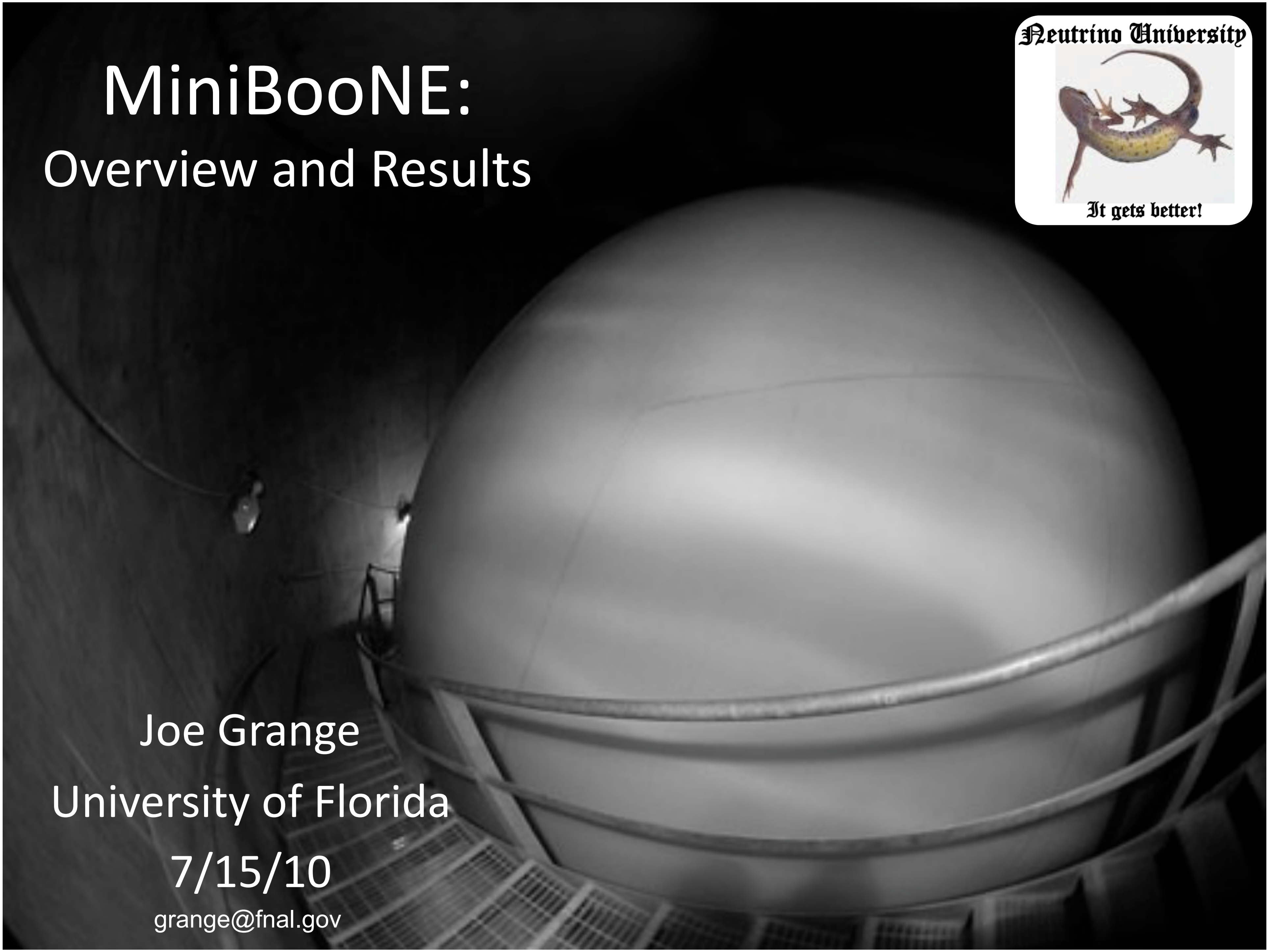


Neutrino University

It gets better!

MiniBooNE:
Overview and Results

Joe Grange

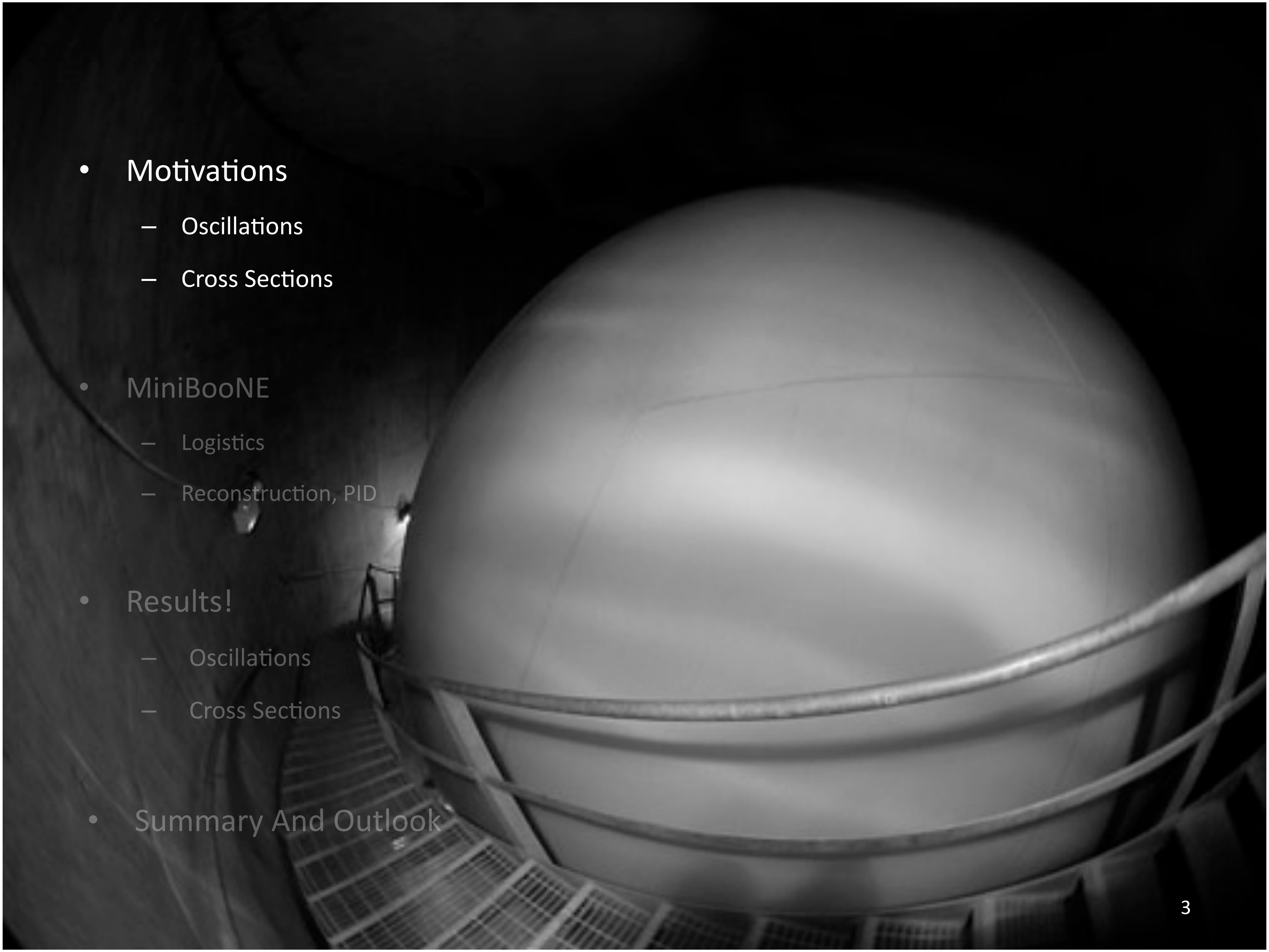
University of Florida

7/15/10

grange@fnal.gov

Outline

- Motivations
  - Oscillations
  - Cross Sections
- MiniBooNE
  - Logistics
  - Reconstruction, PID
- Results!
  - Oscillations
  - Cross Sections
- Summary And Outlook



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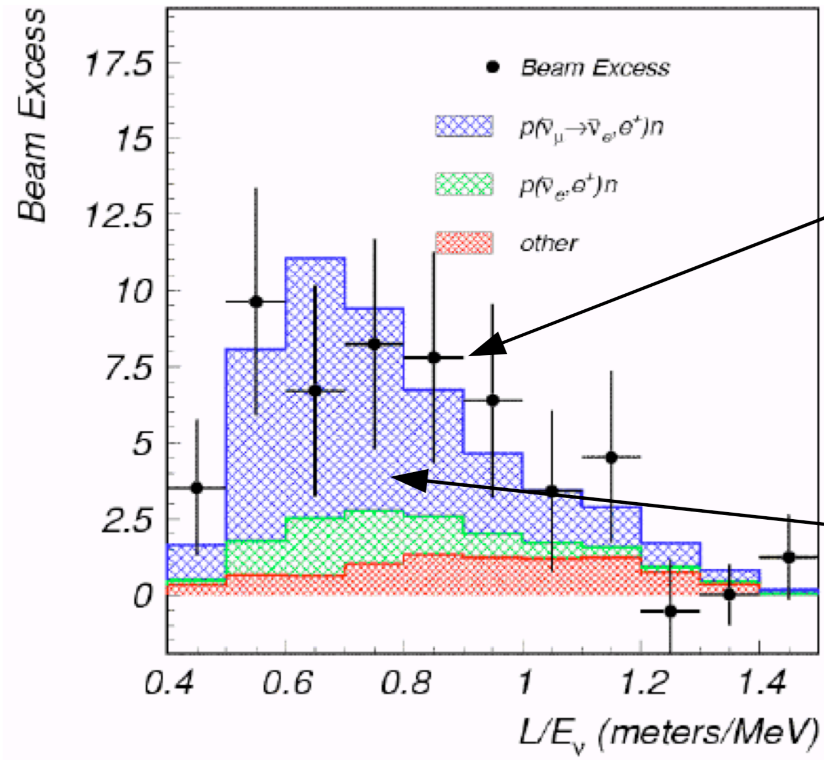
The MiniBooNE Experiment: Motivation

Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos



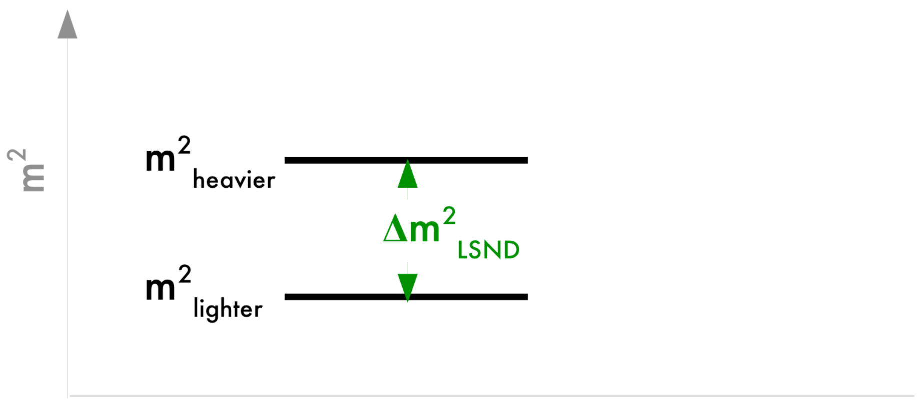
Observed $\bar{\nu}_e$ data in a $\bar{\nu}_\mu$ beam:
In excess of background prediction
(3.8σ significance)

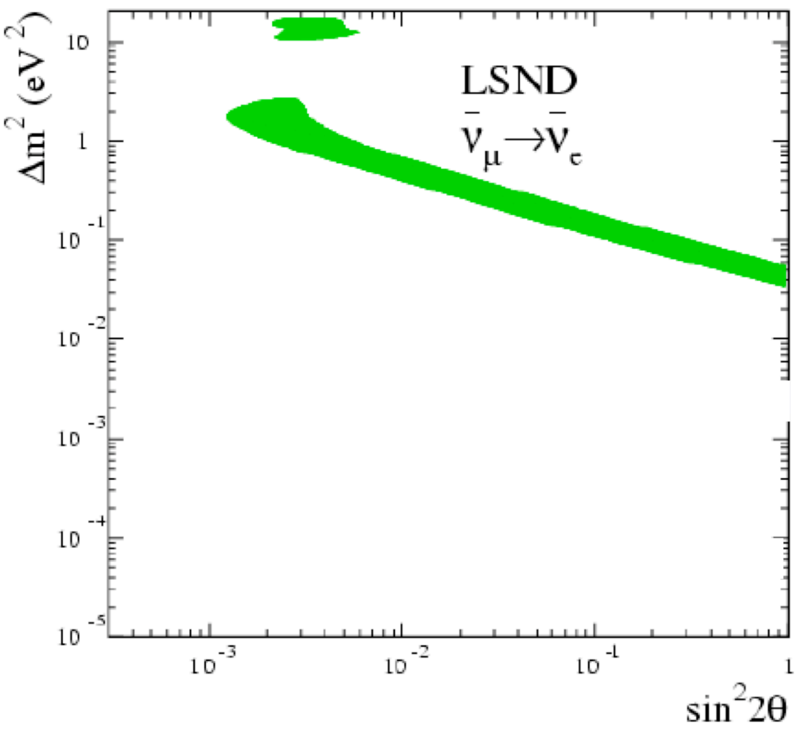
Could be interpreted as
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
with osc. probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L[m]/E_\nu[MeV])$$
$$= 0.26\%$$

The MiniBooNE Experiment: Motivation

(Simplest) oscillation interpretation requires:





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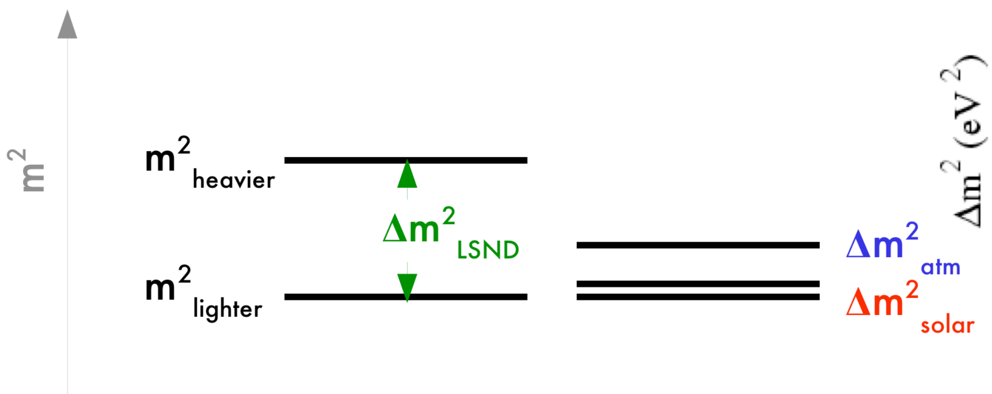
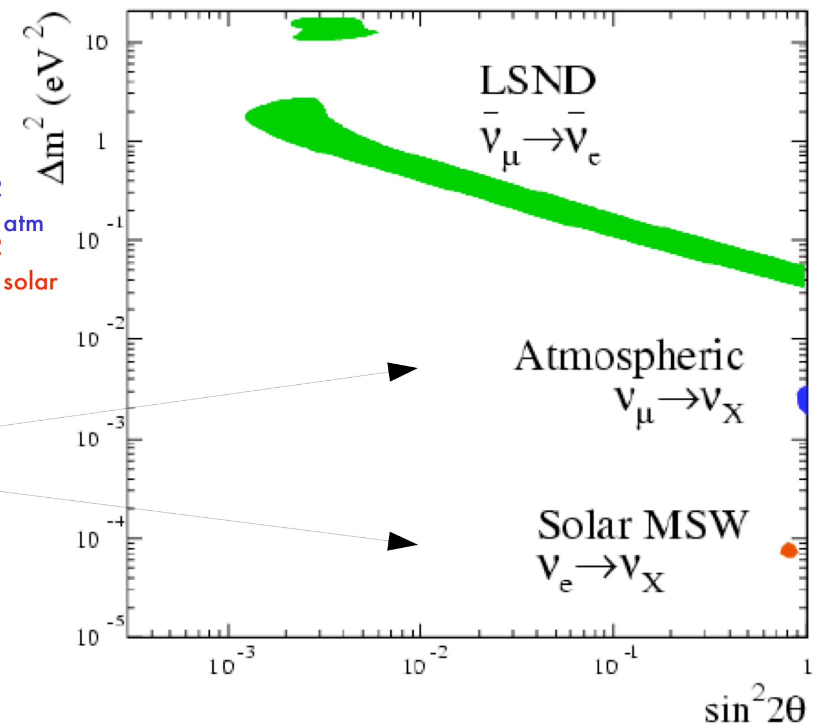




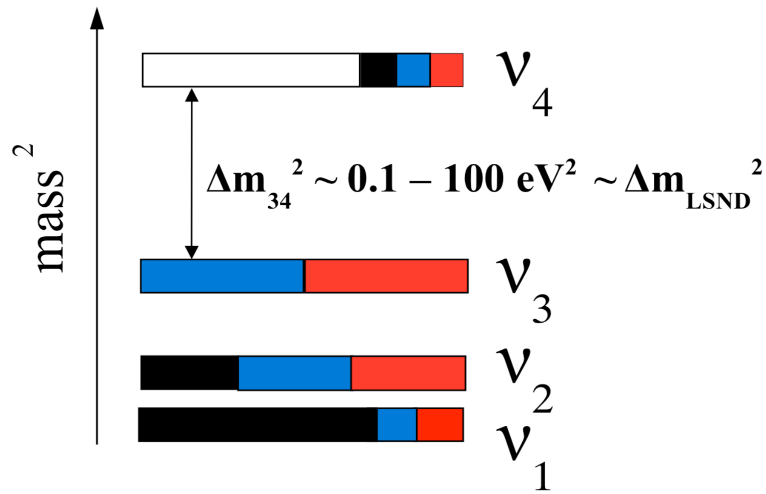
In conflict with well-understood, three-neutrino mixing model in the Standard Model (defined by only two independent oscillation signatures)

$$P(\bar\nu_\mu \to \bar\nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 \, L[m]/E_\nu[MeV])$$
$$= 0.26\%$$

The MiniBooNE Experiment: Motivation

(Simplest) oscillation interpretation requires New Physics:

3 active neutrinos + 1 sterile neutrino: "(3+1)"



"sterile neutrino": a neutrino incapable of interacting via the weak force. Possibly a **right-handed neutrino** or a **left-handed antineutrino**.
(only left-handed neutrinos and right-handed antineutrinos interact weakly)

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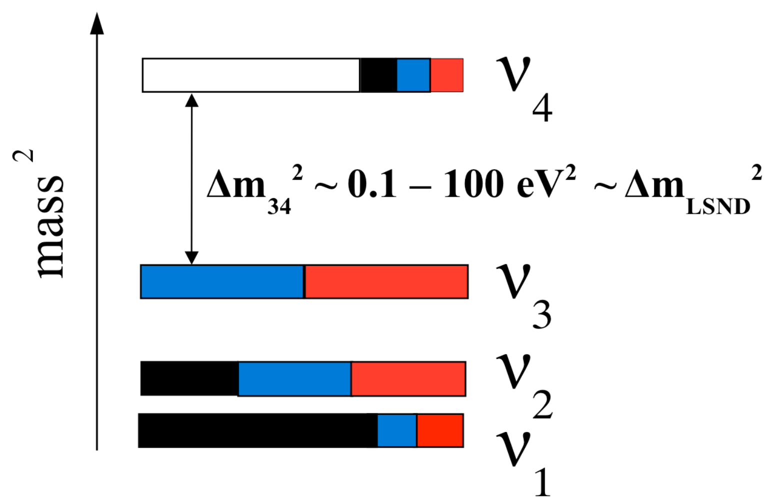

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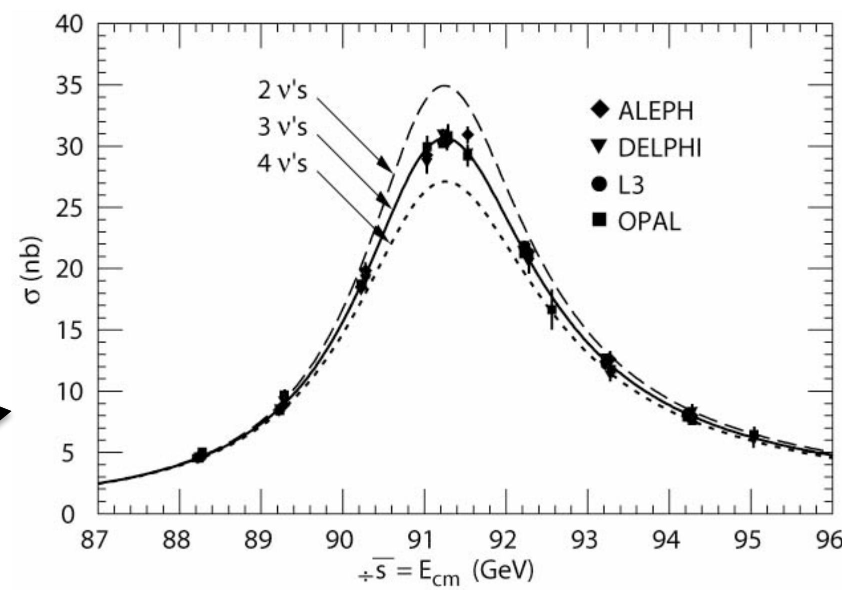
Why sterile?

➢LEP experiments determined definitively there are exactly 3 "active" neutrinos



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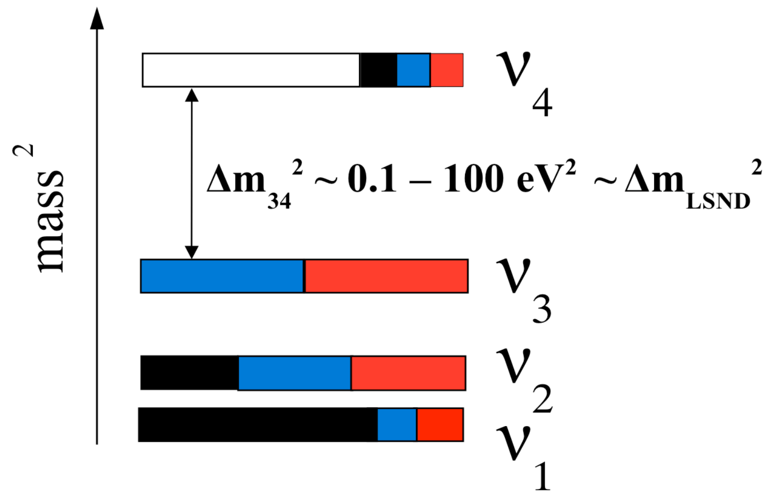

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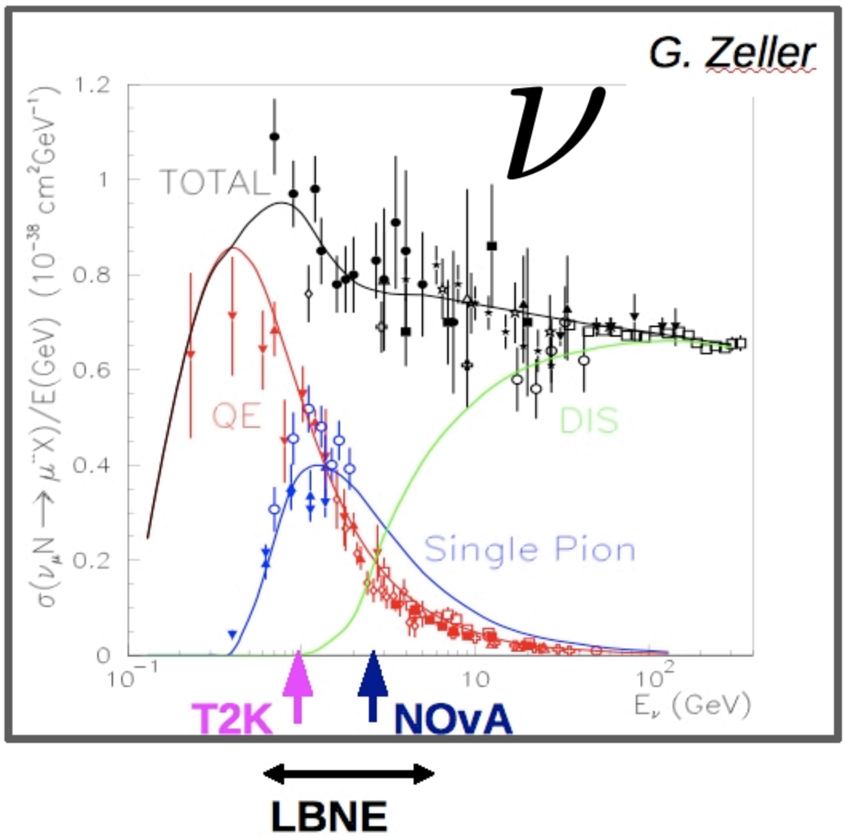
➢ Implies existence of a new particle?!
Clearly this needs to be independently checked!

ENTER MINIBOONE!

