The art of calorimetry part IV

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Answer to your question:

Can one detect the extremely high energetic neutrinos in from cosmic rays by their sound?

- ➔ The Nobel answer: “no, too low energy”
- ➔ The round of guys lecturing at this Grad-days: “maybe possible… ~mJ energy can produce sound in laser experiments”
- ➔ Google: “it is being tried in DESY Zeuthen for IceCube” !!!

Akustische Neutrinosuche: Horchposten für hochenergetische Neutrinos
http//www.weltderphysik.de/de/5128.php

a typical neutrino induced particle shower with an energy of 10^18 eV has in a distance of 400 m to the shower a pressure amplitude of only 5 mPa. in the ice of IceCube you have already a pressure of 25 MPa in 2500 m. therefore your background pressure is 10^9 larger than the signal.
a proton is of 10^-15 m & molecules at 10^-9 m... so six order of magnitudes... with the energy of 10^18 eV, there is enough energy to make this step & still to "move" the molecules.

If you work for:	some relevant calorimeter topics are
LHC	Calorimeter as trigger, missing E_T and jets
ILC	Calorimeter for Particle Flow
ILC and beyond	Dual readout calorimeter

Calorimeters as trigger

Issue:

Define an accept/reject signal for relevant physics in short time (~μsec) with much info in the detector (~MB/event, ~GHz rate)

➔ minimum processing time for huge data volume

Answer:

- No tracking algorithm possible on such time scale

➔ Use the calorimeter information compressed in suitable form

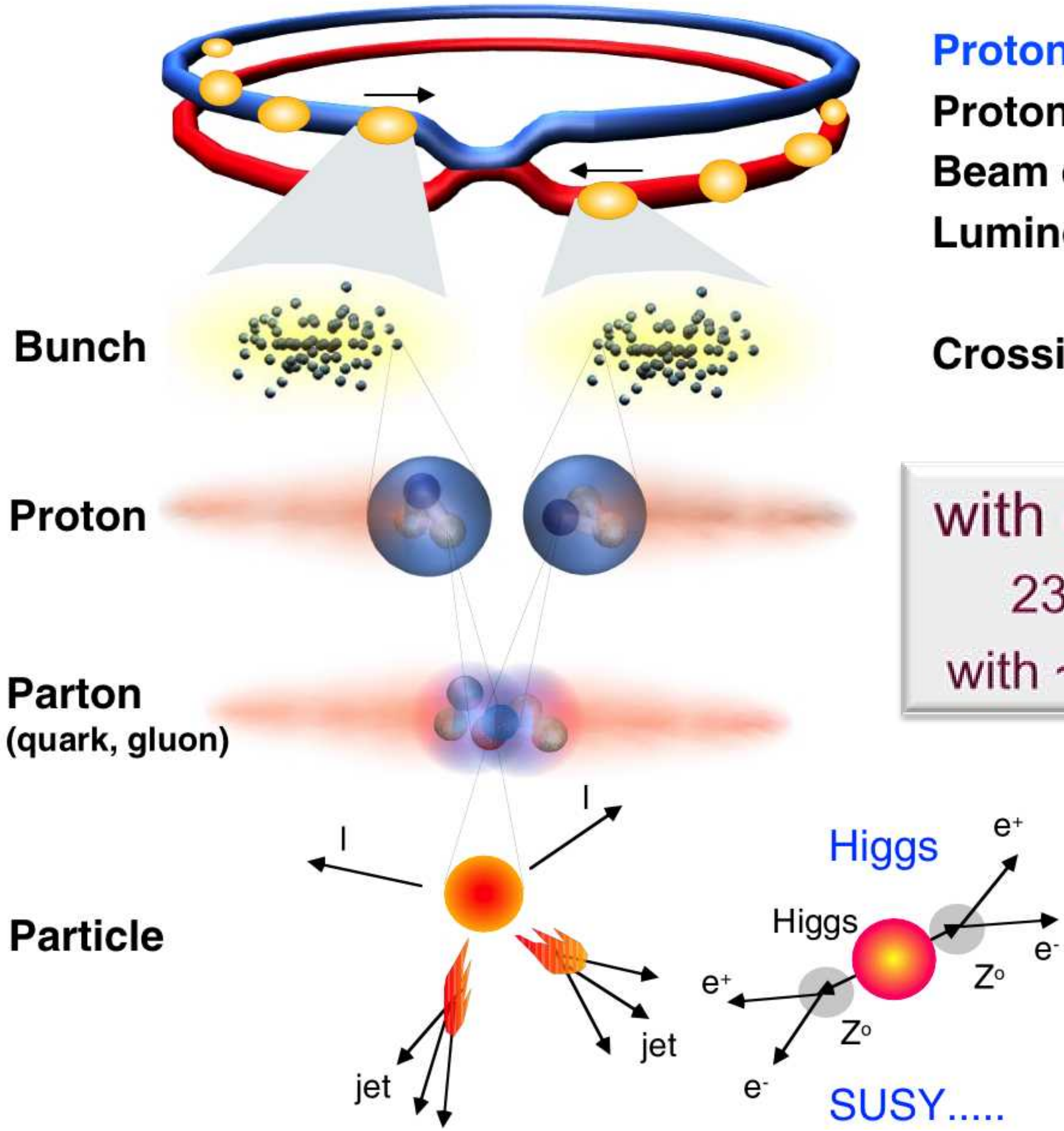
Different way to use a calorimeter:

-emphasis is on fast decision at the cost of precision

-not best E reconstruction, but precise enough for threshold selection

-not ultimate jet reconstruction, but topological information

A short parenthesis: LHC Collisions



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz

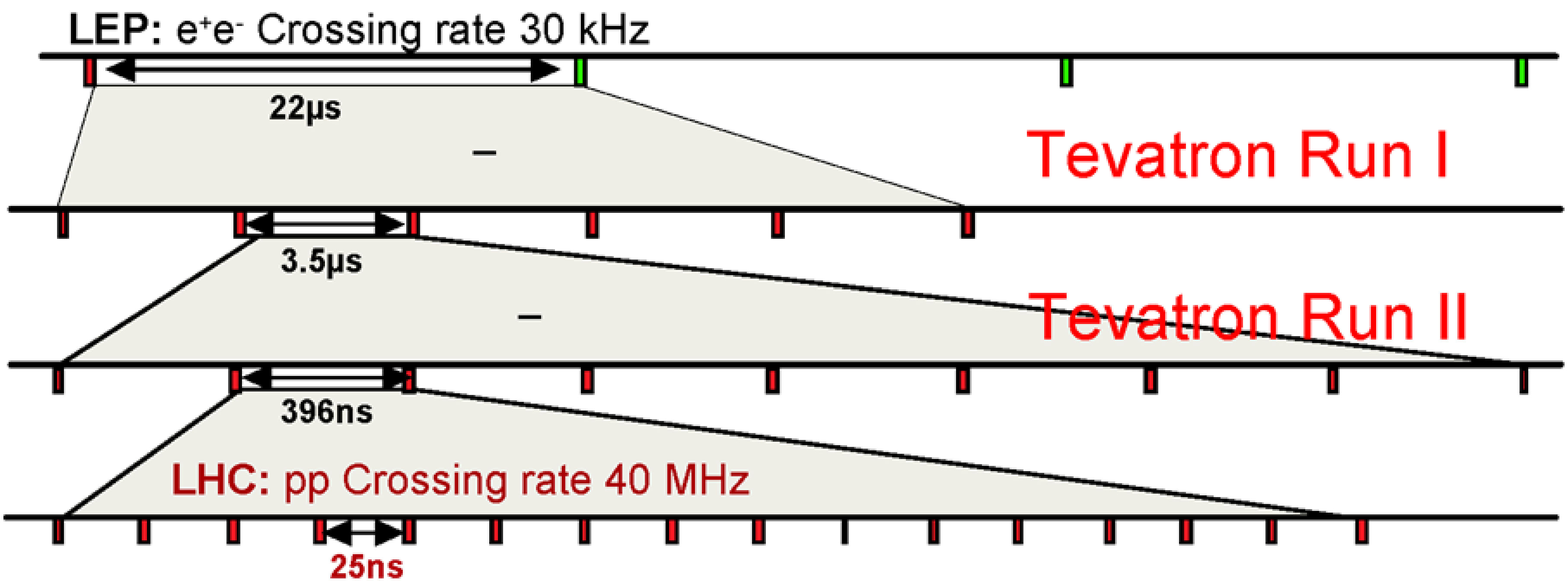
with every bunch crossing
23 Minimum Bias events
with ~1725 particles produced

