Calorimetry performance with CLD
Status and Plans

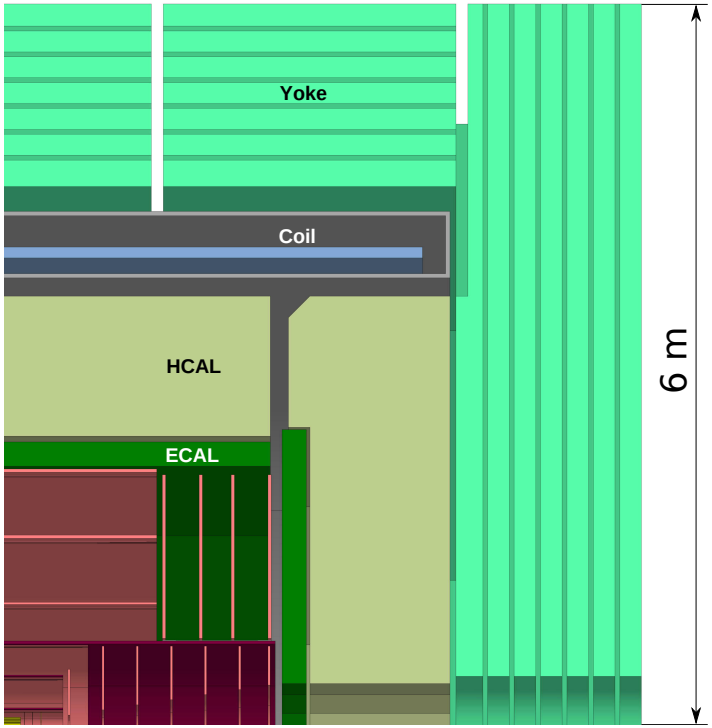
Oleksandr Viazlo
on behalf of the FCC-ee and CLICdp collaborations

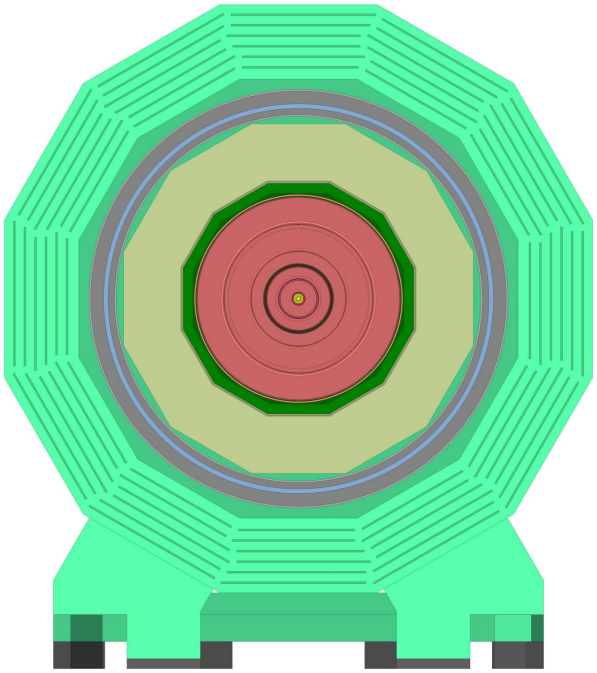
CERN

8 January 2019

Introduction

- Overview of the high granular calorimetry system of the CLD detector model
- Performance studies with particle flow algorithms:
  - particle identification capabilities
  - jet performance
  - ability to distinguish hadronic decays of W- and Z-bosons
- Impact of beam-induced background
- Further plans





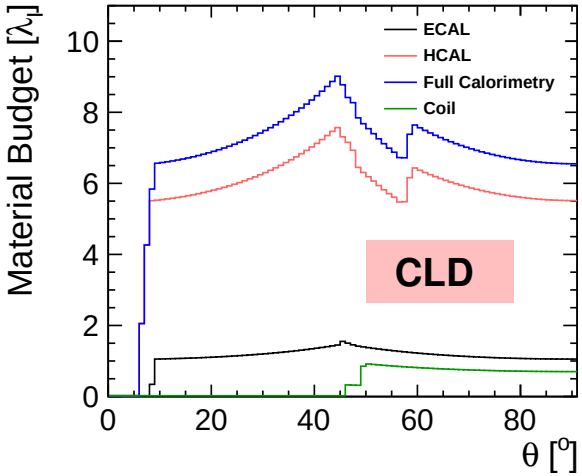
Calorimetry

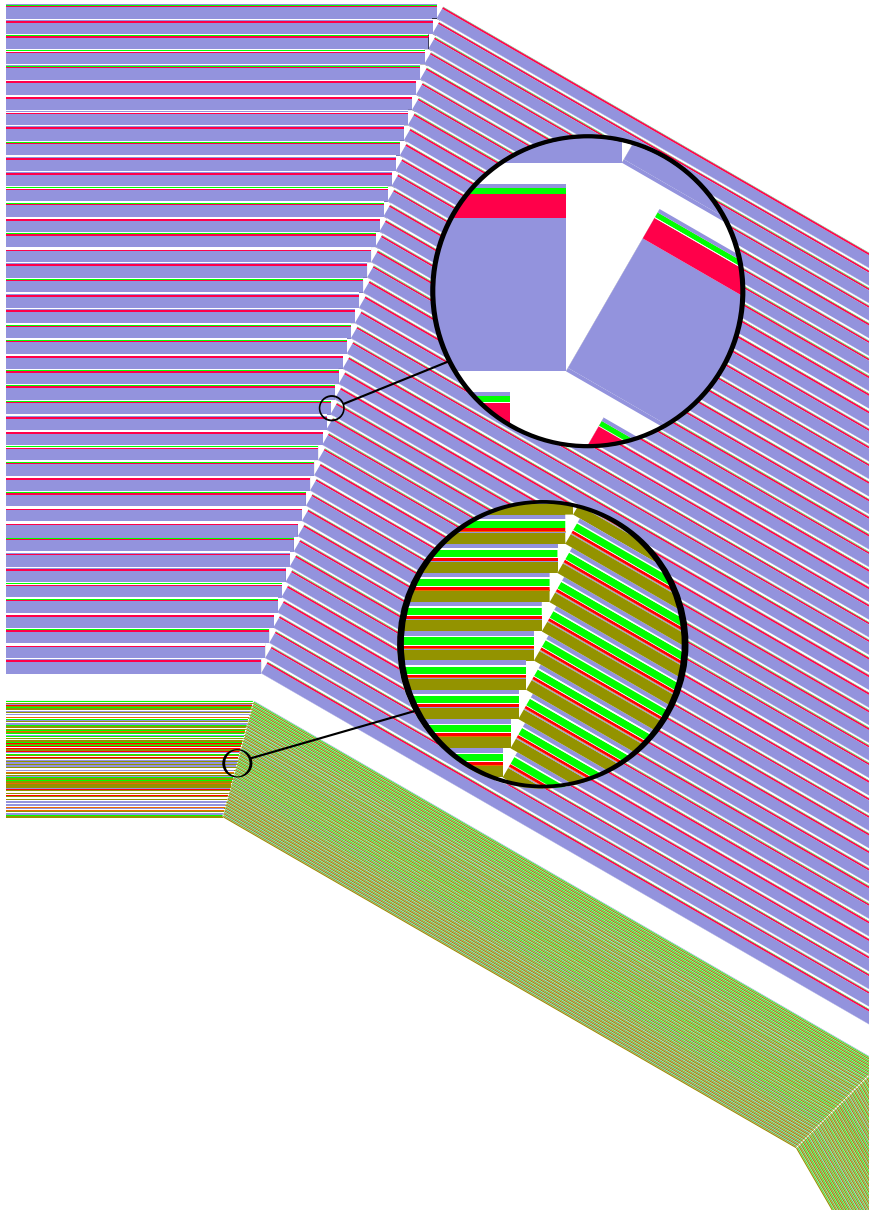
Electromagnetic Calorimeter

- Si-W sampling calorimeter
- cell size 5x5 mm^2
- 40 layers (1.9 mm thick W plates)
- Depth: 22 X_0, 1 λ_I, 20 cm

