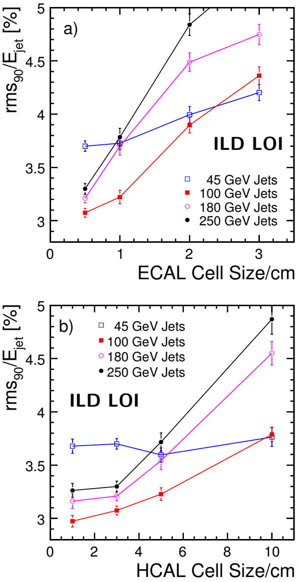
Test beam experiments with the CALICE scintillator tungsten HCAL

Eva Sicking (CERN)

First SAS @ LHC meeting
October 1, 2015

Calorimeters for future collider experiments

- Detector development for experiments at future colliders
- Jet energy resolution goal
  - 4-3 % at ILC
  - 5-3.5 % for 50 GeV-1 TeV jets at CLIC
- Possible solution: **Particle Flow Analysis**
  - Low mass tracker for charged particles
  - High granularity ECAL for photons, electrons
  - High granularity HCAL for neutral hadrons
  - Clever reconstruction algorithms

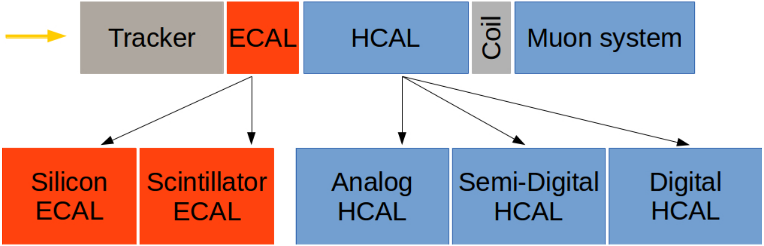


ILD Letter of Intent arXiv:1006.3396

Aim of calorimeter test beam experiments

- Characterisation of novel calorimeter prototypes
  - Linearity: E_{rec} versus E_{beam}
  - Resolution: $\sigma_{E_{\mathrm{rec}}}/E_{\mathrm{rec}}$
- Characterisation of particle showers
  - Shower shapes
  - Shower substructure
  - Time structure
- Electro-magnetic processes
  - Well understood
  - Cross check detector calibration
  - Understand requirements for details needed in simulations
- Hadronic nuclear interactions
  - Not a priori understood
  - Validate models of hadronic showers

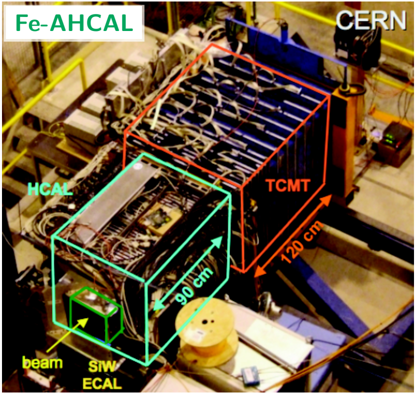
CALICE prototypes for highly granular calorimeters

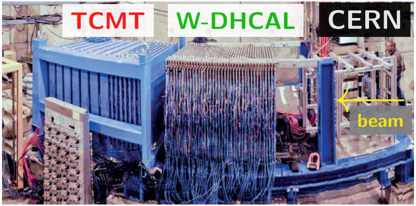


	Silicon ECAL	Scintillator ECAL	Analog HCAL	Semi-Digital HCAL	Digital HCAL
Readout	Silicon PIN diodes	Scint. strips+ Silicon Photo Multipliers	Scint. tiles+ Silicon Photo Multipliers	RPCs (μMegas)	RPCs (GEMs)
Granularity (mm^3)	$10 \times 10 \times 0.5$	$45 \times 5 \times 3$	$30 \times 30 \times 5$	$10 \times 10 \times 1.2$	$10 \times 10 \times 1.15$
Absorber	W	W	Fe or W	Fe	Fe or W
Layer × thickness (mm)	$10\times1.4+$ $10\times2.8+$ 10×4.2	30×3.5	Fe: 38×21.4 W: 38×10	48×20	Fe: 38×20 W: 39×10