Selection of 1 in 10,000,000,000,000

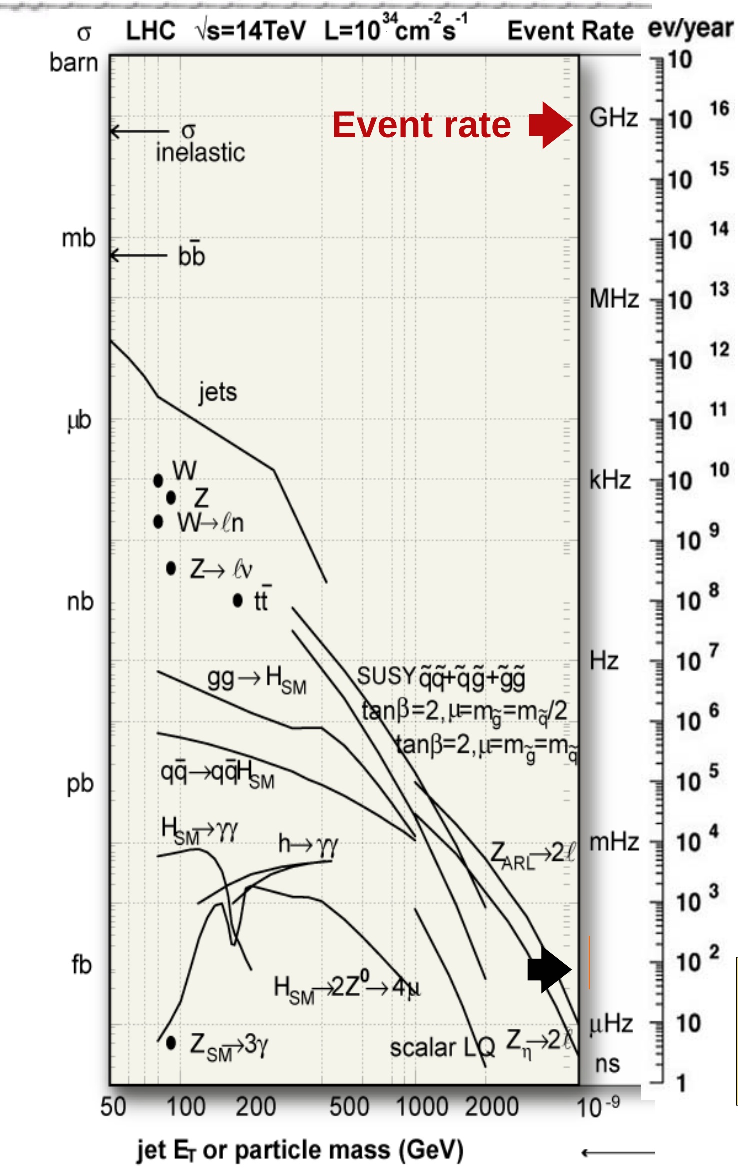
Beam Xings: LEP. TeV, LHC

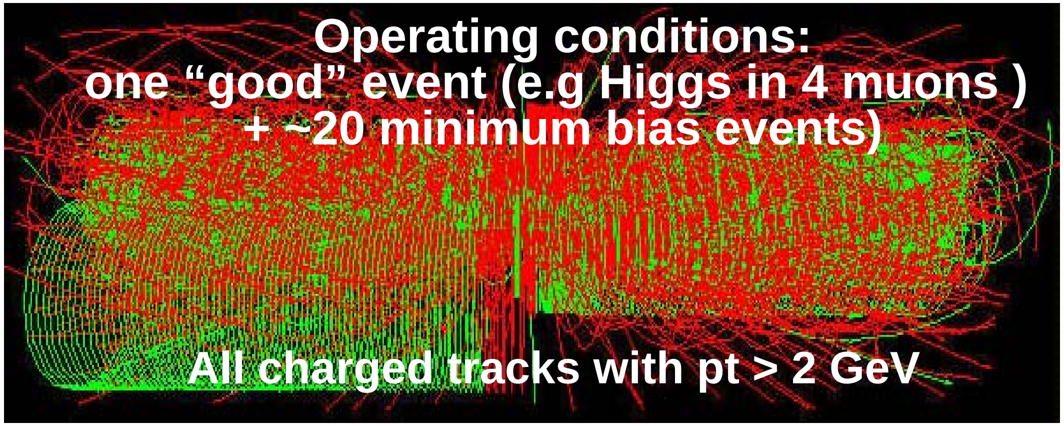
LHC has ~3600 bunches

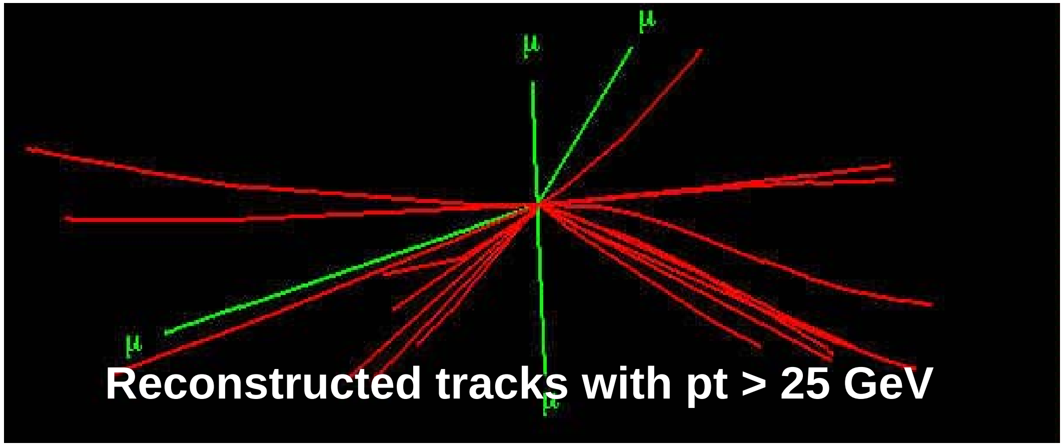
- And same length as LEP (27 km)
- Distance between bunches: 27km/3600=7.5m
- Distance between bunches in time: 7.5m/c=25ns



p-p Collisions at LHC







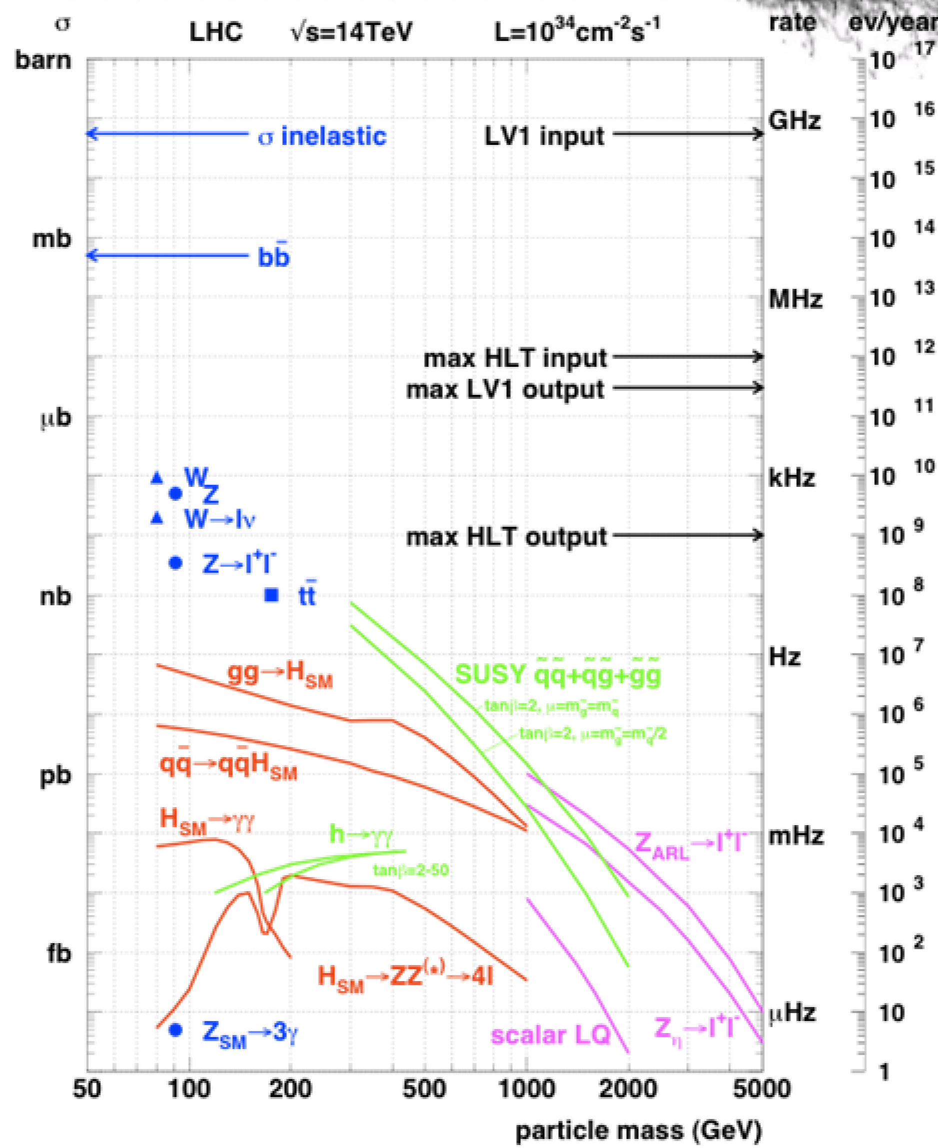
Event size:	**~1 MByte**
Processing Power:	**~X TFlop**

LHC Physics & Event Rates

At design $L = 10^{34} cm^{-2} s^{-1}$
- 23 pp events/25 ns xing
  - ~ 1 GHz input rate
  - "Good" events contain ~ 20 bkg. events
- 1 kHz W events
- 10 Hz top events
- < 10^4 detectable Higgs decays/year

