MiniBooNE Oscillation Update

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Imperial College London

Neutrino Frontiers
University of Minnesota

Outline

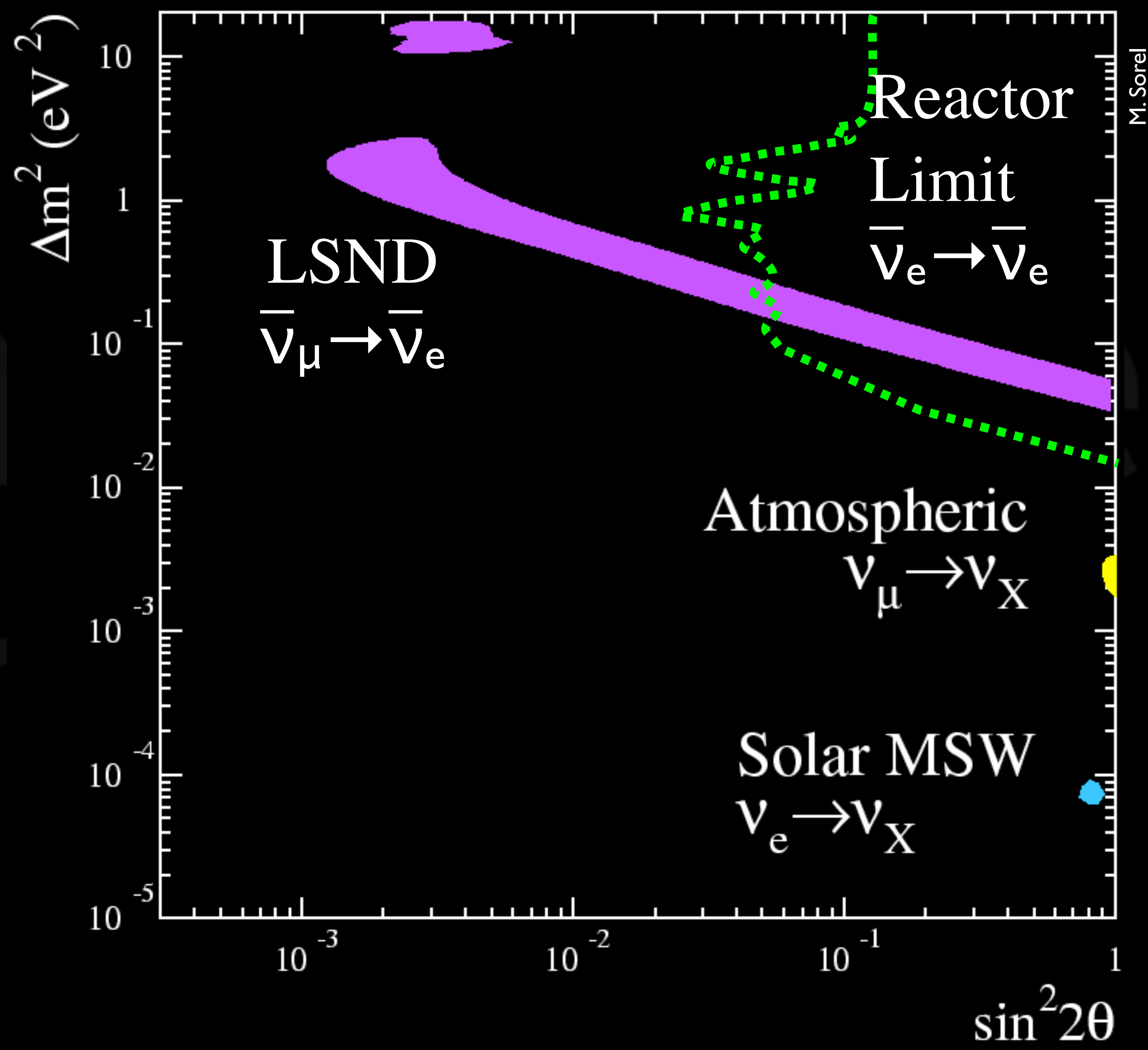
- Introduction
  - MiniBooNE first result
- MiniBooNE $\nu_{\mu} \rightarrow \nu_e$ oscillation updates
- Oscillation outlook

MiniBooNE

SciBooNE

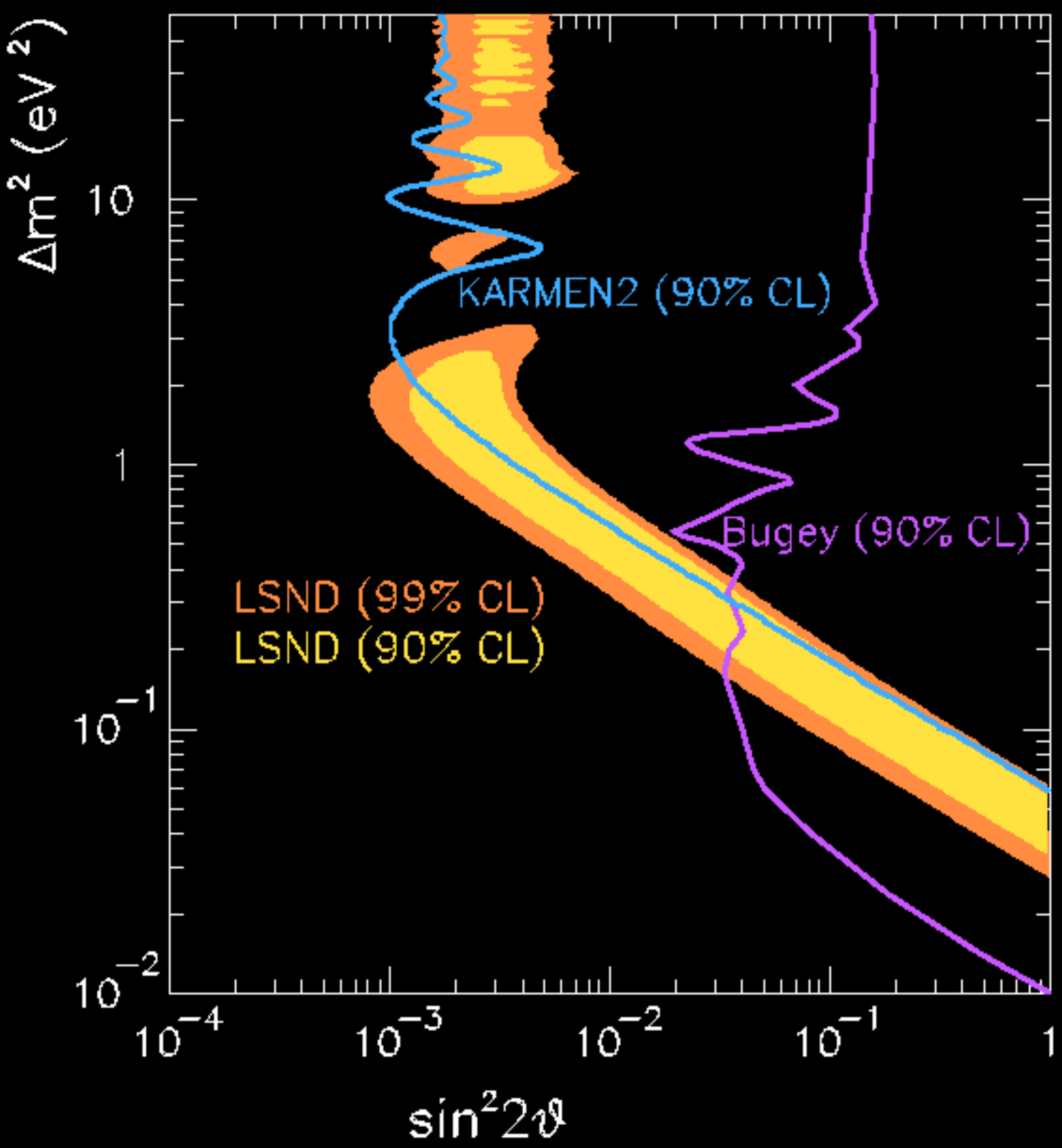
The Problem

- Three different neutrino oscillation signals
- Three independent Δm^2
- Problem:
  We only need two!
- Explanation requires physics well beyond the standard model
- Is it true?



Verifying LSND

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27 \Delta m_{12}^2 \frac{L}{E})$$



- LSND interpreted as 2 ν oscillation
- Verification requires same (L/E) and high statistics
  - Different systematics
- MiniBooNE chose higher L and E
- Strategy: search for ν_e excess in ν_μ beam

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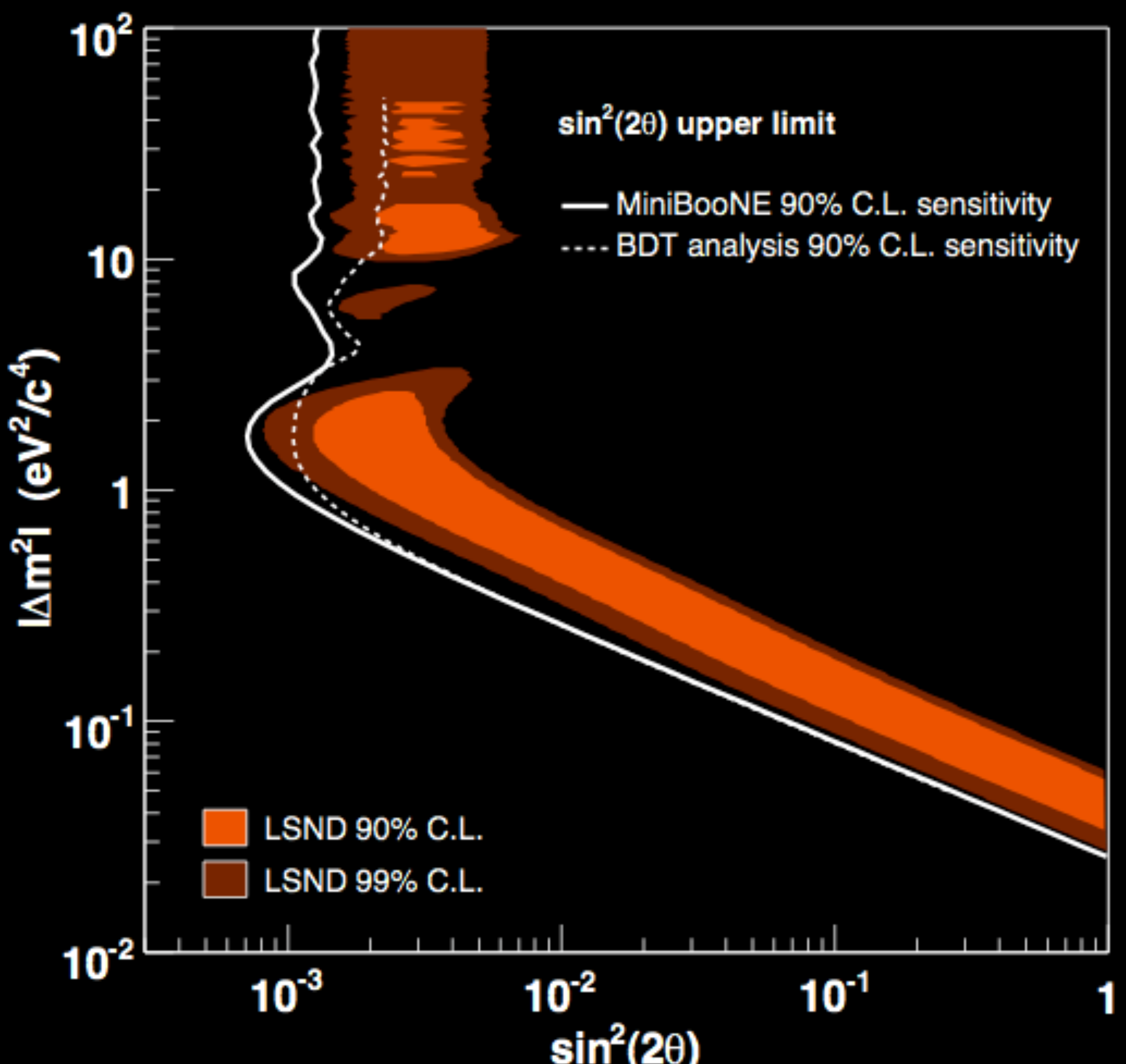


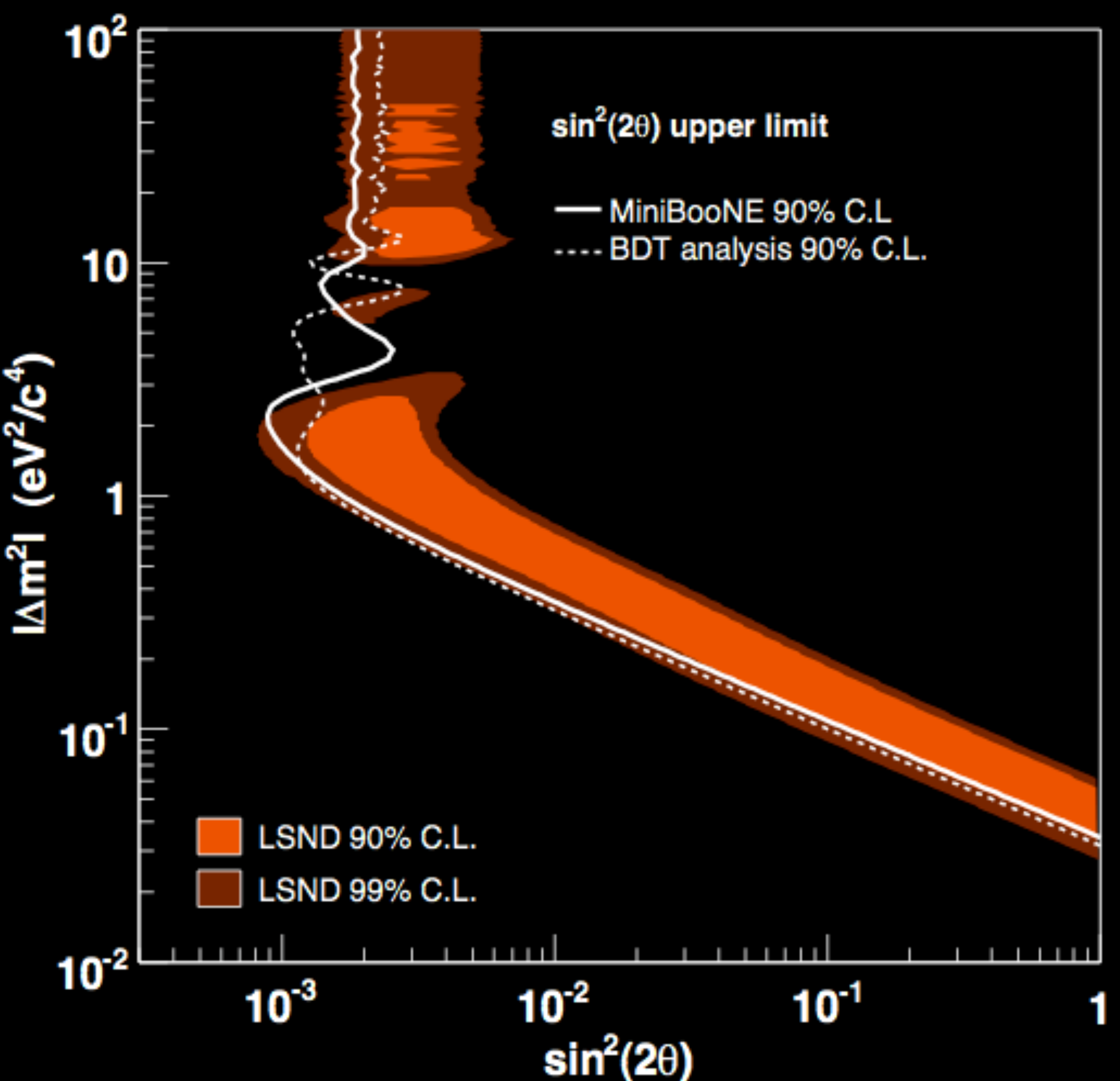
MiniBooNE Sensitivity

- LSND interpreted as 2 ν oscillation
- Verification requires same (L/E) and high statistics
  - Different systematics
- MiniBooNE chose higher L and E
- Strategy: search for ν_e excess in ν_μ beam

First Exclusion Curve

- No evidence for $\nu_\mu \rightarrow \nu_e$ 2ν appearance only oscillation
- Independent second analysis finds similar result
- Incompatible with LSND oscillation hypothesis at 98% CL
  - cf. KARMEN2 compatible at 64%

MiniBooNE First Result



Phys.Rev.Lett. ***98*** *231801 (2007)*

What Does It Mean?

- With the blind analysis, we have asked the question:

Do ν_μs oscillate directly to ν_es with $\Delta m^2 \sim 1eV^2$, ala LSND?

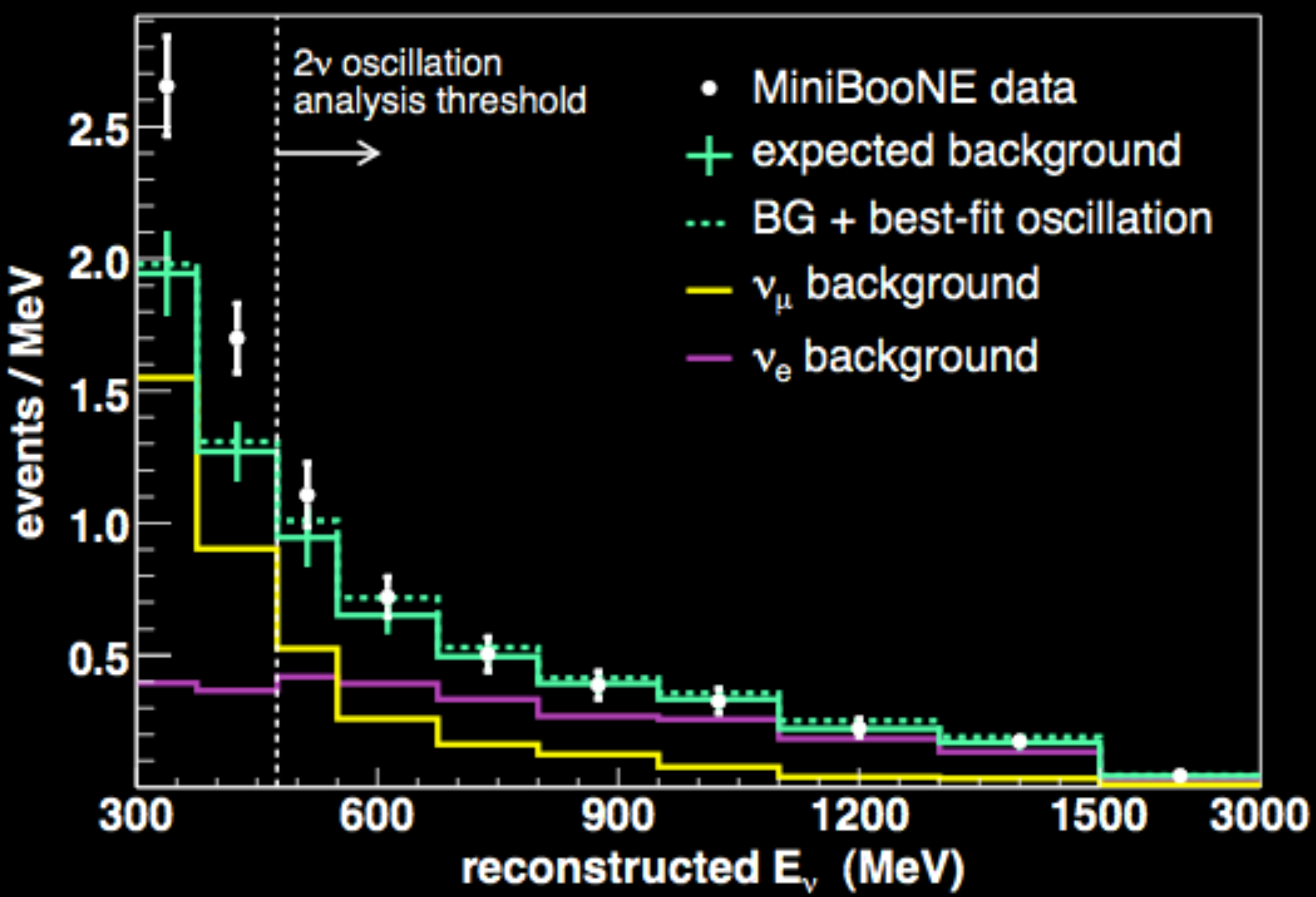
- We have a clear answer:

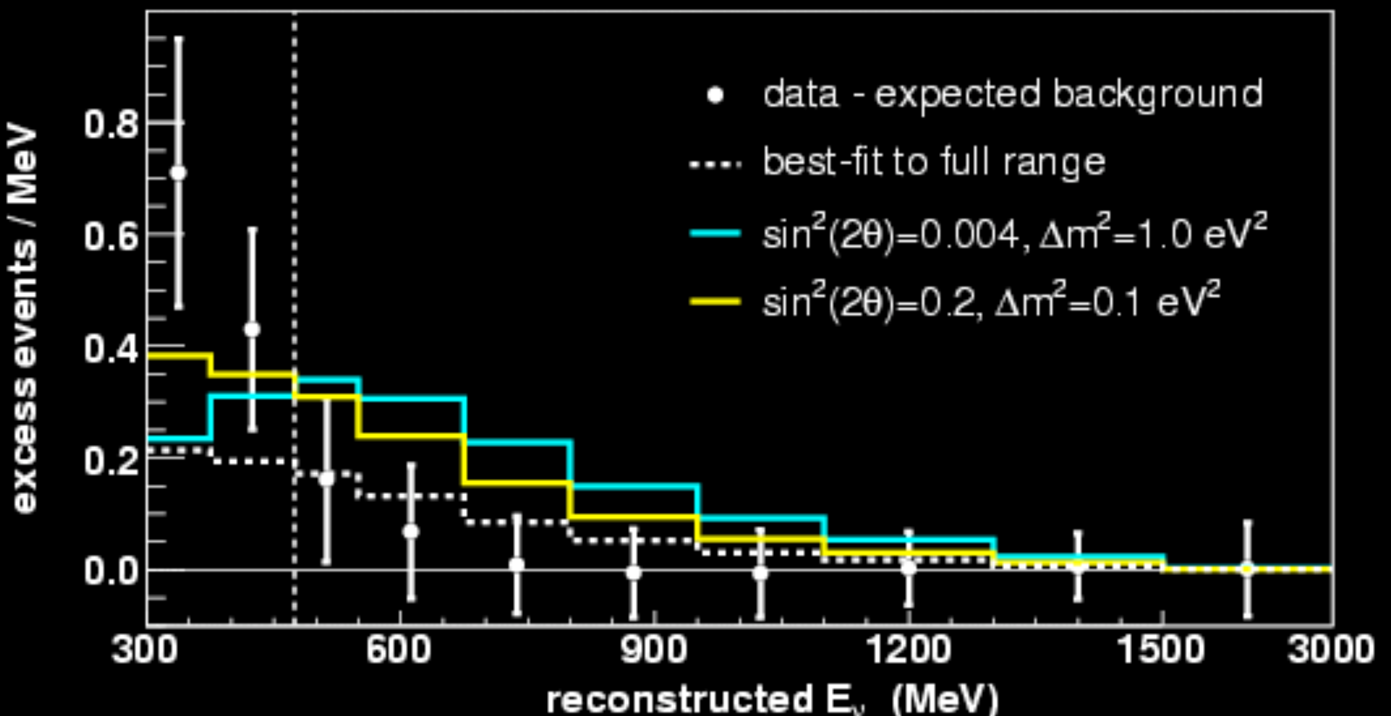
NO

More work yet to do...

At lower energy...

- Lowering the energy threshold reveals ν_e excess
- Excess not consistent with LSND oscillation hypothesis
- But what is it??
- Lots of new work to report...



