FASER's Electromagnetic Calorimeter Test Beam Studies

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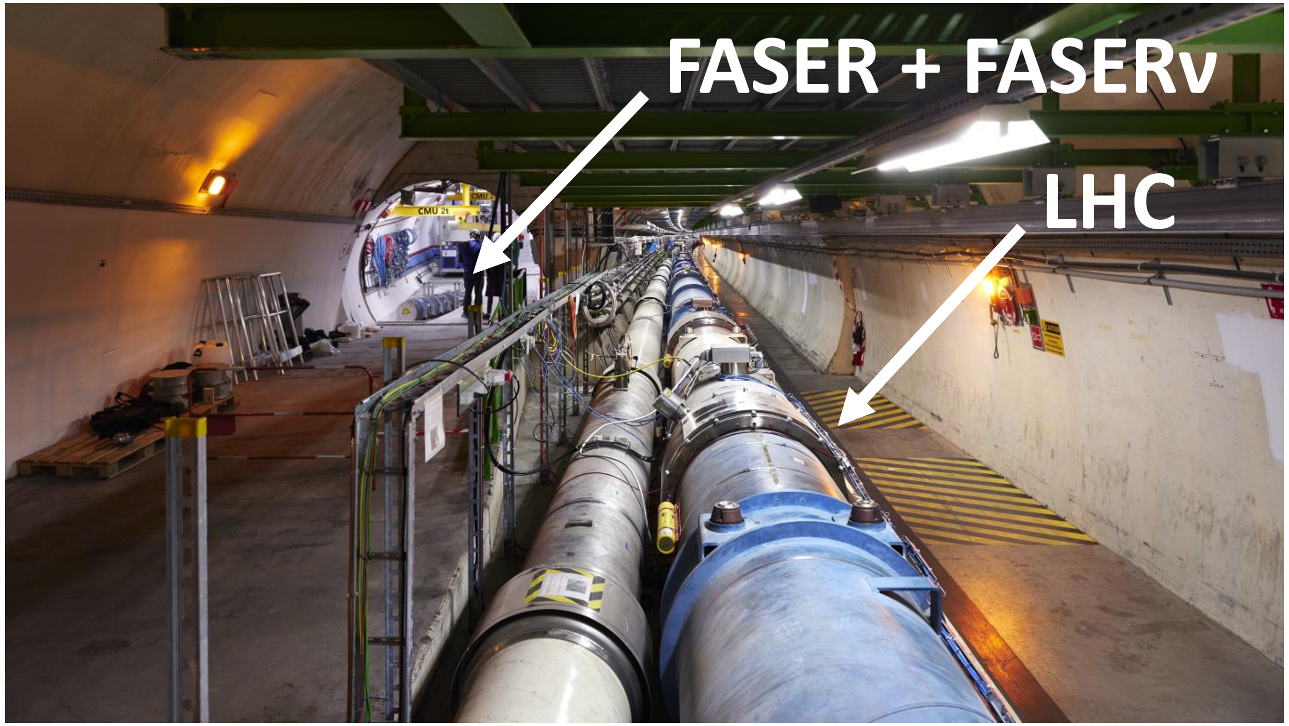
Introduction

There are many pieces of evidence to suggest new physics beyond the Standard Model

For example, the possible existence of Dark Sectors which may contain new, light, weakly-coupled particles that interact only very weakly with ordinary matter

FASER is a new experiment designed to detect potentially long-lived particles (LLPs) produced at the ATLAS Interaction Point in the forward region

- These particles are highly collimated
- LLP decay products have ~ TeV energies



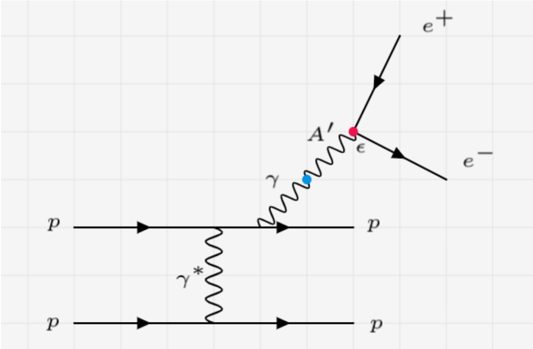
FASERν, an emulsion detector in front of FASER, is designed to directly detect collider neutrinos for the first time.

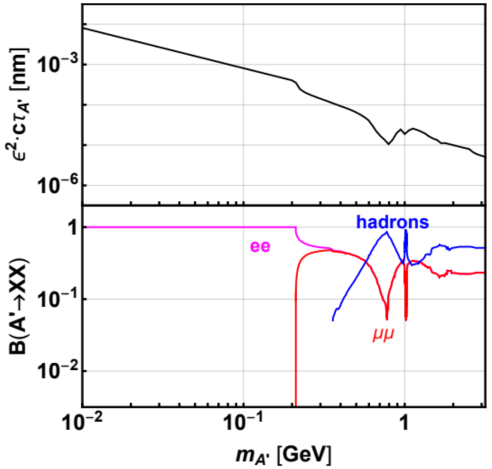
Signal and Sensitivity

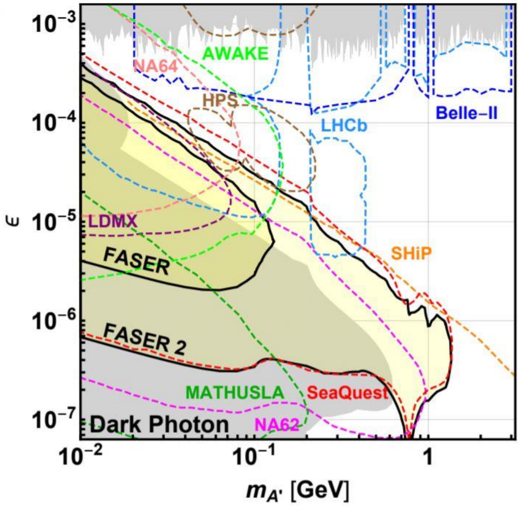
- The physics models targeted by FASER are characterised by the presence of LLPs such as Dark Photons and ALPs

$$pp \to \mathrm{LLP} + X, \quad \mathrm{LLP\ travels} \ \sim 480\ \mathrm{m}, \quad \mathrm{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots$$

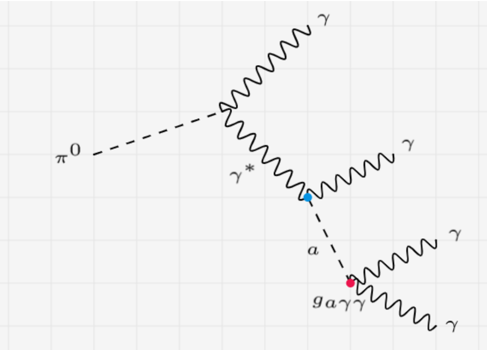
Dark Photon (A') production and decay:

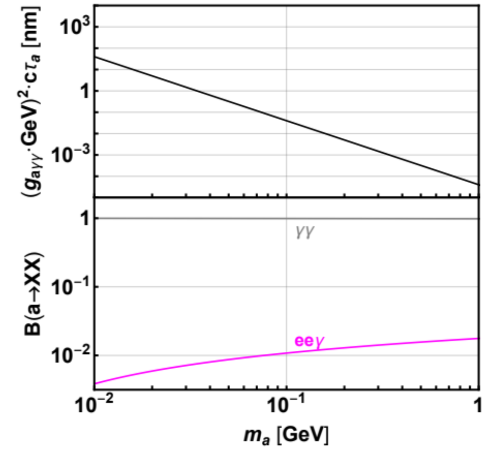


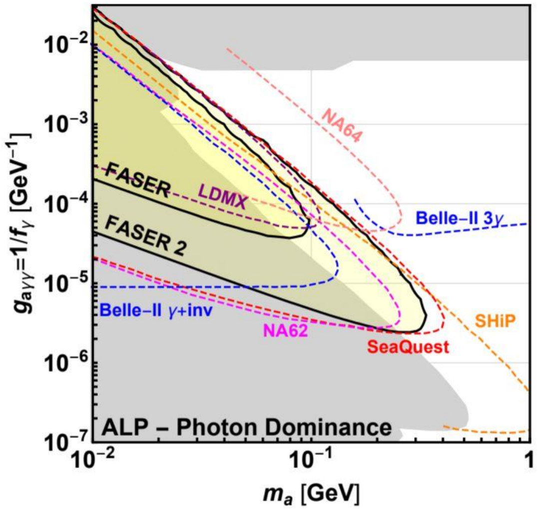




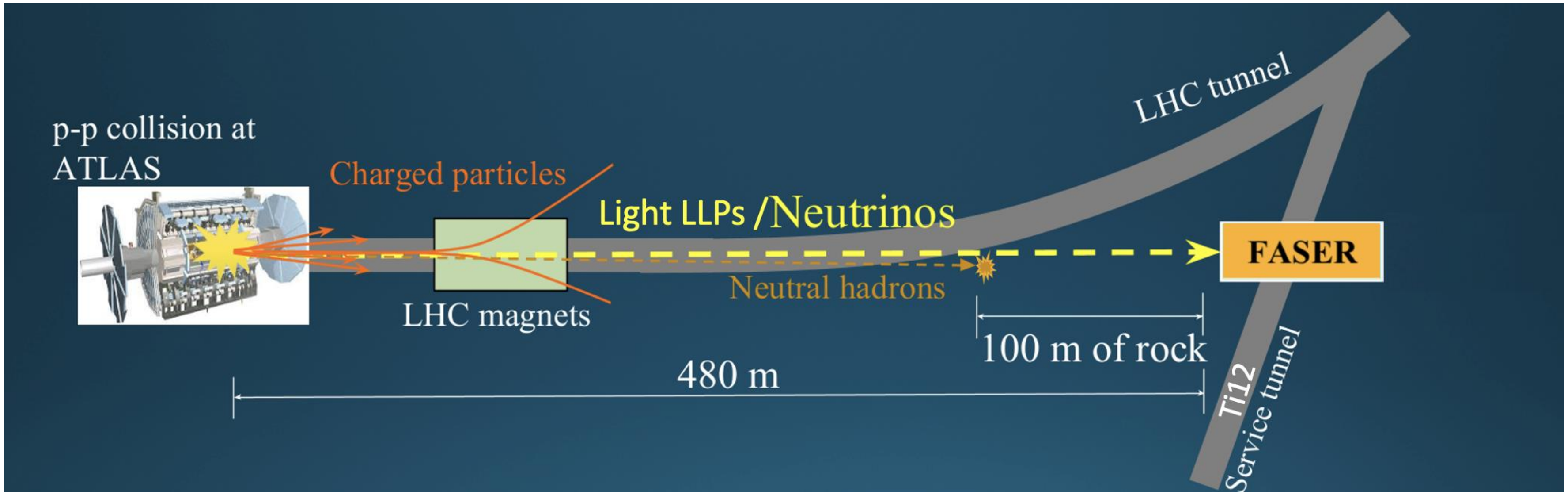
ALP (a) production and decay:



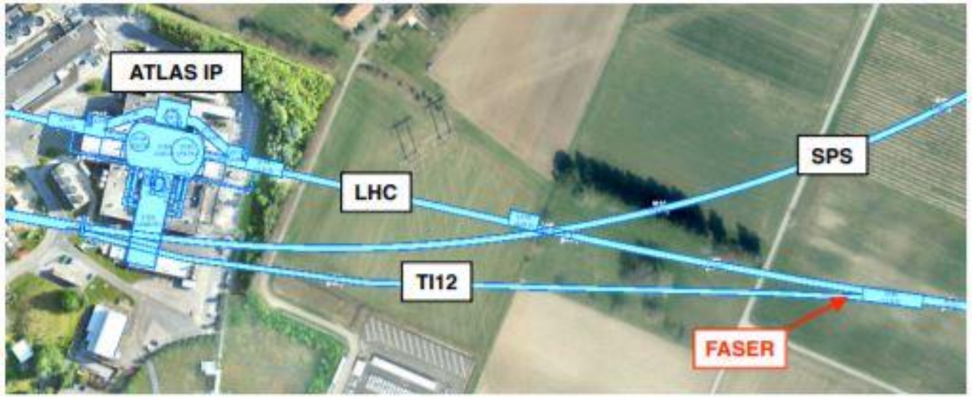




Location



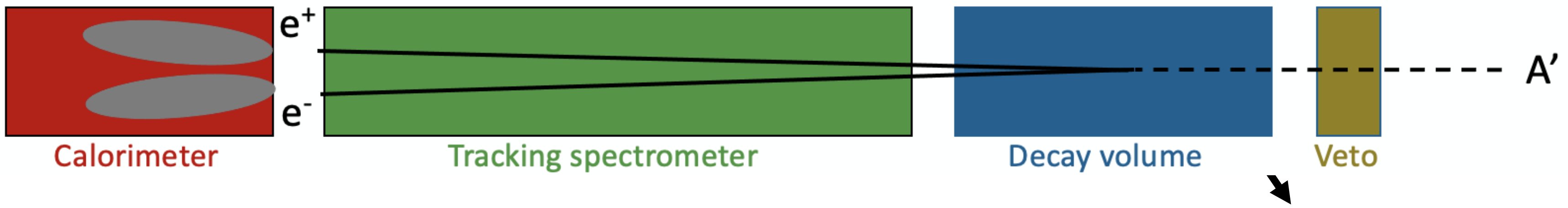
p-p collision at ATLAS
Charged particles
Light LLPs /Neutrinos
LHC tunnel
FASER
Neutral hadrons
LHC magnets
100 m of rock
480 m
Ti12
Service tunnel

