Introduction to Calorimetry

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Outline

- A short overview
- Particle shower basics
- Calorimeters
  - Sampling Calorimeters
  - Homogeneous Calorimeters
- Readout and DAQ
- Example systems
- Advanced Technologies
  - Particle Flow
  - Dual-Readout

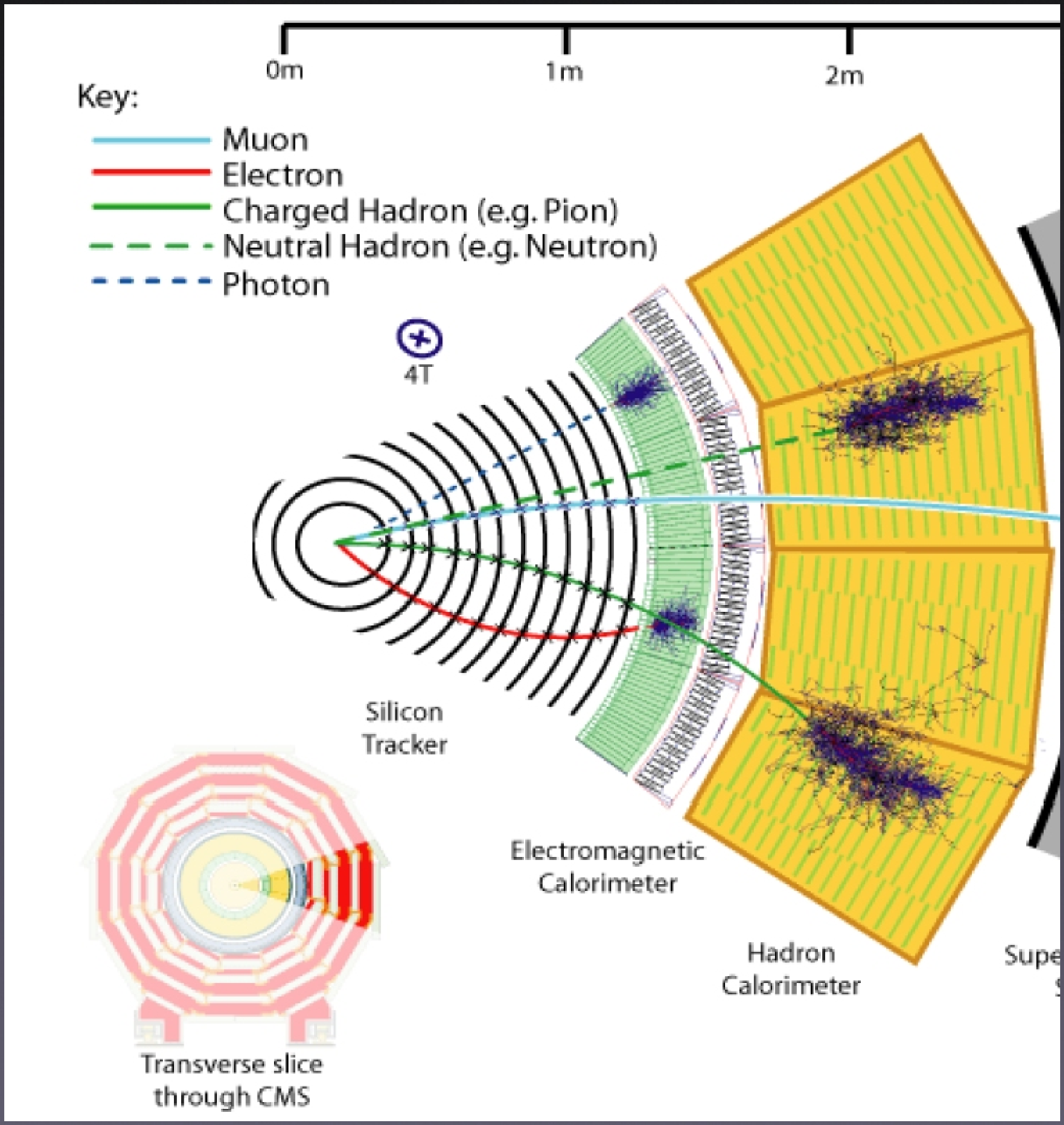
Calorimetry -What is it?

- A calorimeter measures the energy of an incoming particle
  - Stopping the particle
  - Converting the energy into something detectable
  - Basic mechanism: electromagnetic/hadronic showers
  - The measured output is linear to the incoming energy
- It measures the location of the energy deposit
  - Allows “tracking” of neutrals, e.g. photons and neutrons
- A hermetic calorimetry is essential to measure “missing energy”
  - From all particles escaping detection
  - Neutrinos, Neutralinos and all that

Calorimetry & Particles

- Only ~ 13 Particles actually seen by a detector
  - Everything else is too short-lived
- Charged Hadrons
  - $\pi^{\pm}$,$p^{\pm}$, $K^{\pm}$
  - Generate hadronic Showers
- Electrons & photons
  - Generate Electromagnetic showers
- Neutral Hadrons
  - n,K_L
  - Generate hadronic Showers
- Muons
  - Usually only a track through the calorimeters

As done in CMS

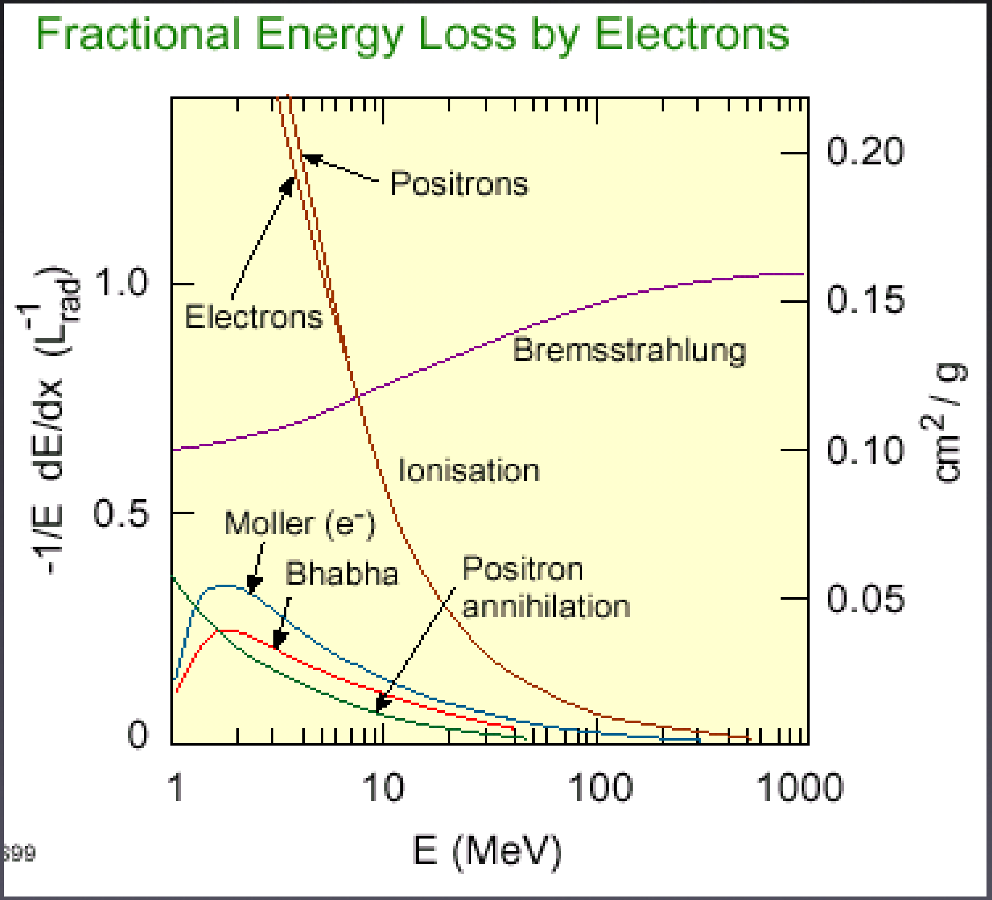


Particle Showers

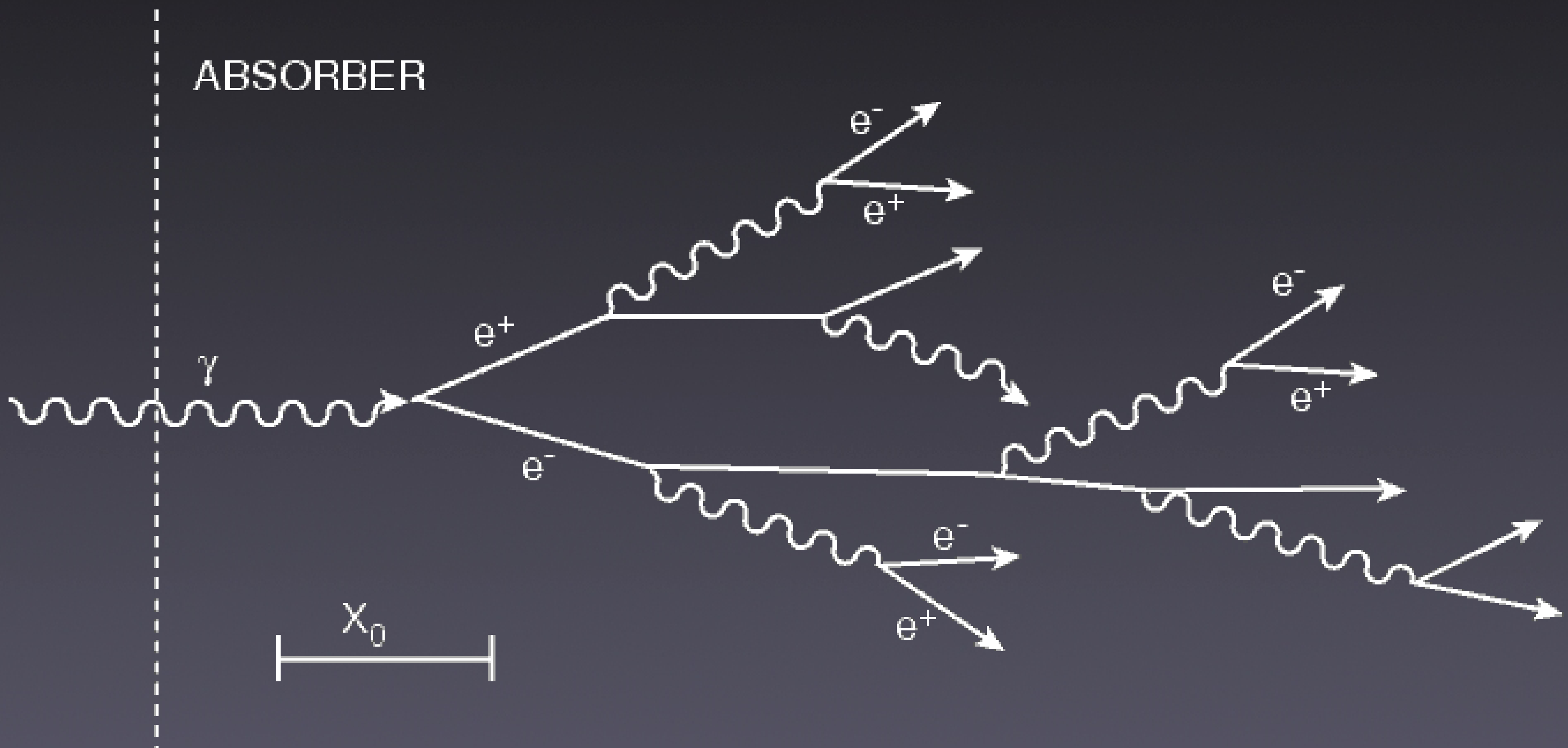
- Calorimeters stop particles by generating particle showers
- Two basic types
  - Electromagnetic showers
  - Hadronic showers
- Electromagnetic Showers
  - Driven by QED
  - Clean and simple
- Hadronic showers
  - Nuclear interactions and EM component
  - Quite complicated
  - Very difficult to model

EM Interaction with Matter

- Electrons and photons as the main components
- Above ~ 1 GeV
  - Electrons: Bremsstrahlung radiating off photons
  - Photons: Pair production
  - Increase of particles
- Below a critical energy E_c
  - Ionization dominates
  - Shower slowly dies out
- Material dependent
  - Density ρ
  - Number of Protons (Z) and nucleons (A)



EM shower basics



From T. Virdee

EM Definitions

- Radiation length (X_0)
  - When the energy has been reduced to 1/e
  - Characterizes the shower depth

$$X_0 = \frac{716.4A}{Z(Z+1)\cdot\ln(287/\sqrt{Z})}\cdot\frac{1}{\rho}$$

- Critical Energy (E_C)
  - Energy, where Ionization takes over

$$E_{C,\,solid/liquid} = \frac{610\,MeV}{Z+1.24}$$

$$E_{C,\,gas} = \frac{710\,MeV}{Z+0.92}$$

- Moliere Radius ($r_{Moliere}$)
  - Radius which contains 90 % of the shower
  - Characterizes the width of the shower

$$r_{Moliere} = 21.2\,MeV\,\frac{X_0}{E_C}$$

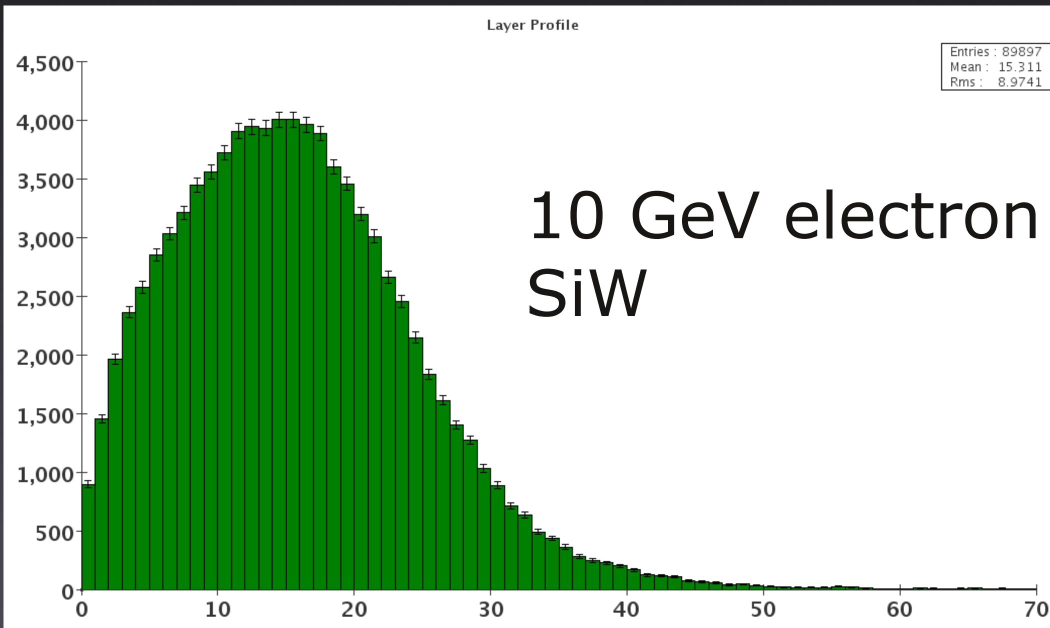
- Shower Max(imum)
  - The peak of the shower

