Pontecorvo, Neutrinos, MINOS

Pontecorvo Prize Talk
JINR, Dubna
February 16, 2012

Stanley Wojcicki
Stanford University

Bruno Pontecorvo
1913-1993

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- Solar neutrinos, 1948
  $^{37}Cl\ (\nu,e^-)\ ^{37}Ar$

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- Different ν flavors, 1957
  Neutrino oscillations
- Accelerator produced ν beams, 1959
  $\pi \rightarrow \mu + \nu,\ K \rightarrow \mu + \nu$

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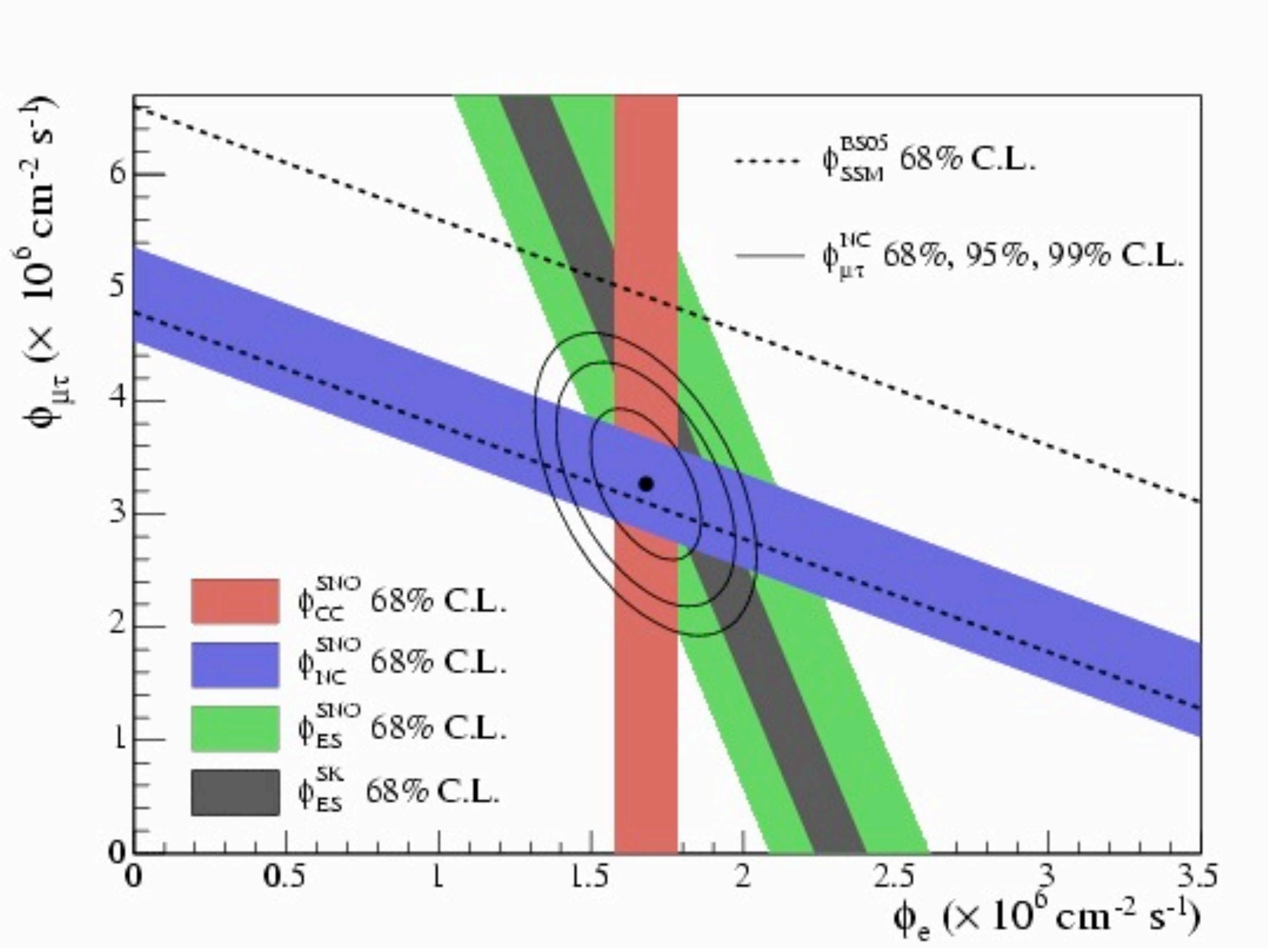
Resolution of the solar neutrino puzzle by SNO and other experiments



Accelerator Neutrinos

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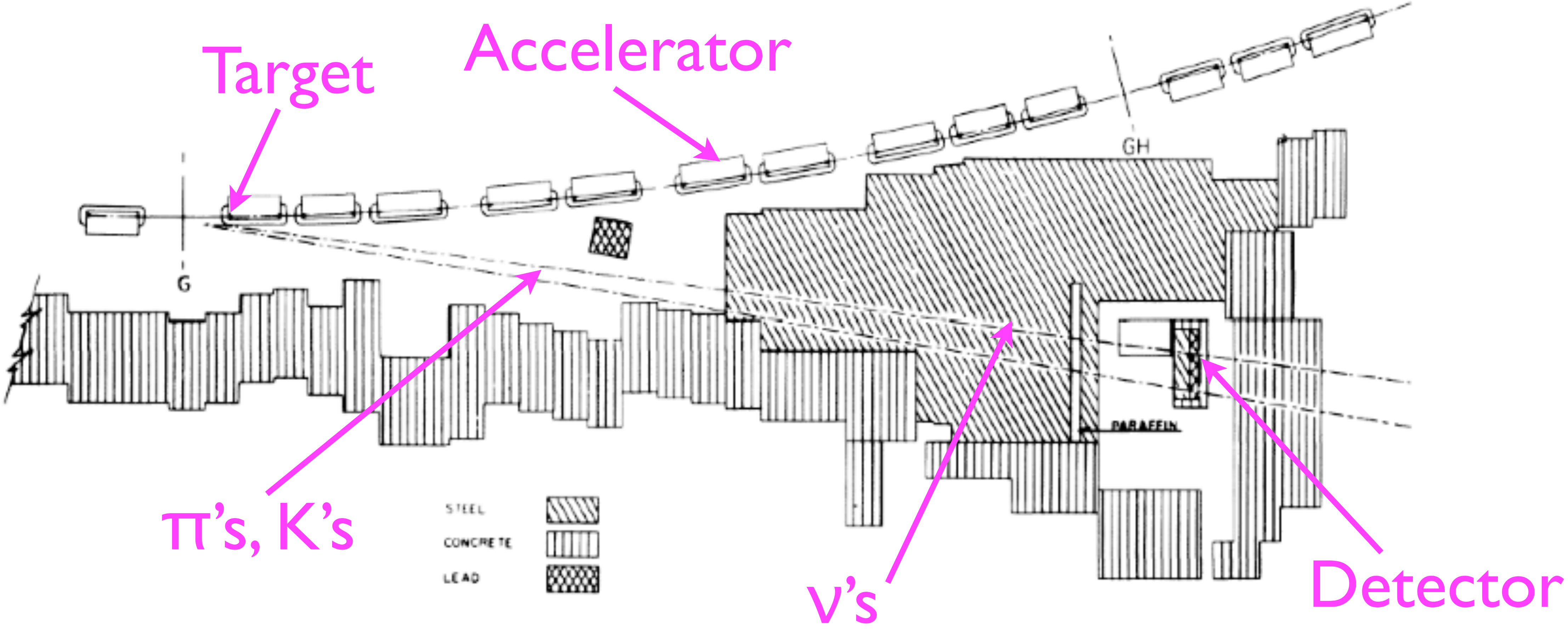

The beam for 2-neutrino experiment (BNL,1960)

“Modern” Neutrino Beam

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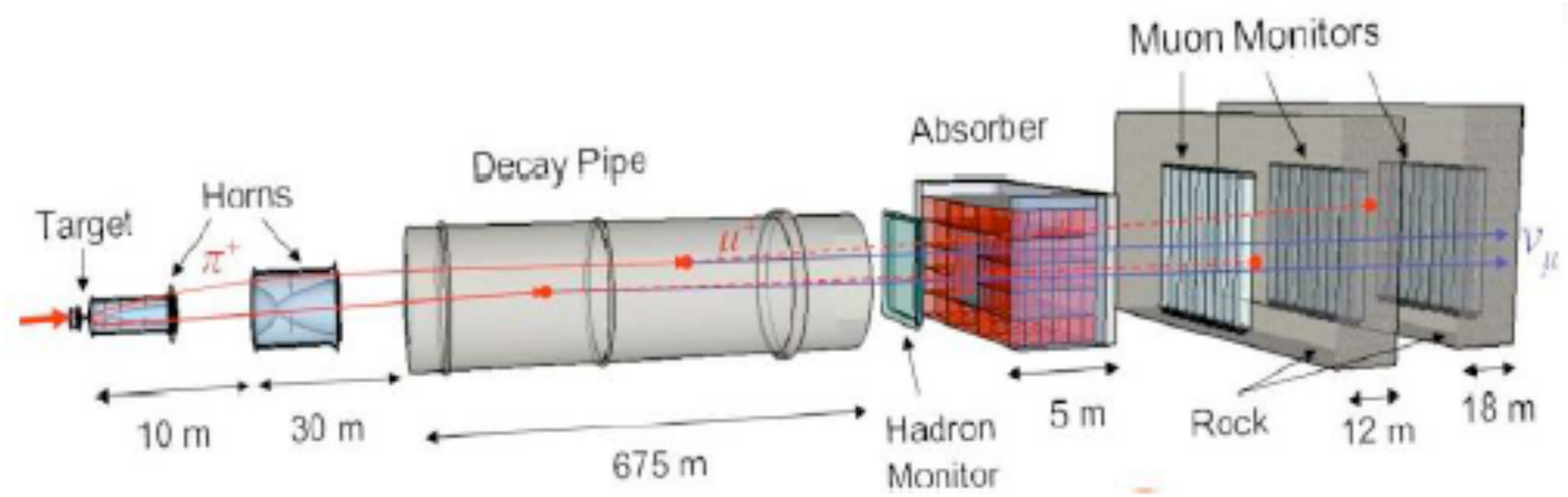

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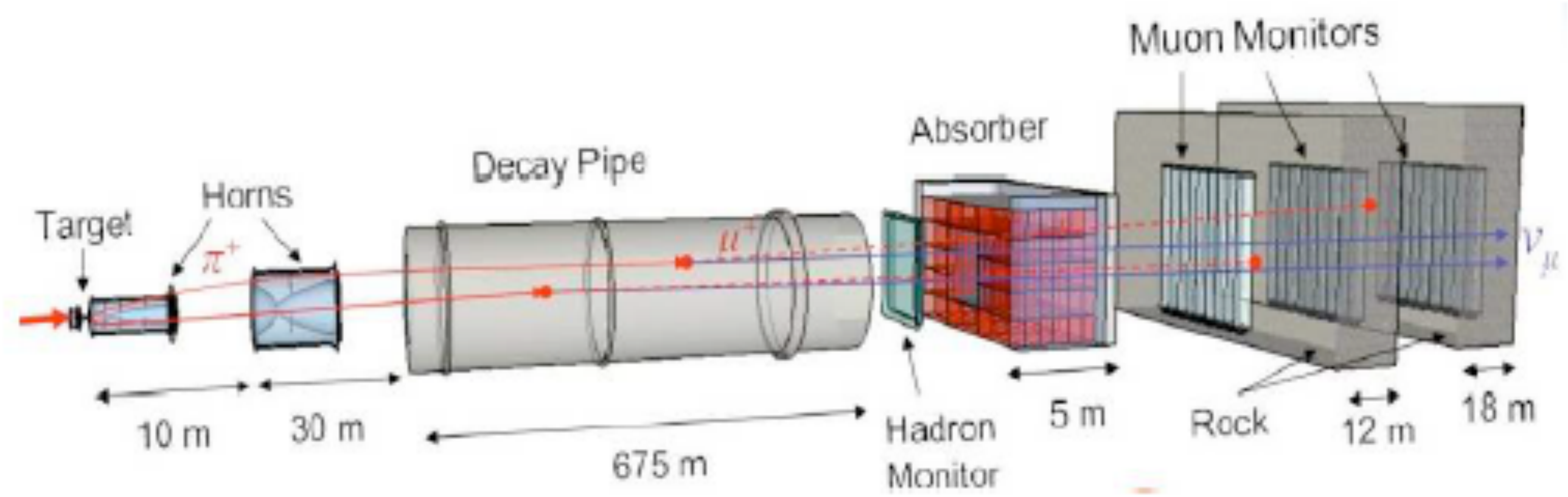
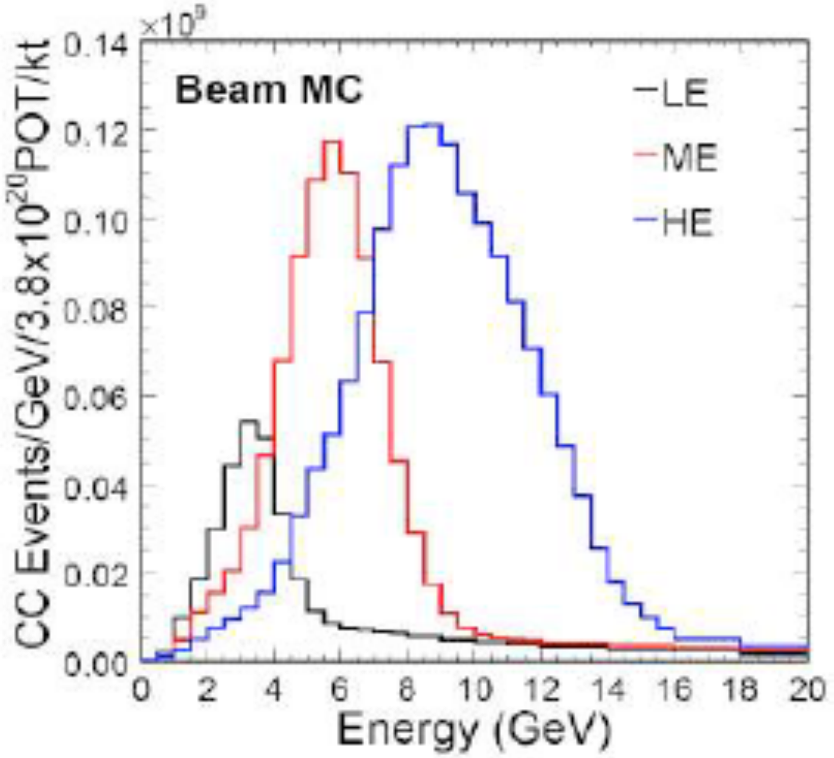
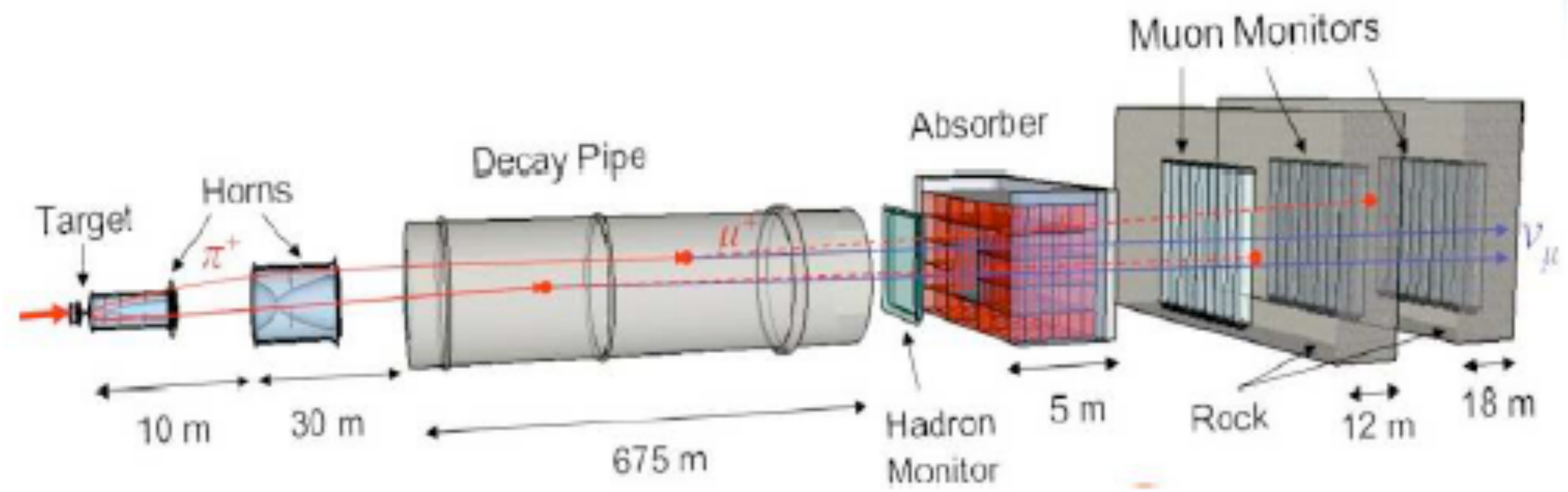
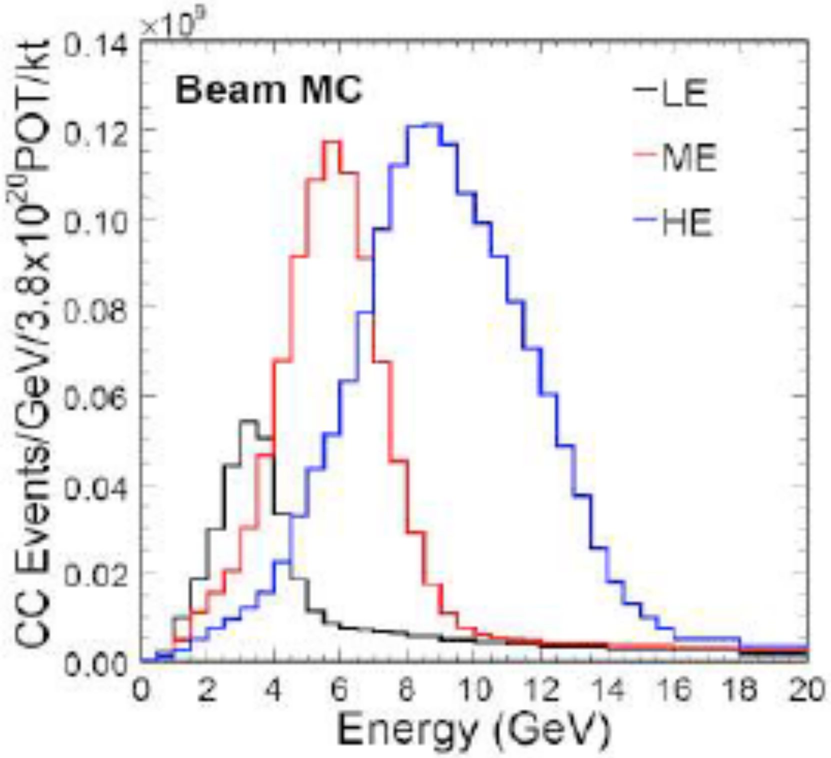




Ability to choose energy by moving the target

“Modern” Neutrino Beam





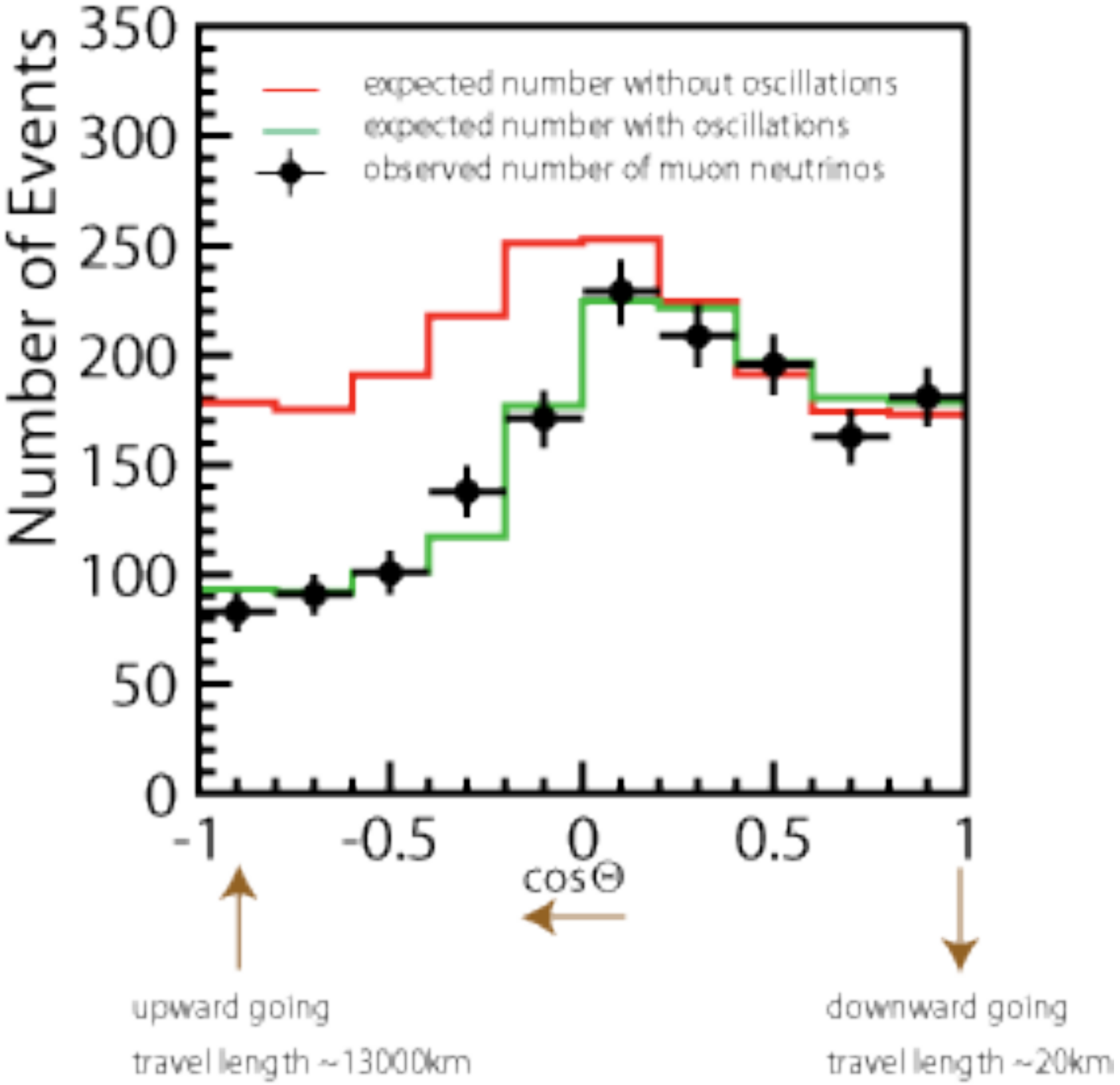
Ability to choose energy by moving the target

In the future:
Super beams ~ 2-4 Mw
Neutrino factory (μ storage ring)

