Hadron calorimetry in Geant - from ZEUS to EIC

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Introduction

- Development of a Geant model for a binary system of electromagnetic and hadronic part
- The assumption for EIC is W/ScFi followed by a Fe/Sc hadron part
- Tests were done about the ability to reproduce ZEUS beam test data with a current Geant
- Simulations were done for EIC configuration to address its compensation and energy resolution

Lead - scintillator Geant model following a ZEUS prototype

- Layers of 10 mm Pb absorbers and 2.5 mm plastic scintillators in 3.5 mm free space
- Construction and test beam results are in NIM A262 (1987) 229-242
- The EM and HAD sections had independent readout, the structure is the same
- Transverse segmentation to modules 1–9 is neglected in Geant model, each layer stands for all modules
- Front size was increased to 700×700 mm^2
- Number of layers in HAD section was increased to 81 for 5λ
- Same 16 layers in EM section
- Birks coefficient is kB = 0.126 mm/MeV

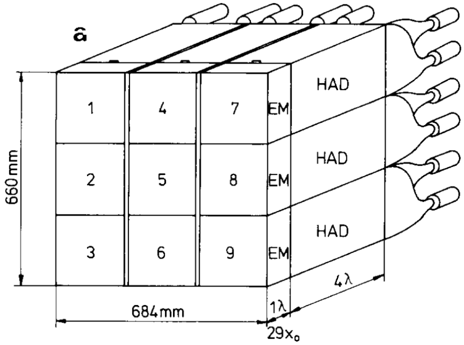
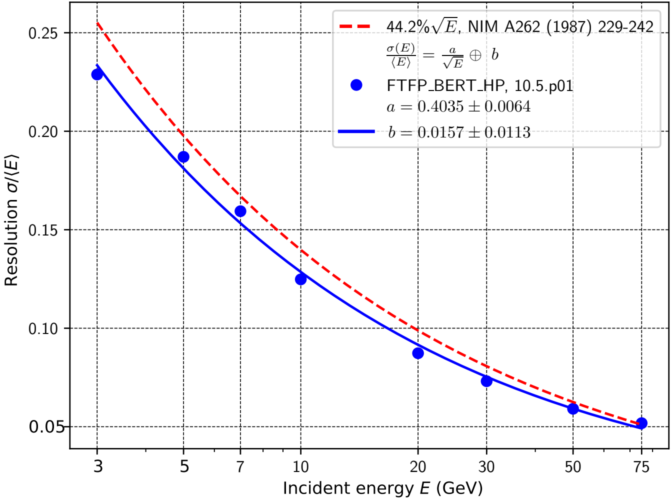


Figure: Calorimeter layout in NIM A262 (1987) 229-242

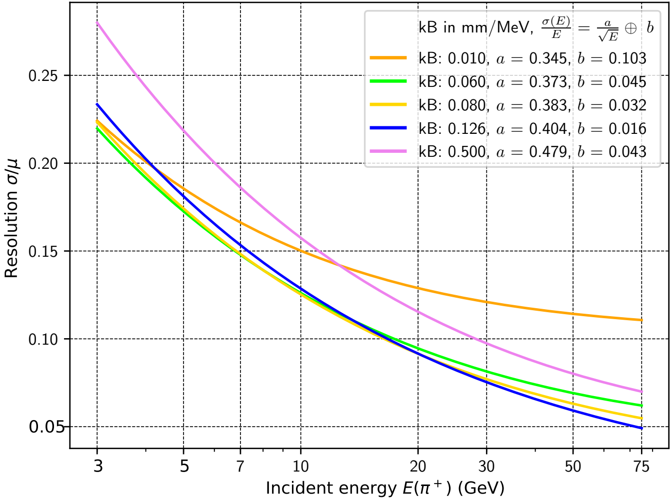
Hadron energy resolution for lead - scintillator

- Samples of 12 000 π^+ events at each incident energy
- Deposited energy is taken as EM + HAD
- Gaussian fit to deposited energy is done at each incident energy to get σ and $\langle E \rangle$
- The resolution is ratio $\sigma / \langle E \rangle$
- Fit is close to NIM results, constant term is consistent with zero at 2σ



