τ Decay Mode Identification in a Liquid Argon Electromagnetic Calorimeter at the FCC-ee

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τ polarisation measurements at FCC-ee

Motivation for measurements of τ polarisation:
Allows for testing $e - \tau$ universality and provides the numerical value of the weak mixing angle

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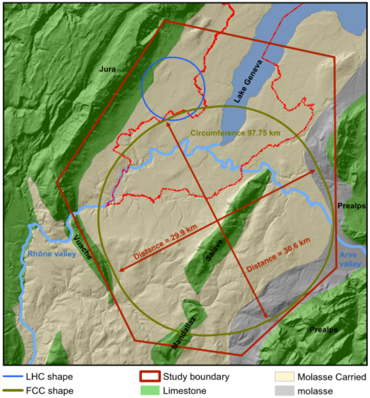
The FCC-ee:



At the Z pole

- Sample size: 5×10^{12} $\Rightarrow$ LEP statistics $\times 10^5$
- 1.7×10^{11} $Z \to \tau\tau$ decays $\Rightarrow$ precision measurements

τ polarisation measurements

Process: $e^+e^- \to Z \to \tau^+\tau^-$

Requirements:

- Precision measurements

$\Rightarrow$ Need a clean and precise separation of τ final states

- Largest sensitivity to polarisation in $\pi\, n\pi^0$ modes, with $n \geq 0$. In particular the $\pi^-\nu$ and $\rho^-\nu \to \pi^-\pi^0\nu$ have the largest sensitivities to P_τ

$\Rightarrow$ Need a precise π^0 counting scheme

Decay modes	Branching fraction [%]
$e^-\,\bar{\nu}_e\,\nu_\tau$	17.82 ± 0.04
$\mu^-\,\bar{\nu}_\mu\,\nu_\tau$	17.39 ± 0.04
$h^-\,\nu_\tau$	11.51 ± 0.05
$h^-\,\pi^0\,\nu_\tau$	25.93 ± 0.09
$h^-\,2\pi^0\,\nu_\tau$	9.48 ± 0.10
$h^-\,3\pi^0\,\nu_\tau$	1.18 ± 0.07
$h^-\,4\pi^0\,\nu_\tau$	0.16 ± 0.04
3 prongs	15.20 ± 0.06

Table: The dominant decay modes and their branching fractions of the τ lepton. h^- represents a K^- or a π^-

Project goal

Investigate the performance of the LAr/Pb ECAL proposed for the FCC-ee wrt. τ polarisation measurements by trying to achieve the best possible τ decay mode identification. This demands:

- A precise π^0 reconstruction scheme
- A separation of single γ and merged π^0's since $\alpha(\gamma,\gamma) \propto \frac{1}{E_{\pi}^{0}}$

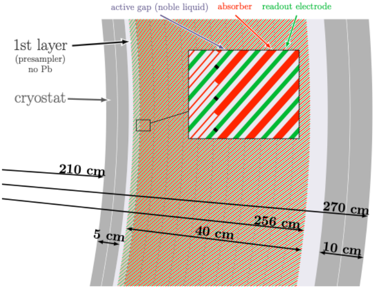


Figure: The proposed LAr/Pb ECAL barrel design [arXiv:2109.00391]

Steps in analysis

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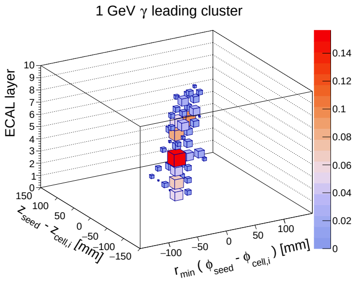
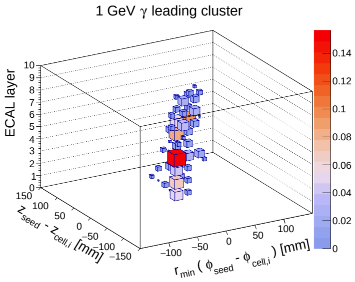


Steps in analysis

1. Set up full detector geometry in FCCSW
2. Develop and optimize a clustering algorithm
3. Build an algorithm for photon reconstruction