Oscillations

Oscillations

Super-Kamiokande



ν_μ's disappear

Oscillations

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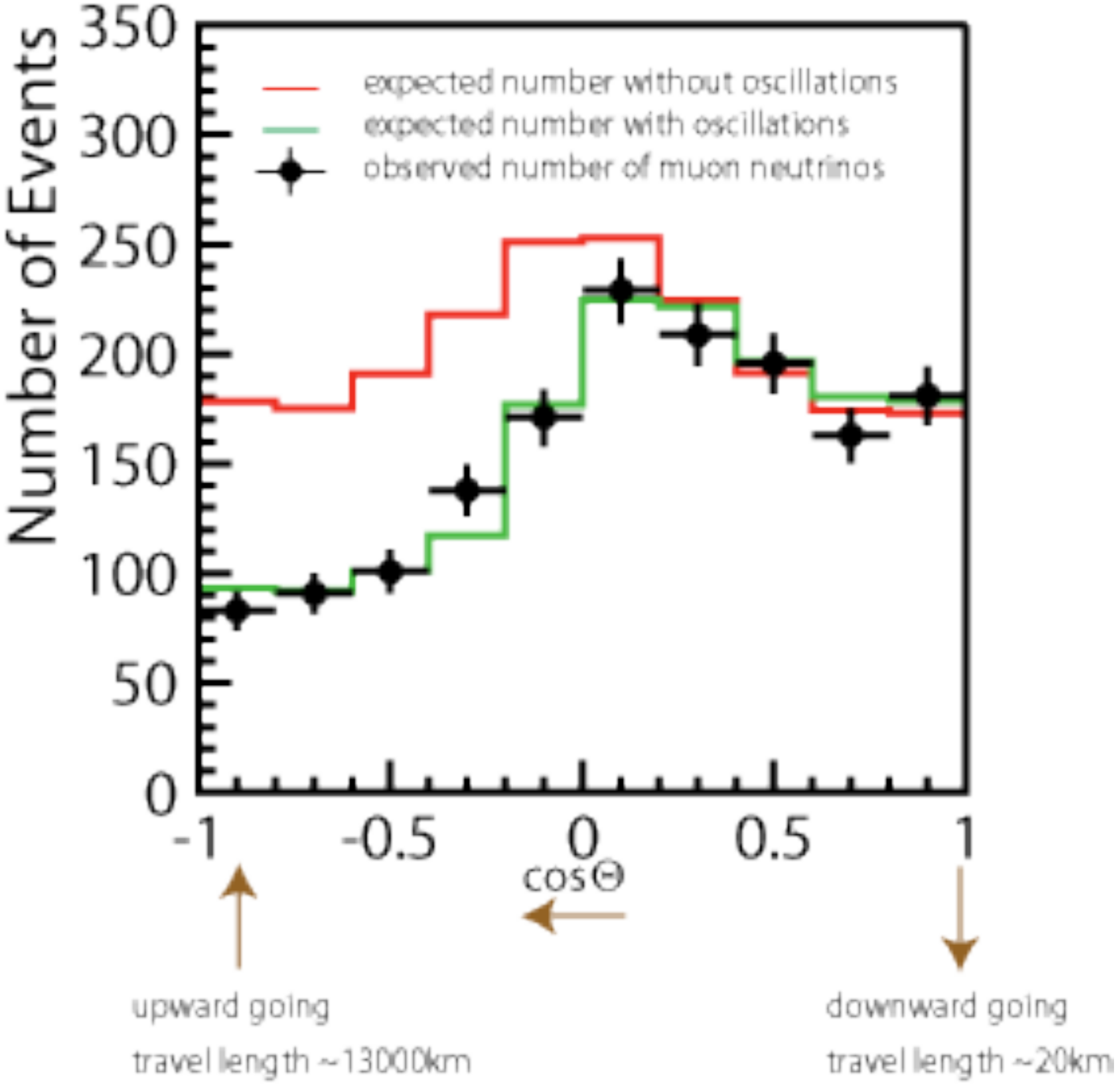

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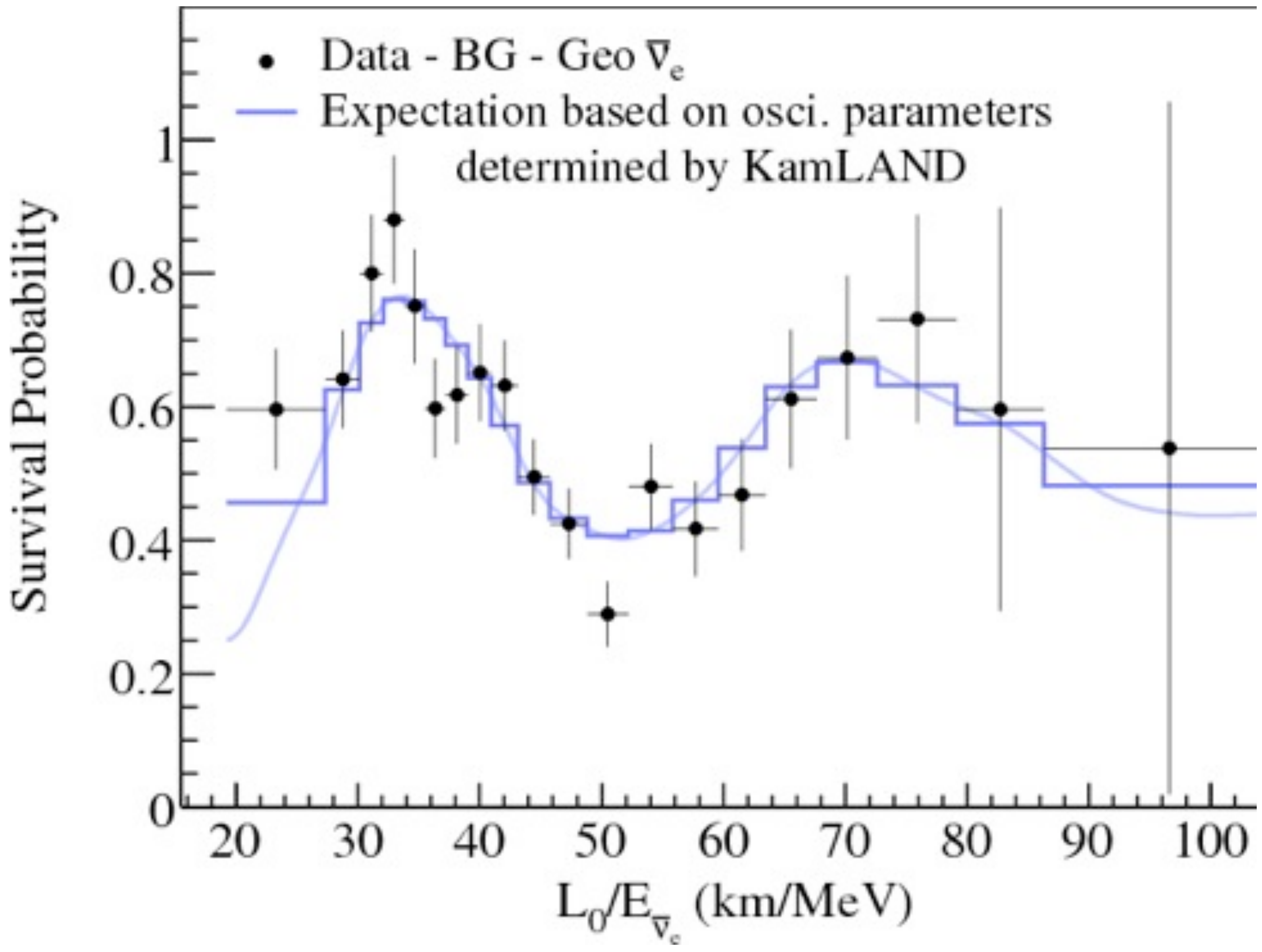
KamLAND Experiment



$\overline{\nu}_e$'s disappear and then reappear

They oscillate!!

MINOS Experiment

- Oscillation Formalism
- Introduction to Experiment (Geography, Detectors)
- Results (Oscillations)
- Prospects for the Future

Oscillations Formalism - PMNS

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The ν flavor and mass states are related by:

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$\alpha = (e, \mu, \tau)$

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2-flavor approximation is often adequate:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2(2\theta)\,\sin^2(1.27\Delta m^2 L/E)$$

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Search for a 4th, sterile neutrino: $\nu_\mu \to \nu_s$

MINOS Geography

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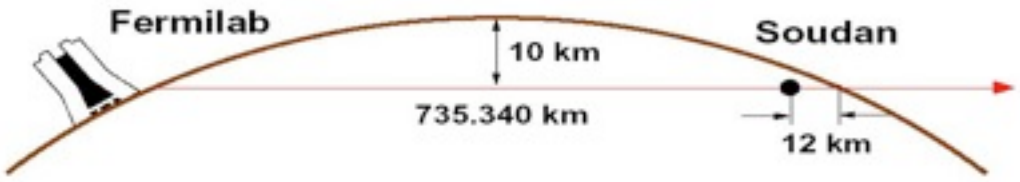

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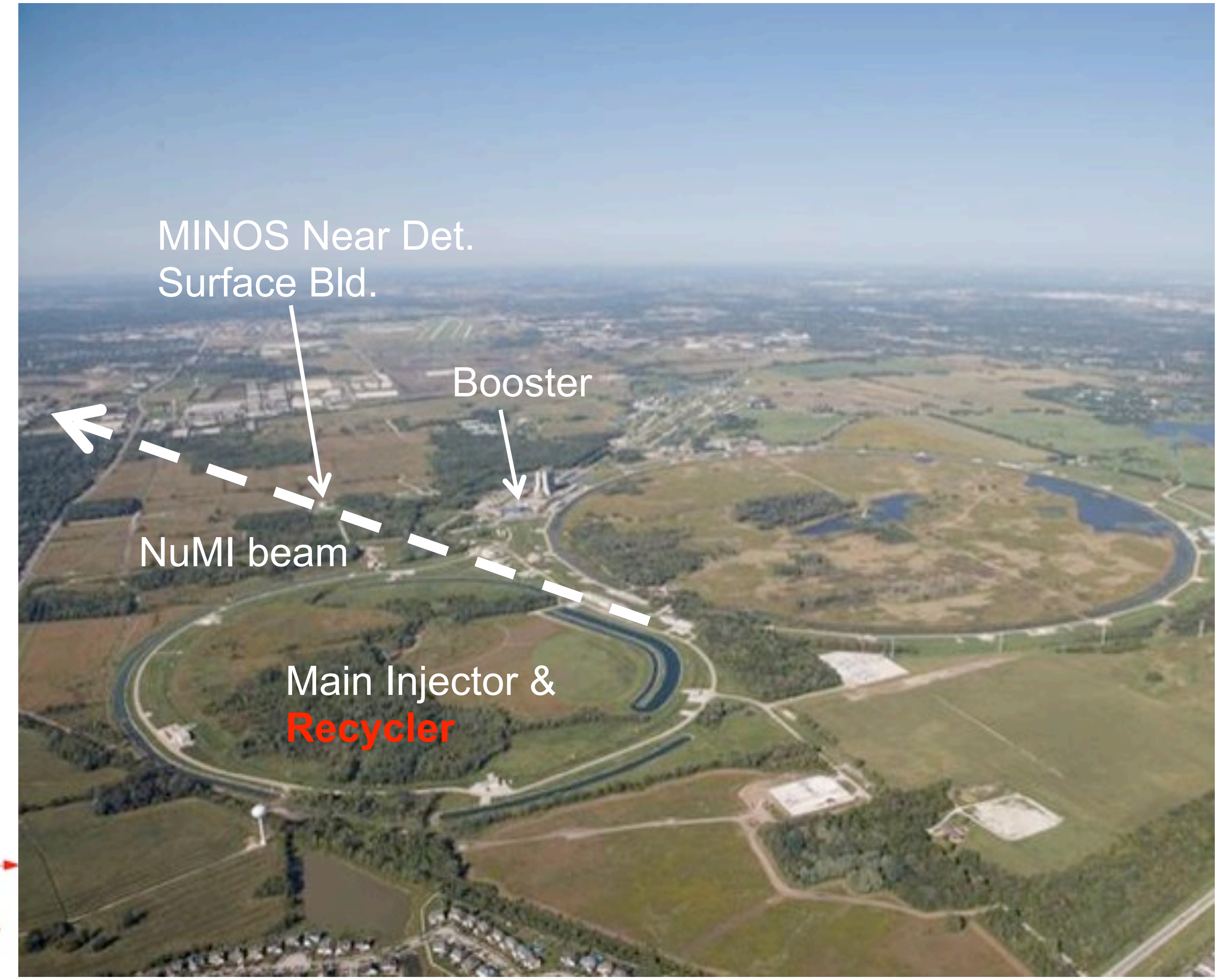

The MINOS Collaboration

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab Goias • Harvard • Holy Cross • IIT • Indiana • Iowa State • Minnesota-Twin Cities Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

MINOS Detectors

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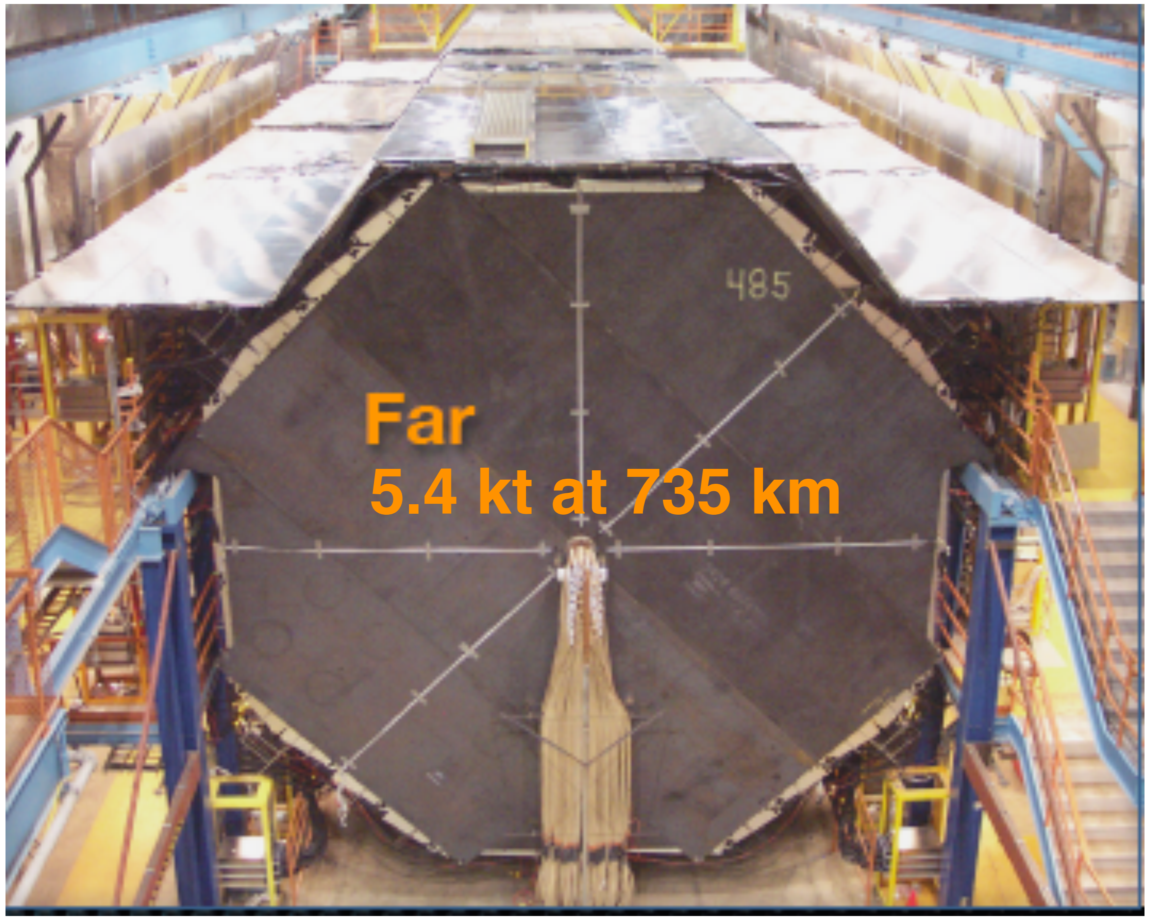

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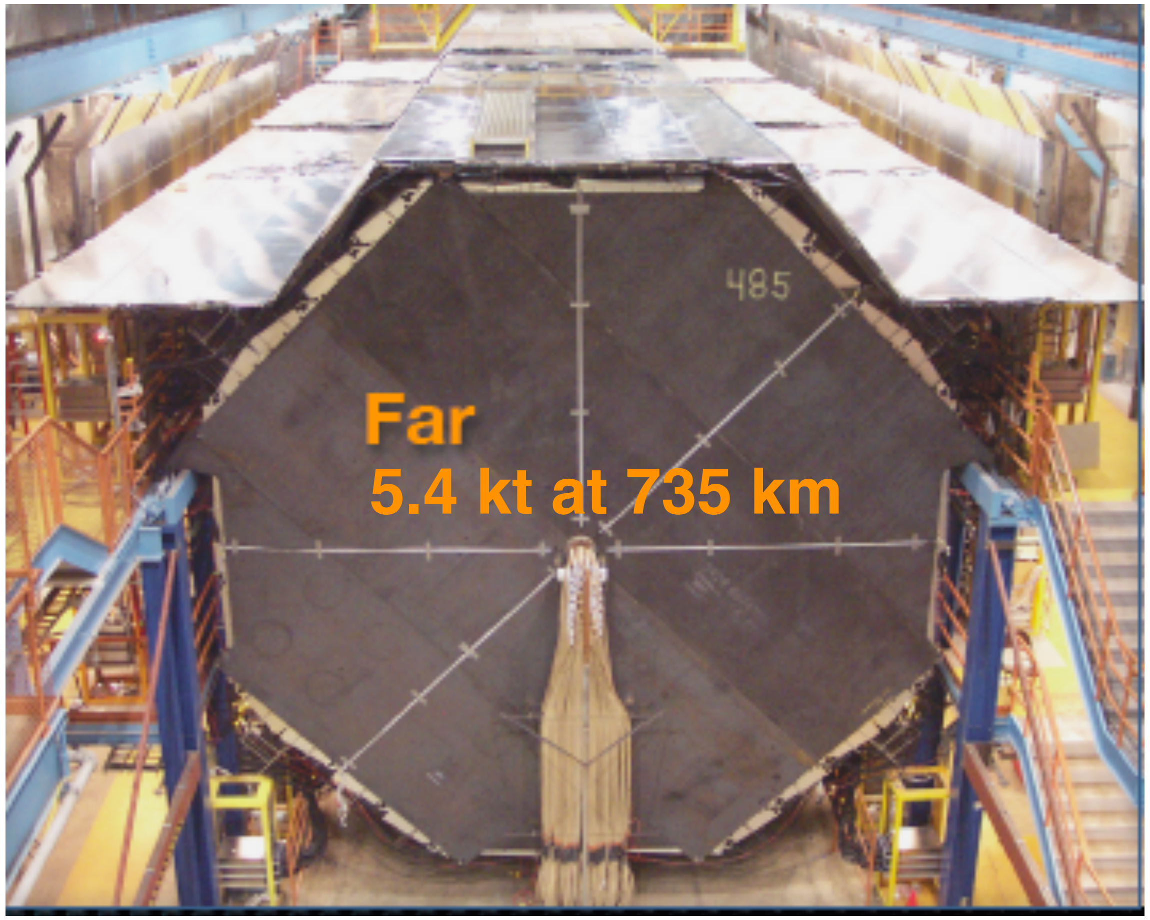
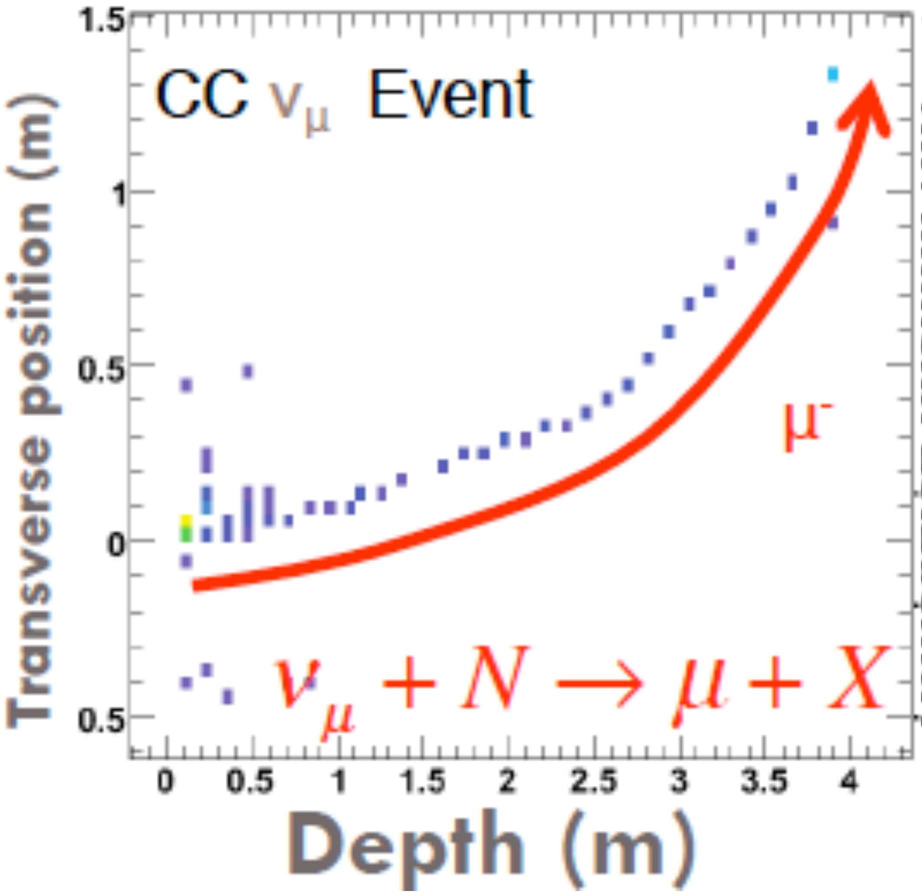
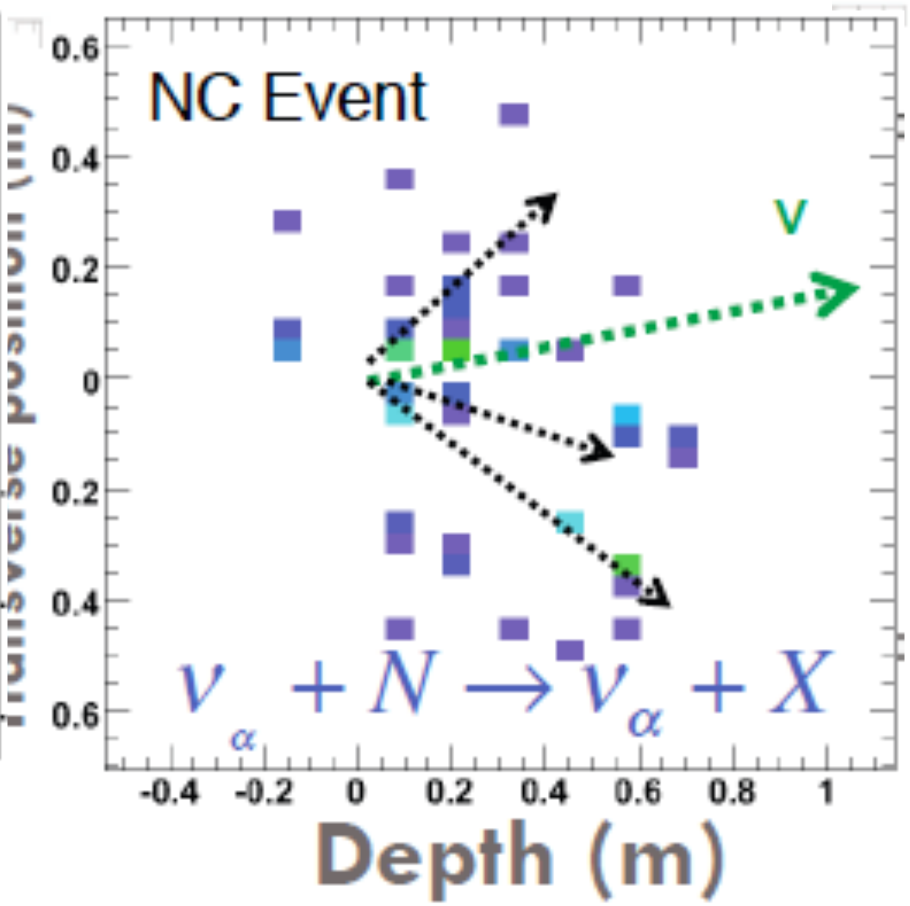
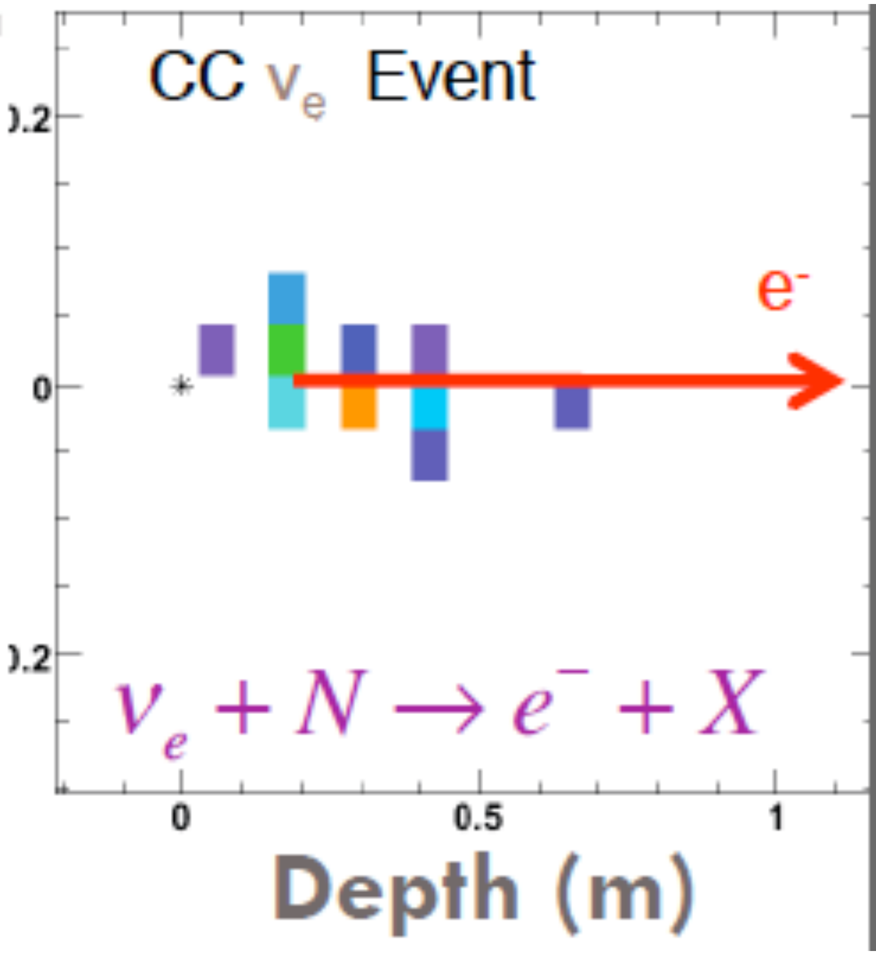