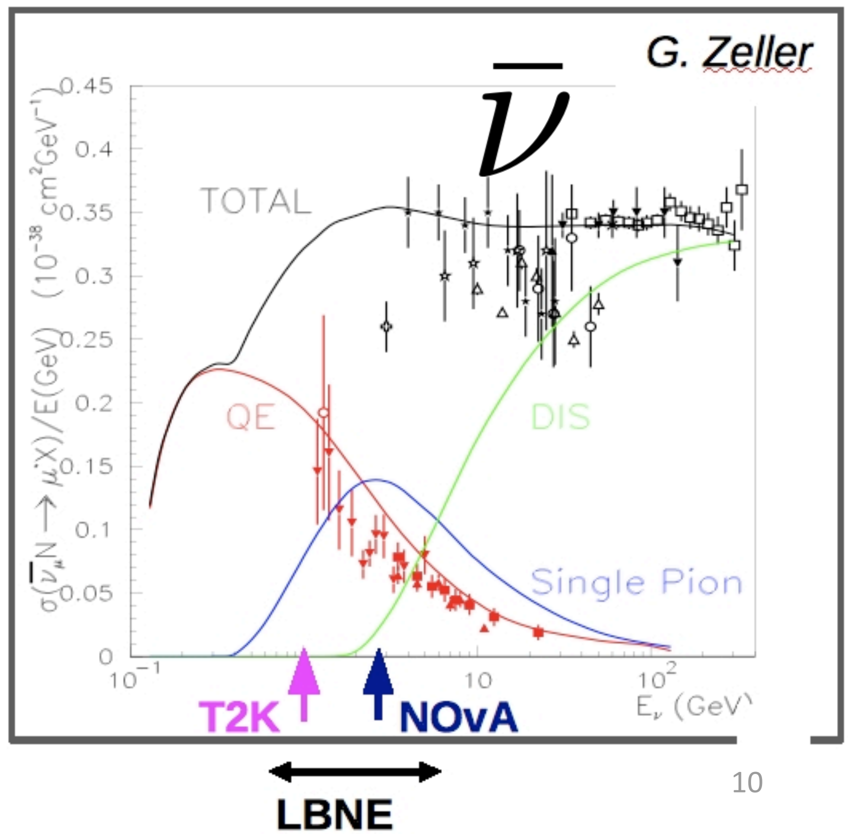
➢ Sensitive to same oscillation region
completely different experimental approach

Cross-Section Motivation

- Previous measurements from 1970's-1980's
- Mostly H_2 & D_2 targets
- Small sample sizes (100's of events)



- No measurements of sub-GeV $\bar{\nu}$ cross-sections
- Important for ~~CP~~ studies
- Very sparsely measured



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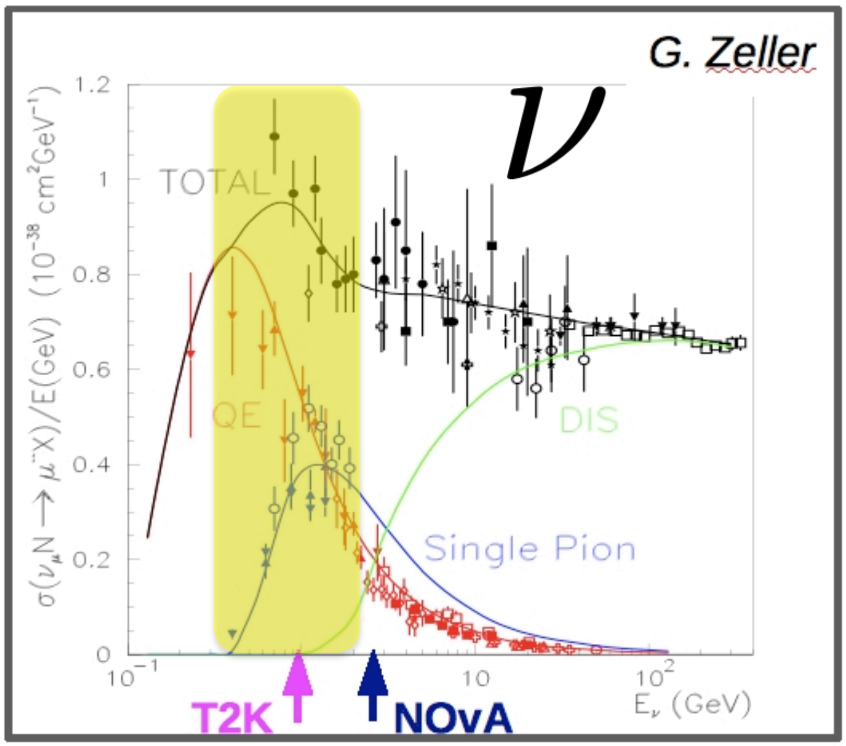

LBNE

- No measurements of sub-GeV $\bar{\nu}$ cross-sections
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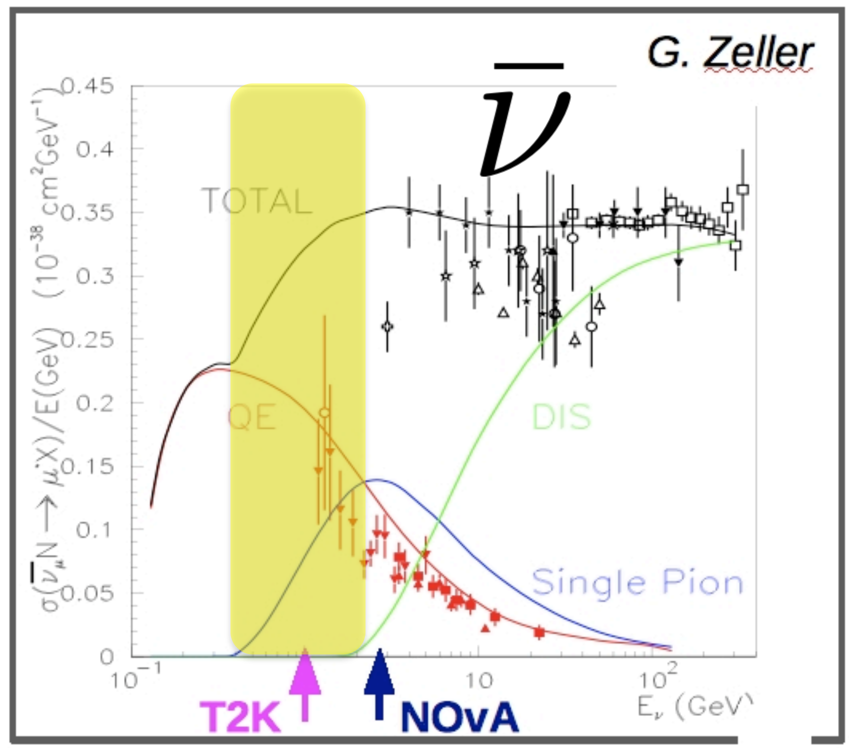
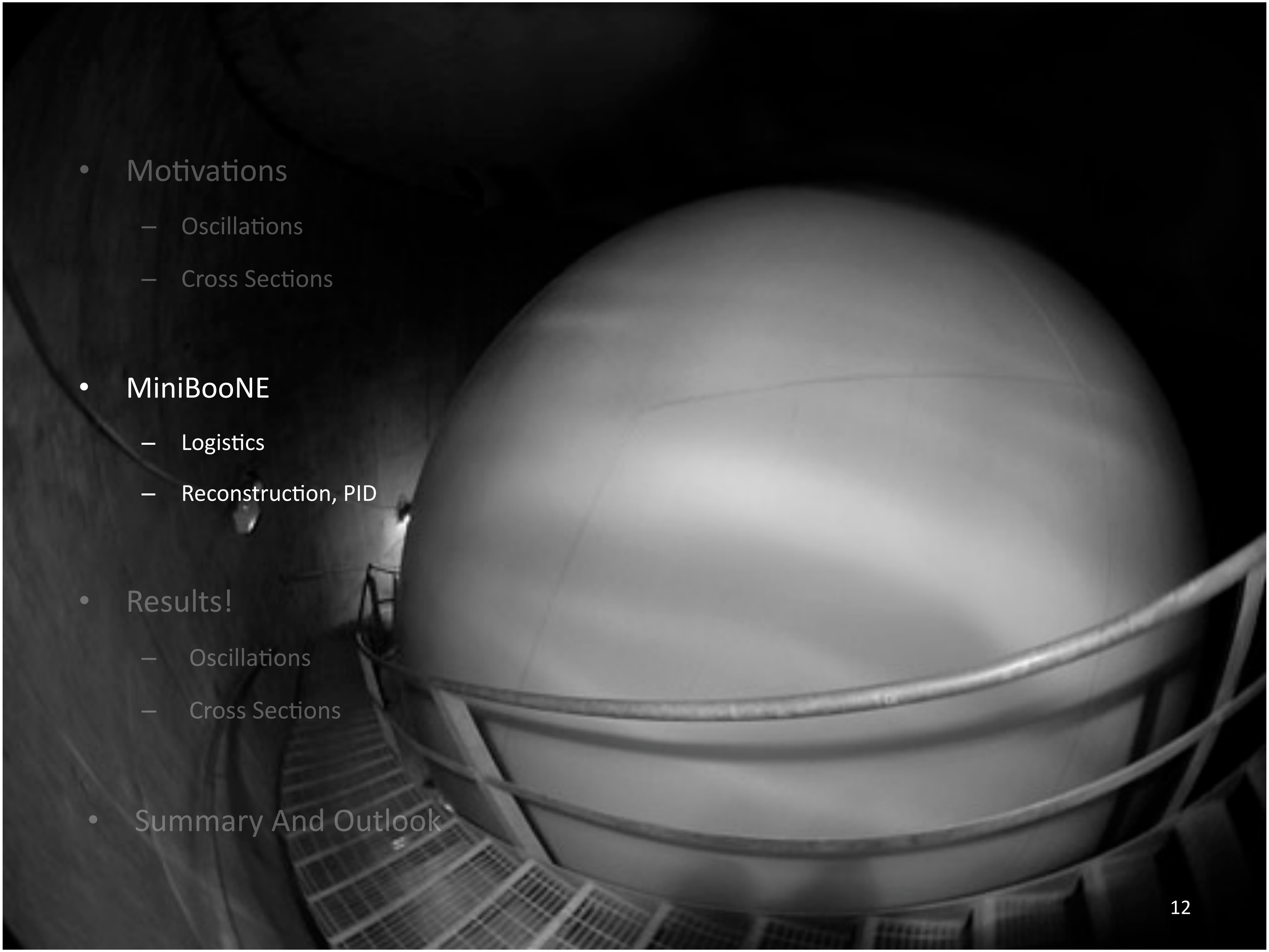


LBNE

MiniBooNE Energies



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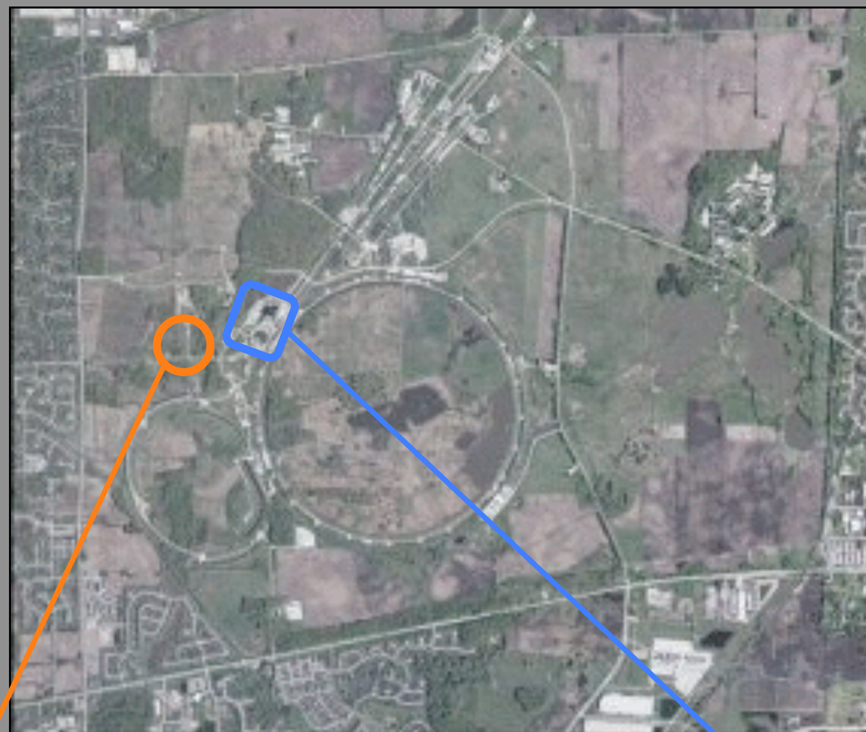
MiniBooNE

Mini Booster Neutrino Experiment



Fermilab
Batavia, IL

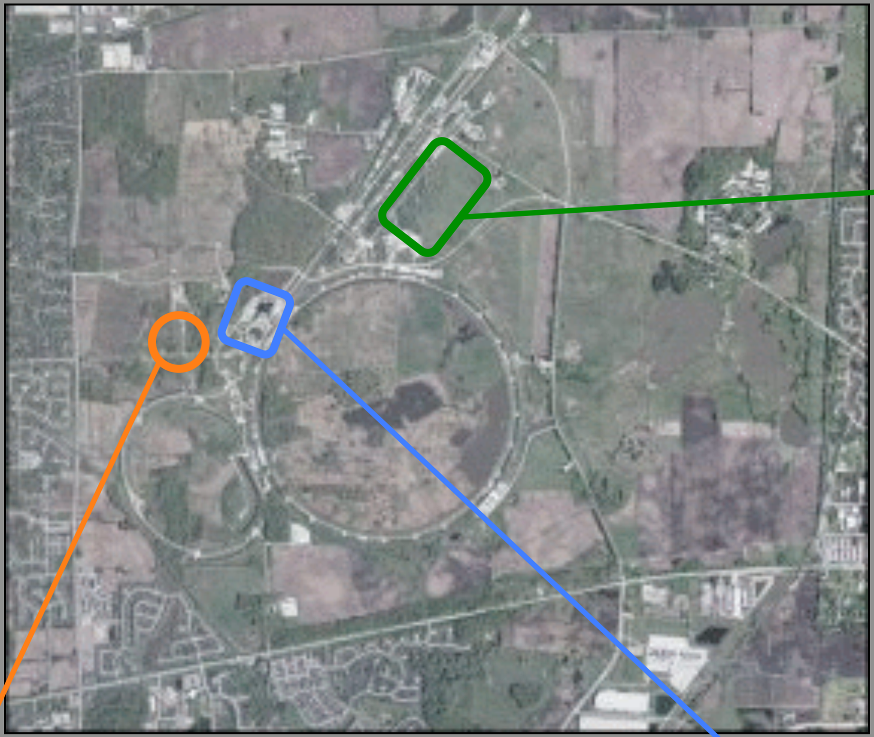
MiniBooNE detector hall

Booster Ring
(8 GeV protons extracted)

Particle beam

MiniBooNE

Mini Booster Neutrino Experiment



Fermilab
Batavia, IL

Bison

MiniBooNE detector hall

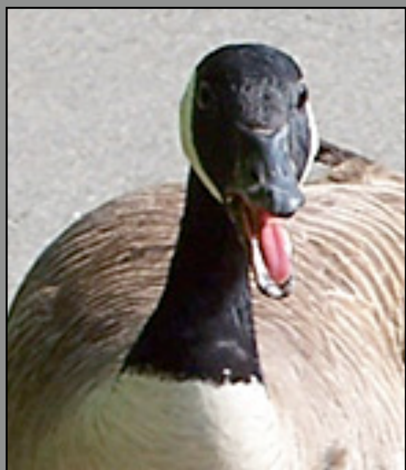
Booster Ring
(8 GeV protons extracted)

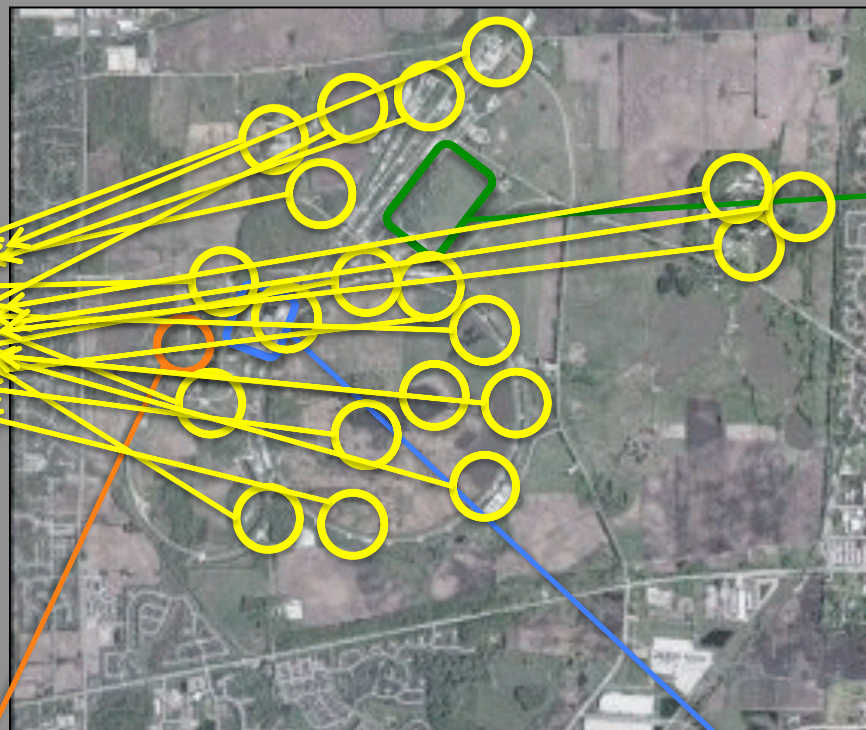
Particle beam

MiniBooNE

Mini Booster Neutrino Experiment

Malevolent geese





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MiniBooNE detector hall

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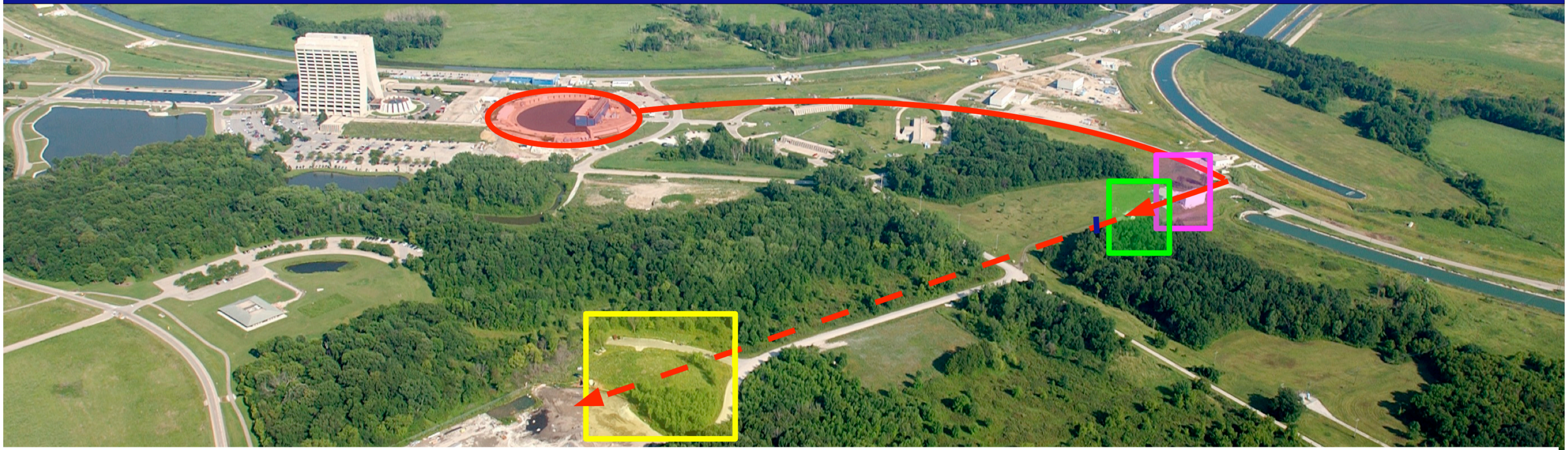
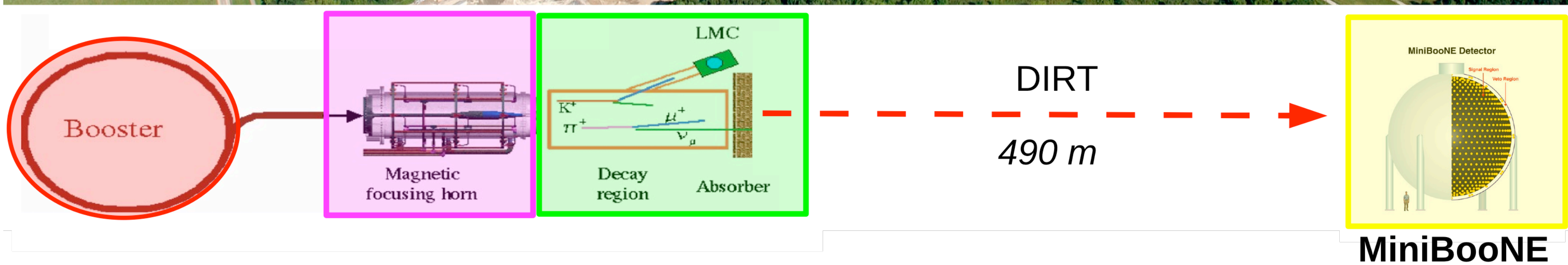
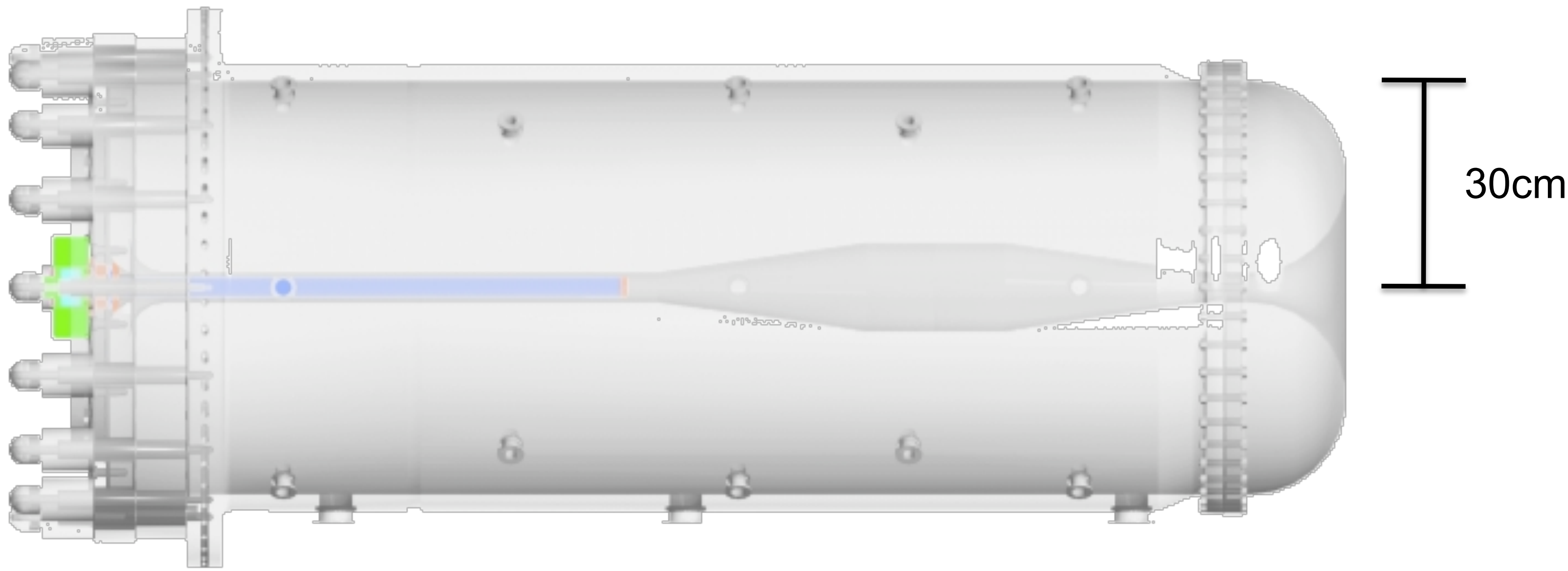
Particle beam

Beam Path

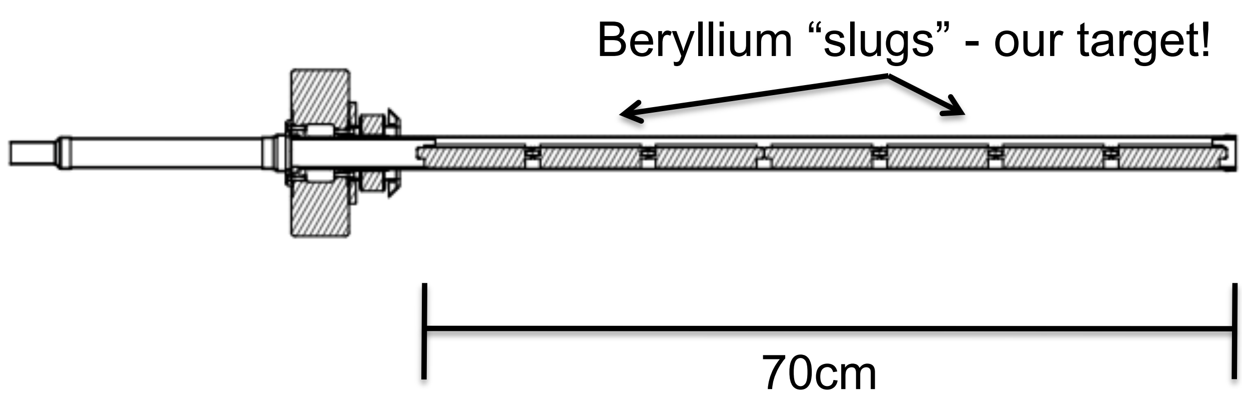


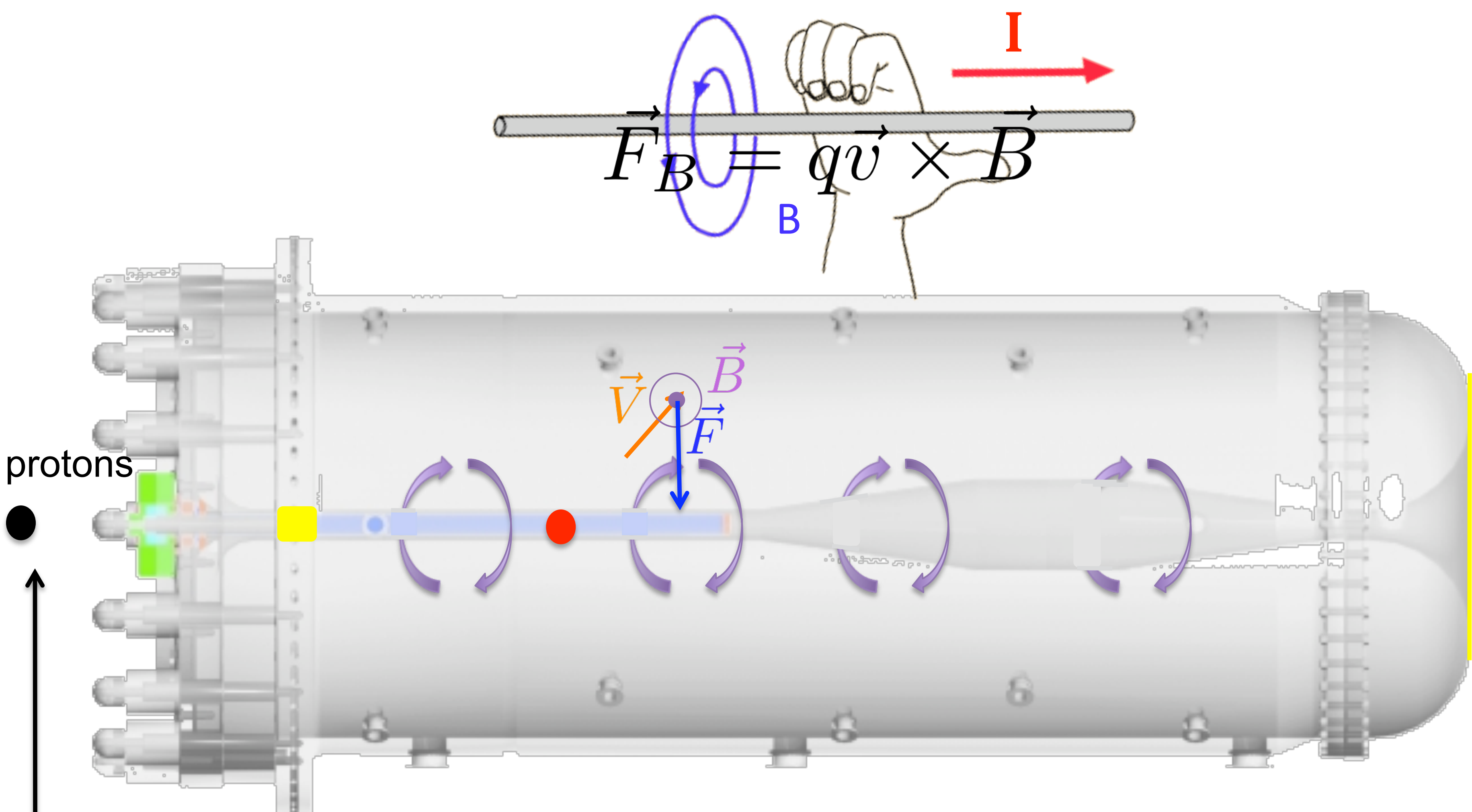


- Booster Proton accelerator: 8 GeV protons sent to target
- Target Hall: Beryllium target. 174kA magnetic horn with reversible horn polarity
- 50m decay volume: Mesons (mostly π, some K) decay to μ and ν_μ.
- 540m baseline



it only takes ~1/10 A to stop a heart… we run 174 **k**A through the horn, around 10^6 times more!





