Electron and Photon Generation in the Long Baseline Neutrino Experiment

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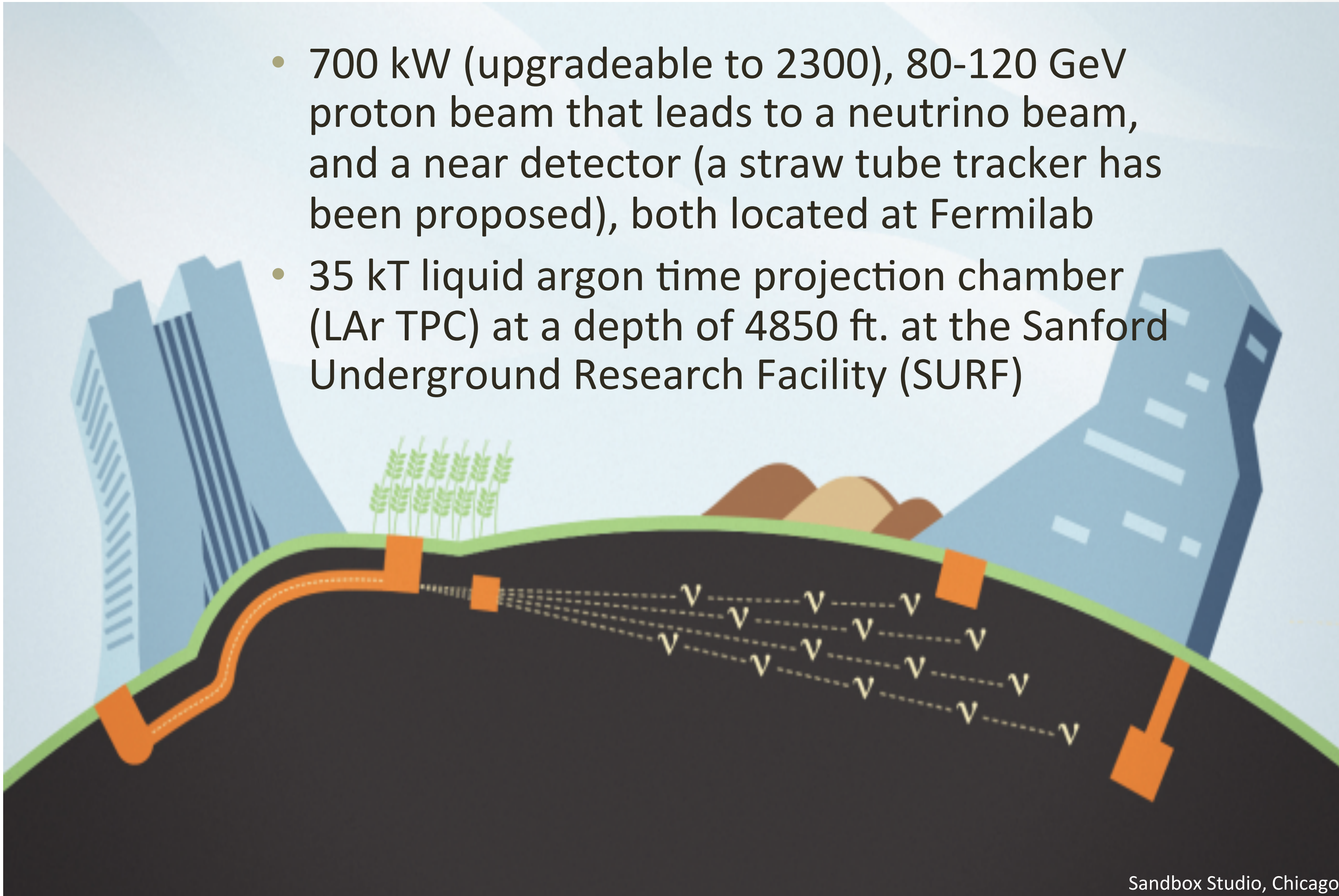
UC Davis Seminar, Tuesday October 22, 2013

Introduction to LBNE

- 700 kW (upgradeable to 2300), 80-120 GeV proton beam that leads to a neutrino beam, and a near detector (a straw tube tracker has been proposed), both located at Fermilab
- 35 kT liquid argon time projection chamber (LAr TPC) at a depth of 4850 ft. at the Sanford Underground Research Facility (SURF)



