First steps

towards a

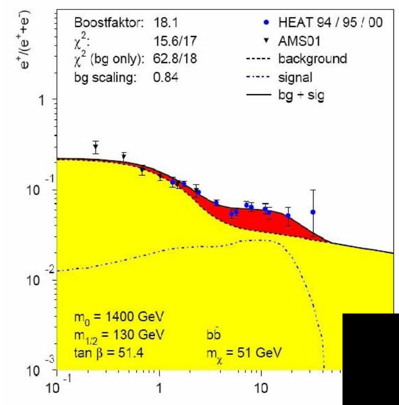
Balloon-borne electron-positron-spectrometer

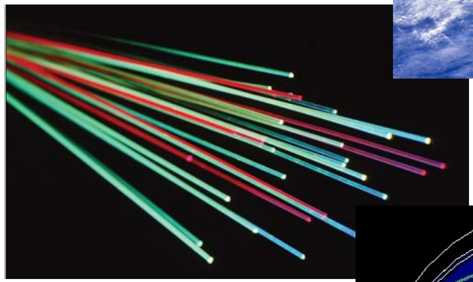
Henning Gast

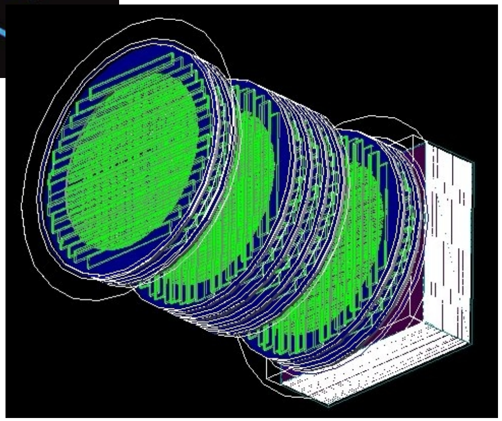
PEBS Workshop, RWTH Aachen, 29th May 2006

Overview

- Motivation
- High-altitude balloons
- Design and projected performance
  - Magnet
  - Tracker
  - Electromagnetic calorimeter (Ecal)
- Scintillating fibres
- Introduction to software
- Summary







Motivation

Previous measurements of cosmic-ray positron fraction: deviations from expected shape, but large errors.

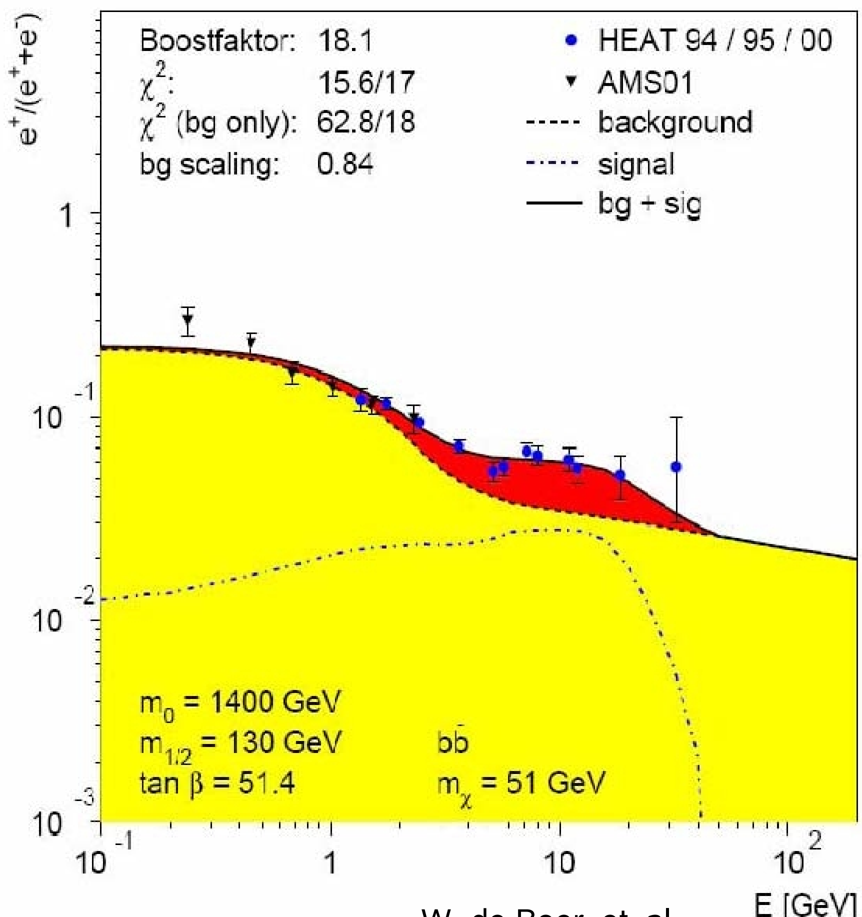
No primary source for positrons known: probe for new physics.

Dark Matter Candidate: SUSY-Neutralino χ

Annihilations can occur, e.g. in the galactic halo:
$\chi\chi \rightarrow b\bar{b}, W^+W^-, \ldots \rightarrow \ldots \rightarrow e^+e^- \ldots$ (stable)

Primary source of positrons in cosmic rays!

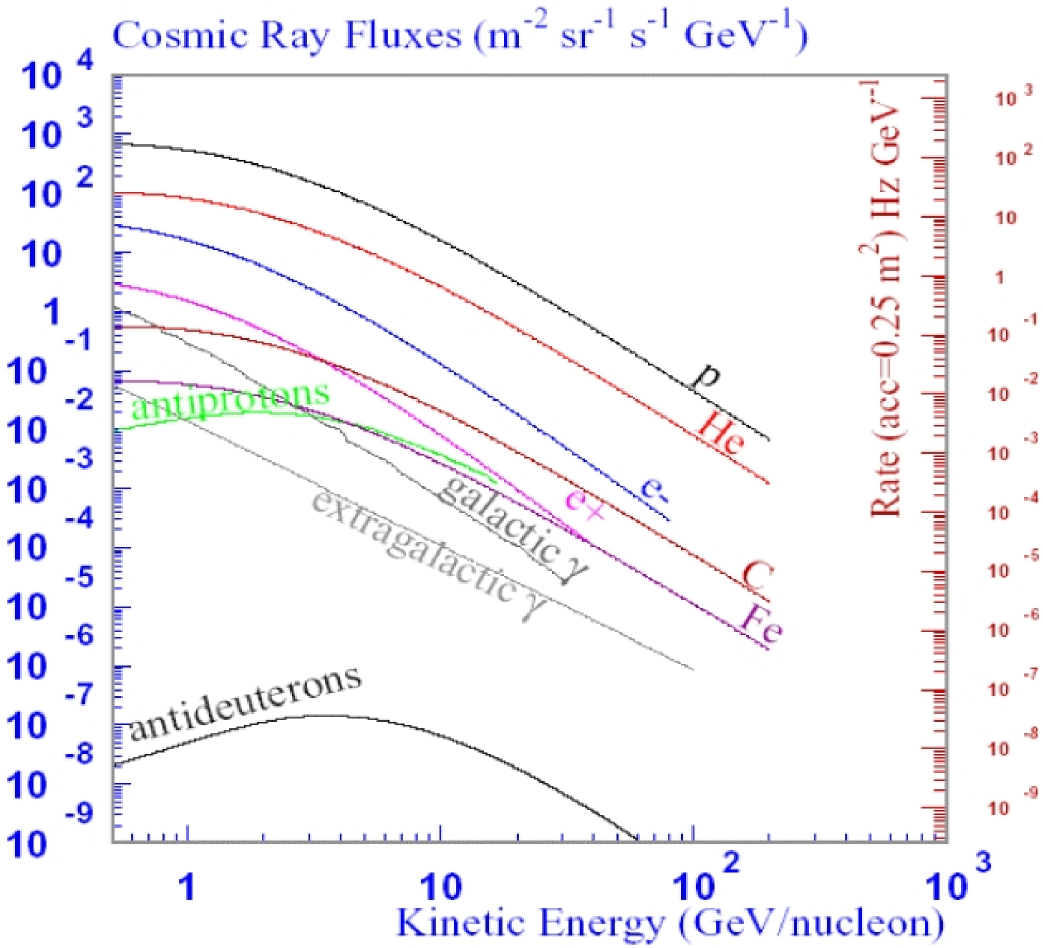
Secondary background arises from hadronic interactions of cosmic ray protons and subsequent decays.

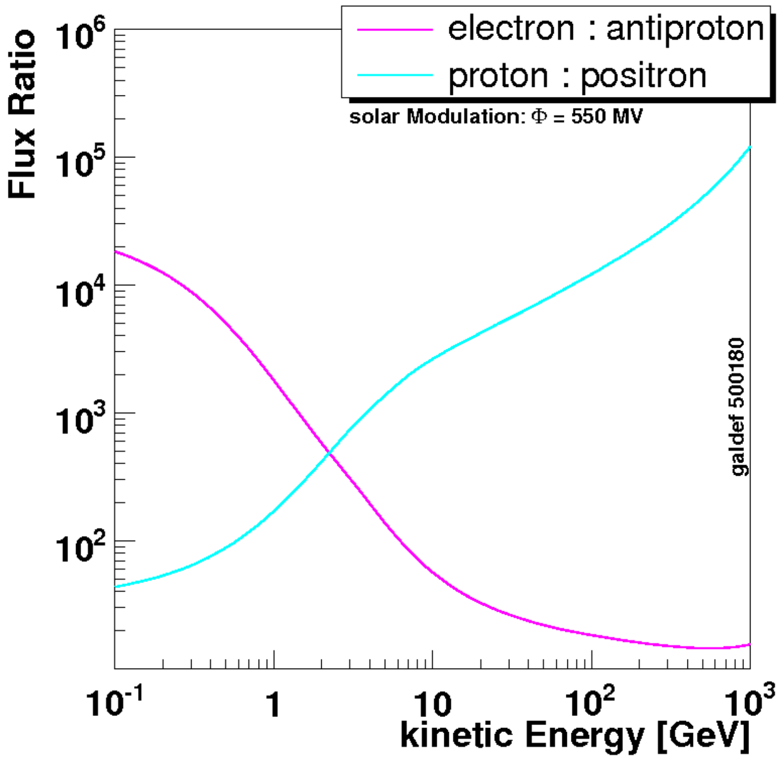


W. de Boer et al.

Atmosphere inhibits ground-based measurement: $20X_0$, $8\lambda_I$, therefore use high altitude balloon as carrier. Advantages: Reproducibility, post-flight calibration possible. Background by atmospheric secondaries must be considered.

Cosmic ray fluxes





Proton suppression of O(10000) needed for measurement of the positron fraction.

Spectra steeply declining with energy:
$\Phi \sim E^{-(2.7-3.0)}$

Composition:
90% protons
8% helium
1% electrons
positrons, antiprotons, heavy nuclei

Systematic effects widely cancel out when measuring positron fraction.

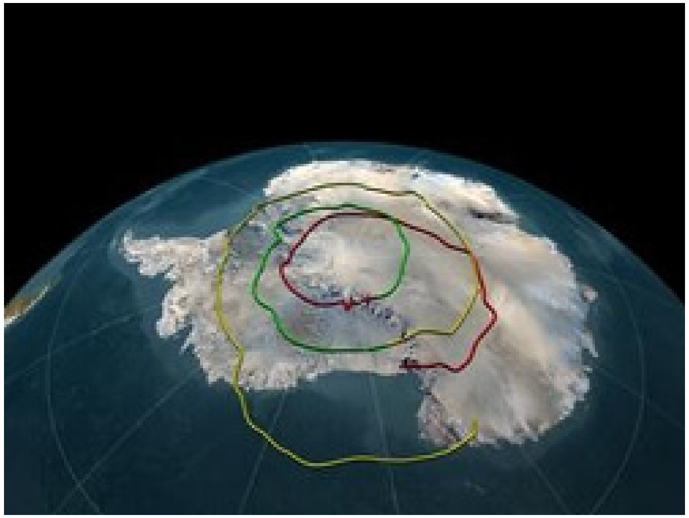
Having fun with balloons

Artist's impression of a ULDB in flight (NASA)

Ultra-long duration balloons (ULDB) under development by NASA:

Payload	3,630 kg
Scientific Payload	1,500 kg
Altitude	138,000 ft (42 km)
Duration	up to 100 days

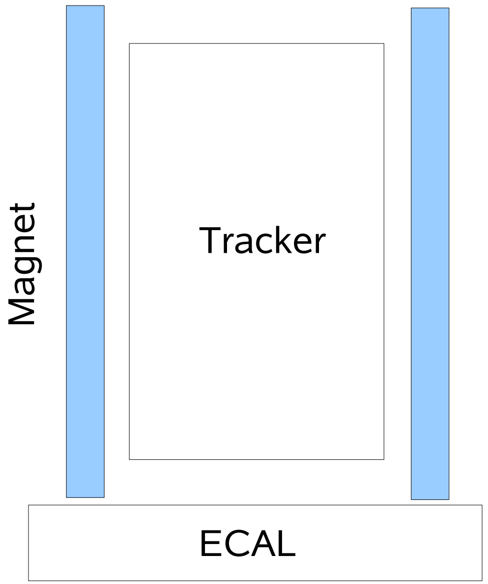
Record-breaking CREAM flight lasted 41d 22h.
Launch pads in Palestine, TX, Fort Sumner, NM (test flights), McMurdo Station, Antarctica, ...
After the CREAM flight: “*Payload recovery operations are in progress.*” (NASA website)



CREAM trajectory (NASA)

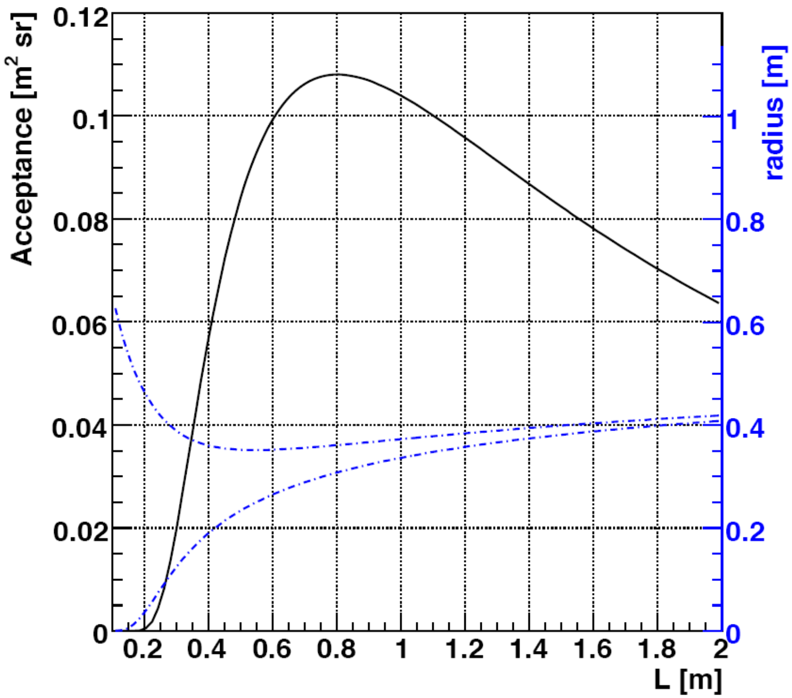
CREAM at launch (NASA)

