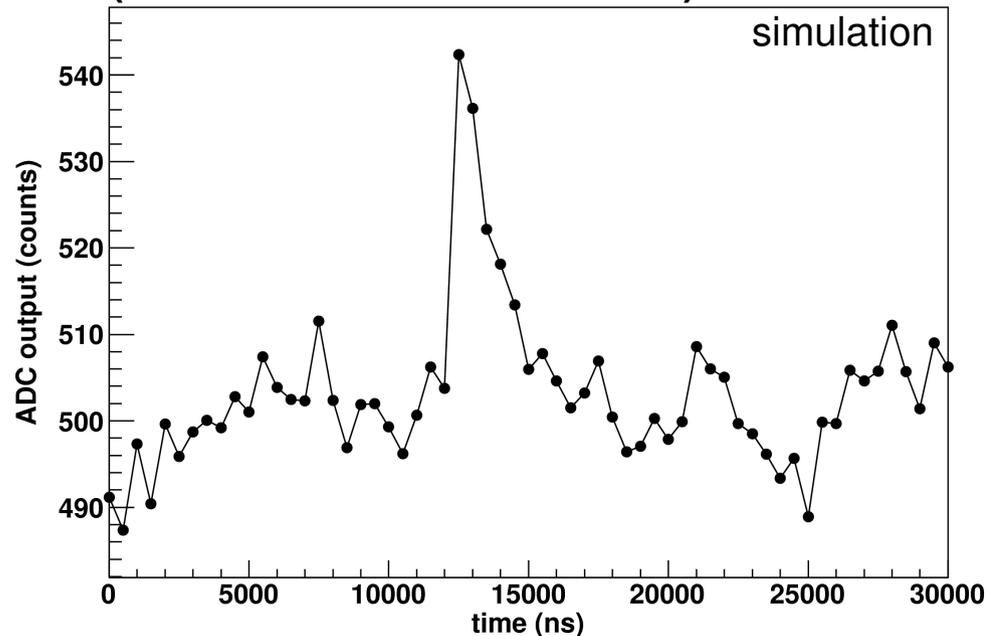
- multiple interactions per spill
- 4x faster shaping, digitization (~125 ns)

light collected,  $\lambda$  shifted, transported by fiber

particle track (MIP ~ 12 MeV)

UV

Approx. smallest signal of interest (MIP at far end of 15.6 m cell)

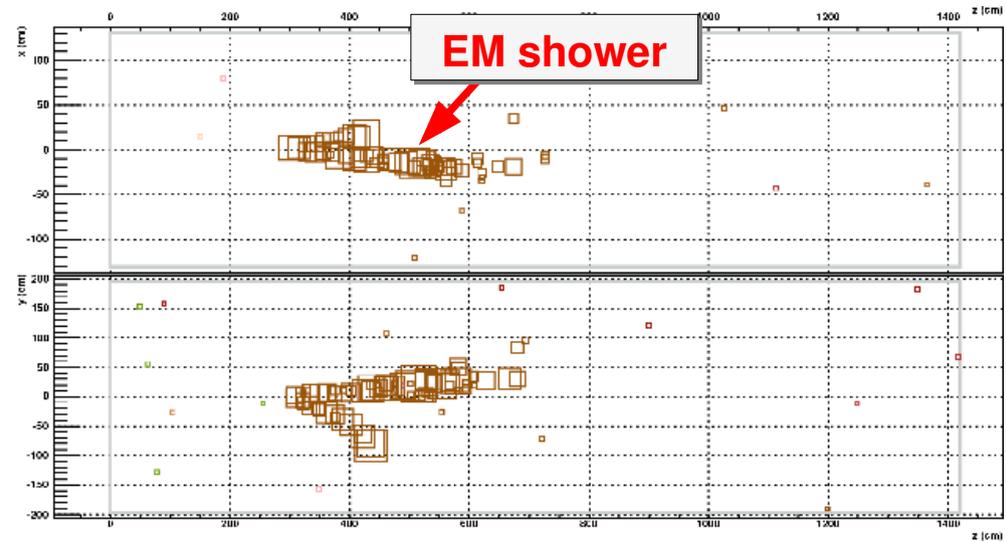
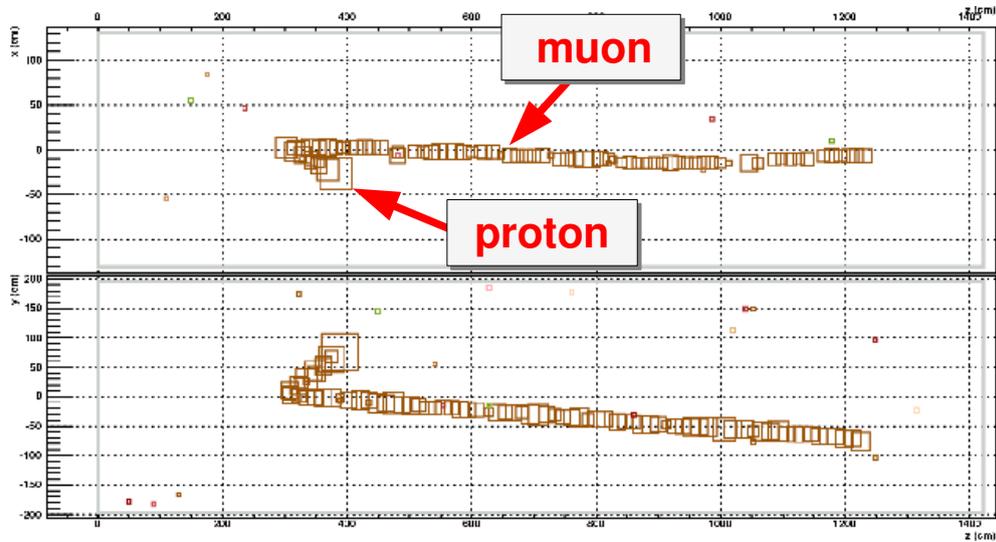


# Some simulated events ( $\mu$ , $e$ , and $\pi^0$ , each with a proton)

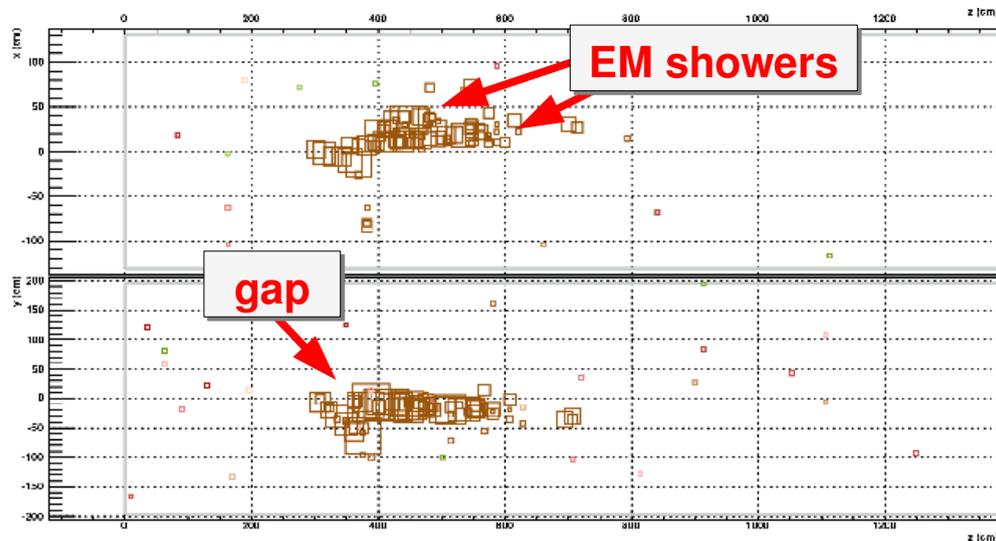
**muon:** long, non-showering, MIP-like track

**proton:** short track; large  $E_{\text{dep}}$  at end

**electron:** compact EM shower



**neutral pion:** multiple, displaced EM showers

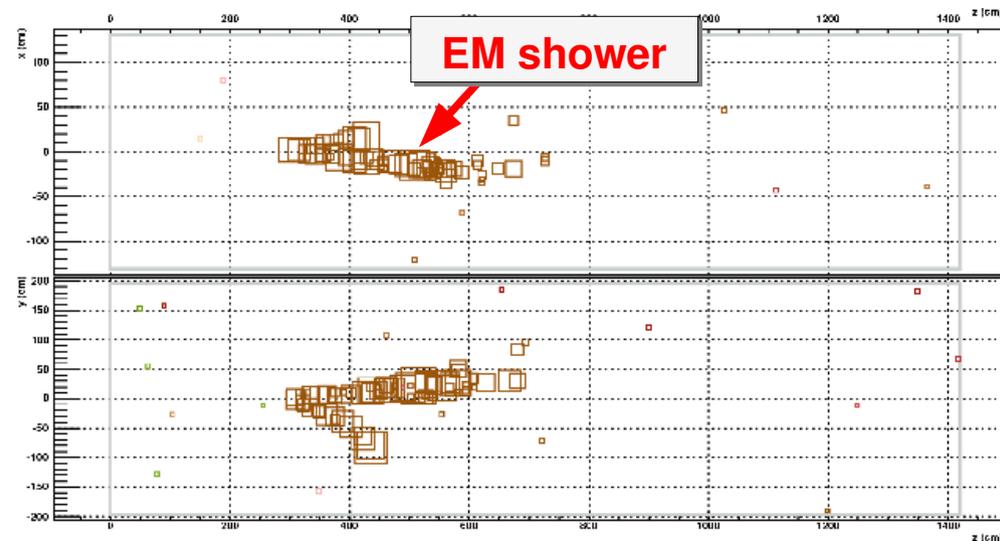
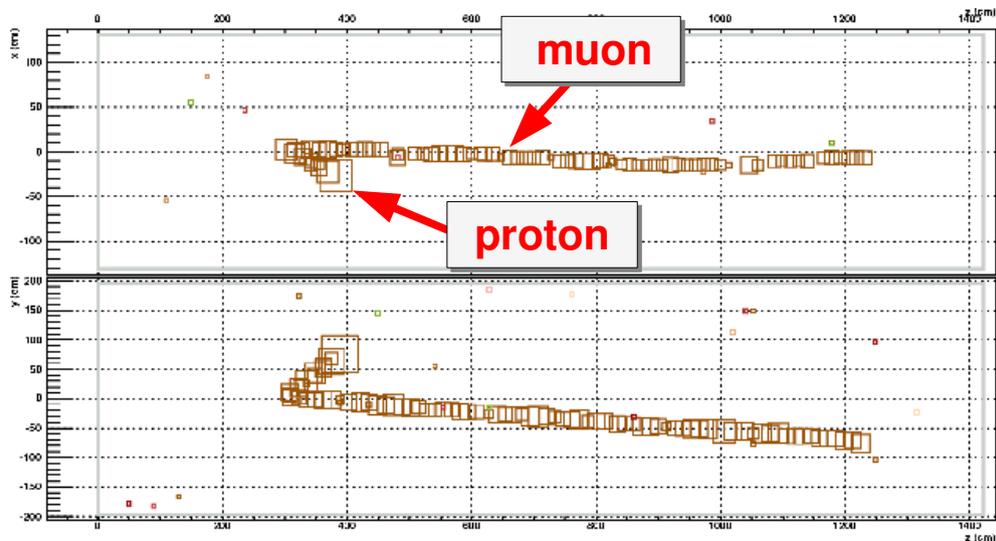


# Some simulated events ( $\mu$ , $e$ , and $\pi^0$ , each with a proton)

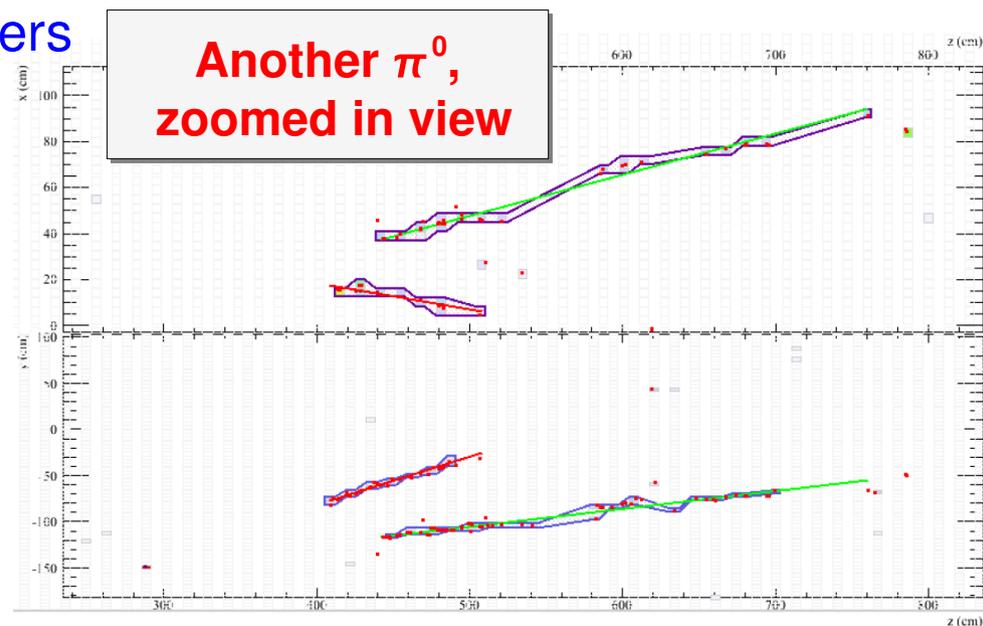
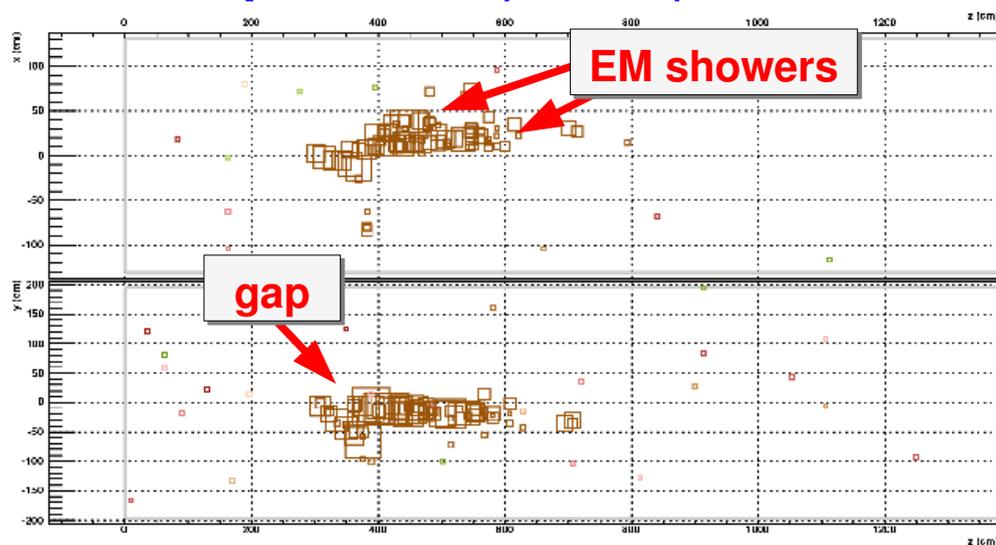
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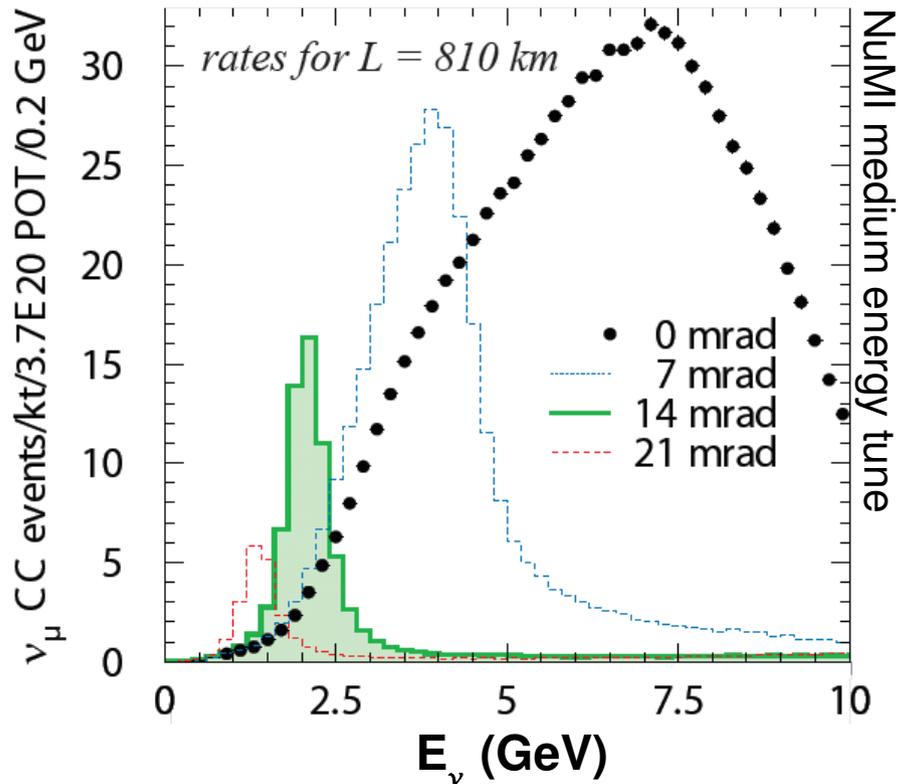