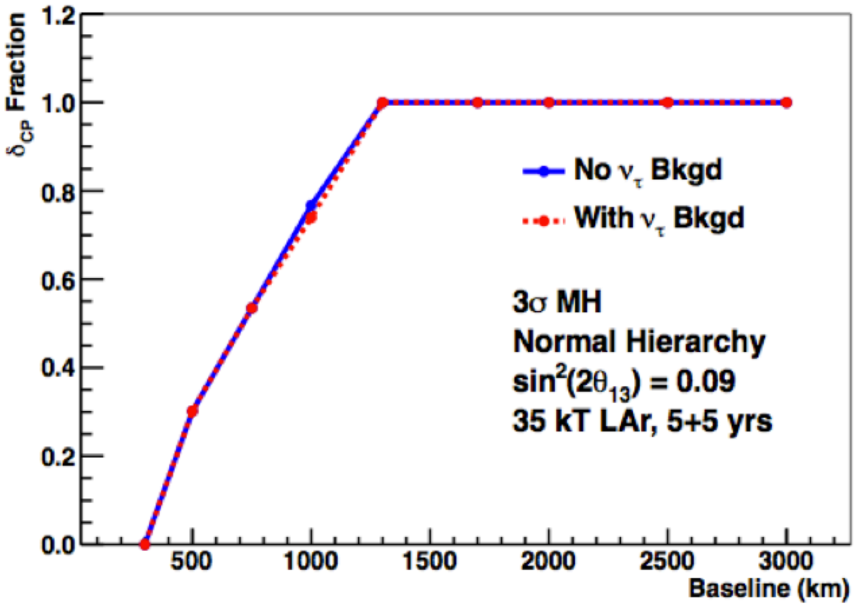
Sandbox Studio, Chicago

Physics Motivations

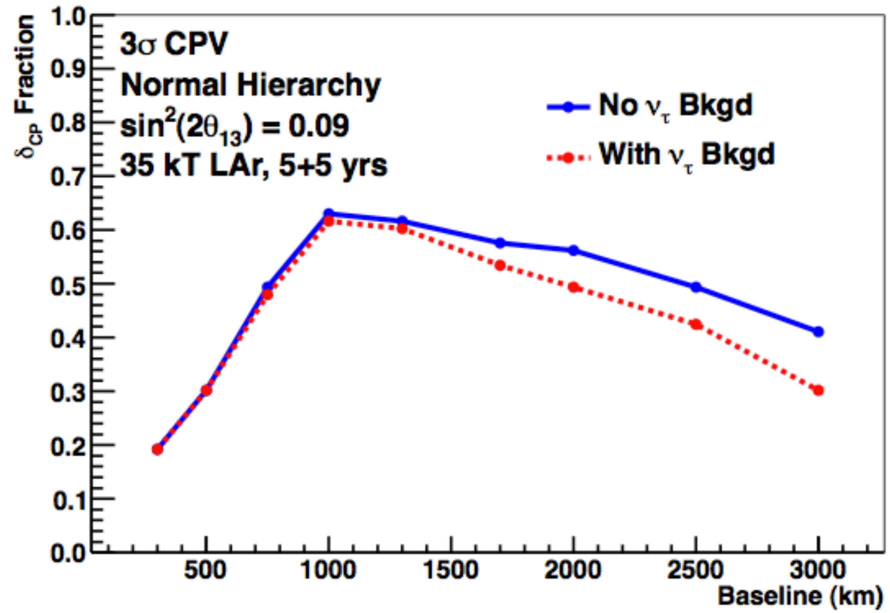
- Neutrinos have mass, and oscillate between different types. The three flavor eigenstates (electron, muon, tau) are not the same as three mass ones. Effect not in Standard Model (SM).
- But what is their mass hierarchy (MH)? Two heavy neutrinos and one light, or vice versa? We know only mass differences
- Does the neutrino mixing matrix have a non-zero CP-violating angle? Are neutrino and anti-neutrino oscillations the same?
- Are there sterile neutrinos, which interact weakly with SM particles but which the normal neutrinos can oscillate into?
- An underground, high-mass liquid argon target will also enable atmospheric and astrophysical neutrino studies, not to mention we could get lucky and see a supernova in LBNE
- Does the proton decay, and on what time scale? Proton decay is predicted by many GUTs, including SUSY, yet unobserved

Optimization of the Baseline

Mass Hierarchy Determination

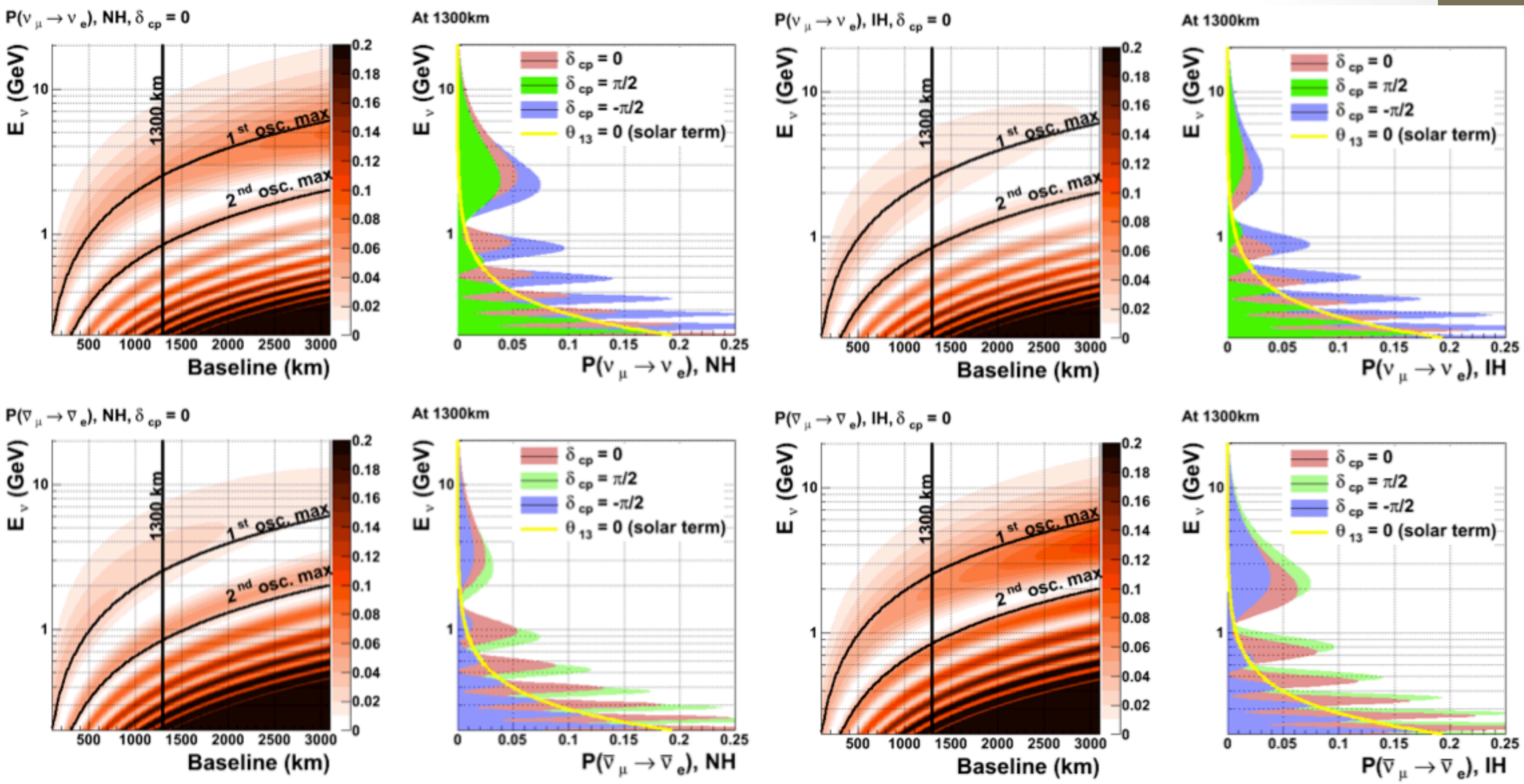


CP Phase Measurement



- 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 same with other baselines, need more mass and more intense beam