Hadronic Calorimeter

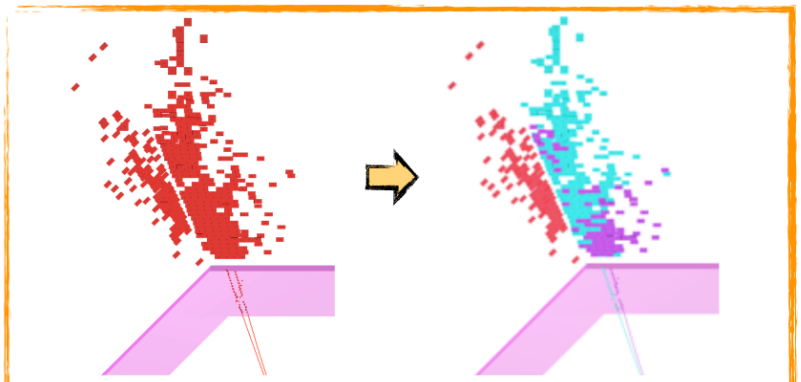
- Scintillator-steel sampling calorimeter
- cell size 30x30 mm^2
- 44 layers (19 mm thick steel plates)
- Depth: 5.5 λ_I, 117 cm (inspired by ILD)



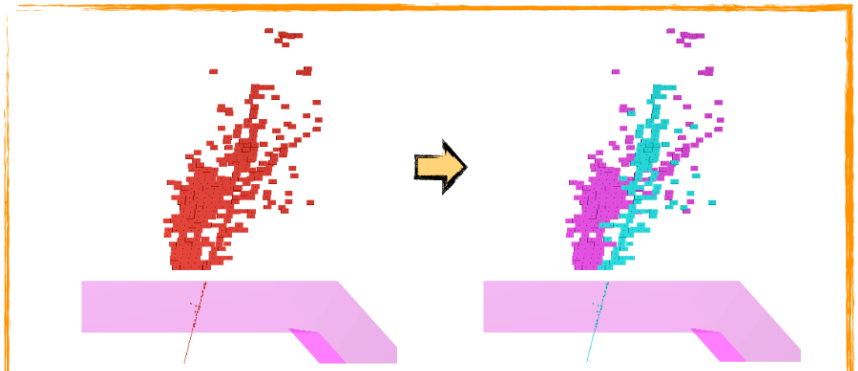


Particle Flow Analysis: PandoraPFA

- Fine grain calorimeters with high segmentation to achieve best possible performance of particle flow identification:
  - PandoraPFA algorithms matching information of all detector subsystems to identify and reconstruct each particle correctly by its type: charged hadrons (assigned type: $\pi\pm$), muons, electrons, photons, neutral hadrons (assigned type: neutrons)
  - The main objective of Pandora algorithm is to achieve very excellent jet energy resolution, needed to achieve the desired precision involving hadronic final states



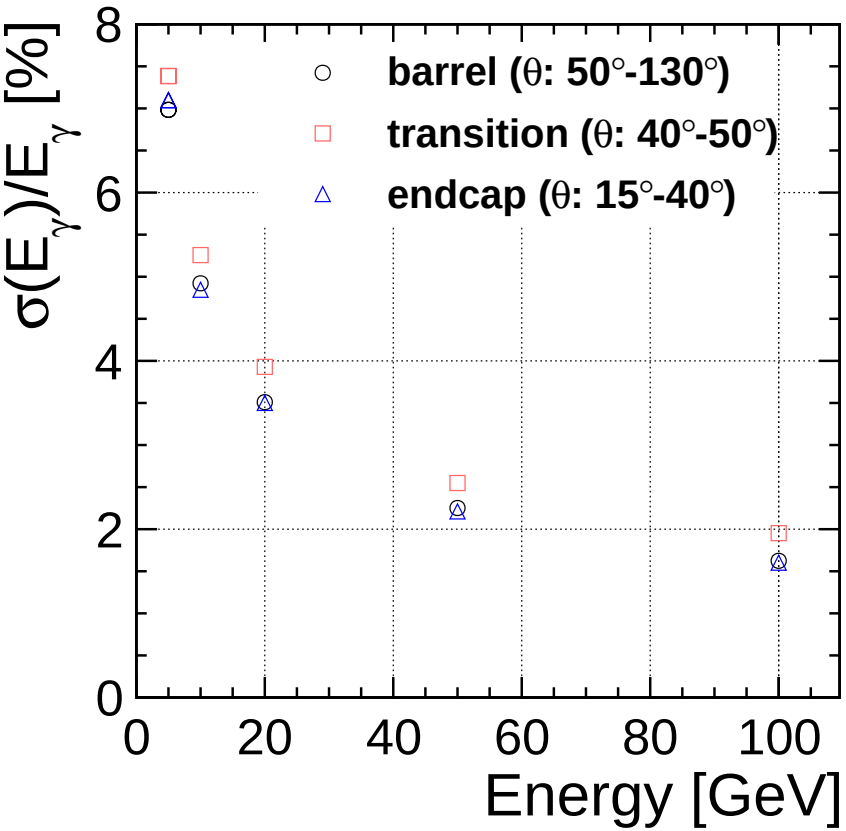
1. Multiple tracks associated to single cluster – split cluster.

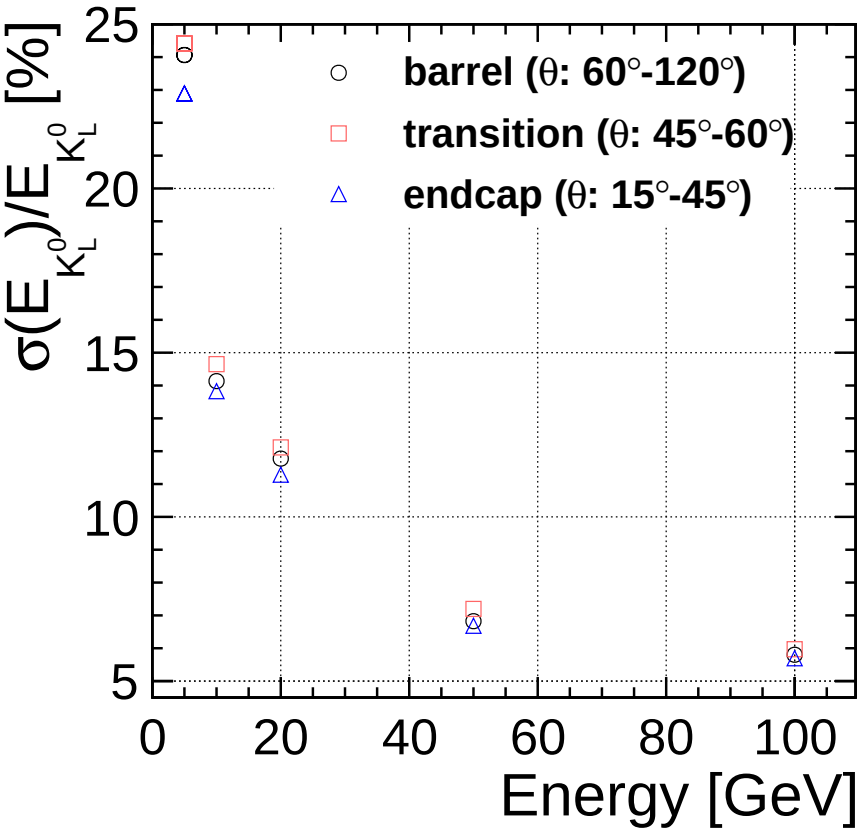


2. Cluster energy much greater than track momentum – split cluster.

Photon and neutral hadron energy resolutions

- The ECAL (HCAL) energy resolution is studied using single photon (K0L) events.
- Calorimeter response distributions are iteratively fitted with a Gaussian within a range $\pm 3\sigma$



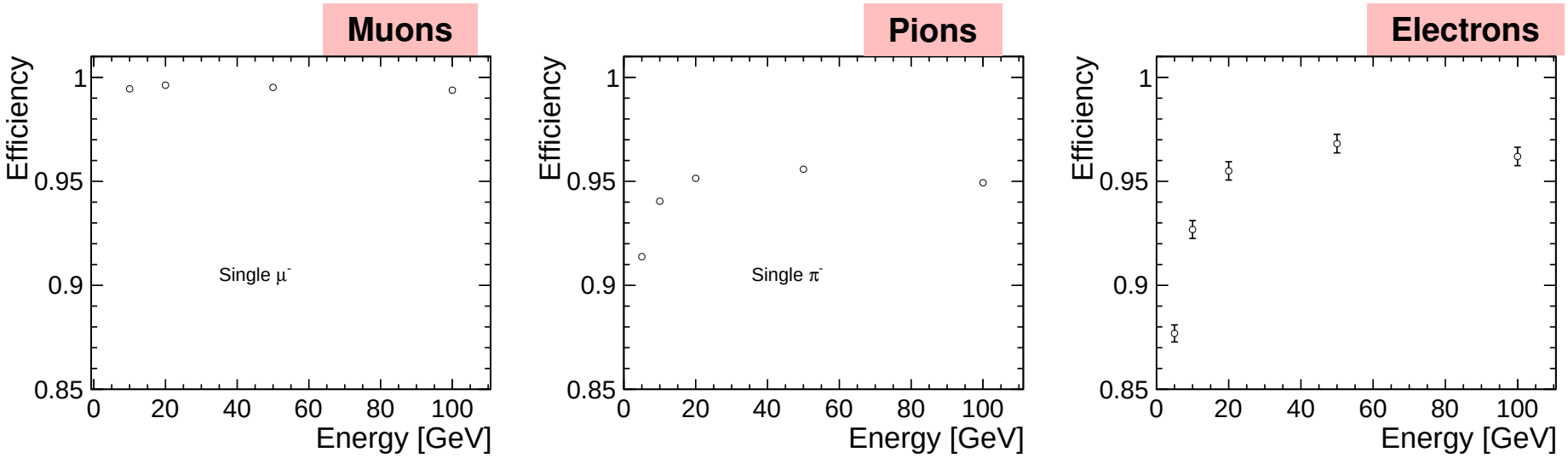


- Resolution is shown as function of particle energy at three different regions (barrel, endcap, and transition region)
- Resolution is better than 2% (6%) for ECAL (HCAL) with 100 GeV particles