CALICE test beam experiments

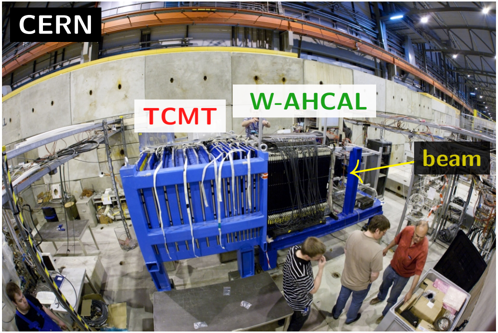
- Test beam experiments in 2006-2015 at DESY, CERN, FNAL
- Prototypes of up to $\sim$1 m^3, $\sim$2 m^3 including Tail Catcher Muon Tracker



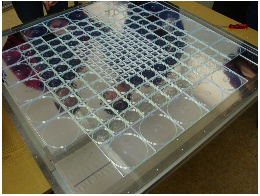


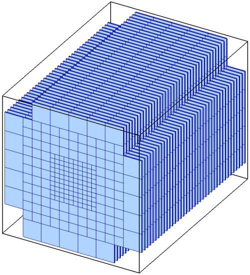
CALICE scintillator-tungsten HCAL

- Test beam experiments with W-AHCAL
- Absorber: 1 cm thick tungsten plates
- Active material: 0.5 cm thick scintillator tiles
- Granularity: $3 \times 3\,\mathrm{cm}^2$ in central region, $6 \times 6\,\mathrm{cm}^2$ and $12 \times 12\,\mathrm{cm}^2$ in outer regions
- Readout: Silicon Photomultipliers (SiPM)



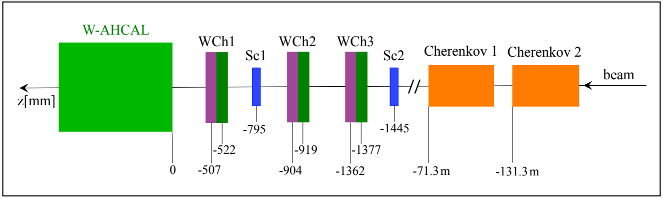
Sensitive layer of the AHCAL





- Prototype of $\sim 1\,\mathrm{m}^3$ with 38 layers

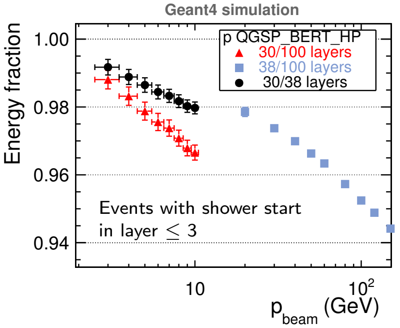
Test beam experiments at CERN SPS in 2011



- **W-AHCAL** (38 layers $\hat{=}$ 5 λ_I) (+ TCMT $\hat{=}$ 5 λ_I)
- $10 \leq p_{\text{beam}} \leq 300$ GeV
- $e^{\pm}$ beam/ mixed beam $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
- Publication ▸ arXiv:1509.00617 [physics.ins-det]

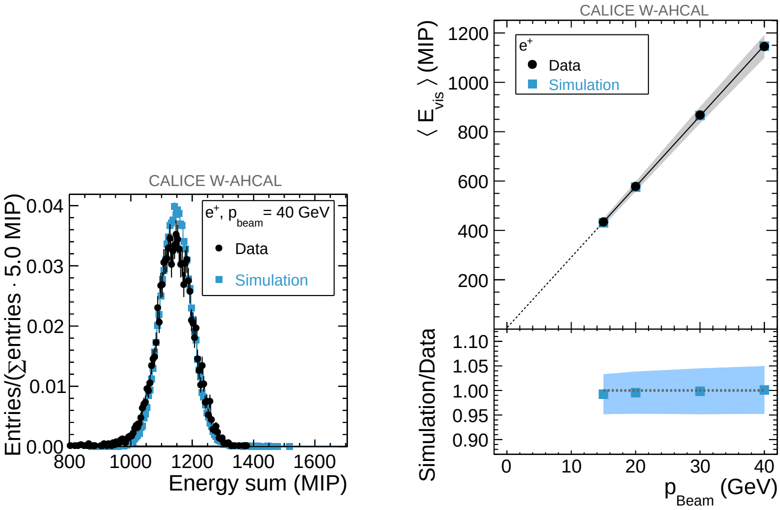
→ Comparison between data and Geant4 for tungsten HCAL