5×10^{12} protons, 5 times a second!

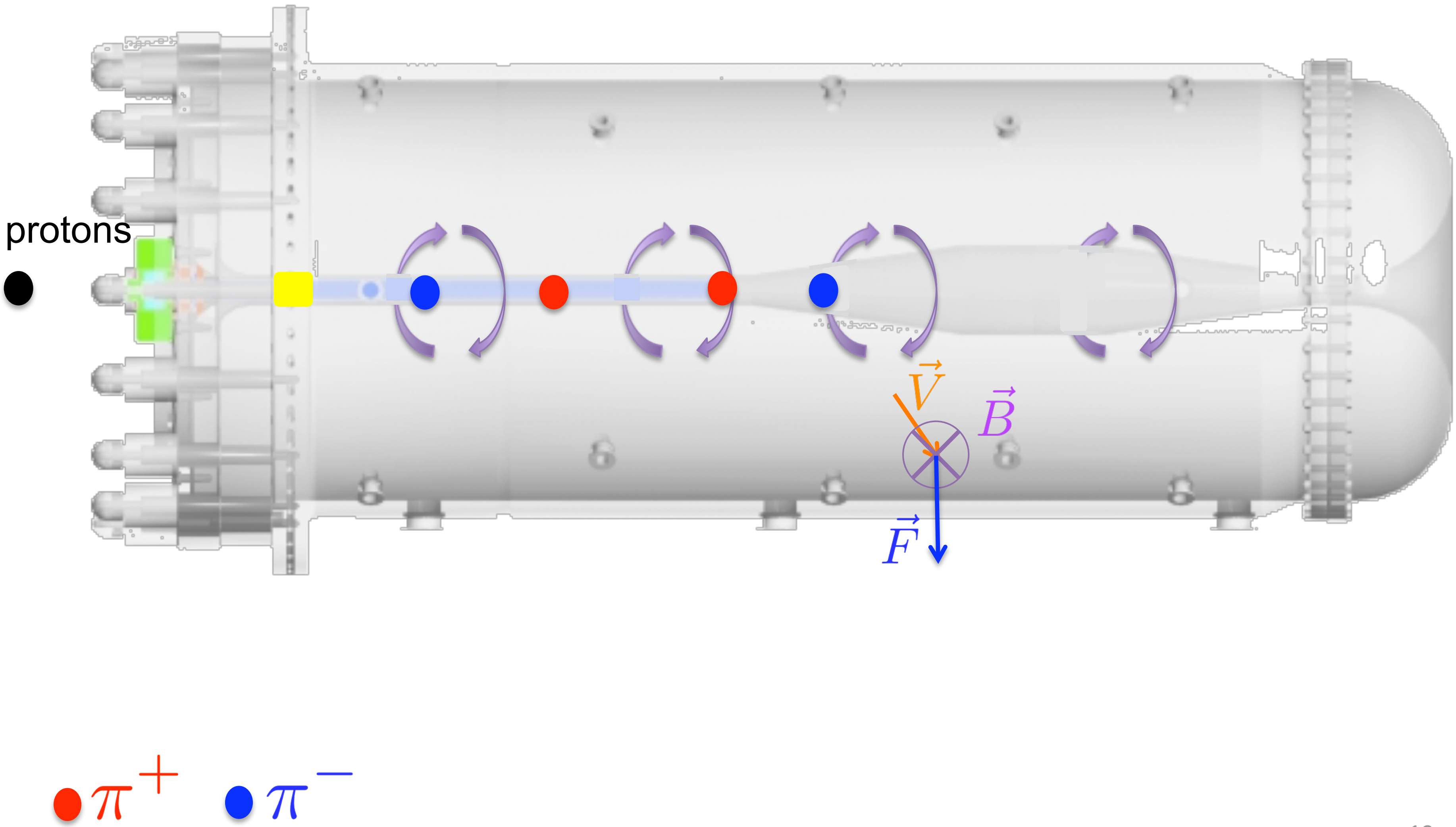
(Ampere's Law)

For current flowing along a long, straight wire,

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 I_{enc}; \vec{B} \sim \frac{1}{r}\hat{\phi}$$

● π^+ ● π^-

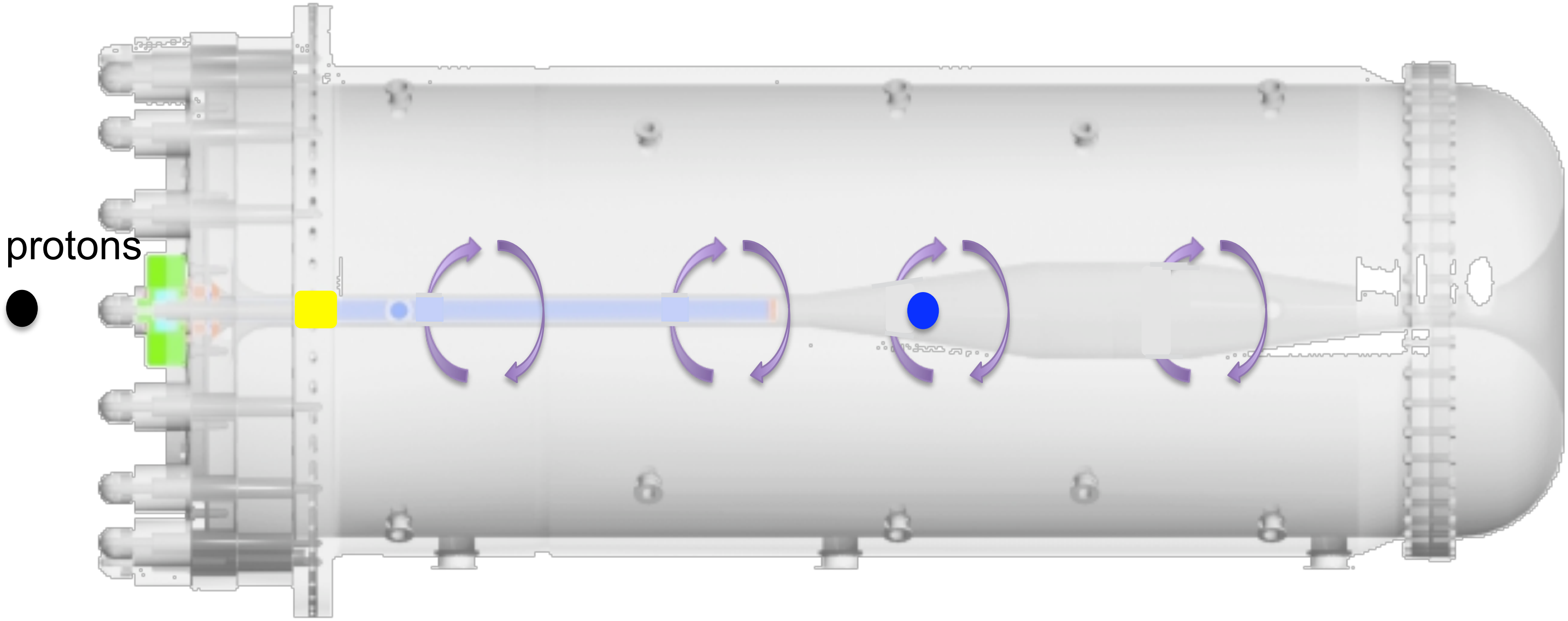
$$\vec{F}_B = q\vec{v} \times \vec{B}$$



However, focusing is **NOT** perfect.

Not all π^- get defocused, mostly due to low angle production and higher energies

- opposite charged particles will not get swept away if they don't "notice" the magnetic field



This leads to beam, hence data, contamination

- Contamination varies based on energy of incoming protons,

current, horn/target geometry, and horn polarity

π^+ π^-

Do We Just Produce Pions?

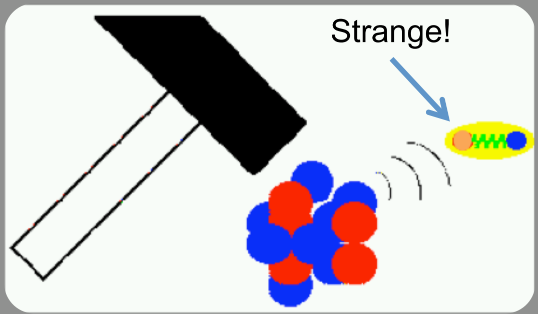
- Of course we also produce a slew of protons and neutrons, but neither contribute to our neutrino flux

- We *do* produce Kaons, and they have leptonic decays which lead to neutrinos
  - Particularly of interest to oscillation experiments, they sometimes decay to electron neutrinos, the very particles whose appearance we search for!

- However, Kaon production is *Cabibbo suppressed:*

<u>Quark content</u>

  - Initial state: protons + Beryllium, tons of up + down quarks *only*
  - Final state: Kaons have strange quarks, not present initially



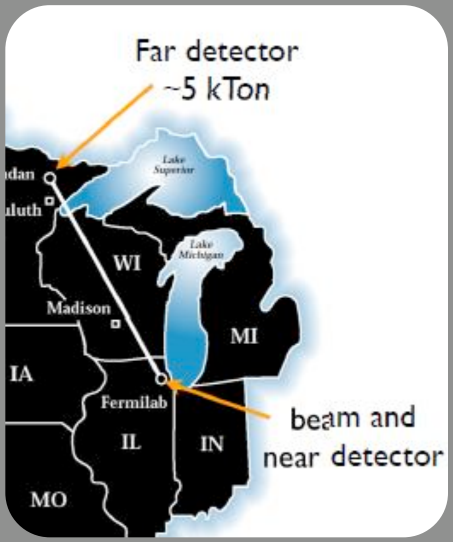
➢ Kaons contribute a few percent to our neutrino beam

Okay, so $p + Be \rightarrow \pi, K; \pi, K \rightarrow \nu_\mu, \bar{\nu}_\mu$

- But how *many* neutrinos, and at what energies?
  (At MiniBooNE, how do we know our flux?)

- Briefly: many other accelerator-based neutrino experiments use a near detector to constrain fluxes (two detectors total)

MINOS



T2K

NOvA

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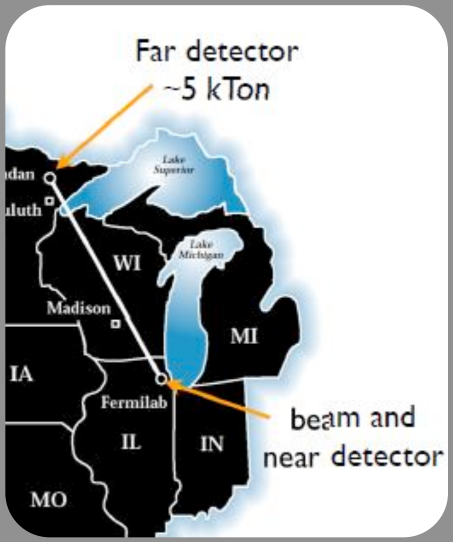

• For much more on MINOS please see NeutU talk July 22

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NOvA

• For much more on NOvA please see NeutU talk August 5 by N Mayer

Flux at MiniBooNE

- At MiniBooNE, our flux determination is a bit more simple:

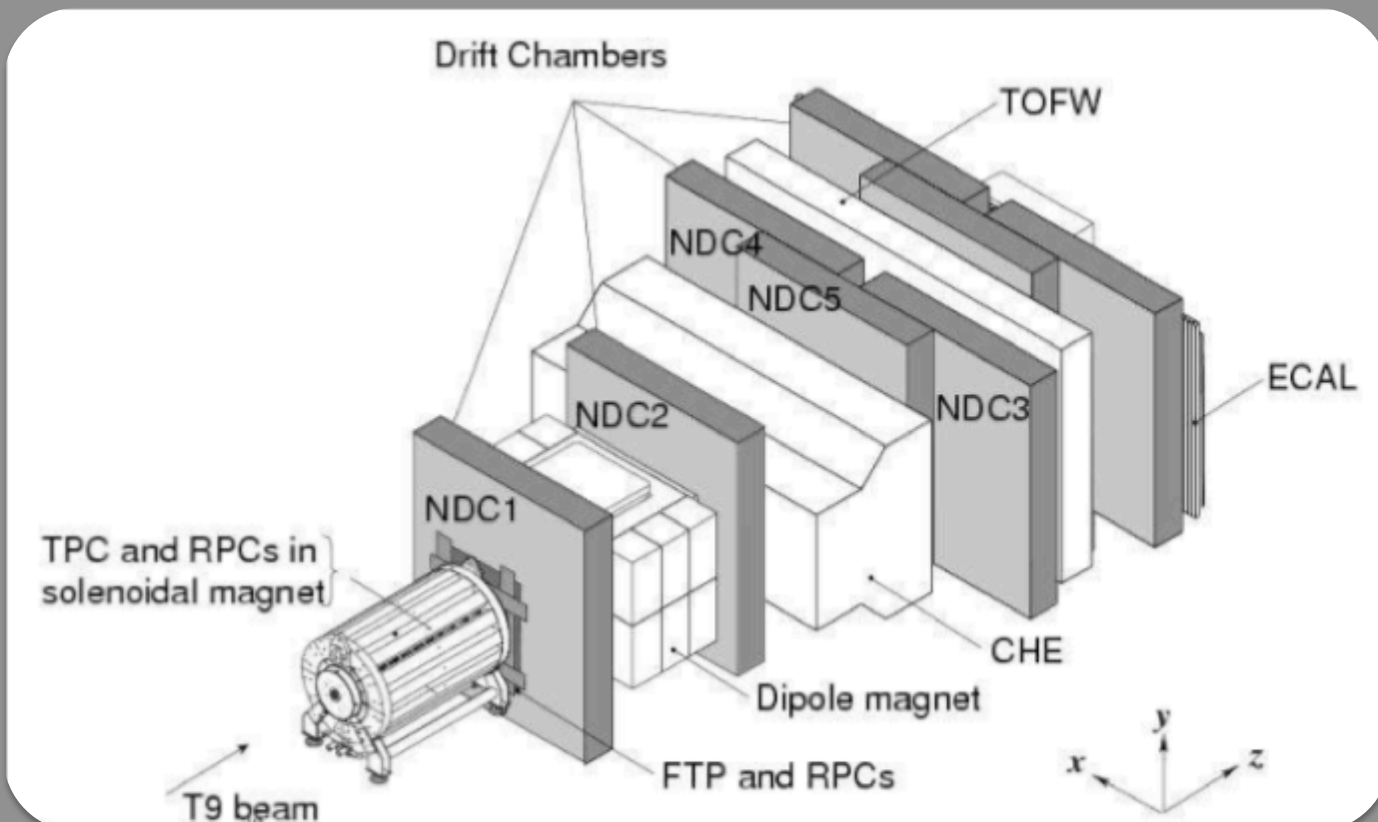
➢ If we know the spectrum of mesons produced from our proton - Beryllium collisions (how many, at what energies, angles), we can predict the flux of the daughter neutrinos!

$$\pi^{+(-)} \rightarrow \mu^{+(-)} + \nu_\mu(\bar{\nu}_\mu)$$

- Enter HARP!
  – (Hadron Production Experiment at CERN)

HARP

- HARP: 8 GeV KE protons from CERN synchrotron incident on Beryllium target, same basic design as MiniBooNE (no horn though). Measures p + Be -> hadrons cross sections.



Flux Prediction

"neutrino mode"

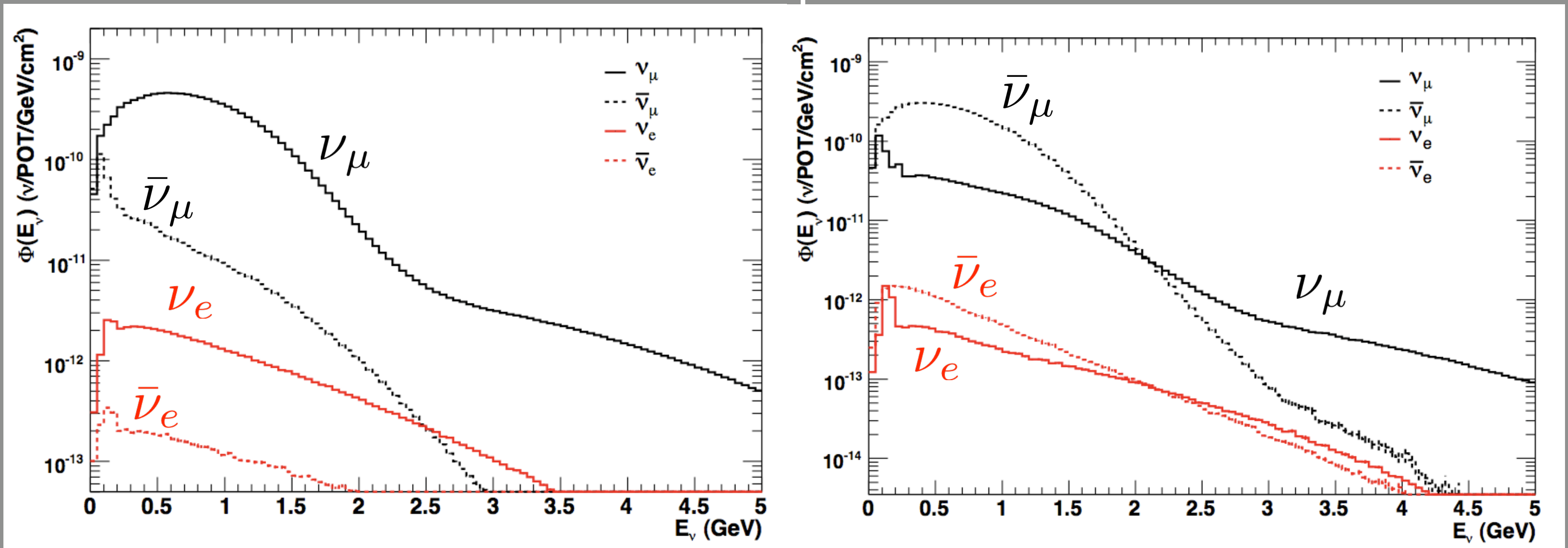
- Focus positively charged mesons
- Main neutrino source is from

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

"antineutrino mode"

- Focus negatively charged mesons
- Main (anti)neutrino source is from

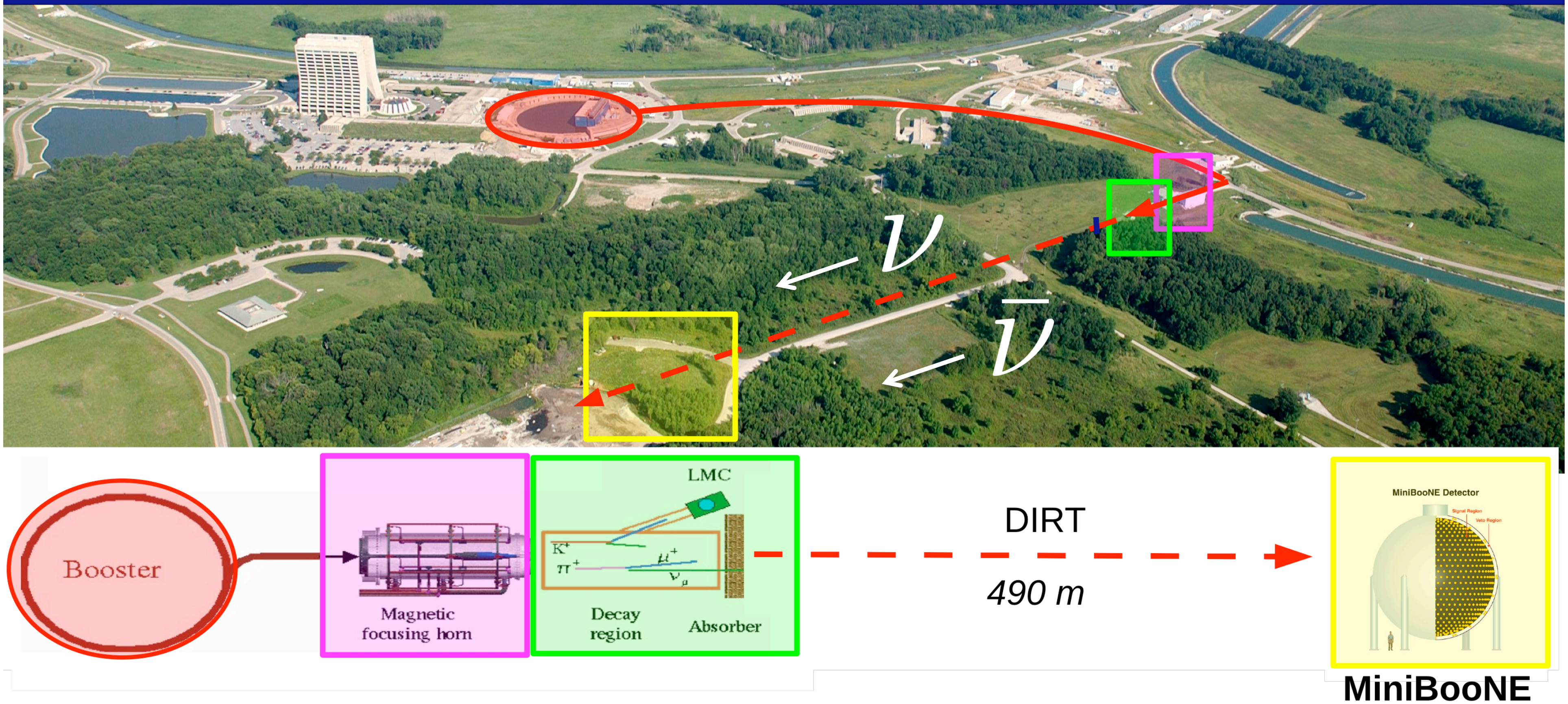
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



Primary difference in fluxes due to

$$p + \mathrm{Be} \rightarrow \pi^+ + X \sim \mathbf{2}\,(p + \mathrm{Be} \rightarrow \pi^- + X)$$

Beam Path



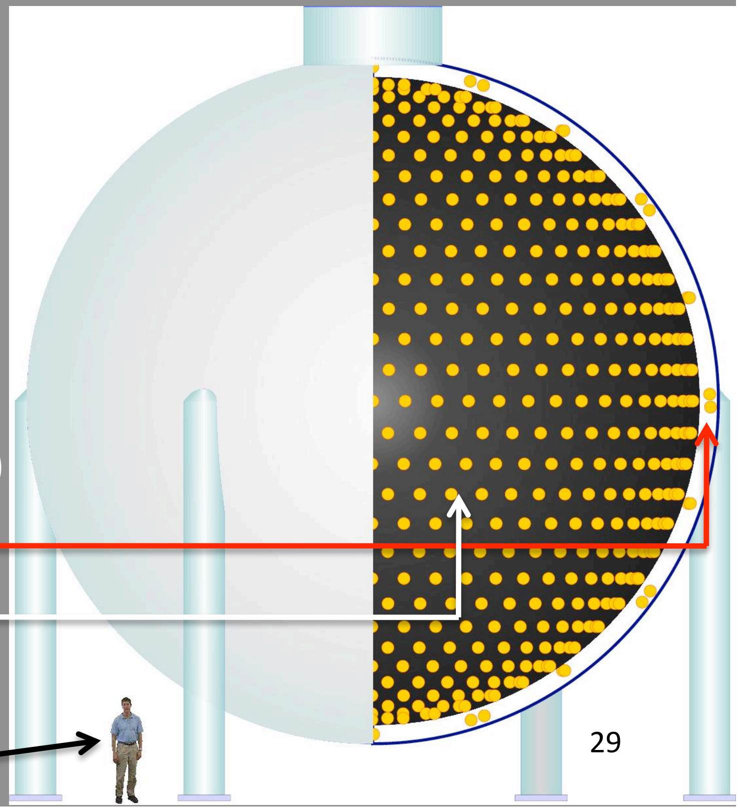
So now that we have our neutrinos, how do we detect them?

MiniBooNE Detector

- 6.1m radius sphere houses **800 tons** of pure mineral oil.