- As similar as possible functionally
- Alternating layers of steel (2.5 cm thick) and scintillator
- Alternating scintillator planes at 90 deg, 4.1 cm strips
- Light collection by wavelength shifting fibers
- Readout by 64 ch(ND) or 16 ch(FD) multi-anode PMT’s
- Magnetized, average B field 1.3 T

Types of Events







Disappearance (ν_μ; θ_{23},Δm^2_{31})

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Relatively easy: long track

Good energy measurement:

Calorimetry for hadronic shower

Range or curvature for muon

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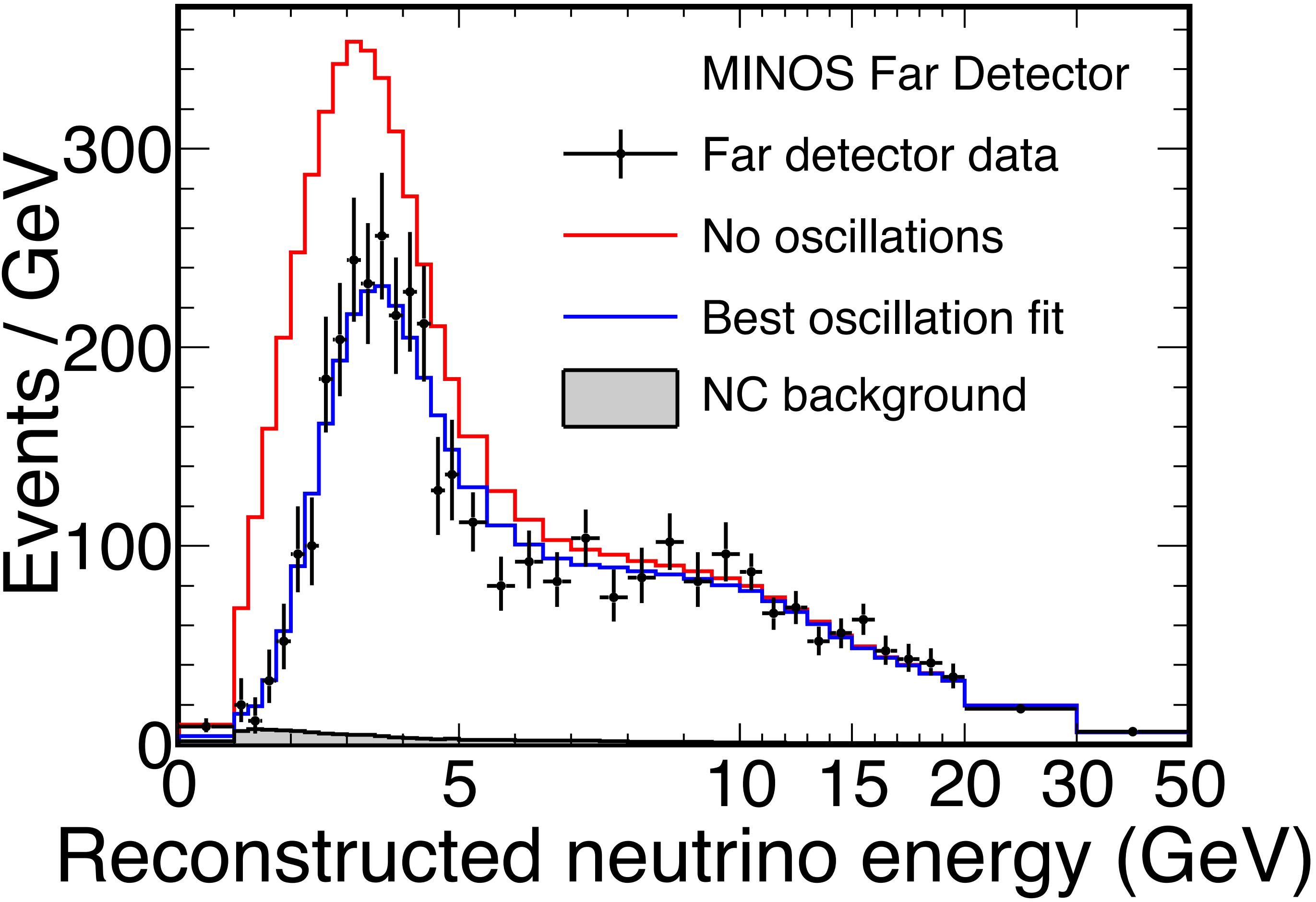

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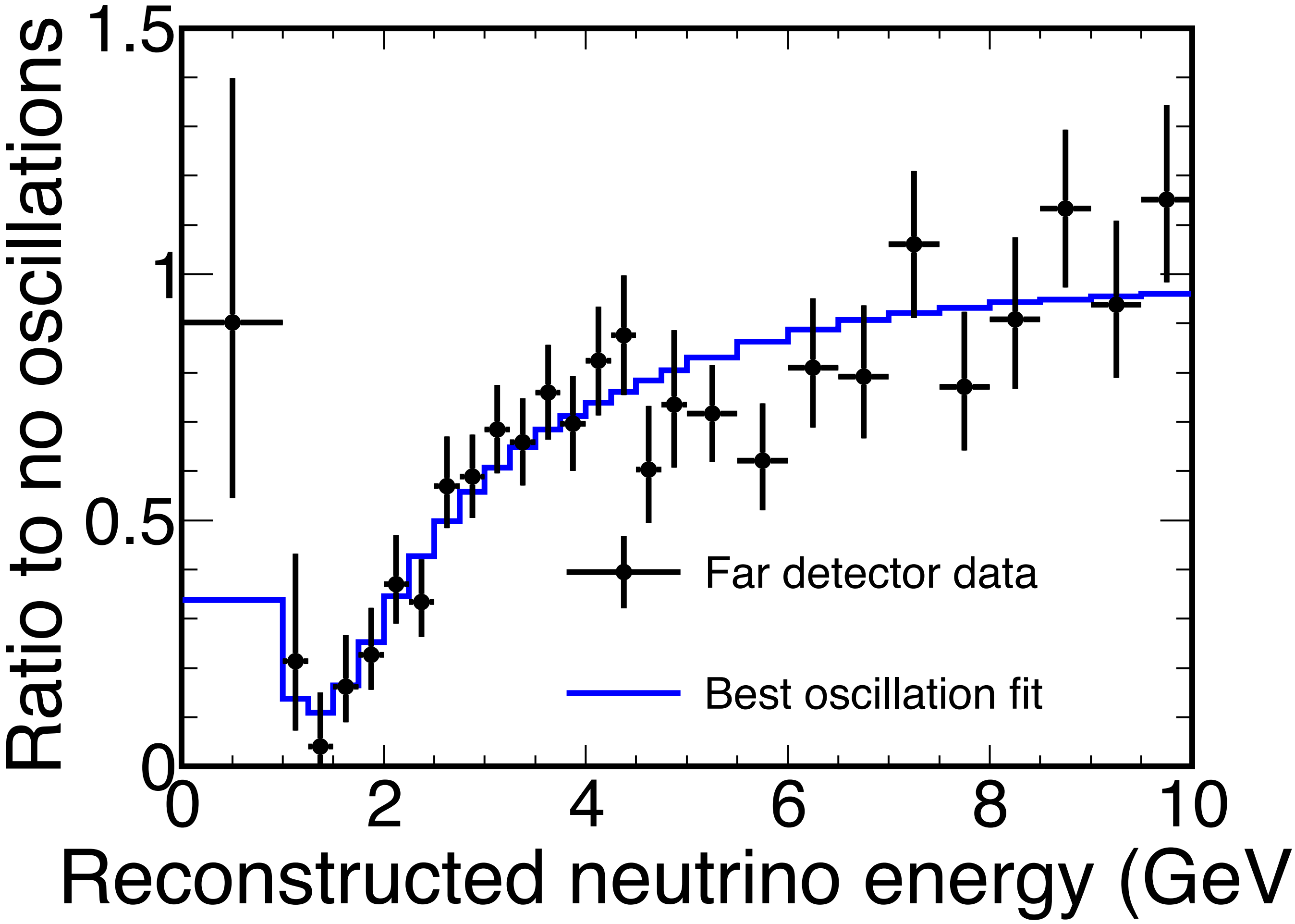

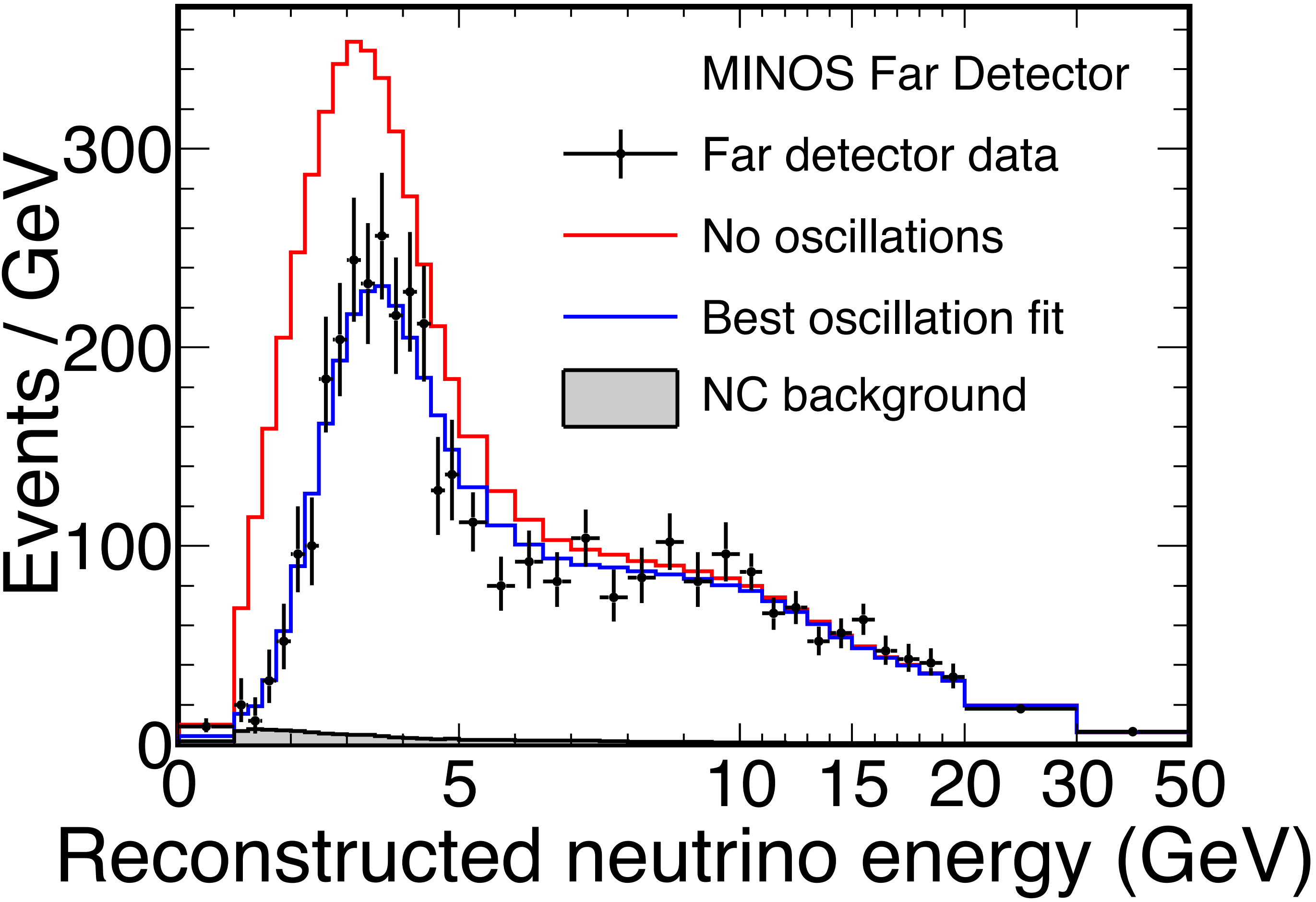

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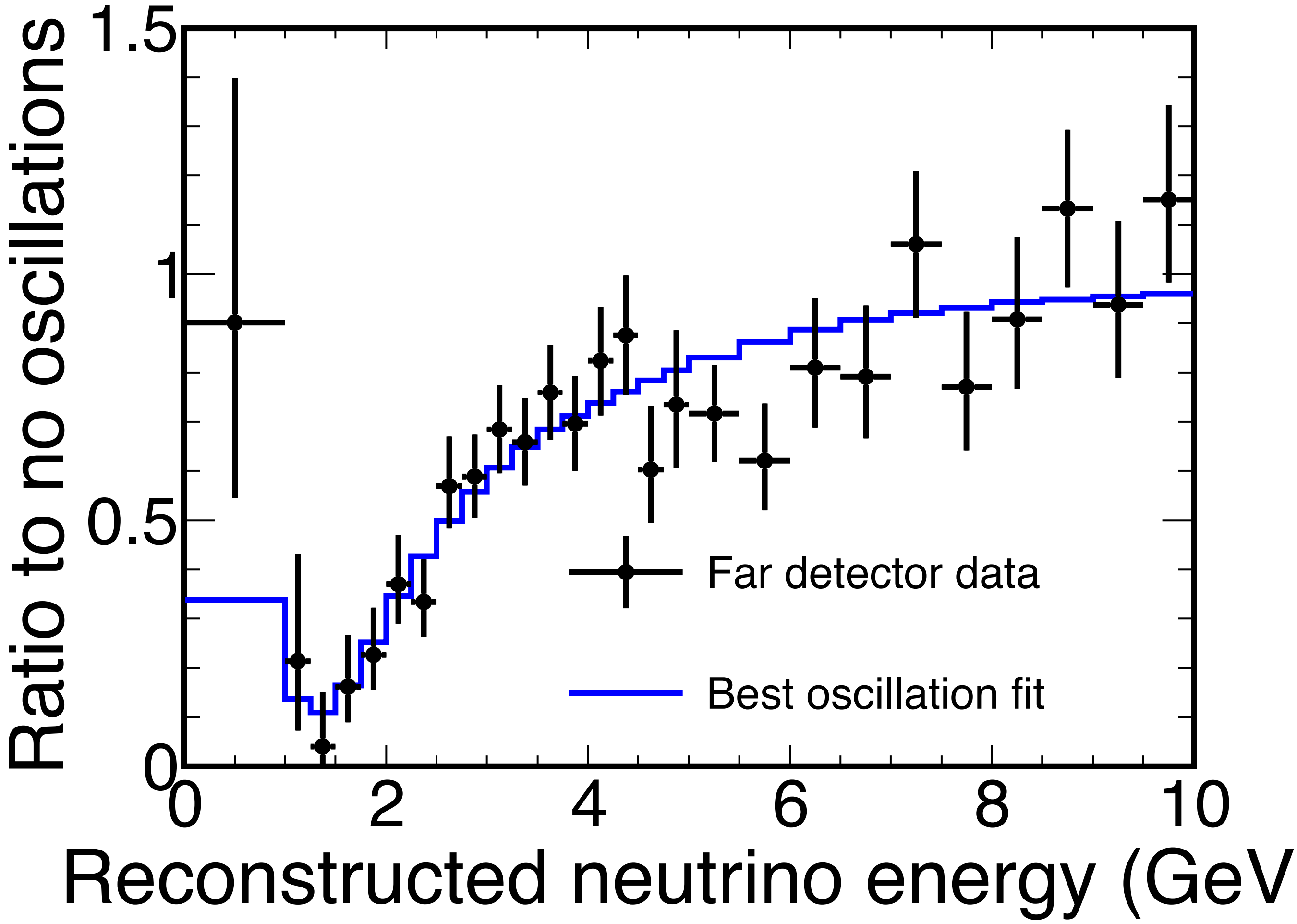

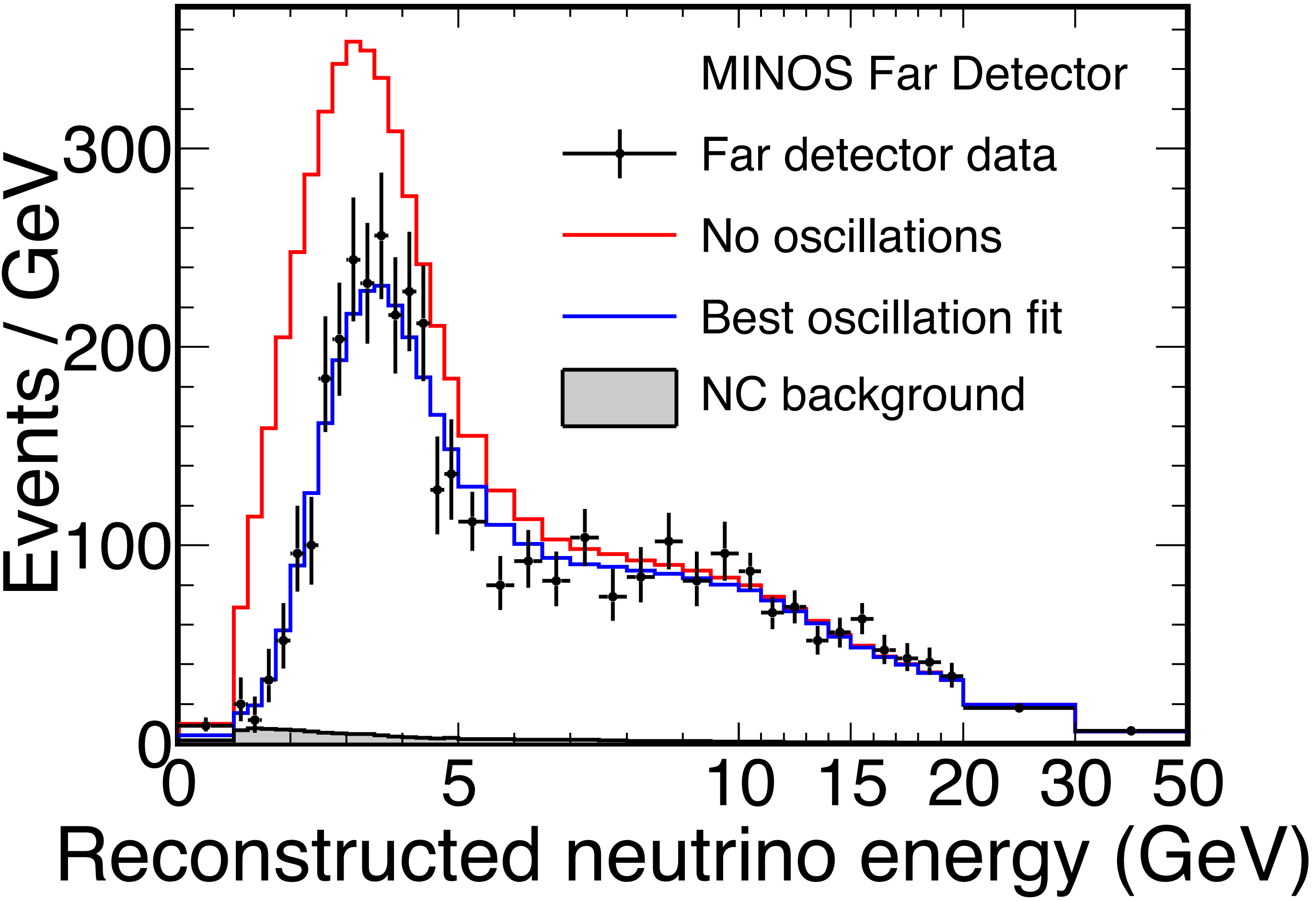

Result

$\Delta m^2 = 2.32^{+0.12}_{-0.08} \times 10^{-3}\ \text{eV}^2$

$\sin^2(2\theta) > 0.90$

Disappearance: 1998 and 2012

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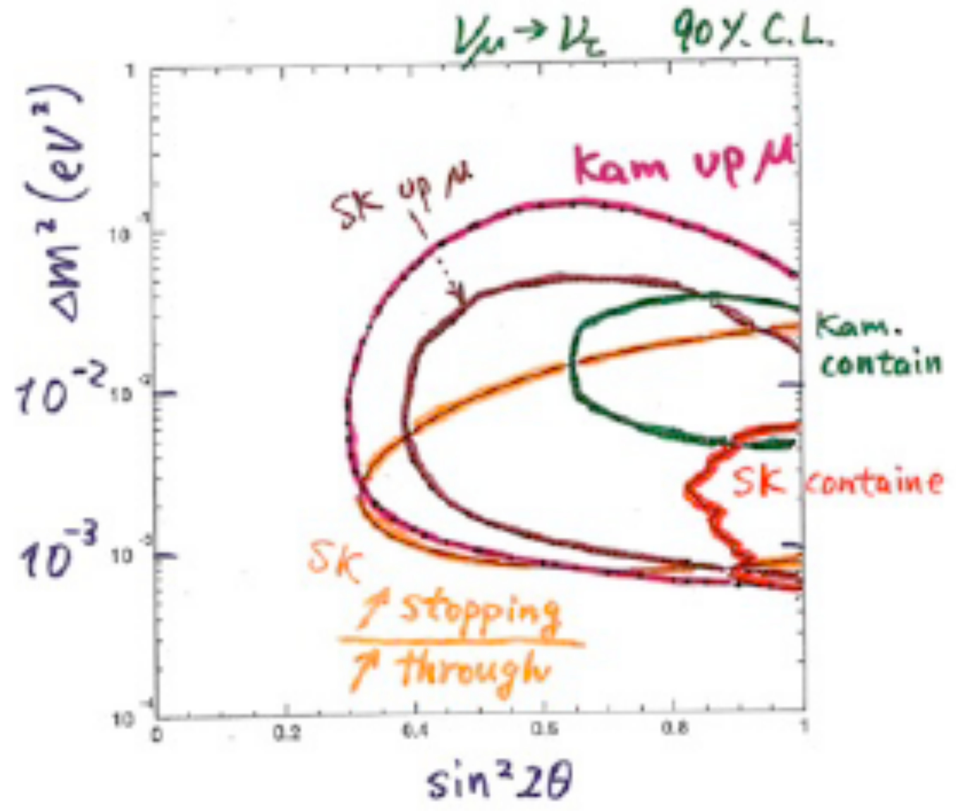
Summary

Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

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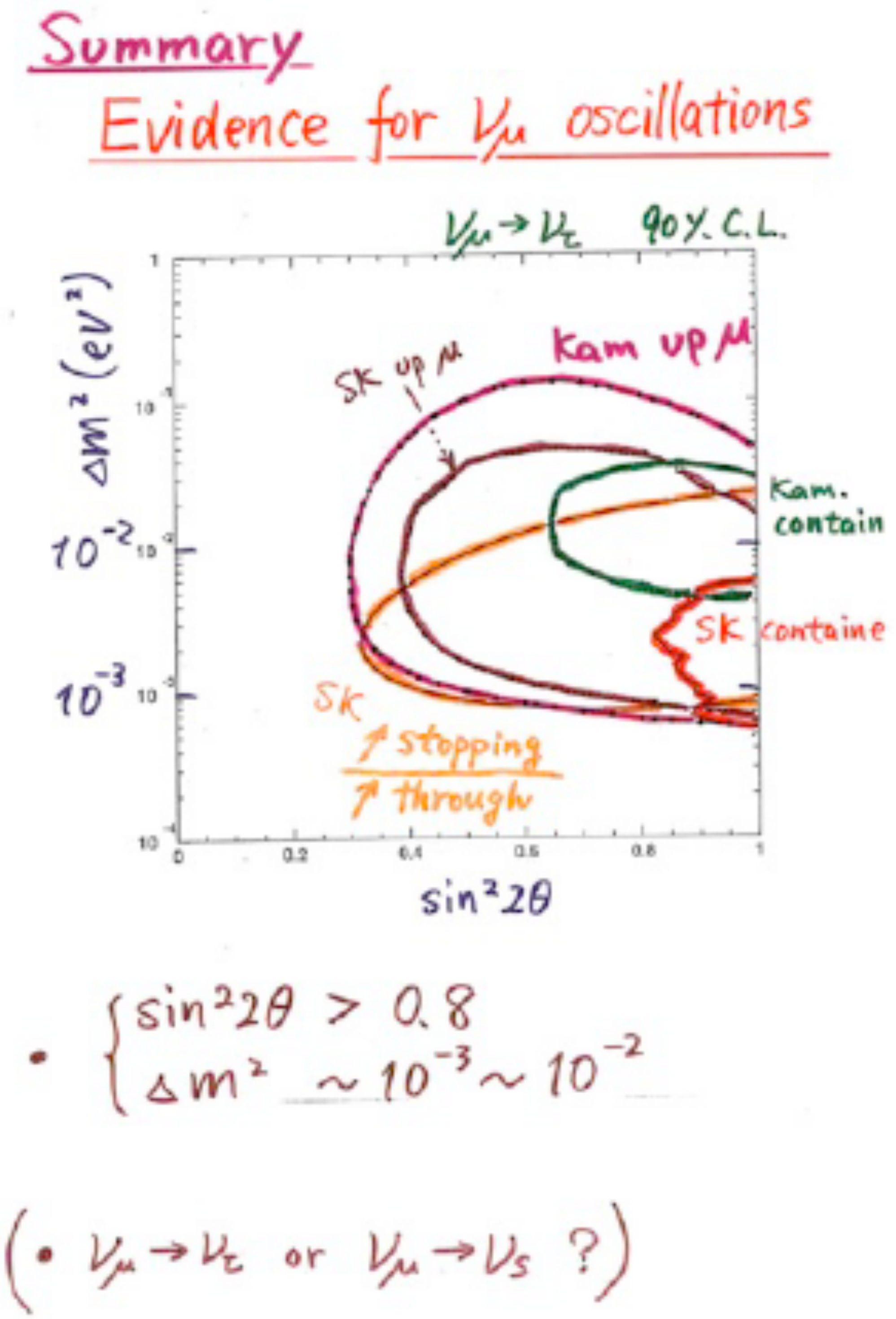

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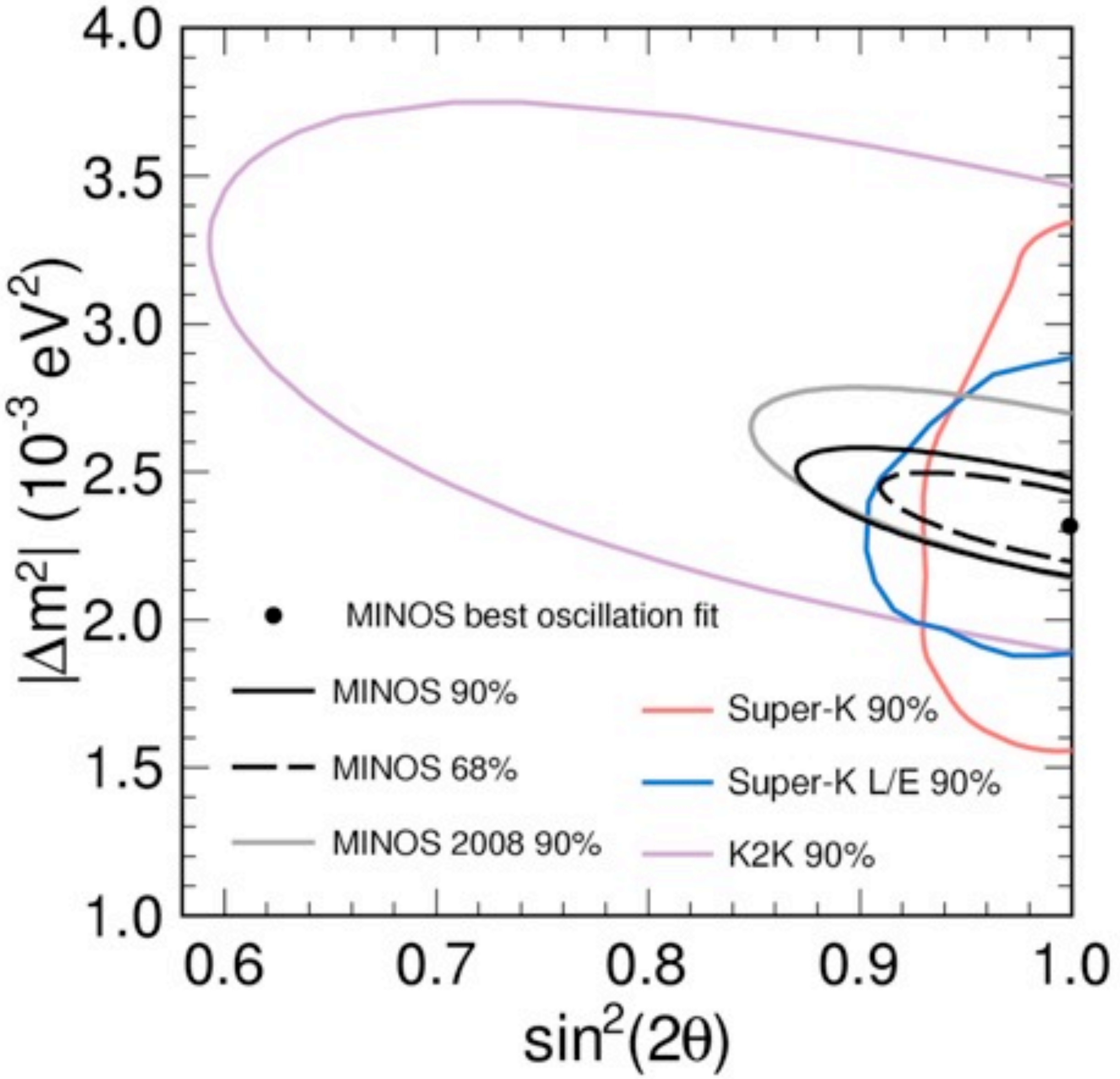

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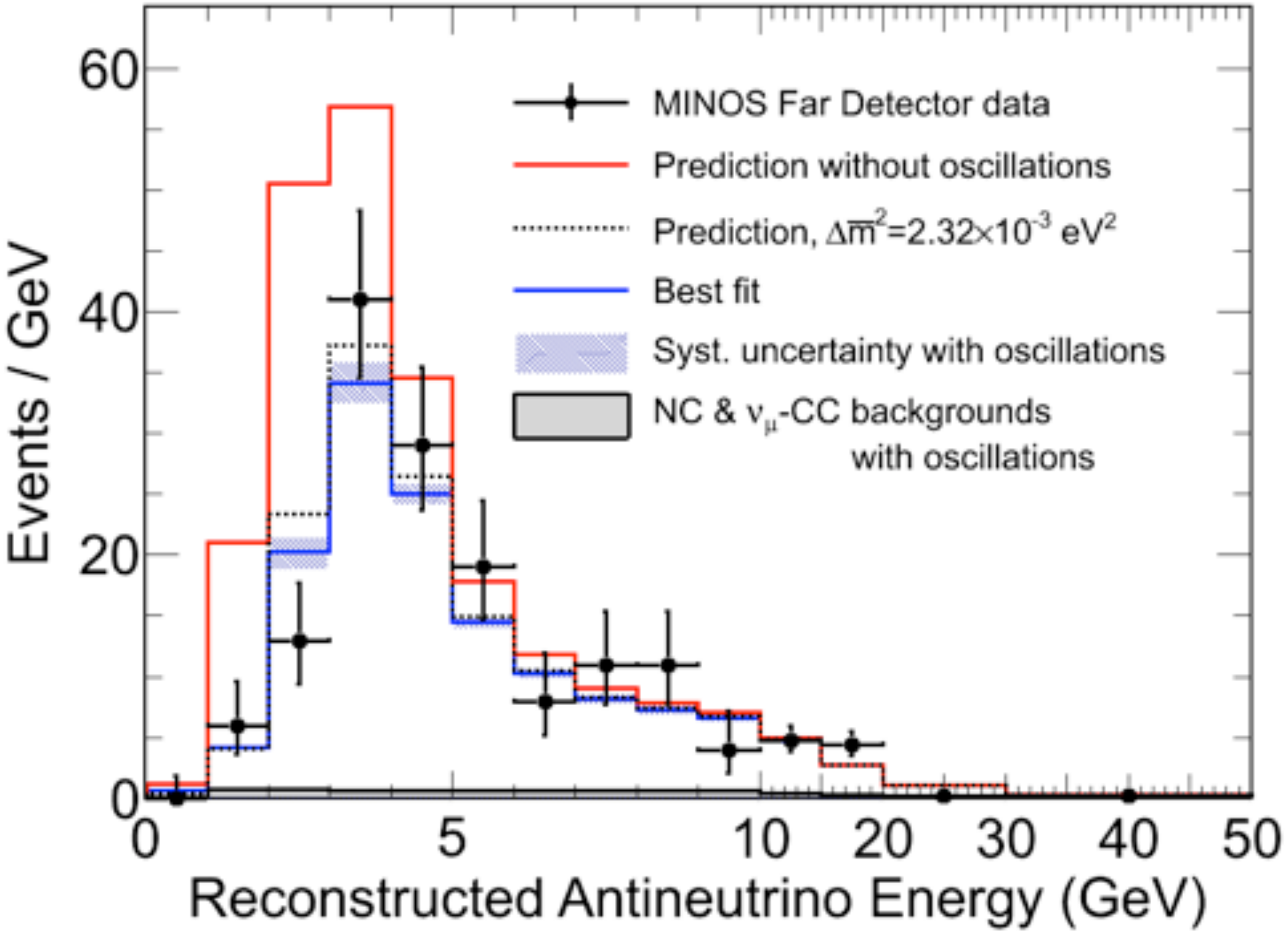

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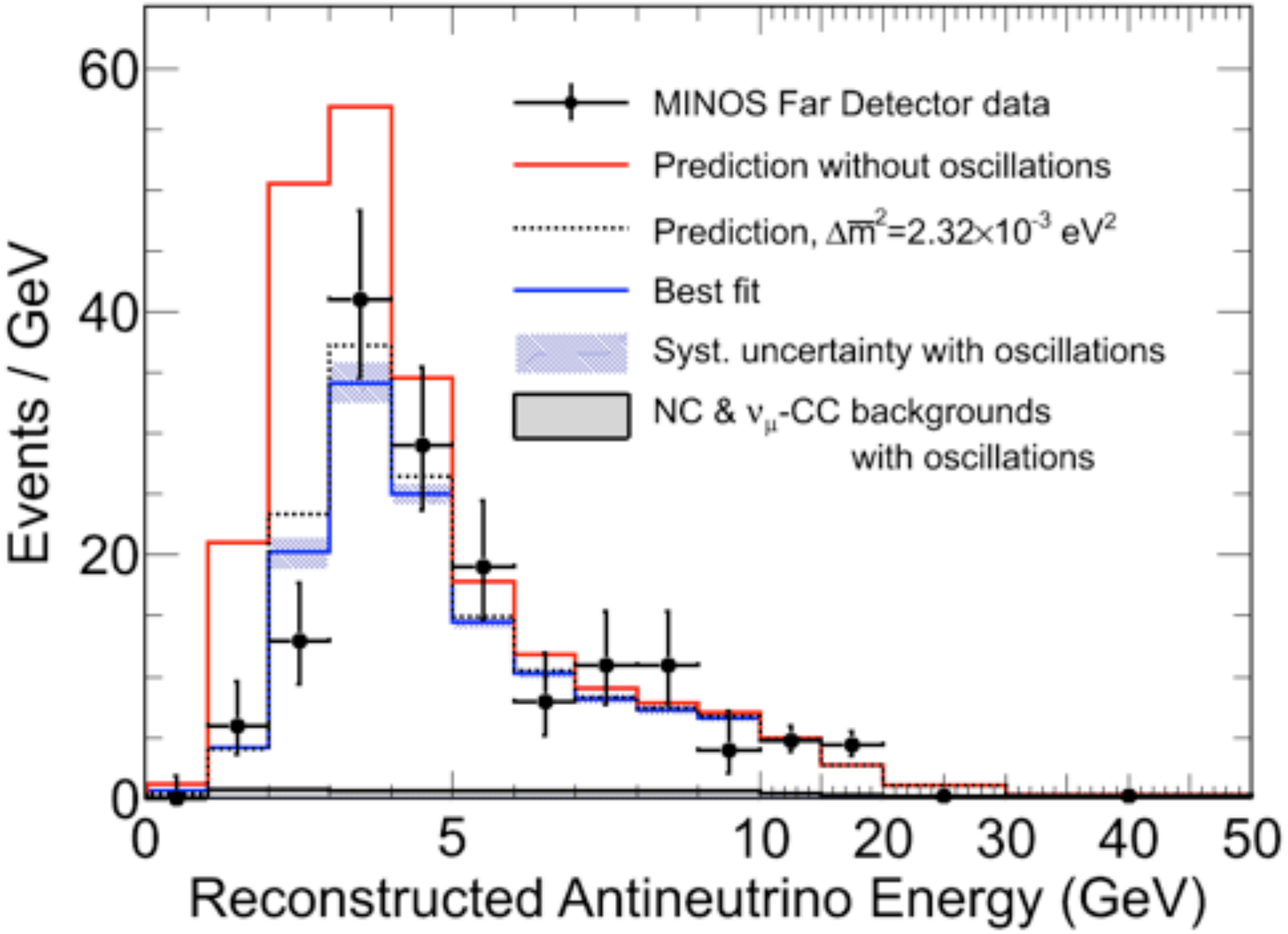

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$\Delta\overline{m}^2=2.62^{+0.31}_{-0.28}$(stat.)±0.09(sys) X 10^{-3} eV^2

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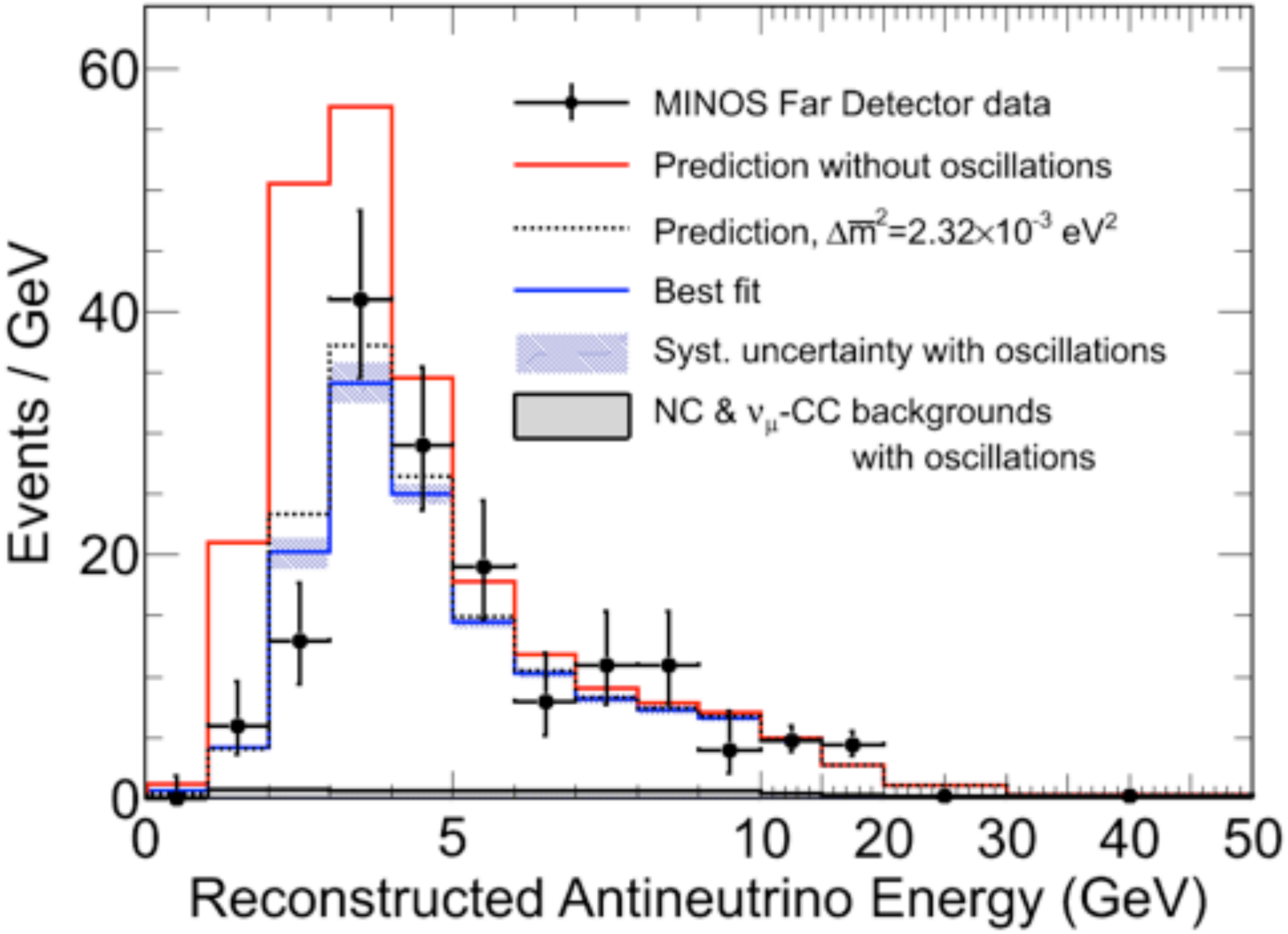

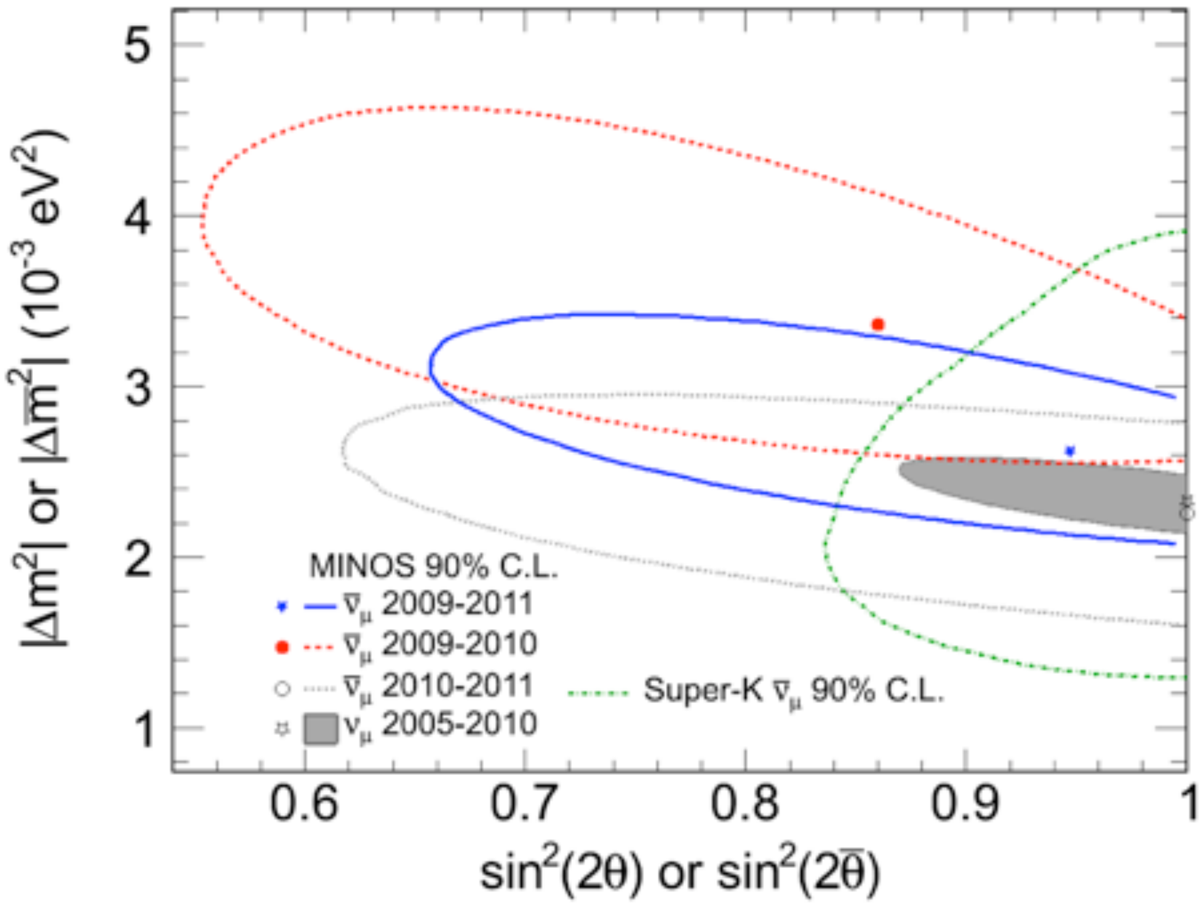

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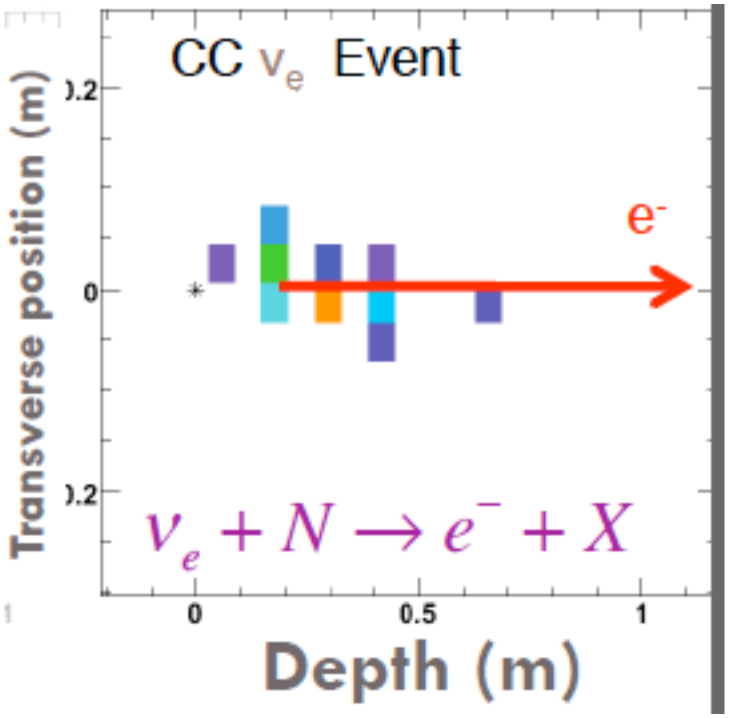
Events characterized by a relatively short and narrow shower