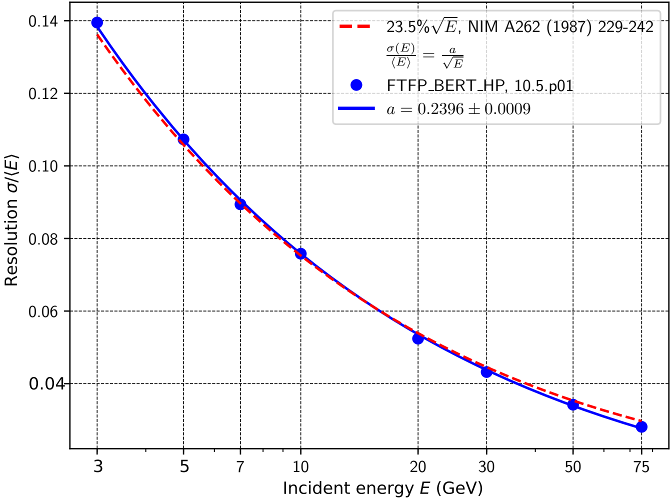
Effect of Birks coefficient to hadron resolution for lead - scintillator

- Each curve is Geant result for a given kB
- All other conditions remained the same
- The default value of 0.126 mm/MeV minimizes the constant term, it becomes higher for all other choices



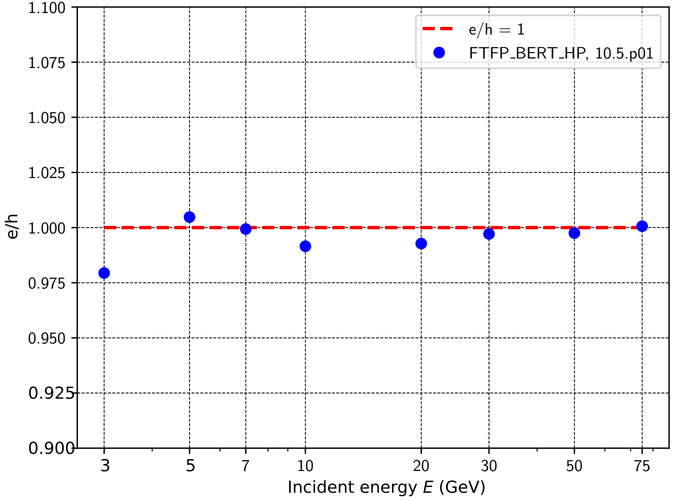
Electron energy resolution for lead - scintillator

- Procedure for energy resolution for π^+ is repeated here for electrons
- No constant term, exact match to NIM results



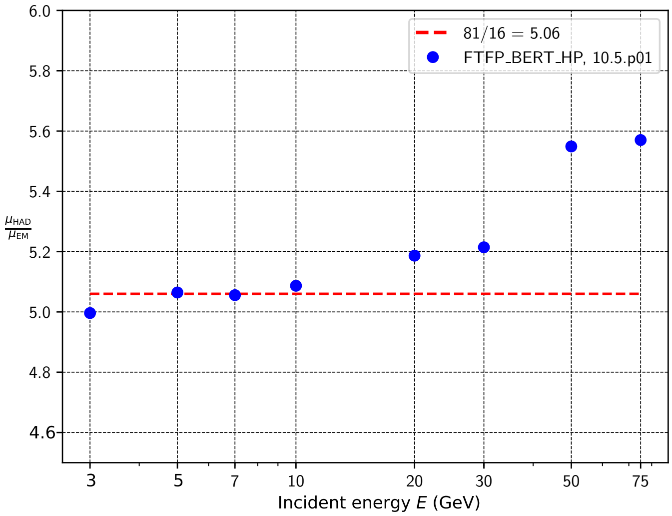
Electron/hadron ratio for lead - scintillator

- Ratio of mean deposited energy for electrons and pions at each incident energy
- Consistent with 1, showing an exact compensation
- Compensation of $e/h = 1.05 \pm 0.04$ for $E > 10$ GeV was measured in NIM beam test



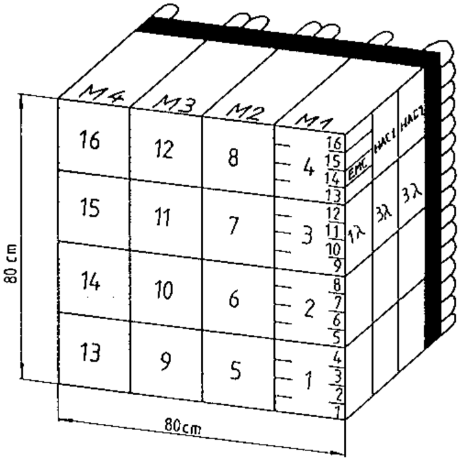
Muon signal in HAD and EM sections for lead - scintillator