Can store ~ 300 Hz events

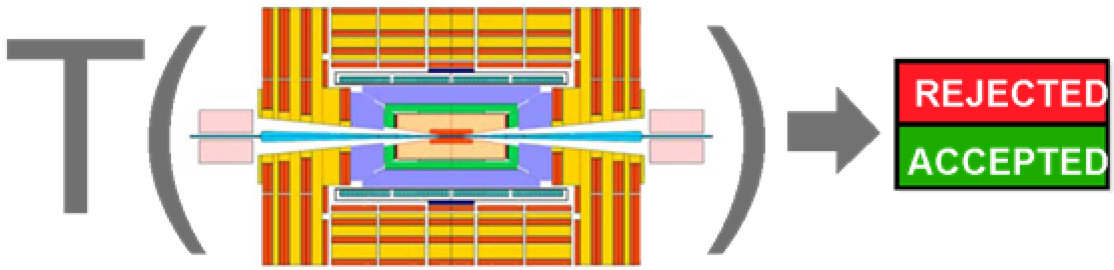
Select in stages
- Level-1 Triggers
  - 1 GHz to 100 kHz
- High Level Triggers
  - 100 kHz to 300 Hz



Triggering

- **Task: inspect detector information and provide a first decision on whether to keep the event or throw it out**

The trigger is a function of :



Event data & Apparatus
Physics channels & Parameters

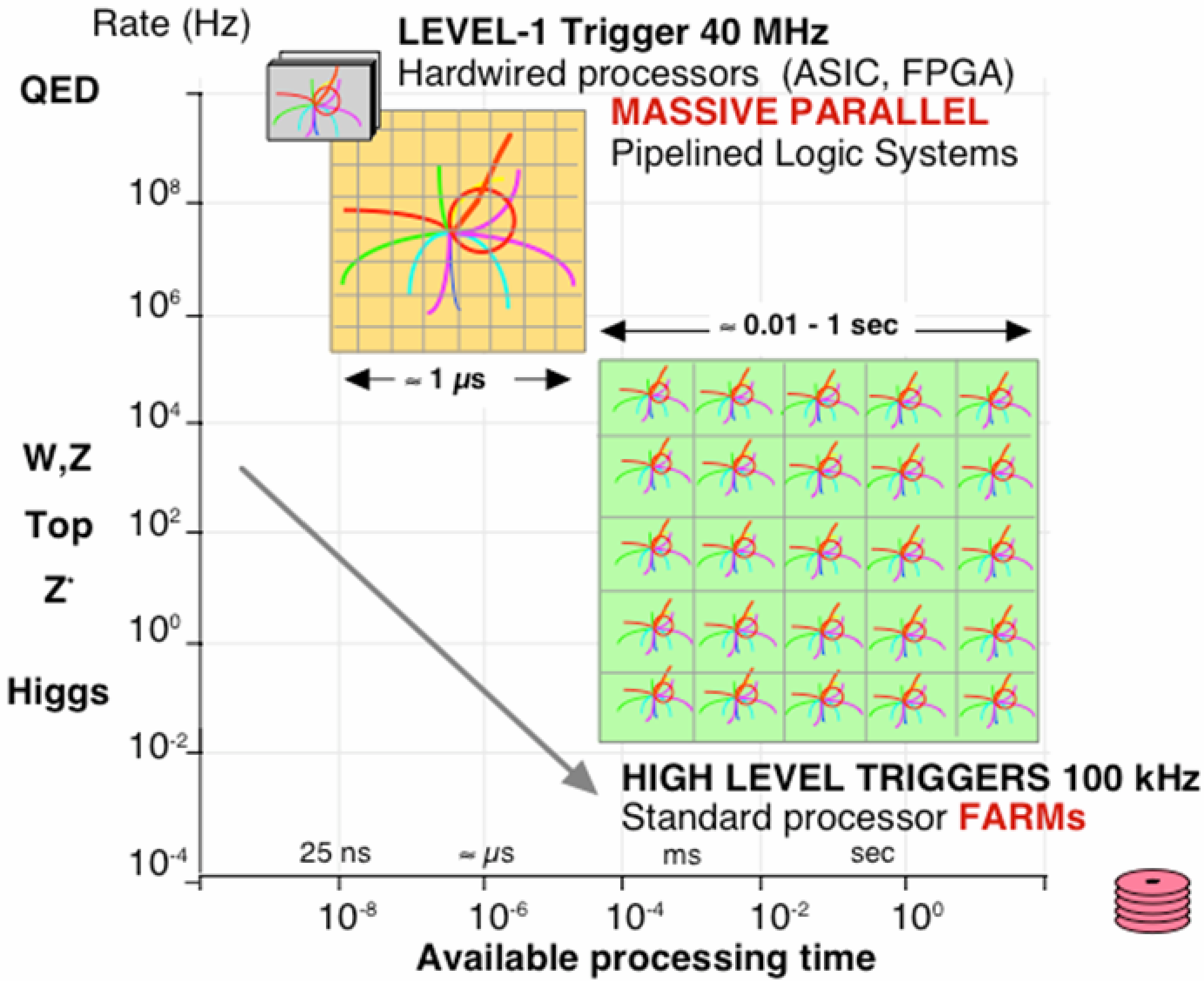
- **Detector data not (all) promptly available**
- **Selection function highly complex**

⇒T(...) is evaluated by successive approximations, the

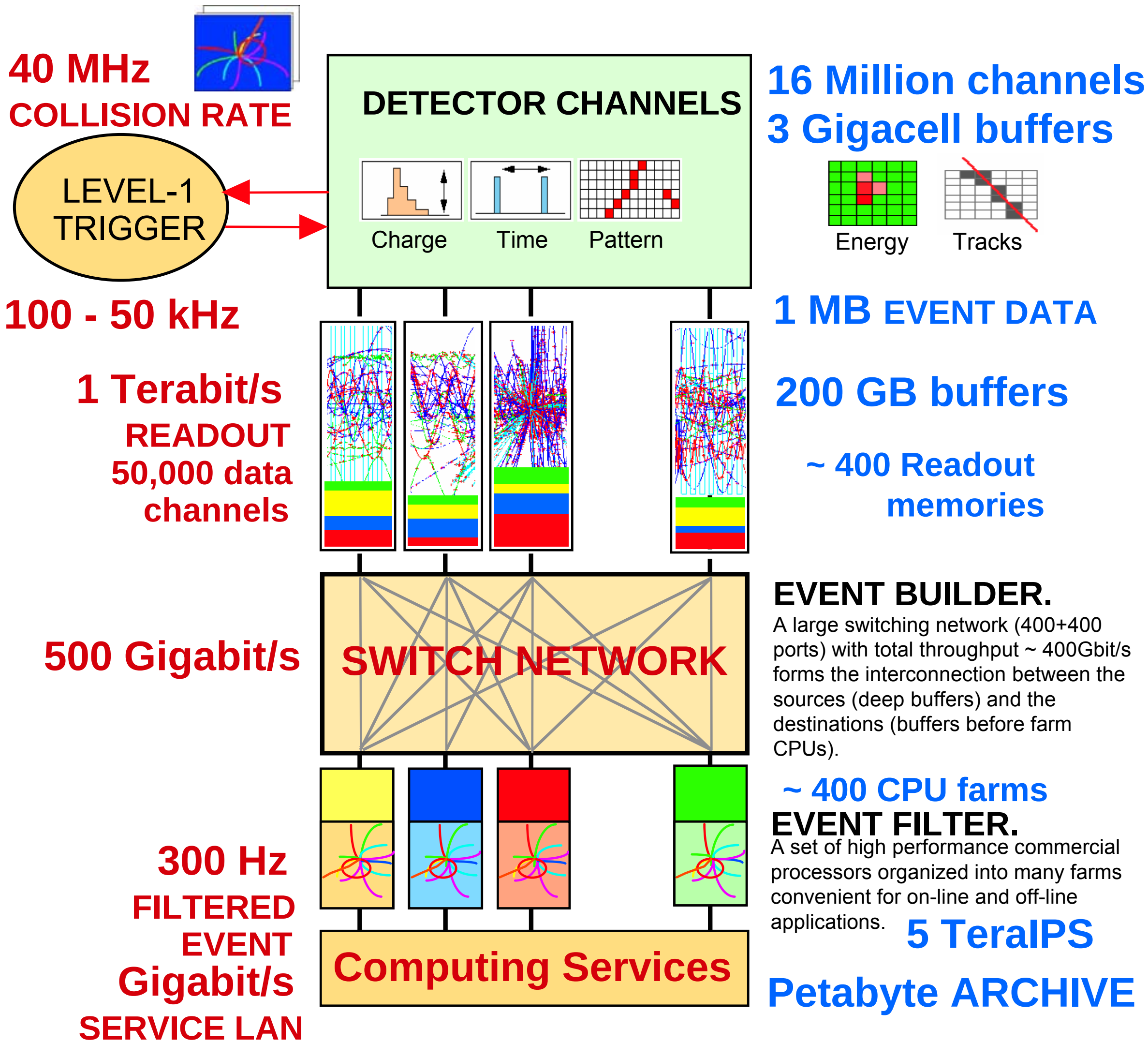
TRIGGER LEVELS

(possibly with zero dead time)

Processing LHC Data



LHC Trigger & DAQ Challenges



Challenges:

1 GHz of Input Interactions

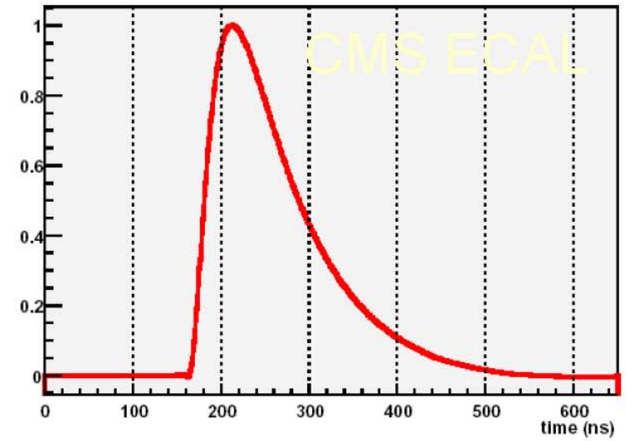
Beam-crossing every 25 ns with ~ 23 interactions produces over 1 MB of data