**neutral pion:** multiple, displaced EM showers



# NuMI off-axis beam

$\text{NO}\nu\text{A}$  detectors are sited  
14 mrad off the NuMI beam axis



*Reduces NC bgnd. (via energy cut)*

2 GeV  $\nu_e$   $\Rightarrow \nu_e$  CC  $\Rightarrow$  2 GeV visible

2 GeV  $\nu_x$   $\Rightarrow \nu_x$  NC  $\Rightarrow$  <2 GeV visible

*(also: beam  $\nu_e$  bgnd.)*

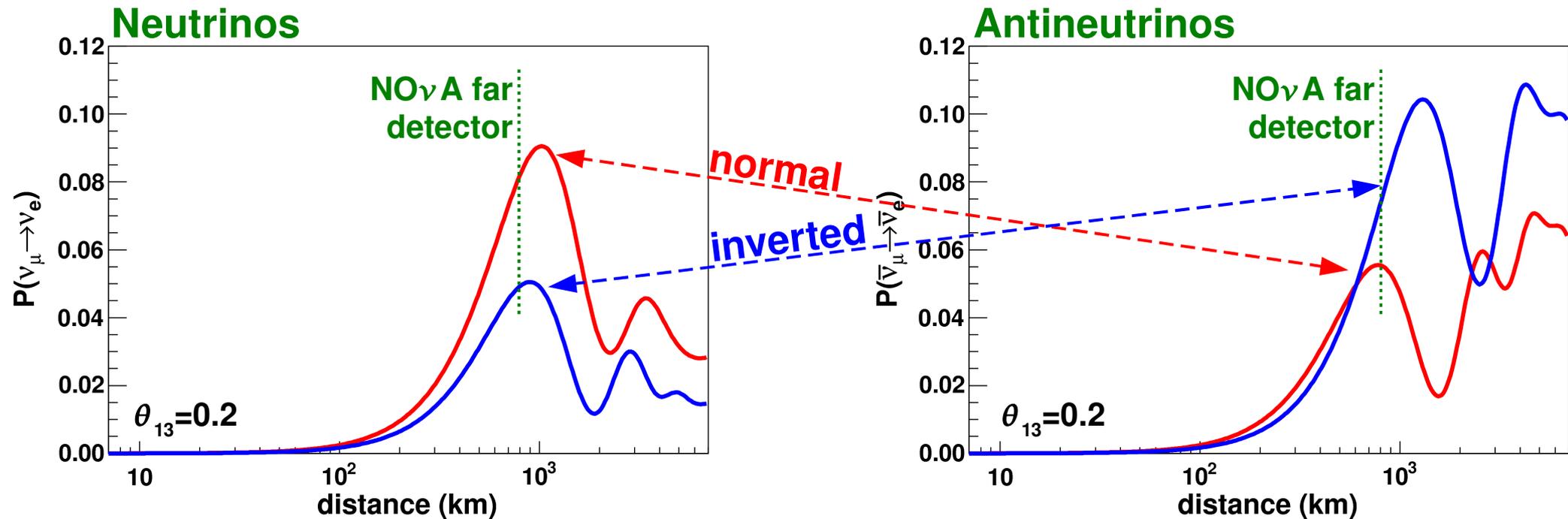
- **NuMI** to go from 320 kW to **700 kW** during 2012  
*Stack in recycler  $\Rightarrow$  MI cycle time goes from 2.2 s to 1.5 s*  
*New extraction/injection lines*  
*Two more RF stations (1.5 s  $\rightarrow$  1.33 s)*  
*New high-intensity NuMI target*
- Result will be  $\sim 6 \times 10^{20}$  p/yr to NuMI

# Utilizing the matter effect

810 km of matter  $\Rightarrow$  different oscillation probabilities for:

**normal** vs. **inverted hierarchy**  
**neutrinos** vs. **antineutrinos**

So: measure **both**  $P(\nu_\mu \rightarrow \nu_e)$  and  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  in NO $\nu$ A

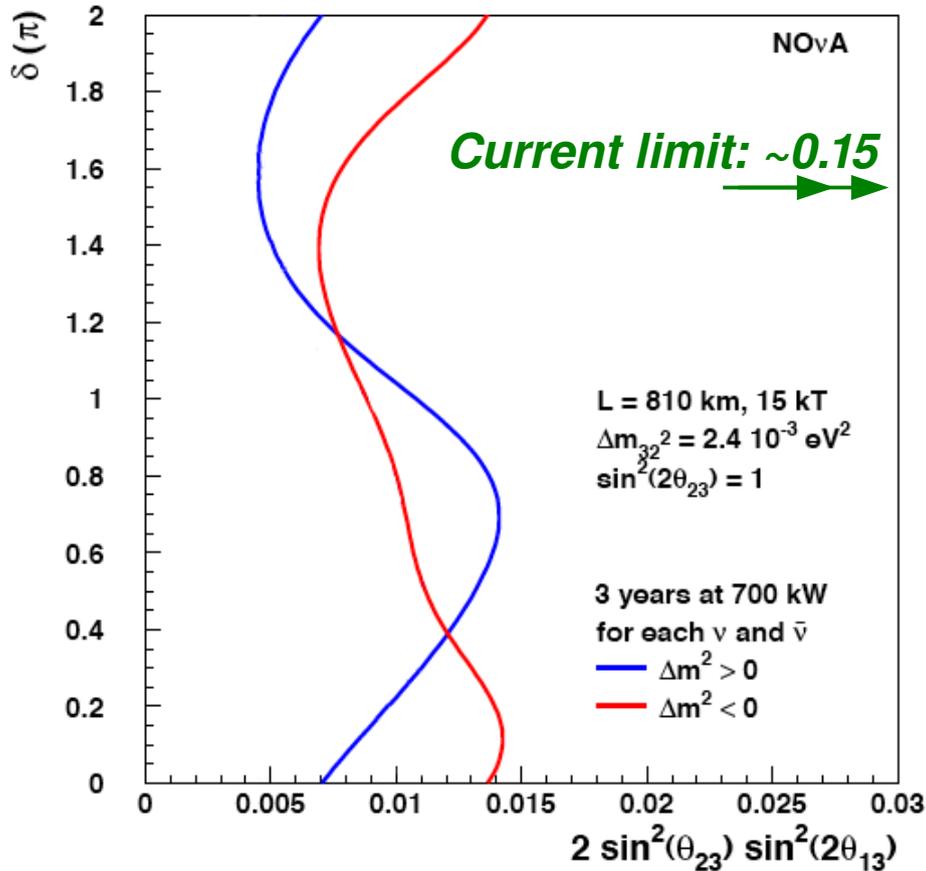


$$P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow \Delta m_{32}^2 > 0$$

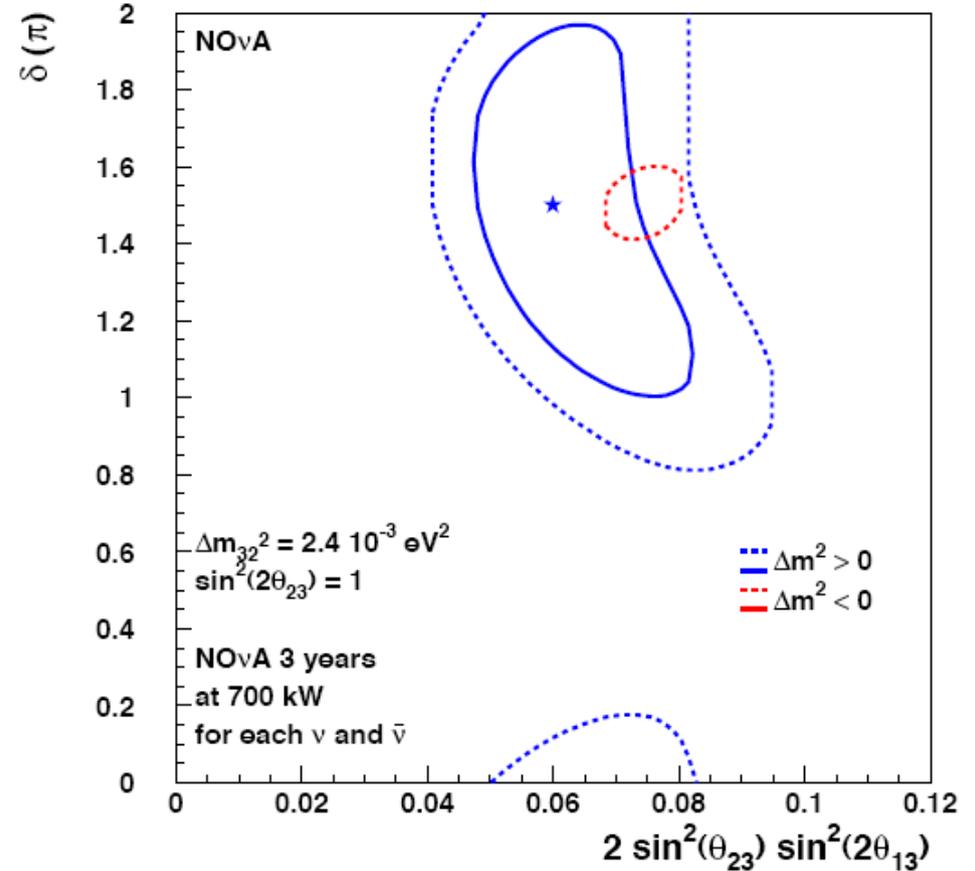
$$P(\nu_\mu \rightarrow \nu_e) < P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow \Delta m_{32}^2 < 0$$

# Example NO $\nu$ A contours

Typical 90% C.L. limits if  $\theta_{13} = 0$



Typical 1 $\sigma$  and 2 $\sigma$  contours for starred true point (normal hier.)



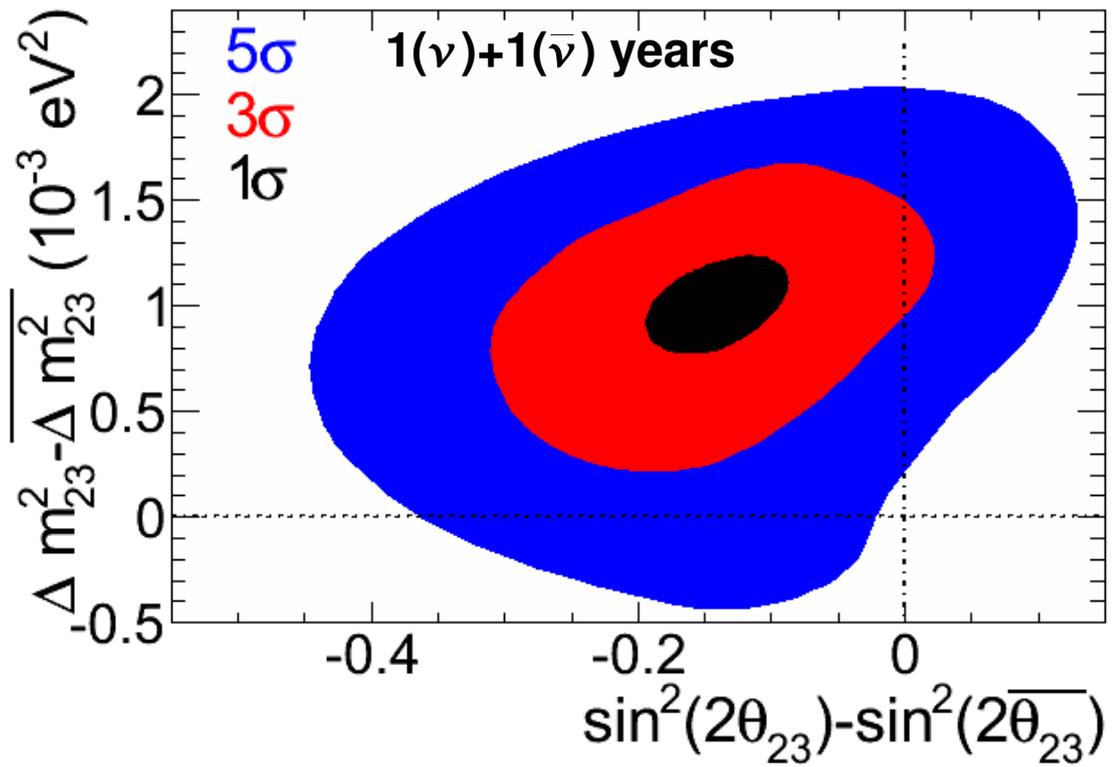
**Above: wrong-hierarchy solutions (red) almost gone at 2 $\sigma$ ...**