→ Limit analysis to momenta ≤ 150 GeV to keep leakage effects in W-AHCAL main stack small



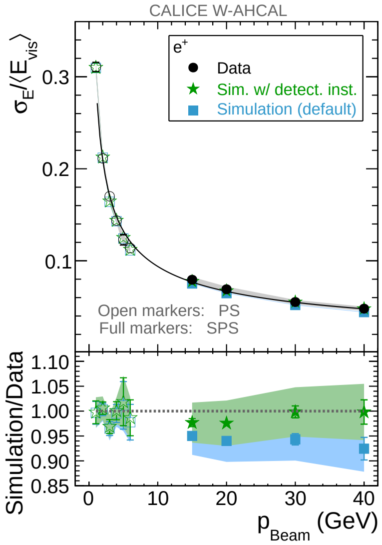
Positrons

Positron energy sum and linearity



- Data and simulation agree well within systematic uncertainties
- Calorimeter response (visible energy) increases linearly with p_{beam}

Positron resolution



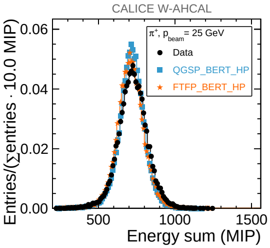
- Implement detector instability measured in data into simulated energy resolution
- Data and MC with detector instability agree well within uncertainties

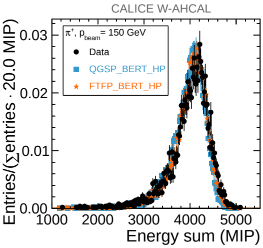
- Energy resolution well described by
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus b \oplus \frac{c}{E[\mathrm{GeV}]}$$
- Include PS data to better constrain the fit

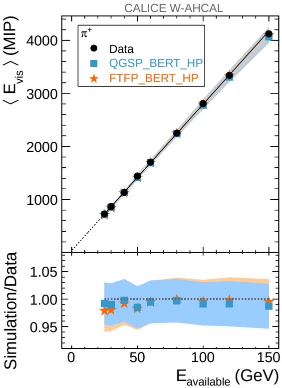
- **W-AHCAL PS+SPS:** $\rightarrow$ 2.80 X_0 per layer
$a_{\mathrm{data}} = (29.5 \pm 0.4)\,\%\sqrt{\mathrm{GeV}}$,
$a_{\mathrm{sim}} = (28.7 \pm 0.5)\,\%\sqrt{\mathrm{GeV}}$
- **W-AHCAL PS:**
$a_{\mathrm{data}} = (29.6 \pm 0.5)\,\%\sqrt{\mathrm{GeV}}$
- **Fe-AHCAL:** $\rightarrow$ 1.24 X_0 per layer
$a_{\mathrm{data}} = (21.5 \pm 1.4)\,\%\sqrt{\mathrm{GeV}}$

