Shower development of particles with momenta up to 150 GeV in the CALICE W-AHCAL

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for the CALICE collaboration

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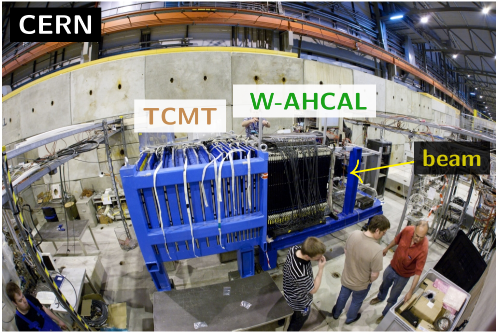
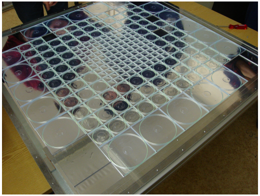
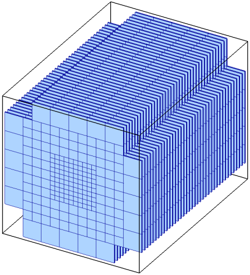
CALICE scintillator-tungsten HCAL

- 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)



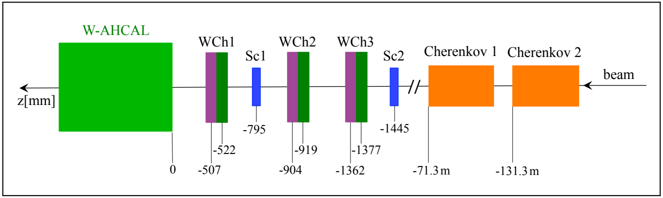
Sensitive layer of the AHCAL





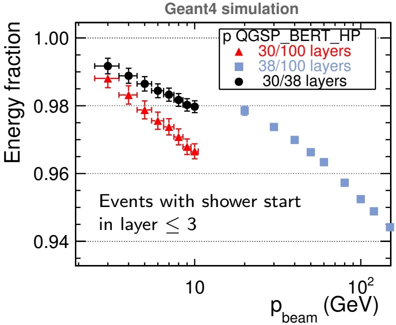
- Prototype of $\sim 1\,\mathrm{m}^3$ with 38 layers

Test beam experiments at CERN SPS in 2011

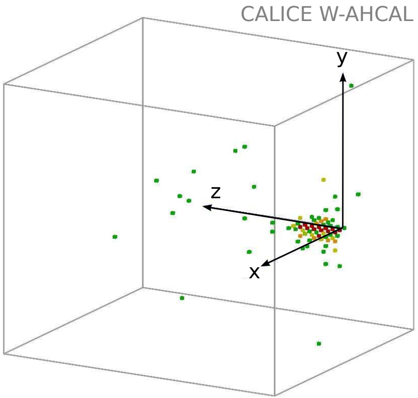


- **W-AHCAL** (38 layers $\hat{=}$ 5 λ_{I}) (+ TCMT $\hat{=}$ 5 λ_{I})
- $10 \leq p_{\text{beam}} \leq 300$ GeV
- $e^{\pm}$ beam/ mixed beam $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
- Focus of study: Comparison between data and Geant4 9.6.p02 for tungsten HCAL

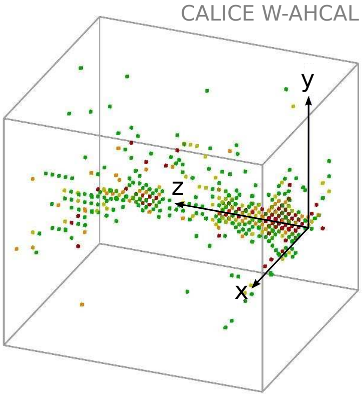
→ Limit analysis to momenta ≤ 150 GeV to keep leakage effects in W-AHCAL main stack small