**Such hierarchy discrimination is possible for  $\sin^2(2\theta_{13}) \sim 0.06$**

$|\Delta m_{32}^2|$  and  $\sin^2(2\theta_{23})$

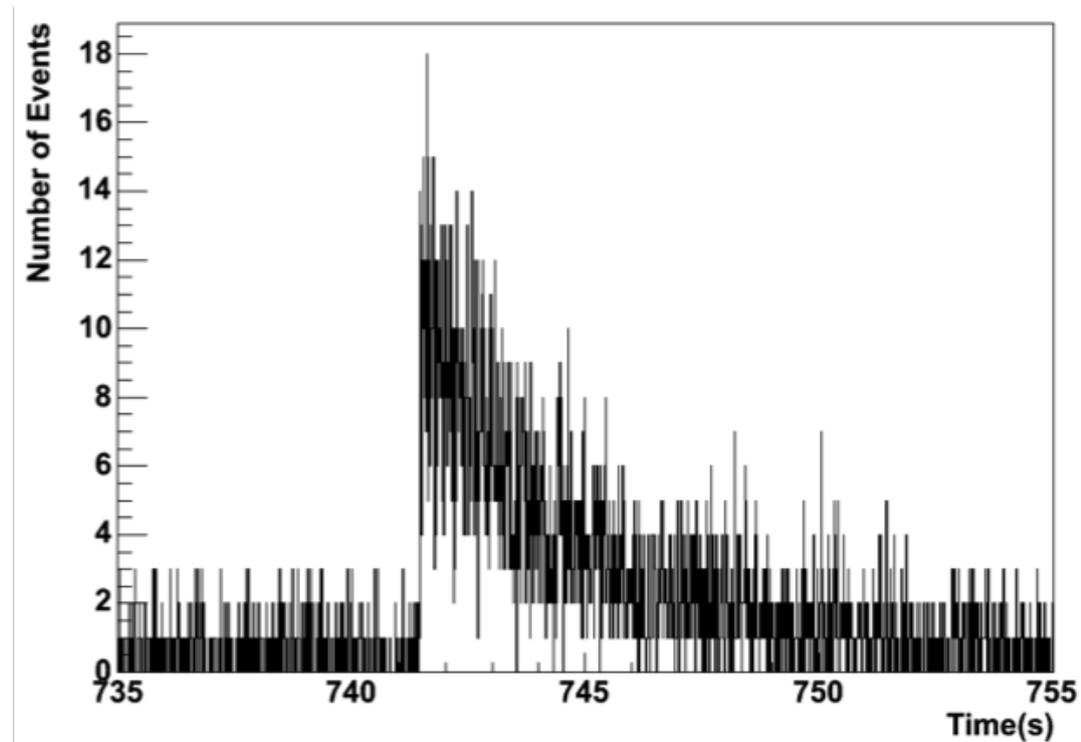
Tremendous precision thanks to rate and  $\sim 3.5\%$   $\nu_\mu$  CC energy resolution.

The MINOS  $\nu / \bar{\nu}$  best fit points would appear as distinct in NO $\nu$ A at  $>5\sigma$  after two years



## Supernova neutrinos

(10-second 5000-event burst for a supernova near the center of the galaxy)



**Far detector site**  
**September 12, 2010**



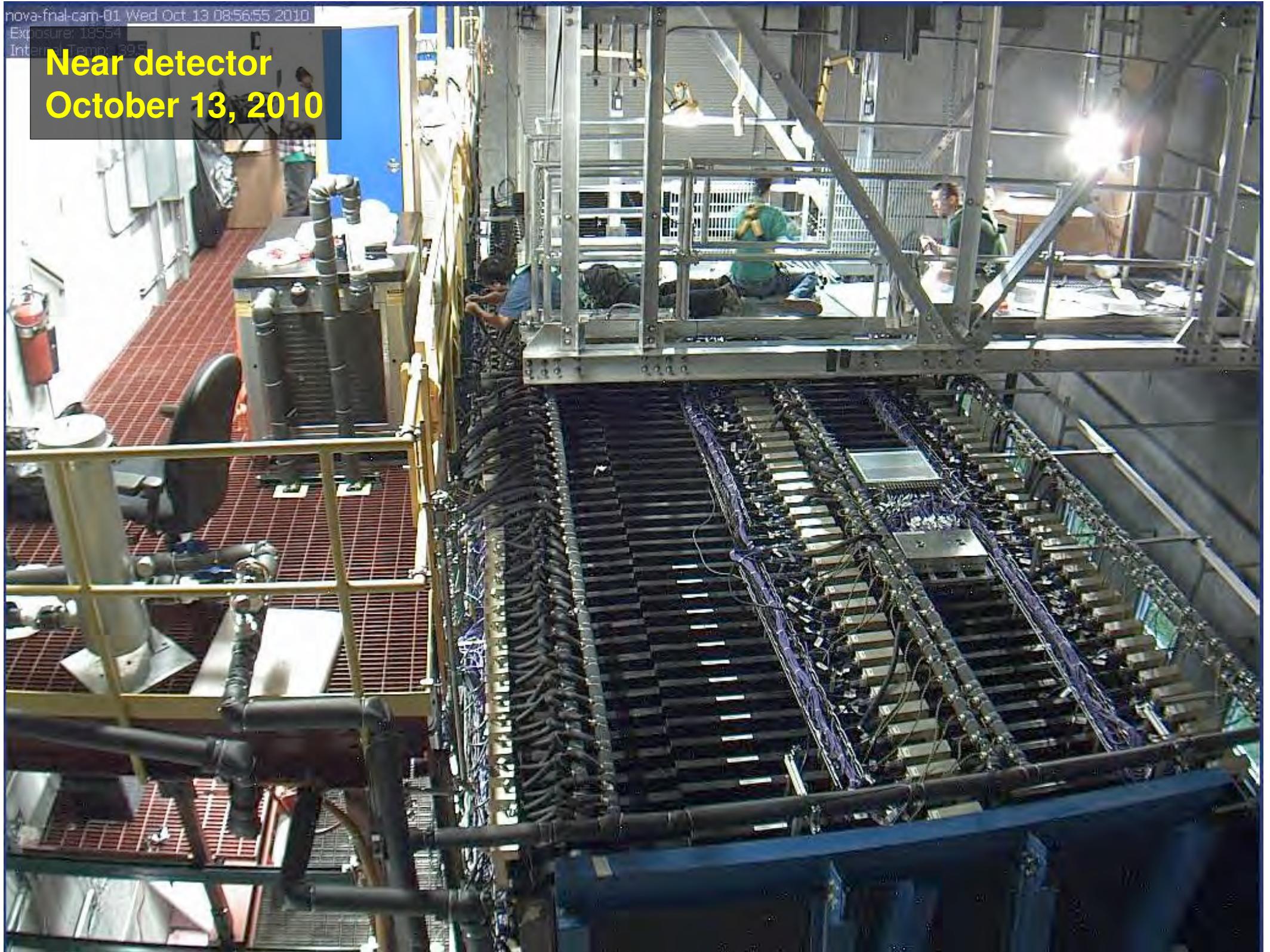
Far detector enclosure  
October 7, 2010



Far detector site  
November 10, 2010



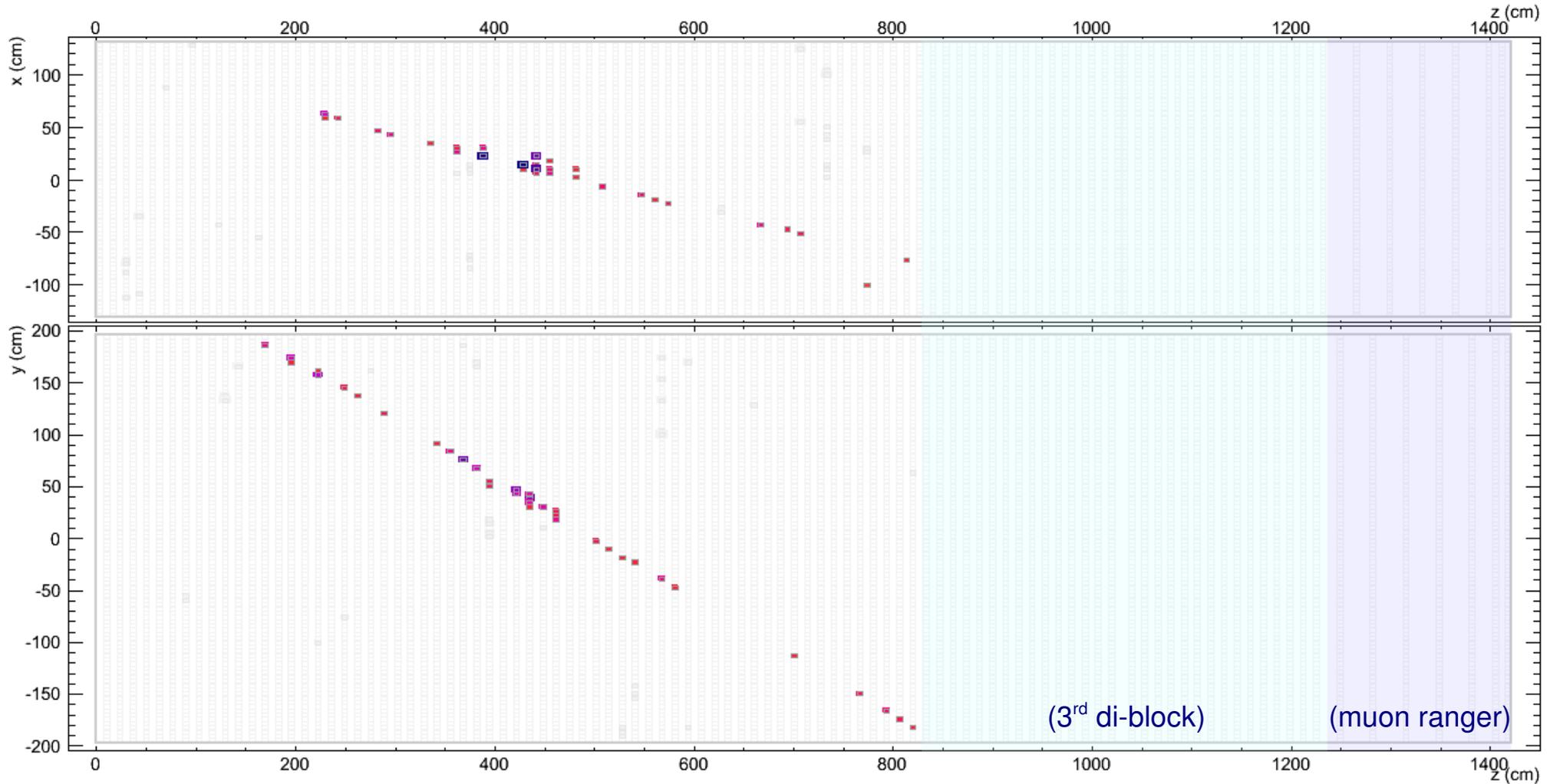
**Near detector**  
**October 13, 2010**



# Cosmic ray events in ND-on-Surface!

First two di-blocks instrumented. Commissioning in progress.

*(Not all channels live yet. High-threshold operation.)*



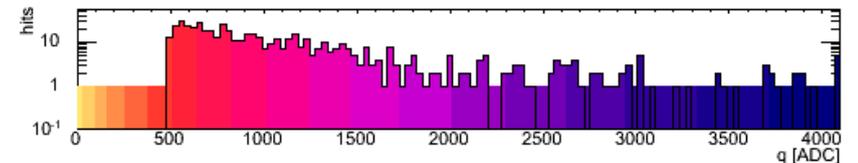
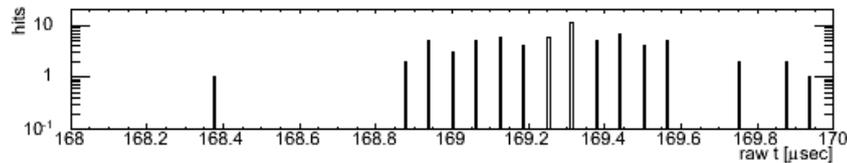
**NOvA - FNAL E929**

Run: 10733/3

Event: 6081

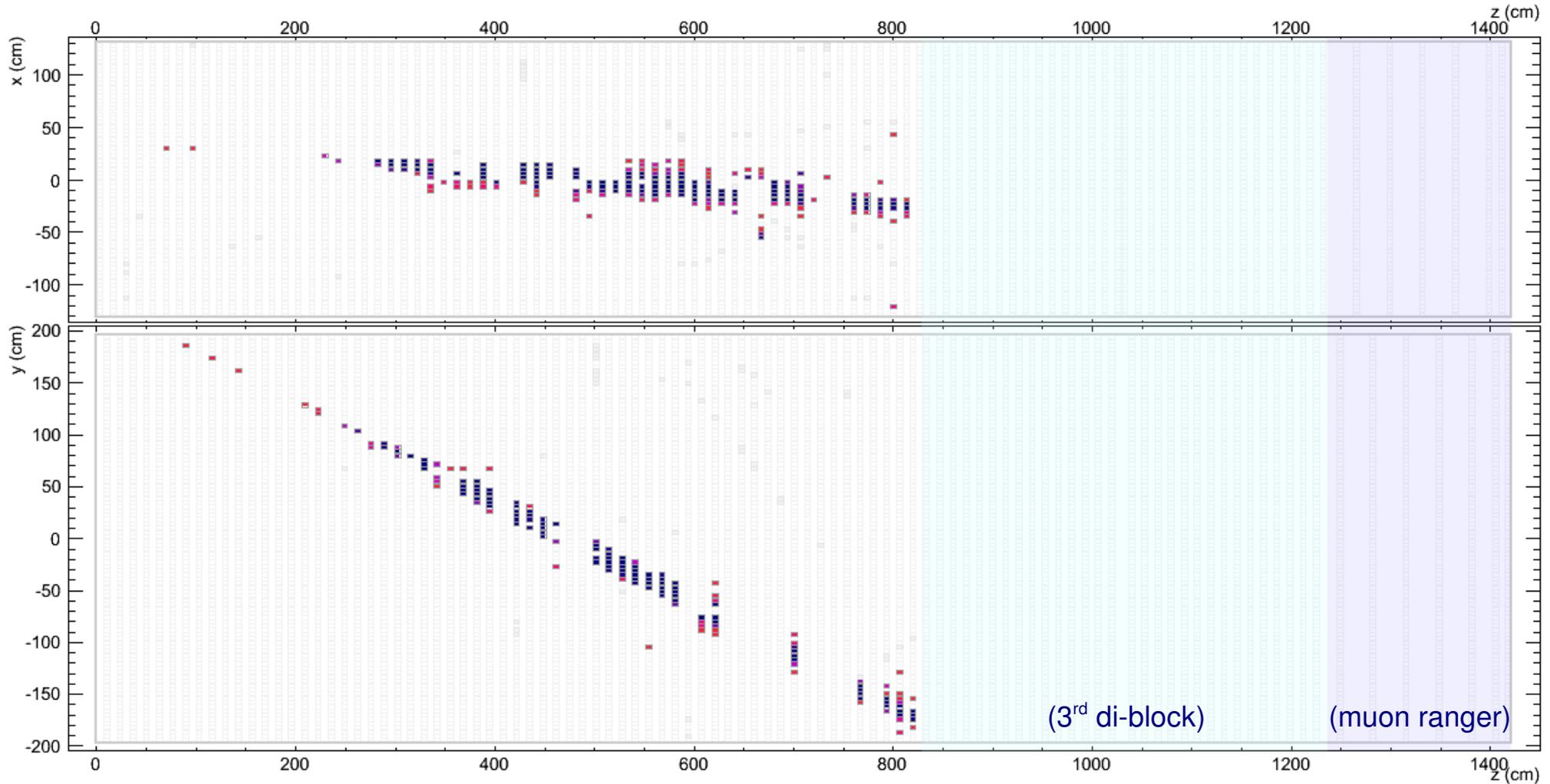
UTC Thu Dec 9, 2010

17:07:34.716710016



# Cosmic ray events in ND-on-Surface!

First two di-blocks instrumented. Commissioning in progress.  
(Not all channels live yet. High-threshold operation.)