- Oil serves as both the nuclear target (CH_2) and medium for particle tracking, ID (PID via scintillation and Cerenkov light, next slides)

- **1520** Photo Multiplier Tubes (PMTs) uniformly dispersed in 2 regions of tank:
  - 240 in veto region
  - 1280 in signal volume (~10% coverage)



Particle Tracking, Identification
Cerenkov and Scintillation Light

- In media, light travels *slower* than in vacuum:
  - In vacuum: $v_{light} = c$
  - In material: $v_{light} = c/n$
    - where n = index of refraction, $n \geq 1$

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Cerenkov and Scintillation Light

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- Particles still subject to the *absolute* "speed limit" ($v_{particle} < c$)

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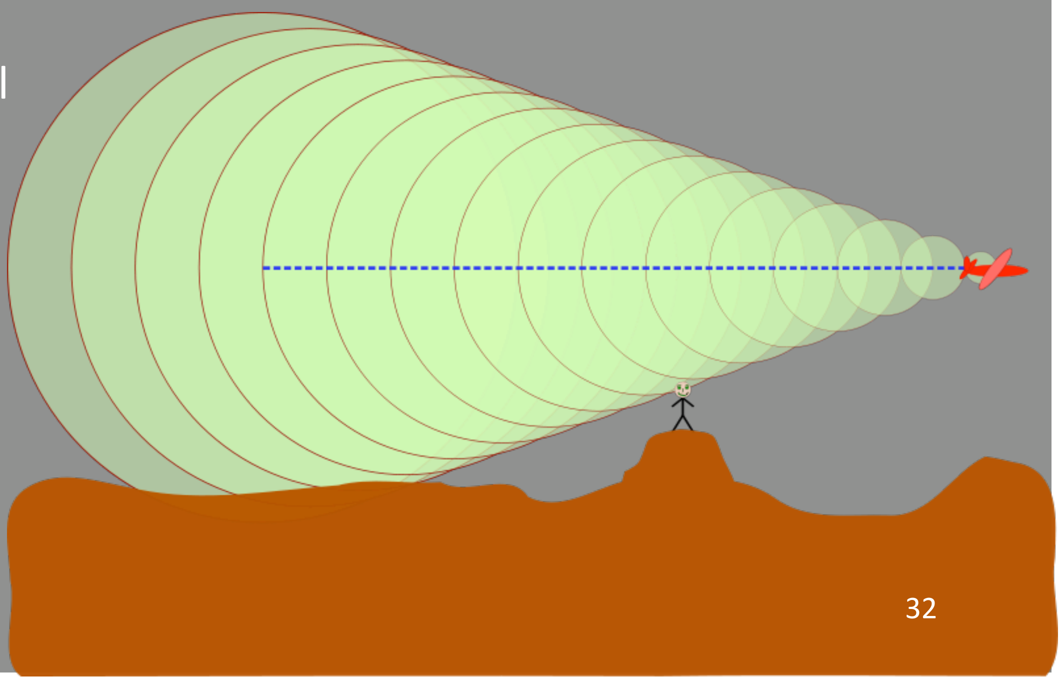
- Particles still subject to the *absolute* "speed limit" ($v_{particle} < c$)

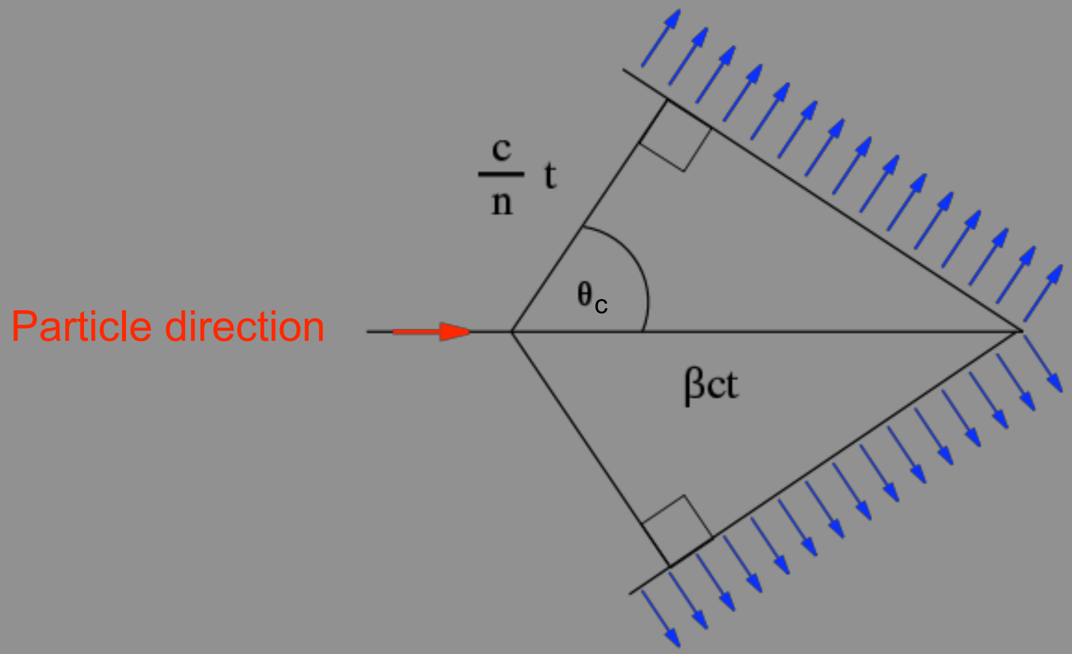
- So in a medium, particles can travel faster than the speed of light (in the medium)!
  - Similar to sonic boom phenomenon, where an aircraft travels faster than the speed of sound



Particle Tracking, Identification

Cerenkov and Scintillation Light

Some Details…



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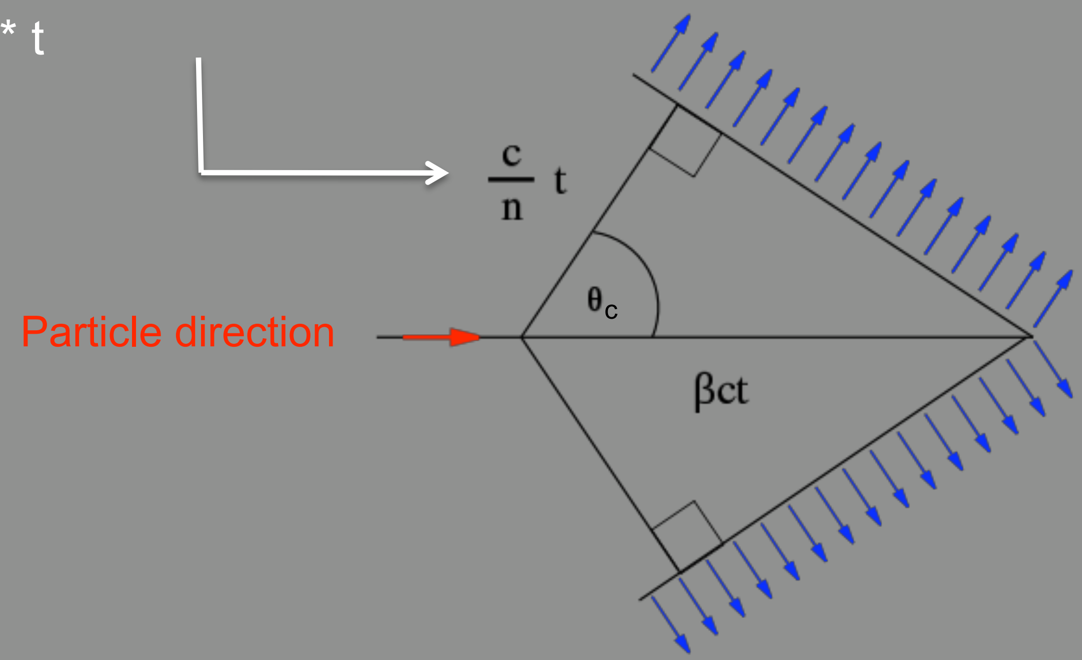
Light in a medium: $v_{light} = c/n$; distance traveled in time t is (c/n) * t



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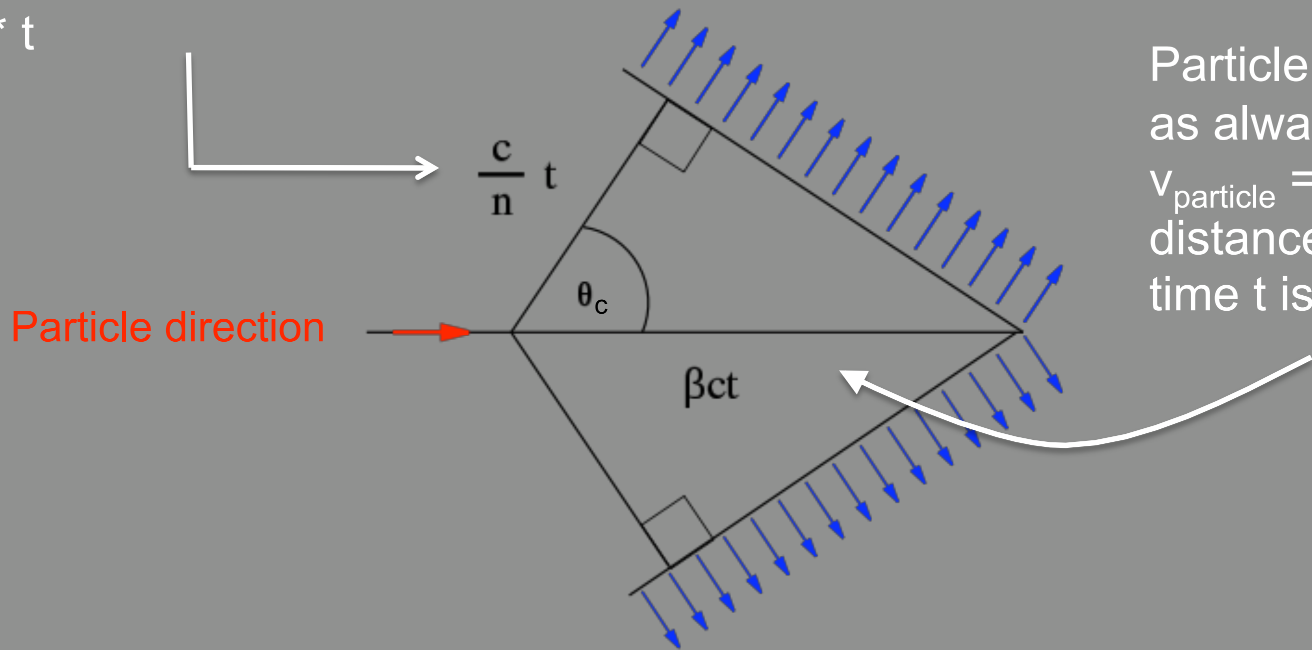

Particle speed:
as always, travels at $v_{particle} = \beta c$;
distance traveled in time t is βct

Particle Tracking, Identification

Cerenkov and Scintillation Light

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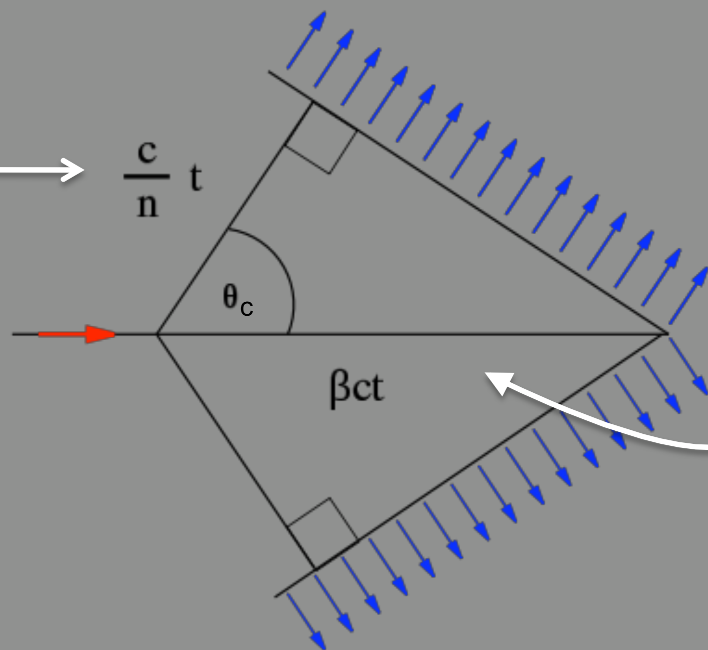
Particle direction

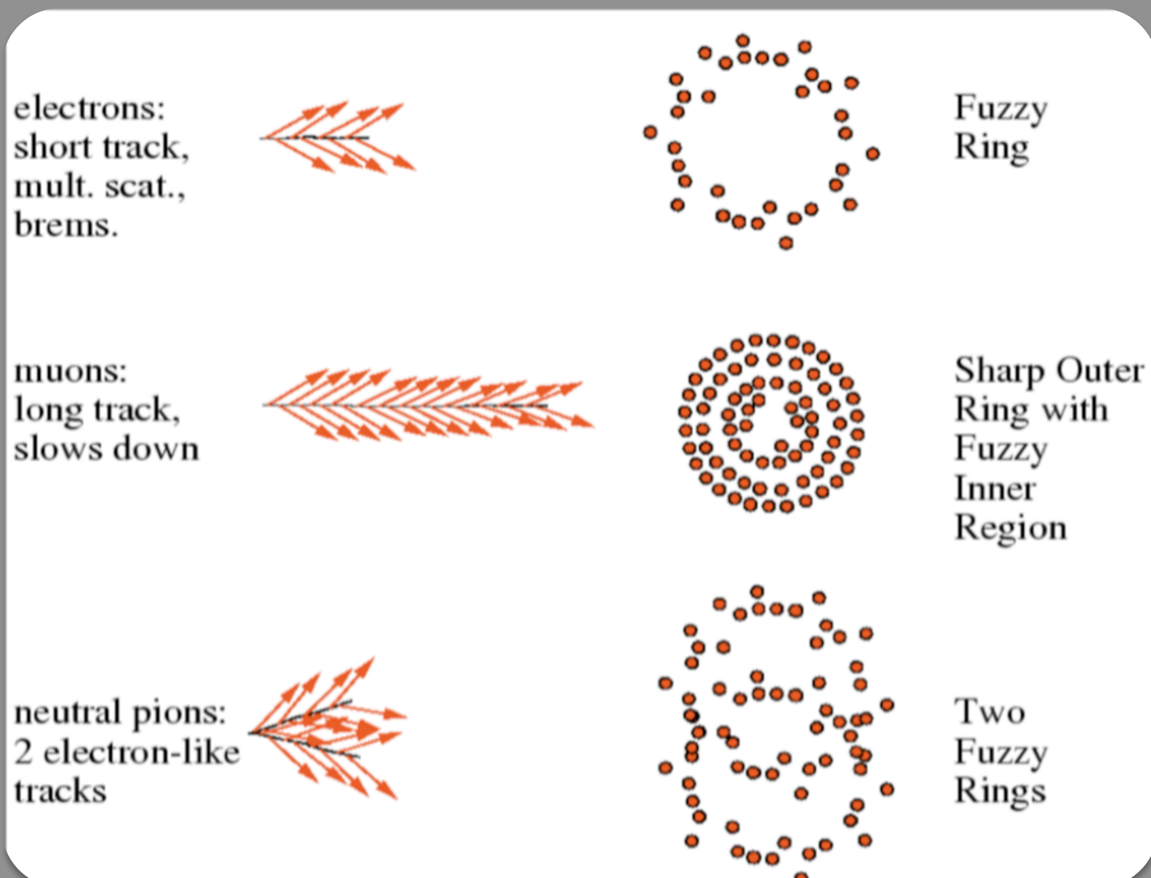


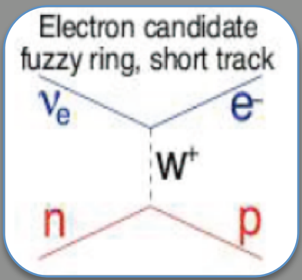
Simple trig: $\cos\theta_C = \frac{ct/n}{\beta ct} = \frac{1}{\beta n}$; $n_{BooNE\ oil} \sim 3/2$

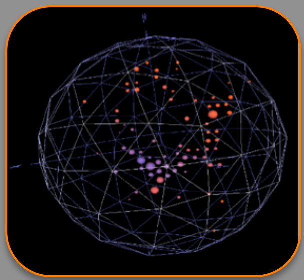
Requiring $\cos\theta_C < 1$ gives $\beta_{cerenkov} > 2/3$

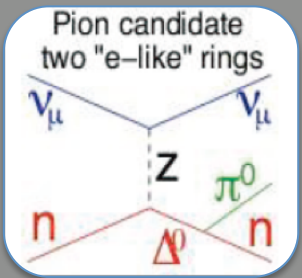
Event Topologies

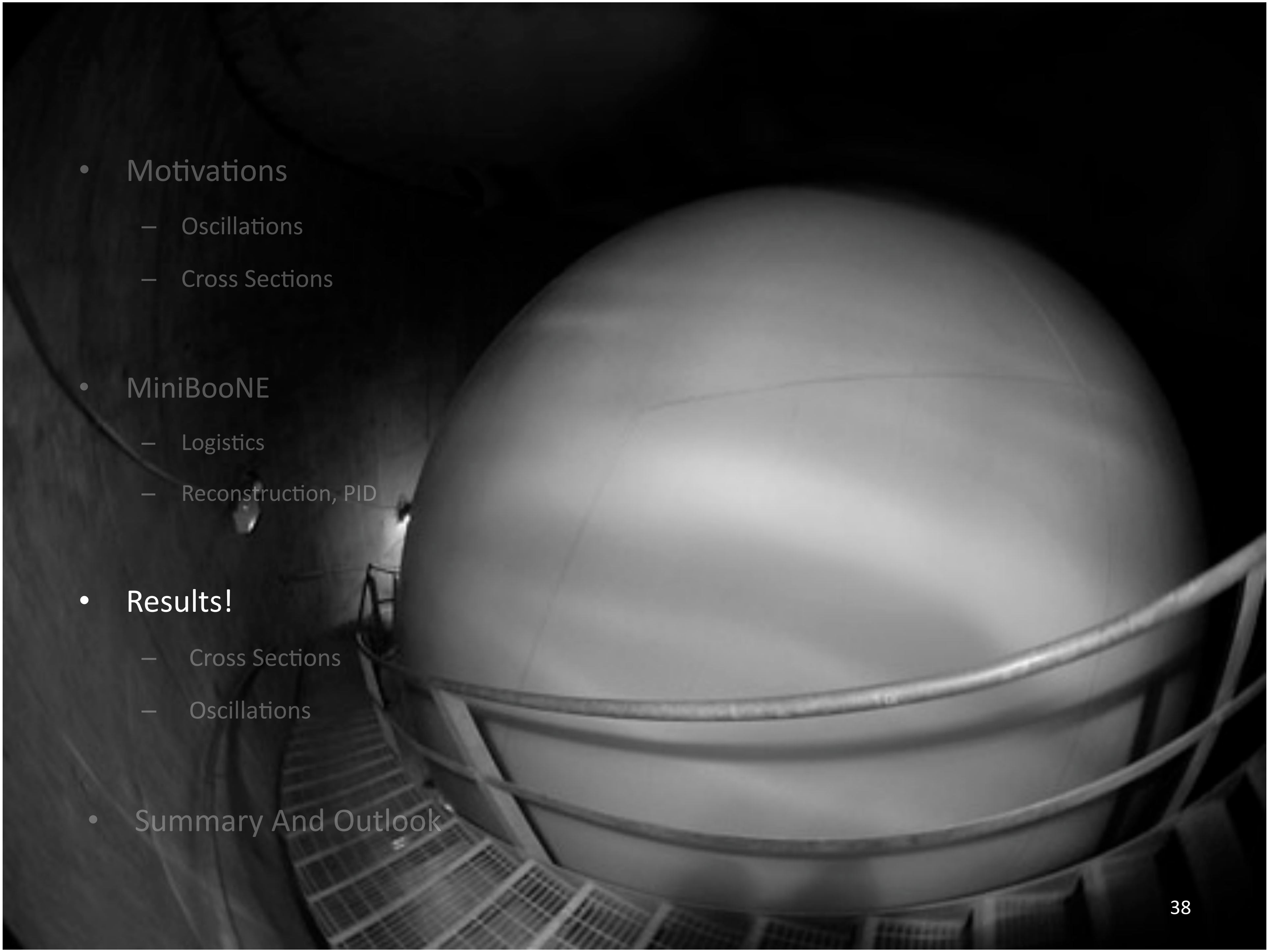
- The pattern the Cherenkov radiation makes on our PMTs differs based on particle type (this is primarily due to different masses)











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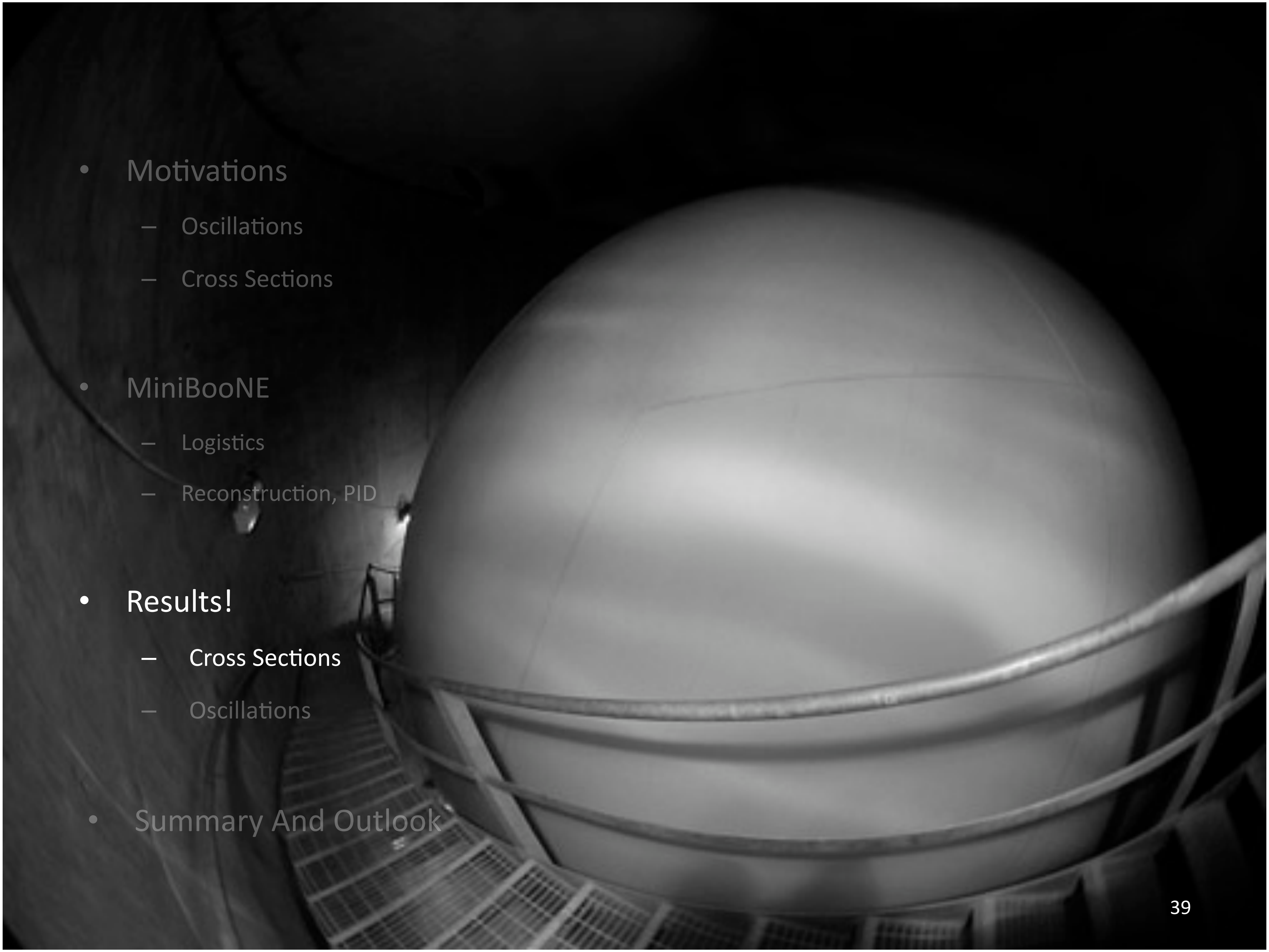


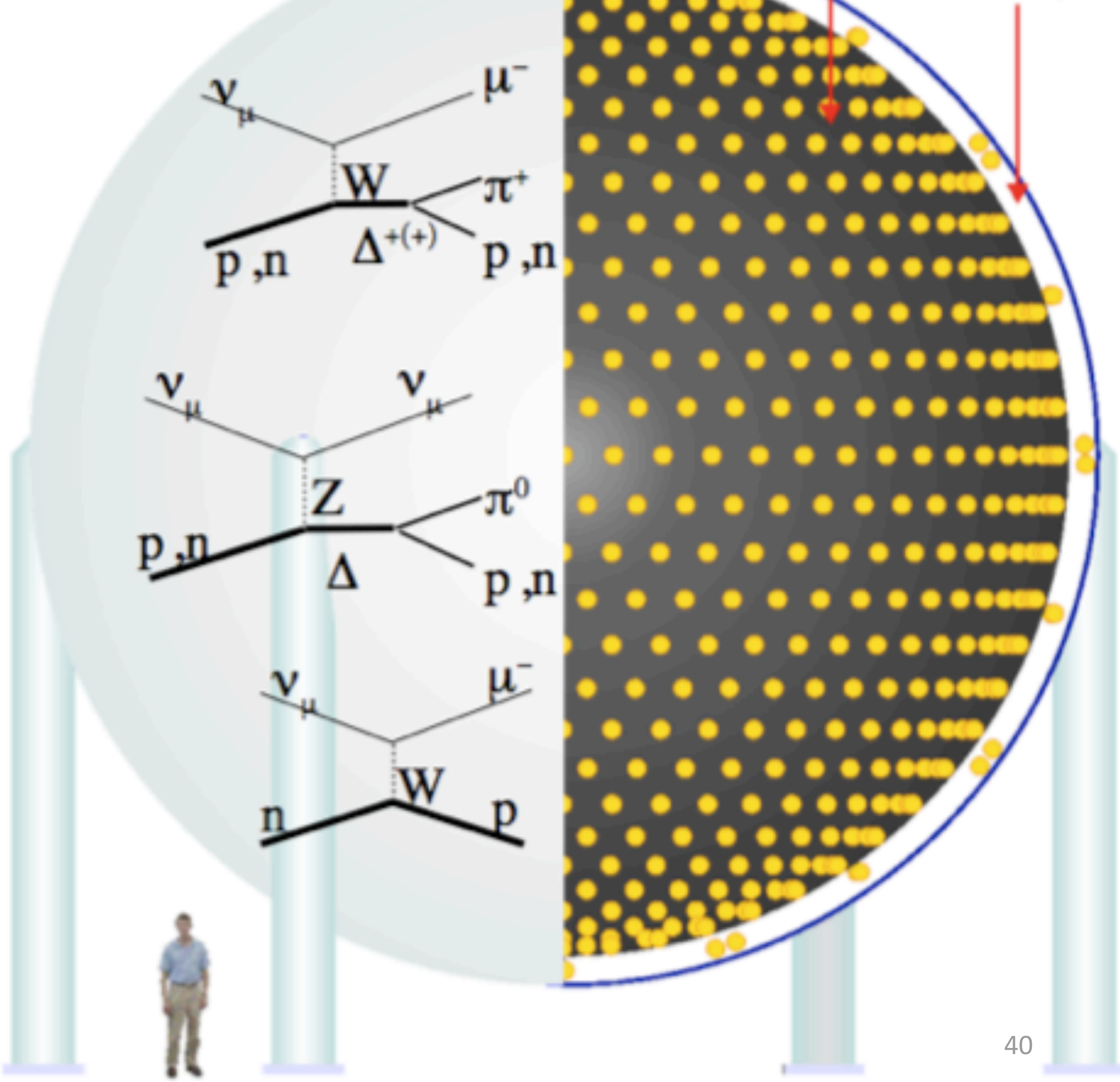
- Motivations
  - Oscillations
  - Cross Sections
- MiniBooNE
  - Logistics
  - Reconstruction, PID
- **Results!**
  - **Cross Sections**
  - Oscillations
- Summary And Outlook

MiniBooNE has *Hundreds of Thousands* of Events!