Hadrons

Pion linearity

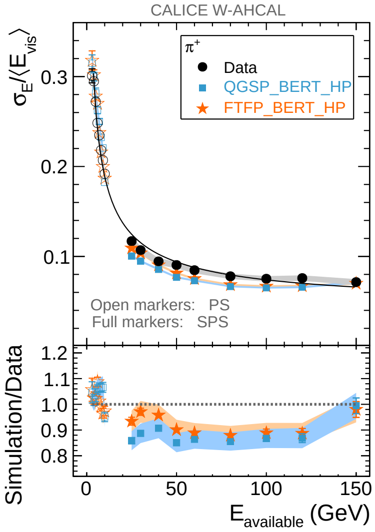






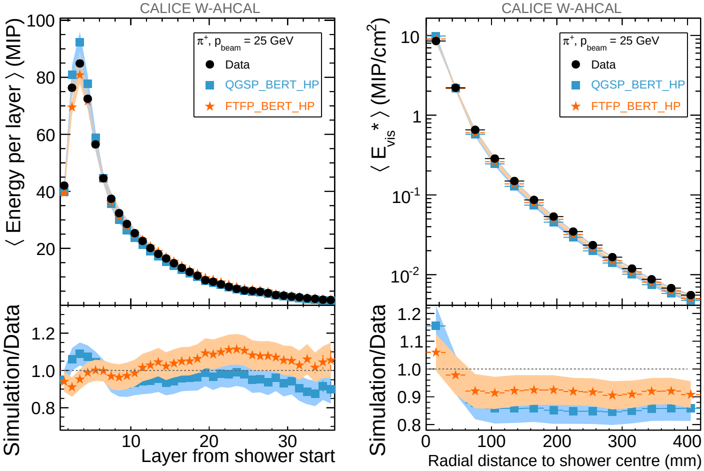
- Hadron E_{sum} distributions at high p_{beam} have low-energy tail due to leakage
- HP = **H**igh **P**recision: Transports neutrons down to thermal energies, needed for realistic simulation of spallation neutrons in high-A absorbers
- QGSP_BERT_HP describes mean slightly better than FTFP_BERT_HP

Pion resolution



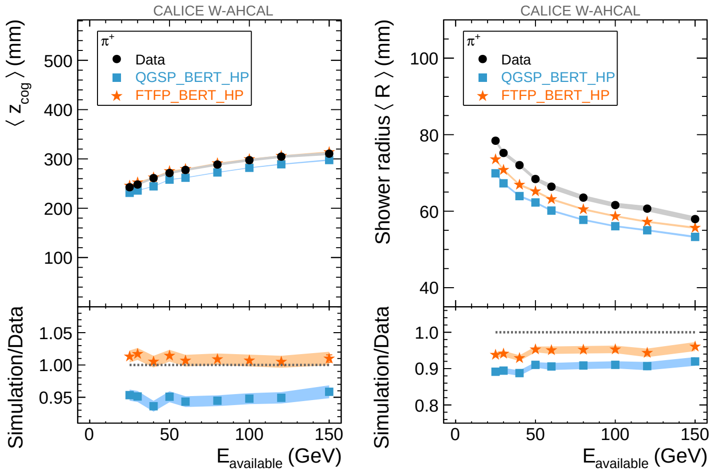
- Energy resolution for π^+ follows
  $$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus b \oplus \frac{c}{E[\mathrm{GeV}]}$$
- Stochastic term:
  - **W-AHCAL PS+SPS** $\rightarrow \sim 0.13\,\lambda_I$ per layer
    $a = (57.9 \pm 1.1)\,\%\sqrt{\mathrm{GeV}}$
    $a = (51.1 \pm 2.8)\,\%\sqrt{\mathrm{GeV}}$
    $a = (54.6 \pm 2.0)\,\%\sqrt{\mathrm{GeV}}$
    $\rightarrow$ Gaussian fit function
  - **W-AHCAL PS**
    $a = (61.8 \pm 2.5)\,\%\sqrt{\mathrm{GeV}}$
    $\rightarrow$ standard deviation and mean
  - **Fe-AHCAL** $\rightarrow \sim 0.13\,\lambda_I$ per layer
    $a = (57.6 \pm 0.4)\,\%\sqrt{\mathrm{GeV}}$
    $\rightarrow$ Gaussian fit function
- $\sigma_E/\langle E\rangle$ lower in MC,
  by 3-12% for FTFP_BERT_HP,
  by 10–15% for QGSP_BERT_HP

Pion shower profiles



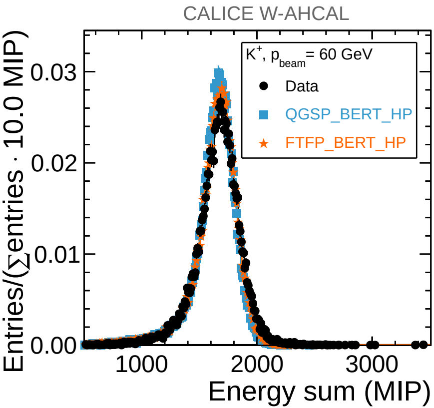
- Longitudinal profile (from shower start): QGSP_BERT_HP overestimates energy deposition in first part of shower, FTFP_BERT_HP overall slightly better
- Radial profile: Models overestimate energy density in shower core and underestimate the tails, FTFP_BERT_HP better than QGSP_BERT_HP