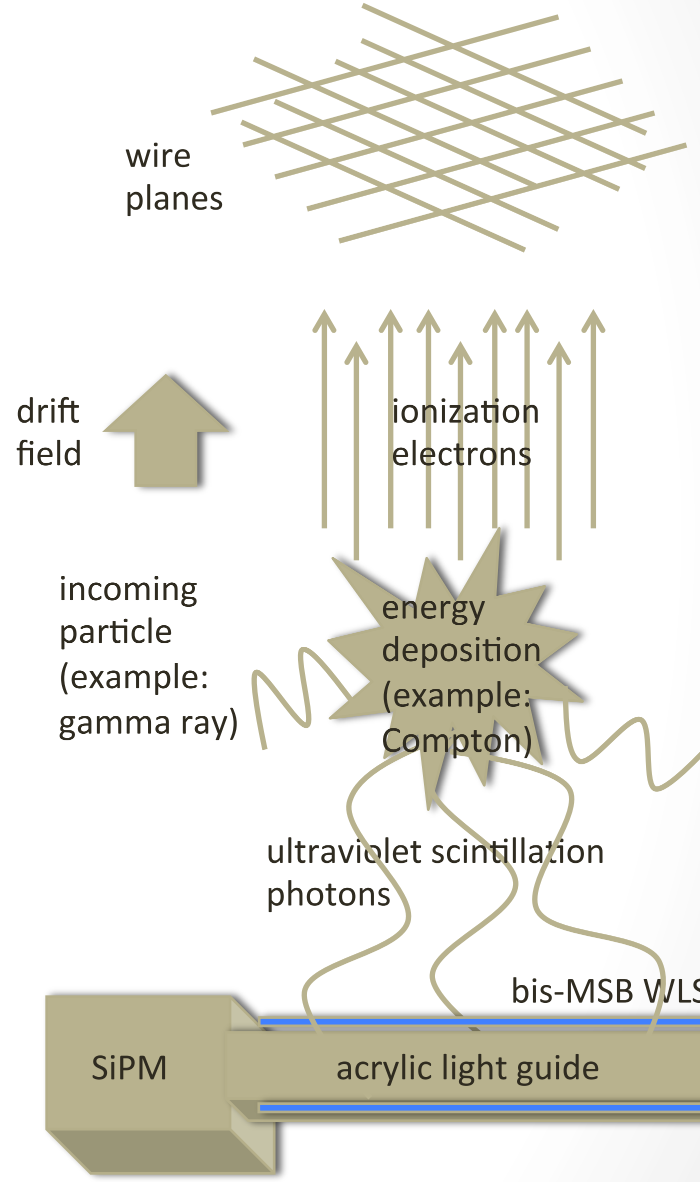
Appearance Oscillogram



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

Liquid Argon Far Detector

- Energy depositions produce both scintillation and ionization in a noble element
- 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 photo-multipliers
- 500 V/cm electric field drifts the liberated electrons, which constitute the primary means of calorimetry, ID



Argon and Detector 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)
- O(1 m) Rayleigh scattering length. Comparable photon absorption length (?) depending on photo-absorbing impurities

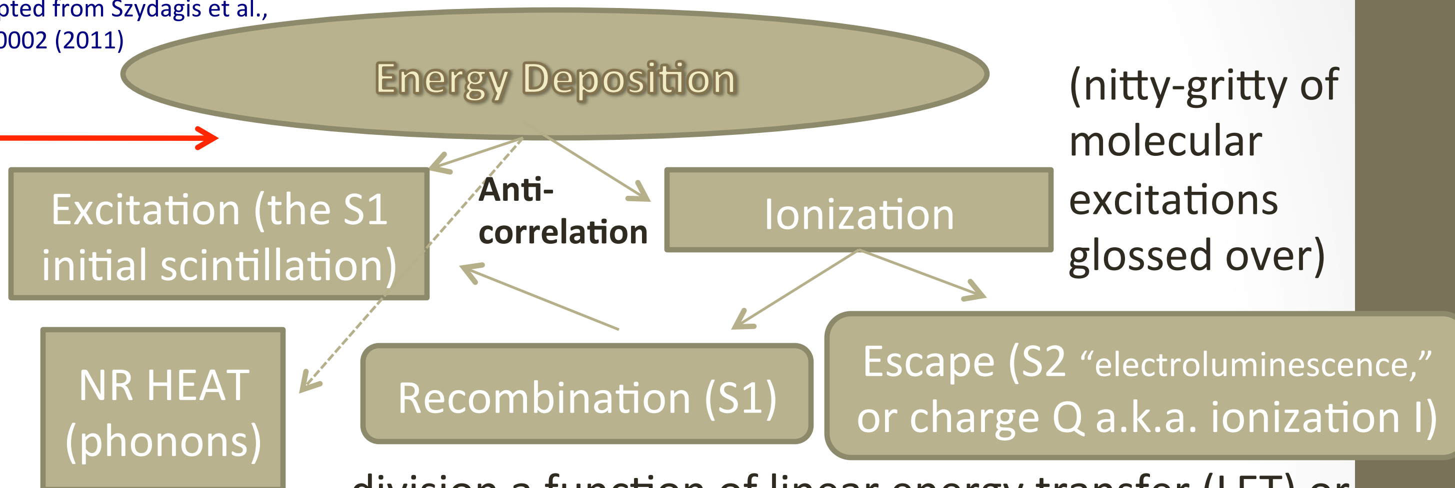
- TPC provides great tracking. It is like a "digital bubble chamber."
- 1.4 ms maximum electron drift time. O(1 ms) purity planned
- 5 mm wire pitch for the anode wires. >100 kV cathode
- 34-35 kT fiducial (50 kT total) at 4300 m.w.e. depth OR 10 kT (9.4 kT fiducial) on surface, segmented into multiple cryostats

What is NEST?

- That name refers to both a model (or, more accurately, a collection of models) explaining the scintillation and ionization yields of noble elements as a function of particle type (ER, NR, alphas), electric field, and *dE/dx* or energy
- … as well as to the C++ code for GEANT4 that implements said model(s), overriding the defaults
- Has goal of providing a full-fledged MC sim with
  - Mean yields (light AND charge, and photons / e-)
  - Energy resolution (includes BG discrimination)
  - Pulse shapes (light AND charge, including single e- scintillation)
- Combed the wealth of data on noble elements and combined all of the underlying physics learned

Basic Physics Principles

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



1st division of energy deposition a function of interaction type (nuclear vs. e-recoil) but not particle type (e.g., e-,γ same), and (~) not a function of the parent particle's initial kinetic energy…

(nitty-gritty of molecular excitations glossed over)

(infamous "quenching" factor, NR)

division a function of linear energy transfer (LET) or stopping power (*dE/dx*), because of ionization density considerations, and of the electric field magnitude

- Exciton-to-ion ratio is 0.20 for e- recoil (argon)
- S1 ≠ energy: energy depositions divide into two channels, S1 and S2, non-linearly: idea from Eric Dahl
- Nuclear recoils also have to deal with Lindhard*

* but it affects BOTH charge and light production

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 TIB (< O(10) keV)
  - Doke's modified Birks' Law Doke et al., NIM A 269 (1988) p. 291

