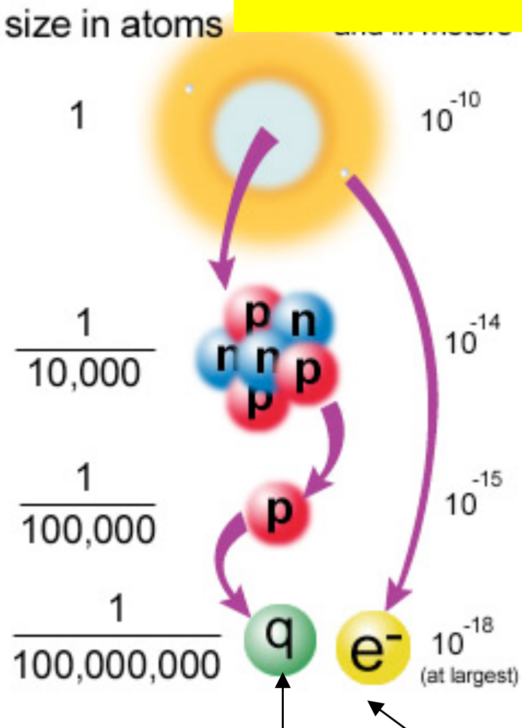
Instrumentation in HEP: Hadronic Calorimeter

Sarajevo School of High Energy Physics 2022

Kerem Cankoçak

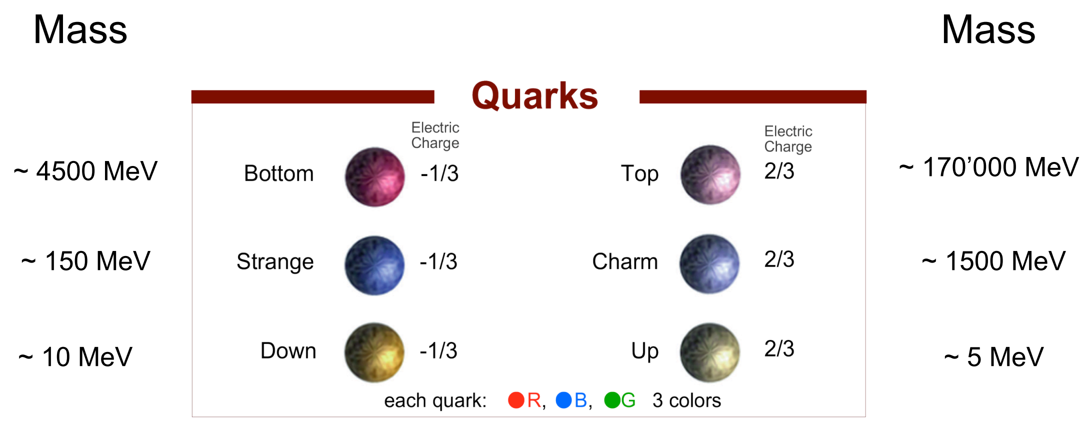
(Istanbul Technical University)

Constituents of Matter



quark

electron (one of the 6 lepton)



- Quarks are held together by gluons (theory of strong force = Quantum Cromo Dynamics)
- Confinement: intensity of interaction increases with distance between quarks
- Quark flavor quantum number (S, C, B, T) is conserved in strong interactions, violated in weak interactions
- Quarks form all known hadrons. Some hadrons were discovered after having been postulated as specific quark combinations.

Quark (antiquark) combinations form all hadrons (baryons and mesons)

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Baryons: (QQQ or $\bar{Q}\bar{Q}\bar{Q}$)

They are fermions

Mesons: ($Q\bar{Q}$)

They are bosons

Leptons

Mass			Electric Charge			Electric Charge	Mass
1777 MeV	Tau	τ	-1	Tau Neutrino	ν_τ	0	< 15.5 MeV
105.7 MeV	Muon	μ	-1	Muon Neutrino	ν_μ	0	< 0.17 MeV
0.511 MeV	Electron	e	-1	Electron Neutrino	ν_e	0	< 0.0000022 MeV

- Leptons are point-like particles (elementary)
- Very special leptons: neutrinos
- Assign to leptons a quantum number L_e, L_μ, L_τ=1 for particles and -1 for antiparticles
- The lepton numbers are individually and, therefore, globally (L_e+L_μ+L_τ) conserved

Examples:

$\pi^+ \rightarrow \mu^+ + \nu_\mu$	$\nu_e + n \rightarrow p + e^-$
L_μ = 0 -1 +1	+1 0 0 +1

Calorimetry in particle physics has three steps:

1. Interaction of Particle with matter: *A* destructive interaction depending on the kind of material and the particle

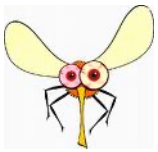
2. Energy loss in a detectable material

3. Signal Collection

Units

$$E^2 = p^2c^2 + m^2c^4 \qquad E = m_0\gamma c^2 \qquad p = m_0\gamma\beta c \qquad \beta = \frac{pc}{E}$$

- **Energy - *electron-volt***
  - **1 electron-volt = kinetic energy of an electron in 1 Volt**
  - 1 eV = 1.6×10^{-19} Joules = 2.1×10^{-6} W•s
    - 1 kW•hr = 3.6×10^{6} Joules = 2.25×10^{25} eV
    - 7 TeV (10^{12} eV) proton ➔ 10^{-6} J
    - 2808 bunch; 10^{11} proton/bunch 7 TeV/proton = 360 MJ



- **mass - *eV/c²***
  - 1 eV/c^2 = 1.78×10^{-36} kg
  - electron mass = 0.511 MeV/c^2
  - proton mass = 938 MeV/c^2
  - Human mass(80 kg) = 4.5×10^{37} eV/c^2

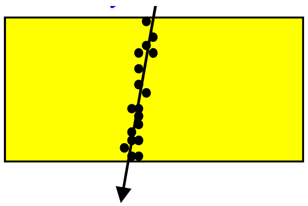
- **momentum - *eV/c*:**
  - 1 eV/c = 5.3×10^{-28} kg m/s
  - Tenis ball= 10 kgm/s = 9.9×10^{27} eV/c

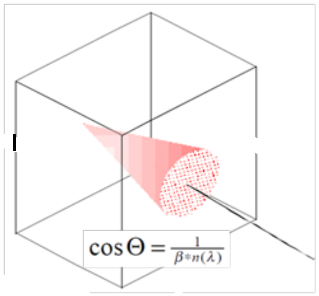
1.Very short summary of the interaction of Particle with matter

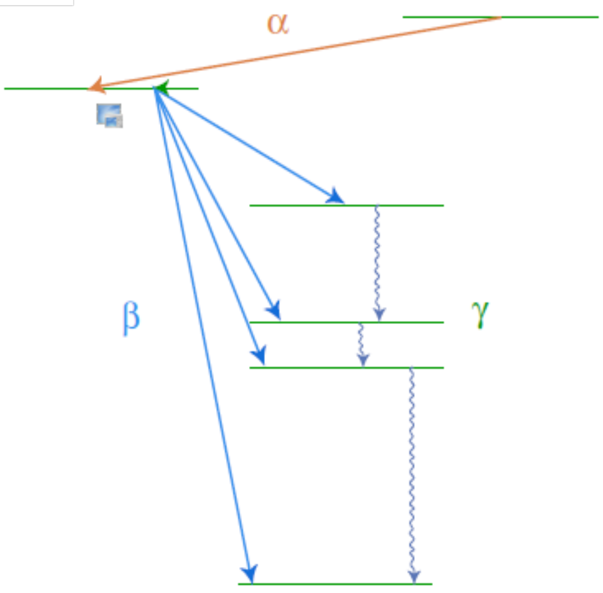
more in Damir Lelas presentation….

Particle Interacting with matter

- **Electromagnetic interaction**
  - Ionization
  - excitation
  - Cherenkov radiation
  - transmission radiation
  - bremsstrahlung
  - Photoelectric effect
  - Compton scattering
  - pair production
- **Nuclear interaction**
  - secondary hadrons
  - Hadronic shower

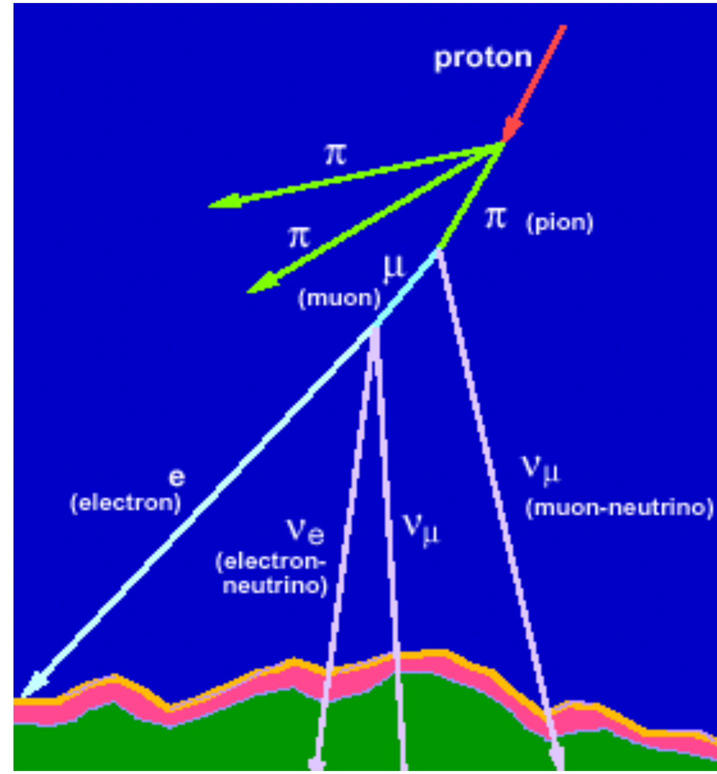




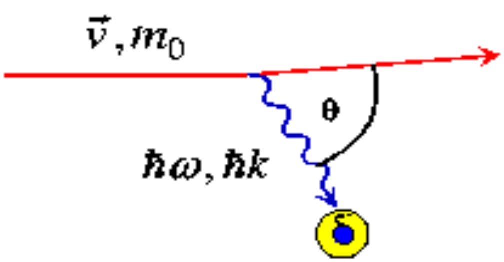


Charged particle through matter

- ionization
- Cherenkov radiation
- Breemstrahlung



Energy deposited in the material $\left\langle \frac{dE}{dx} \right\rangle = -\int_0^\infty NE \frac{d\sigma}{dE} \hbar \, d\omega$



$\omega = 2\pi\nu = 2\pi \frac{c/n}{\lambda} = k\frac{c}{n}$ $\qquad \omega^2 - \frac{k^2c^2}{\varepsilon} = 0$ $\qquad \varepsilon = n^2$

Energy / (length*density)

MeV / (cm * (gram / cm^3) = MeV cm^2 /gram

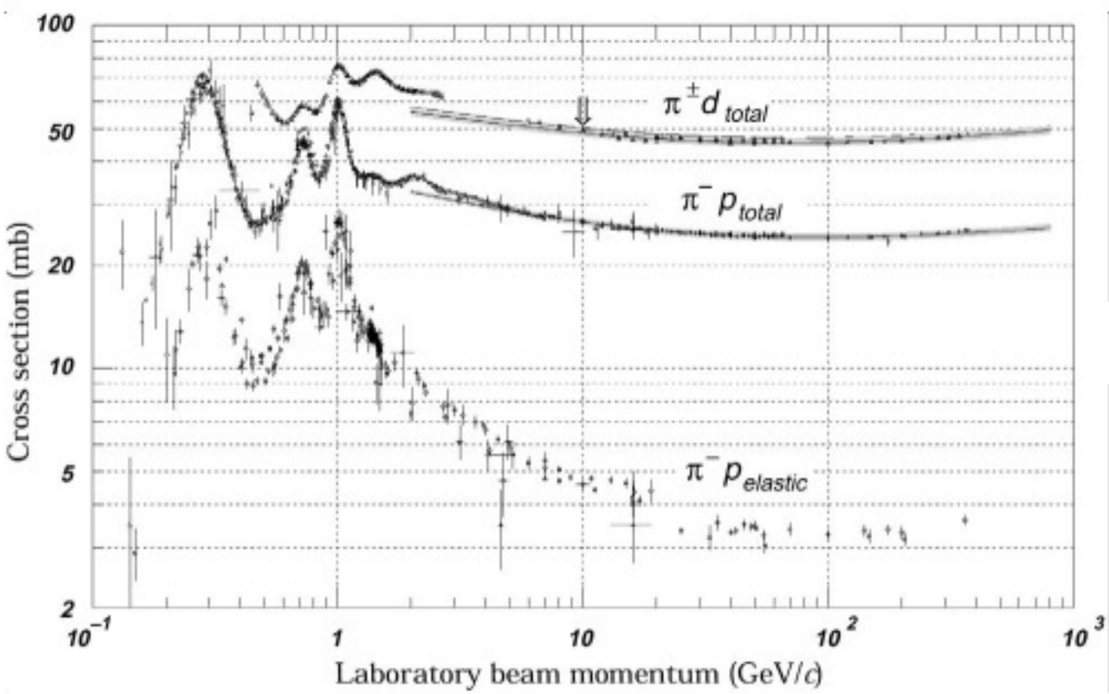
Cross section: σ

Probability that a particle interact with matter is proportional to the "cross section"

millibarns: $1\ mb \equiv 10^{-31}\ m^2$

elastic scattering: only momentae of incident particles are changed, for example, $\pi^- p \rightarrow \pi^- p$

inelastic scattering: final state particles differ from those in initial state, like in $\pi^- p \rightarrow K^0 \Lambda$



hadron-hadron scattering, cross-sections are of the same order with the geometrical "cross-sections" of hadrons: assuming their sizes are of order

$$r = 1\ fm \equiv 10^{-15}\ m \Rightarrow \pi r^2 \approx 30\ mb$$

$$N_{events} = L\ \sigma$$

Luminosity

Cross Sections and Luminosity

- “fundamental equation of high energy physics”

$$N = L\sigma\epsilon$$

efficiency (acceptance)

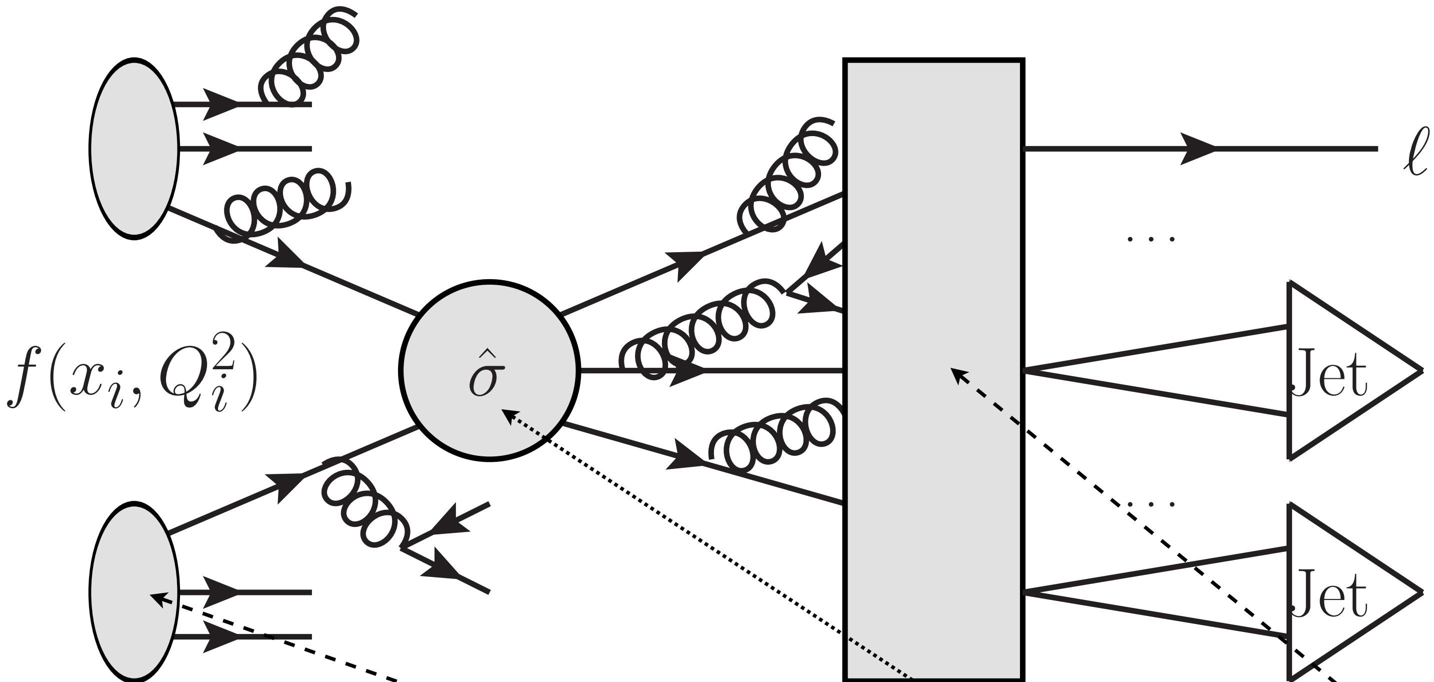
number of events observed

integrated luminosity (m^{-2})

production cross section (m^{2})

- luminosity: number per unit scattering area per unit time

Partonic vs Hadronic Cross Sections



$$\sigma_{\mathrm{QCD}} = \sum_{jk} \int \mathrm{d}x_j \, \mathrm{d}x_k \; \boxed{f_j(x_j, \mu_F^2)\, f_k(x_k, \mu_F^2)} \cdot \boxed{\hat{\sigma}(x_j x_k s, \mu_F^2, \mu_R^2)} \otimes \boxed{\text{Hadronization}}$$

Complicated Collisions

A simulated event in ATLAS (CMS) $H \rightarrow ZZ \rightarrow 4\mu$

pp collision at $\sqrt{s}$ = 14 TeV, $\sigma_{inel.} \approx$ 70 mb

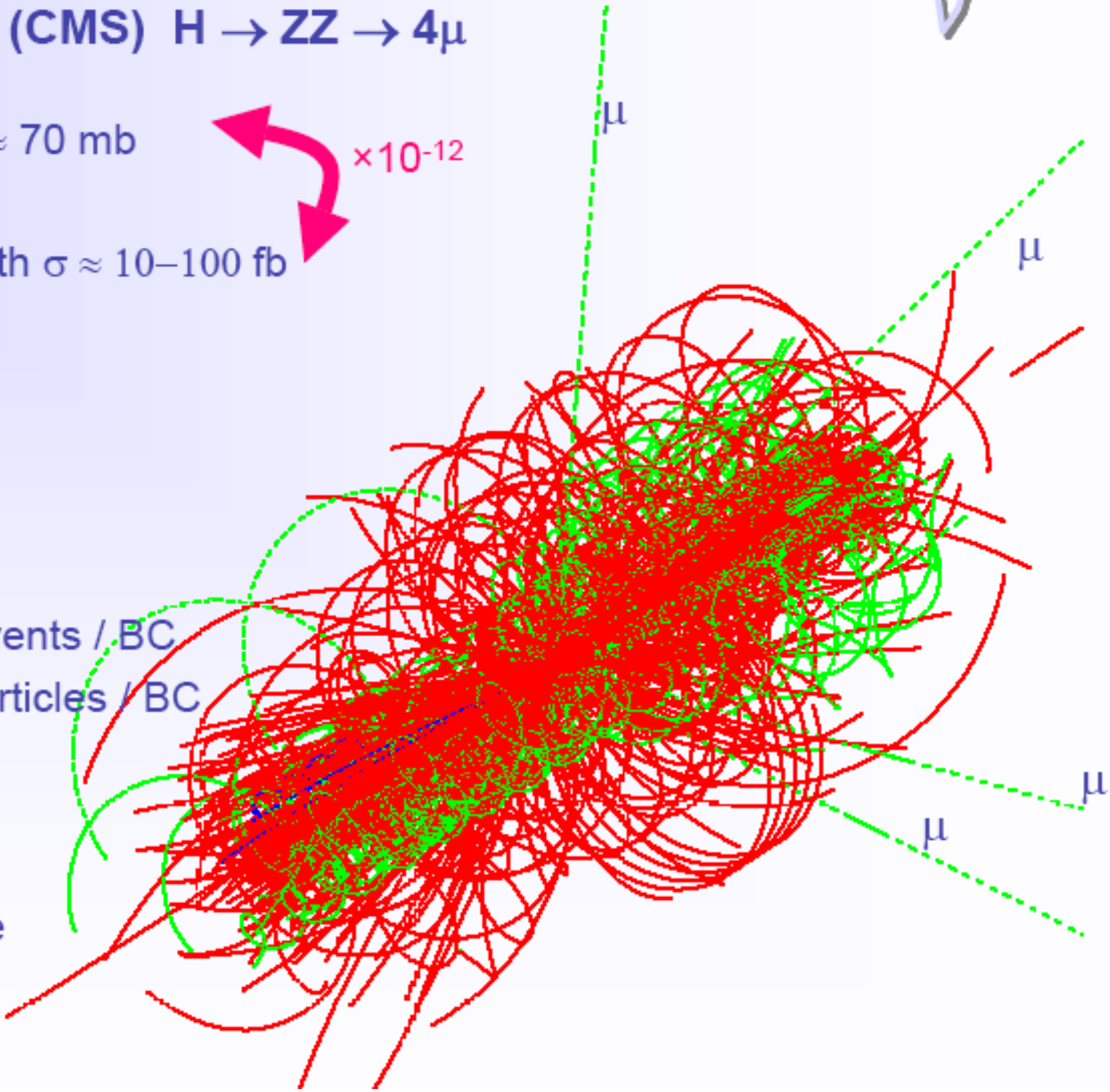
$\times 10^{-12}$

We are interested in processes with $\sigma \approx$ 10–100 fb

L = 10^{34} cm^{-2} s^{-1},
bunch spacing 25 ns

$\approx$ 23 overlapping minimum bias events / BC
$\approx$ 1900 charged + 1600 neutral particles / BC

Brave people have started to think about a Super LHC upgrade to L = 10^{35} cm^{-2} s^{-1} !!!



Knowing cross-sections and number of nuclei per unit volume in a given material n, one can introduce two important characteristics:

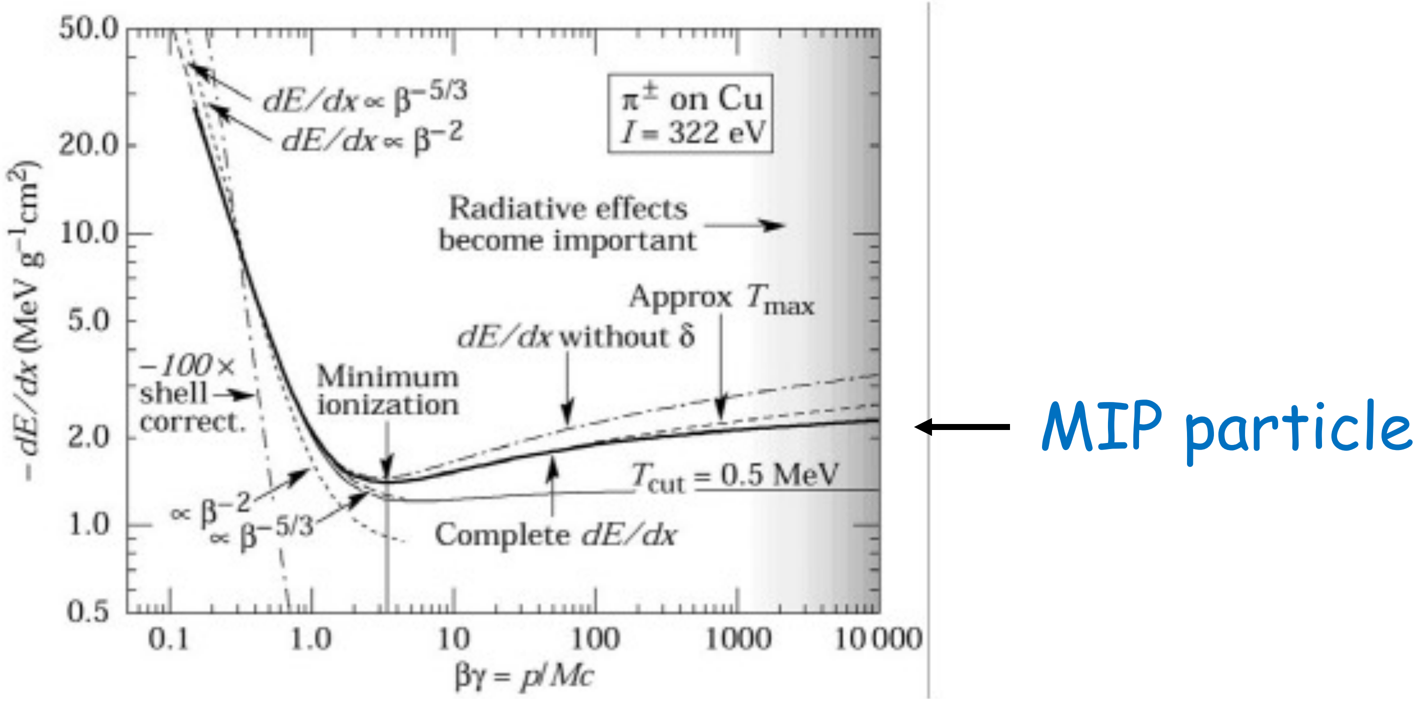
- *nuclear collision length*: mean path between collisions, $l_c \equiv 1/n\sigma_{tot}$
- *nuclear absorption length:* mean path between inelastic collisions, $l_a \equiv 1/n\sigma_{inel}$

At high energies, short-range nuclear interactions involve mainly hadrons, facilitating their detection.

Neutrinos and photons have much smaller cross-sections of interactions with nuclei, since former interact only weakly and latter – only electromagnetically.

Ionization energy losses

- Energy loss per travelled distance : dE/dx
  - Important for all charged particles
  - Mostly due to Coulomb scattering of particles off atomic electrons



Energy loss rate for pions in copper. At low β, dE/dx is proportional to $1/\beta^2$. At high β, dE/dx proportional to $\ln(\beta)$

Constants (characteristics to the medium)

$$-\frac{dE}{dx} = \frac{Dn_e}{\beta^2}\left[\ln\left(\left(\frac{2mc^2\beta^2\gamma^2}{I}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right)\right]$$

n_e is the electron density

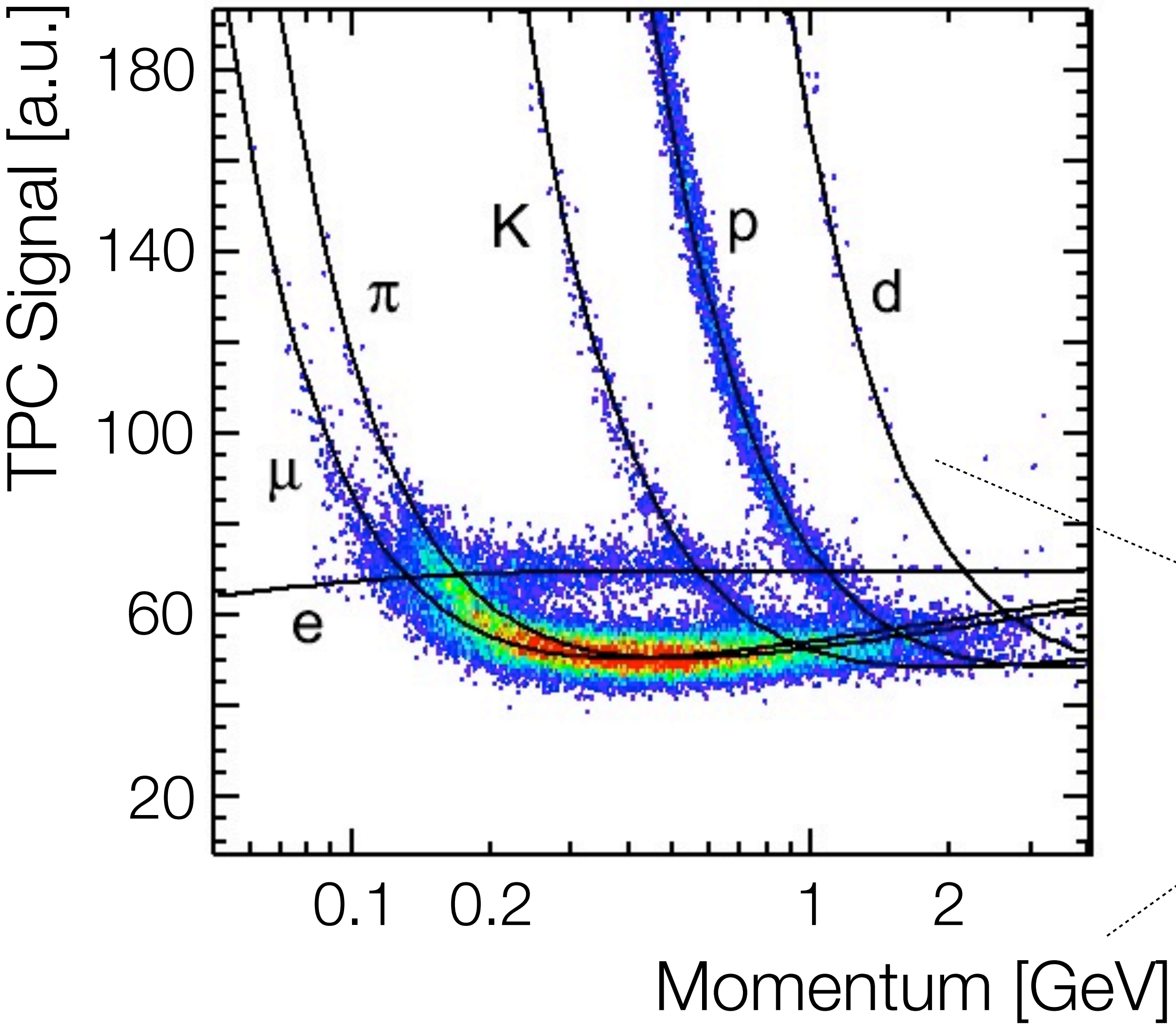
$$n_e = \rho N_A Z/\tilde{A}$$

Mass density of the medium

$$D = \frac{4\pi\alpha^2\hbar^2}{m} = 5.1\times10^{-25}\ MeV\ cm^2$$

I is the mean ionization potential, $I \approx 10Z\ eV$ for $Z > 20$

dE/dx and Particle Identification



Measured
energy loss

[ALICE TPC, 2009]

Bethe-Bloch

Remember:
dE/dx depends on β!

Mean Particle Range

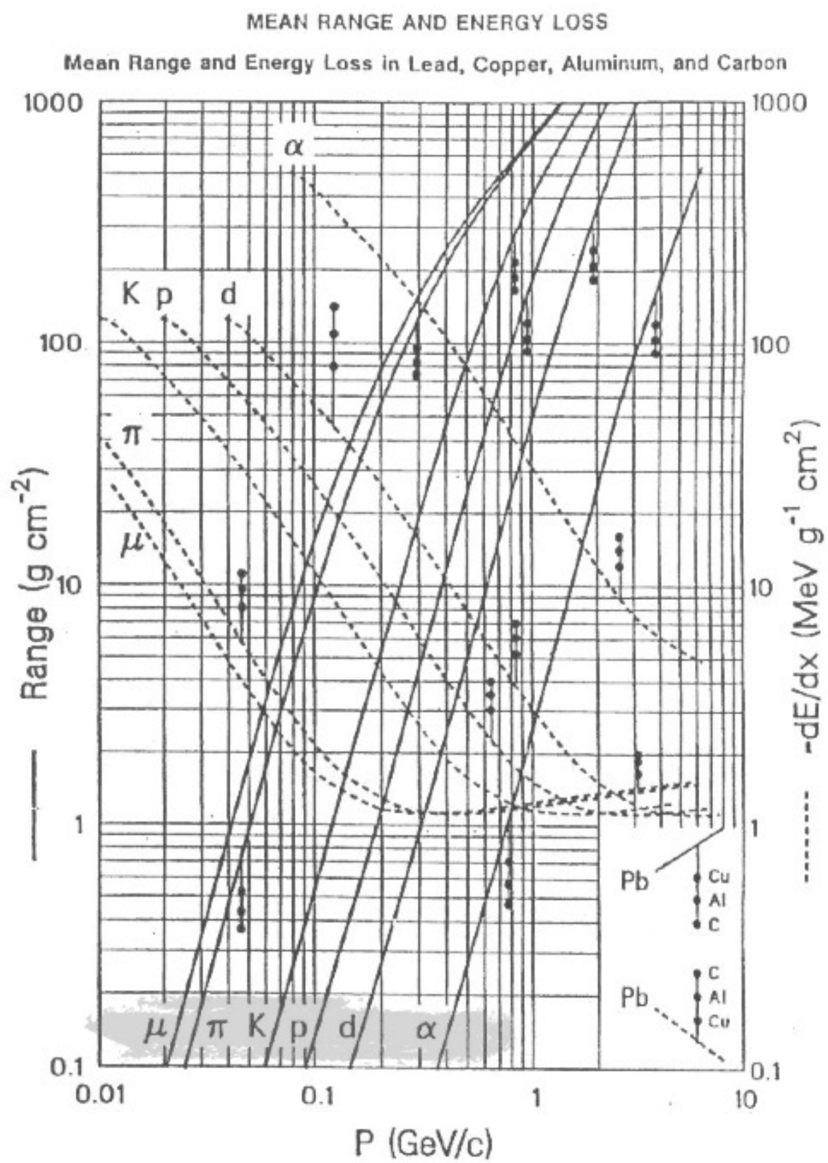
Integrate over energy loss
from E down to 0

$$R = \int_E^0 \frac{dE}{dE/dx}$$

Example:

Proton with p = 1 GeV
Target: lead with ρ = 11.34 g/cm^3

R/M = 200 g cm^{-2} GeV^{-1}
→ R = 200/11.34/1 cm ~ 20 cm



Cherenkov radiation

Charged particle moving faster then light :

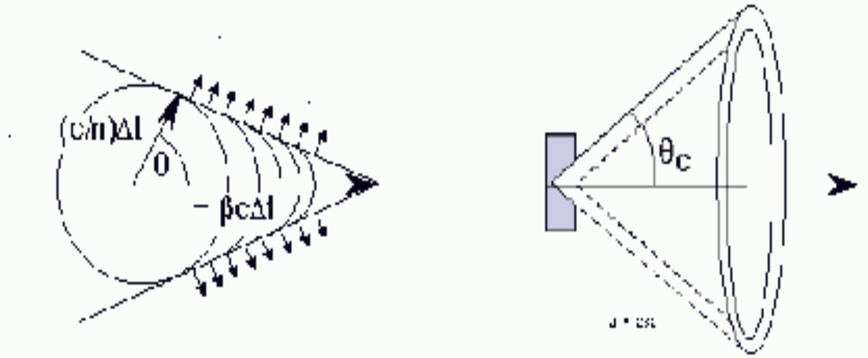
$$\omega \cong \bar{v} \cdot \bar{k} = v \cdot k \cos\theta$$

$$v_{particle} > \frac{c}{n} \quad or \quad \beta \geq \beta_{thr} = \frac{1}{n}$$

$$\cos\theta = \frac{\omega}{vk} = \frac{1}{n\beta} = \frac{1}{\beta\sqrt{\varepsilon}}$$

$\rightarrow$ Cherenkov

$\beta \geq 1/n$



$$\cos\theta_C = \frac{1}{n\beta} \qquad n = n(\lambda) \geq 1$$

$$\theta_{max} = \cos^{-1}(1/n)$$

Photon number

dE/dx 1% of ionization

Can be detected by PMTs

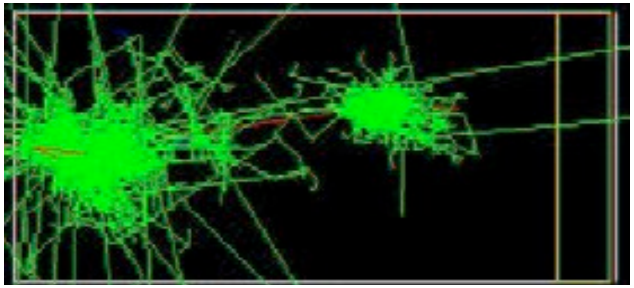
$$\frac{d^2N}{dxdE} = \frac{\alpha}{\hbar c} \sin^2\theta_C \approx 365 \ \sin^2\theta_C \ eV^{-1}cm^{-1}$$

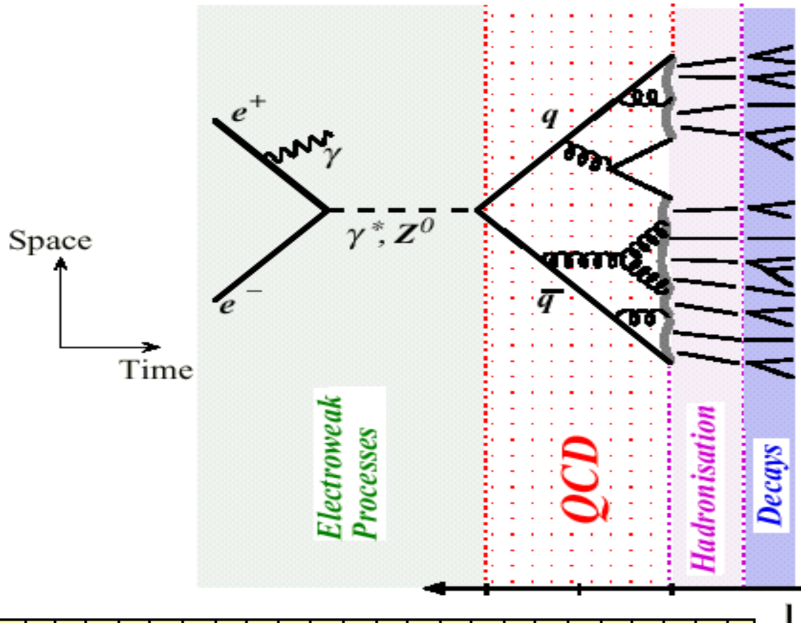
$$\frac{dN}{dx} \approx 475 \ \sin^2\theta_C \quad \text{foton/cm} \qquad Z = 1$$

2. Energy loss in a detectable material (in HEP)

Hadronic shower

Simulation in copper

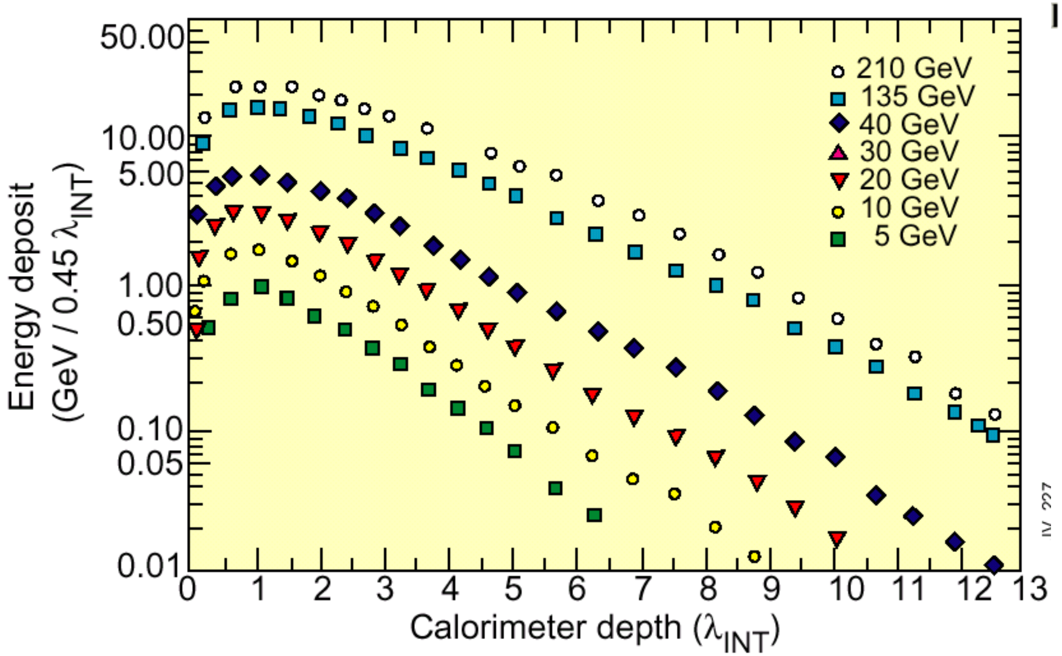




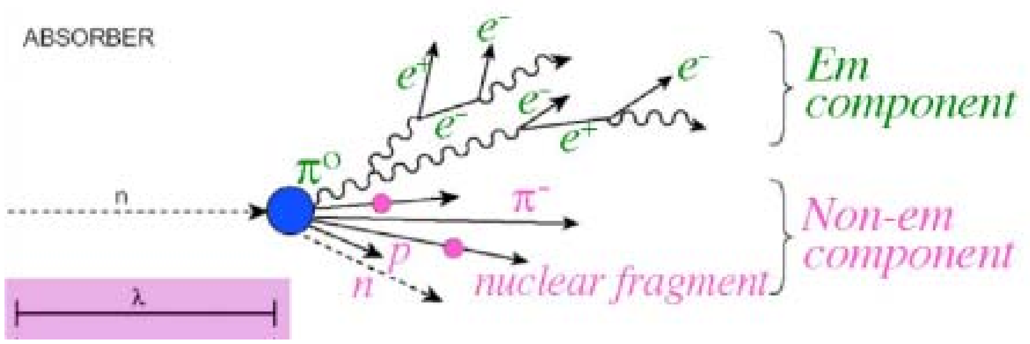
Shower development by strong interaction

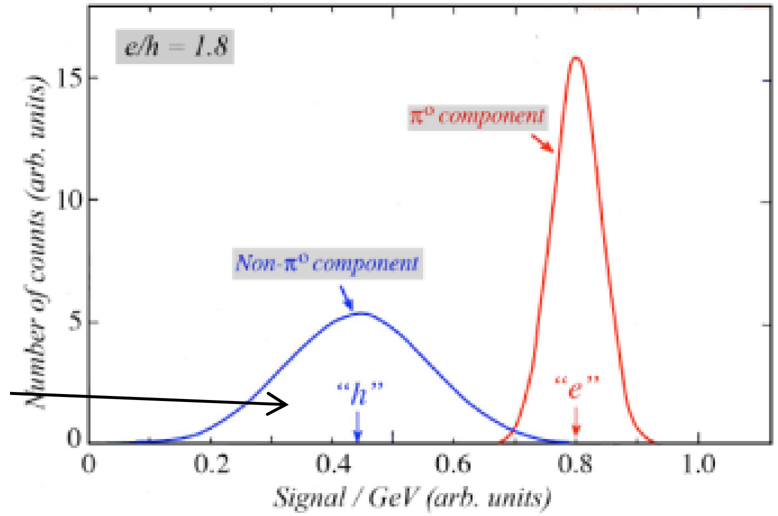
An energetic hadron interacting with matter leads to multi-particle production, these in turn interact with further nuclei or decay (pion)

Multiplication continues until the pion production threshold.



Hadronic Interactions





Hadrons create showers via strong interactions just like electrons and photons create them via EM.

Mean energy of pion with initial energy E_0 after traversing material depth λ (interaction length):

$$\langle E \rangle = E_0 e^{-X/\lambda}$$

Mean energy of electron with initial energy E_0 after traversing material depth X_0 (radiation length):

$$\langle E \rangle = E_0 e^{-X/X_0}$$

X_0 and λ for some materials

Material	X_0	λ
H_2	63	52.4
Argon	18.9	119.7
Iron	13.8	131.9
BGO	8.0	164

Units of g/cm^2

E.g., a pion takes ~10x the depth in Iron to loose its energy than an electron with the same energy.

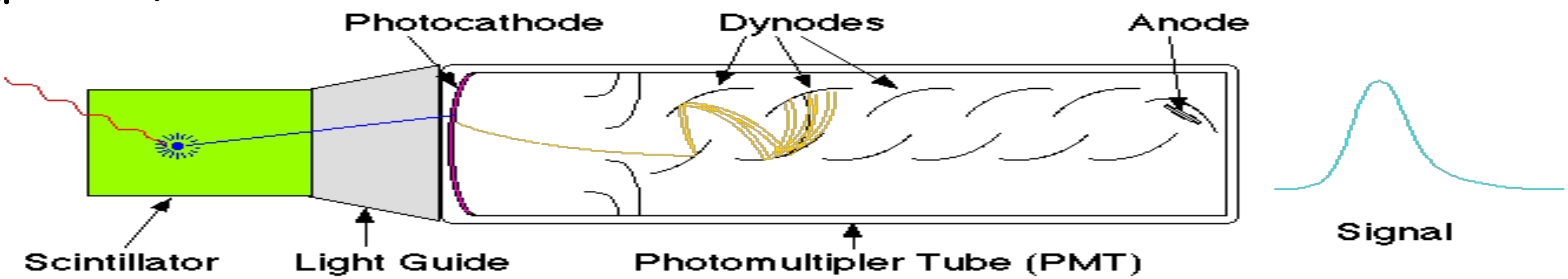
E.g. within the depth of X_0 in BGO, a pion looses only 5% of its energy, while an electron looses 63% of its energy, on average.

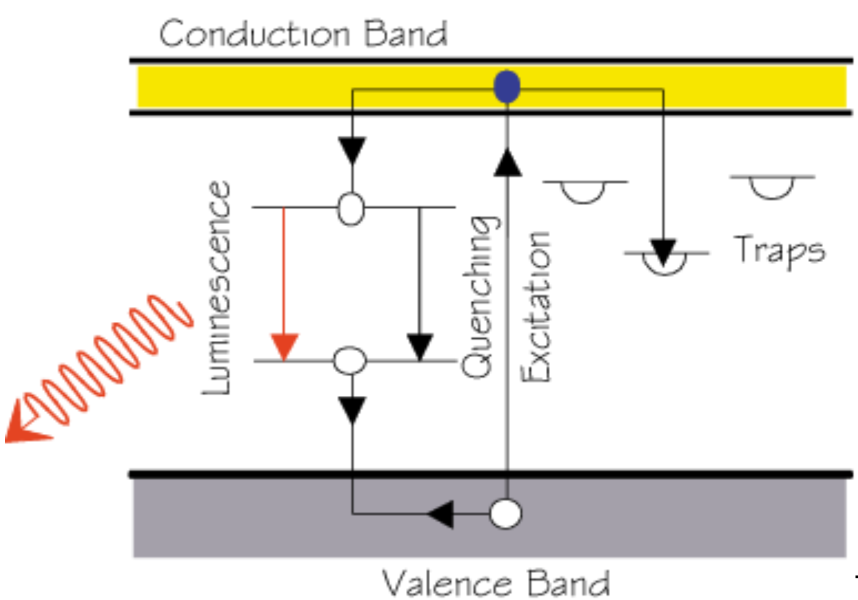
3. Signal collection

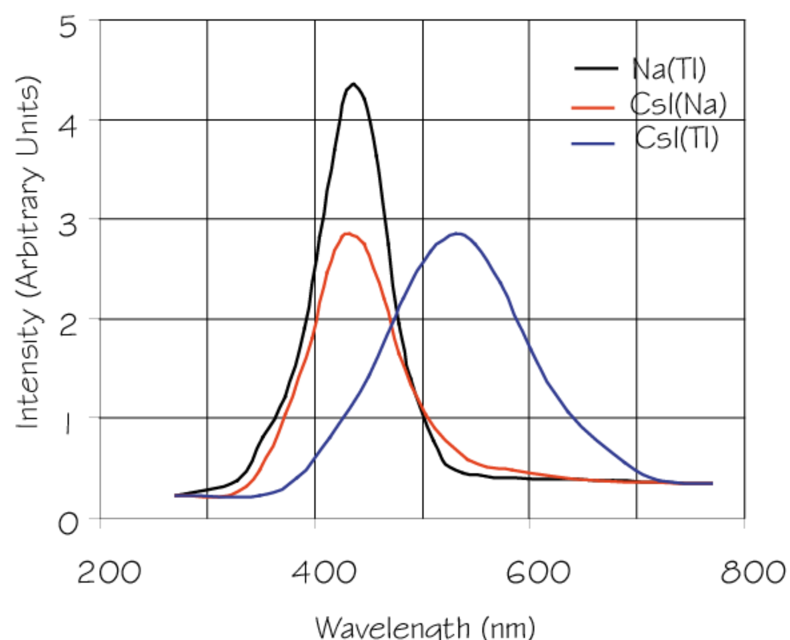
Scintilators (Scintillation counter)

Excitation and ionization creates scintillation light which are sent then to the Photomultipliers (PMT)

Scintillatiors: crystalline (thallium-sodium iodide [NaI(Tl)]) or organic (plastics)





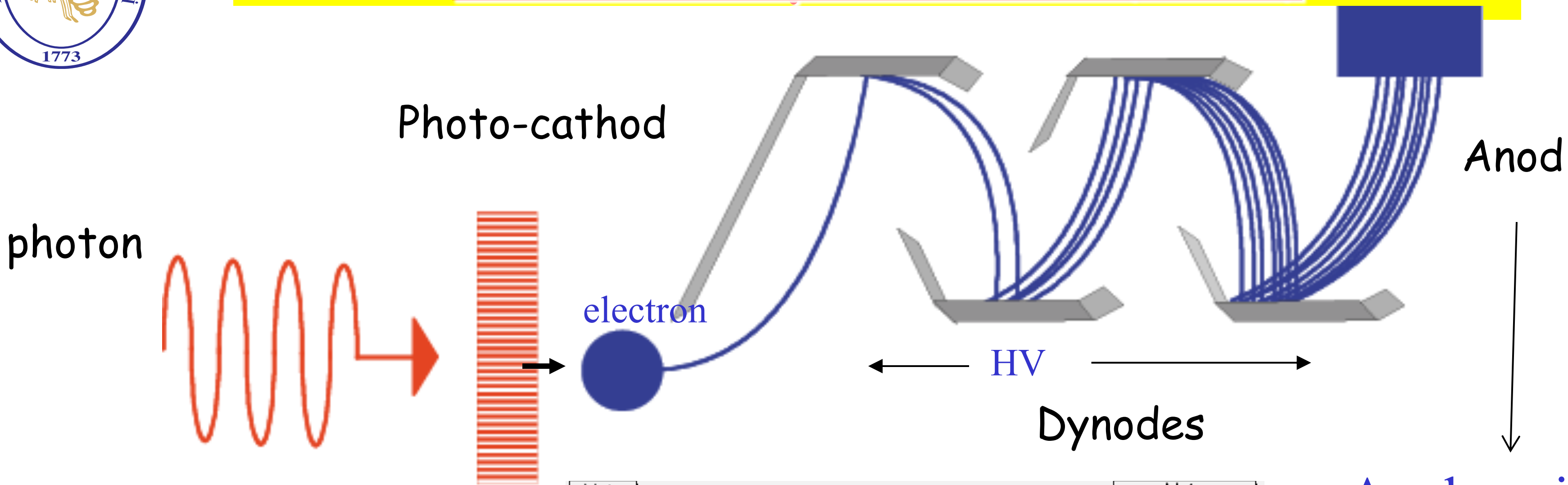


Some examples of scintillators

anorganic scintillators

Scintillator composition	Density (g/cm³)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (µs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

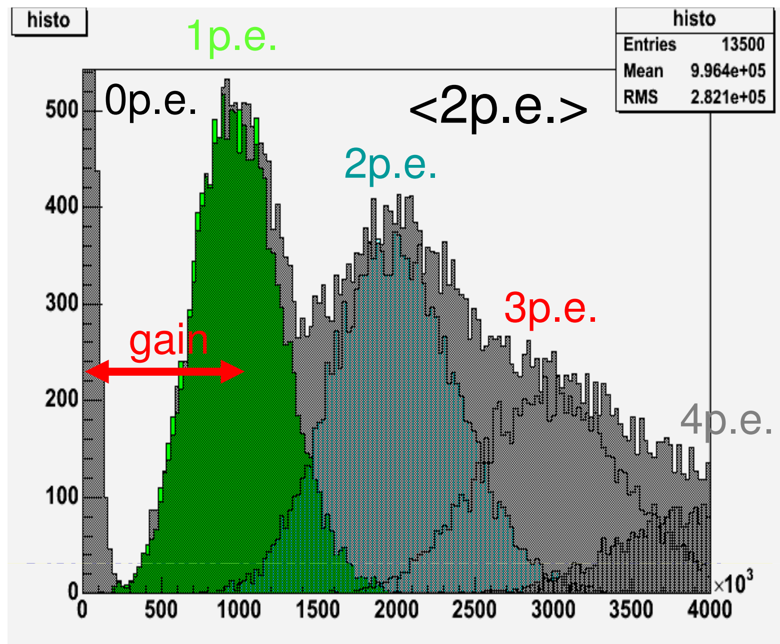
Photomultiplier tube (PMT)



Analog signal

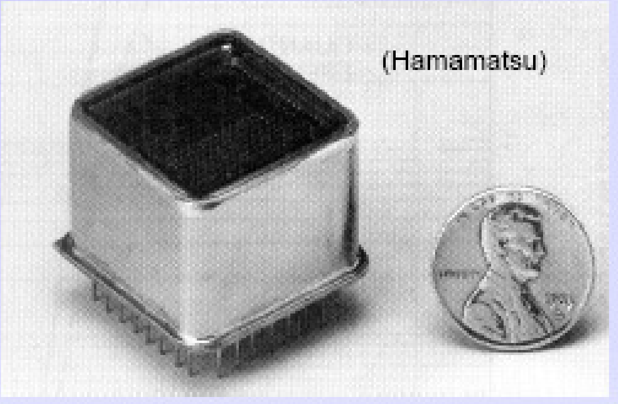
ADC

Digital signal



Typical gain 10^6 . In 200 ps

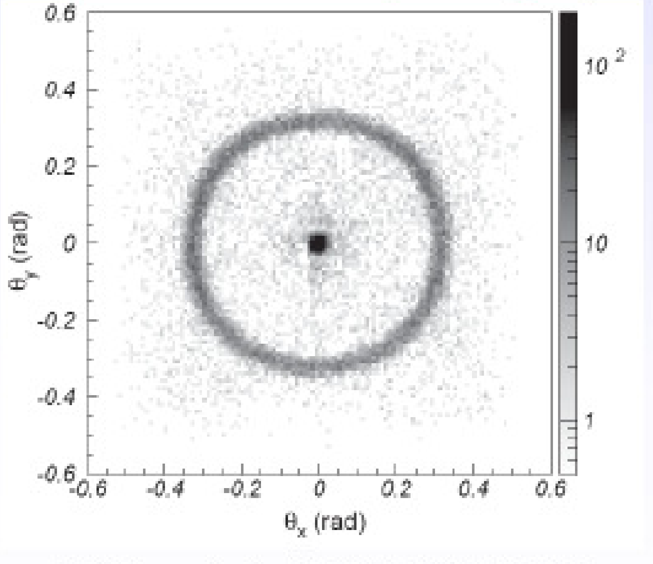
Some examples of PMTs...



Multi-anode (Hamamatsu H7546)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Active area 18.1 × 18.1 mm^2 (41%);
- Bialkali PC: QE ≈ 20% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

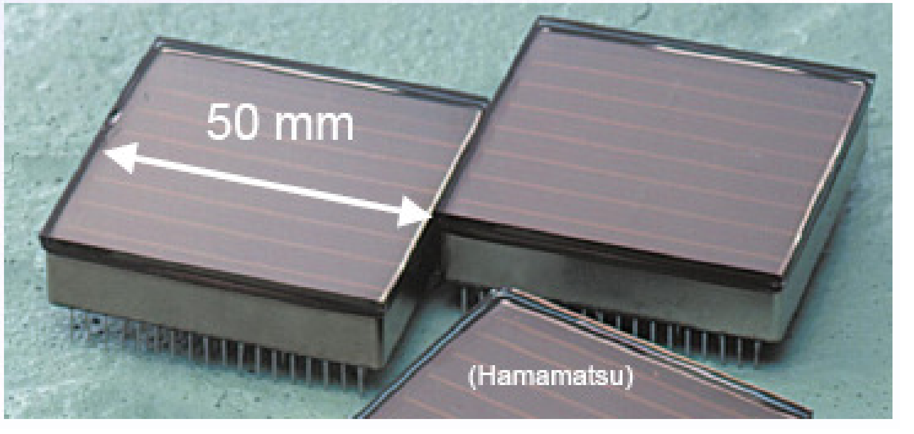
Cherenkov rings from 3 GeV/c π^- through aerogel



(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

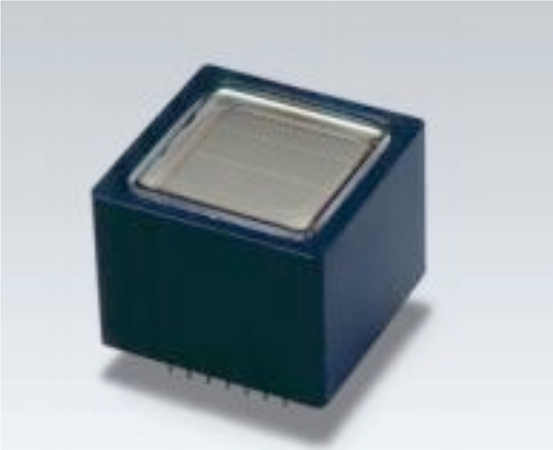
- 8 x 8 channels (5.8 x 5.8 mm^2 each);
- Excellent surface coverage (89%)



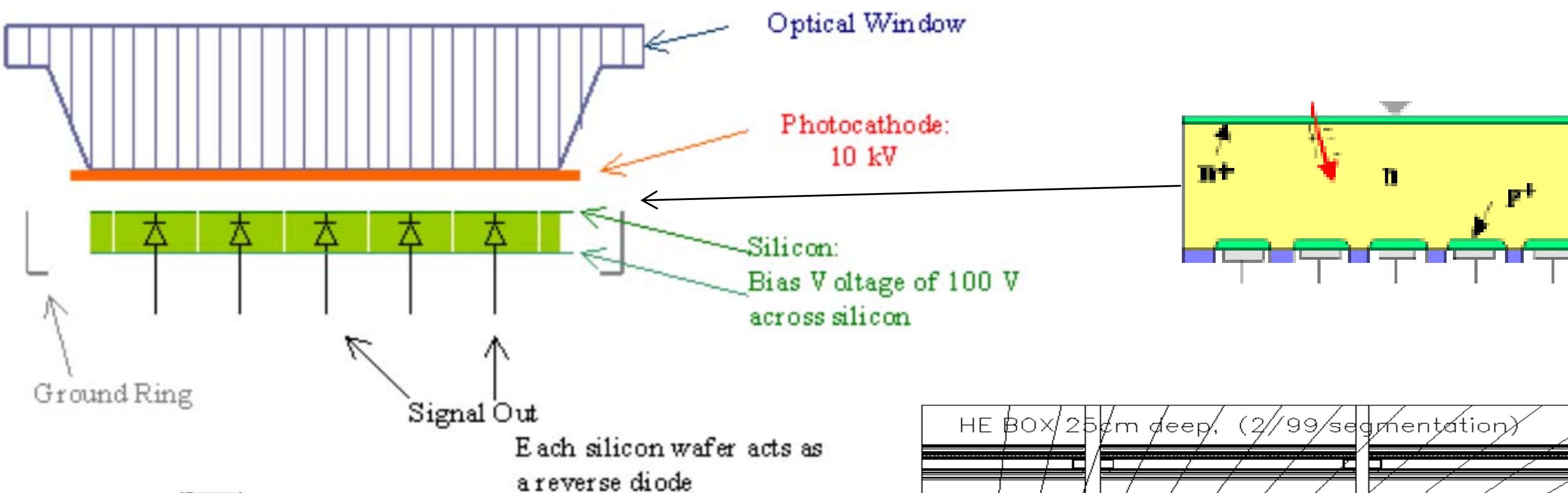
New PMTs advantages

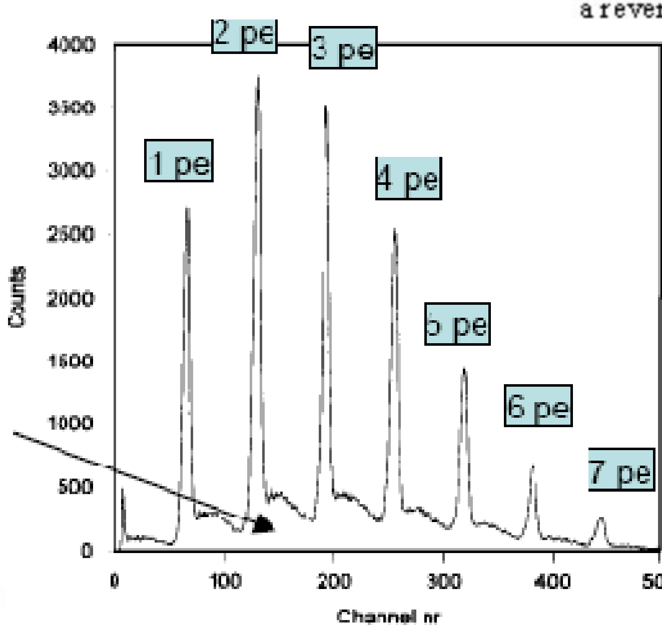
- Higher quantum efficiency that enables better energy resolution and long term use.
- Multi anode improve the event selection.
- PMT Hit signal recovery based on multi-anode hit information.
- Thinner window will produce lesser Cherenkov photons in the case of a PMT hit.

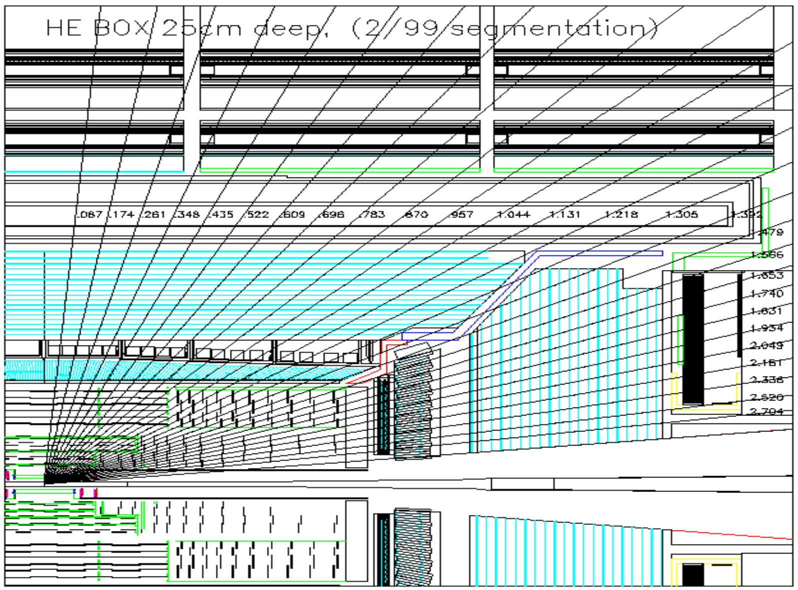
  (Background/nose elimination)
- Has more protection surface surrounds the PMT.



Hybrid photodiodes (HPD)

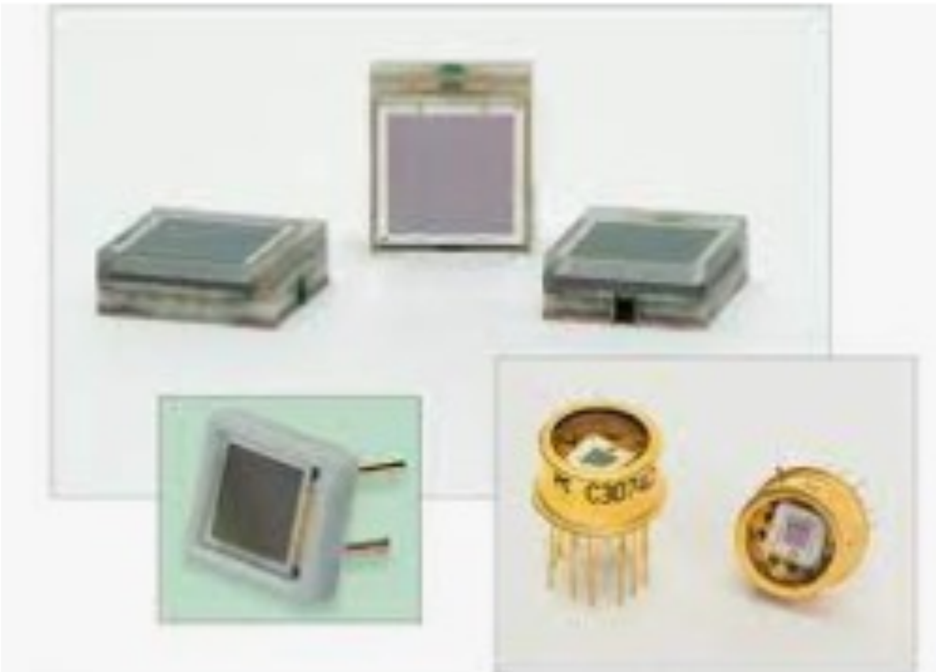






HPD's are replaced by SiPMs in HCAL

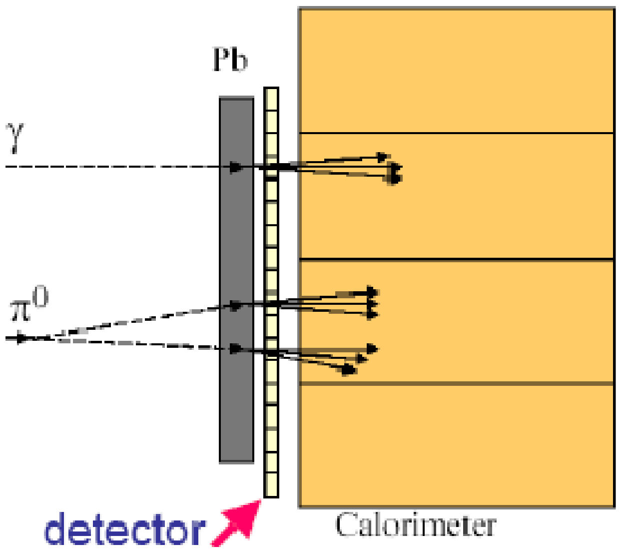
Silicon Photomultiplier (SiPM)

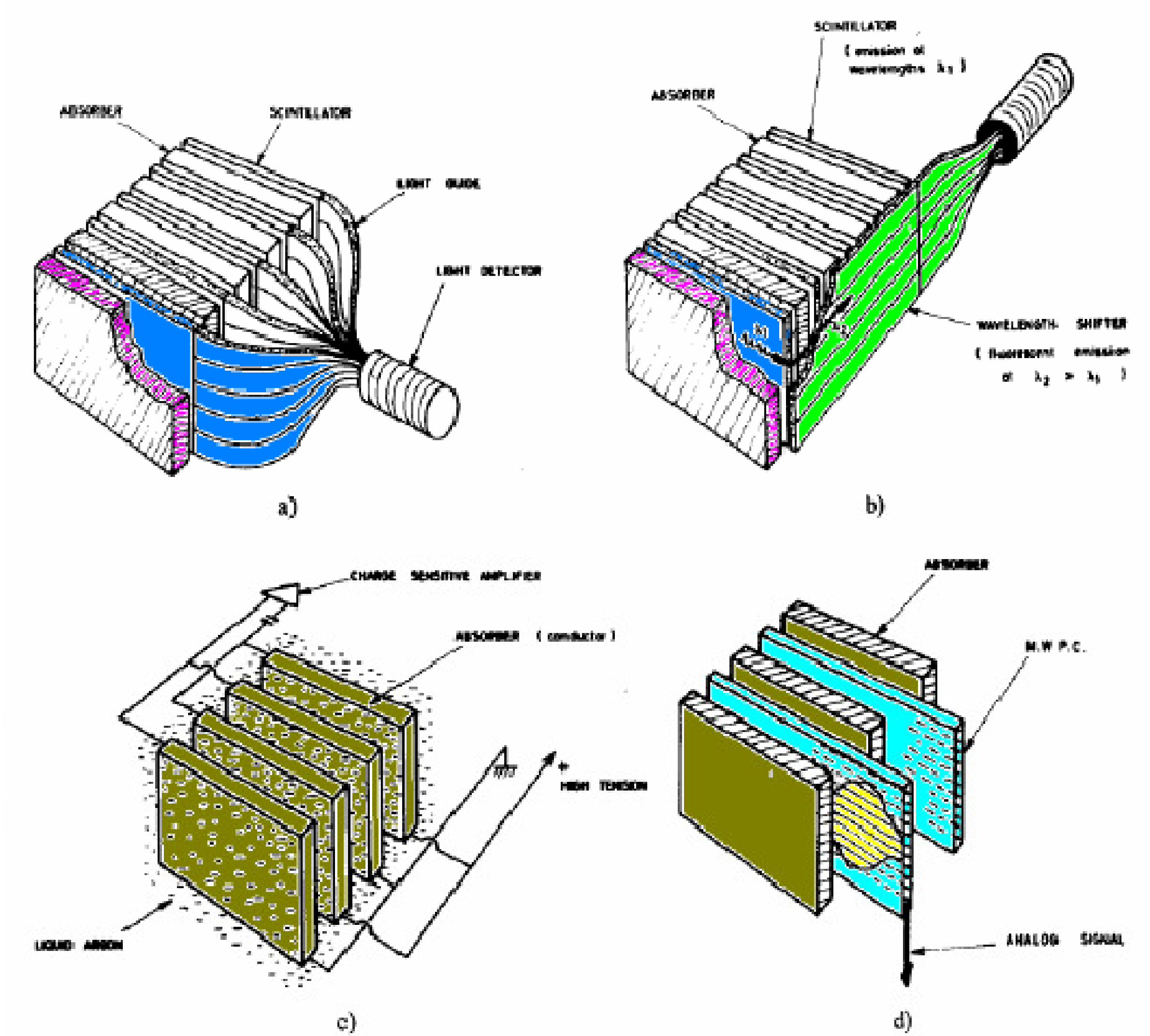


- attractive candidates for the replacement of the conventional PMT
- high gain with low voltage and fast response, they are very compact and compatible with magnetic resonance setups.
- Gain (G) is also similar to a PMT, being about 10^6

the microcells are read in parallel,
generate signals within a dynamic range from a single photon to 1000 photons for a device with just a square-millimeter area.

Sampling calorimeters: Absorber+sampler





Global Detector Systems

Overall Design Depends on:

–Number of particles

–Event topology

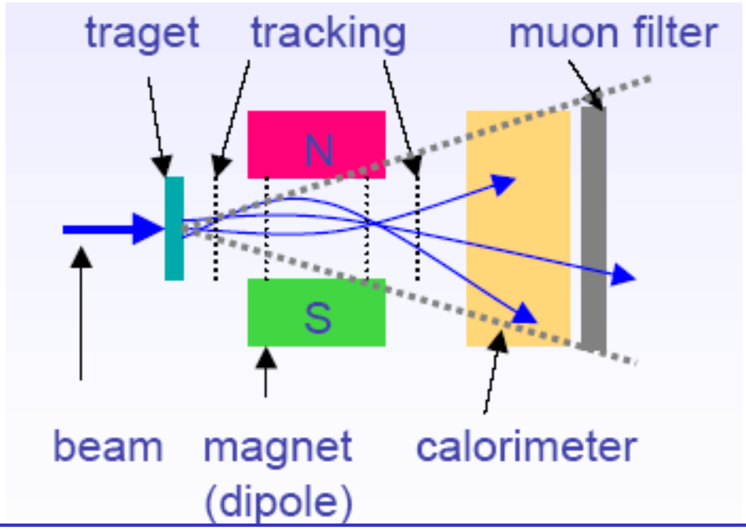
–Momentum/energy

–Particle identity

No single detector does it all…

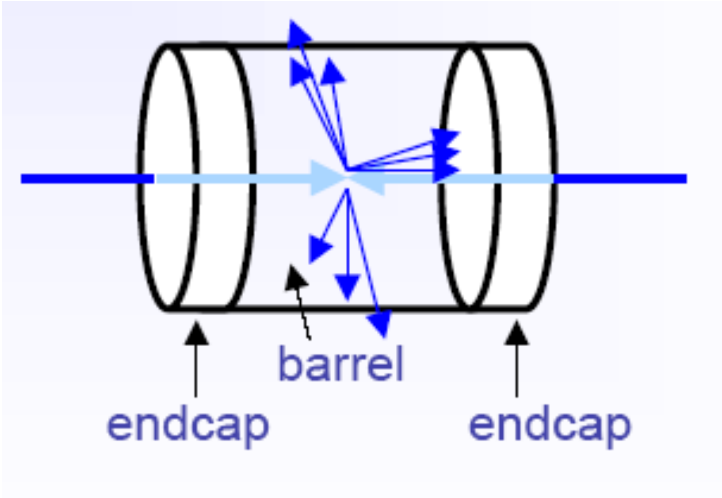
→ Create detector systems

Fixed Target Geometry



- Limited solid angle ($d\Omega$) coverage (forward)
- Easy access (cables, maintenance)

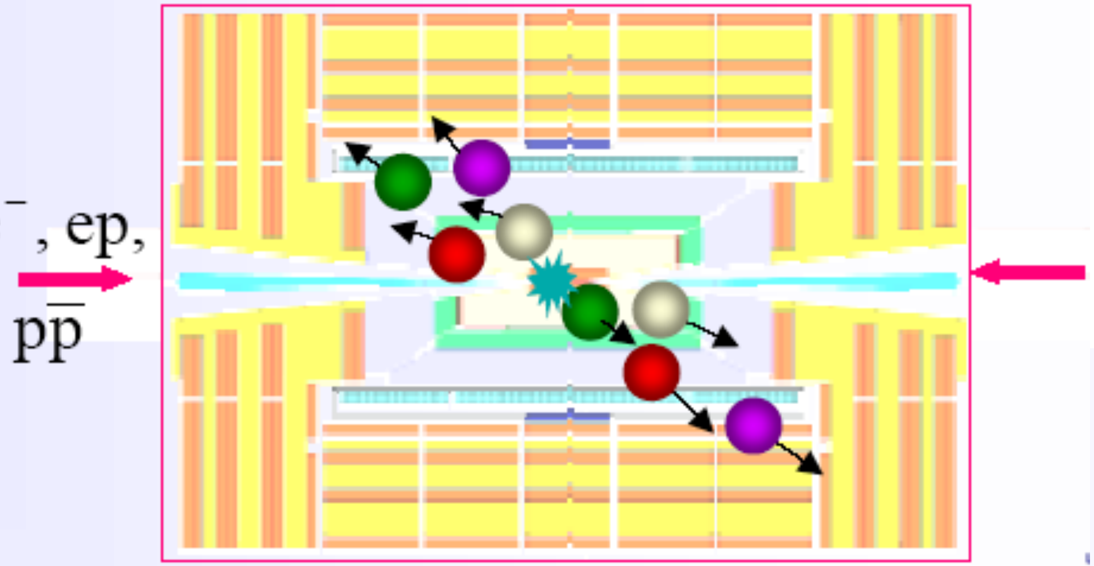
Collider Geometry



- "full" solid angle $d\Omega$ coverage
- Very restricted access

Ideal Detectors

e^+e^-, ep, pp, $p\bar{p}$



End products

- charged particles
- neutral particles
- photons

An "ideal" particle detector would provide...

- Coverage of full solid angle, no cracks, fine segmentation (why?)
- Measurement of momentum and energy
- Detection, tracking, and identification of all particles (mass, charge)
- Fast response: no dead time (what is dead time?)

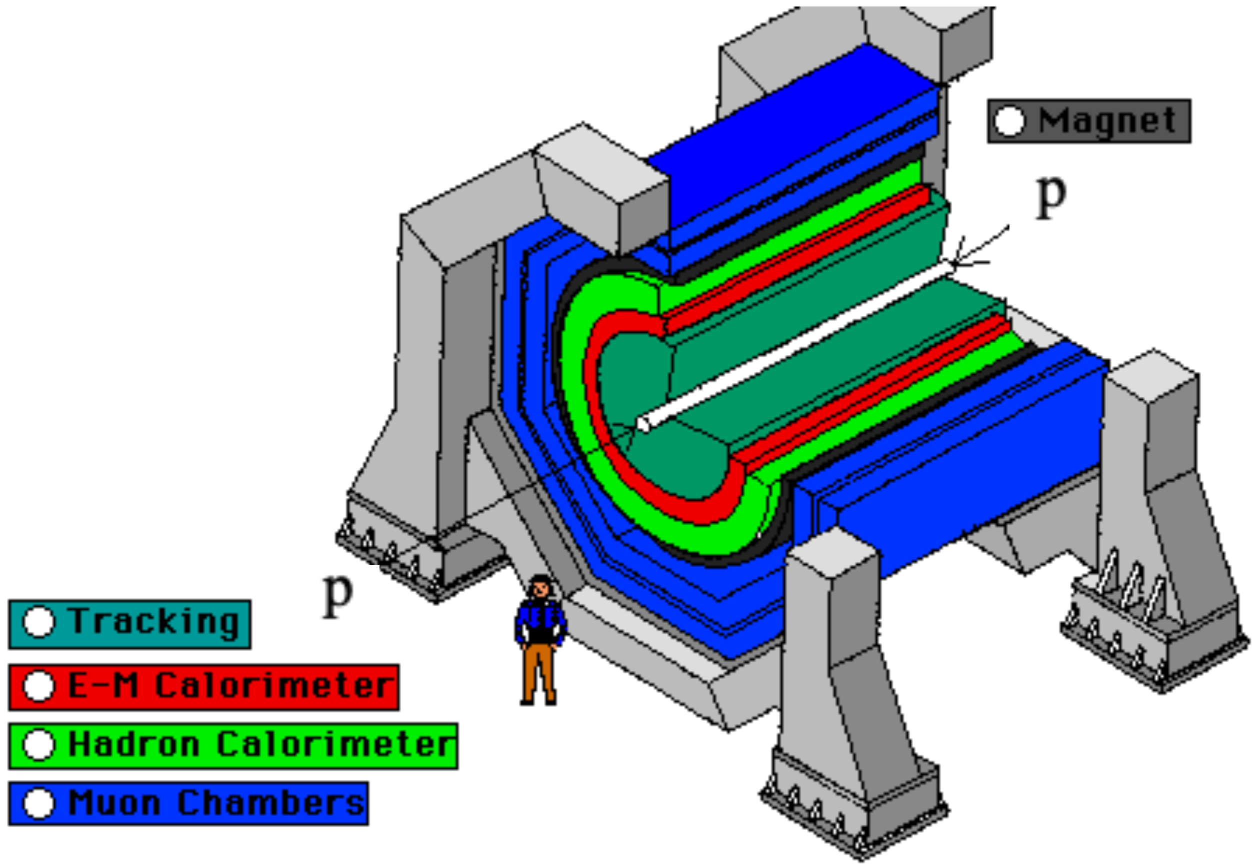
However, practical limitations: Technology, Space, Budget

Individual Detector Types

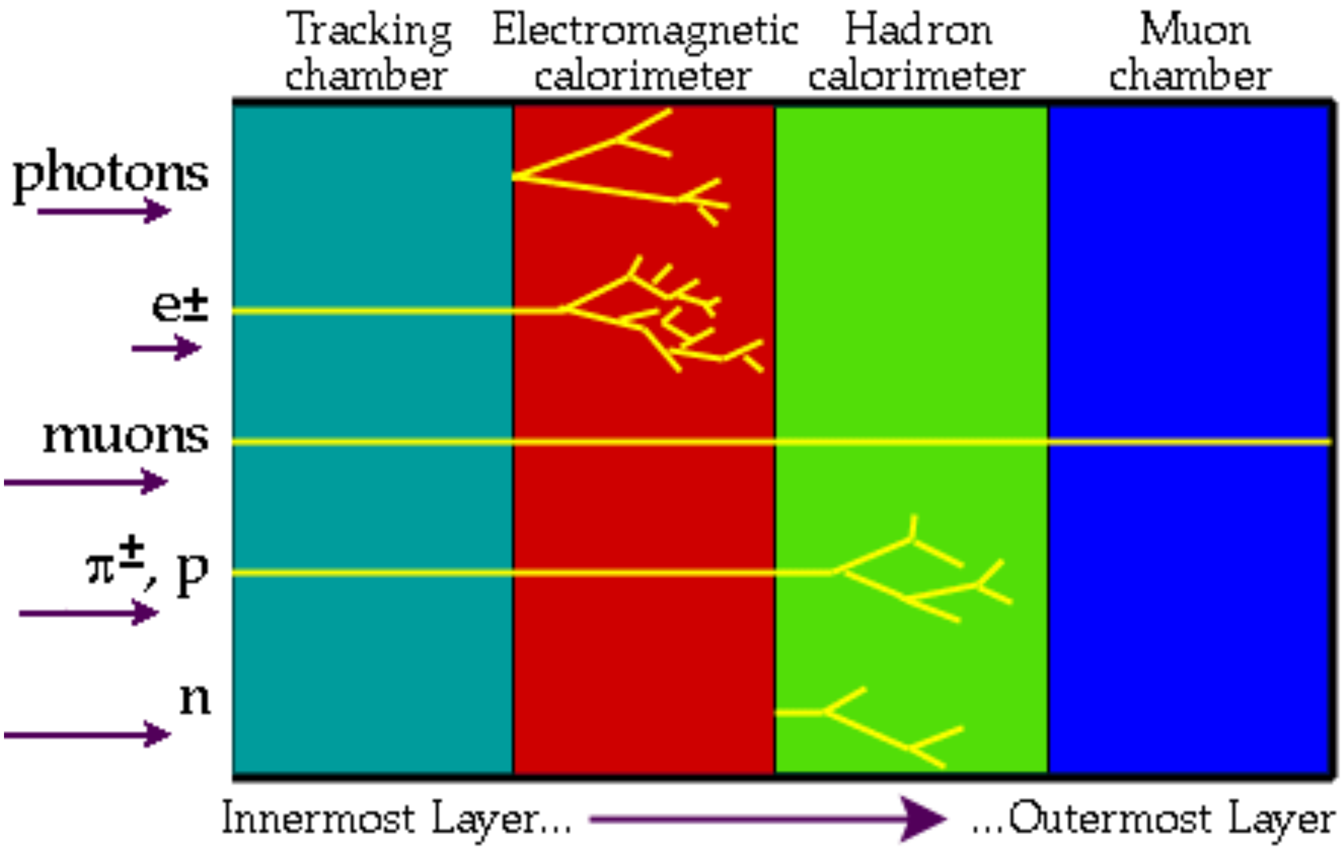
Modern detectors consist of many different pieces of equipment to measure different aspects of an event.

Measuring a particle's properties:

- → Position
- → Momentum
- → Energy
- → Charge
- → Type



Particle Decay Signatures

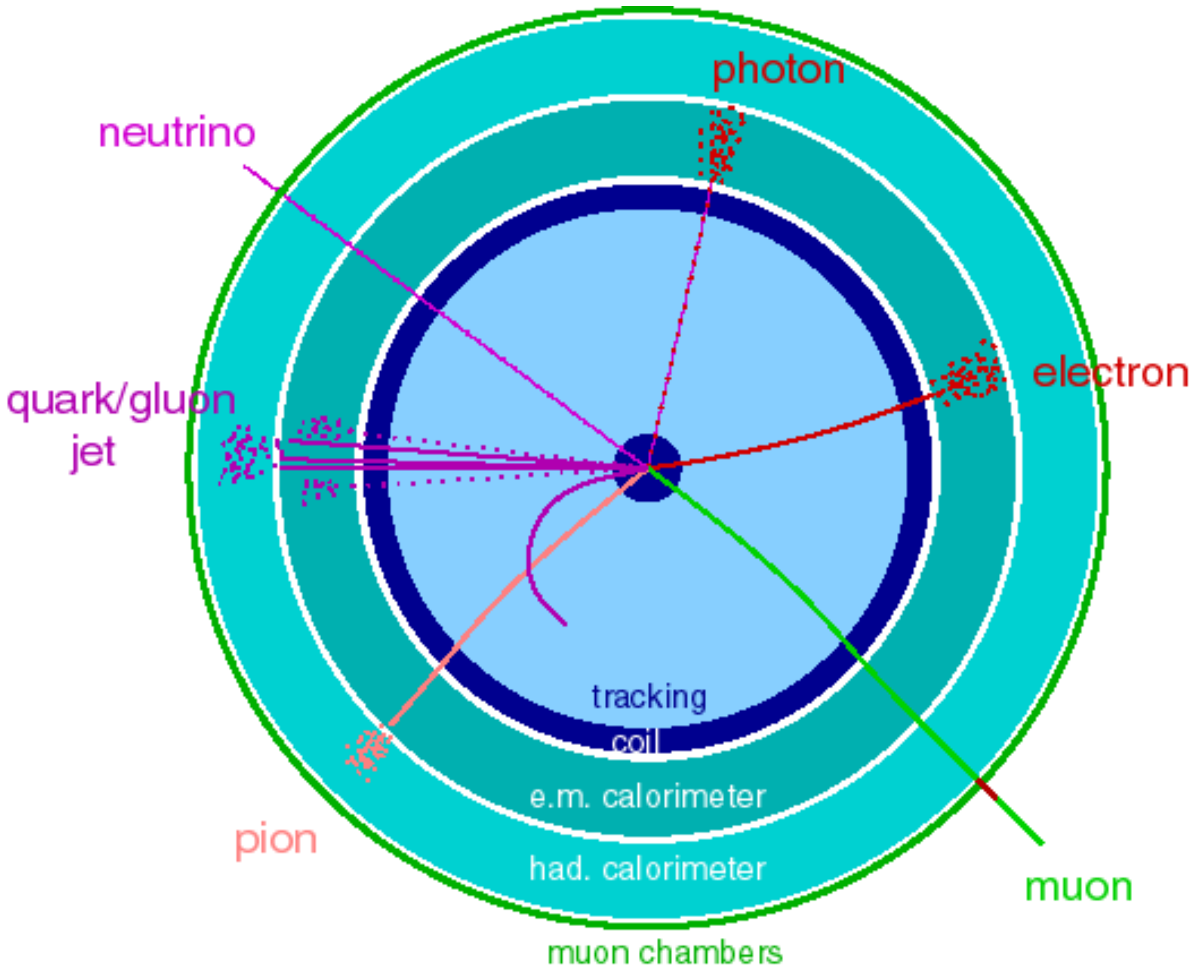


Particles are detected via their interaction with matter.

Many types of interactions are involved, mainly electromagnetic.
In the end, always rely on ionization and excitation of matter.

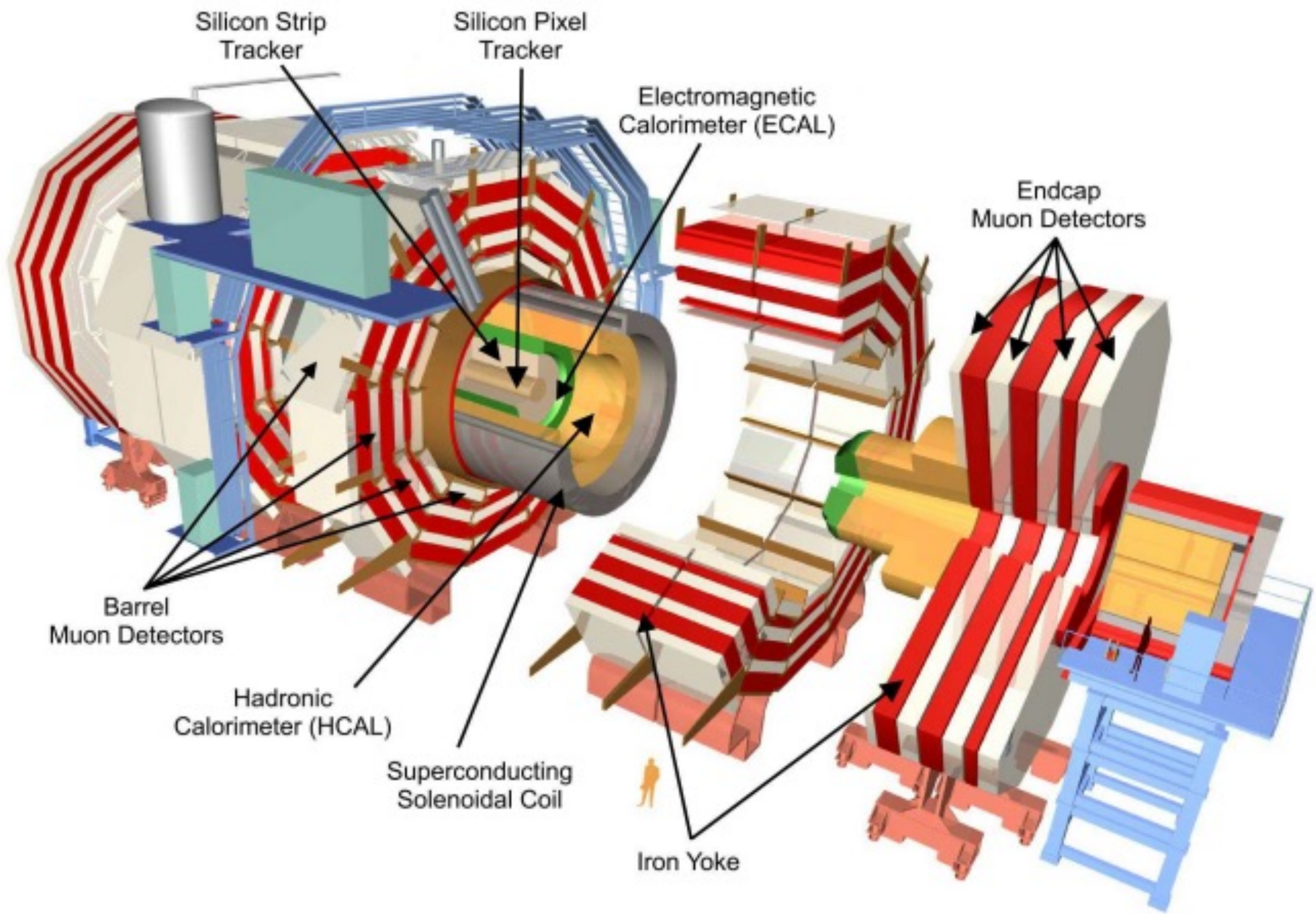
Modern Collider Detectors

- the basic idea is to measure charged particles, photons, jets, missing energy accurately
- want as little material in the middle to avoid multiple scattering
- cylinder wins out over sphere for obvious reasons!



CMS calorimetry: ECAL & HCAL

ECAL: see Damir Lelas presentation



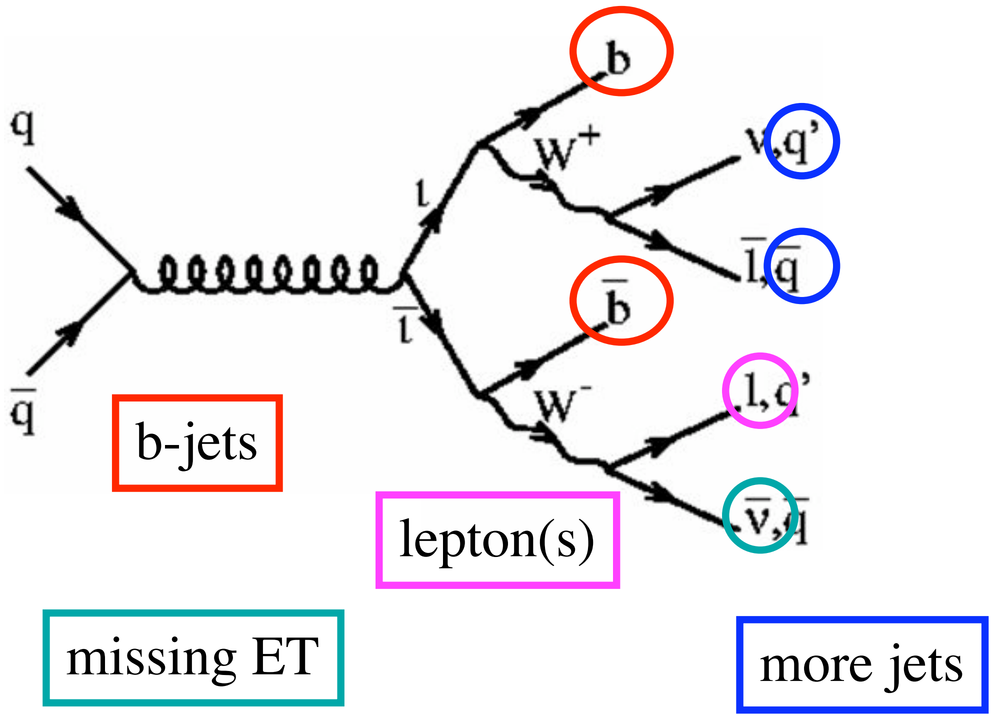
A typical event

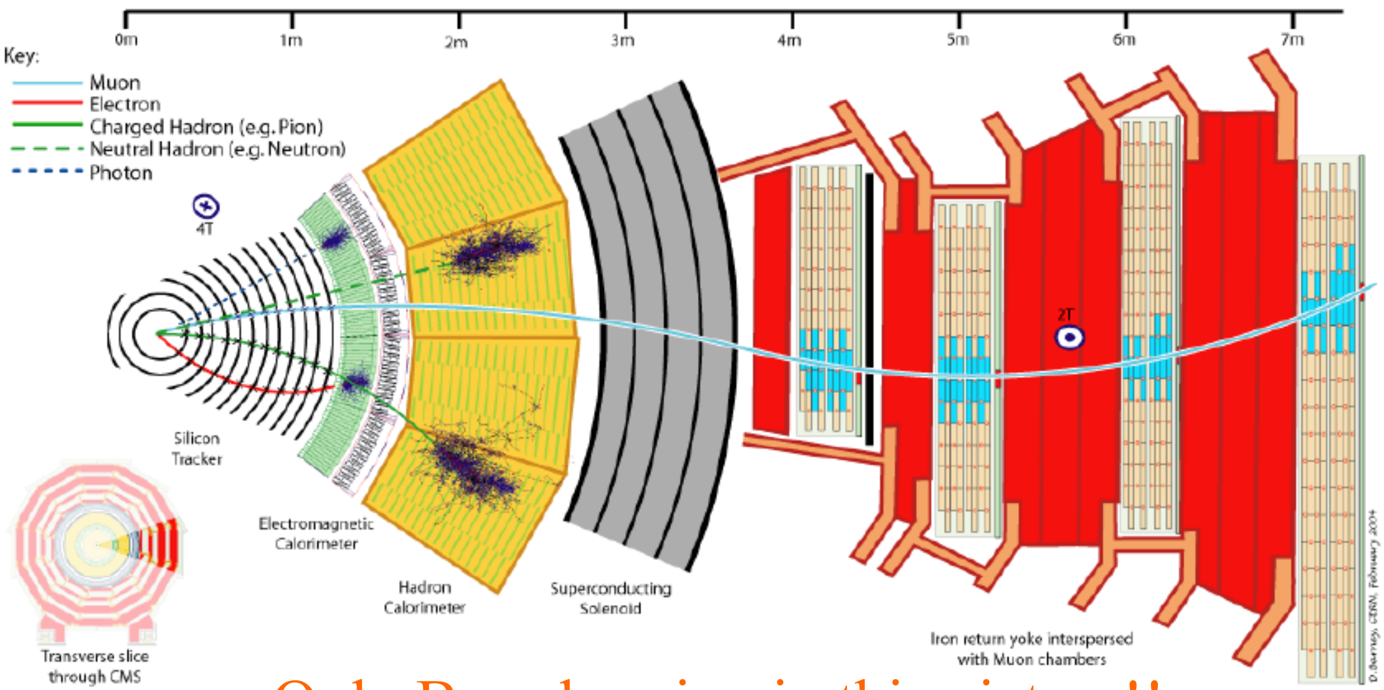
SM: $t\bar{t}$ pair production, Br(t→bW)=100% , Br(W->lν)=1/9=11%

dilepton (4/81) 2 leptons + 2 jets + missing E_T

lepton+jets (24/81) 1 lepton + 4 jets + missing E_T

fully hadronic (36/81) 6 jets





Only Barrel region in this picture!!

- measurement of hadron jets and neutrinos
exotic particles resulting in apparent **missing E_T**
- Counting jets, Measuring jet energies and angles
- Use jets to estimate SM backgrounds , Vetoing events with jets
- Measure missing transverse energy,

- Searches for SUSY including the high multiplicity of jets

- "Simple" jet kinematics, such as the jet Et spectrum or Dijet mass spectrum provide windows into the highest energy scales at the LHC

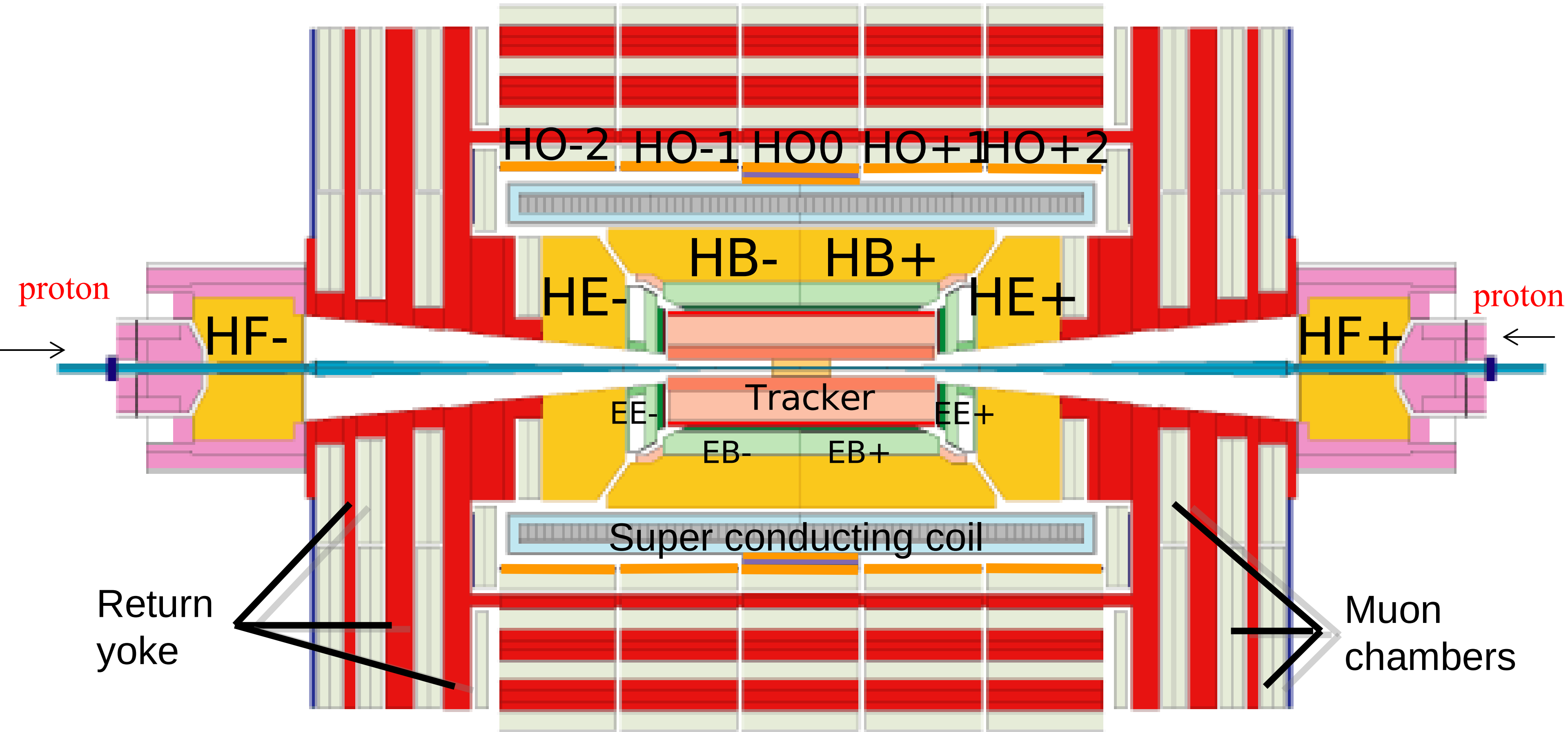
- Weak Boson Fusion production of the Higgs boson, where jets must be detected and well measured in the forward region of the detector and vetoed in the central region of the detector.

Fundamental elementary particles in the Standard Model, their detection in particular detector subsystems and a signature allowing for particle identification in those subsystems.

Particle	Signature	Detector
$u,c,t \to W+b$ d,s,b g	Jet of hadrons (λ_o)	Calorimeter
e,γ	Electromagnetic Shower (X_o)	Calorimeter (ECAL)
ν_e,ν_μ,ν_τ $W \to \mu+\nu_\mu$	"Missing" transverse energy	Calorimeter
$\mu,\tau \to \mu+\nu_\tau+\bar{\nu}_\mu$ $Z \to \mu+\mu$	Only ionization interactions dE/dx	Muon Absorber
c,b,τ	Decay with $c\tau > 100\mu m$	Silicon Tracking

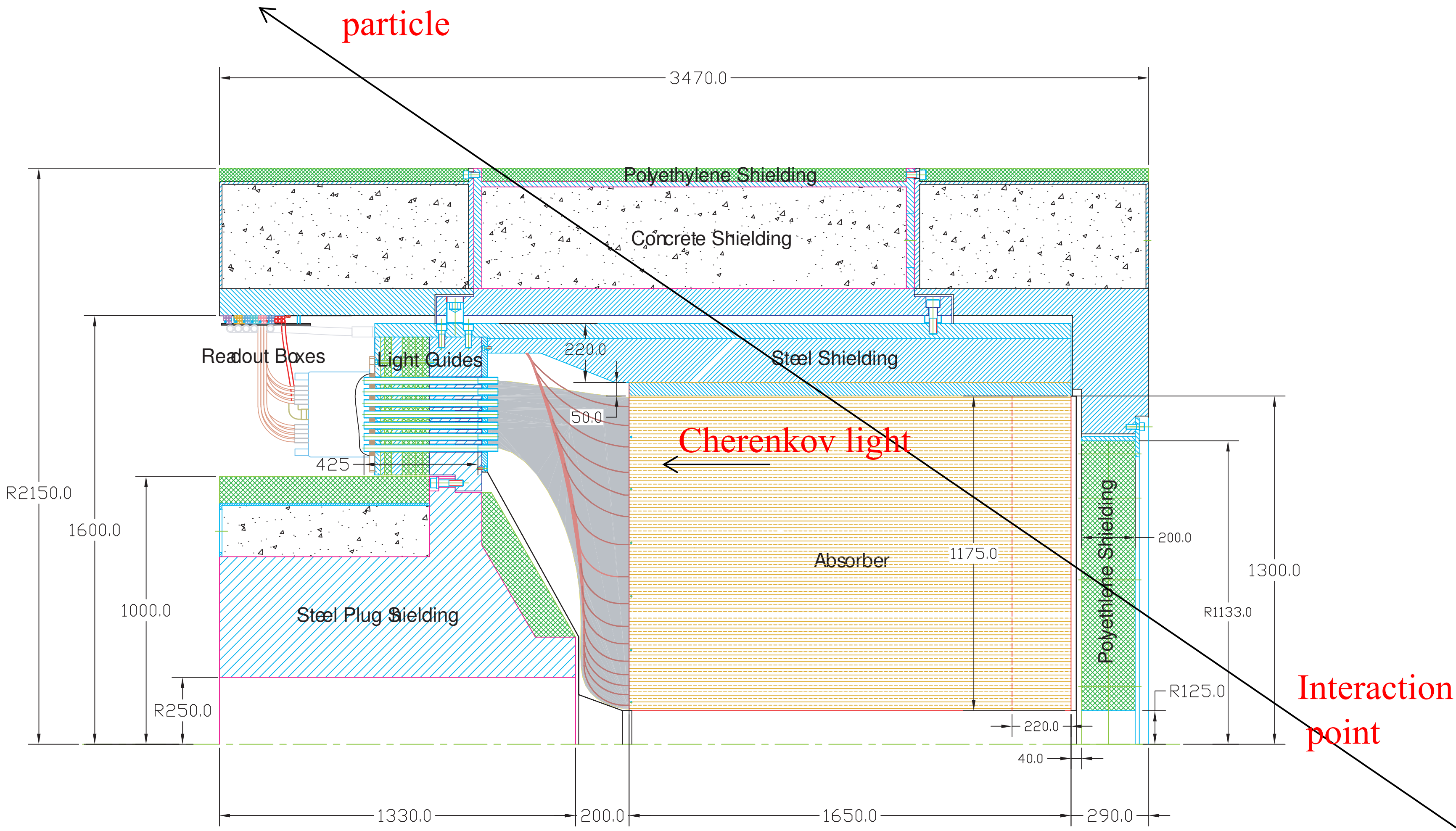
z-y view of CMS

CMS Calorimeter (ECAL+HCAL) - Very hermetic (>10λ in all η, no projective gap)

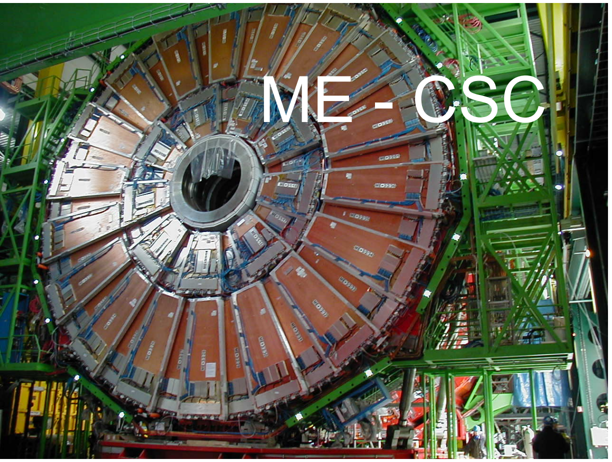


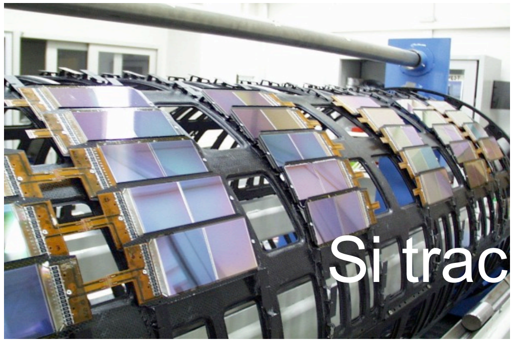
HB	Brass Absorber (5cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	|η|	0.0 ~ 1.4
HE	Brass Absorber (8cm) + Scintillator Tiles (3.7mm)	Photo Detector (HPD)	|η|	1.3 ~ 3.0
HO	Scintillator Tile (10mm) *outside of solenoid*	Photo Detector (HPD)	|η|	0.0 ~ 1.3
HF	Iron Absorber + Quartz Fibers	Photo Detector (PMT)	|η|	2.9 ~ 5.2

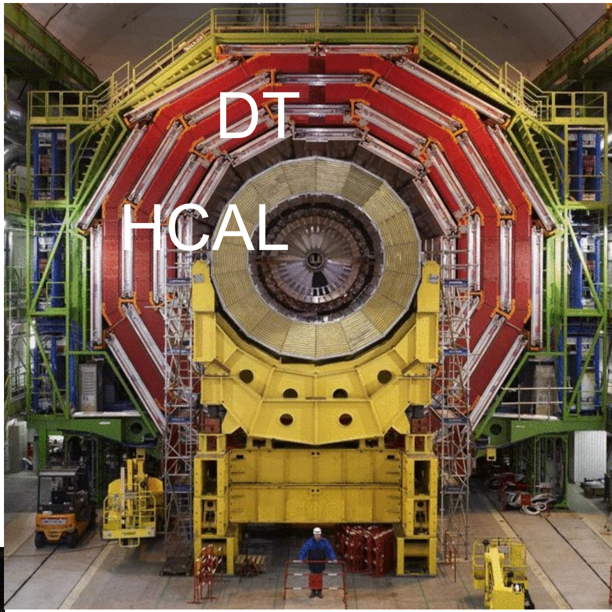
HF (Forward Hadronic Calorimeter)

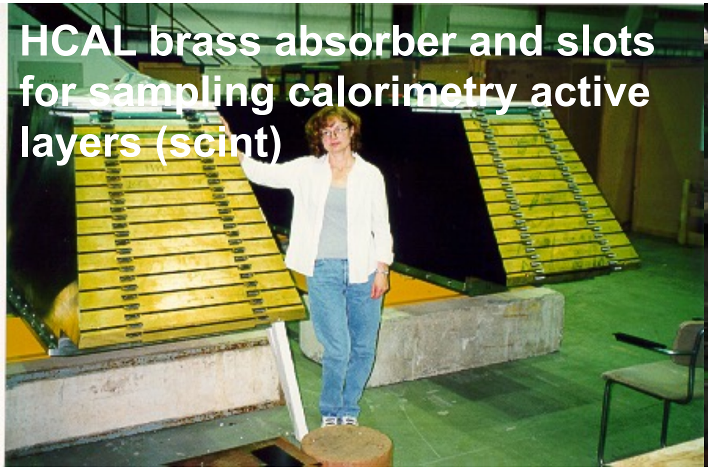


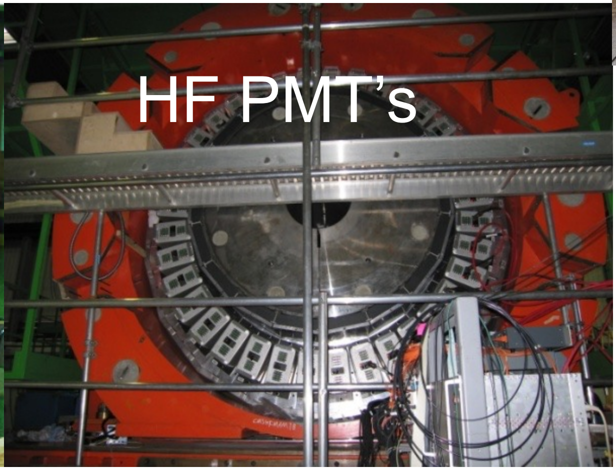
Some pictures ..



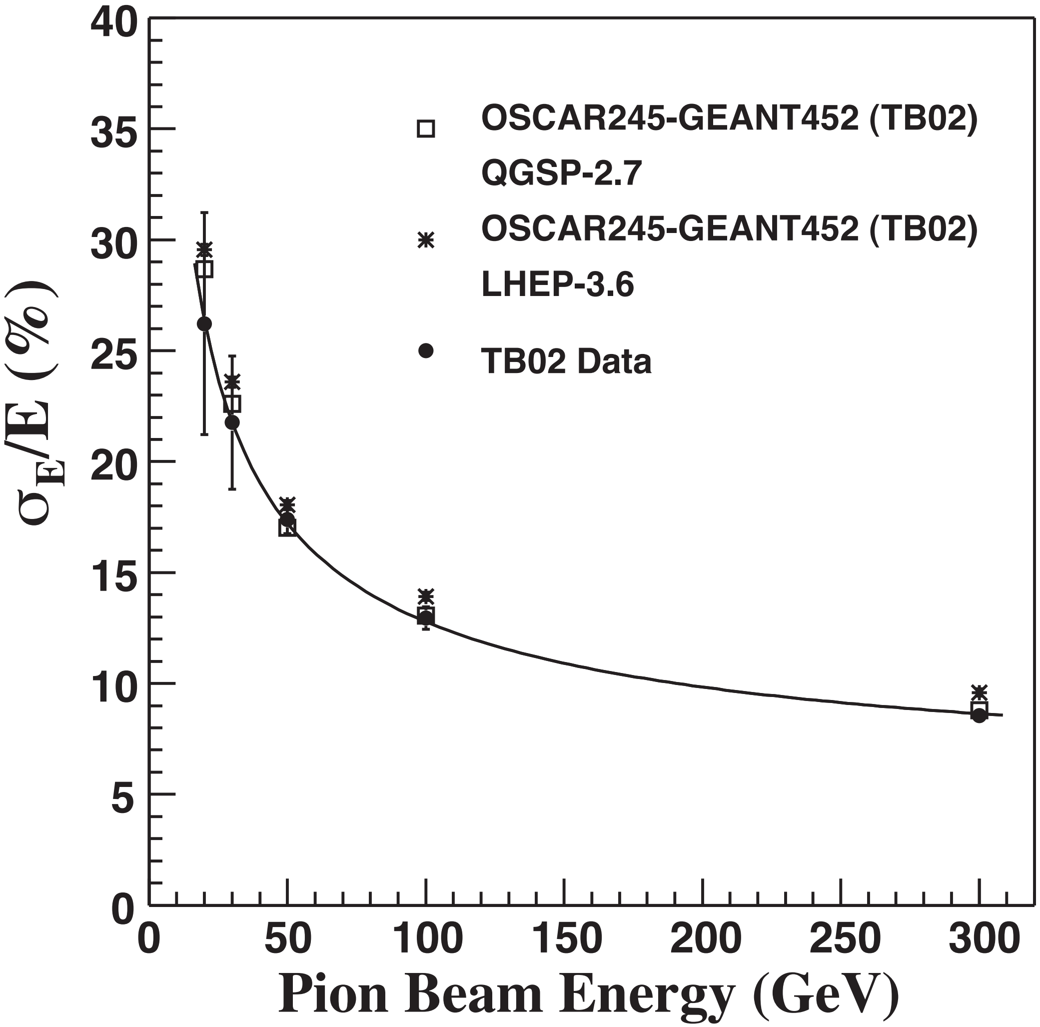








HCAL energy resolution



comments in HCAL

Primary purpose of HCAL is to identify the jets from quarks and hadrons.

More than just single particle response!

1/3 of the hadronic shower is in EM energy because of pi0 decay to 2 photons.

Want a "compensating" HCAL.

Only stable hadrons and muons reach the HCAL

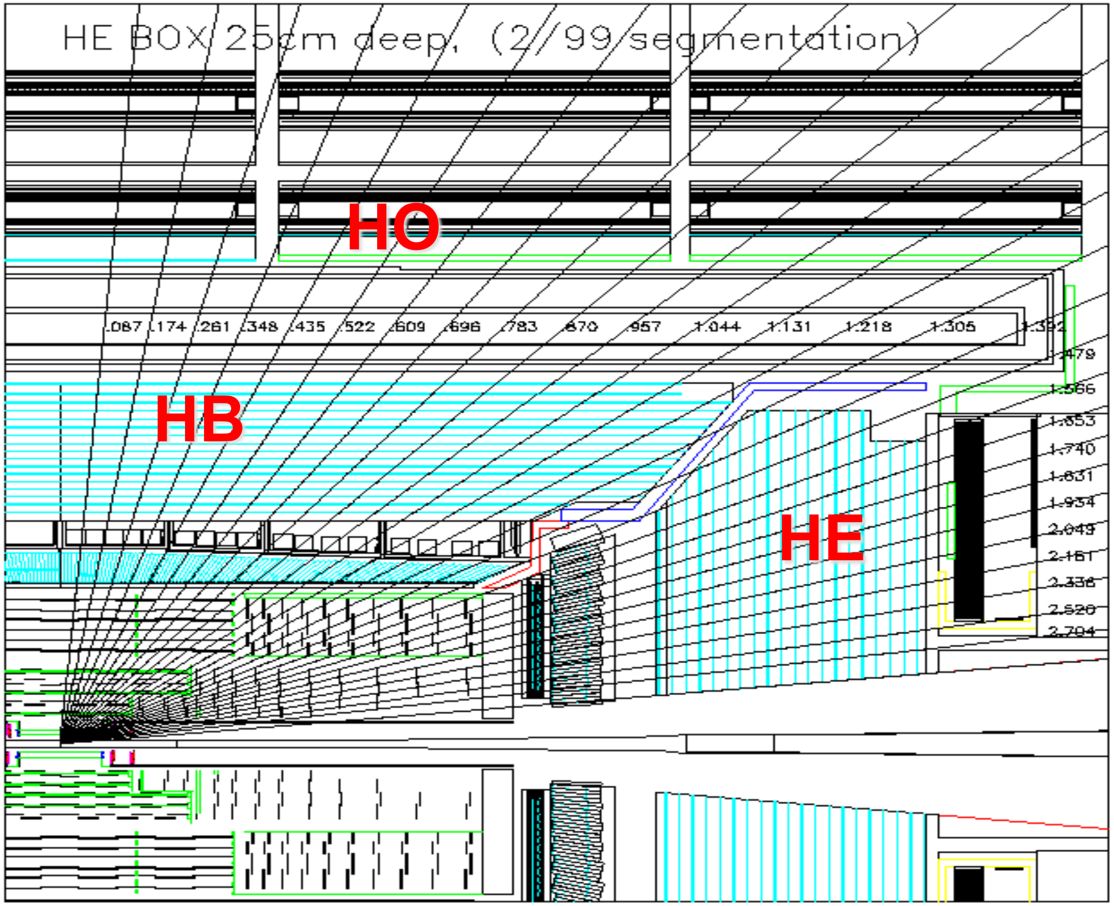
“Compensating” Calorimeter

Due to isospin, roughly half as many neutral pions are produced in hadronic shower than charged pions.

However, only charged pions “feed” the hadronic shower as pi0 immediately decay to di-photons, thus creating an electromagnetic component of the shower.

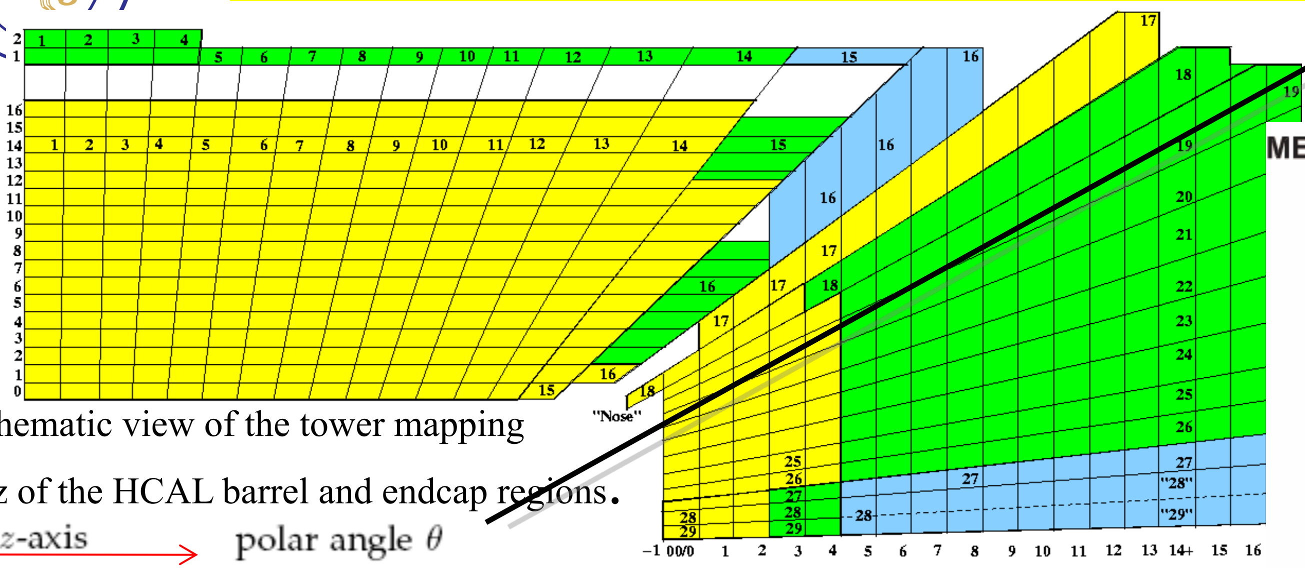
Resolution is best if the HCAL system has similar energy response to electrons as charged pions.

CMS HADRON CALORIMETER (HCAL)



- Central Barrel (HB) is 9 meters long, one meter thick and 6 meters in the outer diameter, consisting of two half barrels of 18 wedges each made of brass and scintillator, with WLS readout.
  The two End Caps (HE) are also made of brass and scintillator, with a diameter of 0.8 to 6.0 m. and a thickness of 1.8 meters.
- HB and HE are inside the 4-tesla solenoid coil and have a η-ϕ segmentation of 0.087 × 0.087, except near η = 3.0, where the size of the segmentation is doubled. The depth segmentation for HB is one unit while for HE from one to three.
- The two forward calorimeters (HF) are made of quarts fibers imbedded in iron cover the η range of 3.0 to 5.0.
- Central shower containment in the region |η| < 1.26 is improved with an array of scintillators located outside the magnet in the outer barrel hadronic calorimeter (HO).
- ~10K channels, Hybrid PhotoDiode readout for all but HF (PMT)
- 100 "Calotower" for 0.5 Jet cone radius

HCAL tower mapping (before upgrade)



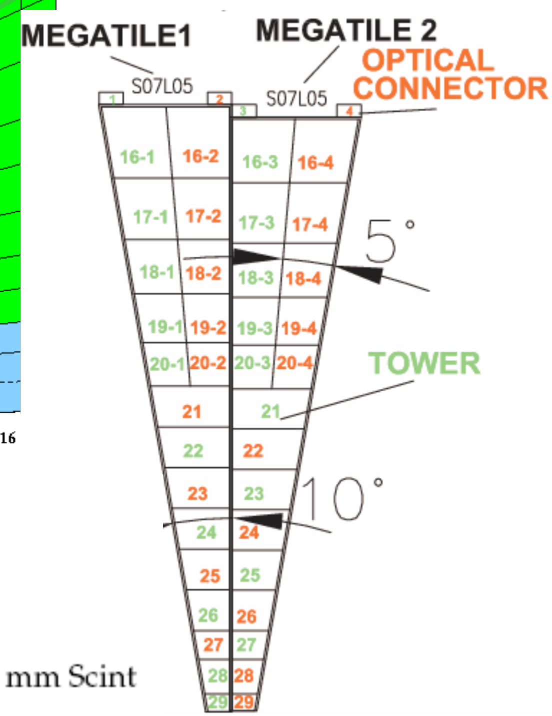
A schematic view of the tower mapping in r-z of the HCAL barrel and endcap regions.

(Layer 0) 9 mm Scint/61 mm Stainless Steel

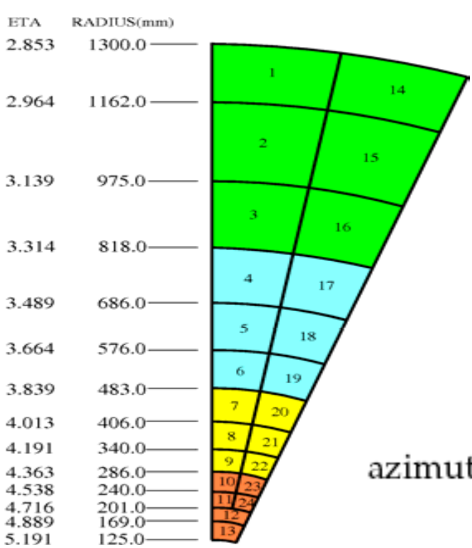
(Layers 1-8) 3.7 mm Scint/50.5 mm Brass

(Layers 9-14) 3.7 mm Scint/56.5 mm Brass

(Layers 15+16) 3.7 mm Scint/75 mm Stainless Steel/9 mm Scint



Numbering scheme for the tiles in adjacent scintillator trays.



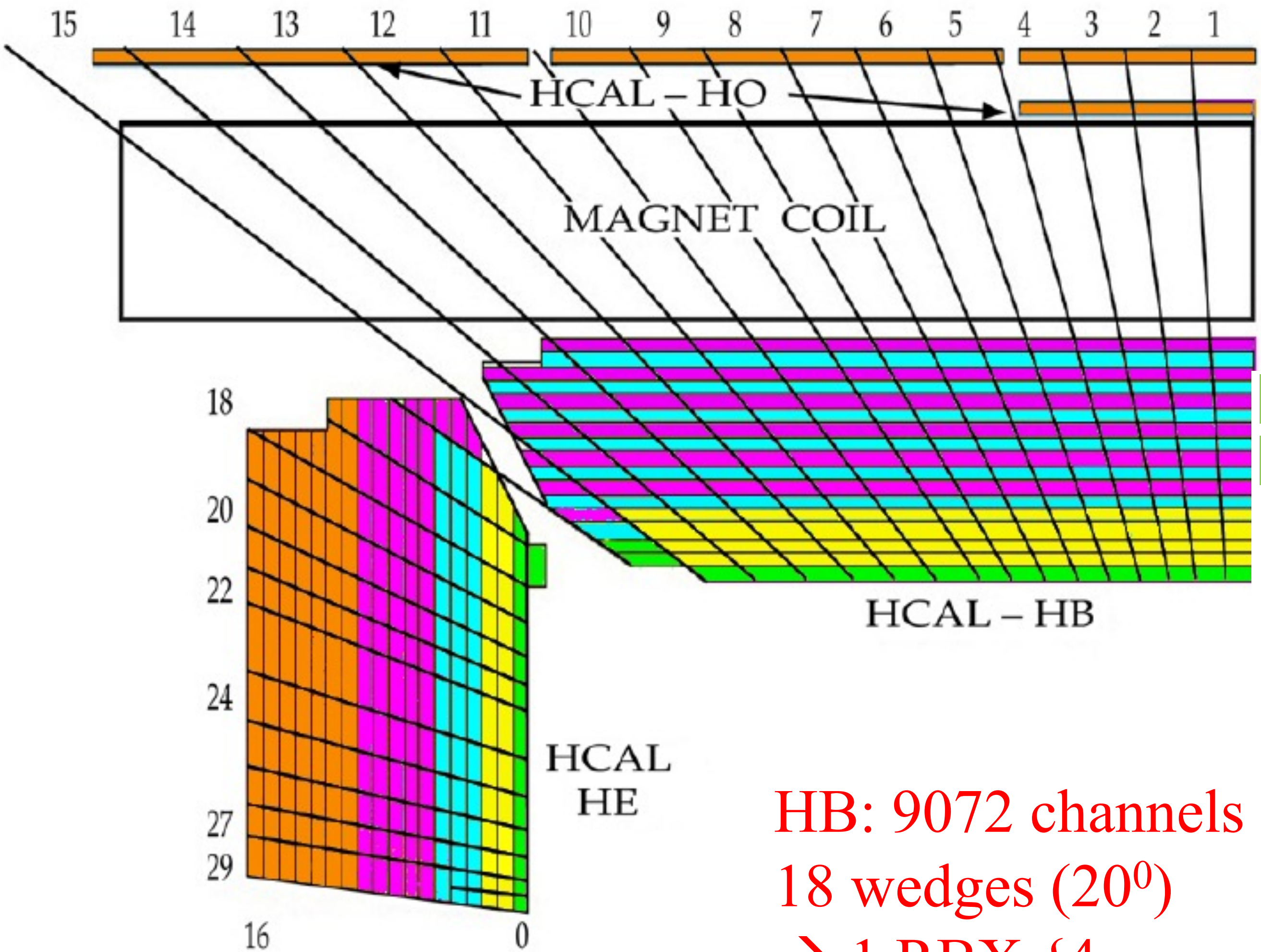
azimuthal angle ϕ x-y plane

-x axis is horizontal, pointing south to the LHC center.
-y axis is vertical pointing upwards.
- z axis is horizontal pointing west.
-sign of eta=- sign of z.
theta=0 is +z axis, theta=pi is -z axis

phi=0 is +x axis, phi=pi/2 is +y axis, phi=atan2(y,x)

The r- φ view of an HF wedge (at z = 11.2 m)

upgrade



4 depths (except 16.)

D1: 9mm scint/3 (NDF) =3mm BC408

D2: 4*3.7mm scint=14.8 mm SCSN81

D3: 5*3.7mm scint=20.5 mm SCSN81

D4: 4*3.7mm scint=14.8 mm SCSN81

HB: 9072 channels

18 wedges (20^0)

→ 1 RBX {4 segments (5^0)}

- HO is located in all 5 barrel wheels of CMS and is split in **30** $i\eta$ **sections** along the Z-axis (beam-pipe).
- In the transverse plane HO consists of 12 sectors à 6 trays and is split thereby in **72** $i\phi$ **sections**.
- Each $i\eta - i\phi$ tile is read-out by a separate channels making 2160 physical channels.
- In addition, some readout modules [RM] have several "dark" channels for noise measurements and calibration.

$\Rightarrow$ **Each of the 2376 channels has to be tested.**

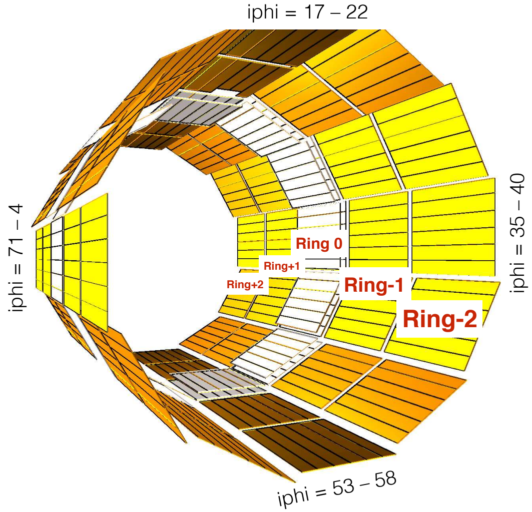
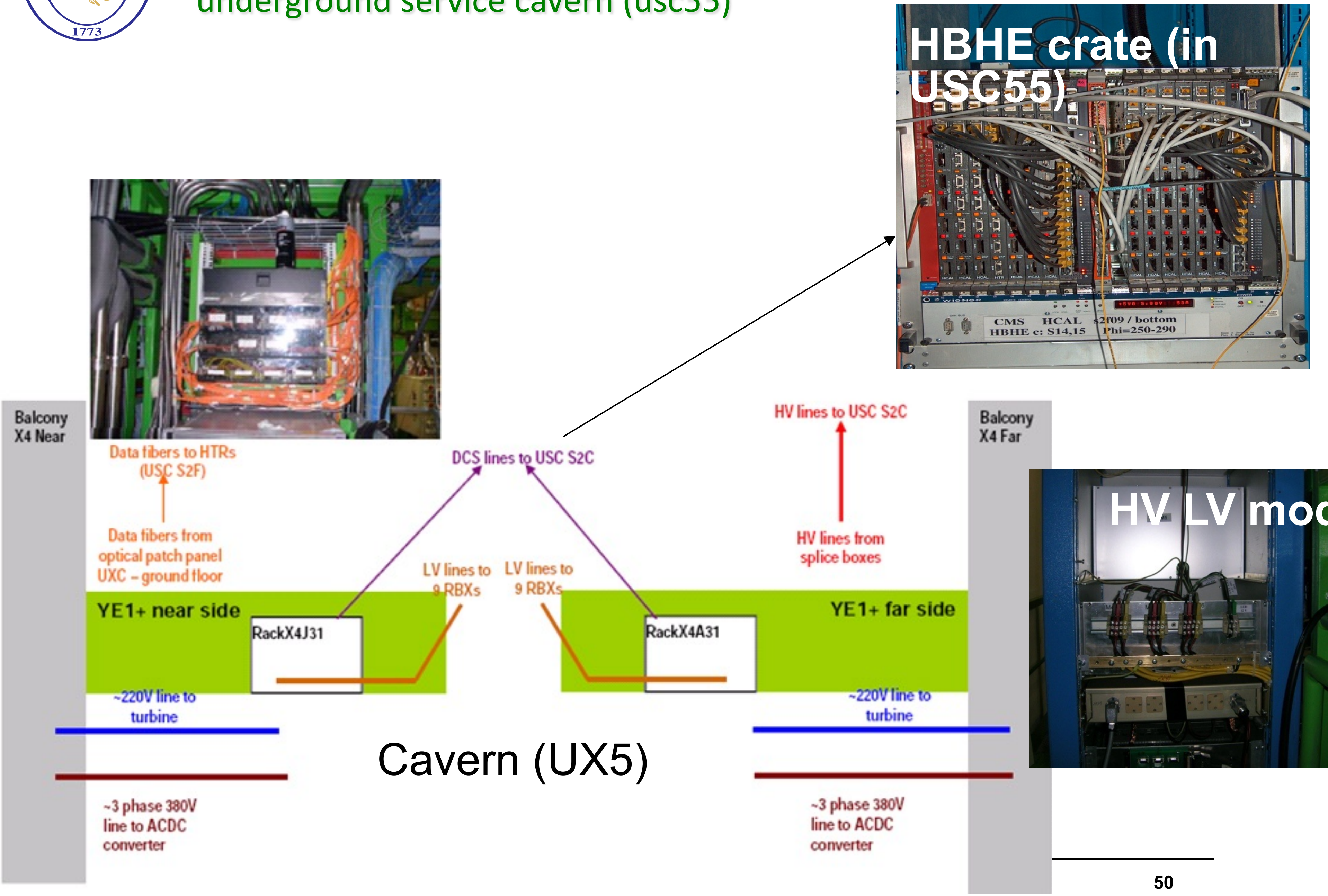


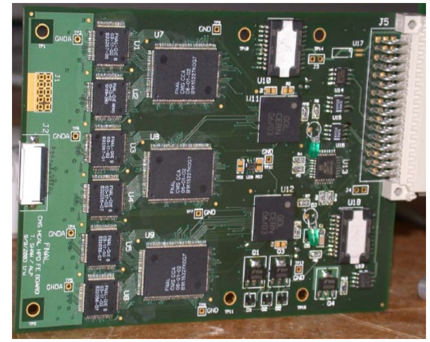
Figure : Layout of all the HO trays in the overall CMS detector

installation of readout and service cables between UX5 and underground service cavern (usc55)

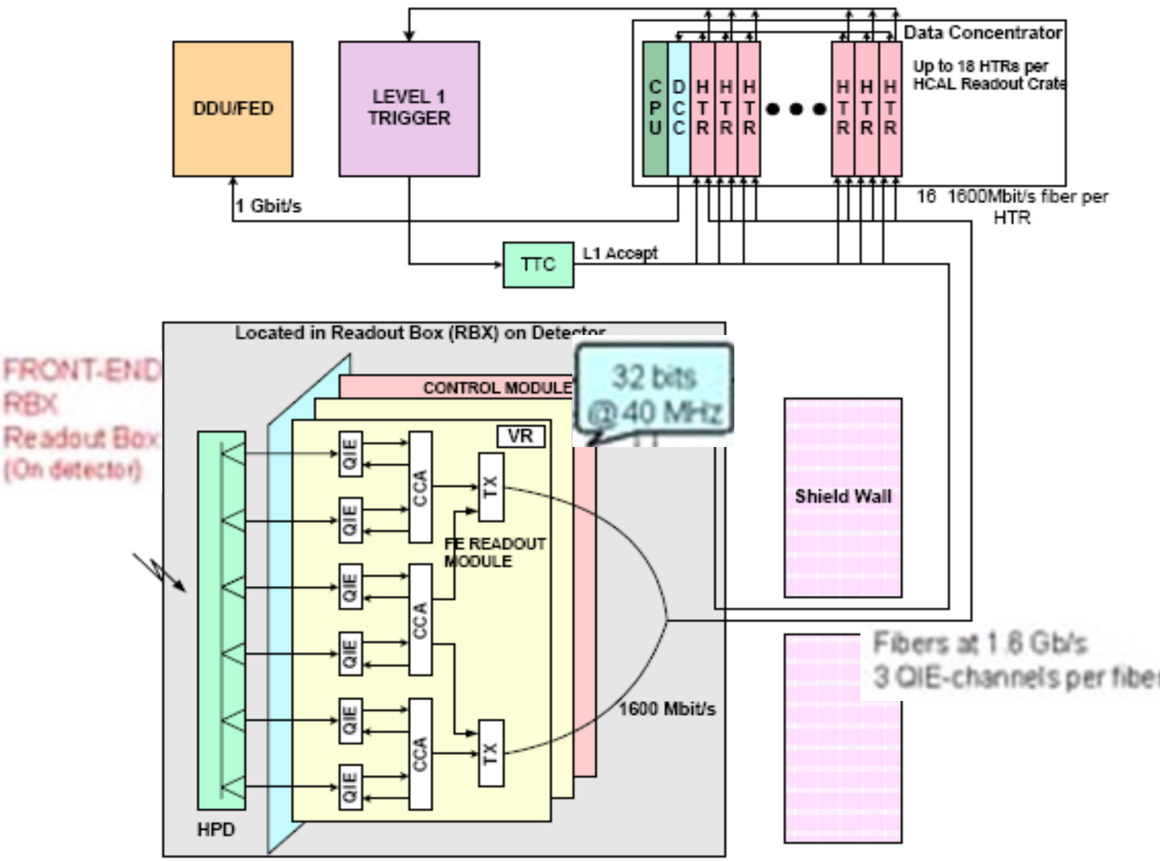


HCAL readout electronics

QIE (charge integrator and encoder)
Fermilab ASIC -done
CCA (channel control ASIC)
Fermilab ASIC -done
GOL (gigabit optical link)
4200 good chips from Engineering Run wafers in hand



12 HTR, 2 DCC per crate

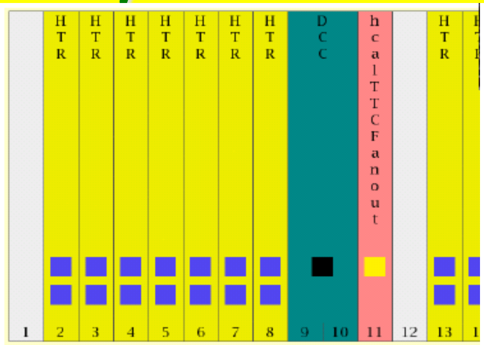


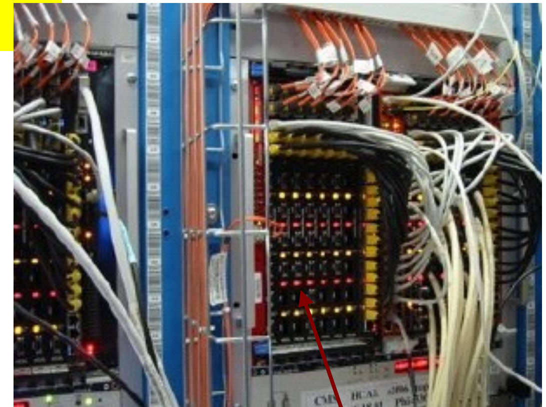
analogue signal from the HPD/SiPMs or photomultiplier → digital signal by QIE (Charge-Integrator and Encoder)

QIE →Gigabit Optical Link (GOL) at a rate of 40 MHz and transmitted to the counting house (USC55) → HCAL Trigger Readout (HTR) board, containing the Level-1 pipeline.

The trigger primitives are sent to the Regional Calorimeter trigger (RCT) via Serial Link Board mezzanine cards.

HCAL Trigger System

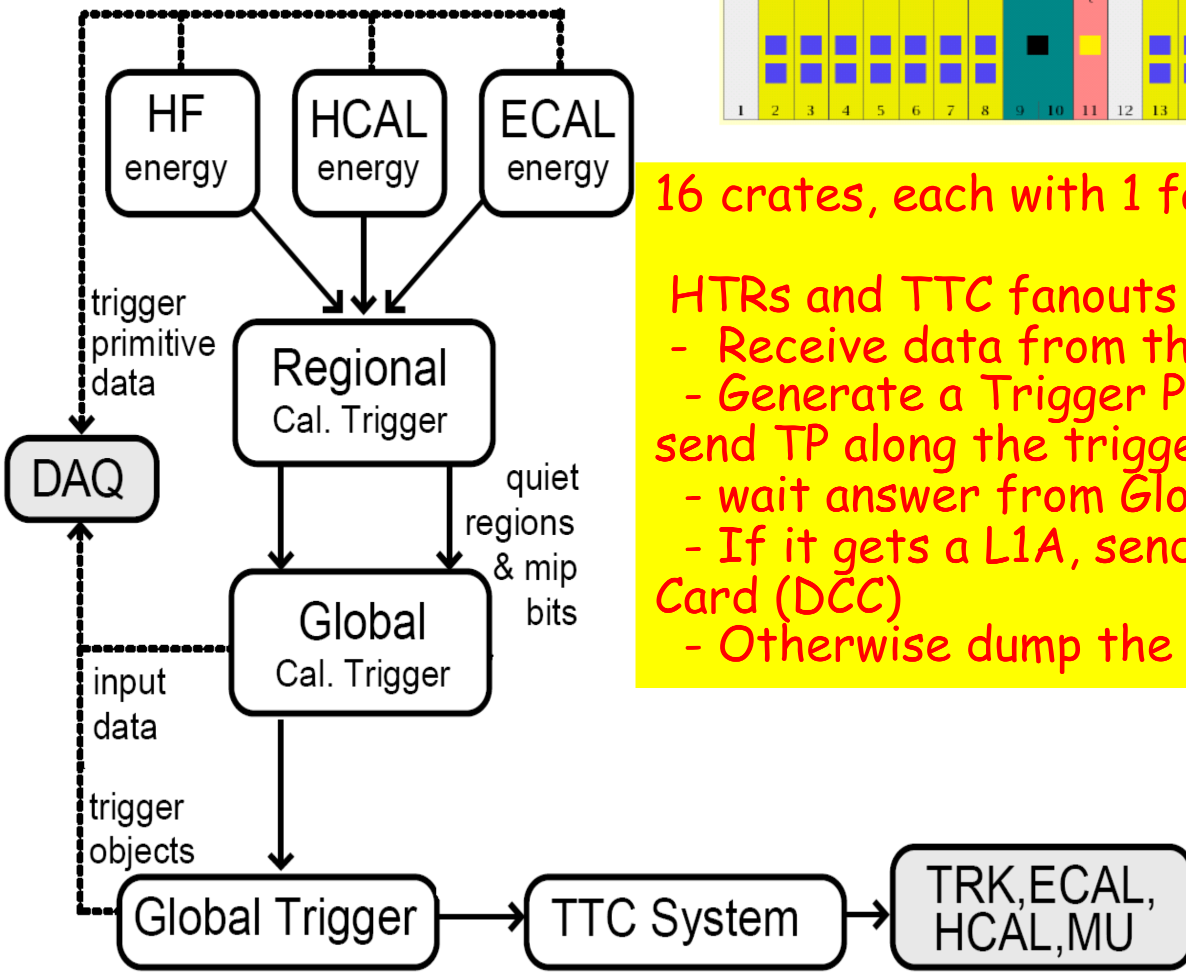




16 crates, each with 1 fanout, 2 DCCs, 13 HTRs

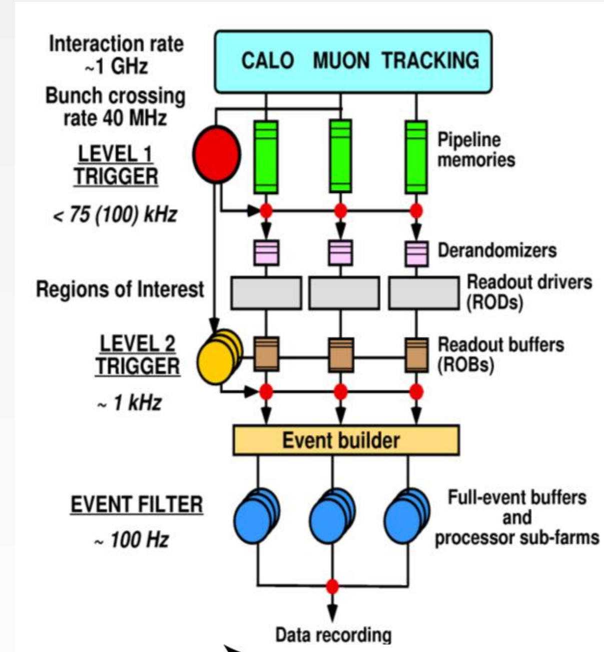
HTRs and TTC fanouts in thetrigger path

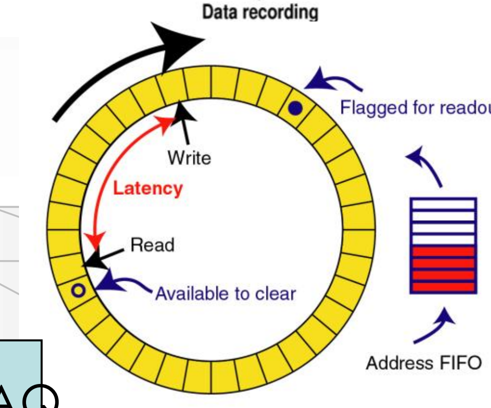
- Receive data from the FE and put it in a pipeline
- Generate a Trigger Primitive (TP) for the data and send TP along the trigger path
- wait answer from Global Trigger (GT).
- If it gets a L1A, send data to Data Concentrator Card (DCC)
- Otherwise dump the event

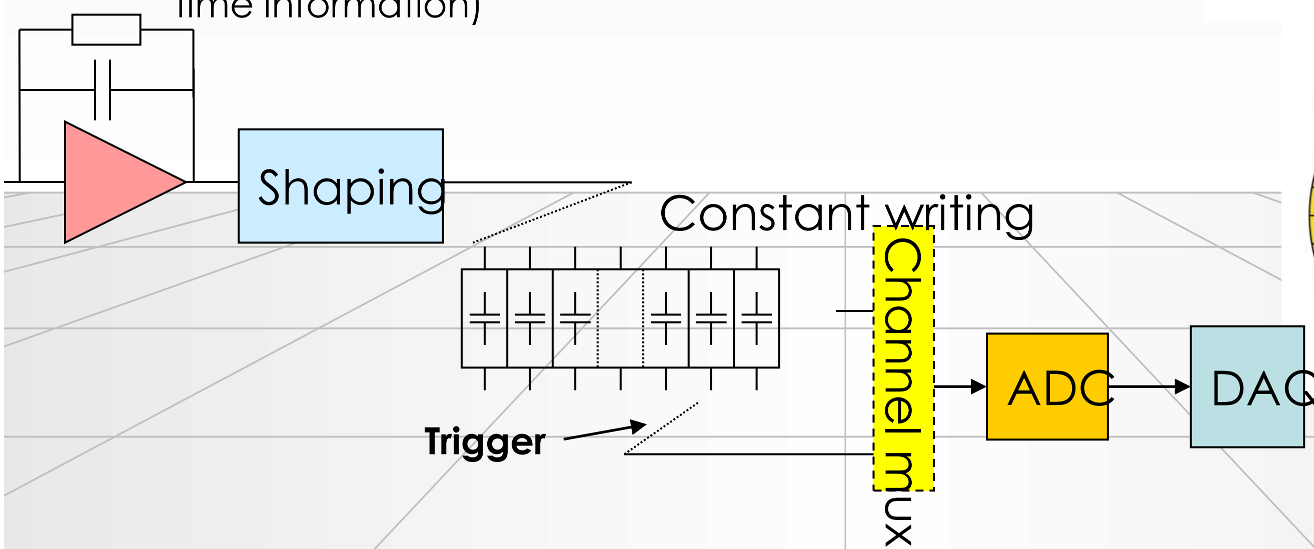


Triggered read-out

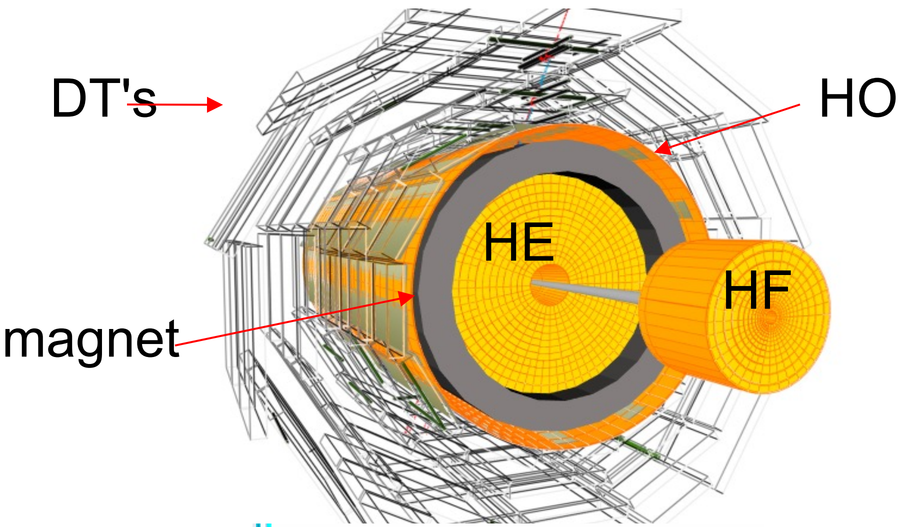
- Trigger processing requires some data transmission and processing time to make decision so front-ends must buffer data during this time. This is called the trigger latency
- For constant high rate experiments a “pipeline” buffer is needed in all front-end detector channels: analog or digital
  1. Real clocked pipeline (high power, large area, bad for analog)
  2. Circular buffer
  3. Time tagged (zero suppressed latency buffer based on time information)

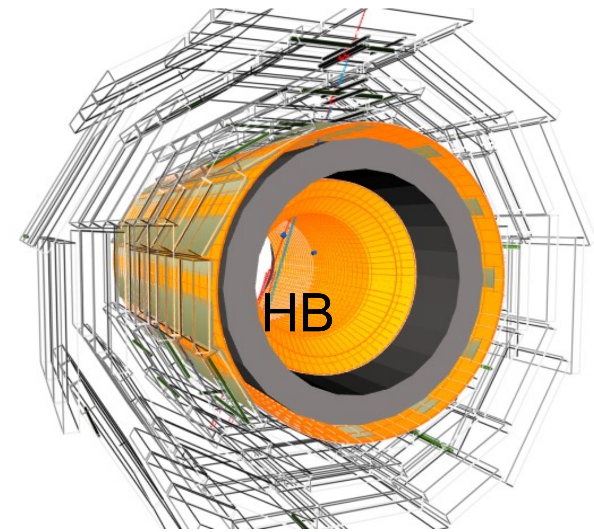


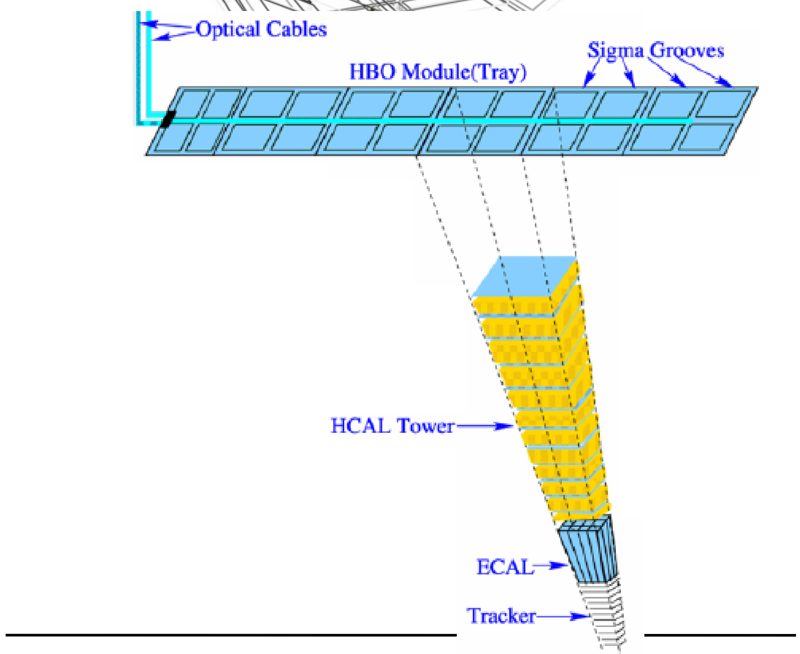


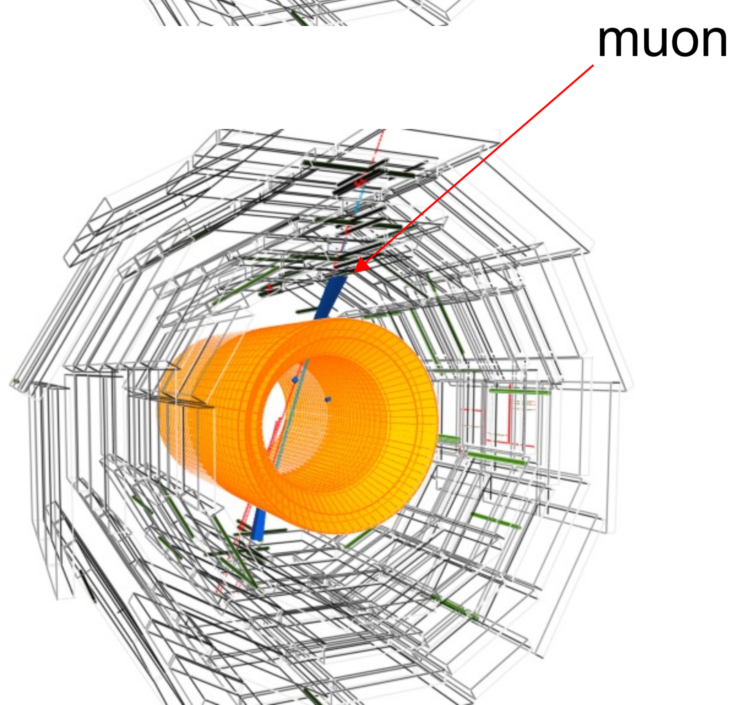


A Cosmic muon in HCAL

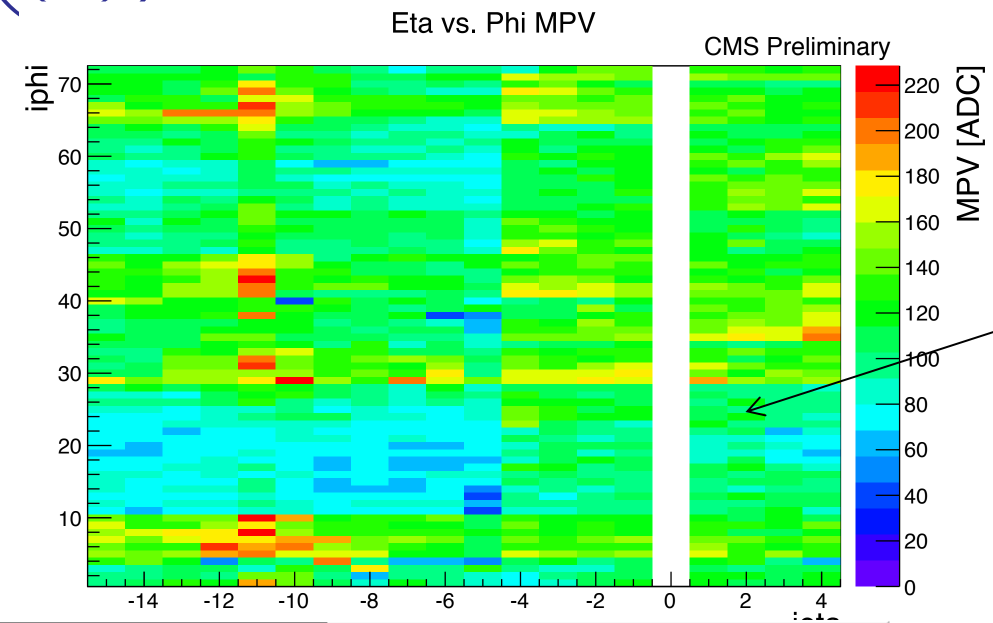


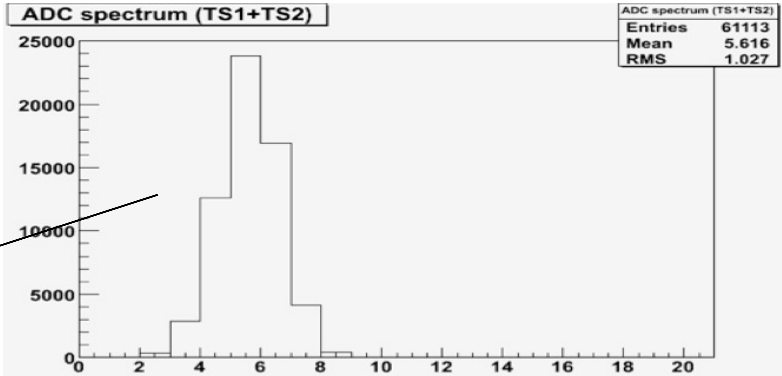




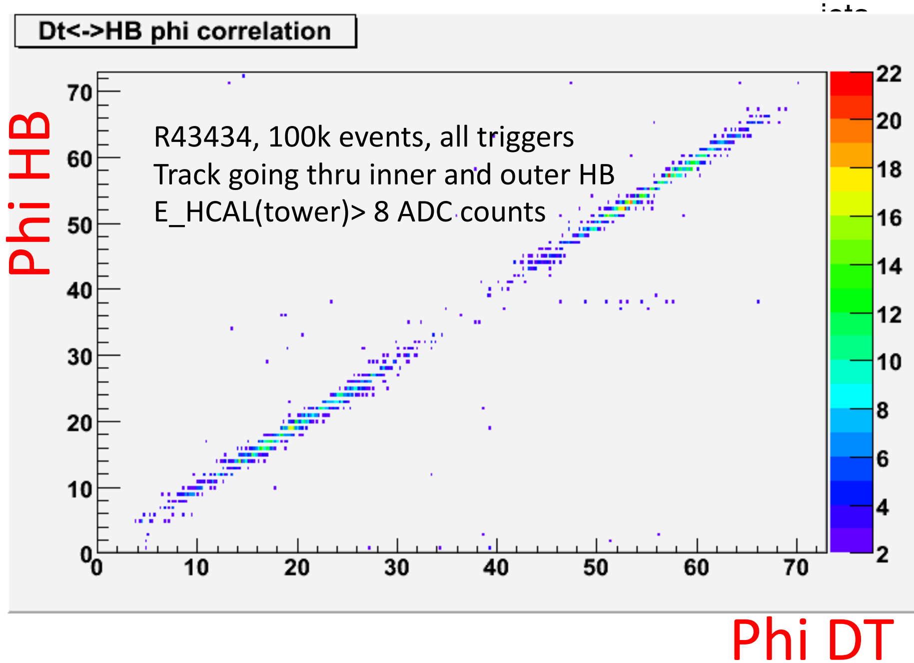


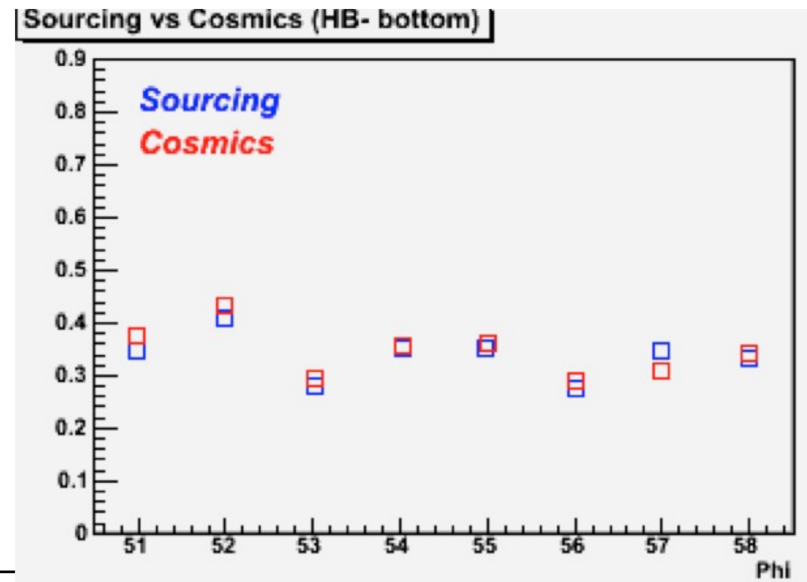
HCAL calibration works…



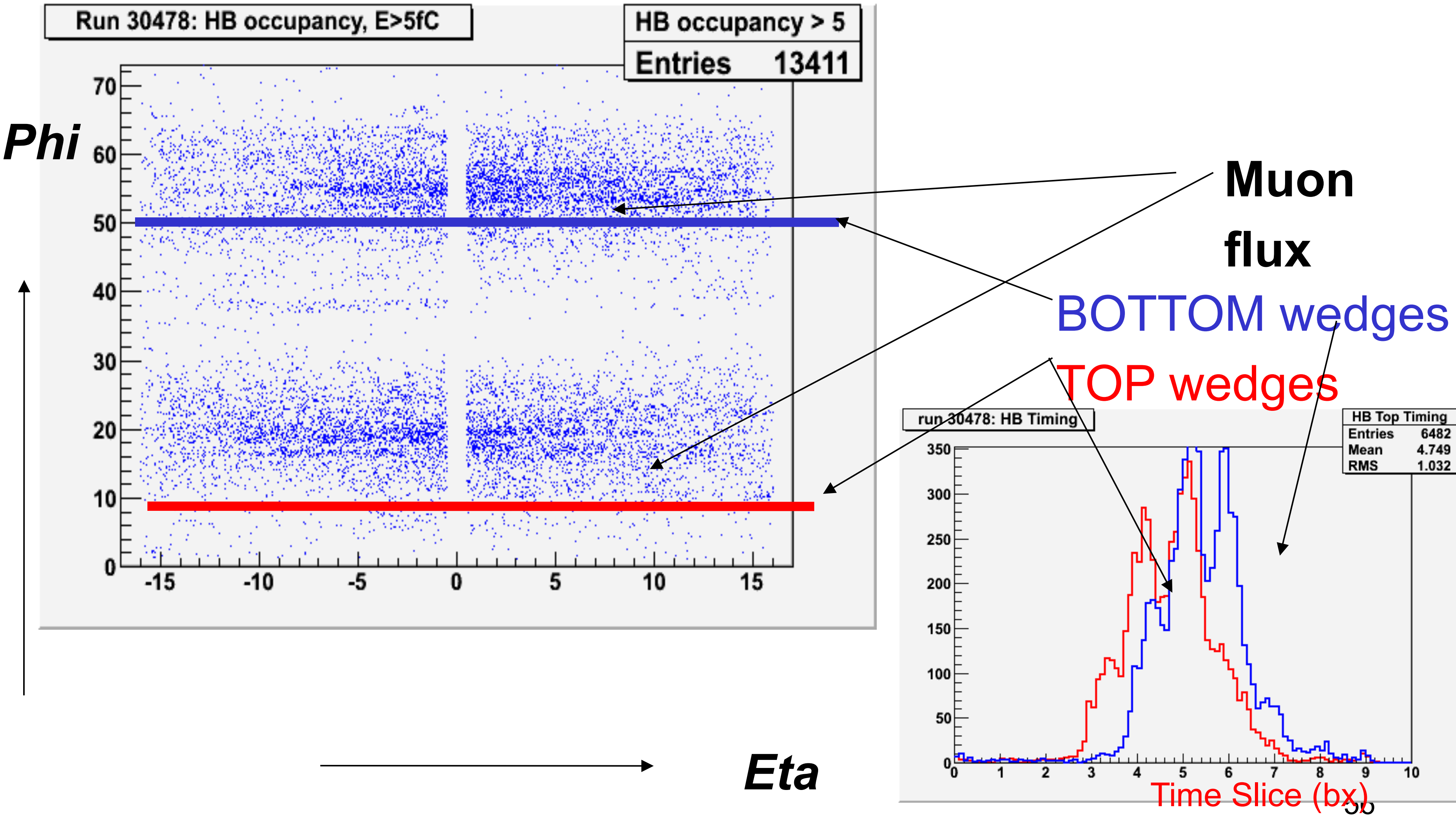


Signal from 1 channel in 1 bx

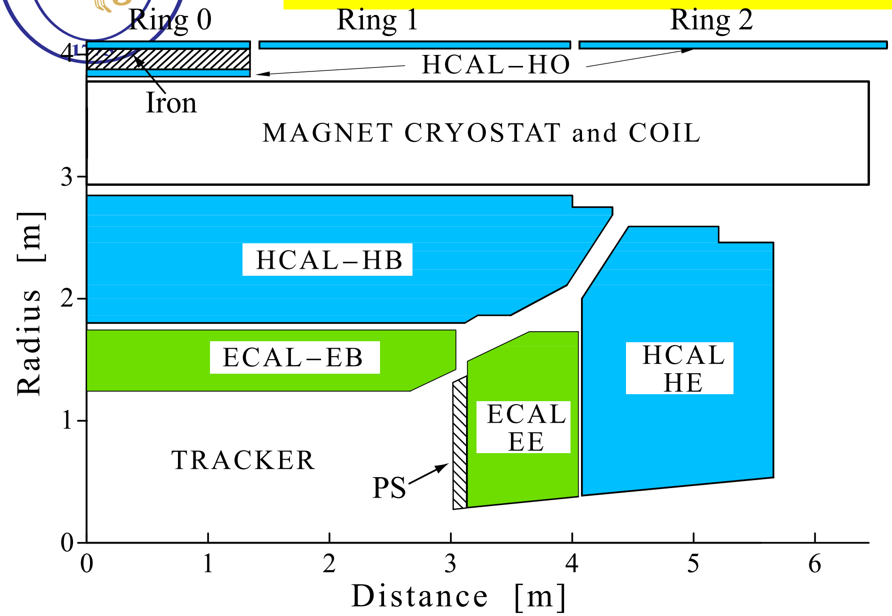




Another example:Cosmic Muons in HB

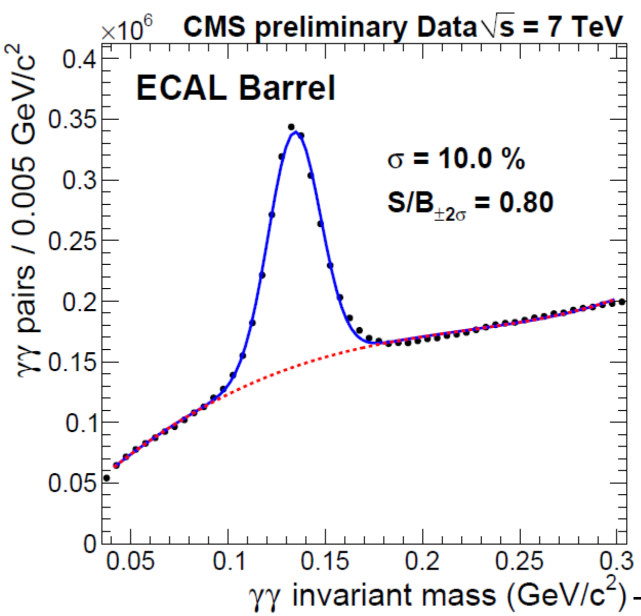


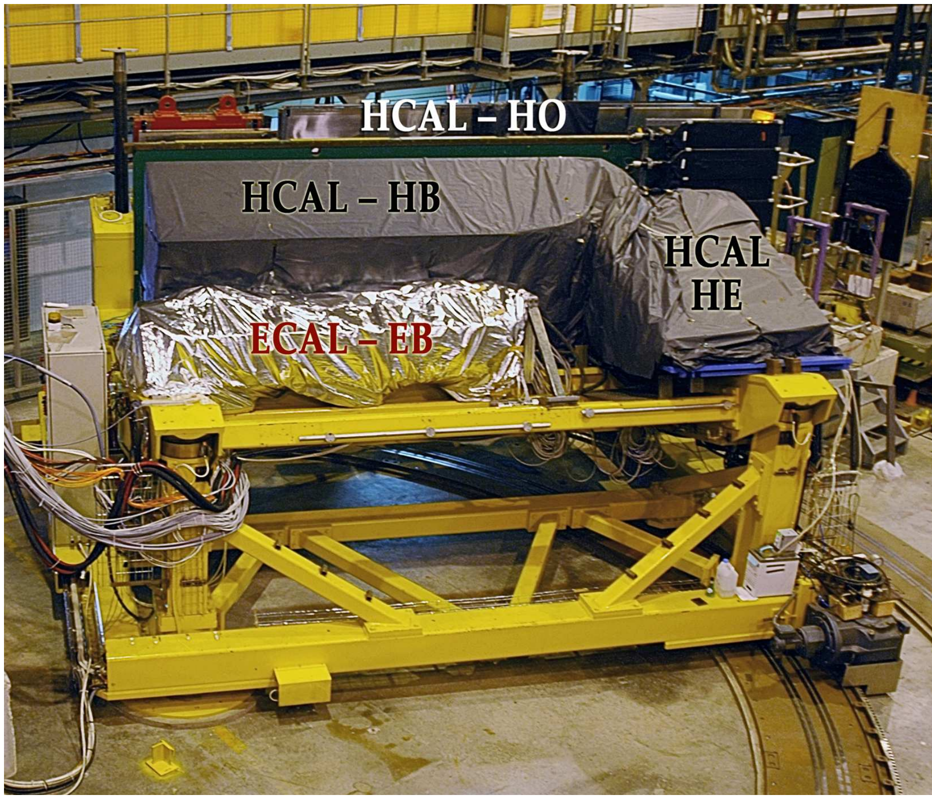
ECAL/HCAL Performance



Calibrating detectors with a well known particle in test beam

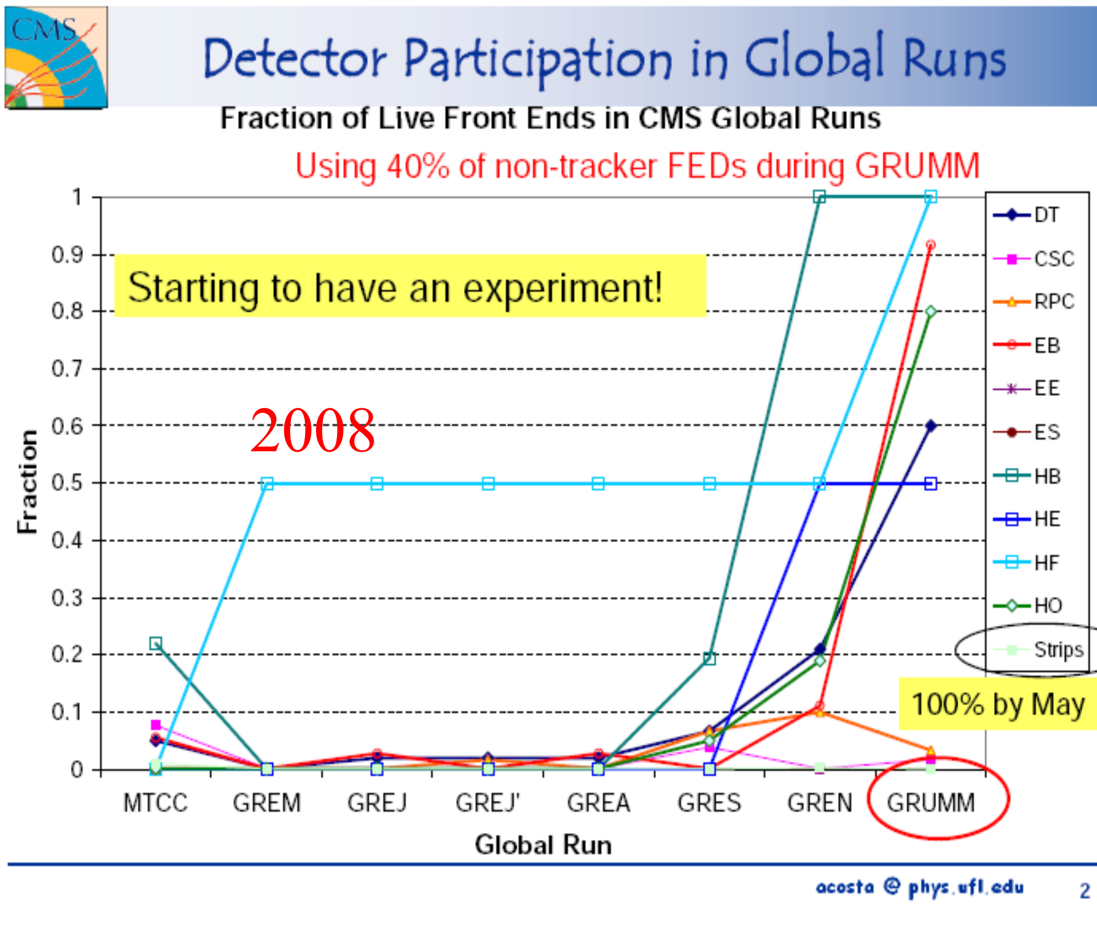
↓

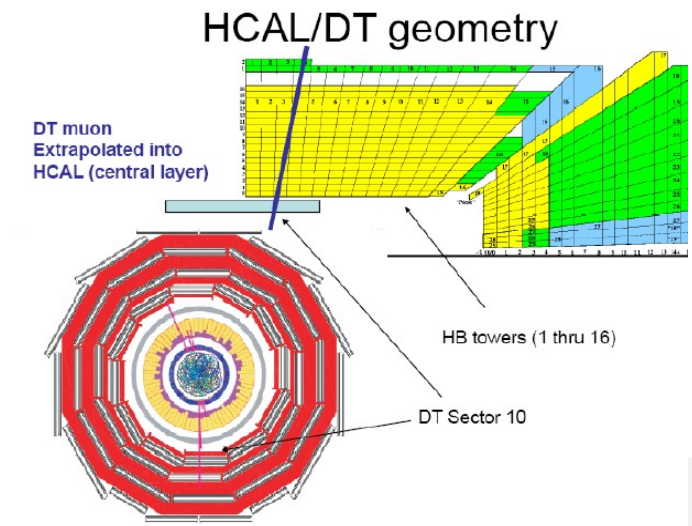


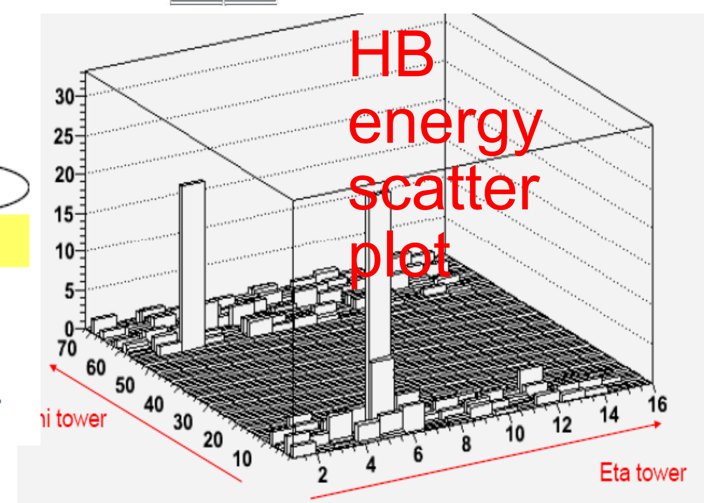


CMS Global Runs

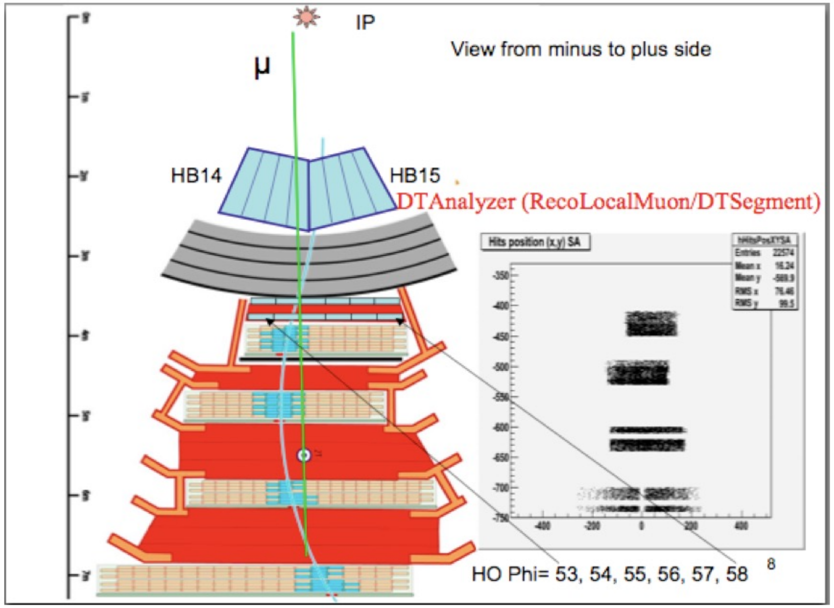
turning set of commissioned subsystems (HCAL, Muon, ECAL, Tracker) into fully integrated detector

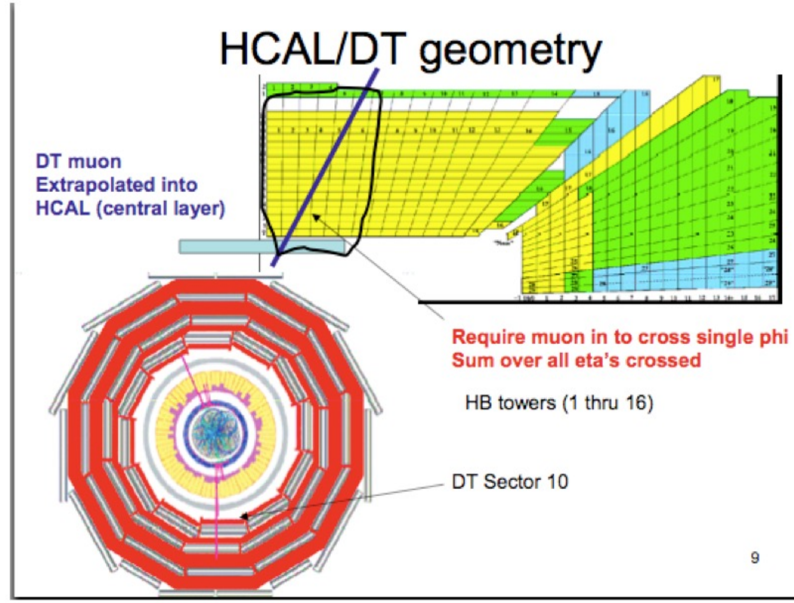


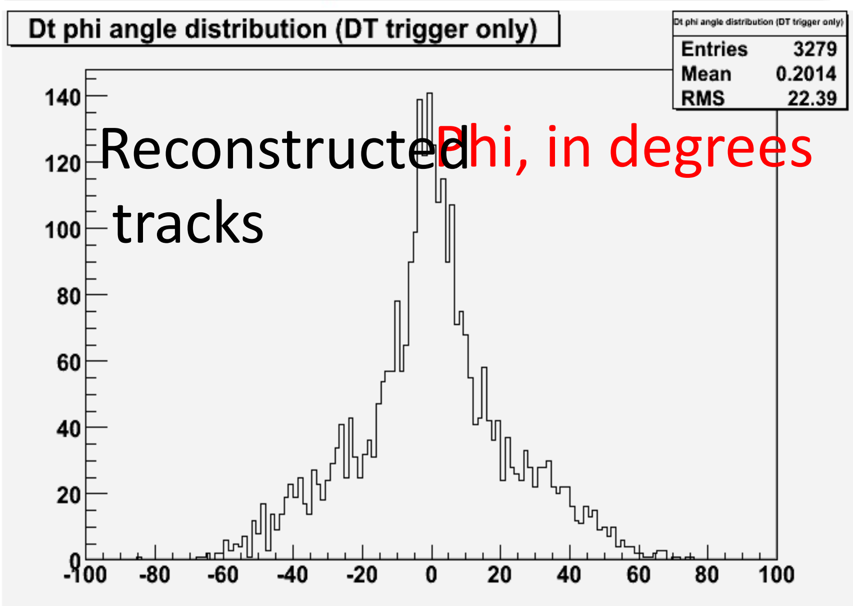


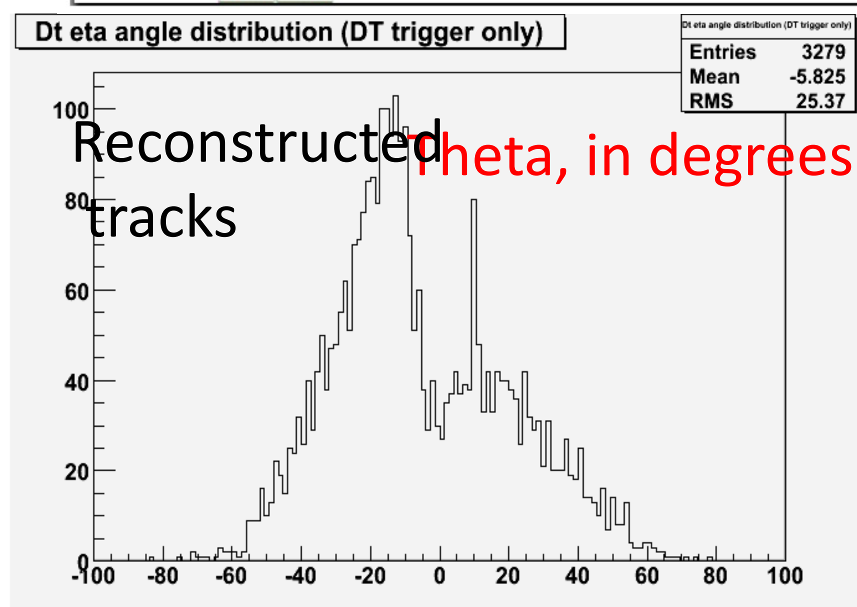


DT track distributions (r43434, DT trigger, 10k events)



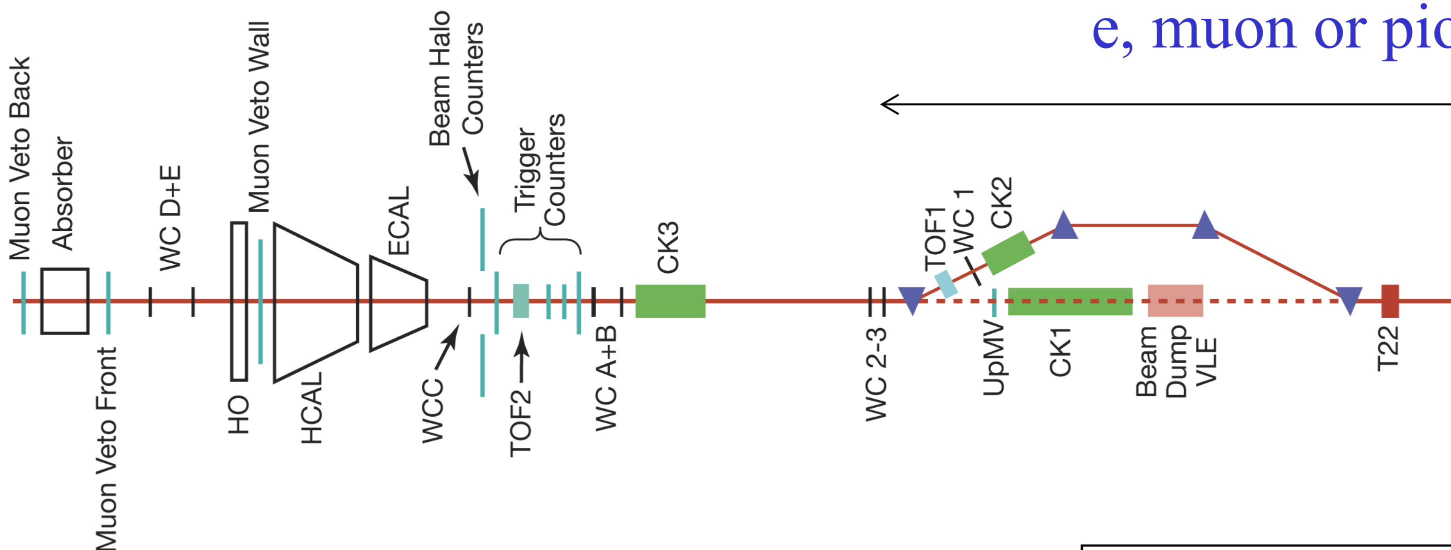


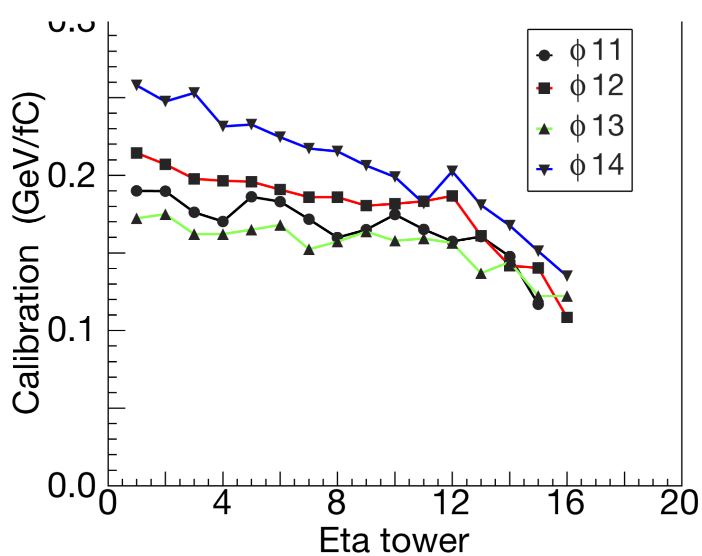


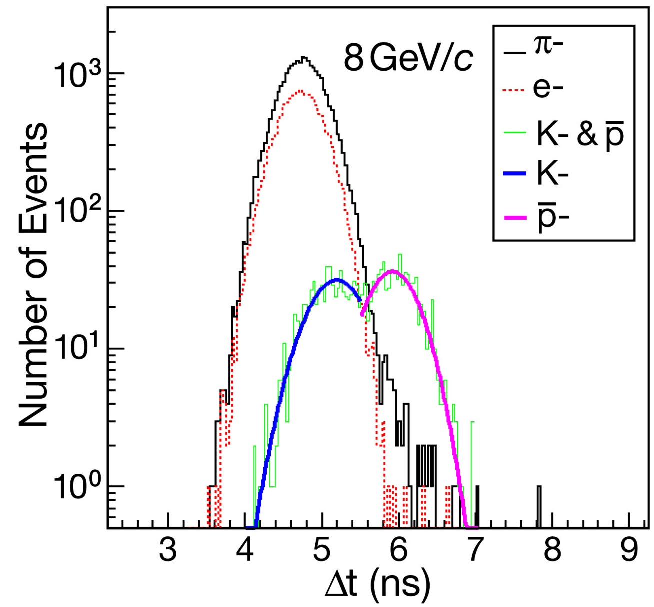


Calibration with a Test Beam

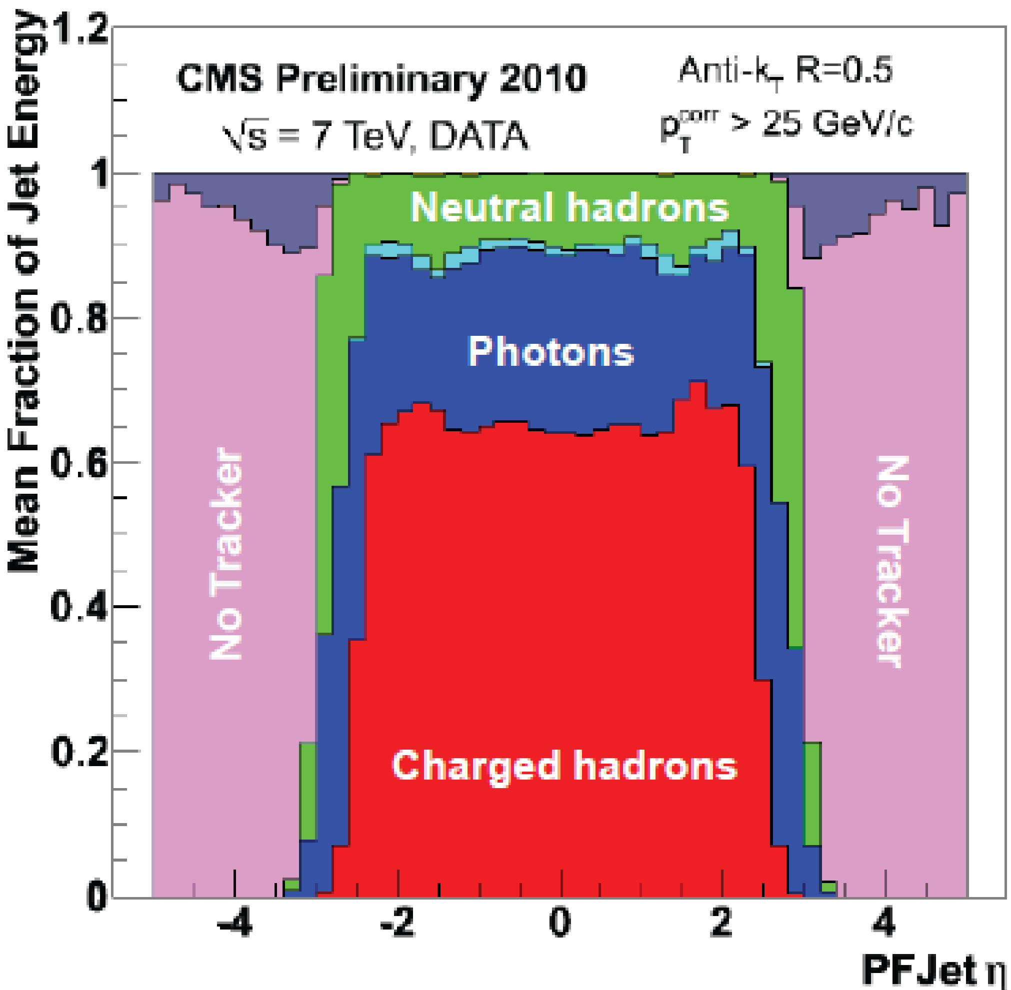
e, muon or pion beam







Particle flow



Using "best measurement" of each component
Charged tracks = Tracker
e/photons = Electromagnetic E calorimeter
Neutral hadrons from HCAL

Critical points:
Very fine granularity
Confusion due to shower overlaps in calorimeter Very large number of channels


Thank you!