HD Supercell efficiency measurements in Liquid Argon @ Milano-Bicocca: updated results

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Setup to measure the XA-HD-SC PDE in LAr

The XA-SC installed in the test chamber to measure the PDE along its z-axis.

Supercell equipped with:
- PMMA WLS (ELJ&G2P)
- dichroic filters

Method as published in JINST 16 (2021) 09027: z-scanning with an 241Am exposed α source.
z-scanning of the SC with the $^{241}$Am $\alpha$ (5.480 MeV) source at the following positions:

1. **pos0**: (the lowest possible): ~2 cm above the flange.
2. **pos1, 2, 3, 4, 5, 6**: the center of each dichroic filter. Acquired: $10^4 \times 4$ wfms; 20 μs length; ~5 μs pretrigger.

3. Source at the topmost position (~49 cm from the flange) and ~ out of LAr:
   - one **μ run** ($10^4 \times 4$ events; 20 μs, 5 μs pretrigger)
   - one **s.ph.e. run** ($10^4 \times 8$ events; 20 μs length; 1.6 μs pretrigger)

**Source-to-dichroic filter distance: (55 +/- 1) mm.**
What we updated

- Corrected the evaluation of the source position
- Improved evaluation of statistical errors
- New analysis of $F_{\text{int}}$ and LAr purity correction using a new template
- Introduction of a systematic error for the non-uniformity of the PDE
Fit of alpha spectra: an example

pos.1: $\sigma/\mu = 4.9\%$

pos.4: $\sigma/\mu = 4.2\%$

SC equipped with FBK & G2P
Single Photoelectrons spectrum

HPK S/N = 4.7

FBK S/N = 4.1
Solid angle evaluation

- Analytically computed as the solid angle of a pyramid with rectangular base (the SC):

\[
\Omega_{SC}(x) = 2 \arctan \left( \frac{ab\ h}{2R_1(x^2 + h^2) + 2R_2[x(x - b) + h^2]} \right) + 2 \arctan \left( \frac{ab\ h}{2R_1(x(x - b) + h^2) + 2R_2[(x - b)^2 + h^2]} \right)
\]

- The plastic frame that holds the alpha source shadow a fraction of the solid angle:

\[
\Omega_s(x) = 2 \arctan \left( \frac{wh(b - x - h \cot \alpha)}{2R_3[h \cot \alpha(b - x) + h^2] + 2R_4[(h \cot \alpha)^2 + h^2]} \right) + 2 \arctan \left( \frac{wh(b - x - h \cot \alpha)}{2R_3[(b - x)^2 + h^2] + 2R_4[h \cot \alpha(b - x) + h^2]} \right)
\]

- The total solid angle is:

\[
\Omega(x) = \begin{cases} 
\Omega_{SC}(x) - \Omega_s(x) & \text{if } x < b - h \cot \alpha \\
\Omega_{SC}(x) & \text{if } x \geq b - h \cot \alpha
\end{cases}
\]
Fraction of integrated light

Synthetic wfms: SPHE © LAr profile ($A_s=0.77; \tau_s=7\text{ns}$ $A_t=0.23; \tau_t=1400\text{ ns}$)

Fraction of integrated light

Fraction of integrated light

Fraction of integrated light

Fraction of integrated light

Fraction of integrated light

HPK SPHE wfm

FBK SPHE wfm
Previous deconvoluted muon waveform

Average muon waveform with FBK

Deconvoluted muon waveform with FBK

\[ \chi^2 / \text{ndf} \quad 0.002854 / 325 \]

\[
\begin{align*}
I_0 & \quad 2.182 \pm 0.01988 \\
\tau_\nu & \quad 54.14 \pm 0.3047 \\
I_1 & \quad 0.3259 \pm 0.001043 \\
\tau_1 & \quad 848.9 \pm 3.384
\end{align*}
\]

residual negative part
Since the deconvolution of the muon average waveform using the sphe mean waveform failed, we tried using a different “template”

- Selected an alpha event with few photoelectrons (~70pe), with a high $F_{\text{prompt}}$ ($F_{\text{prompt}} > 0.9$) and normalized its amplitude
- Used this new template for the determination of $F_{\text{int}}$ and the LAr purity correction
Mpe $F_{\text{int}}$ evaluation

HPK

~3% difference from spe template

FBK

< 1% difference from spe template
Mpe muon convolution

- Convolution of the mpe template with LAr scintillation profile
- Fit the function with the average muon waveform and extract $\tau_T$
- Achieved a good fit and a reliable value of $\tau_T$
- We did it only for the FBK&G2P data