- Typical earlier neutrino experiments produced 100s - 1000s of events

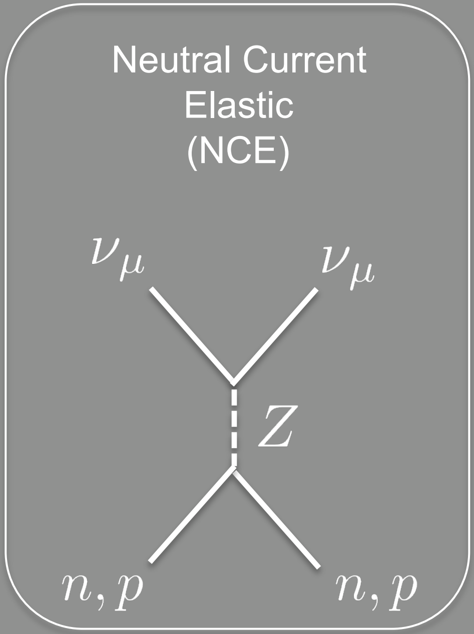
- Some BooNE cross sections have more events than in all previous measurements combined!

- Fantastic for measuring cross sections, probing nuclear structure



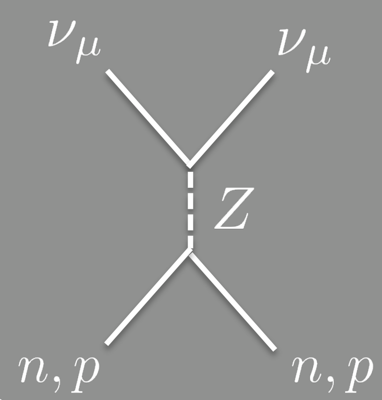
Cross sections produced at MiniBooNE:

Cross sections produced at MiniBoONE:

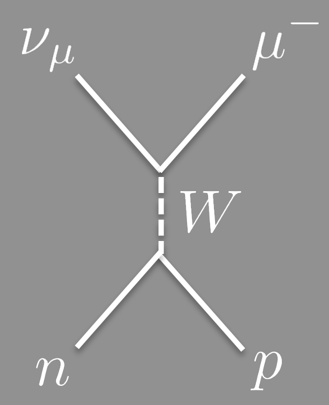


Cross sections produced at MiniBoONE:

Neutral Current Elastic (NCE)

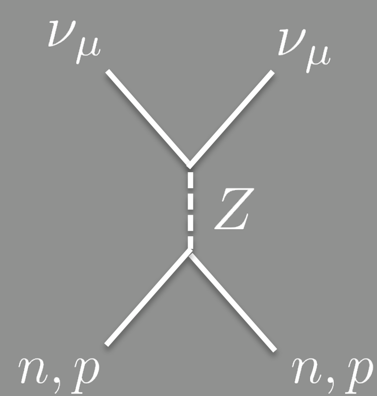


Charged Current Quasi-Elastic (CCQE)

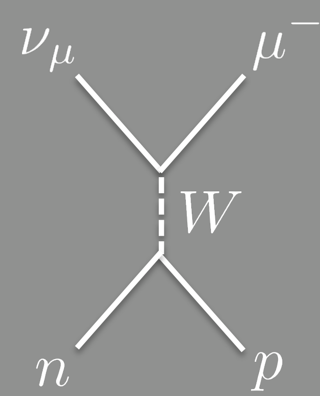


Cross sections produced at MiniBooNE:

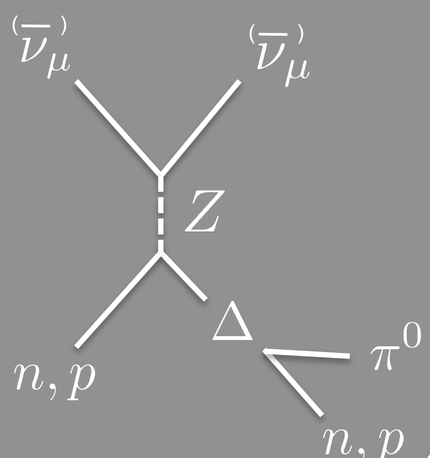
Neutral Current Elastic (NCE)



Charged Current Quasi-Elastic (CCQE)

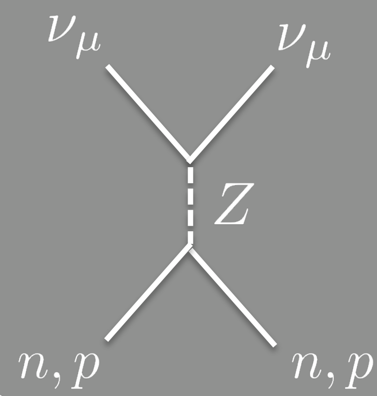


Neutral Current Neutral Pion Production (NCπ^0)

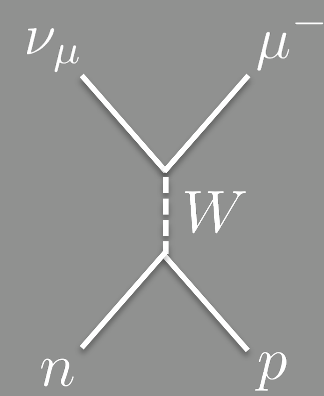


Cross sections produced at MiniBooNE:

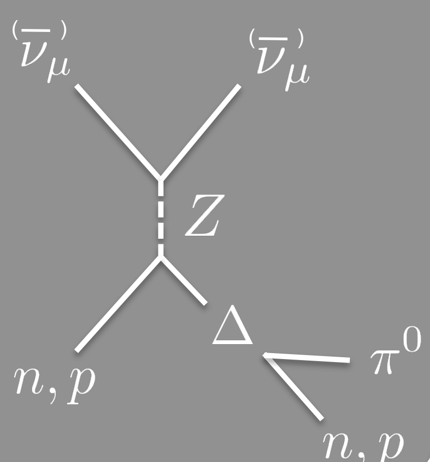
Neutral Current Elastic (NCE)



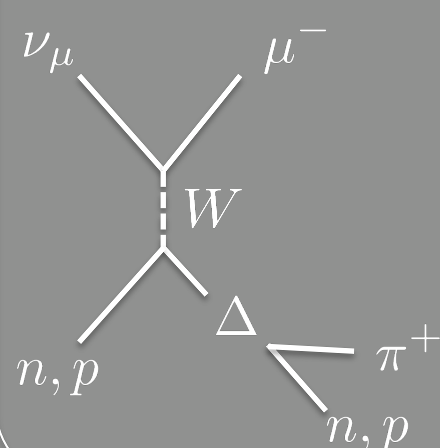
Charged Current Quasi-Elastic (CCQE)



Neutral Current Neutral Pion Production ($NC\pi^0$)

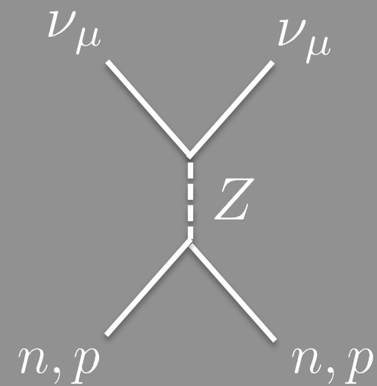


Charged Current Charged Pion Production ($CC\pi^+$)

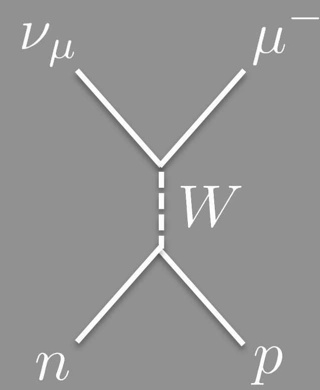


Cross sections produced at MiniBooNE:

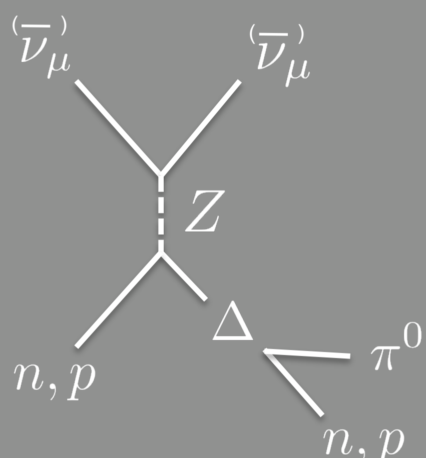
Neutral Current
Elastic
(NCE)



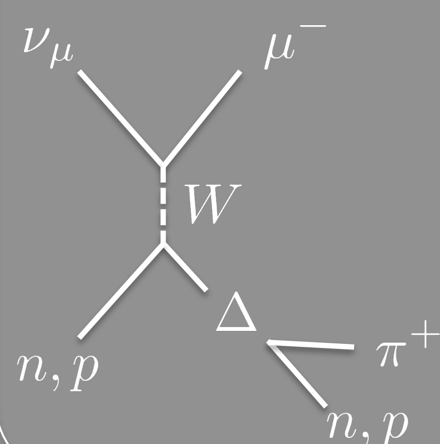
Charged Current
Quasi-Elastic
(CCQE)



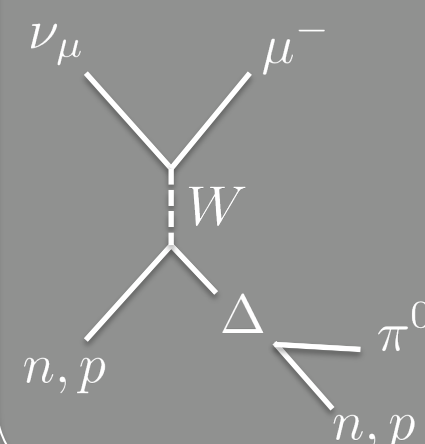
Neutral Current
Neutral Pion
Production
(NCπ^0)



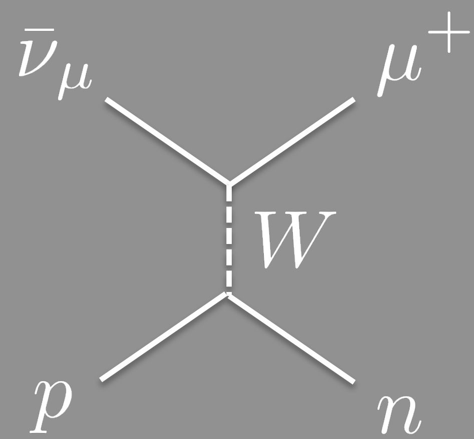
Charged Current
Charged Pion
Production
(CCπ^+)



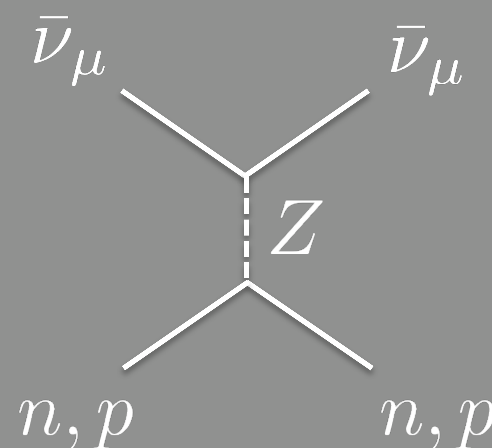
Charged Current
Neutral Pion
Production
(CCπ^0)



A few more (antineutrino) cross sections in the pipeline…

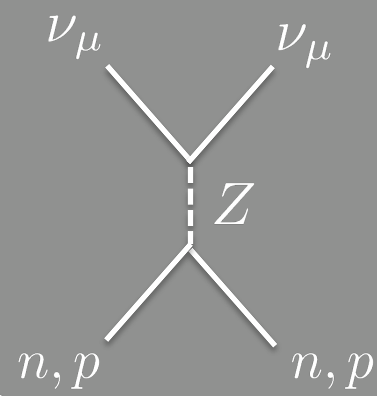


(Antineutrino)
Charged Current
Quasi-Elastic
(CCQE)

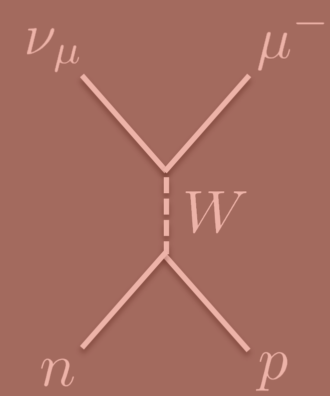


(Antineutrino)
Neutral Current
Elastic
(NCE)

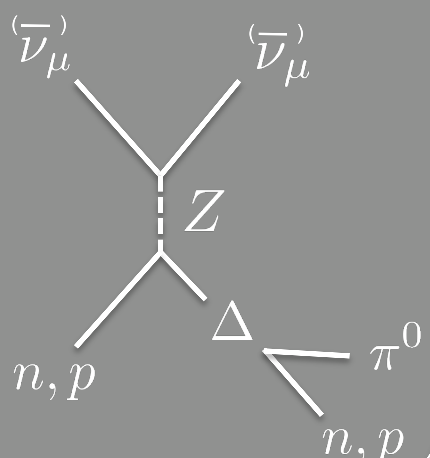
Neutral Current
Elastic
(NCE)



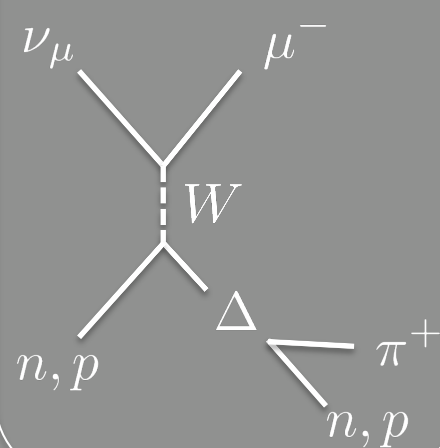
Charged Current
Quasi-Elastic
(CCQE)



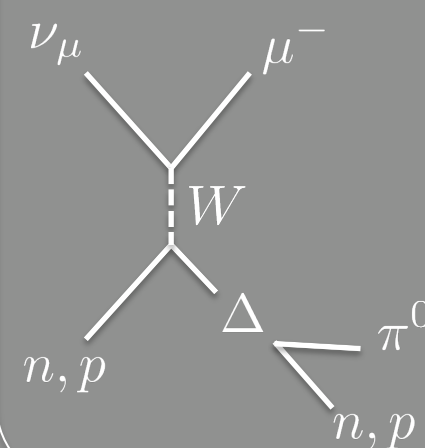
Neutral Current
Neutral Pion
Production
($NC\pi^0$)



Charged Current
Charged Pion
Production
($CC\pi^+$)

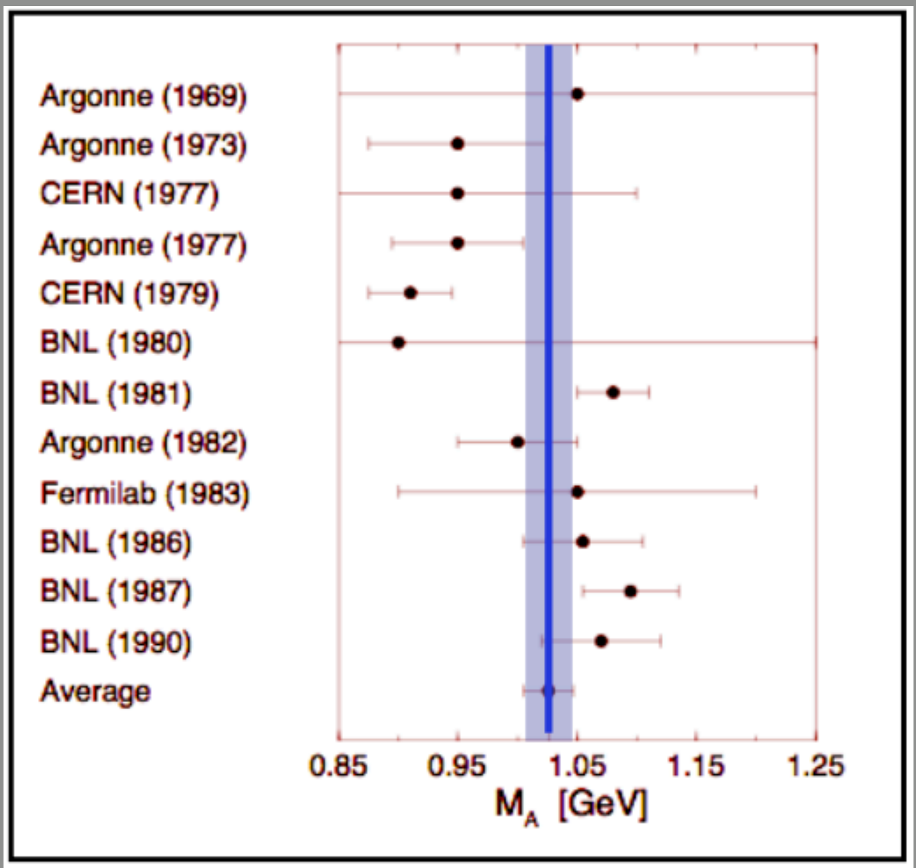


Charged Current
Neutral Pion
Production
($CC\pi^0$)



CCQE Cross Section

Measure CCQE Cross Section ⟷ Measure Axial Mass M_A



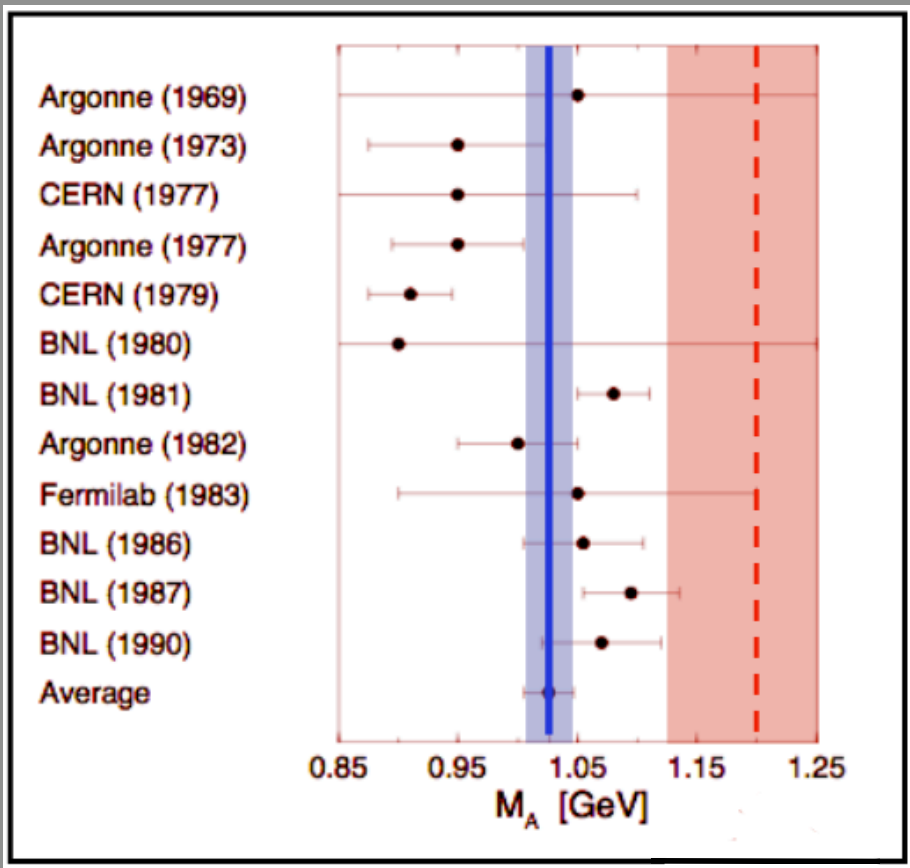
Picture through 1990

- Measurements made on mostly H_2 and D_2 (simple nuclear structure)
- 100s of events
- Mostly consistent measurements give $M_A = 1.03 \pm 0.02$ GeV

But not for long…

CCQE Cross Section

Measure CCQE Cross Section ⟷ Measure Axial Mass M_A



Since…

Significantly higher M_A with larger nuclear target experiments

Source	Measured M_A (GeV)
K2K SciFi	1.20 ± 0.12
K2K SciBar	1.14 ± 0.11
MINOS	1.26 ± 0.17
NOMAD	1.07 ± 0.07
MiniBooNE	1.35 ± 0.17

including MiniBooNE

Overheard at NuInt '09 (Sitges, Spain) when MiniBooNE measurement presented:

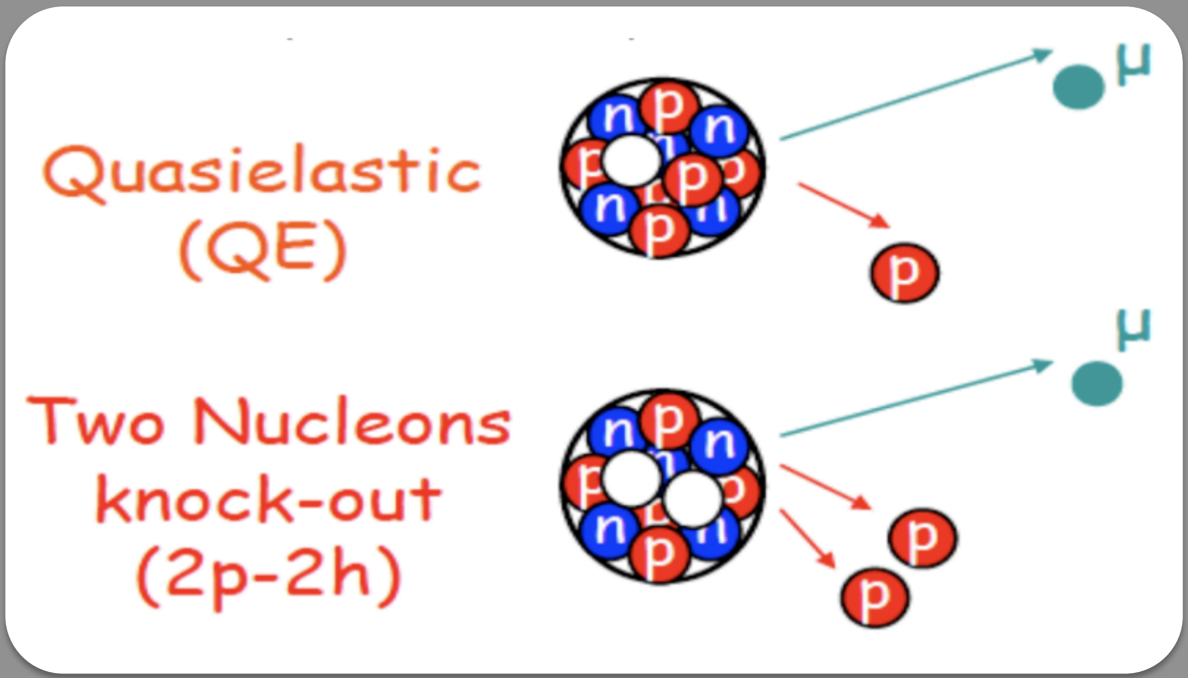
"M_A is *ONE!*"

CCQE Cross Section

Measure CCQE Cross Section $\longleftrightarrow$ Measure Axial Mass M_A

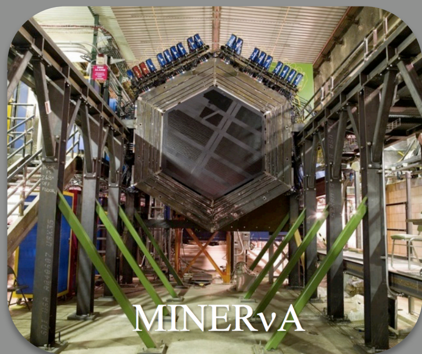
Possible reconciliation…

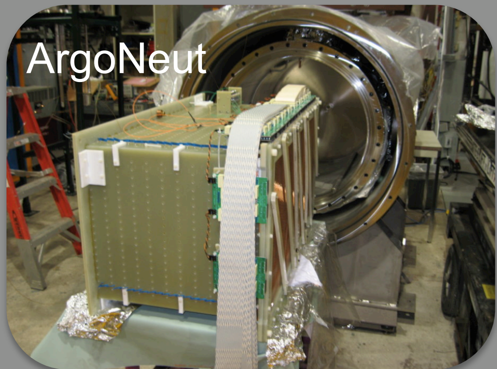
Nuclear effects from MiniBooNE's carbon target may be responsible for enhancing the *effective* M_A by ~30%. This may be due in part to a double nucleon knockout process (we previously considered this process small, unimportant)



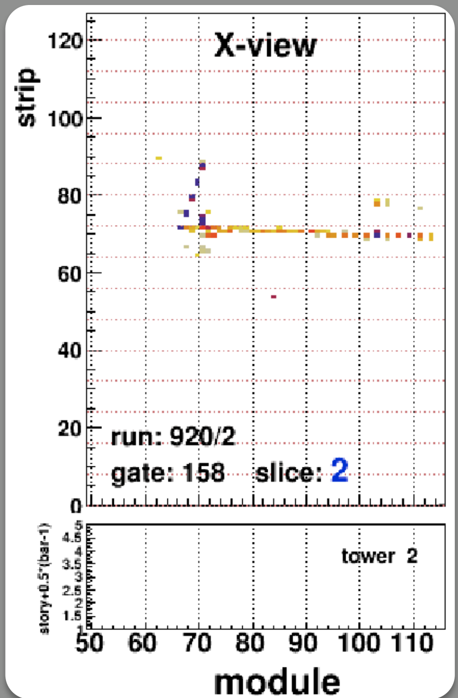
Is This Right?!