- Mean deposited energy for muons in EM and HAD sections
- Ratio HAD/EM scales by number of layers (81 in HAD and 16 in EM section) at lower energies and gets larger at higher energies
- Same observation is shown in NIM



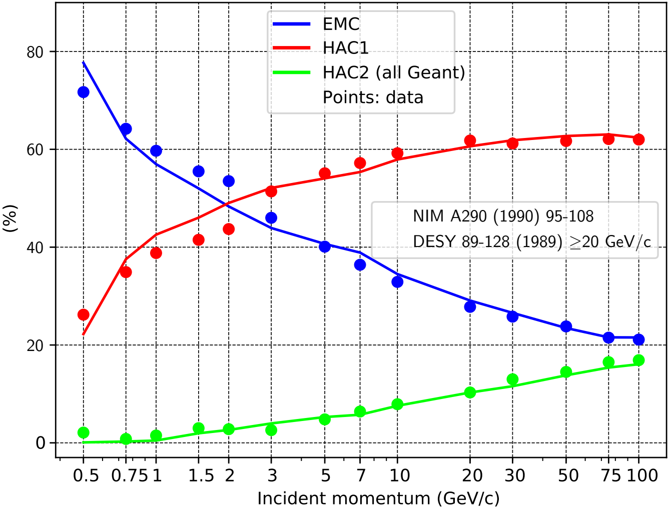
Depleted uranium (DU) - scintillator setup from ZEUS

- Layers of 3.3 mm DU layers with stainless steel cladding and 2.6 mm plastic scintillators in 4 mm free space
- Construction and test beam data are in NIM A290 (1990) 95-108, and DESY 89-128 (1989)
- Geant model implements the DU isotopic composition and cladding as in NIM
- Individual EMC, HAC1 and HAC2 sections have separate readout
- Number of layers in EMC is 25, HAC1 and HAC2 have 80 layers each
- Transverse segmentation to modules 1–16 is neglected in the model, each layer stands for all modules



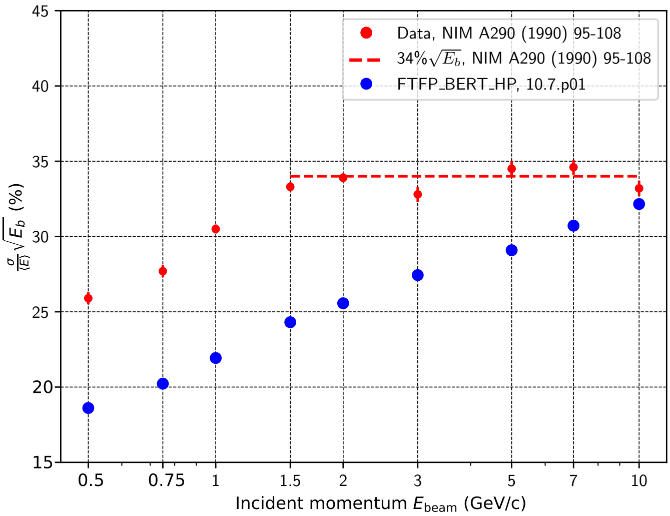
Energy deposition in individual sections for DU - scintillator

- Fraction of deposited energy in each section
- Samples of 12 000 π^+ at each incident momentum
- Lines connect Geant results taken at each energy as it is in the data



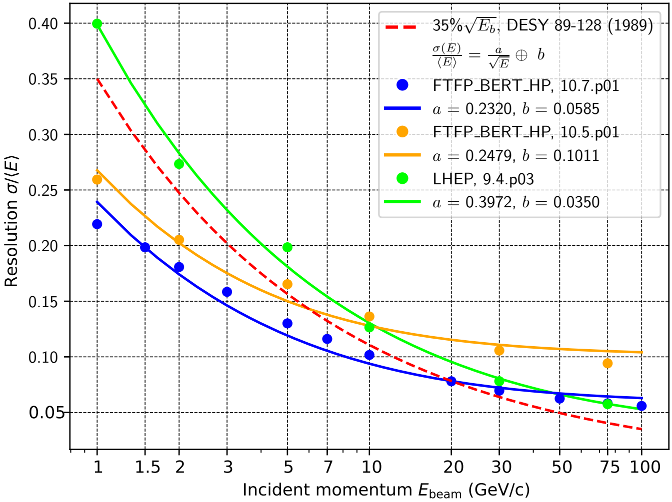
Hadron energy resolution at low momenta for DU - scintillator