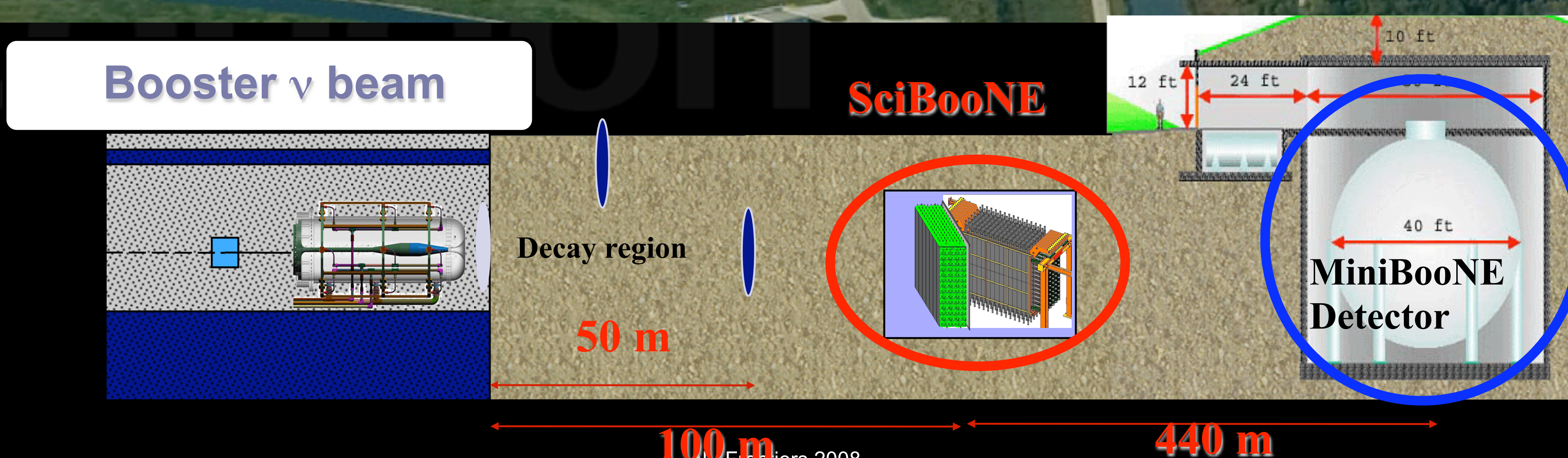


Low Energy Updates

(Experimental Overview)

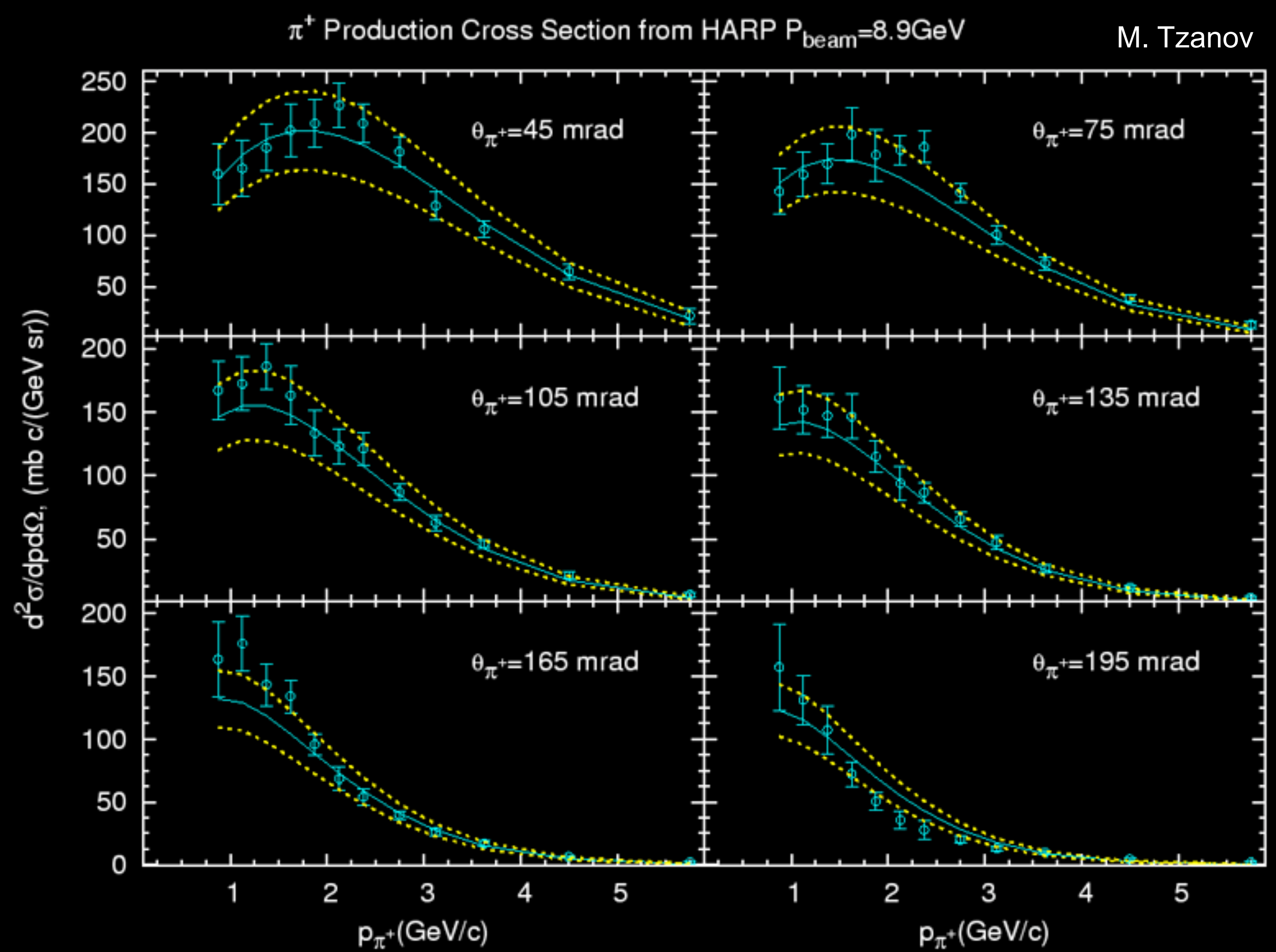
- $NC\pi^0$ and delta decays
- Hadronic processes and uncertainties
- “Dirt” BGs
- Looking at new/more data

Experimental Overview

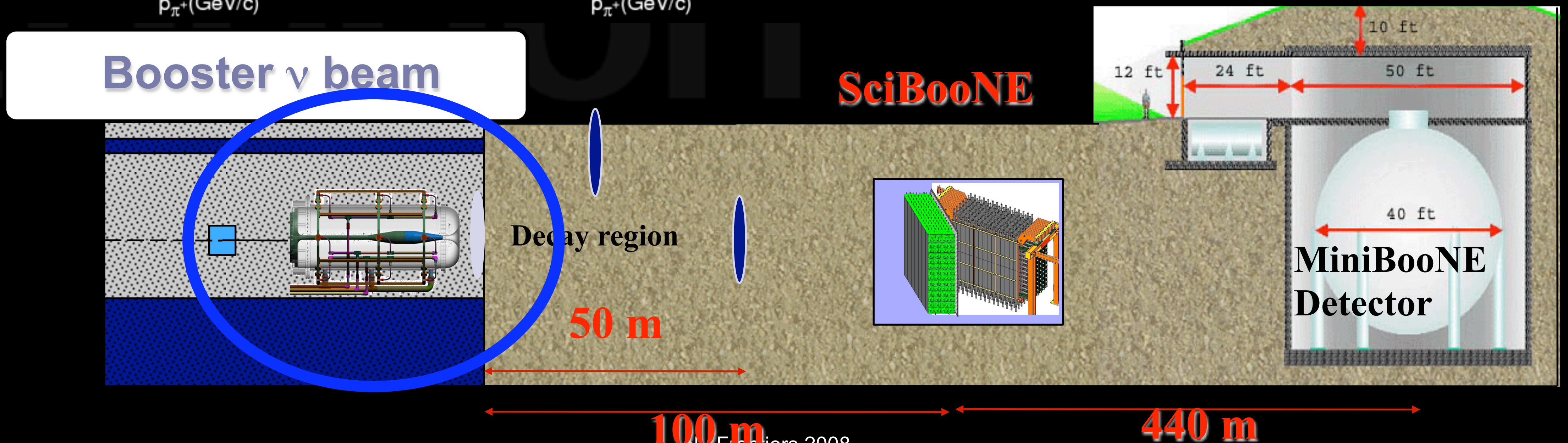


ν Flux Prediction

- External meson production data
  - E910 (BNL), HARP (CERN)
- Parametrisation of cross sections
  - Sanford-Wang for pions
  - Feynman scaling for kaons
  - Now directly use HARP data to estimate flux uncertainties



arXiv:0806.1449 [hep-ex]



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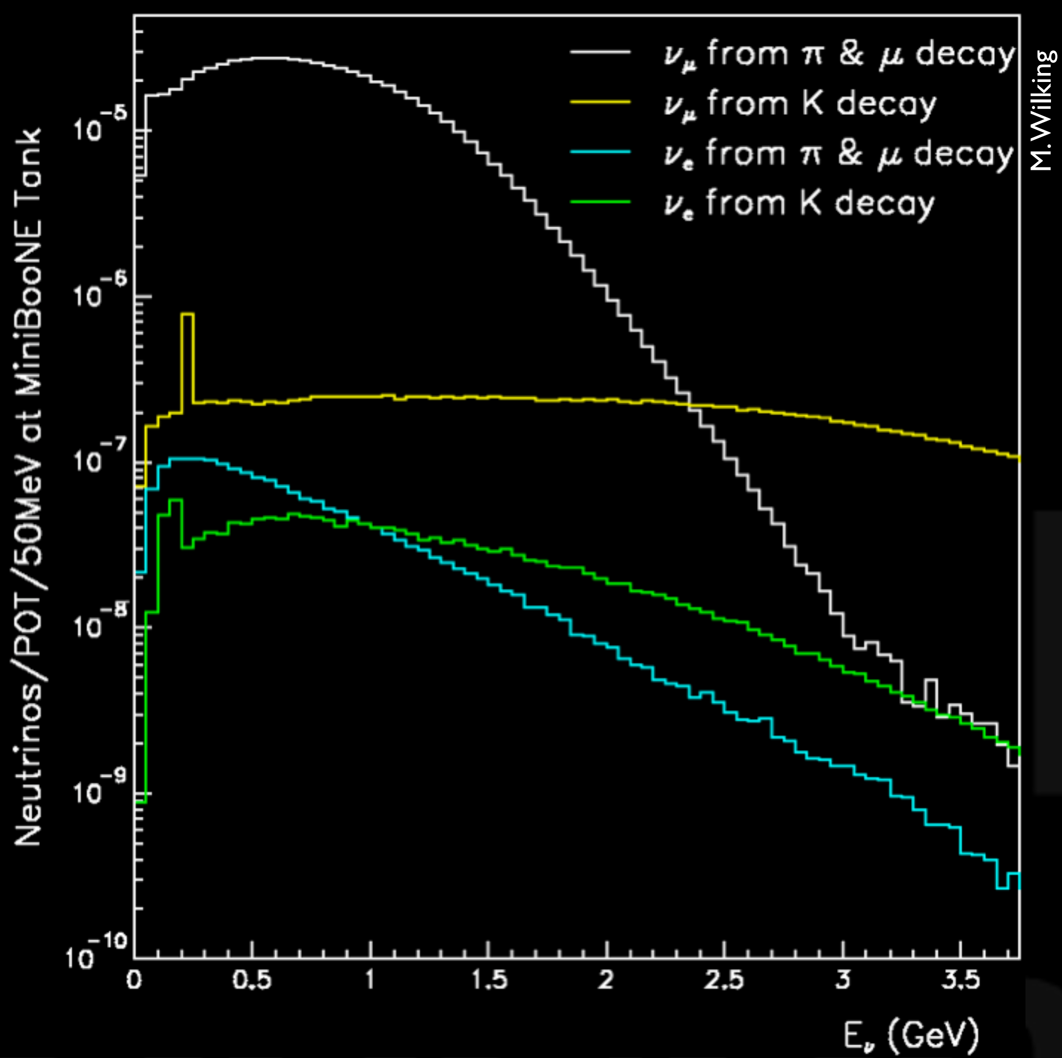

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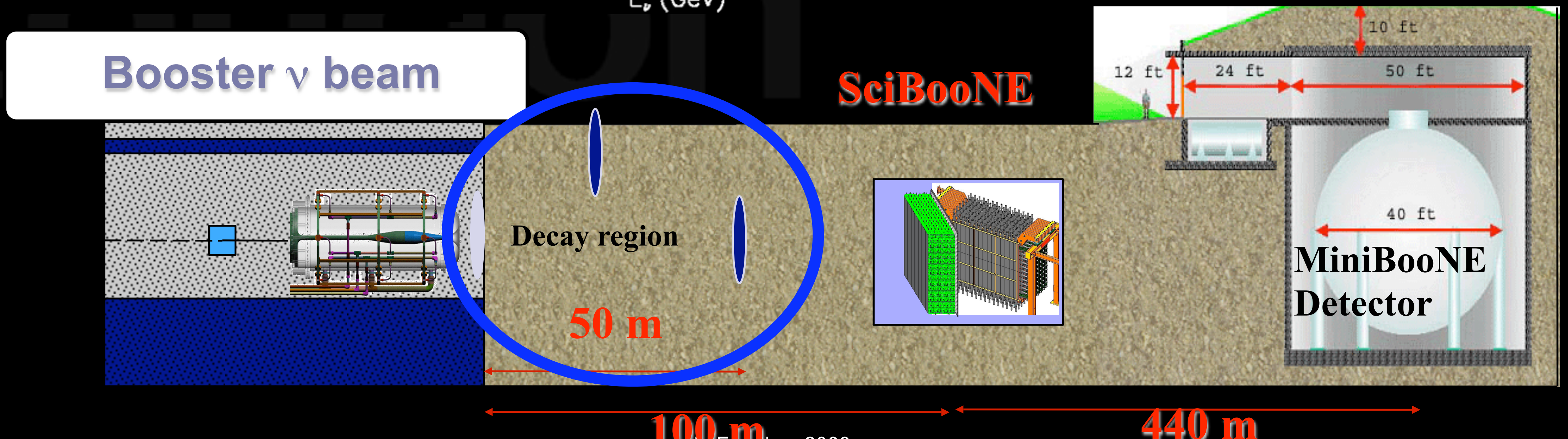
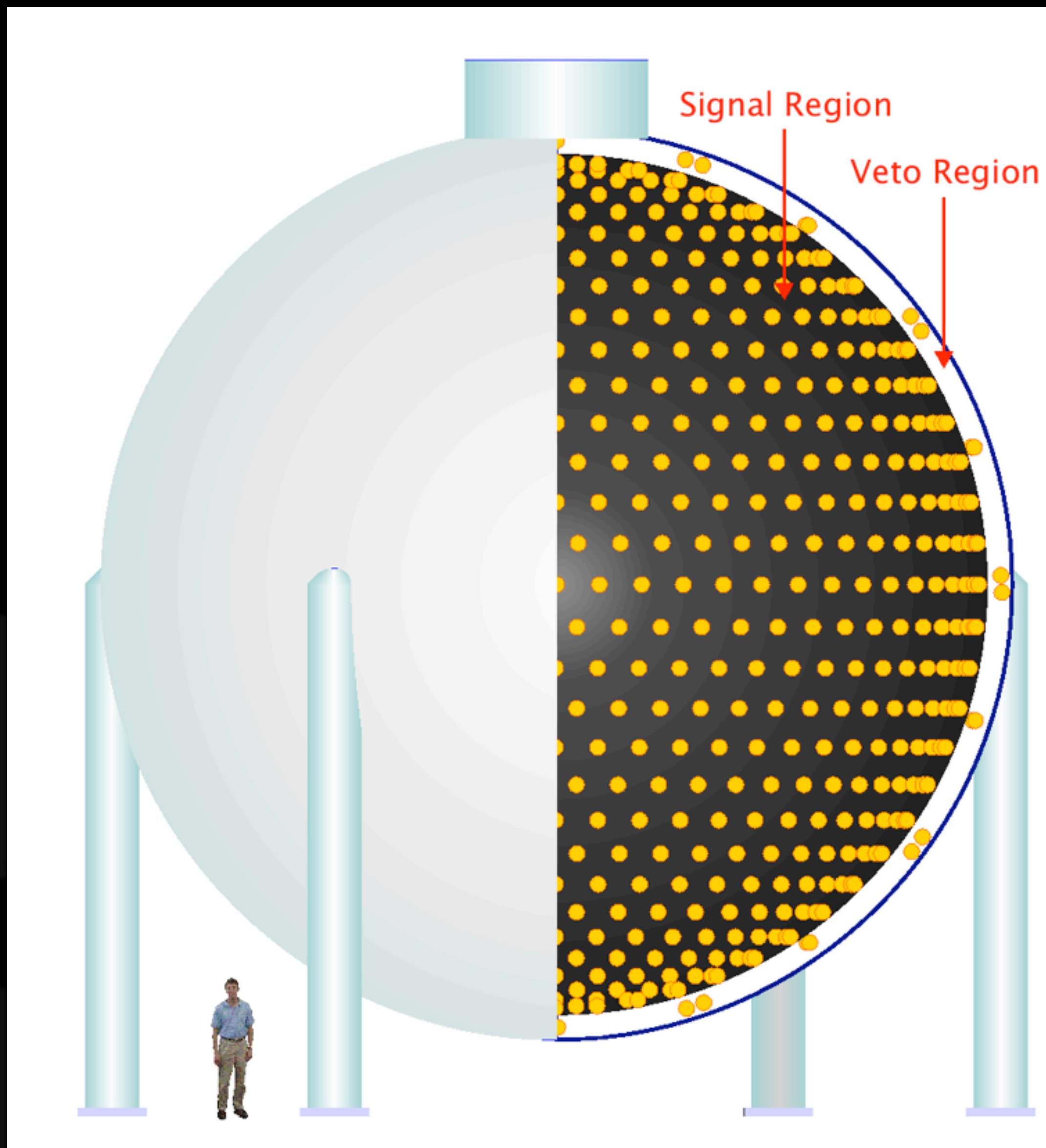
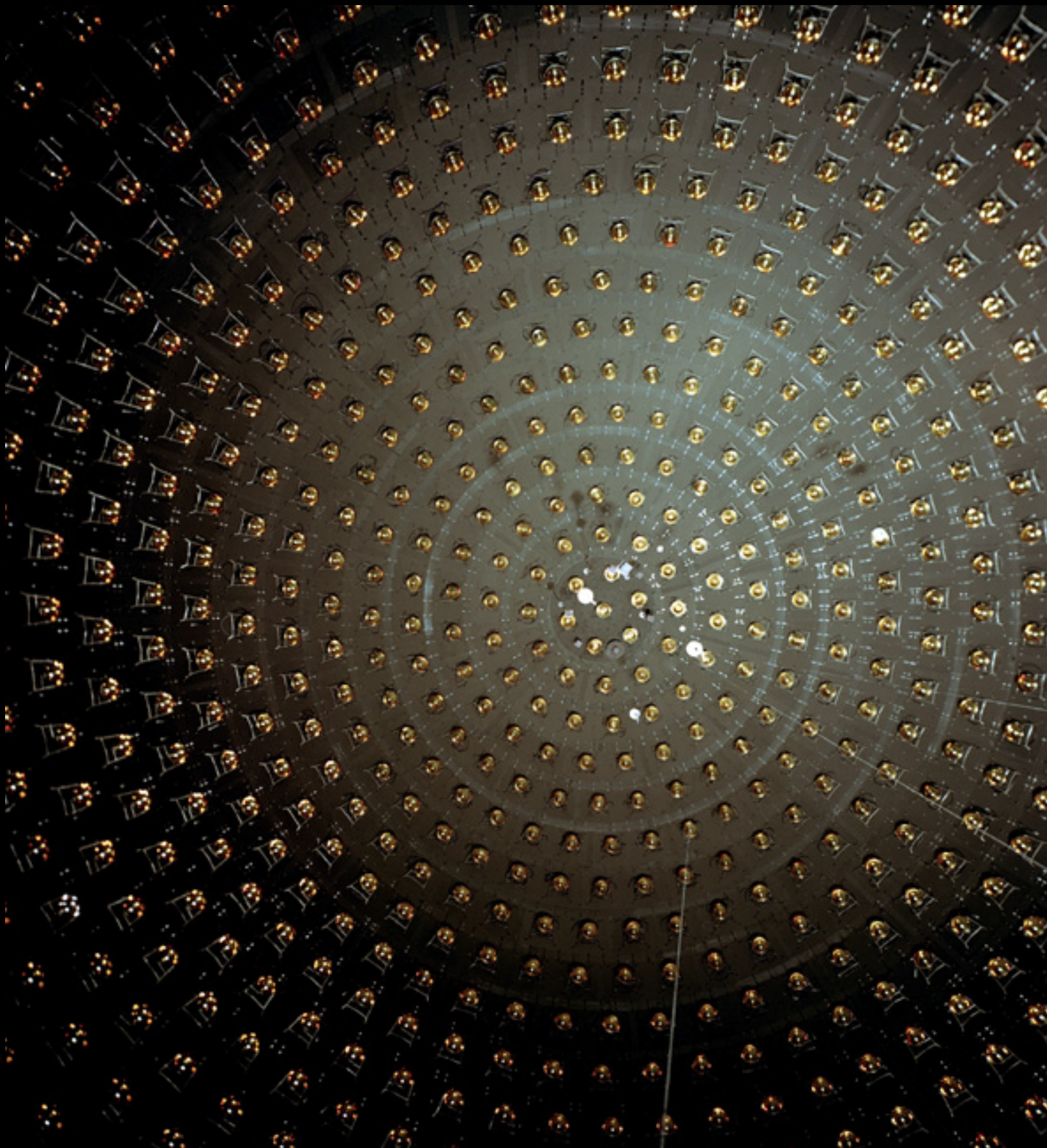
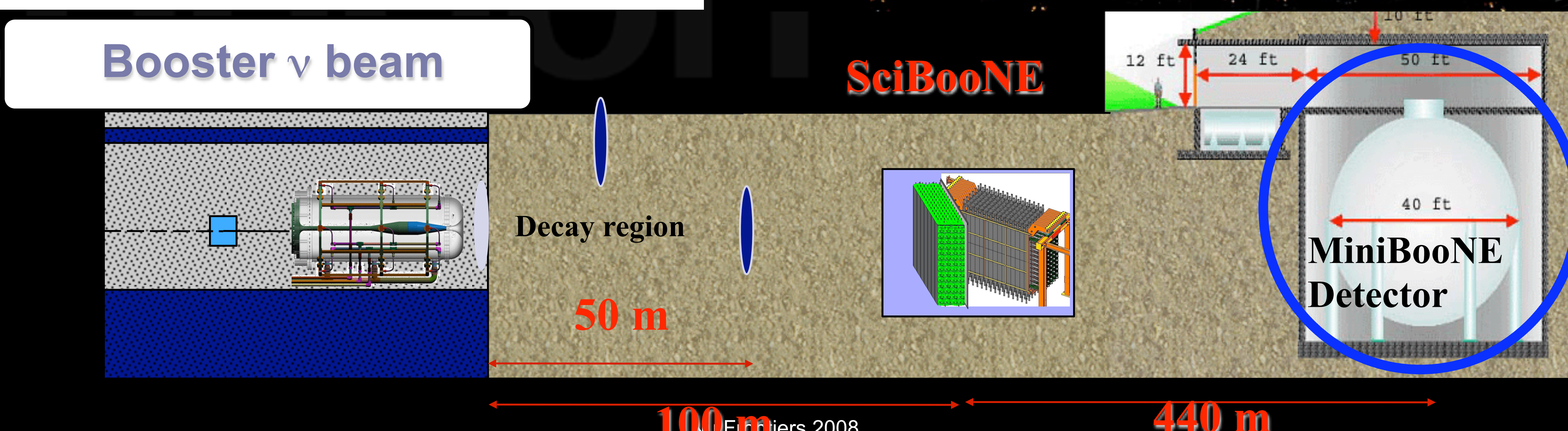


Detector



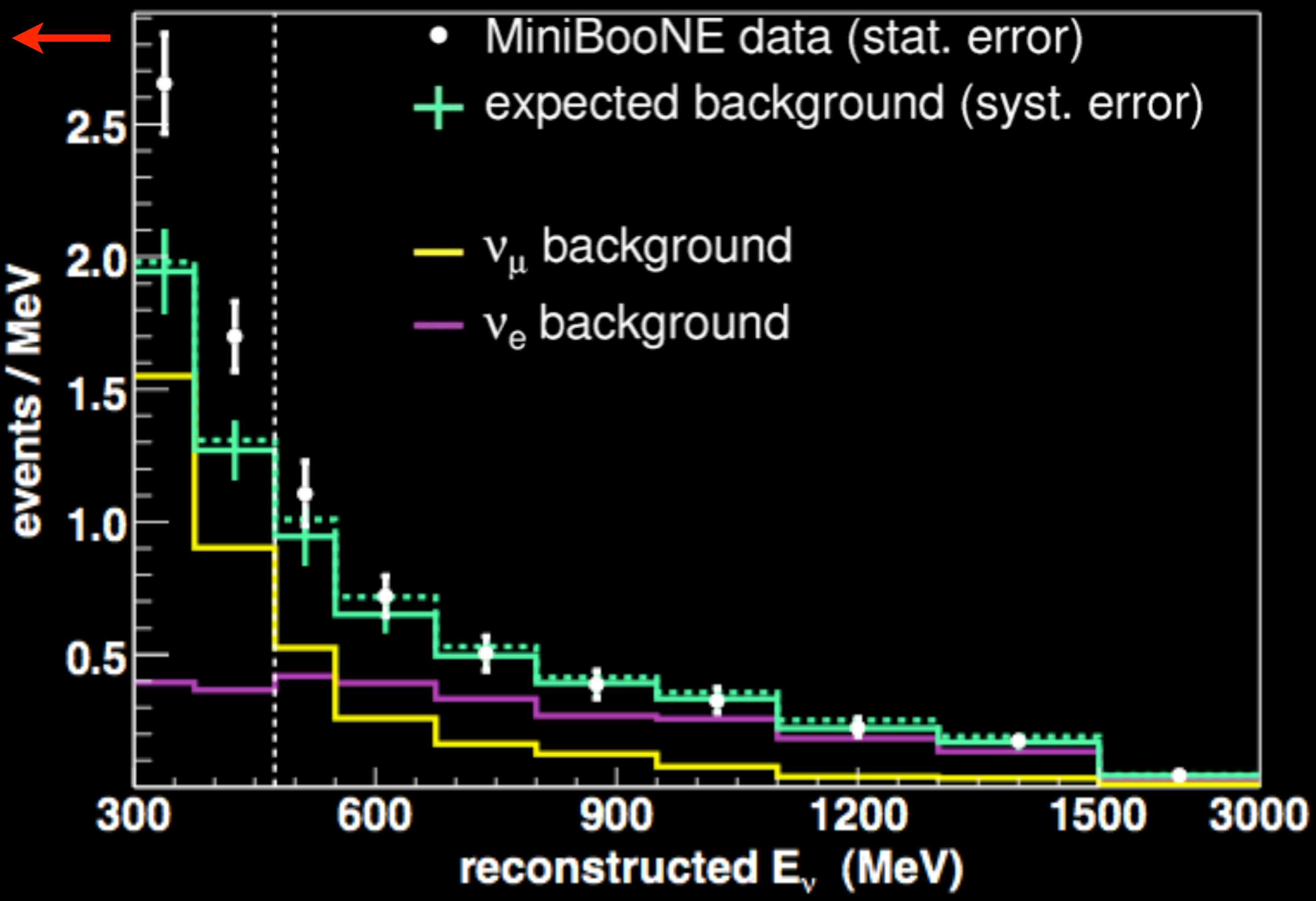


Detector NIM article:
arXiv:0809.2447v1 [hep-ex]