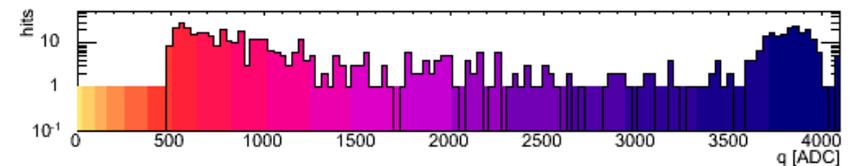
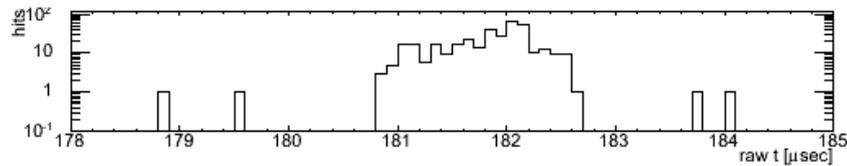
**NOvA - FNAL E929**

Run: 10705/10

Event: 16694

UTC Tue Dec 7, 2010

11:48:56.494454304



# Timeline and Status

## Now:

**NDOS** – *taking first data!*

## This winter:

**FD hall** – *beneficial occupancy*

## Early 2012

**NDOS** → **ND** begins  
**Accelerator and NuMI**  
*upgrades begin (1 yr)*

## Early 2013

**700 kW beam with 6 kton FD**

## Fall 2013

**Full 14 kton FD operational**

On-hand:

*all FD fluors, 35% of fiber*

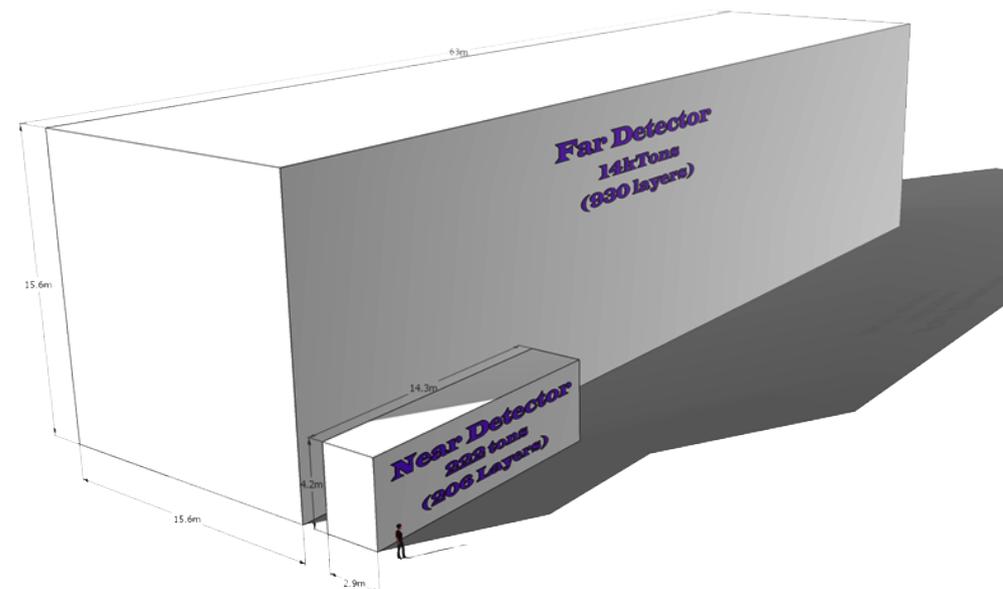
Purchased/contracted:

*all FD fiber, oil, PVC, extrusion*

FD building near completion

All components testing well

NDOS commissioning underway



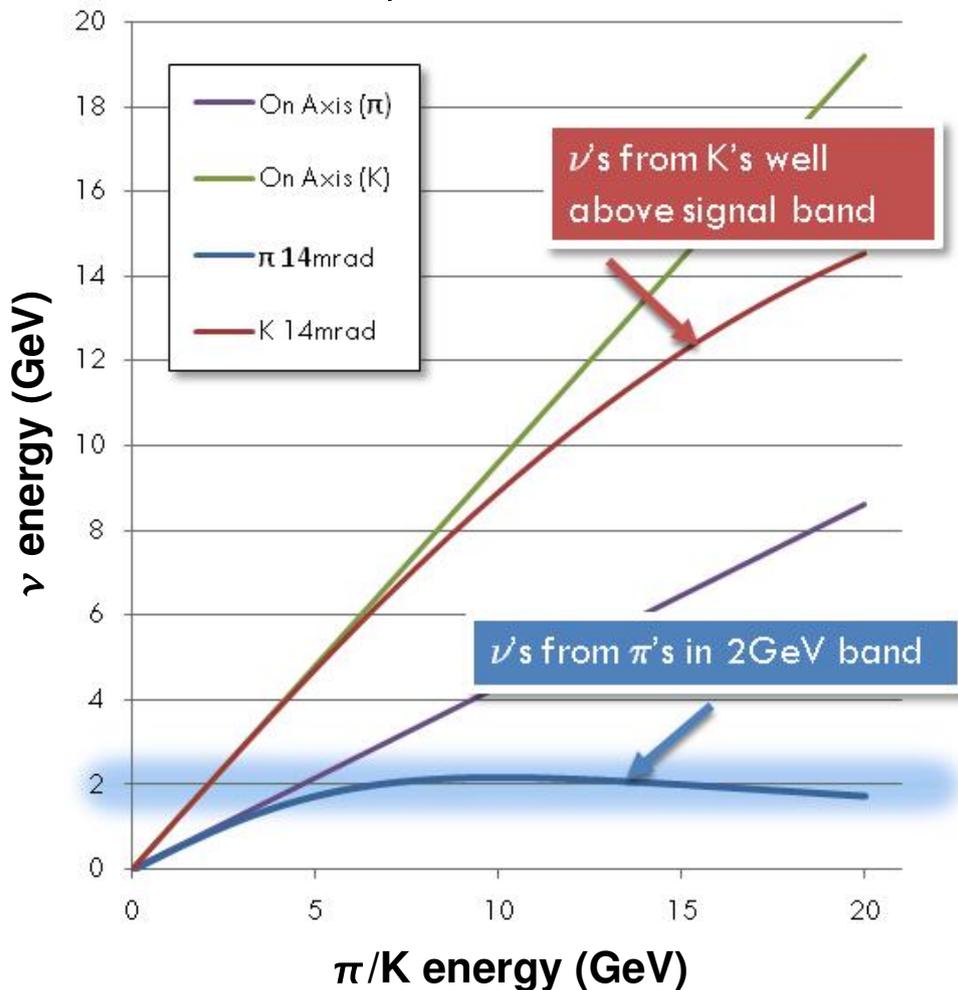


**Extra slides**

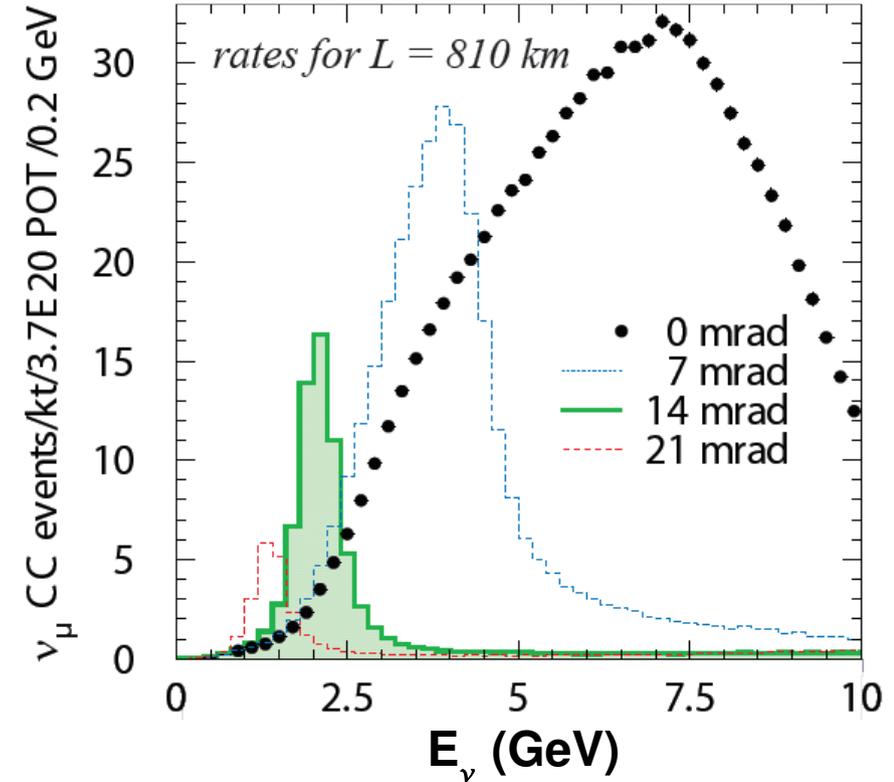
# NuMI off-axis beam

NO $\nu$ A detectors are sited **14 mrad** off the NuMI beam axis

## Off-axis $\nu_\mu$ energies from $\pi$ , K



## NuMI medium energy tune



*Reduces NC bgnd. (via energy cut)*

2 GeV  $\nu_e$   $\nu_e$  CC  $\Rightarrow$  2 GeV visible

2 GeV  $\nu_x$   $\nu_x$  NC  $\Rightarrow$  <2 GeV visible

*also: beam  $\nu_e$  bgnd.*

## Beam upgrades

- **NuMI** to go from 320 kW to **700 kW** during 2012  
*Stack in recycler  $\Rightarrow$  MI cycle time goes from 2.2 s to 1.5 s*  
*New extraction/injection lines*  
*Two more RF stations (1.5 s  $\rightarrow$  1.33 s)*  
*New high-intensity NuMI target*
- Result will be  $\sim 6 \times 10^{20}$  p/yr to NuMI

## Example run plan / event counts

- **3 years with  $\nu$**  and **3 years with  $\bar{\nu}$**
- Example **events counts** after  $\nu_e$  CC selection for  $\sin^2(2\theta_{13})=0.1$

<u>Signal:</u>	$\nu$	$\bar{\nu}$
$\nu_e$ CC	46	29
efficiency	26%	41%
<u>Bkgnd:</u>		
NC	4	6
$\nu_e$ CC	4	4
$\nu_\mu$ CC	1	<1

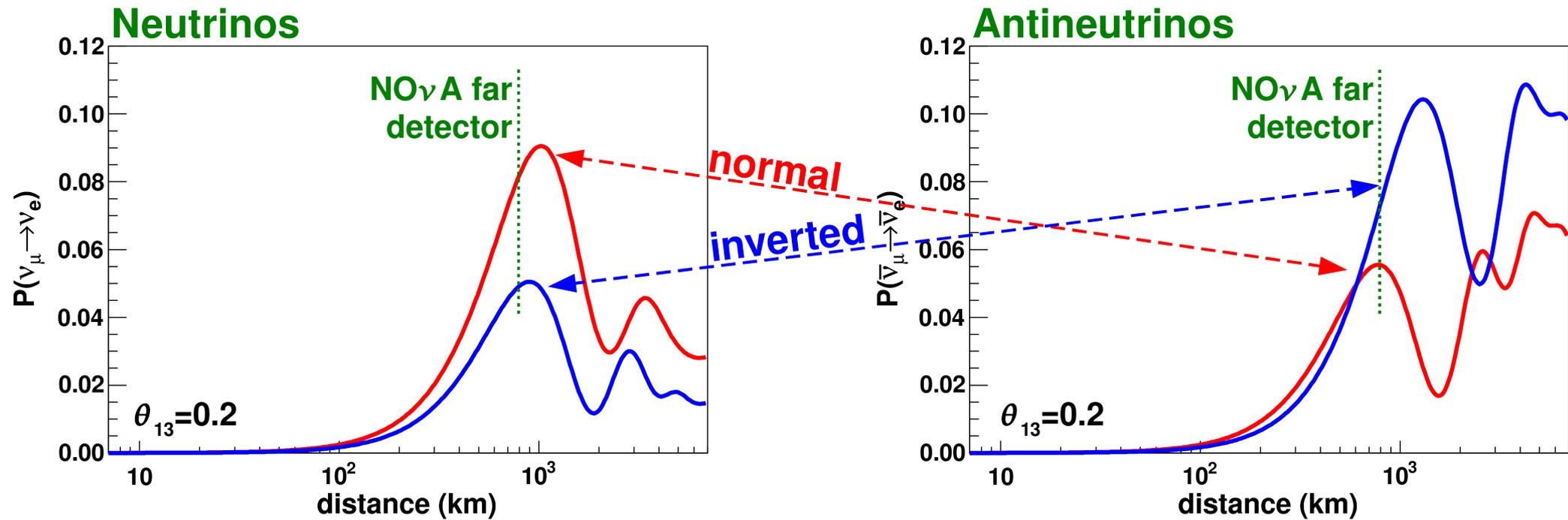
*Using rudimentary reconstruction, event selection, optimization*

# Utilizing the matter effect

810 km of matter  $\Rightarrow$  different oscillation probabilities for:

*normal* vs. *inverted hierarchy*  
*neutrinos* vs. *antineutrinos*

So: measure **both**  $P(\nu_\mu \rightarrow \nu_e)$  and  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$  in NO $\nu$ A