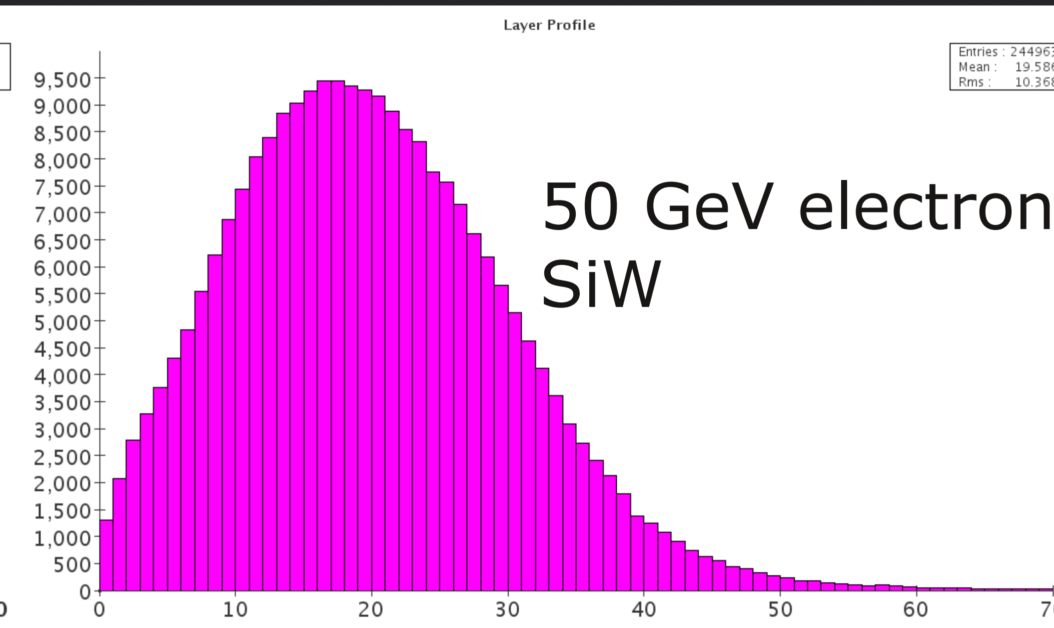
$$S_{max} = \ln\left(\frac{E_{Incoming}}{E_C}\right)$$

Material Dependence

	Z	ρ (g/cm^3)	X_0 (cm)	λ_{Int} (cm)
C	6	2.2	19	38.1
Al	13	2.7	8.9	39.4
Fe	26	7.87	1.76	16.8
Cu	29	8.96	1.43	15.1
W	74	19.3	0.35	9.6
Pb	82	11.35	0.56	17.1
U	92	18.7	0.32	10.5

Shower Shapes



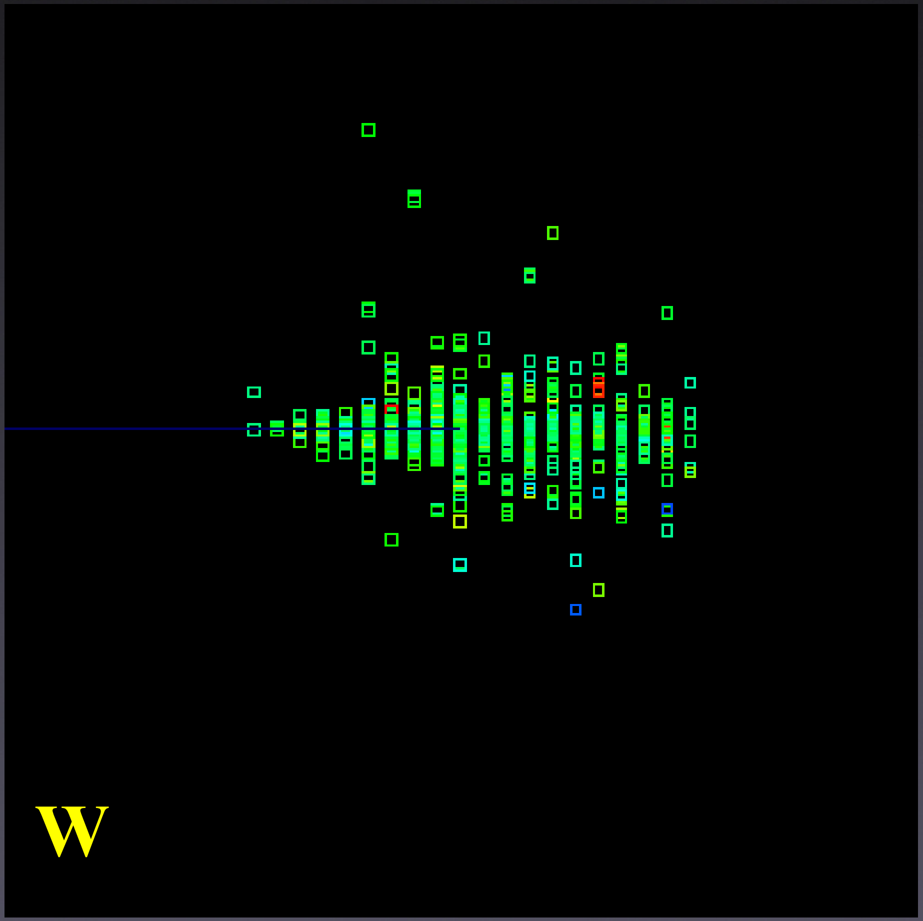


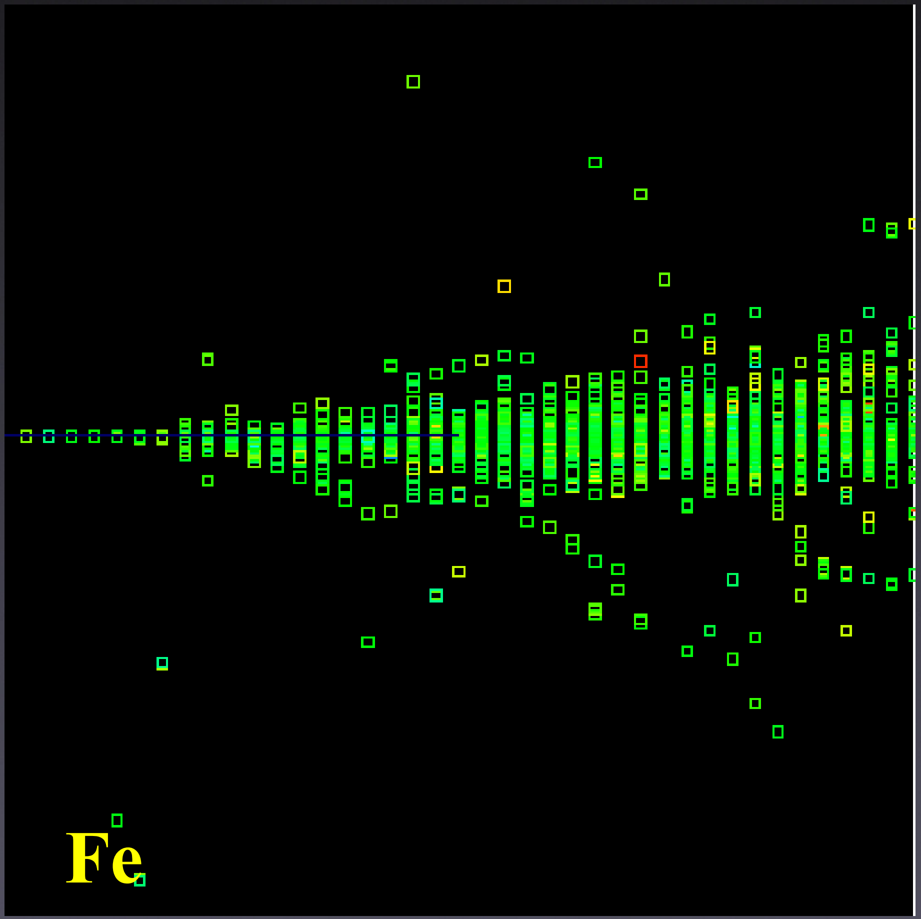
Layer

Layer

25 cm

EM Showers Pictures





20 GeV electrons
longitudinal shower profile

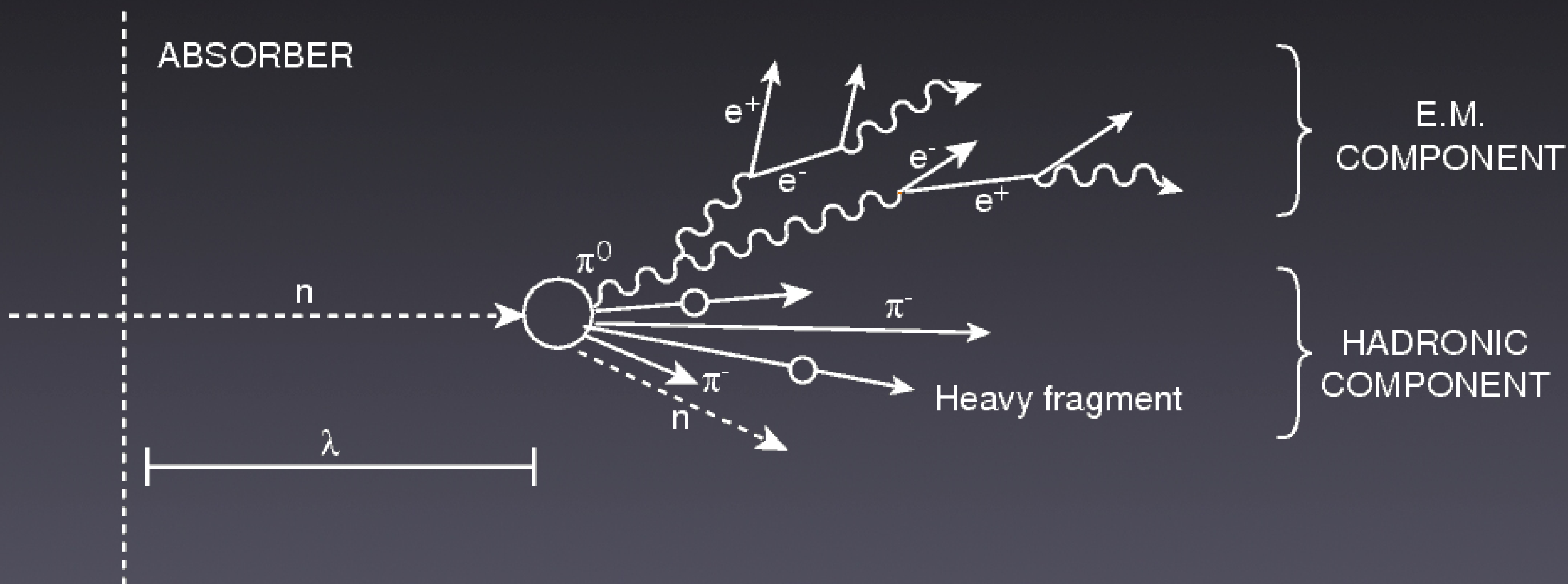
Short Summary

- EM showers
  - dependent on density and Z
- As Z increases
  - shower maximum shifts to greater depth
  - Slower decay after the Shower maximum
- The typical scale of EM showers is mm
  - A EM Calorimeter is not a very thick object
- Location of Shower max scales with ln(E)
  - Allows to build compact calorimeters !

Hadronic Showers

- Hadronic showers are much more complex
- Incoming particle hits nucleus $\rightarrow$ secondaries
  - electromagnetic component (from π^0)
  - strong interaction component (from n,p, π^+)
    - fission ...
    - knock-off ...
    - Delayed photons
- Hadronic Showers are
  - much broader
  - extend deeper in the calorimeter
  - have significant event-by-event fluctuations

Hadronic Shower basics



From T. Virdee

Hadronic shower definitions

- Basic quantity is the nuclear interaction length
  - Analog to the radiation length
  - Order of magnitude larger

$$\lambda_I = \frac{A}{N_A \cdot \sigma_{Total}}$$

$$\lambda_I \sim A^{\frac{1}{3}}$$

- Only approximations for
  - Shower max

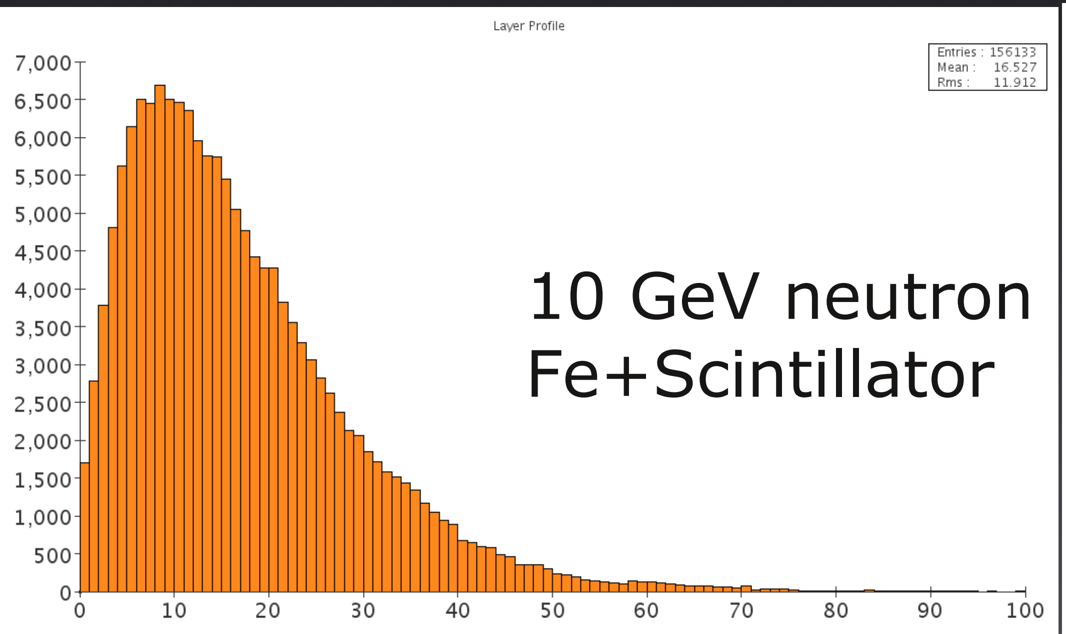
$$S_{max}(\lambda_I) \sim 0.2 \cdot \ln(E) + 0.7$$

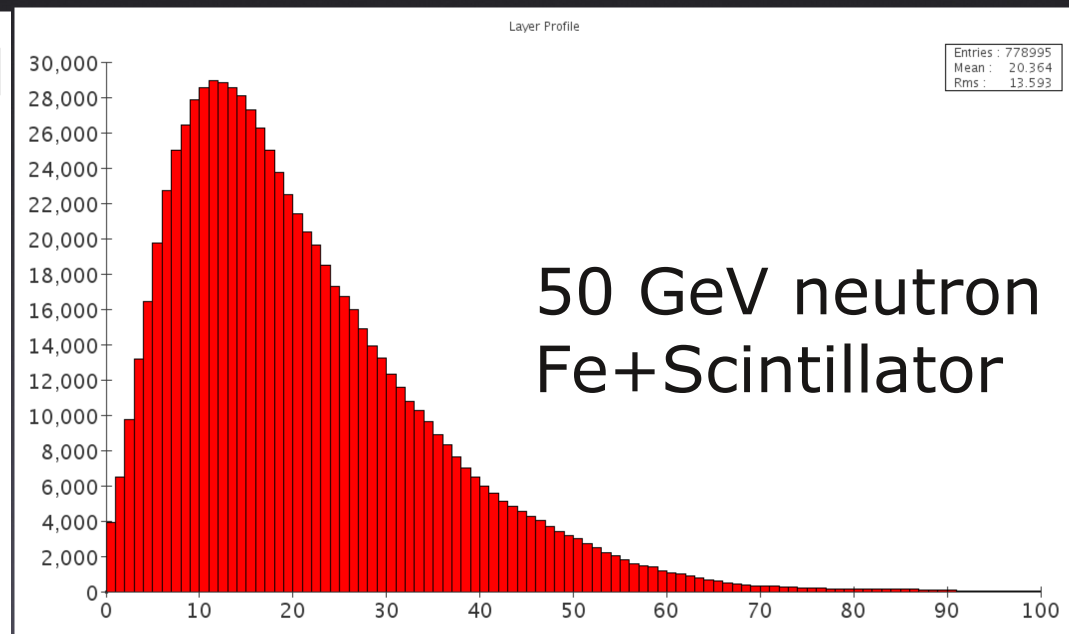
- Shower fractions
  - f_{EM} as electromagnetic fraction
  - f_{had} for the strong interaction fraction
  - Generally f_{EM} increases with energy

$$f_{em} = 1 - (1 - \frac{1}{3})^n$$

$$f_{em} = 1 - \left(\frac{E}{E_0}\right)^{(k-1)}$$

Hadronic Shower Shapes





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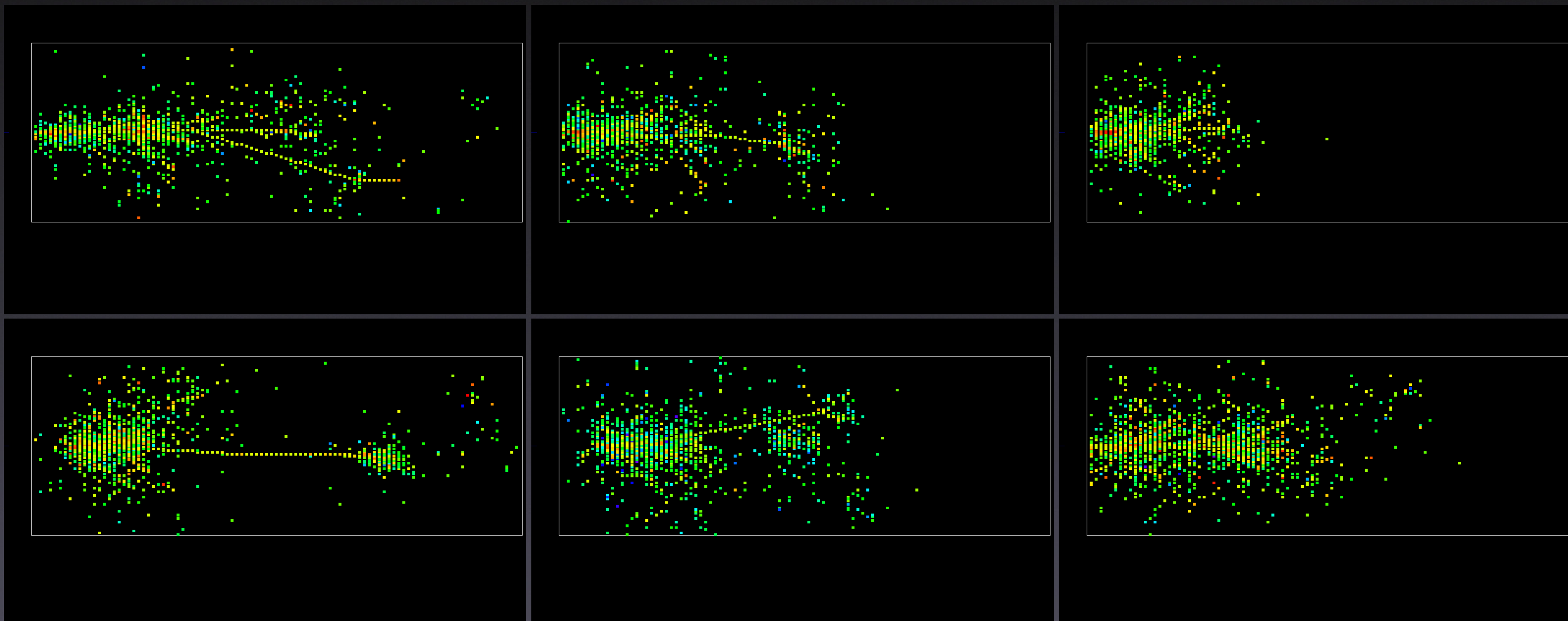
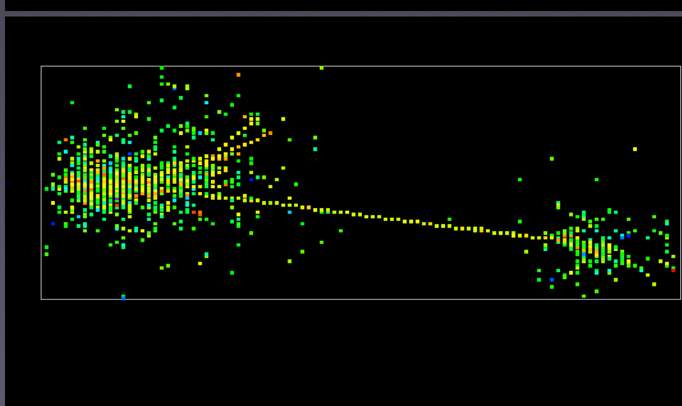
Layer

275 cm

Individual Showers



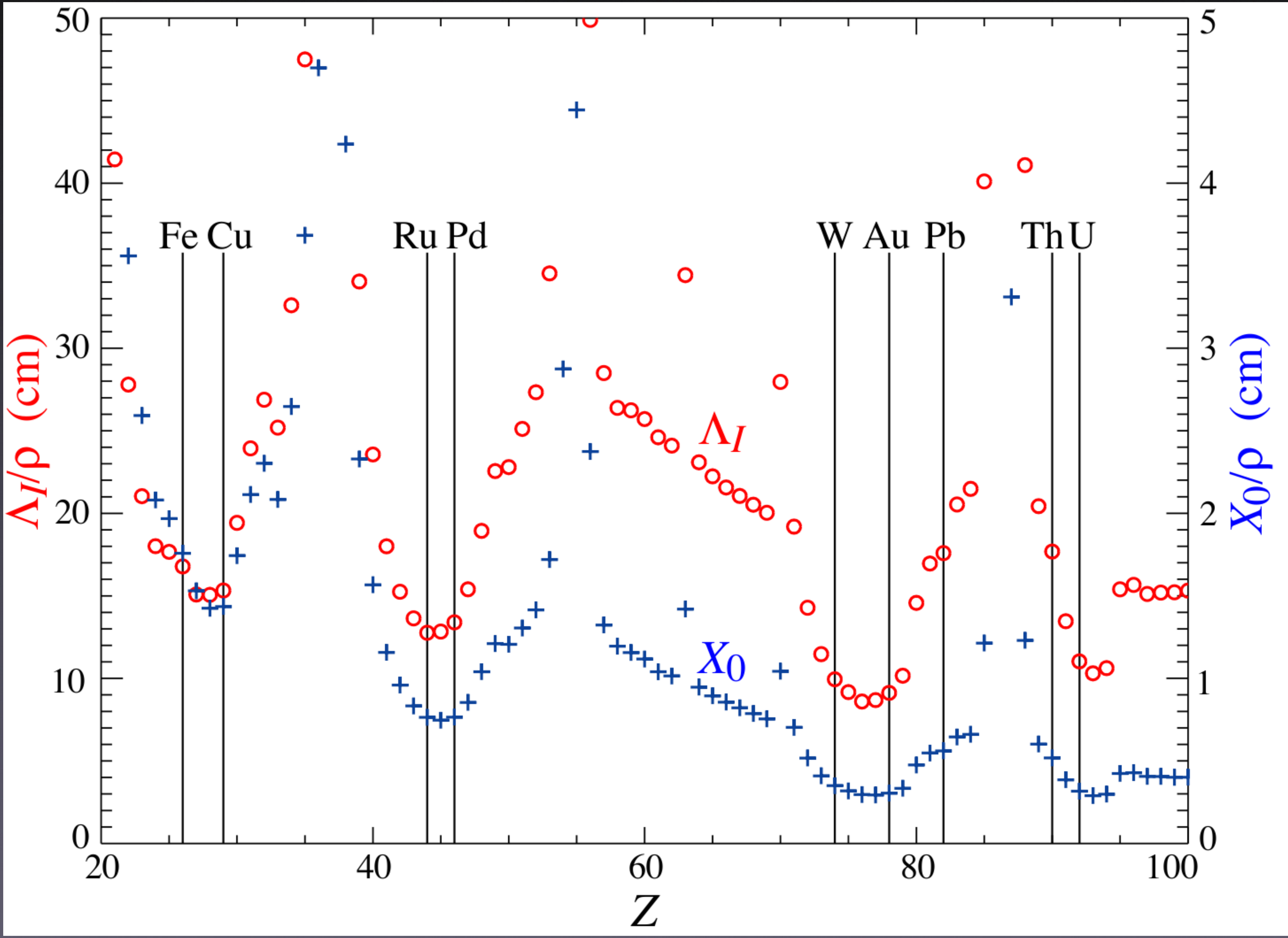


50 GeV neutrons on Fe-Scintillator Stack

Selecting HCAL material

	Z	ρ (g/cm³)	X_0 (cm)	λ_{Int} (cm)
C	6	2.2	19	38.1
Al	13	2.7	8.9	39.4
Fe	26	7.87	1.76	16.8
Cu	29	8.96	1.43	15.1
W	74	19.3	0.35	9.6
Pb	82	11.35	0.56	17.1
U	92	18.7	0.32	10.5

Materials again



Compensation

- As already stated, hadronic showers have
  - electromagnetic component (e)
  - strong interaction component (h)
  - $e/h \neq 1$
- EM fraction increases with energy
  - Non-linearities
- Event by Event fluctuations
  - tend to be non-gaussian
  - Affect the resolution
- What can be done ?
  - Compensating calorimeters to achieve $e/h=1$

How to compensate ?

- Software-based
  - Try to reweight on a shower-by-shower basis
  - difficult
- Reduce EM-Component
  - High Z material for filtering out photo-electrons
- Boost hadronic response
  - mainly the neutron component
- Use of
  - Organic (hydrogen-rich) materials have a large neutron cross-section
  - Uranium (Nuclear fission triggered by neutrons)

The Uranium question

- Depleted Uranium was en vogue for a while as absorber
    - Several Calorimeters, e.g. ZEUS, D0
- But compensation mainly due to
    - EM suppression
    - Boosting hadronic response
- The fission fragments carried lots of energy
    - But to slow to matter
- Uranium is a nasty material
    - Radioactive
    - Very reactive (grinds catch fire)
    - Mechanical properties
- These disadvantages made it unpopular

Short summary

- Hadronic Showers
  - are very complex
- They have two components
  - electromagnetic
  - strong-interaction
- Electromagnetic fraction increases with energy
  - leads to non-linearity
- Compensation
  - trying to achieve e/h=1

Shower simulations

- EM Showers
  - Well-modeled using EGS4 or GEANT4 packages
  - Extensively validated using test beam data
- Hadronic showers
  - no preferred model
  - GEANT4 and FLUKA are most popular packages
  - Various compositions of models, so-called physics lists
  - One fit all doesn't exist
  - Test beam data used to tune the physics lists

Calorimeter Resolution

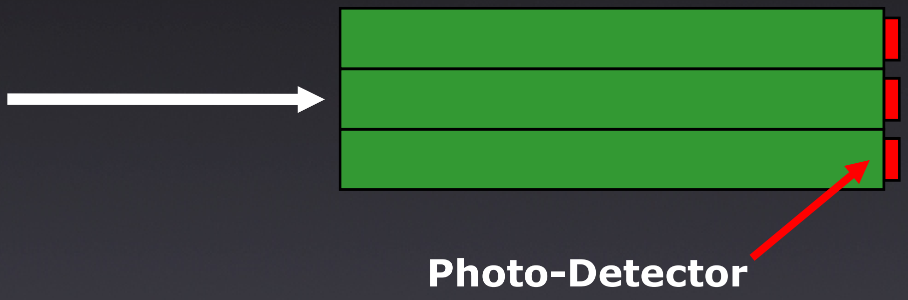
- Resolution is parametrized as

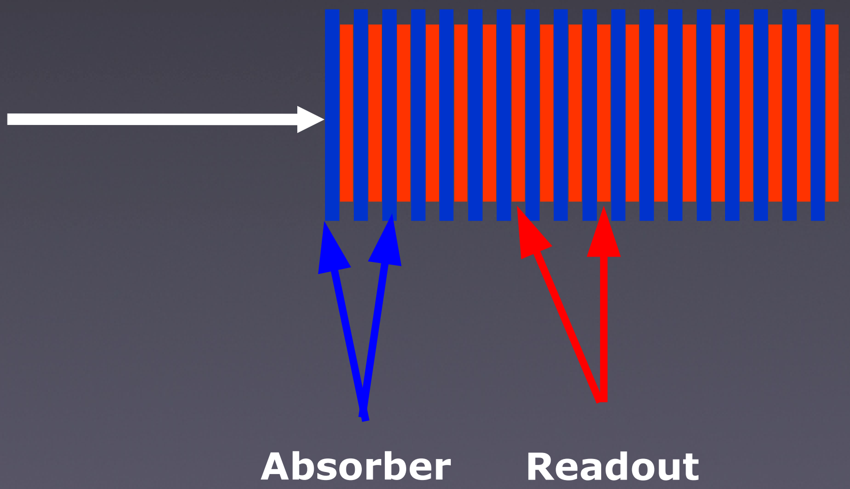
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{(E)}} \oplus \frac{b}{E} \oplus c$$

- a: Stochastic term
  - Fluctuations is the signal generating processes
- b: Noise Term
  - Due to read-out electronics
- c: Constant Term
  - Non-uniform detector response
  - Channel to channel inter-calibration errors
  - Fluctuations in longitudinal energy containment
  - Energy lost in dead material, before or in detector

Calorimeter types

- Basically there are two classes
  - Homogeneous Calorimeters
  - Sampling Calorimeters
- Either type is extensively used for ECALs
- HCALs are almost exclusively sampling calorimeters
- Decision for either depends on application





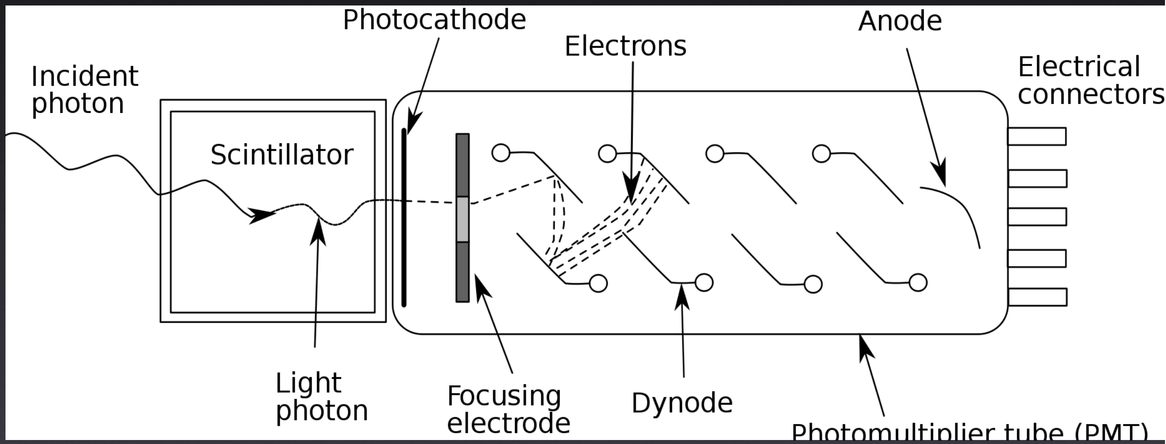
Homogeneous Calorimeters

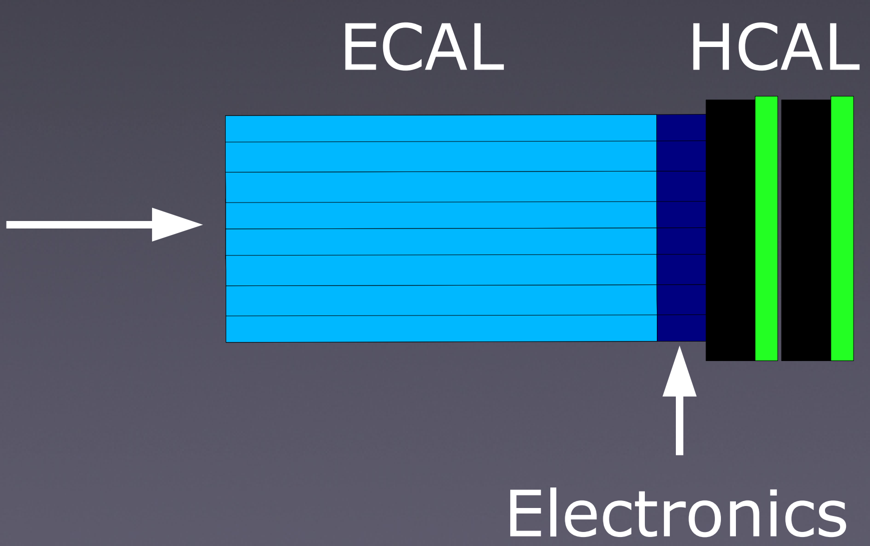
- Three ways to make one
  - Scintillating crystals
  - lead glass (Cerenkov light)
  - Noble gas liquids
- Either offers very good resolution
- Disadvantages
  - no direct longitudinal shower information
  - Crystals are expensive
  - very non-linear for hadrons

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	$\lambda_{\max}$
Units:	g/cm^3	$^\circ$C	cm	cm	MeV/cm	cm	ns	nm
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	630^s	300^s
							0.9^f	220^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35^s	420^s
							6^f	310^f
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s
							10^f	420^f
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356

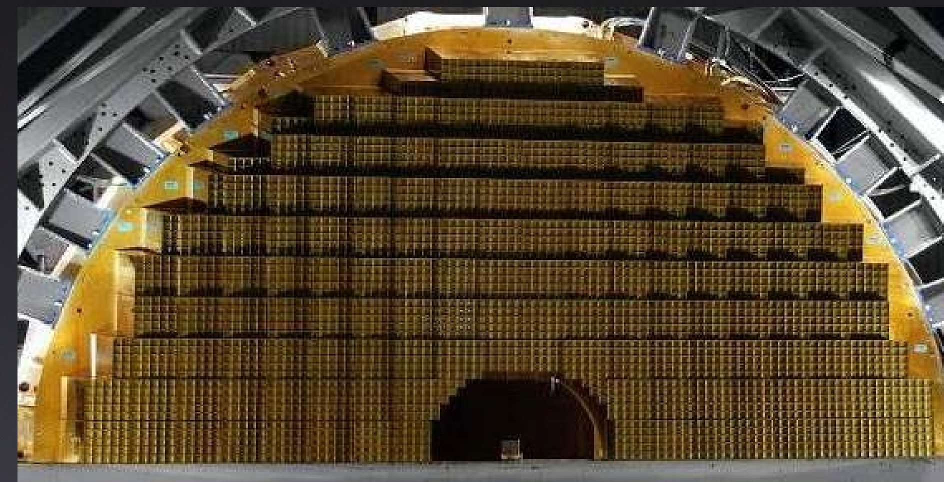
Read-out

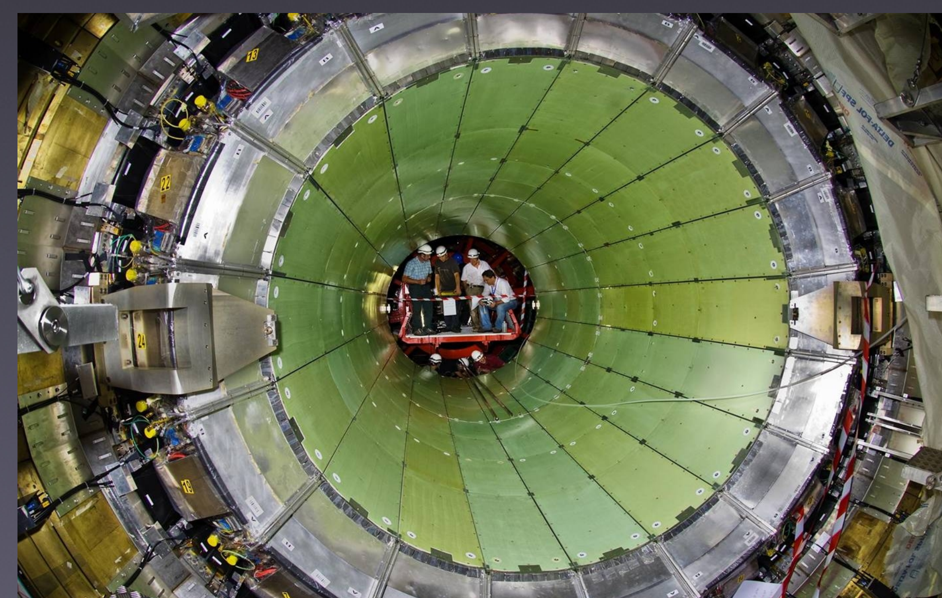
- Mostly light-based
  - tends to be blue
- Classical
  - Photomultiplier
- Advanced
  - Avalanche Photo-Diodes
  - Silicon-Photo-multipliers
- Caveat
  - Readout electronics always at the end
  - highly non-linear for hadrons





The CMS ECAL





Target Applications

- ECAL only systems
  - e.g. B-Factories
  - generally medium energy machines
- Good ECAL is essential
  - no Jet physics at all
- Examples
  - BaBar, Belle
  - KTeV

- ECAL+ HCAL
  - If ultimate ECAL resolution is needed
  - e.g. $H \rightarrow \gamma\gamma$
- Necessary compromise on HCAL performance
- Examples
  - CMS
  - L3

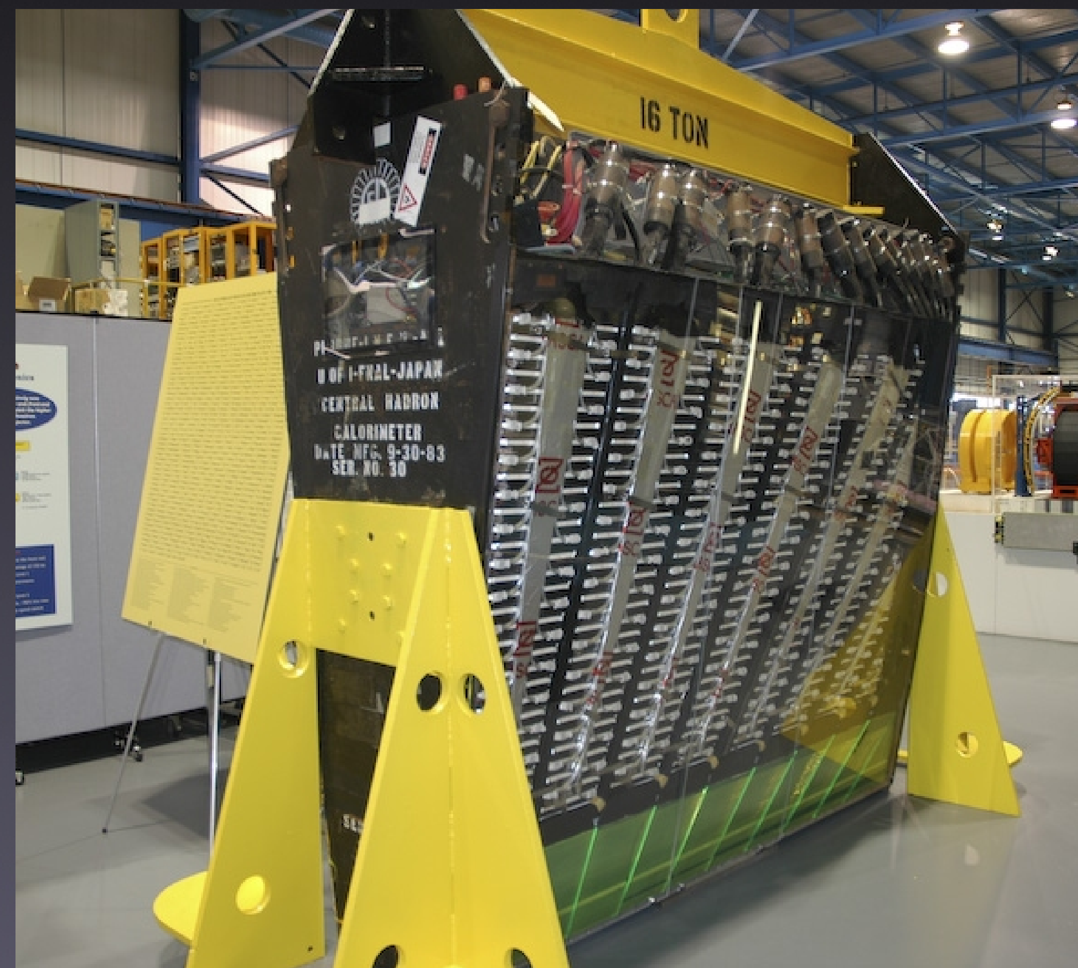
Example systems

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

Sampling Calorimeters

- Most Calorimeters in HEP are sampling calorimeters
- Provide high granularity both lateral and longitudinal
- Two ingredients
  - active (readout)
  - passive(absorber)
- Sampling fraction as key parameter $$SF = \frac{\Delta E_{active}}{\Delta E_{active} + \Delta E_{passive}}$$
- May ways of building sampling Calorimeters
  - Sandwich
  - Spaghetti
  - ....
- Sandwich Calorimeters have been the most popular

The CDF calorimeter

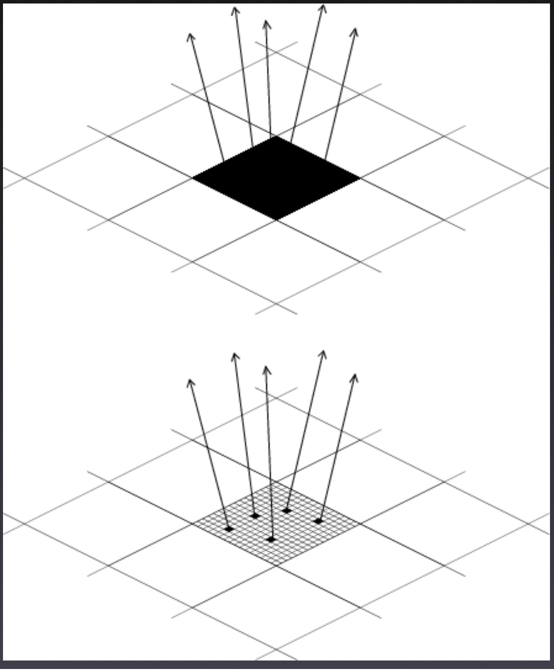


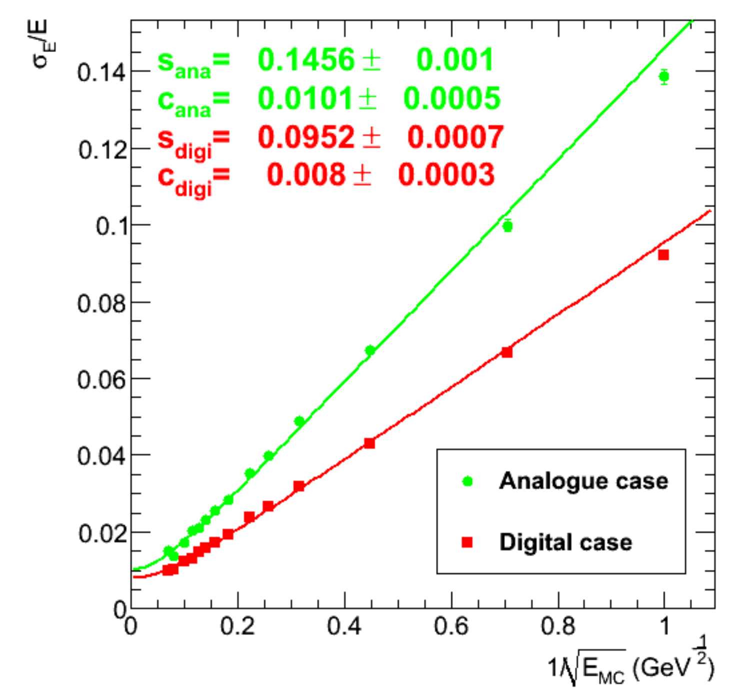
Read-Out strategies

- Two main ideas
- Light
  - Scintillator
- Charge
  - Silicon
  - Gas detectors
  - Liquid noble gases
- Either with the benefits and disadvantages
- First question is, though
- Analog (classic) or digital (new fashion)

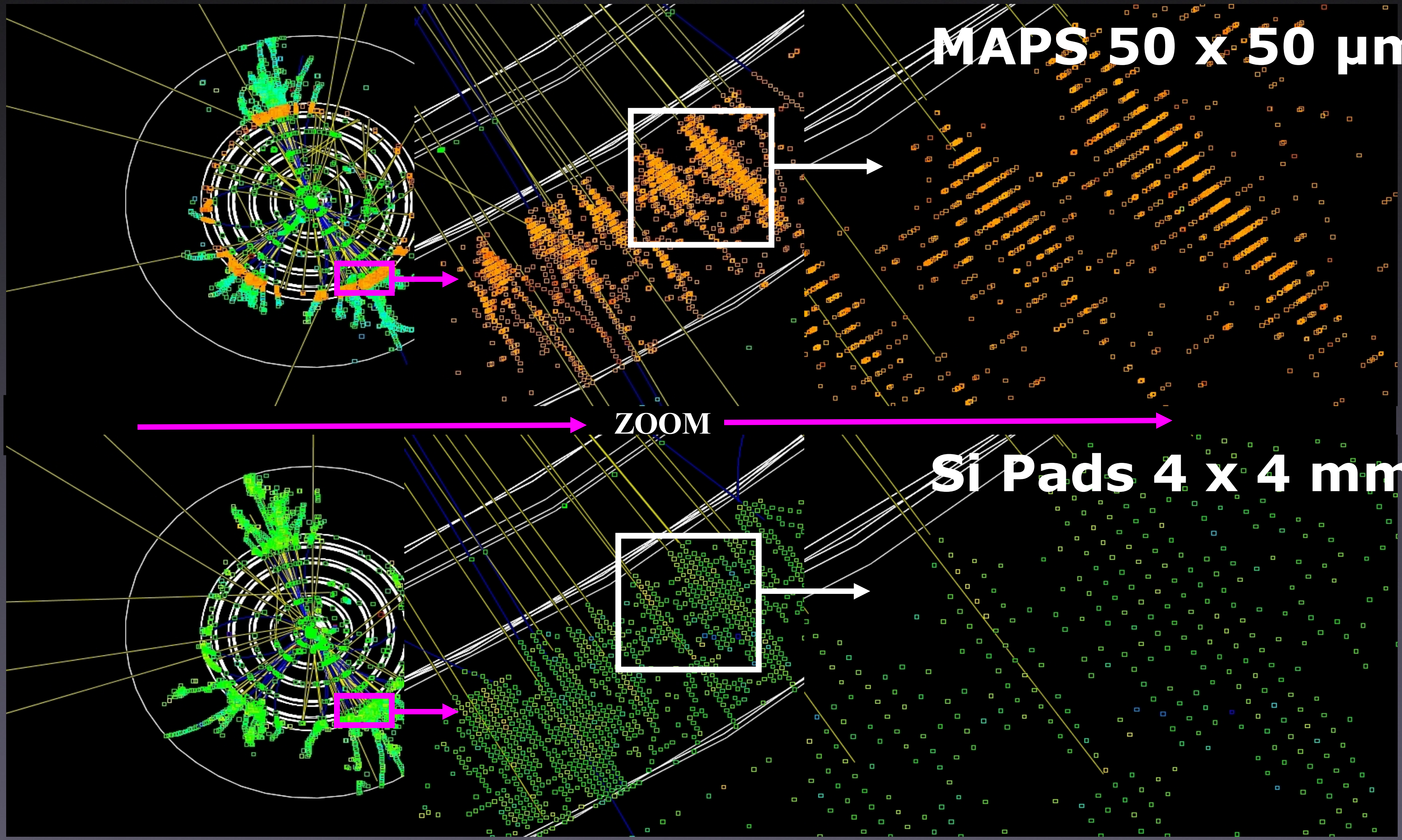
Analog vs. digital readout

- Analog Readout
  - measures the energy deposited by the shower
  - Fluctuations around the average occur due to angle of incidence, velocity and Landau spread
- Digital Readout
  - counts the number of particles in a shower
  - Number of charged particles is an intrinsically better measure than the energy deposited
  - Needs very high granularity otherwise limited by multiple hits per cell



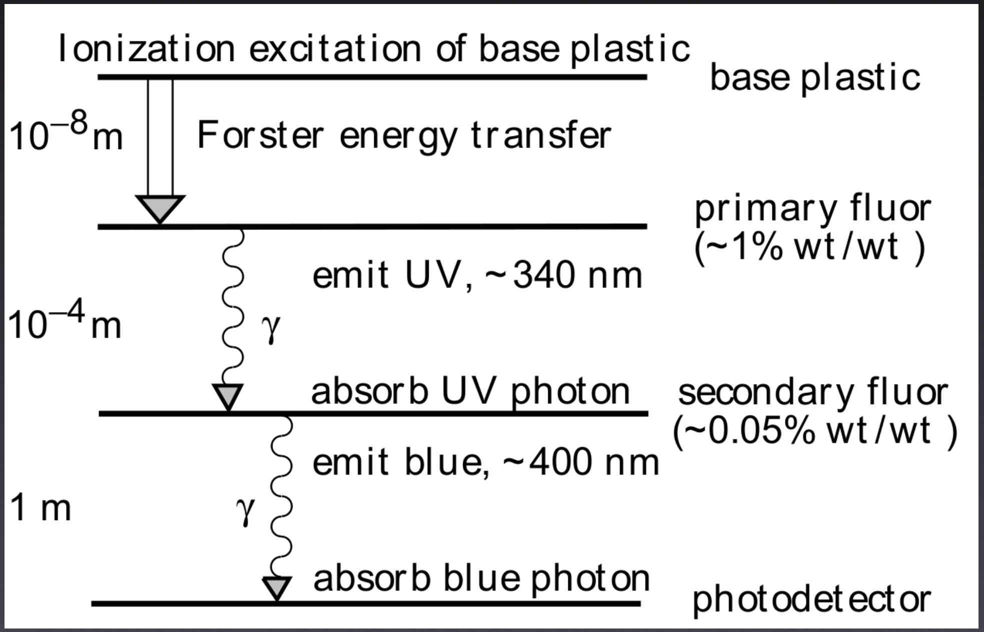


An Example



Scintillator-based readout

- Usually talking about
  - organic scintillators
  - aka plastic
- Wave-length shifting to improve light detection
- Fibers to connect the read-out
  - read out same as for e.g. crystals
- Easy to build calorimeter towers
- Lots of experience already with this technology



However

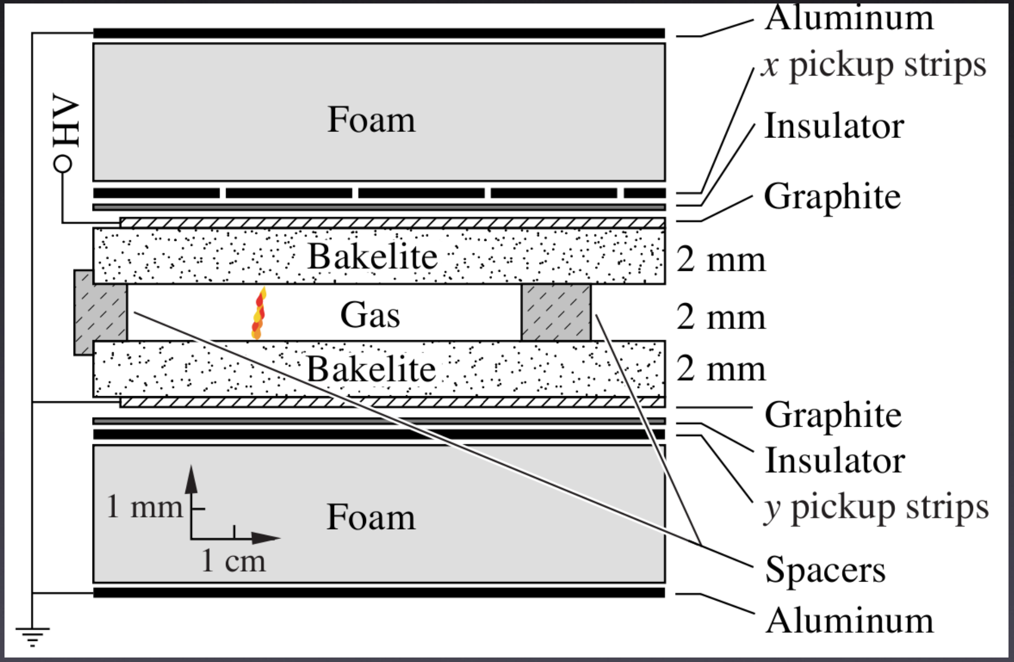
- A word of warning (R. Wigmans, Calorimetry)
  - The detector is inherently non-uniform
  - The detector is inherently unstable
- Reasons
  - Scintillation is very sensitive to the environment
  - Moving light to the readout is necessarily non-uniform
  - Aging ...
  - PMTs, Silicon-PMs etc are all temperature dependent
- This means careful monitoring and calibration

Other approaches

- Silicon-Pads
  - analog to a Silicon tracker
  - See Giulio Villani's talk
- Liquid Noble Gases
  - Argon is most popular
- Micro-Pattern Gas detectors
  - RPC
  - GEM
  - Micromegas
  - Most of them suited as digital counters

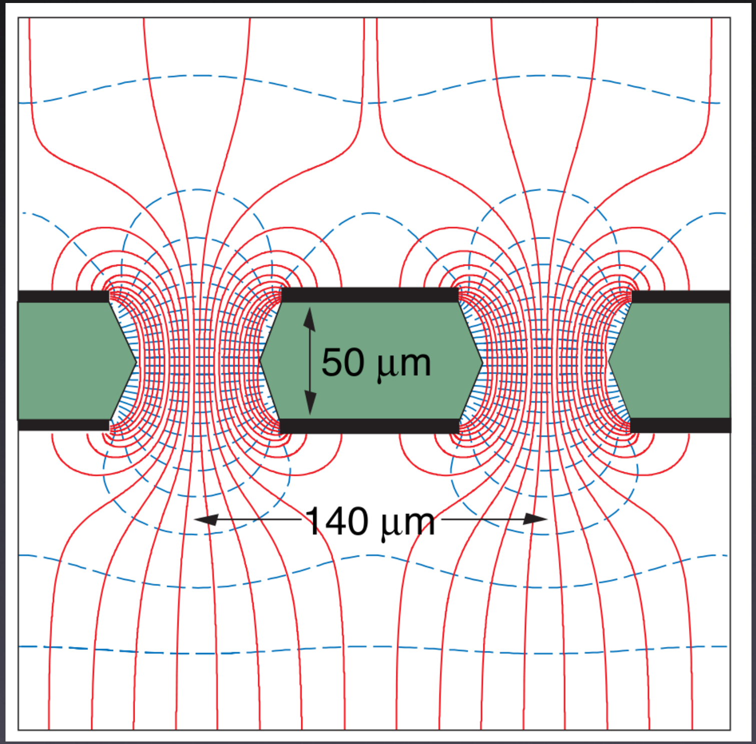
RPC

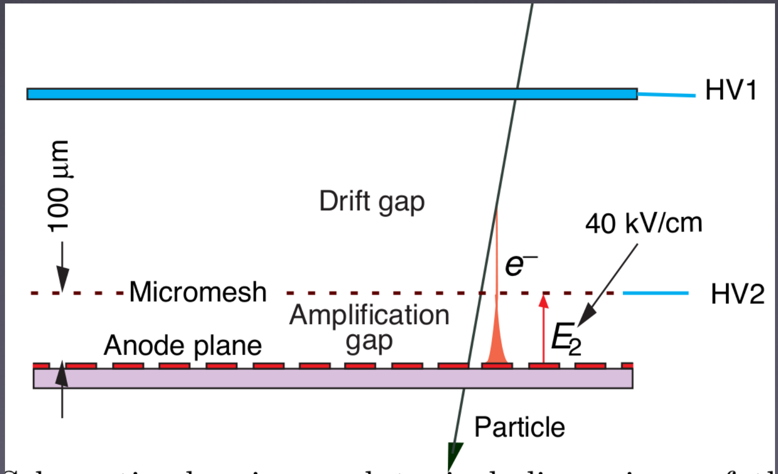
- Resistive Plate Chambers
  - cheap alternative to scintillators
- Idea
  - 2 high resistivity plates with gas in between
  - Particle triggers discharge
  - Self-resetting
- Signal readout capacitive coupling
- Very high segmentation is possible



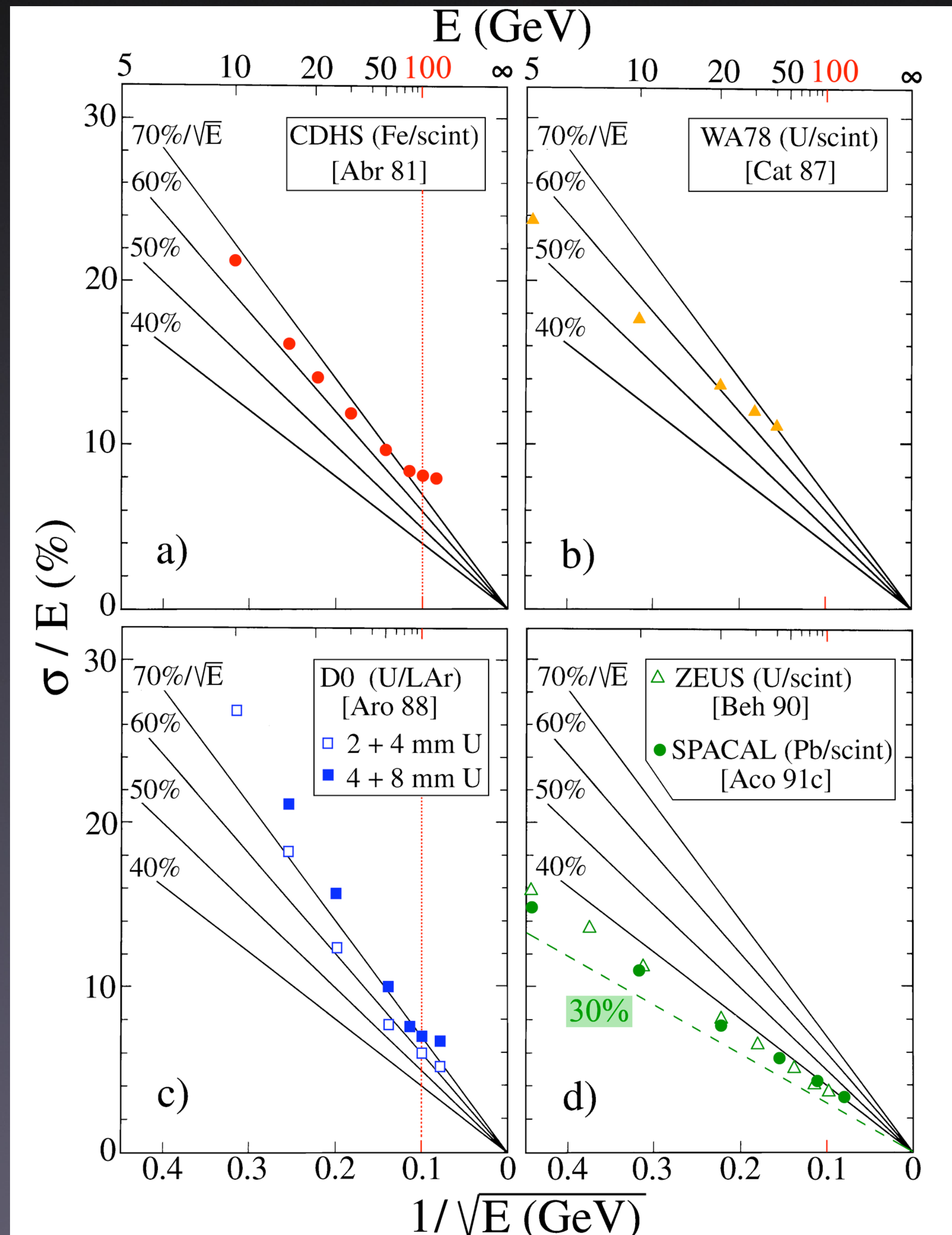
GEM & Micromegas

- GEM
  - perforated copper-kapton foil with field
  - pitch ~ 100 μm
  - Charge amplification in the holes
- MicroMegas
  - large Drift region
  - small amplification region
  - small metal mesh as separator
- Both of hight-rate and fast signals





Typical HCAL performance



Short summary

- Two types of calorimeter
  - homogeneous
  - sampling
- Each with the unique advantages
- Readout can be realized in many ways
  - light collection
  - charge collection
- The target application drives the technology choice

System design

- So far only talked about “the building blocks”
- A complete system is a different matter
- Various constraints
  - Space
  - Channel count
  - Services
  - Costs
- and derived parameters
  - Depth & Leakage
  - Segmentation
  - Dead areas

The ideal calorimeter

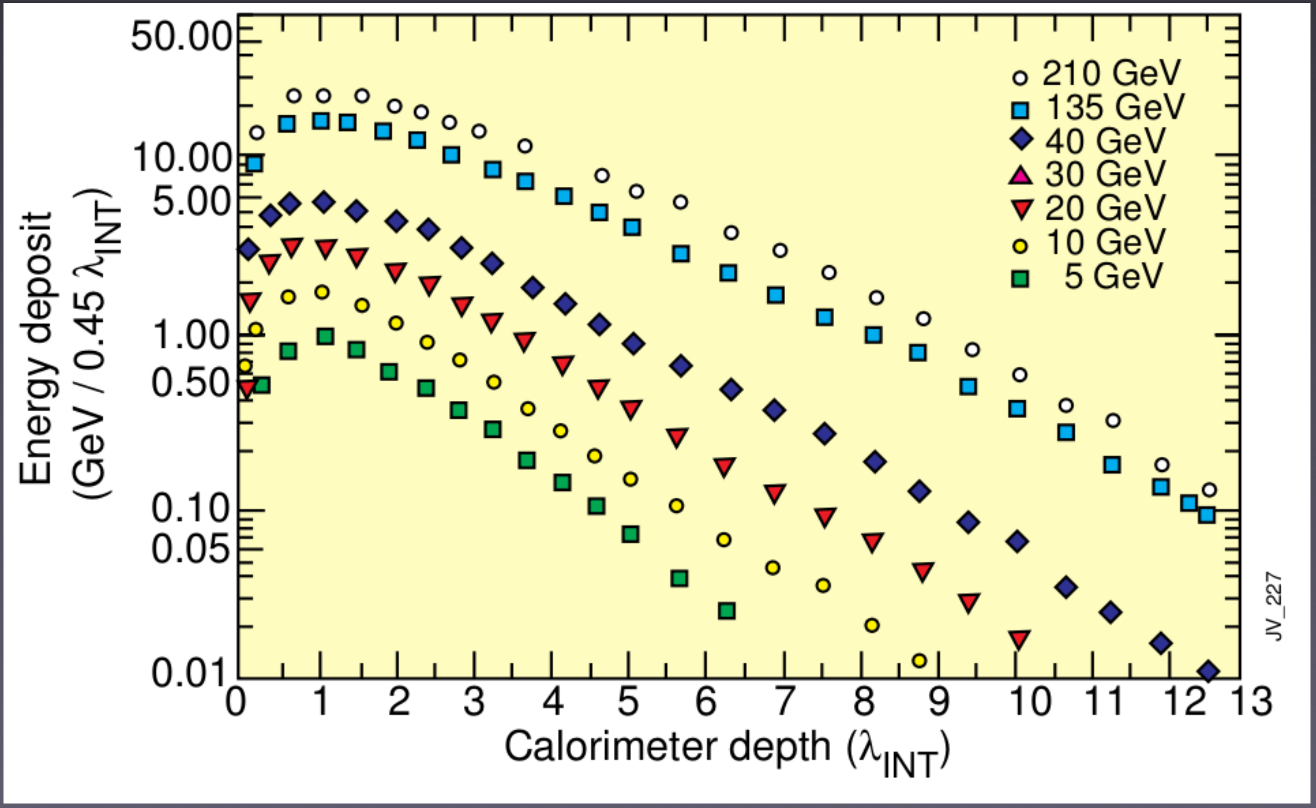
- Is infinitively deep
  - no leakage
- if infinitely fine segmented
  - and has no cracks
- needs no power or readout
  - hence no services
- Weighs nothing
  - no mechanical support

Space Constraints

- Calorimeter sits
  - either between tracker and coil
  - or is located (partially) outside the coil
- In the first case, the coil limit the size
  - of both tracker and calorimeter
  - Limiting factor are coil forces and cost
- This forces the choice of very dense material
  - like e.g. Tungsten or Steel
- Locating the calorimeter outside
  - impacts the physics as well
  - Coil is dead material

Leakage

- Can't make a calorimeter infinitely deep
  - So need a compromise
- Adding radiation length is expensive …
  - Solid physics case required



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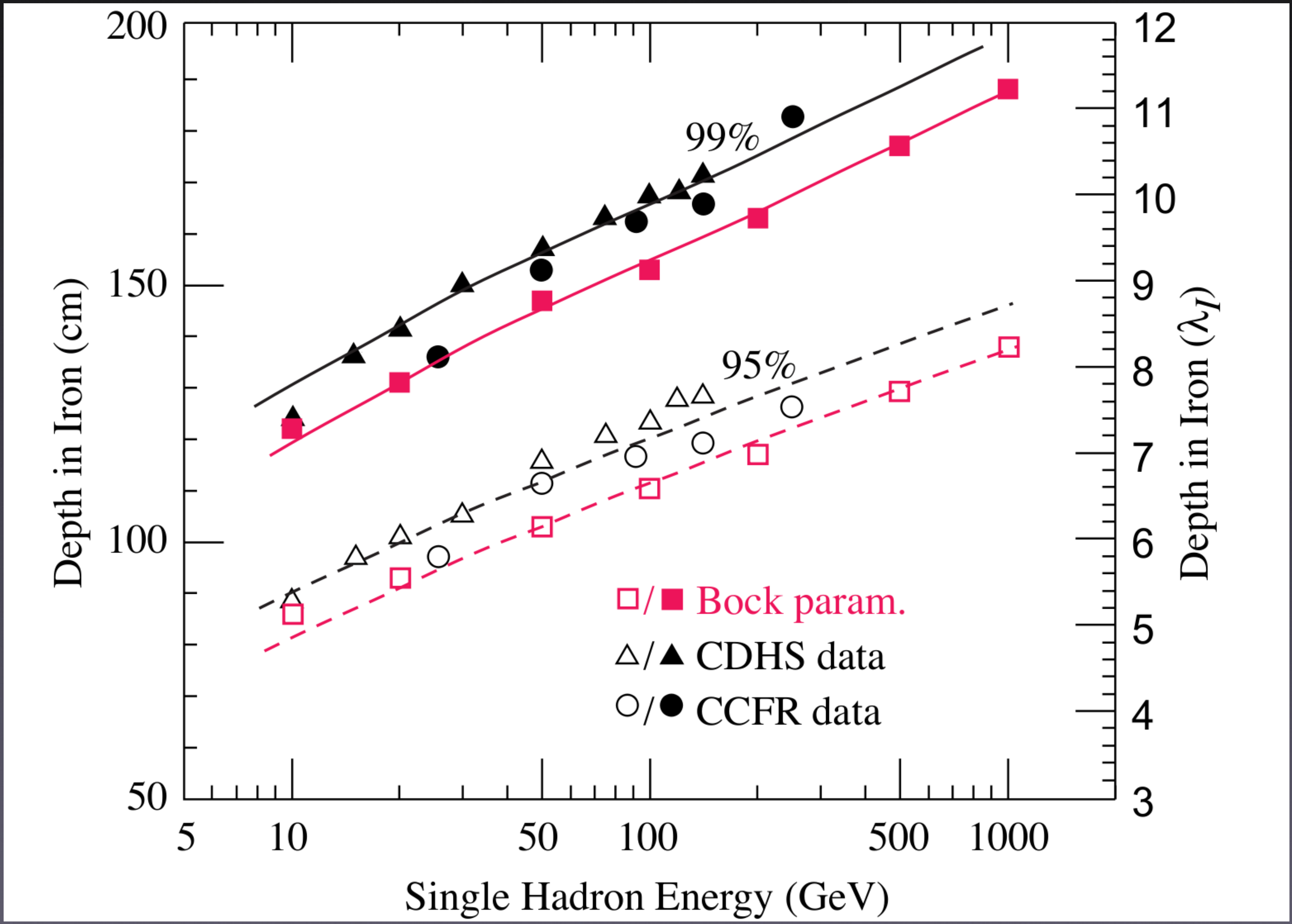


200
150
100
50
12
11
10
9
8
7
6
5
4
3
99%
95%
Depth in Iron (cm)
Depth in Iron (λ_I)
□/■ Bock param.
△/▲ CDHS data
○/● CCFR data
5
10
50
100
500
1000
Single Hadron Energy (GeV)

Mechanics and Services

- Given the materials, Calorimeters are massive objects
  - CMS ECAL Barrel 68 t ($PbWO_4$ crystals)
  - ZEUS Calorimeter (Uranium) 700 t
- Mechanical support becomes crucial design feature
- Power consumption is equally impressive
  - Single channel ~ a few 10 mW
  - But 10^6 channels so, 10 kW
- Cables
  - Running cables & fibers leads to cracks
  - Impact on performance

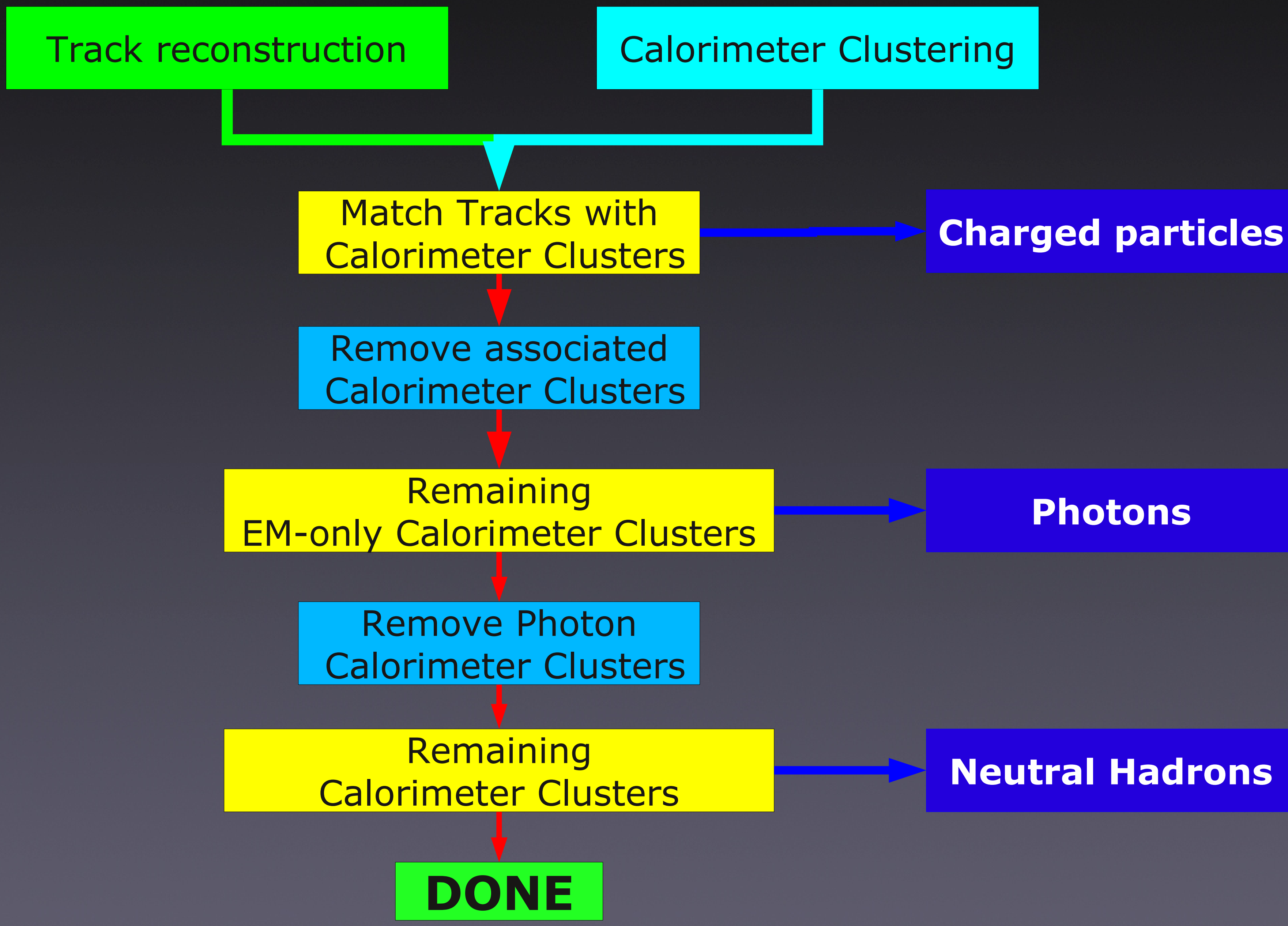
Advanced ideas

- Calorimetry R&D is an active field
- Advances in both electronics and material
  - Dealing with large amount of channels
  - new crystal materials
  - Silicon Photomultiplier & Large Area Silicon Detectors
- These allows exploring new ideas
  - Particle Flow Algorithms
  - Dual Readout Calorimetry

Particle Flow Algorithms

- Observation : Track measurements much better than calorimetric ones
  - Usually true up to several 100 GeV
  - Average particle momentum is more O(10 GeV)
- So use Tracker to measure the energy
  - Assuming all charged hadronic tracks are pions
  - Lepton-ID for electrons, muons
- Use Calorimeter only for
  - Neutral hadrons and photons
- Remove Calorimetry from the energy measurement

PFA in a nutshell



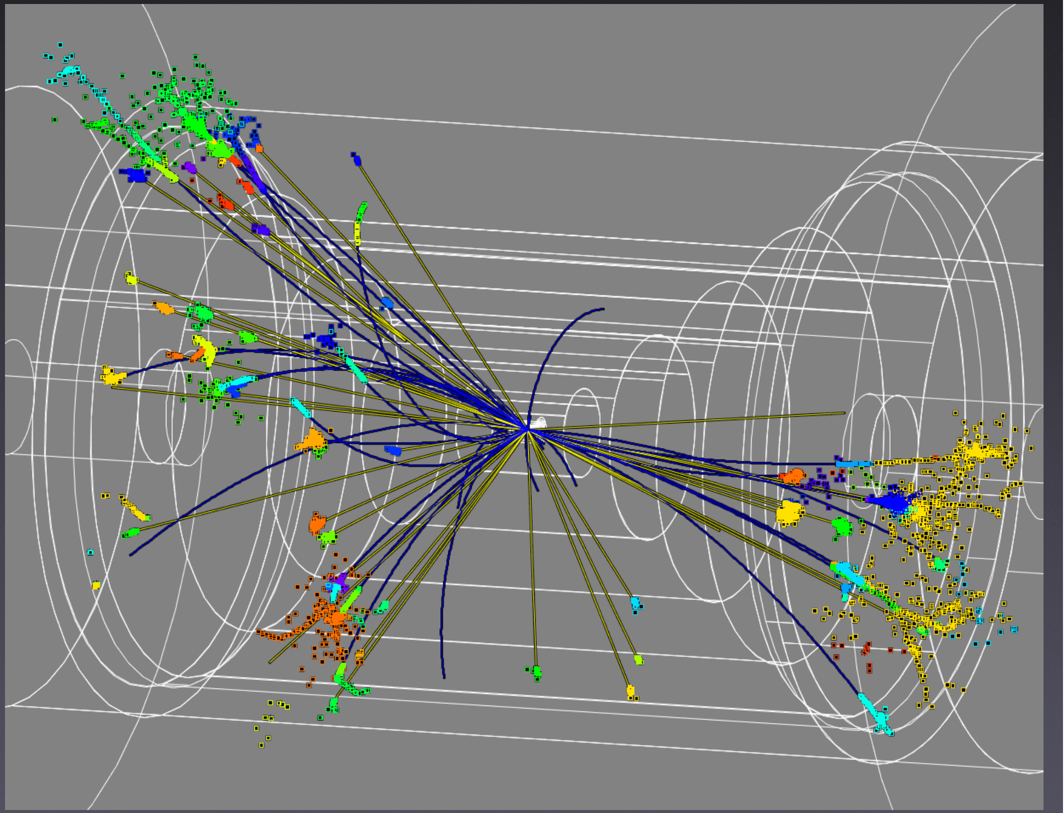
Jet Resolutions

Particle Class	SubDetector	Jet energy fraction	Particle Resolution	Jet Energy Resolution
Charged	Tracking	60%	$10^{-4}\ \sqrt{E}_{charged}$	neg.
Photons	ECAL	30%	$11\ \%\ \sqrt{E}_{EM}$	$6\ \%\ \sqrt{E}_{jet}$
Neutral Hadrons	HCAL (+ECAL)	10%	$40\ \%\ \sqrt{E}_{hadronic}$	$13\ \%\ \sqrt{E}_{jet}$

- Energy resolution about 14% (driven by HCAL)
- Confusion terms have bigger impact
  - $\sigma_{jet}^2 = \sigma_{charged}^2 + \sigma_{EM}^2 + \sigma_{hadronic}^2 + \sigma_{confusion}^2 + \sigma_{threshold}^2 + \ldots$
- Performance not limited by Calorimetry
  - Need high granularity to reduce confusion !

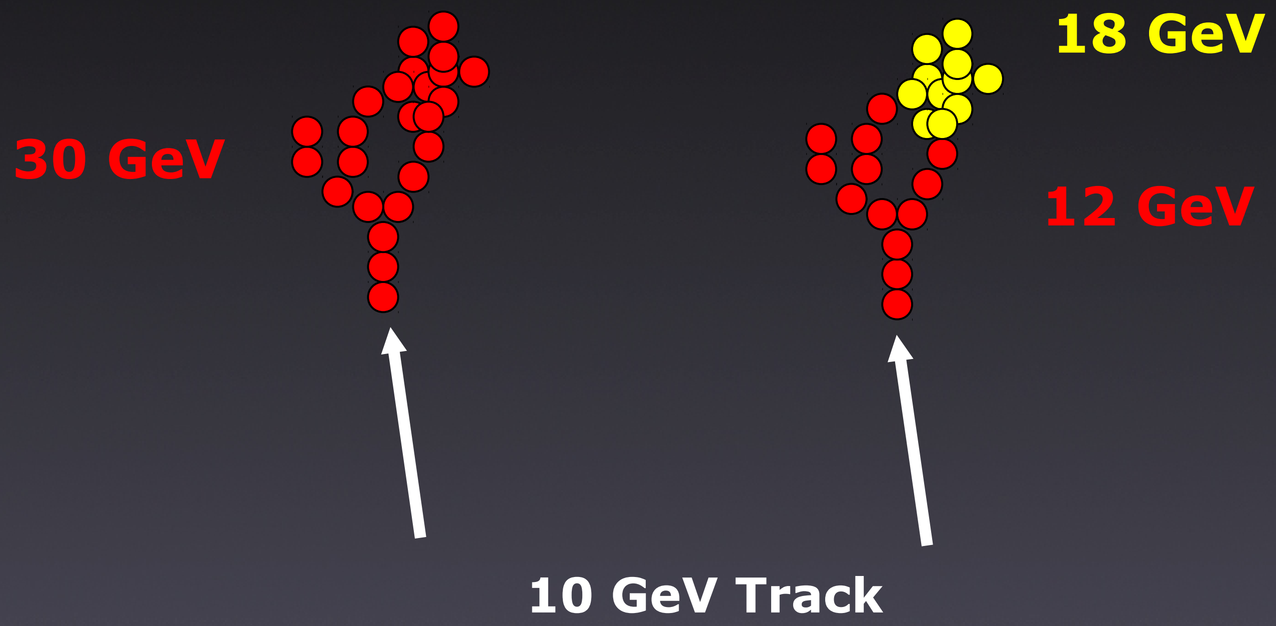
Sounds easy

- Associating showers to tracks
  - showers can overlap
  - track ambiguities
  - leakage
- Hadronic showers are very difficult
  - As you already know

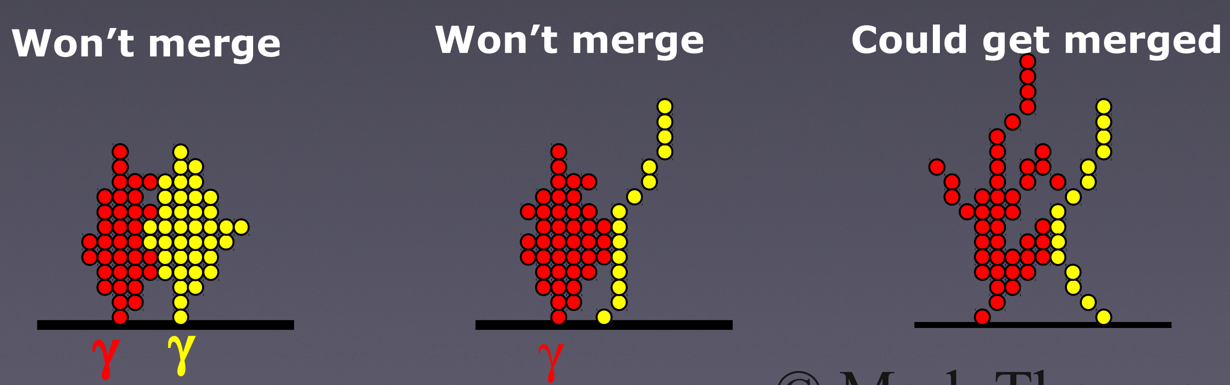


Matching problems

Shower matching



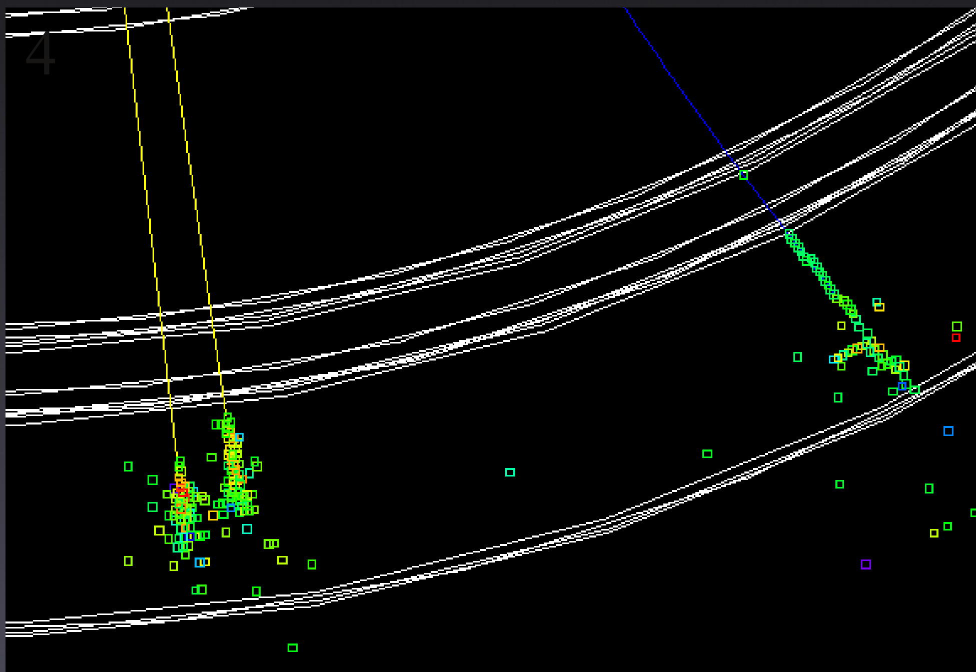
Shower merging



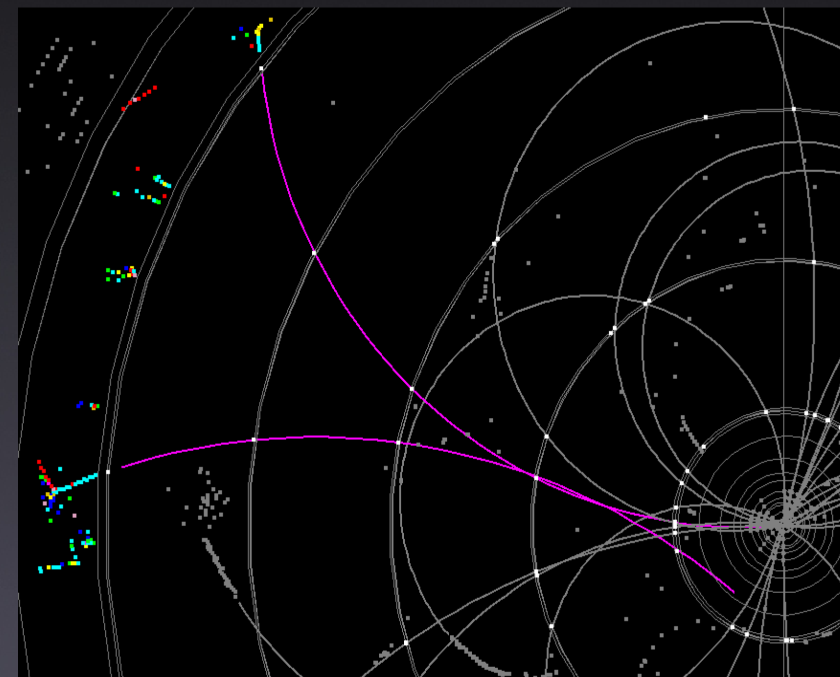
PFA design considerations

- Highly granular
  - For Shower separation and matching
  - mm for ECAL, cm for HCAL
- Sampling Calorimeters with decent energy resolution
  - containment is an issue
- Minimize dead material
  - Fit inside the coil
  - Compact
- Calorimetry must also
  - Pass engineering constraints
  - Affordable

Other benefits

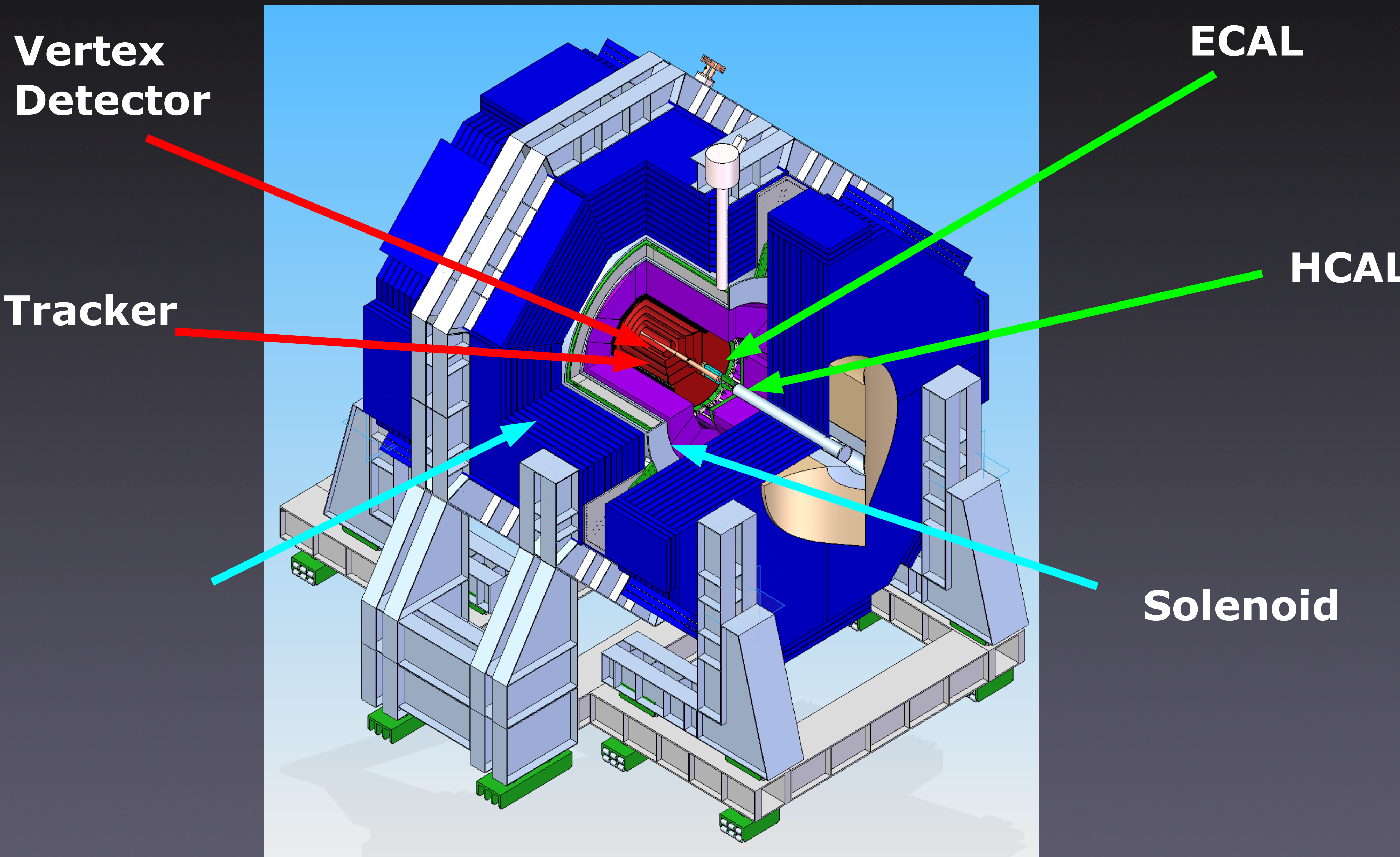


$\tau^+ \rightarrow \rho^+\nu \quad (\pi^+\pi^0\nu)$

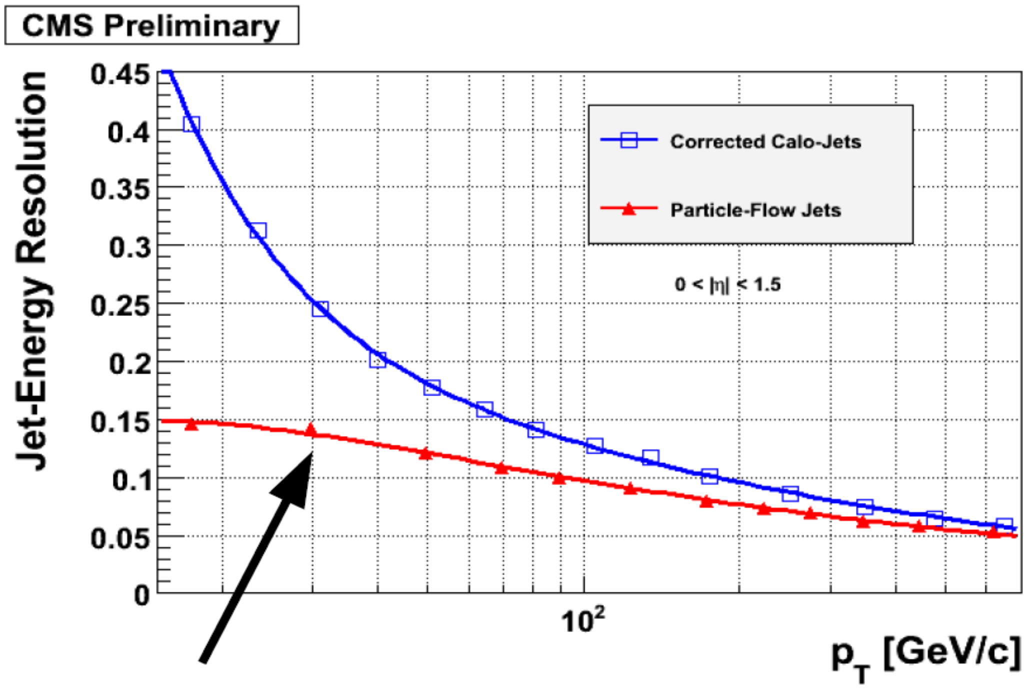


Calorimeter Aided Tracking
V^0 finder

A PFA Detector

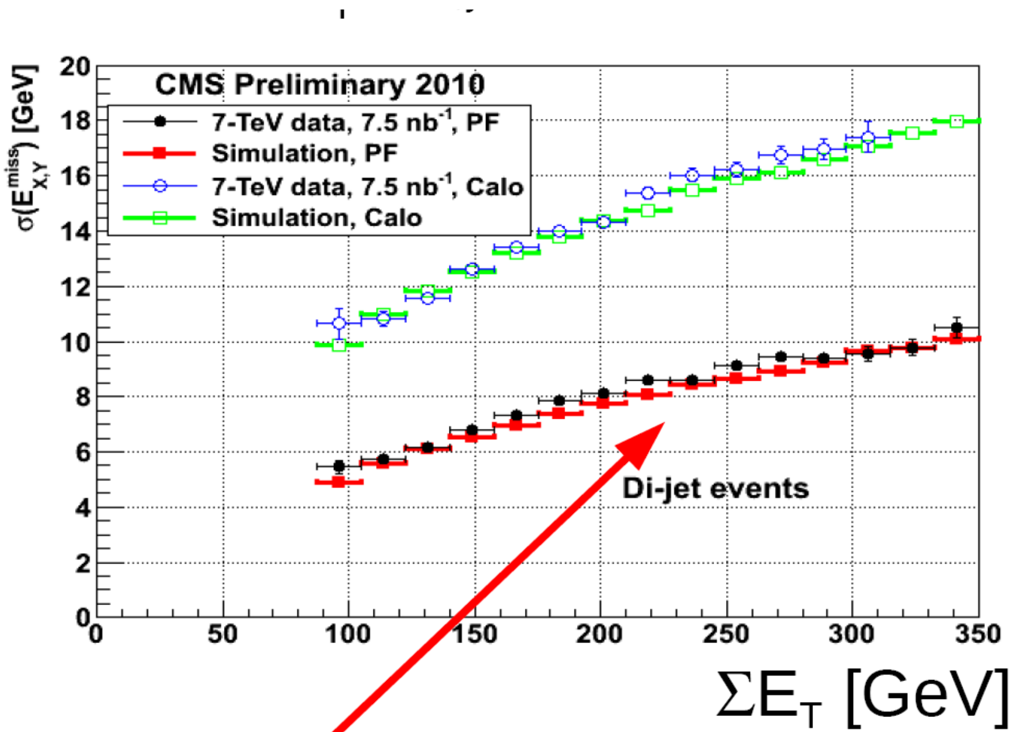


PFA at CMS



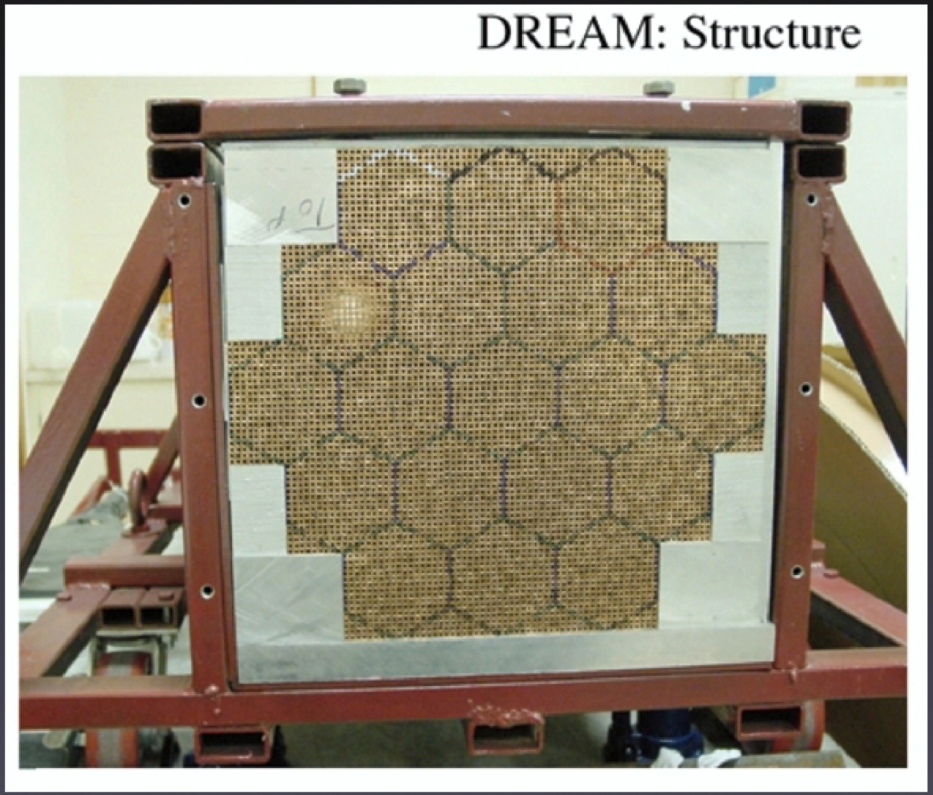
Jet energy resolution
Simulated QCD-multijet events in the CMS barrel

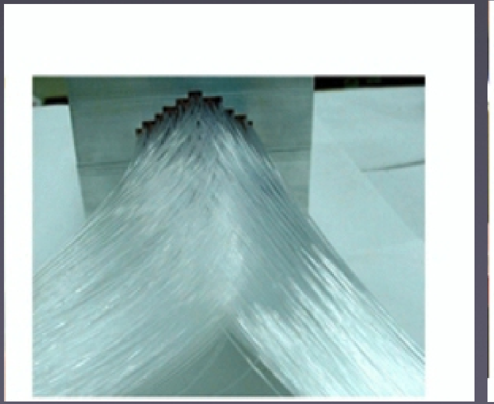
Missing E_T resolution for Di-jet events

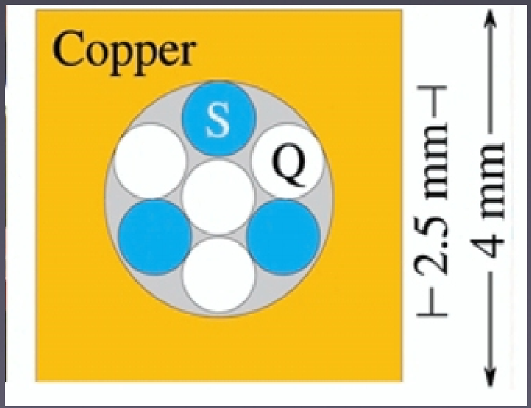


Dual-Readout Calorimetry

- As already mentioned
  - Two components in hadronic showers
- Dual Readout Idea
  - Two active media
  - Scintillating Fibers measure visible energy
  - Quartz Fibers measure Cerenkov light from em component
- Implemented in the DREAM calorimeter







Dual Readout in Detail

- Scintillation signal (S) and Cerenkov signal:

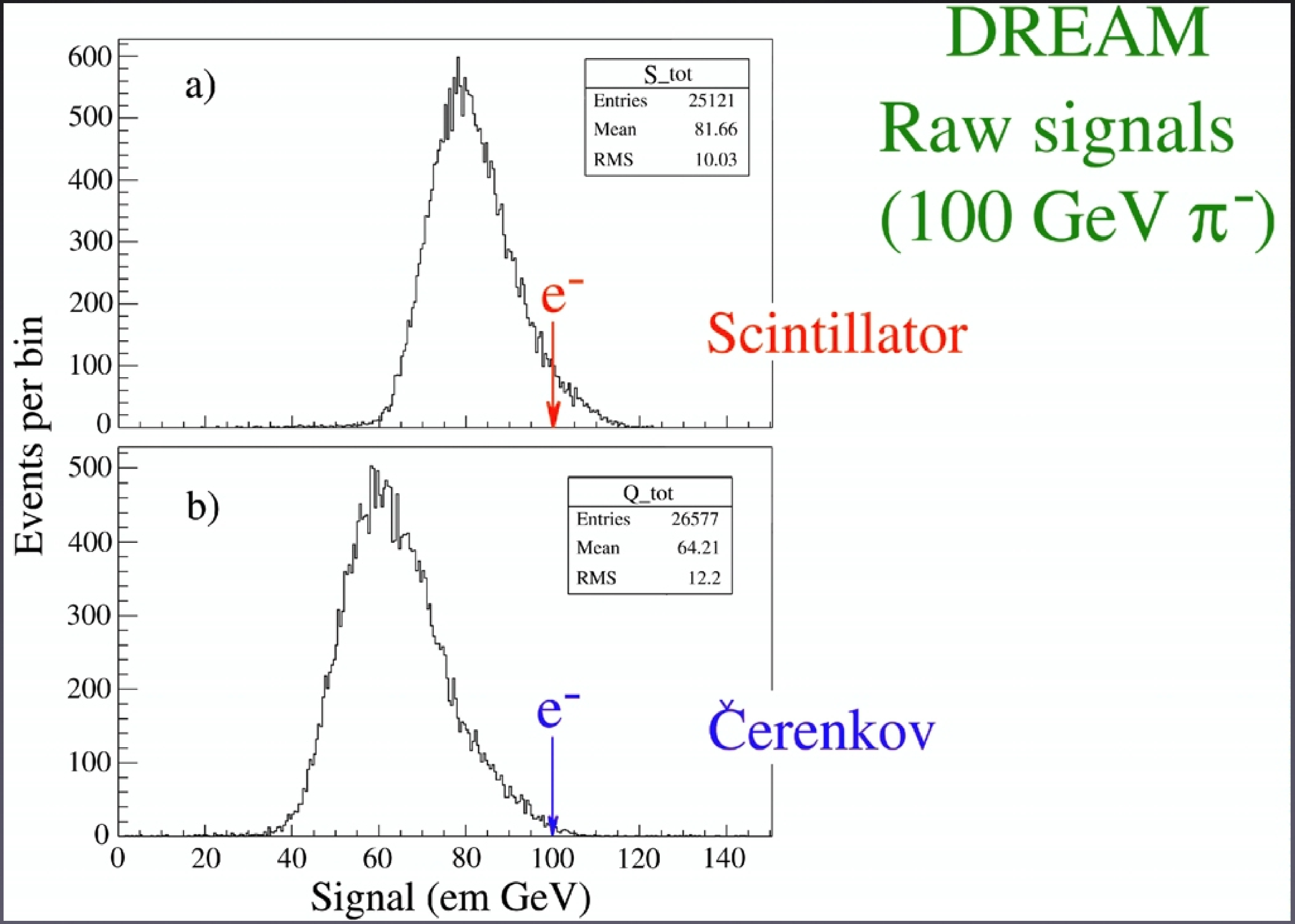
$$Q = E\left(f_{em} + h/e_Q\left(1 - f_{em}\right)\right)$$
$$S = E\left(f_{em} + h/e_S\left(1 - f_{em}\right)\right)$$

- This can be written as

$$E = \frac{RS - Q}{R - 1}$$
$$R = \frac{1 - h/e_Q}{1 - h/e_S}$$

- R will be taken from calibrations

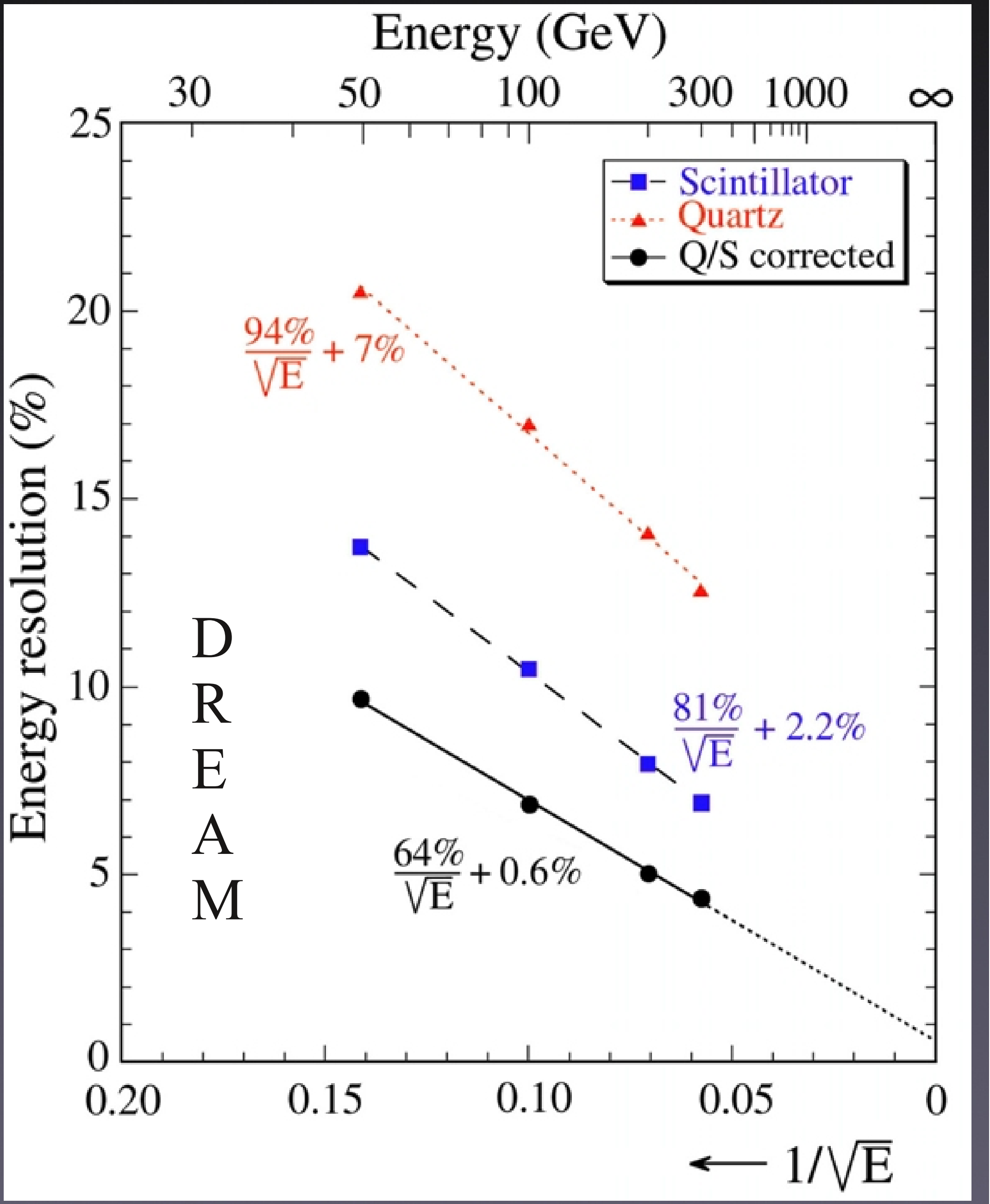
Some plots



DREAM
Raw signals
(100 GeV π⁻)
a)
S_tot
Entries 25121
Mean 81.66
RMS 10.03
e⁻
Scintillator
b)
Q_tot
Entries 26577
Mean 64.21
RMS 12.2
e⁻
Čerenkov
Events per bin
Signal (em GeV)

Energy Resolution

- DREAM prototype
  - Achieves linear hadronic response
  - Dual readout demonstration
- Limitations
  - Size of prototype (leakage)
  - Light yield
  - Fluctuations in visible energy
- Principle can be applied to other calorimeters with optical readout



Summary

- Calorimeters are not black magic
  - Hope you got an idea, how they work
- Lots of things I couldn't cover
  - Material for several lectures
- Calorimeter R&D is an active field
  - CALICE, DREAM ...
- Recommended Literature
  - R. Wigmans : Calorimetry
  - Review of Particle Physics 2009
  - T. Virdee : Experimental Techniques