$\tau_T = 1069 \text{ ns}$
Efficiency results: HPK & G2P

\[ \epsilon = \frac{4\pi \cdot \alpha \text{ peak}(\text{ADC})}{\text{s.p.h.e.}(\text{ADC}) \cdot f_{\text{int}} \cdot LY_{\text{LAr}} \cdot En_{\alpha} \cdot q_{\alpha} \cdot \Omega} \]

LY_{\text{LAr}} = 5.0 \ E+4

\[ q_{\alpha} = 0.7 \]

\[ En_{\alpha} = 5.480 \ 	ext{MeV} \]

\[ f_{\text{int}} = 0.862 \]

No X-talk and LAr purity corrections
Efficiency results: FBK & G2P

\[ \epsilon = \frac{4\pi \cdot \alpha \cdot \text{peak(ADC)}}{s.\text{h.e.(ADC)} \cdot f_{\text{int}} \cdot \text{LY}_{\text{LAr}} \cdot E_{\text{n}} \cdot q_{\alpha} \cdot \Omega} \]

\(LY_{\text{LAr}} = 5.0 \times 10^4\)
\(q_{\alpha} = 0.7\)
\(E_{\text{n}} = 5.480\ \text{MeV}\)
\(f_{\text{int}} = 0.86\)

No X-talk and LAr purity corrections

FBK & G2P Measurements

\(\chi^2 / \text{ndf} = 13.14 / 7\)
Mean value \(1.724 \pm 0.03379\)
Efficiency results: FBK & Eljen

\[ \epsilon = \frac{4\pi \cdot \alpha \cdot \text{peak(ADC)}}{\text{s.ph.e. (ADC) \cdot f_{int} \cdot LY_{\text{LAr}} \cdot E_{\alpha} \cdot q_{\alpha} \cdot \Omega}} \]

FBK & Eljen Measurements

\[ \chi^2 / \text{ndf} = 22.6 / 9 \]

mean value \( 1.502 \pm 0.02433 \)

LY\text{\_LAr} = 5.0 \times 10^4

\[ q_{\alpha} = 0.7 \]

\[ E_{\alpha} = 5.480 \text{ MeV} \]

\[ f_{\text{int}} = 0.86 \]

No X-talk and LAr purity corrections
Systematic uncertainty

- Lowest positions (x < 15cm) with FBK show a worse PDE
  - May be caused by one (or more) SiPM board with a higher $V_{bkd}$ or by dichroic filters with worse performances in the lowest positions
  - Systematic error as the difference between the average PDE with all position $\varepsilon_{\text{all}}$ and average PDE with higher positions (x>15cm) $\varepsilon_c$
# Efficiency: X-talk and $P_{L\text{Ar}}$ corrections

<table>
<thead>
<tr>
<th></th>
<th>OV</th>
<th>PDE</th>
<th>Uncorrected $\varepsilon_{X\text{A}}$</th>
<th>Measured Xtalk</th>
<th>$P_{L\text{Ar}}$</th>
<th>Position systematic</th>
<th>Corrected $\varepsilon_{X\text{A}}$ x talk only</th>
<th>Corrected $\varepsilon_{X\text{A}}$ x talk and $P_{L\text{Ar}}$</th>
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</thead>
<tbody>
<tr>
<td><strong>this work</strong></td>
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<td></td>
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<tr>
<td>HPK** &amp; G2P</td>
<td>3.0V</td>
<td>50%</td>
<td>1.94 (0.03)</td>
<td>6.62%</td>
<td>TBD</td>
<td>0.08</td>
<td>1.82 (0.08)</td>
<td></td>
</tr>
<tr>
<td>FBK*** &amp; G2P</td>
<td>4.5V</td>
<td>45%</td>
<td>1.72 (0.03)</td>
<td>15.7%</td>
<td>1.06</td>
<td>0.10</td>
<td>1.49 (0.10)</td>
<td>1.58 (0.10)</td>
</tr>
<tr>
<td>FBK*** &amp; Eljen</td>
<td>4.5V</td>
<td>45%</td>
<td>1.50 (0.02)</td>
<td>15.7%</td>
<td>TBD</td>
<td>0.06</td>
<td>1.29 (0.07)</td>
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<tr>
<td><strong>JINST work</strong></td>
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</tr>
<tr>
<td>HPK commercial*</td>
<td>2.7V</td>
<td>45%</td>
<td>3.5 (0.1)</td>
<td>22%</td>
<td></td>
<td></td>
<td>2.9 (0.1)</td>
<td></td>
</tr>
</tbody>
</table>

* S14160-6050HS (6 × 6) mm$^2$, 50 μm
** 75um-HQR
*** Triple Trench

$$P_{L\text{Ar}} = \left(0.77 + 0.23 \times \frac{\tau_T}{1414 \text{ ns}}\right)^{-1}$$
Conclusions