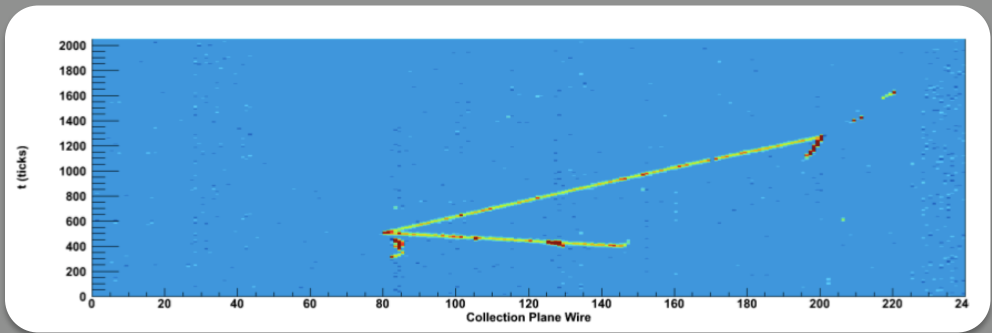
Can test double knockout hypothesis with some next generation neutrino experiments:



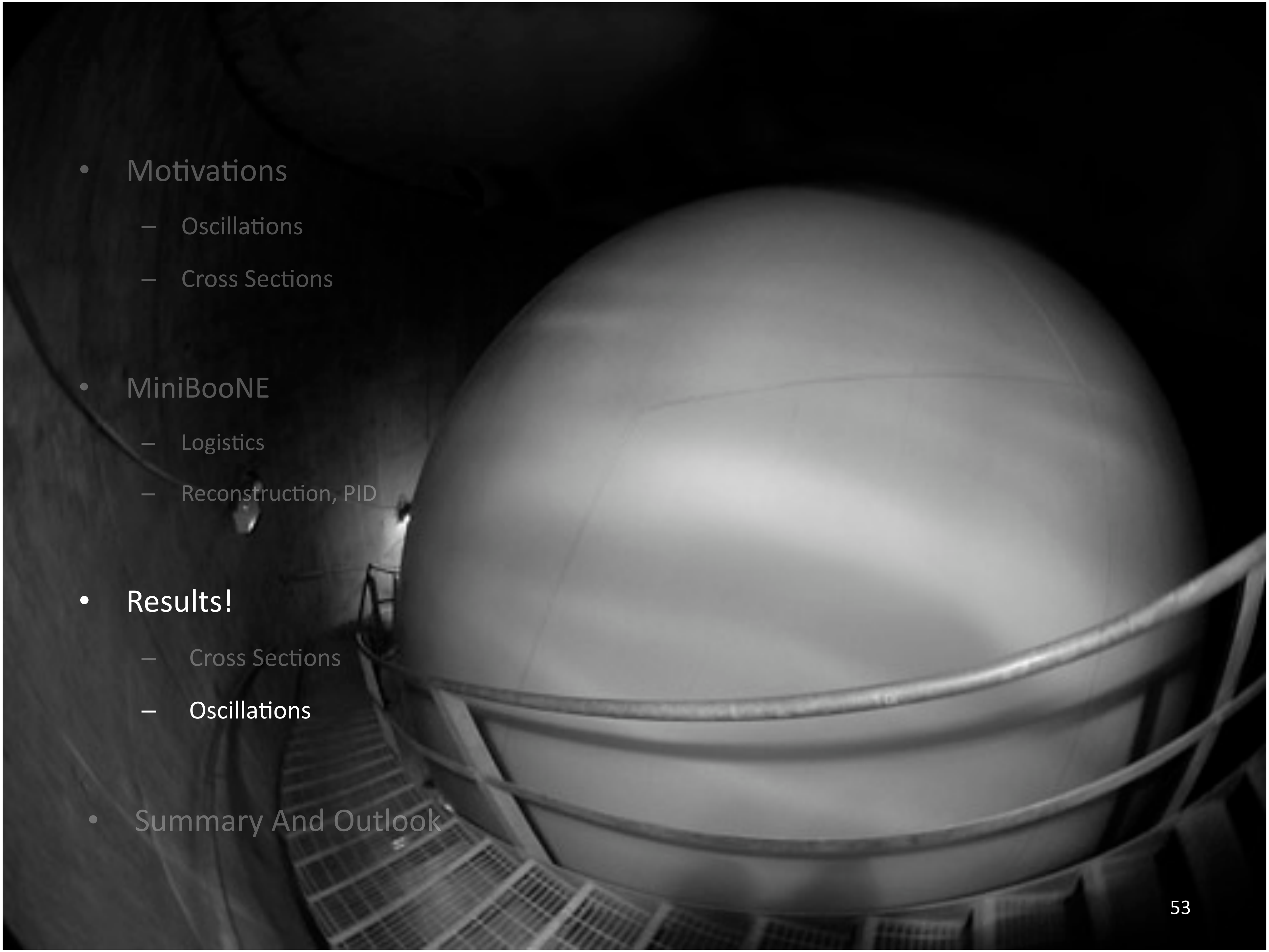


- Great vertex resolution (MiniBooNE insensitive to how many protons ejected)





- For much more!
  - MINERvA NeutU talk on July 29 by B Ziemer
  - ArgoNeut NeutU talk on August 12 by J Spitz


• Motivations
– Oscillations
– Cross Sections
• MiniBooNE
– Logistics
– Reconstruction, PID
• Results!
– Cross Sections
– Oscillations
• Summary And Outlook
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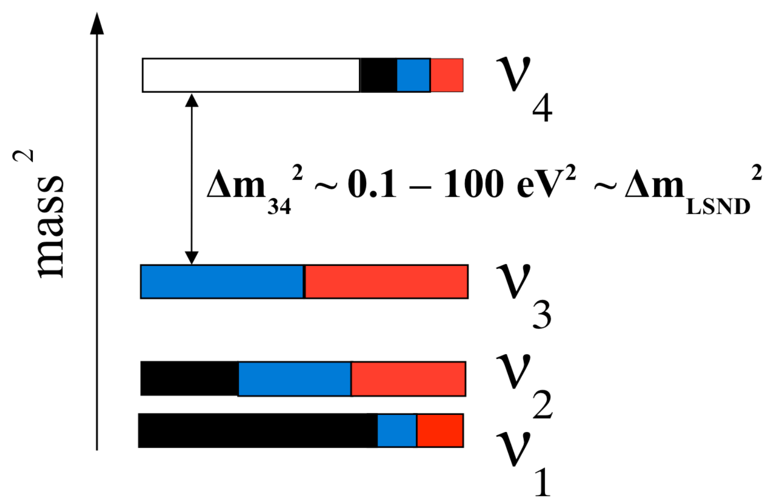
The MiniBooNE Experiment: Motivation

(Simplest) oscillation interpretation requires New Physics:

3 active neutrinos + 1 sterile neutrino: "(3+1)"



So what have we learned?!

Neutrino Mode

(search for $\nu_\mu \to \nu_e$ oscillations)

- To compare to LSND results, must assume CP symmetry

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = P(\nu_\mu \to \nu_e)$$

Neutrino Mode

(search for $\nu_\mu \rightarrow \nu_e$ oscillations)

- To compare to LSND results, must assume CP symmetry

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = P(\nu_\mu \rightarrow \nu_e)$$

LSND signal

MiniBooNE initial search

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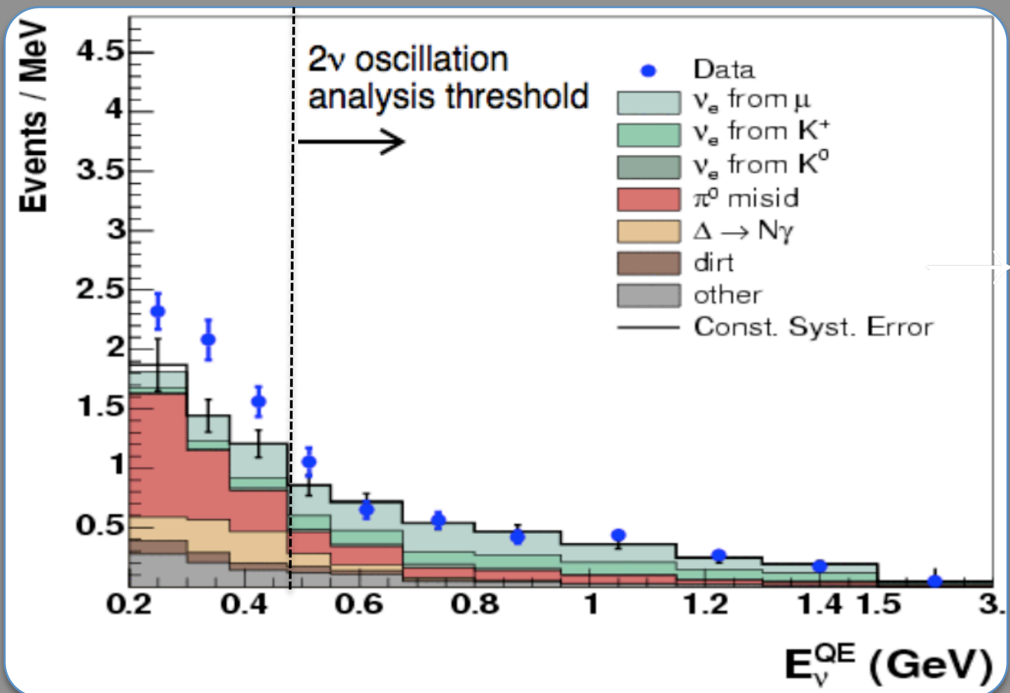
Neutrino Mode

(search for $\nu_\mu \rightarrow \nu_e$ oscillations)

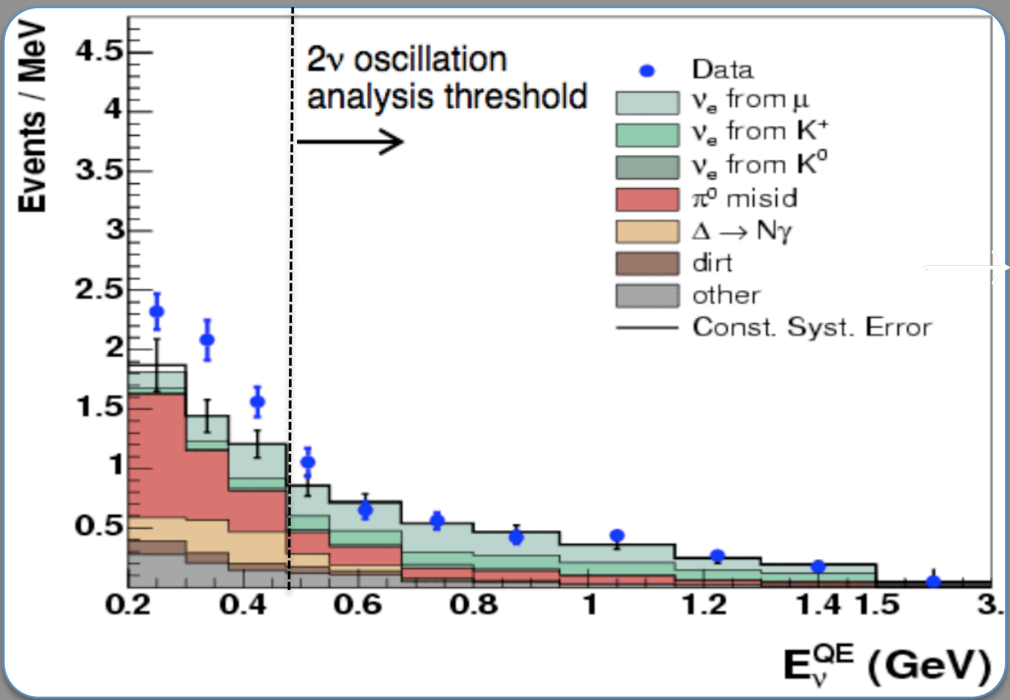
- Results!

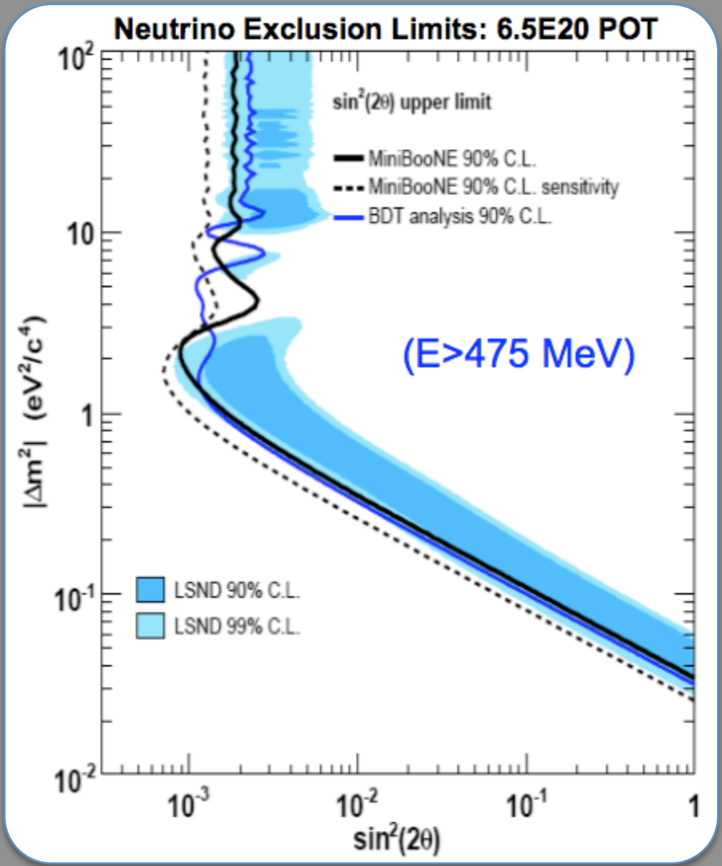


Neutrino Mode

(search for $\nu_\mu \rightarrow \nu_e$ oscillations)

- Results!

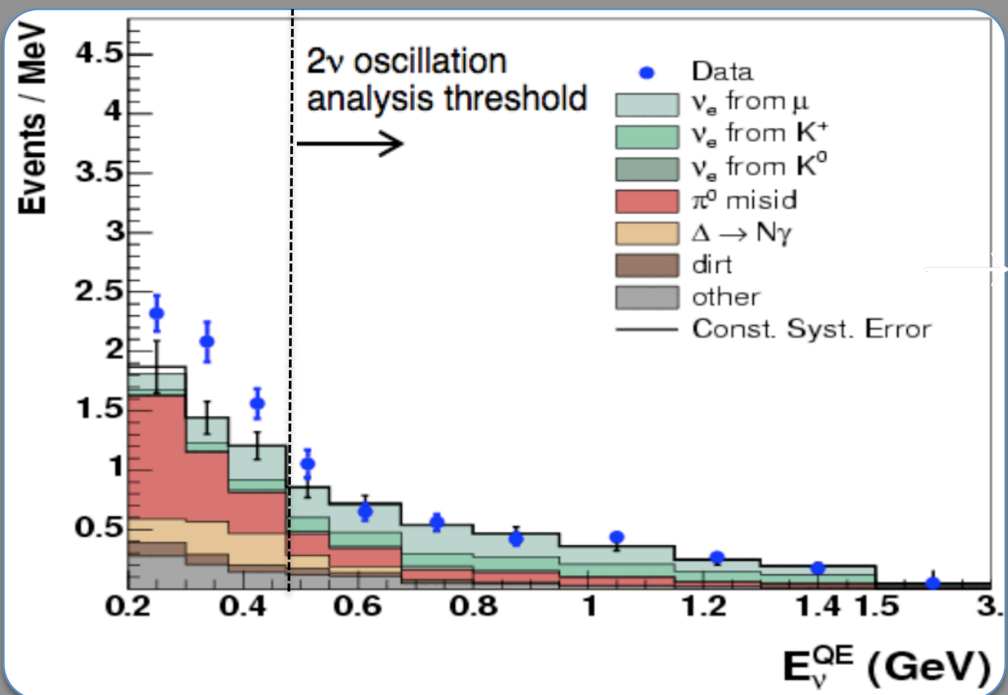


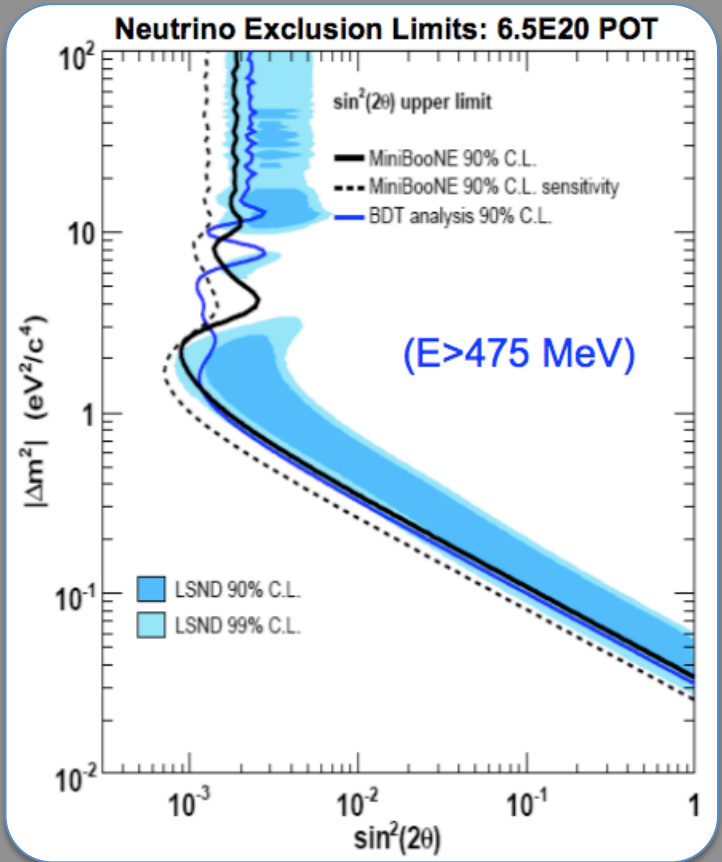


Neutrino Mode

(search for $\nu_\mu \rightarrow \nu_e$ oscillations)

- Results!





- Interpretation of LSND signal as two-neutrino mixing not confirmed!
- Unexplained excess at low energy revealed

Antineutrino Mode

(search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations)

- Directly tests LSND (don't have to assume CP symmetry)
- Ongoing analysis: still collecting data

60

Antineutrino Mode

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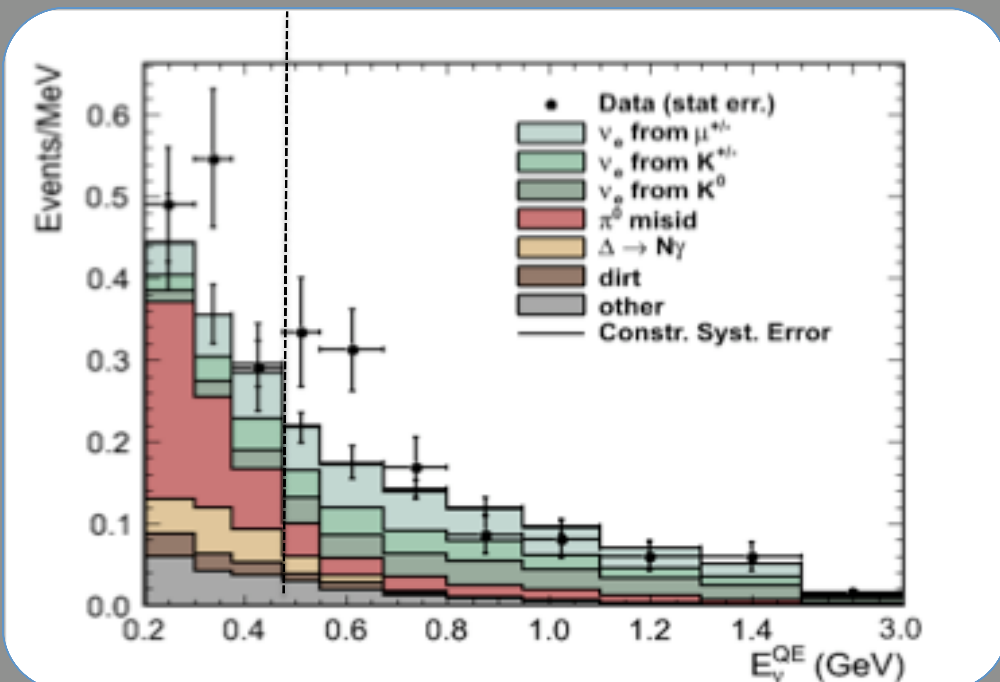

Antineutrino Mode
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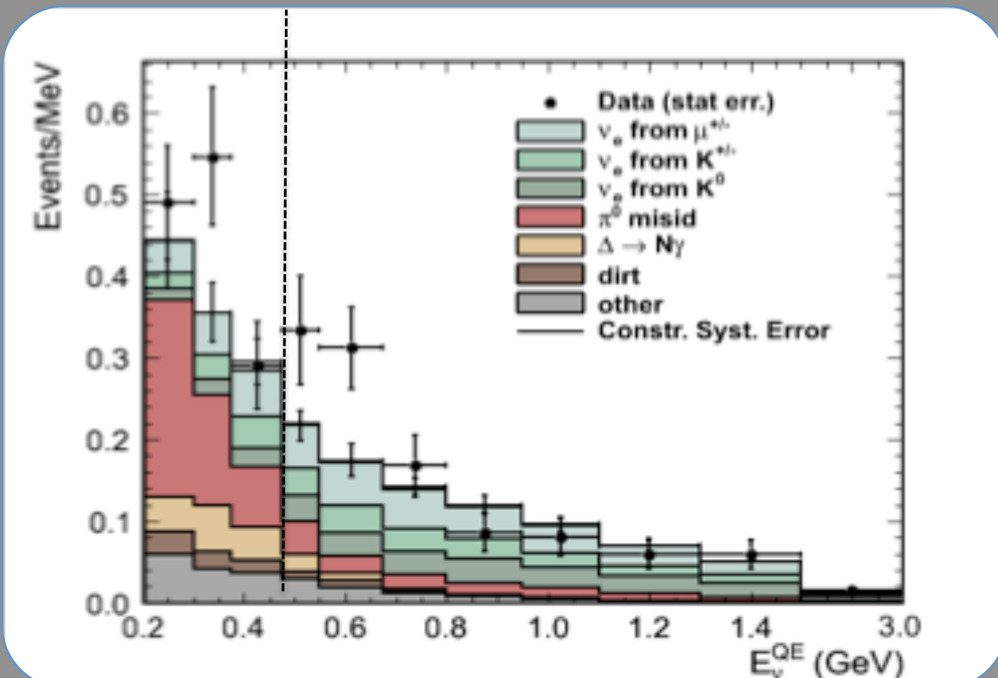
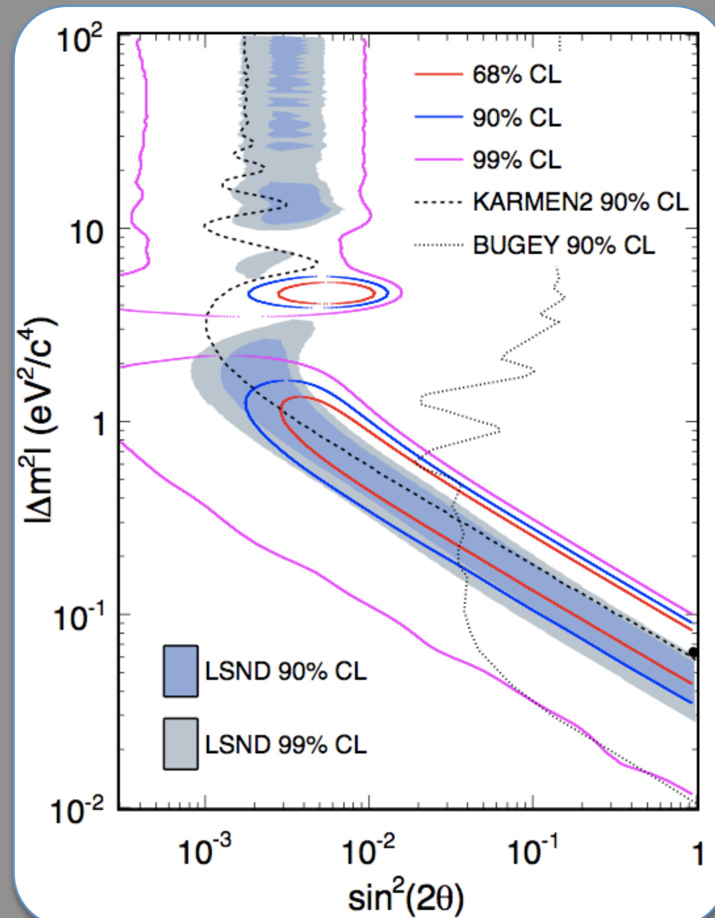


$\longrightarrow$



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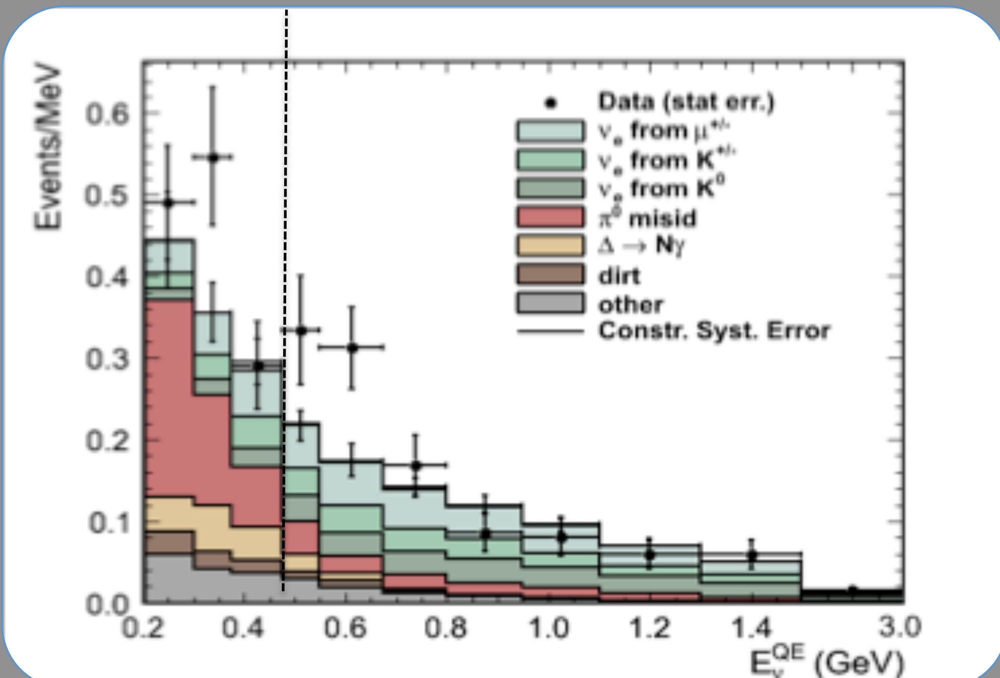
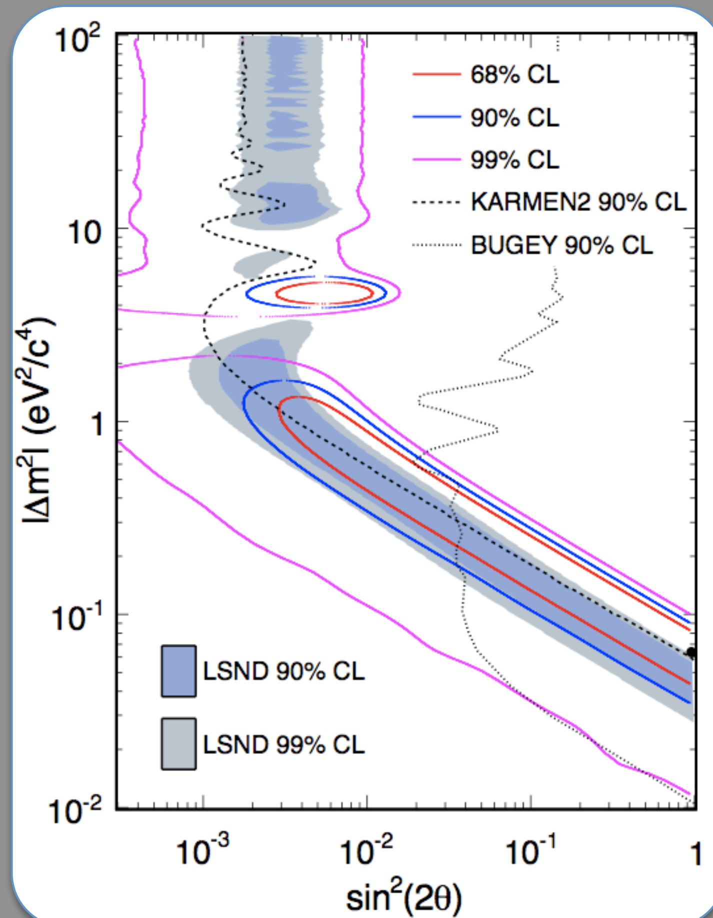