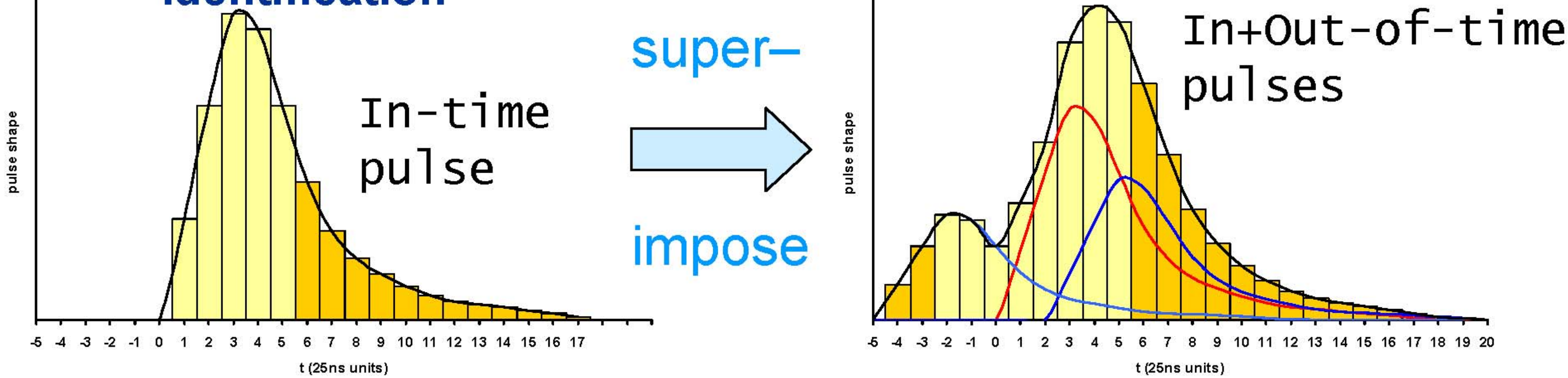
Archival Storage at about 300 Hz of 1 MB events

Challenges: Pile-up

- "In-time" pile-up: particles from the same crossing but from a different pp interaction

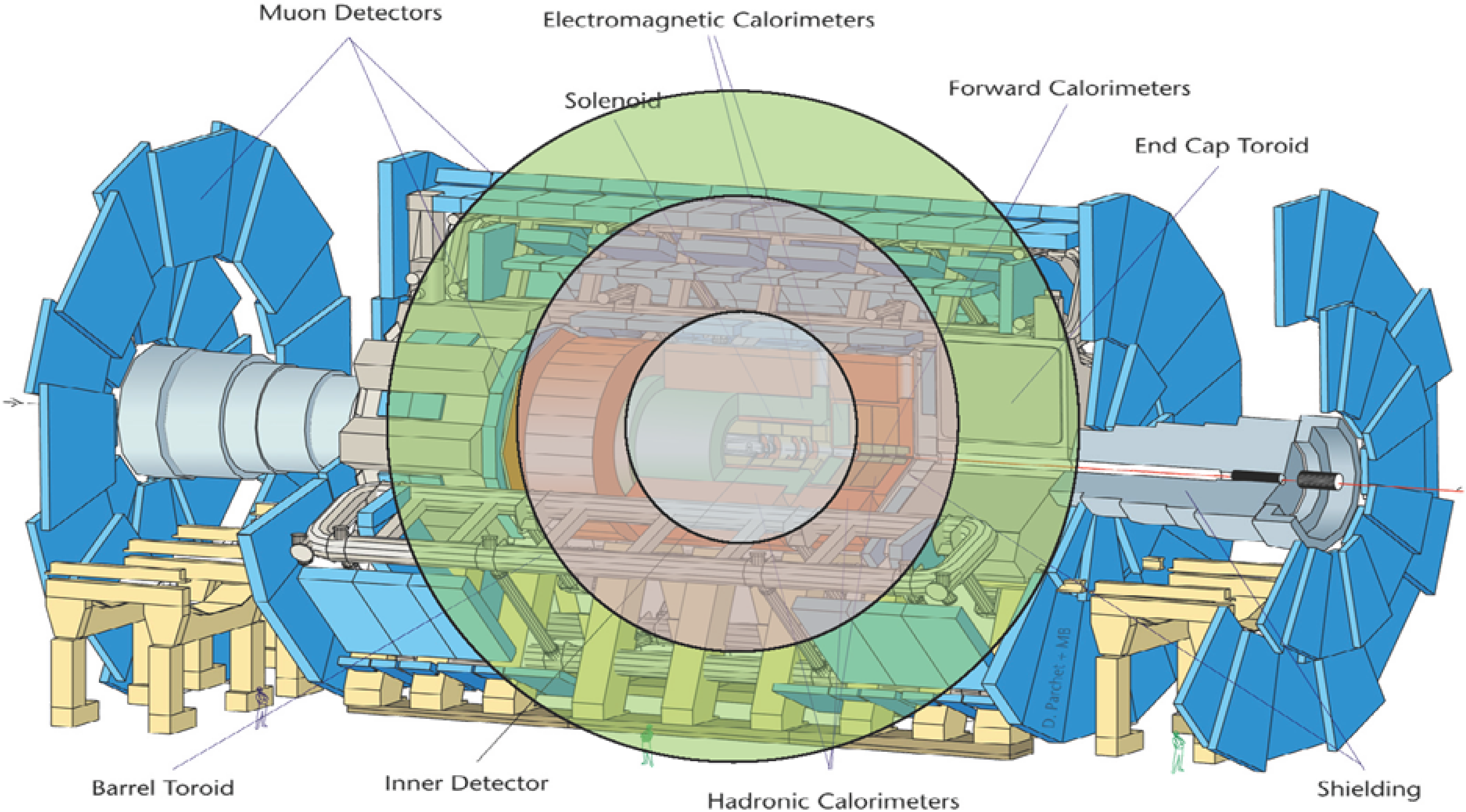
- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"



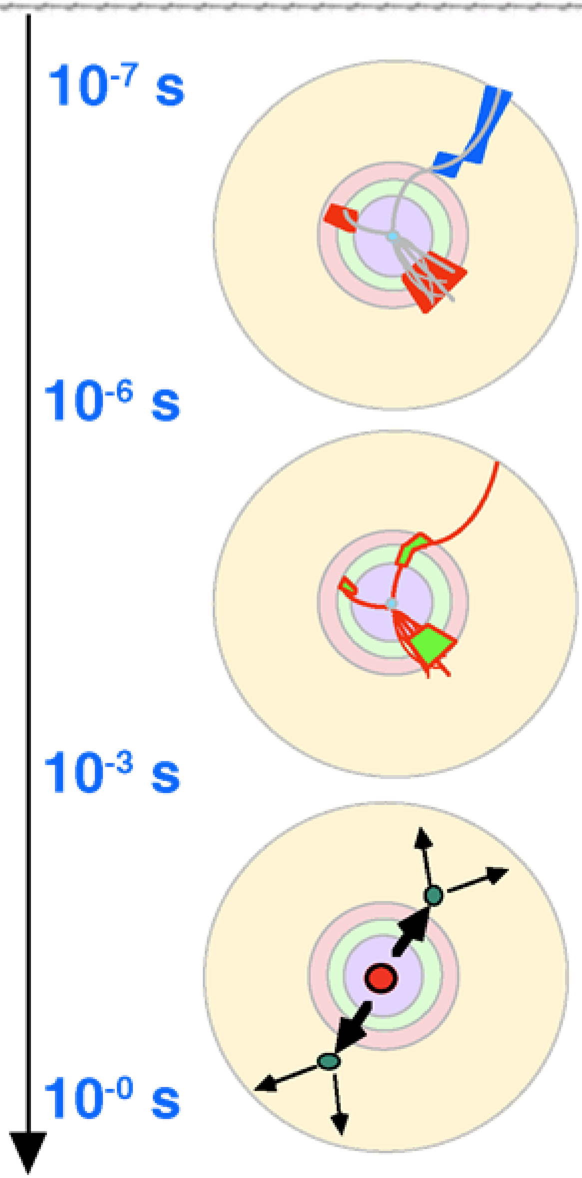


Challenges: Time of Flight

c = 30 cm/ns → in 25 ns, s = 7.5 m



LHC Trigger Levels



Collision rate 10^9 Hz

Channel data sampling at 40 MHz

Level-1 selected events 10^5 Hz

Particle identification (High p_T e, μ, jets, missing E_T)

- Local pattern recognition
- Energy evaluation on prompt macro-granular information

Level-2 selected events 10^3 Hz

Clean particle signature (Z, W, ..)