Event displays



e^+ event at 15 GeV

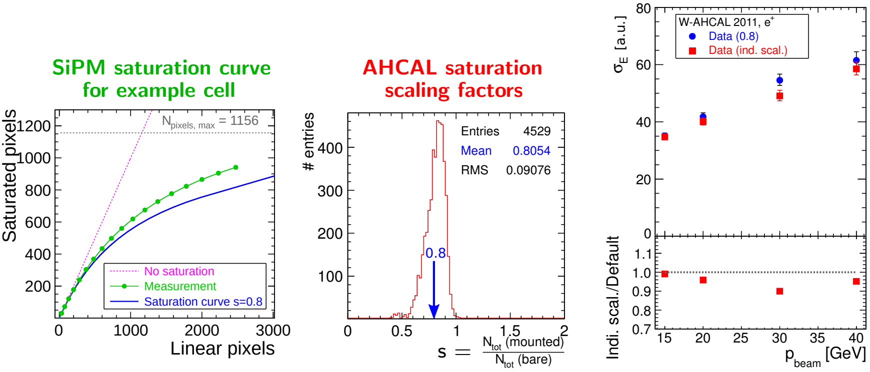


π^+ event at 80 GeV

Recent refinements

SiPM saturation scaling factor *s*

- Saturation scaling factor *s*: effective number of SiPM pixels for mounted SiPMs
- *s* plays important role in energy reconstruction at high cell energies



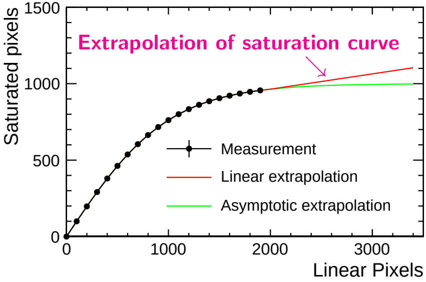
→ Use individual scaling factors (available for 60% of cells) for W-AHCAL SPS study

→ Improves energy resolution

→ Improves agreement between data and simulation for e^+, where only few cells contribute to energy sum

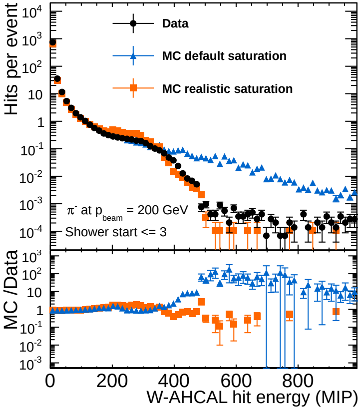
More realistic saturation simulation

- Higher energy density in W than in Fe



- **Data**
  - Linear extrapolation in reconstruction
- **MC with default saturation**
  - Linear extrapolation in digitization and reconstruction
- **MC with more realistic saturation**
  - Asymptotic extrapolation in digitization, linear extrapolation in reconstruction

- Hit energy distribution in data can be described well by more realistic MC
- Energy resolution values increase at high beam momenta



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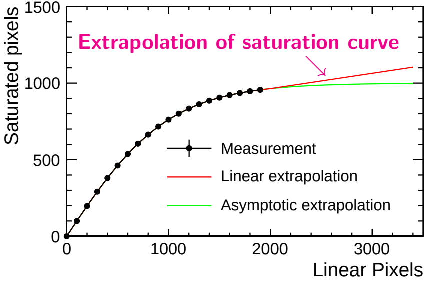

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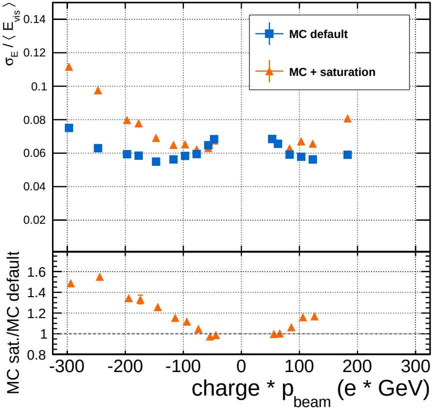
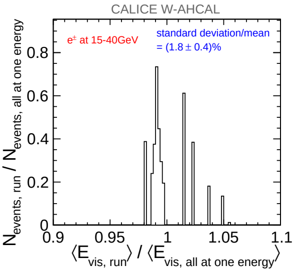
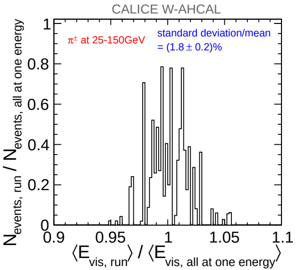


Systematic uncertainties

- Comprehensive study of systematic uncertainties for all observables
- Example: detector stability over several data taking periods