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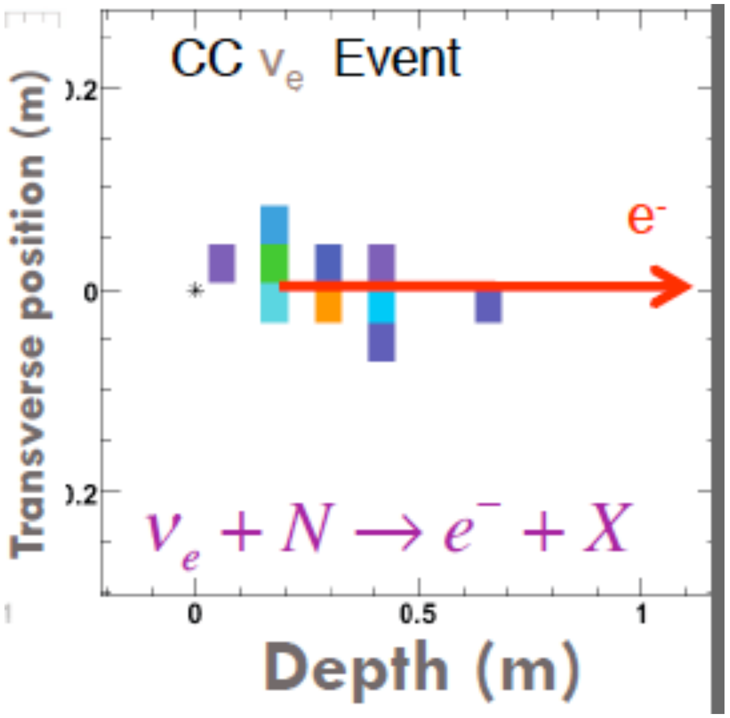
Separation from more numerous NC background done on statistical basis



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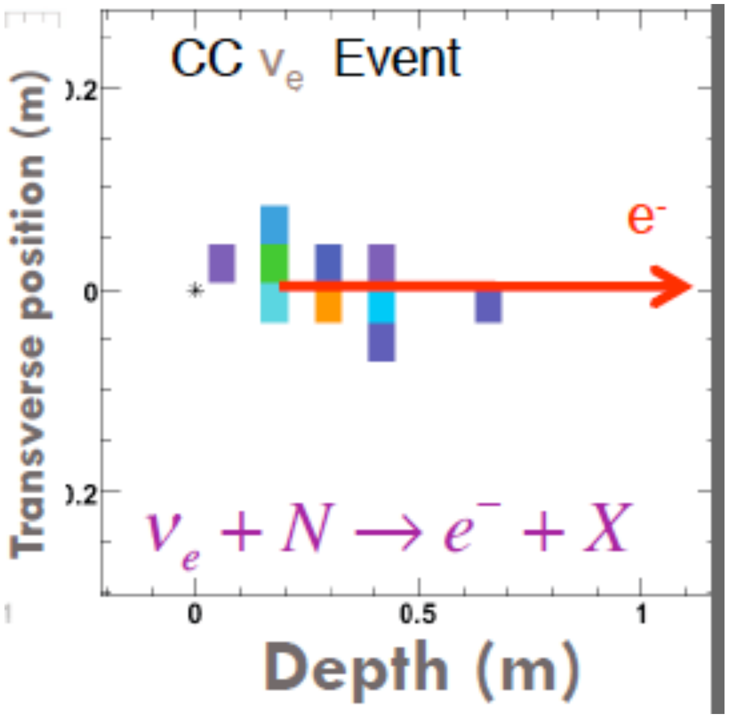
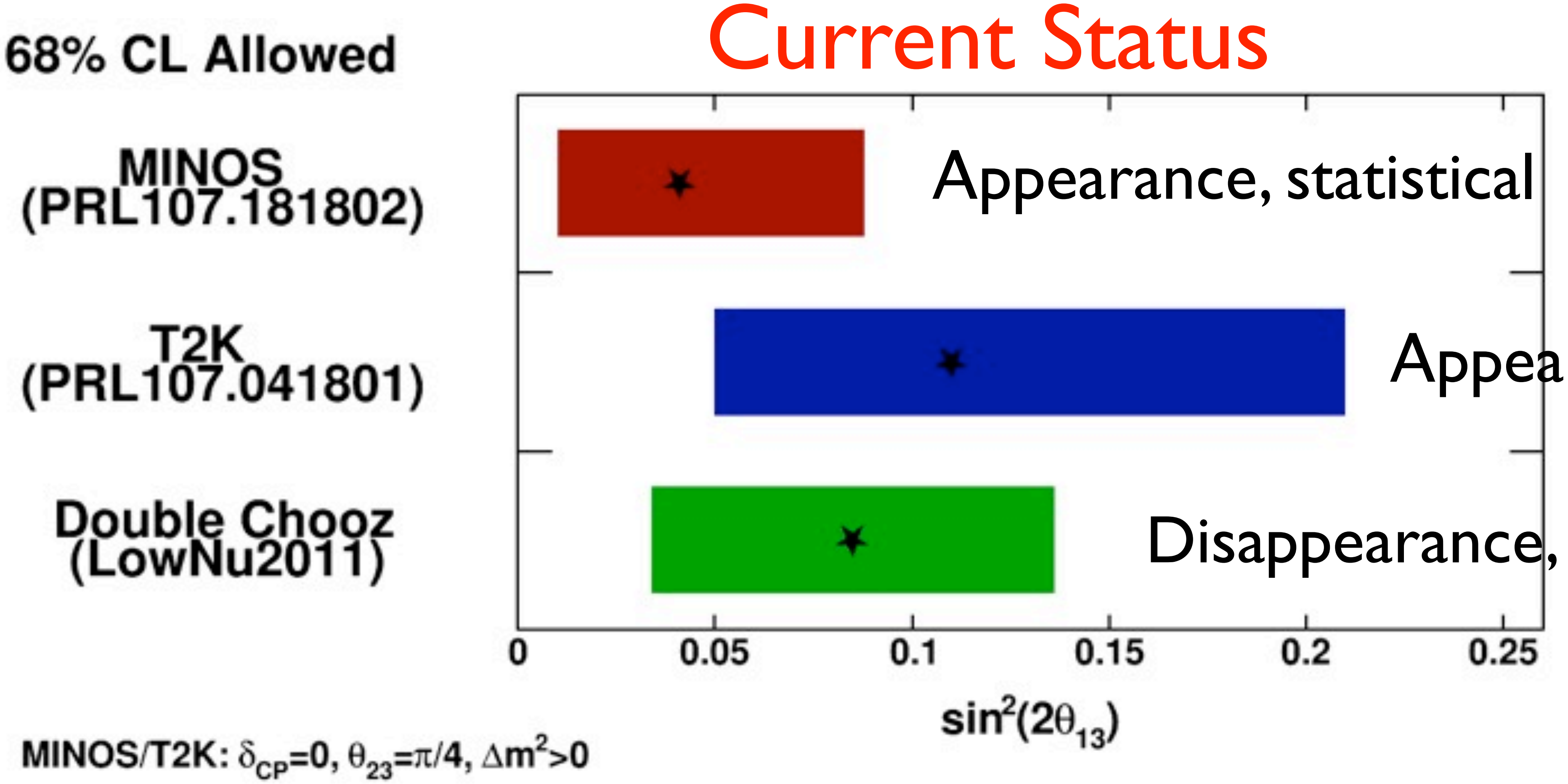


Current Status



Appearance, statistical

Appearance, individual events

Disappearance, reactor

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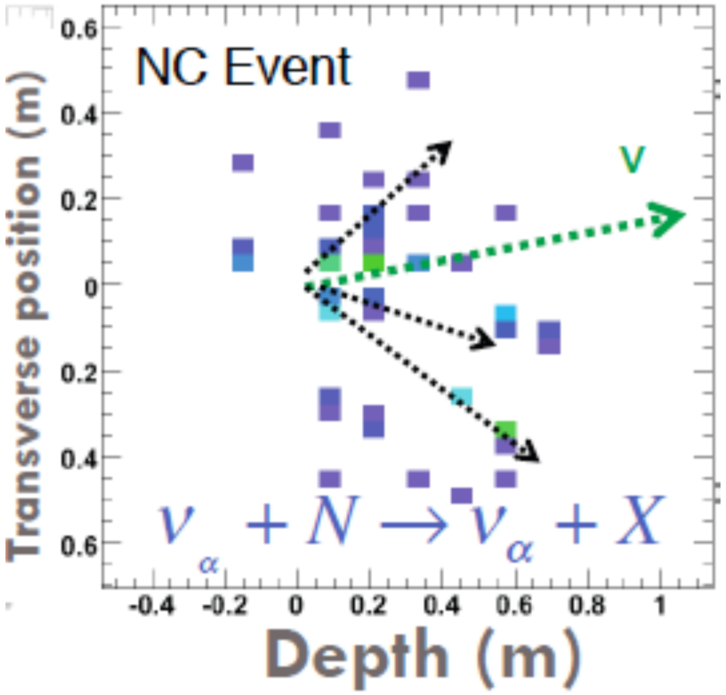
Partial energy measurement (shower only):



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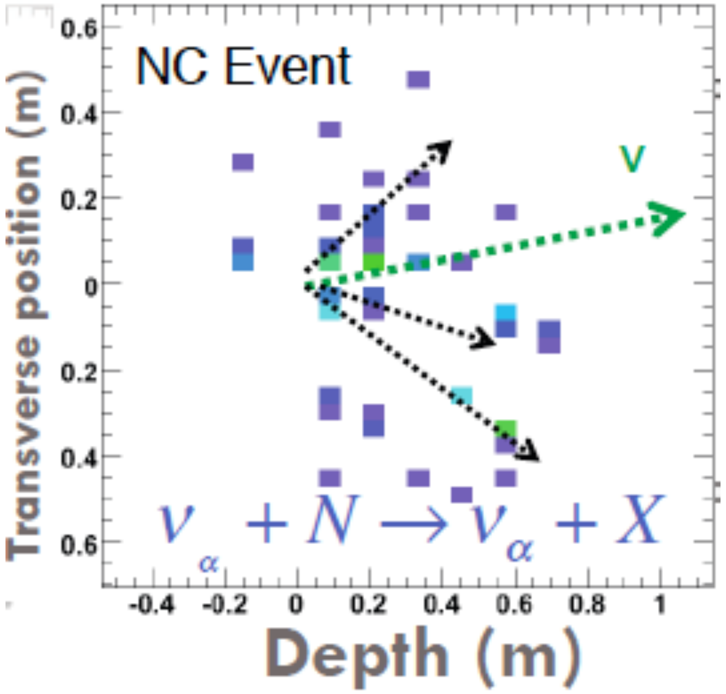
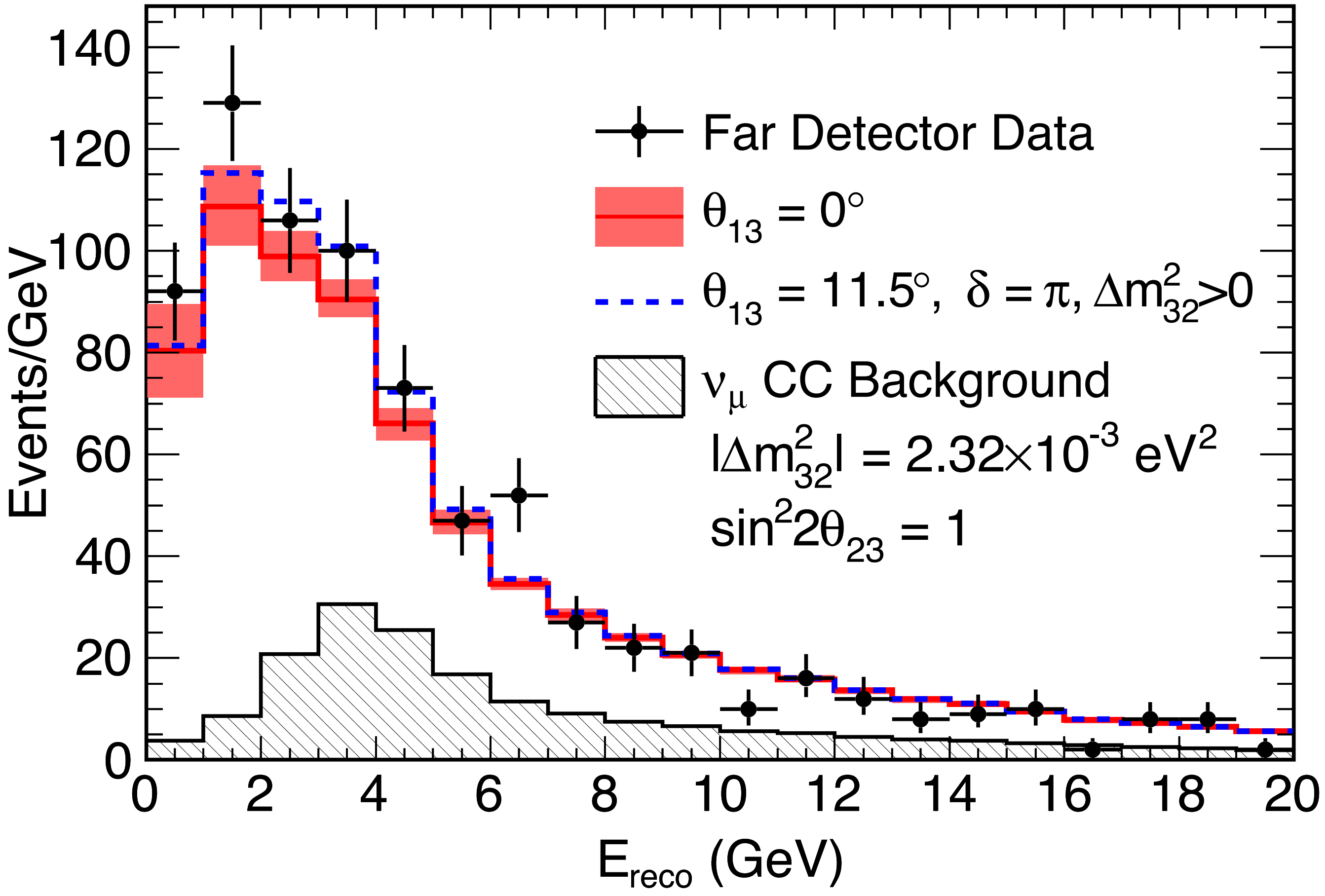
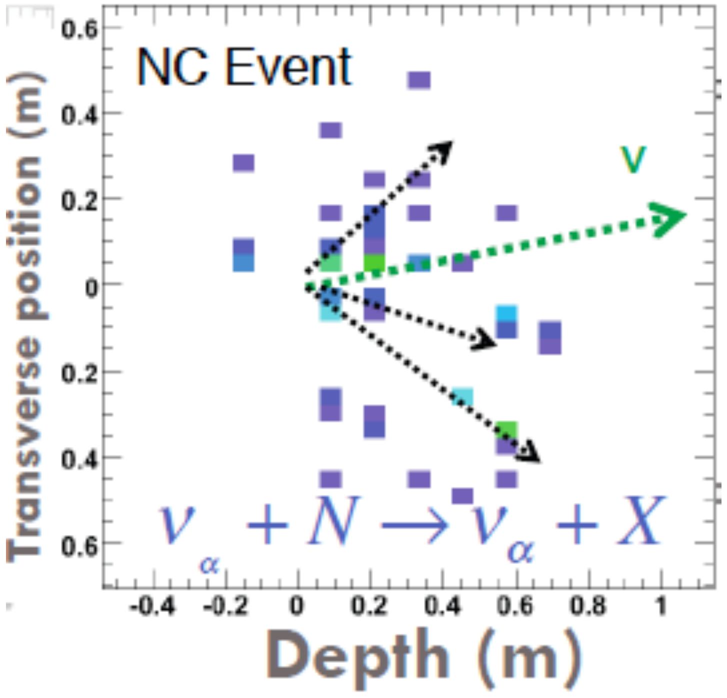
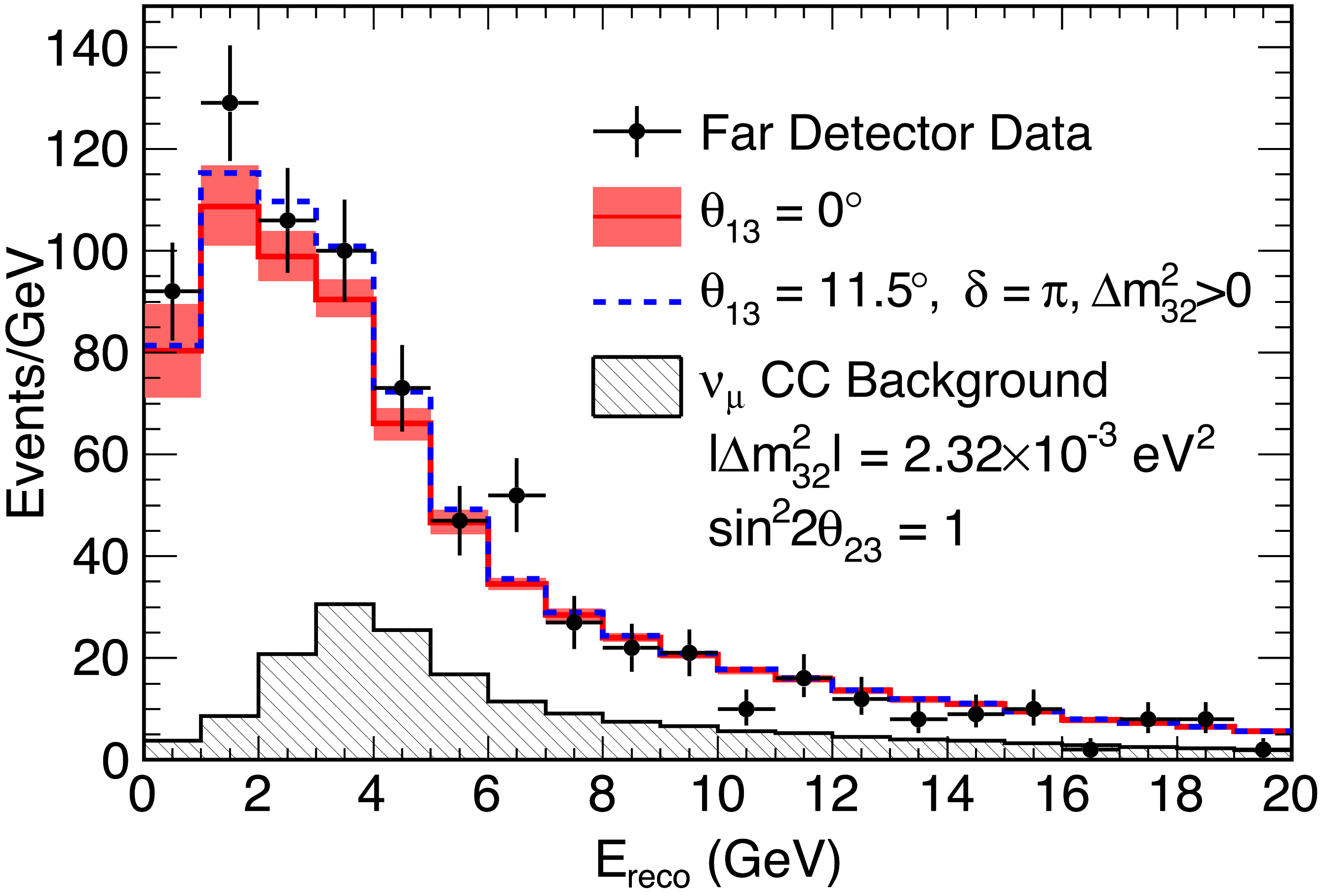




Sterile Neutrinos (?)

Relatively easy to identify: NO long track
Partial energy measurement (shower only):





No evidence for sterile ν's

Result

$P(\nu_\mu \rightarrow \nu s)/(1 - P(\nu_\mu \rightarrow \nu_\mu)) \leq 0.22$(90% CL)

Graphical Summary

Graphical Summary

$|\Delta m^2|$ now known to ~5%

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$|U_{\alpha i}|$ also known today to ~5%

(except U_{e3})

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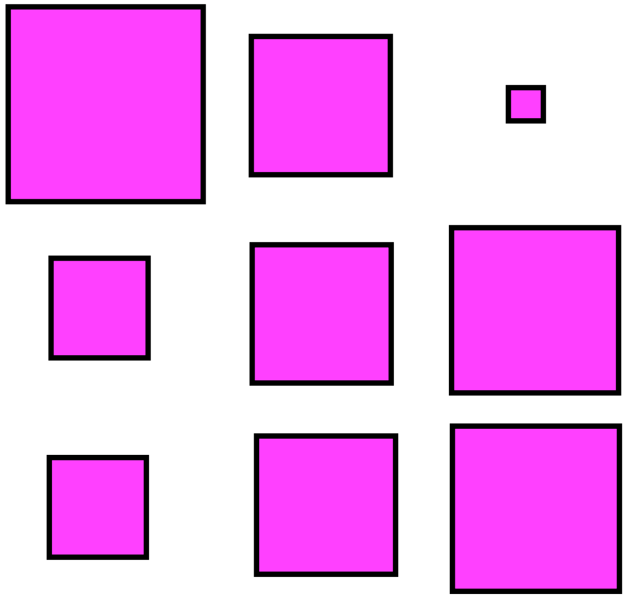
Area of each square $\propto |U_{\alpha i}|^2$



PMNS Matrix, graphically

Graphical Summary

$|\Delta m^2|$ now known to ~5%

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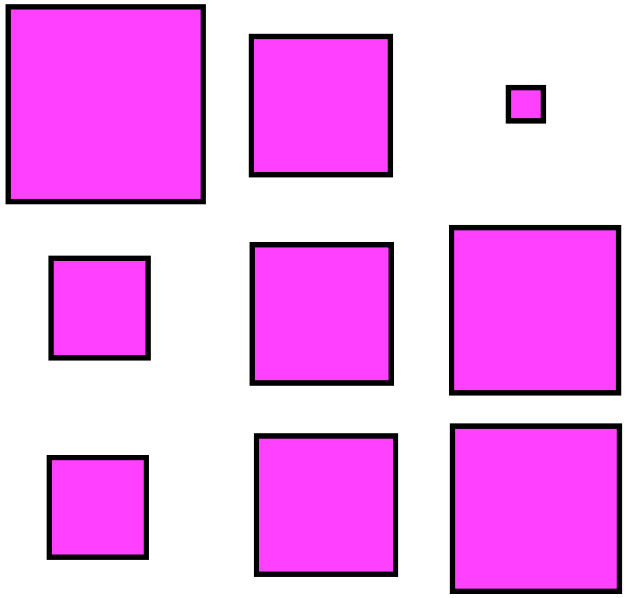
(except U_{e3})

Area of each square α $|U_{\alpha i}|^2$



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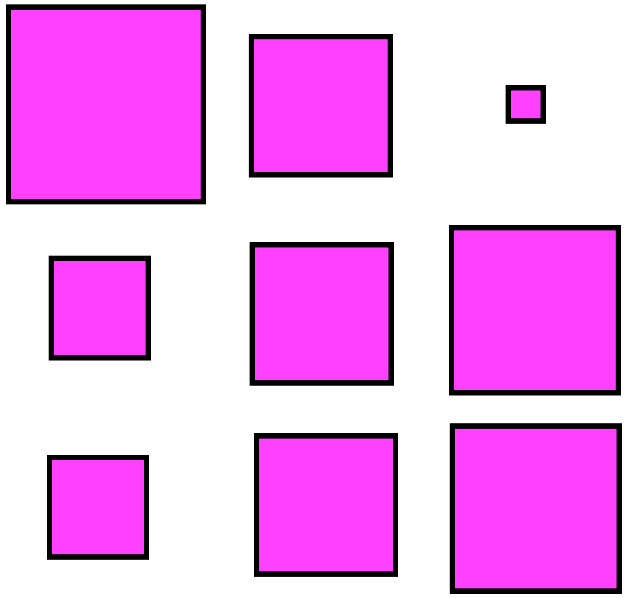
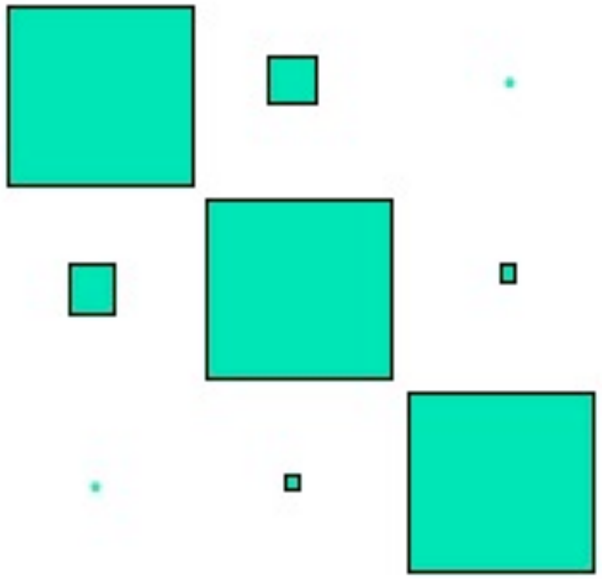