$\longrightarrow$



- Current MiniBooNE antineutrino data consistent with LSND signal

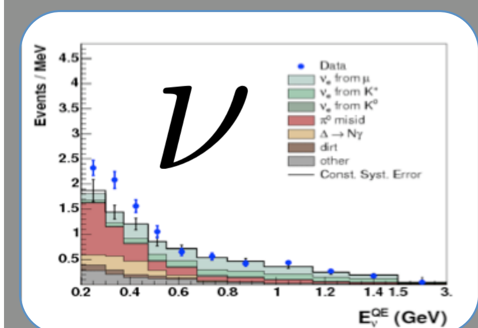
Comment on Theory

- If neutrinos and antineutrinos oscillate differently, and one wishes to explain the antineutrino excess by means of sterile neutrinos, it is necessary to add two sterile neutrinos to the picture

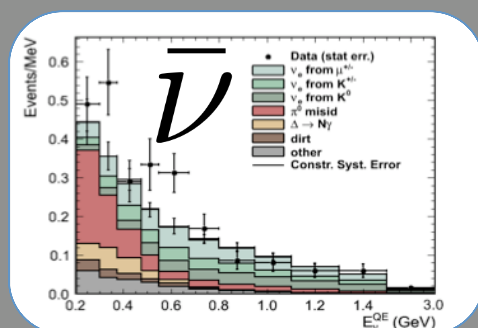
64

Comment on Theory

- If neutrinos and antineutrinos oscillate differently, and one wishes to explain the antineutrino excess by means of sterile neutrinos, it is necessary to add two sterile neutrinos to the picture



+



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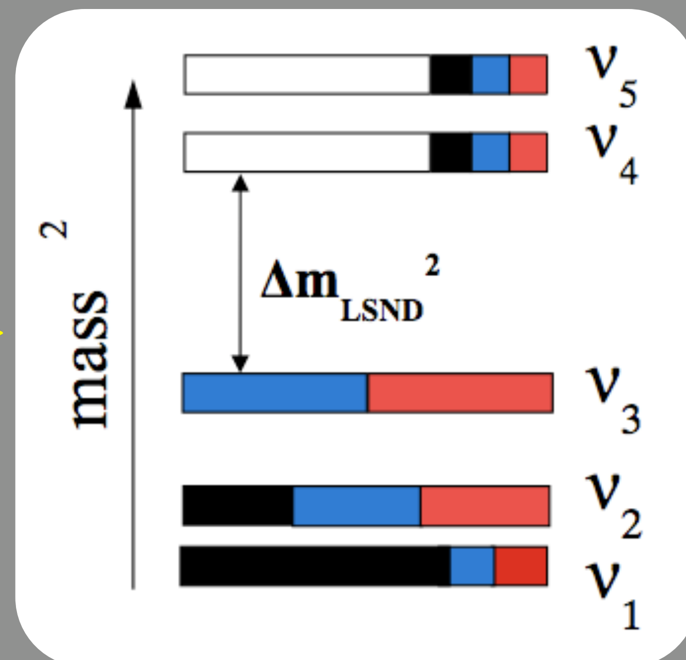
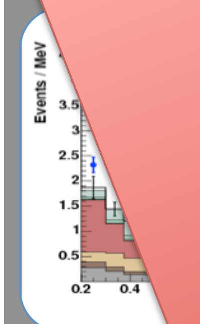
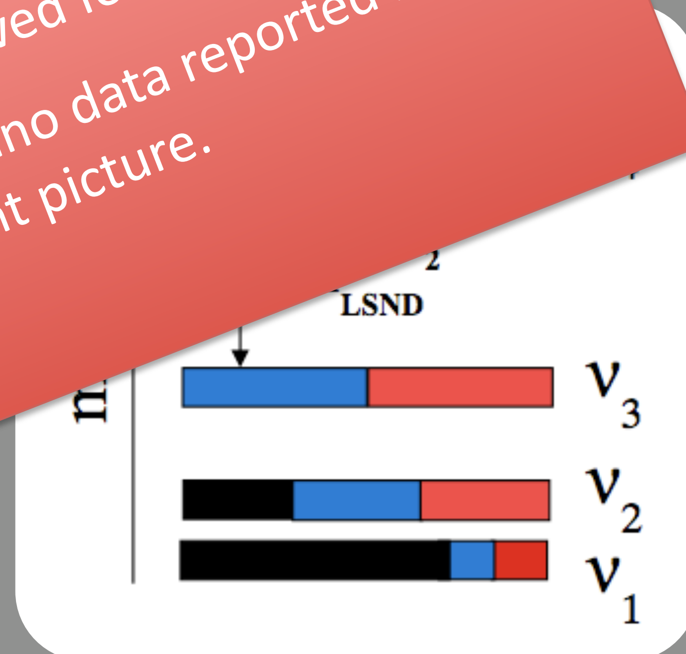


- However…

Comment on Theory

- If neutrinos and antineutrinos o… wishes to explain the ant… neutrinos, it is n… picture





- H…

We cannot get ahead of ourselves!

Currently the statistical significance sits under 3σ, while discovery proclamations are typically reserved for ~4σ.

MiniBooNE will roughly double antineutrino data reported here, will help clarify the current picture.

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- Motivations
  - Oscillations
  - Cross Sections
- MiniBooNE
  - Logistics
  - Reconstruction, PID
- Results!
  - Cross Sections
  - Oscillations
- Summary And Outlook

Looking ahead…

- Oscillations:
  - MiniBooNE still taking data in antineutrino mode, has been promised roughly double the data discussed today, may clarify true origin of observed excess
  - MicroBooNE has been granted CD-1 approval, will sit in MiniBooNE's current physical spot and will weigh in on oscillation questions (neutrino data low energy excess, antineutrino LSND-like excess)
  - BooNE proposal: Put a MiniBooNE-like detector in a near location to study flux, backgrounds
- Cross Sections:
  - A few more antineutrino cross sections will be published, may be very important for nuclear structure studies

Thanks for your attention!

grange@fnal.gov


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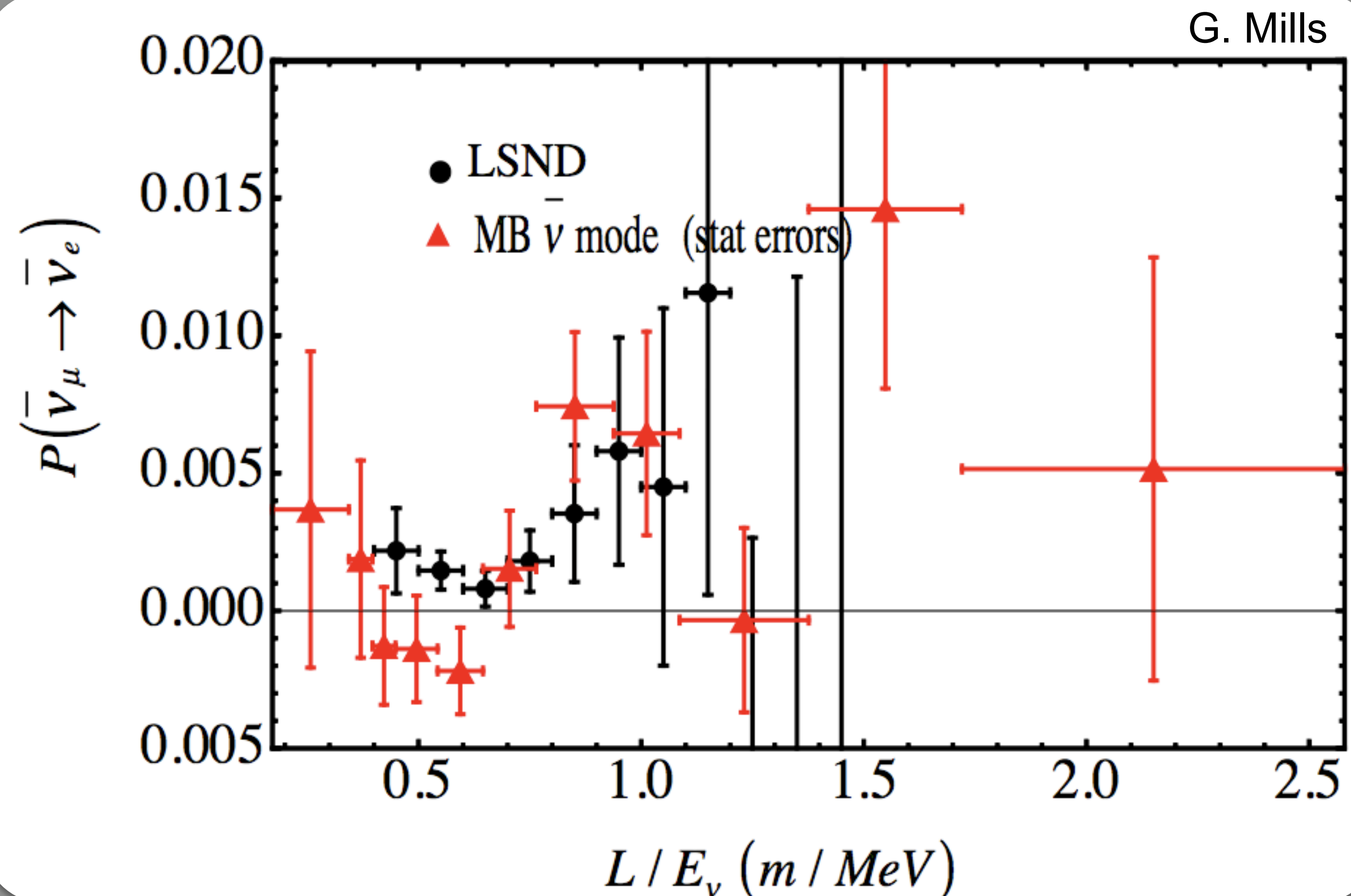
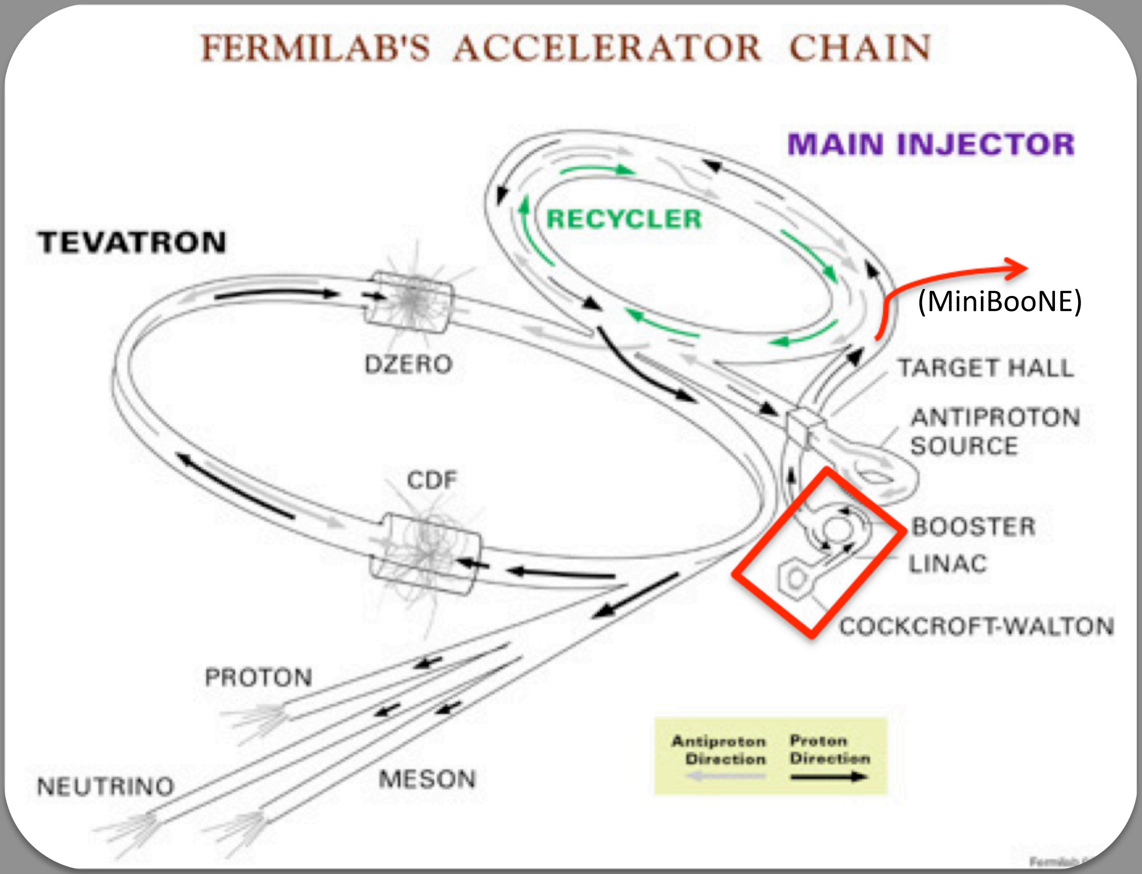
L/E plot



G. Mills
LSND
MB $\bar{\nu}$ mode (stat errors)
0.020
0.015
0.010
0.005
0.000
0.005
0.5
1.0
1.5
2.0
2.5
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
L / E_ν (m / MeV)

Booster Neutrino Beamline

- Three stages:
  1. Cockroft-Walton
  2. Linac
  3. Booster Ring

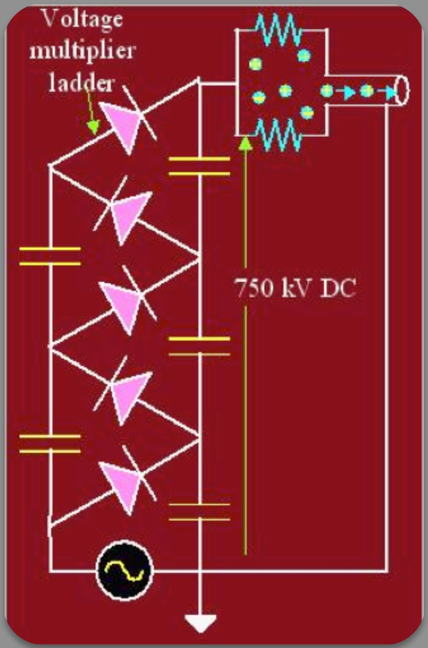


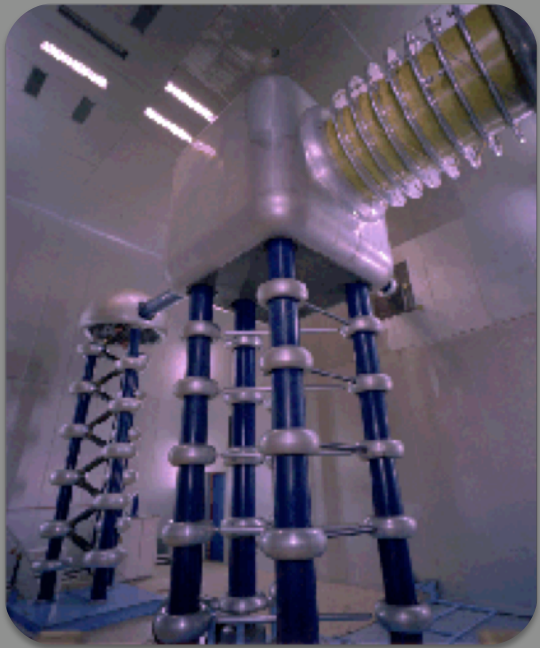
Booster Neutrino Beamline

1. Cockroft-Walton Voltage Multiplier

- Pulsed DC signal switches polarity in tune with diodes coming on/off. This allows voltage doubling at each successive stage.

- Details:
  Initially DC signal negative, allows charge from ground to pile on first capacitor. When DC current switches, 1st diode switches off, 2nd diode switches on and the 2nd capacitor receives charge from both first DC signal *and* 1st capacitor. When DC signal switches again, 2nd capacitor has twice the charge the 1st capacitor did.





- Assuming perfect capacitors,
  Charge on nth capacitor = $2 \times n \times$ (input voltage)

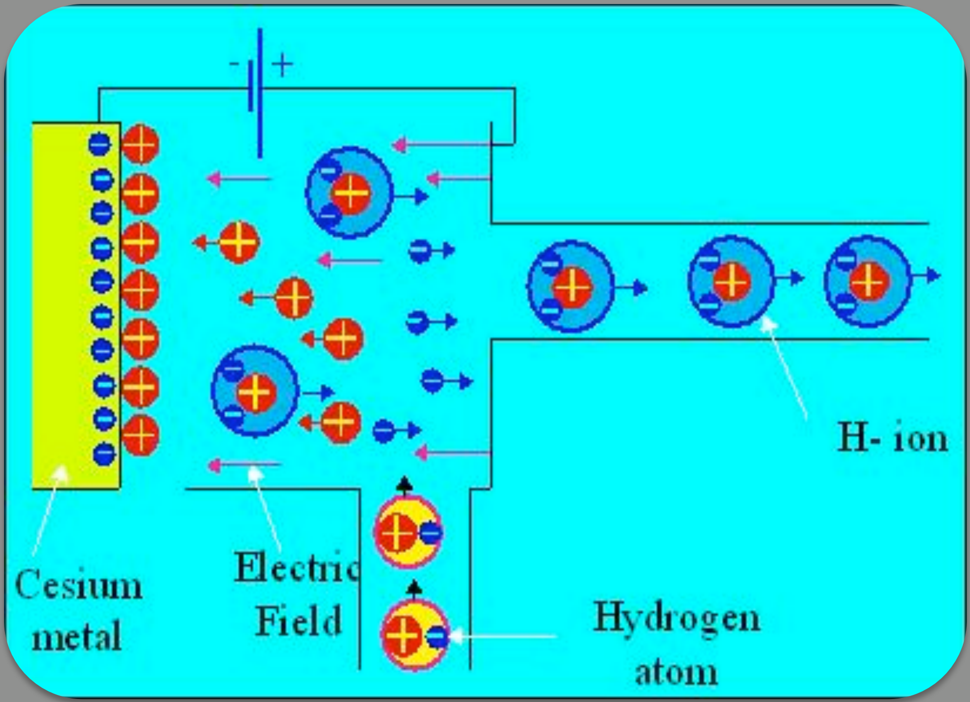
- 750 kV at end of Fermilab's CW multiplier

Booster Neutrino Beamline

1. Cockroft-Walton Voltage Multiplier

- Hydrogen atoms injected into ionization care of strong E field created by CW ladder.

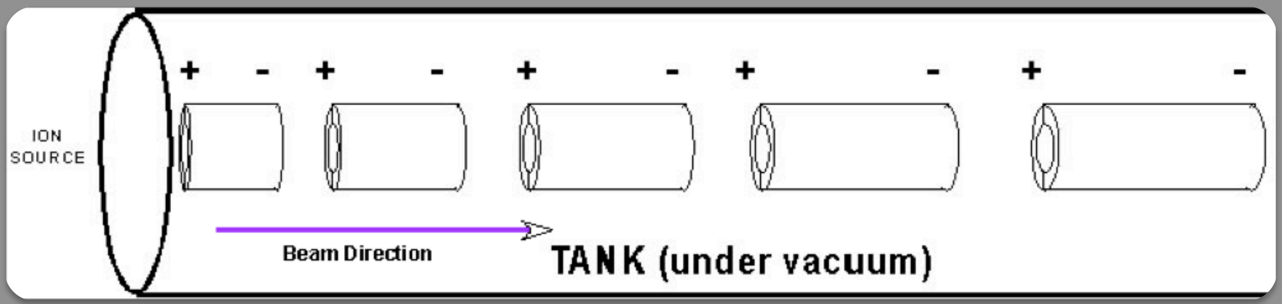
- Electron stipped off hydrogen,
bare proton drifts to Cesium edge of chamber.



- Electrons easily ripped off Cesium (low work function), occasionally an incoming proton knocks off resting proton with two electrons (H^-), because negatively charged, H^- drifts away from wall, on to the linear accelerator.

Booster Neutrino Beamline

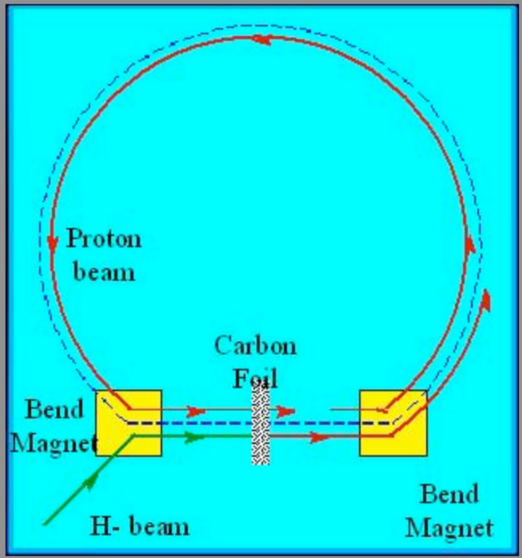
2. Linear Accelerator



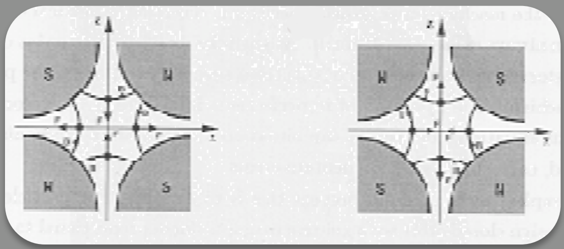
- Alternately polarized electric field accelerates H^- ions in between gaps of Faraday cage drift tubes
- 130 m long
- Typical pulse length 20 ms
- Beam bunches spaced 5 ns apart
- H^- ions accelerated to 400 MeV KE

Booster Neutrino Beamline

3. Booster Ring



- H^- ion beam bent to accelerate along with proton beam in ring (beams converge in this region instead of diverge - sole reason for starting with H^- instead of p)
- Both beams incident in thin carbon foil - this strips electrons while not slowing down protons.

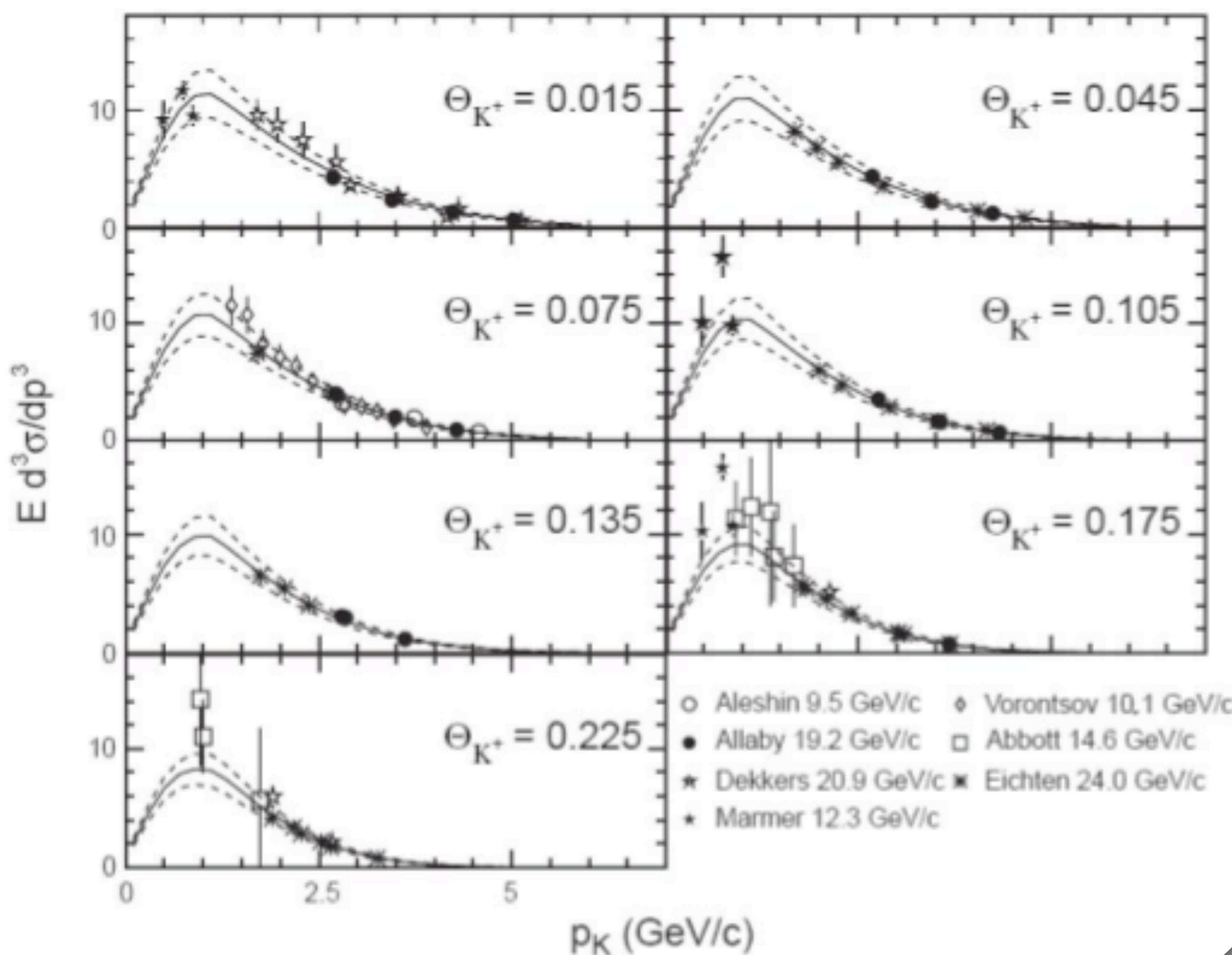


- Booster turns protons using alternating focusing - defocusing quadrupole magnets
- Booster cirumference: 475 m (~3/40 circ. of Tevatron)
- Proton KE: 400 MeV -> 8 GeV in 33 ms, 16,000 turns