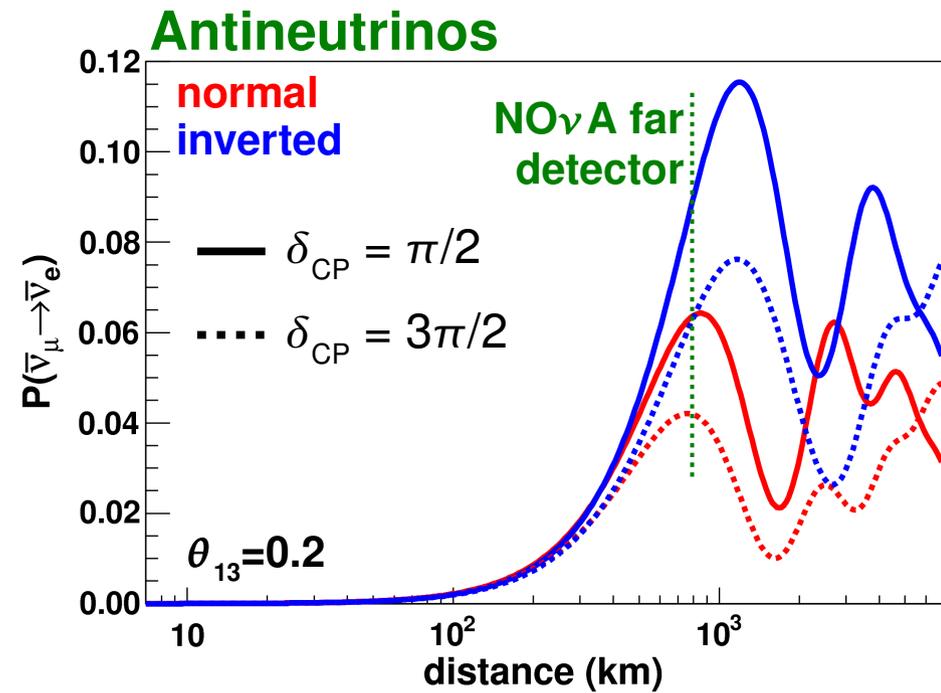
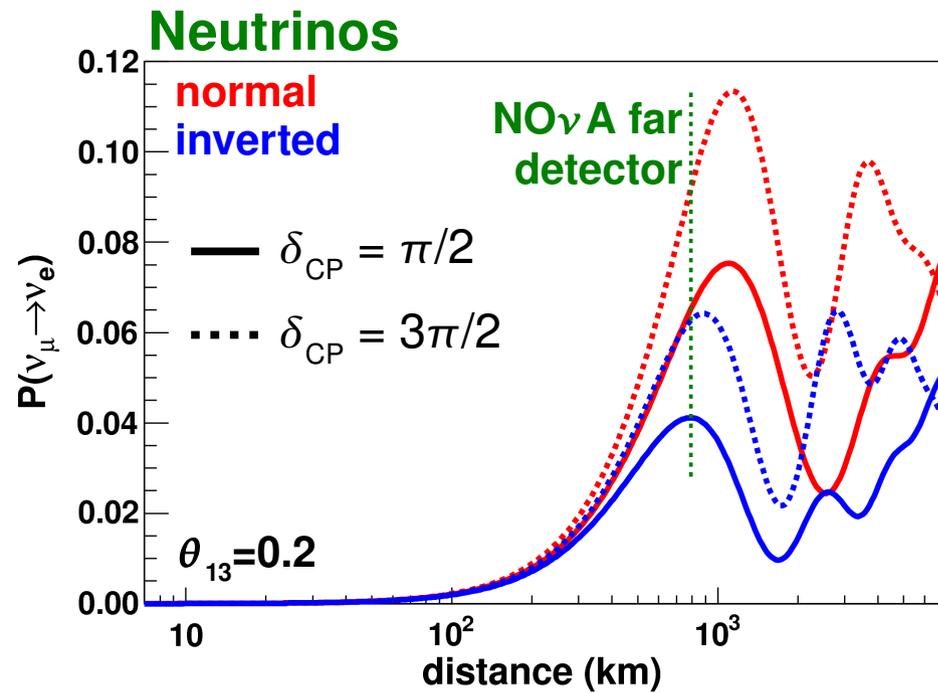


$$P(\nu_\mu \rightarrow \nu_e) > P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow \Delta m_{32}^2 > 0$$

$$P(\nu_\mu \rightarrow \nu_e) < P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow \Delta m_{32}^2 < 0$$

# Utilizing the matter effect... with CP violation

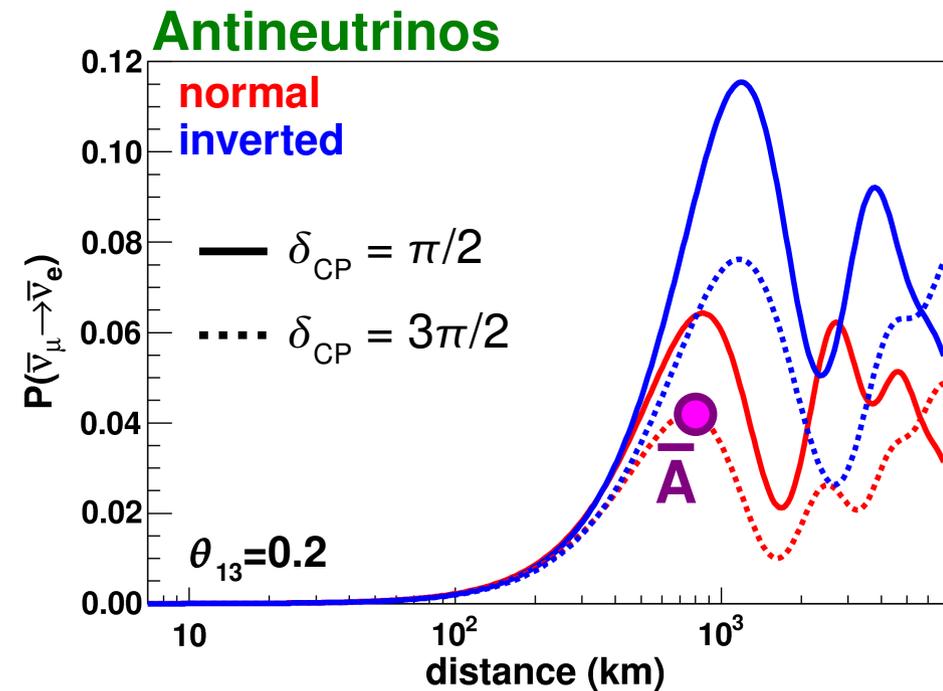
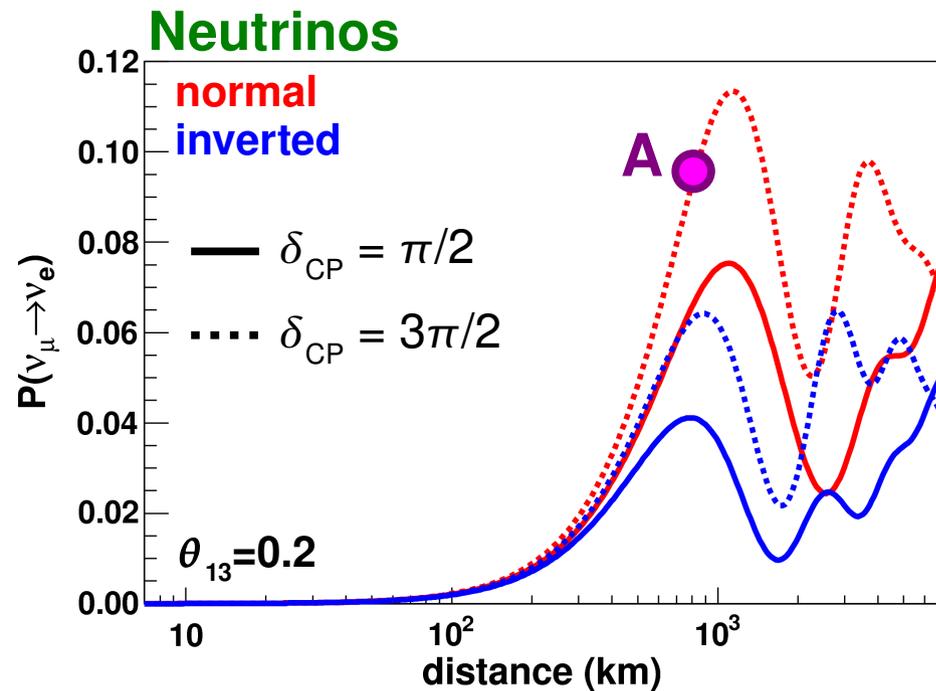
CP violation also splits appearance probability



# Utilizing the matter effect... with CP violation

**CP violation** also splits appearance probability

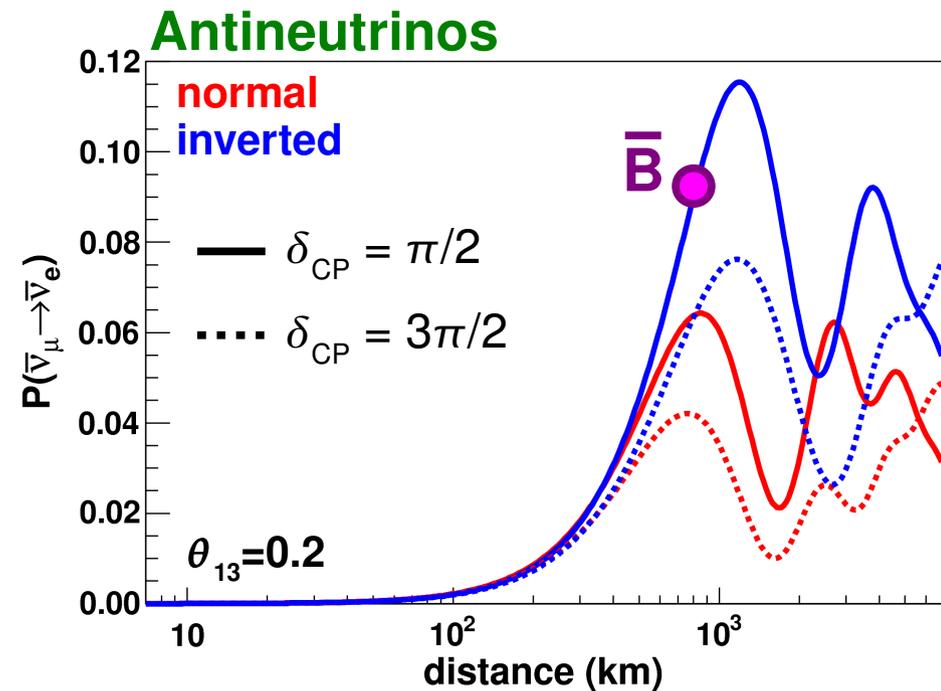
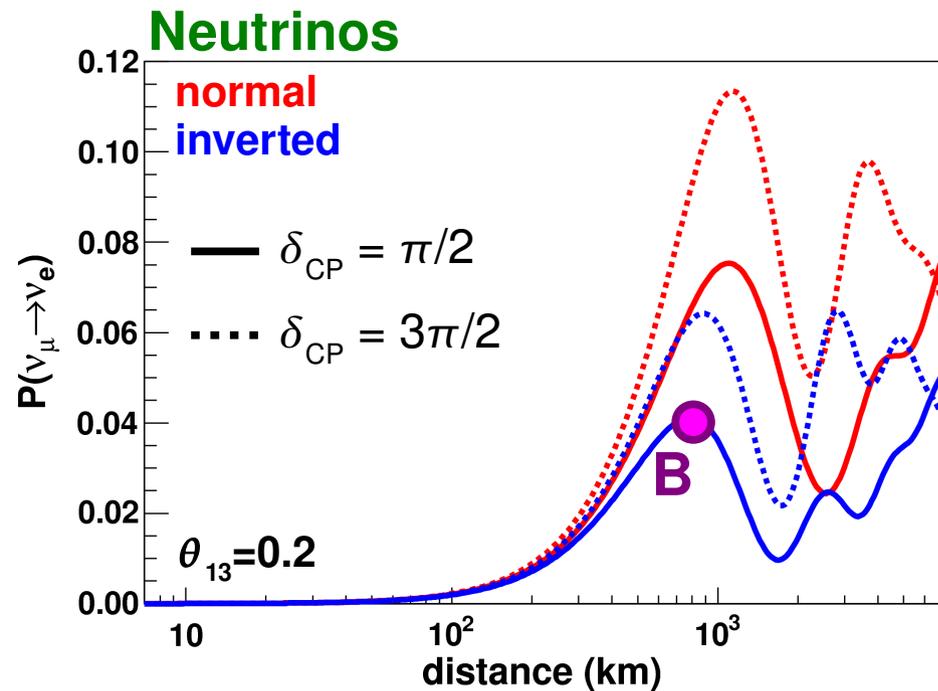
If we measure **A** and  $\bar{\mathbf{A}}$  below  $\Rightarrow$  **normal**,  $\delta \approx 3\pi/2$



# Utilizing the matter effect... with CP violation

**CP violation** also splits appearance probability

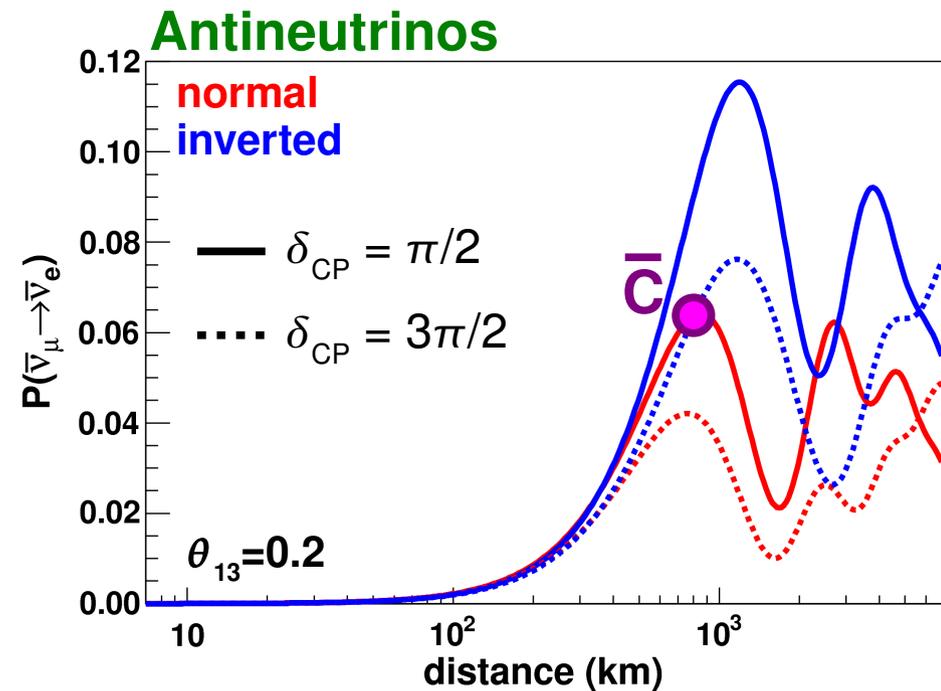
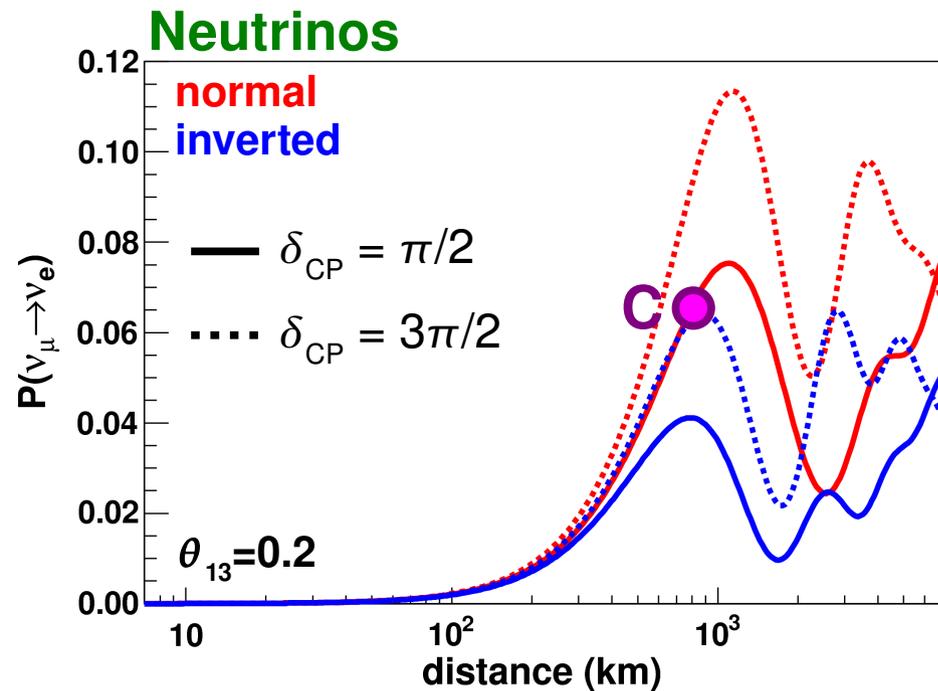
If we measure **B** and  $\bar{\mathbf{B}}$  below  $\Rightarrow$  **inverted**,  $\delta \approx \pi/2$