PMNS Matrix, graphically



CKM Matrix, graphically

Oscillations - Summary

- There has been great progress in the last decade and a half in determination of oscillation parameters
- But few (mass hierarchy, CP phase) remain to be determined
- Equally importantly is the possibility of surprises
- And then there are the really BIG questions:
  - Why is the mixing matrix the way it is?
  - Why is it so different from the quark sector?
  - Why are neutrino masses so small?
  - Are neutrinos responsible for us being here today?
- Too bad Pontecorvo is not around today

Velocity (Speed)

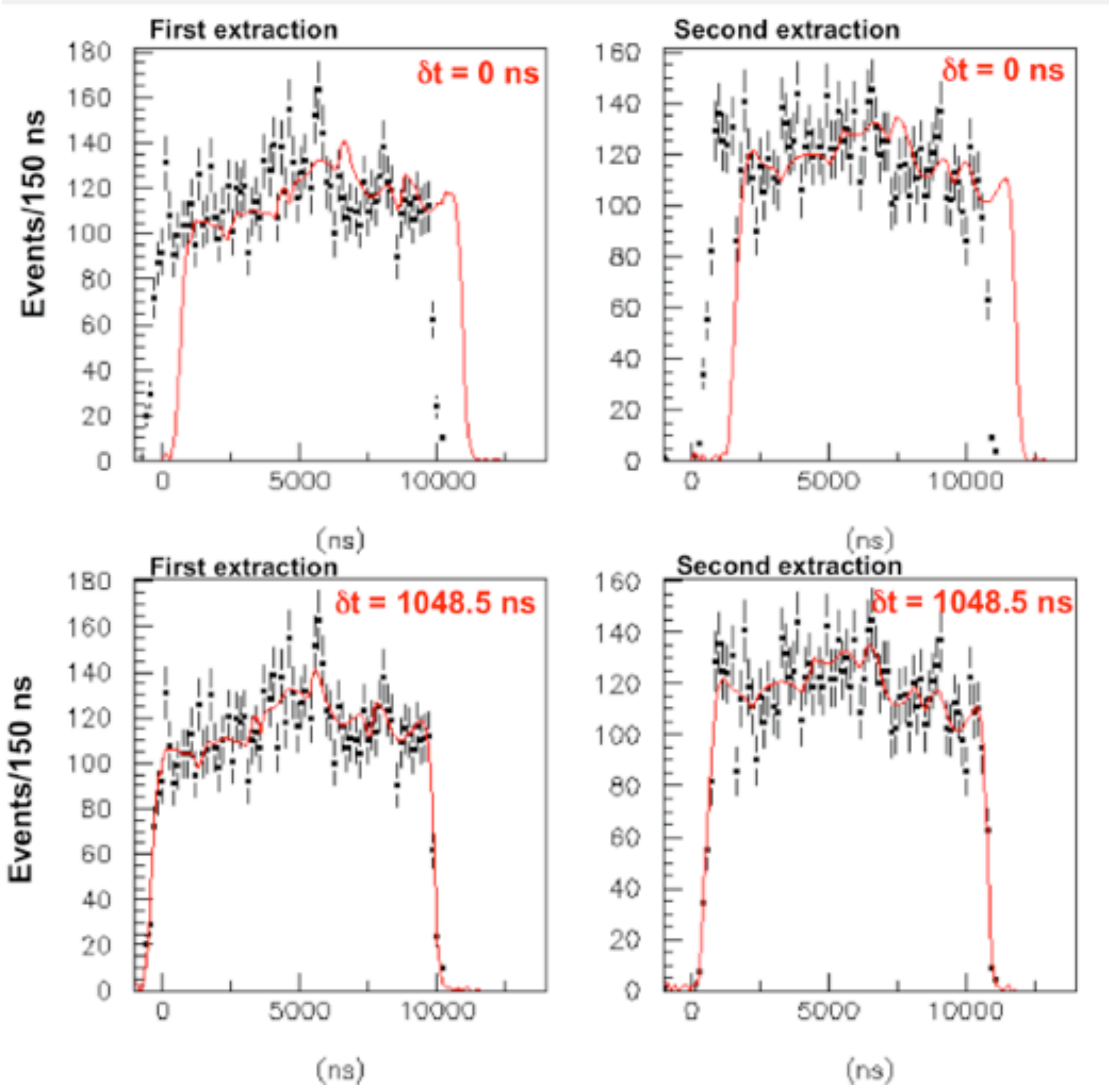
Velocity (Speed)

Velocity = Distance/Time = $D/(t_{stop} - t_{start})$

t_{start}

t_{stop}

OPERA Results - 1st Run



— Proton beam time structure

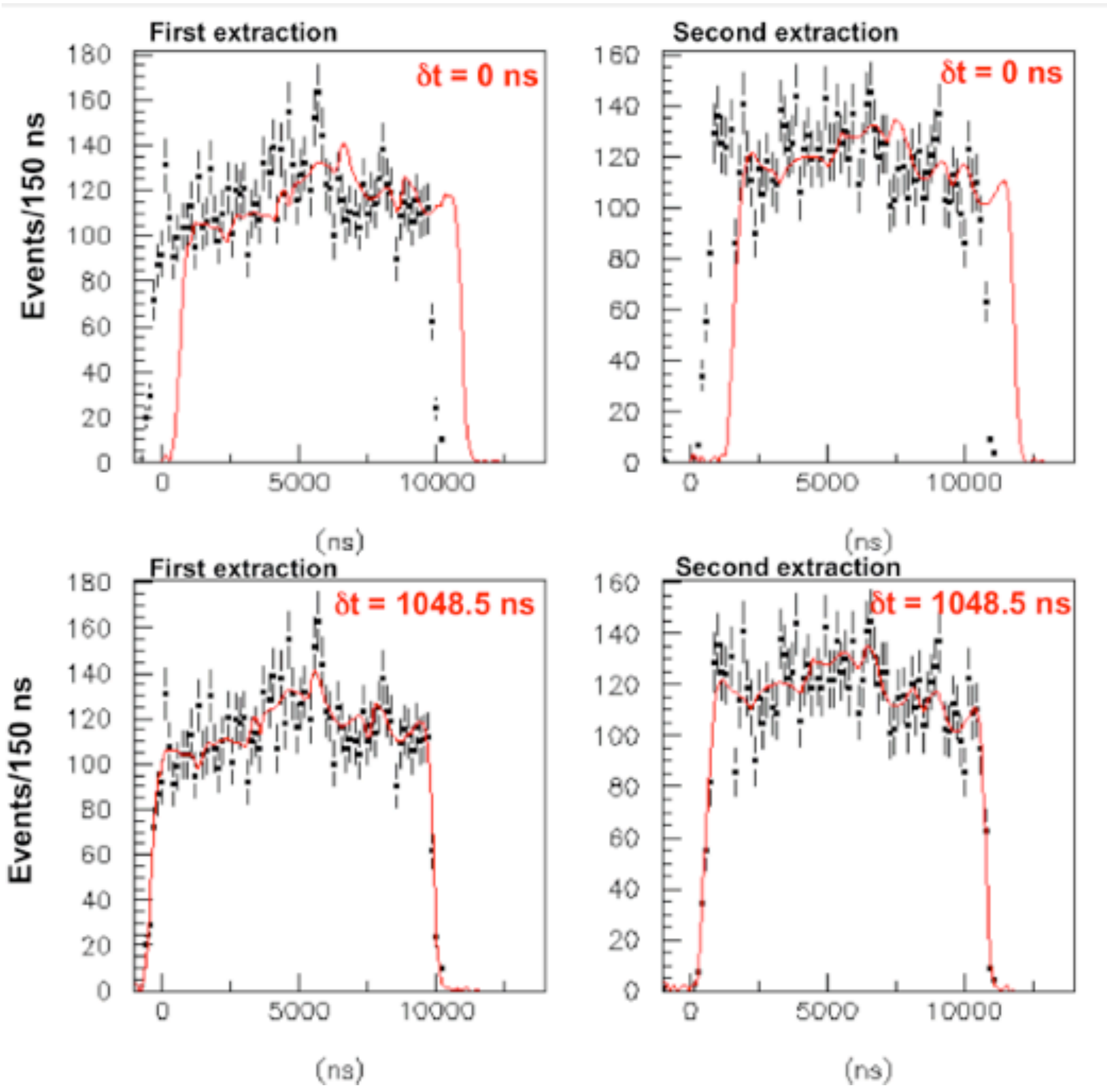
ϕ v event time distribution

Result

$\delta t = (57.8 \pm 7.8(\text{stat.})\ {}_{-5.9}^{+8.3}(\text{sys.}))$ ns

$(v-c)/c = (2.37 \pm 0.32(\text{stat.})\ {}_{-.24}^{+.34}(\text{sys.}))\text{x}10^{-5}$

OPERA Results - 1st Run



7235 internal events (CC and NC)

7988 external events (CC)

Proton beam time structure

ν event time distribution

Result

$$\delta t = (57.8 \pm 7.8(\text{stat.})\ {}_{-5.9}^{+8.3}(\text{sys.}))\ \text{ns}$$

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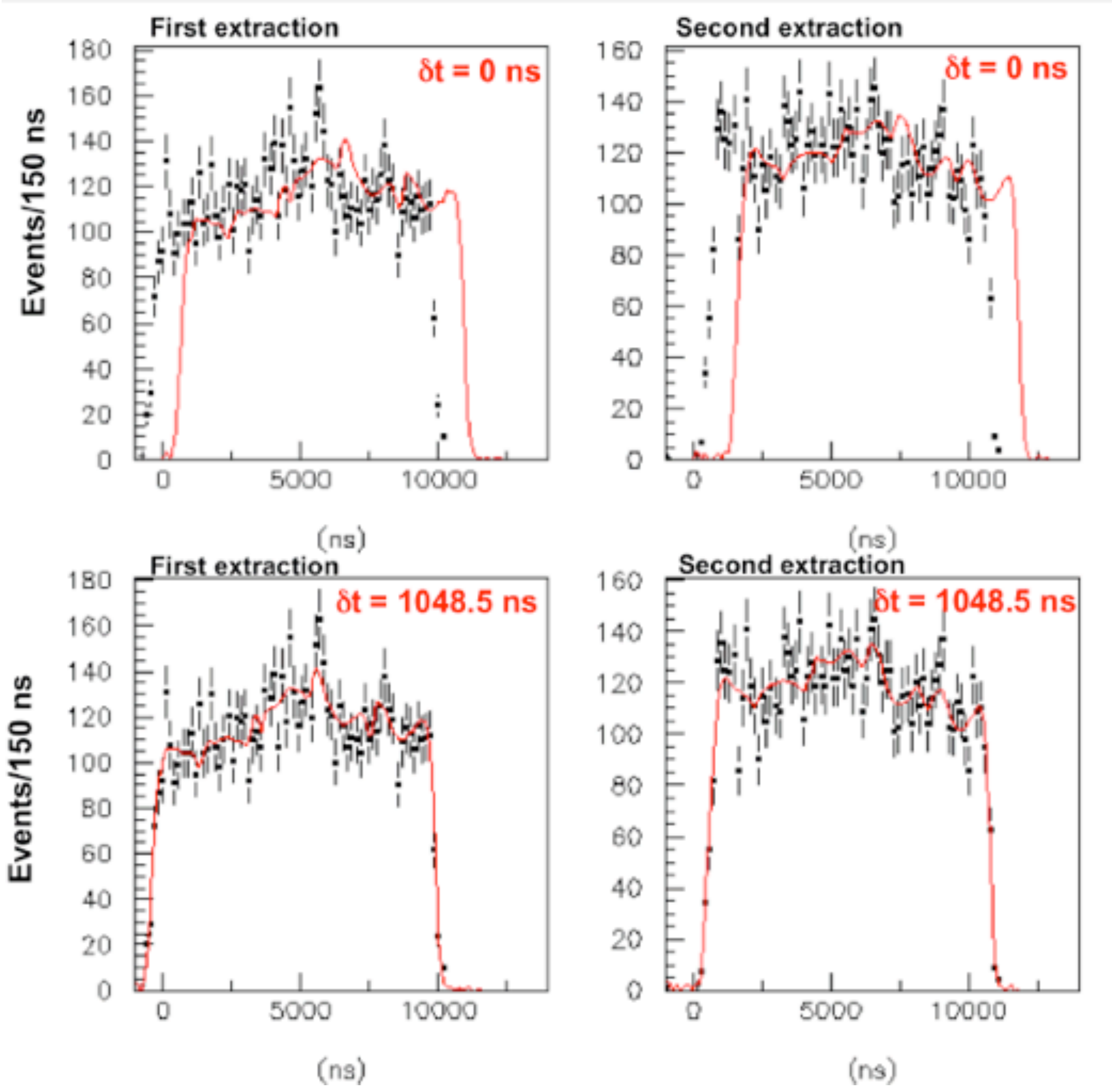

7235 internal events (CC and NC)

7988 external events (CC)

— Proton beam time structure

ɸ v event time distribution

Clearly the most useful information comes from neutrino events at either the leading or trailing edges

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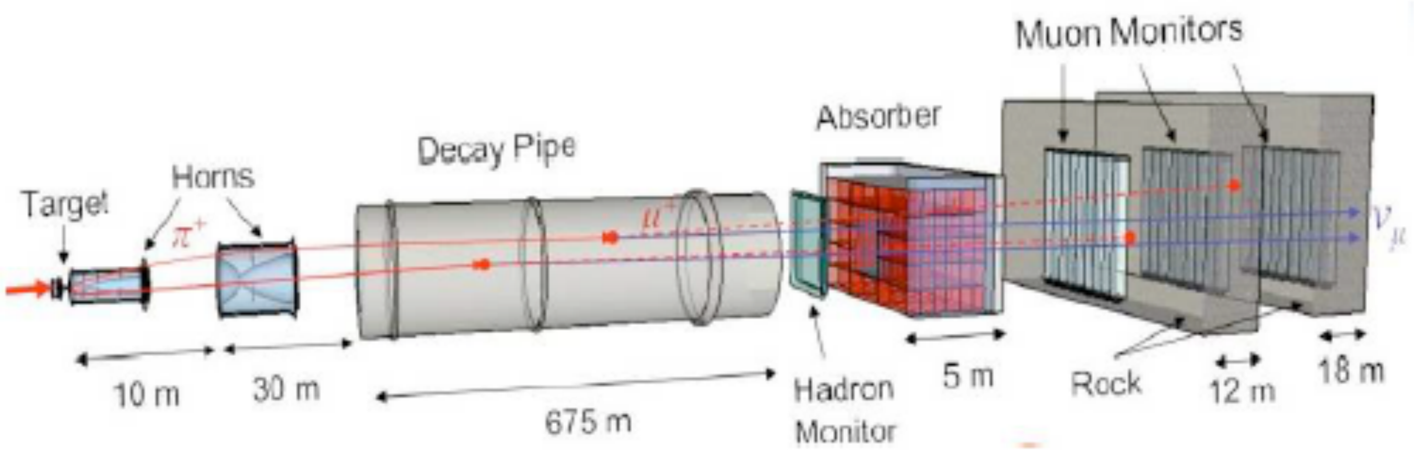
OPERA / MINOS Comparison

OPERA / MINOS Comparison

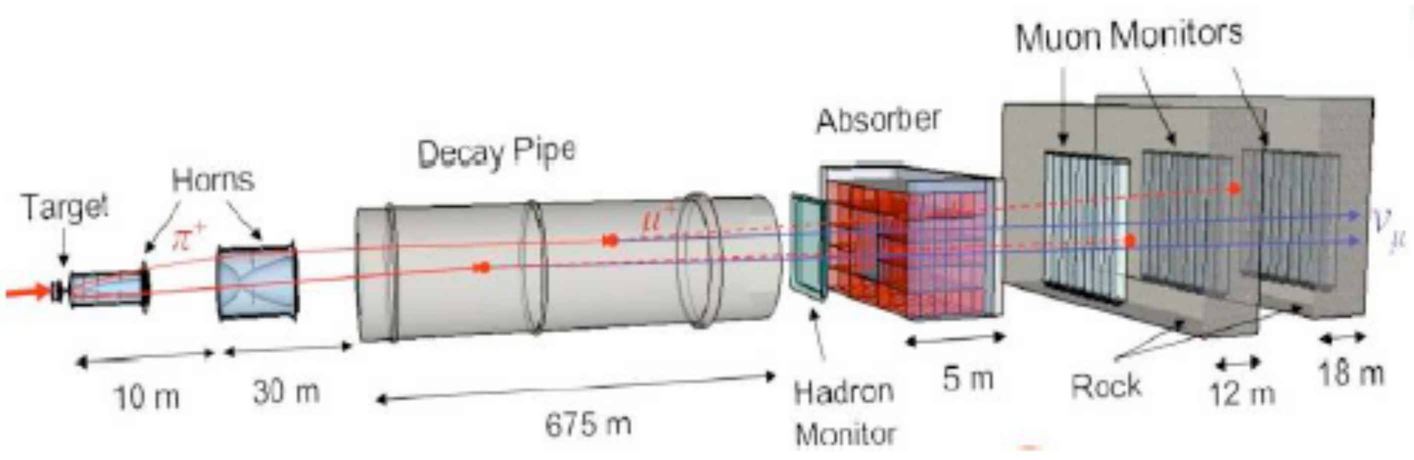
Parameter	OPERA	MINOS
Location	CERN->Gran Sasso	Fermilab->Soudan
Distance	731 km	735 km
Main Physics Goal	ν_τ appearance	ν_μ disappearance
Configuration	No Near Detector	Near Detector
Det. composition	Emulsion/Pb	Scintillator/Fe
ν Energy	High, <17 GeV>	Low, <3 GeV>
Data taking	2009-2011	2005-2006,2011
Beam structure	2 10.5μs, 200 MHz	6 1.6μs, 53 MHz
Access to FD	Highway (10 km)	Elevator (2000 ft)

MINOS Beam

MINOS Beam


Muon Monitors
Absorber
Decay Pipe
Horns
Target
π^+
μ^+
ν_μ
10 m
30 m
675 m
Hadron Monitor
5 m
Rock
12 m
18 m

MINOS Beam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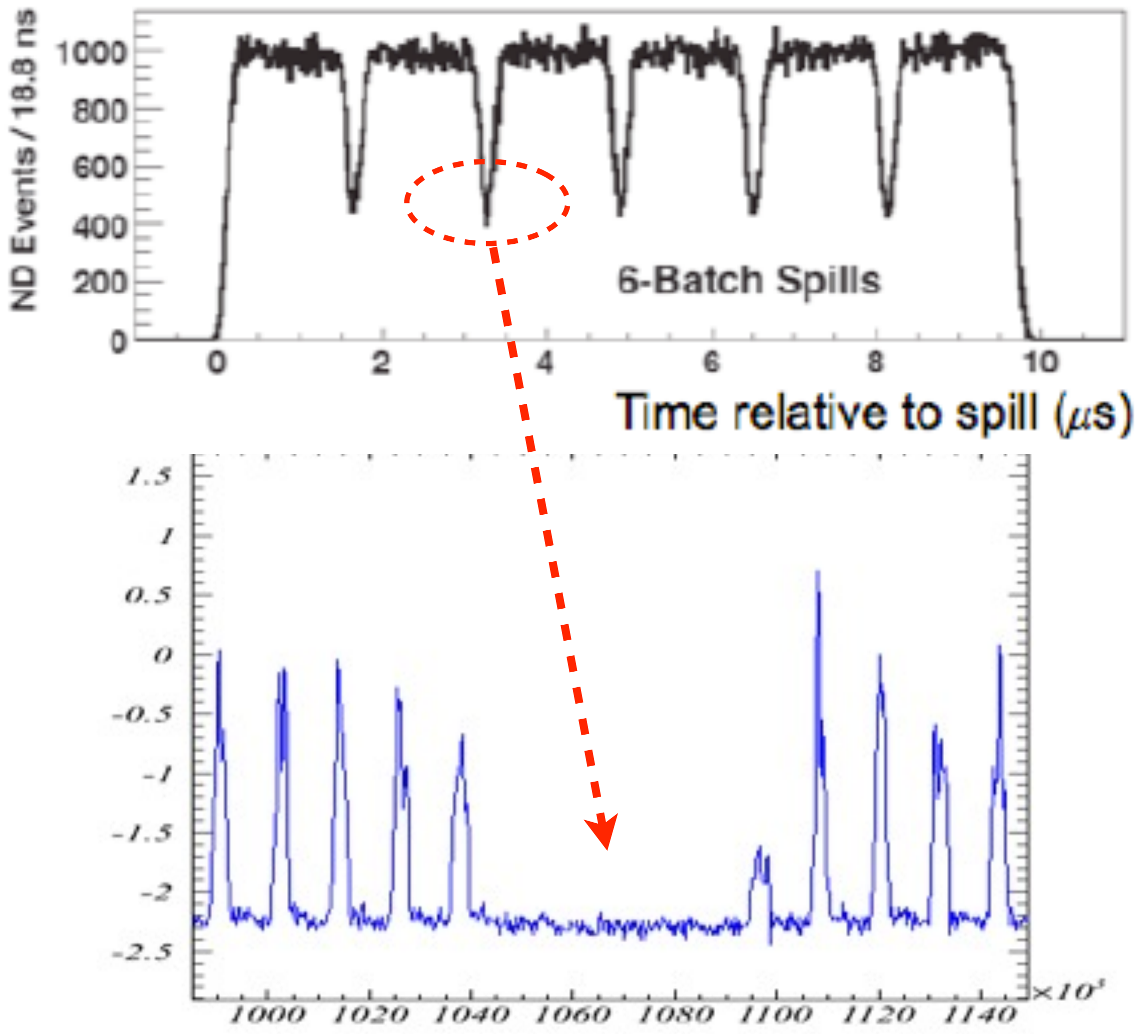
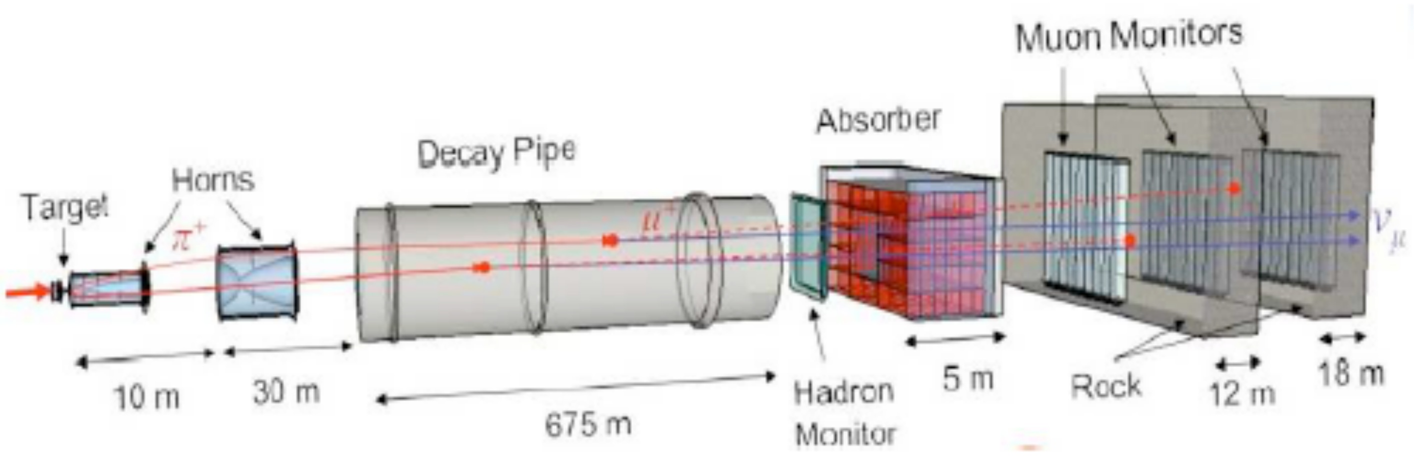
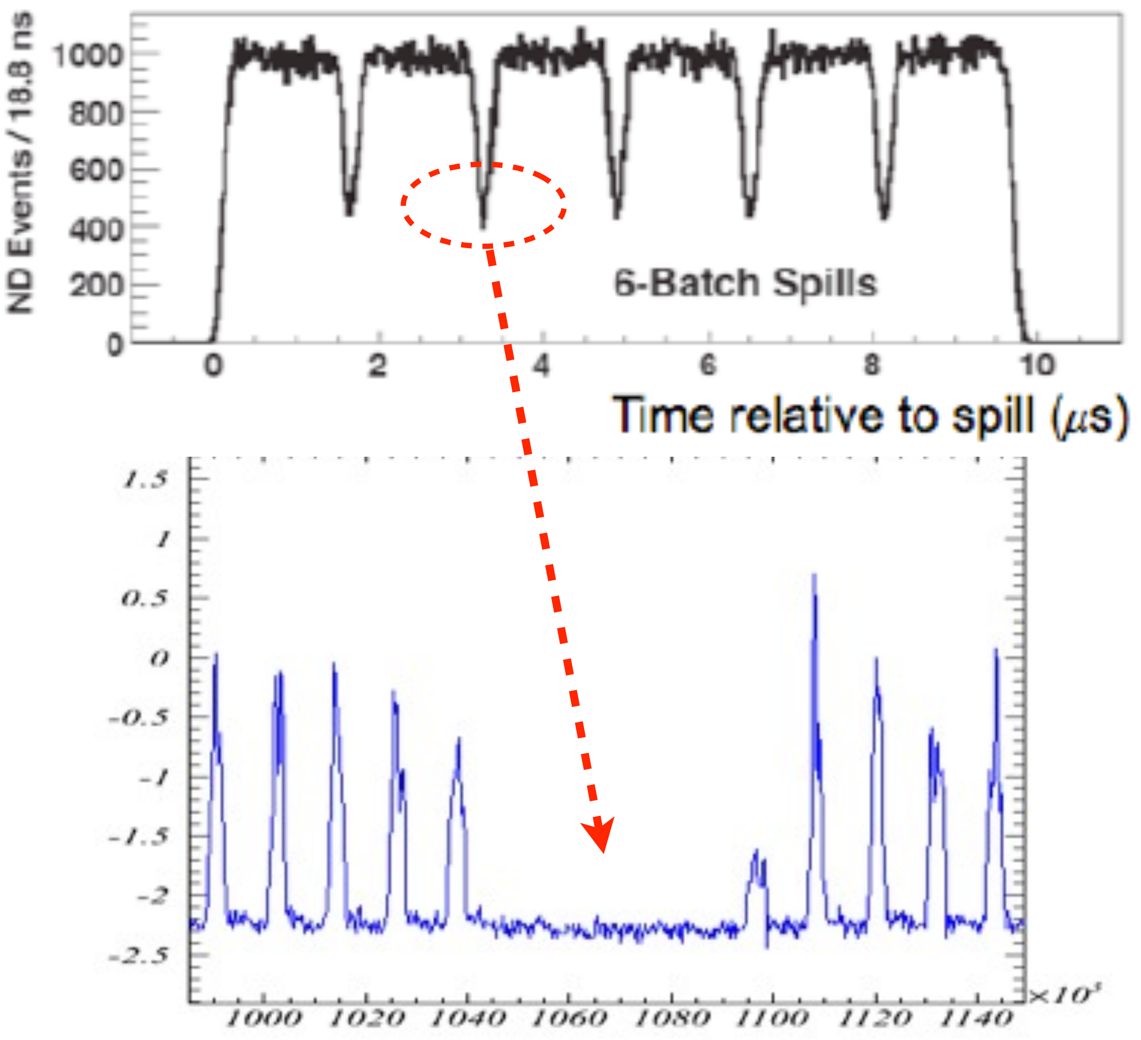