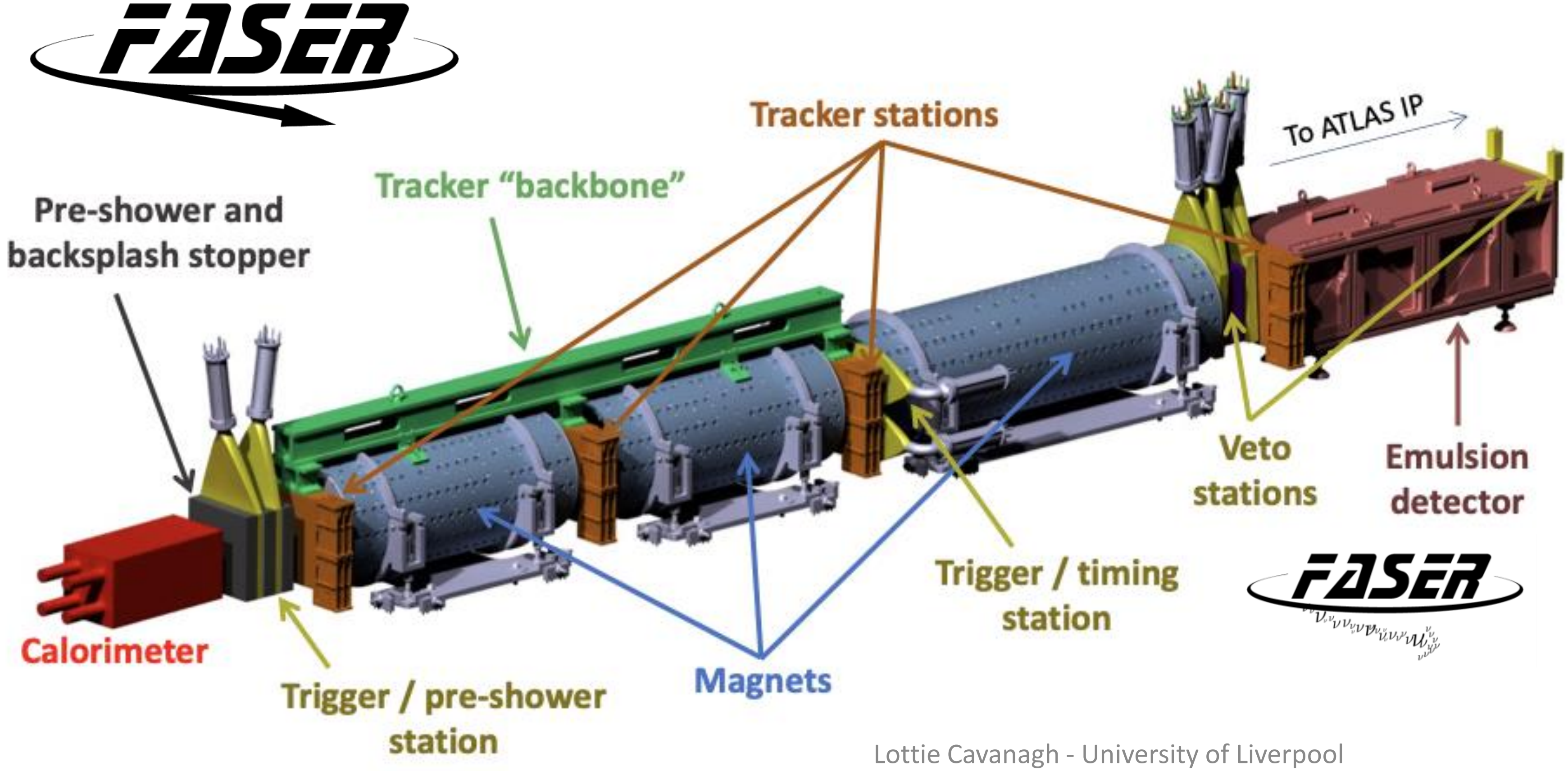


ATLAS IP
LHC
SPS
TI12
FASER

CMU 2t
CMU 2t
2t

The detector in TI12





Tracking Stations:
- each made up of layers of silicon strip detectors
- measures momentum
- uses ATLAS SCT modules

Dipole magnets:
- 0.6T with 10cm radius
- acts as the decay volume
- separates particle tracks
- includes spectrometer

Scintillators:
- to veto charged particles
- used for triggering and time measurements
- PID studies

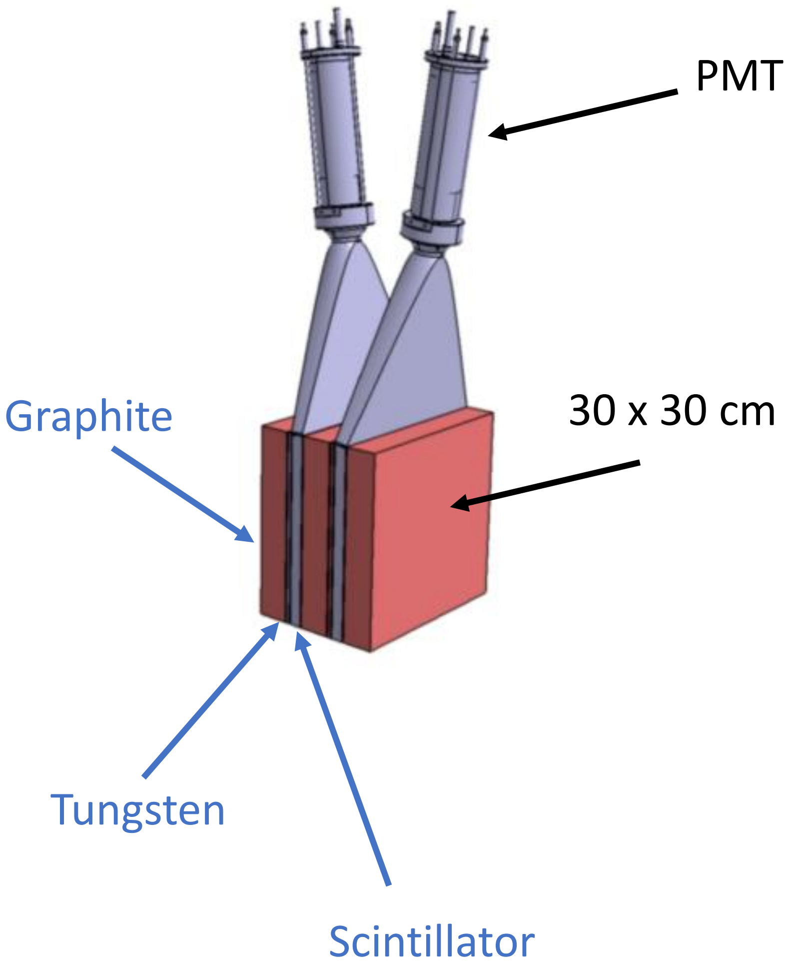
Calorimeter:
- sampling EM calorimeter
- measures deposited energy
- uses 4 LHCb ECAL modules

FASER’s Preshower Station

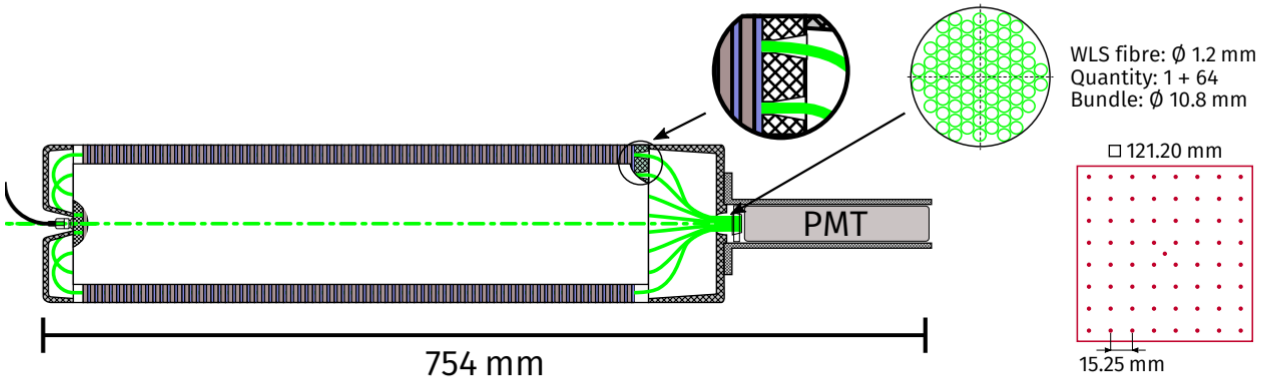
The preshower is composed of 2 scintillator stations, each readout by a single PMT

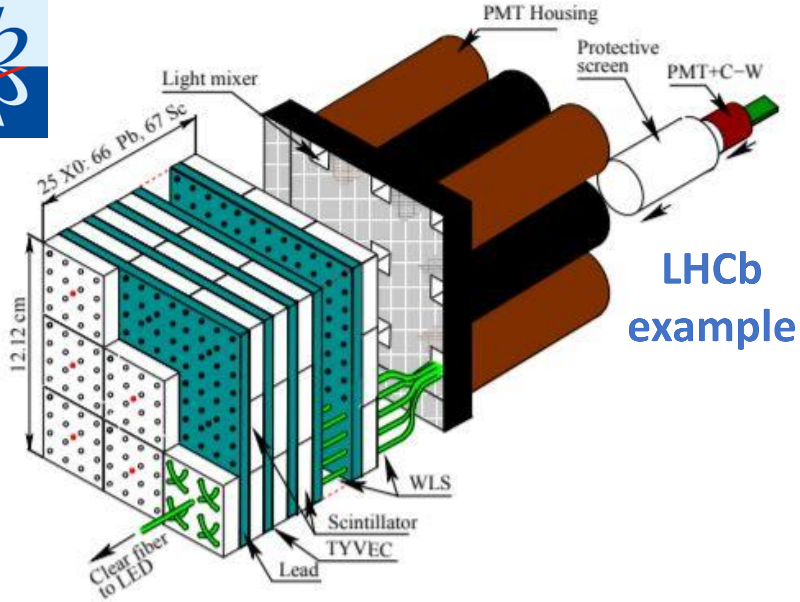
- Each scintillator is proceeded by 3 mm radiator (tungsten) layer ~ 2 radiation lengths
- In front of each layer of tungsten, and at the rear of the preshower (before calorimeter), is ~ 5 cm graphite block to reduce backsplash