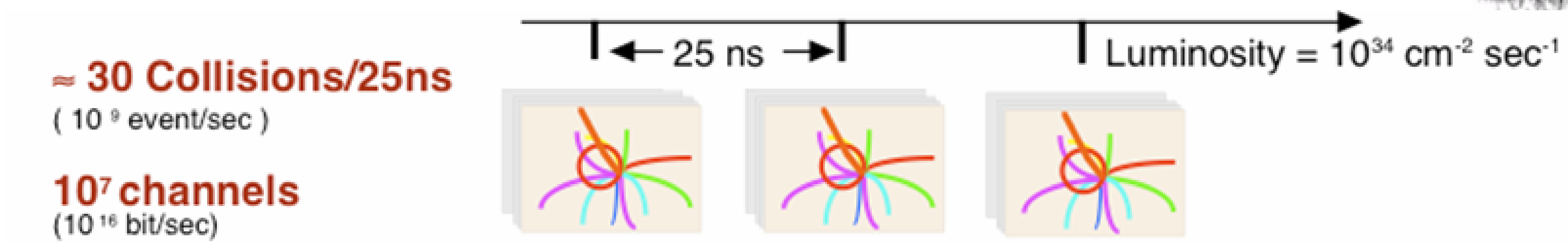
- Finer granularity precise measurement
- Kinematics. effective mass cuts and event topology
- Track reconstruction and detector matching

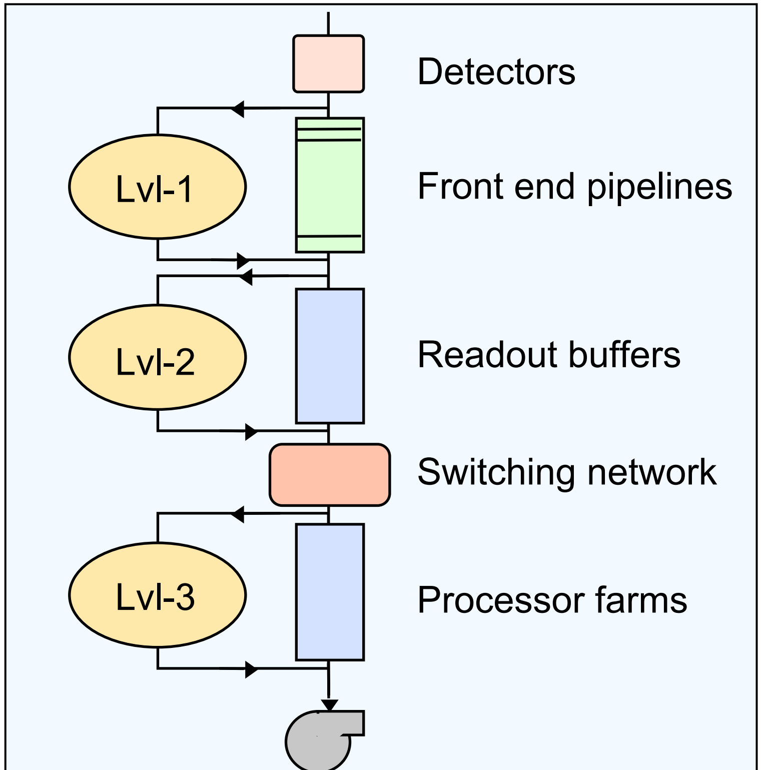
Level-3 events to tape 100- 300 Hz

Physics process identification

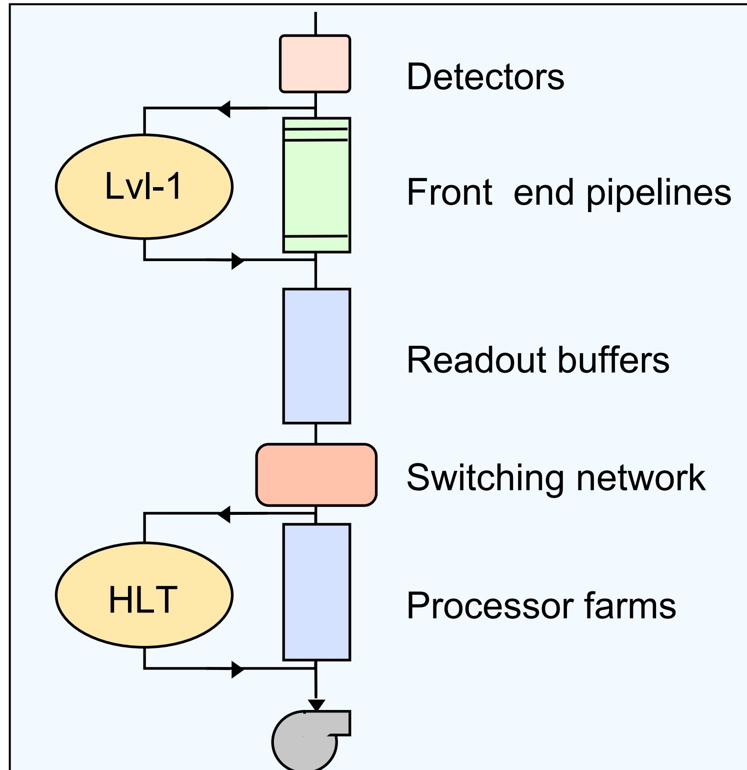
- Event reconstruction and analysis

ATLAS & CMS
Trigger & Readout Structure





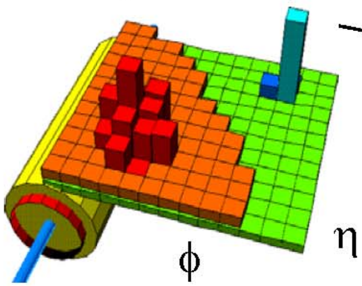
ATLAS: 3 physical levels



CMS: 2 physical levels

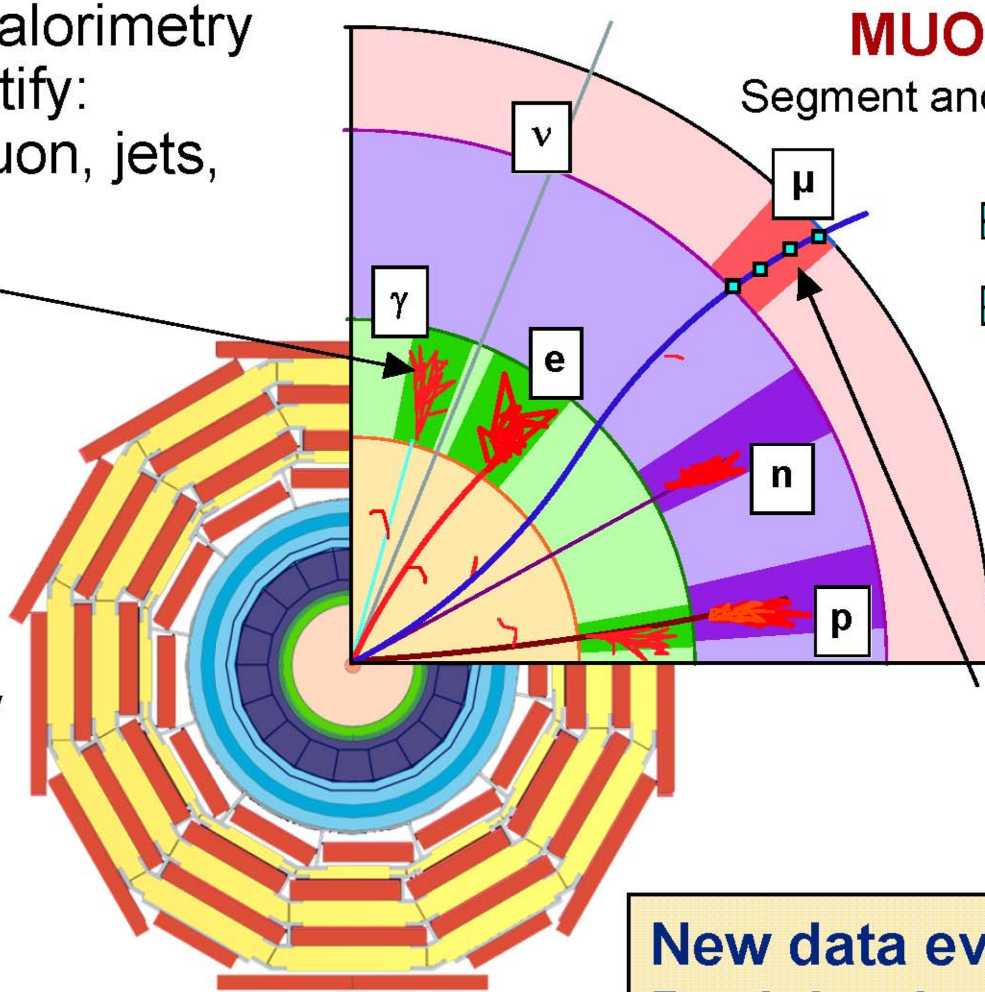
ATLAS & CMS
Trigger Data

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T



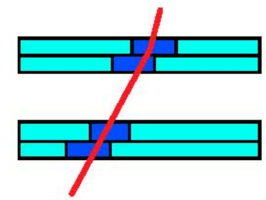
CALORIMETERs

Cluster finding and energy deposition evaluation



MUON System

Segment and track finding

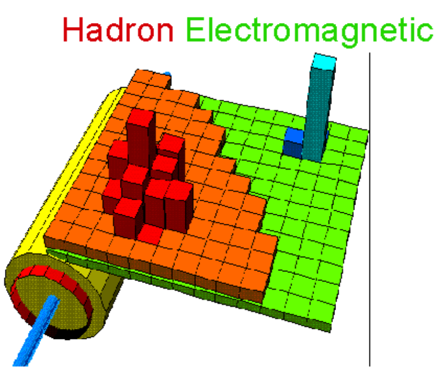


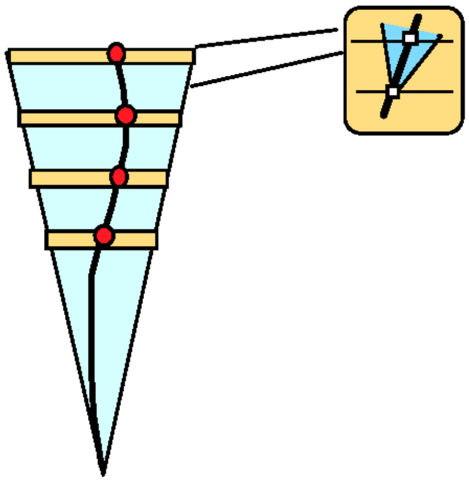
New data every 25 ns
Decision latency ~ μs