ND Events / 18.8 ns
1000
800
600
400
200
0
0
2
4
6
8
10
6-Batch Spills
Time relative to spill (μs)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
1000
1020
1040
1060
1080
1100
1120
1140
×10³

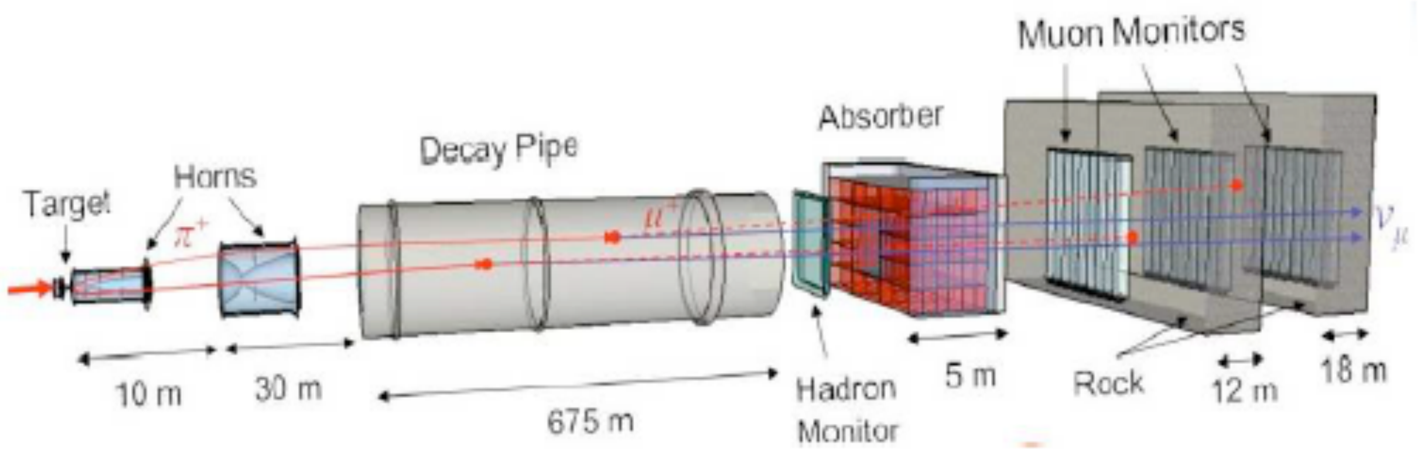
MINOS Beam

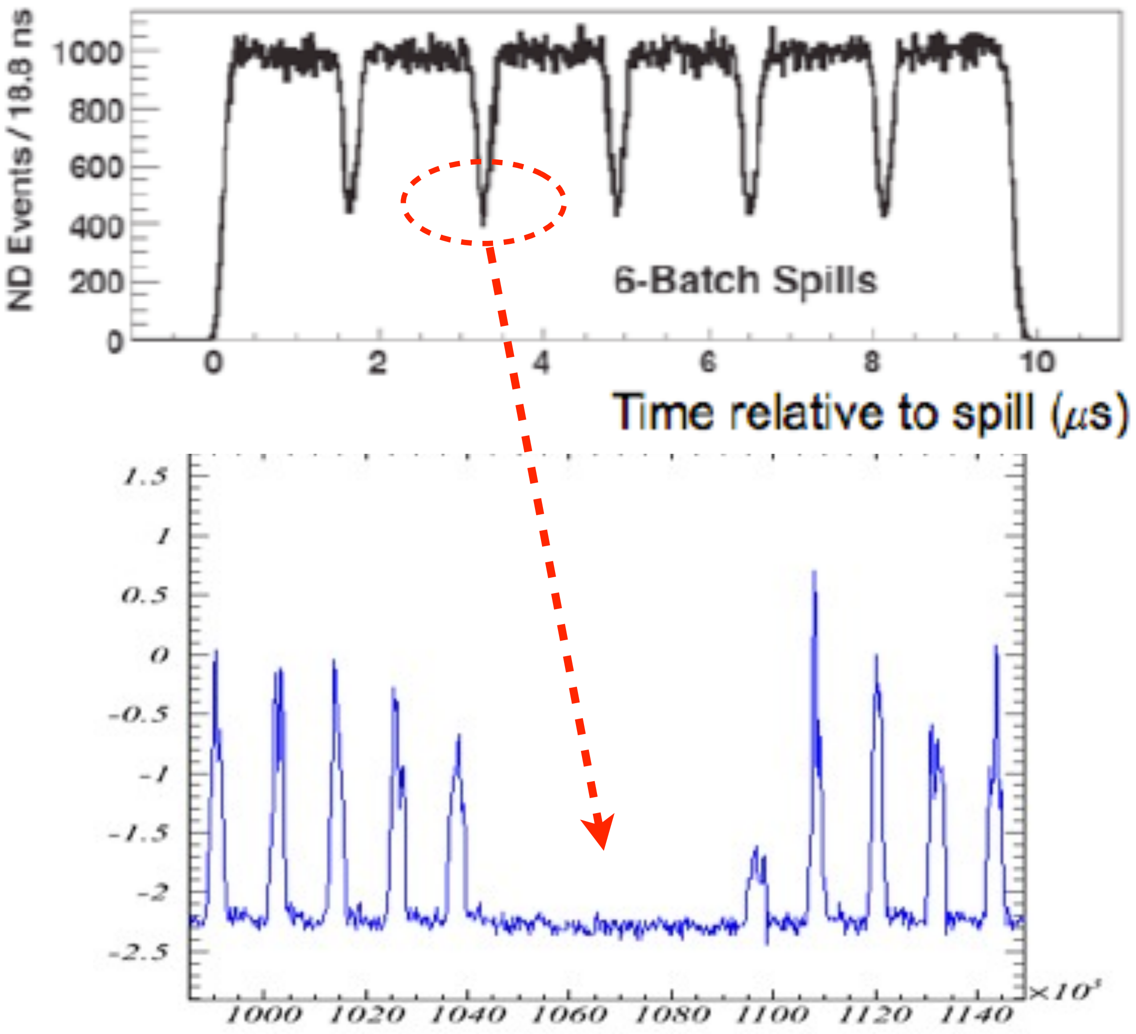




- ~ 1.8 s cycle

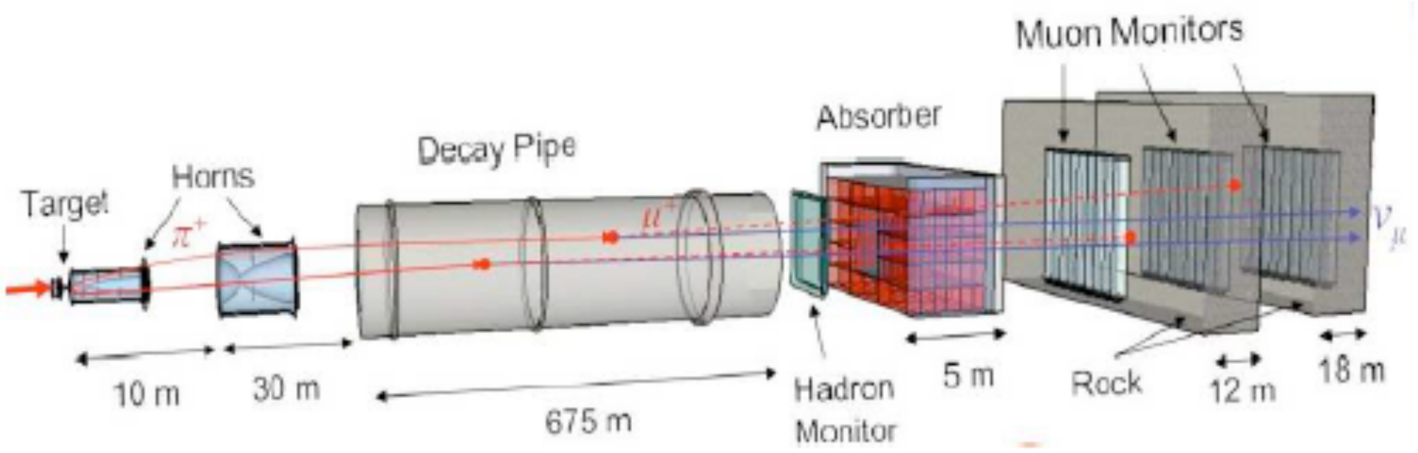
MINOS Beam

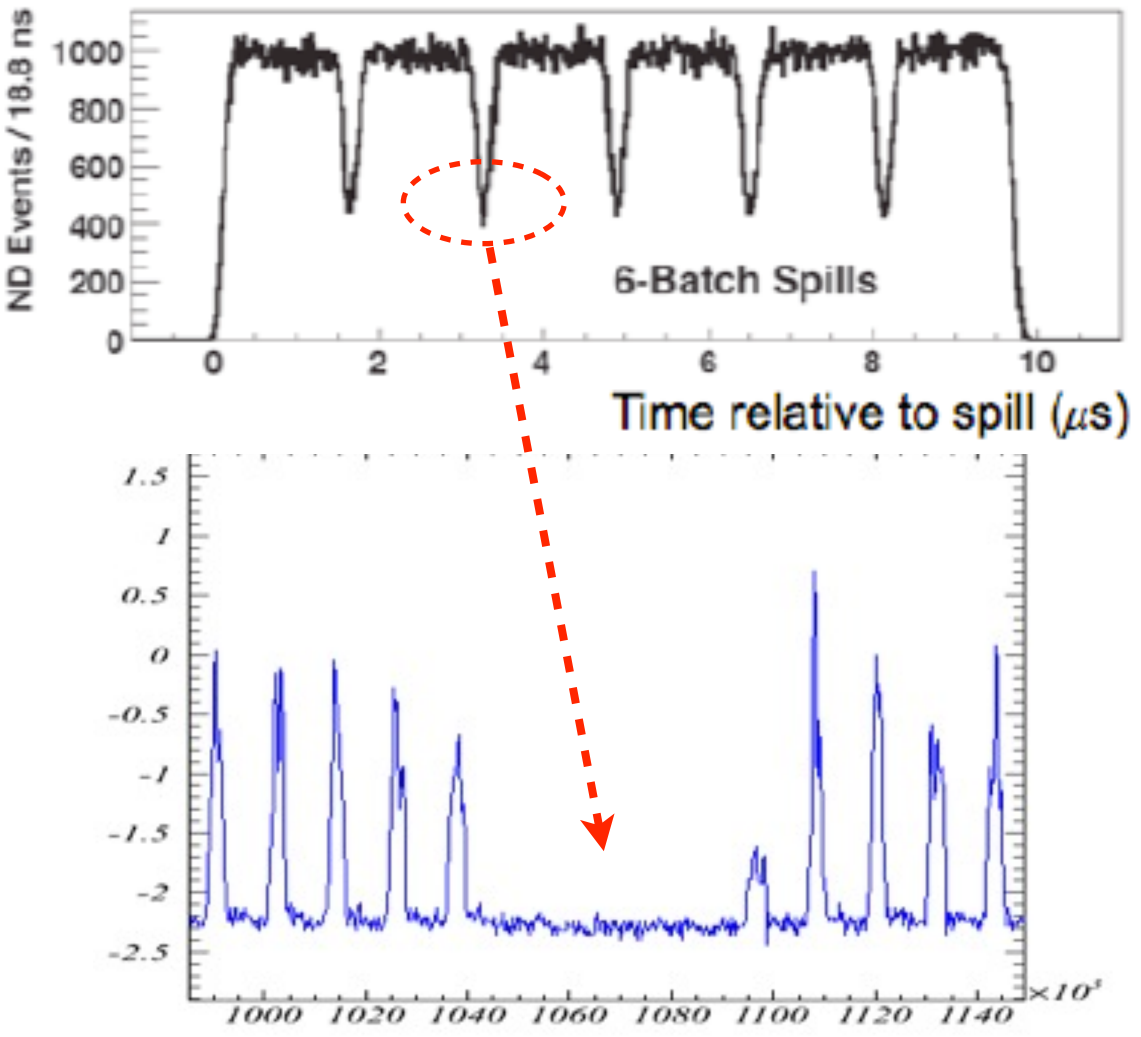




- ~ 1.8 s cycle
- Beam spill 9.6 μs long

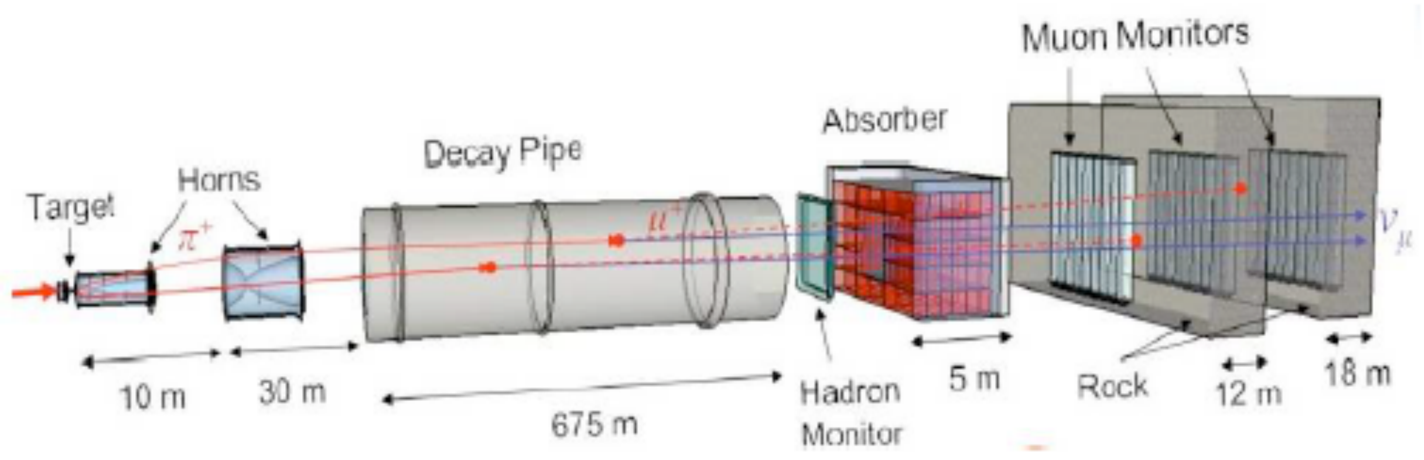
MINOS Beam

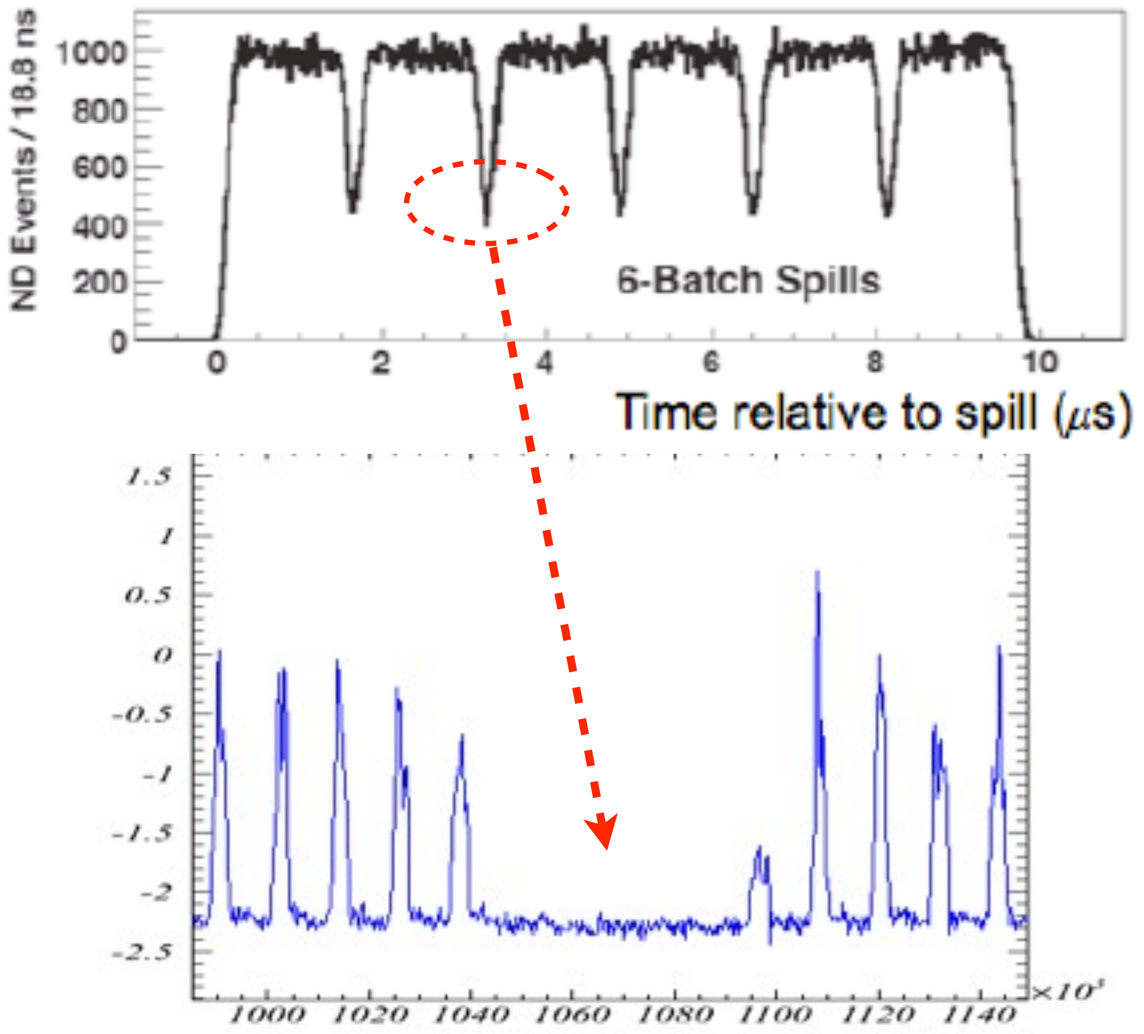




- ~ 1.8 s cycle
- Beam spill 9.6 μs long
- 5 or 6 batches in spill

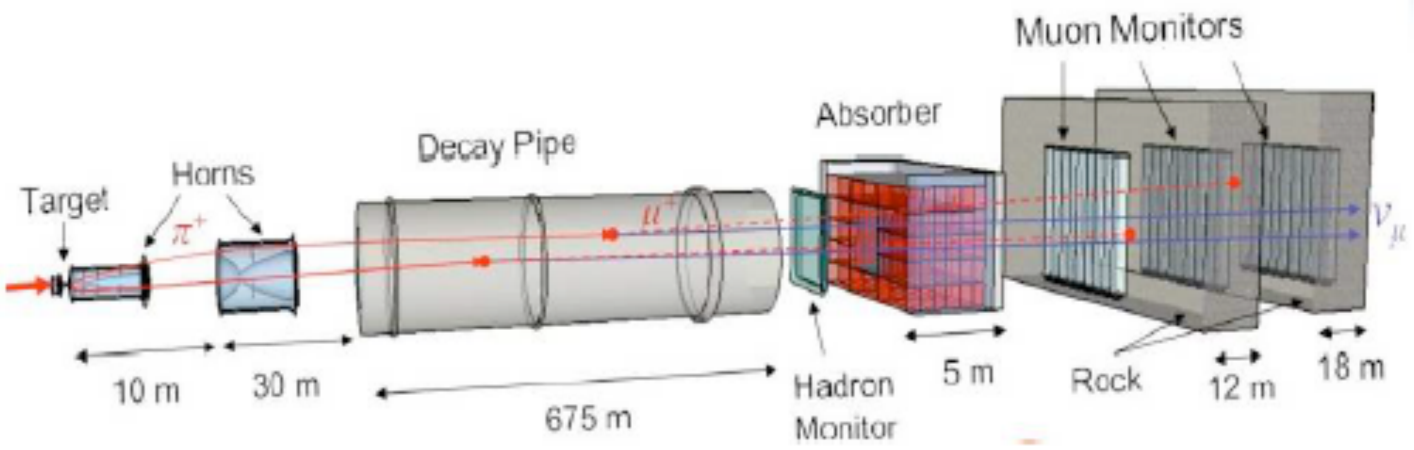
MINOS Beam

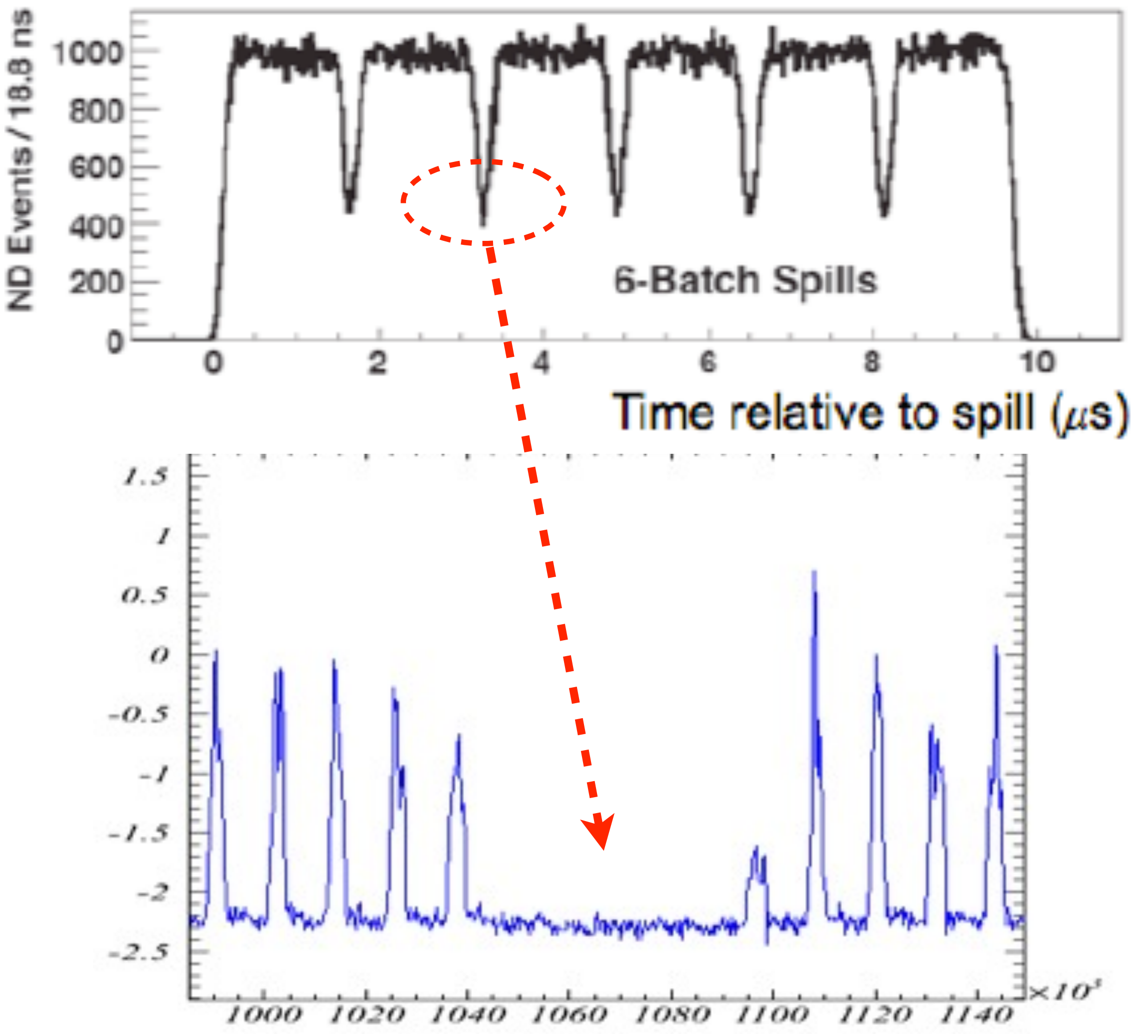




- ~ 1.8 s cycle
- Beam spill 9.6 μs long
- 5 or 6 batches in spill
- Each batch 1.52 μs long, separated by 90 ns

MINOS Beam





- ~ 1.8 s cycle
- Beam spill 9.6 μs long
- 5 or 6 batches in spill
- Each batch 1.52 μs long, separated by 90 ns
- Modulated by 53 MHz (18.8 ns)

3 Measurement Phases

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1. Analysis of data already taken

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   - Build on experience from initial 2 phases
   - Aim for single RF bucket resolution
   - Remeasurement of distance (?)

MINOS Beam

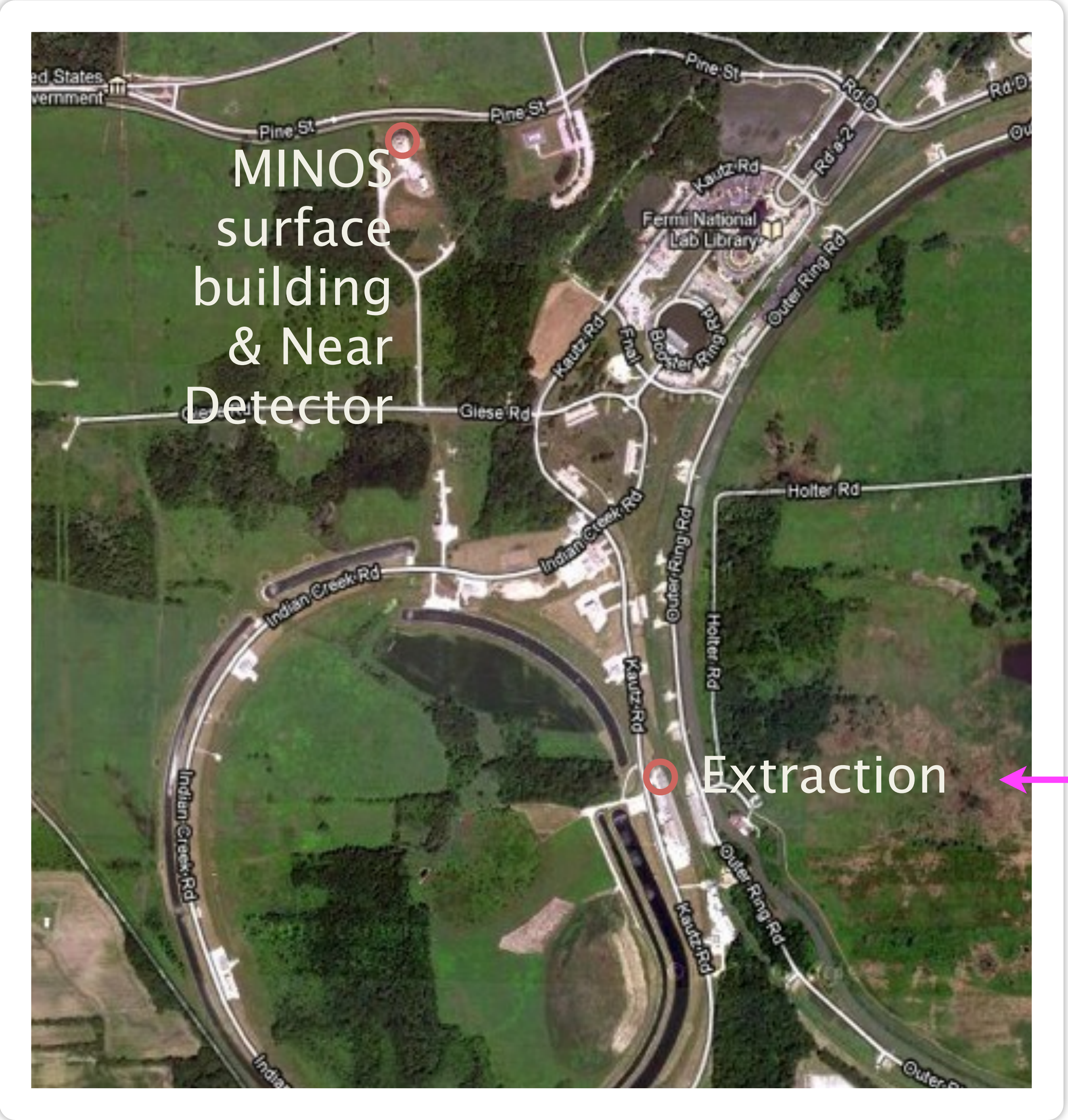
Modified J.Thomas slide

MINOS Beam

MINOS surface building & Near Detector

Modified J.Thomas slide

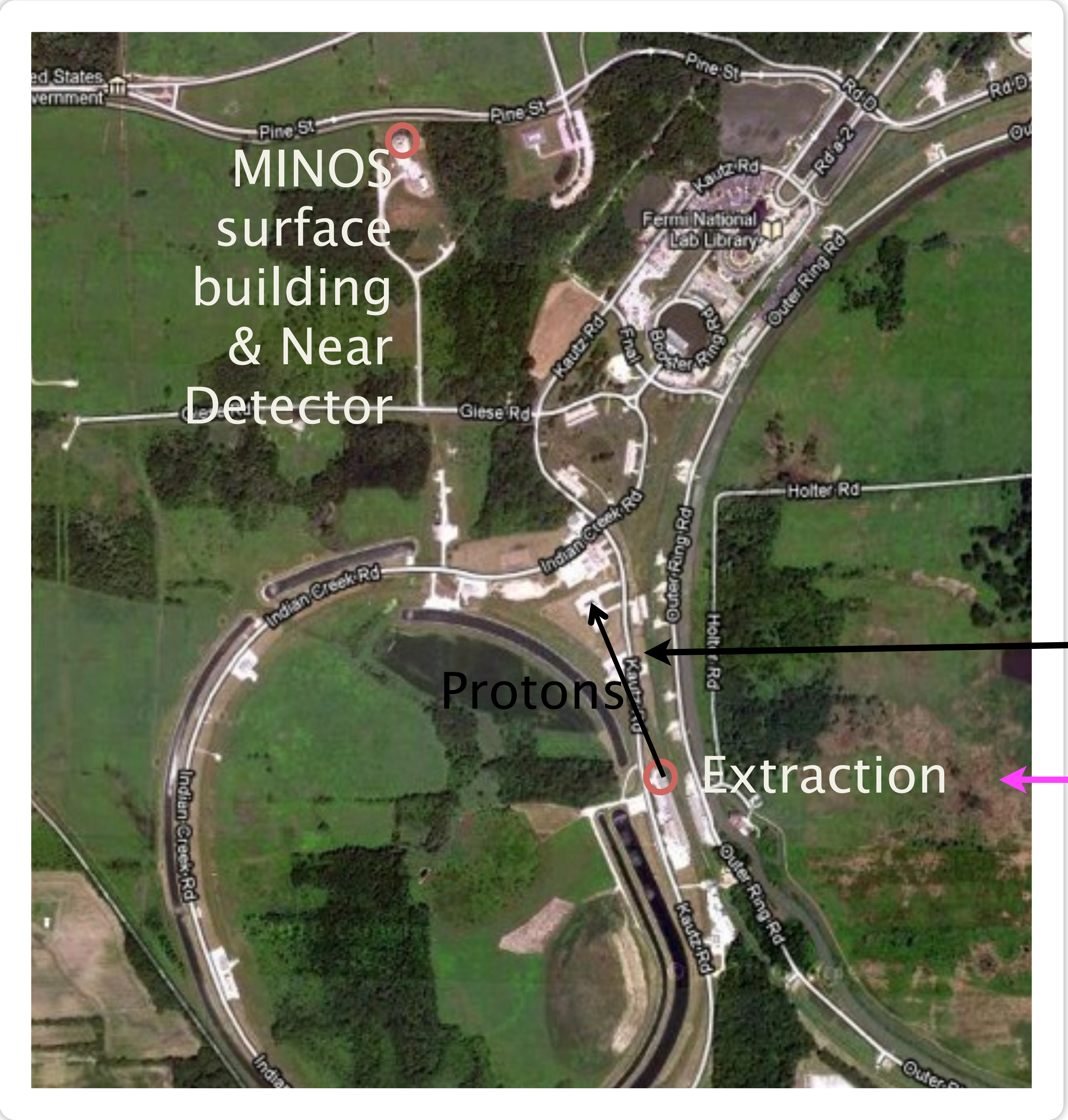
MINOS Beam



t'$_{start}$ measurement from wall current monitor