volume/bulk or columnar recombination

$$r = \frac{A\frac{dE}{dx}}{1 + B\frac{dE}{dx}} + C, \quad B = A/(1-C)$$

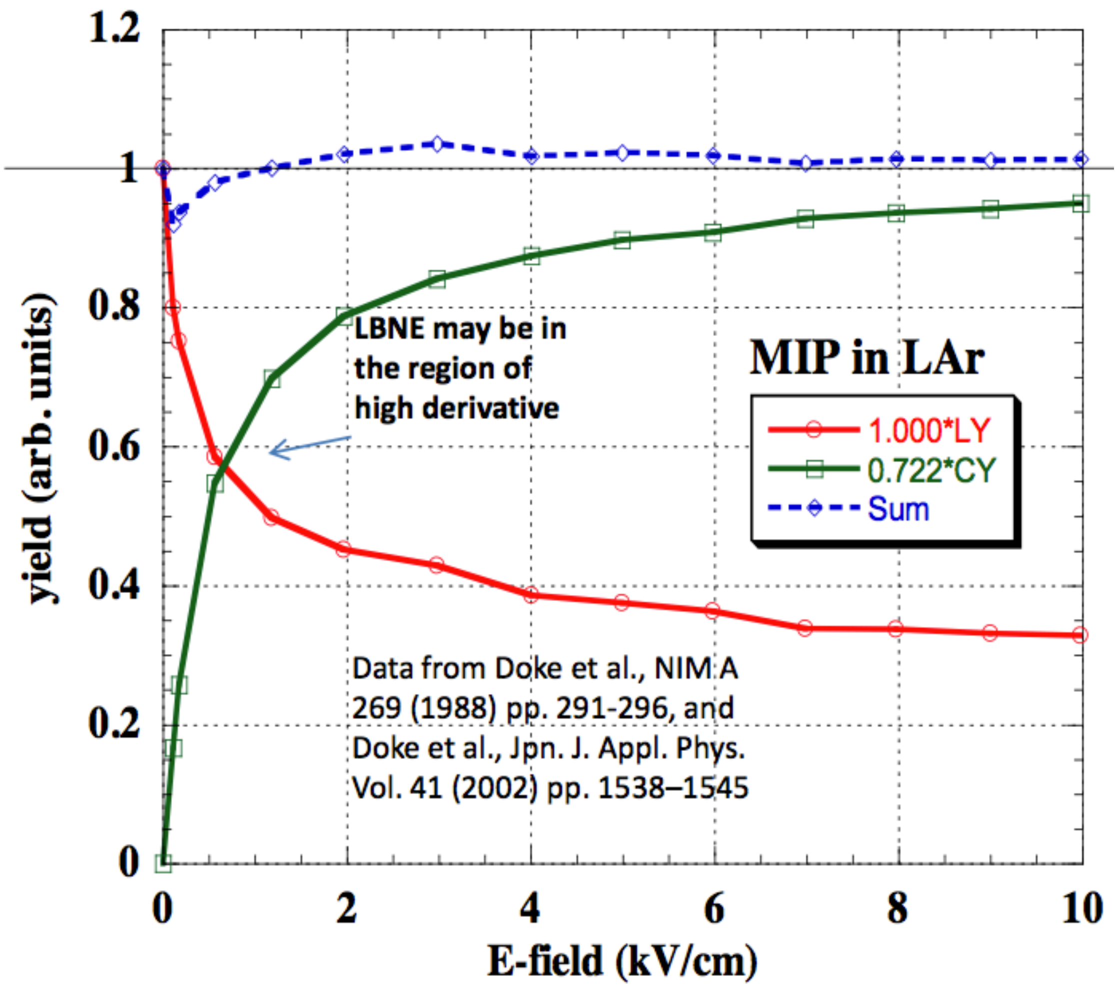
geminate (parent ion)

OR

$$r = 1 - \frac{\ln(1+\xi)}{\xi}, \quad \xi \equiv \frac{N_i \alpha'}{4a^2 v}$$

- Probability r makes for non-linear yield per keV

Combined Energy Scale



- In LAr, anti-correlation between light yield (LY) and charge (CY) missed
- Combining lets you empirically eliminate non-detector systematics, especially 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
- dL/dE = A (dE/dx) / (1+B dE/dx) becomes
- r = A (dE/dx) / (1+B dE/dx), which goes from 0 to 1 (if A = B)
- (NEST adds a '+C ' for geminate recombination, at zero field)
- dQ/dE can be thought of as escape probability, or, one minus the recombination probability. Let's derive the ICARUS formula used by default in LArSoft. R = Q/Q0 = 1 – r =

$$1-\frac{k_B\frac{dE}{dx}}{1+k_B\frac{dE}{dx}}=\frac{1+k_B\frac{dE}{dx}}{1+k_B\frac{dE}{dx}}-\frac{k_B\frac{dE}{dx}}{1+k_B\frac{dE}{dx}}=\frac{1}{1+k_B\frac{dE}{dx}}$$

← 0.8 in Amoruso

Amoruso et al., NIM A 523 (2004) p. 275–286

- ICARUS adds a normalization factor, but that breaks the (anti-) correlation between LY, CY. Non-unity normalization can not be easily justified if looking at a dimensionless recombination factor (as opposed to raw charge yield).

Field Dependence

- k_B= k / field (ICARUS, and other past works)
- Simple formula -- is proportionality strict?
- Can "repair" the normalization constant (make it 1.0) if we generalize this equation to a power law, and break up the track structure of an interaction utilizing the thermalization radius for ionization electrons and ions

Saturation curves and energy resolution of LRG ionization spectrometers

I. Obodovskiy

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Abstract: **Energy resolution of LRG ionization spectrometers is up to now very important and not fully understandable parameter. It is no doubt that at least part of contributions into overall energy resolution determines by the free-ion yield non-linearity. Two opportunities of free-ion yield definition are discussed – Jaffe approach and Birks' law. Experimental results known up to now are analyzed to receive parameters that can be used for energy resolution calculations.**

INTRODUCTION

The considerable part of energy resolution of LRG ionization spectrometers is determined by free-ion yield nonlinearity, i.e. by the dependence of free-ion yield on electron energy.

One way is to choose some function that gives the best fit of the dependence of free-ion yield on electric field strength, the so called saturation curve. Then one needs to consider the dependence of the parameter of this function on electron energy or energy transfer and dopant concentration in mixtures.

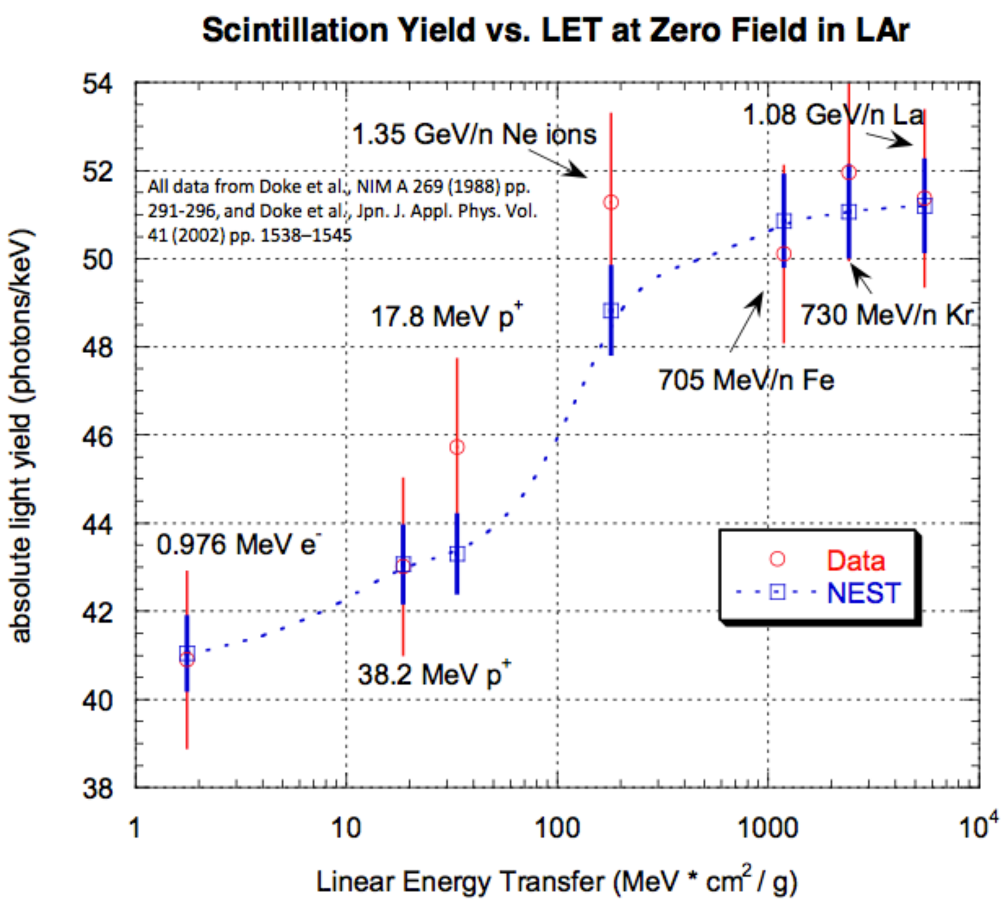
The other way to parameterize the saturation effect is to take a function which describe the dependence of free-ion yield on electron energy or energy transfer. Then one needs to consider the dependence of the parameter of this function on electric field strength and dopant concentration in mixtures.