- Deposited energy is added from individual sections, EM + HAC1 + HAC2
- Energy resolution is determined the same way as for lead - scintillator case
- The data show only stochastic term at momenta beyond 1.5 GeV/c
- Not reproduced by Geant results



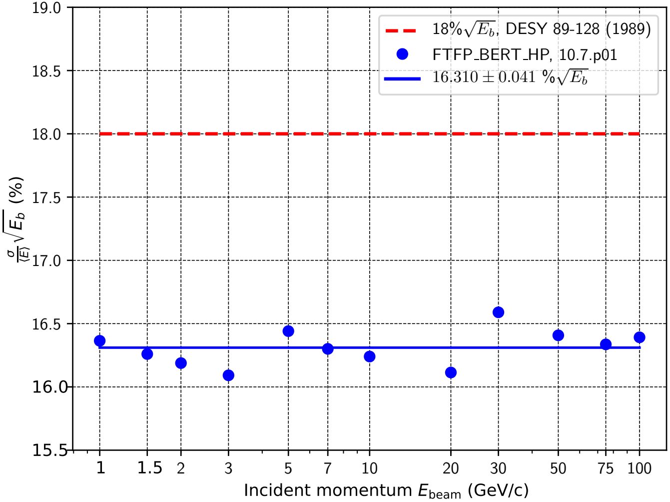
Hadron energy resolution at high momenta for DU - scintillator

- Comparison to fit to the data at higher incident momenta
- FTFP_BERT_HP for two Geant versions and LHEP
- 10.7.p01 (very latest) has new data neutron library based on JEFF-3.3 and contains transuranic elements, recommended by Geant4 group
- Improvement is seen with 10.7.p01 compared to older 10.5.p01, but the change in neutron data does not account for all effects
- LHEP parametrizations approximately follow the data



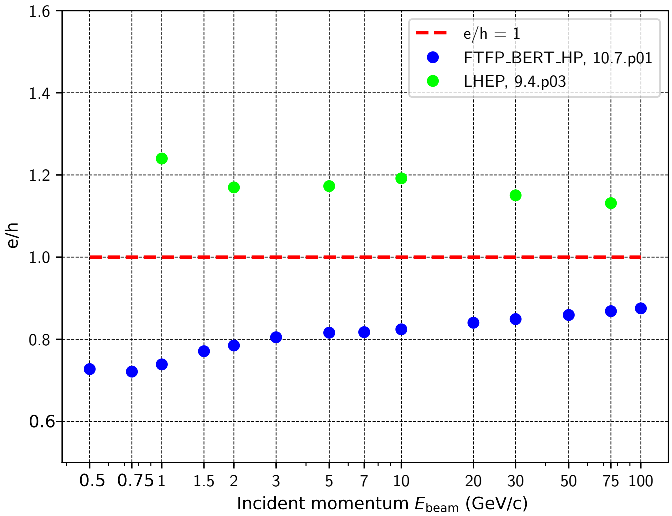
Electron energy resolution for DU - scintillator

- No constant term, stochastic term is below the data



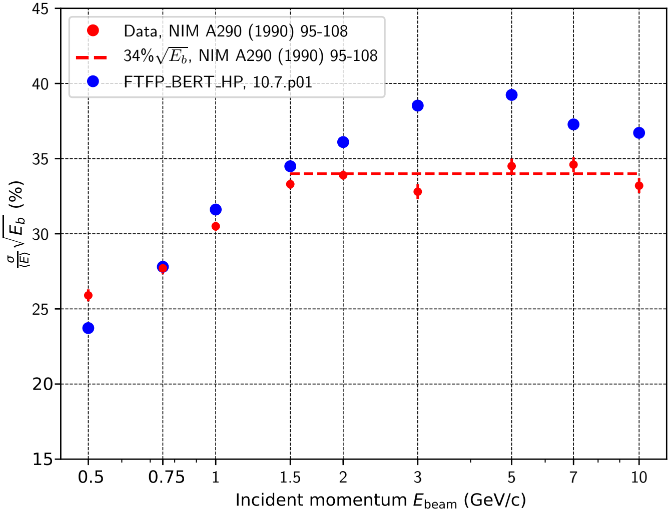
Electron/hadron ratio for DU - scintillator