Detector concept



momentum measurement

e/p separation



sagitta (deviation from straight line)

$$\frac{\Delta p}{p} \propto \frac{1}{BL^2} \qquad s = \frac{L^2 QB}{8p} \sim \sigma(fibre)$$

fixes $BL^2 = 0.133\ \mathrm{Tm}^2$: s(100 GeV)=50µm

flux density of "magic ring"

residual induction $B_r \sim 1.3$ T

$$B = B_r \log\left(\frac{R_o}{R_i}\right)$$

weight $\quad m_M \propto L(R_a^2 - R_i^2) \qquad m_{ecal} \propto R_i^2 h$

m_{tot} fixed, h from Ecal design

geometrical acceptance

$$G(L, R_i) = 1/2\,\pi^2 \left(2R_i^2 + L^2 - \sqrt{L^2(4R_i^2 + L^2)}\right)$$

optimum:
L=0.8m
R_i=0.3m

acceptance and mission duration

PEBS	1000 cm²sr
AMS02	500 cm²sr
	1000 days
PAMELA	20 cm²sr

40d PEBS=
80d AMS02
2000d PAMELA

Detector layout

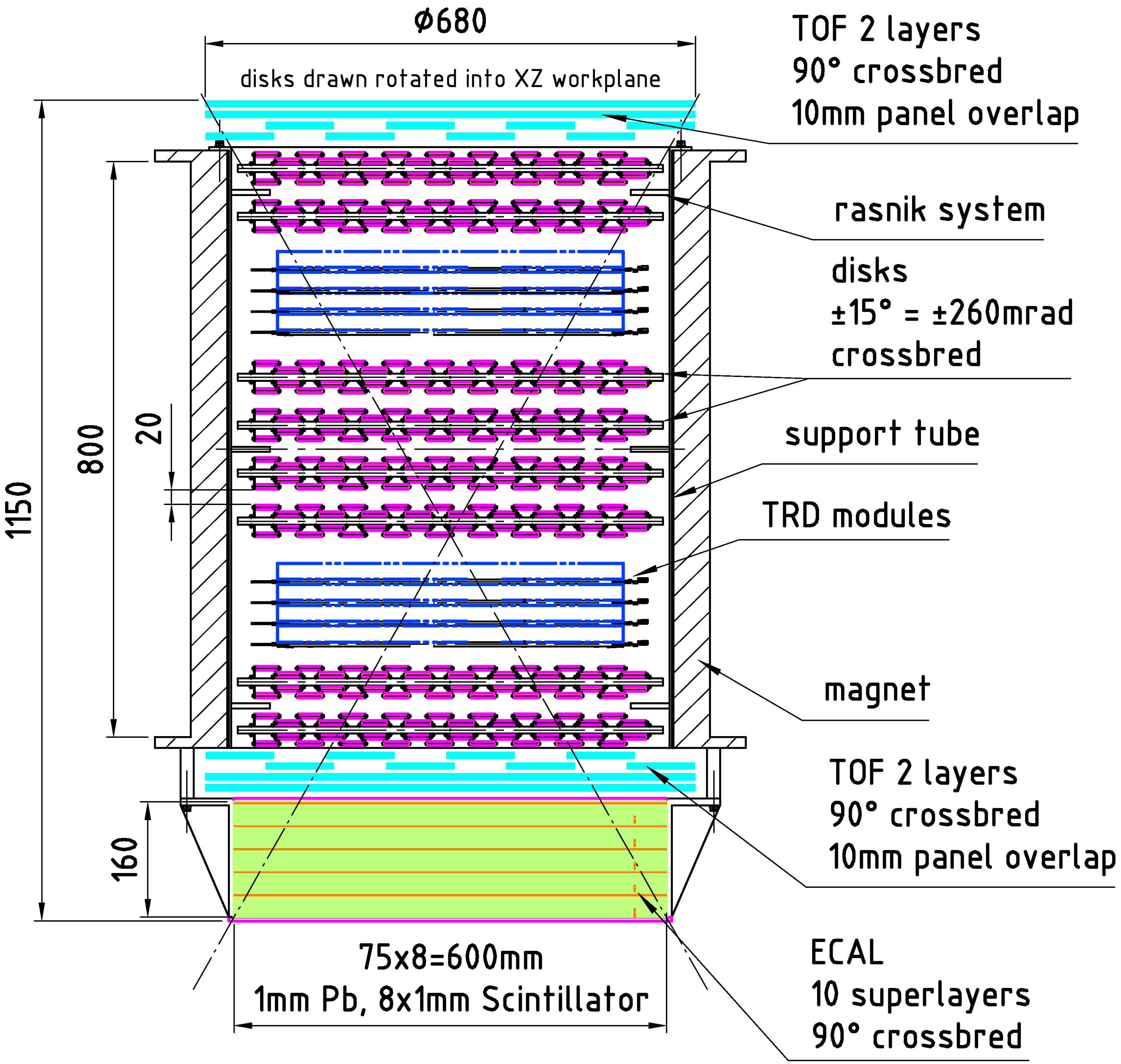
Time of Flight (TOF)
trigger system
velocity measurement

Tracker
momentum measurement

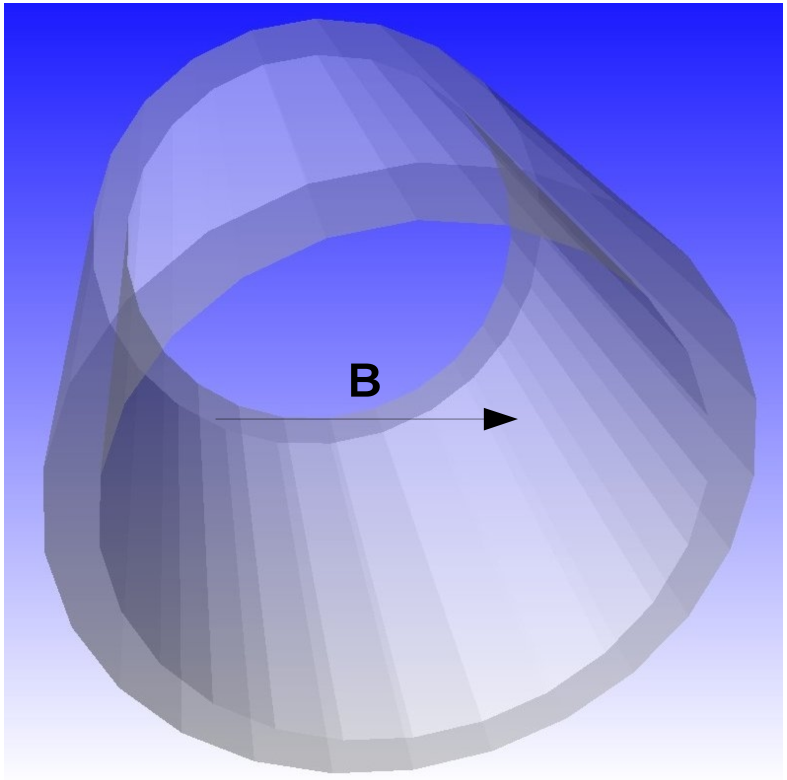
Transition Radiation Detector (TRD)
proton rejection 10^1-10^2

Electromagnetic calorimeter (ECAL)
proton rejection 10^3-10^4

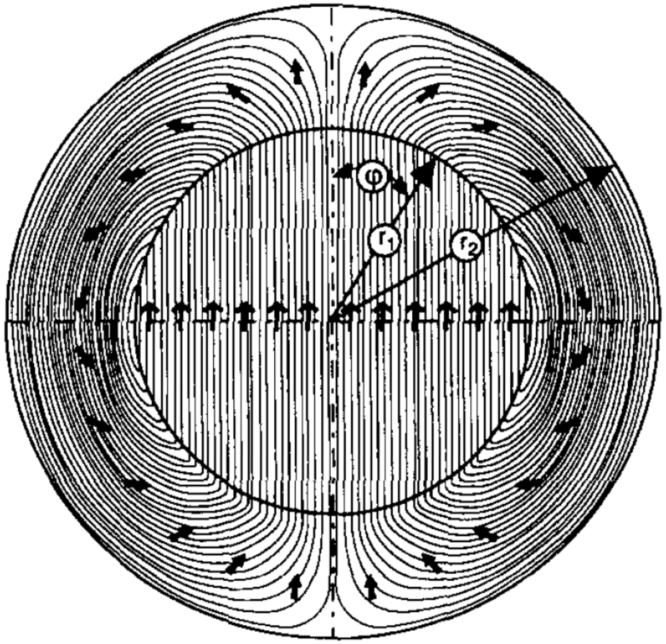
Rasnik system
stabilty control



Magnet / Weight budget



permanent magnet of cylindrical shape around tracker: “magic ring”



flux density	0.2 T
length	80 cm
inner diameter	62 cm
outer diameter	72 cm
material	Nd-Fe-B
weight	650 kg

small dipole moment and leakage flux

Weight budget

Magnet	~650 kg
Ecal	~250 kg
Tracker	~100 kg
Electronics	~100 kg
TOF	~ 30 kg
TRD	~ 20 kg

dominated by magnet and Ecal

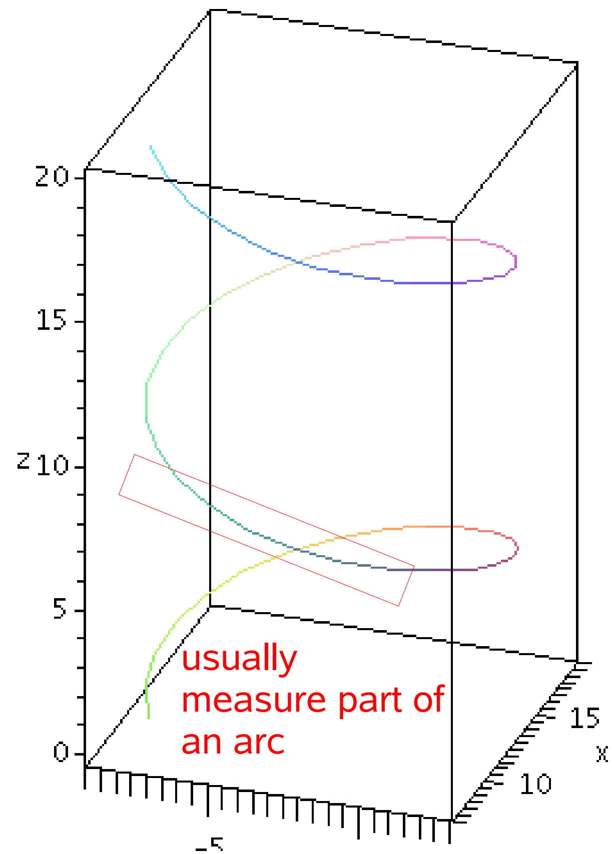
Basics of momentum measurement

Measurement of the momentum vector of an incident particle is essential:

- sign allows distinction between electrons and positrons
- absolute value necessary to measure a spectrum:
  dark matter features much more apparent than in integrated fluxes
- direction important for geomagnetic cutoff calculation
- needed for tracker/ECAL matching

trajectory of a charged particle in a uniform magnetic field is a helix

$$p\cos(\lambda) = 0.3\,\frac{GeV/c}{Tm}\,z\,B\,R$$



Momentum resolution

curvature (κ=1/R) error arises from two effects:

- finite measurement resolution

$$\delta k_{res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}$$

improve position measurement
increase detector length (bad for acceptance)

- multiple scattering

$$\delta k_{ms} \approx \frac{(0.016)(GeV/c)z}{L\,p\,\beta\cos^2\lambda}\sqrt{\frac{L}{X_0}}$$

minimize material budget

addition in quadrature leads to $$\frac{\Delta p}{p} = \sqrt{a_{ms}^2 + b_{res}^2\,p^2}$$

maximize magnetic field

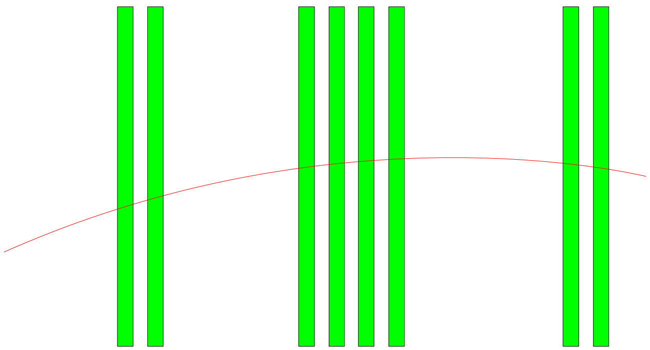
equidistant spacing:

$$\delta k_{res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}$$

"sagitta" geometry:

$$\delta k_{res} = \frac{\epsilon}{L'^2}\sqrt{\frac{256}{N}} \qquad s = \frac{x_1 - x_3}{2} - x_2$$

→ concentrate layers at centre and sides

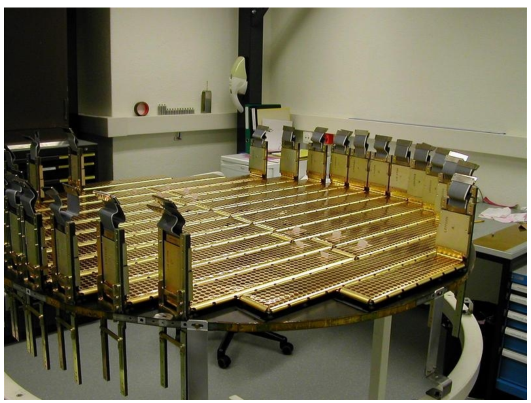


Designing the tracker

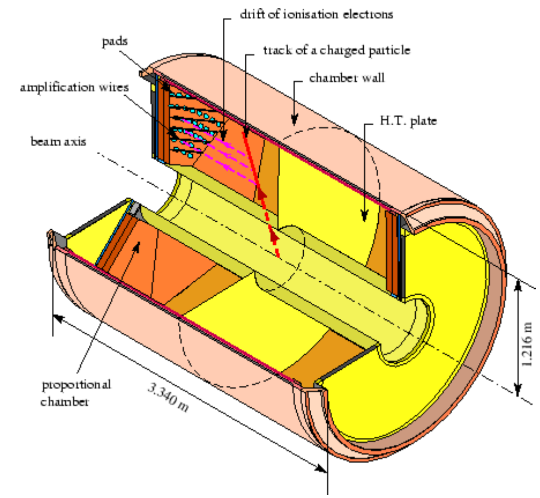
purpose: momentum measurement inside magnetic field

principal choices:

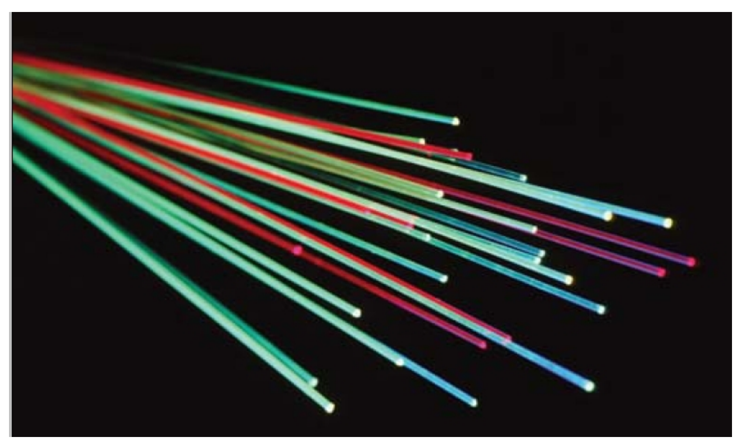
silicon semiconductor detectors
delicate and expensive



time projection chamber
gas-filled detector
problematic in near-space environment

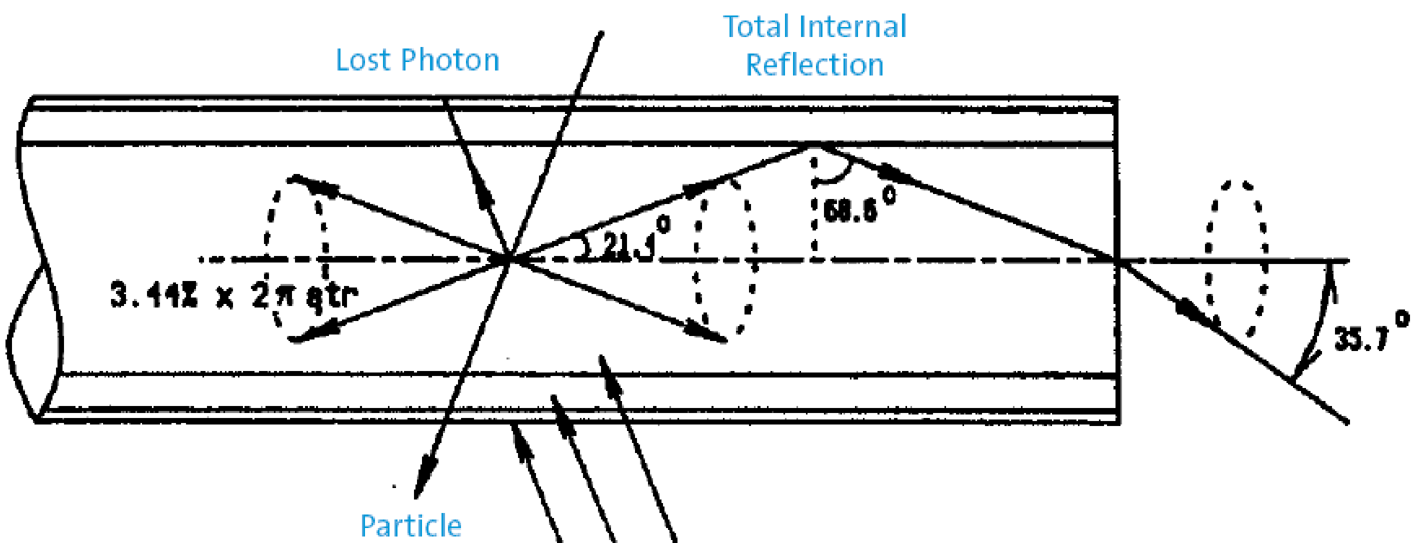


scintillating fibres
cheap and effective
uniform tracker/ECAL R+D
low material budget



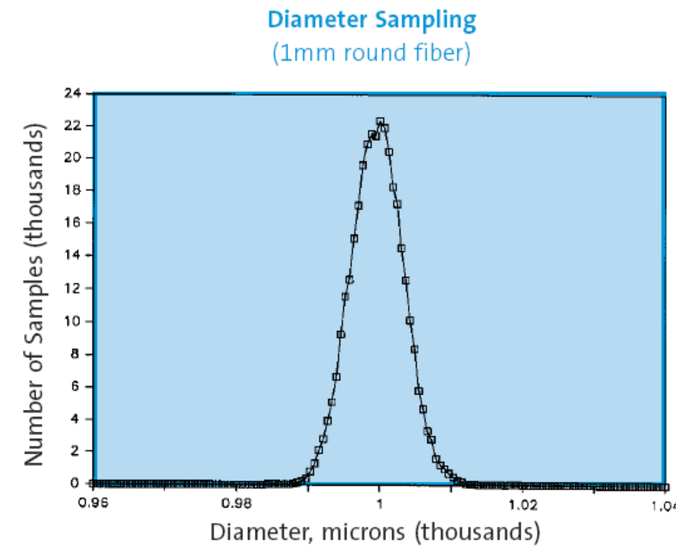
Scintillating fibres: principle

A Typical Round Scintillating Fiber –



Saint-Gobain Crystals

Optical cladding thickness:
>5λ (~3 microns),
typically 3 - 5% x OD



standard size	0.25 mm to 5 mm square or round cross section
emission peak	430 ~ 530 nm
decay times	~3 ns
1/e length	2~4 m
photons per MeV	~8000
radiation length	42 cm
operating temperature	-20°C to +50°C

Scintillating fibres: Simulation

physics of optical photons implemenented in Geant4

- scintillation
- reflection, refraction, transmission at optical boundaries
- absorption and scattering in matter

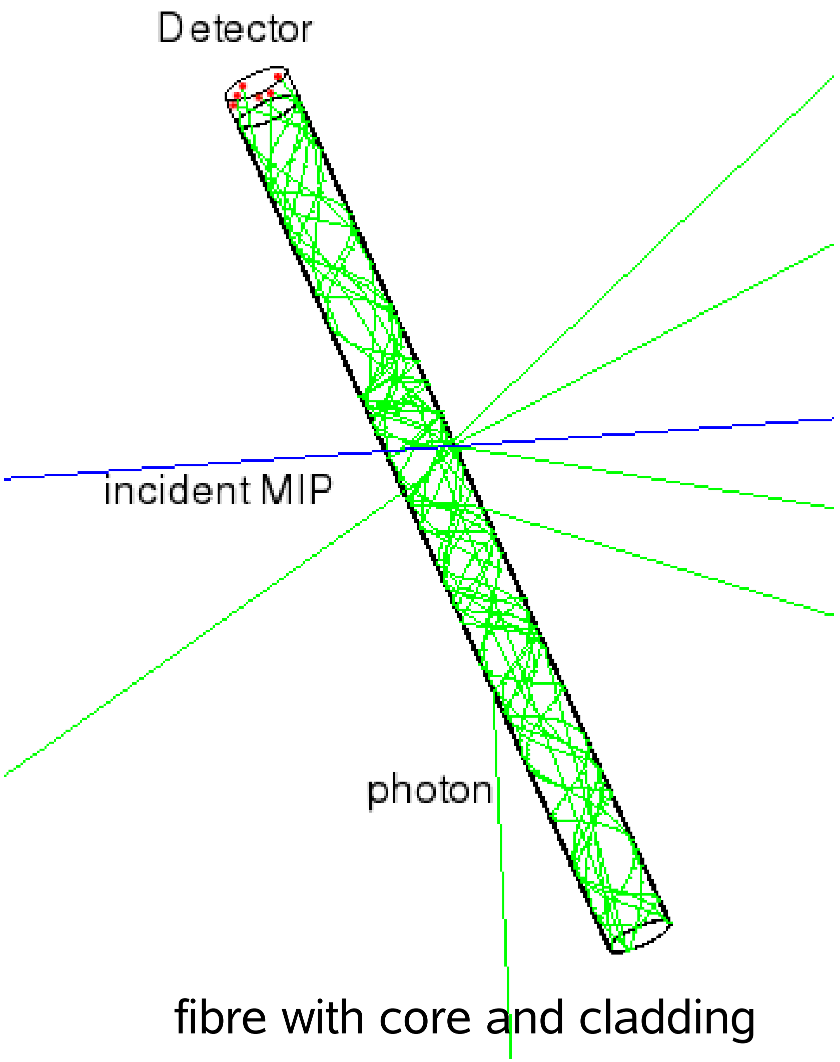
free parameters of the simulation

- fibre geometry
- surface quality

number of photons:

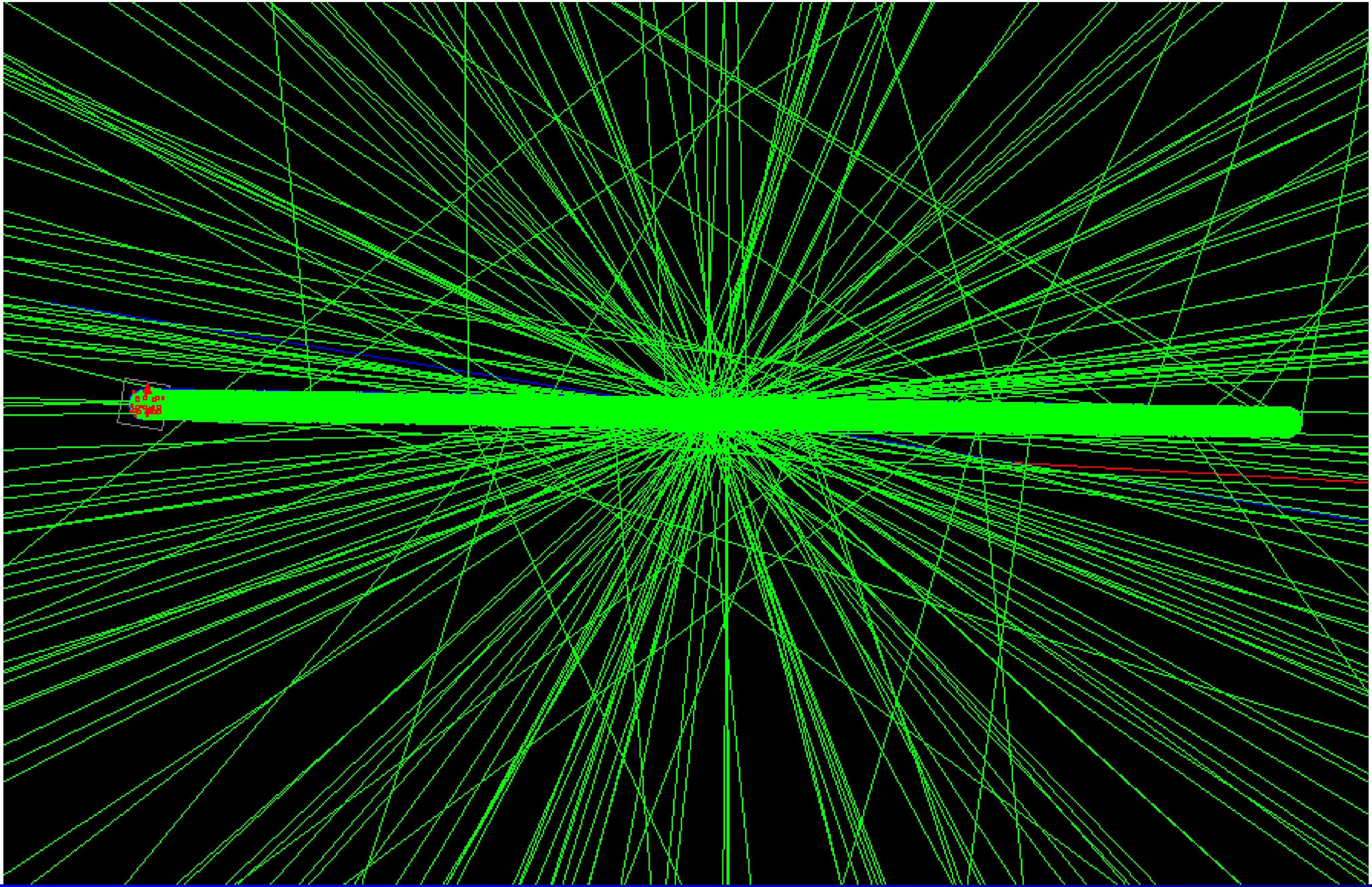
$$n_\gamma = \epsilon_{SiPM} \cdot \epsilon_{trap} \cdot f_{Mirror} \cdot G_{scint} \cdot \frac{dE}{dx} \cdot d_{core}$$

$$n_\gamma = 0.2 \cdot 0.073 \cdot 1.6 \cdot 8000\ MeV^{-1} \cdot 40\ keV = 7.5$$