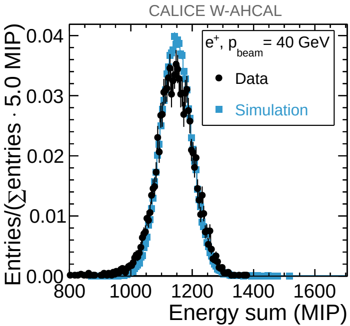


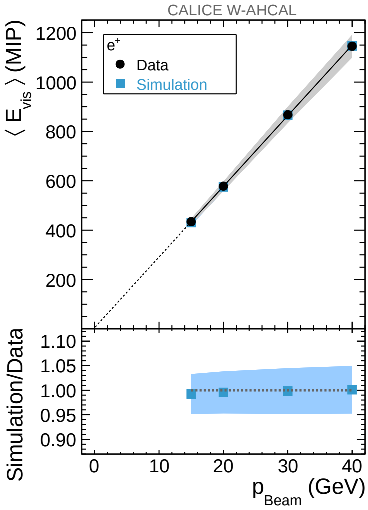


Source	— Systematic uncertainty on $\langle E_{vis} \rangle$ — for e (%)	for π, K, and protons (%)	Assigned to
SiPM saturation scaling	1.4–3.0	0.4–1.5	data
MIP constants	2.0	2.0	data
Detector stability	1.8	1.8	data
Shower start	-	0.1	data
Inter-tile cross-talk	2.7	2.7	MC

Positrons

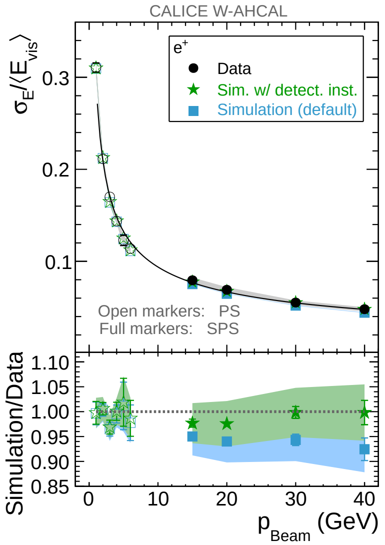
Positron energy sum and linearity





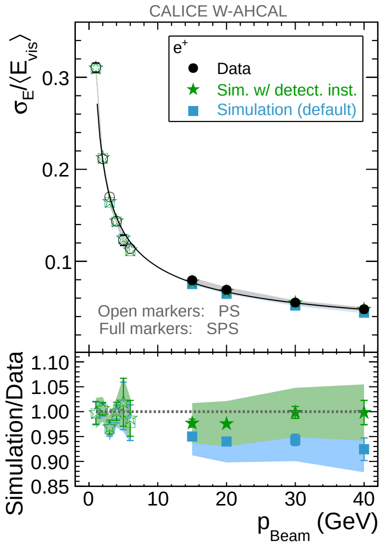
- Data and simulation agree well within systematic uncertainties
- Calorimeter response (visible energy) increases linearly with p_{beam}

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
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\text{GeV}]}} \oplus b \oplus \frac{c}{E[\text{GeV}]}$$
- Include PS data to better constrain the fit
- **W-AHCAL PS+SPS:** $\rightarrow 2.80\,X_0$ per layer
$a_{data} = (29.5 \pm 0.4)\,\%\sqrt{\text{GeV}}$,
$a_{sim} = (28.7 \pm 0.5)\,\%\sqrt{\text{GeV}}$
- **W-AHCAL PS:**
$a_{data} = (29.6 \pm 0.5)\,\%\sqrt{\text{GeV}}$
- **Fe-AHCAL:** $\rightarrow 1.24\,X_0$ per layer
$a_{data} = (21.5 \pm 1.4)\,\%\sqrt{\text{GeV}}$