JAFFE SATURATION CURVES

<= Obodovskiy collected ALL available LAr excitation and ionization data, and he got a different answer than ICARUS (though he included their data in his parameter fitting…)

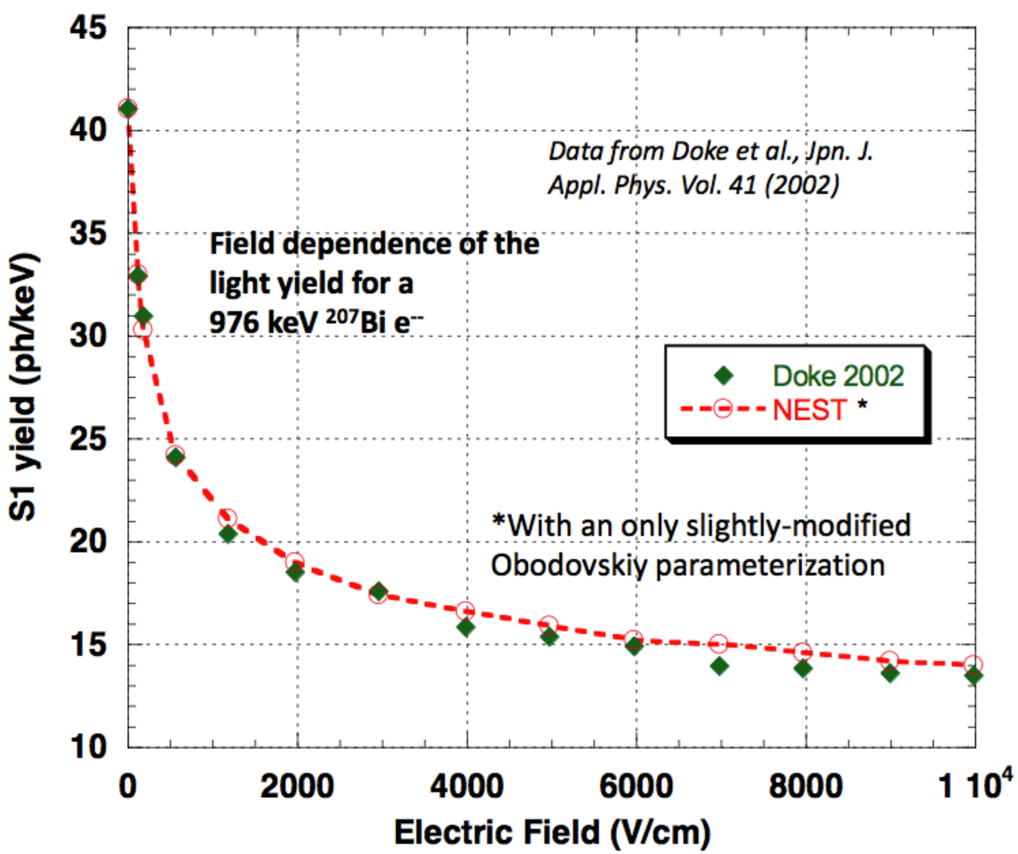
$$kB = 0.05F^{-0.85}$$

Zero Field



- NEST does not have HIPs (highly-ionizing particles) yet, but eventually
- NEST grew out of lower energies (for DM 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