- A non-linearity of the system response affected the determination of $\tau_T$
  - Using a new mpe template we achieved a reliable better estimation of $\tau_T$ and the LAr purity correction
  - We also re-computed $F_{\text{int}}$ showing a significant difference in the HPK data
- We observed a non-uniformity in the PDE along the SC dimension
  - There are several effects that may cause a disuniformity in the SC PDE (different $V_{\text{bkd}}$, dichroic filters, gap between SiPMs and WLS bar...)
  - The “real” PDE of the SC average all those effects
Backup
## Features of the XA HD Supercell under tests

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size/type of the WLS slab</td>
<td><strong>G2P</strong> 480 x 93 mm², NO Vikuiti on short edges</td>
</tr>
<tr>
<td>Dichoics (sipm/WLS) area</td>
<td>6 x dichroics (Opto-Campinas)</td>
</tr>
<tr>
<td></td>
<td>3.9%</td>
</tr>
<tr>
<td>SIPMs</td>
<td>HPK DUNE-75um-HQR, +3V OV (50% PDE)</td>
</tr>
<tr>
<td></td>
<td>FBK TT, +4.5V OV (45% PDE)</td>
</tr>
<tr>
<td>Ganging</td>
<td>x 48 SiPMs by MiB cold Amplifier</td>
</tr>
<tr>
<td># electronic channels</td>
<td>1</td>
</tr>
<tr>
<td>SiPMs -Cold Amp.</td>
<td>AC</td>
</tr>
<tr>
<td>Cold Amp dyn. range</td>
<td>2000 ph.e.</td>
</tr>
<tr>
<td>s.ph.e. (50 Ω, 45 V)</td>
<td>~ 2.0 mV on 50 Ω for both HPK and FBK</td>
</tr>
<tr>
<td>Chamber volume</td>
<td>~ 10 l</td>
</tr>
<tr>
<td>Digitizer</td>
<td>CAEN 14-bit 250 MS/sec, 4 ns/sample</td>
</tr>
</tbody>
</table>
Hardware

- Cold cables: a bundle of five Kapton RG178 coaxial cables. No DUNE blue cable & Hirose connector due to mechanical (dimension, stiffness) constraints of the setup

- Warm cables: 2.5 m, 50 Ω LEMO cables

- Cold-to-warm flange: 10 contacts vacuum/pressure connector mounted on a CF40 flange - No Hirose:
  - the chamber and its payload are pumped down to $10^{-4}$ mbar prior filling
  - high LAr purity achieved with high reproducibility
  - the purity is maintained w.o. any recirculation along several days from filling
Efficiency: Updated results
HPK & G2P

\[ \epsilon = \frac{4\pi \cdot \alpha \text{ peak(ADC)}}{\text{s.ph.e.(ADC)} \cdot f_{int} \cdot LY_{LA\text{r}} \cdot E_{n\alpha} \cdot q_{\alpha} \cdot \Omega} \]

\[ \chi^2 / \text{ndf} \quad 2.723 / 12 \]

mean value \quad 2.151 \pm 0.06008

\[ LY_{LA\text{r}} = 5.0 \text{ E+4} \]
\[ q_{\alpha} = 0.7 \]
\[ E_{n\alpha} = 5.480 \text{ MeV} \]
\[ f_{int} = 0.862 \]

No X-talk and LAr purity corrections
Efficiency: Updated results
FBK & G2P

\[ \epsilon = \frac{4\pi \cdot \alpha \text{ peak(ADC)}}{s.\text{ph.e.}(ADC) \cdot f_{\text{int}} \cdot L Y_{\text{LAr}} \cdot E n_{\alpha} \cdot q_{\alpha} \cdot \Omega} \]

FBK & G2P Measurements

\[ \chi^2 / \text{ndf} \quad 3.123 / 9 \]
mean value \[ 1.833 \pm 0.05866 \]

LY_{LAr} = 5.0 E+4
\[ q_{\alpha} = 0.7 \]
En_{\alpha} = 5.480 MeV
\[ f_{\text{int}} = 0.86 \]

No X-talk and LAr purity corrections

18/12/2021
Efficiency: Updated results
FBK & Eljen

\[ \epsilon = \frac{4\pi \cdot \alpha \cdot \text{peak(ADC)}}{s.p.h.e.(ADC) \cdot f_{\text{int}} \cdot L_{\text{LY}} \cdot E_{n} \cdot \alpha \cdot q_{\alpha} \cdot \Omega} \]

FBK & Eljen Measurements

\[ \chi^2 / \text{ndf} \quad 1.1 / 6 \]

mean value \[ 1.522 \pm 0.05771 \]

\[ L_{\text{LY}} = 5.0 \ E+4 \]
\[ q_{\alpha} = 0.7 \]
\[ E_{n} = 5.480 \ MeV \]
\[ f_{\text{int}} = 0.86 \]

No X-talk and LAr purity corrections