PMT module provides readout pulses



FASER's ECAL Modules





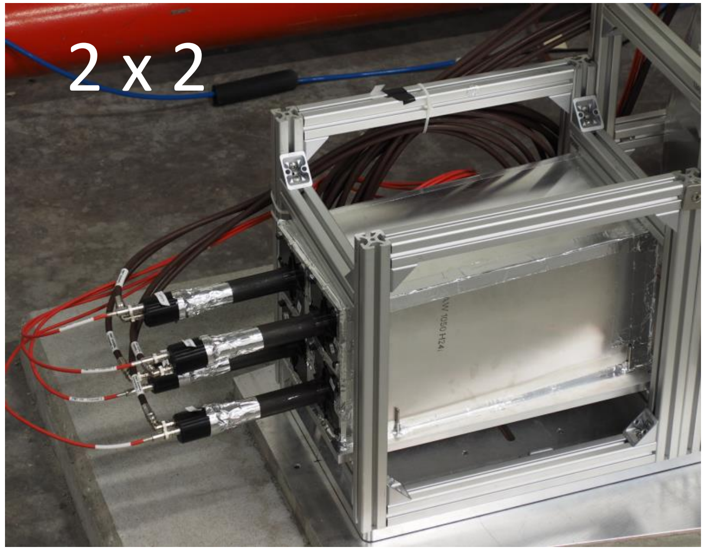
LHCb example

Shashlik-type calorimeters with interleaved plastic scintillator and lead plates

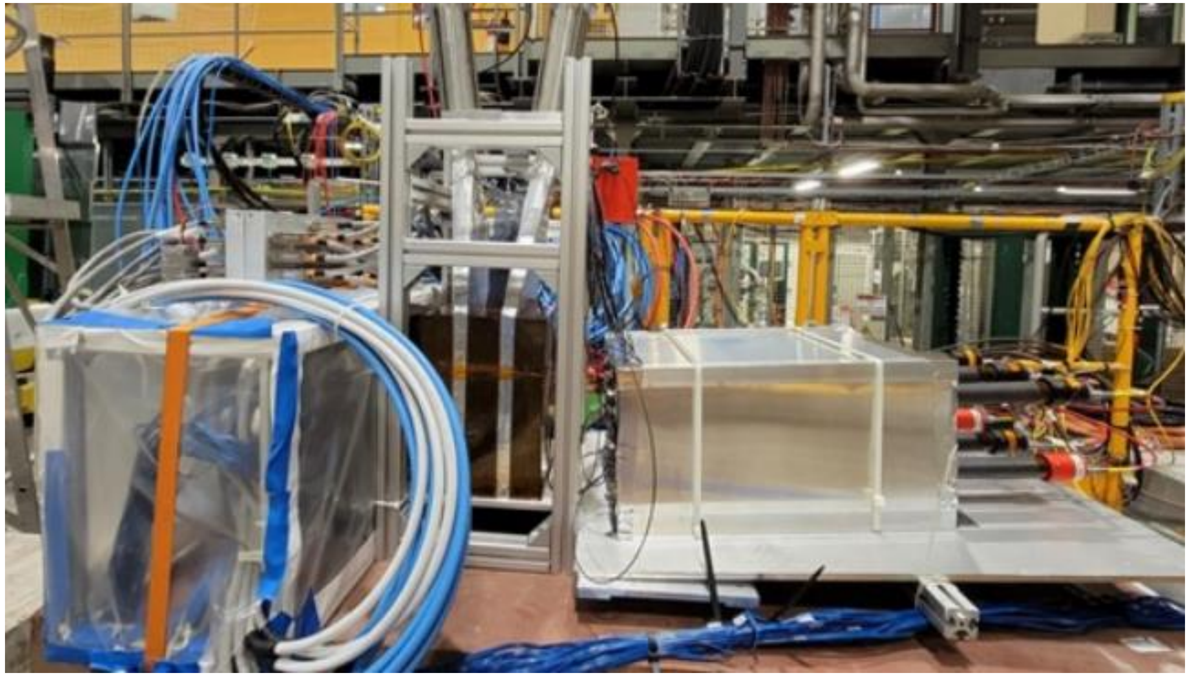
- Each module contains 66 layers of 2 mm lead and 4 mm plastic scintillator
- Total depth of 25 radiation lengths
- Includes a layer of TYVEK paper between lead and scintillator

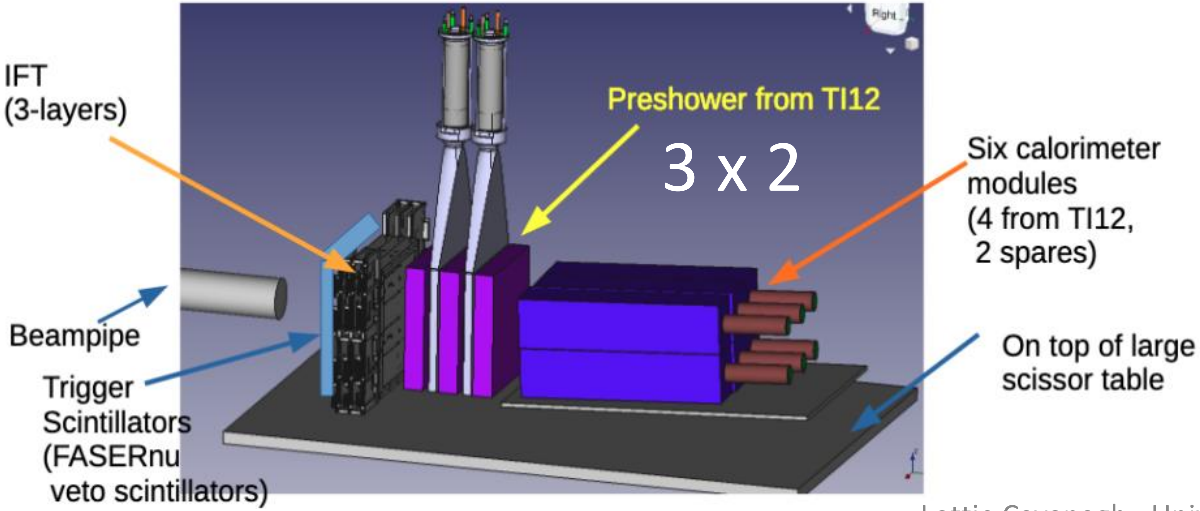
PMT module provides readout pulses

A 10 dynode-stage head-on PMT with a cathode diameter of 22 mm



The 2021 FASER Calorimeter Test Beam





CERN H2 beam line 28th July – 4th August 2021

The aims of the test beam were to:

- Calibrate the calorimeter and preshower modules
- Study electron response
- Perform muon response to study uniformity of MIP response
- Perform pion scan to study hadronic response

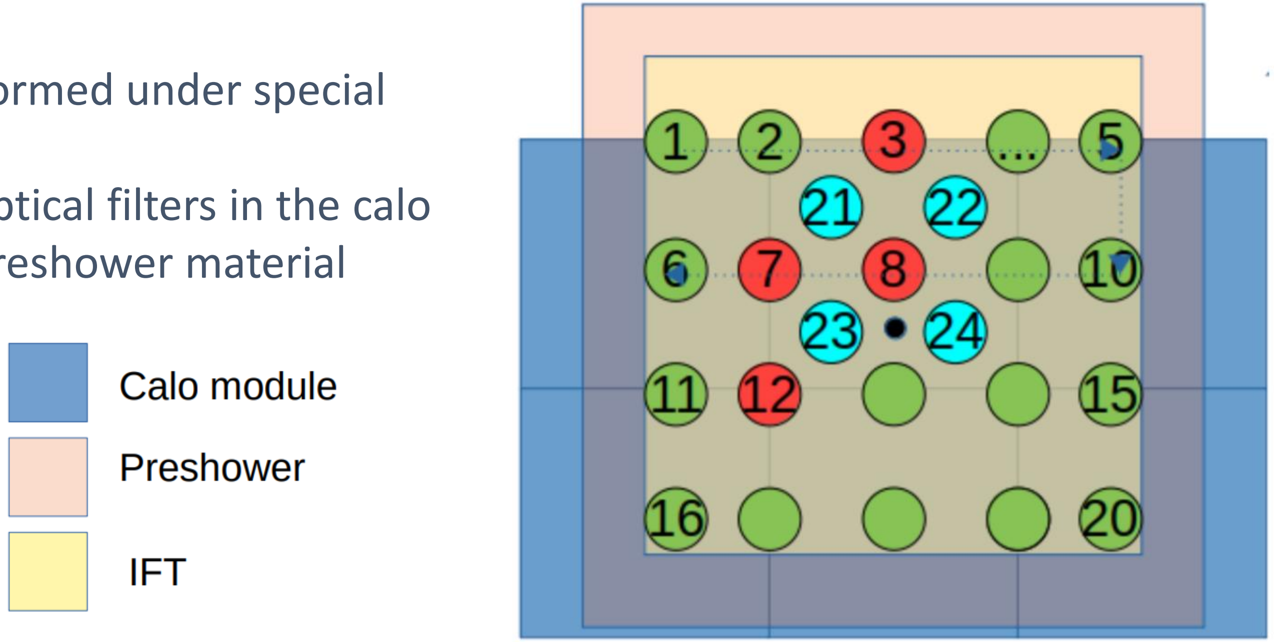
Secondary goal: operation and performance measurement of interface tracker (IFT) station in actual beam conditions

Test Beam Overview

Over 150 million events (1.8 TB) recorded, scanning through 24 spatial points across 6 ECAL modules

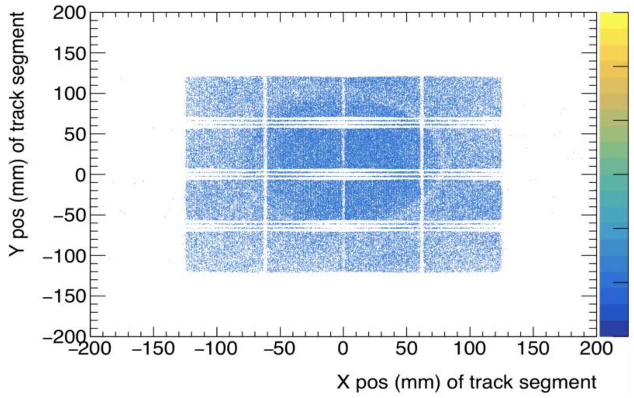
- Electron, μ-, π- beams at different energies and settings
- Low, medium and high calo PMT gain settings
  - Gain offsets: 0 V – 500 V in 50 V steps

Some runs were performed under special conditions:
- Removal of optical filters in the calo
- Removal of preshower material



Electron beam
- 12 energies: 5 – 300 GeV
- Primarily used 30, 75 and 200 GeV

Muon beam
- 200 GeV
- Large beam size (> 5 cm)



Pion beam
- 200 GeV
- Study hadronic response

Test Beam Reconstruction

- The raw data is reconstructed to produce the xAOD analysis format
- **FASER**'s Calypso analysis framework is based on **Gaudi** and **Athena**

Steps:

PMT modules provide a readout signal in the form of PMT pulses

- signal must pass a certain threshold

Subtract baseline rms threshold from PMT signal

Invert and fit the distribution with a crystal ball

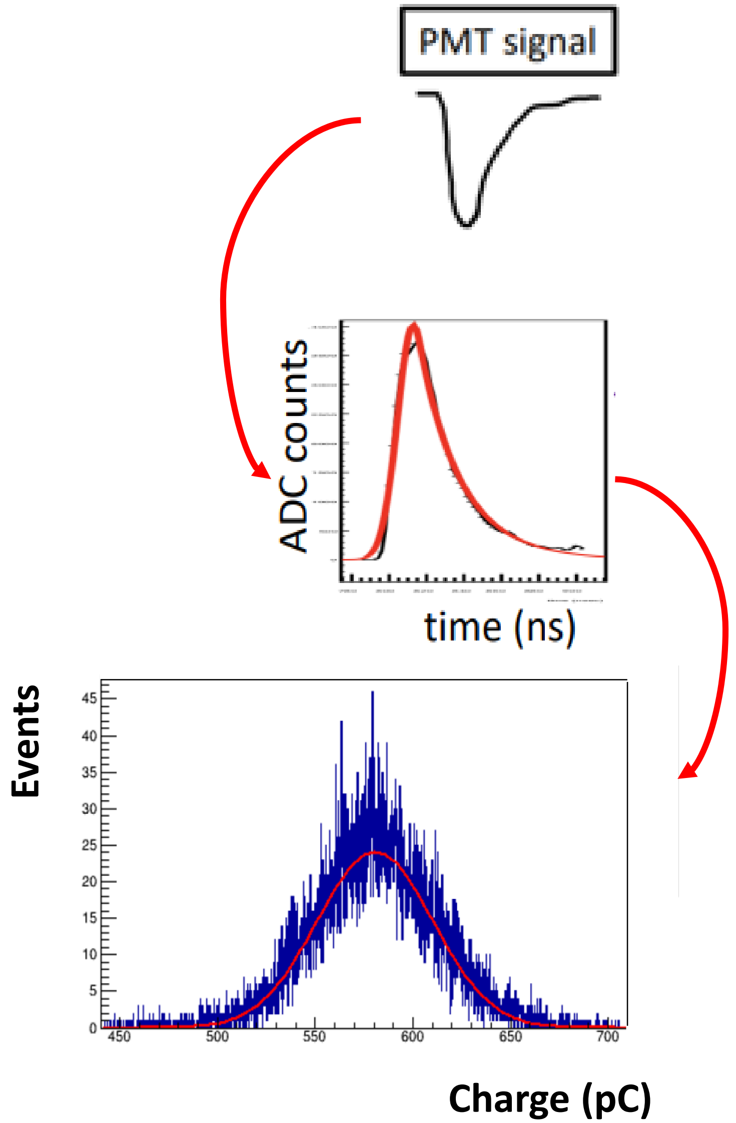
Get the integral and convert ADC counts to deposited charge