Single particle identification efficiency

- Efficiency = fraction of matched reconstructed particles out of the simulated MC particles:
  - reconstructed particle of the same type as simulated MC particle
  - angular matching: $\Delta\theta < 1$ mrad and $\Delta\phi < 2$ mrad
  - energy matching:
    - charged particles: $|p_T^{truth} - p_T^{PFO}| < 5\%\ p_T^{truth}$
    - photons: $\Delta E < 5 \times \sigma(\text{ECal}) \approx 0.75 \times \sqrt{E}$

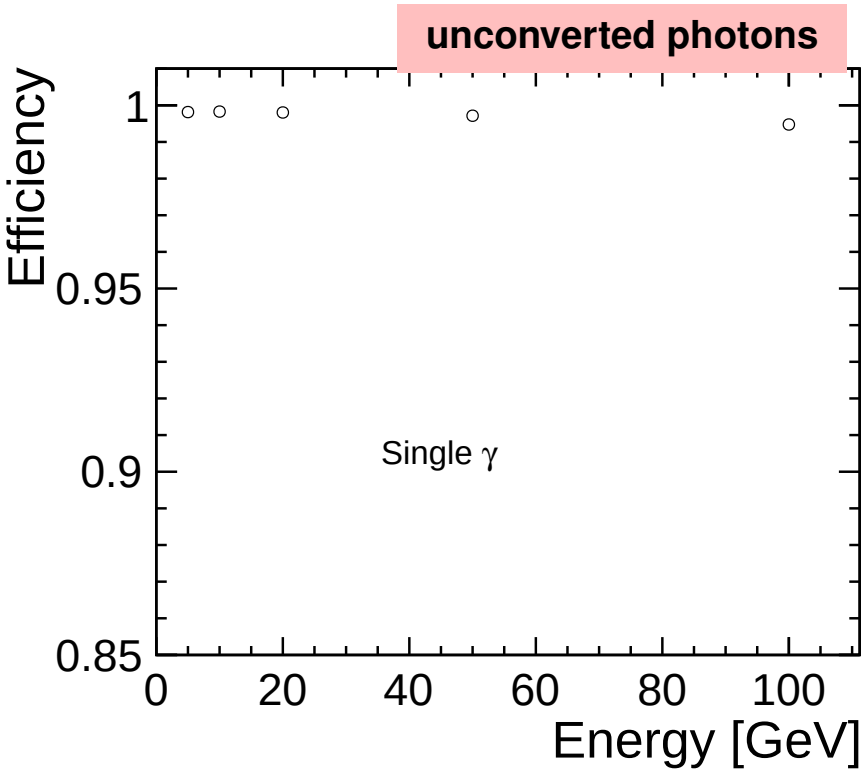
Sample: single particles with flat $\cos(\theta)$ distribution and fixed energy

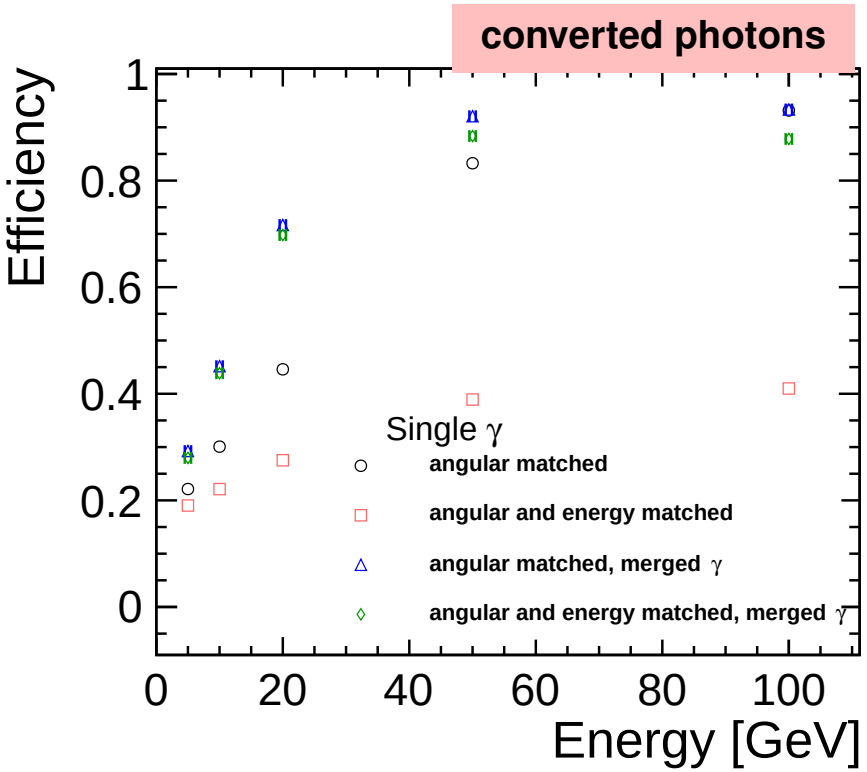


- >99% muon efficiency and 93-97% pion and electron efficiency for E>10 GeV
- Pion inefficiency at high energies is caused by pions being mis-reconstructed as muons
- Electron inefficiency is caused by Bremsstrahlung

Single particle identification efficiency

- The signatures for unconverted and converted photons are considered separately
- Photon merging procedure is used to recover inefficiency due to photon conversion

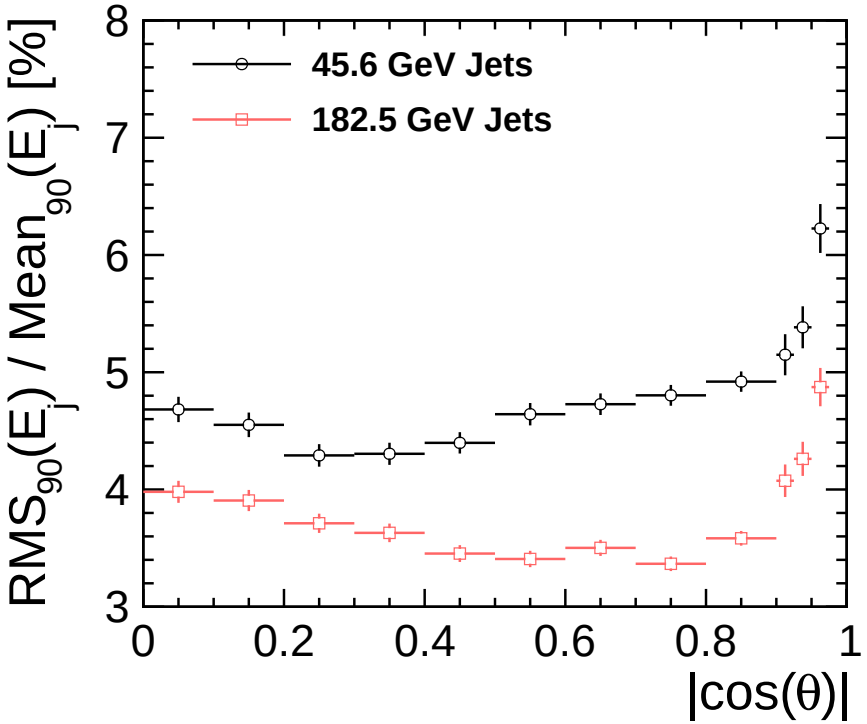




- $>$ 99% efficiency for unconverted photons
- $>$ 90% for $>$50 GeV converted photons
- Further optimization may improve these numbers