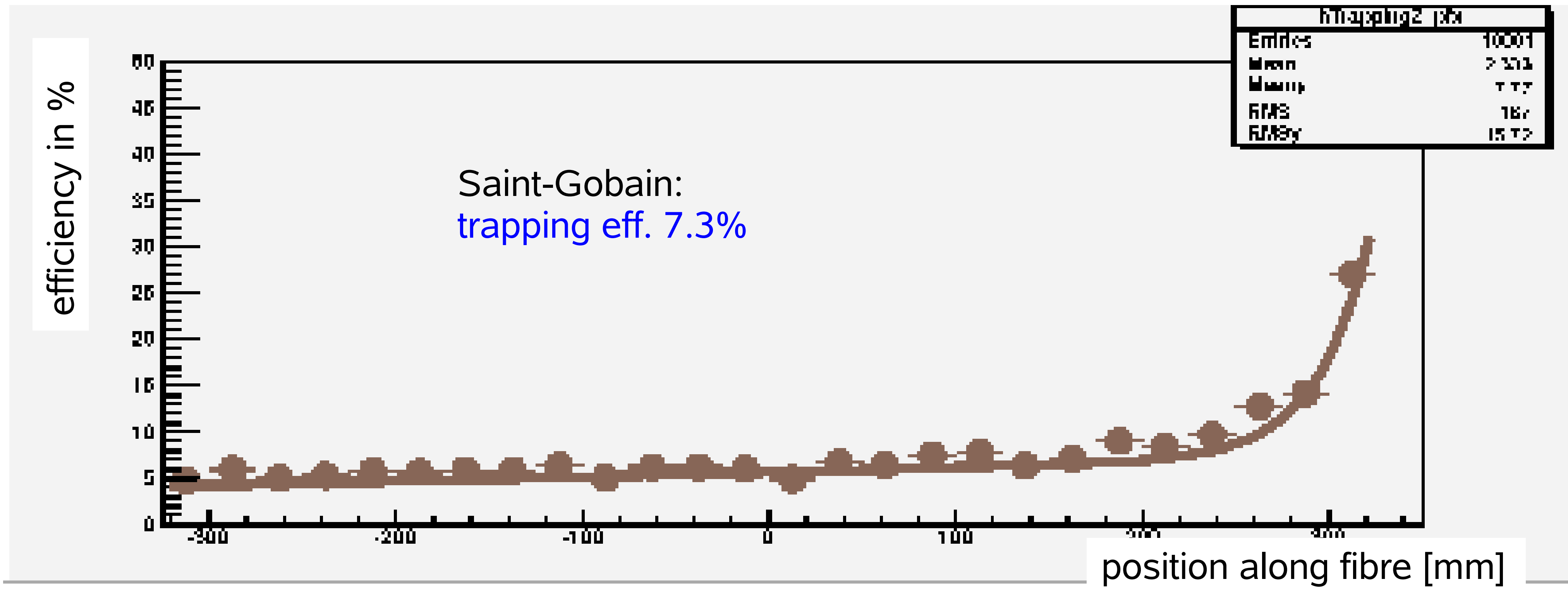


fibre with core and cladding

Scintillating fibres: Picture



Scintillating fibres: Photon yield parameterization



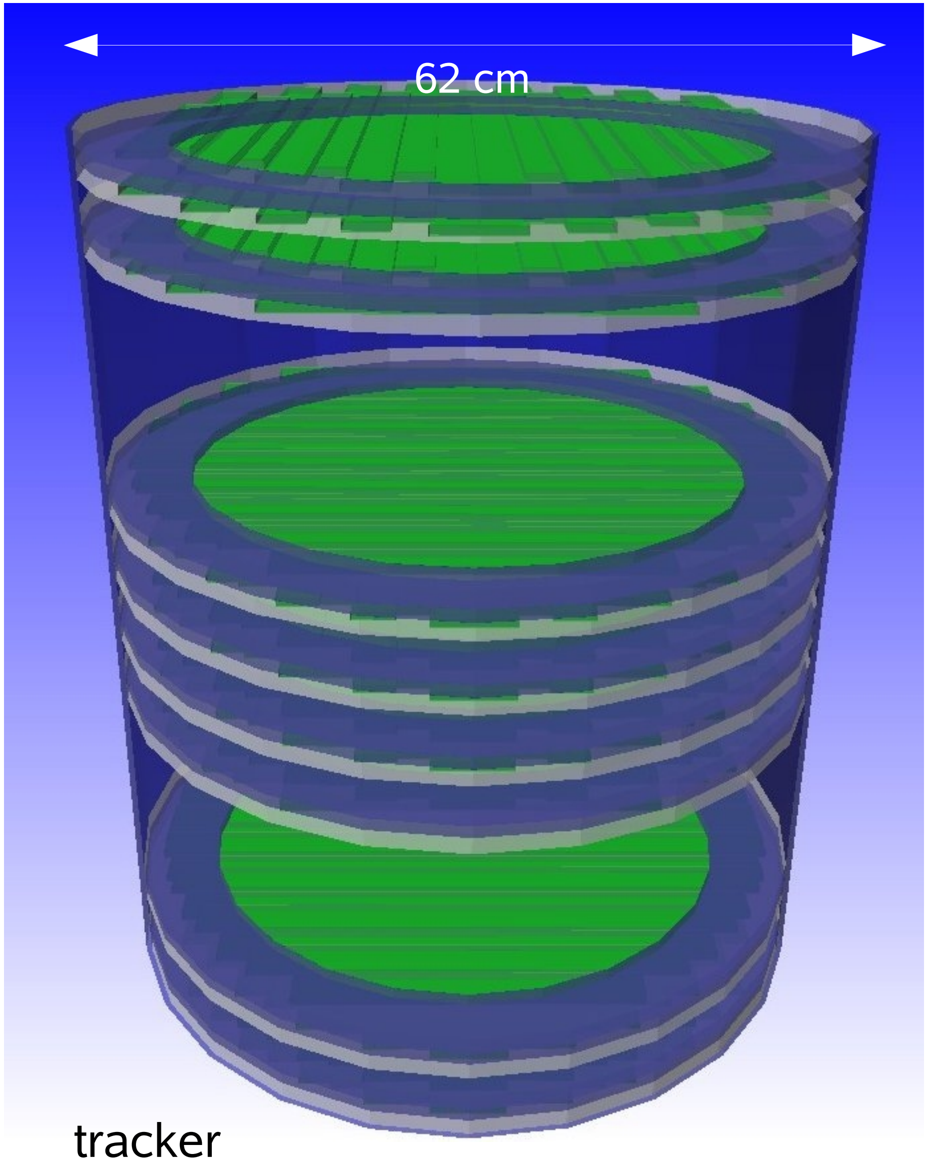
square fibres with double cladding and white coating

$$p_{eff}(x) = a_0 + a_1 x + a_2 e^{\frac{x}{a_3}}$$

core light — cladding light

a_0 ... a_3 are functions of fibre length

Tracker layout

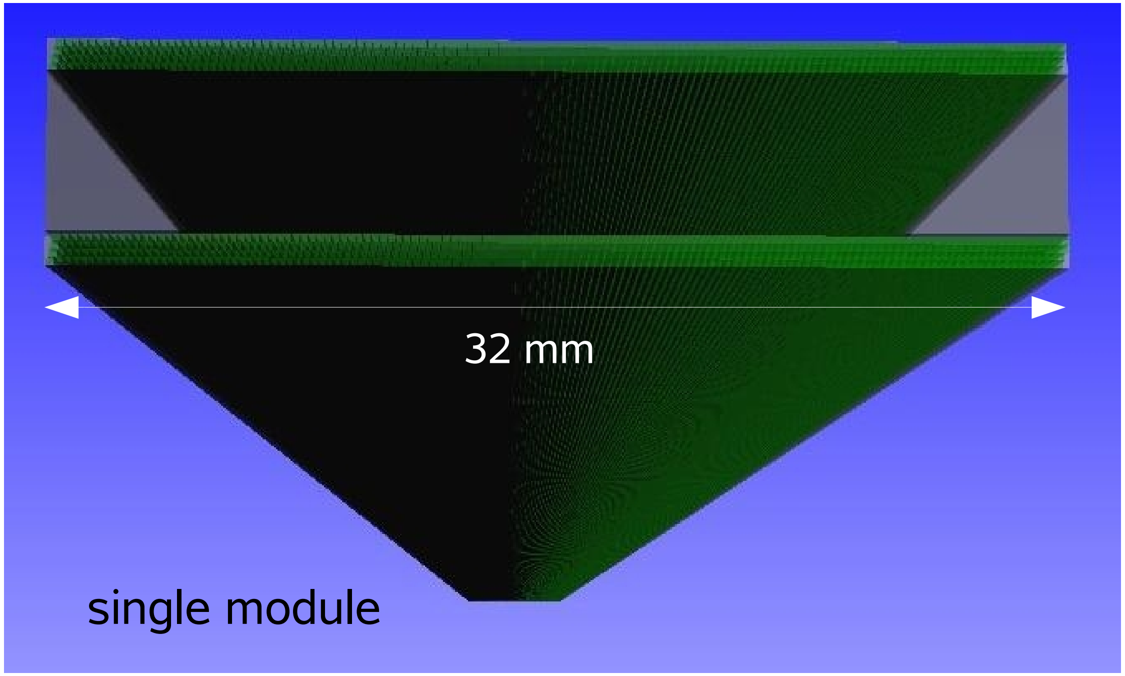


tracker module:

2x4x128 250µm scintillating fibres
2x 100µm CF skin
1x 5 mm Rohacell

tracker:

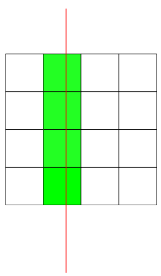
2x8 layers of staggered modules, mounted on 7cm wide, 250µm thick CF skin rings, 1cm Rohacell
12 layers measuring bending-plane
4 layers rotated to measure slope
~10% X_0



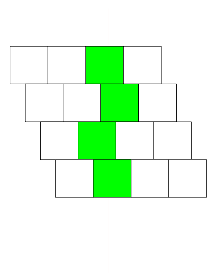
Improving the resolution

intrinsic resolution of a single 250 μm fibre: $\sigma = \frac{250\,\mu m}{\sqrt{12}} \approx 75\,\mu m$

this can be improved:

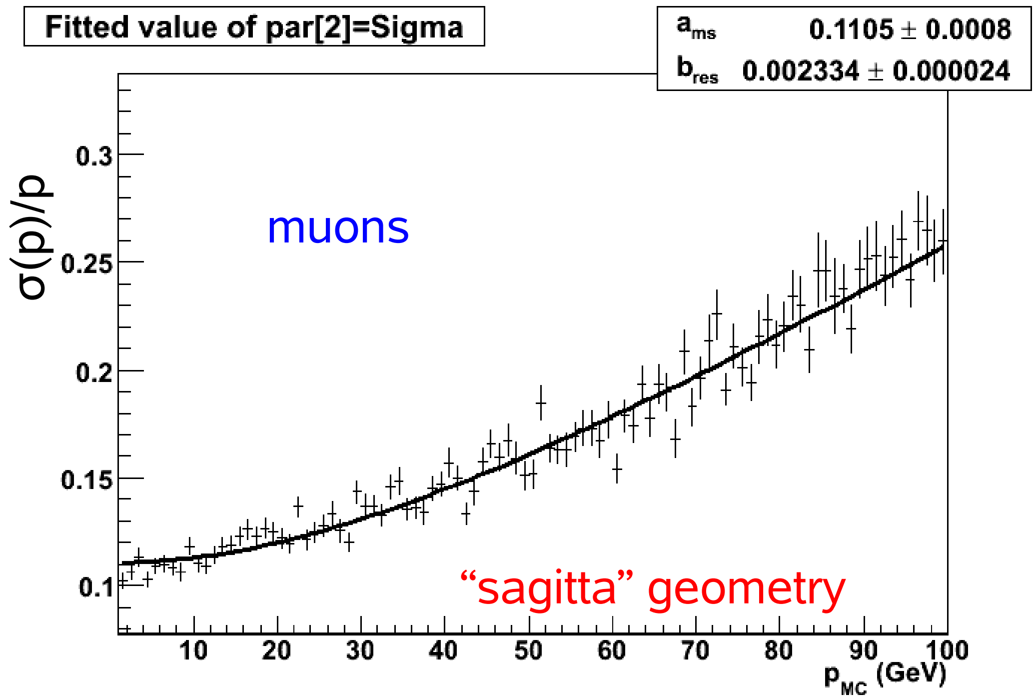


4x same measurement

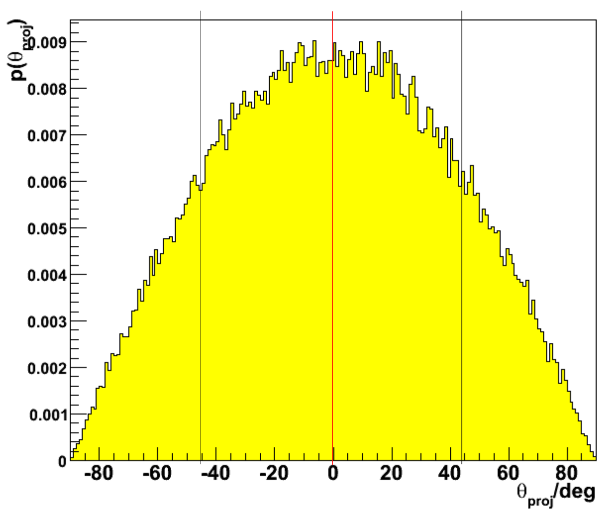


“quarters” fibre

$$\sigma = \frac{250\,\mu m}{4\sqrt{12}} \approx 18\,\mu m$$



distribution of projected angle in bending plane

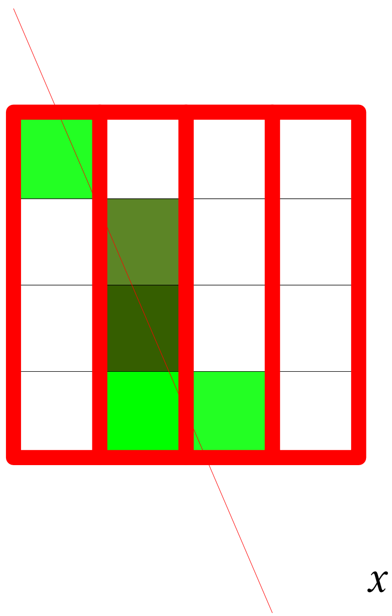


uniform $\cos^2\theta$, ϕ

but ~300000 channels, 450 W power consumption

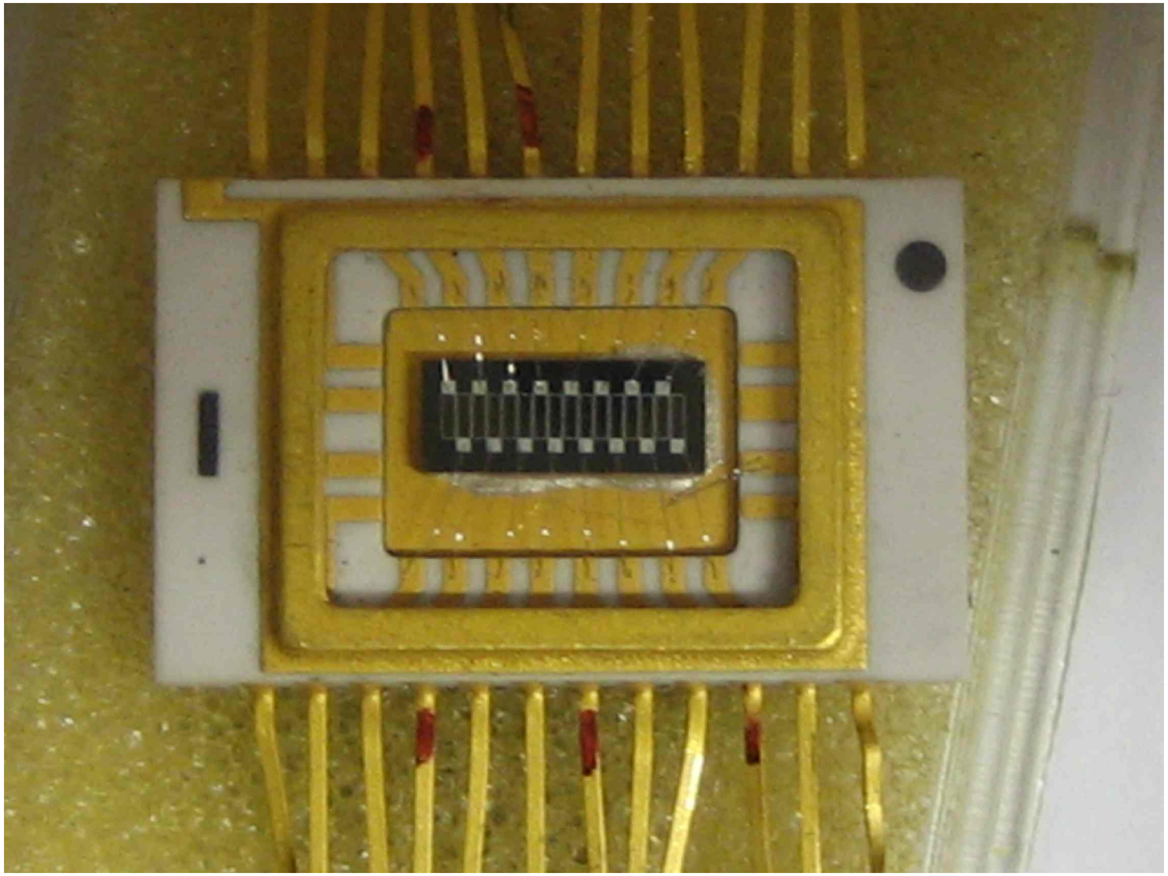
could put several fibres onto same channel, but need to sort fibres and acceptance suffers