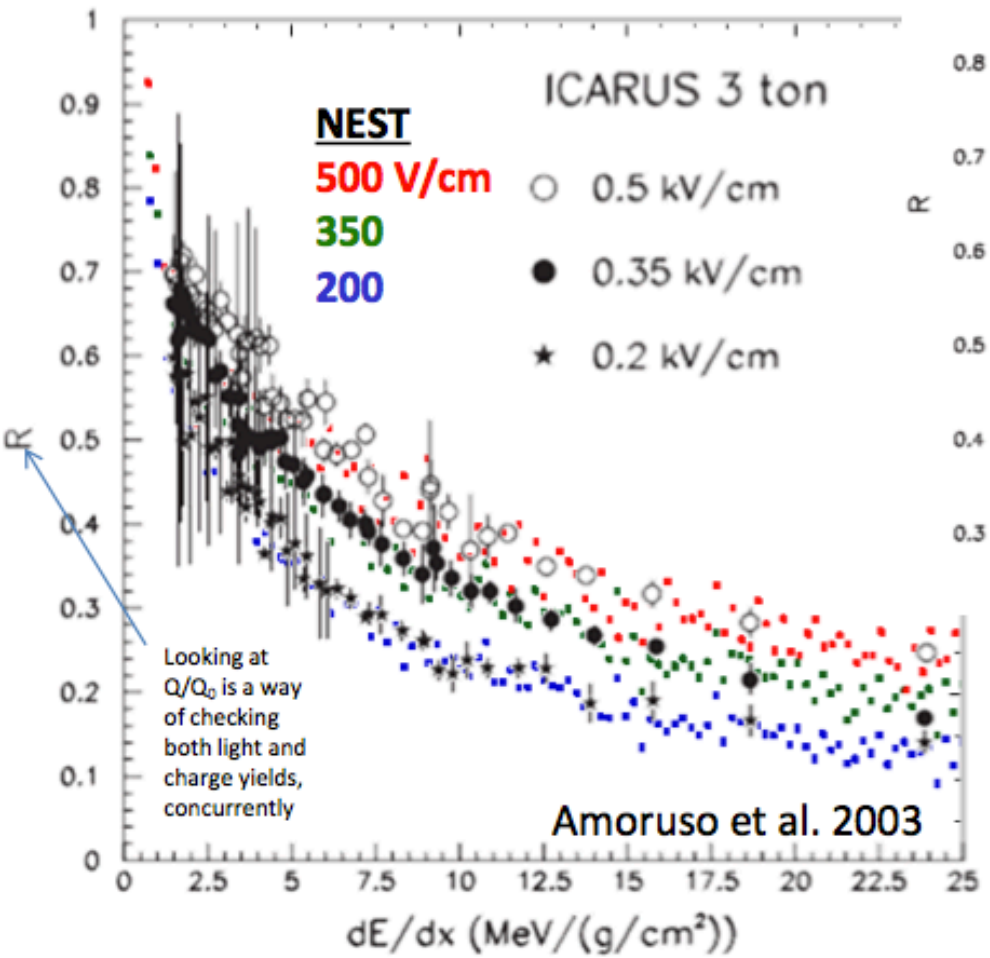
MIPs at any Field

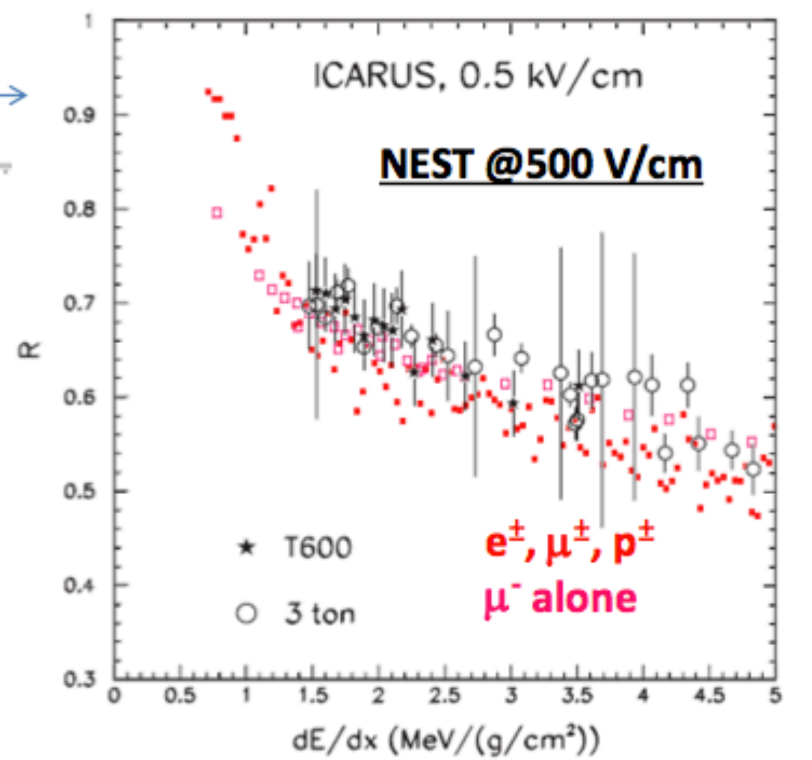


- Generalization for any field possible, not just the common low fields such as 500 V/cm
- Makes it simple to use NEST to optimize the field for a detector: energy resolution and energy (LY) threshold considerations

More Comparison with Data

Particle type does matter!

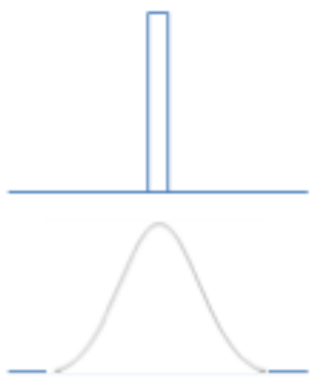




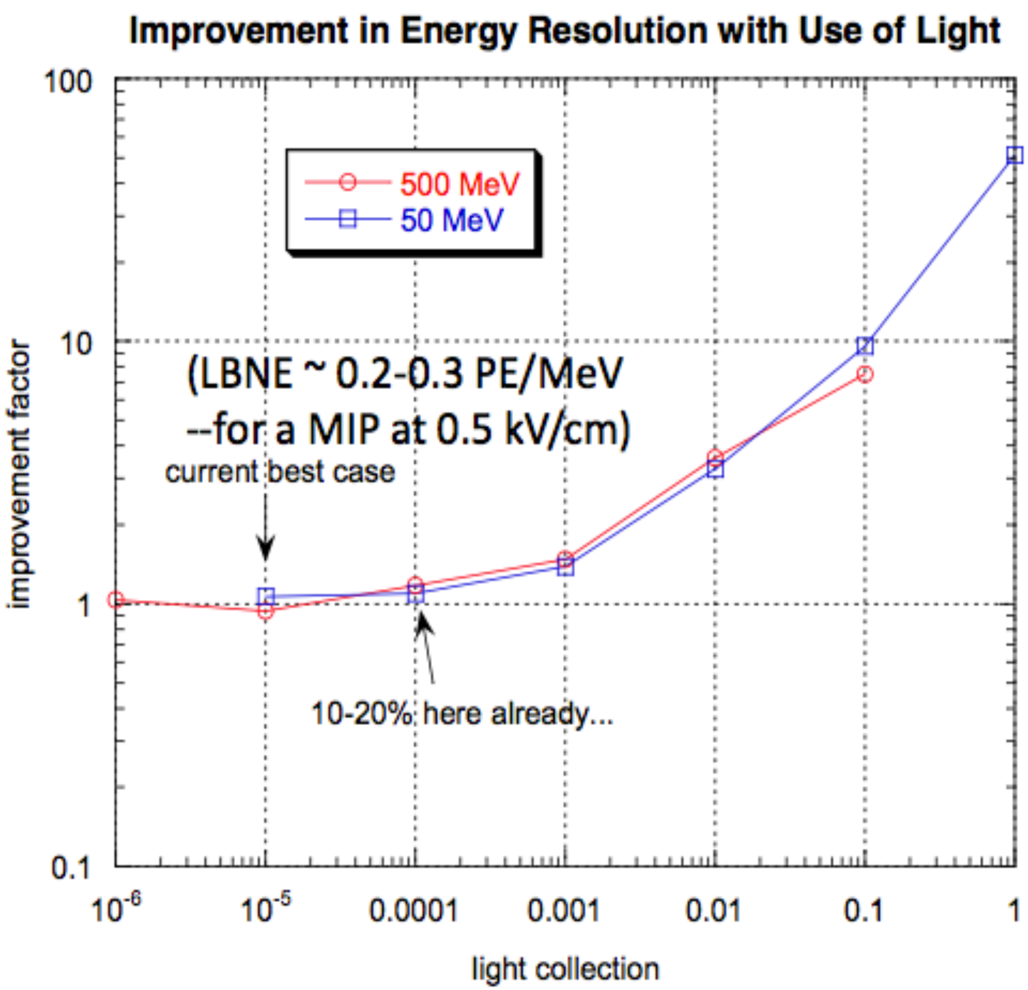
- Demonstration that a -0.85 instead of a -1 power law for the Birks field dependence OK

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)
  - Non-binomial for LXe (no fudge factor for LAr)
- 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



Energy Reconstruction



	LC (frac)	CY [%]	LY [%]	comb [%]	opt [%]	<-- with	improv
500 MeV	1.00E-06	0.33	79.32	0	0.32	0.001	1.0313
	1.00E-05	0.31	9.07	3.28	0.33	0.1	0.93939
	1.00E-04	0.34	3.96	1.19	0.29	900	1.1724
	0.001	0.34	1.2	0.33	0.23	300	1.4783
	0.01	0.36	0.72	0.12	0.1	90	3.6
	0.1	0.27	0.48	0.037	0.036	11	7.5
50 MeV	1.00E-06	0.98	100				
	1.00E-05	1.21	29.01	10.96	1.14	0	1.0614
	1.00E-04	1.01	9.95	3.51	0.92	900	1.0978
	0.001	0.93	3.8	1.11	0.67	300	1.3881
	0.01	1.11	2.39	0.37	0.34	90	3.2647
	0.1	1.05	2.18	0.11	0.11	10	9.5455
	1	0.97	1.91	0.019	0.019	1	51.053