Some Branching Ratios

Particle	Lifetime (ns)	Decay mode	Branching ratio (%)
π^+	26.03	$\mu^+ + \nu_\mu$	99.9877
		$e^+ + \nu_e$	0.0123
K^+	12.385	$\mu^+ + \nu_\mu$	63.44
		$\pi^0 + e^+ + \nu_e$	4.98
		$\pi^0 + \mu^+ + \nu_\mu$	3.32
K^0_L	51.6	$\pi^- + e^+ + \nu_e$	20.333
		$\pi^+ + e^- + \overline{\nu}_e$	20.197
		$\pi^- + \mu^+ + \nu_\mu$	13.551
		$\pi^+ + \mu^- + \overline{\nu}_\mu$	13.469
μ^+	2197.03	$e^+ + \nu_e + \overline{\nu}_\mu$	100.0

Systematic Errors



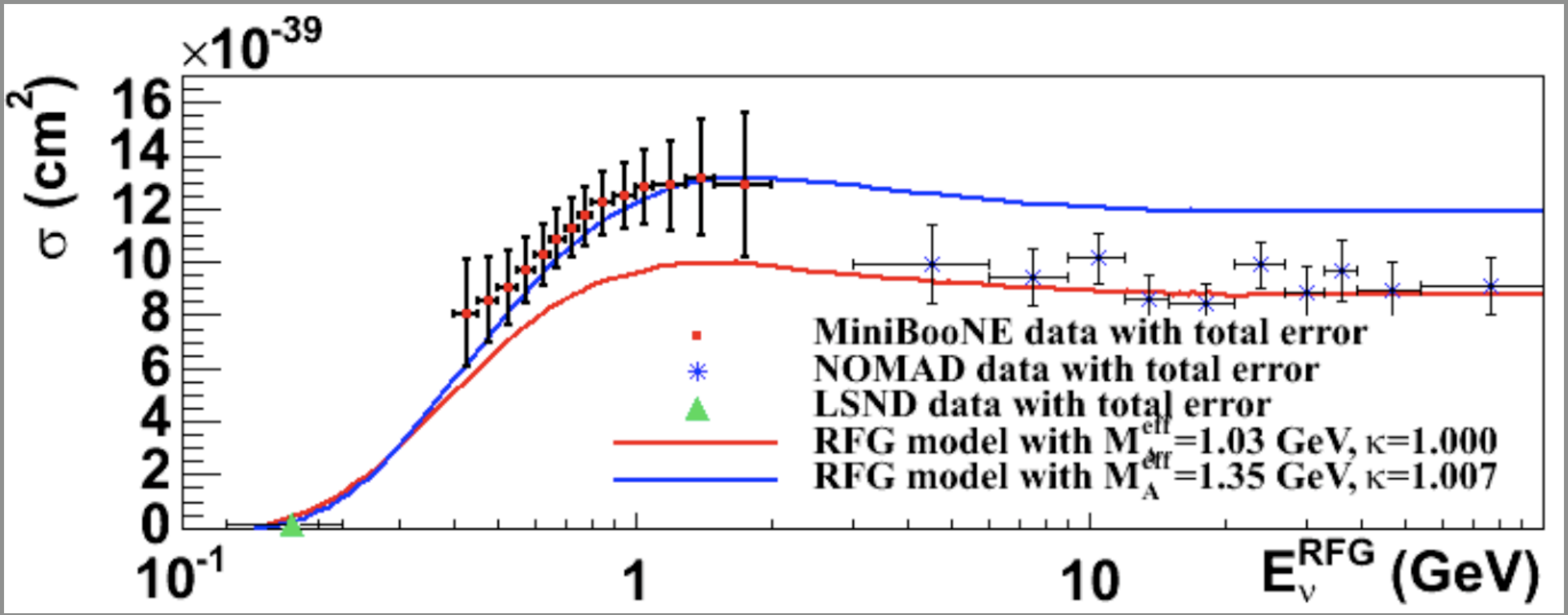
— Best Fit Sanford-Wang Model

--- Sanford-Wang Model Uncertainty

Kaon production from proton - Beryllium data EXTRAPOLATED using Feynman scaling to match MiniBooNE's 8.89 GeV/c incident proton momentum

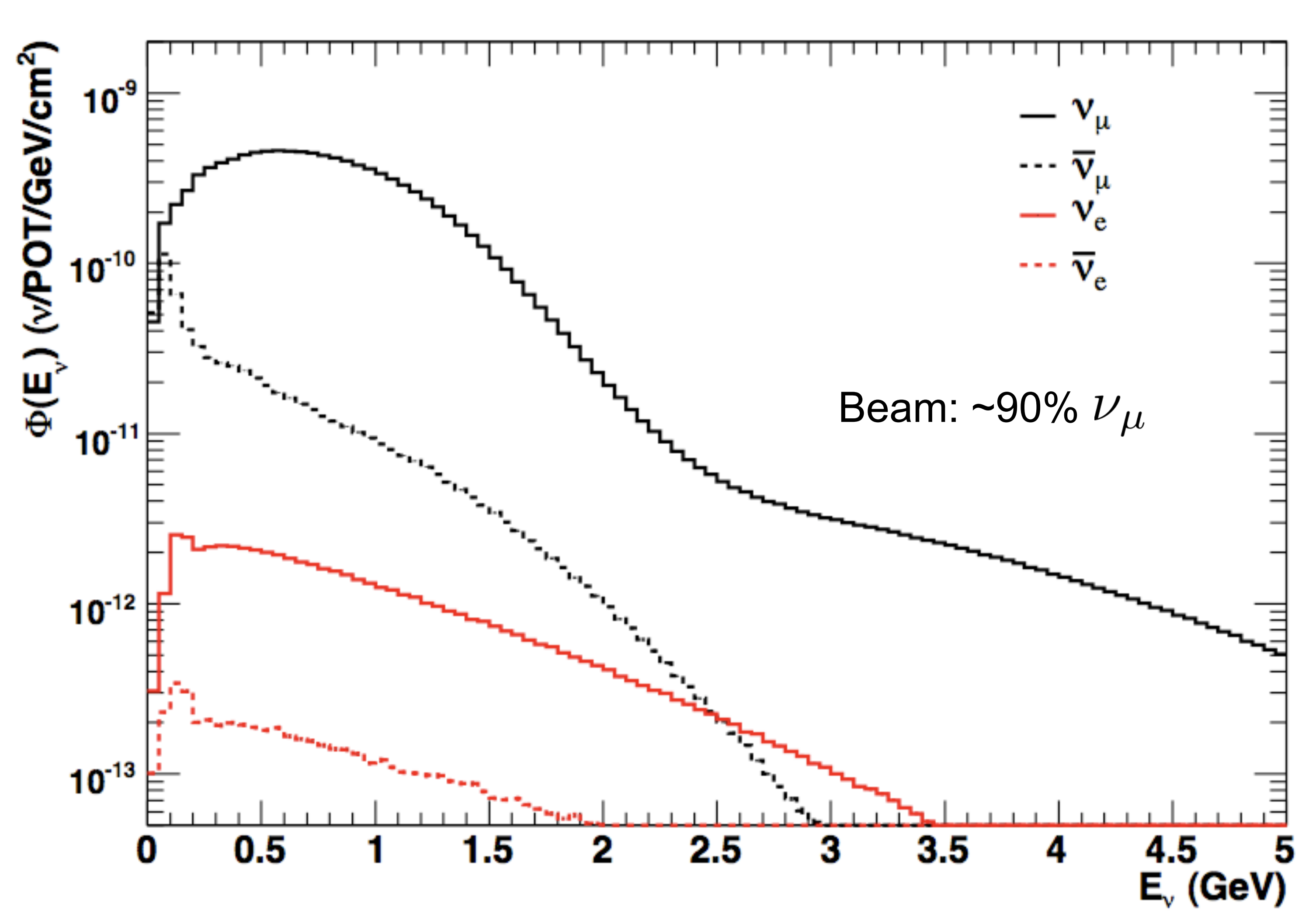
Nu Mode MiniBooNE Result

T. Katori, MIT



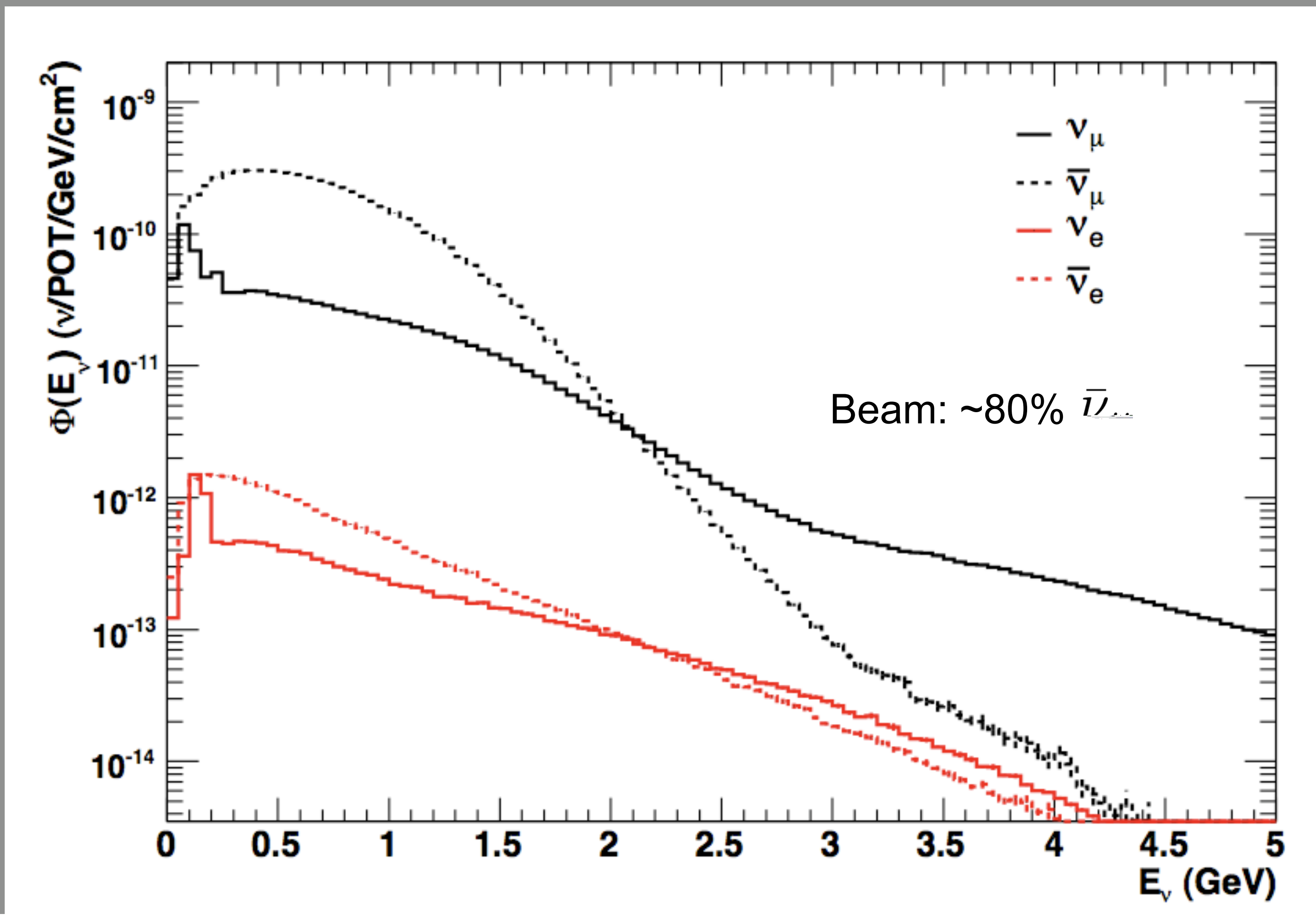
Focus π^+, defocus π^-: "ν_μ mode"

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



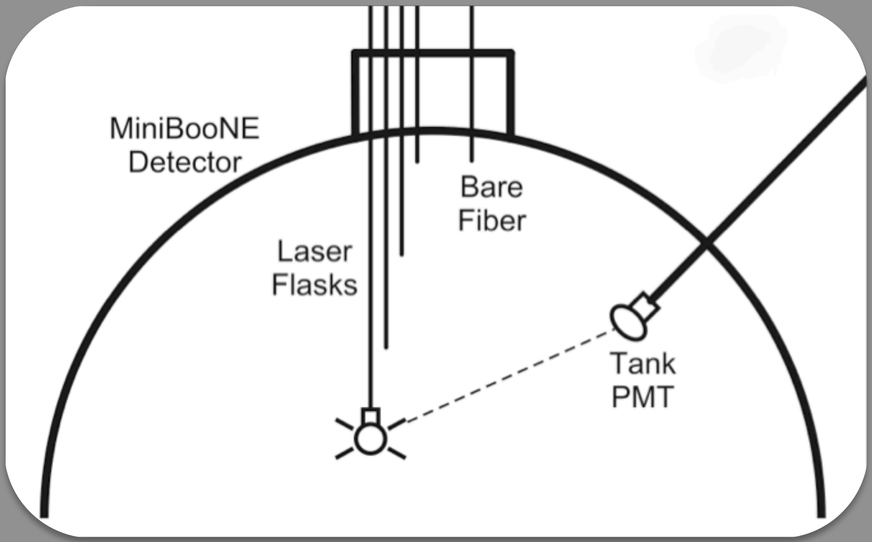
Focus π^-, defocus π^+: "$\bar{\nu}_\mu$ mode"

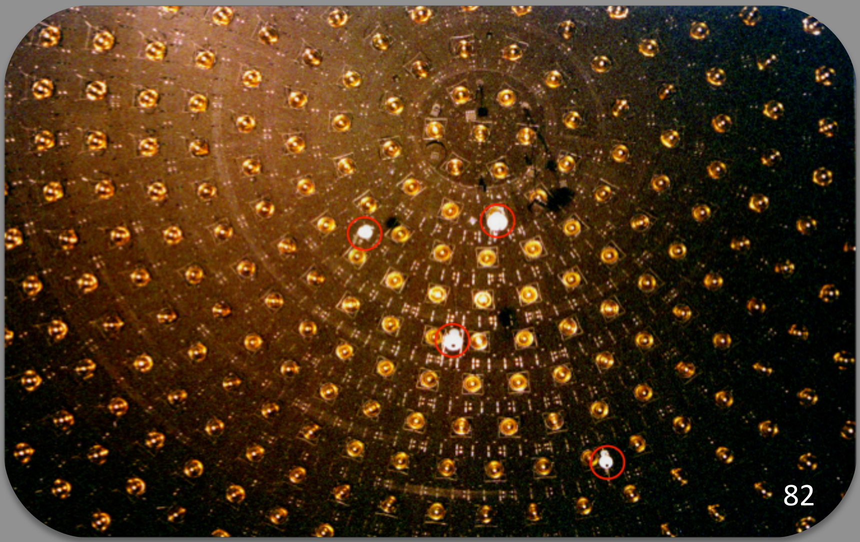
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



PMT, Oil Calibration[1]

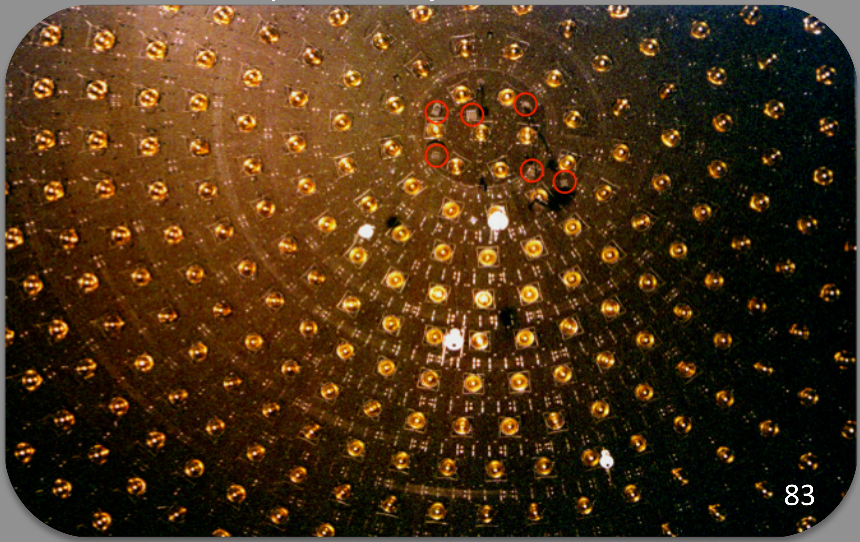
- During beam off conditions, a pulsed diode laser flashes into main tank at 3.33 Hz to check PMT health and light attenuation of oil
- Light pulse (< 1 ns, 397nm peak λ) distributed to one of four dispersion flasks placed at different depths. Flasks designed to illuminate all PMTs with ~ equal intensities
- Time offsets for individual PMT/QT readouts are calculated by taking difference of hit time - expected arrival time from flask flashes
- The bare wire sits near top of tank, emits conical light with 10° opening, illuminating a small circle of PMTs at detector bottom - used to study light propagation in tank over time





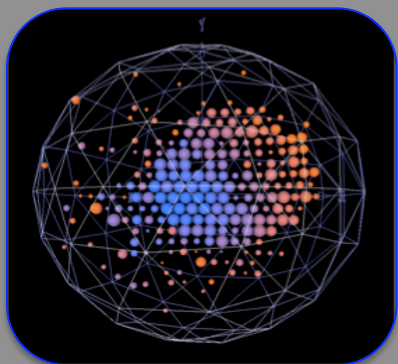
Muon, Electron Calibration

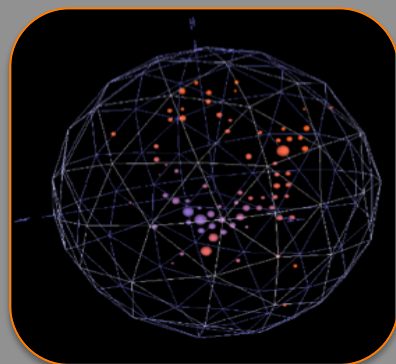
- Track cosmic muons to better understand detector response.
- Including veto PMTs, system consists of a scintillator hodoscope (to measure incident E) directly above the detector and several scintillator cubes deployed in signal volume
- Scintillator cubes: side = 5cm, each with own 1in PMT
- Some cosmic ray muons stop inside scintillator cube, along with subsequent electron decay produce coincident signals in both tank PMTs and cube PMT
- Location, E of the muon and origin of the electron can be independently determined from the muon hodoscope and cube geometry
- This provides a means of tuning and verifying event reconstruction algorithms.
- Rate of cosmic muon stopping in scintillator cube: ~100/month

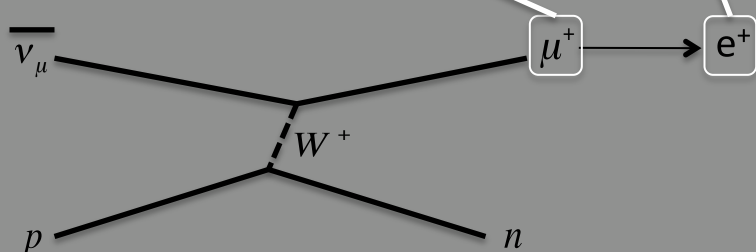


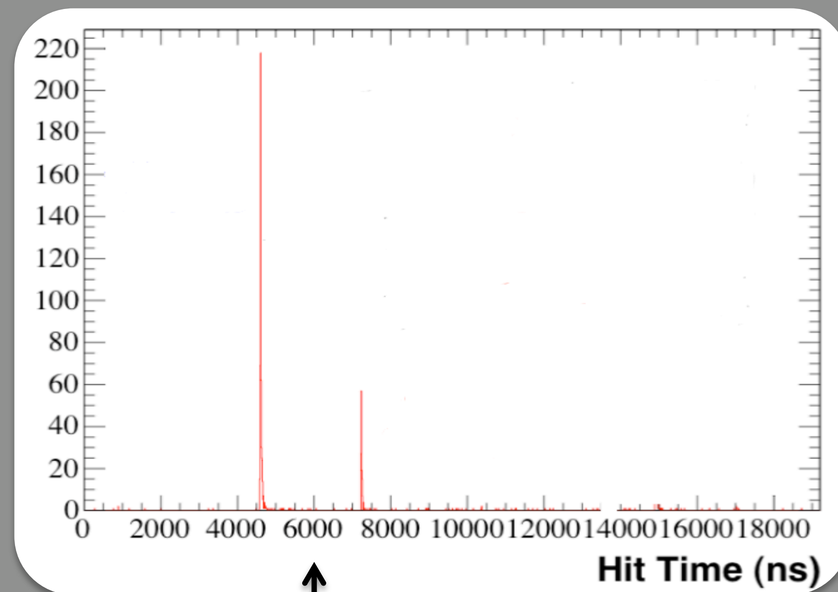
CCQE Detection

- CCQE identification relies on time correlated muon, electon - like rings



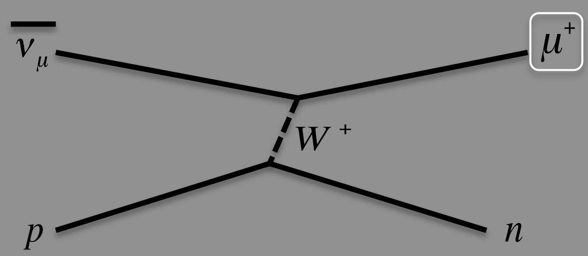






(Electron hit time) - (muon hit time) ~ μ lifetime = 2.2μs

CCQE Observables



Only the outgoing muon from the primary interaction is observed, but we can reconstruct incident (anti-)neutrino energy and momentum transfer based on muon kinematics

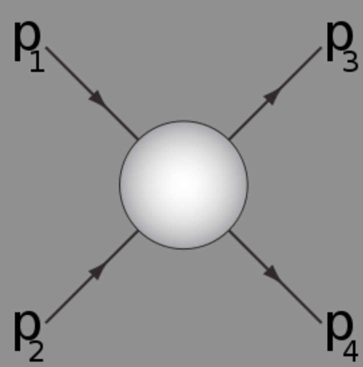
Assuming target proton at rest ($p_2 = 0$),

$$E_{\bar{\nu}}^{CCQE} = \frac{2m_p E_\mu + m_n^2 - m_p^2 - m_\mu^2}{2\left(m_p - E_\mu + p_\mu \cos\theta_\mu\right)}$$

$$Q^2 = 2E_{\bar{\nu}}^{CCQE}\left(p_\mu \cos\theta_\mu - E_\mu\right) + m_\mu^2$$

$$= 2m_p T_n + \left(m_n - m_p\right)^2$$

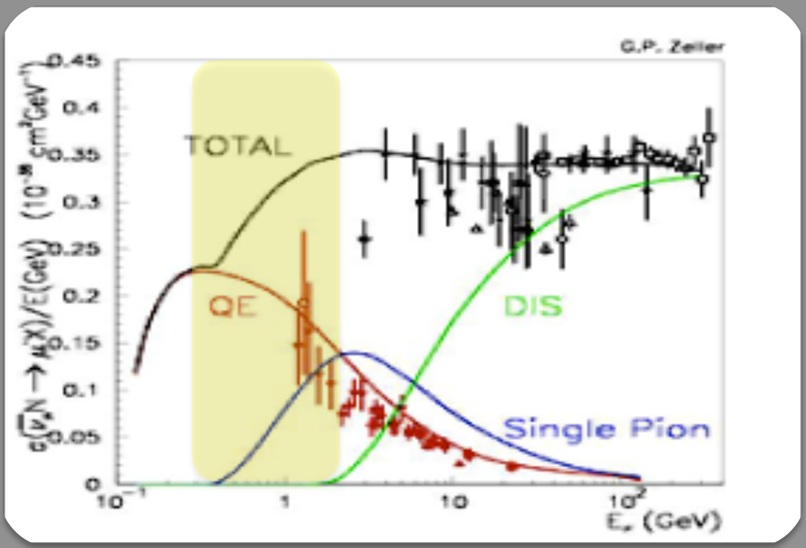
Mandelstam $t = (p_3 - p_1)^2 = (p_4 - p_2)^2 = -q^2 = Q^2$
= invariant four-momentum transfer



t-channel

MiniBooNE Events

- Events at MiniBooNE energies:



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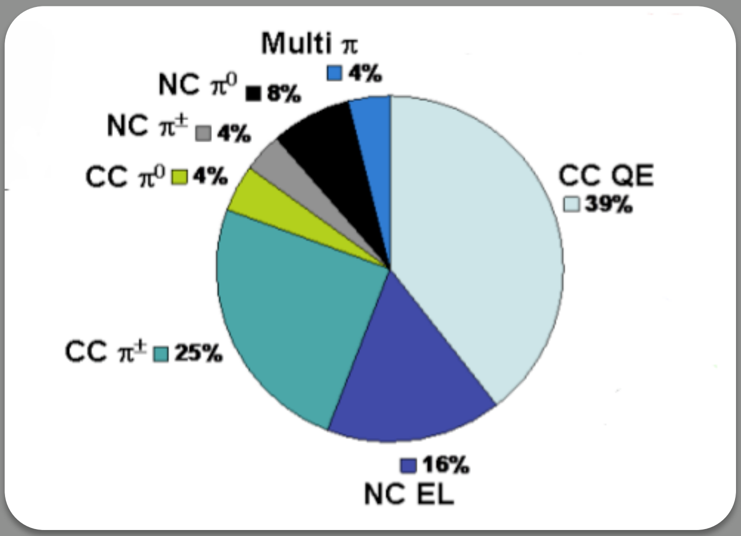


- Main interaction channel at MiniBooNE's energies is Charged Current Quasi-Elastic, ~40% of all interactions in detector. (CCQE, or simply QE)

$$\overset{(-)}{\nu_l} + N \rightarrow N' + l^{-(+)}$$

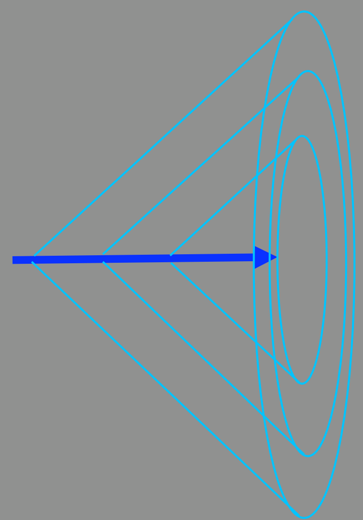
$$\overset{(-)}{\nu_l} + {}^{12}C \rightarrow X + l^{-(+)}$$

l = μ, e; N, N' = n, p as allowed by conservation laws
(ν only scatters off neutron, $\bar{\nu}$ off proton)

Particle Tracking, Identification
Cerenkov and Scintillation Light

- Most effective reconstruction, ID come from particles producing directional Cerenkov light

$$\cos\theta_C = (\beta * n_{BooNE\ oil})^{-1}; \quad n_{BooNE\ oil} \sim 3/2 \ \rightarrow \ \beta_{cerenkov} > 2/3$$



Particle	Minimum KE, Cerenkov radiation for BooNE oil
Electron	170 keV
Muon	35 MeV
Proton	350 MeV

- Isotropic scintillation light has been shown to reconstruct effectively for protons, too
  - Recent neutral current elastic cross section measurement tracks $KE_P < 350$ MeV