Tracker readout scheme



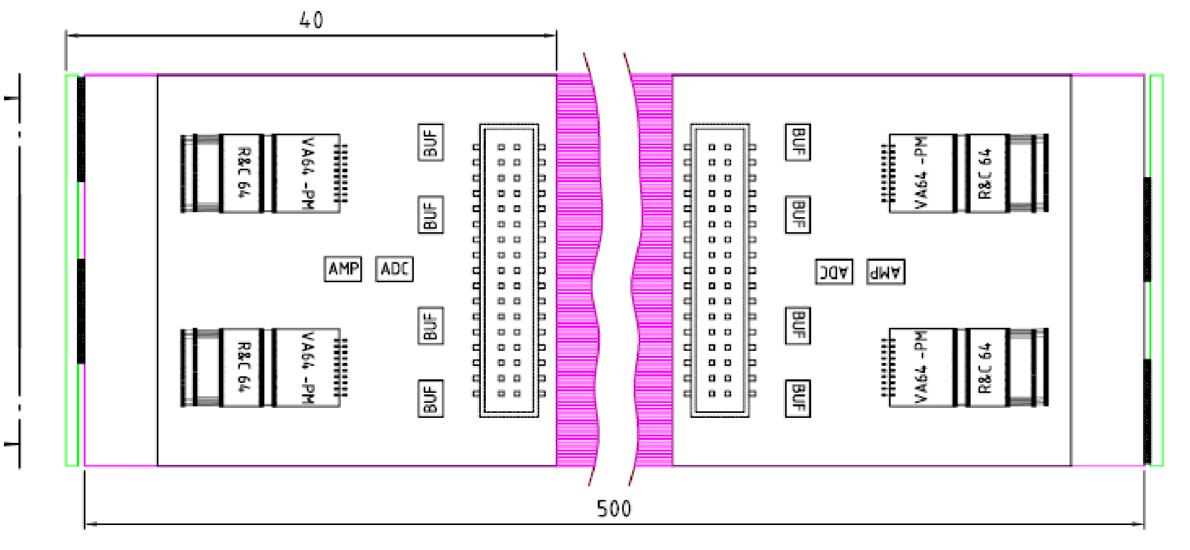
$$x = \frac{\sum x_i A_i}{\sum A_i}$$

4x1 readout scheme (column-wise) with weighted cluster mean
p resolution depends on width, not height
lower number of channels



16x1 silicon photomultiplier, strip width 380 μm
need 32x1, 250μm strip width

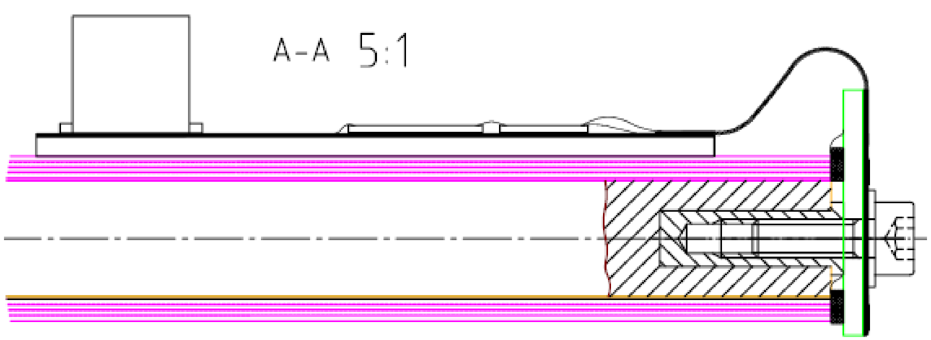
Readout electronics



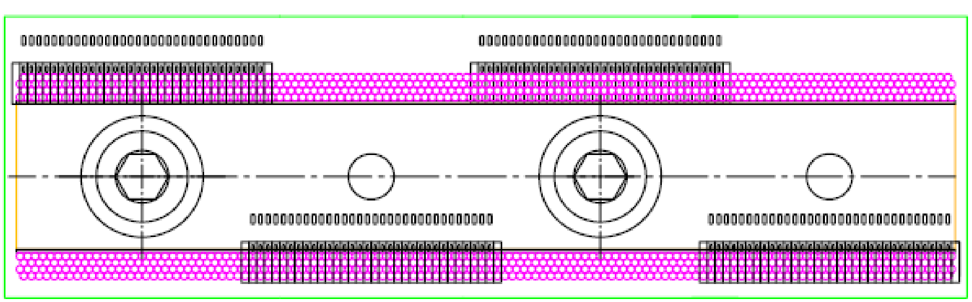
top view

fibres to be read out by silicon photomultipliers

~8x2x17x256=69632 channels
~1.5 mW per channel
→ 100W power consumption

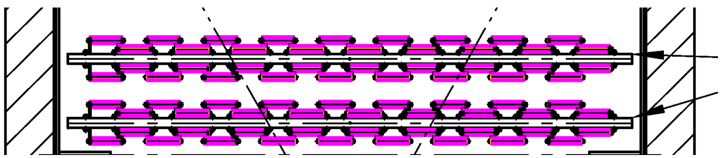


side view



front view

Tracker performance

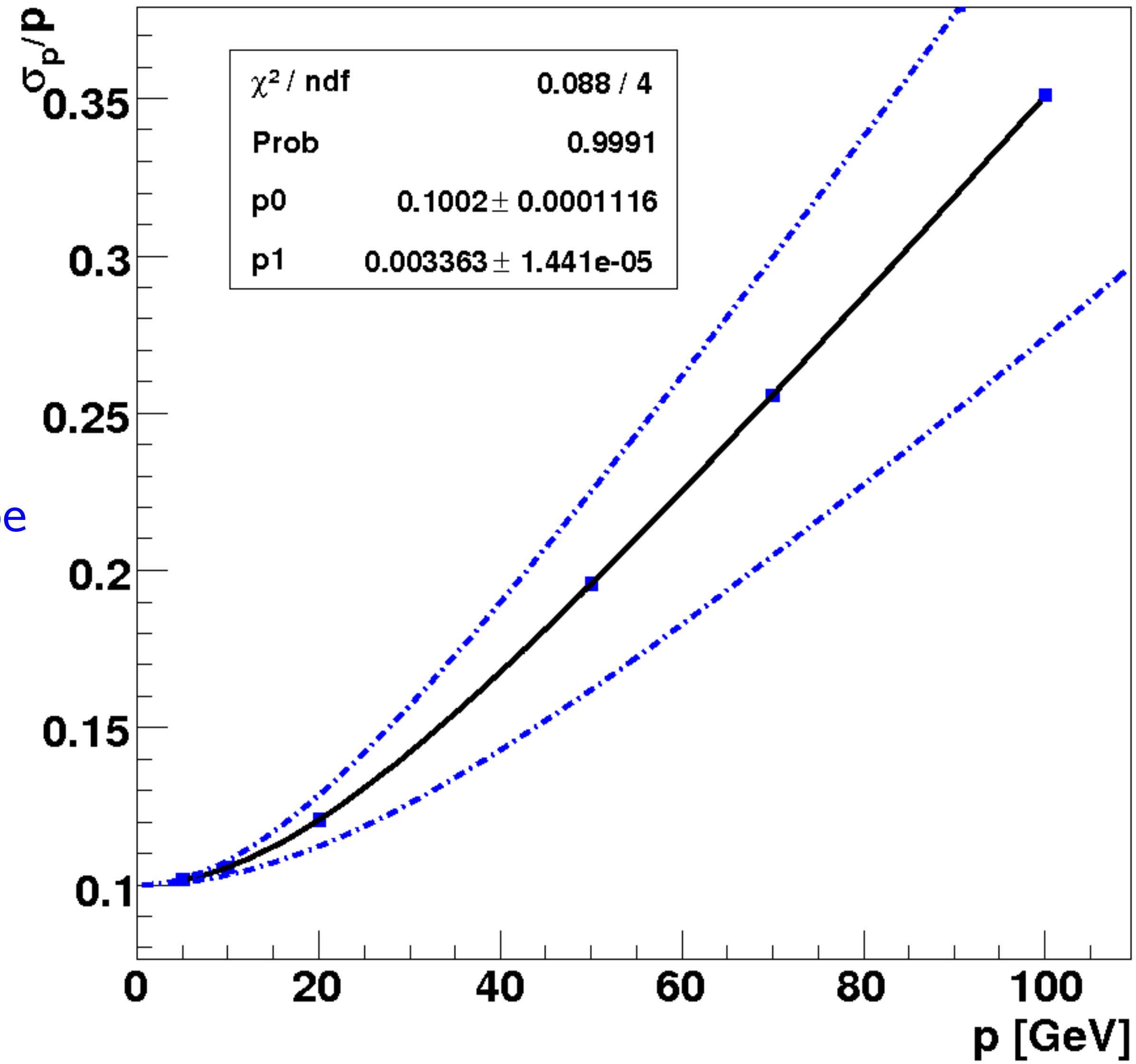


improve resolution:

stereo angle ~±15° between tracker layers

effectively more layers in bending plane, while still able to measure slope

redundancy



momentum resolution for 4x1 readout and stereo angle from fast simulation

Designing the Ecal

Limitations:

Weight	~250 kg
Readout channels	<10000

Choice of absorber material:

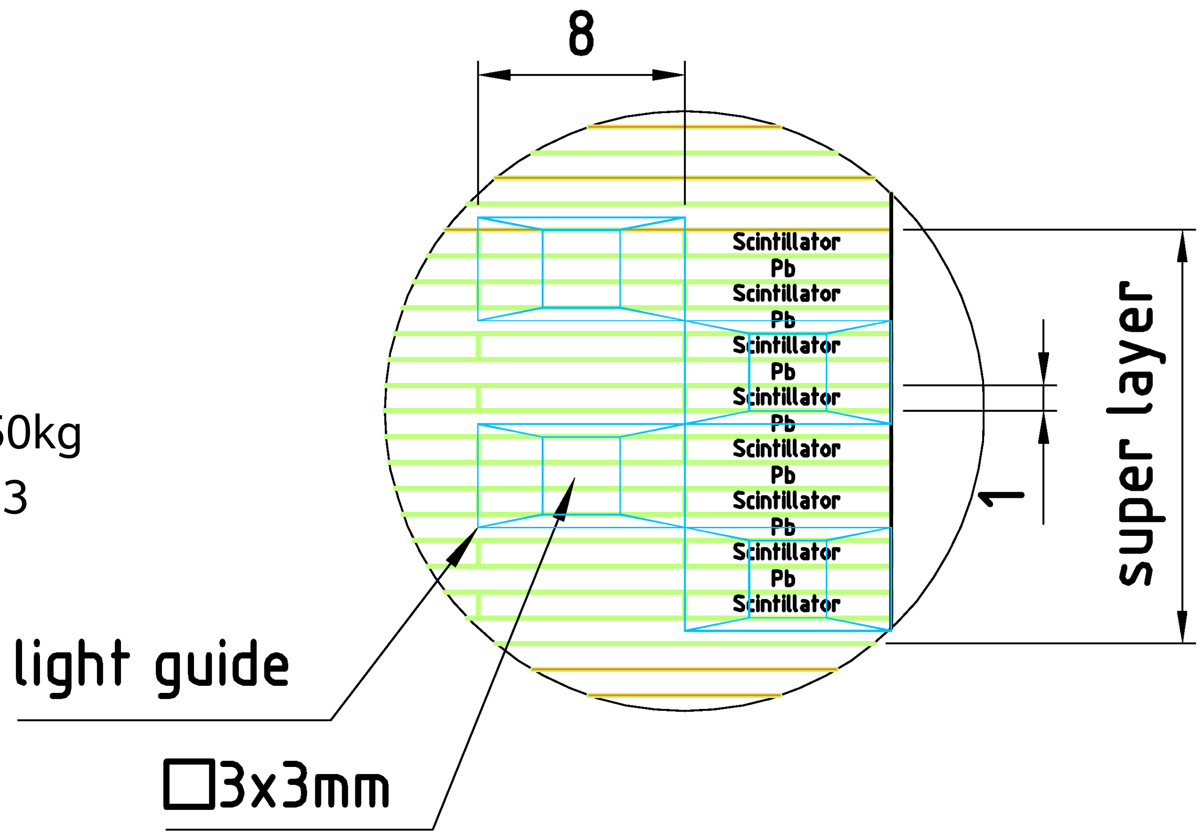
	X_0/λ_I	ρX_0	X_0 in 250kg
lead	0.0328	6.37 g/cm^2	15.3

sampling calorimeter:

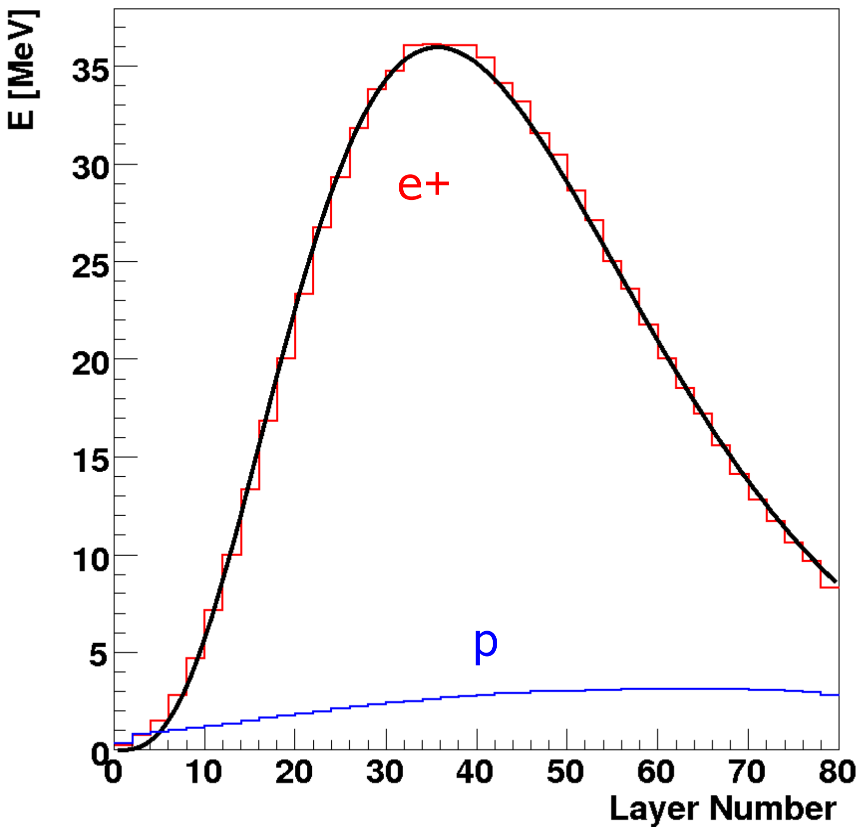
80 layers

1mm absorber

1mm scintillating fibres

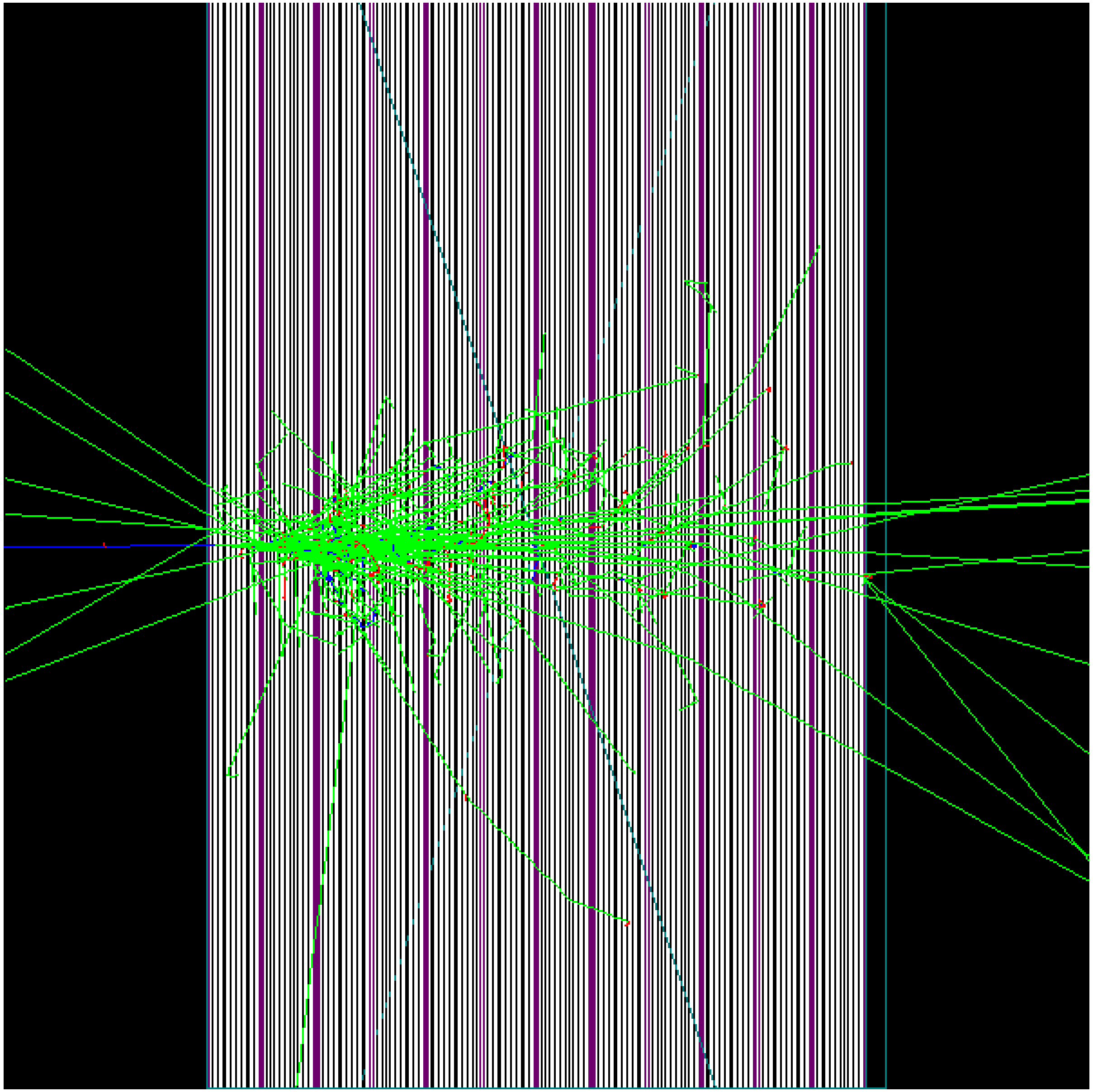


Ecal shower



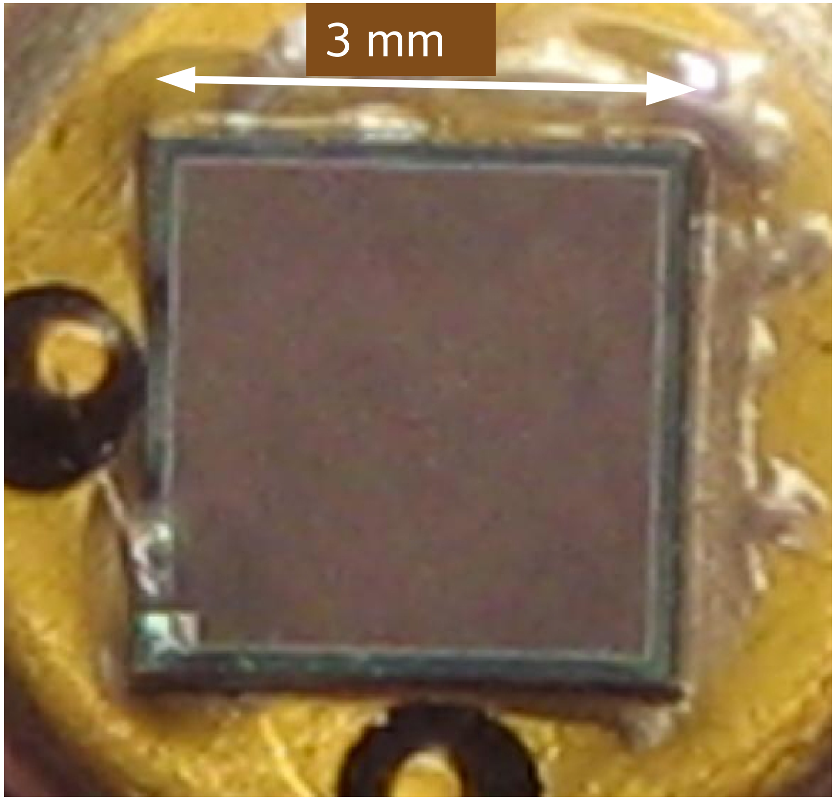
$$\frac{dE}{dt} = E_0 \frac{b^{\alpha+1}}{\Gamma(\alpha+1)} t^{\alpha} e^{-bt}$$

$t = x/X_0$

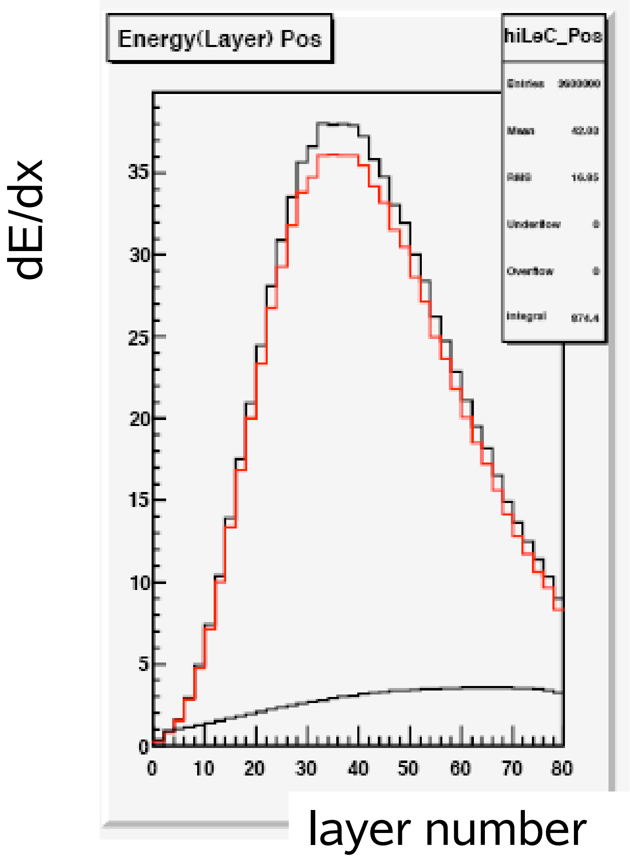


1 GeV e+ ECAL shower simulated by Geant4 simulation

Ecal digitization

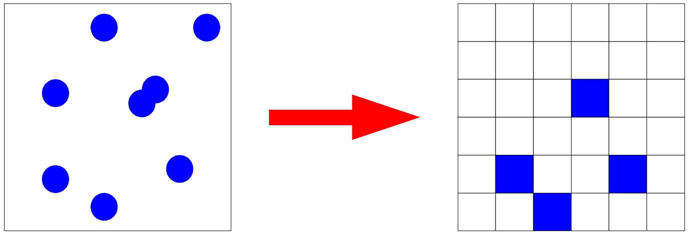


3x3 mm array: 8100 pixel



before digitization
after digitization

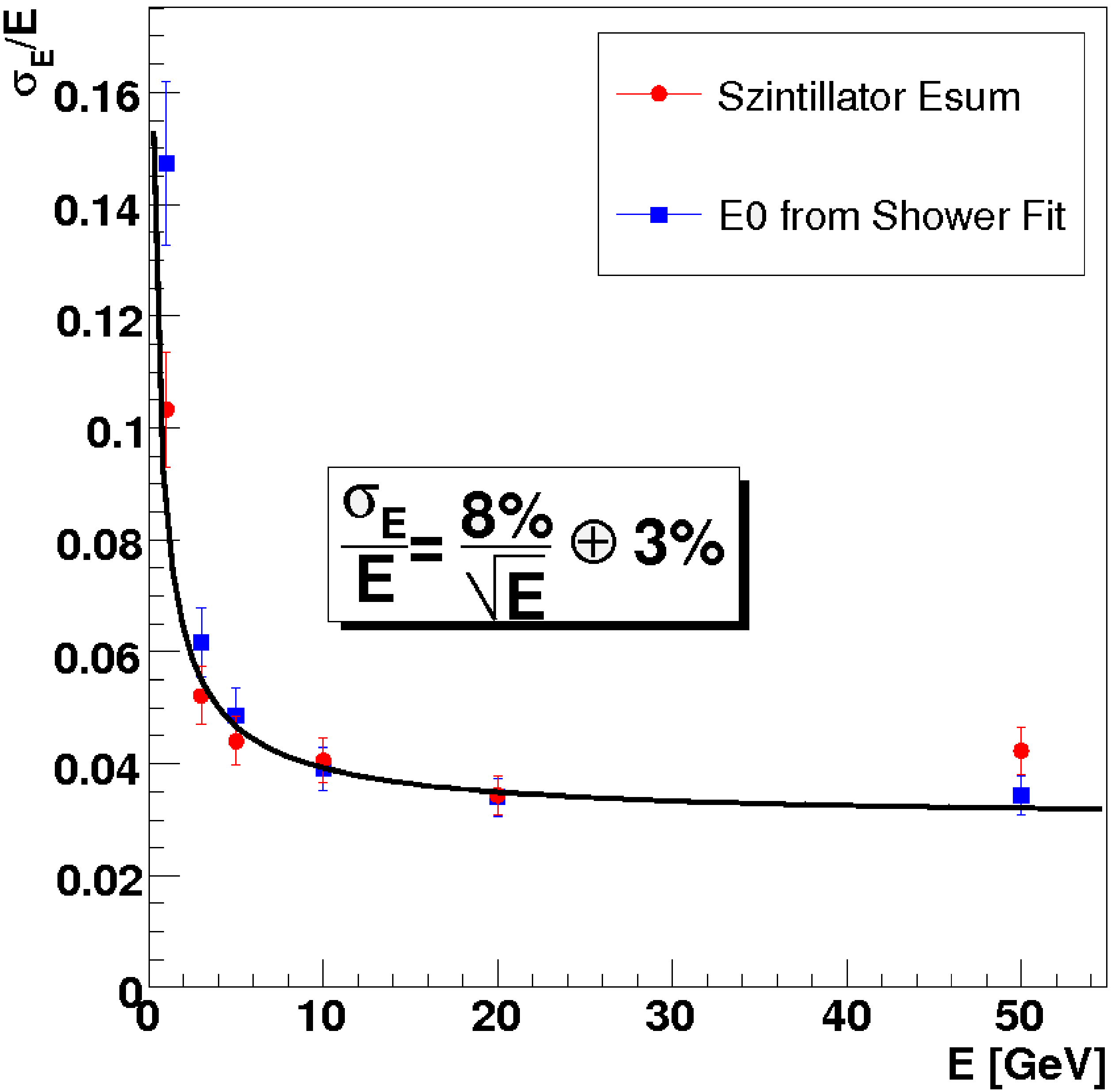
digitization:



photons at fibre end

pixel array

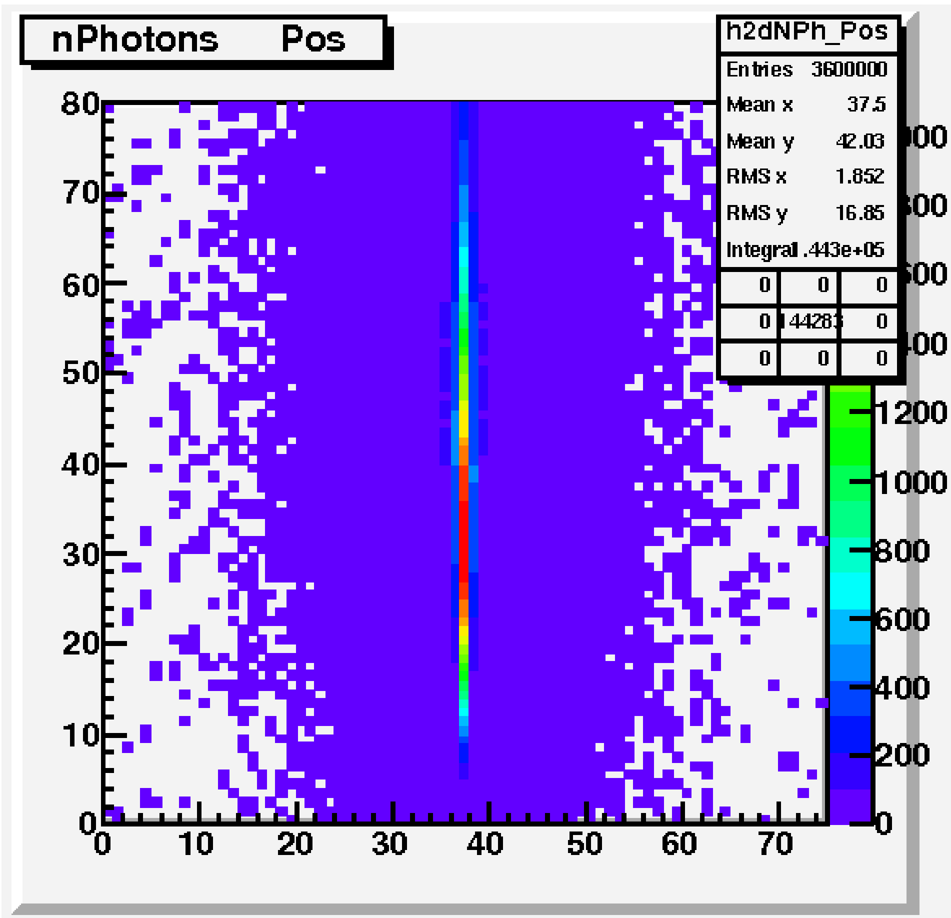
Ecal energy resolution



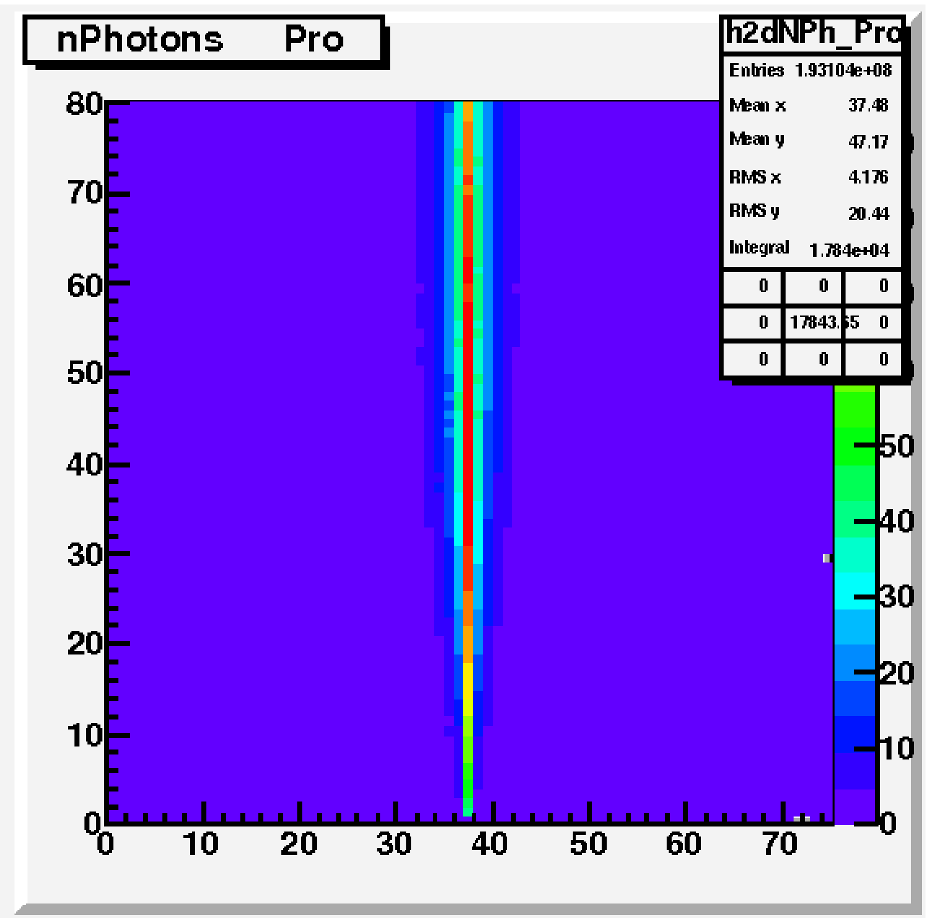
$$\sigma\frac{(E)}{E}=\sqrt{\left(\frac{a}{\sqrt{E}}\right)^2+b^2}$$

Shower shape analysis

fast simulation of Ecal showers

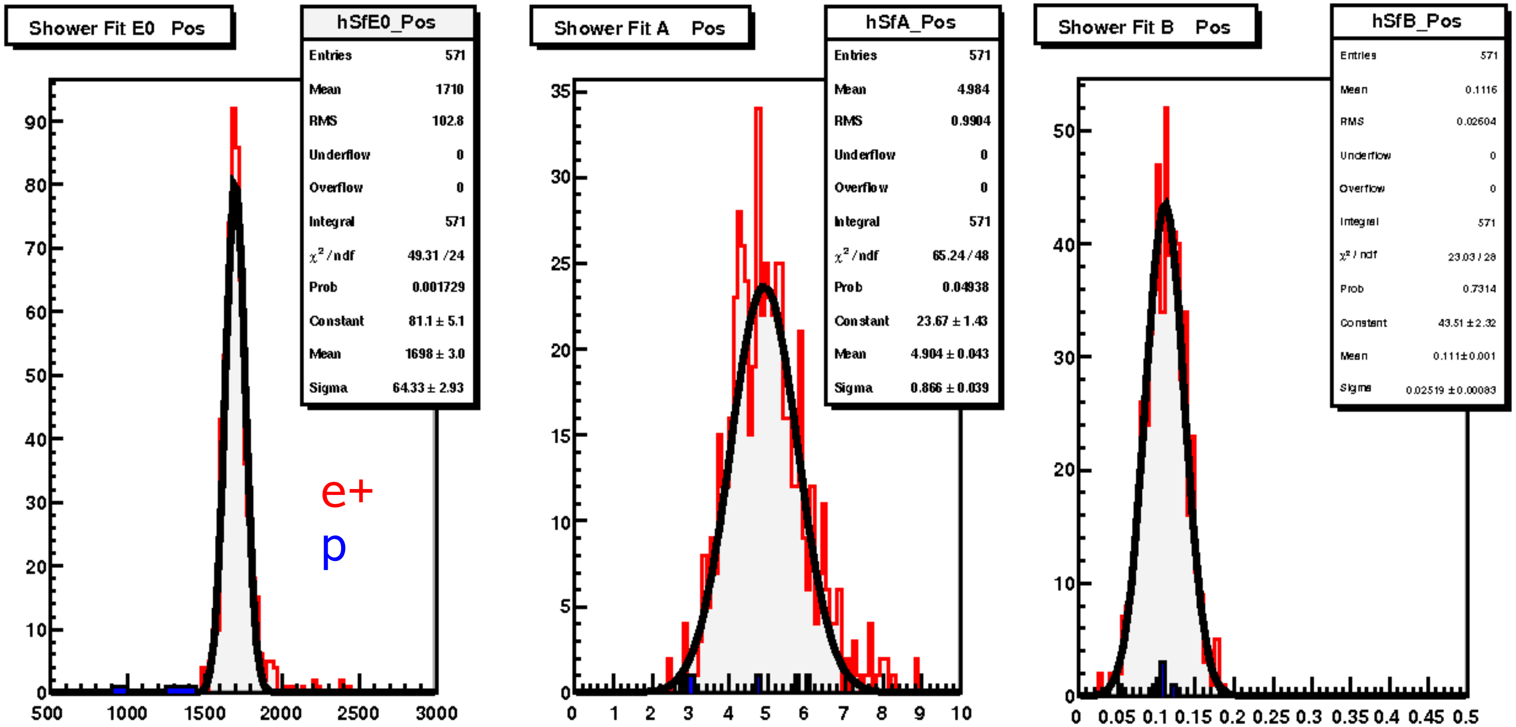


positrons

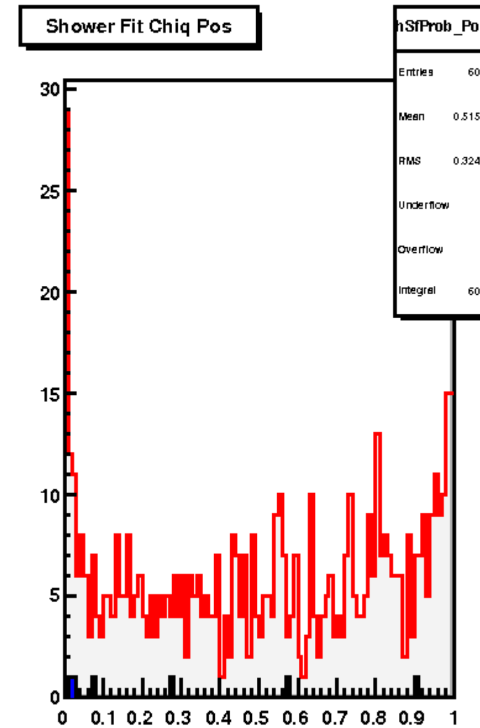


protons

Shower shape fits



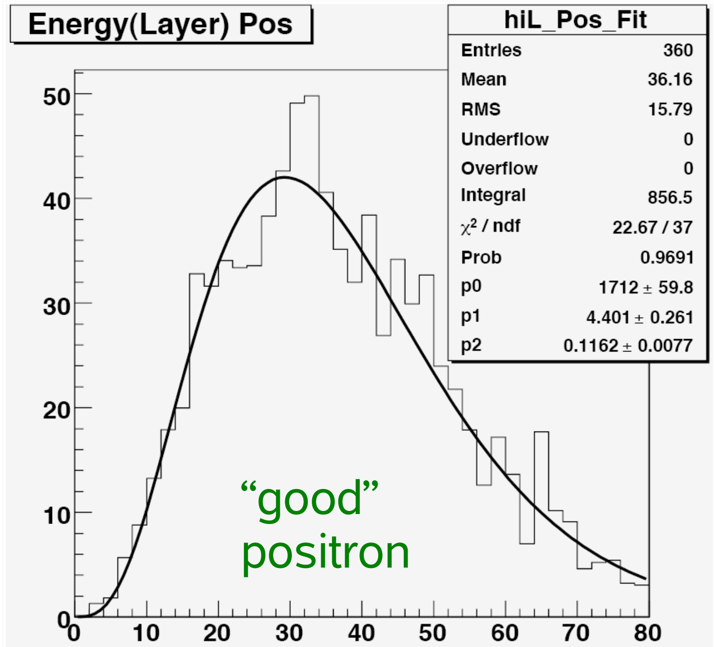
shower shape fits for parameters E_0, a, b from fast simulation

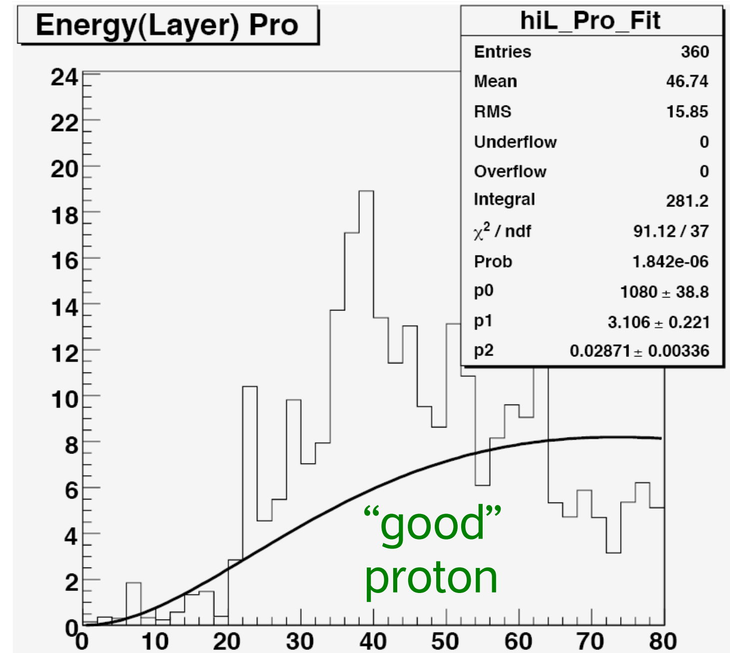


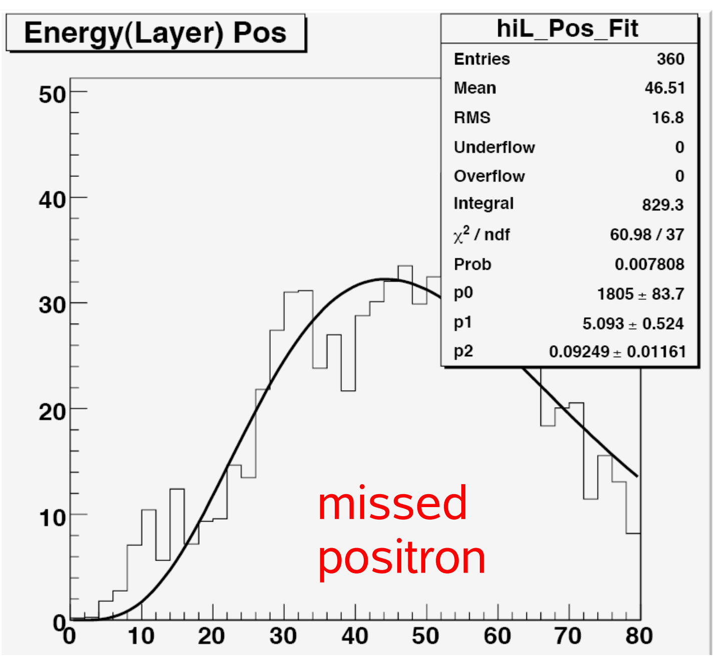
shower fit χ^2 probability distribution

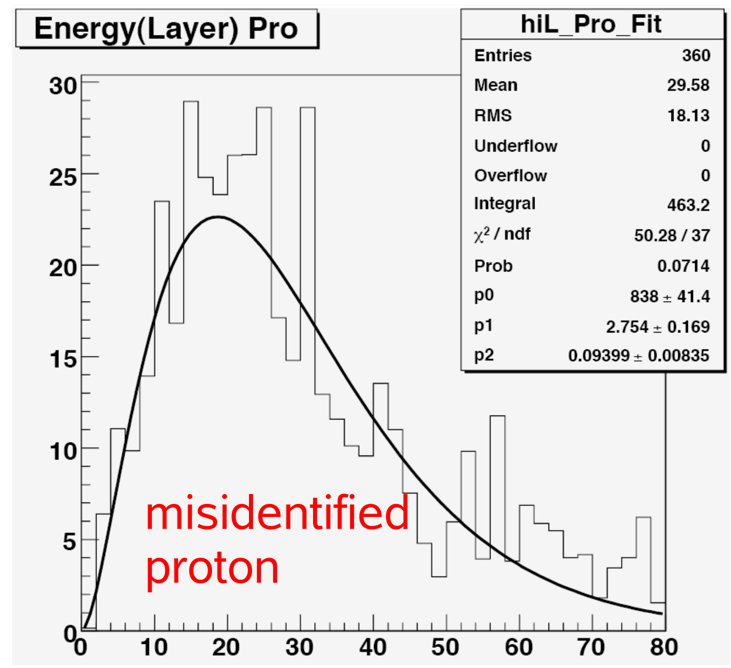
proton rejection at 10 GeV: 5000^{+3800}_{-1600}
at 90±2% positron efficiency