Jet Energy Resolution

- Jet performance is studied with dijet events of a Z-like particle decaying into a pair of light quarks (u, d, s) at 91.2 and 365 GeV centre-of-mass energies



- Jet Energy Resolutions:
  - 45.6 GeV jets: 4-5 %
  - 182.5 GeV jets: 3-4 %

Jet energy E_j is measured as a half of total energy E_{jj} of Z→ $q\bar{q}$ (q=u,d,s) dijet event

$$\frac{\mathrm{RMS}_{90}(E_j)}{\mathrm{mean}_{90}(E_j)} = \frac{\mathrm{RMS}_{90}(E_{jj})}{\mathrm{mean}_{90}(E_{jj})}\sqrt{2}$$

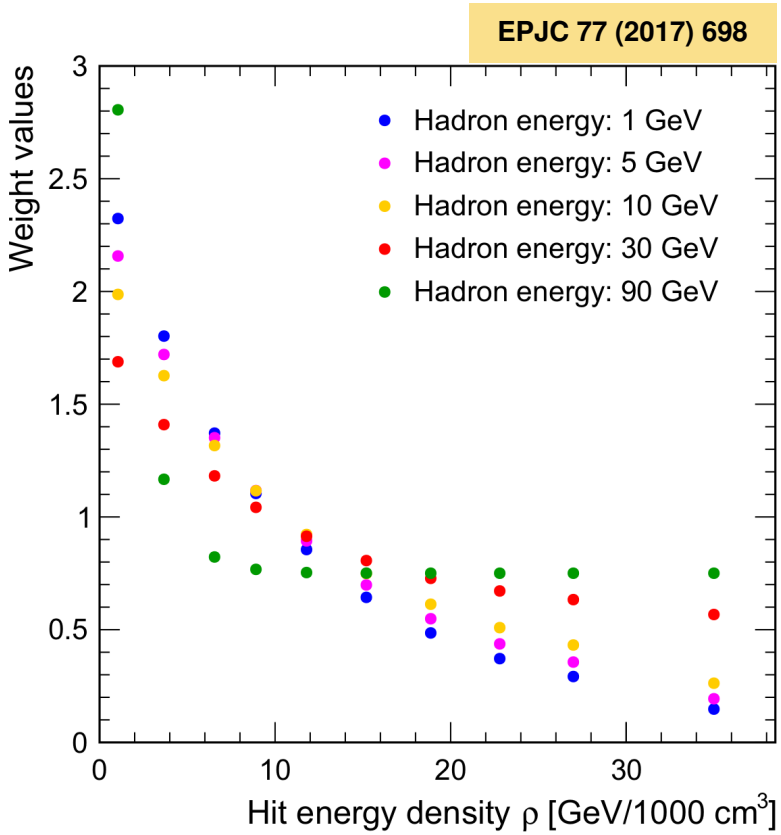
Software Compensation

- Software compensation is an energy "regularisation" technique (JINST 7 (2012) P09017)
- Idea is to correct with software for (on average) larger response of hadron showers with large electromagnetic component → improves energy measurement of cluster energies
- Software compensation technique (developed by CALICE) is implemented in PandoraPFA now

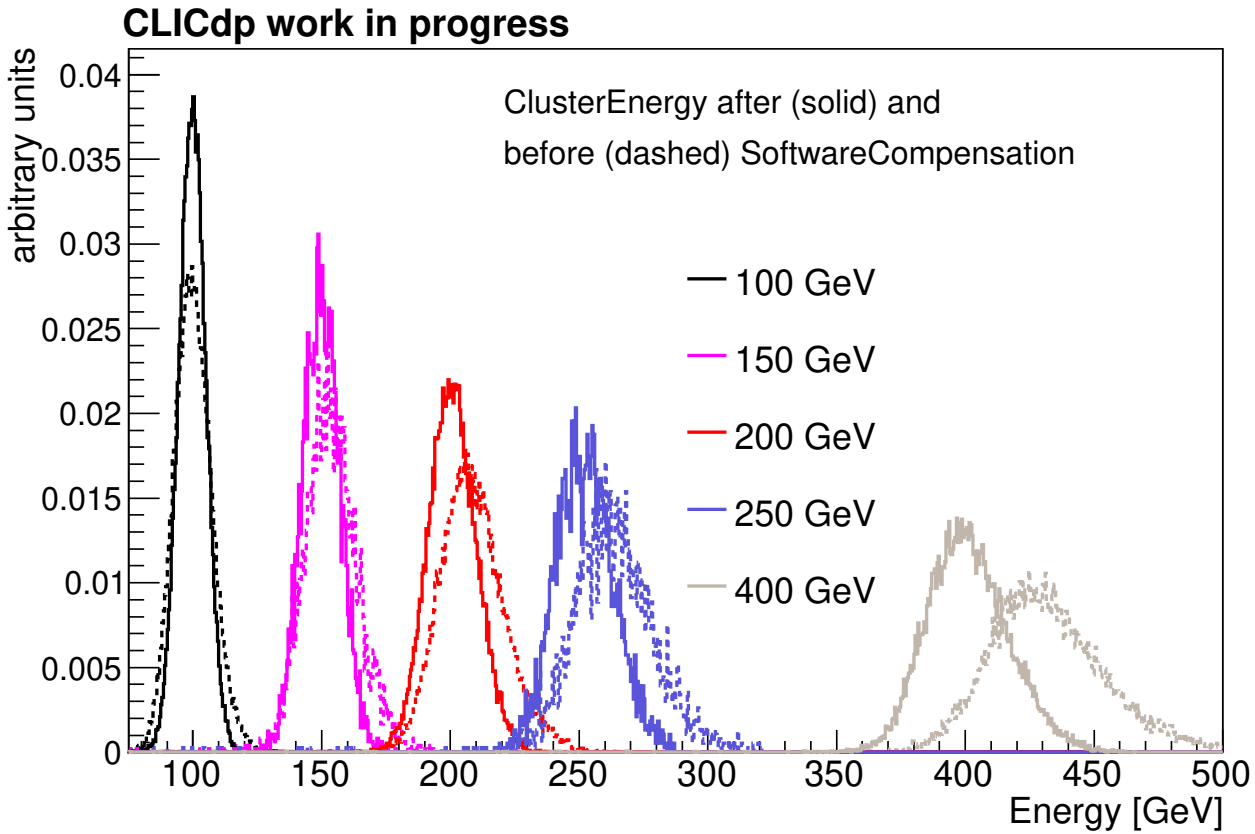
Software compensation:

- Electromagnetic component of shower typically denser
- Software compensation reweights hits in HCAL depending on the hit energy density
- Weights are calculated by formula:
  $\omega(\rho) = p_1 \exp(p_2 \rho) + p_3$
  where each parameter is energy dependent
  → 9 different parameters are used in total

Detector specific software compensation weights were obtained for CLD

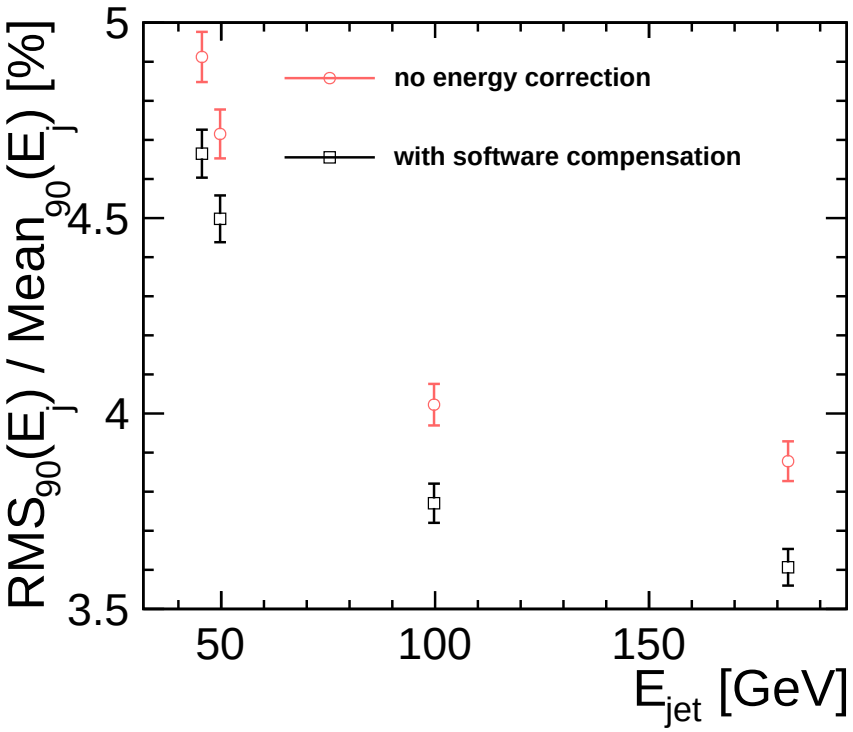


Hadron response with Software Compensation



- Software compensation weights derived using several fully simulated neutron and K0L single particle datasets
- Mean and resolution after software compensation largely improved
- Software compensation corrects for nonlinear response of hadrons on the fly