Pion shower shapes



- z_{cog}: energy weighted centre of gravity in z-direction
  $\langle z_{cog} \rangle$ well described by FTFP_BERT_HP, too early showers in QGSP_BERT_HP
- R: energy weighted shower radius:
  both models underestimate $\langle R \rangle$, FTFP_BERT_HP better

Kaon energy sum distribution

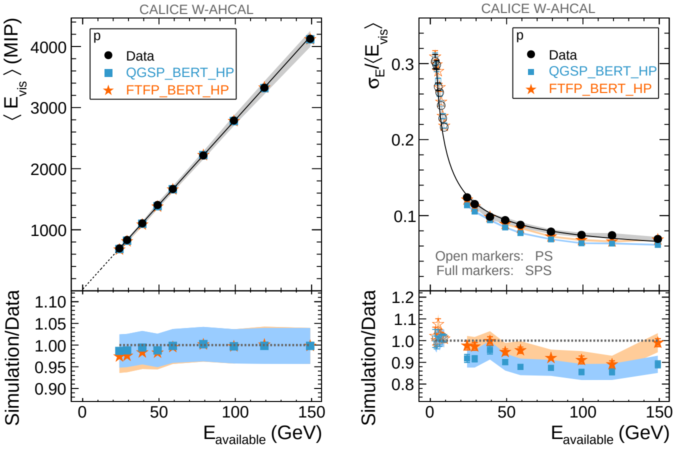


- Kaon data available at 50 GeV and 60 GeV
- Data, QGSP_BERT_HP and FTFP_BERT_HP agree well for K^+ energy sum

- Kaon energy showers very similar to pion and proton showers

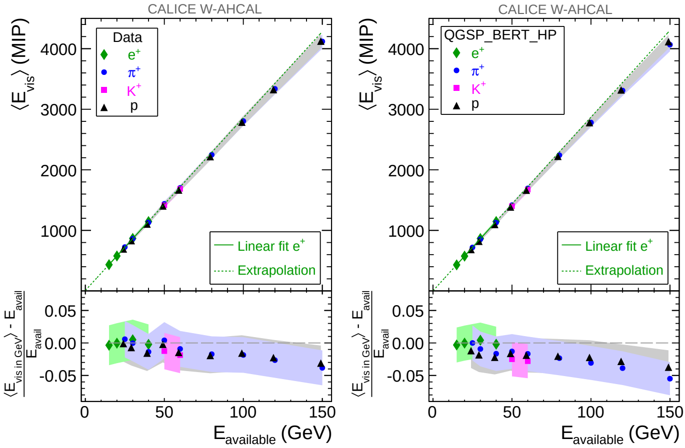
→ Limited potential for $\pi^+/K^+/p$ separation based on shower shapes only

Proton linearity and energy resolution



- Linearity and resolution similar to π^+ results
- QGSP_BERT_HP describes mean slightly better than FTFP_BERT_HP
- $\sigma_E/\langle E\rangle$ lower in MC, FTFP_BERT_HP more close to data

Comparison of response for different particle types

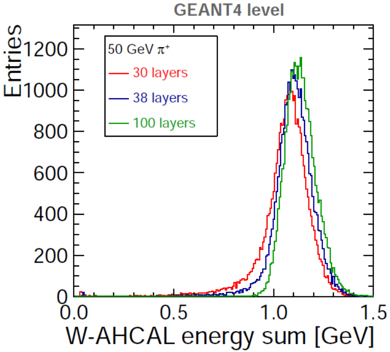


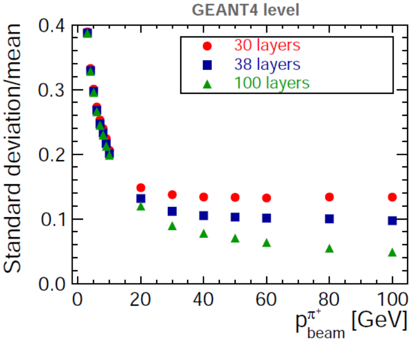
- Quantify compensation level: Compare visible energy in GeV with available energy
- Convert E_{vis} from MIP to GeV based on e^{+} linearity fit parameters
- Hadron and positron response agree up to approximately 60 GeV
- Behaviour reproduced by MC