ATLAS & CMS Level 1: Only Calorimeter & Muon

High Occupancy in high granularity tracking detectors

- **Pattern recognition much faster/easier**

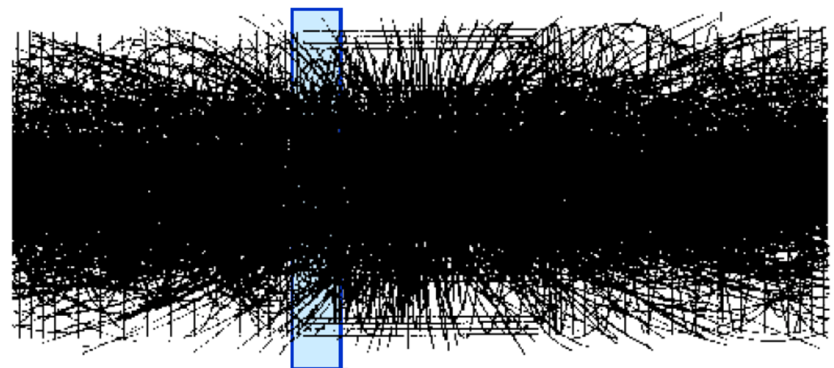




Simple Algorithms
mainly logical sums & comparators

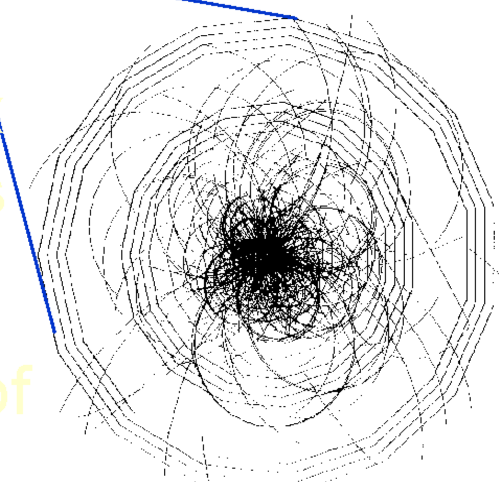
Small amounts of data
~O(7000) towers in parallel

- **Compare to tracker info**



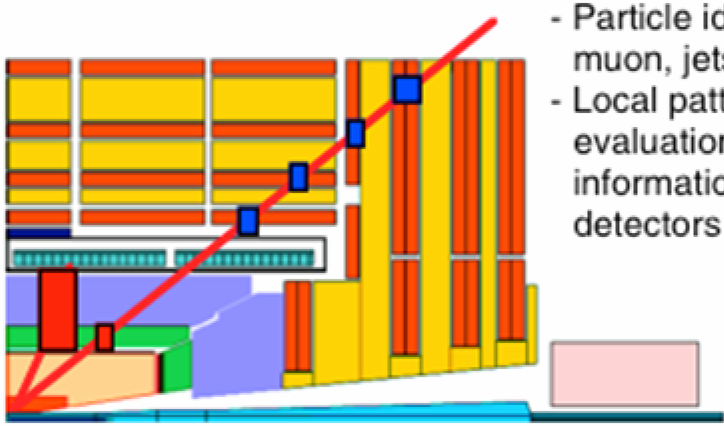
Complex Algorithms

Huge amounts of data



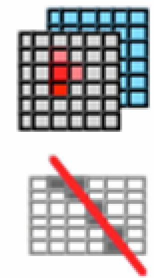
CMS Trigger Levels

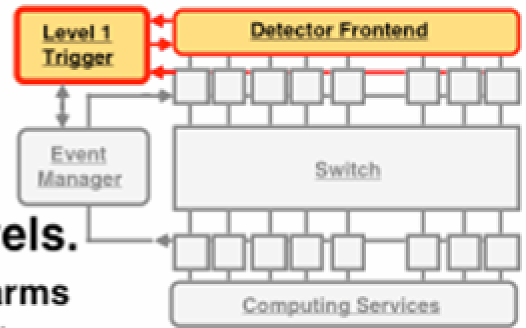
40 MHz



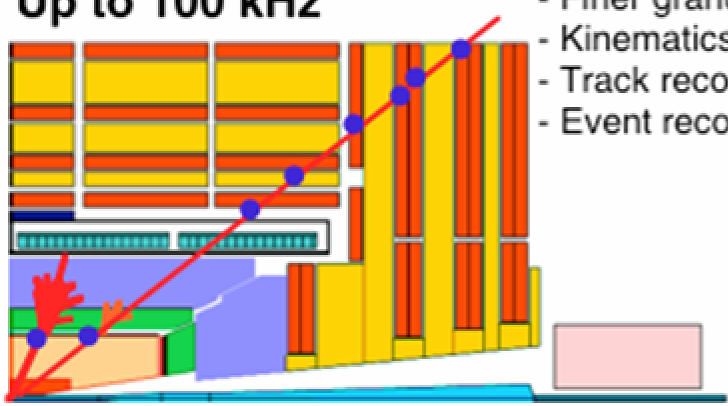
Level-1. Specialized processors

- Particle identification: high p_T electron, muon, jets, missing E_T
- Local pattern recognition and energy evaluation on prompt macro-granular information from calorimeter and muon detectors





Up to 100 kHz

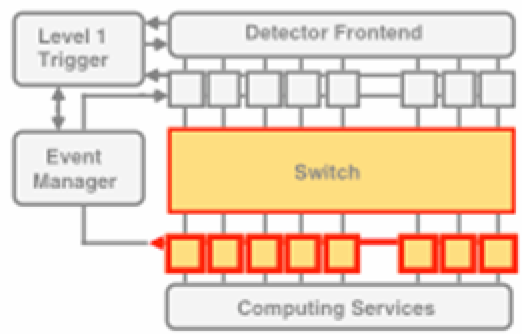


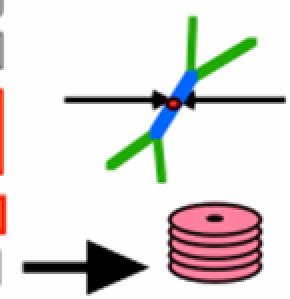
High trigger levels.

Network and CPU farms

- Clean particle signature
- Finer granularity precise measurement
- Kinematics. effective mass cuts & event topology
- Track reconstruction and detector matching
- Event reconstruction and analysis

≈ 100 Hz





ATLAS Level-1 Trigger

The idea behind the system:

"... cope with higher rates and adapt to new insights from the first years of LHC physics."

Fast, integrated & configurable electronics

Level-1:

Fast custom electronics (ASICs & FPGA)

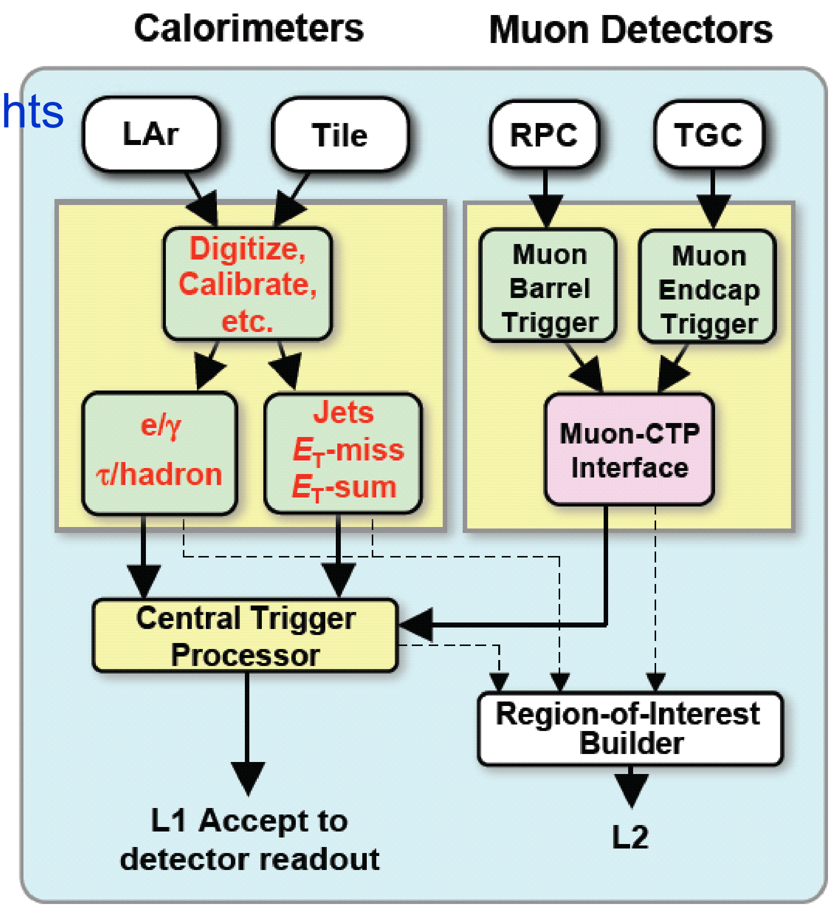
- ➔ synchronous
- ➔ algorithms implemented in firmware
- ➔ max. Latency: ***2,5 μs***
  - including transmission delays