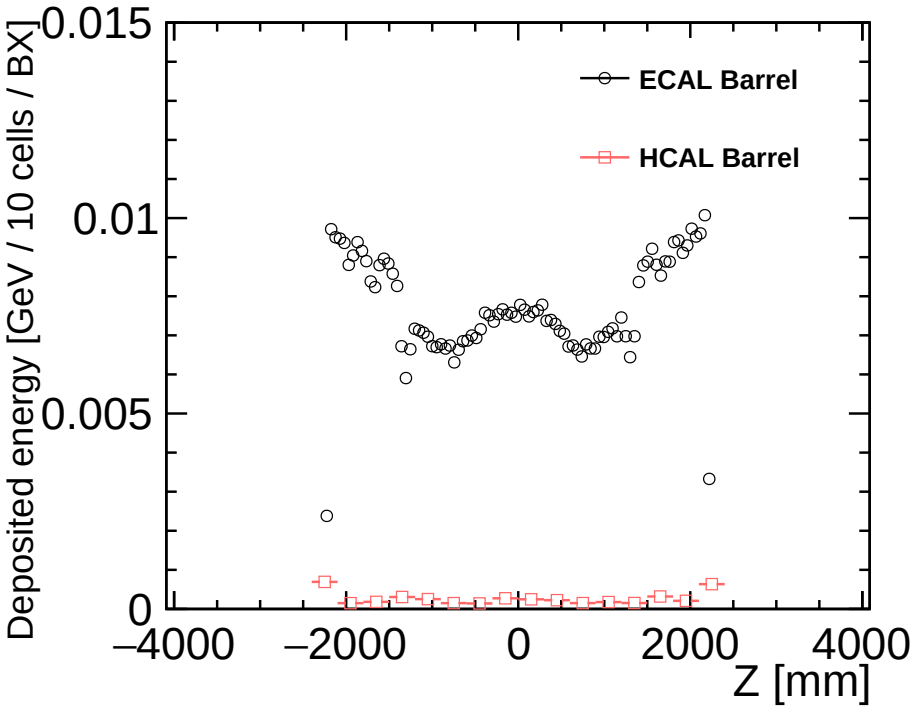
- Jet energy resolution for central jets with $|\cos\theta| < 0.7$

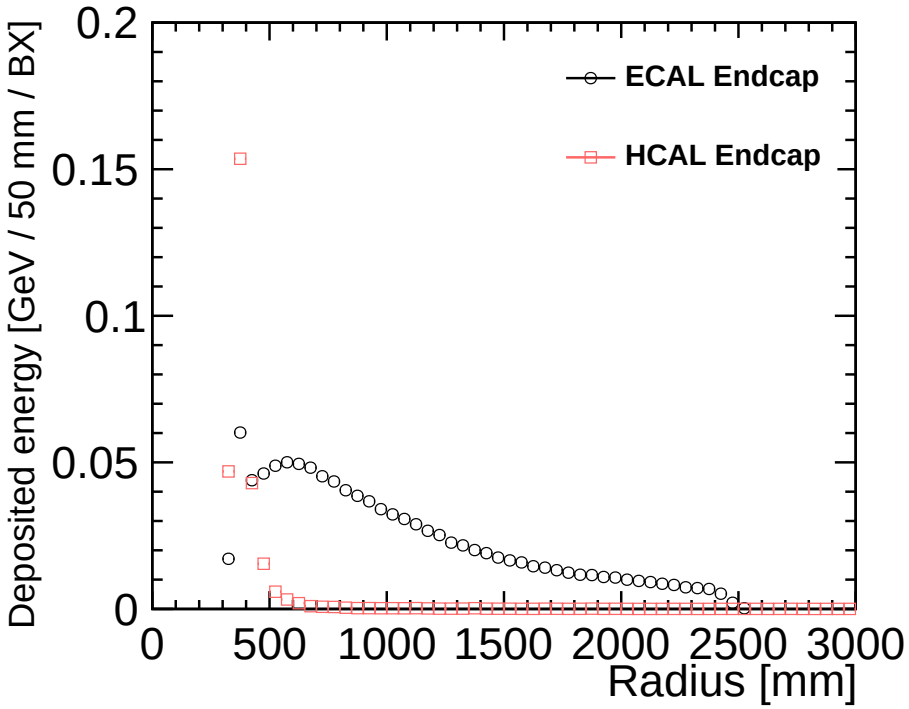


- 5-7% of improvement of the jet energy resolution due to software compensation depending on the jet energy

Background in the Calorimeter Region at 91.2 GeV

- The energy from incoherent pairs deposited in the ECAL and HCAL
- Has been studied as a function of z in the barrel and as function of a radius in the endcap

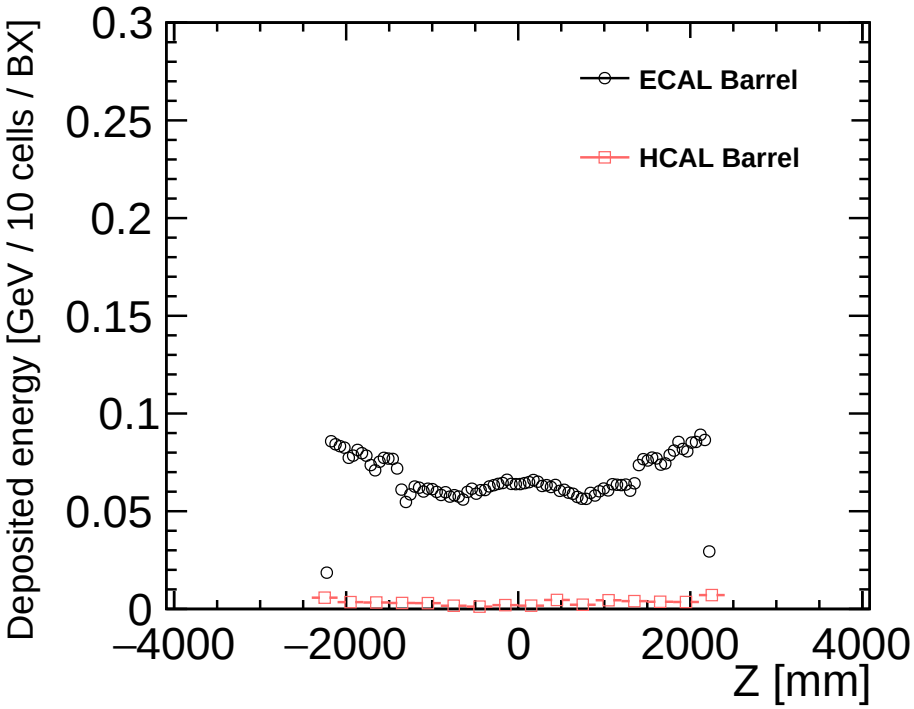


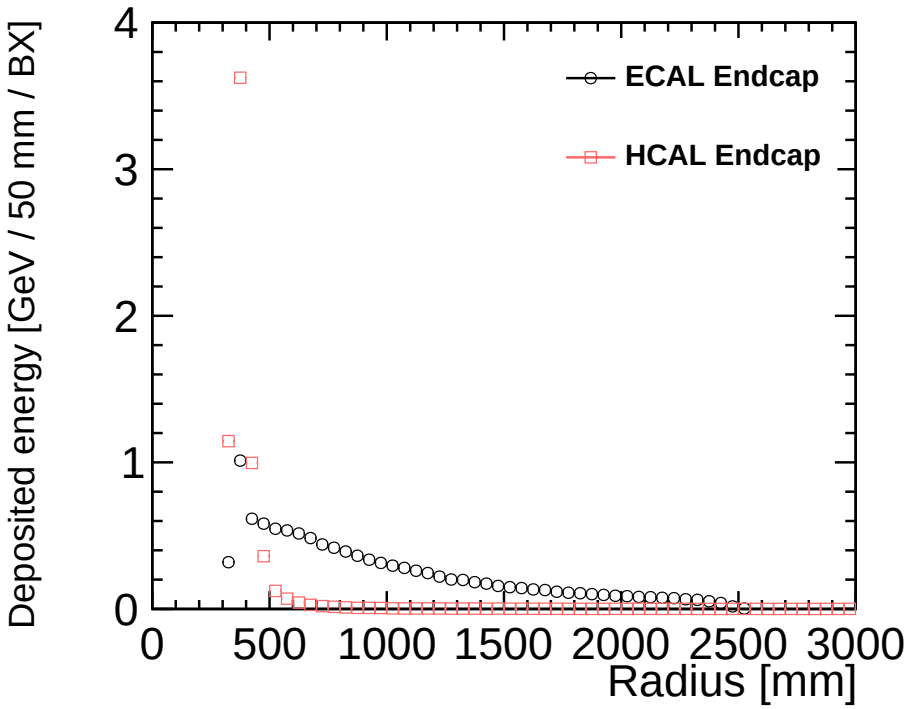


- Assuming 20 BX (400 ns) integration time window at 91.2 GeV
- Energy deposits reach up to 0.2 GeV / 10 cells in ECAL Barrel and 3 GeV / 50 mm in HCAL Endcap