# Utilizing the matter effect... with CP violation

CP violation also splits appearance probability

If we measure  $C$  and  $\bar{C}$  below  $\Rightarrow$  *two solutions*



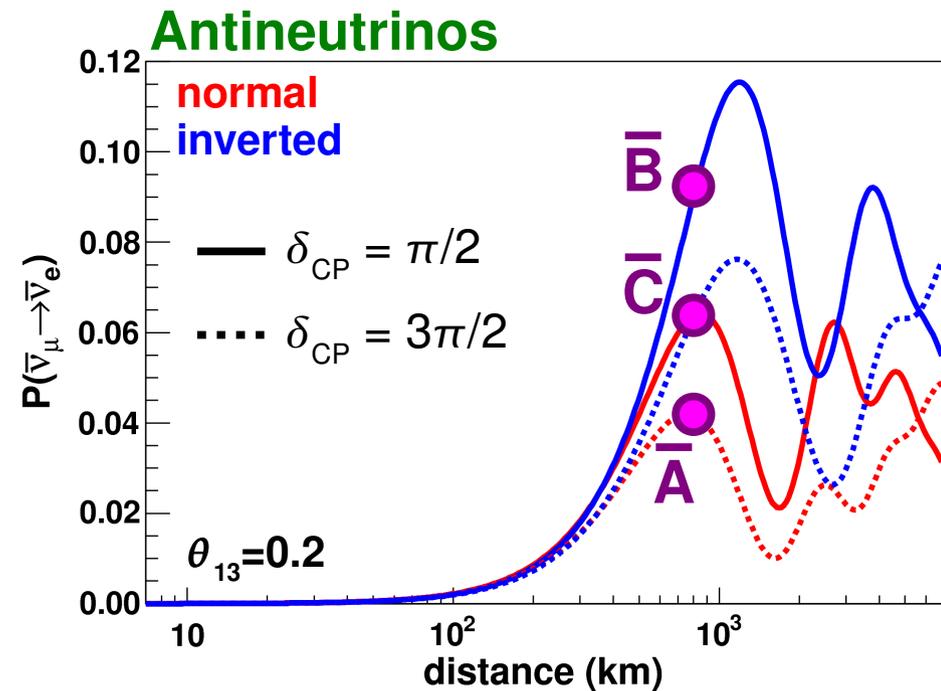
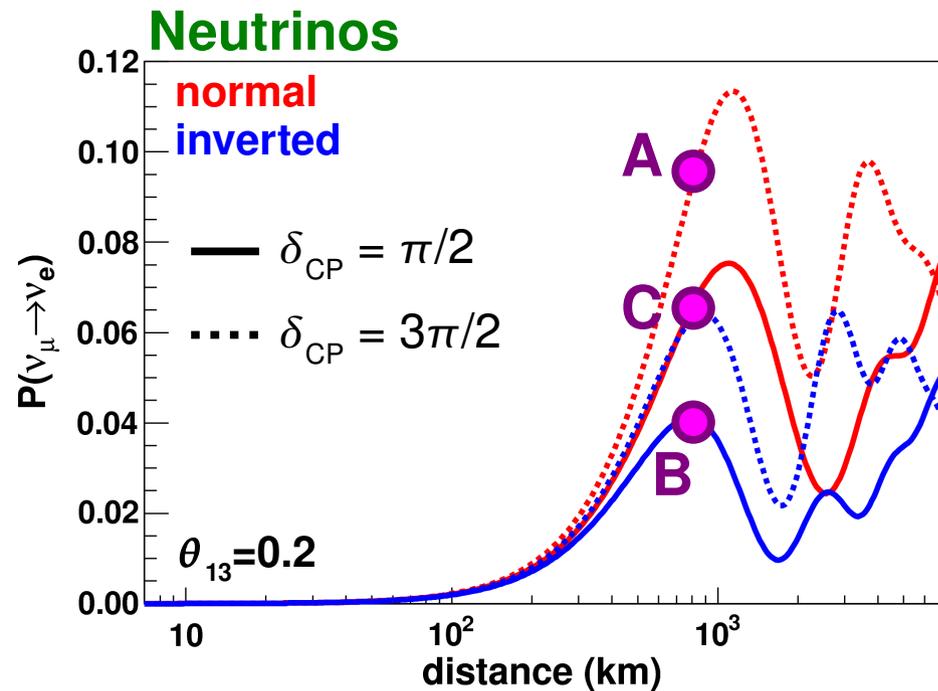
# Utilizing the matter effect... with CP violation

**CP violation** also splits appearance probability

If we measure **A** and  $\bar{\text{A}}$  below  $\Rightarrow$  **normal**,  $\delta \approx 3\pi/2$

If we measure **B** and  $\bar{\text{B}}$  below  $\Rightarrow$  **inverted**,  $\delta \approx \pi/2$

If we measure **C** and  $\bar{\text{C}}$  below  $\Rightarrow$  **two solutions**



The **degenerate regime** can be helped with **outside data**:

$$P(\nu_{\mu} \rightarrow \nu_e) \text{ in T2K}$$

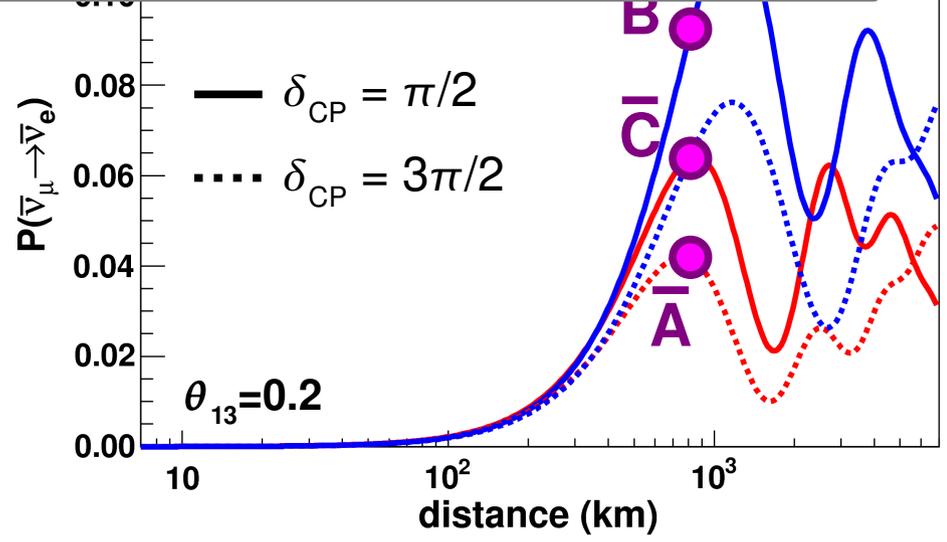
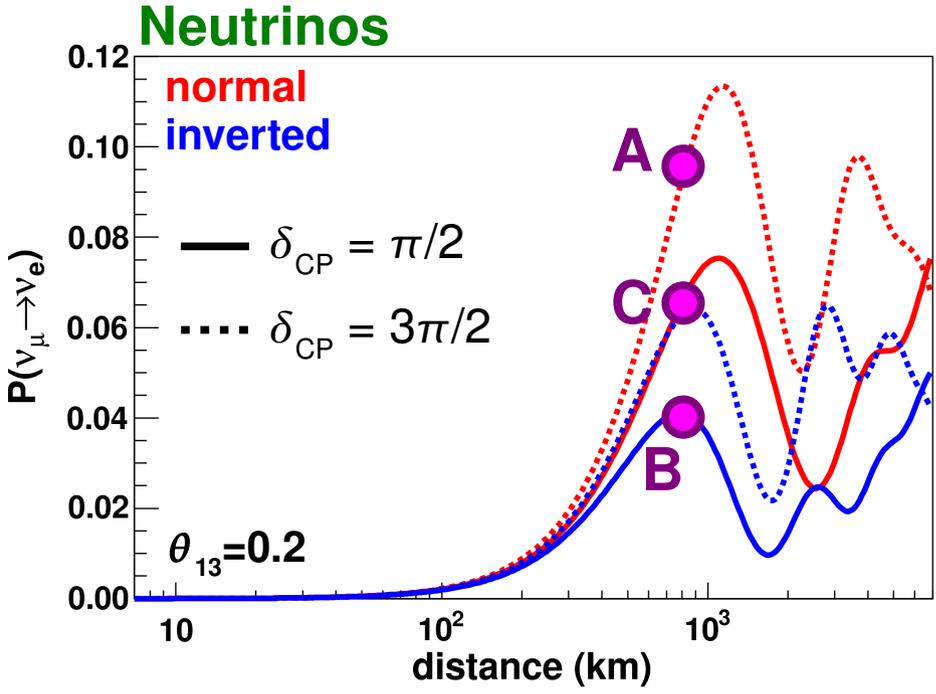
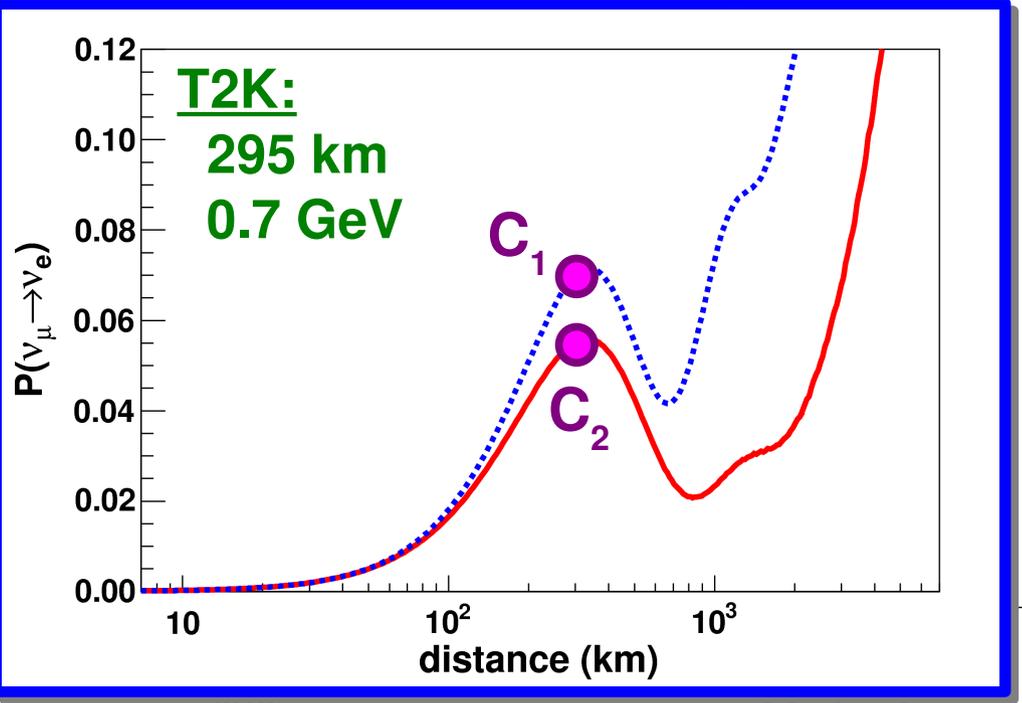
# Utilizing the matter effect