Calorimeter and Muon detectors

- reduced granularity (7000 towers + 280 sectors)

Input rate: ***40 MHz***

Max. L1 accept rate: ***<100 kHz***



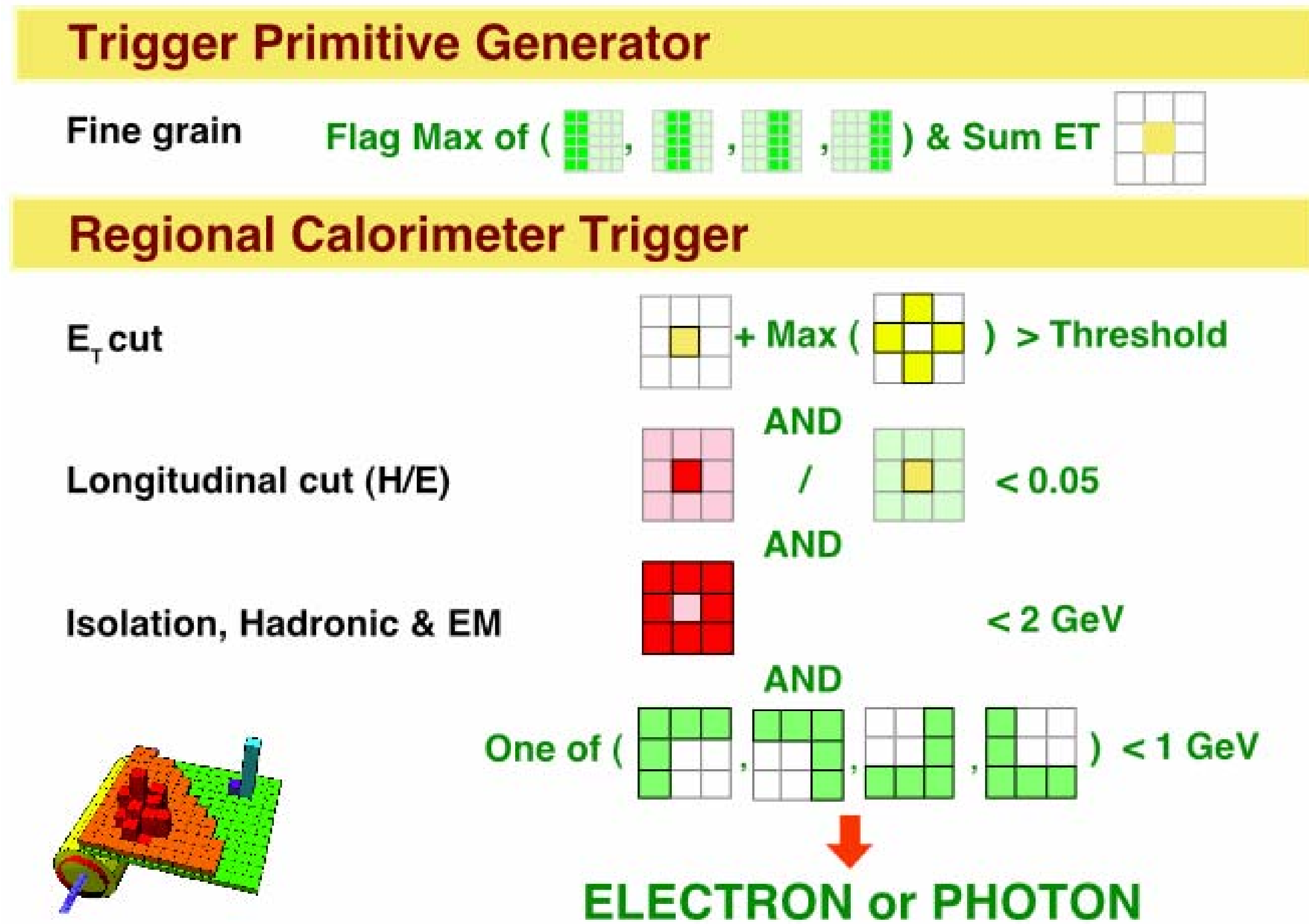
Trigger objects:

High p_T electrons/photons, tau, muons, Jets, EtSum, Etmiss and EtJet

handling high multiplicities and high-ET objects (beyond SM)

Higgs measurements – triggering on W/Z decays

CMS Electron/Photon Algorithm

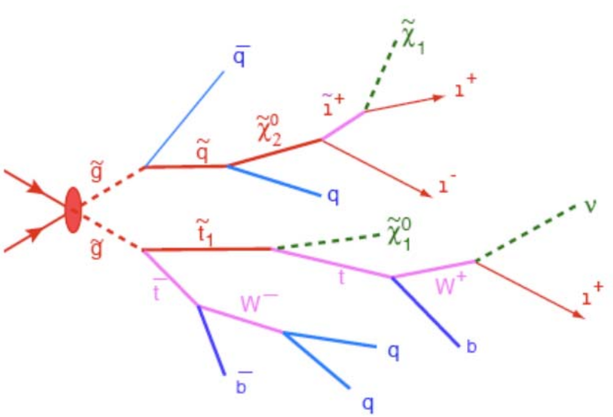


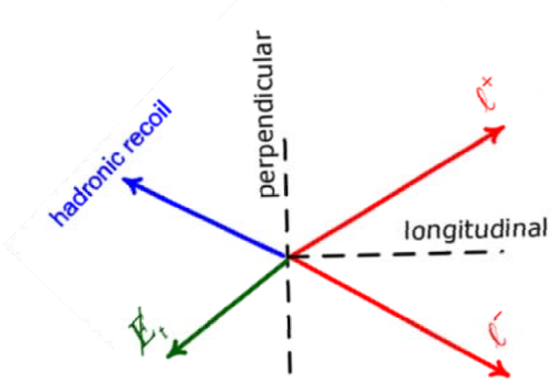
Missing E_T

Missing E_T (MET) — clear signature of new physics originated from many weakly interacting exotic particles in the final state.

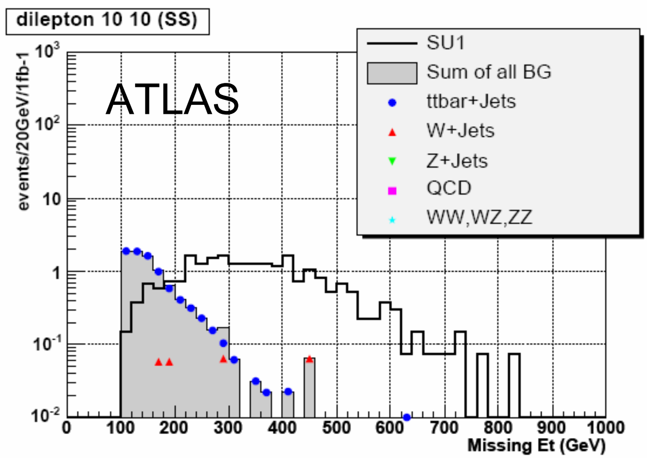
Example: SUSY ➔ undetectable LSP (lightest SUSY particle) in the final state

gluino pair-production … in the detector





MET measured in the calo + muon system



MET distribution for events selected requiring two same sign leptons

Missing E_T reconstruction

- Missing E_T is based on the calorimeter information and defined as a 2D-vector sum of transverse energy deposits in the calorimeter cells:

$$\vec{\not{E}}_T = -\sum_n (E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) = -\not{E}_x \hat{\mathbf{i}} - \not{E}_y \hat{\mathbf{j}}$$

- In case of muons in the event, it receives an additional correction:

$$\vec{\not{E}}_T = -\sum_{i=1}^{\text{towers}} \vec{E}_T^i - \sum^{\text{muons}} \vec{p}_T^{\,\mu} + \sum_{i=1}^{\substack{\text{deposit}\\ \text{towers}}} \vec{E}_T^i .$$