Background in the Calorimeter Region at 365 GeV

- The energy from incoherent pairs deposited in the ECAL and HCAL
- Has been studied as a function of z in the barrel and as function of a radius in the endcap

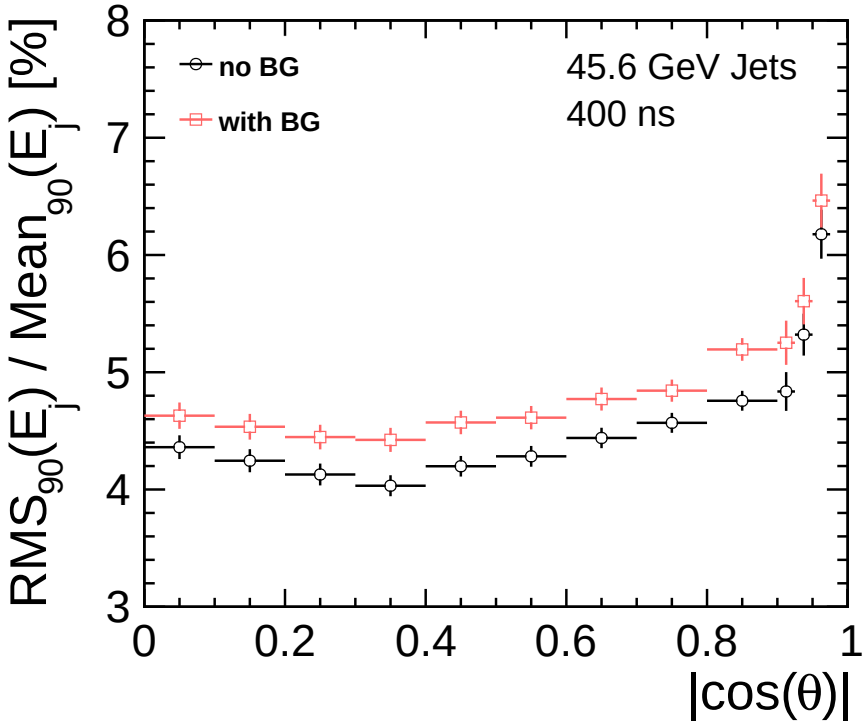


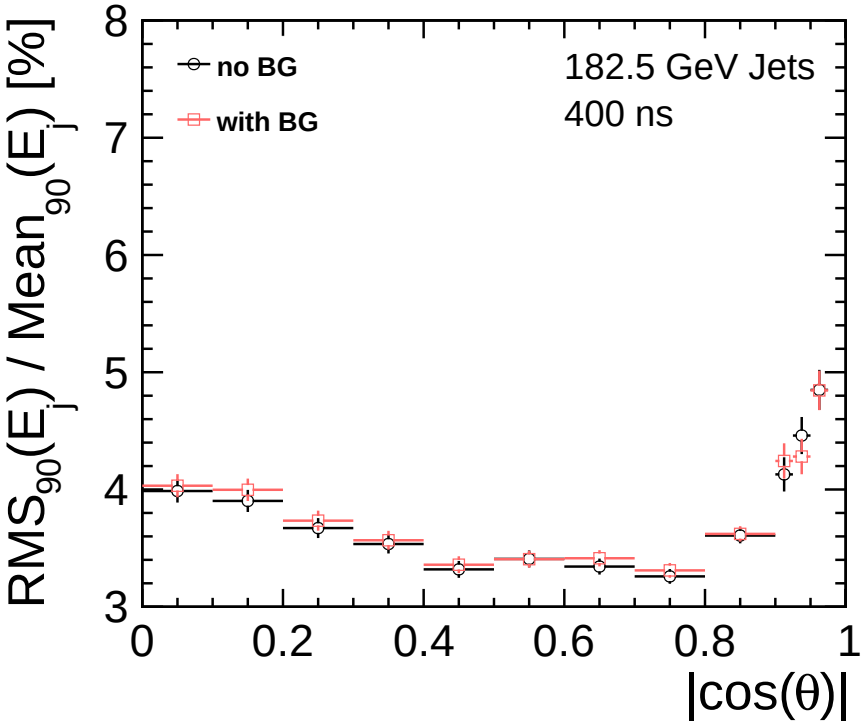


- Assuming the same integration time window (400 ns) at 365 GeV
- Energy deposits reach up to 0.1 GeV / 10 cells in ECAL Barrel and 4 GeV / 50 mm in HCAL Endcap

Jet Energy Resolution with background overlaid

- 400 ns integration time window:
  - 20 BX at 91.2 GeV
  - 1 BX at 365 GeV





- visible impact of the background on JER at 91.2 GeV
- negligible impact at 365 GeV

Jet energy E_j is measured as a half of total energy E_{jj} of $Z \to q\bar{q}$ (q=u,d,s) dijet event

$$\frac{\mathrm{RMS}_{90}(E_j)}{\mathrm{mean}_{90}(E_j)} = \frac{\mathrm{RMS}_{90}(E_{jj})}{\mathrm{mean}_{90}(E_{jj})}\sqrt{2}$$