More Data

- More data always helps
- Extended threshold to lower energy
  - *Excess persists below 300 MeV*
- Collected 0.84E20 POT more during SciBooNE neutrino run
  - *Excess persists in new data*



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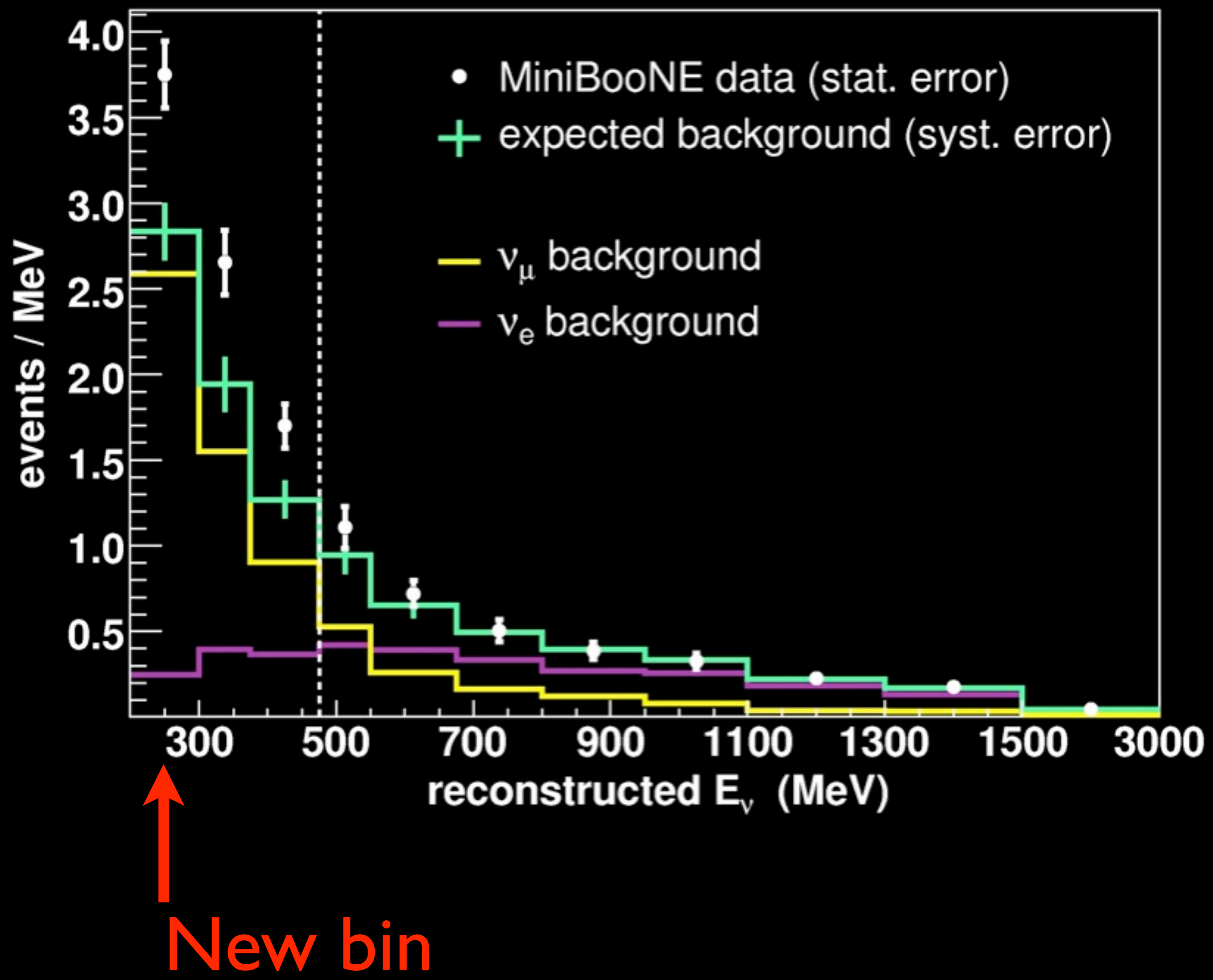

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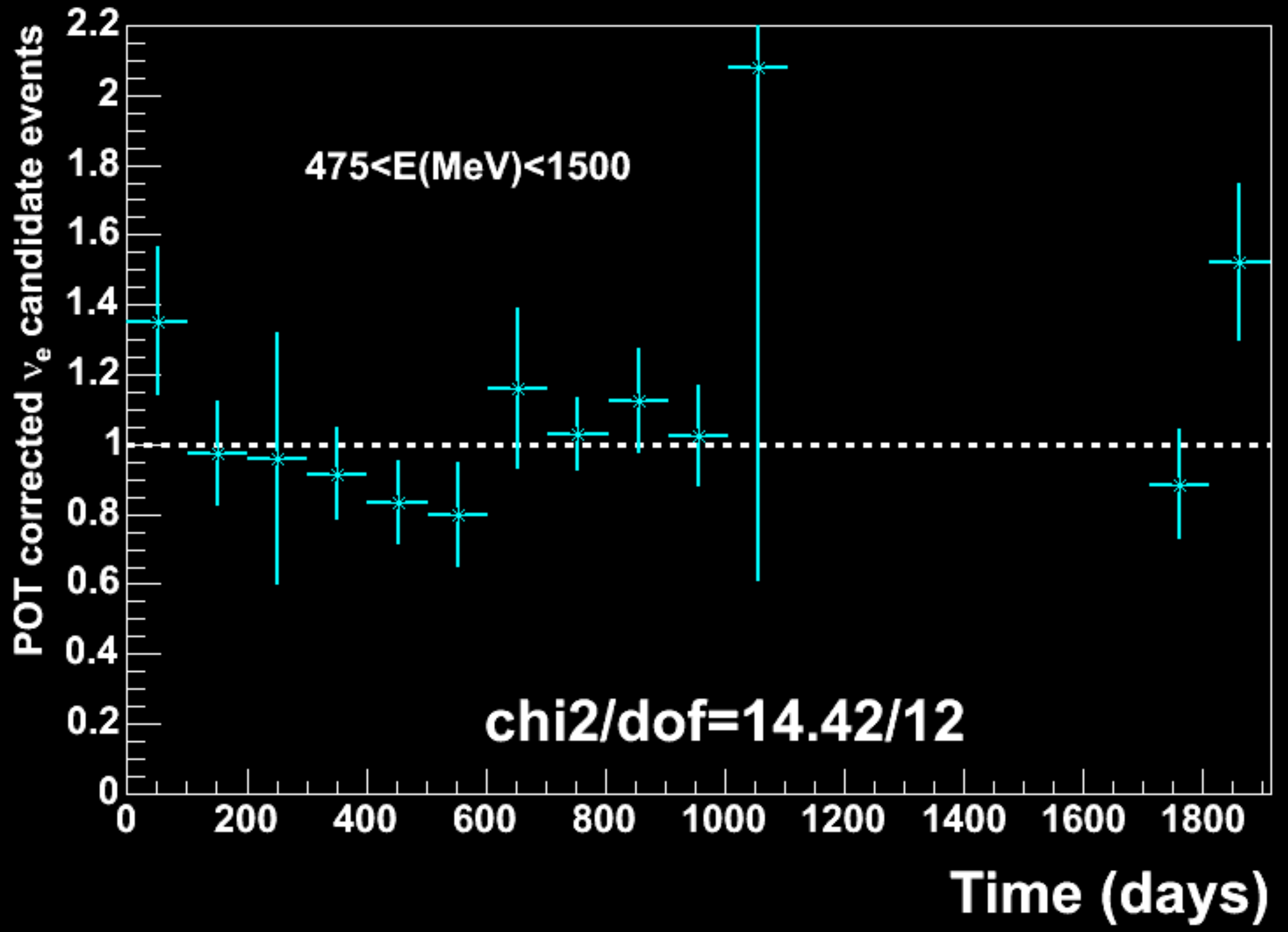

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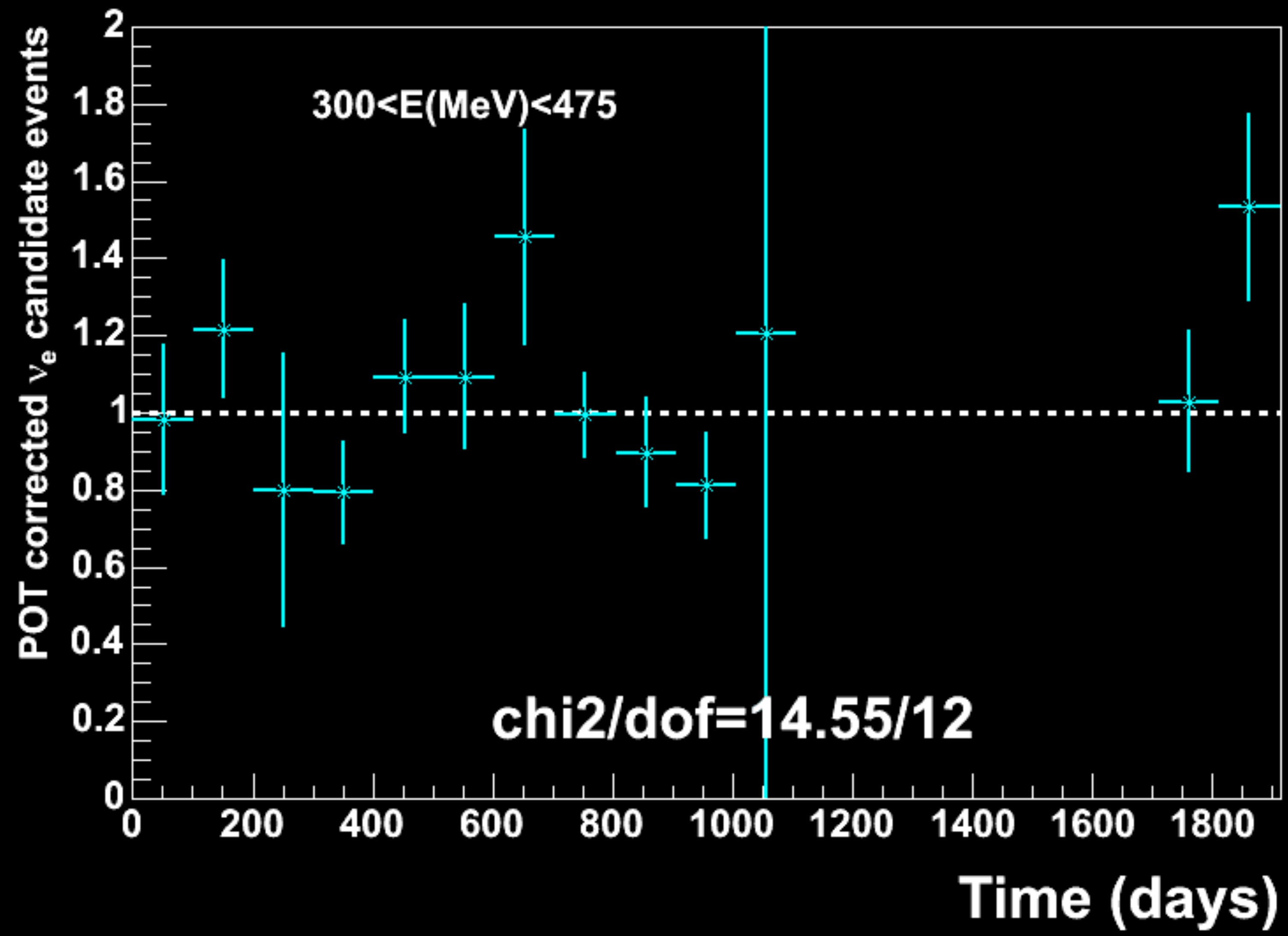
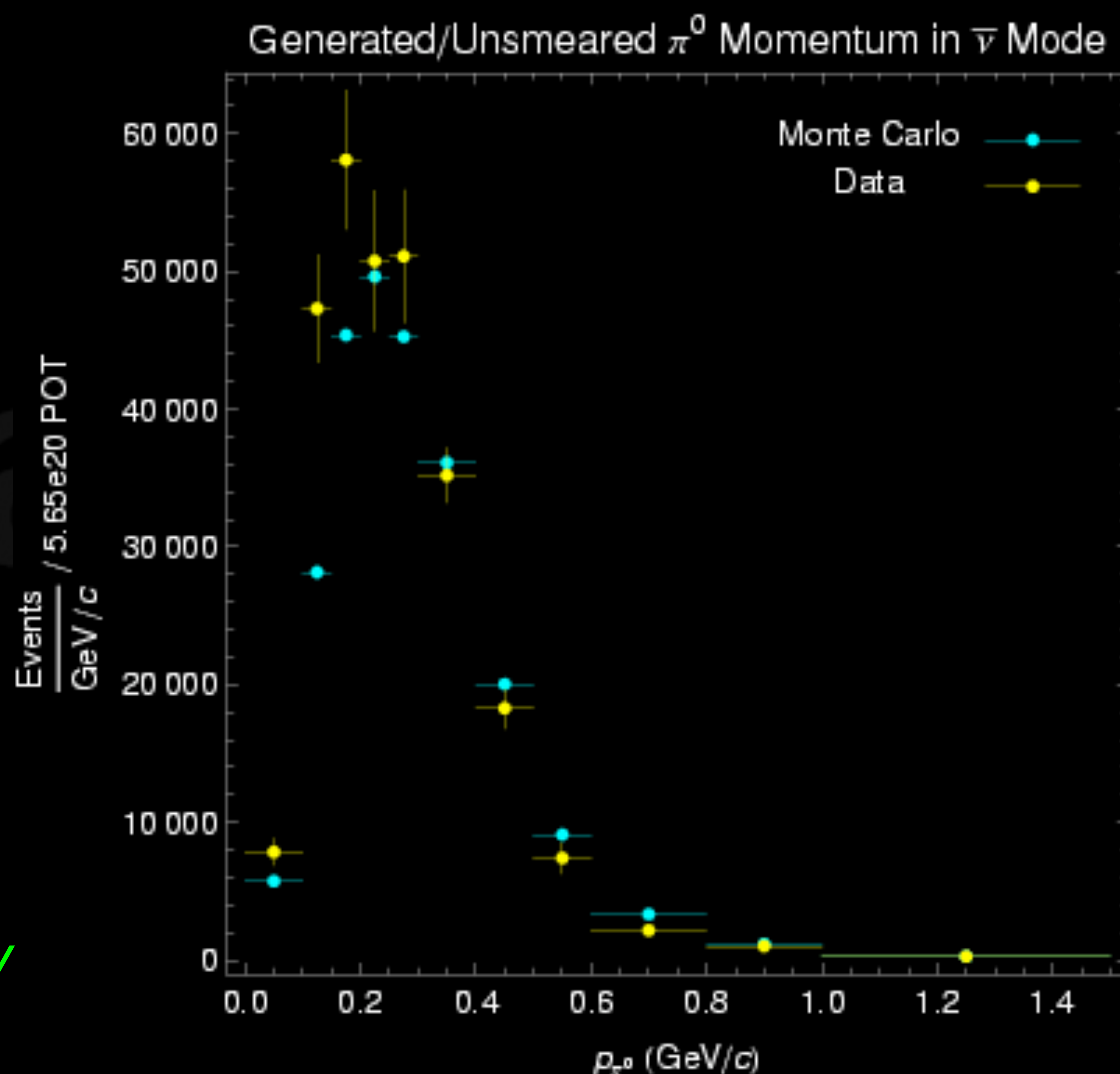


π^0 Backgrounds

- Complete redo of π^0 analysis
- Use *in-situ* measurement of NC coherent pion fraction
- Improvement of $\Delta \rightarrow N\gamma$ prediction
- Bottom line:
  - *small change in BG*
  - *slight increase in uncertainty*



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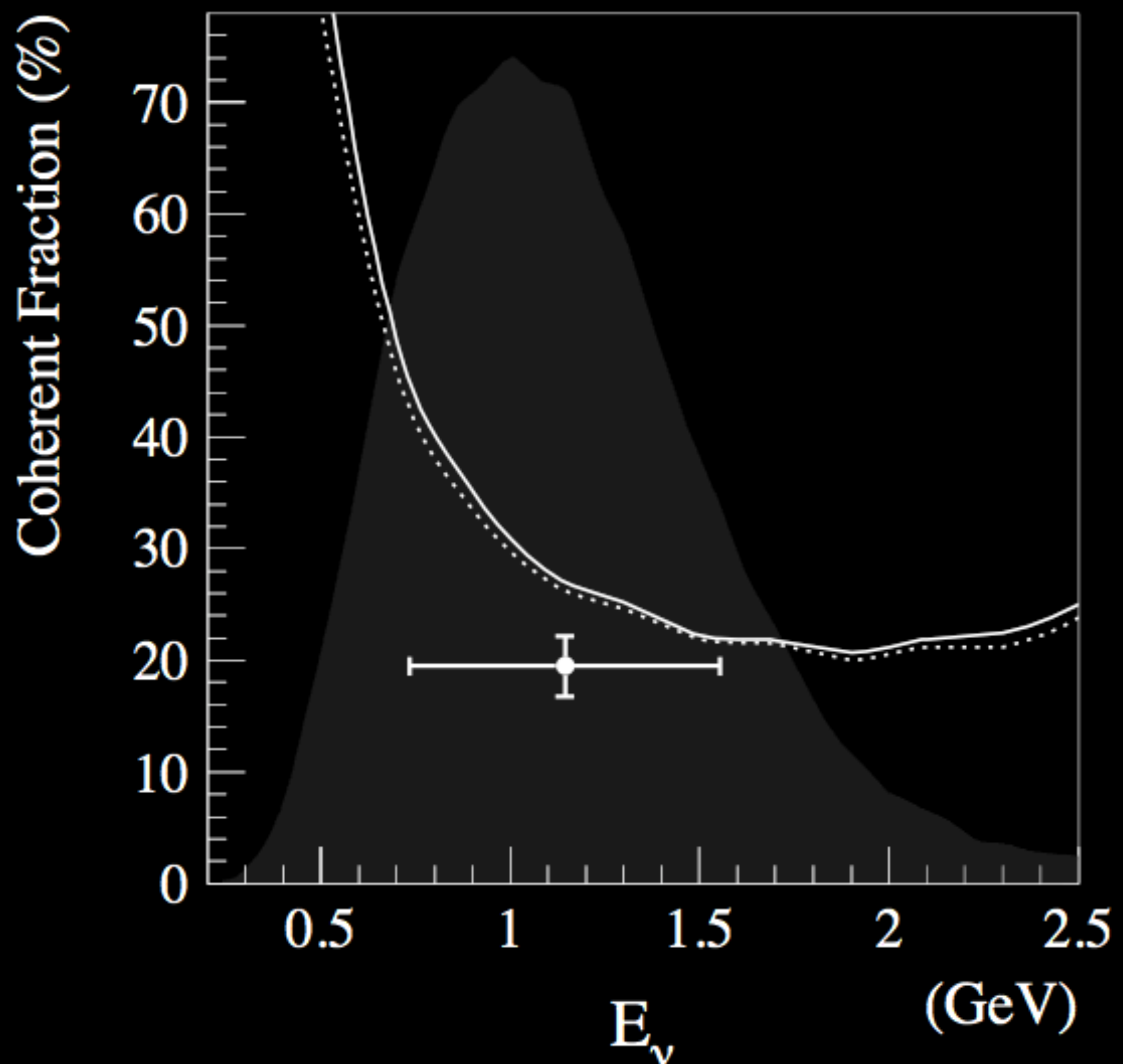
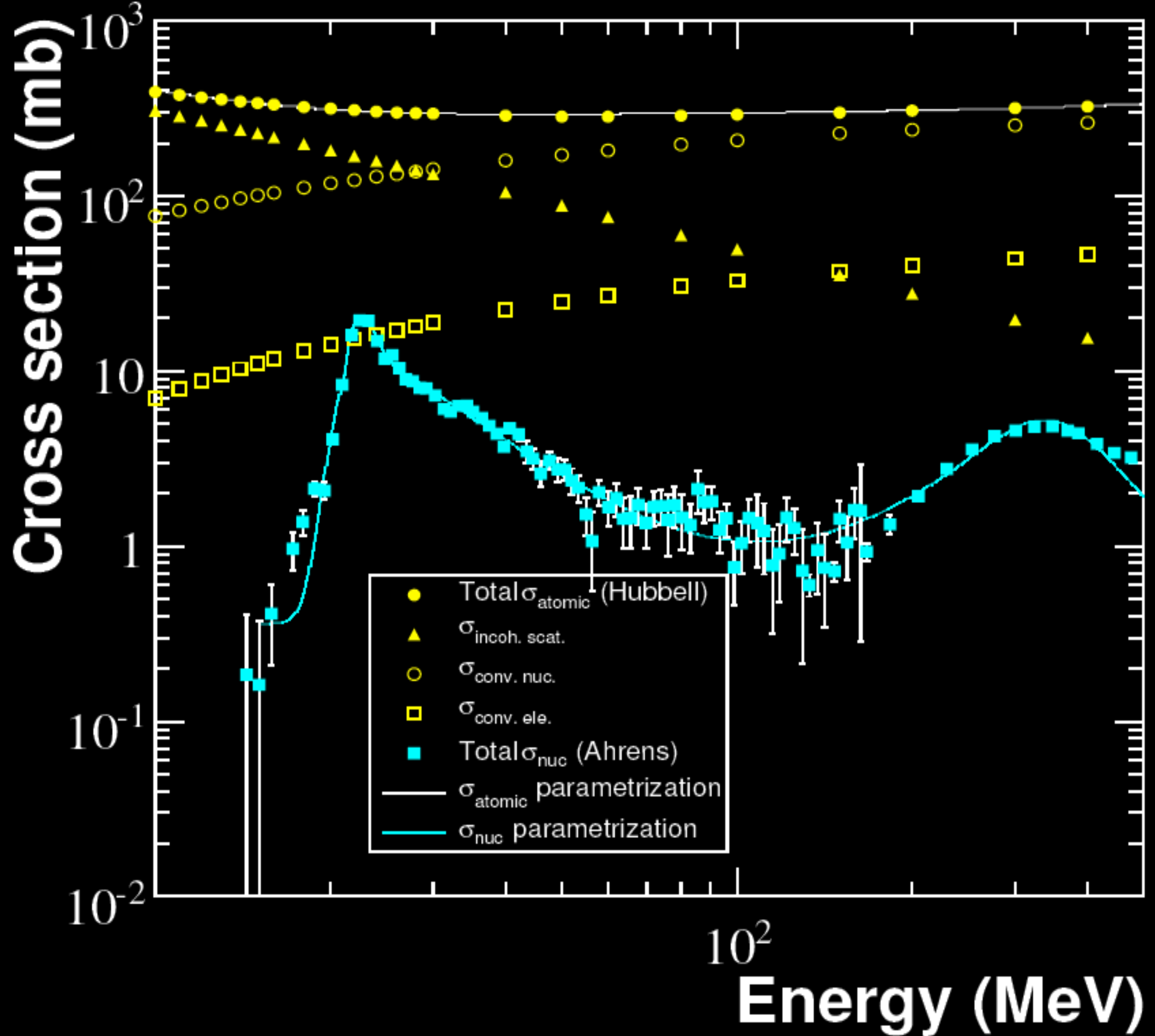


Phys. Lett. B. 664, 41 (2008)