Steps in analysis

1. Set up full detector geometry in FCCSW
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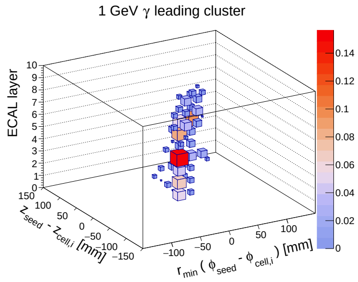
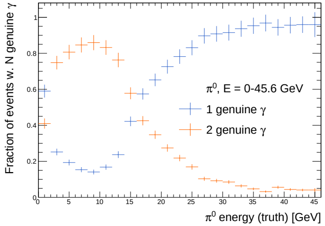
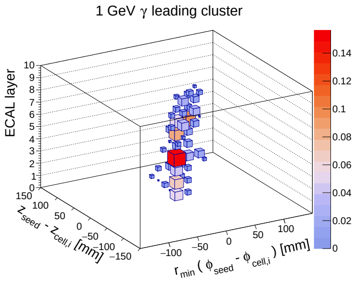
3. Build an algorithm for photon reconstruction
4. Develop a method for separating photons from (merged) π^0's

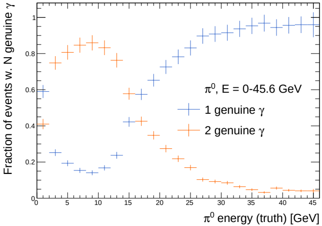




Steps in analysis

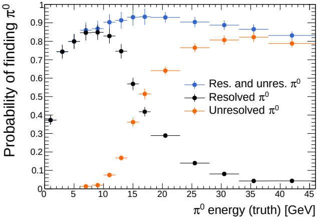
1. Set up full detector geometry in FCCSW
2. Develop and optimize a clustering algorithm
3. Build an algorithm for photon reconstruction
4. Develop a method for separating photons from (merged) π^0's
5. Minimizing the off-diagonal terms of the migration matrix by forming a separation mechanism for different τ decay channels



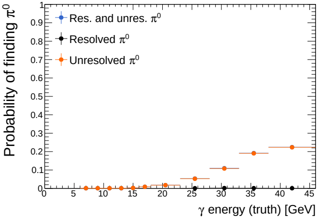


π^0 reconstruction

Signal:



Background:



$\Rightarrow$ Probability of reconstructing π^0: $\epsilon = 84\%$ which is competitive with ALEPH results of $\epsilon_{ALPEH} \sim 84\%$

$\Rightarrow$ Probability of accepting a true γ as π^0: $\epsilon_{bg} = 4.5\%$ heavily dominated by photons with $E > 25$ GeV

τ decay mode identification

This thesis:

Recon → / Gen ↓	$\pi^{\pm}\nu$	$\pi^{\pm}\pi^{0}\nu$	$\pi^{\pm}2\pi^{0}\nu$	$\pi^{\pm}3\pi^{0}\nu$	$\pi^{\pm}4\pi^{0}\nu$
$\pi^{\pm}\nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^{\pm}\pi^{0}\nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^{\pm}2\pi^{0}\nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^{\pm}3\pi^{0}\nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

Table: Each row shows the fraction of e.g. $\tau \to \pi^{\pm}\nu$ decays classified as each of the considered channels

ALEPH results (normalized to 1. for easy comparison):

Recon → / Gen ↓	$h\nu$	$h\pi^{0}\nu$	$h2\pi^{0}\nu$	$h3\pi^{0}\nu$	$h4\pi^{0}\nu$
$h\nu$	**0.9270**	0.0670	0.0047	0.0010	0.0003
$h\pi^{0}\nu$	0.0457	**0.8756**	0.0728	0.0053	0.0006
$h2\pi^{0}\nu$	0.0044	0.1470	**0.7499**	0.0900	0.0087
$h3\pi^{0}\nu$	0.0008	0.0288	0.3098	**0.5768**	0.0837

τ decay mode identification

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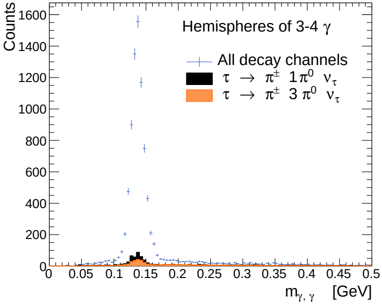
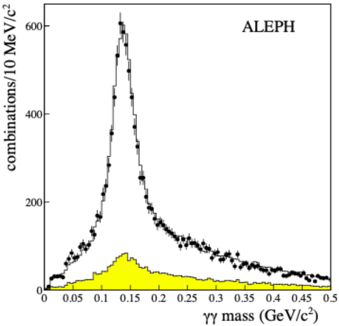


ALEPH results:



Figures show the invariant mass of two photons in three-four photon events, where one π^0 has already been identified.