- we recorded the full waveforms of all pulses at 500 Hz with 14-bit ADCs

Apply an event selection

- position and angle cuts

Response can be normalised by dividing by beam energy



Test Beam Data: Energy Resolution

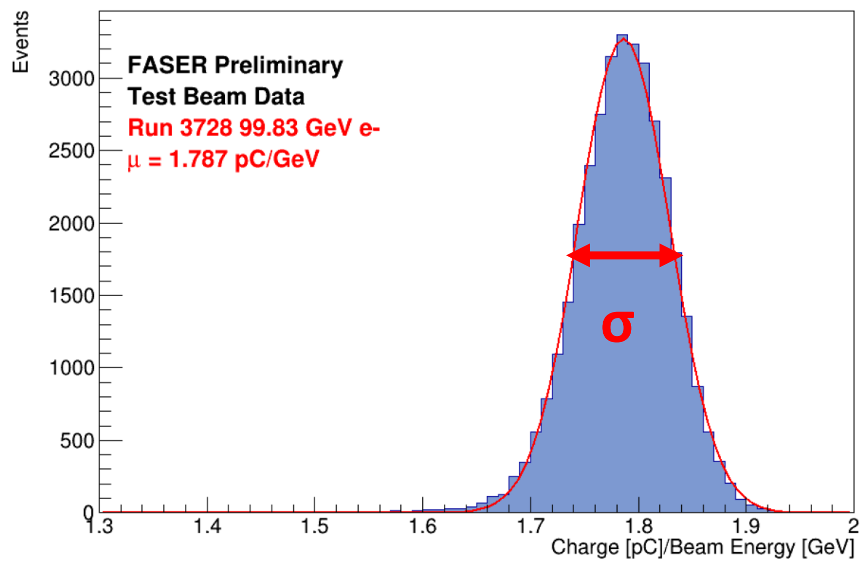
$$\sigma_E / E = a/\sqrt{E} \oplus b/E \oplus c$$

Stochastic Term – due to fluctuations related to the physical development of the particle shower

Noise Term – due to electronic noise of the readout chain

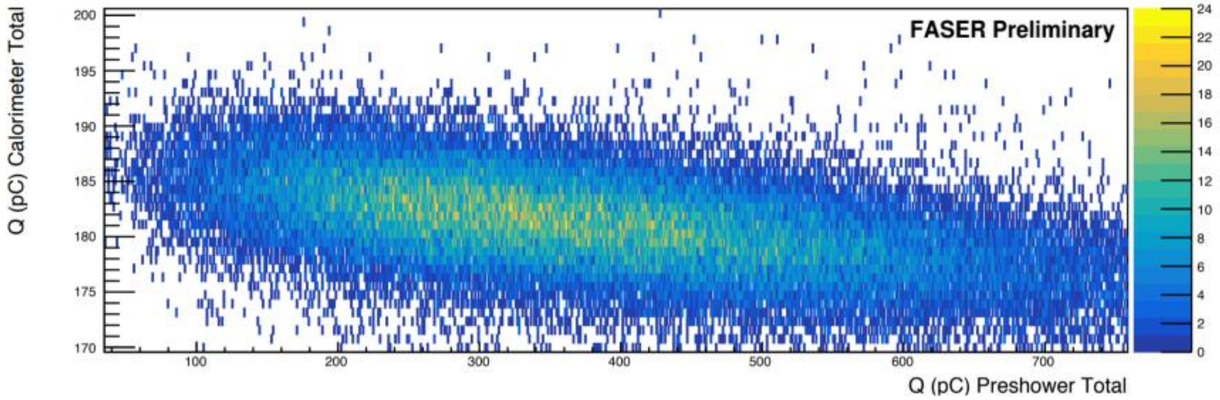
Constant Term – due to imperfections and non-uniformity in detector response

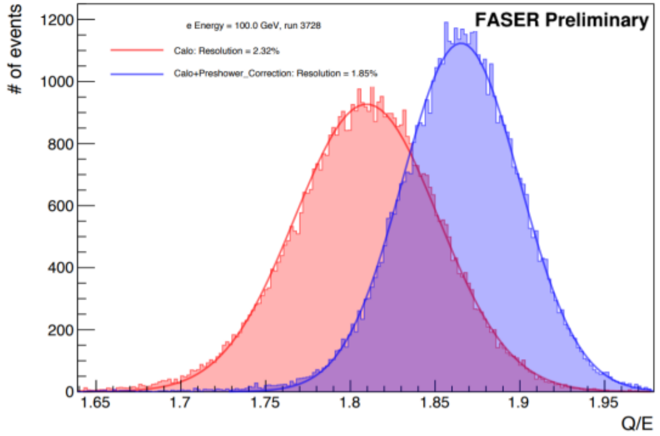
Charge deposited in the calorimeter:



- Fit distribution with a crystal ball or Gaussian to extract resolution

Preshower Correction



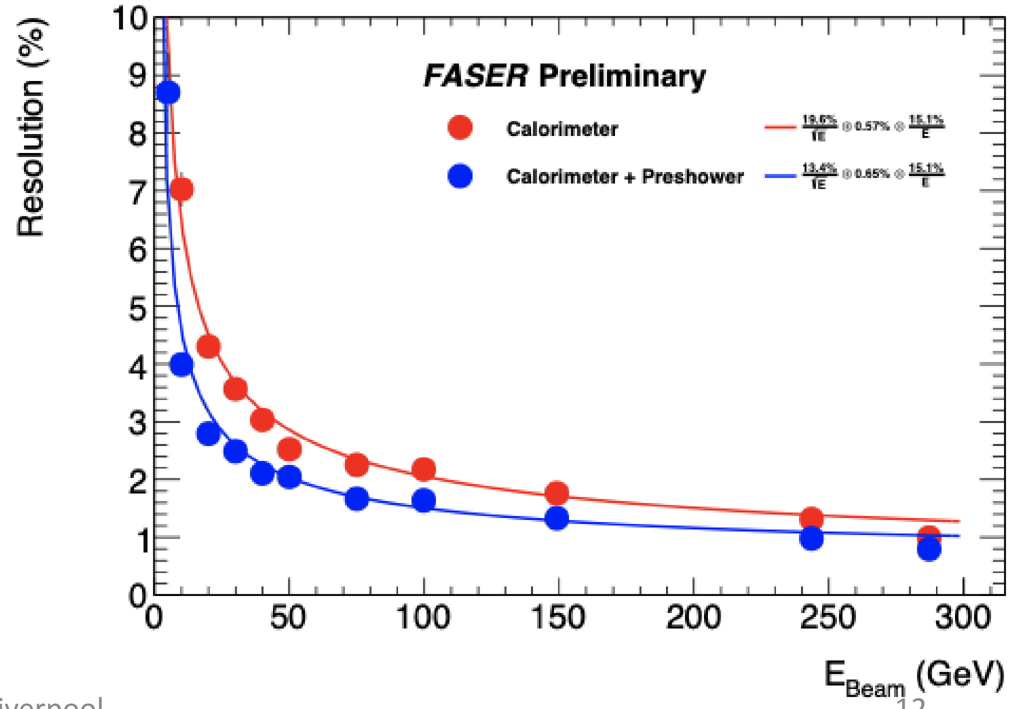


Preshower correction

m = slope of $Q_{preshower}$ vs Q_{calo} plot

$$Q_{corrected} = Q_{calo} + m * Q_{preshower}$$

- The preshower steals a portion of the EM shower from the calorimeter
- This needs to corrected for
  - An event by event correction that improves resolution



Now that we've looked at data, we need to study the response in simulation!

Test Beam Simulation

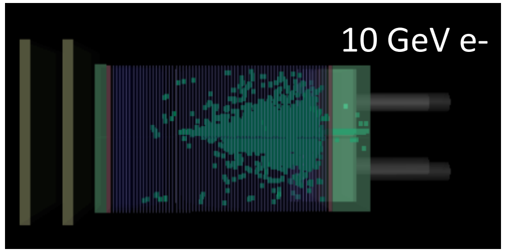
Simulation is based on the Geant4 package

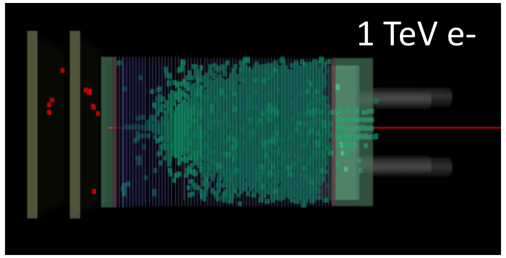
- Includes detailed description of the detector geometry
- Event display based on **ATLAS** VP1 software

Before we were able to validate with our own test beam results, the simulation was based on **LHCb** test beam results – since we use their ECAL modules

A dedicated framework was developed for the test beam simulation

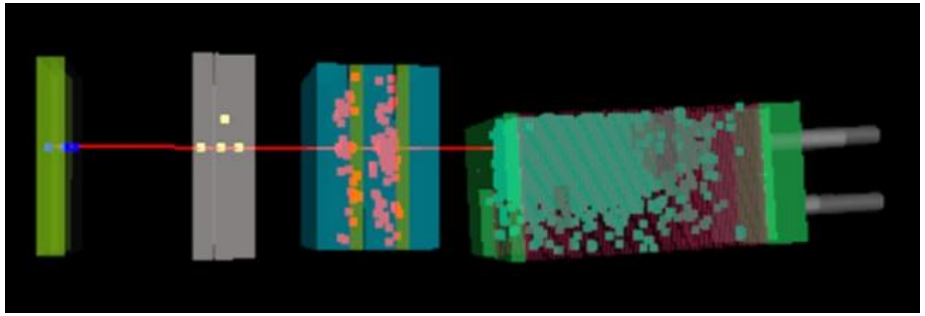
So far more than 2 million events have been simulated in the test beam geometry that mimic test beam runs





Comparison between data and simulation:

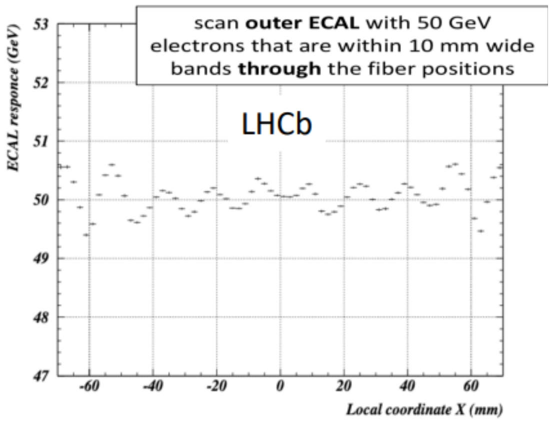
- We do not expect 100% agreement between MC and data
- Currently implementing the digitization based on the waveforms measured in the test beam
- Digitization not yet applied, simulation gives the energy directly from Geant4
- There are several effects that have not been implemented in simulation yet, although their impact is expected to be secondary

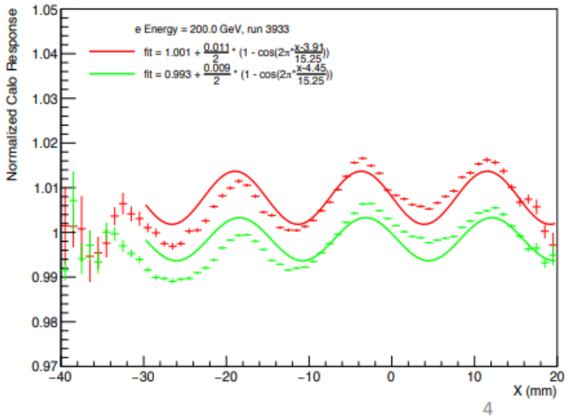


Calorimeter Studies: Local Effects

WLS Fibre effects

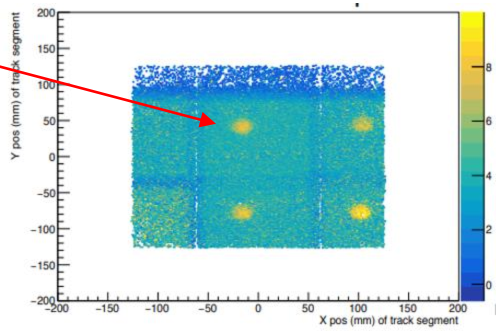
- Light collection improves when near a fibre
    - This effect is at a similar scale to what LHCb saw in their studies
- **Not currently implemented in simulation**
    - Can now adjust this in simulation based on measurements in data

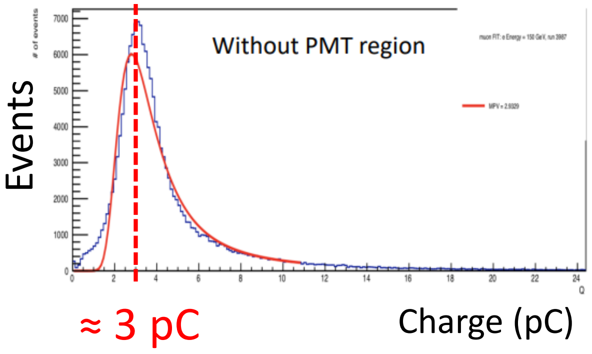


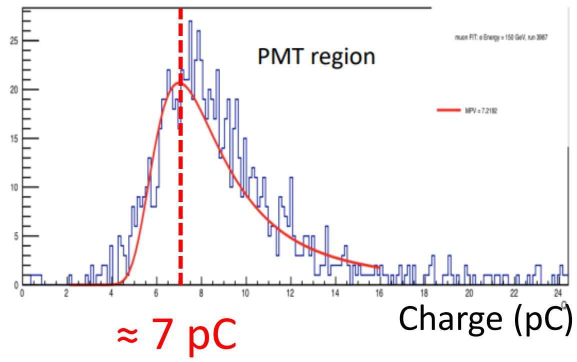


MIP deposited charge in PMT region of calo

- More charge collected when a MIP goes through a PMT
    - This has a large effect
- **Not currently implemented in the simulation**