CP violation also splits appearance

If we measure **A** and  $\bar{\mathbf{A}}$  below

If we measure **B** and  $\bar{\mathbf{B}}$  below

If we measure **C** and  $\bar{\mathbf{C}}$  below



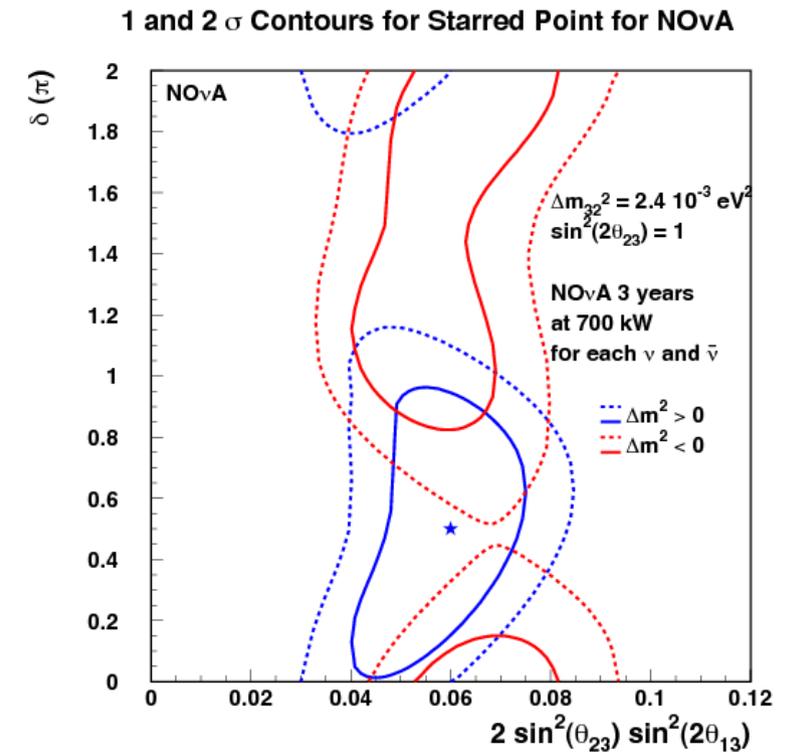
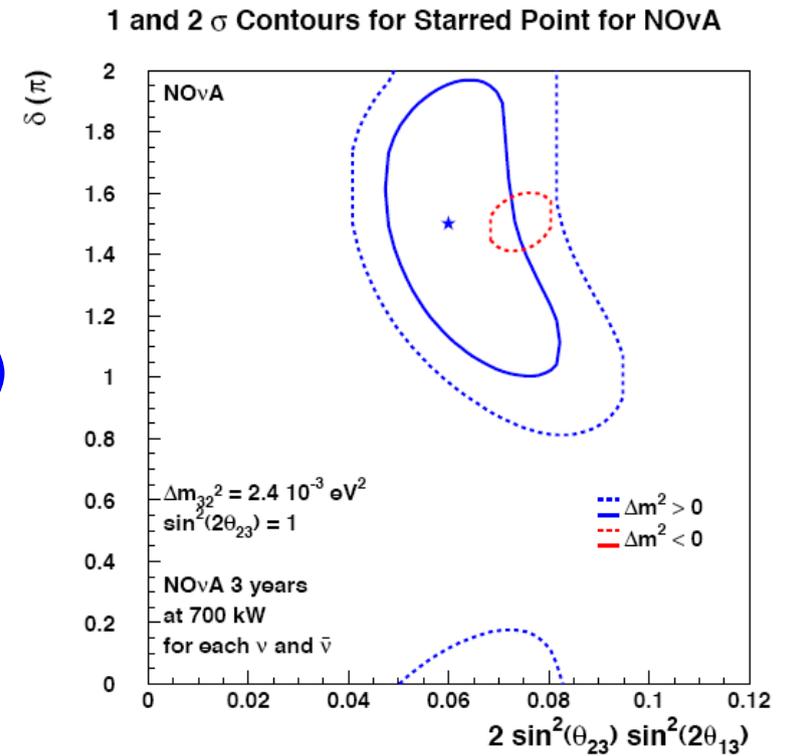
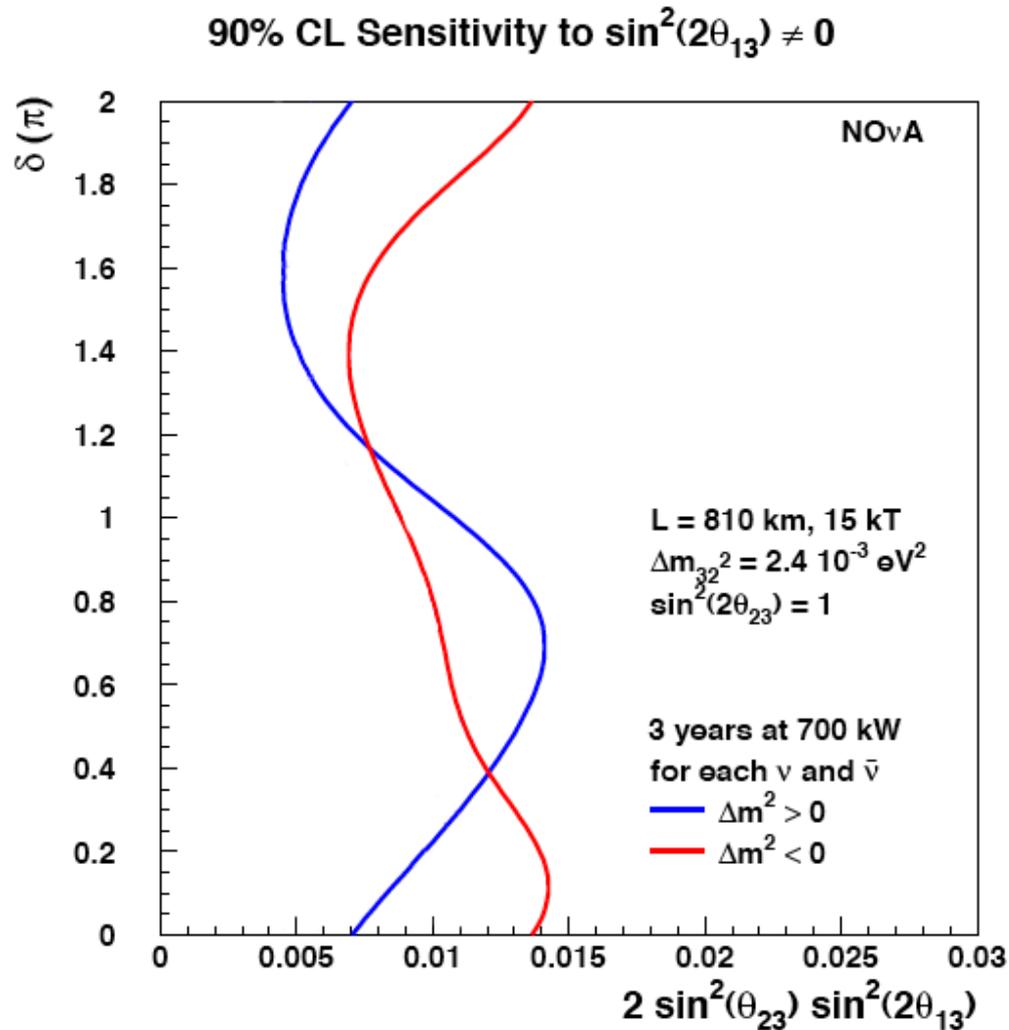
The degenerate regime can be helped with outside data:

$$P(\nu_{\mu} \rightarrow \nu_e) \text{ in T2K}$$

# NO $\nu$ A sensitivities

*Below:  $\theta_{13}$  reach*

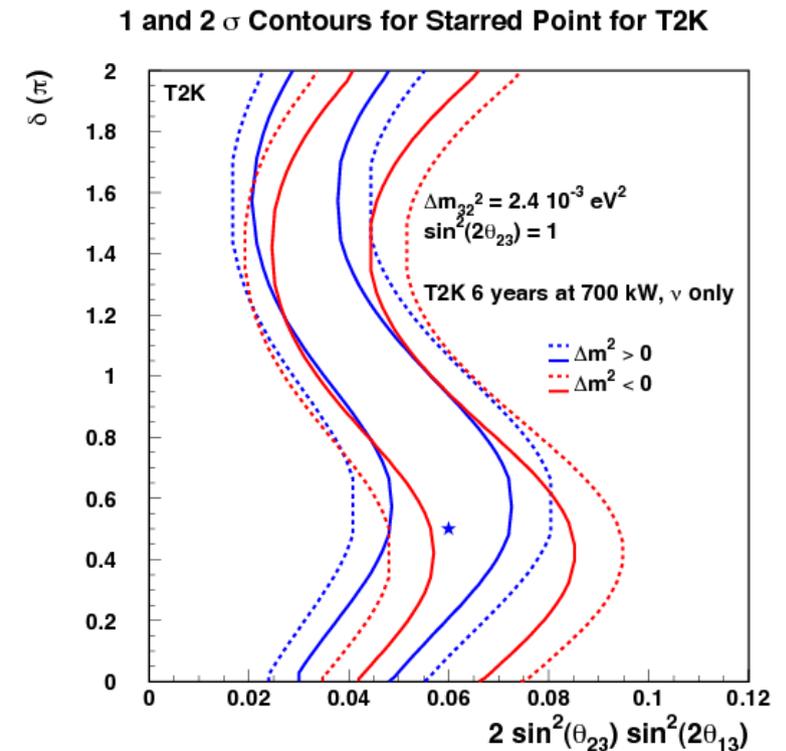
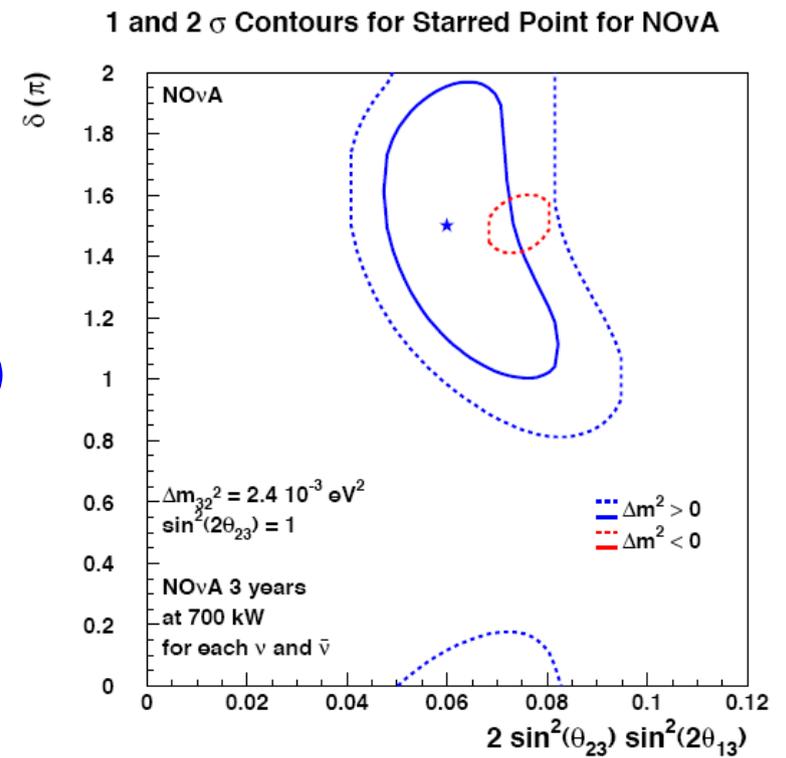
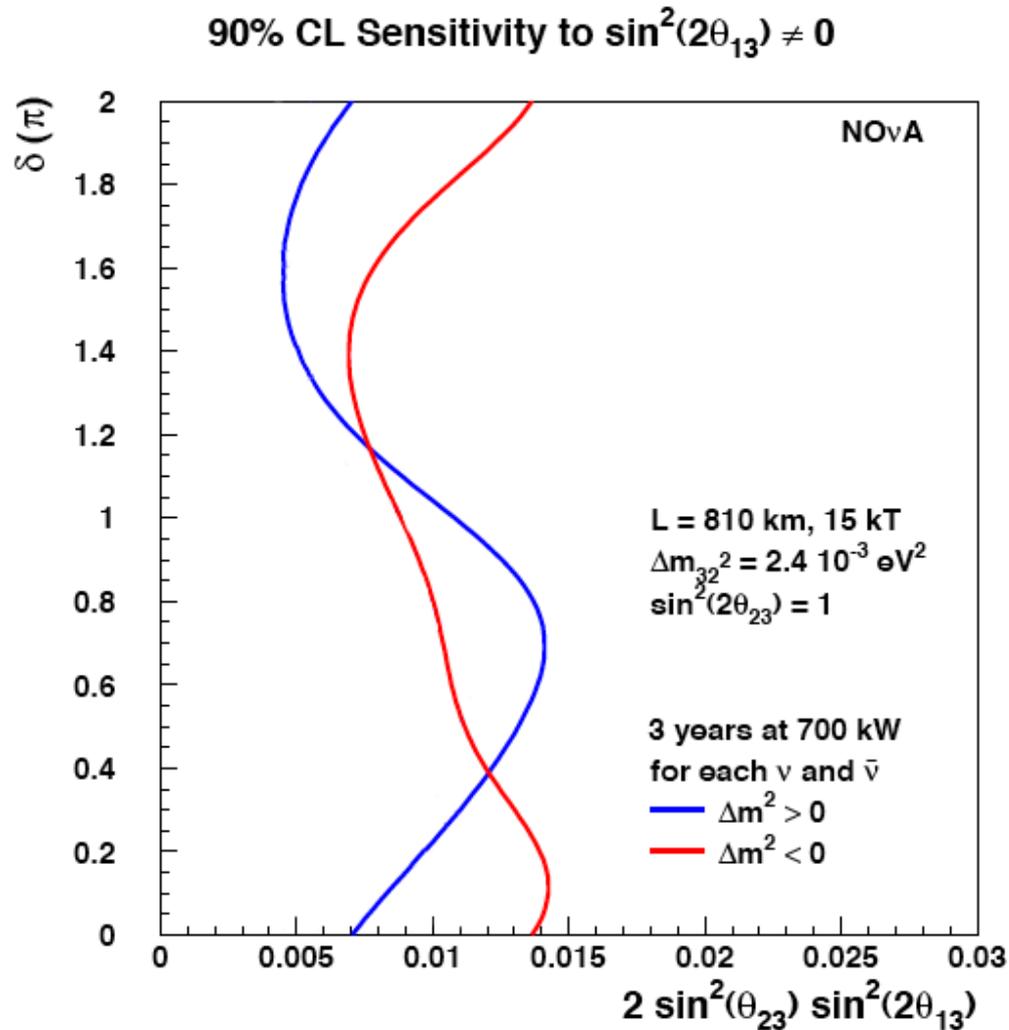
*Right: two example points (easy and hard)*



# NO $\nu$ A sensitivities

**Below:  $\theta_{13}$  reach**

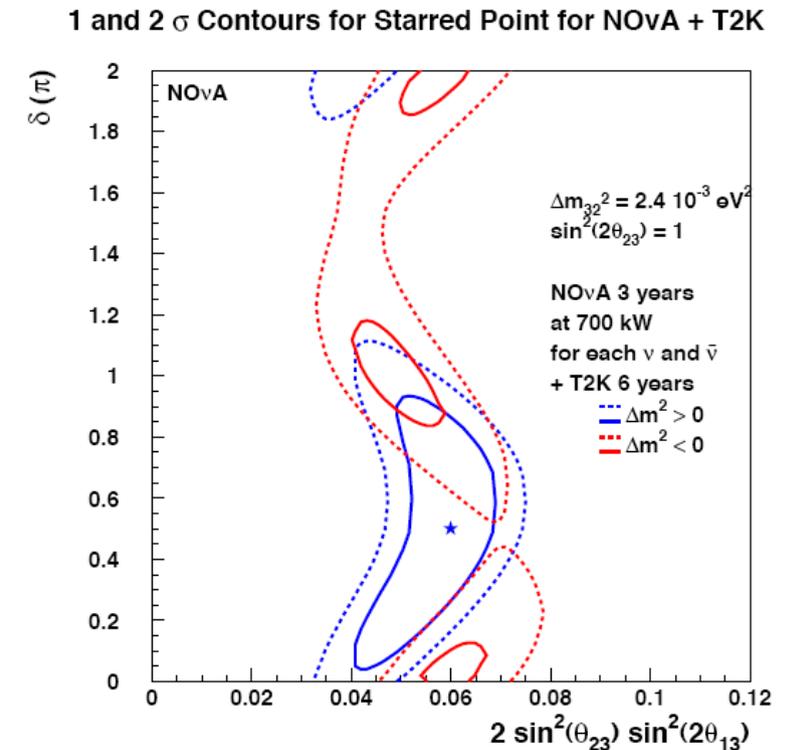
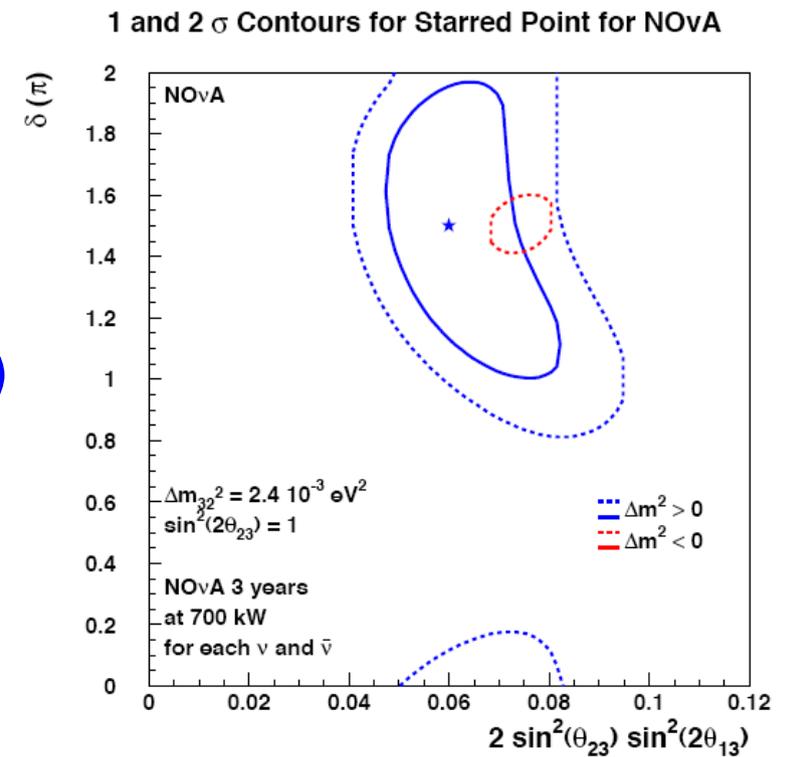
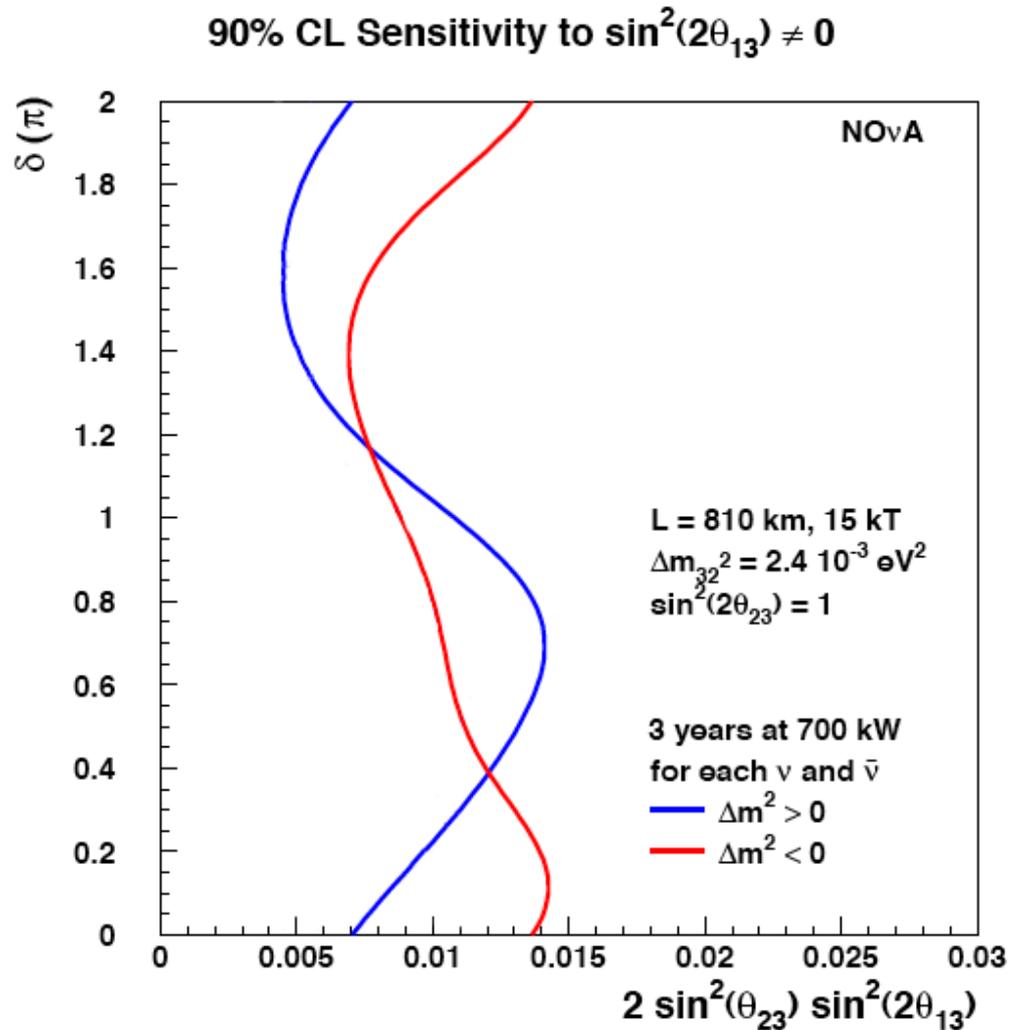
**Right: two example points (easy and hard)**