Modified J.Thomas slide

MINOS Beam



protons highly relativistic (120 GeV/c) Δt<100 ps

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Modified J.Thomas slide

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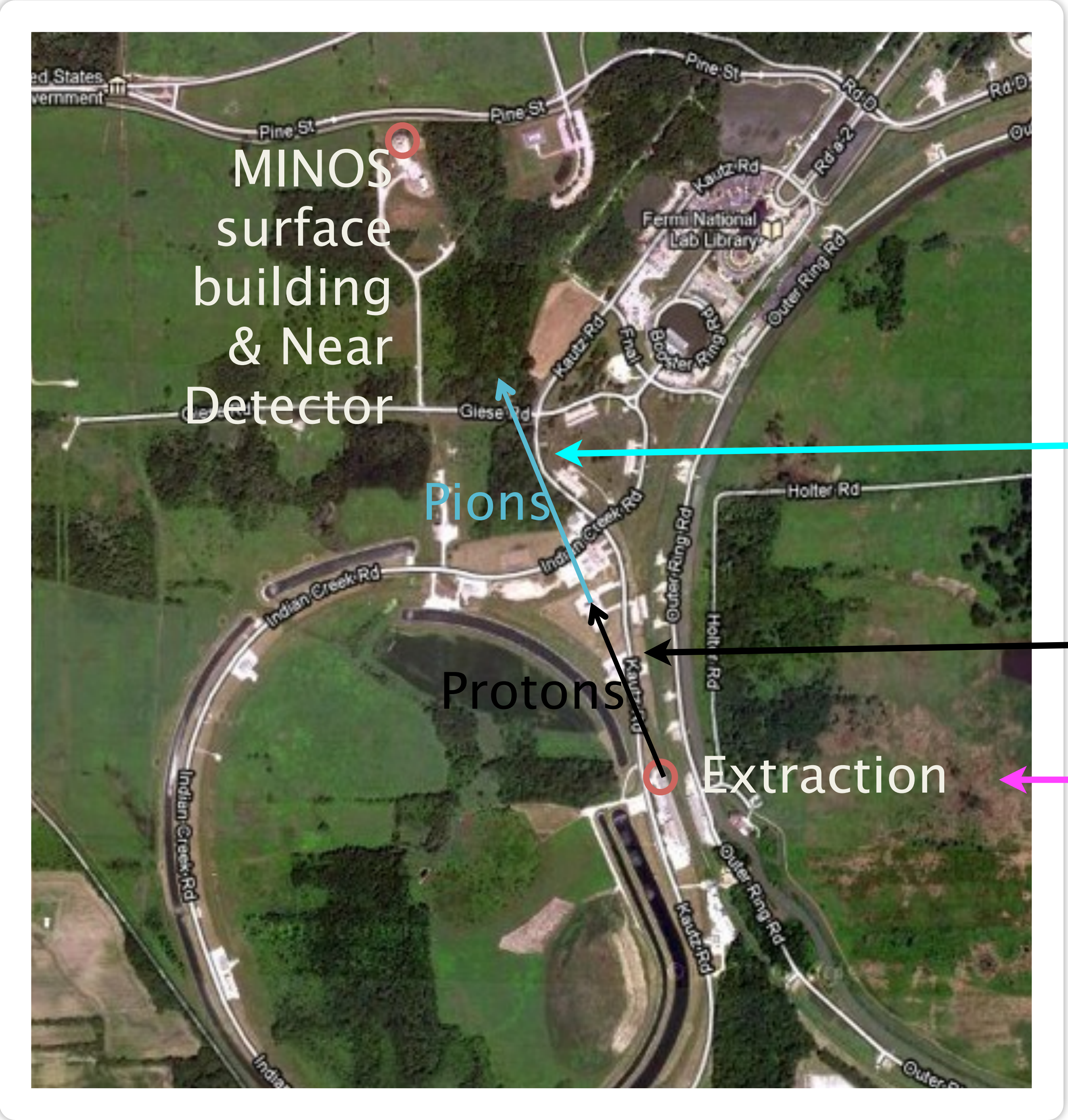

pions highly relativistic, ~10 GeV/c, decay point not very relevant, Δt~few hundred ps, calculable

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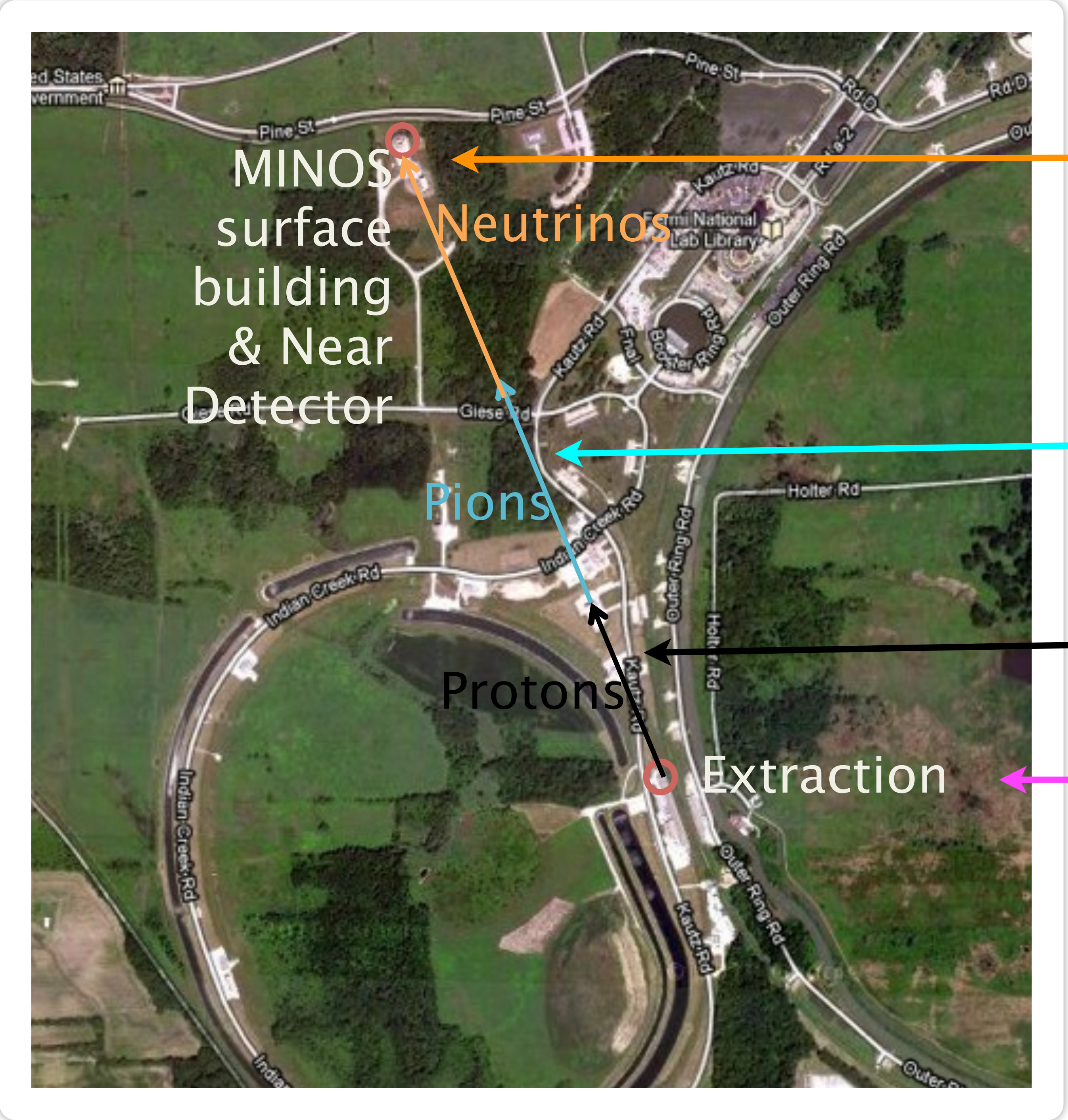

t_{start} measurement from neutrinos in the Near Detector

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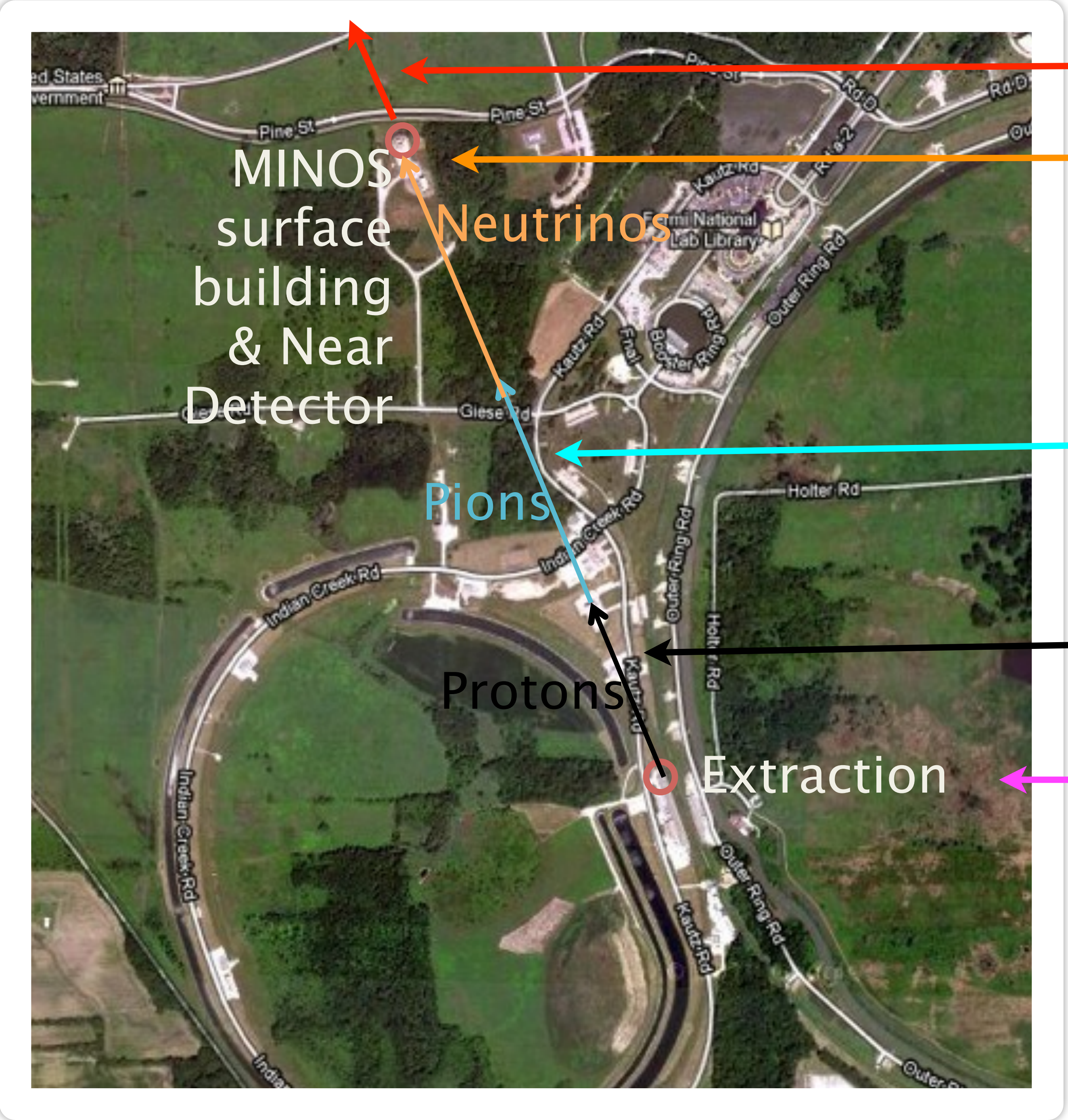

Neutrinos to Soudan (t_{stop})

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protons highly relativistic (120 GeV/c) Δt<100 ps

t'_{start} measurement from wall current monitor

Modified J.Thomas slide

Final Comments re TOF

- Superluminal neutrinos would drastically alter our picture of physics
- Even though no problem has been found in the OPERA analysis, physics community remains sceptical
- An independent experiment is required to test the results of OPERA
- Personally I am sceptical - it was NOT suggested as a neutrino property by Pontecorvo

Acknowledgements

- In my professional career I have been very fortunate in having a chance to collaborate with many younger, very gifted and very hard working colleagues
- Any success that I might have had is very much due to these collaborative efforts, both today and in the past
- I want to thank all my present and past collaborators for their many contributions