These are secondary effects

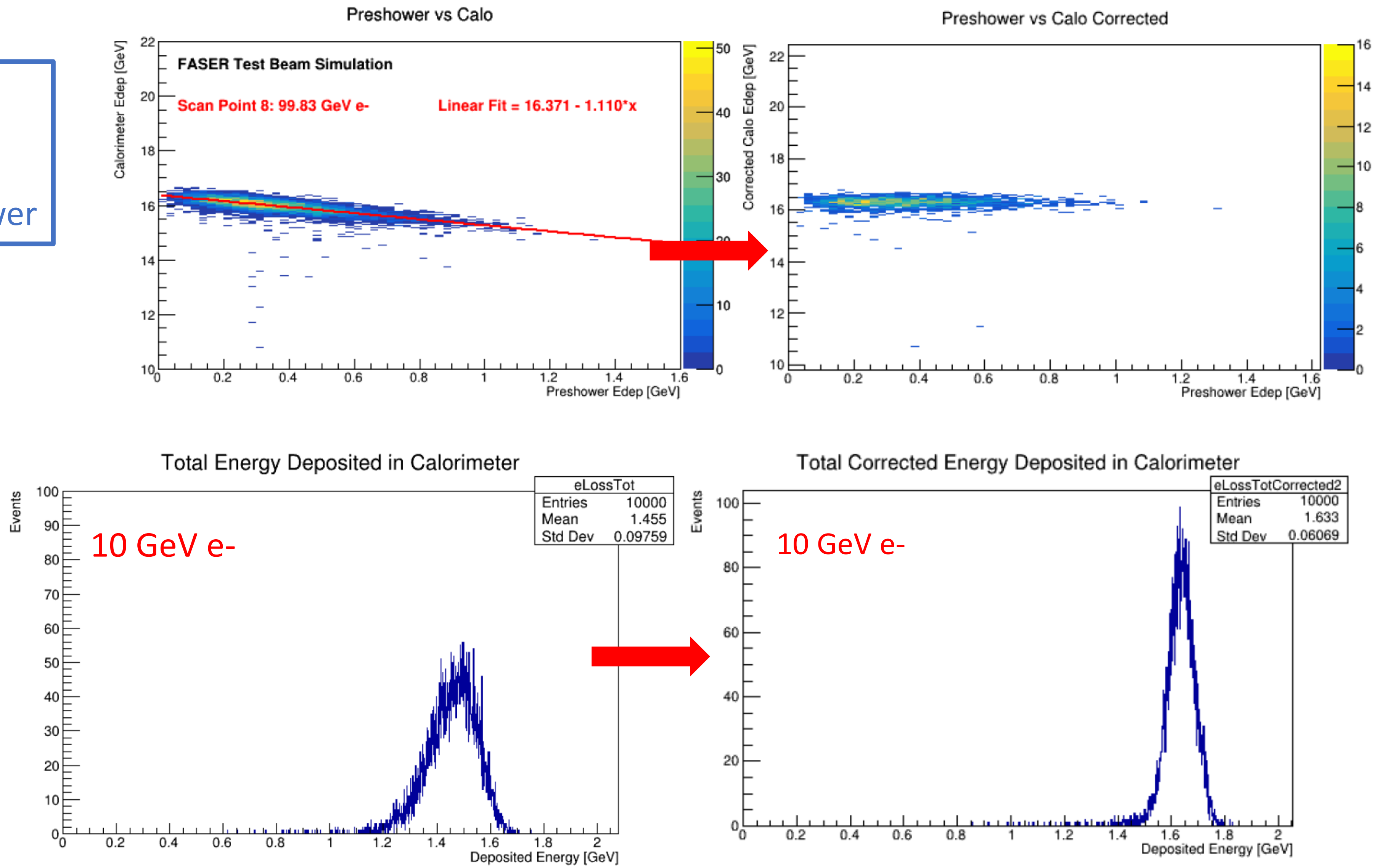
Test Beam Simulation: Preshower Correction

Preshower correction

m = -1.11

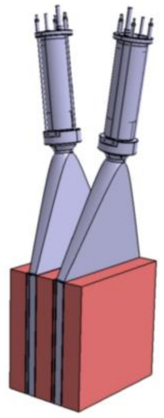
Ecorrected = Ecalo + m*Epreshower

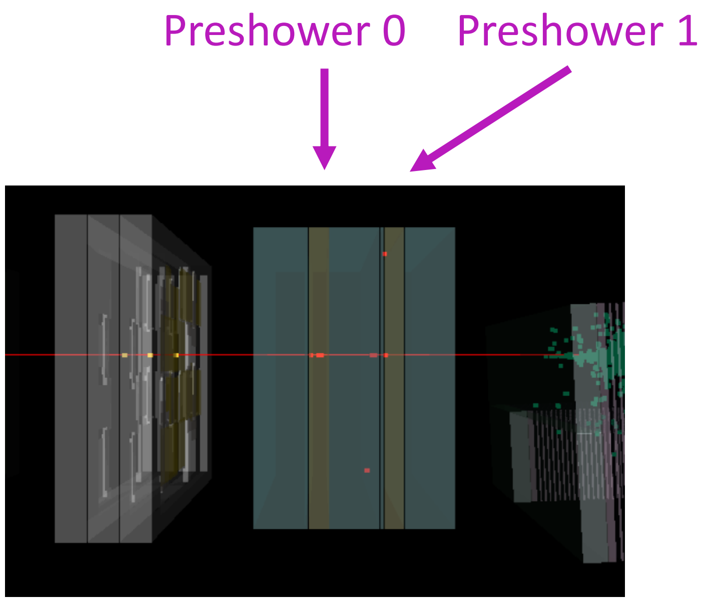
- We can also apply a preshower correction to the simulation
- Changes distribution
- Important note: simulation gives deposited energy rather than deposited charge

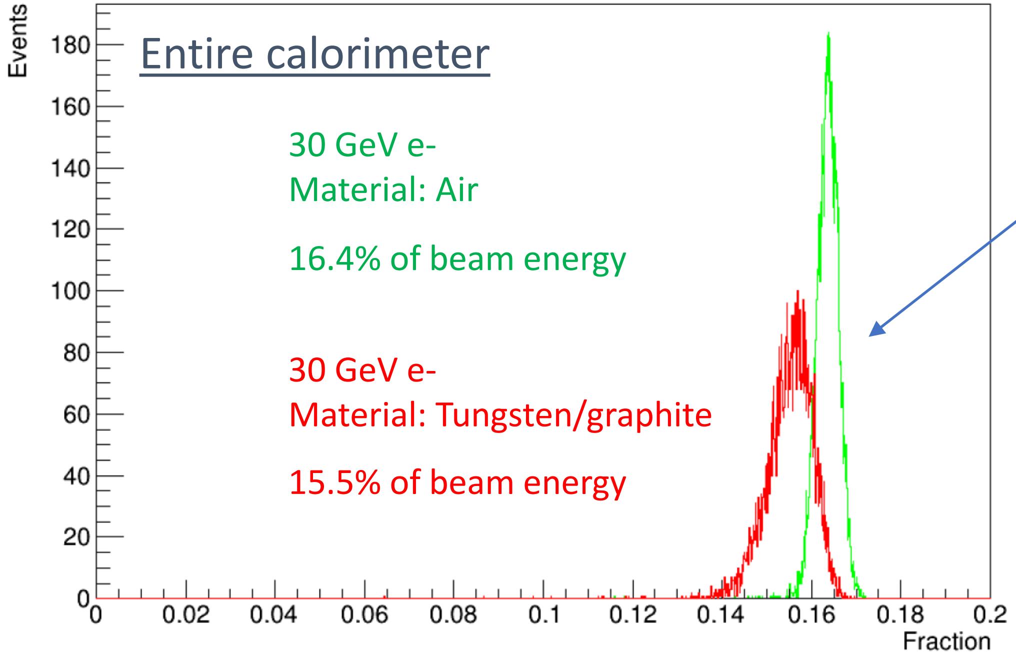


Test Beam Simulation: Preshower Material

- Some test beam runs were performed with the preshower material (tungsten/graphite blocks) removed
- This was also carried out in simulation, and the change in edep % was studied
- We can compare with results from preshower correction







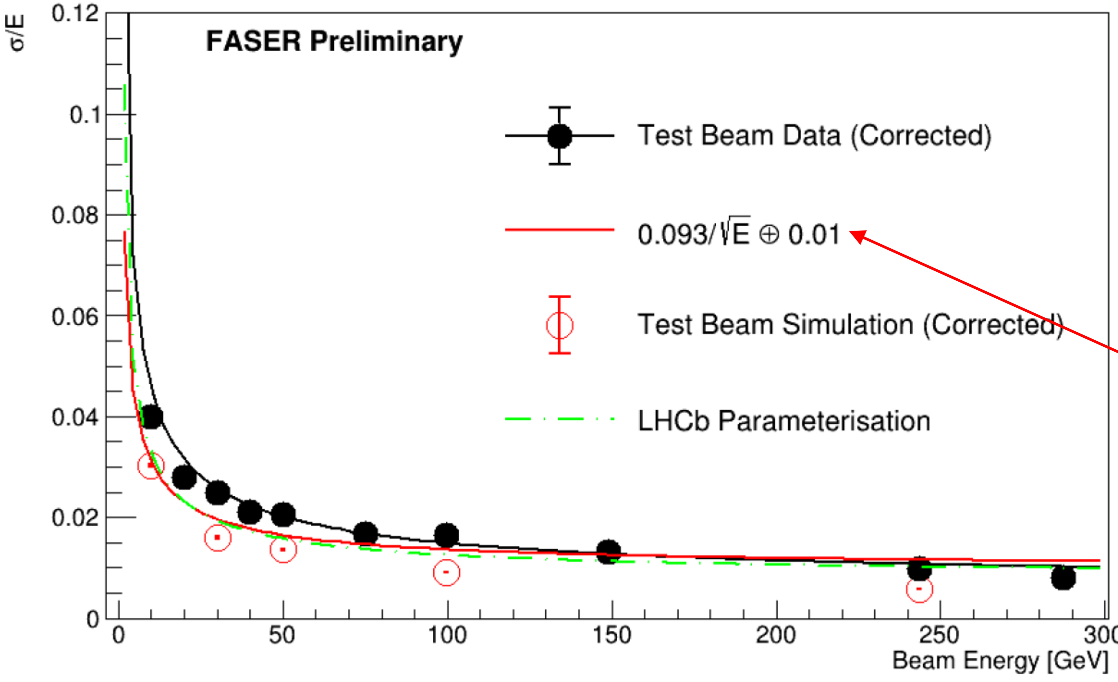
Mirrored in the preshower correction on previous slide

This was validated by data:

	With Preshower	W and C removed	With Preshower + correction
Resolution (30 GeV)	3.76 ± 0.03 %	2.84 ± 0.02 %	2.88 ± 0.02 %
Resolution (200 GeV)	1.89 ± 0.01 %	1.67 ± 0.01 %	1.66 ± 0.01 %

Data and Simulation

- Comparing energy resolution of corrected data measurements with corrected simulation
- Aim to fully understand the differences
  - Some effects aren't yet implemented in simulation

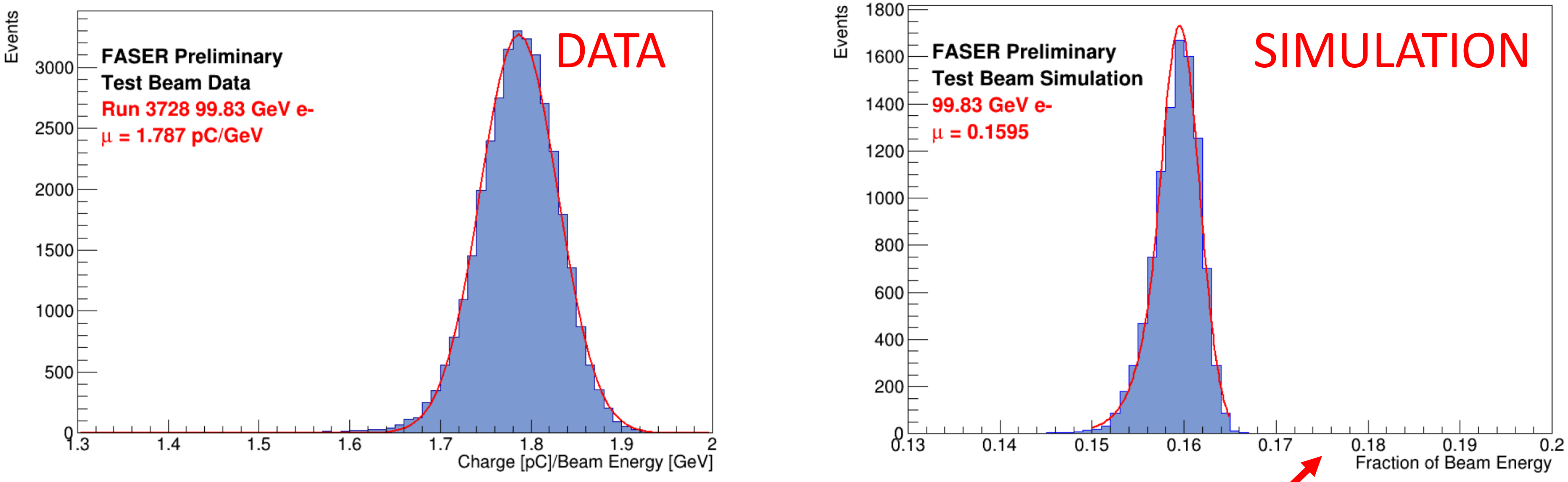


$$\sigma_E/E = a/\sqrt{E} \oplus b/E \oplus c$$

	a	b	c
Data (Corrected)	0.134	0.151	0.0065
Data	0.196	0.151	0.0057
Simulation (Corrected)	0.093 ± 0.003	-	0.0000 ± 0.0004
Simulation	0.135 ± 0.001	-	0.0000 ± 0.0017
LHCb	0.094 ± 0.004	0.108 ± 0.029	0.0083 ± 0.0002