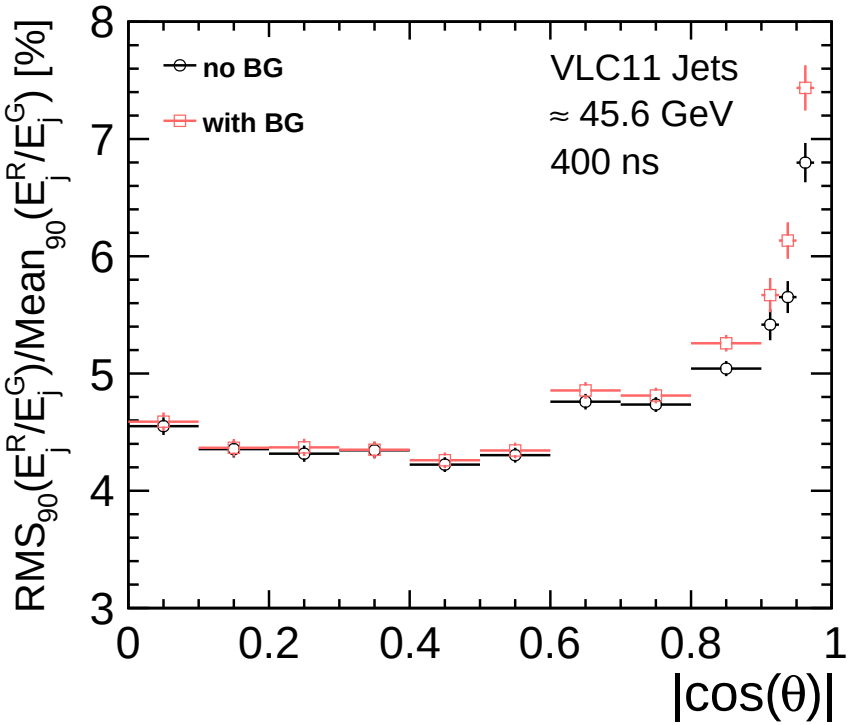
Jet Clustering algorithms

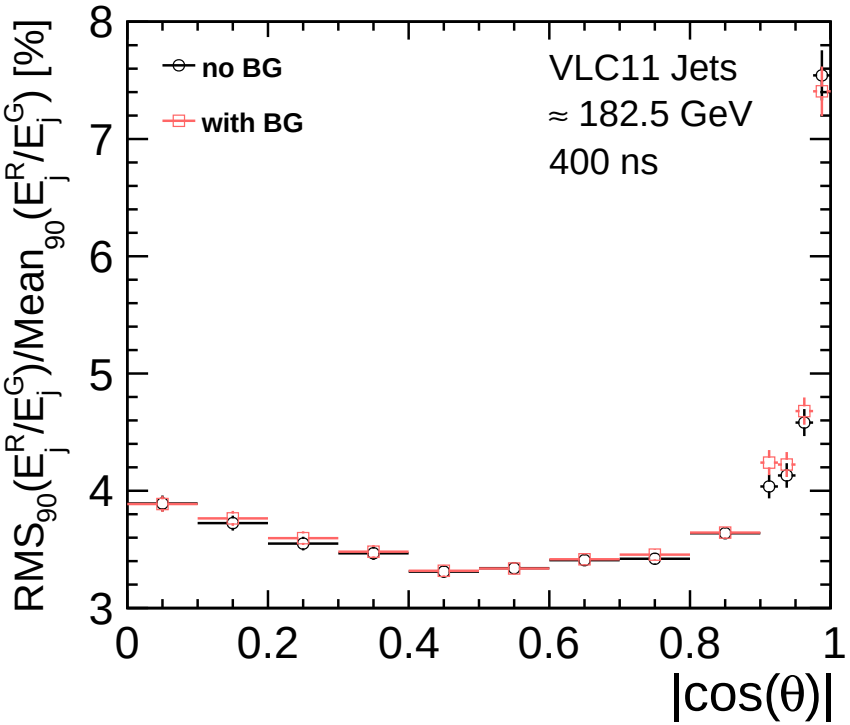
- Jet reconstruction with exclusive Valencia algorithm (VLC) with 2 jets (fixed $\alpha = \beta = 1.0$, varied ΔR parameter):
  - Generated particle jets (true) defined from all stable visible MC particles
  - Reconstructed jets defined from Pandora PFO

- Generated particle jets have to be matched to the reconstructed jets within 10°
- Jet Energy Resolution is defined as: $\frac{\mathrm{RMS}_{90}(E_j^R/E_j^G)}{\mathrm{mean}_{90}(E_j^R/E_j^G)}$
  - E_j^G - energy response of the particle level jets
  - E_j^R - energy response of the reconstructed jets

Jet Energy Resolution with background overlaid

- Jets are reconstructed with Valencia clustering algorithm with $\Delta R = 1.1$

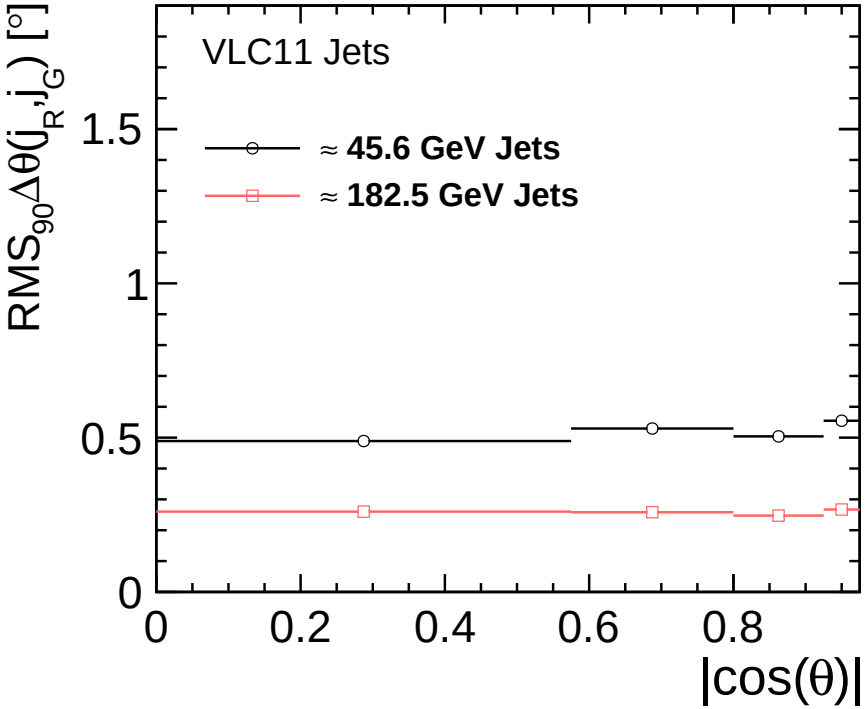


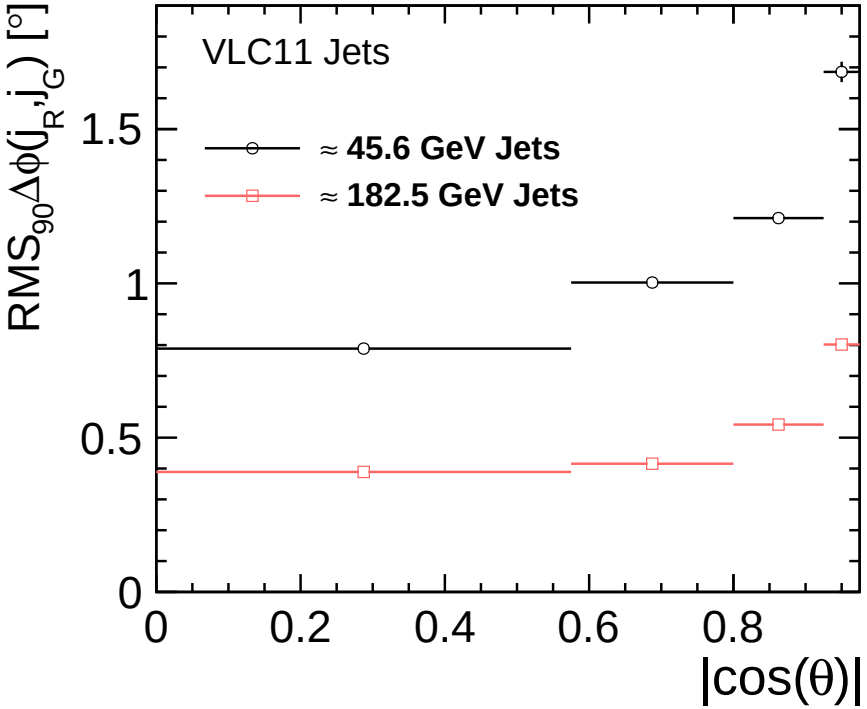


- overall the impact of the background is negligible at both centre-of mass energies
- except in the forward region at 91.2 GeV, where energy deposits from background particles is the largest
- no timing or p_T cuts were applied

The angular resolution of jets

- The angular resolution of jets have been studied by comparing azimuthal ϕ and polar θ angles of reconstructed and particle level jets