Hadronic Processes



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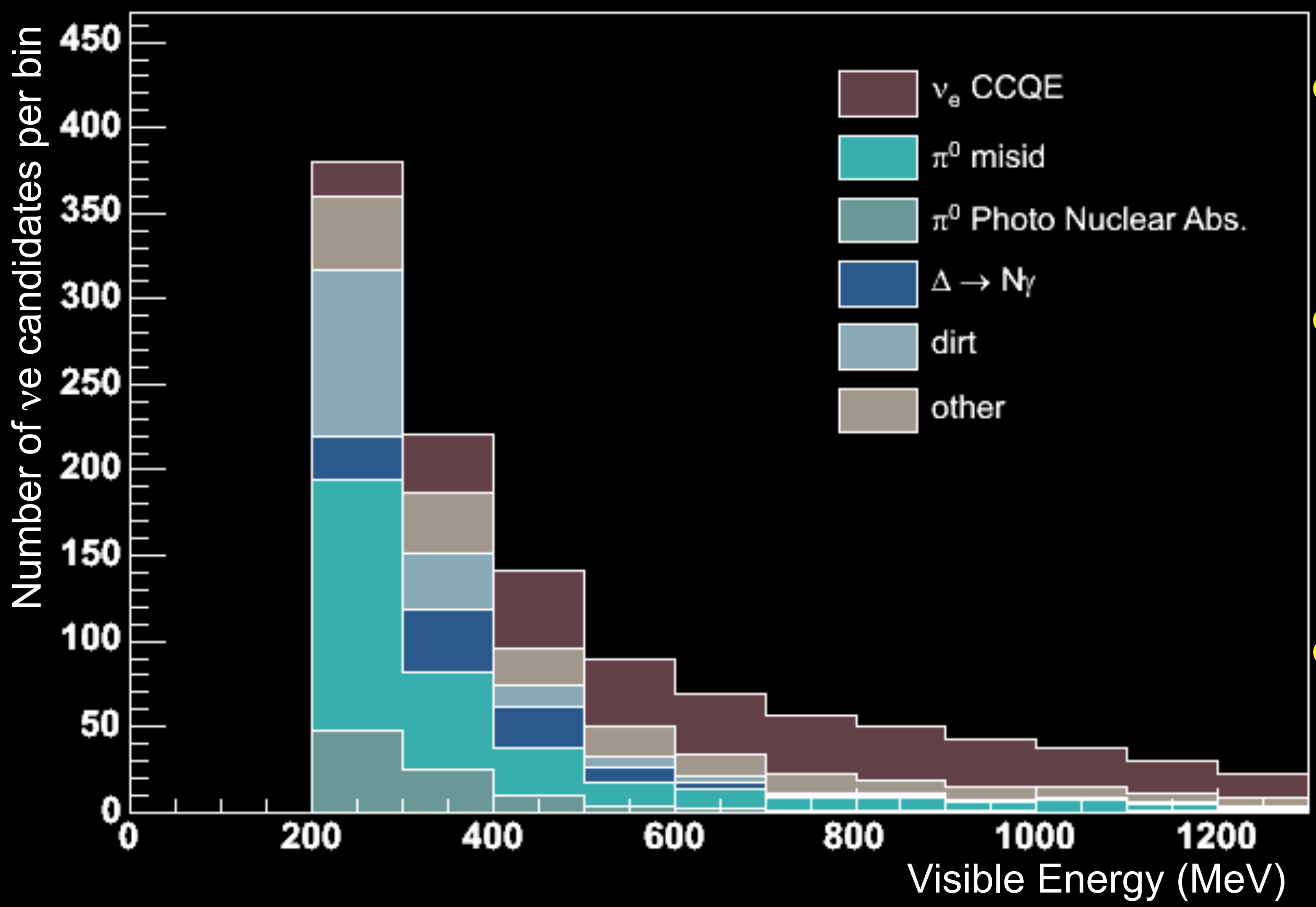

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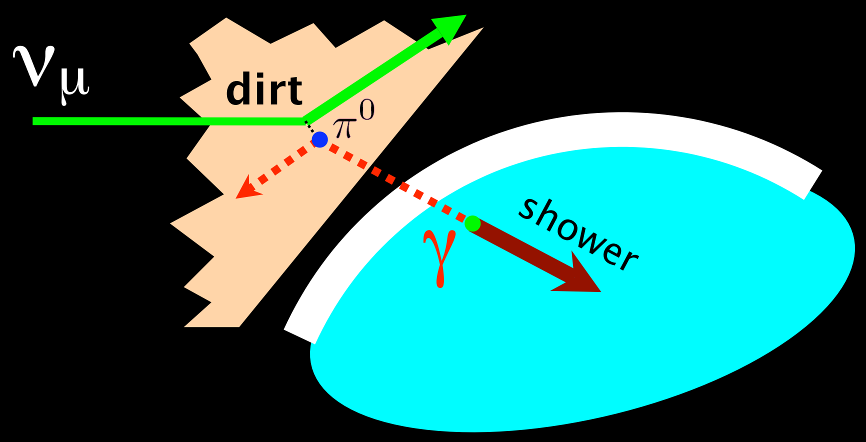
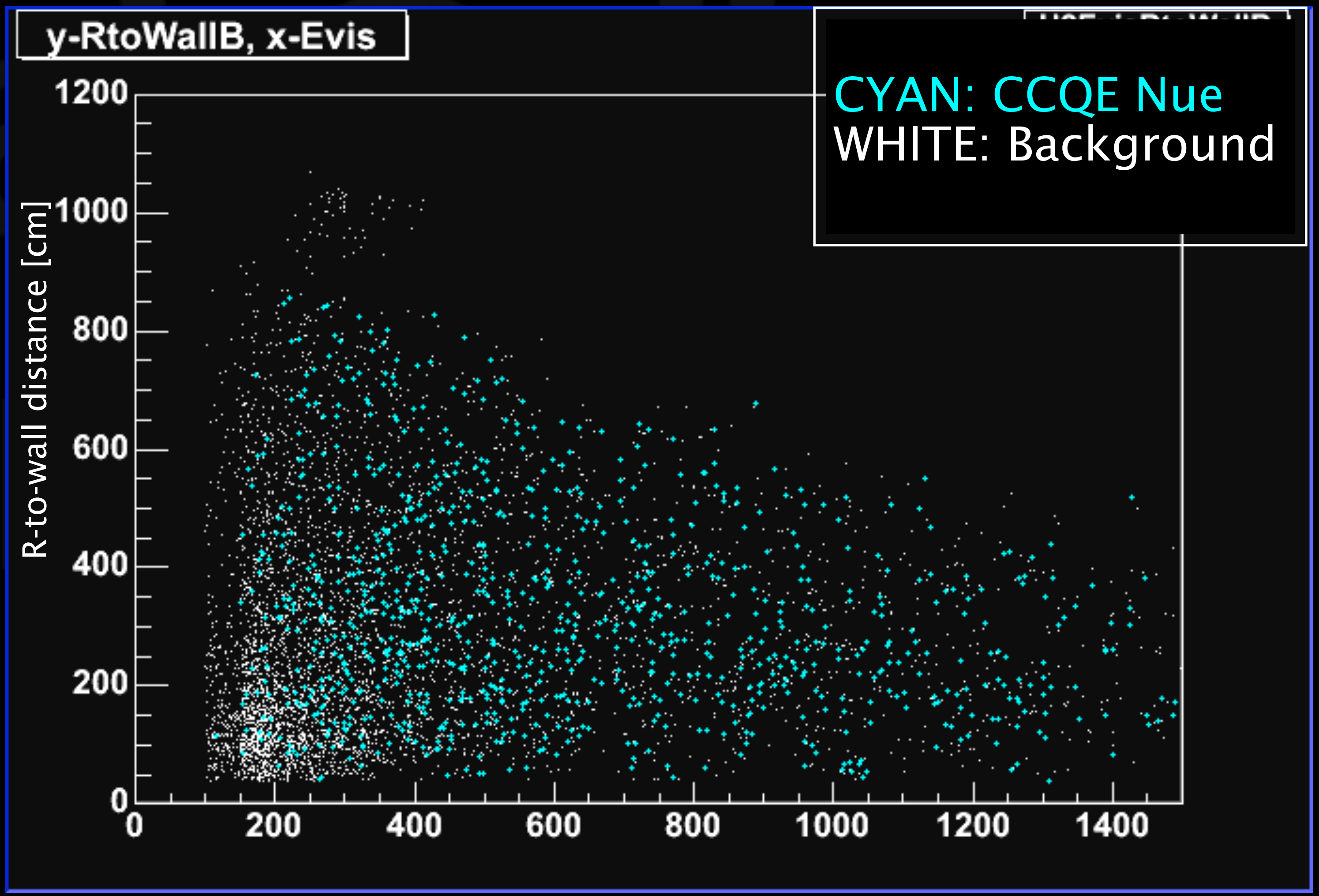


- “Dirt” events are neutrinos interacting outside the detector and sending secondary particles into the fiducial volume
  - Neutral particles can pass through veto
- Use energy-distance cut to remove most dirt backgrounds



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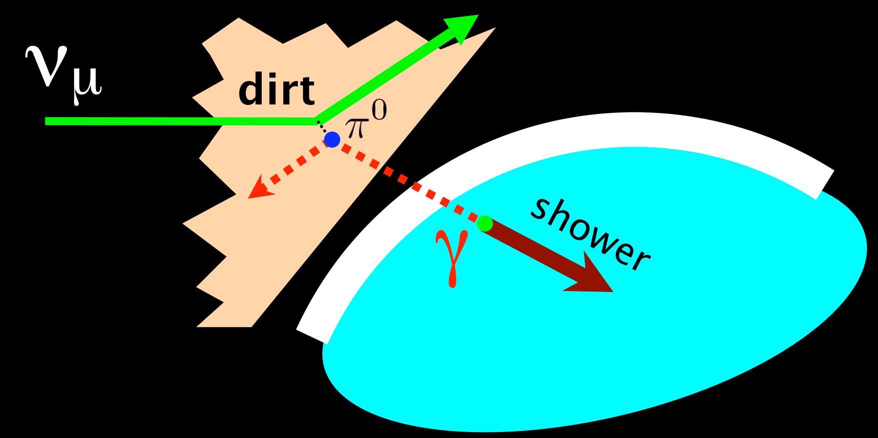
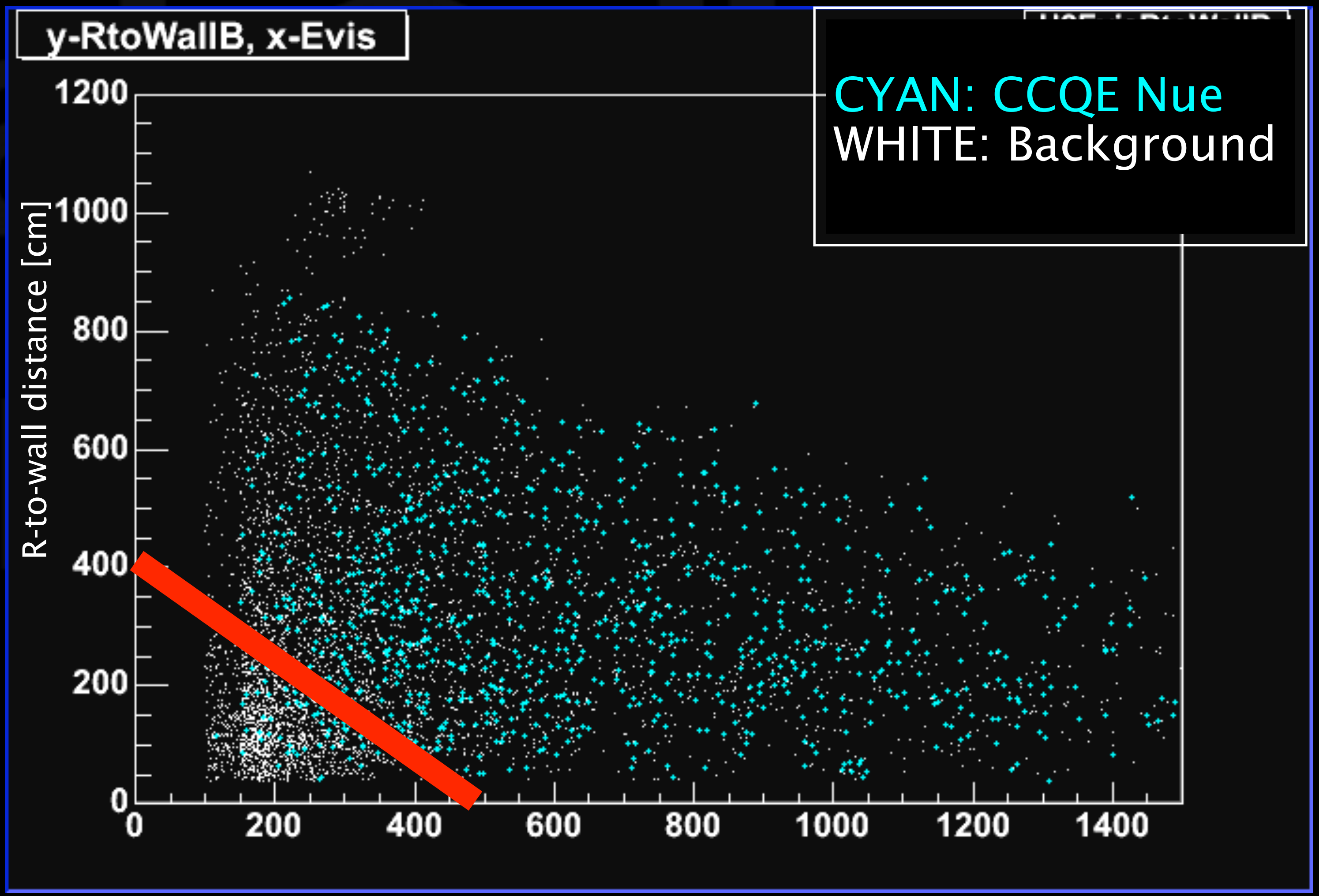


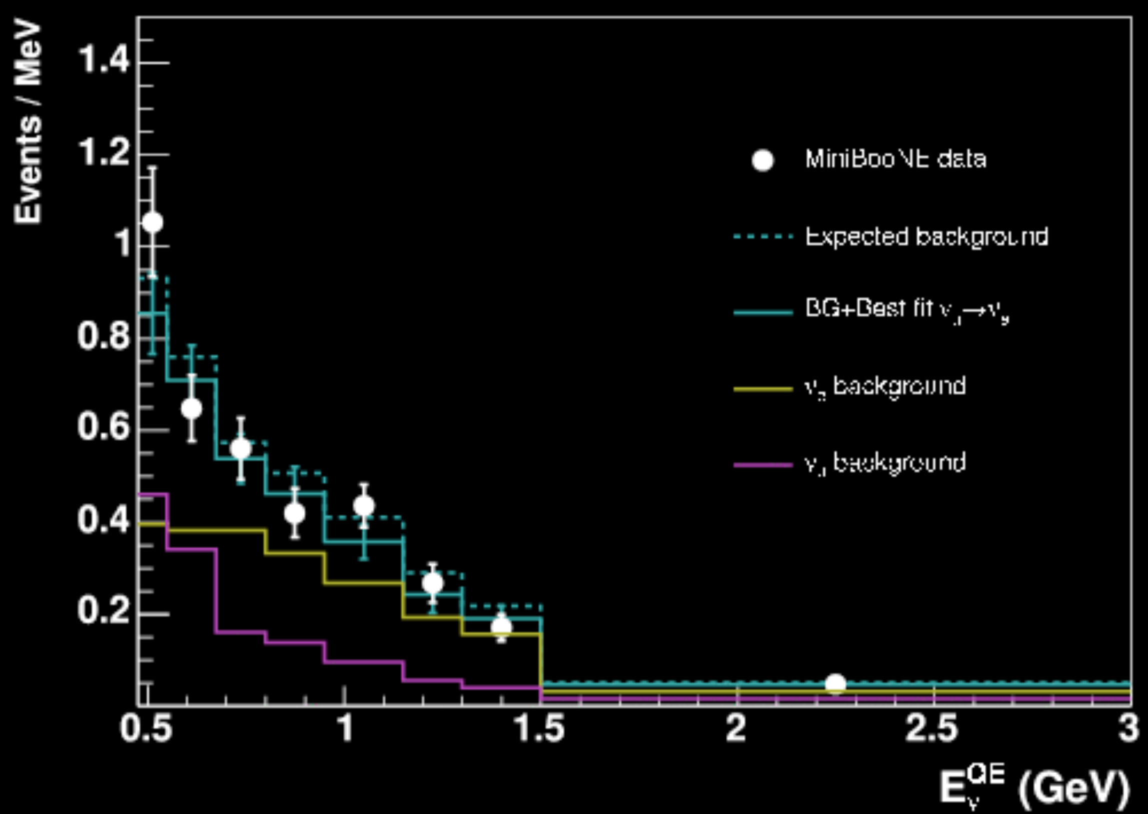


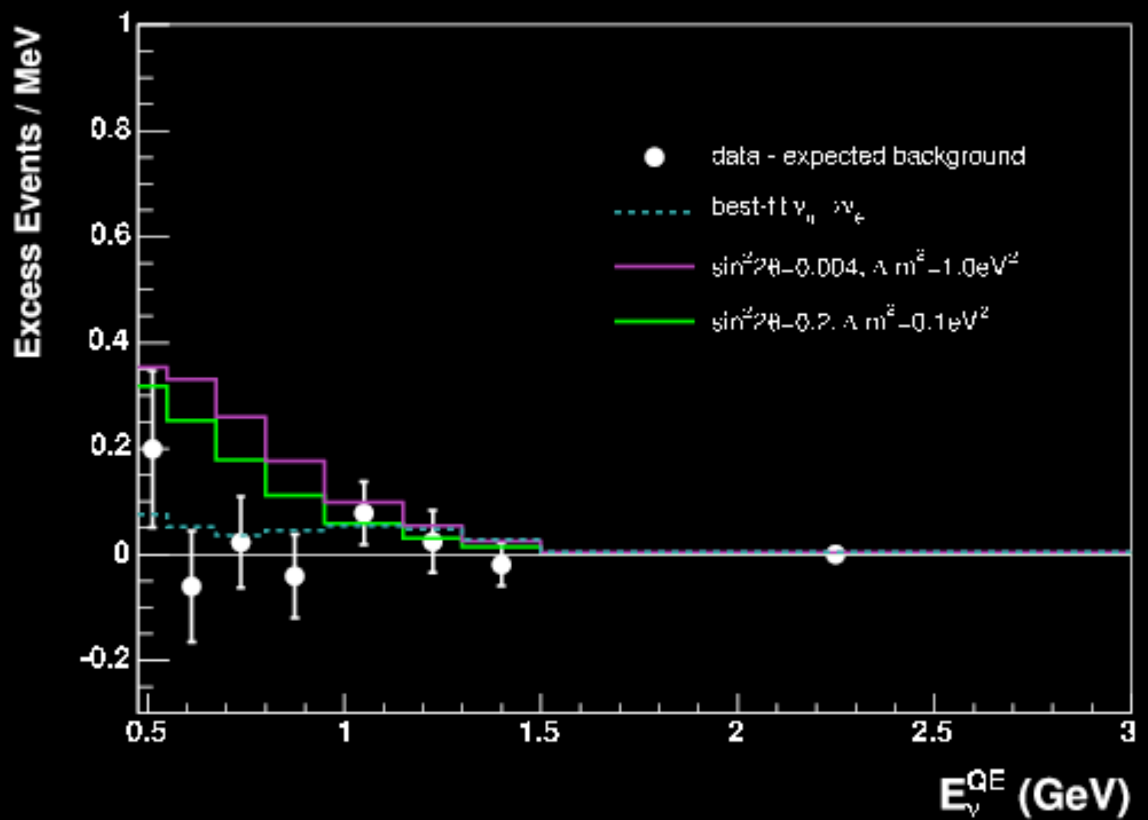
Update Summary

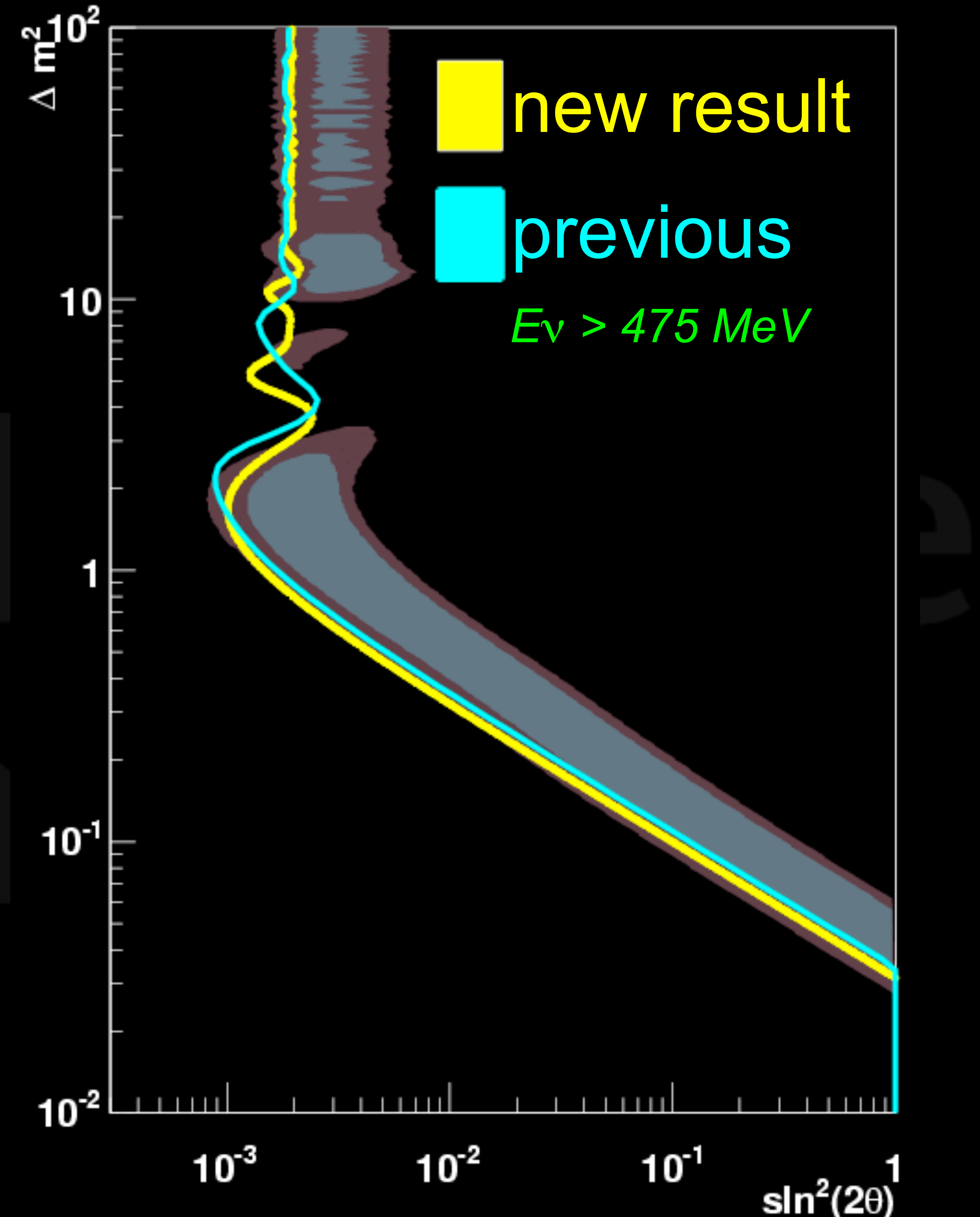
- ↓ Photonuclear effects
- ↔ Hadronic errors
- ↓ Better handling of beam π^+ errors
- ↑ Improved measurements of π^0s
- ↑ Incorporation of coherent π^0 fraction
- ↓ Better handling of Δ radiative decays
- ↔ Better modeling and cuts to remove dirt BGs
- ↔ Use of improved final fitting (“CombinedFit”)