- A noise term (b/E) improves the fit in the case of data
  - Calculated from the measured noise of digitizer signal using the same data being studied at the moment
- The simulation does not have a way to replicate the value of the constant (c) term
  - 1% was chosen to study the impact on the resolution fit on plot
  - Brings tail end of distribution higher, towards data and LHCb's measurement

Energy Calibration



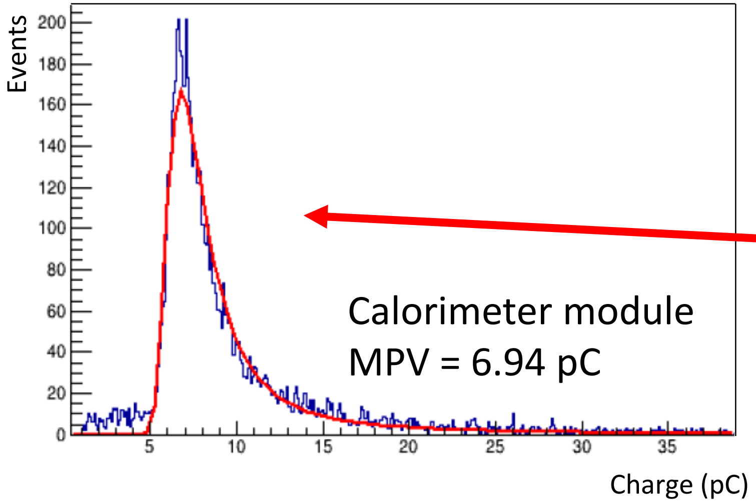
Still cannot directly compare pC and GeV

Need to:

i) Calibrate using MIP response

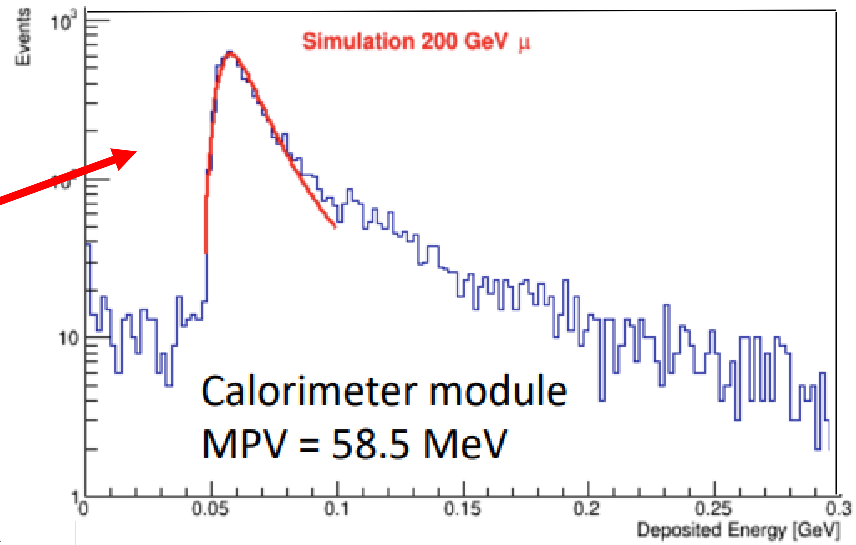
ii) Convert pC to GeV

DATA: MIP

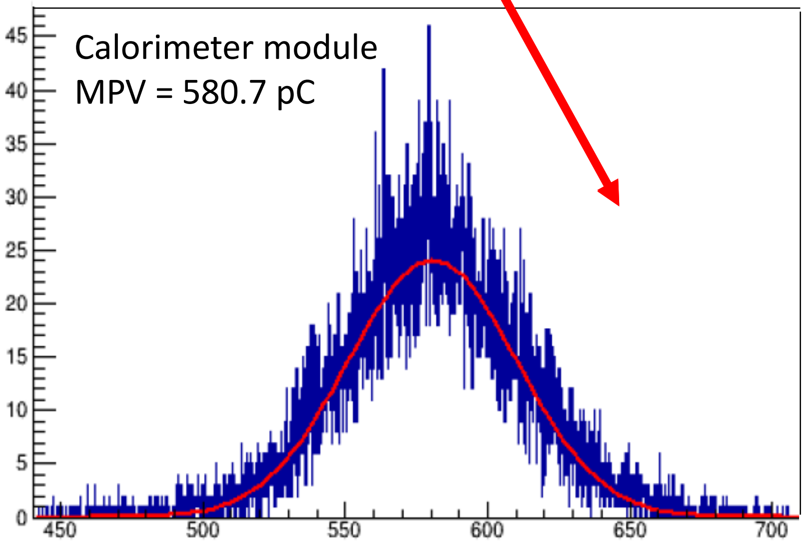


$$\frac{Q(e^-)}{Q(\mu^-)} = \frac{E(e^-)}{E(\mu^-)}$$

Simulation: MIP



DATA: Electron



We use MIP response as a reference because calibration will change when modules are moved to TI12

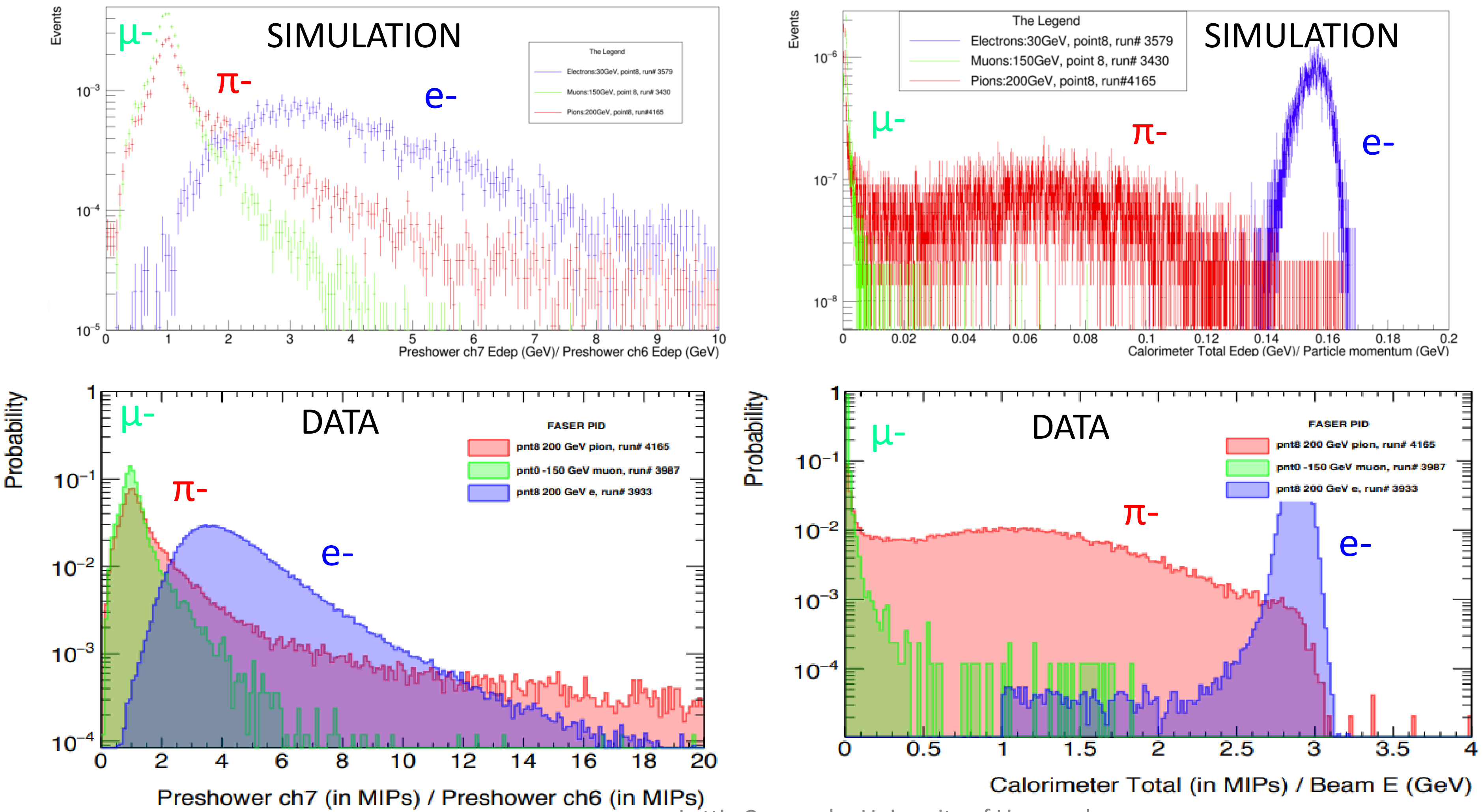
- In TI12 the only reference signal will be μ
- Compare with MC so we can extrapolate for other types of signal

$$E(e^-) \approx 16.5\%$$

Around 16% is what we expect from simulation

PID capabilities

With GeV conversion in place, we can now directly compare data and simulation PID plots



Summary and Outlook

- The test beam saw efficient data taking with good overall beam quality and purity
  - Results have been compared with simulation
  - Currently studying PID capabilities
- Most of FASER's physics signal will be at energies above the test beam
  - The resolution that we see in data and simulation is more than sufficient for what we need
- Simulation
  - Continue studying additional effects to implement in simulation
  - Final digitization step is being finalised and applied to data
- Detector once again situated in TI12, Run 3 data taking has started and we have first results!

FASER is supported by:

HEISING-SIMONS FOUNDATION

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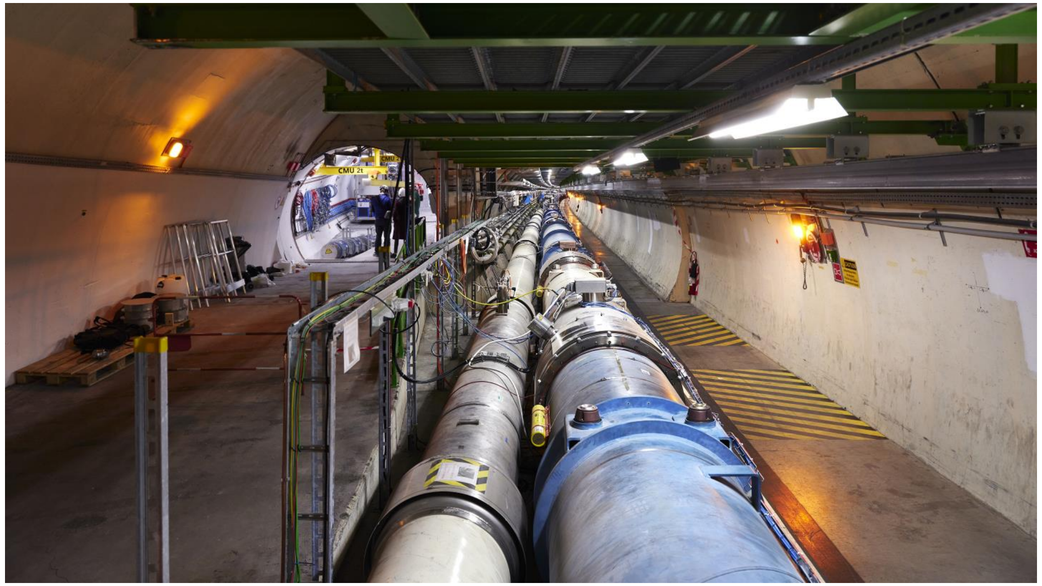
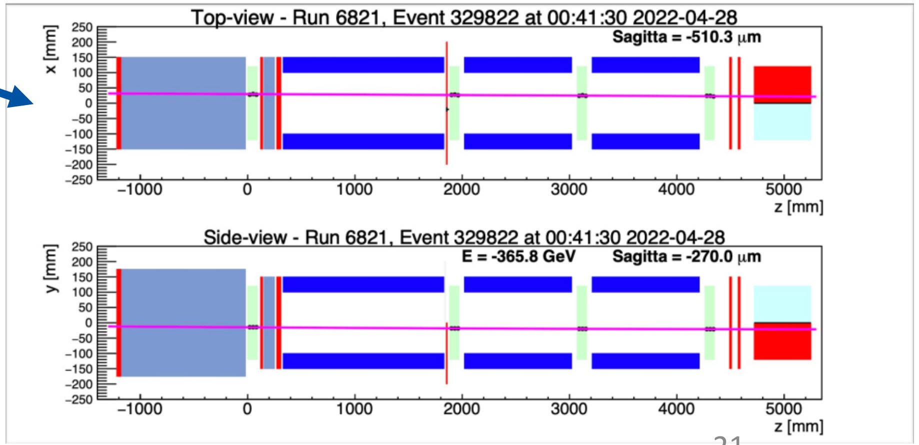
CERN