- In LBNE, we have some ways to go before seeing an enhancement, but this simulation result tells us that we should NOT neglect optimization of LY
- 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 too (look at slide 11)

Understanding Pulse Shape

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

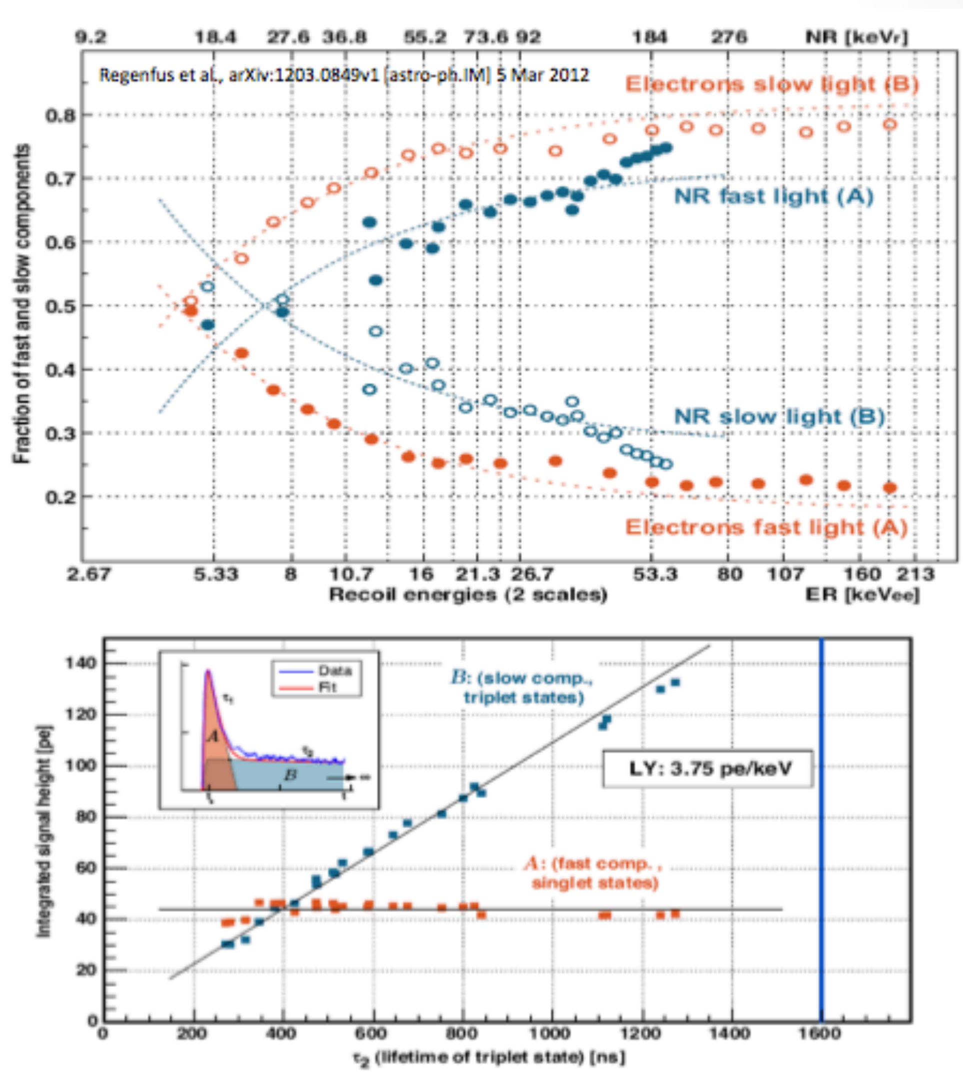
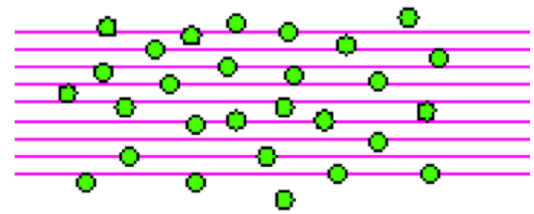


Figure 3. *Yield of the fast and slow scintillation components under different purity conditions.*

Understanding Charge Collection



- New G4Particle for drift e-'s
- Analogous to optical photons versus gamma rays
- Normal electrons, if born with tiny energies, are absorbed immediately in GEANT
- Full sims take much longer than parameterized ones, but this new particle (the "thermalelectron") allows tracking of individual ionization sites, and simulated 3-D electric field, purity, and diffusion mapping
- To decrease simulation time, NEST has a built-in feature for charge yield reduction

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*************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 5,   Parent ID = 3
*************************************************************************

