Photon Detector Designs for the Deep Underground Neutrino Experiment

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On behalf of the DUNE Collaboration
Outline

➢ Principles of photon detection in DUNE
➢ Light guides for a single-phase TPC
  ➢ Baseline design
  ➢ Alternatives
➢ Silicon photomultipliers
➢ Design testing in LAr at FNAL
  ➢ Data-simulation comparisons
➢ Scintillation structure analysis
➢ Continuing hardware R&D
Scintillation from de-excitation of argon molecular state
- 128 nm UV, two components
  - Prompt (singlet state) signal ($\tau \sim 6$ ns)
  - Slow (triplet state) signal ($\tau \sim 1.5$ μs)

Photon signal gives $t_0$ for transverse position determination
- Calculate drift distance from time of arrival and known drift velocity in TPC E-field
- Resolution of < 100 ns easily attainable

Important for non-beam events
- Proton decay events
- Atmospheric neutrinos
- Supernova burst neutrinos
- Cosmic ray rejection

Particle identification/discrimination
- Ratio of prompt to total light depends on ionization density of track
Light Guides for Large-Area Photon Detection

- Large active-area UV-collecting light guides
  - Acrylic or polystyrene imbued with wavelength-shifting compound
  - Based on design pioneered by MIT
  - Dip-coating w/ TPB in solvent (after studying many different methods)
  - 430 nm light propagated by total internal reflection to end

- Imbed PD paddles inside anode plane assembly behind collection wires
  - Large photosensitive area with small photocathode area
  - Low-voltage SiPM bias
  - Easily scalable
Multiple alternative designs under investigation

- Decouple UV wavelength shifter (WLS) from transport for improved attenuation length

- Dip-coated acrylic bars
  - Baseline design
  - Indiana U, right-most paddle

- WLS panel (VUV → blue) + imbedded WLS fibers
  - Louisiana State U, center

- WLS radiator (VUV → blue) + WLS fibers (blue → green)
  - Colorado State U, left-most

- WLS Radiator (VUV → Blue) + WLS bar (blue → green)
  - Indiana U, cartoon below
Silicon Photomultipliers

- Strongly reverse-biased array of photodiodes
  - Low noise (few Hz in cryo)
  - Excellent charge resolution

Dark noise characteristics in LN2 at $V_{bias} = 24.5$ V

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- SiPM Signal Processor (SSP)
  - 150 MHz waveform digitizer
    - Argonne Natl. Lab HEP Elec. Group
  - Resolve fine waveform details
    - $\sim 3$ ns timing resolution
    - 13 $\mu$s waveform buffer
Design Tests in LAr at Fermilab

➢ “TallBo” facility at FNAL
  ➢ 84” LAr dewar

➢ Ultra-high purity liquid argon
  ➢ Vacuum to remove residual atmosphere
  ➢ Condenser to maintain closed system

➢ Multiple lightguide designs (fall 2014)
  ➢ Dip-coated acrylic bars
  ➢ Cast acrylic and polystyrene bars
  ➢ Flash-heated spray-coated acrylic bars
  ➢ Y11 fibers w/ TPB-coated acrylic radiator

➢ Hodoscope (cosmic ray) trigger
  ➢ 2 8x8 Arrays of PMTs + BaF crystals
    ➢ CREST cosmic-ray balloon exp't.
  ➢ 2 scintillator paddle planes
    ➢ Allows shower rejection, reconstruction of single tracks
Preliminary Performance Results

- Signals from example hodoscope trajectory
- Data: integrated charge in 10 us waveform [PE]
- Sim: number of incident photons from the line source (toy MC)
Preliminary Performance Results (Baseline Designs)

- Estimated detector efficiency
  - Ratio = [ Mean #γ Detected (data) ] / [ Mean #γ Incident (sim) ]

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<th>Technology</th>
<th>UV Wavelength Shifter</th>
<th>Detector Efficiency</th>
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<td>acrylic (uncoated)</td>
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<td>acrylic, doped</td>
<td>bis-MSB</td>
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<td>bis-MSB (+50%)</td>
<td>0.13%</td>
</tr>
<tr>
<td>acrylic, dip-coated</td>
<td>bis-MSB (+50%)</td>
<td>0.15%</td>
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<tr>
<td>acrylic, dip-coated</td>
<td>TPB (+50%)</td>
<td>0.16%</td>
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Goal: > 0.3%

- Alternative designs will likely show an improvement by a factor of 2-3
  - Strongly driven by improvements to attenuation
  - Design comparisons at TallBo currently underway
  - Can also explore double-ended readout, more paddles per APA

- Caveats
  - Reflections estimated using WARP measurements
  - Rayleigh scattering not yet modeled (efficiencies underestimated → good!)
Scintillation Structure Analysis

- Time structure of signal at SiPM
  - Deconvolve average waveform from cosmic rays using measured single-PE response (dark noise)

- Three- or four-component models capture all features, including prompt singlet signal (~25%) and 1.5 μs “late light”
  - Evidence for long (~7 μs) component in acrylic light guides (not present in polystyrene)

- Important to understand for timing resolution and pulse-shape discrimination

- Publication in preparation
Continuing Photon Detector R&D

- DUNE Far Detector simulation development (ongoing)
  - Estimate sensitivity of various photon detector system configurations to physics events (proton decay, SN, etc.)

- Current TallBo testing (summer 2015)
  - Direct comparisons of baseline design with all four alternatives

- 35-ton Phase 2 (winter 2015)
  - First test of light guide photon detectors in APA coupled with single-phase TPC

- CERN single-phase TPC prototype (2018)
  - Down-selected photon detector design deployed in single-phase TPC
  - New charged particle beam in CERN north area
  - Comparisons to WA105 dual-phase TPC performance
Conclusions

➢ Lots of progress developing a light guide photon detector for the DUNE LAr TPC
   ➢ Variety of designs have been explored
   ➢ Successful performance comparison tests
   ➢ SiPM readout quite promising for LAr operation
   ➢ Several TPC+PD tests on the horizon

➢ Big effort with thanks to many folks
   ➢ Indiana U.
     • Stuart Mufson, Jim Musser, Jon Urheim, Mark Gebhard, Brice Adams, Mike Lang, Brian Baugh, Paul Smith, Bryan Martin, Bruce Howard, Jonathon Lowery
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