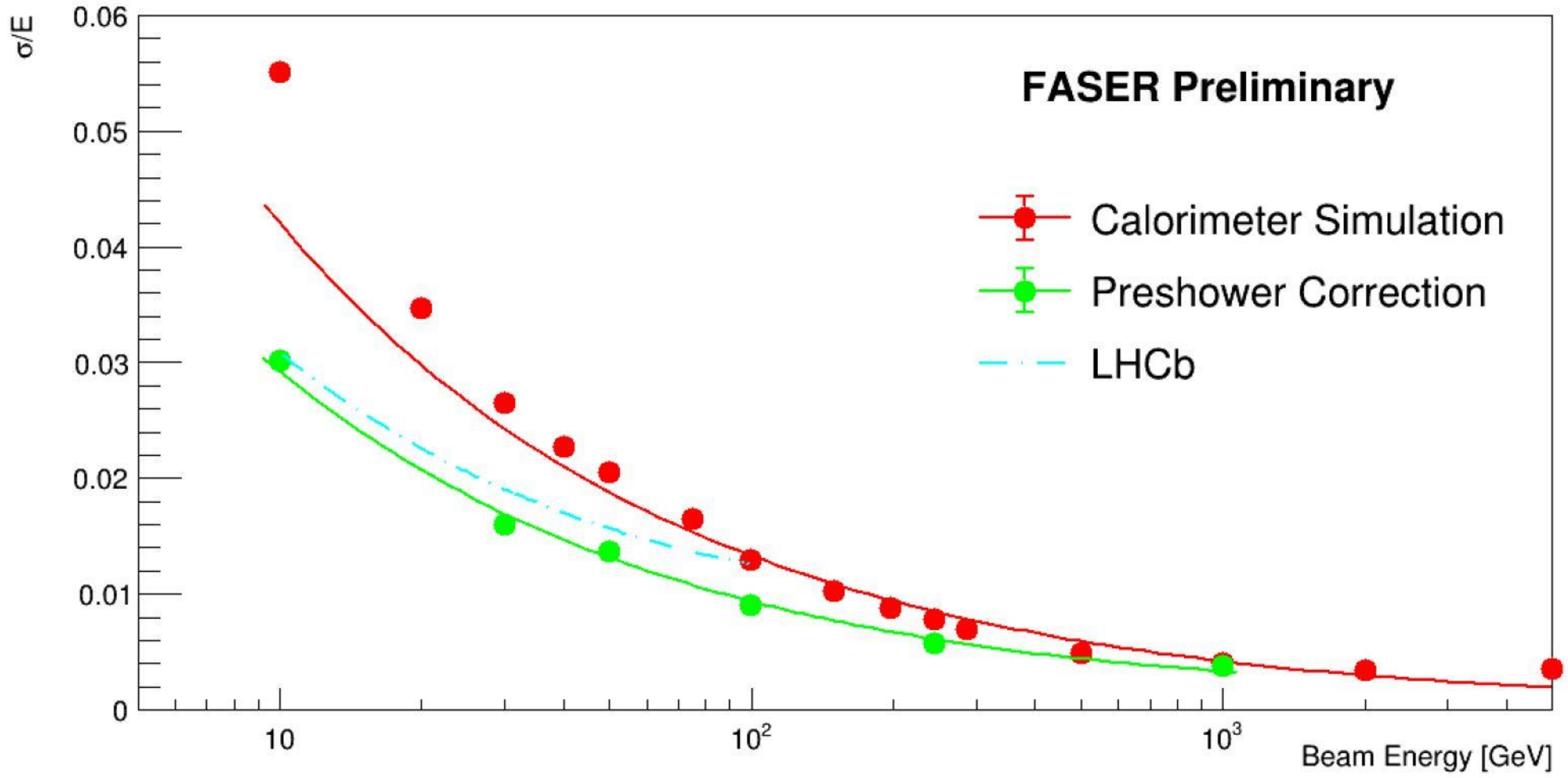


Background (beam) muon traversing the full FASER detector and leaving signals in all detector systems:



Backup Slides

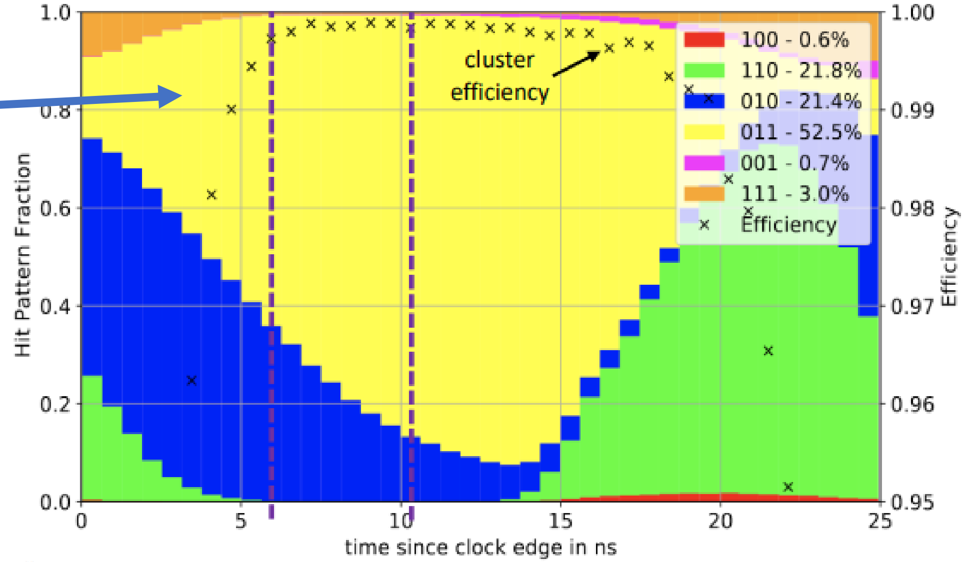
Test Beam Simulation: Resolution

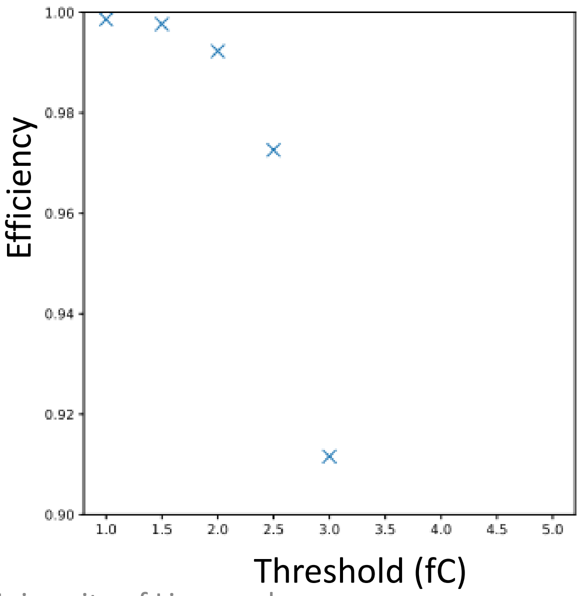


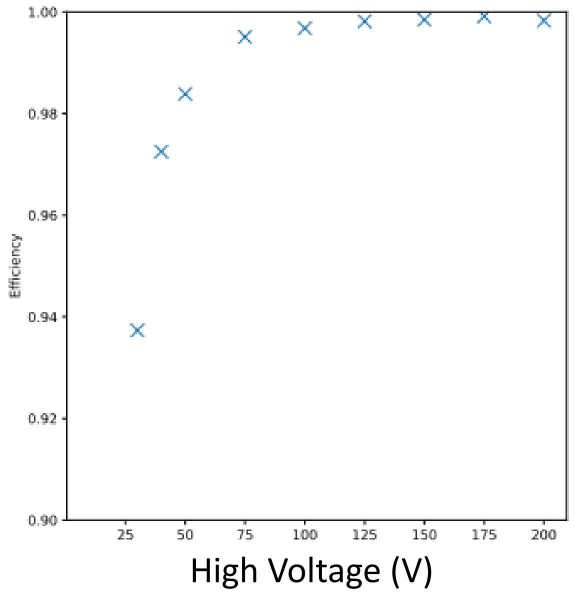
- As with data, deposited energy in the calo needs to be corrected due to Edep in the preshower
  - Improves the fit, particularly for lower energy points

Tracking Studies: Efficiency

- Measured the cluster efficiency of each sensor in the IFT
- No agreement yet between cluster efficiency and bad strips
- Measured an average efficiency of 99.86 ± 0.04 % which agrees well with MC and ATLAS (99.74 ± 0.04 %)
- This was done using a masked sensor for unbiased measurement
- Also measured the threshold and HV dependence of the cluster efficiency
- Working on extracting tracking efficiency estimate, in addition to the tracker hit efficiencies shown here



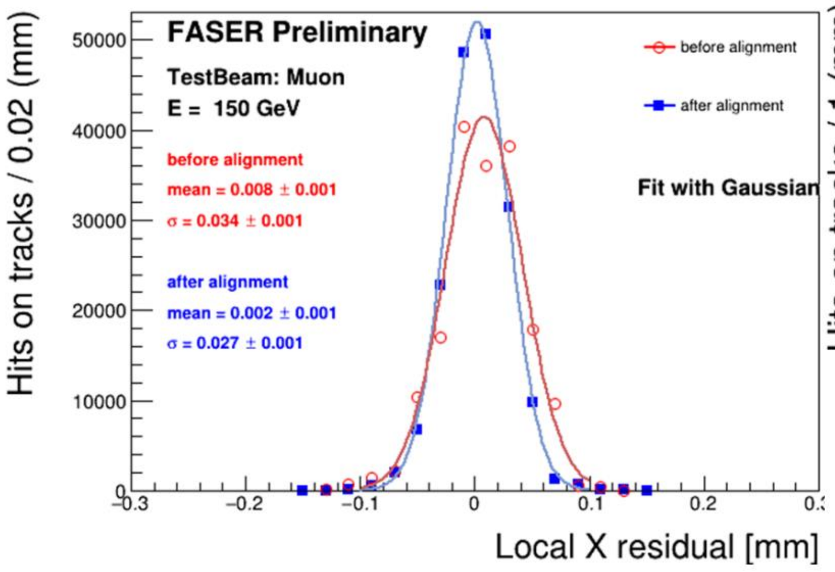


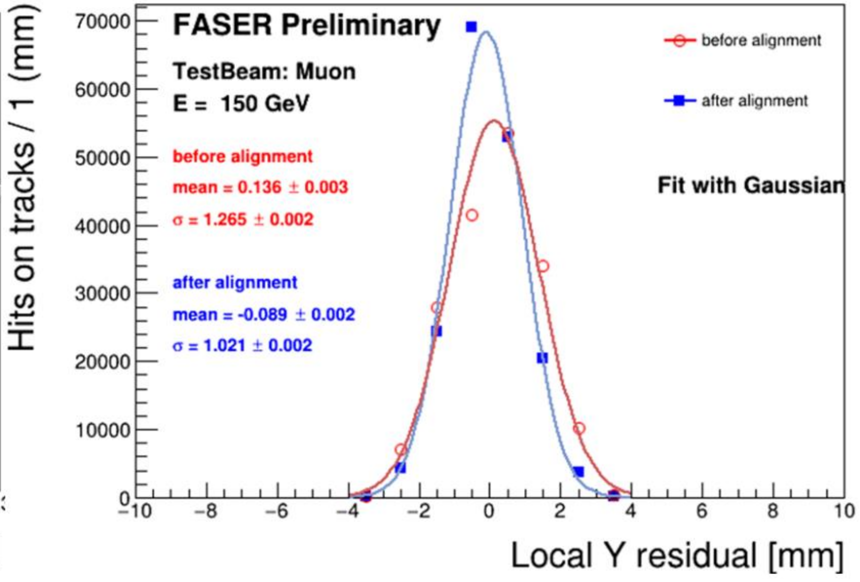


Tracking Studies: Alignment

Local Tracker Alignment

- A 150 GeV muon beam with approx. 3.5M tracks was used to study local alignment in middle layer of 1 station
- Results from 150 GeV muon run at point 4 (run 3426)