Extrapolation to SAS

Extrapolation to longer HCAL

- Default W-AHCAL with 38 layers ($\sim 5\lambda_\mathrm{I}$, 1 m depth)
- Extrapolated W-AHCAL with 100 layers ($\sim 13\lambda_\mathrm{I}$, 2.5 m depth)

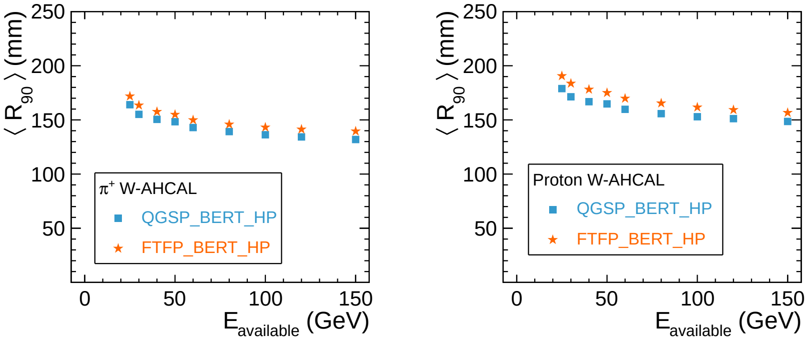




- Reduced leakage effect for longer HCAL
- Energy resolution of $\sim$ 5% could be reached for laterally contained showers at hadron energies of 100 GeV with 100-layer W-AHCAL
- Additional studies for TeV particles and realistic detector layout needed

Lateral containment of hadron showers

- Which detector size is needed to laterally contain hadron shower?
- R_{90}: Radius containing 90% of shower energy



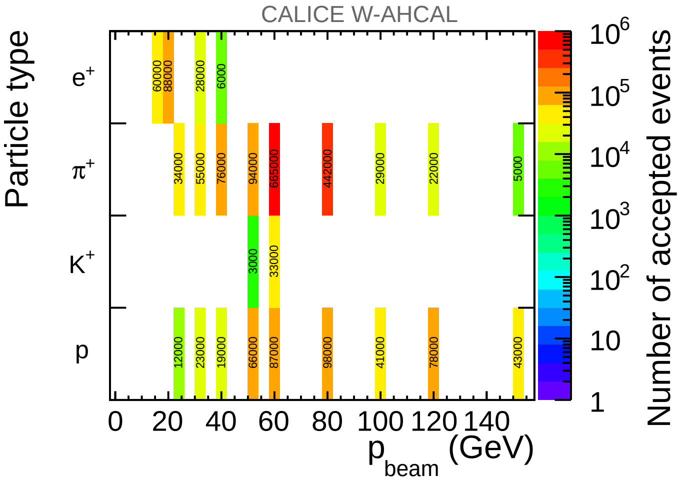
- Hadron showers slightly more collimated at higher energies
- W-AHCAL with 40 cm lateral dimensions would contain 90% of the shower energy, if the hadron hits centrally
- Additional studies for TeV particles and realistic detector layout needed

Summary

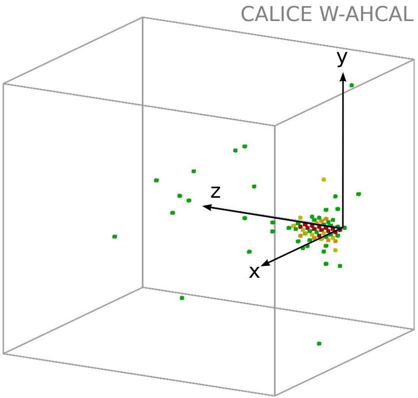
- Analysis of test beam data of W-AHCAL ▸ arXiv:1509.00617 [physics.ins-det]
  - e^+, π^+, K^+, and p at $p_{beam} = 15\,GeV$–$150\,GeV$
- Study of response, energy resolution, and shower shapes
  - Response is linear
  - Response is similar for e^+, π^+, K^+, and p up to 60 GeV
  - Energy resolution:
    e^+: $a = (29.5 \pm 0.4)\,\%\sqrt{GeV}$
    π^+: $a = (57.9 \pm 1.1)\,\%\sqrt{GeV}$
    p: $a = (60.7 \pm 1.2)\,\%\sqrt{GeV}$
- Comparison to Geant4
  - **H**igh **P**recision neutron tracking needed for tungsten simulation
  - Agreement between data and Geant4 lists on percent level for average shower properties, within 15% or better for spatial shower profiles
  - FTFP_BERT_HP better than QGSP_BERT_HP for all observables except E_{vis}
- High granularity calorimetry and W-AHCAL are interesting option for SAS