Publication circulating in collaboration

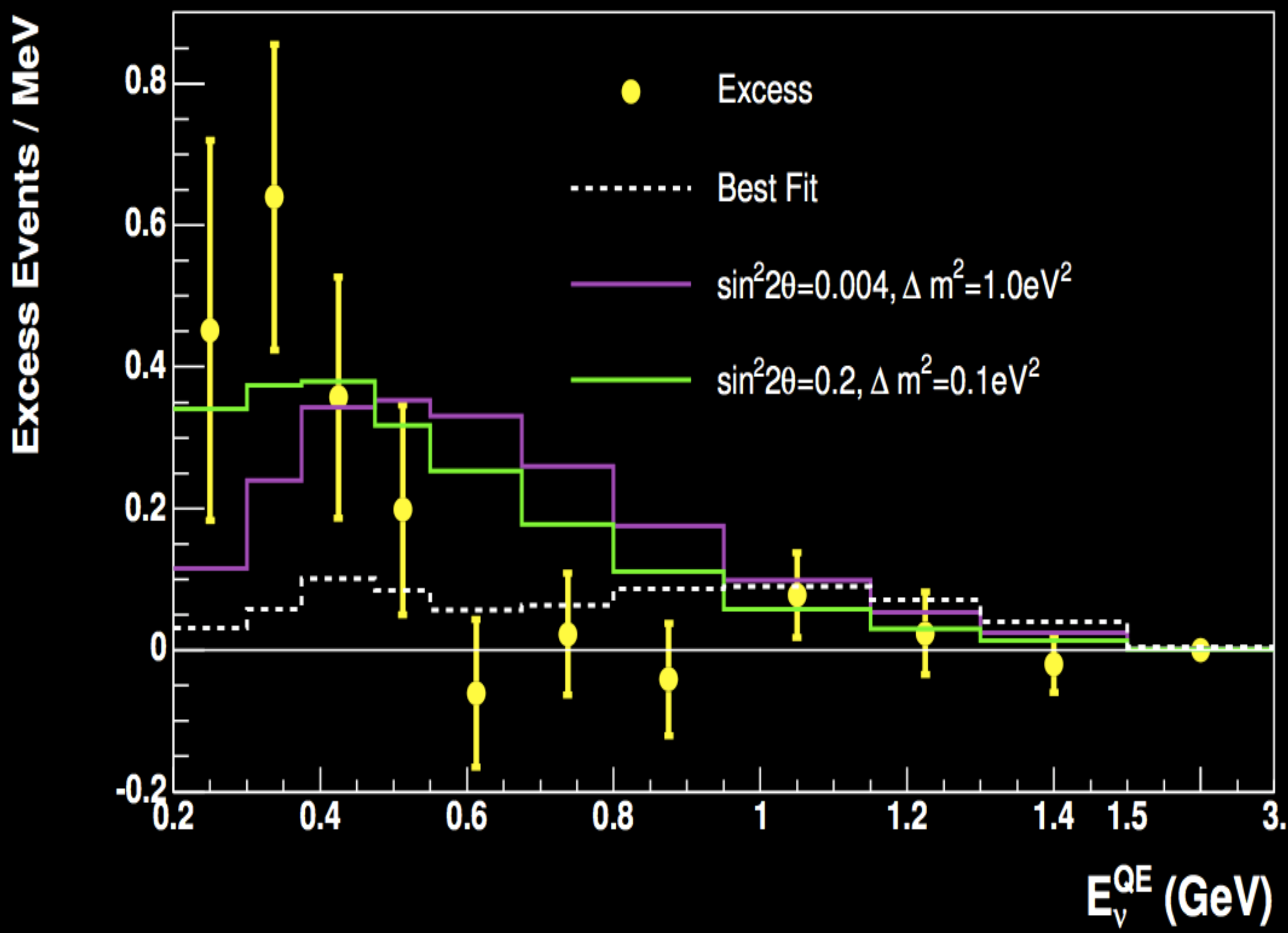
New ν_e Result





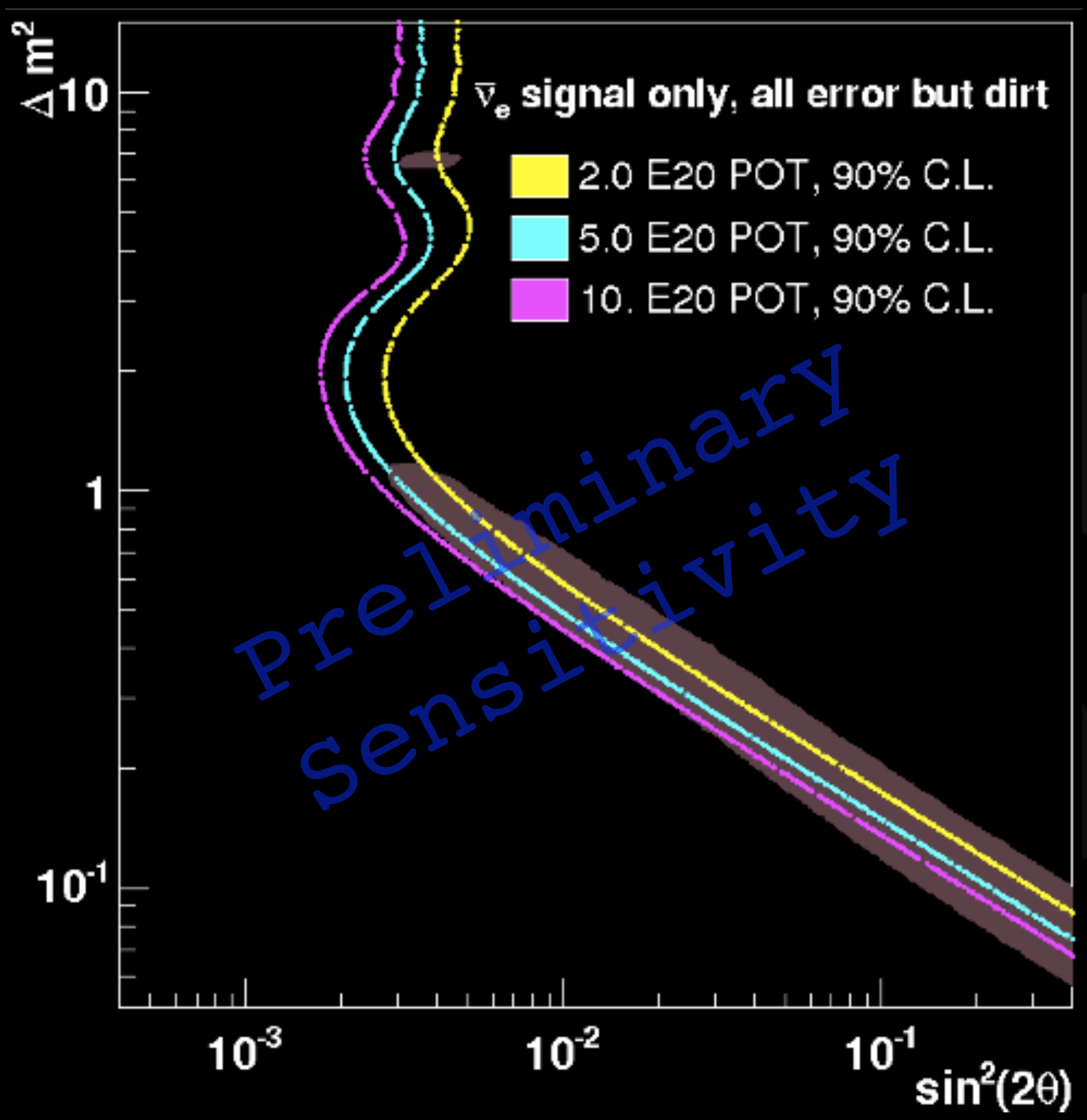


New Low Energy Excess



- Low energy excess has not vanished!
  - Oscillation energy region unaffected
- Final excess:
  - 128.8±43.4 (200-475 MeV)
  - 3.0σ significance of excess
- Shape of excess is not consistent with 2-ν oscillation hypothesis
- Hypothesis comparisons being processed now
- *Paper draft in circulation*

$\bar{\nu}_e$ Appearance



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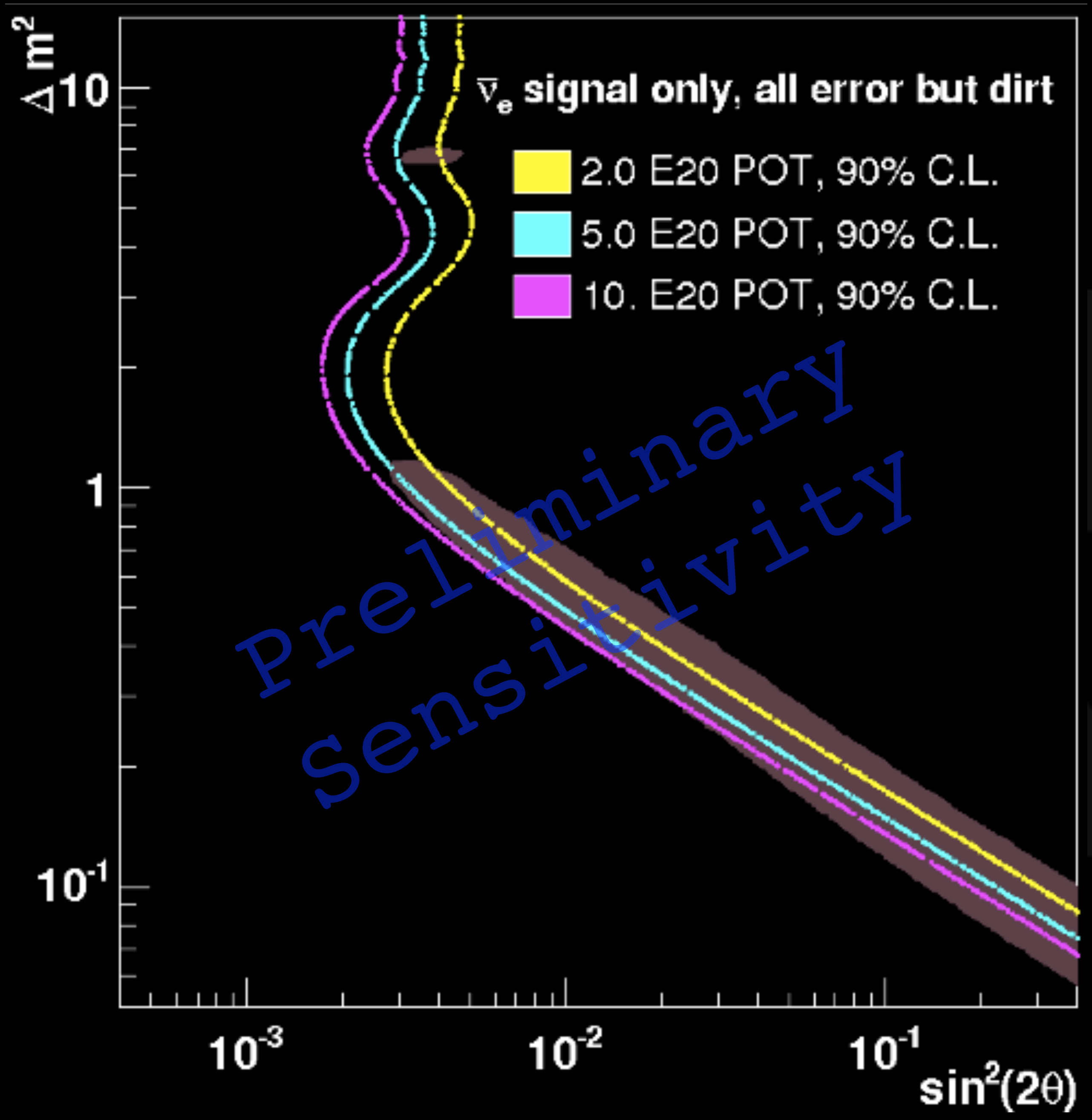
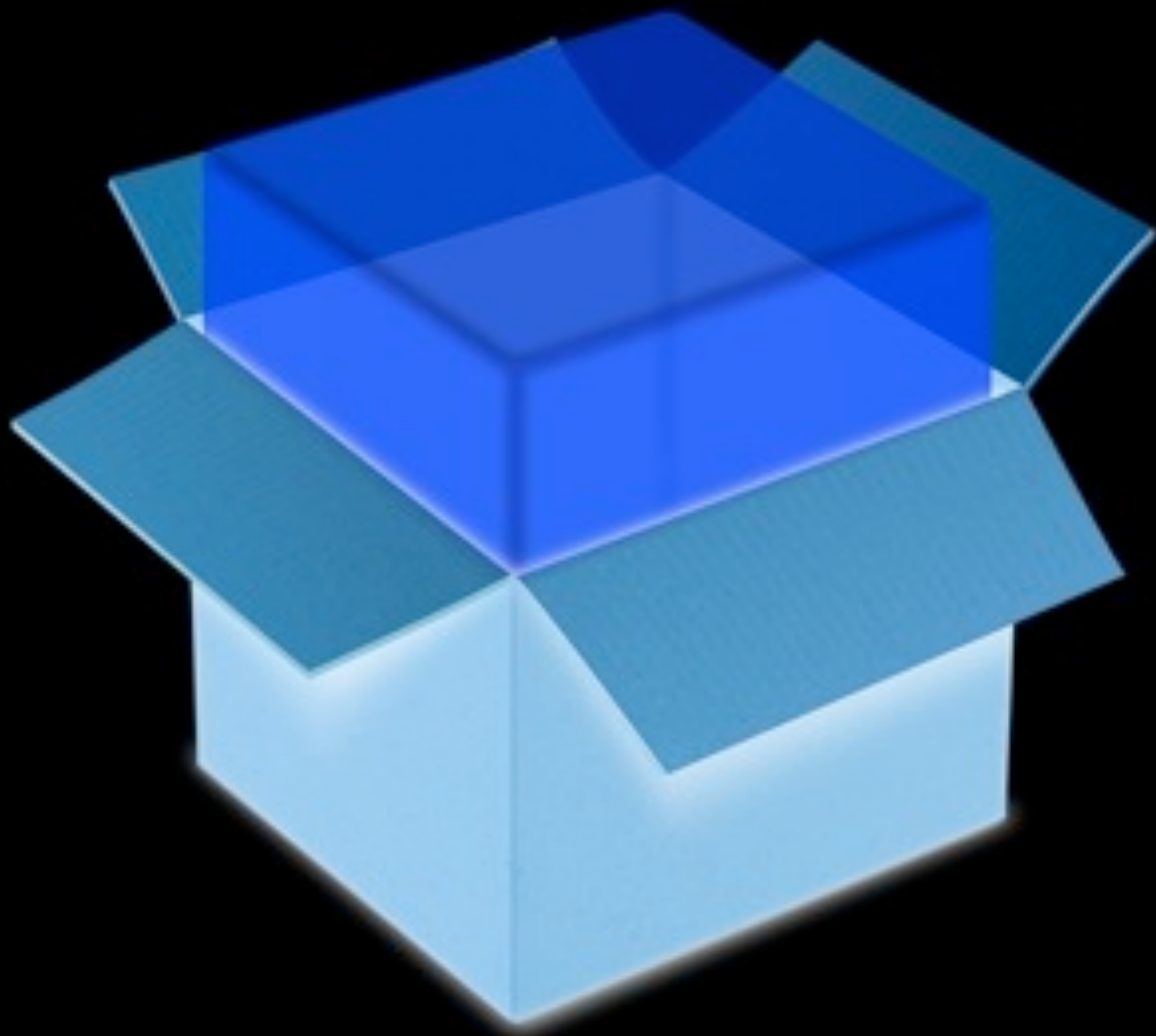


- Goal is to search for $\bar{\nu}_e$ appearance with sensitivity similar to ν_e appearance search

$\bar{\nu}_e$ Appearance



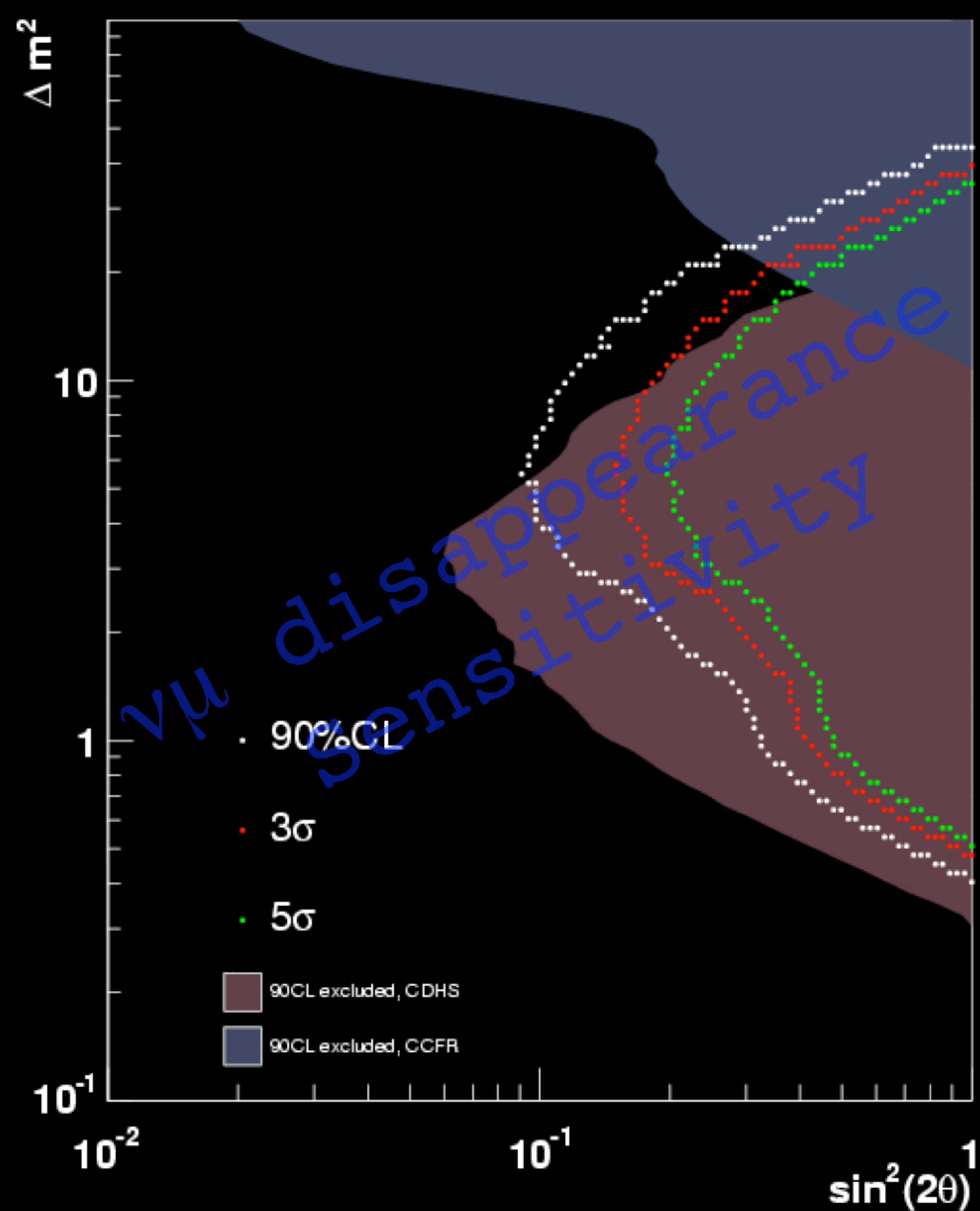
- Goal is to search for $\bar{\nu}_e$ appearance with sensitivity similar to ν_e appearance search
- The box has been opened!
- *Fermilab seminar announcing final result in Dec!*

ν_μ Disappearance

K. Mahn

- With one detector, compare $E\nu$ data to MC and look for shape distortions
  - Analysis with SciBooNE as near detector in progress

    (See Hide Tanaka's talk Sunday)
- Also search for $\bar{\nu}_\mu$ disappearance



Fermilab seminar announcing final result Oct 31

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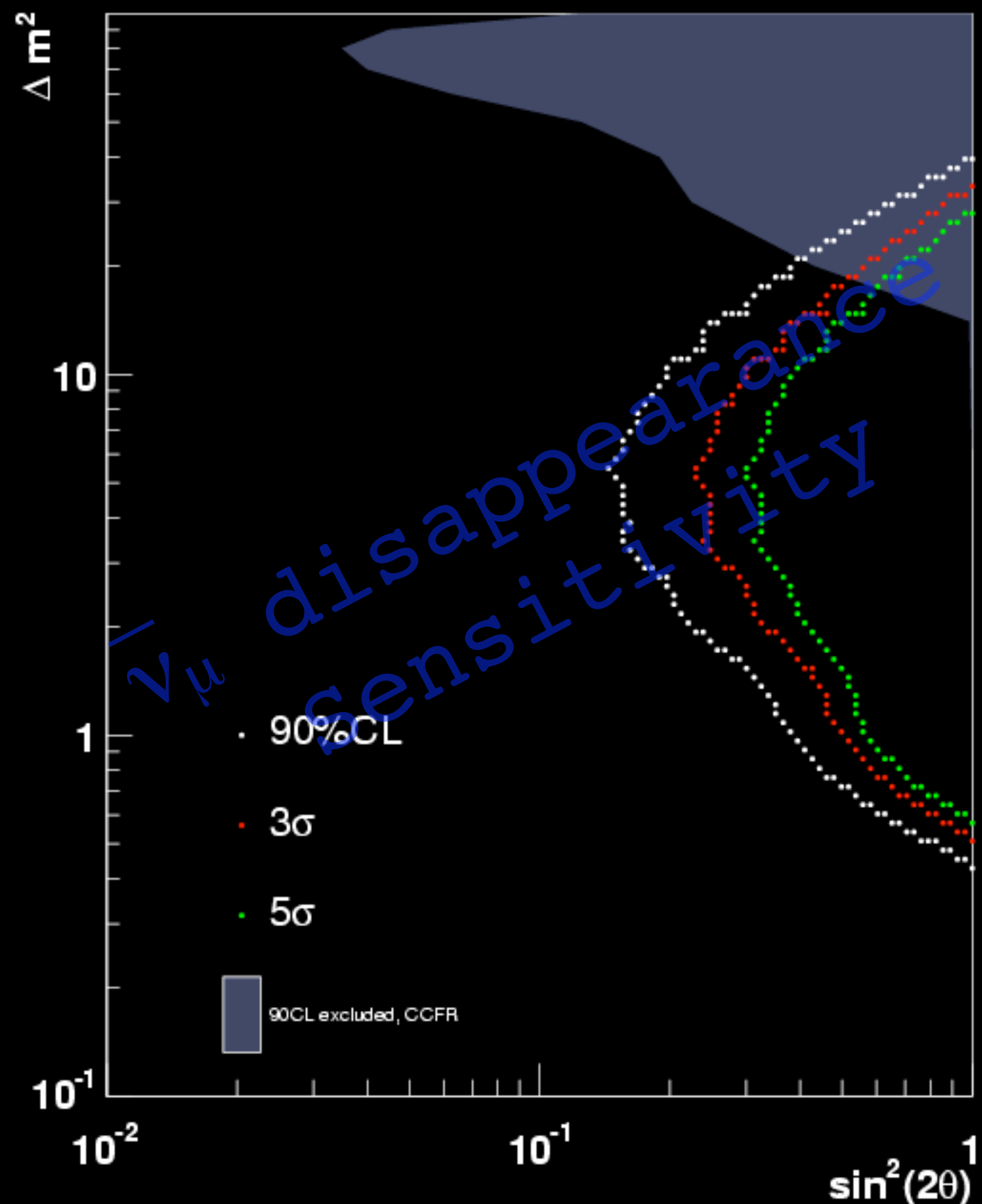
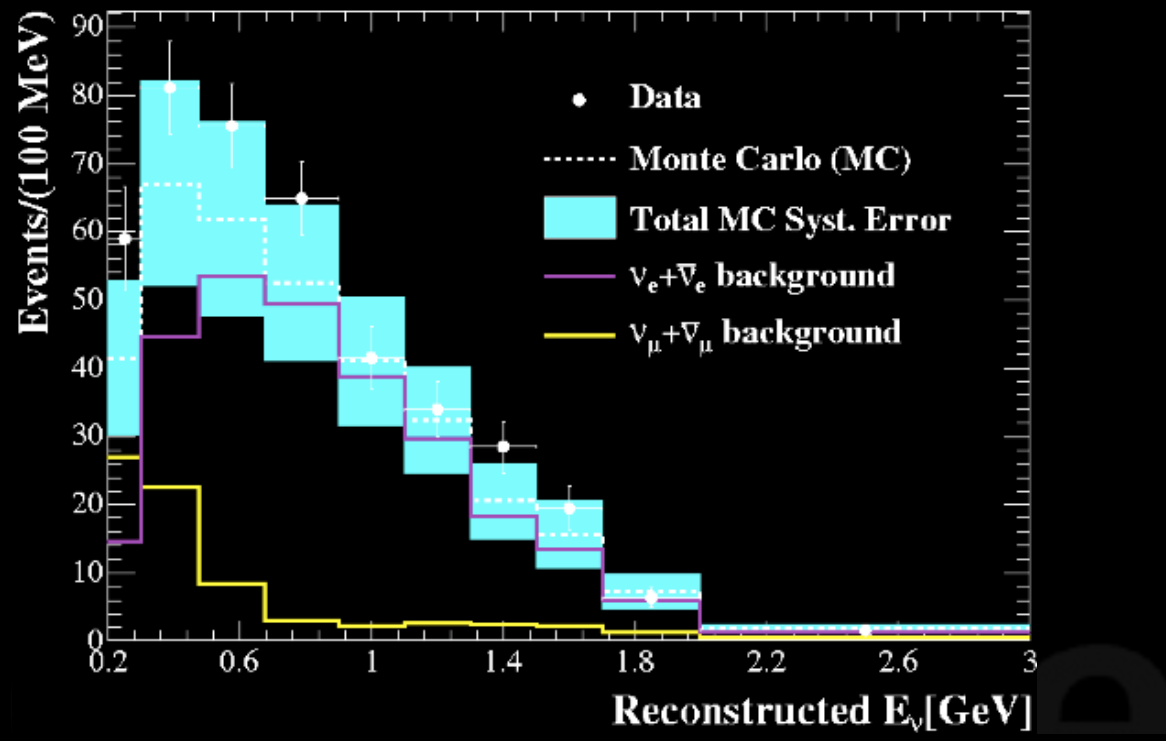
Fermilab seminar announcing final result Oct 31

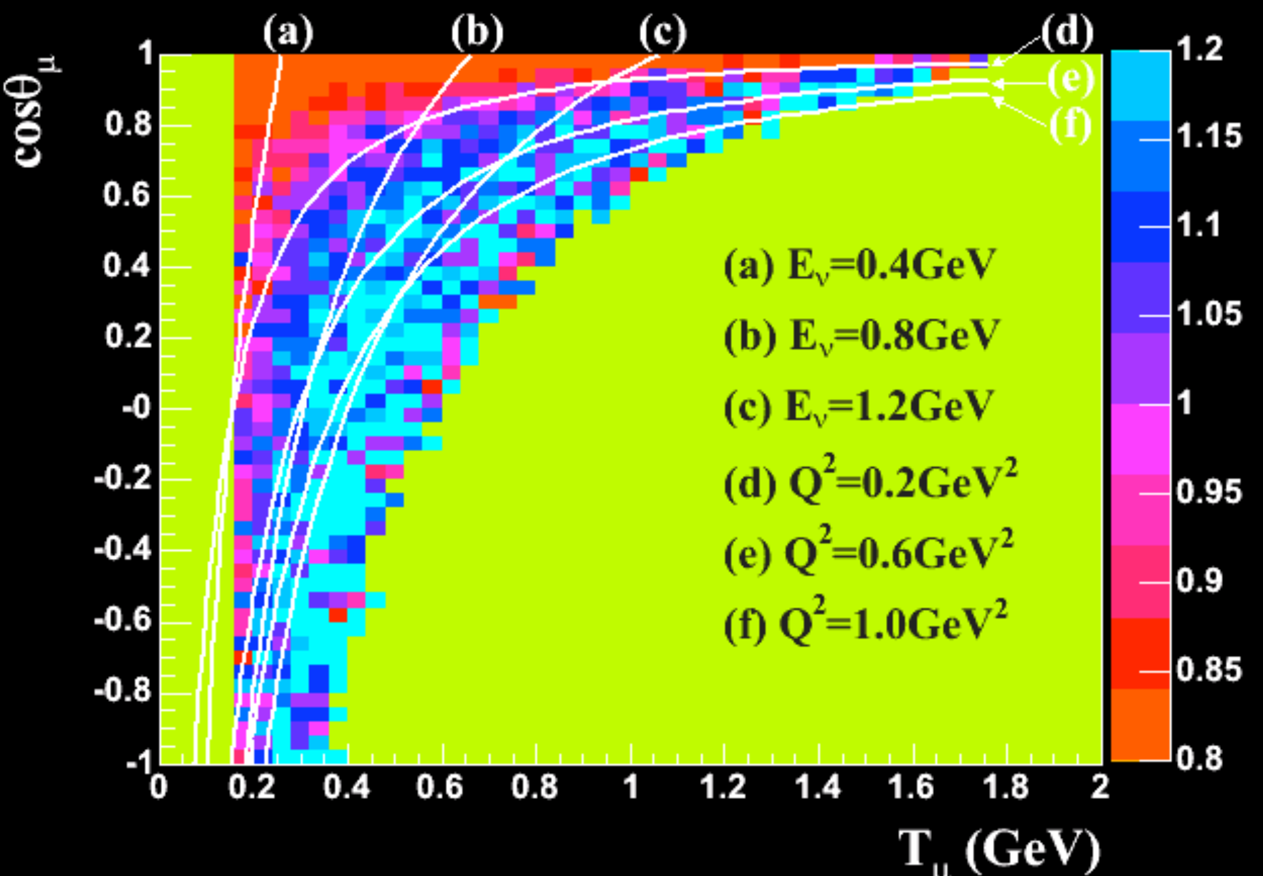
K. Mahn



Things I Skipped

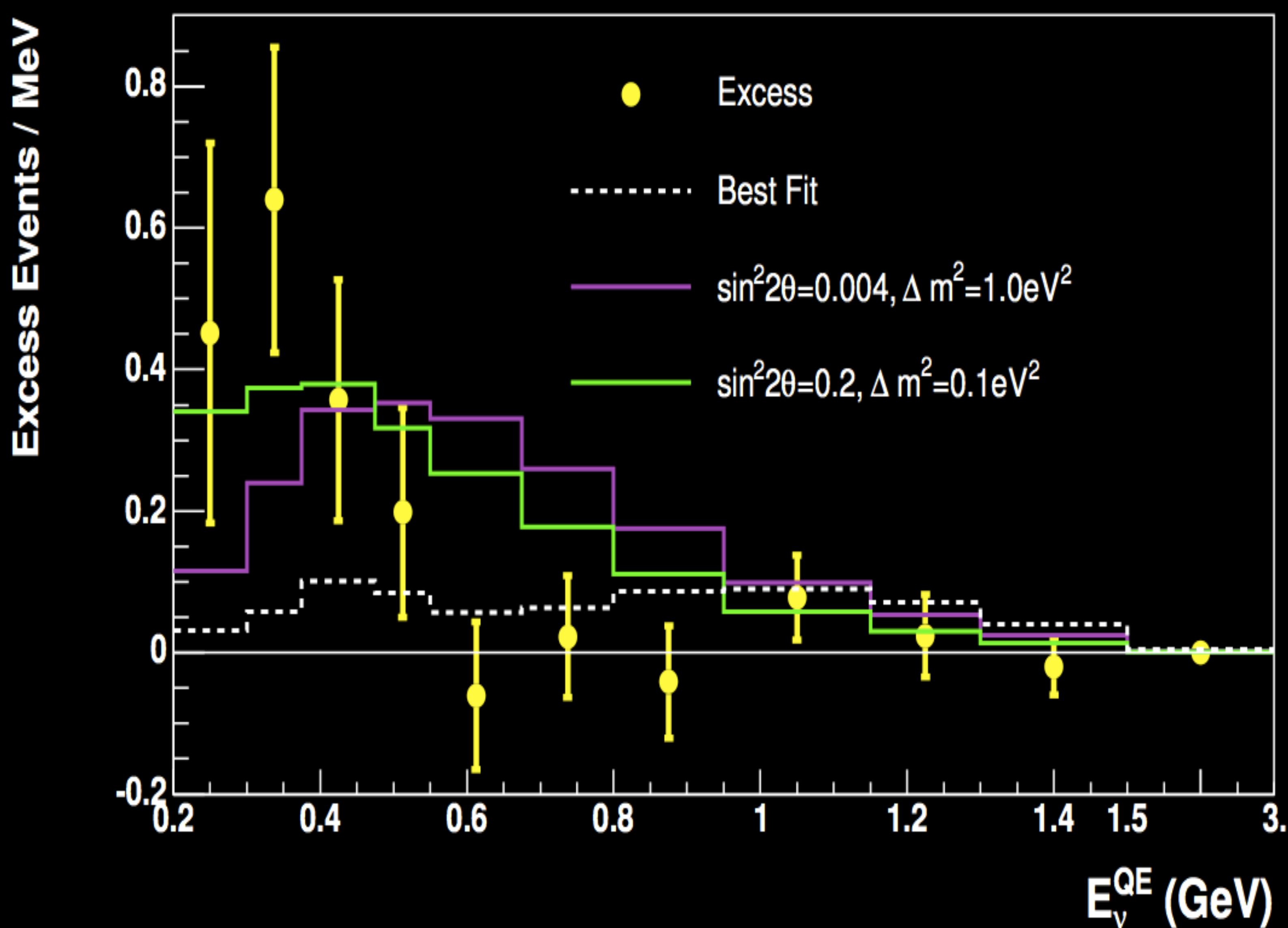
- Global oscillation fits
  Phys. Rev. D. 78, 012007 (2008)
- NuMI neutrinos in MinBooNE
  arXiv:0809.2447[hep-ex]
- Many cross section analyses
  - CCQE
    Phys. Rev. Lett. 100, 032301 (2008)
  - NCπ^0
    Phys. Lett. B. 664, 41 (2008)
  - CC1π+
  - NC elastic
- Exotic analyses...





Summary

- MiniBooNE's low energy excess is real!
- Source of events is under investigation
- $\bar{\nu}_e$ appearance results coming out soon
  - *Dec FNAL Seminar*
    - Completes the true tes of LSND oscillation hypothesis
- ν_μ and $\bar{\nu}_\mu$ disappearance results soon
  - *Oct 31 FNAL Seminar*




Thanks!
MINNESOTA

Backups

MiniBooNE Collaboration

A. A. Aguilar-Arevalo[5], A. O. Bazarko[12], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[11], L. Coney[5], J. M. Conrad[5], D. C. Cox[8], A. Curioni[16], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[16], R. Ford[7], F. G. Garcia[7], G. T. Garvey[9], J. A. Green[8,9], C. Green[7,9], T. L. Hart[4], E. Hawker[15], R. Imlay[10], R. A. Johnson[3], P. Kasper[7], T. Katori[8], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[12], J. M. Link[14], Y. Liu[11], Y. Liu[1], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[7], P. S. Martin[7], G. McGregor[9], W. Metcalf[10], P. D. Meyers[12], F. Mills[7], G. B. Mills[9], J. Monroe[5], C. D. Moore[7], R. H. Nelson[4], P. Nienaber[13], S. Ouedraogo[10], R. B. Patterson[12], D. Perevalov[1], C. C. Polly[8], E. Prebys[7], J. L. Raaf[3], H. Ray[9], B. P. Roe[11], A. D. Russell[7], V. Sandberg[9], R. Schirato[9], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[12], D. Smith[6], M. Sorel[5], P. Spentzouris[7], I. Stancu[1], R. J. Stefanski[7], M. Sung[10], H. A. Tanaka[12], R. Tayloe[8], M. Tzanov[4], M. O. Wascko[10], R. Van de Water[9], D. H. White[9], M. J. Wilking[4], H. J. Yang[11], G. P. Zeller[5], E. D. Zimmerman[4]


Fermilab Visual Media Services

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[2] *Bucknell University, Lewisburg, PA 17837*
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[4] *University of Colorado, Boulder, CO 80309*
[5] *Columbia University, New York, NY 10027*
[6] *Embry Riddle Aeronautical University, Prescott, AZ 86301*
[7] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
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[9] *Los Alamos National Laboratory, Los Alamos, NM 87545*
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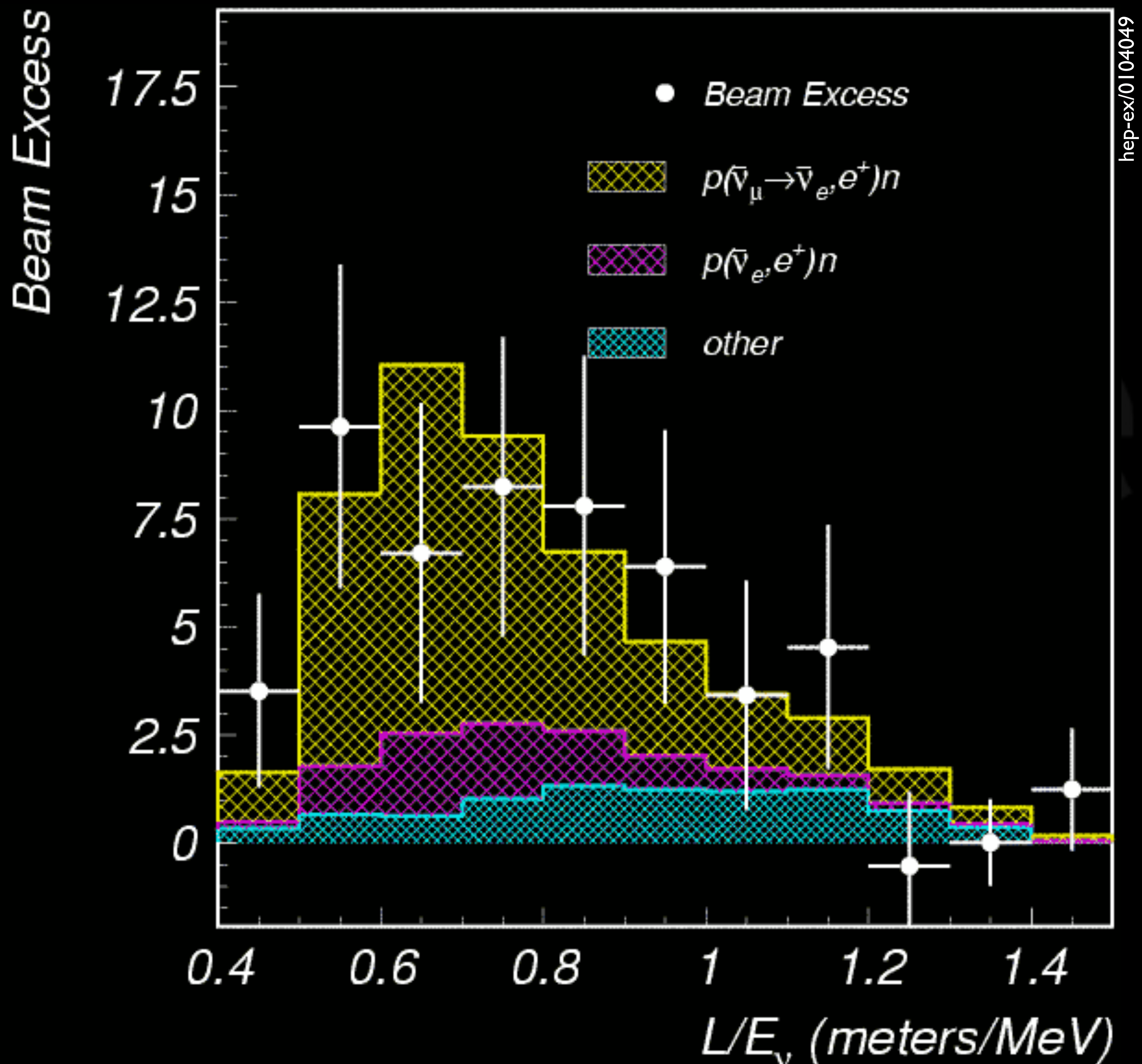
[11] *University of Michigan, Ann Arbor, MI 48109*
[12] *Princeton University, Princeton, NJ 08544*
[13] *Saint Mary's University of Minnesota, Winona, MN 55987*
[14] *Virginia Polytechnic Institute & State University, Blacksburg, VA 24061*
[15] *Western Illinois University, Macomb, IL 61455*
[16] *Yale University, New Haven, CT 06520*

Our task: Dead reckon the background estimates and uncertainties with just one detector.

LSND Signal

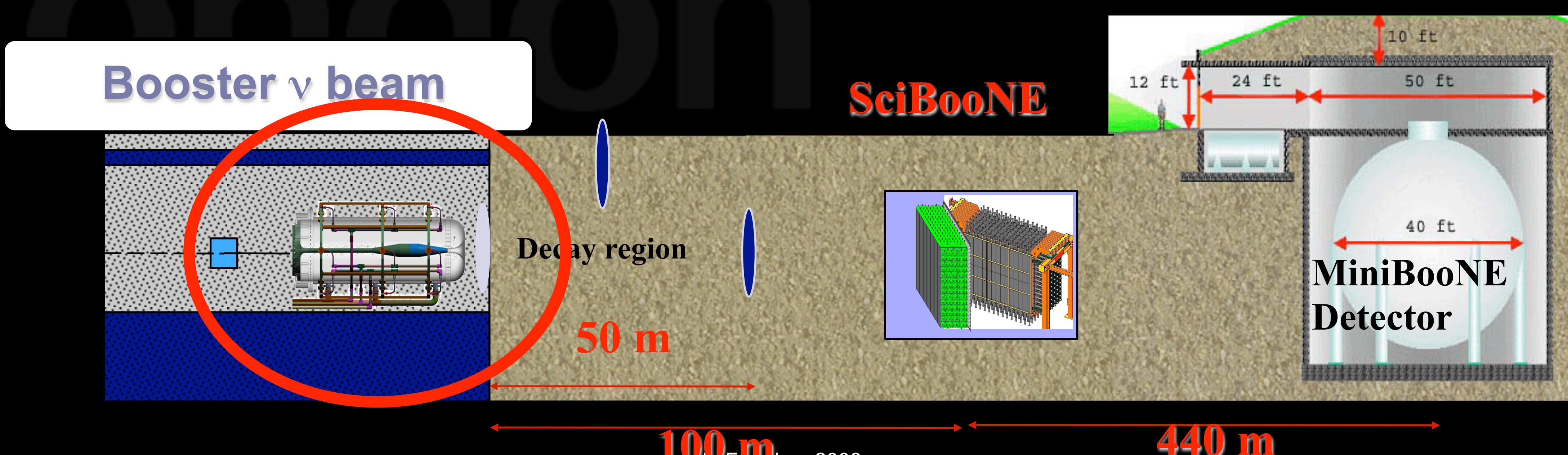
- Clean experimental signature
  - Stopped pion neutrino source
  - Delayed coincidence detection signal
- excess: 87.9 ± 22.4 ± 6.0
- Interpreted as 2 ν oscillation
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.26\%$



Target & Horn

Main components of Booster Neutrino Beam (BNB)

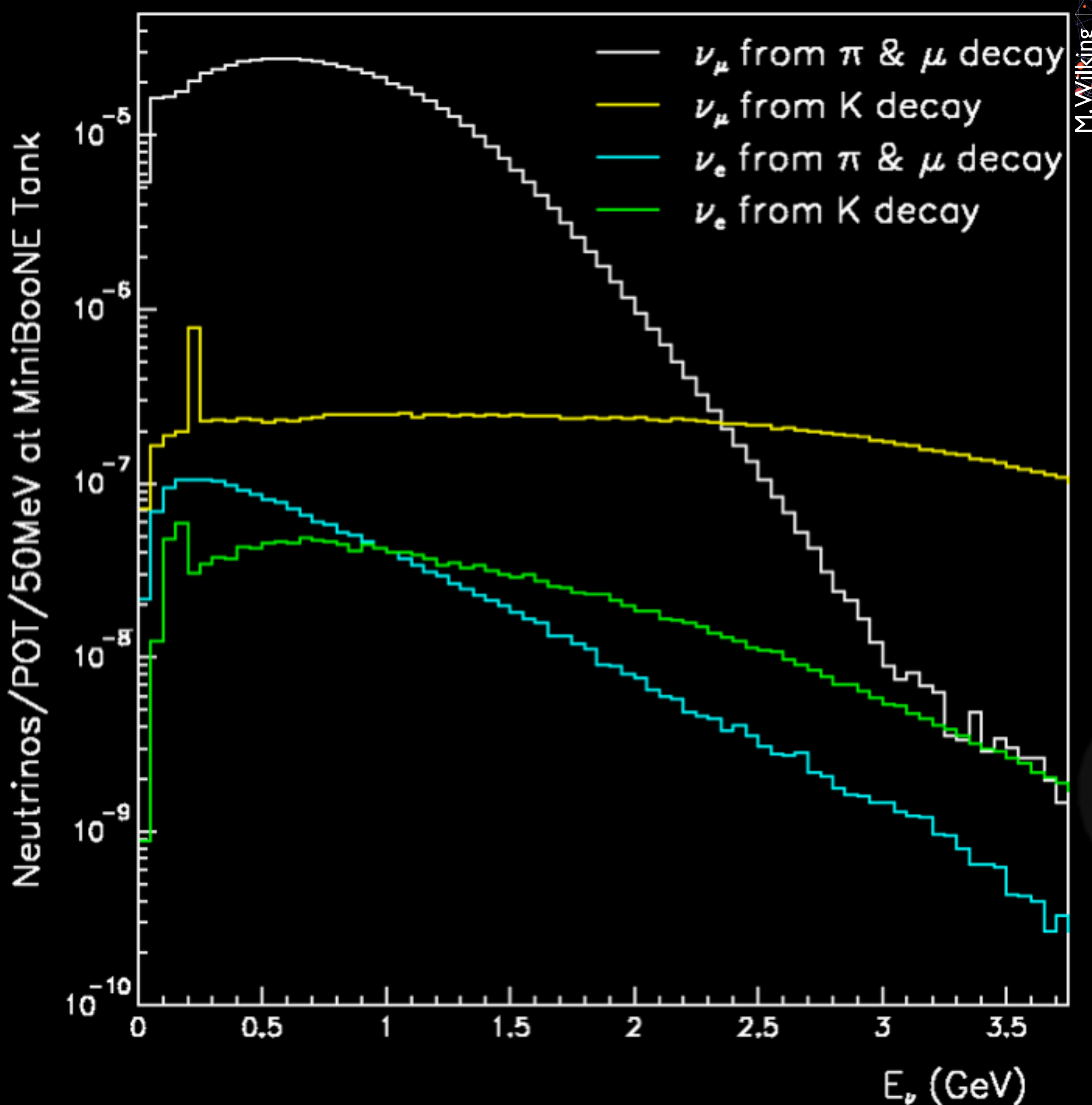
(96M and 200M+ pulses)

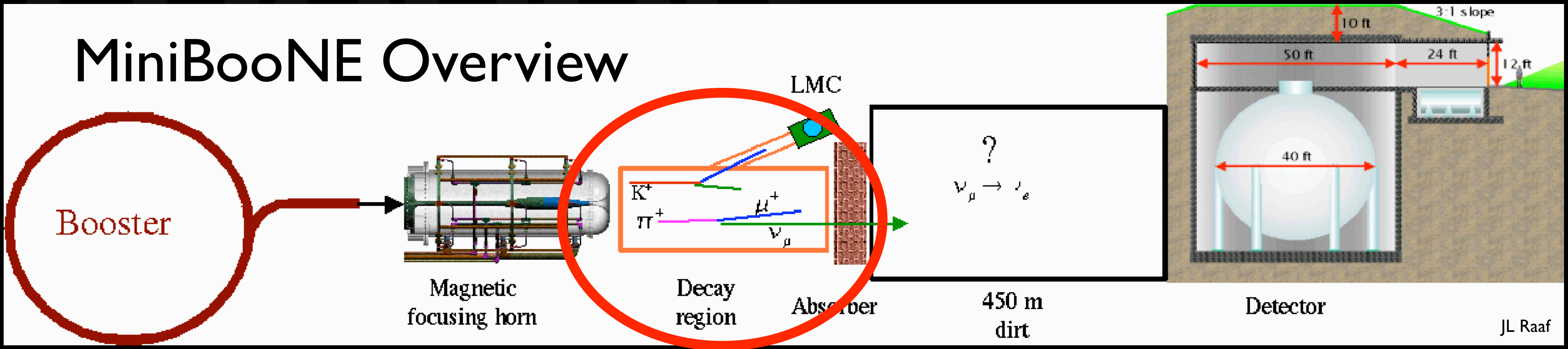


JL Raaf

ν Flux

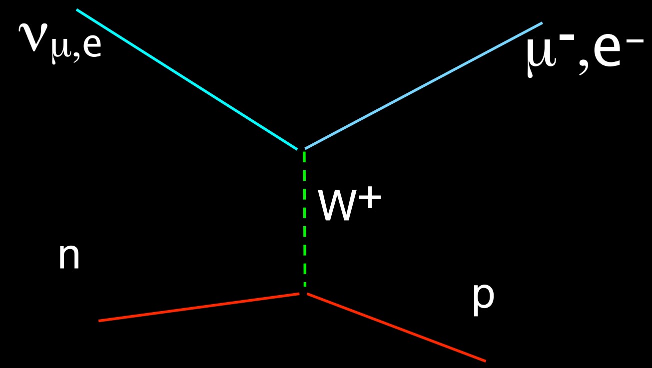
- 99.5% pure muon flavour
- 0.5% intrinsic ν_e
- Constrain ν_e content with ν_μ measurements

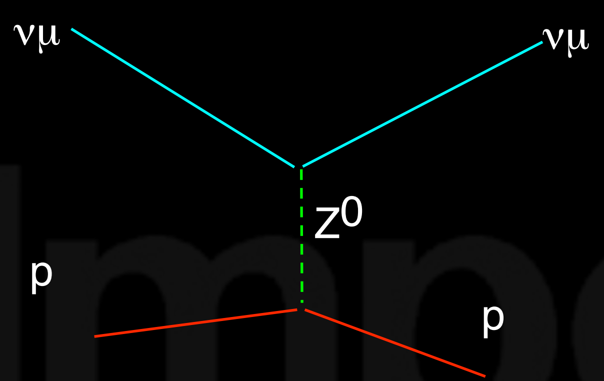




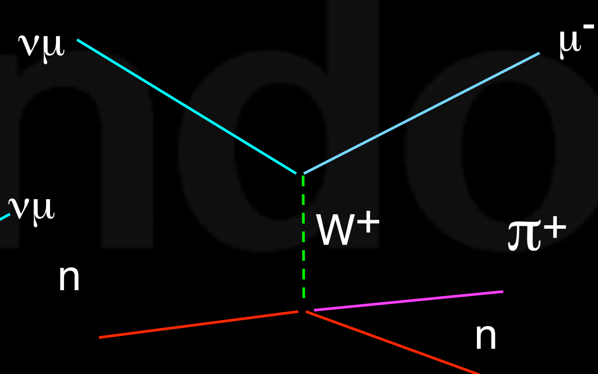
Cross Sections

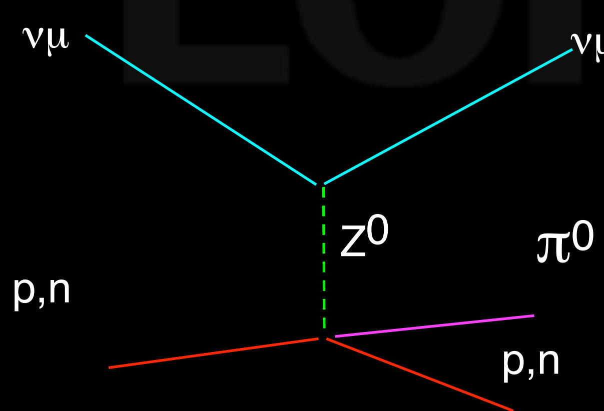
CC / NC quasi-elastic scattering (QE) 42% / 16%

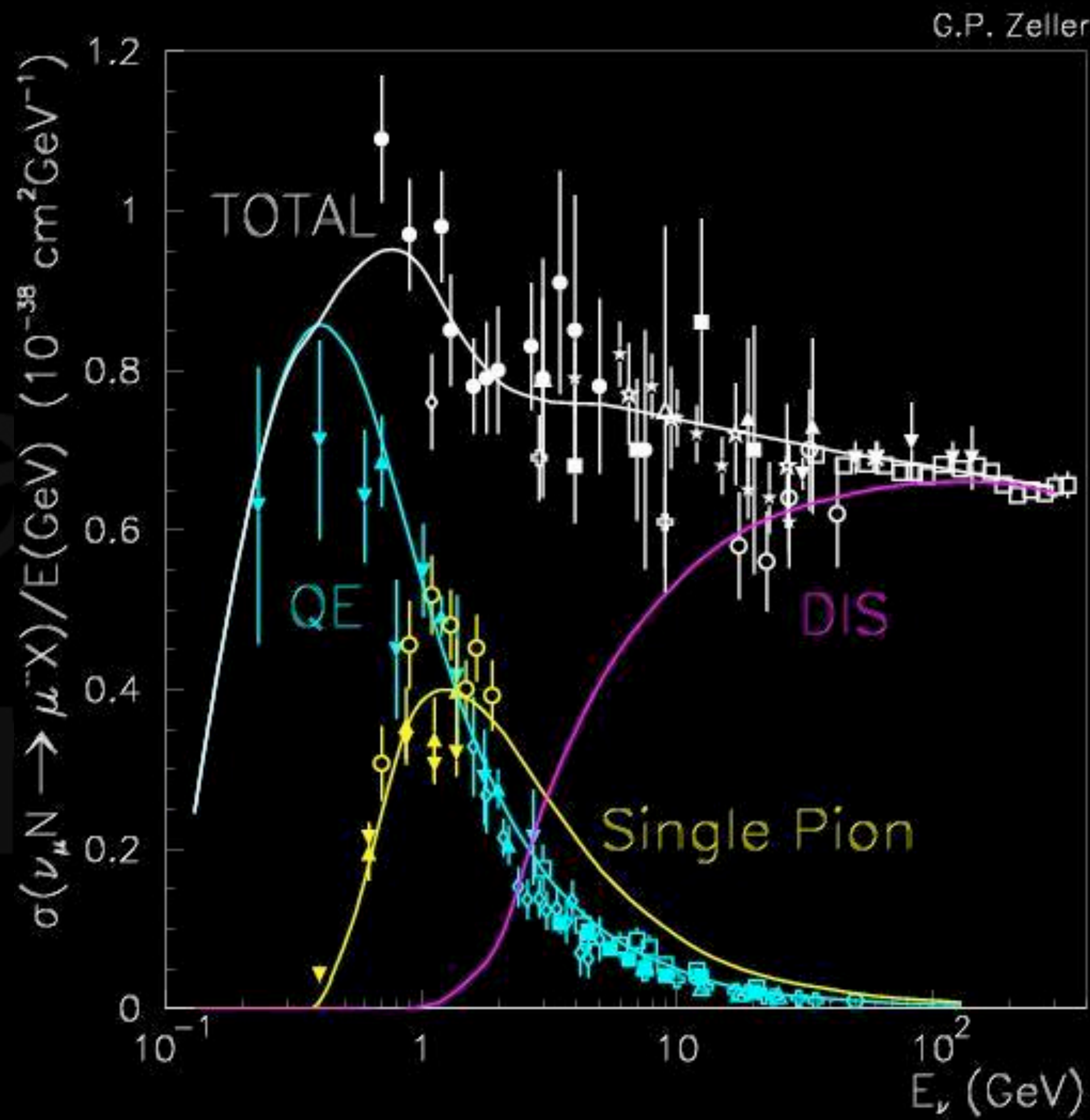




CC / NC resonance production (1π) 25% / 7%

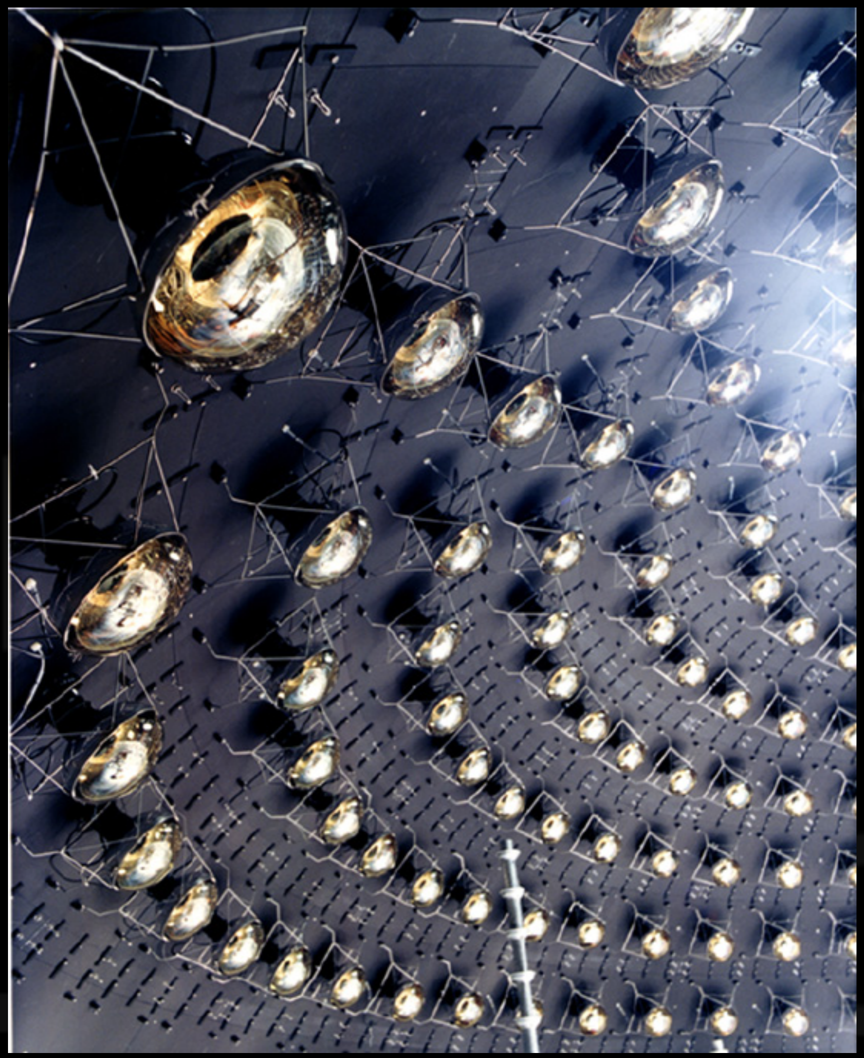






Track Reconstruction

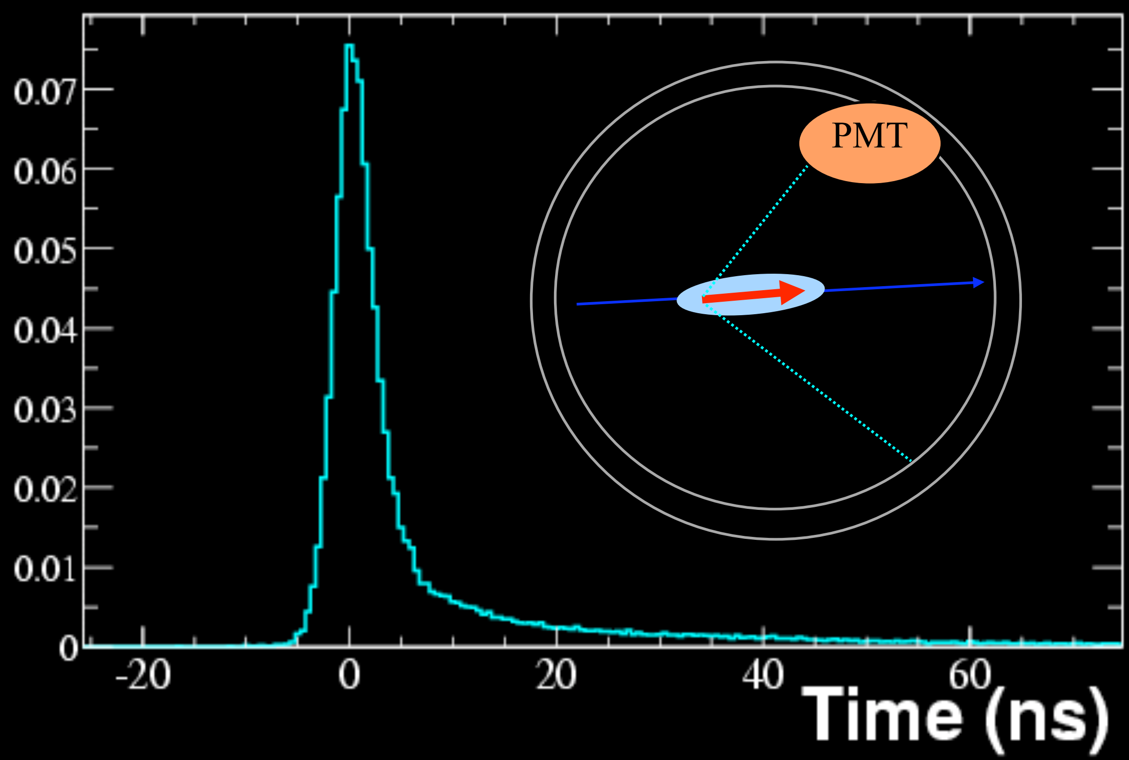
Charged particles produce Cherenkov and scintillation light in oil

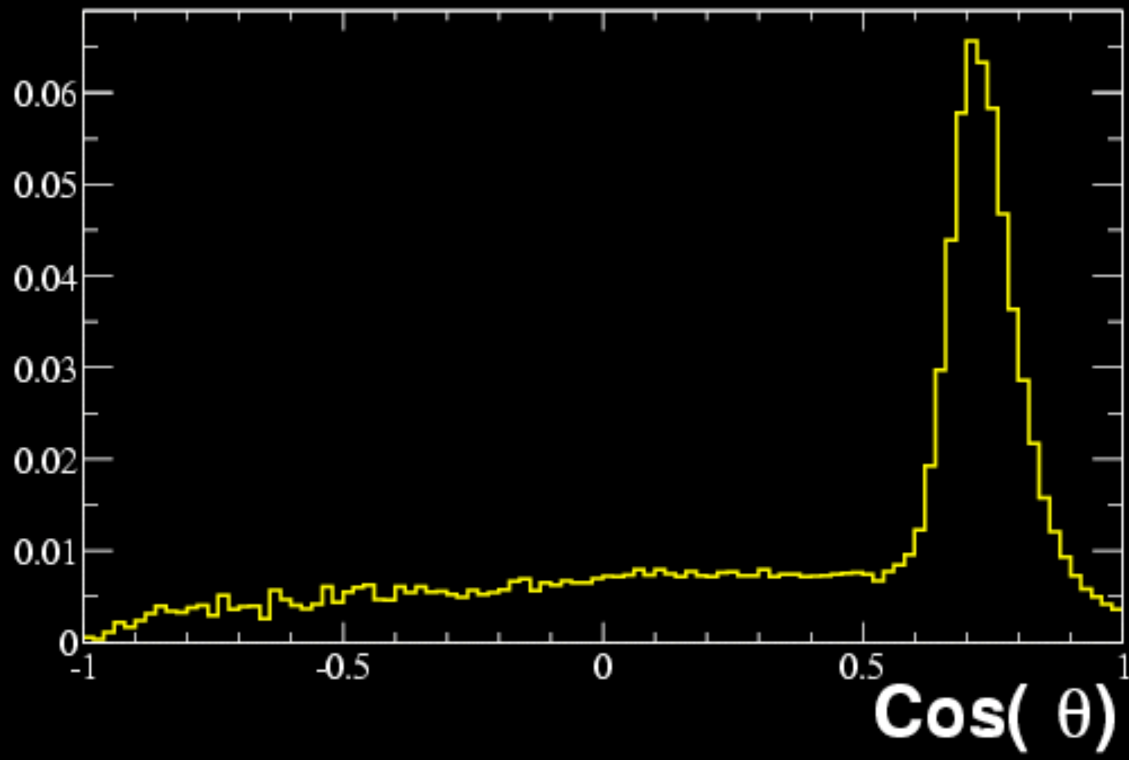


PMTs collect photons, record t,Q

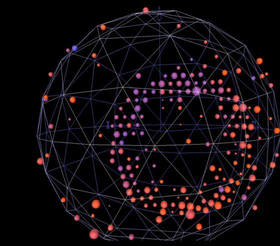
Reconstruct tracks by fitting time and angular distributions

Find position, direction, energy

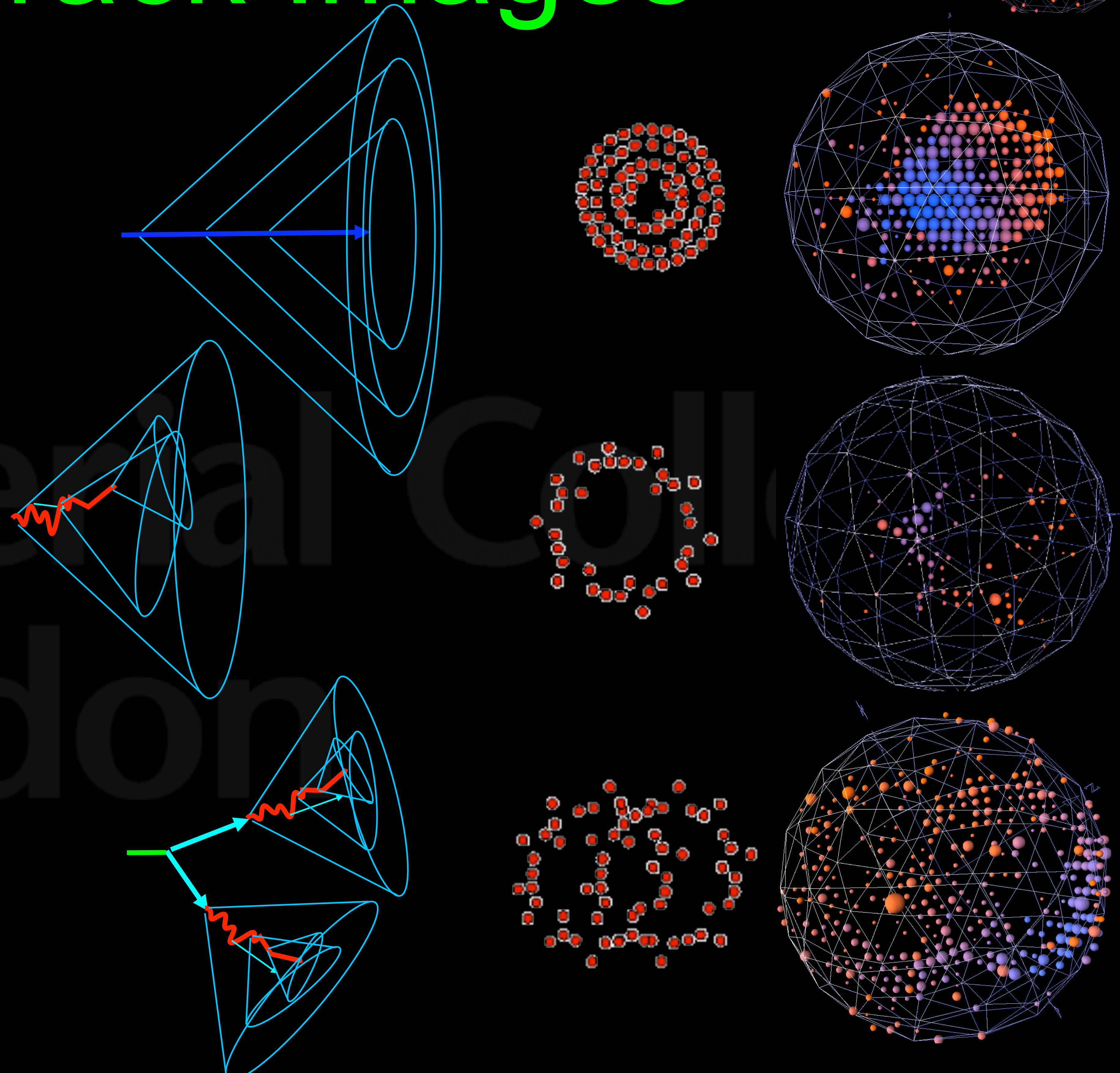




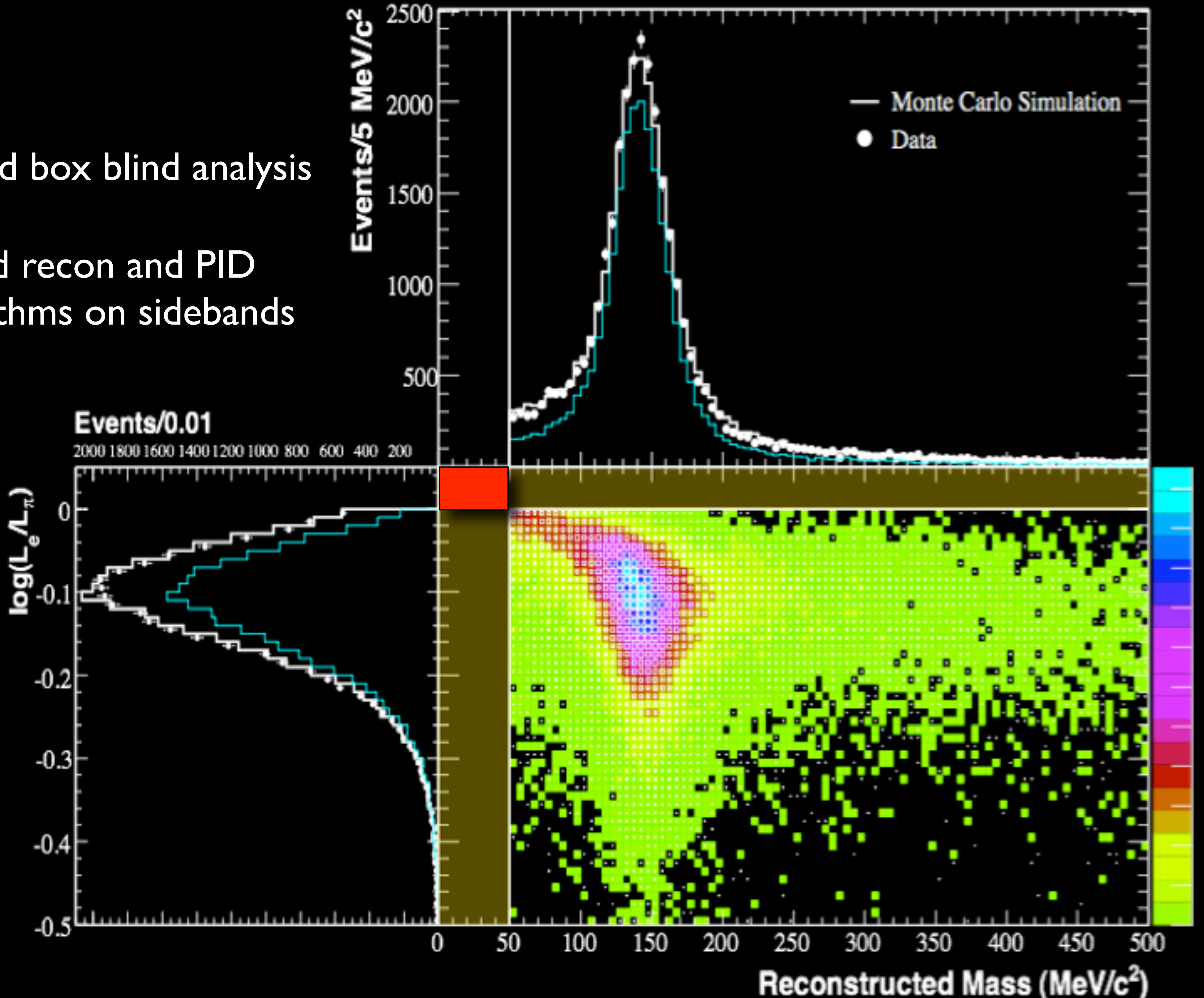
Track Images



- Muons
  - full rings
- Electrons
  - fuzzy rings
- Neutral pions
  - double rings

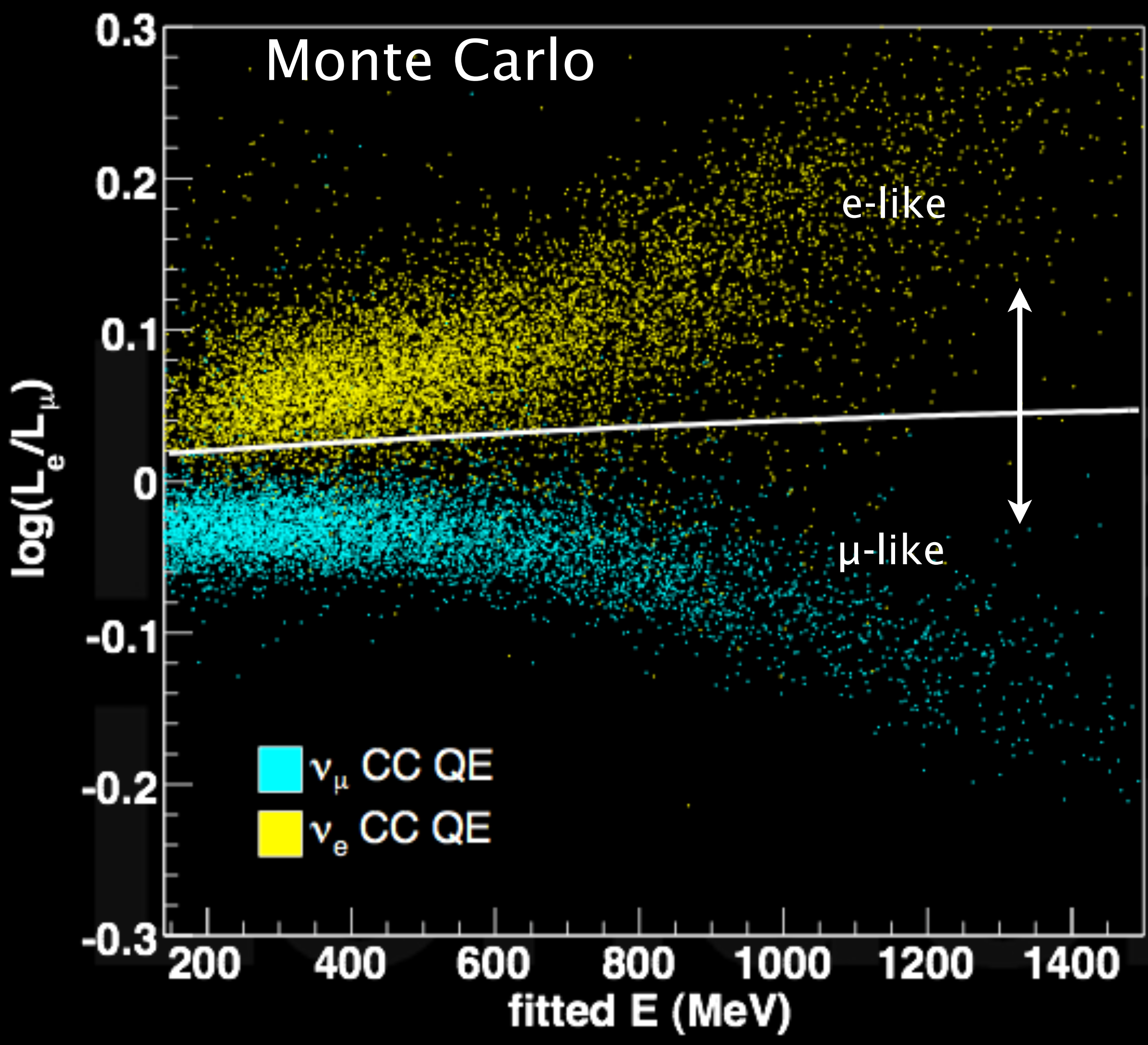


- Closed box blind analysis
- Tested recon and PID algorithms on sidebands

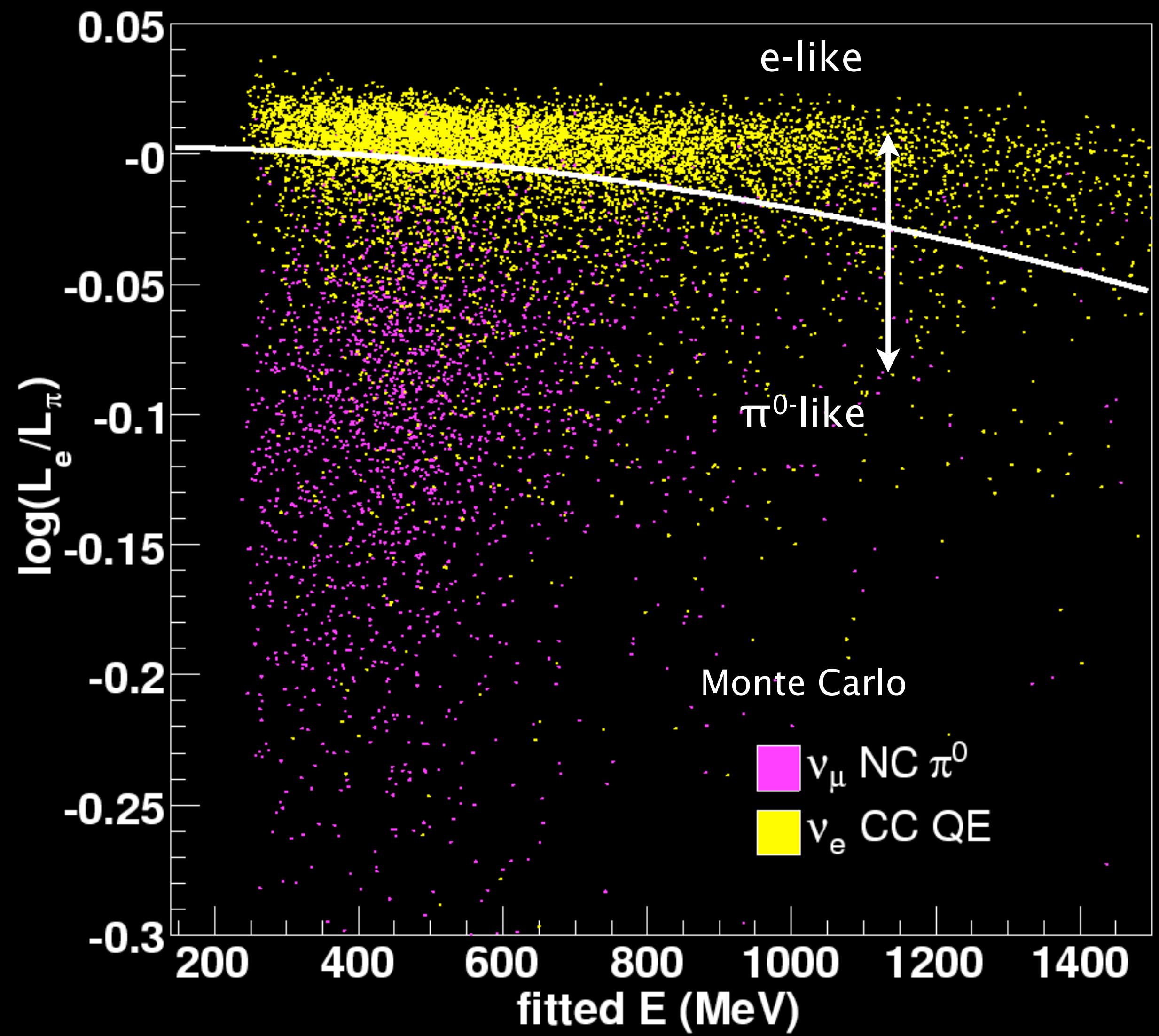


Particle Identification

Reconstruct under 3 possible hypotheses: μ-like, e-like, π^0-like



Reconstruction produces likelihoods for the three hypotheses

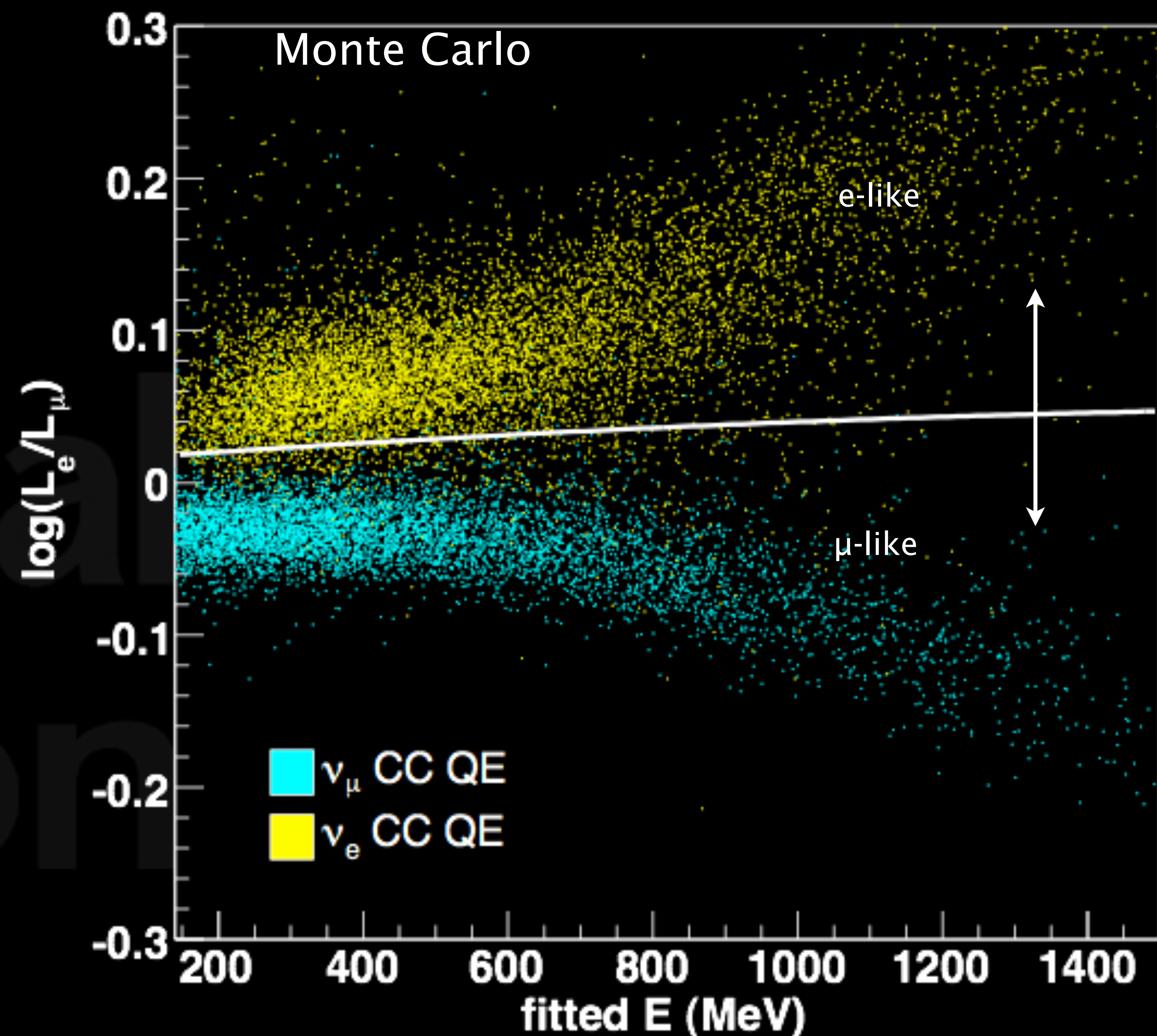


ν_e particle ID cuts on likelihood ratios

cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation

Particle Identification

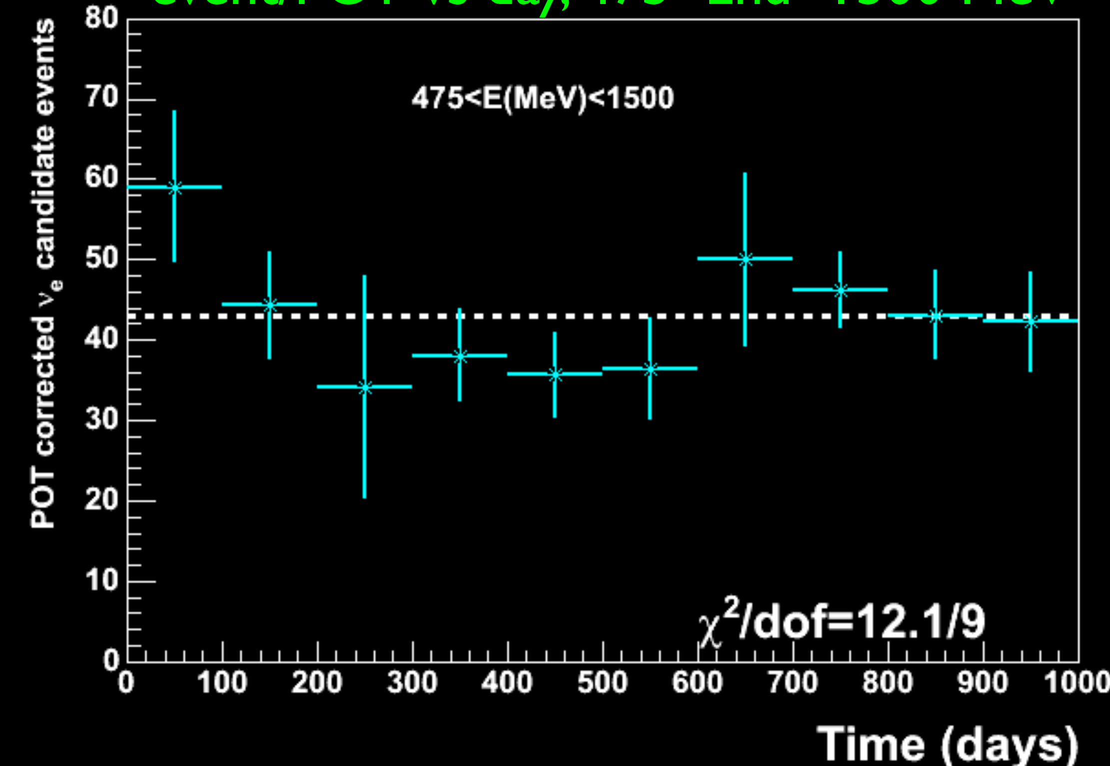
- Reconstruct under 3 possible hypotheses: μ-like, e-like, π^0-like
- ν_e particle ID cuts on likelihood ratios
- cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation



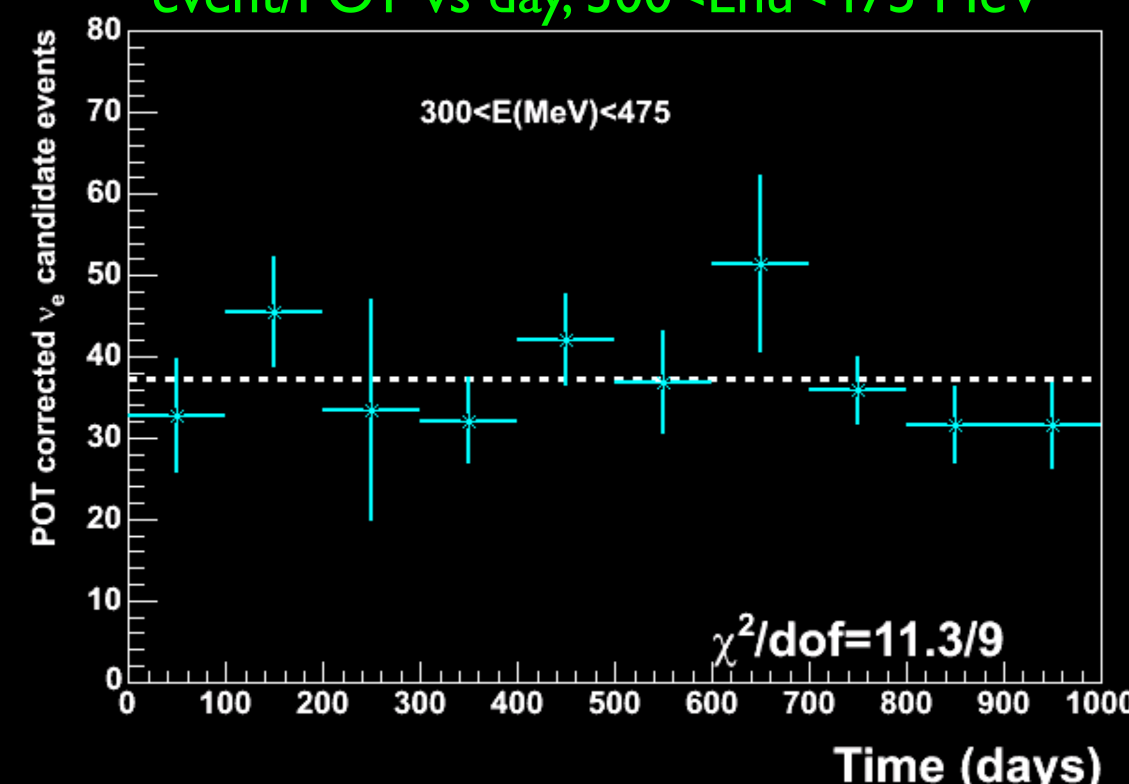
Integrity checks

- Detector anomalies: none found
  - Example: time distribution of ν_e events is flat
- Hand scanned all events: nothing pathological found

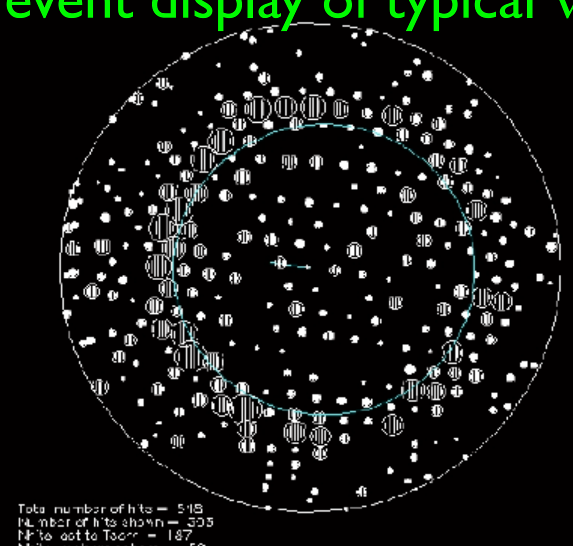
event/POT vs day, 475<Enu<1500 MeV



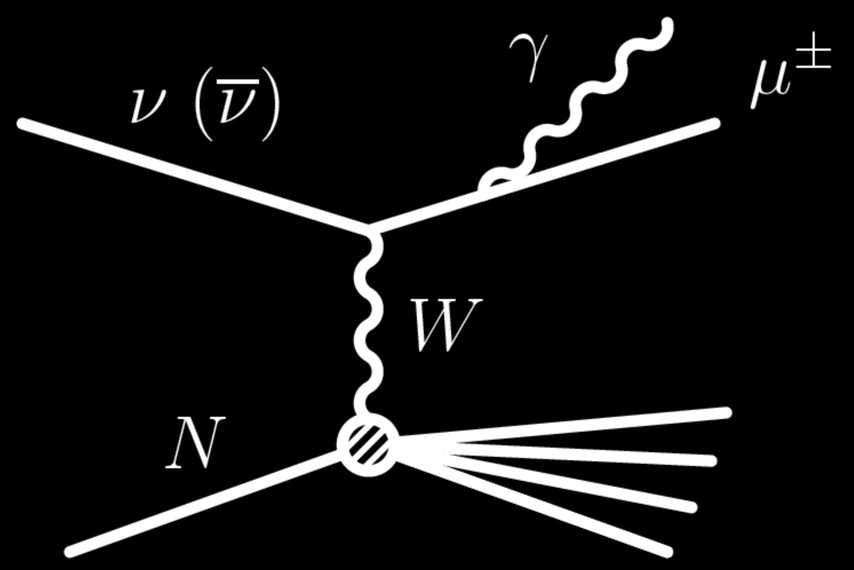
event/POT vs day, 300<Enu<475 MeV



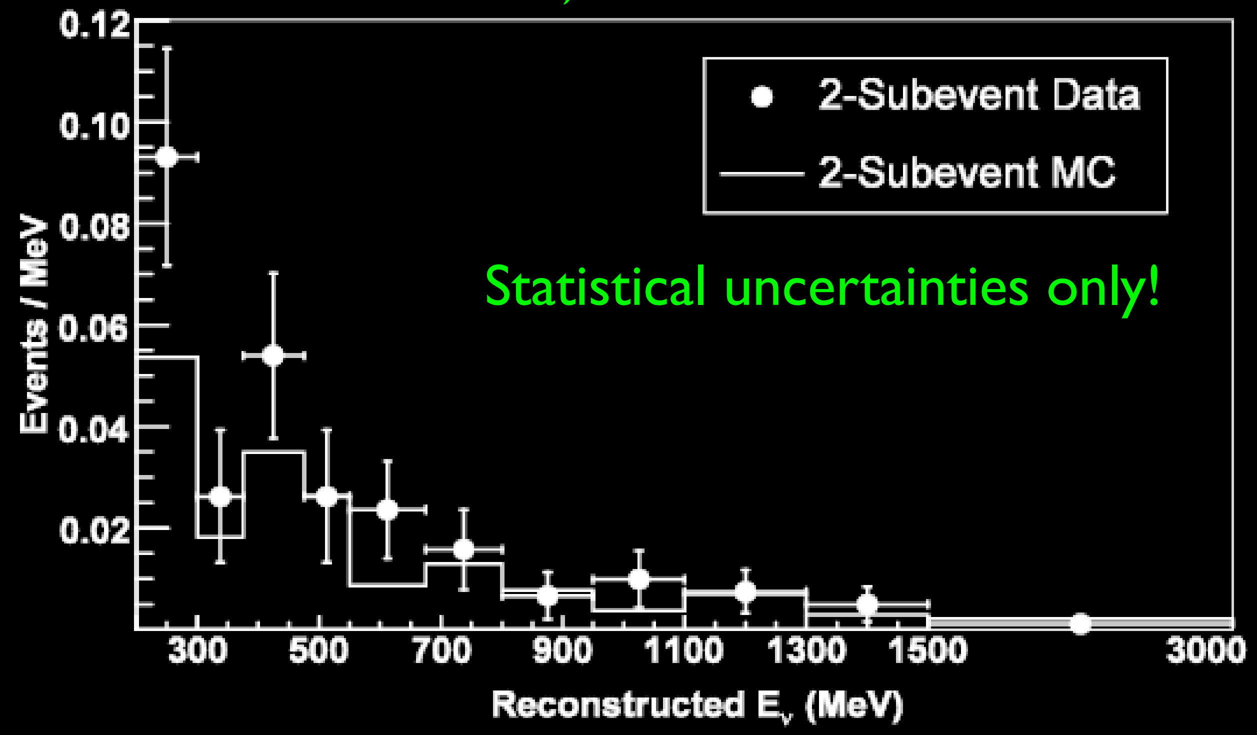
event display of typical ν_e



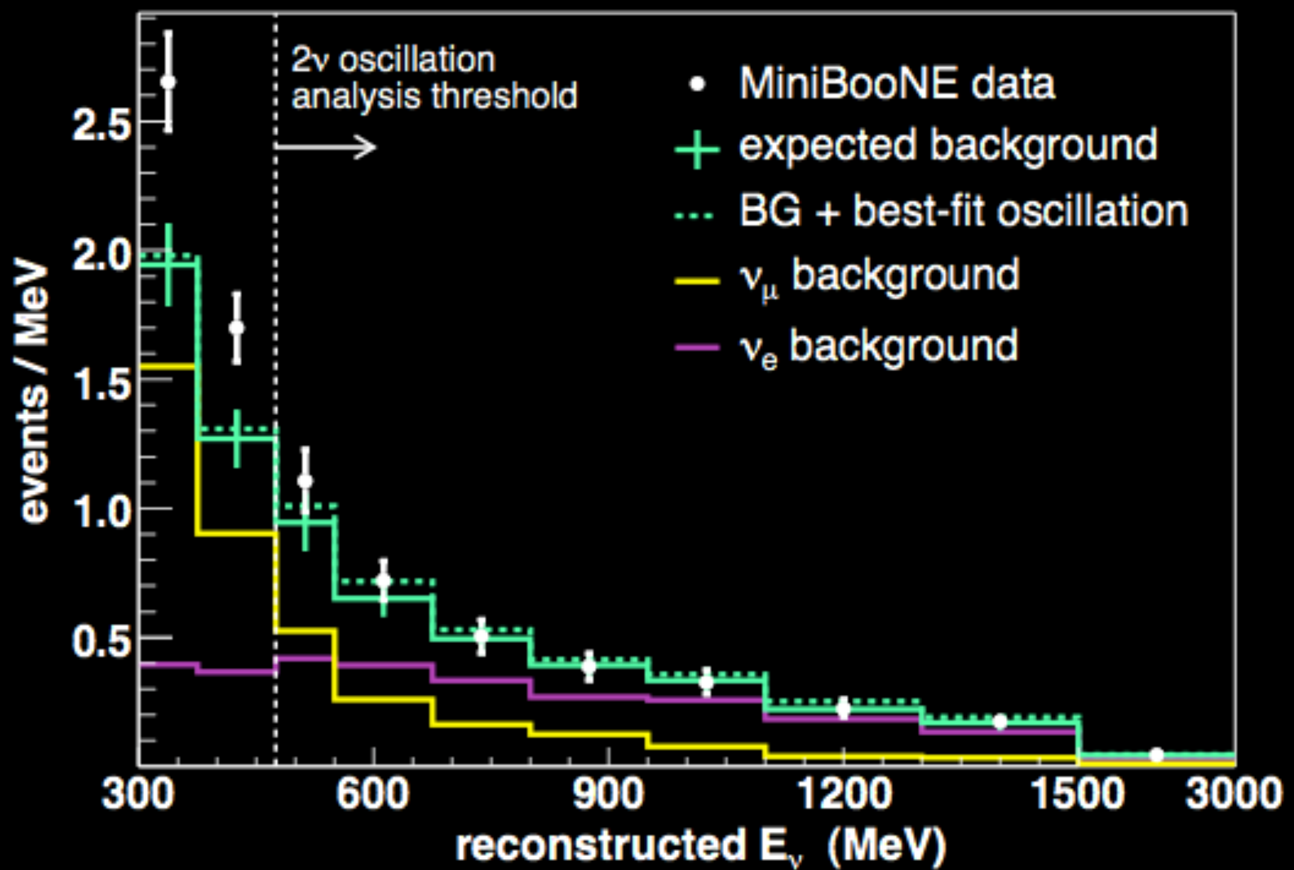
Muon Internal Brem



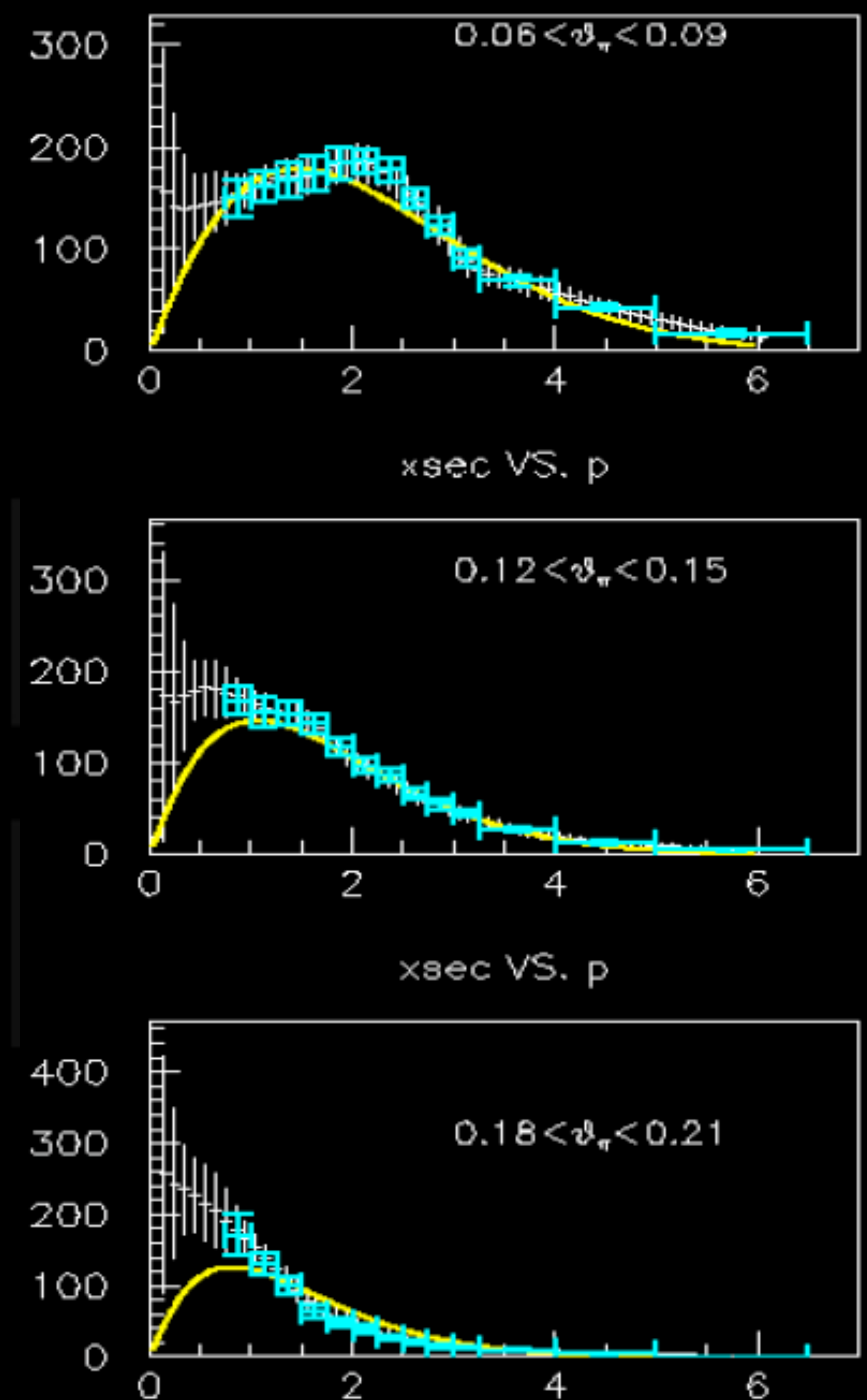
Data-MC excess, but note the scale!



- Apply recon and PID to clean muon CCQE events
- Directly measure rate of final state muon ν_e backgrounds



ν Flux Uncertainties



- Now use HARP data and covariance matrix to directly estimate flux uncertainty
  (instead of Sanford-Wang)
- Excellent coverage of HARP data makes this possible
- 15%-->8%