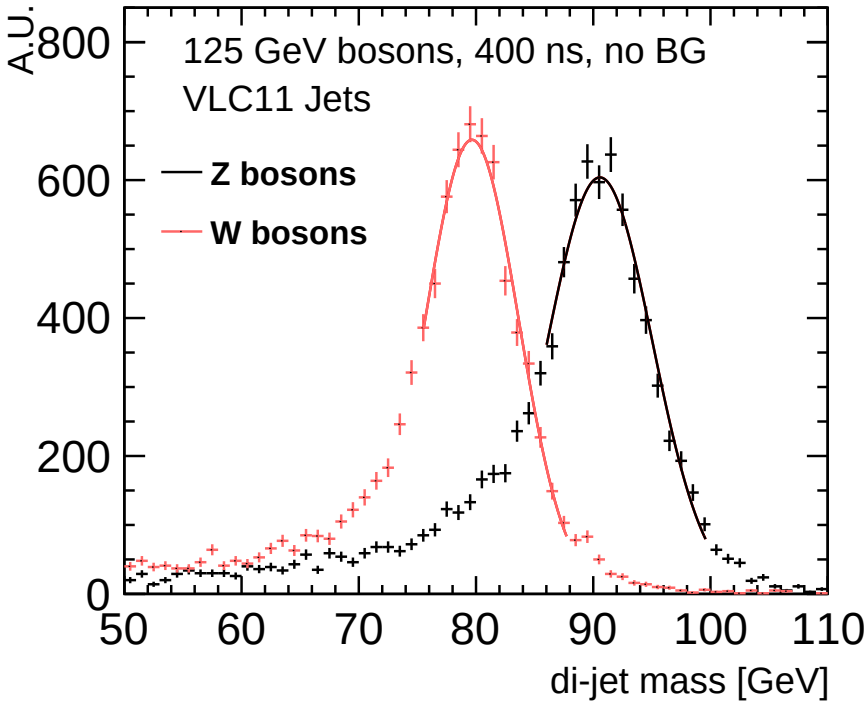


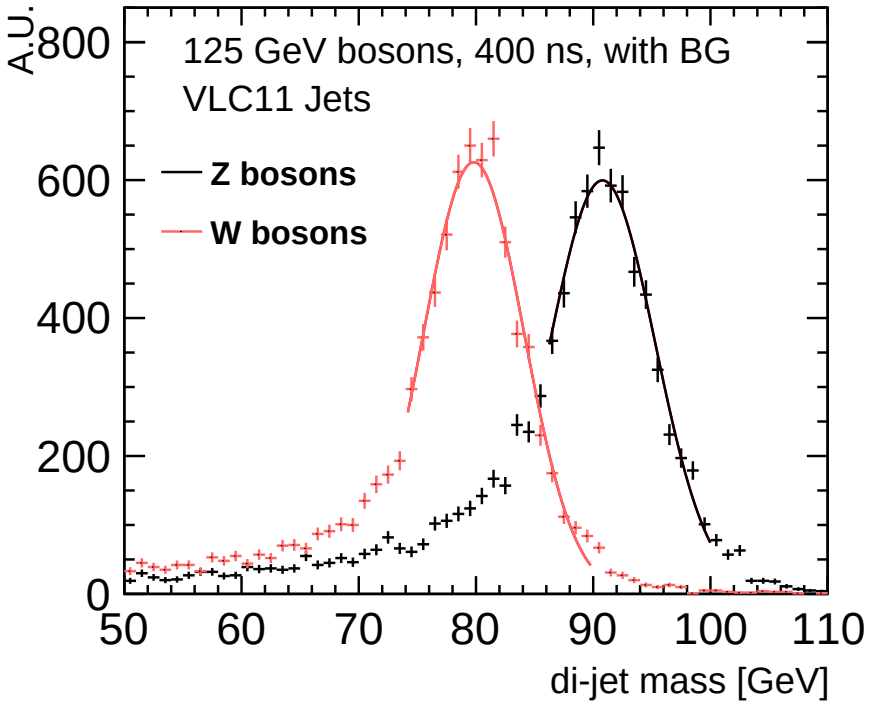


- The ϕ resolution for jets is worse than the θ resolution due to the effect of the magnetic field
- Degradation of the ϕ resolution with $\cos(\theta)$ can be explained with detector granularity

W-Z Mass Peak Separation

- Study of the ability to distinguish hadronic decays of W- and Z-bosons
- Two processes of interest: $WW \to \mu\nu_\mu qq$ and $ZZ \to \nu\nu qq$ (250 GeV)
  - decay products from leptonic decays of bosons are excluded from the jet reconstruction





- Invariant W and Z mass peaks are iteratively fitted with a Gaussian in the range $[\mu - \sigma, \mu + 2\sigma]$ until σ of the fit stabilises within $\pm 5\%$
- Fit is also done with 365 GeV background overlaid (right plot)

W-Z Mass Peak Separation

- The separation power is calculated from the fit parameters as: $(m_Z - m_W)/\sigma_{average}$ (where $\sigma_{average} = (\sigma_Z + \sigma_W)/2$)
- The separation power is calculated using two different methods:
  - the mass of W- and Z-boson is obtained as the mean of the Gaussian fit
  - the mass distributions are scaled such that the mean of the fit becomes equal to the PDG values of the W- and Z-boson mass.

background overlay	ΔR	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.9	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.5	2.45

- small effect from the background
- CLD detector provides 2.5σ W- and Z-bosons mass peak separation power

Summary and Outlook

Full simulation studies of single particles and di-jets demonstrate excellent performance of CLD calorimetry with:

- Good single particle ID efficiency
  ($>$95% from 20 GeV for charged particles)
- Excellent jet energy resolution (3-5 %) up to the endcaps
- 2.5σ W- and Z-bosons mass peak separation power

Further plans

- ECAL layout optimization
  - Reduce cost by decreasing the number of layers while still satisfying physics requirements (detailed requirements on photon and jet resolutions are needed)
  - More realistic cooling system may require to reduce compactness of the calorimeter
- HCAL layout optimization

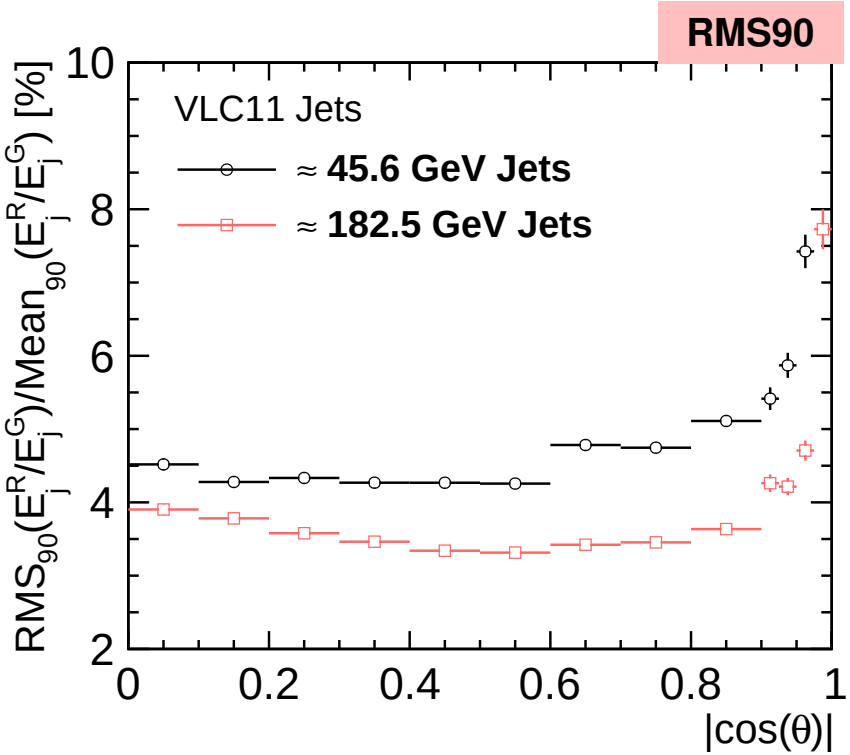
Full simulation physics studies

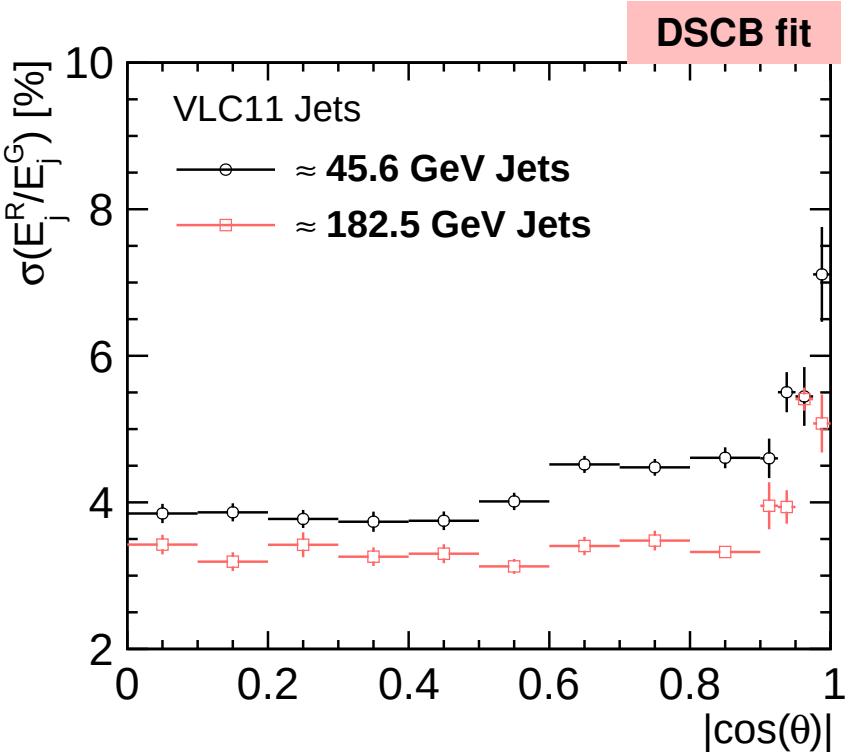
- Mature detector model and well-tested software chain allow to perform full simulation physics studies $\rightarrow$ you are all welcome to join this effort, we are here to help you!
  - Propose to start with $e^+e^- \rightarrow ZH$; $Z \rightarrow qq$, $H \rightarrow WW^* \rightarrow qqqq$

Thank you for your attention!

BACKUP

Comparison of RMS90 and double-sided Crystal Ball fit methods





- Overall, the two methods give comparable results, with the RMS90 method yielding slightly more conservative values at low energy