Positron resolution



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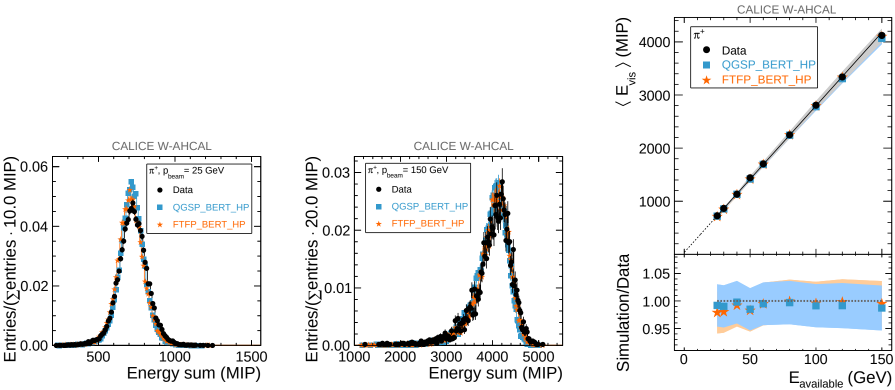
  $a_{\mathrm{data}} = (21.5 \pm 1.4)\,\%\sqrt{\mathrm{GeV}}$
- Expectation for el.-mag. energy resolution:
  $$\frac{a_W}{a_{Fe}} = \sqrt{\frac{t_W}{t_{Fe}}}$$ but $1.35 \pm 0.09 \neq 1.5$

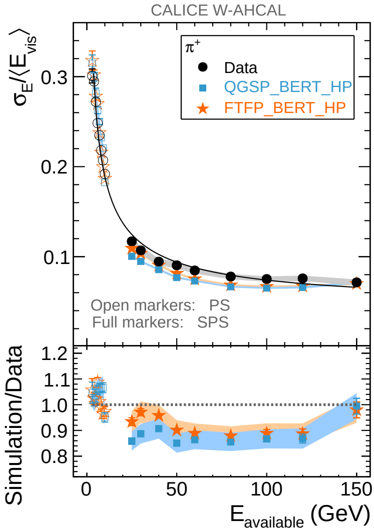
Hadrons

Pion linearity



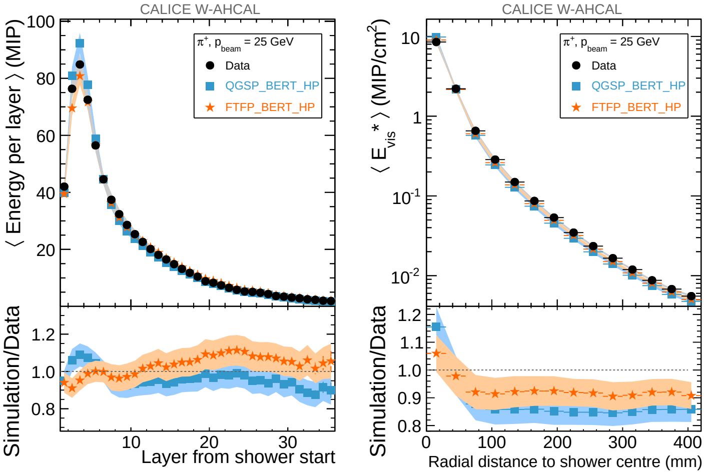
- Hadron E_{sum} distributions at high p_{beam} have low-energy tail due to leakage
- HP = **H**igh **P**recision: Transports neutrons down to thermal energies, needed for realistic simulation of spallation neutrons in high-A absorbers
- QGSP_BERT_HP describes mean slightly better than FTFP_BERT_HP

Pion resolution



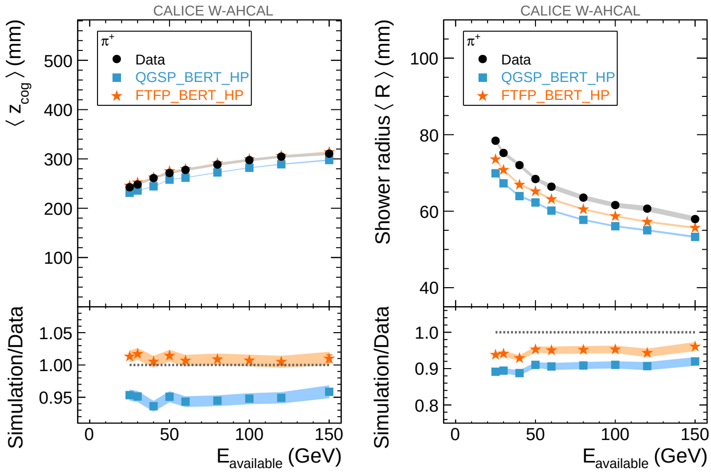
- Energy resolution for π^+ follows
  $$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus b \oplus \frac{c}{E[\mathrm{GeV}]}$$
- Stochastic term:
  - **W-AHCAL PS+SPS** $\rightarrow \sim 0.13\,\lambda_I$ per layer
    $a = (57.9 \pm 1.1)\,\%\sqrt{\mathrm{GeV}}$
    $a = (51.1 \pm 2.8)\,\%\sqrt{\mathrm{GeV}}$
    $a = (54.6 \pm 2.0)\,\%\sqrt{\mathrm{GeV}}$
    $\rightarrow$ 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



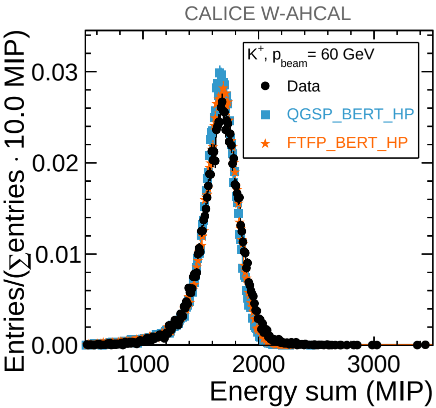
- Longitudinal profile (from shower start): QGSP_BERT_HP overestimates energy deposition in first part of shower, FTFP_BERT_HP overall slightly better
- Radial profile: Models overestimate energy density in shower core and underestimate the tails, FTFP_BERT_HP better than QGSP_BERT_HP

Pion shower shapes



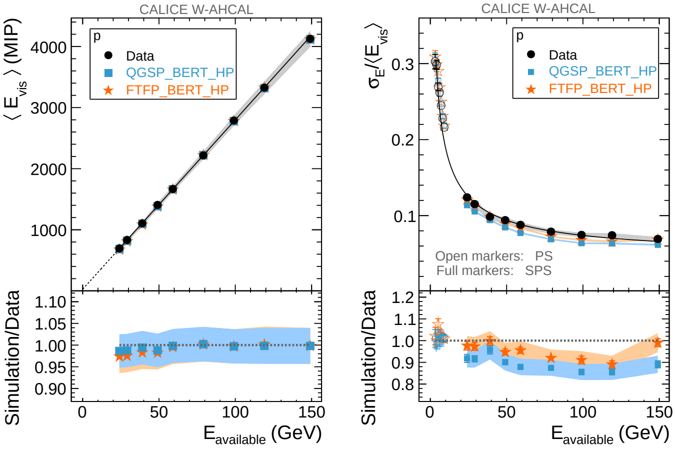
- z_{cog}: energy weighted centre of gravity in z-direction
  $\langle z_{cog} \rangle$ well described by FTFP_BERT_HP, too early showers in QGSP_BERT_HP
- R: energy weighted shower radius:
  both models underestimate $\langle R \rangle$, FTFP_BERT_HP better

Kaon energy sum distribution



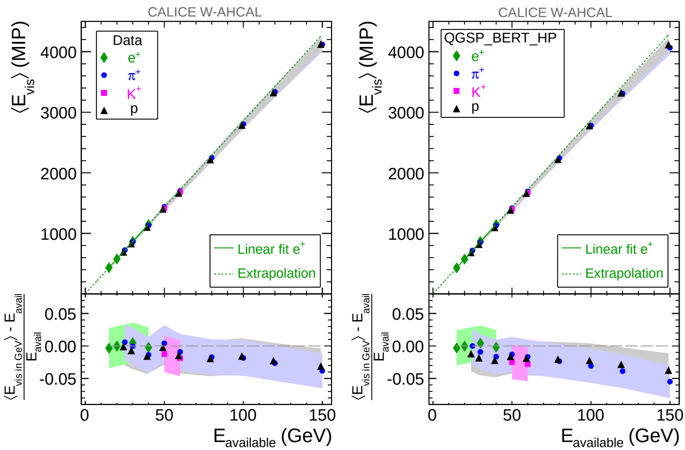
- Kaon data available at 50 GeV and 60 GeV
- Data, QGSP_BERT_HP and FTFP_BERT_HP agree well for K^+ energy sum
- Kaon energy showers very similar to pion and proton showers