Thank you for listening!

Back-up

τ polarisation measurements

The polarisation

$$P_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau\left(1+\cos^2\theta\right) + 2\cos\theta\,\mathcal{A}_e}{\left(1+\cos^2\theta\right) + 2\mathcal{A}_\tau\mathcal{A}_e\cos\theta} \tag{1}$$

with the fermion asymmetry parameter

$$\mathcal{A}_\mathrm{f} = \frac{\left(c_L^\mathrm{f}\right)^2 - \left(c_R^\mathrm{f}\right)^2}{\left(c_L^\mathrm{f}\right)^2 + \left(c_R^\mathrm{f}\right)^2} \tag{2}$$

$$\equiv \frac{2c_V^\mathrm{f}c_A^\mathrm{f}}{\left(c_V^\mathrm{f}\right)^2 + \left(c_A^\mathrm{f}\right)^2} \tag{3}$$

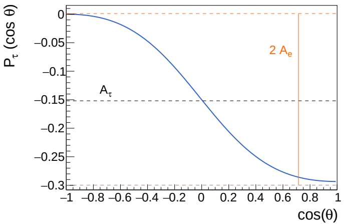


Figure: $P_\tau(\cos\theta)$ for $\mathcal{A}_\mathrm{e} = \mathcal{A}_\tau = 0.15$

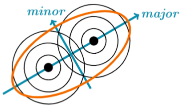
Clustering algorithm

Methods uses two (adjustable) thresholds: $\mathrm{thrs}_{low} = 10$ MeV, $\mathrm{thrs}_{high} = 20$ MeV

1. For each cell, point to highest energy (of 26) neighbours exceeding thrs_{low}
   - If the cell is local maximum and exceeds thrs_{high} it will be a seed
   - For each cell, define list of followers (cells that point to it)
2. Start by seed cells (local energy maximum) and collect followers iteratively $\rightarrow$ proto-clusters
3. Merging of proto-clusters

$\Rightarrow$ A reconstruction threshold of $E_{clus} > 200$ MeV is used

Single photon/unresolved π^0 separation



$\Rightarrow$ Major axis correlated with opening angle of photons

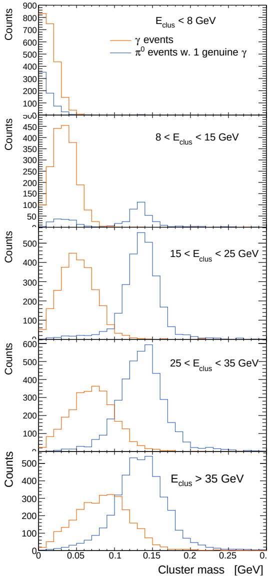
The major/minor axis lengths can be re-formulated to calculate a cluster mass:

$$m_{\text{clus}} = c_1 E_{\text{clus}} x \qquad (4)$$

with

$$x^2 = major^2 - minor^2 \; . \qquad (5)$$

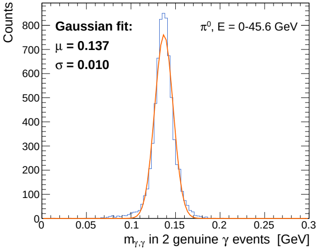
Calibration factor: $c_1 \sim 1$.



π^0 reconstruction

1. Combine all genuine photons to find resolved π^0's
   - Photon pair accepted if $m_{\gamma,\gamma}$ is consistent with m_{π^0} within $4\sigma_{m_{\gamma,\gamma}}$

   $\Rightarrow$ $\epsilon_{E<16\text{GeV}} > 98\%$



2. Identify all unresolved π^0's
   - Cluster accepted as unresolved π^0 if $m_{clus} > 0.1$ GeV

   $\Rightarrow$ $\epsilon_{E>16\text{GeV}} = 82 - 90\%$, with efficiency decreasing at higher energies

3. Accept remaining genuine photons as residual single photons if $\alpha(\pi^{\pm}, \gamma) < 0.3$ rad