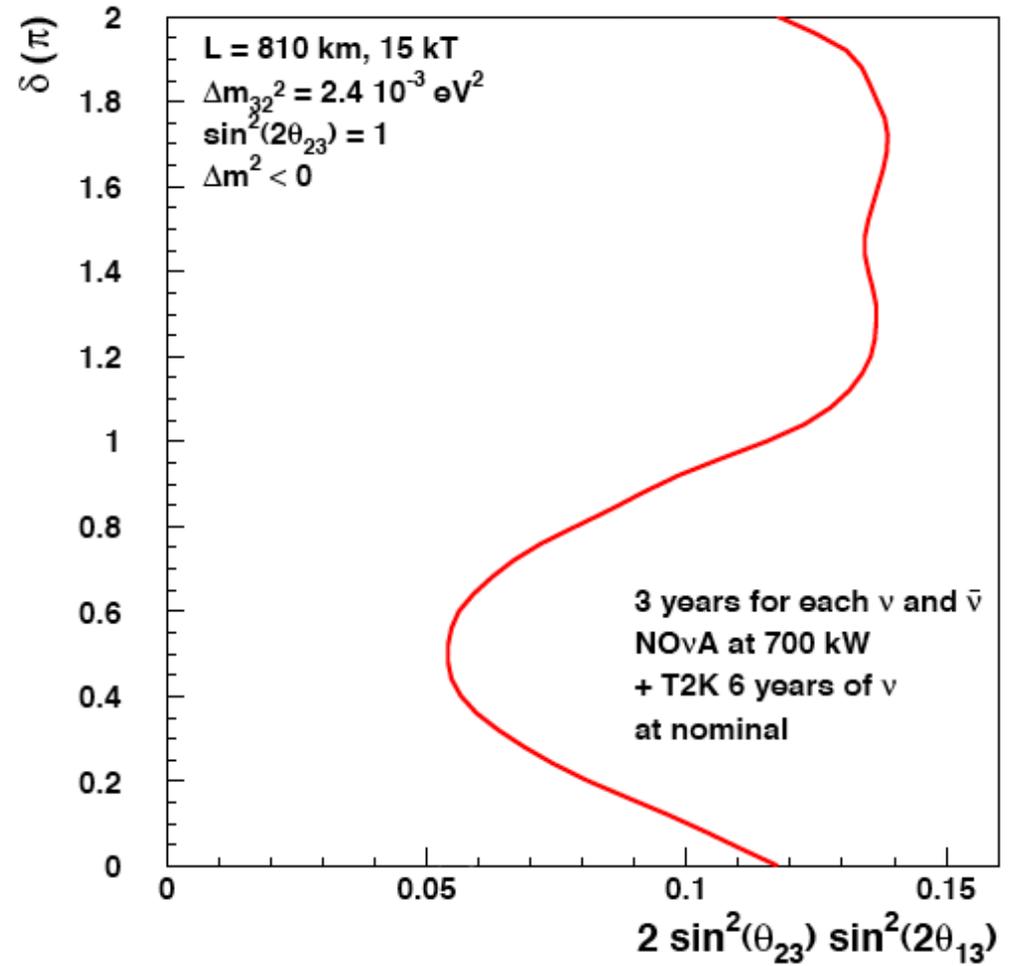
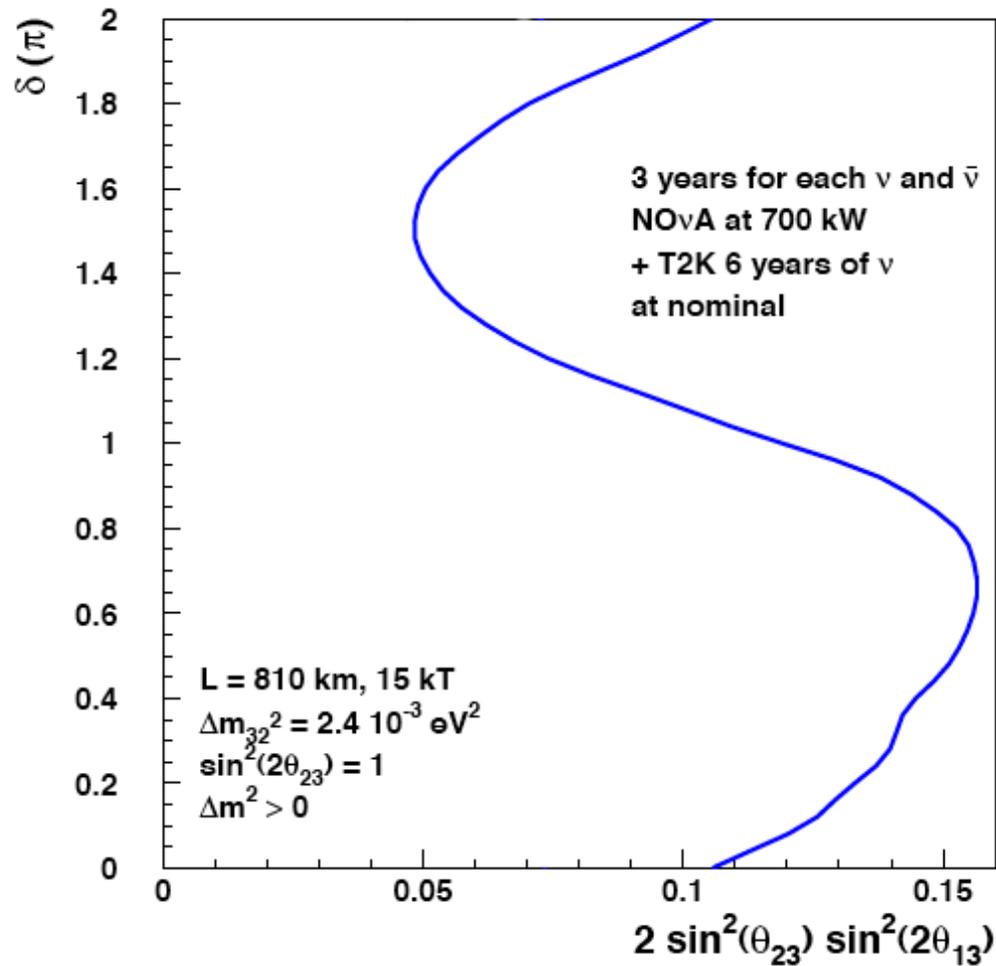
# NO $\nu$ A sensitivities

*Below:  $\theta_{13}$  reach*

*Right: two example points (easy and hard)*

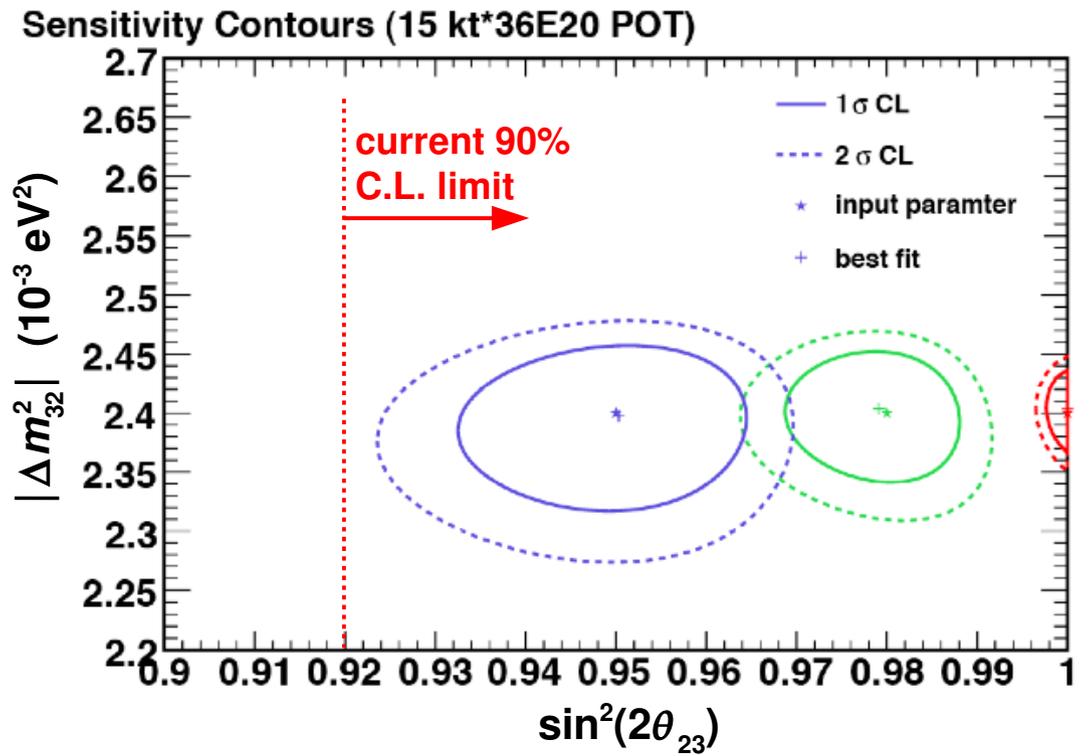


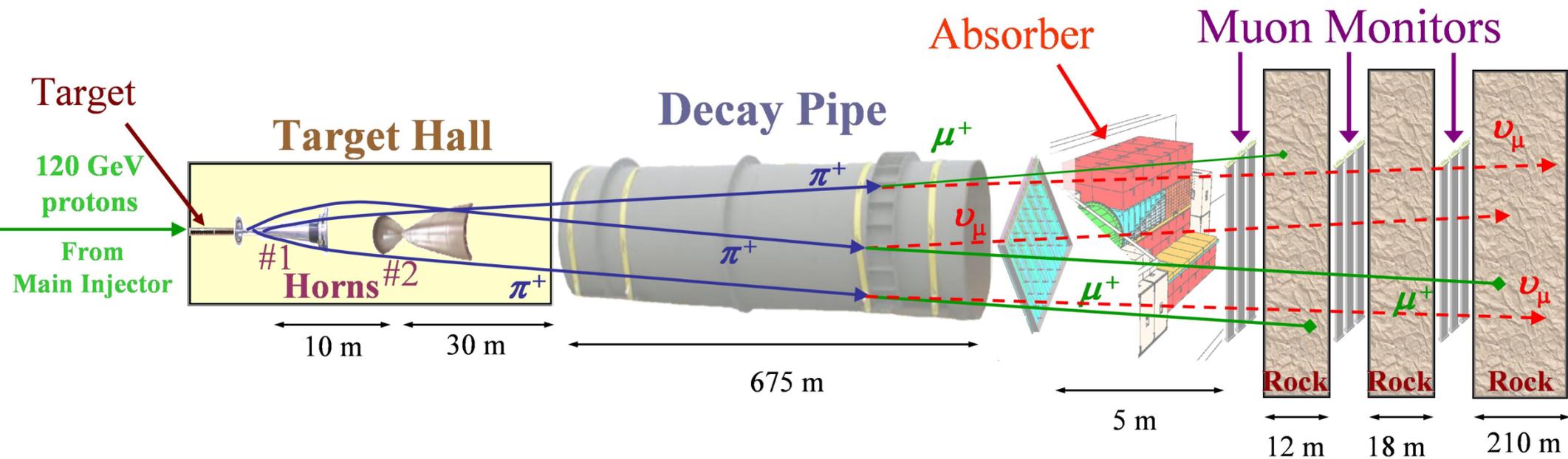
**95% C.L. hierarchy resolution for points to the right of these curves**



*Only completely non-degenerate determination is counted here.  
 $\delta_{CP}$ -dependent determination possible well below these.*

$|\Delta m_{32}^2|$  and  $\sin^2(2\theta_{23})$





- Magnetic **focusing horns** send positive secondaries ( $\pi^+$  mostly) down **decay pipe**
- Target and horn positions are adjustable:  
***tunable neutrino energy spectrum*** →