Misreconstructed showers



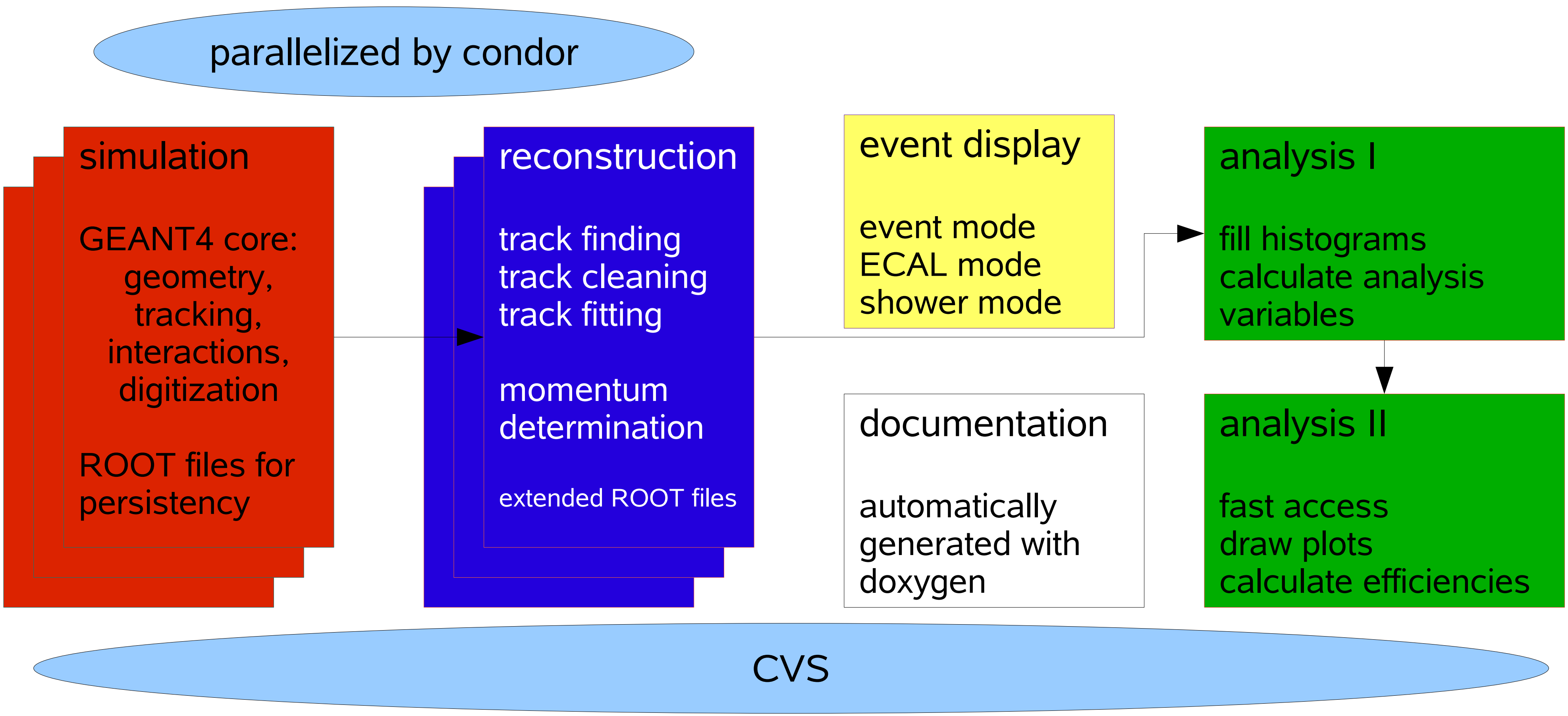






Introduction to software

- A software package for simulation, reconstruction, event display and analysis has been developed.
- Written in C++, uses GEANT4 and ROOT and some external libraries.



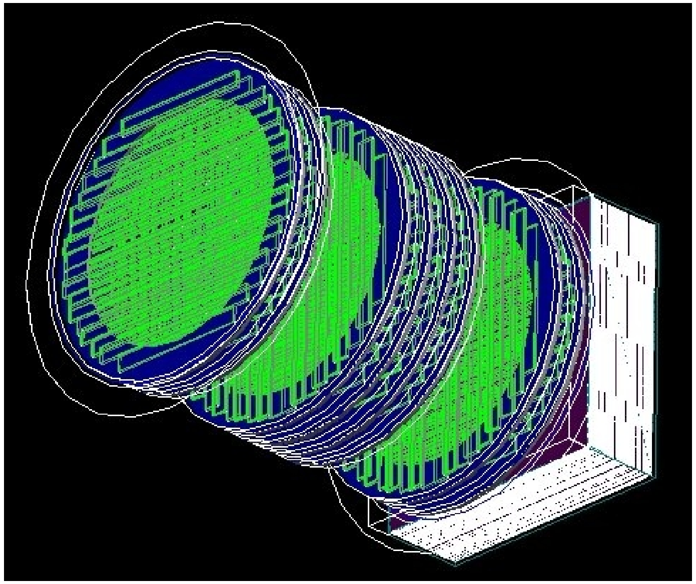
Software: Simulation

GEANT 4: C++ toolkit for simulation of passage of particles through matter, with applications in high energy, nuclear and accelerator physics, as well as medical and space sciences.
User input by implementations of abstract base classes.

detector construction	particle gun	physics list
tracker, ECAL, magnet, support structures	random momentum, direction, origin	“best-guess” QGSP: theory-driven modeling for reactions of energetic hadrons; quark-gluon string model; Berini cascade below 3 GeV

parameters adjustable through GEANT4 interactive command system

tracking	4^{th} order Runge-Kutta stepper in customizable magnetic field
interactions	Geant4 offers very flexible, but complicated framework secondaries are produced and tracked
hits	produced by sensitive detectors, detailed information available
digitization	simulates output by true detector; simulation of noise $Amp = \sum_{fibre} E_{dep} \cdot \epsilon(L,x) \cdot g$
persistency	ROOT files: run header, events: tracker and ECAL digis, MC tracks

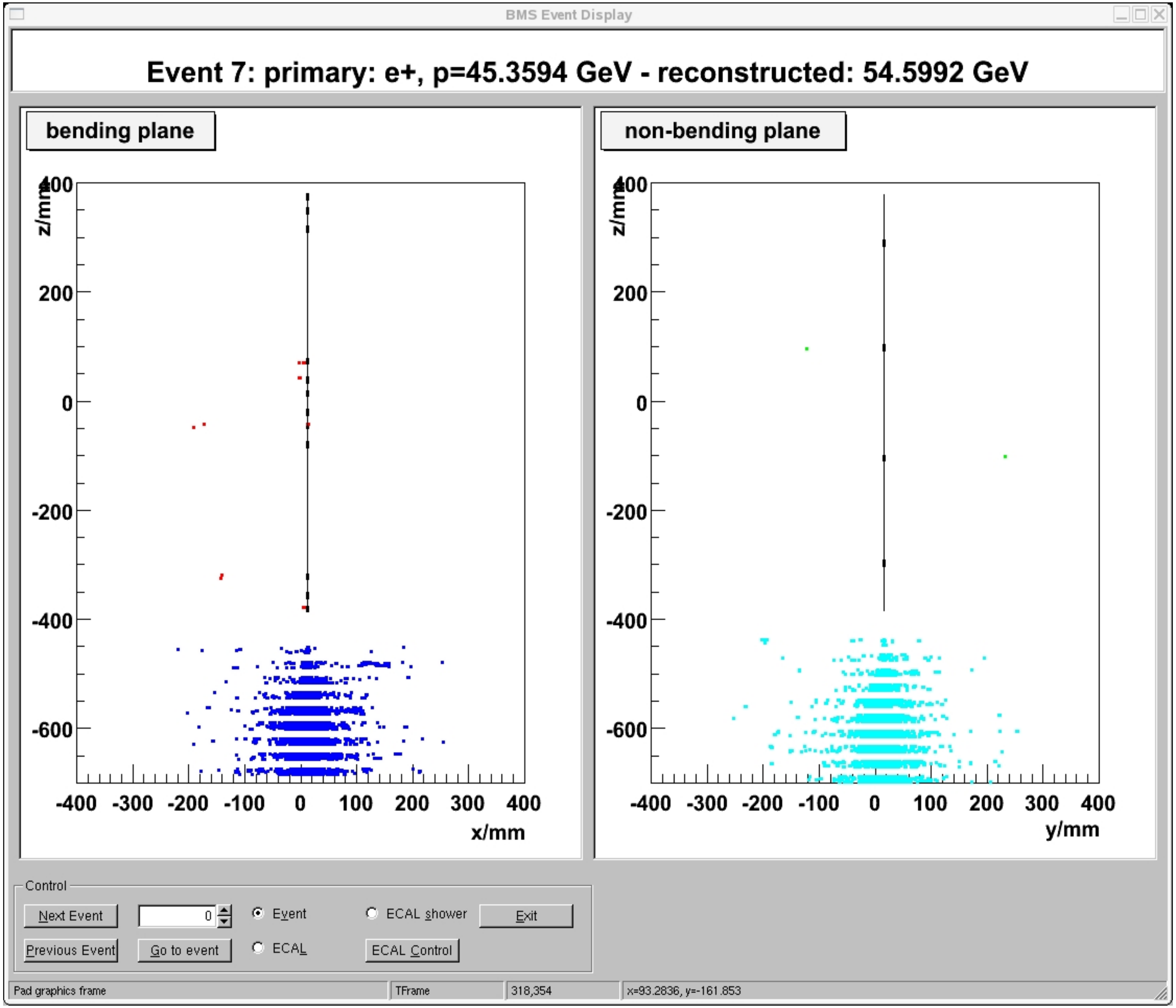


Software: Event display and reconstruction

Reconstruction:
Track finding, cleaning, fitting.
Different algorithms available.

Fast event display exists for browsing simulation and reconstruction result files.
Based on ROOT GUI facilities.

event mode:
tracker digis
ECAL digis
reconstructed tracks
digis used in track

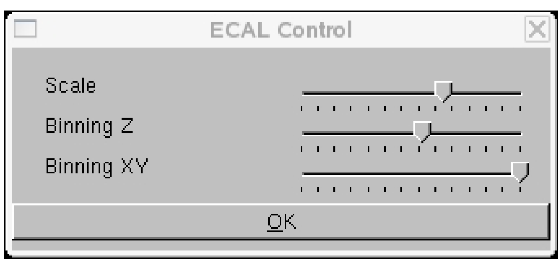


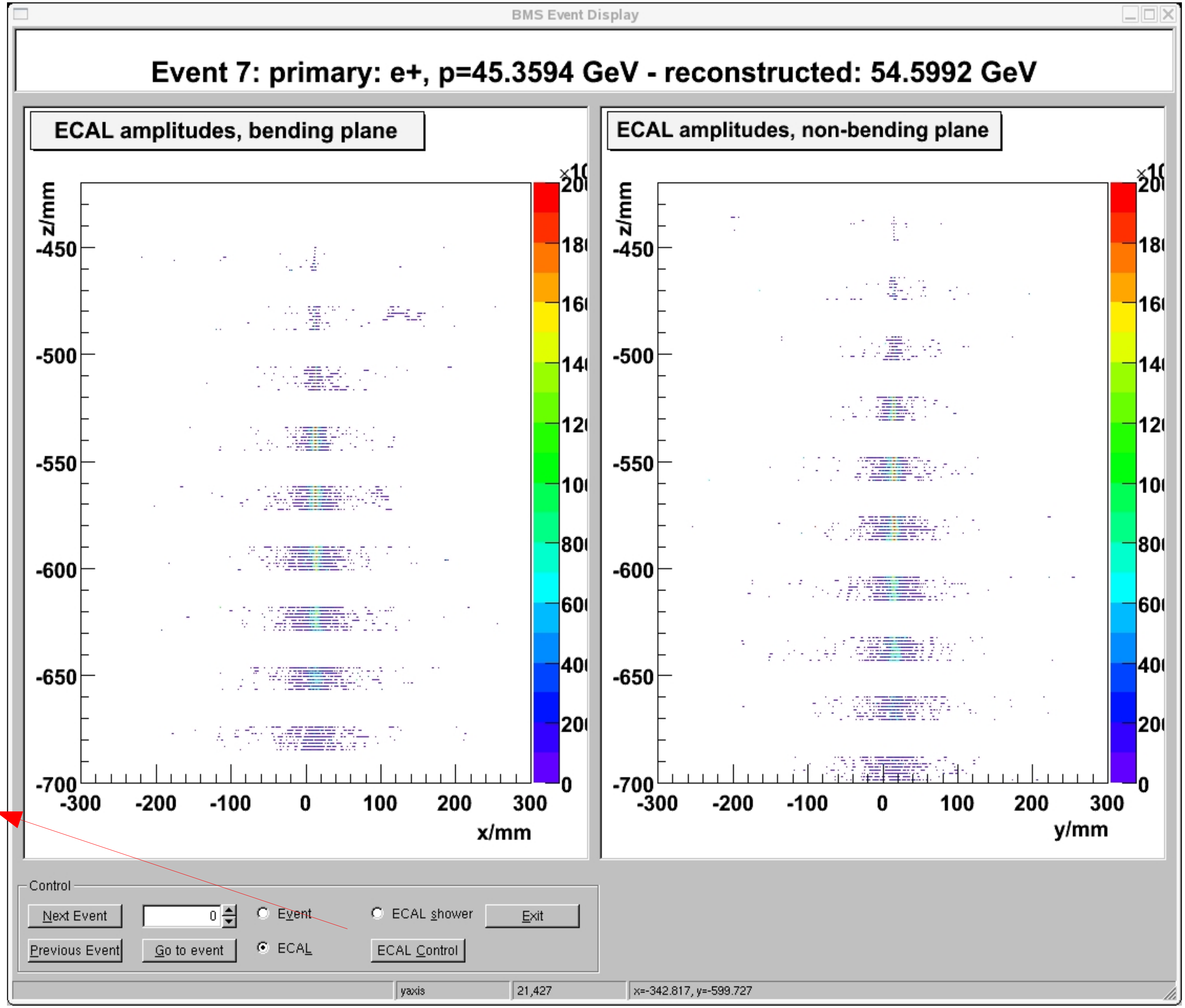
Software: Event display

ECAL mode:

ECAL shower histogram

scale and binning adjustable online





Summary

- Indirect dark matter search relies on precise measurement of the cosmic-ray positron fraction, not yet done.
- Dedicated balloon-borne detector proposed, based on scintillating fibre tracker and sampling e.m. calorimeter.
- Software framework for simulation, reconstruction, display and analysis exists.
- Atmospheric background under study.
- First measurements of fibre properties have begun.
- A lot of work ahead...