Global Tracker Alignment

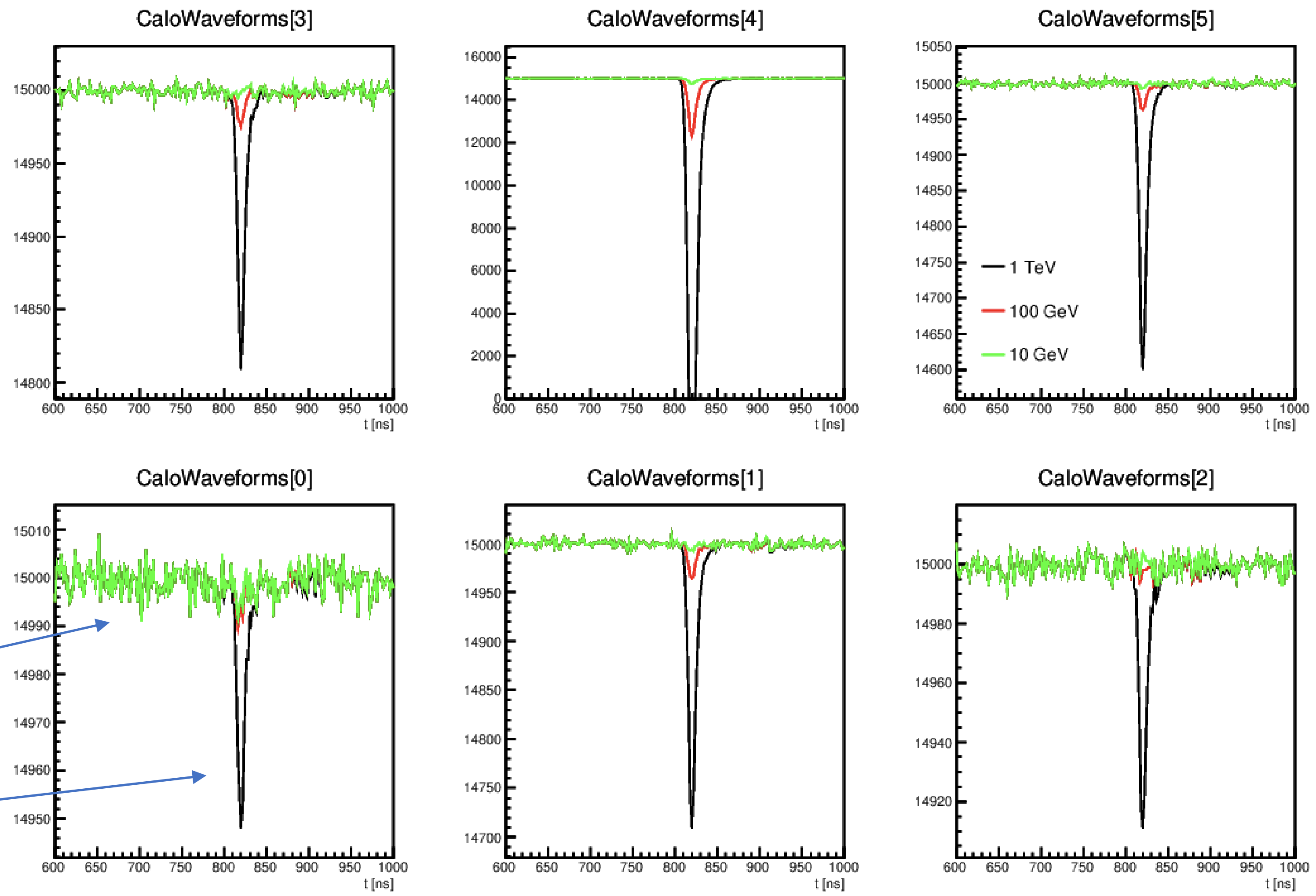
- Global alignment takes into account correlations and aligns everything at once
- Results are in progress

Tracking stations = 3
Planes per station = 3
Modules per plane = 8

Digitization

- Mimics the detector electronics
    - Converts simulation hits into PMT output which can then be reconstructed and compared with data
- Replicates pulses from PMTs of calo and scintillator components by:
    - Hit energies convolved with CB time kernel PDF with parameters set from data
- Since last update:
    - Baseline rms has been set to correct value and fluctuations implemented
    - Signal has been scaled to ADC counts (from energy)
    - Prevents failed fits

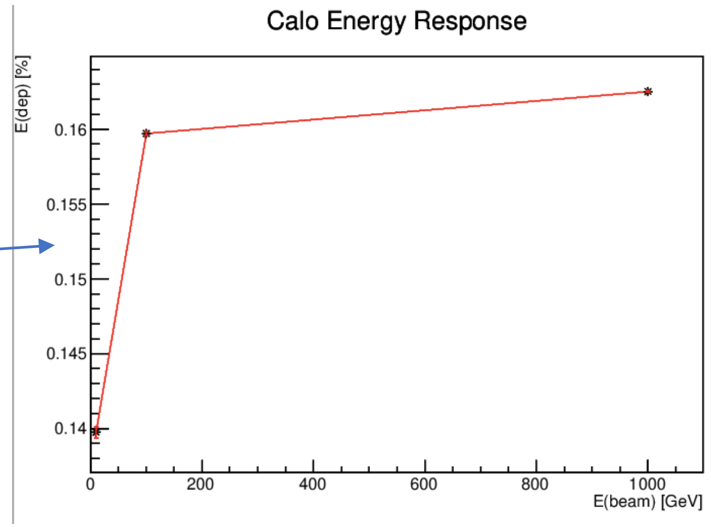
<u>Example digitized ECAL pulses</u>

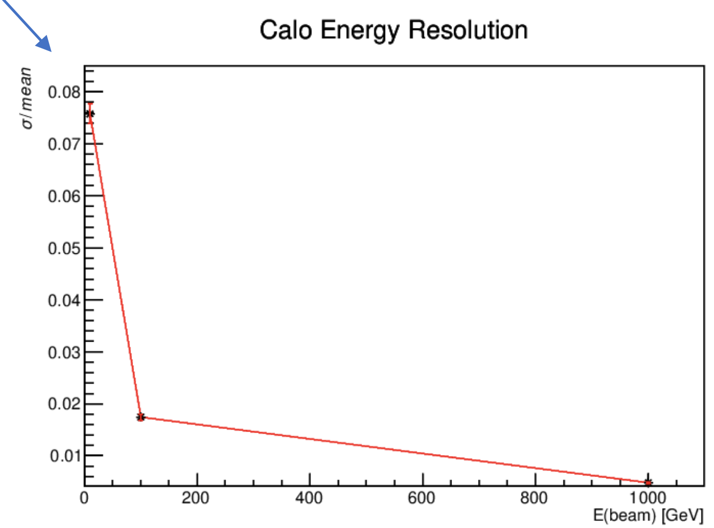


Digitization (2)

- This digitization is not used in the other simulation studies shown in these slides
- Sum integral over channels to get total deposited E for each beam E
  - Calo energy response and resolution at 10 GeV, 100 GeV and 1TeV
- The response is pretty consistent with simulation results
- Significant difference in resolution at low energies
  - Linked to the baseline rms eating into the signal

Energy	Simul Resp. %	Digi Resp. %	Sim Reso. %	Digi Reso. %
10 GeV	14.7	13.93(4)	0.0551(7)	0.087(2)
100 GeV	16.0	16.00(1)	0.0130(1)	0.0185(5)
1 TeV	16.3	16.253(4)	0.0040(1)	0.0049(2)

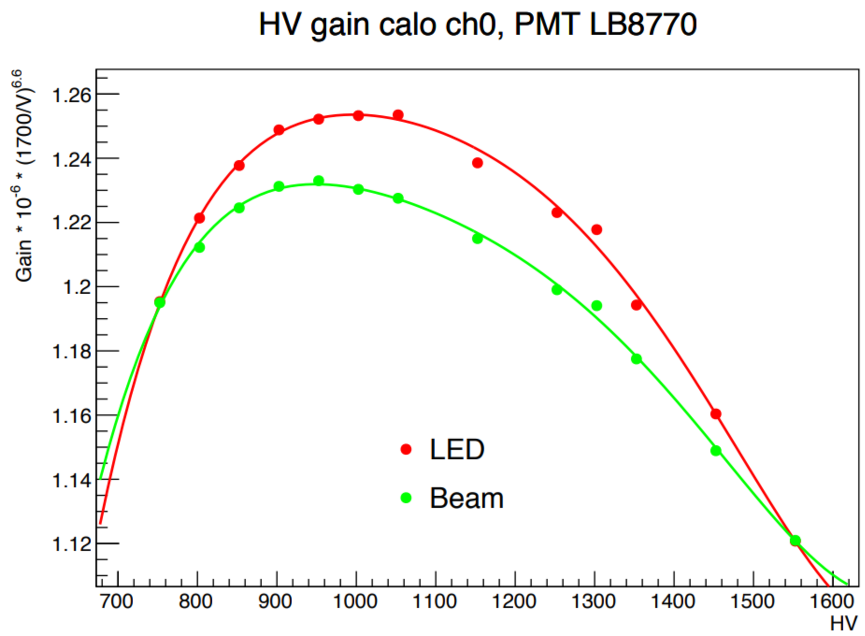




Calorimeter Studies: PMT Gain Dependence on HV

- Normalised to the nominal voltage for each PMT, which should be tuned to the same beam signal
- Allows us to correct for different gains in each calo module

	Low gain		Medium gain		High gain	
Channel	Nominal Voltage	Expected Current	Nominal Voltage	Expected Current	Nominal Voltage	Expected Current
Calo 0	-700 V	-160 muA	-1220 V	-277 muA	-1552 V	-353 muA
Calo 1	-700 V	-160 muA	-1120 V	-255 muA	-1425 V	-324 muA
Calo 2	-700 V	-160 muA	-1124 V	-225 muA	-1431 V	-325 muA
Calo 3	-700 V	-160 muA	-1100 V	-225 muA	-1400 V	-319 muA
Calo 4	-700 V	-160 muA	-1104 V	-225 muA	-1406 V	-320 muA
Calo 5	-700 V	-160 muA	-1228 V	-225 muA	-1562 V	-356 muA



- So far analysis performed on high and medium energy electrons
- Gain curves are used to calculate expected charge at high gain

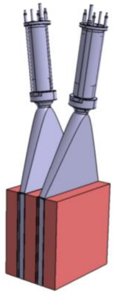
$$\text{Gain correction} = \frac{f(V_{high})}{f(V_{medium})} \times \left(\frac{V_{high}}{V_{medium}}\right)^{6.6}$$

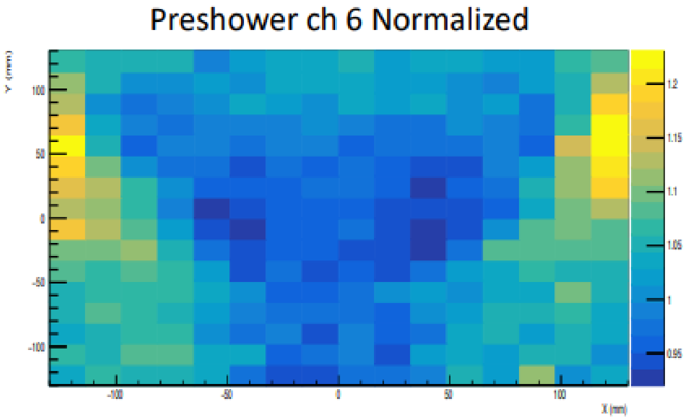
Scintillator Studies: Local Effects

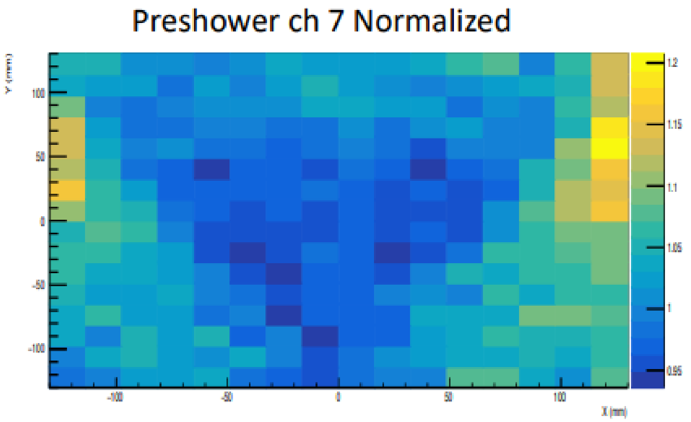
Preshower response

- Even though we have implemented the preshower correction in calorimeter studies, still need to study preshower response to be able to distinguish data from background

Heat Maps of MIP Charge:
(Trigger layers vs Track position)







Light collection efficiency in the preshower:

- As seen in the calorimeter PMTs, MIP deposited charge in preshower layers shows light collection dependence on position
  - More charge near PMTs

- A similar effect is seen in FASERν scintillators: