Calorimeters inside Detectors at Colliders

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Outline

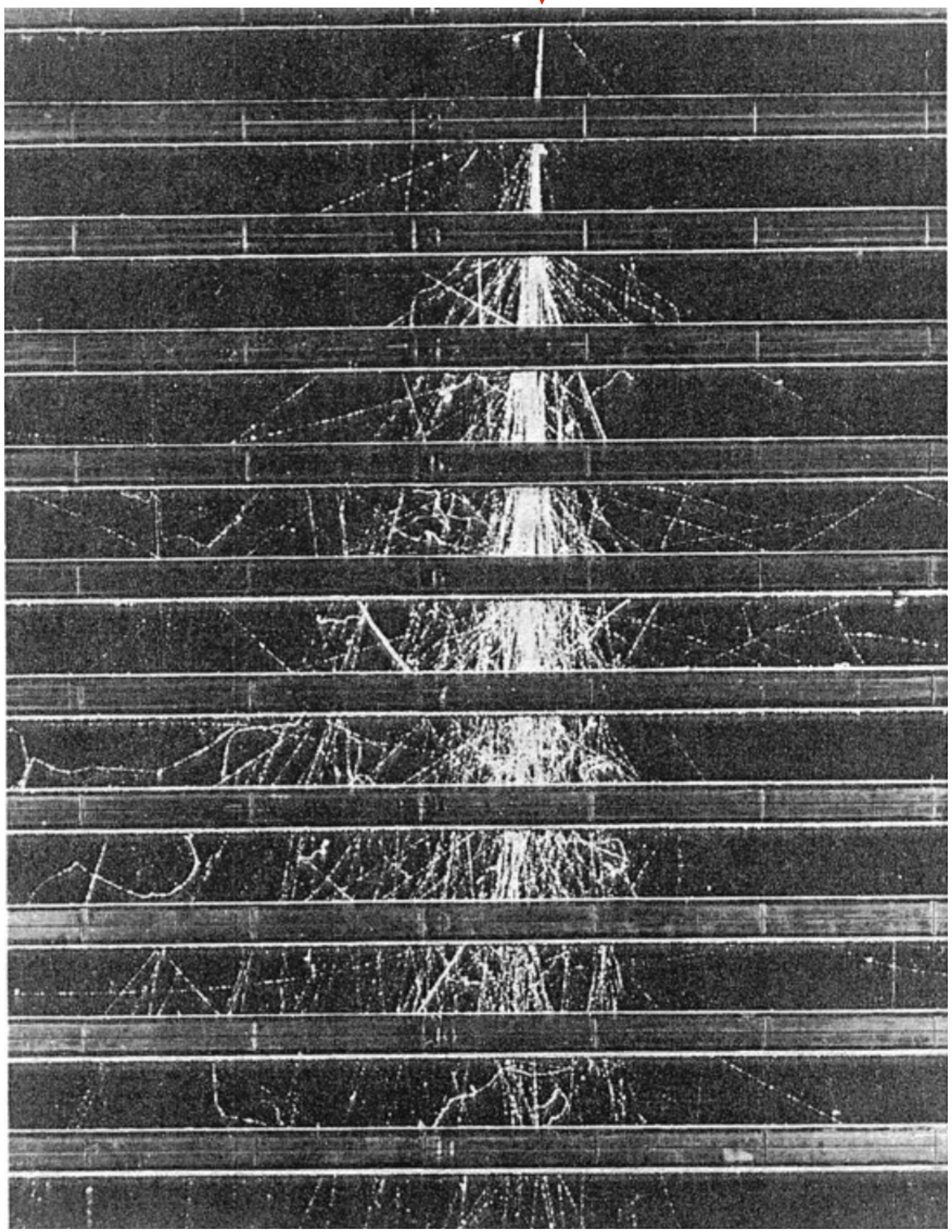
- Images of events in calorimeters, both data and simulation
- Calorimeters in relation to other sub-detectors
- Basics: energy, spatial and time resolutions
- "Unification" of all particles of the standard model
- How to get there (two leading well-studied options)
  * Classic absorption calorimetry (e.g., RD52, dual-readout)
  * Particle Flow analysis (e.g., CALICE)
- Free advice

Deep Background

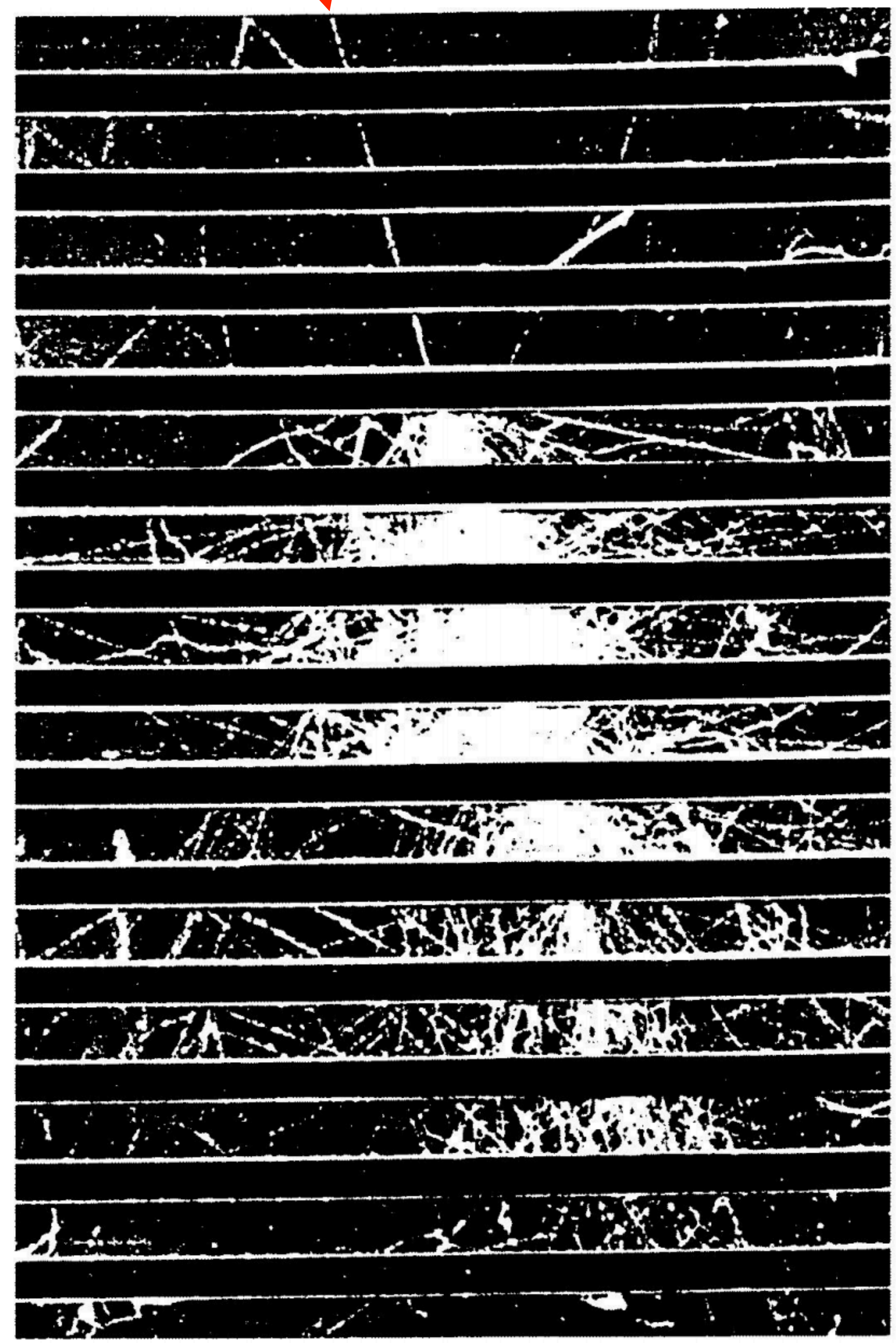
- *Calorimetry - Energy Measurement in Particle Physics*, R. Wigmans, Oxford University Press, 2ed (2017)
- RD52 http://www.phys.ttu.edu/~dream/
- CALICE https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

Cloud chamber photographs ~ 1950. *Calorimeter measurement is totally destructive.*

electron
(~5 GeV)

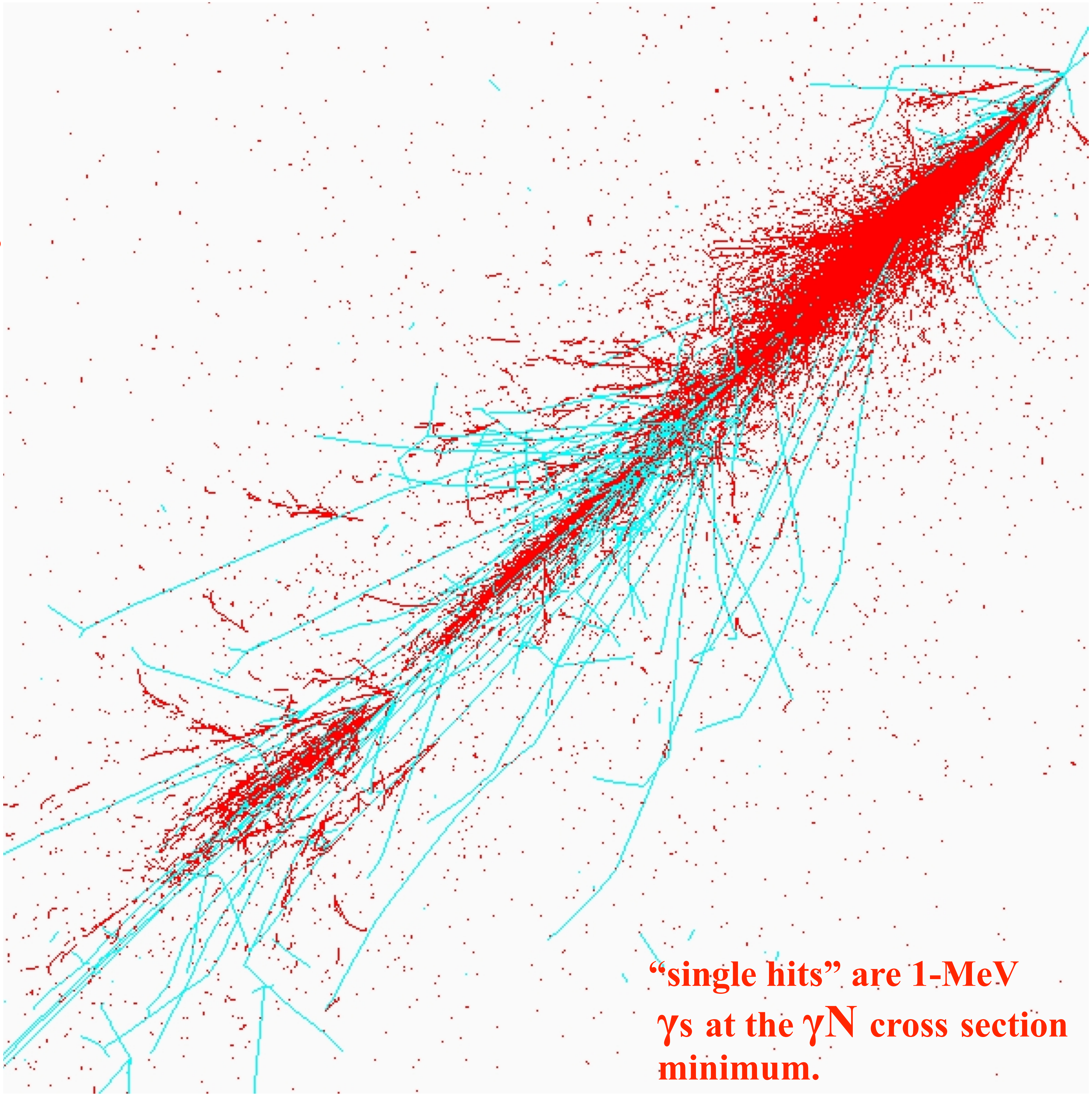


proton
(~10 GeV)



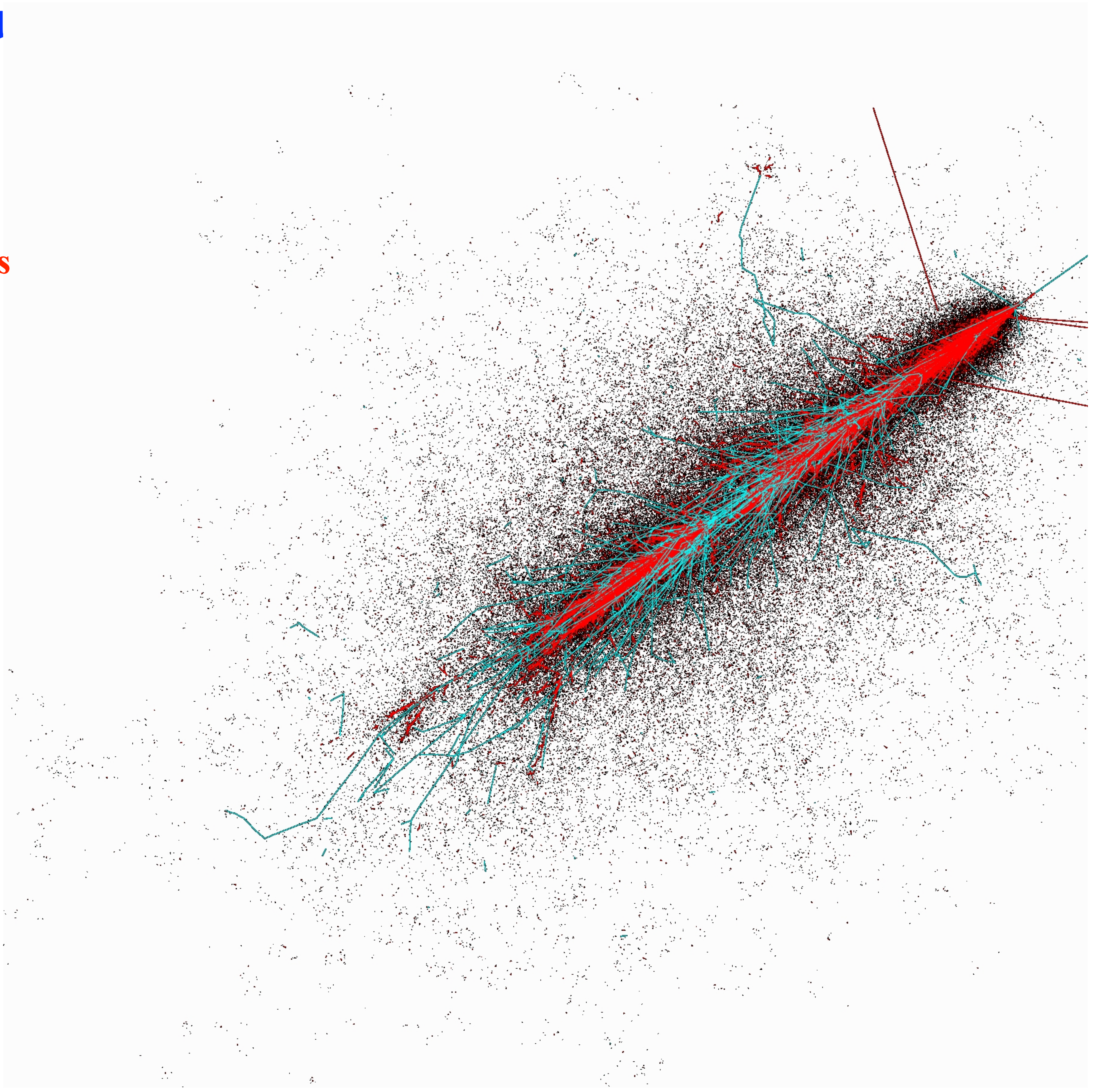
500 GeV p-Cu

Red: electrons & positrons
Blue: charged hadrons



1000 GeV p-Cu

Red: electrons & positrons
Blue: charged hadrons
Black: photons



1000 GeV p-Cu

Red: electrons & positrons
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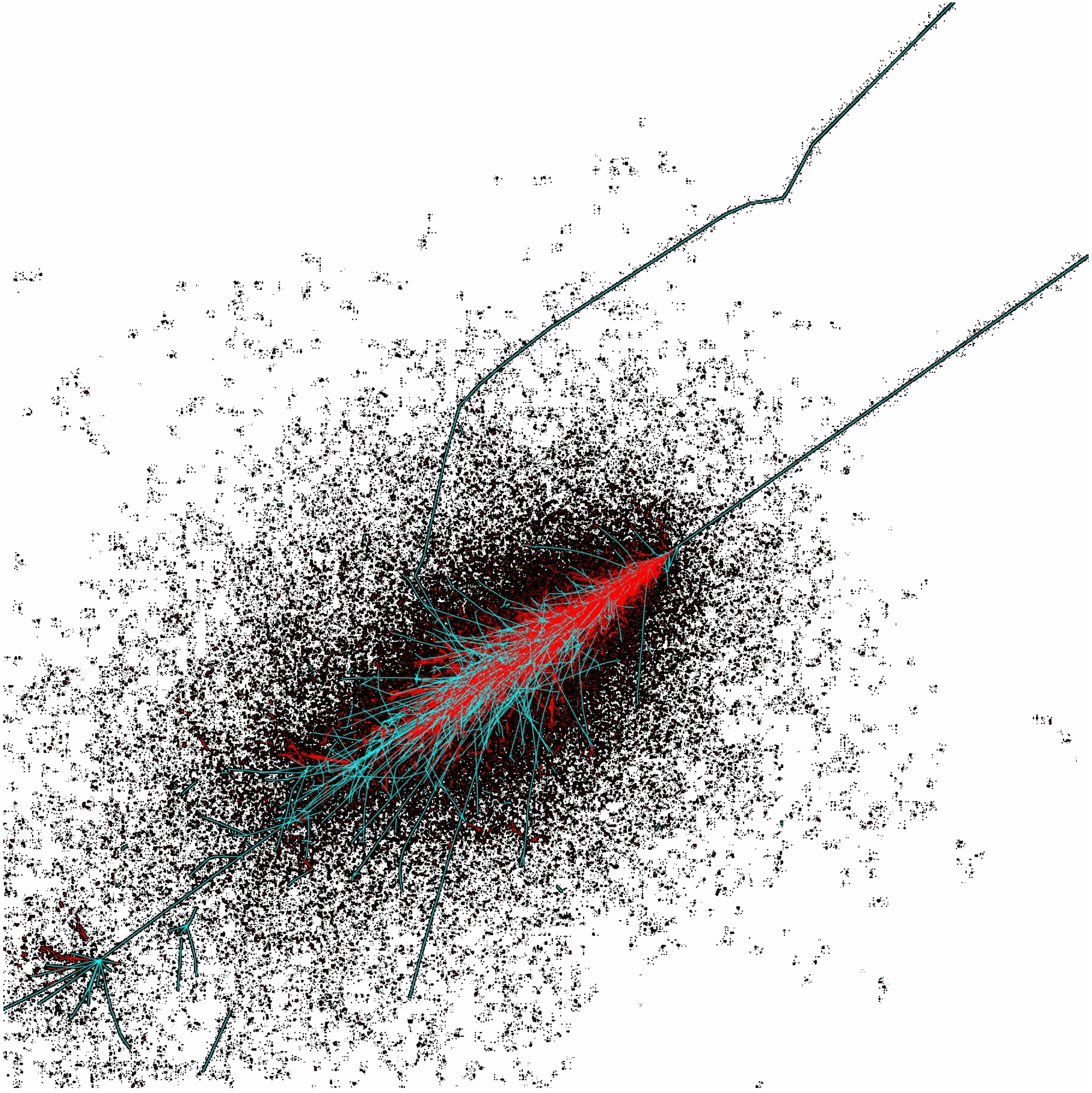
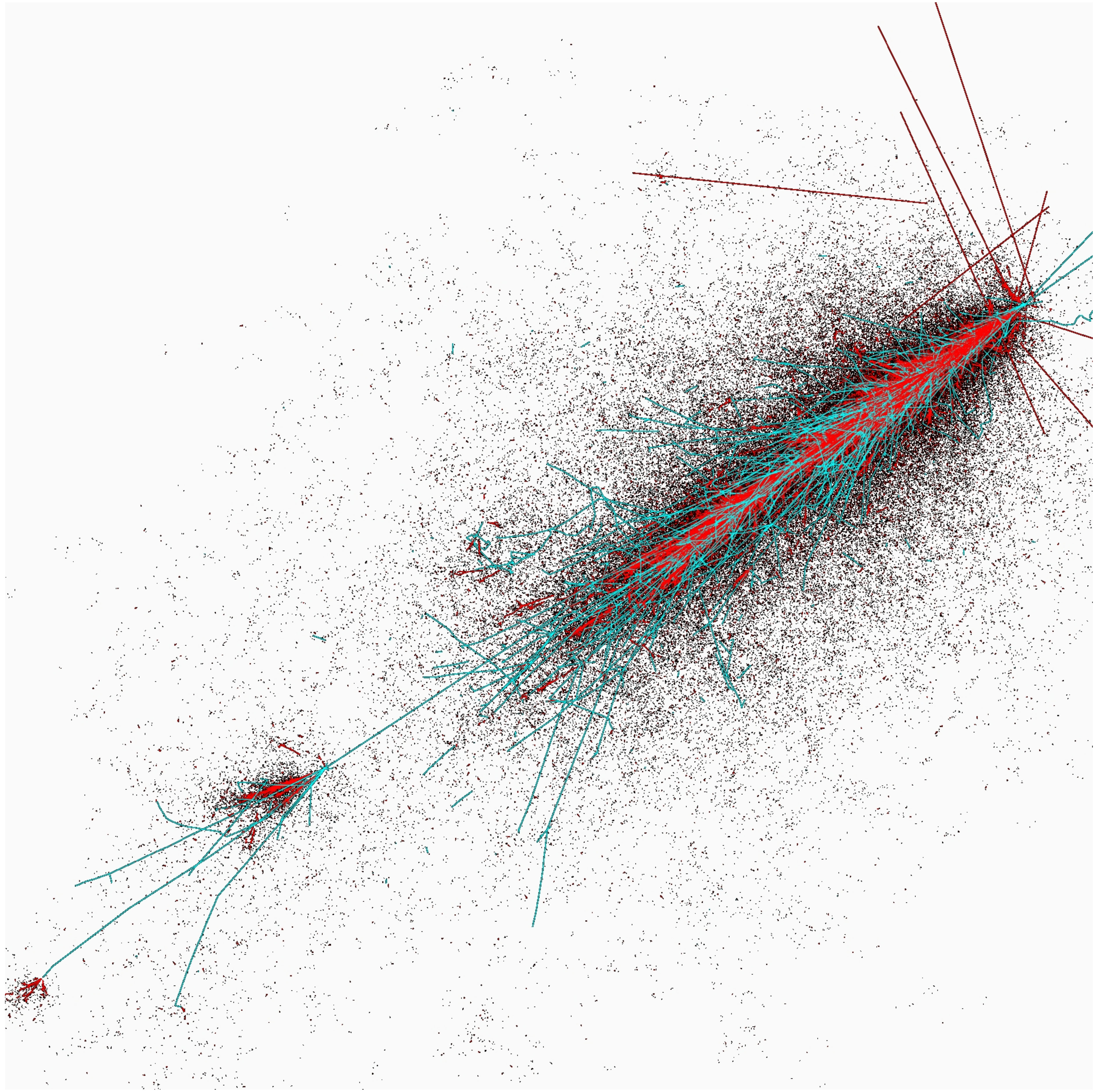


1000 GeV p-Cu

Red: electrons & positrons
Blue: charged hadrons
Black: photons



Calorimeters in relation to other sub-detectors: Magnetic Detector

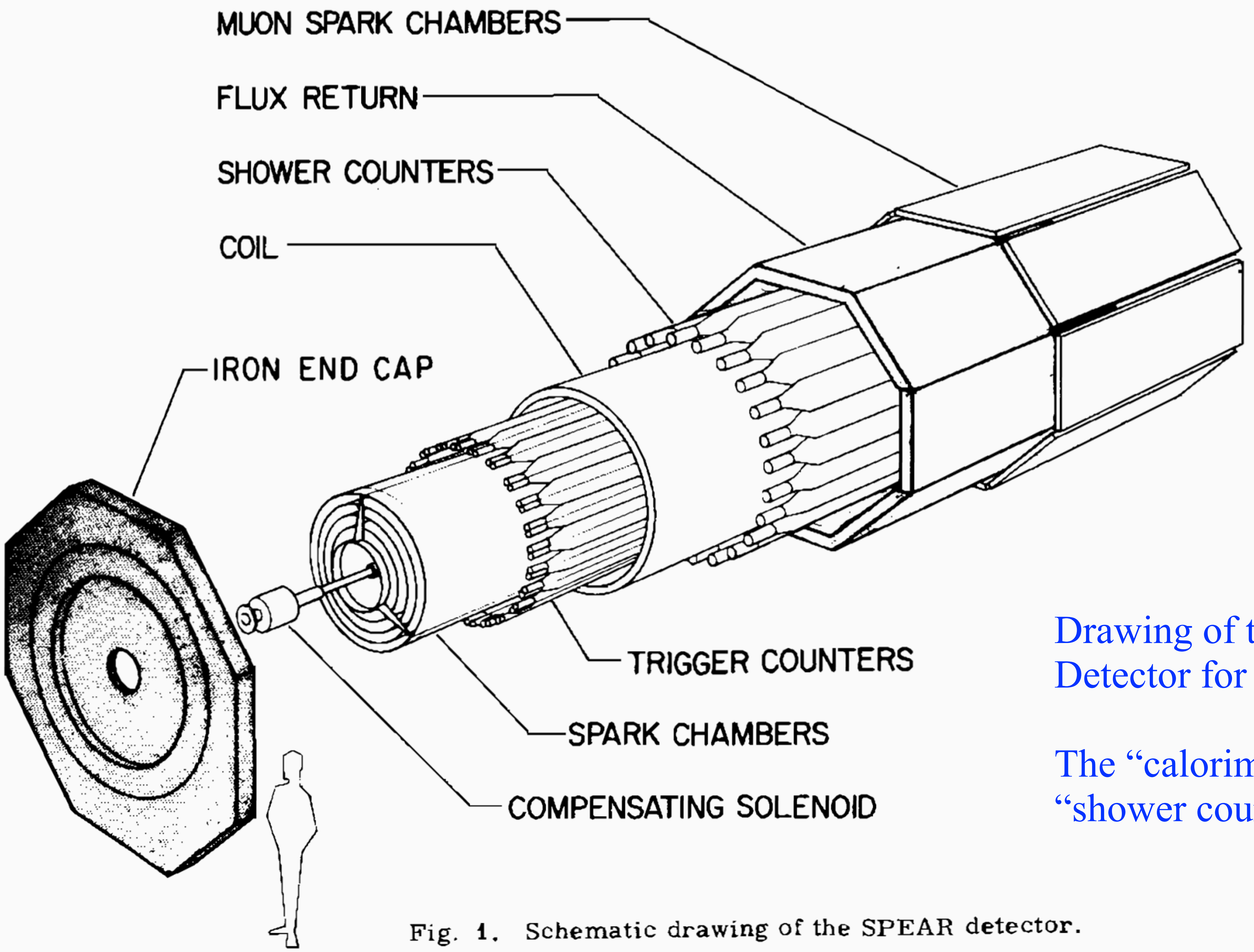


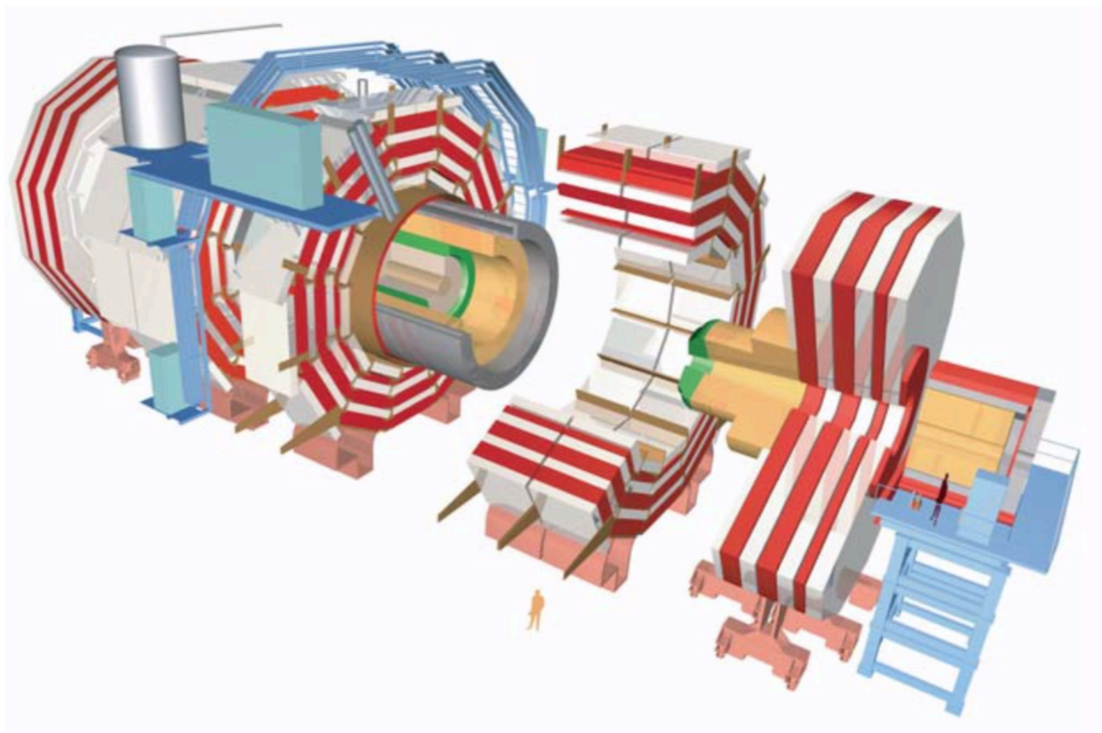
Fig. 1. Schematic drawing of the SPEAR detector.

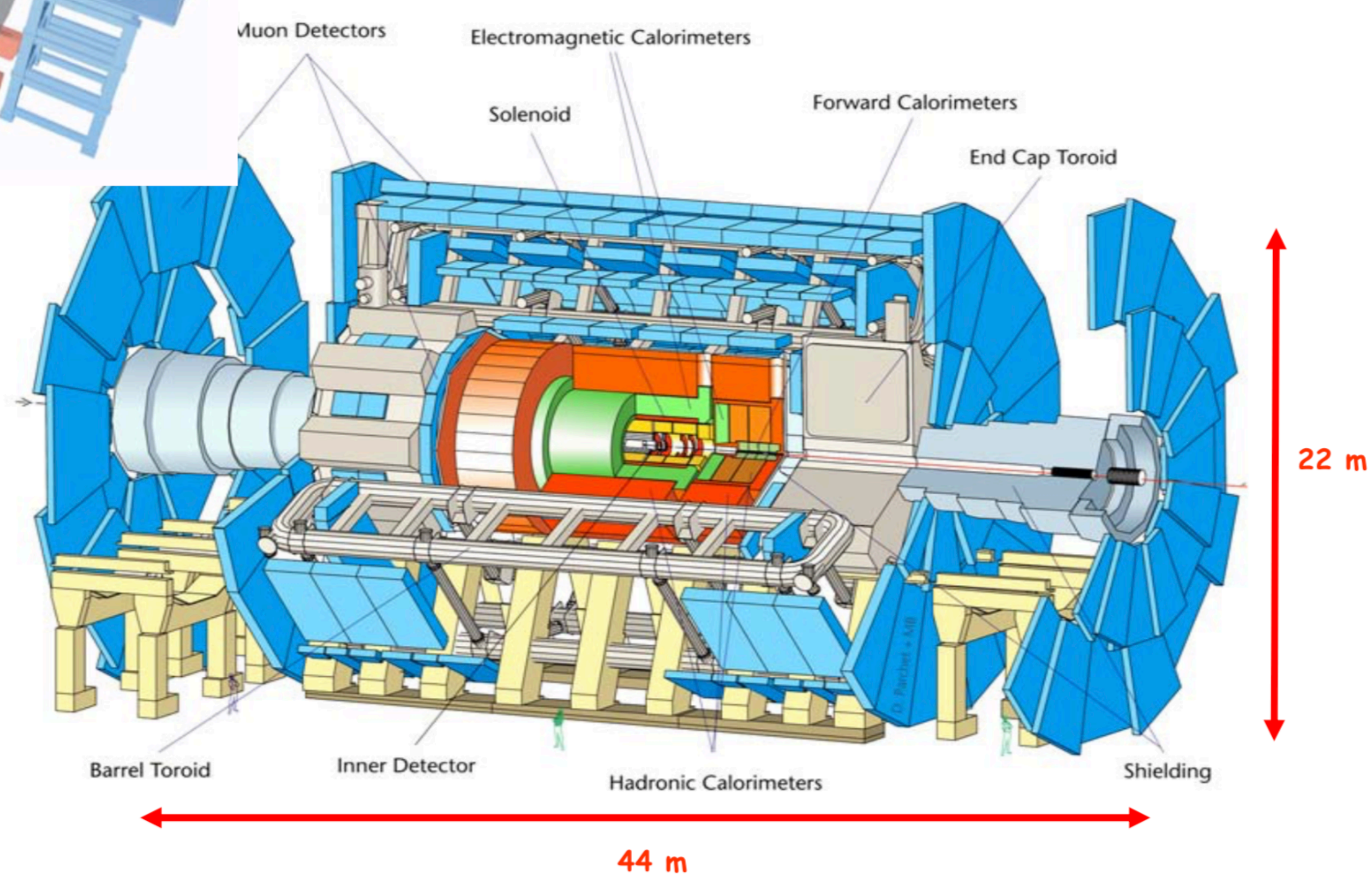
Drawing of the Magnetic Detector for SPEAR in 1972.

The "calorimeter" is the "shower counter."

… same idea

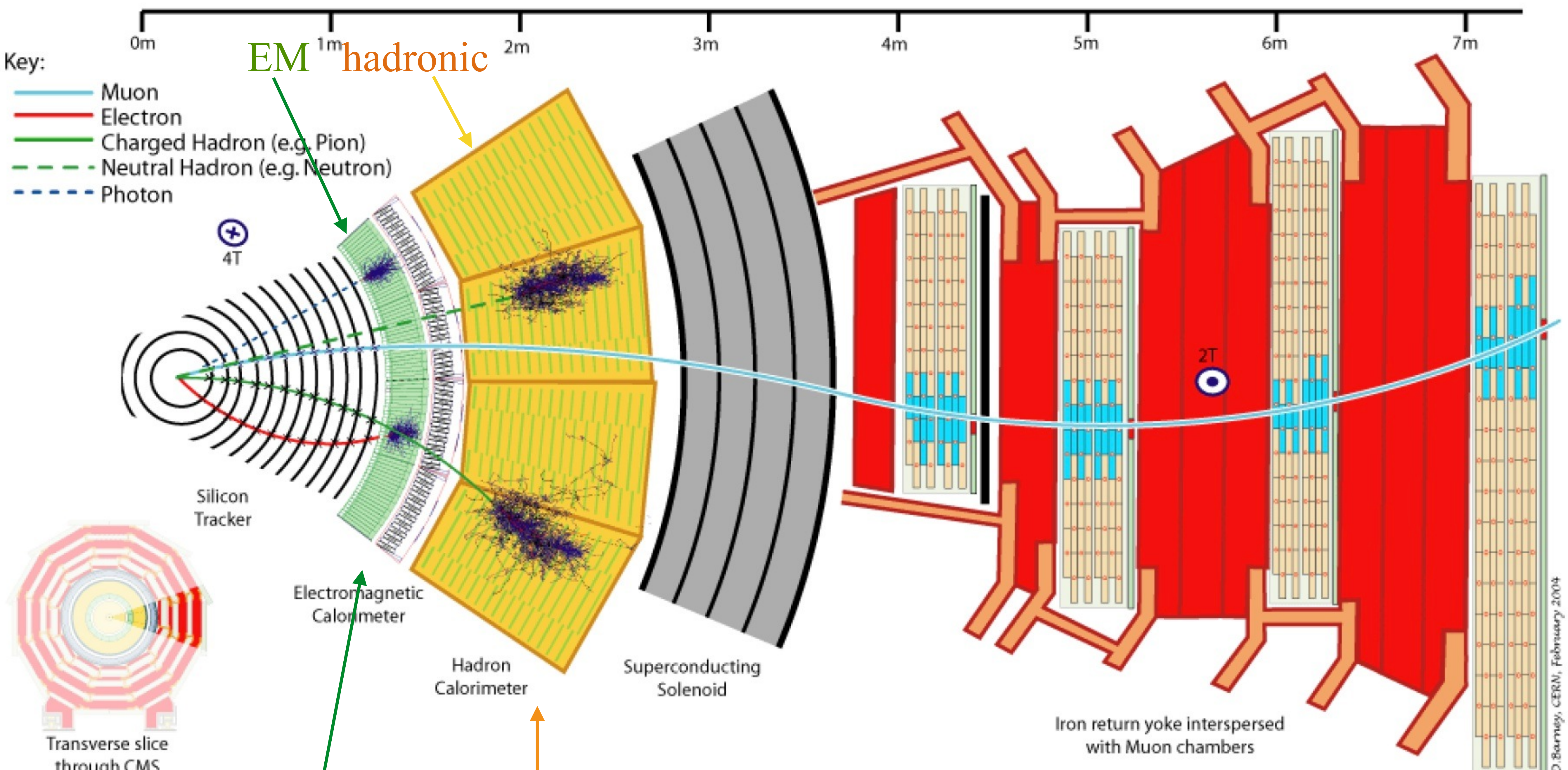
ATLAS and CMS Detector





Calorimeters in relation to other sub-detectors: CMS

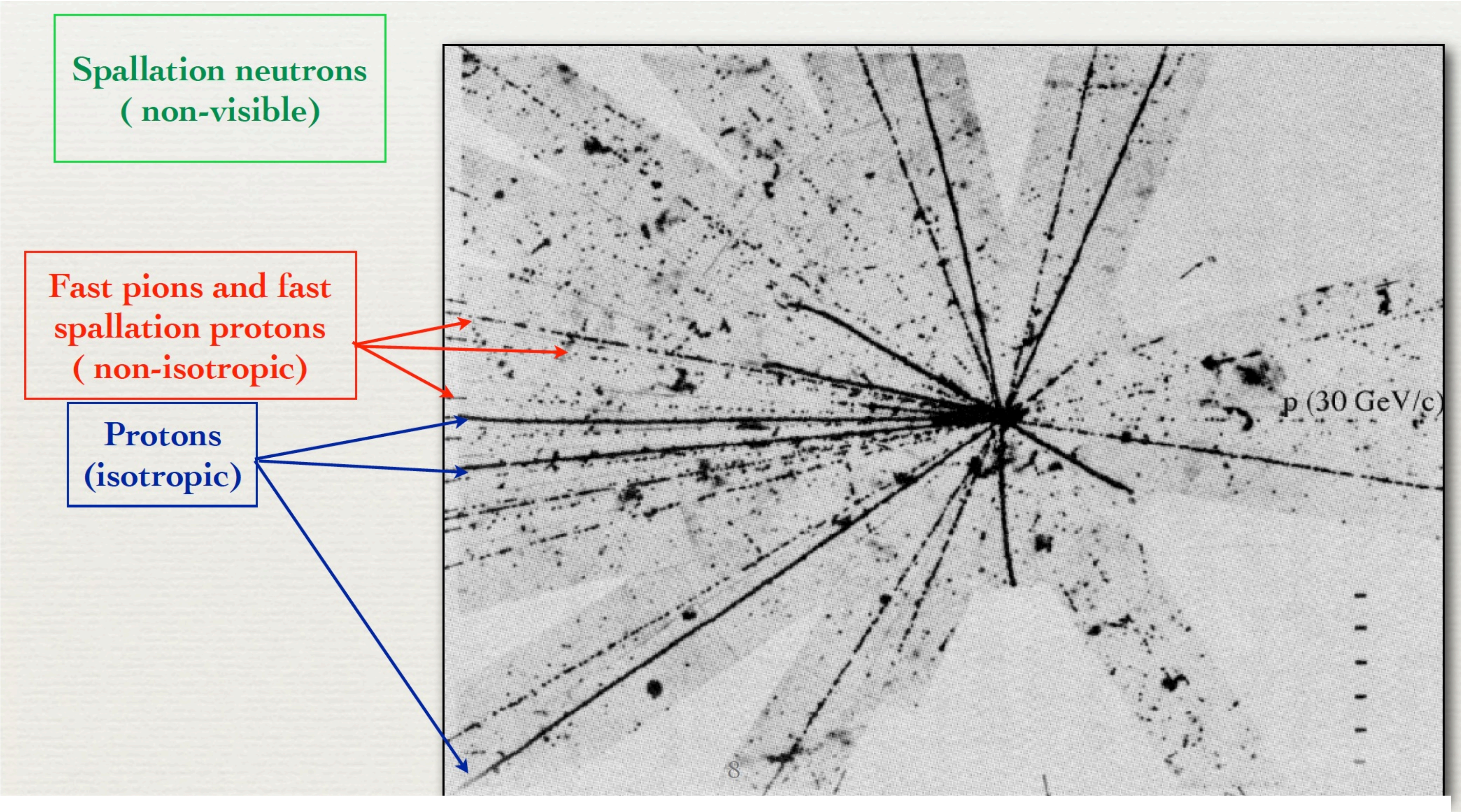
("zero-mass tracker & infinite-mass calorimeter")

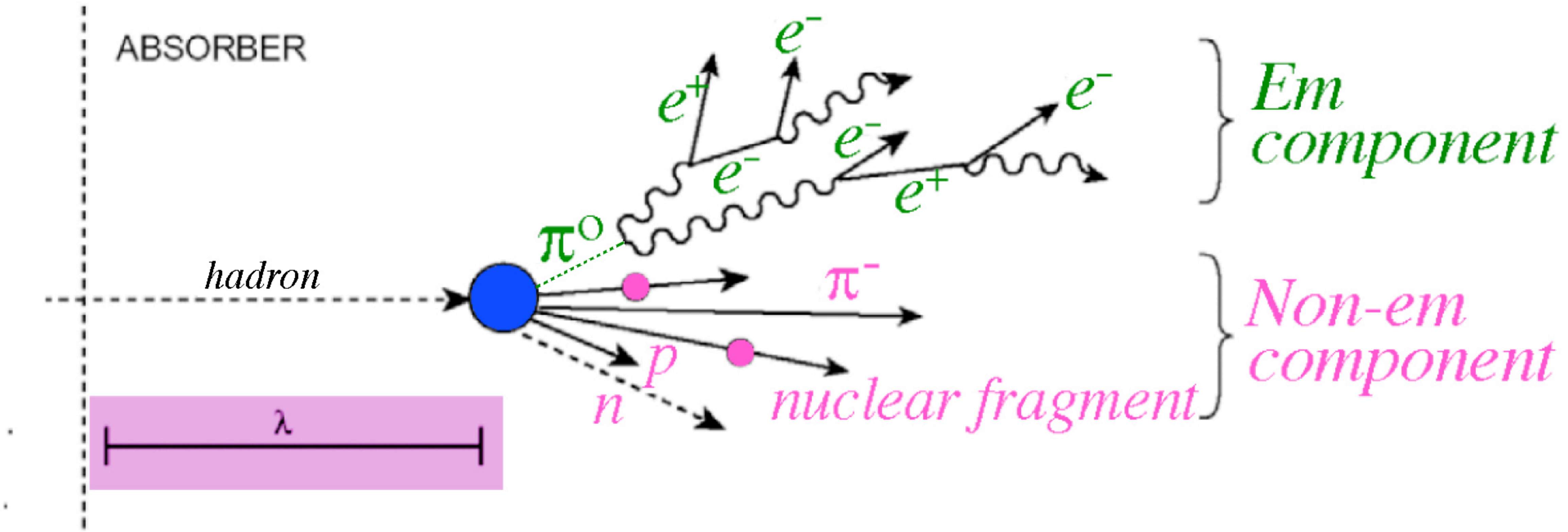


hadronic depth scales as "interaction length" λ_{Int} ~ 20cm

EM scales in depth as "radiation length" X_0 ~ 1cm

Basics: What happens at an individual nucleus:





- Main fluctuation: $\pi^{\pm}$ and $\pi^0 \to \gamma\gamma$ (“EM fraction” fluctuation)
- Next fluctuation: binding energy losses —> liberated neutron kinetic energies.

By observation … and basic nuclear physics

- Large fluctuations in particle content
- … in spatial distributions
- … in particle species
- For almost all calorimeters, detector response is larger for electromagnetic particles (electrons, positrons and photons) than for hadrons (pions, kaons, protons, …)
- Breaking up a nucleus costs ~ 8 MeV per nucleon (so-called "invisible energy" loss)
- Almost all of the detector signal (the "energy measurement") is generated by low-energy particles

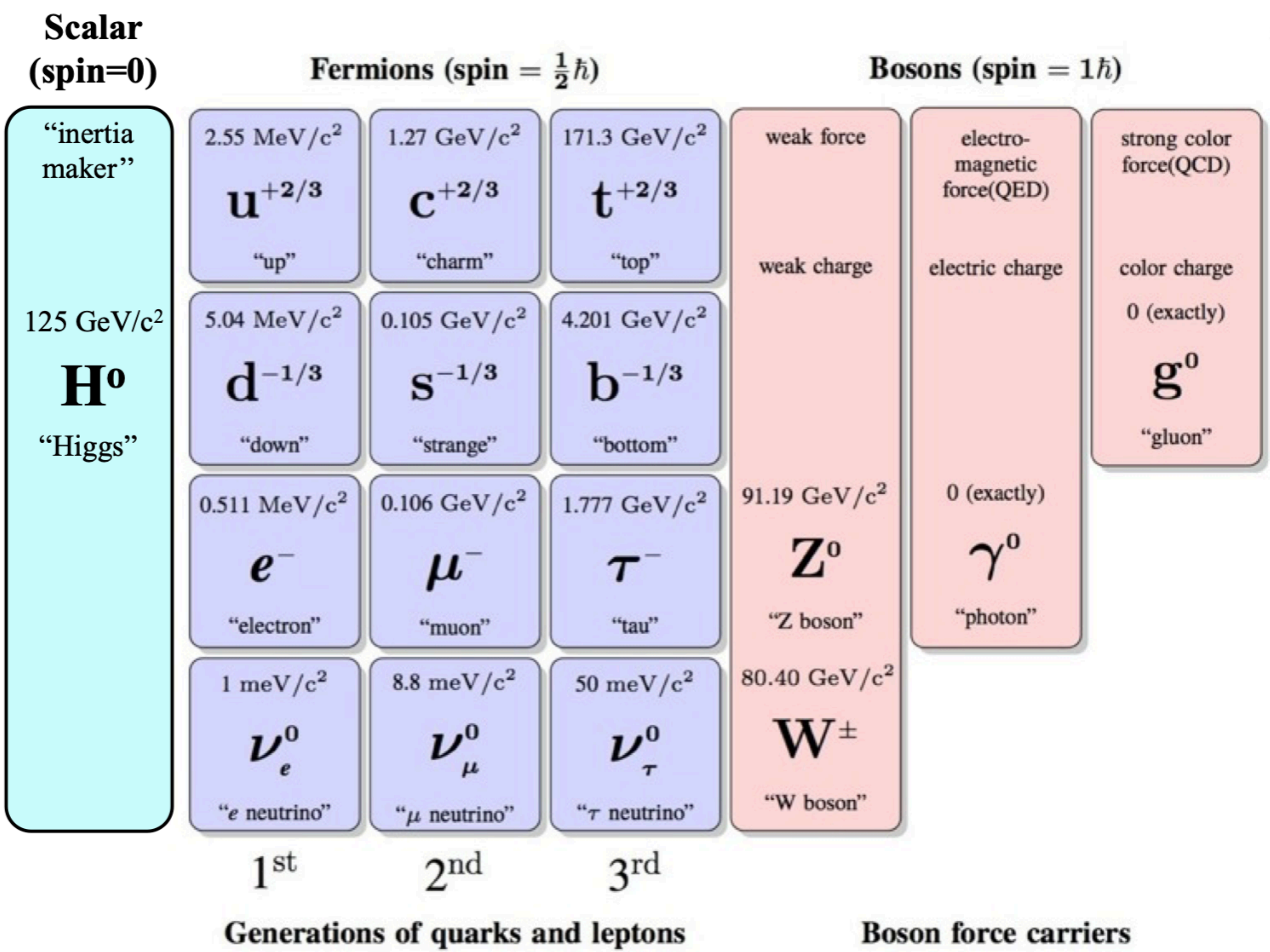
Energy resolution (fluctuation in numbers of particles is Poisson)

$$\frac{\sigma}{E} \approx \frac{a}{\sqrt{E}} \oplus c$$

$a \sim 10\%$ (EM)
$a \sim 30\text{-}100\%$ (hadrons)

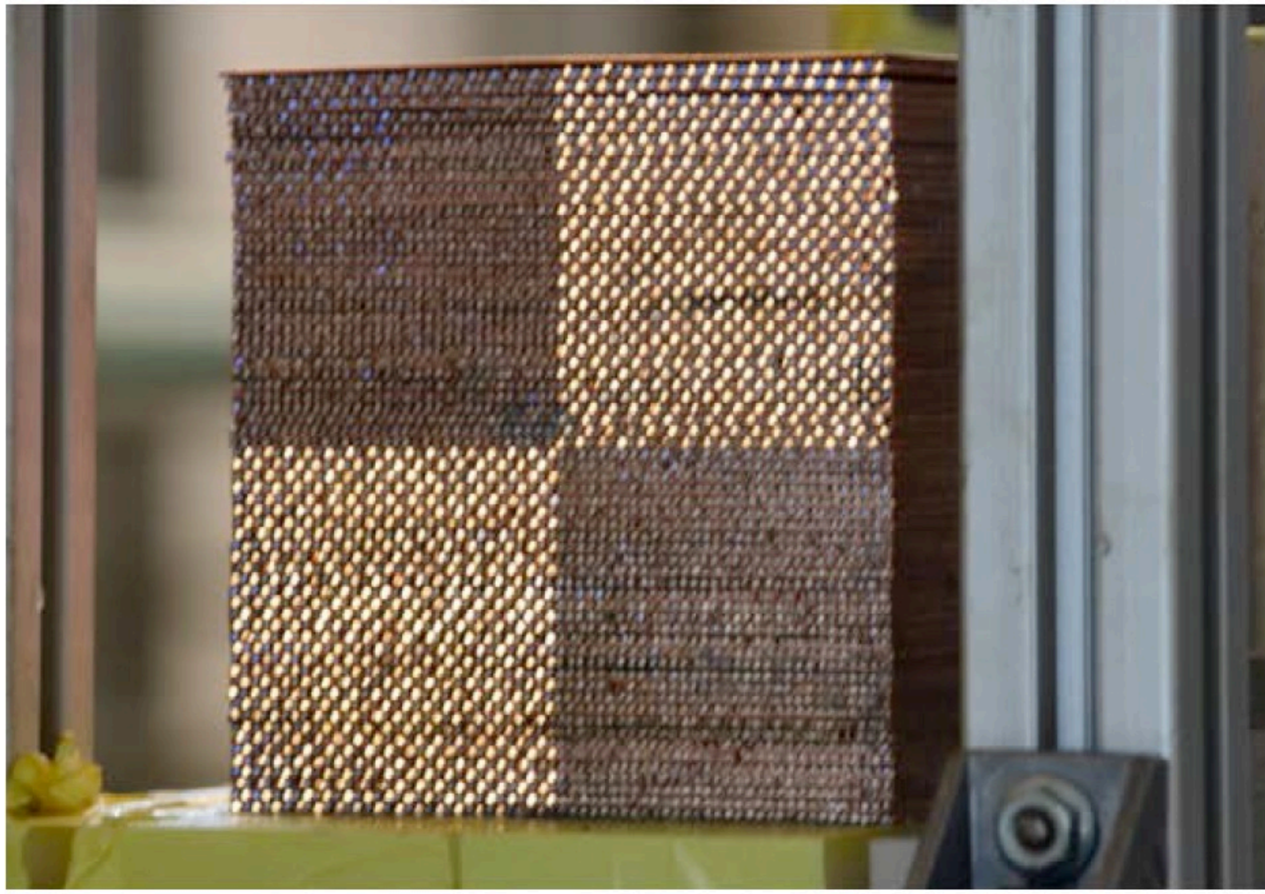
Let's not forget why we are here:

A good detector at a future collider must be able to measure every known particle to 1-2% precision around 100 GeV.



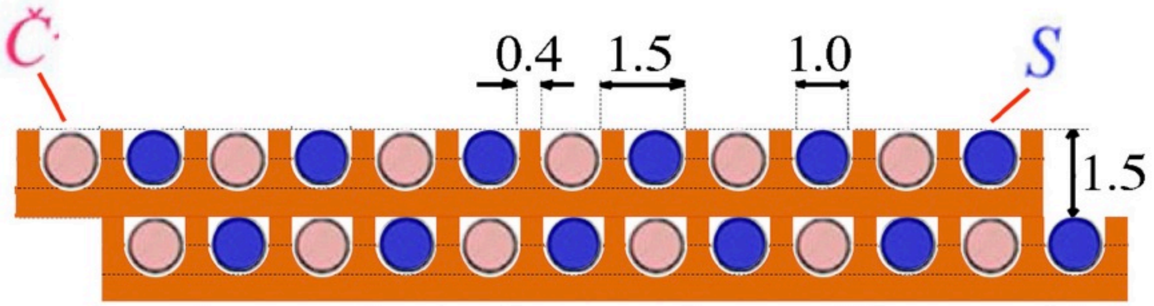
(see www.4thconcept.org/4LoI.pdf for details)

Dual-readout (classic total absorption calorimetry) RD52/DREAM



Fill calorimeter volumes with two kinds of fibers: Scintillating and Clear (Cerenkov)

Write S and C responses as linear combinations of the mean response to EM and non-EM energy deposits. Two equations in two unknowns, solve for E and fem.



$$C = E_{\mathrm{hadron}}\ [f_{em} + \eta_c(1 - f_{em})]$$
$$S = E_{\mathrm{hadron}}\ [f_{em} + \eta_s(1 - f_{em})]$$

Dual-readout: you have an expert just down the road.

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Dual-readout calorimetry

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In the past 20 years, dual-readout calorimetry has emerged as a technique for measuring the properties of high-energy hadrons and hadron jets that offers considerable advantages compared with the instruments that are currently used for this purpose in experiments at the high-energy frontier. The status of this experimental technique and the challenges faced for its further development are reviewed.

DOI: 10.1103/RevModPhys.90.025002

Dual-readout: we have finished all that we intended. The final paper on the fundamental limitations to hadronic energy measurement is recently published.

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On the limits of the hadronic energy resolution of calorimeters

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A R T I C L E I N F O

This paper is dedicated to the memory of our long-time friend and collaborator Guido Ciapetti

Keywords:
Hadron calorimetry
Compensation
Dual-readout method

A B S T R A C T

In particle physics experiments, the quality of calorimetric particle detection is typically considerably worse for hadrons than for electromagnetic showers. In this paper, we investigate the root causes of this problem and evaluate two different methods that have been exploited to remedy this situation: compensation and dual readout. It turns out that the latter approach is more promising, as evidenced by experimental results.

Particle Flow Analysis (CALICE)

- Use charged particle momentum measurements plus calorimeter
- Momentum is precisely measured below 100 GeV/c, while calorimeter is more precise at higher energies

$$\sigma_p/p \approx 5 \times 10^{-5}\; p(GeV/c)$$

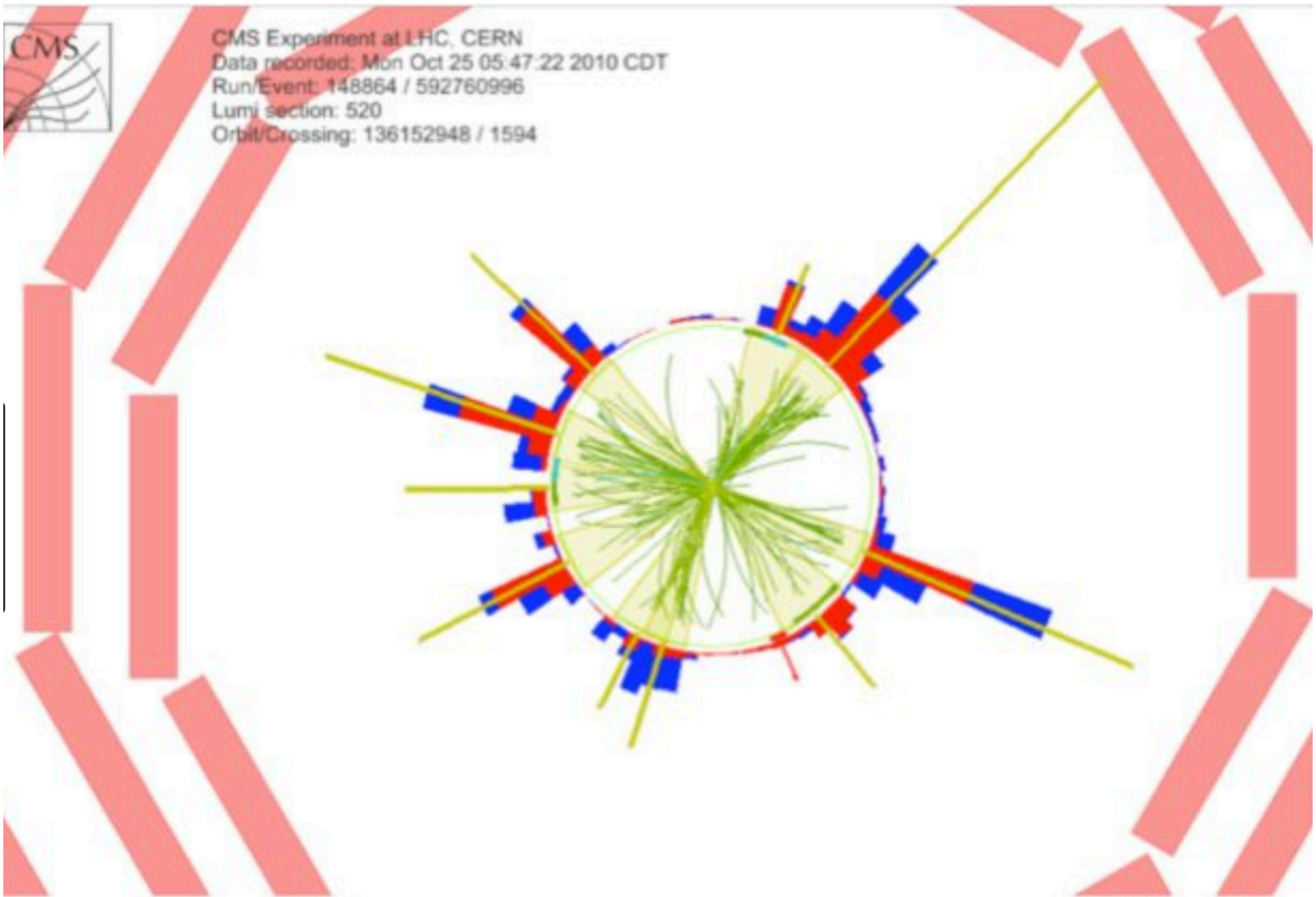
(e.g., 0.5% resolution at 100 GeV/c)

- Need strong magnetic field, large tracking chamber and highly segmented calorimeter.

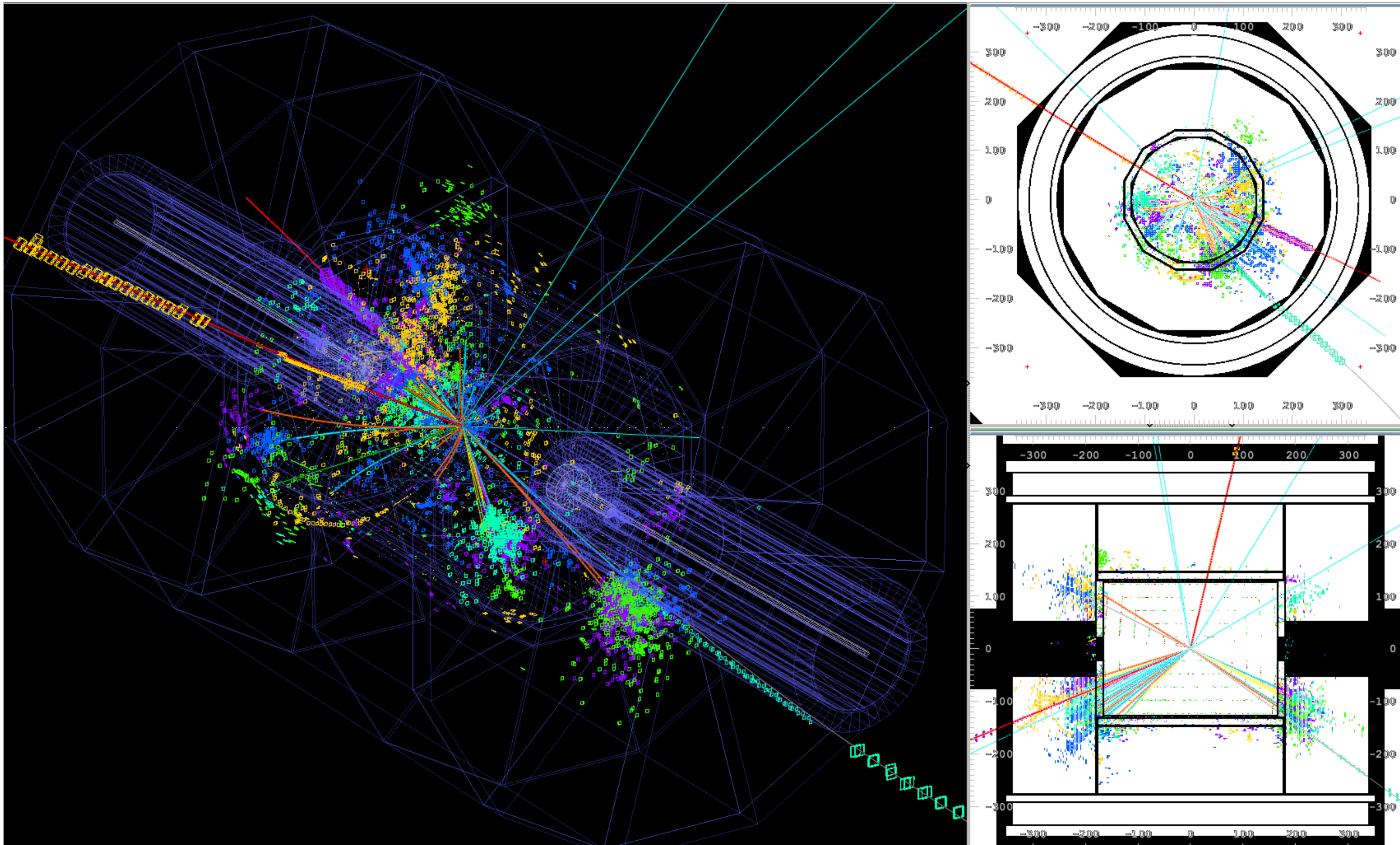
- All of these have been simulated to the point of validating beam test data on individual particles

Particle Flow Analysis (CALICE):

A CMS event showing calorimeter energies in towers and charged particle momenta in the tracking chamber.

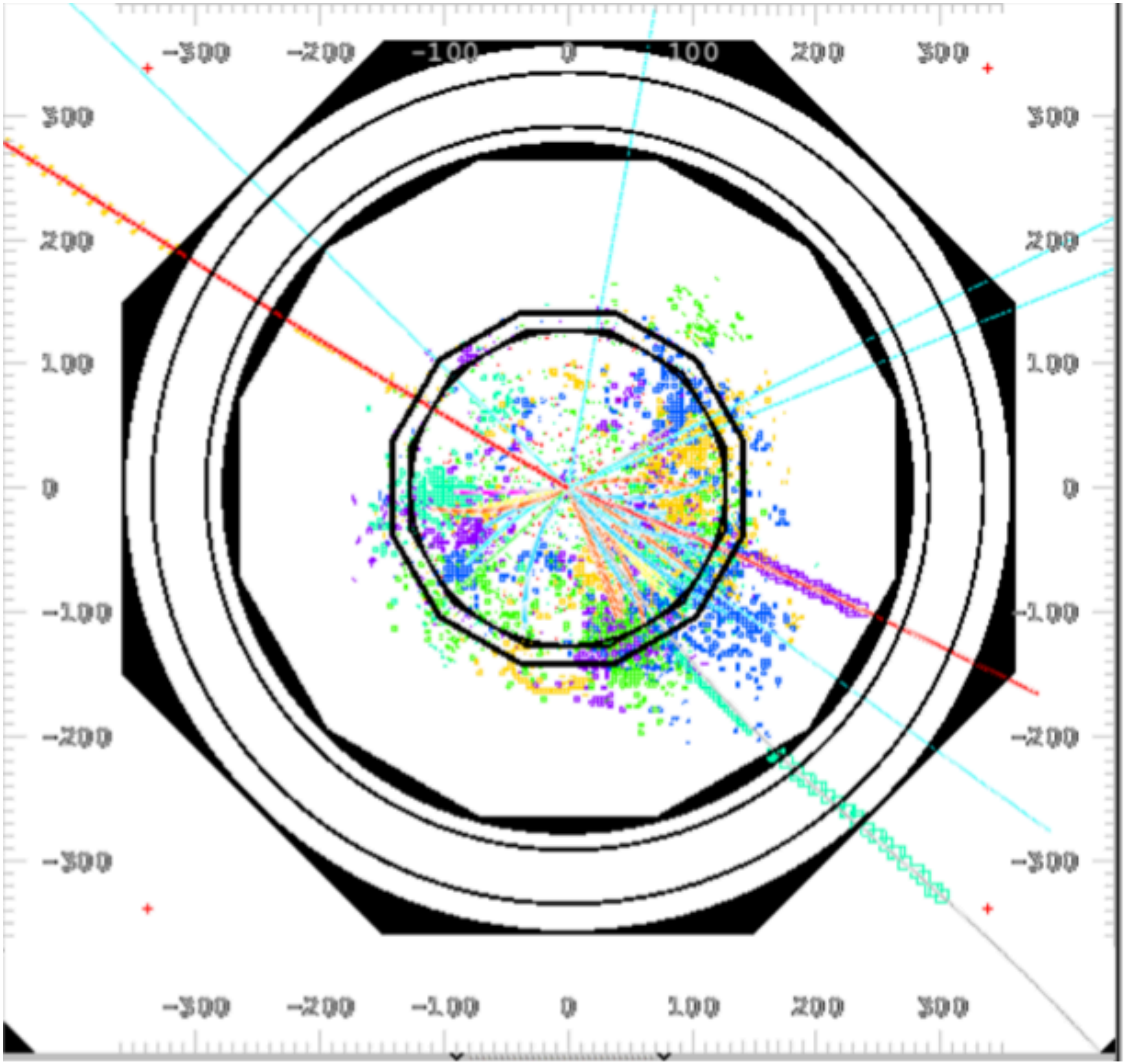


Particle Flow Analysis (CALICE): a simulated *ttH* event



Simulated
ttH event:

It is not easy to unravel the energy deposits from the visible charged tracks



Particle Flow Analysis

CALICE

Recent paper

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Hadronic energy resolution of a combined high granularity scintillator calorimeter system

The CALICE collaboration

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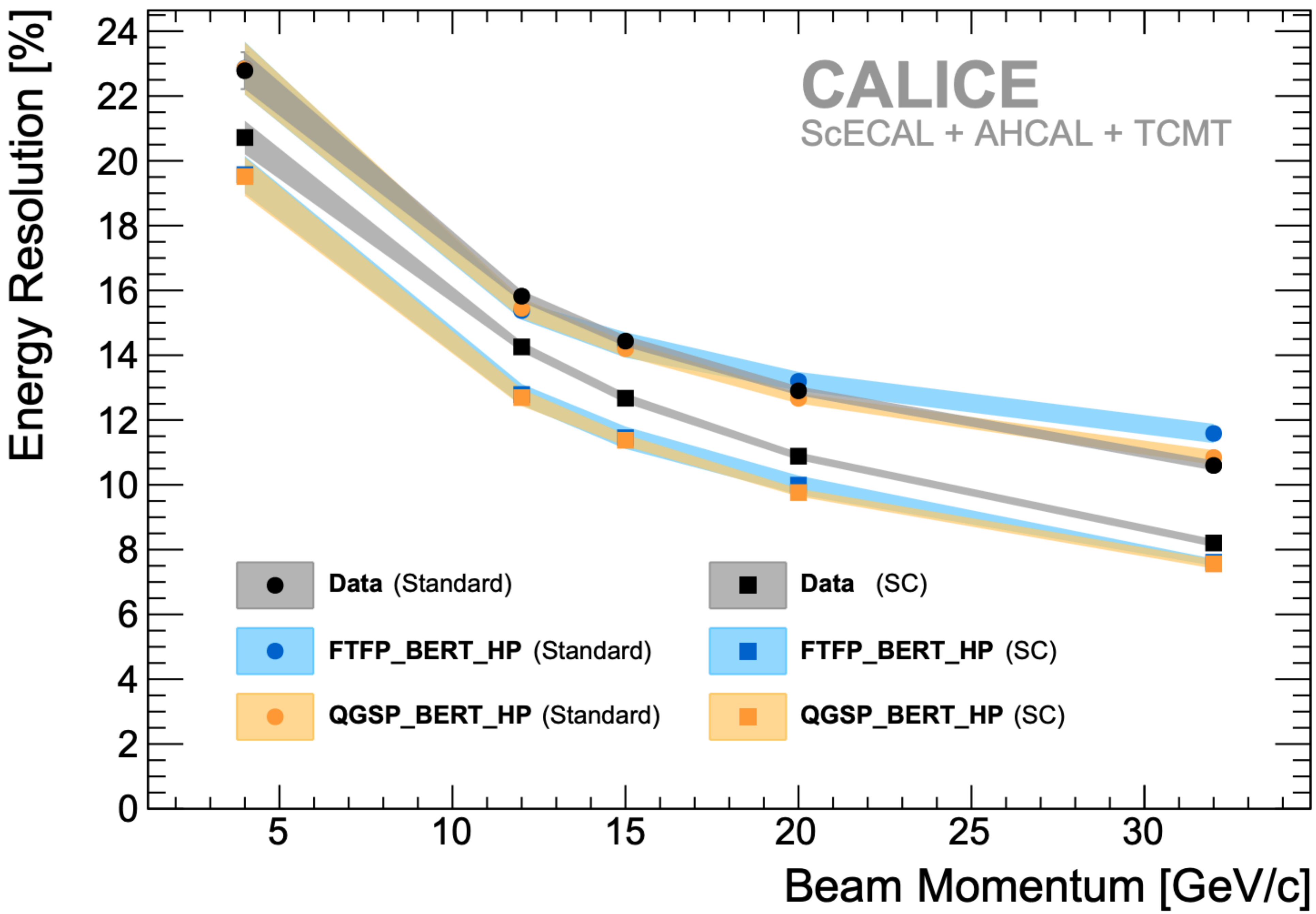
Particle Flow Analysis (CALICE)

Energy Resolution for hadrons



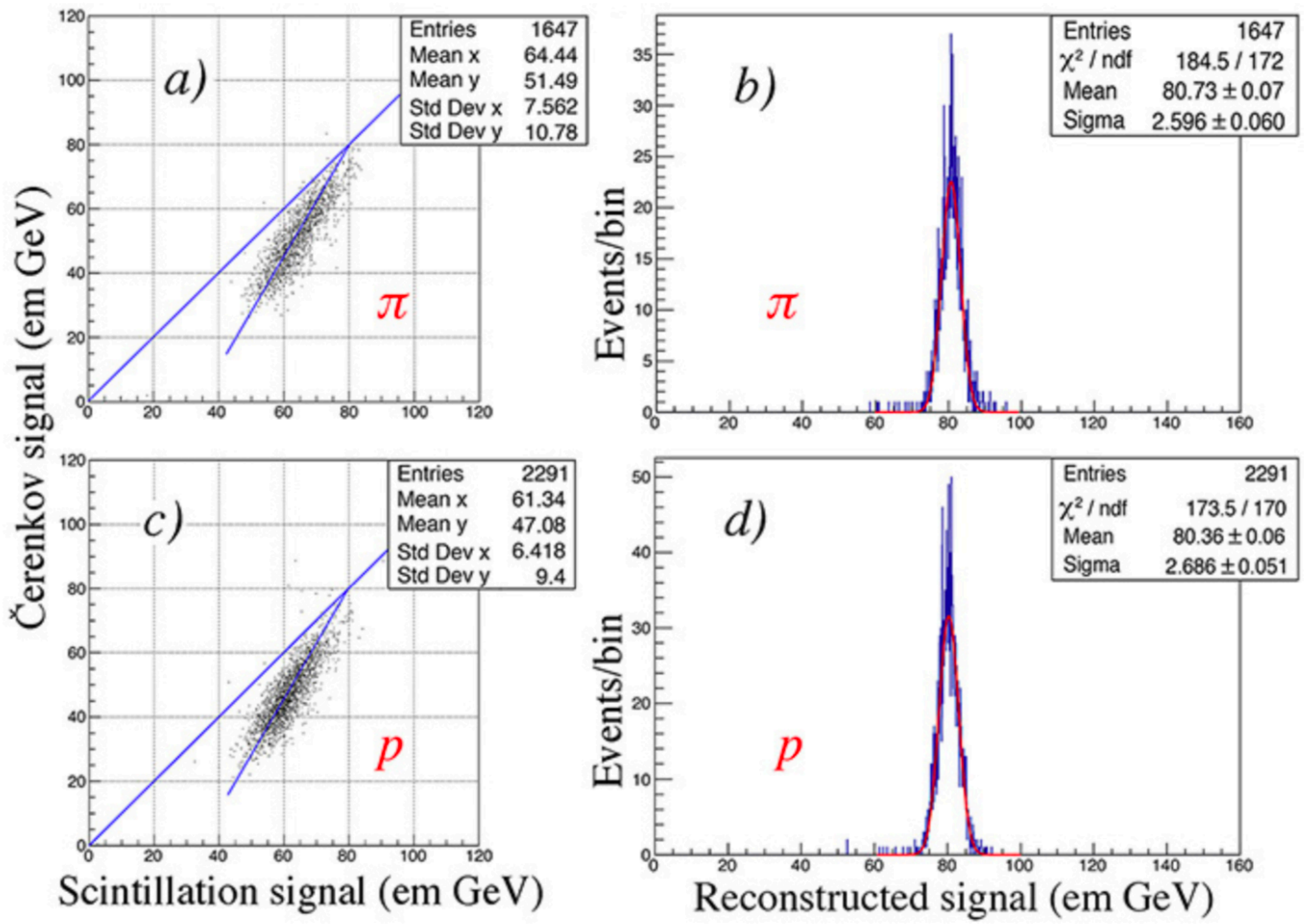
Final brief comments

- Don't be fooled by the nice plots and photos: calorimetry is difficult, especially hadronic calorimetry, but the hard problems are the good problems
- It takes a minimum of one tonne of instrumentation for a simple beam test
- Quote (in private) from a prominent European physicist:
  "Calorimetry was the low point of my life."
- Calorimeters are expensive: ILC detectors: calorimeter ~ solenoid ~ 40%.
- Excellent existing hadronic calorimeters (ZEUS/HERA & ATLAS/LHC)
- Do both instrumentation and physics analysis. Then you will, some day, be able to lead an experiment of your own

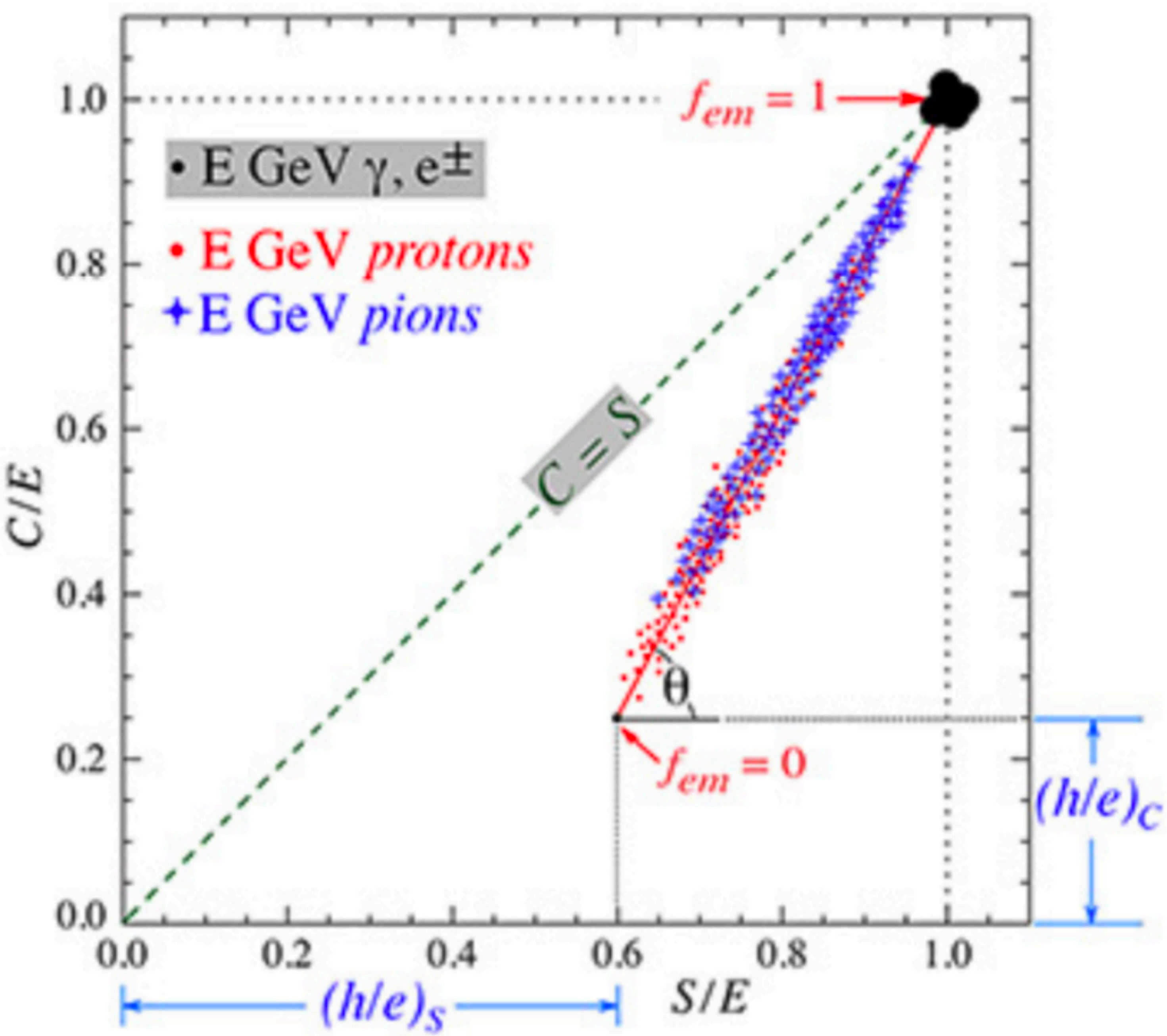
Thank you for your attention

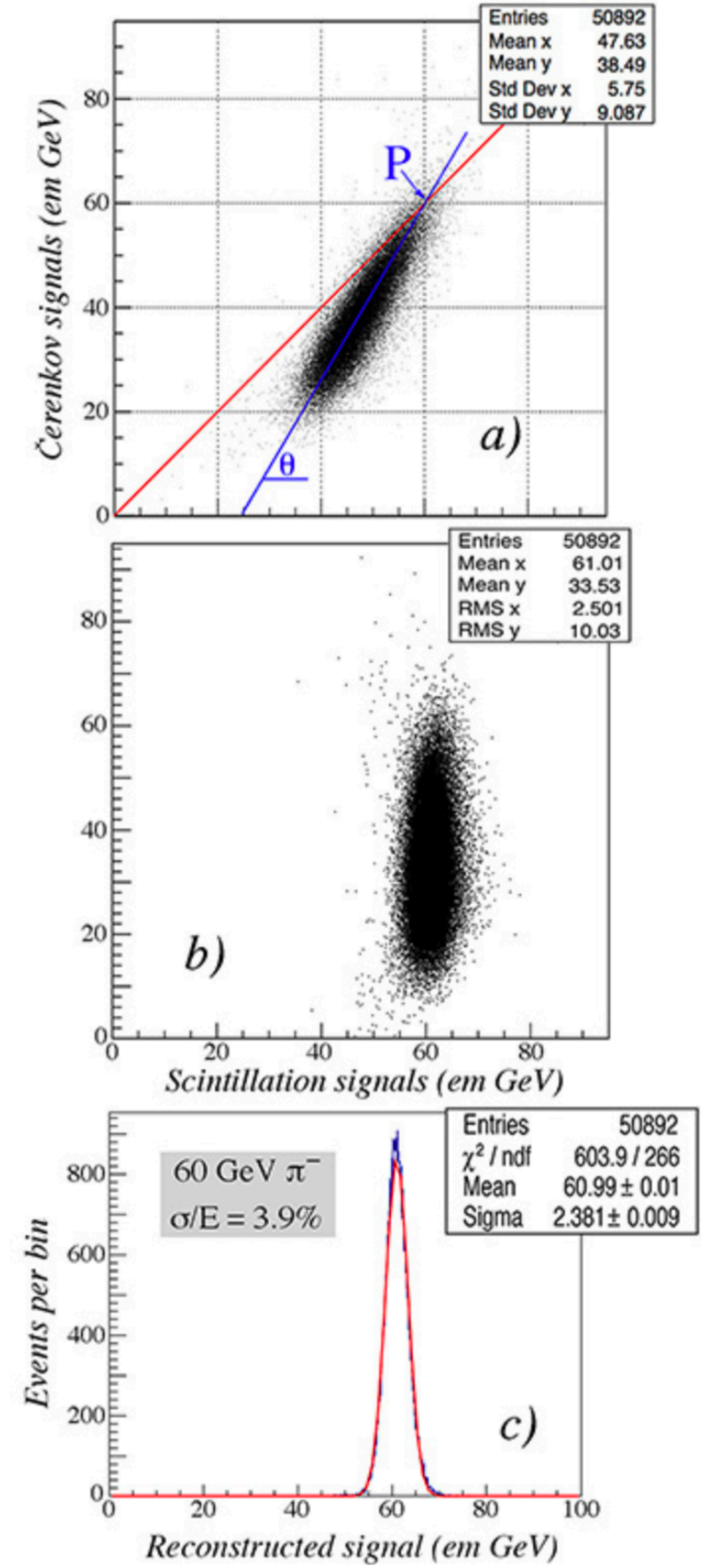
Extras

Protons differ from pions in a calorimeter

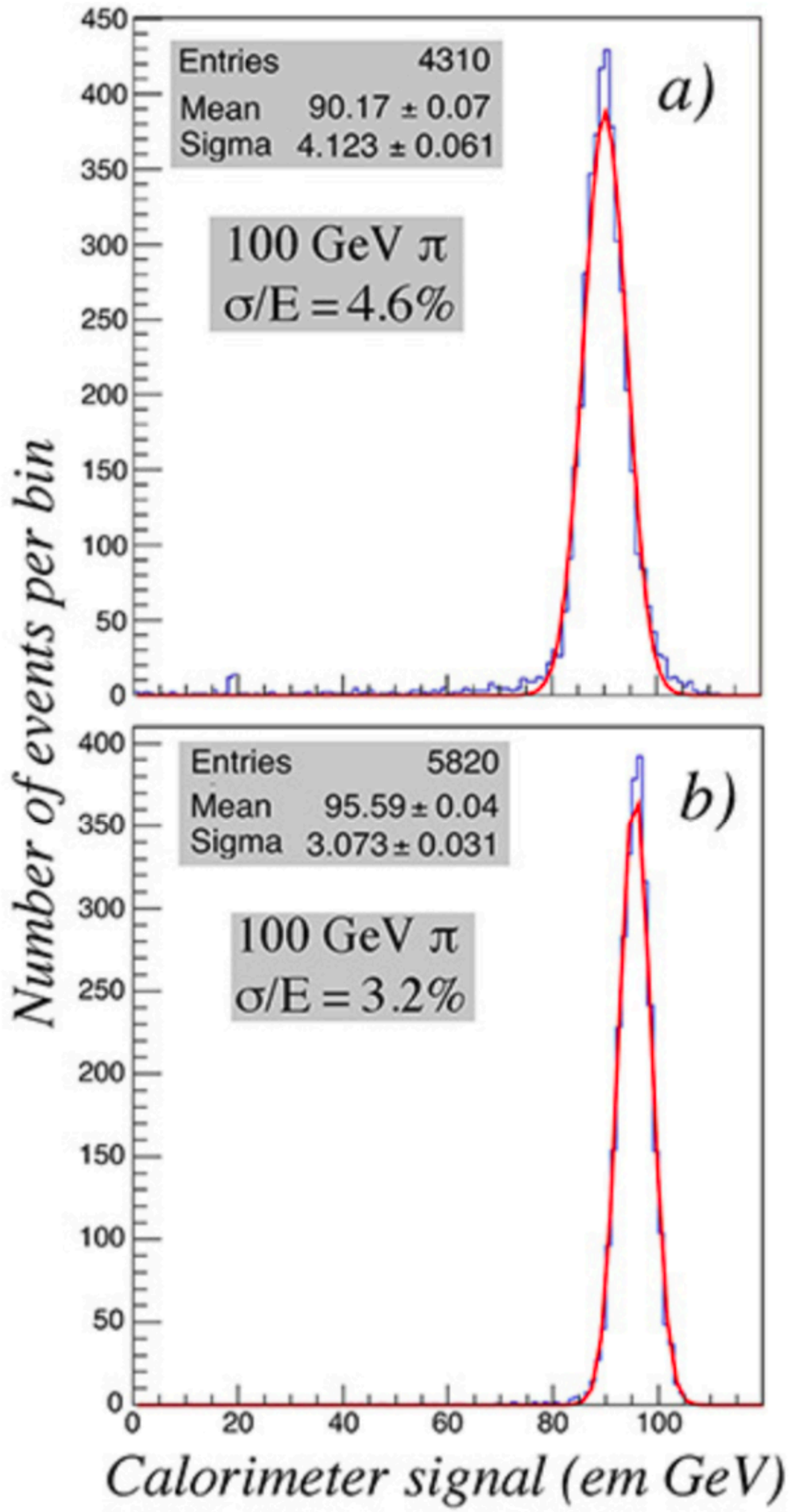


Dual-readout in a nut shell

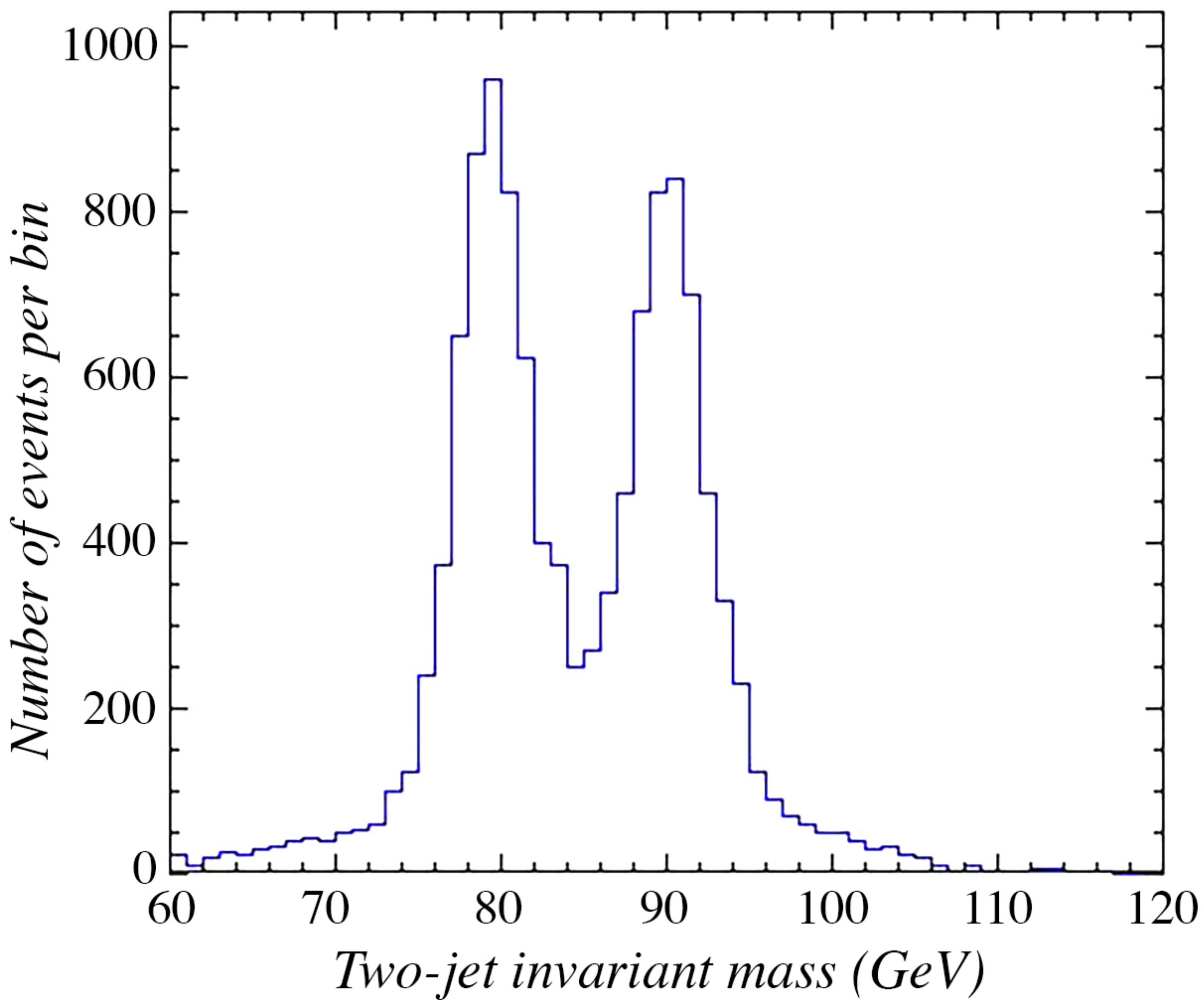




GEANT4 - high precision



W and Z invariant mass reconstruction (RD52 resolution)



Calorimetry

- Calorimeter types:
  - Sampling calorimeters
    - distinct detector and absorber elements
    - limited energy resolution
    - good longitudinal segmentation
    - Many different active media: gas, LAr, scintillator, …
    - Many different absorbers: lead, Uranium, W, Cu, …