Electron and Photon Generation in the Long Baseline Neutrino Experiment

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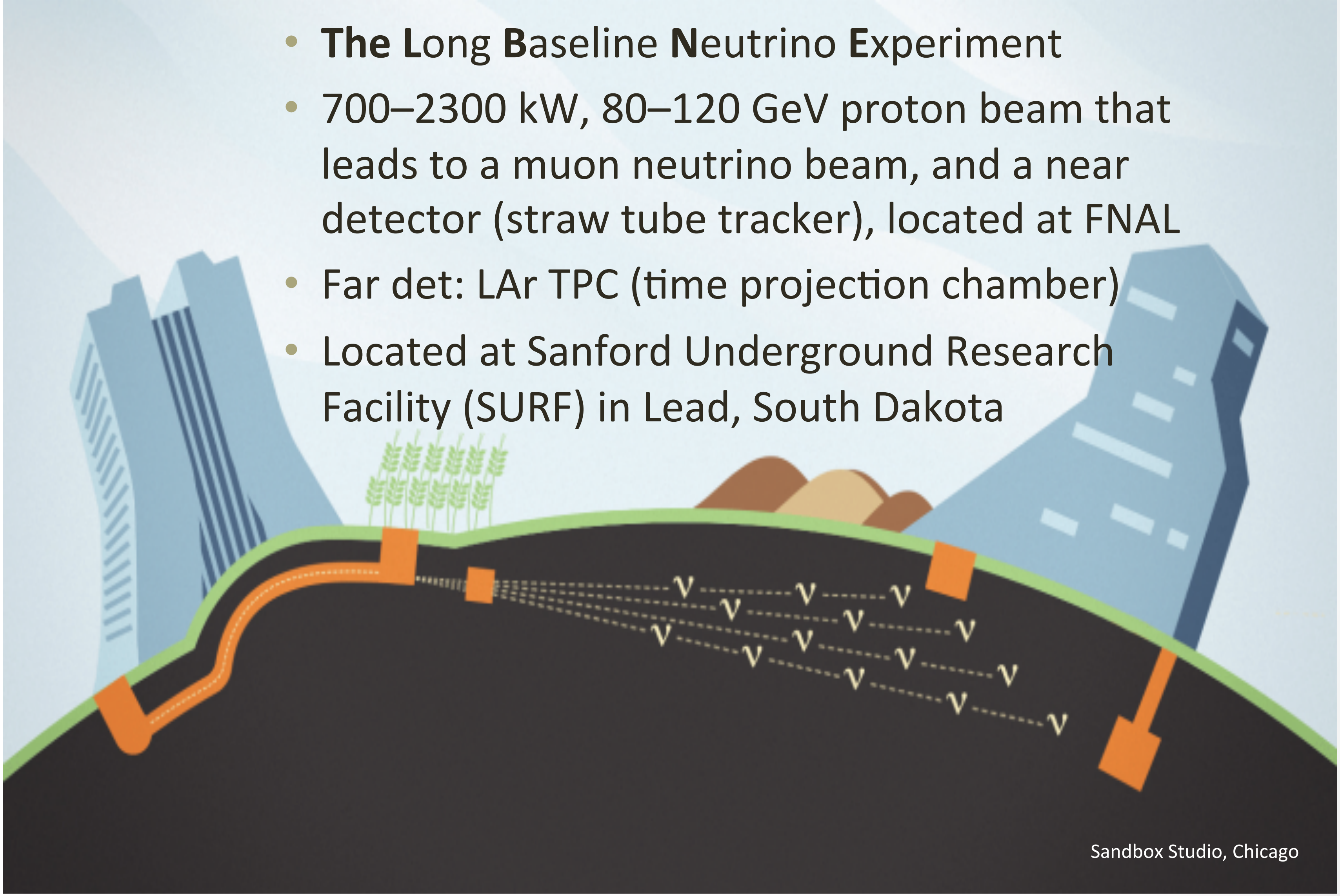
SLAC Seminar, Tuesday January 21, 2014

Introduction to LBNE

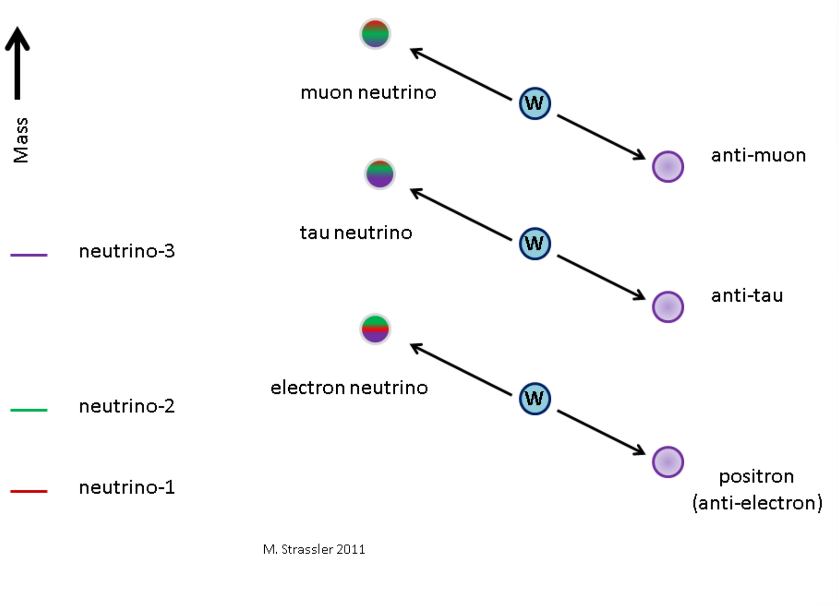


- **The L**ong **B**aseline **N**eutrino **E**xperiment
- 700–2300 kW, 80–120 GeV proton beam that leads to a muon neutrino beam, and a near detector (straw tube tracker), located at FNAL
- Far det: LAr TPC (time projection chamber)
- Located at Sanford Underground Research Facility (SURF) in Lead, South Dakota

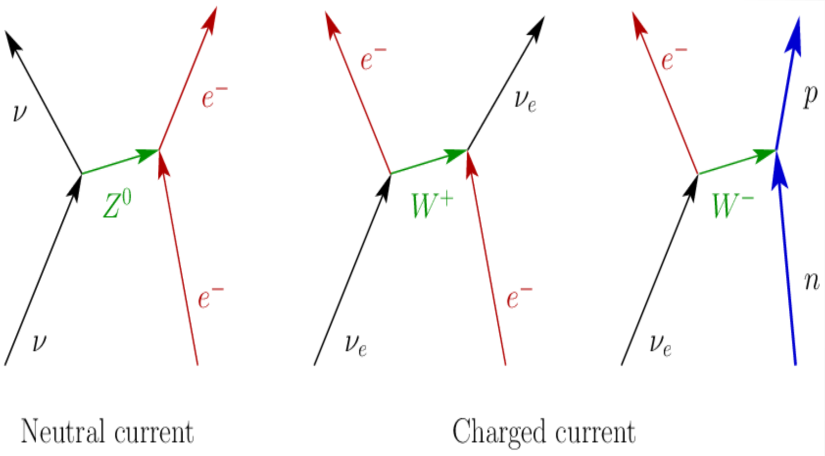
Sandbox Studio, Chicago

Physics Motivations

- Neutrinos have mass, and oscillate between different types. The three flavor eigenstates (electron, muon, tau) are not the same as the three mass ones. This effect not in the Standard Model.
- But what order is their mass hierarchy (MH)? Two heavy neutrinos and one light, or vice versa? We know only the differences, not absolute numbers

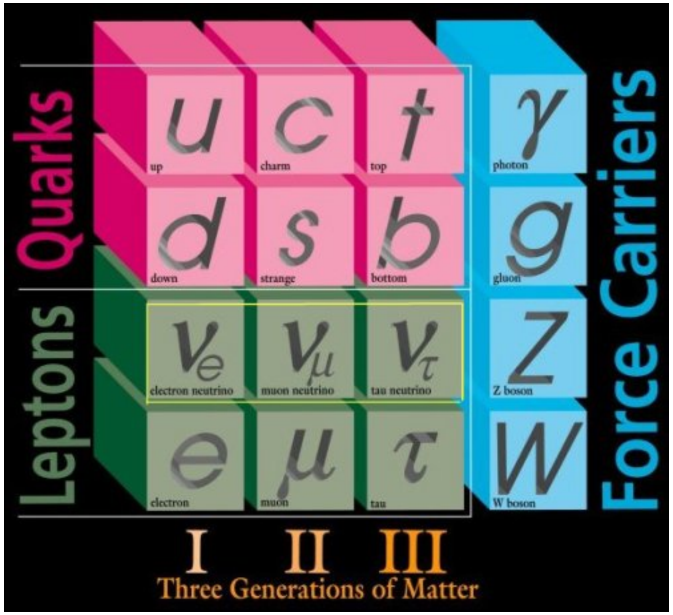


M. Strassler 2011



Further Questions

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



$$p \to e^+\pi^0$$
$$p \to \nu K^+$$
$$p \to \mu^+ K^0$$

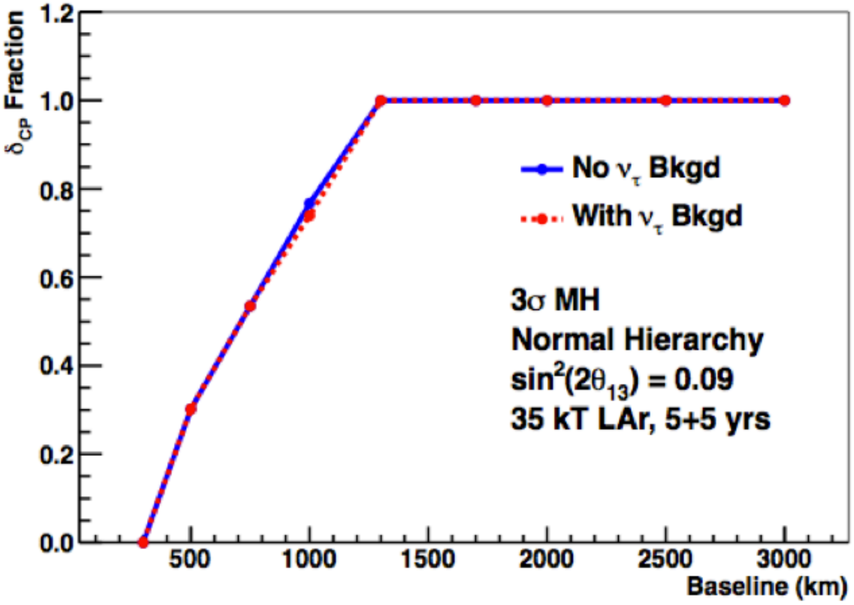
$$p \to \mu^-\pi^+ K^+$$
$$p \to e^+ K^+$$

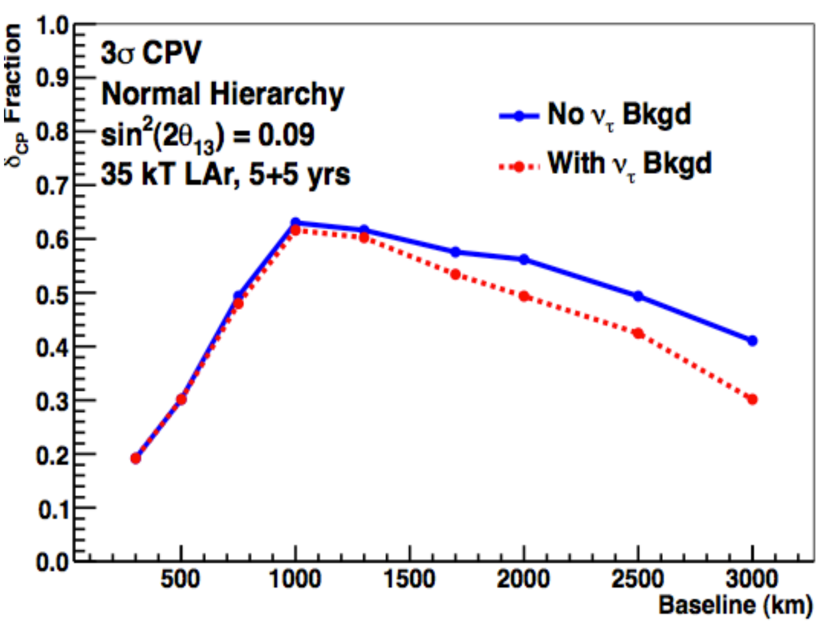
- Does the neutrino mixing matrix have a non-zero CP-violating (charge-parity) phase? Are neutrino and anti-neutrino oscillations equal?
- Are there sterile neutrinos, which interact rarely with Standard Model but which the known neutrinos are able to oscillate into?
- Bonus question: Do protons decay?

An underground, high-mass LAr target would also enable atmospheric and astrophysical neutrino studies, including supernova neutrinos

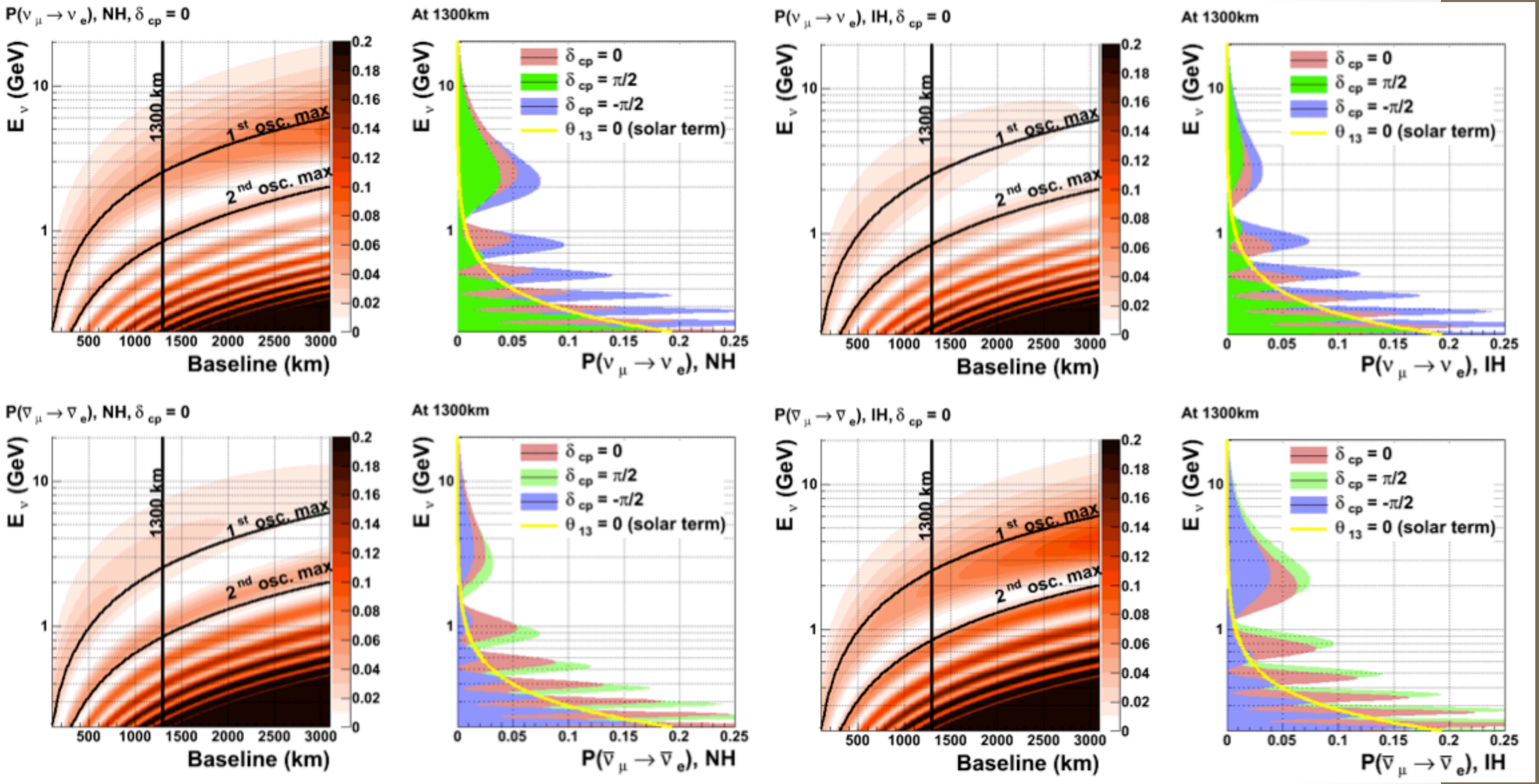
Optimization of the Baseline

- A 1300 km baseline is a pragmatic way to get a comprehensive scientific program that covers both MH and CP violation
- Normal hierarchy assumed for these example plots, and 5 years of neutrino running coupled with 5 years of anti-neutrino running
- Fraction of δ_{CP} parameter space covered. To achieve the same with other baselines, need more mass + a more intense beam





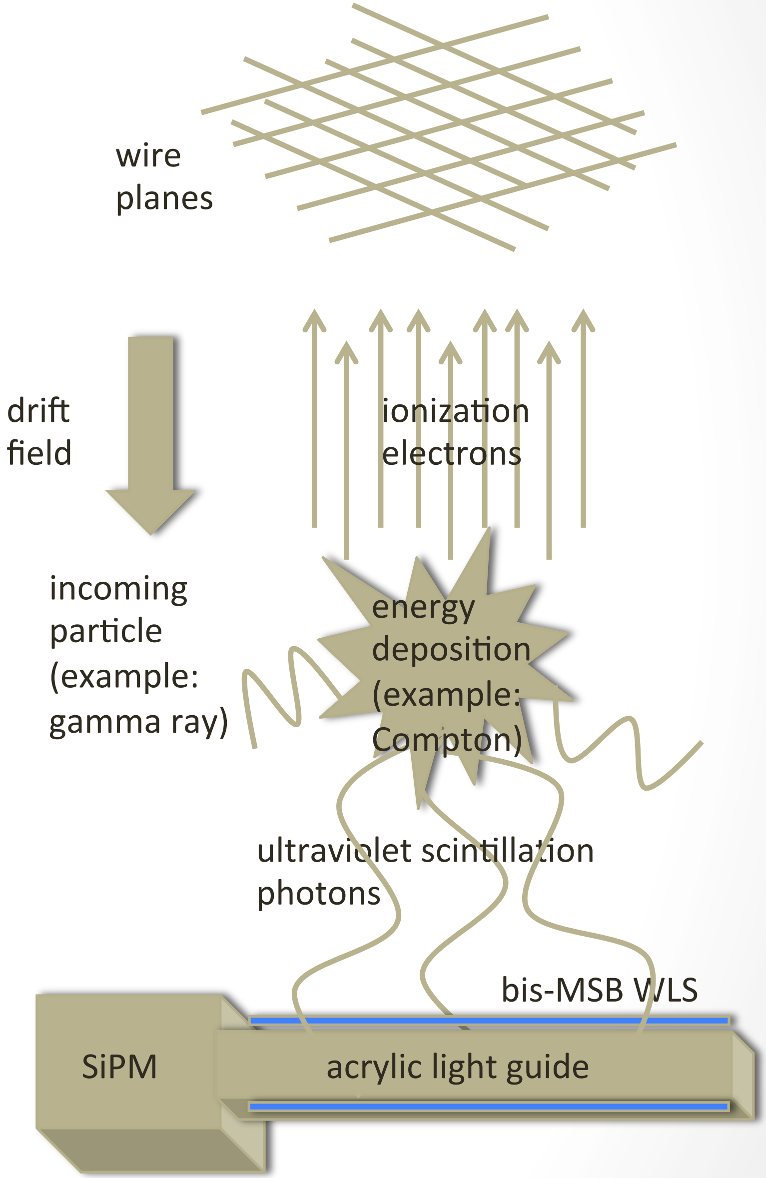
ν_e Appearance Oscillograms



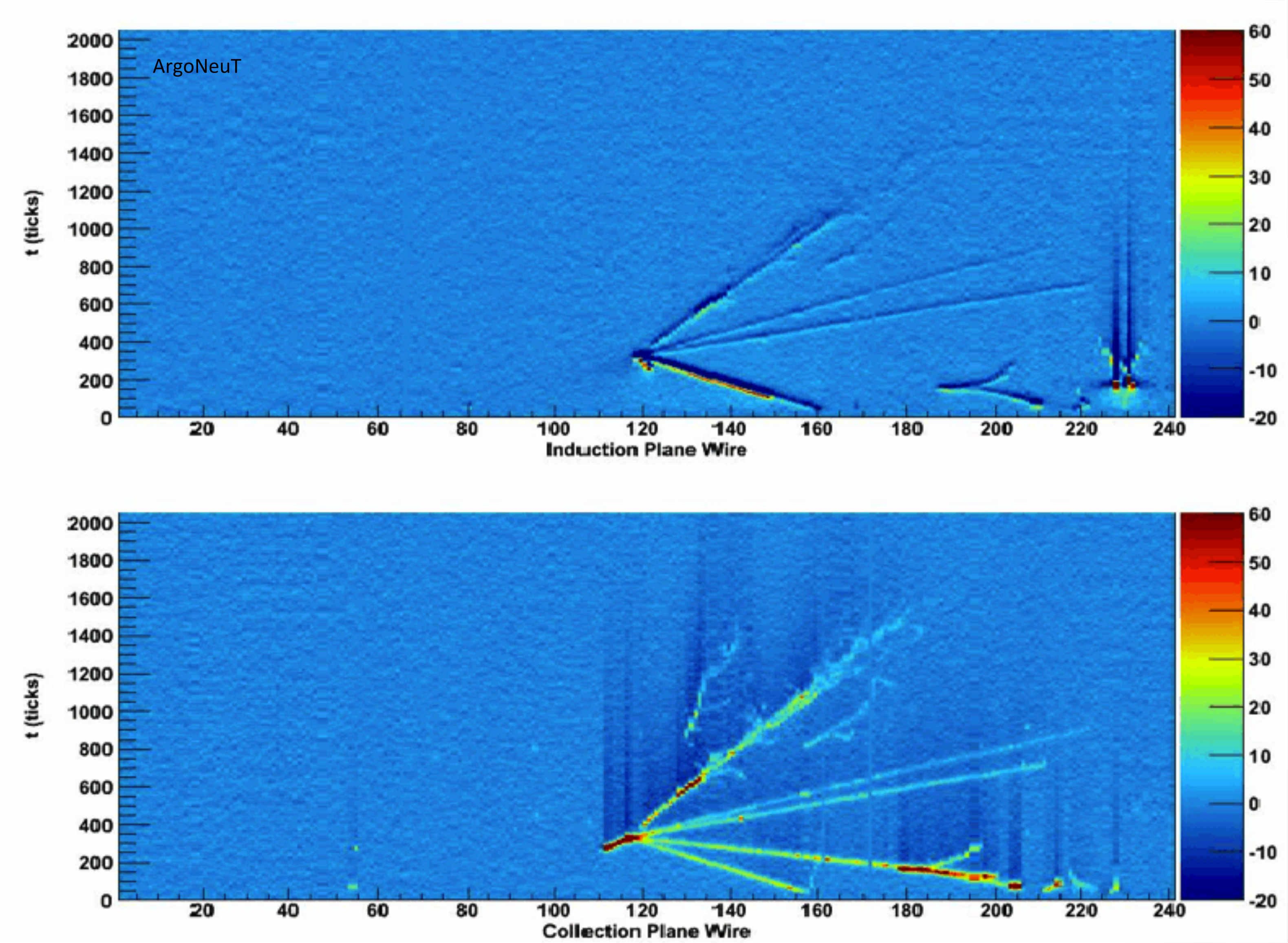
- First and third columns (orange-red plots): neutrino oscillations vs. energy and baseline for neutrinos (top) and anti-neutrinos (bottom), for $\delta_{CP} = 0$
- Second and fourth columns: neutrino oscillations as a function of energy, for different values of δ_{CP}, with the θ_{12} contribution (solar) plotted in yellow

Liquid Argon Far Detector

- Liquid argon scintillation is in the extreme UV (128 nm / 9.69 eV mean) and thus difficult to detect, so it must first be wavelength-shifted into the visible (blue 425 nm)
- Light, which determines the time of an event, detected by silicon photomultipliers
- 500 V/cm electric field drifts the liberated electrons, which constitute the primary means of calorimetry and particle ID
- Great tracking in argon, like a "digital bubble chamber"



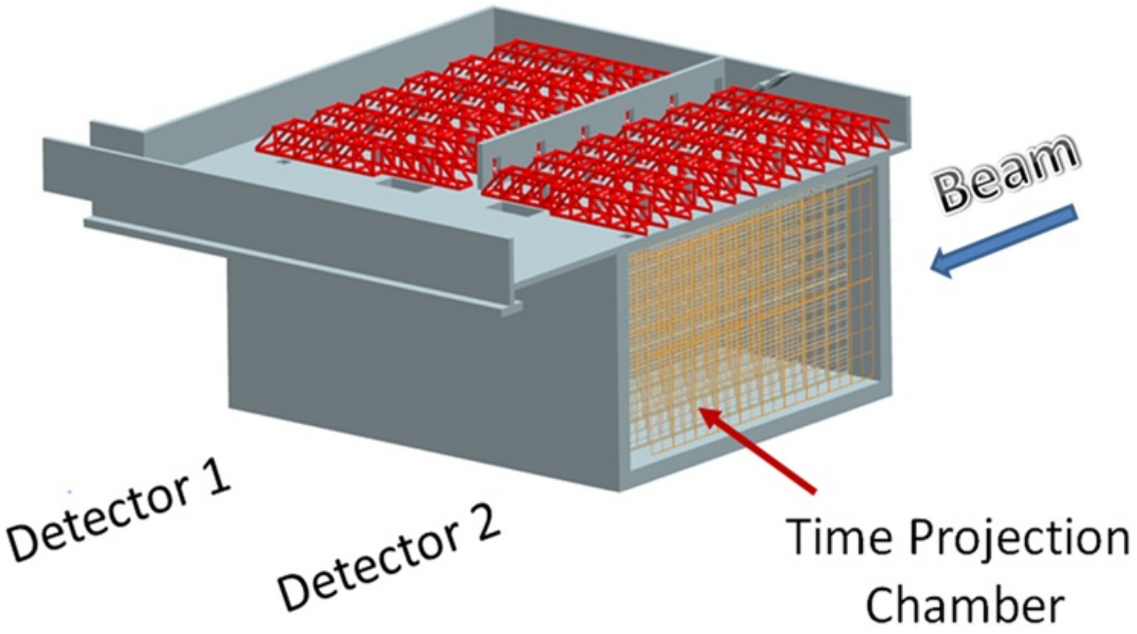
Event Example



Argon Properties

- For a MIP at 500 V/cm an estimated 29,000 electrons per MeV and 22,000 photons per MeV (NEST: exact values depend on *dE/dx* and electric field magnitude, which affect recombination)
- ~Quintuple the scintillation light compared to Cerenkov
- Triplet (slow) and singlet (fast) decay times of ~1.6 us and ~6 ns respectively (purity-dependent time constants!)
  - ~2/3-3/4 late and 1/3-1/4 prompt (depends on LET and particle type)
  - Xe doping at ppm level may shrink triplet time constant, increase yields
- O(1 m) Rayleigh scattering length. Comparable photon absorption length (?) depending on photo-absorbing impurities

Detector Properties



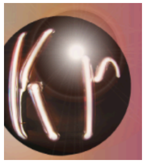
- 1.4 ms maximum electron drift time. O(1 ms) purity planned
- 5 mm wire pitch for the anode wires. > 100 kV cathode
- 34-35 kT fiducial (50 kT total) at 4300 m.w.e. depth, segmented into multiple cryostats, detecting ν_e appearance via electrons

Far-reaching Noble Applications

- Well suited to the direct detection of dark matter WIMPs (see Karen Gibson seminar)
  - Xenon and argon both used, in both large dark matter experiments and small-scale calibrations
  - 1- and 2-phase, and zero and non-zero field (TPCs)

- Neutrino physics, besides LBNE
  - Neutrinoless double-beta decay (^{136}Xe): EXO, NEXT
  - Coherent ν-scattering, and reactor monitoring: RED

- PET scans for medical applications (511 keV γ's)
- μ^- => e^- + γ (evidence of new physics): MEG, not to mention countless HEP detection applications

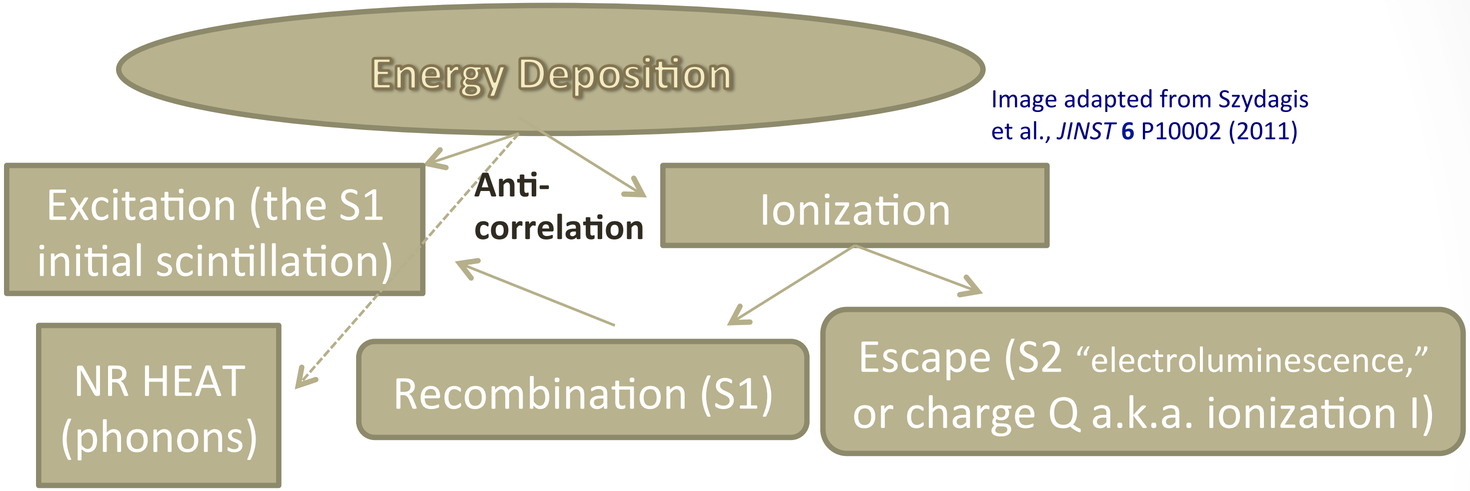


- Why LAr? Cheap, tested, 2 channels, easier field

What is NEST?

- Noble element physics is interesting on its own, and a cohesive simulation of it did not exist previously
- NEST: collection of models explaining the scintillation and ionization yields of noble elements as a function of particle type, electric field, and the *dE/dx* or energy
- Has goal of providing a full-fledged Monte Carlo with
  - Mean yields (light AND charge)
  - Energy resolution (critical for understanding background discrimination)
  - Pulse shapes (light AND charge)
- Combed the wealth of data on noble elements at Davis and combined all of the underlying physics learned

Basic Physics Principles



Energy Deposition

Excitation (the S1 initial scintillation)

Anti-correlation

Ionization

NR HEAT (phonons)

Recombination (S1)

Escape (S2 “electroluminescence,” or charge Q a.k.a. ionization I)

Image adapted from Szydagis et al., *JINST* **6** P10002 (2011)

- Exciton-to-ion ratio is 0.20 for e^- recoils (for argon)
- Q ≠ energy: energy depositions divide into two channels, S1 and Q, non-linearly: idea from Eric Dahl
- Roughly half of the energy goes into the scintillation

Formulae

- Cornerstone: one effective work function *W* for production of *either* a scintillation photon or an ionization electron. All others **derive** from it
- W_{LAr} = 19.5 +/- 1.0 eV $N_q = (N_{e-} + N_\gamma) = E_{dep} / W$

Doke et al., Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1538–1545

C.E. Dahl, Ph.D. Thesis, Princeton University, 2009

- $N_\gamma = N_{ex} + r\,N_i$ and $N_{e-} = (1 - r)\,N_i$ $(N_{ex} / N_i$ fixed)
- Recombination different for short and long tracks
  - Thomas-Imel “box” model (< *O*(10) keV): delta rays
  - Doke’s modified Birks’ Law Doke et al., NIM A 269 (1988) p. 291

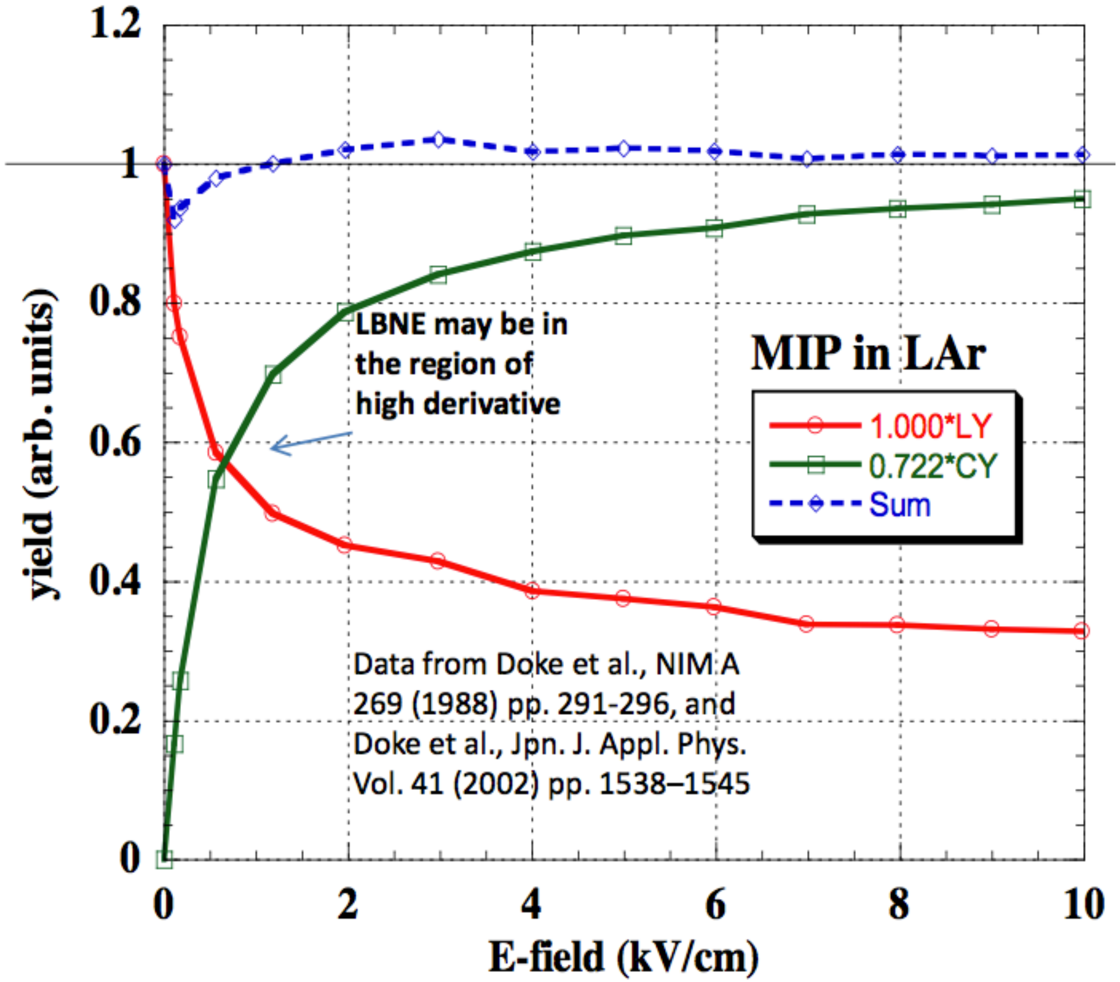
volume/bulk or columnar recombination

$$r = \frac{A\frac{dE}{dx}}{1+B\frac{dE}{dx}} + C, \quad B = A/(1-C) \quad \textbf{OR} \quad r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$

geminate (parent ion)

- Probability *r* makes for non-linear yield per keV

Combined Energy Scale



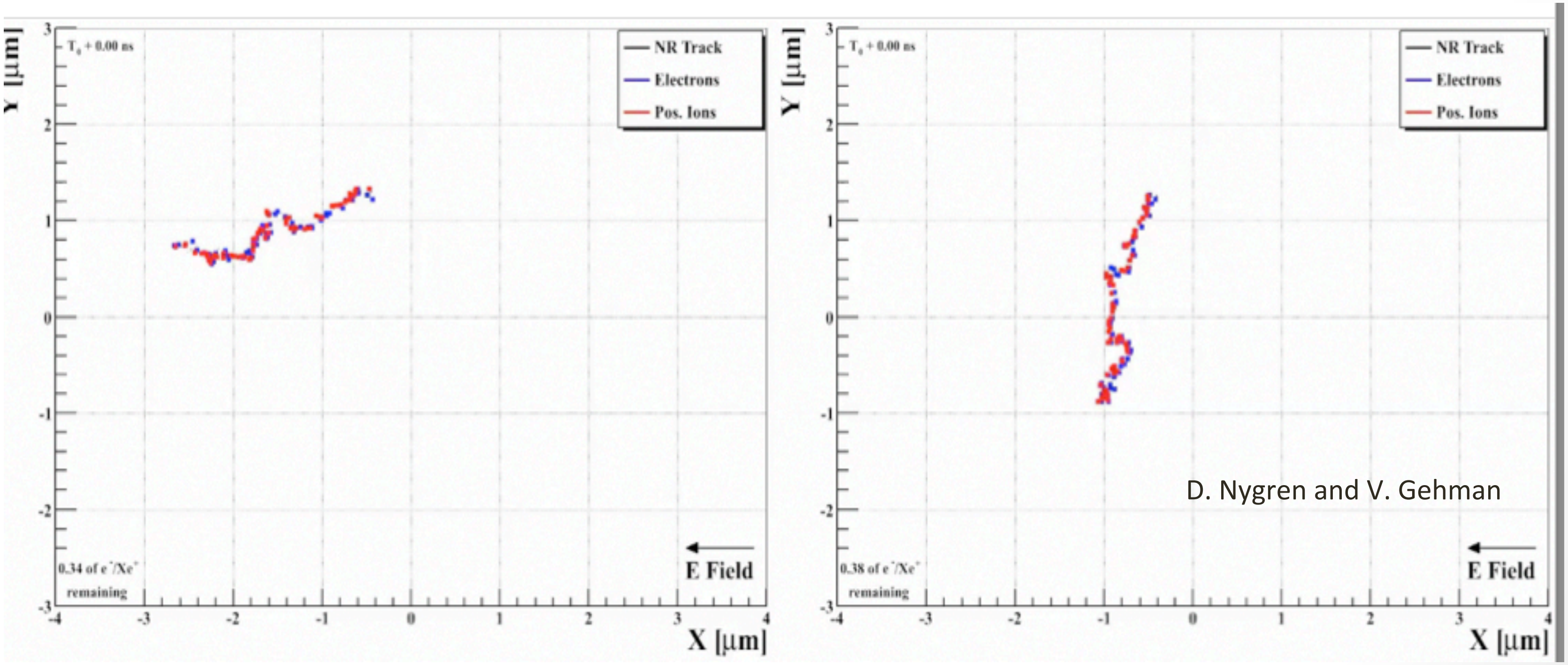
LBNE may be in the region of high derivative

Data from Doke et al., NIM A 269 (1988) pp. 291-296, and Doke et al., Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1538–1545

- In LAr, the anti-correlation between light yield (LY) and charge (CY) missed in the past
- Combining helps you empirically reduce the non-detector systematics, most especially the recombination
- In pre-LBNE TPC calibrations, we can use mono-energetic sources and sweep the field to gather further evidence of anti-correlation

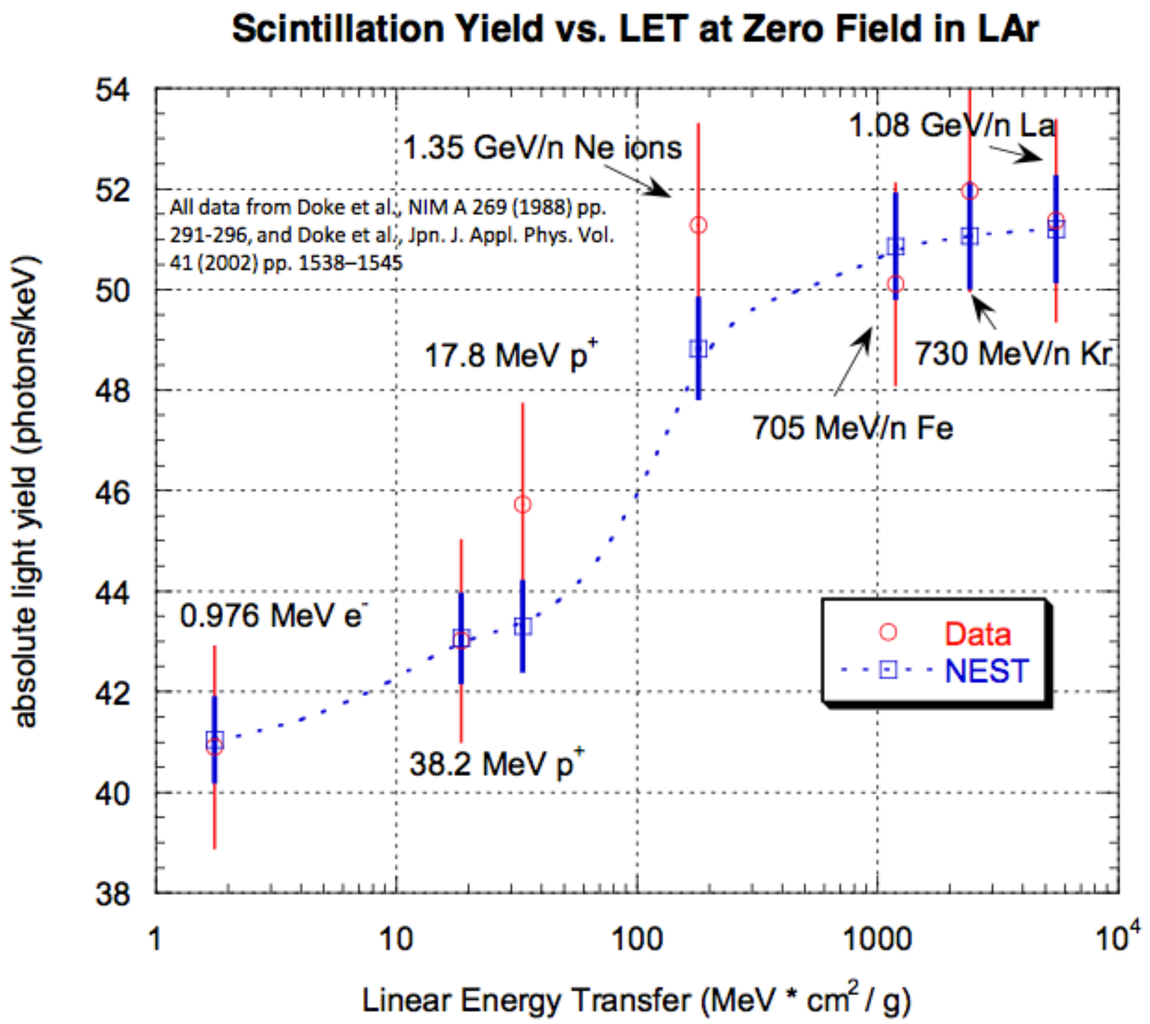
Recombination Probability

- NEST takes the Birks' Law for scintillation yield and converts it into a recombination probability instead
- dQ/dE can be thought of as escape probability, or, one minus the recombination probability



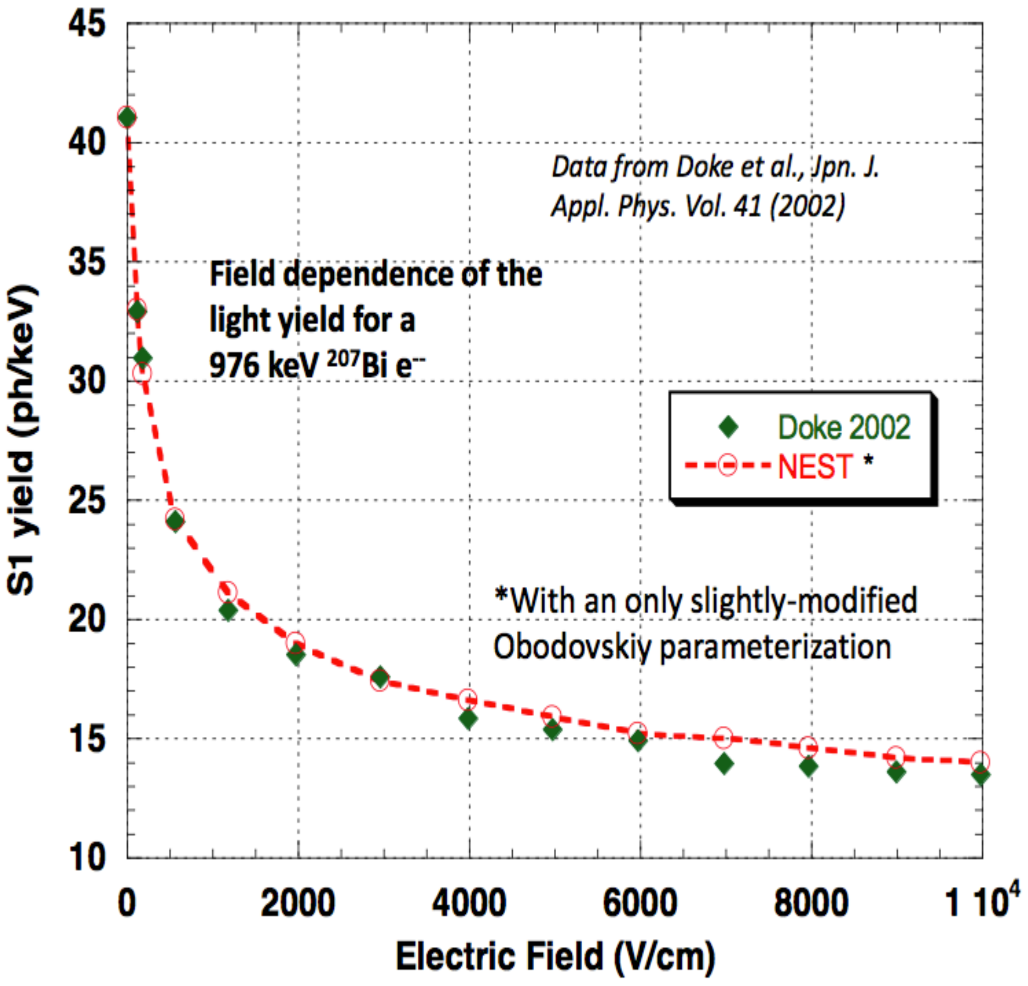
D. Nygren and V. Gehman

Zero-Field Yield



- NEST grew out of lower energies (for WIMP searches in Xe), graduating to the multi-MeV to GeV regime quite successfully
- Summing all the sources of LY: excitons plus recombination, both geminate (fast) and volume recombination
- NEST does not have HIPs (highly-ionizing particles) yet, but this is planned

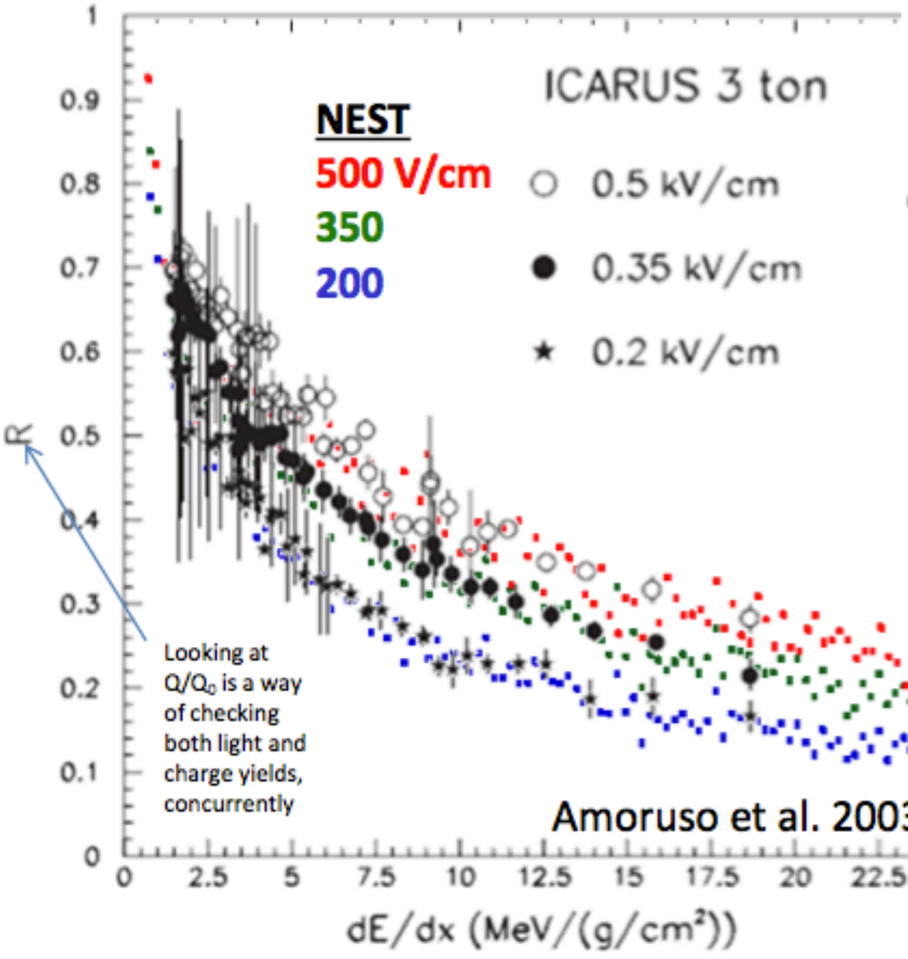
MIPs at any Field



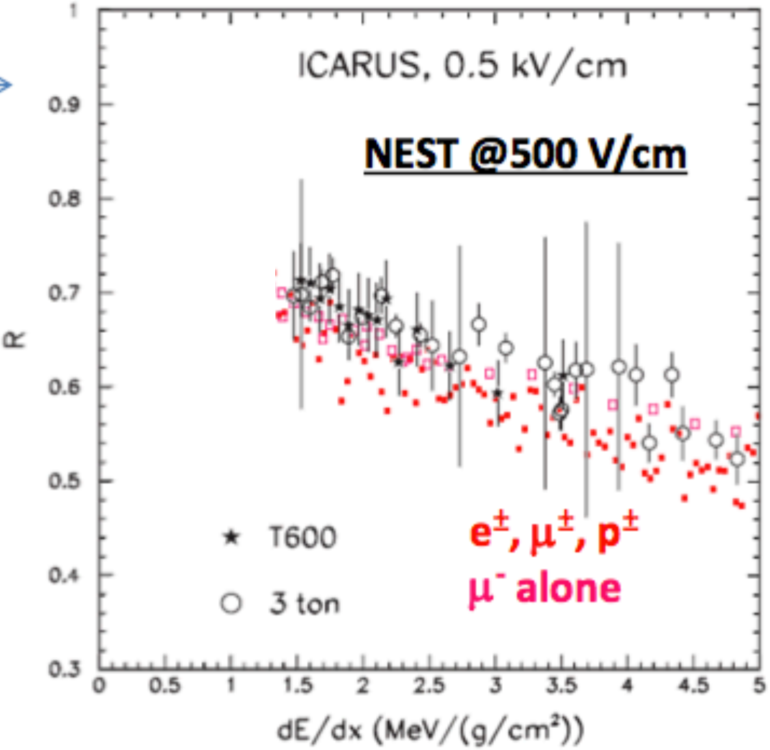
- Generalization for any field possible, not just the common low fields such as 500 V/cm
- Makes it simple to use NEST to optimize the field for a detector: neutrino energy resolution and low energy threshold (LY-driven) considerations
- Low threshold critical for any supernova burst neutrino studies

More Comparison with Data

Particle type does matter! →

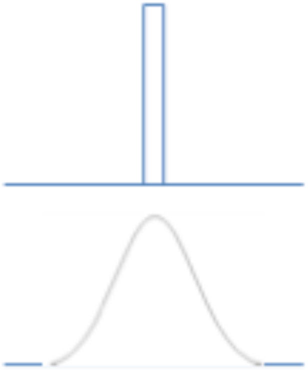


Looking at Q/Q_0 is a way of checking both light and charge yields, concurrently



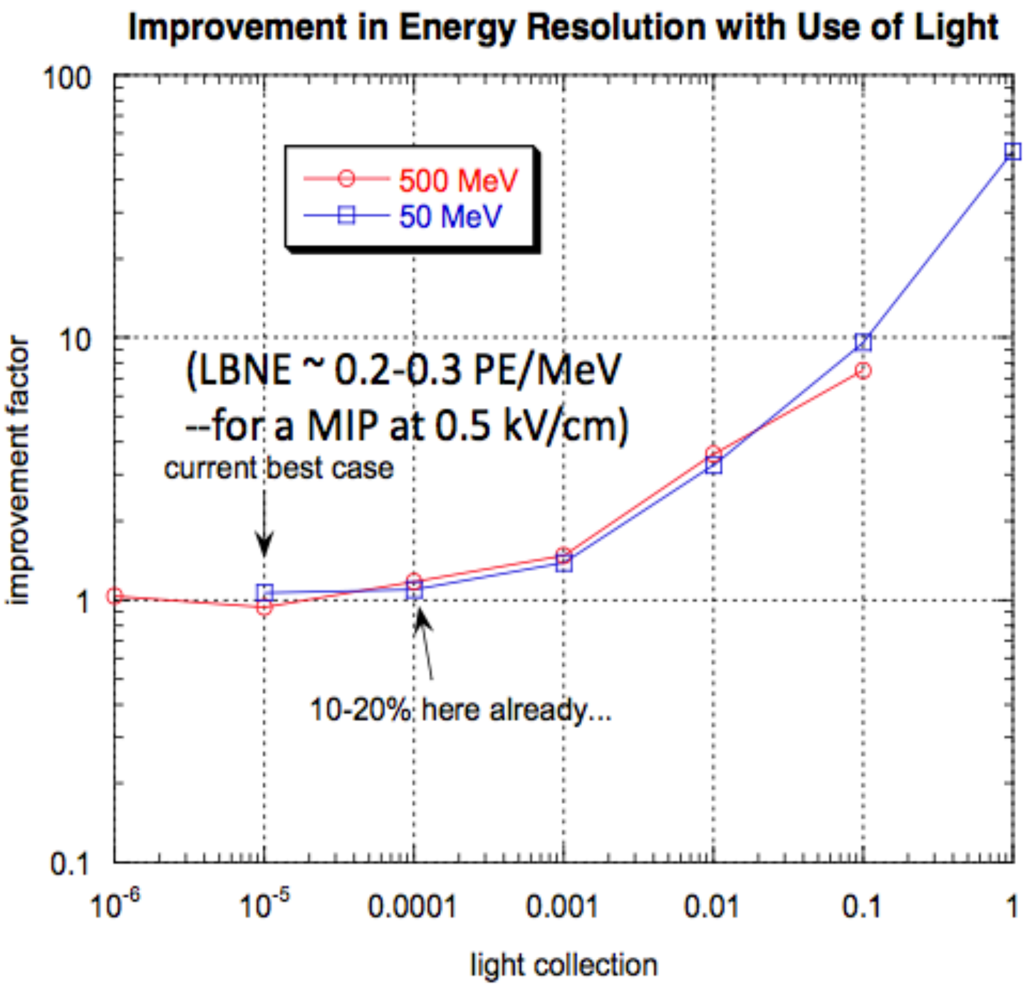
dE/dx is more important than energy, and the tracking of the stochastic variation in the secondary track history, step by step, is also crucial to get right

Energy Resolution



- Long list of effects now included in NEST
- Fano factor (a very small effect)
- N_{ex} vs. N_i (binomial fluctuation)
- Recombination fluctuations
  - Binomial (to recombine, or not to recombine)
- Geant4 stochastic dE/dx variation
- Particle track history (also Geant4)
- Finite quantum efficiency (end-user)
- Imperfect light collection (Geant4)
- Angle of particle track with respect to the electric field vector not yet included, but can be soon (small effect)

Energy Reconstruction


Improvement in Energy Resolution with Use of Light

(LBNE ~ 0.2-0.3 PE/MeV --for a MIP at 0.5 kV/cm)

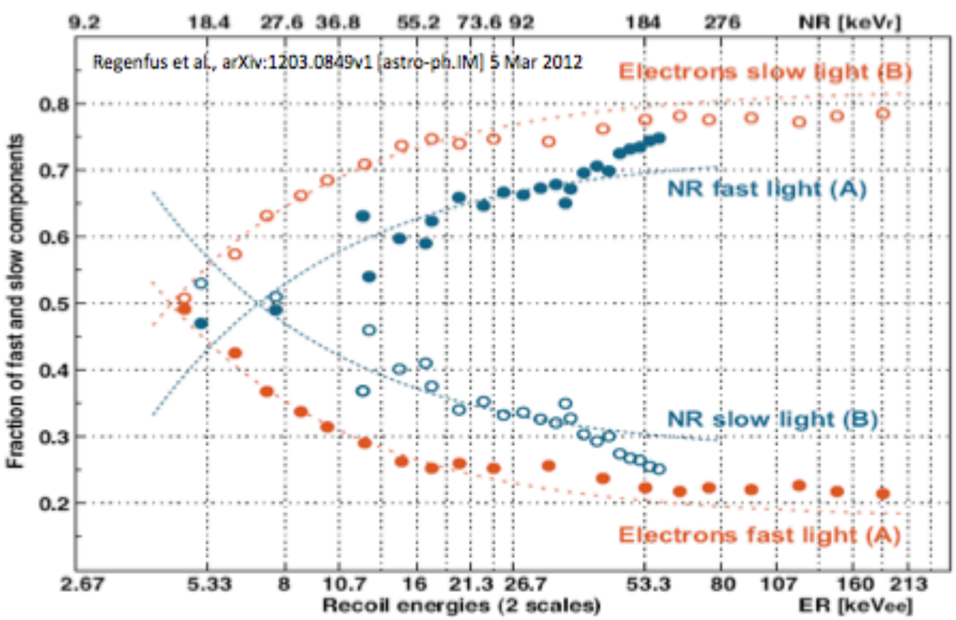
current best case

10-20% here already...

- In LBNE, we have some ways to go before seeing an enhancement using LY, but simulation results tell us that we should NOT neglect optimization of the photon detection
- Proven in LXe: see "Correlated fluctuations between luminescence and ionization in liquid xenon," Conti et al., Phys. Rev. B 68 054201 (2003). Real in LAr (slide 15, plus DarkSide talk IDM '12)

Understanding Pulse Shape

- The upper plot has been converted into a function of LET instead of E (soon impurity concentration too)
- Latest version of NEST has incorporated these results at right
- This should be a significant step forward in LAr modeling, giving us the correct, non-constant ratio of the triplet to singlet



Regenfus et al., arXiv:1203.0849v1 [astro-ph.IM] 5 Mar 2012

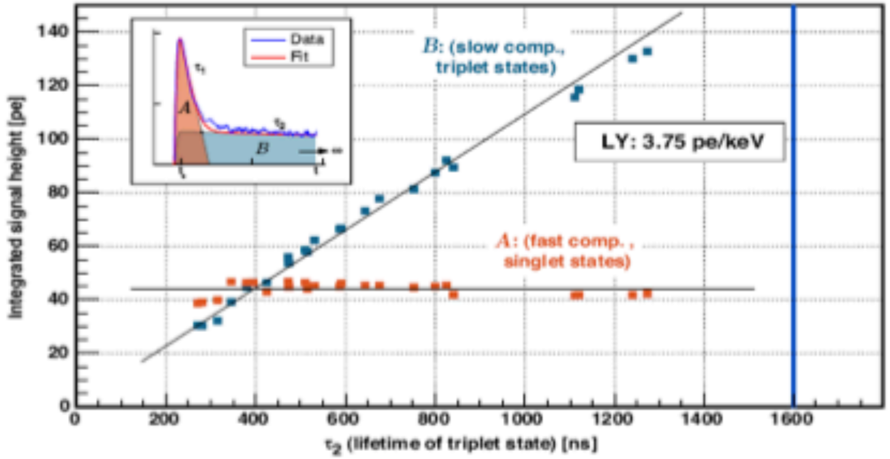
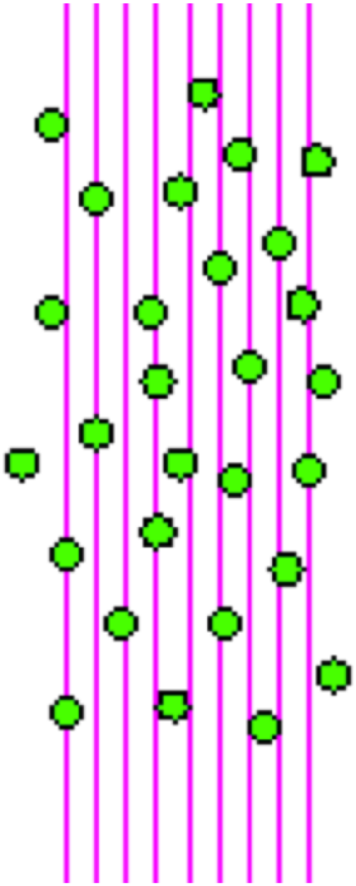


Figure 3. *Yield of the fast and slow scintillation components under different purity conditions.*

Understanding Charge Collection

- New G4Particle for drift electrons
- Analogous to optical photons versus gamma rays in GEANT simulation
- Normal electrons, if born with tiny (~eV) energies, are absorbed immediately instead of being tracked
- Full sims take much longer than parameterized ones, but this new particle (the “thermalelectron”) allows tracking of individual ionization sites
- Unlocks possibilities for simulated drift electric field, purity, and diffusion mapping fully in three dimensions



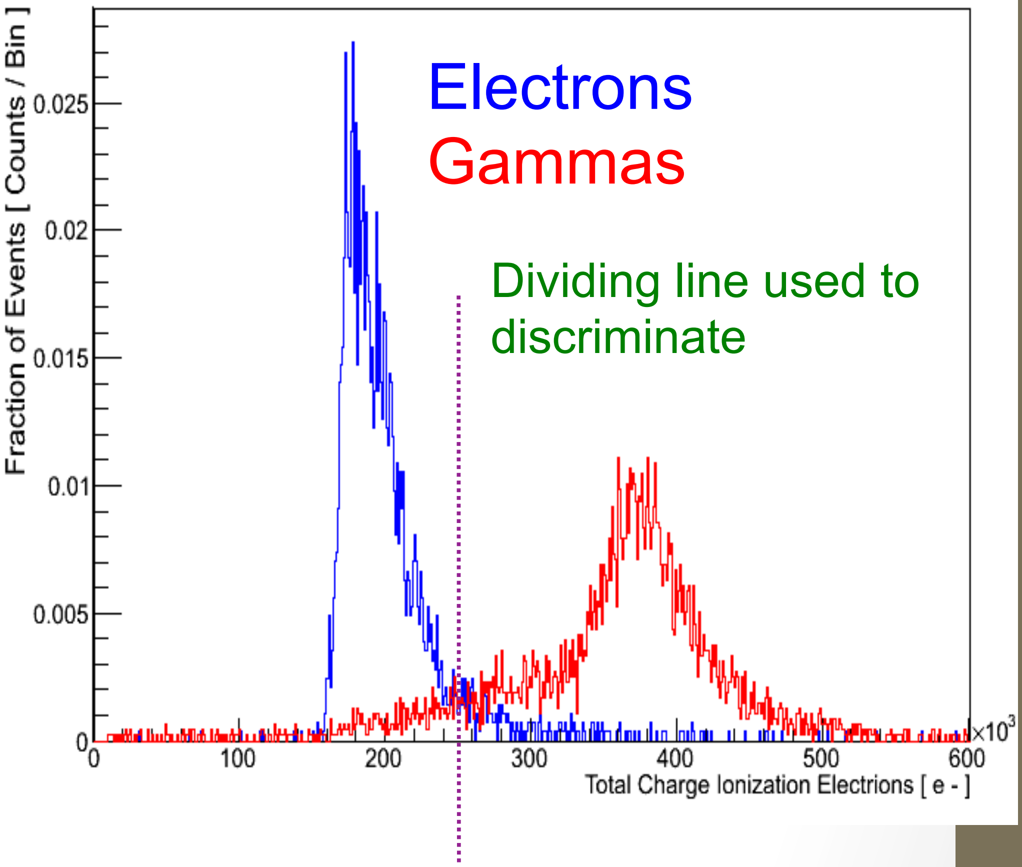
Application: e-/γ Separation

- Want to detect electrons from a neutrino interaction (such as charge current ν_e + n -> p^+ + e-) but discriminate against gamma rays from background radioactivity, and gammas stemming from pion decays: these high-energy electrons make scintillation light and liberate drift electrons (charge yield)

- Electrons and gammas have different CY: gammas will pair produce and the resulting lower-energy e^- and e^+ have different *dE/dx* in their first few centimeters of track than one electron of energy equal to the sum of their individual energies

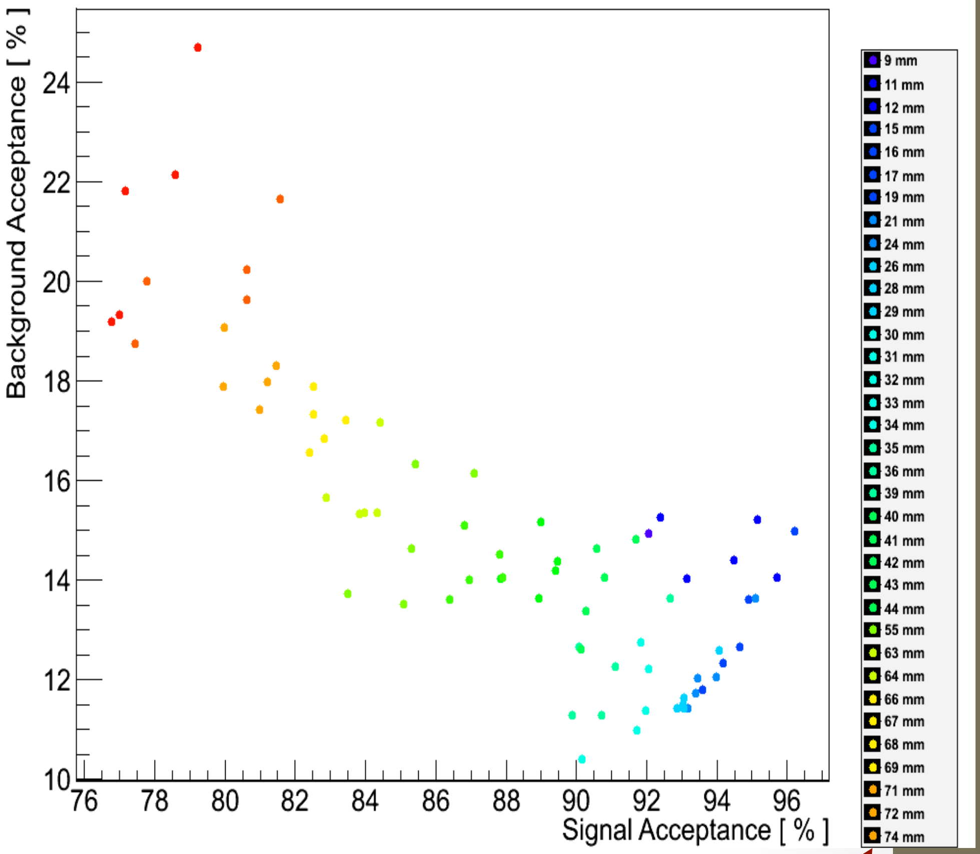
Yield Histograms

- Track length segment of the first 2 cm
- Example of a best-case scenario for both signal acceptance and background rejection
- Acceptance of signal (electrons) ~ 95%
- Acceptance of background (gammas) ~ 10%
- Lower individual energies means more charge loss early on



Background vs. Signal Acceptance

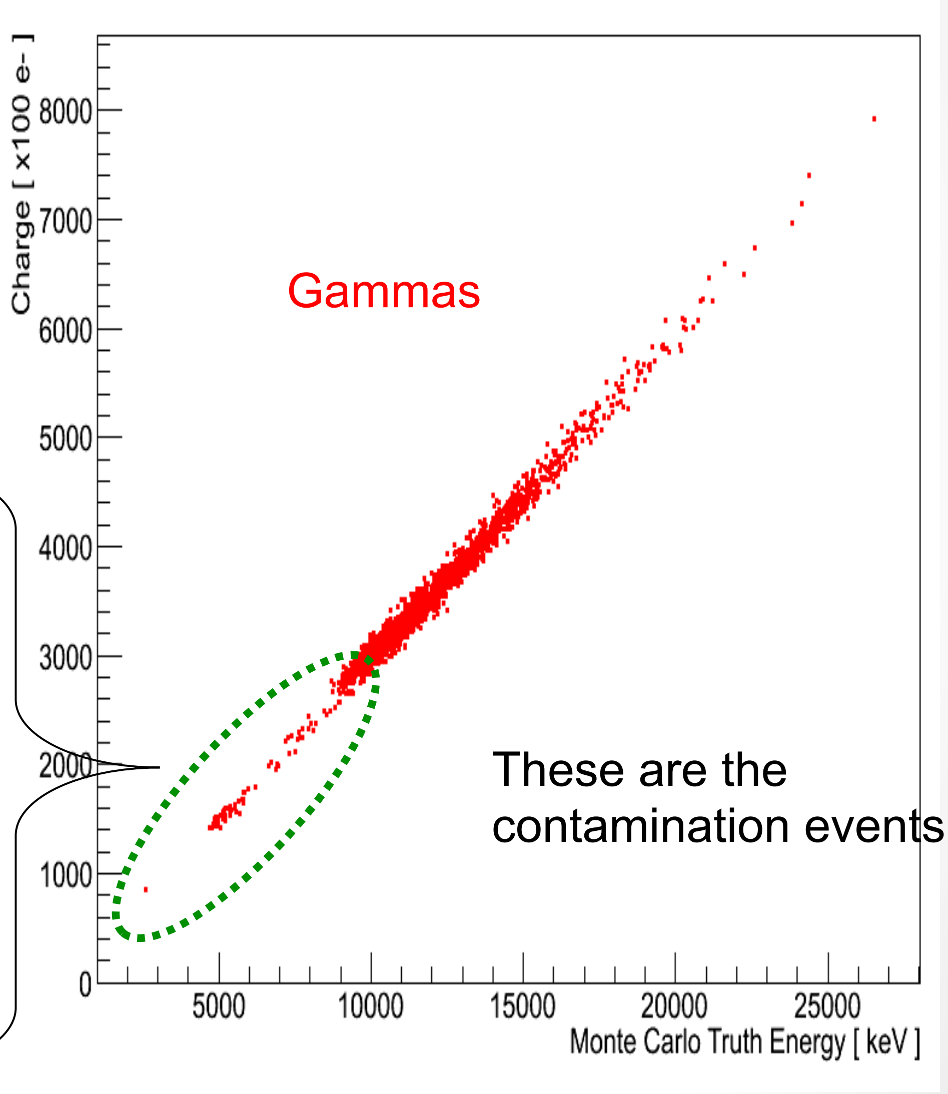
- Current state of the art
- Working on understanding the spread (not statistical)
- The minimum background acceptance is ~10% for a 3 cm portion of track, with ~90% signal acceptance
- Gamma rays simulated as isotropic, and electrons as along neutrino beam angle
- Future work: machine learning, more variables



Track Segment

Contamination Event Clues

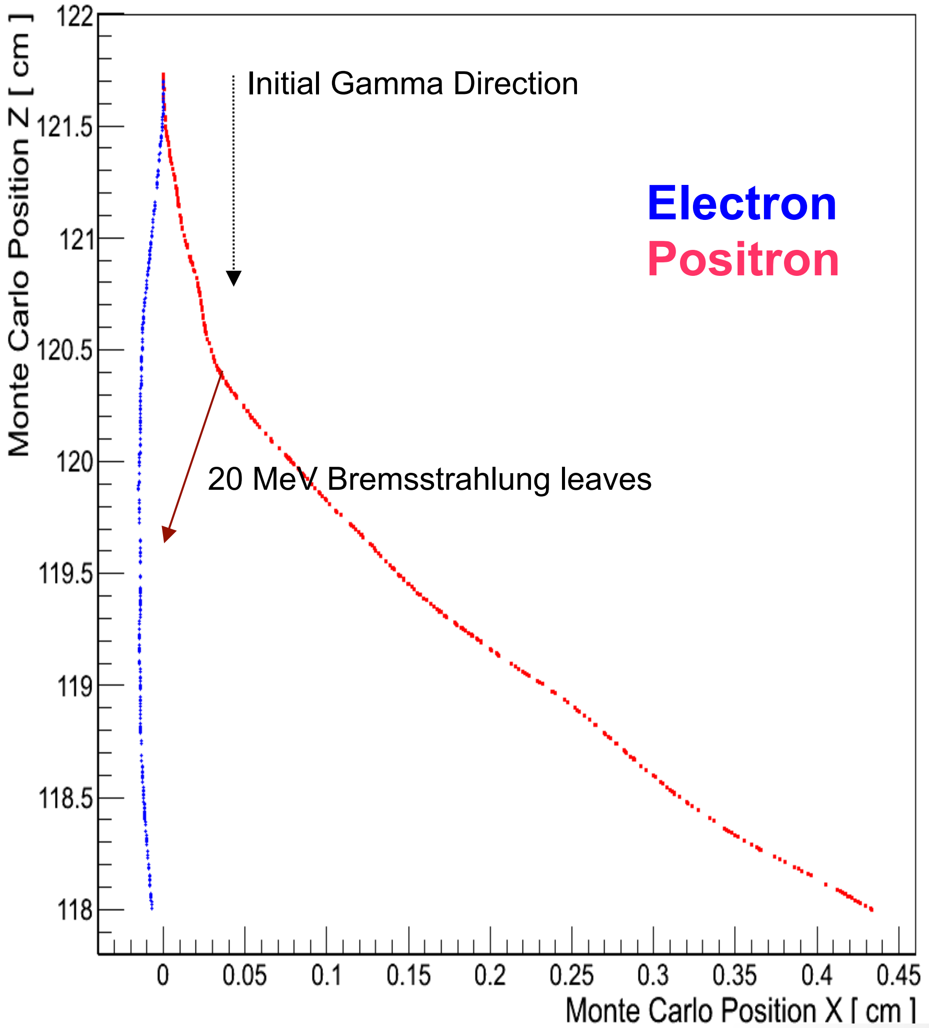
- Investigations of the more electron-like gamma events: low charge, energy.
- Hand-scanning coupled with the Monte Carlo tracking verbosity hint at the following causes:
  - Møller or Bhabha scattering
  - Bremsstrahlung radiation where the gamma rays produced escape very far from the e+ and e- tracks
  - e+ annihilation where the 0.511 MeV gammas can stray from original direction



These are the contamination events

3D Track Example

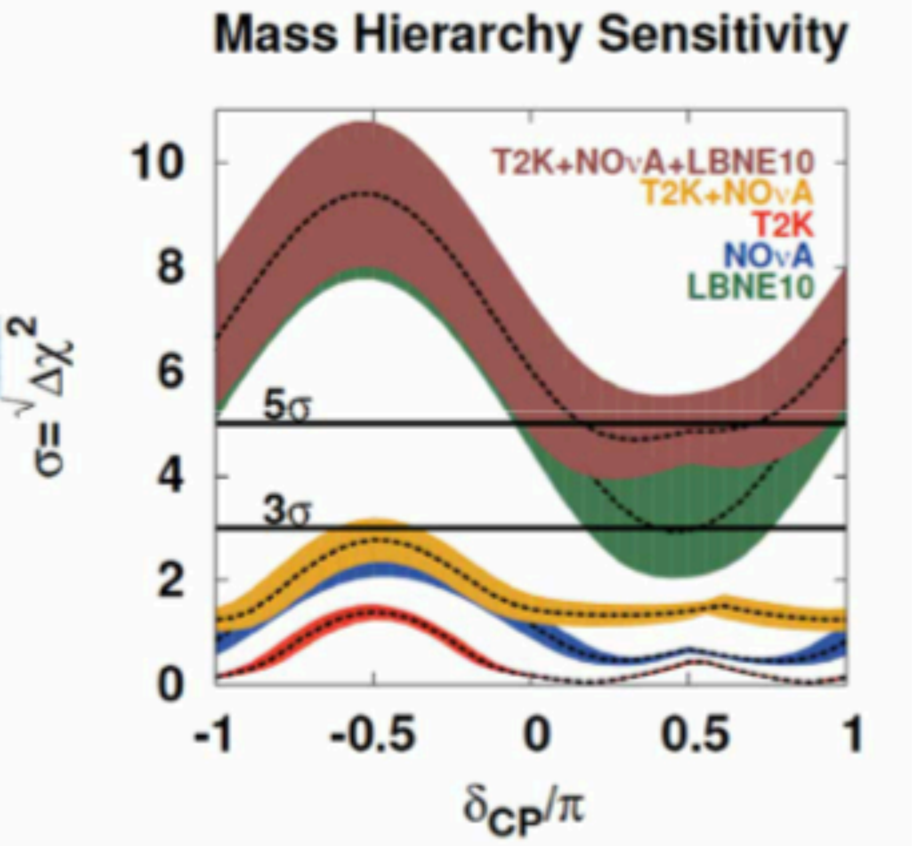
- Visually inspecting events one by one, examining the tracks for clues to where missing energy went.
- Collecting all the charge perpendicular to the initial direction does not recover all missing energy that makes events contaminate the signal region.
- Supports the idea that Bremsstrahlung radiation that heads downstream is main cause for gamma contamination in argon

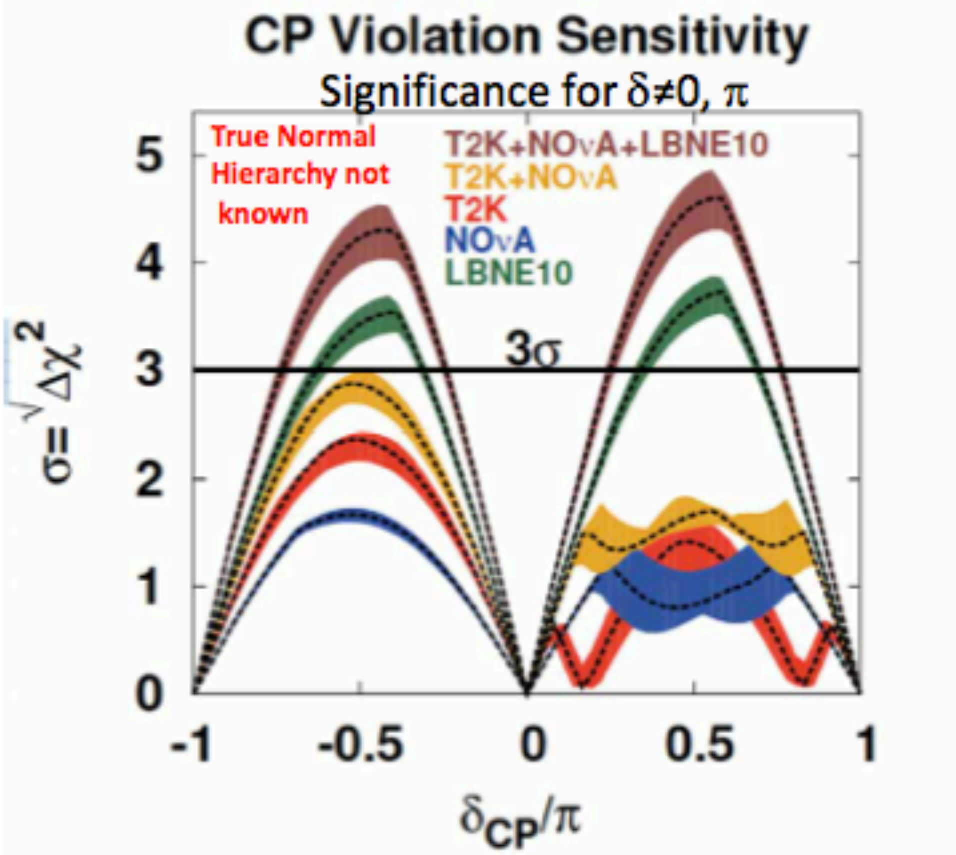


Conclusion

- LBNE can achieve a large suite of physics results, with a noble element (liquid argon) far detector
- NEST models the microphysics of noble elements, including argon, quite well, assuming a combined energy scale
- An understanding of the underlying physics of the signals in noble detectors has consequences for calorimetry and particle identification techniques

Just 10 kt LArTPC Would be a Major Advance





LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$) T2K 750 kW x 5 yr (7.8×10^{21} pot) ν NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$) (3.8×10^{21} pot)

*Improved over CDR 2012 120 GeV MI proton beam Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

LBNE10 does much better than full program for existing experiments