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



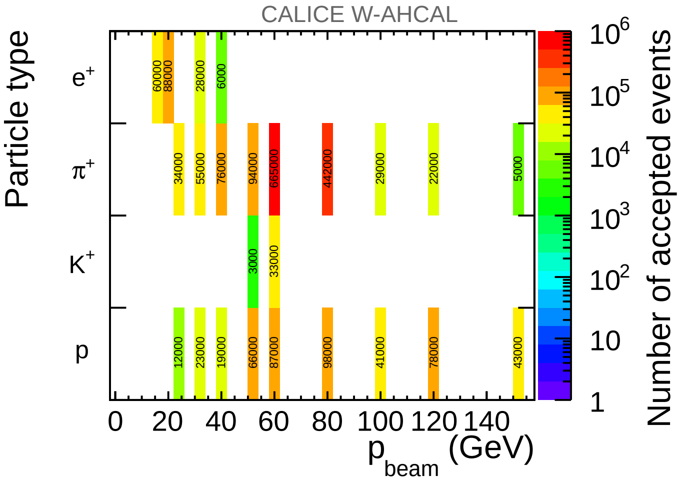
- Quantify compensation level: Compare visible energy in GeV with available energy
- Convert E_{vis} from MIP to GeV based on e^+ linearity fit parameters
- Hadron and positron response agree up to approximately 60 GeV
- Behaviour reproduced by MC

Summary

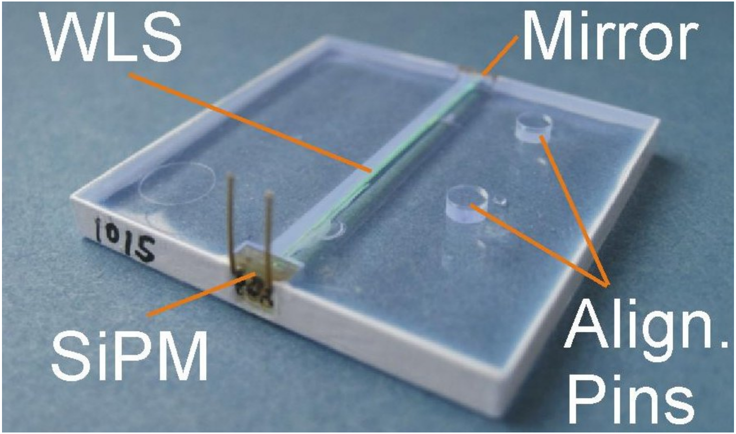
- Analysis of test beam data of W-AHCAL
  - e^+, π^+, K^+, and p at $p_{\mathrm{beam}} = 15\,\mathrm{GeV}$–$150\,\mathrm{GeV}$
  - Exploring limitations of SiPM technology and modeling
- Study of response, energy resolution, and shower shapes
  - Response is linear
  - Response is similar for e^+, π^+, K^+, and p up to 60 GeV
  - Energy resolution:
    e^+: $a = (29.5 \pm 0.4)\,\%\sqrt{\mathrm{GeV}}$
    π^+: $a = (57.9 \pm 1.1)\,\%\sqrt{\mathrm{GeV}}$
    p: $a = (60.7 \pm 1.2)\,\%\sqrt{\mathrm{GeV}}$
- Comparison to Geant4
  - High Precision (HP) neutron tracking needed for tungsten simulation
  - Agreement between data and Geant4 lists on few-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}
- Publication available at arXiv:1509.00617 [physics.ins-det] and accepted by JINST

Backup

Number of events after selection

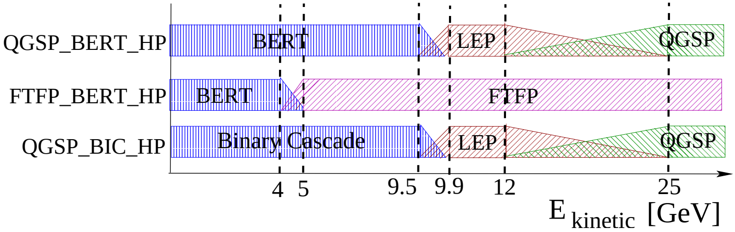


Scintillator tile and SiPM

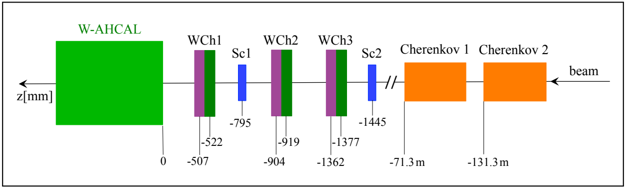


Comparison with Geant4 Simulations

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



Detector simulations



- 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

AHCAL layer as implemented in Mokka