- Comparison between 10.7.p01 (new neutron data) and LHEP
- Beam test data show compensation at $e/h \approx 1$ beyond 3 GeV
- Approximately constant trend with incident momentum but not near 1



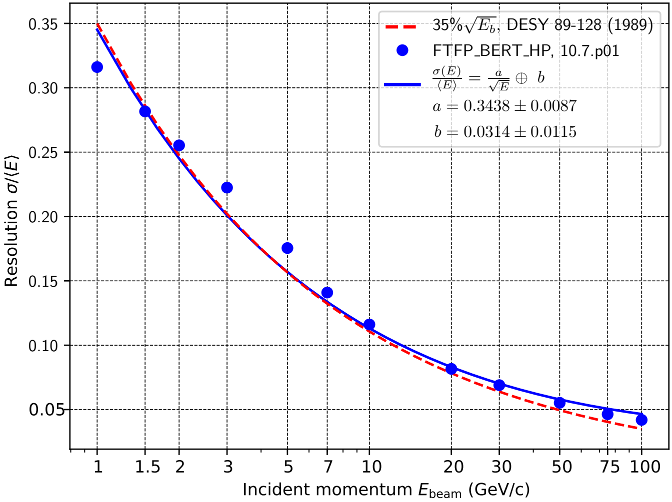
Pb absorbers instead of DU in model of DU - scintillator, hadron energy resolution

- Absorber layers of DU with cladding were replaced by 10 mm Pb
- All Geant codes and analysis macros for DU - scintillator model remain the same
- Geant results are much closer to the data
- Vanishing constant term is seen at larger incident momenta



Pb absorbers instead of DU in model of DU - scintillator, hadron energy resolution at high energies

- Resolution at higher momenta when DU + cladding absorbers were replaced by 10 mm Pb
- All Geant codes and analysis macros for DU - scintillator model remain the same
- Almost identical description to the data



Intermediate summary

- Good description was achieved to lead - scintillator data
- New neutron data in version 10.7.p01 were suggested by Geant4 group
- Despite some improvement the 10.7.p01 does not account for all effects in DU - scintillator description
- Cross-checks were done by variations in cladding material, Birks coefficient and integration time with no significant difference to the results presented here
- Original simulations for ZEUS were done with effective corrections to GEANT in DESY-95-005 and with CALOR89 package in NIM A349 (1994) 106-111
- Data from ZEUS beam tests are a good source to validate Geant and analysis codes

EIC configuration with W/ScFi and Fe/Sc

- EM part is W/ScFi of 18 X_0
- Hadron part (HAD) is Fe/Sc of 20 mm Fe and 3 mm plastic scintillator layers
- The Fe/Sc part has 51 layers for 6 λ_I
- Front size is 800×800 mm^2
- Primary particles are generated at 3° along x and 1° along y, in the front middle of W/ScFi part

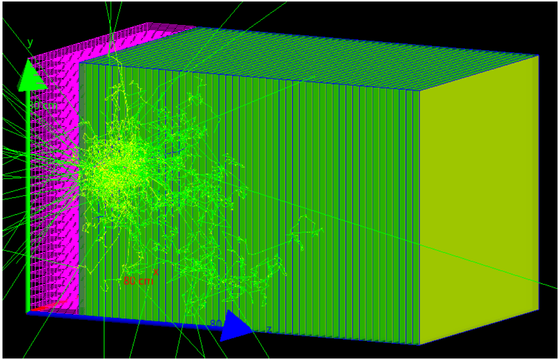
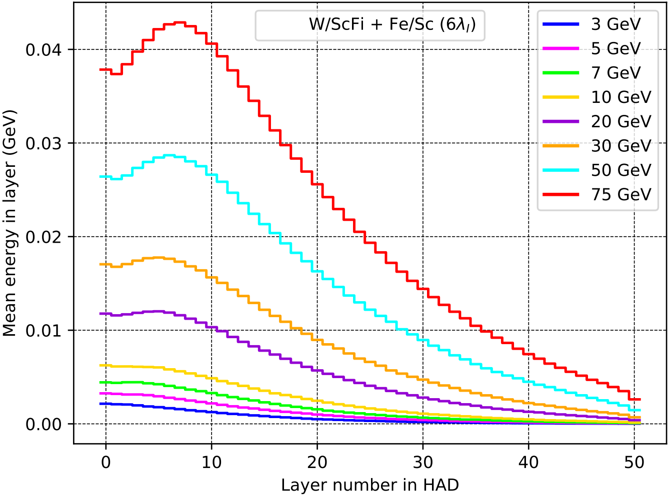


Figure: Event of π^+ at 20 GeV in EM (magenta) and HAD (green and yellow) parts

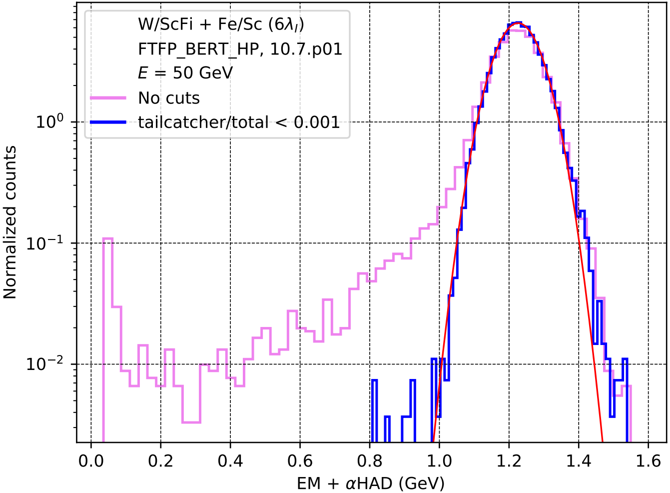
Shower profile in hadronic section in EIC configuration

- Mean deposited energy in individual Fe/Sc layers
- Set of incident π^+ energies
- Non-negligible leak only above 20 GeV (for 6 λ_I)



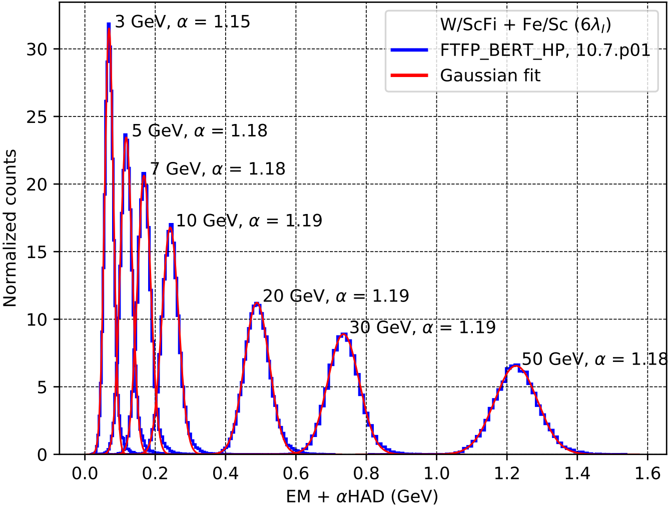
Effect of last three hadron layers as tail catcher

- Last three HAD layers will have independent readout (at least at high rapidities), called the *tail catcher*
- The plot shows deposited energy for π^+ at 50 GeV
- Upper limit on signal in tail catcher removes the non-Gaussian tail
- About 62% of events satisfy the cut



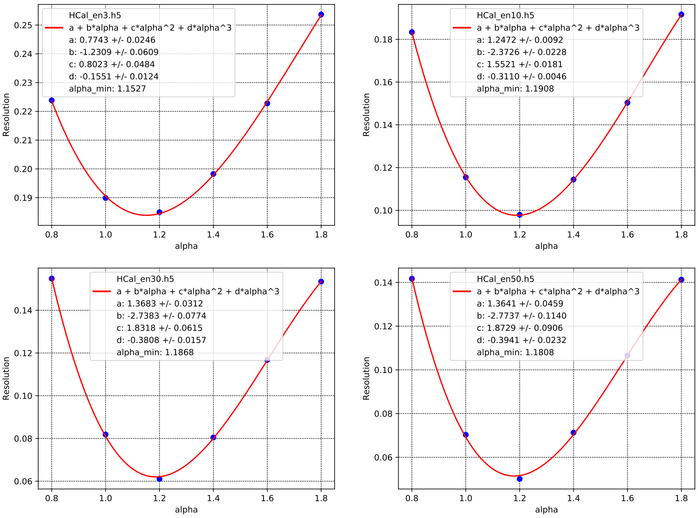
Signal response to $\pi+$ in EIC configuration

- Signal of energy deposition for a set of incident π^+ energies
- An upper limit on tail catcher is implemented
- Deposition from EM and HAD parts is added with a weight (or intercalibration) α
- Value of α is found my minimizing energy resolution as a function of α at each incident energy
- The α is constant from 5 GeV



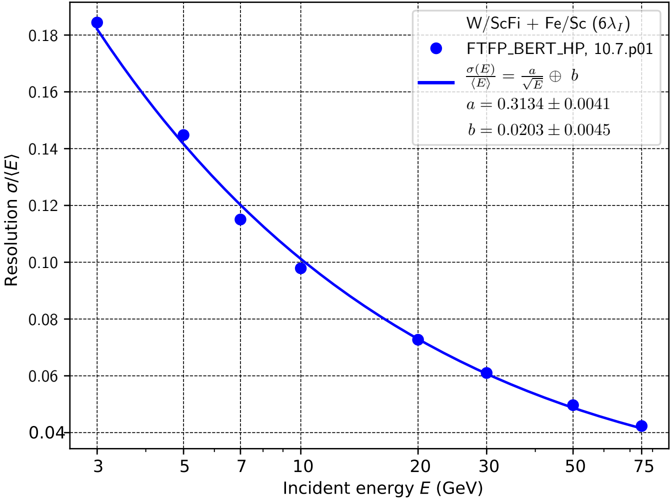
Weighting between electromagnetic and hadronic part

- Example plots for 3, 10, 30 and 50 GeV
- Energy resolution is evaluated for a set of α
- Fit is made by a cubic polynomial
- Value of α is found where the resolution has a minimum



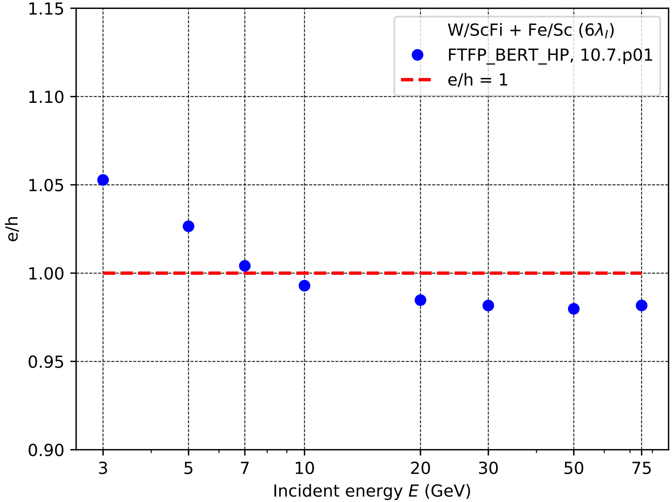
Hadron energy resolution for EIC configuration

- Following the same procedure as for ZEUS results
- Gaussian fit to α-weighted energy deposition, ratio of width to mean at each incident π^+ energy
- The result is about 30% stochastic term and a small constant term



Electron - hadron ratio for EIC configuration

- Mean response to electrons (e^+) and π^+, same procedure as for ZEUS results
- Compensation at about $e/h = 1$ can be achieved for W/ScFi + Fe/Sc



Summary

- Geant models and analysis codes were developed with ZEUS data
- We can have a compensated system of W/ScFi + Fe/Sc for hadron endcap
- Hadron resolution to a single particle is about 30% stochastic with a small constant term
- Working on DD4hep implementation
- Geant model for lead - scintillator and Fe/Sc is github.com/adamjaro/lmon/blob/master/calo/src/HcalA262.cxx
- Model for W/ScFi is github.com/adamjaro/lmon/blob/master/calo/src/WScFiZXv3.cxx
- Macros to submit the production are in `/eic/u/jadam/sim/hcal/macro/productions/hcal3e/`
- Analysis macro for EIC results is github.com/adamjaro/lmon/blob/master/calo/macro/HcalA262/plots_alpha.py