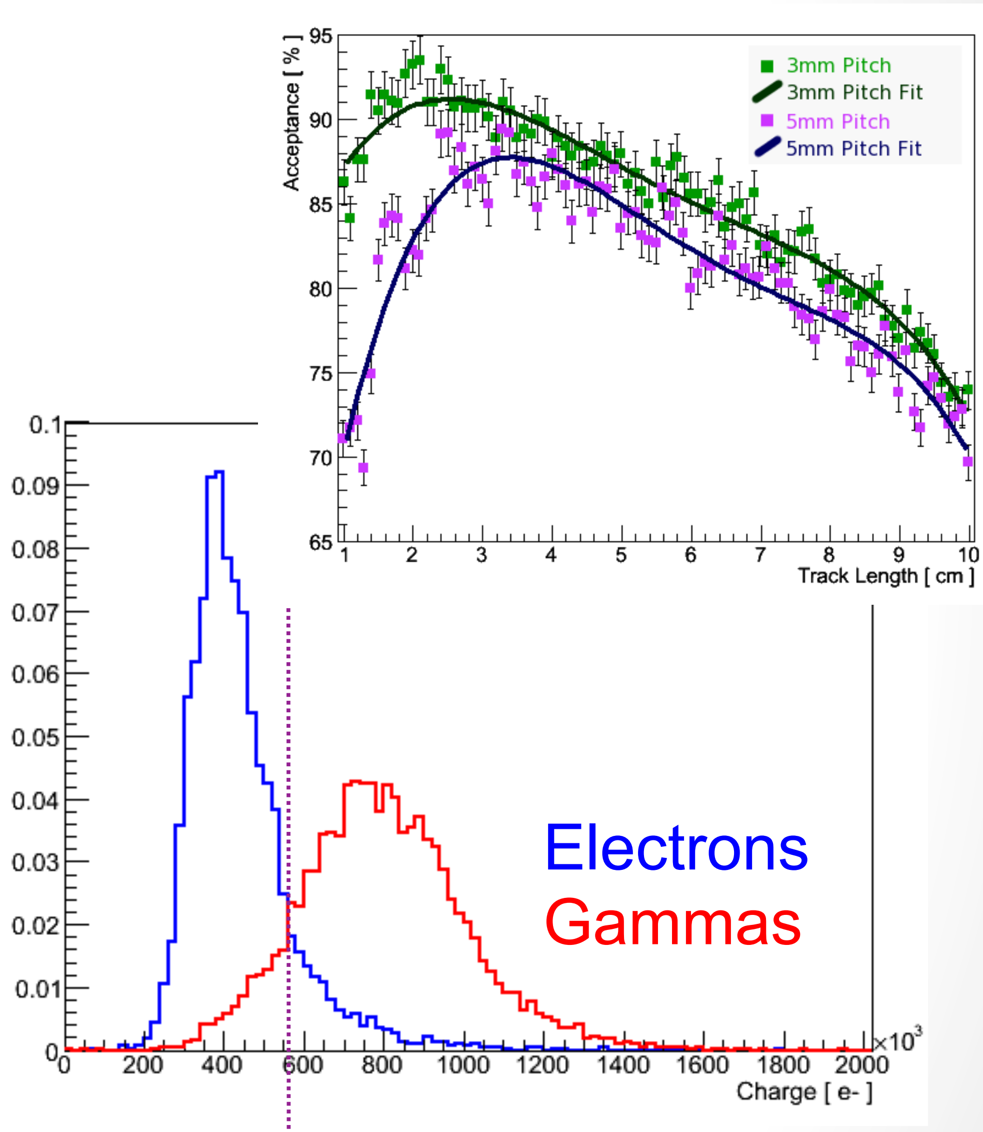
Step#    X(mm)    Y(mm)    Z(mm)  KinE(MeV)  dE(MeV)  StepLeng  TrackLeng
```

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
- Electrons and gammas have different charge yields: gammas will pair produce and the resulting lower-energy e- and e+ have different dE/dx in their first few centimeters of track than an electron of energy equal to their sum

Example

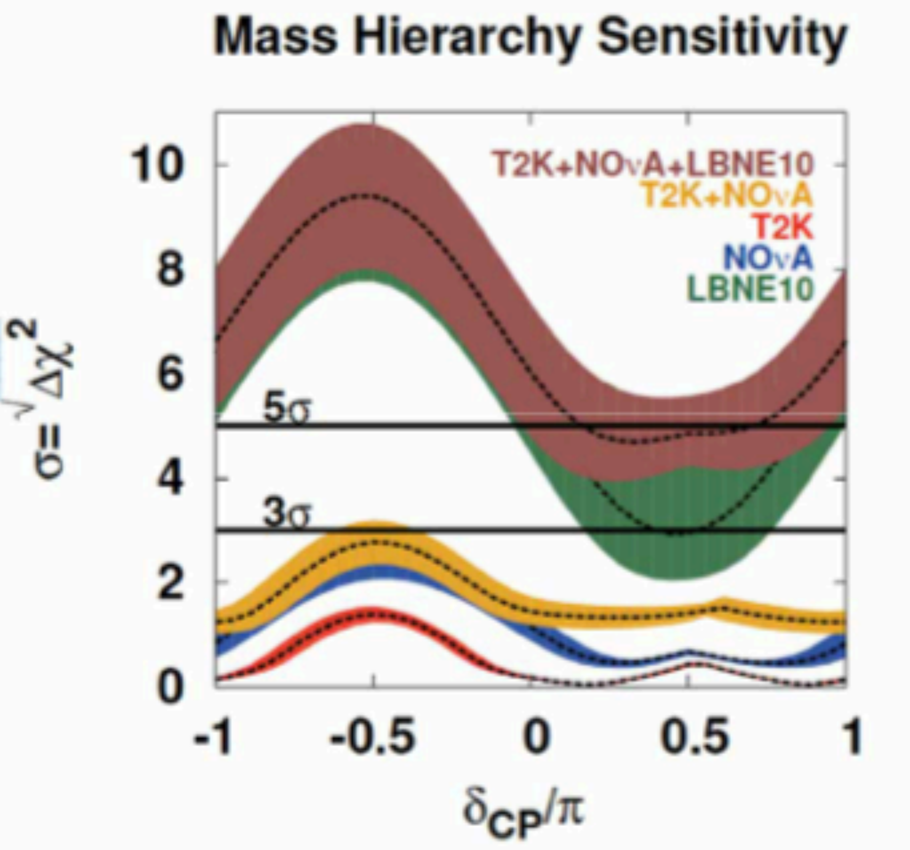
- Track length segment of 3.3 cm
- Acceptance ~ 90%
- Contamination ~ 10%
- Example of a best scenario for both acceptance as well as contamination

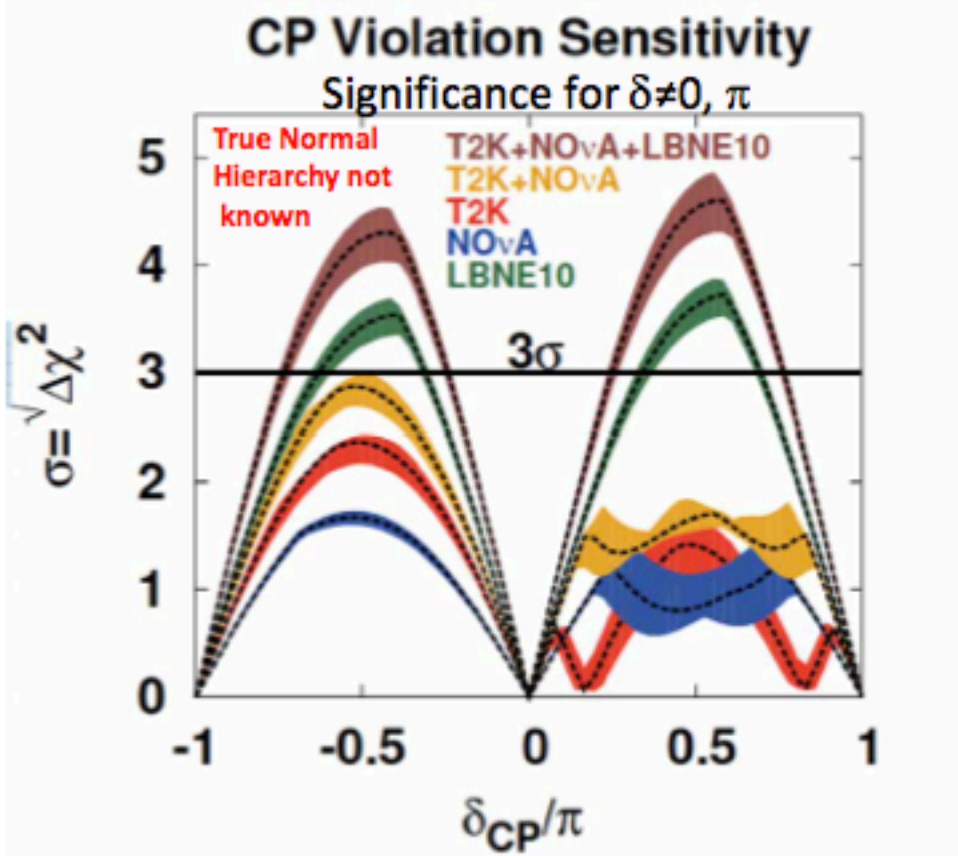


Conclusion

- 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