Backup

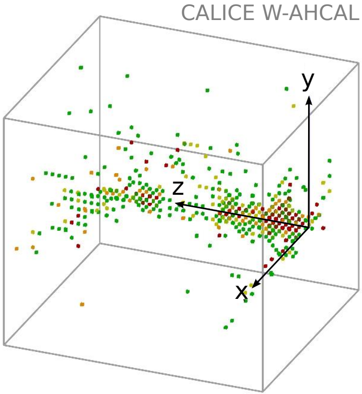
Number of events after selection



Event displays

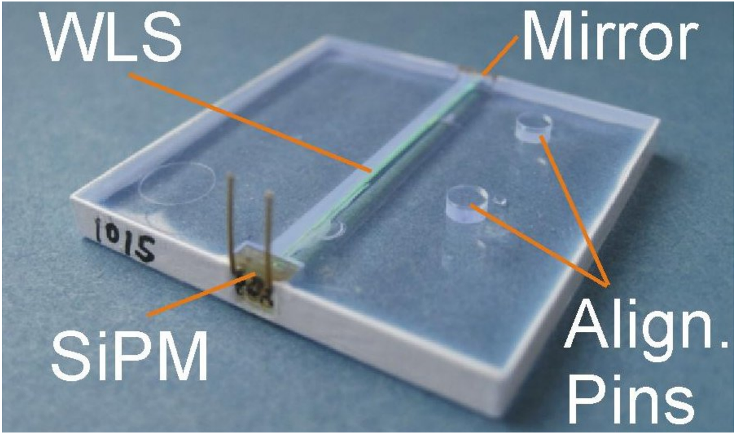


e^+ event at 15 GeV



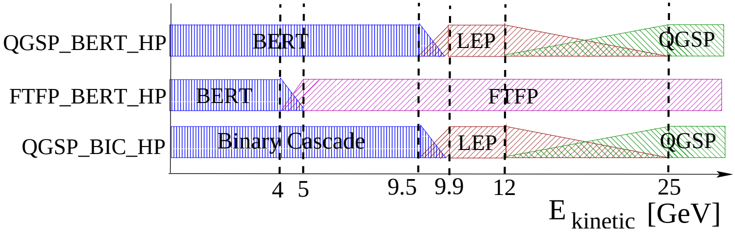
π^+ event at 80 GeV

Scintillator tile and SiPM

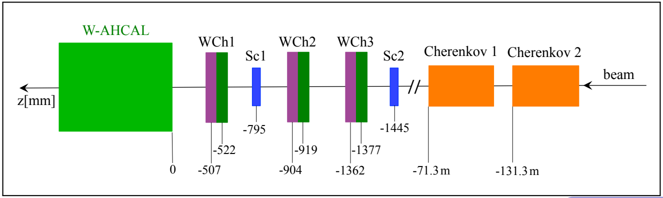


Comparison with Geant4 Simulations

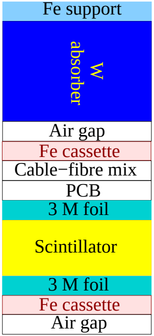
- Comparison of test beam data with Geant4 simulations
- Test various physics models combined to so-called physics lists
- Three example physics lists



Detector simulations



AHCAL layer as implemented in Mokka



- Geant4 detector simulation
  - Full setup including beam instrumentation
  - Particle generation using gun simulation
  - Beam position, direction and spread corresponding to data runs
- Digitisation
  - Realistic detector granularity
  - Optical cross talk between scintillator tiles
  - Birks' law
  - Readout electronics: signal shaping time, noise
  - Saturation effects