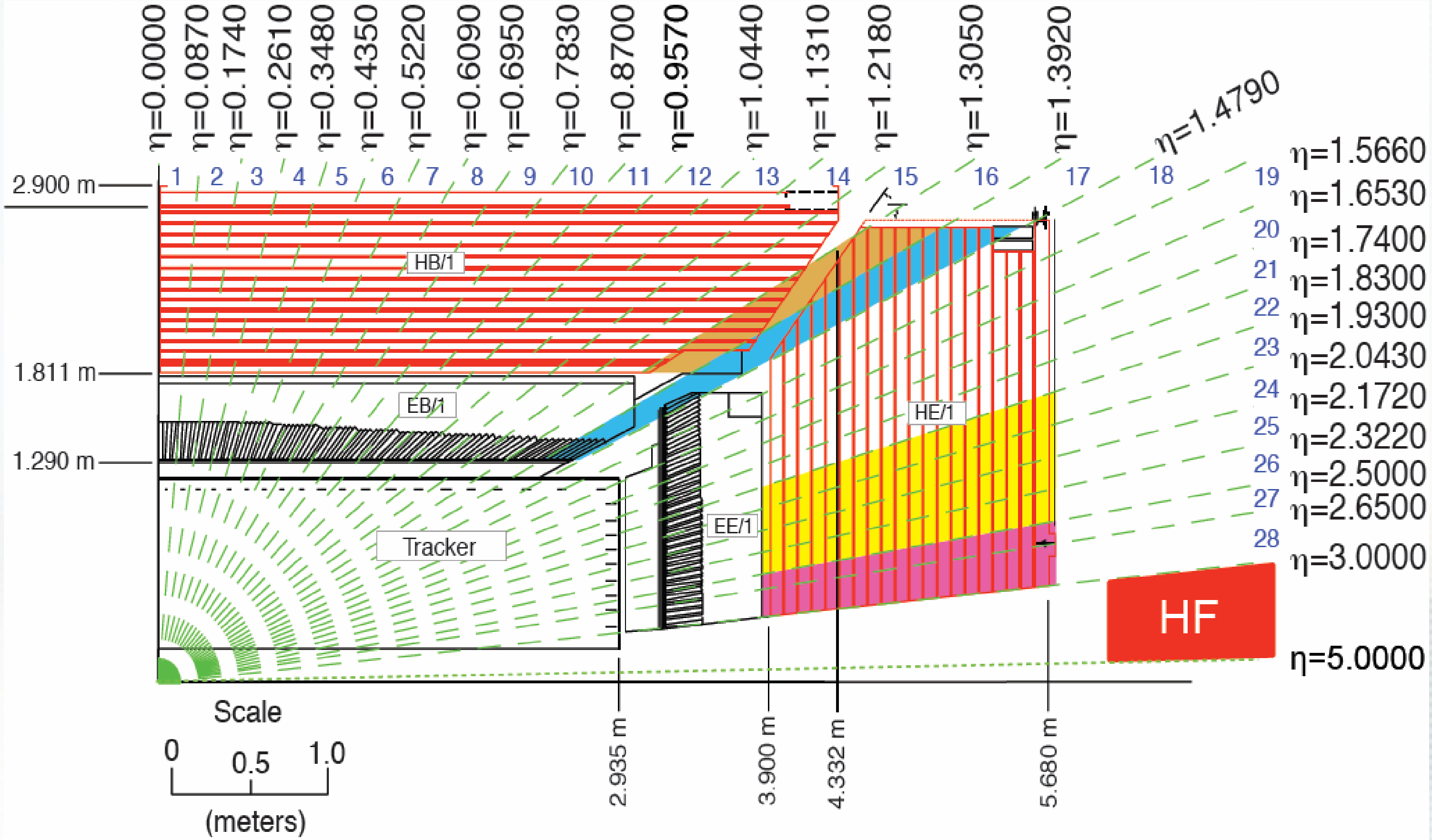
- ME_T resolution in QCD events depends on total transverse energy deposit in the calorimeter and is often parameterized as a function of scalar E_T sum over the calorimeter cells, or S_T:

$$\sigma(\not{E}_T) = A \oplus B\sqrt{\Sigma E_T - D} \oplus C(\Sigma E_T - D)$$

Noise (A) Stochastic (B) Constant (C) Offset (D)

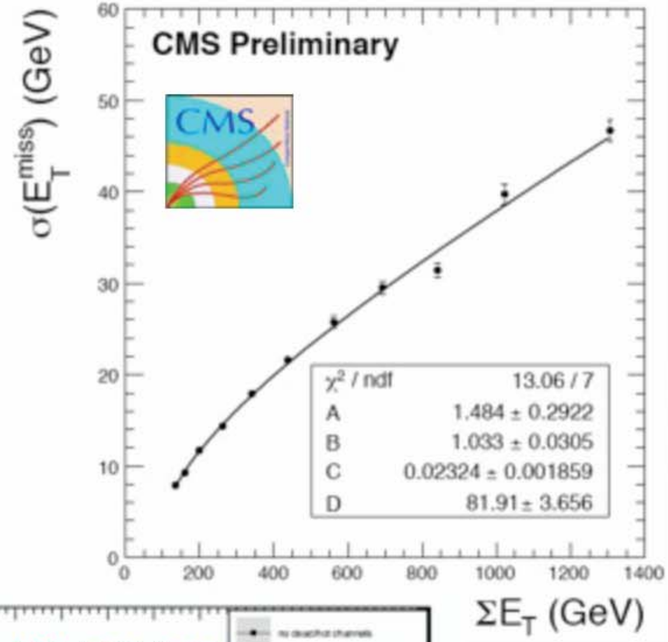
Detector hermeticity

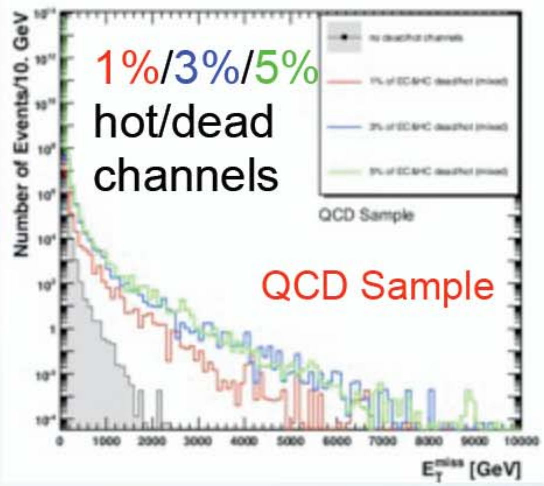
- CMS calorimeter coverage:
  - Central region: |η| < 3.0
  - Forward region (HF): 3.0 <|η| < 5.0



Missing E_T at CMS

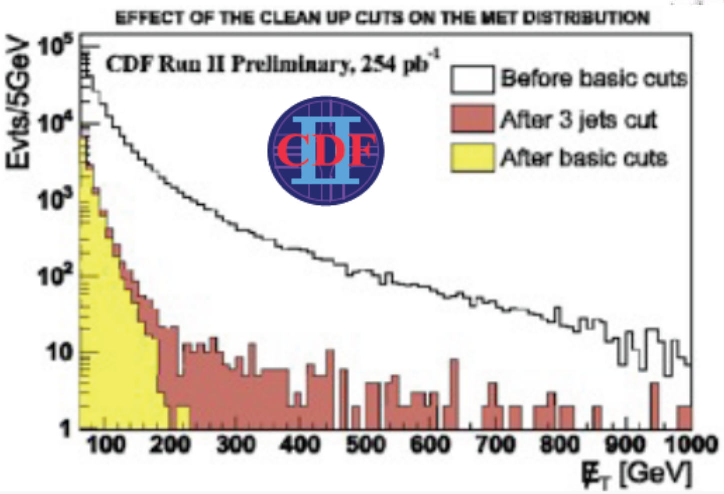
- Parameters:
  - A = 1.48 GeV
  - B = 1.03 GeV$^{1/2}$
  - C = 0.023 (dominates at large S_T)
  - D = 82 GeV
- Apart from the resolution an important characteristic is the non-Gaussian tails
- Very hard to simulate; will have to wait for real data to see how large the effect is
  - A few special cases have been looked at already, e.g. the effect of hot/dead channels

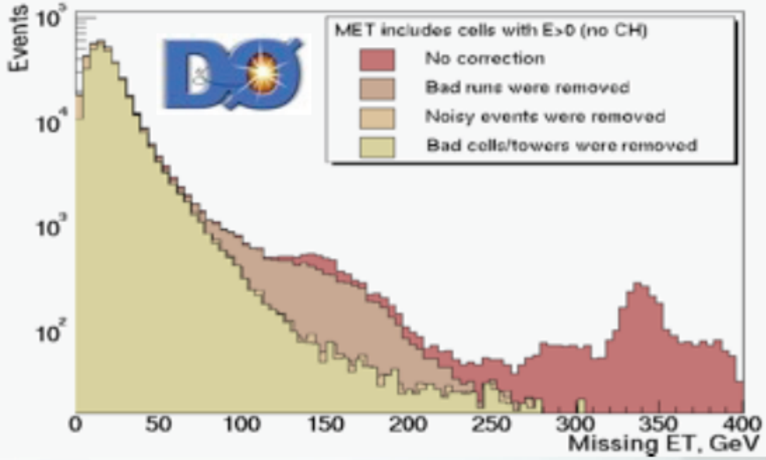




Missing E_T is tough

- Fake ME_T appears naturally in multijet events, which have enormous rate at the LHC
- Jets tend to fluctuate wildly:
  - Large shower fluctuation
  - Fluctuations in the e/h energy ratio
  - Non-linear calorimeter response
  - Non-compensation (i.e., $e/h \neq 1$)
- Instrumental effects:
  - Dead or "hot" calorimeter cells
  - Cosmic ray bremsstrahlung
  - Poorly instrumented area of the detector
- Consequently, it will be a challenge to use in early LHC running
- Nevertheless, ME_T is one of the most prominent signatures for new physics and thus must be pursued





- Raw ME_T spectrum at the Tevatron and that after thorough clean-up

Summary

Calorimeter: only detector component capable of providing fast topological event selection

- @ LHC hardware trigger decision in ~1 μs reduced event rate from 40MHz to 1-0.1 MHz
- Fast topological algorithms provide list of trigger objects:
  High p_T electrons/photons, tau, muons, Jets
- in addition to integral quantities:
  E_TSum, $E_T$miss and E_TJet
- Extended use of missing E_T to select new physics

Calorimeter for Particle Flow

Back to calorimeters for calorimetry,
i.e. to provide the best energy resolution for the detected particles

We saw that:
jet energy resolution is worse than or at most as good as hadron resolution
➔for the precision physics planned for the next machines we need more

Next ➔ how to improve jet energy resolution to match the requirement of the new physics expected in the next 30-50 years

➔ Need to “get rid of” fluctuations
Two approaches:
- minimize the influence of the calorimeter ➔ use combination of all detectors
- measure the shower components in each event ➔ access the source of fluctuations

The first idea: Energy flow

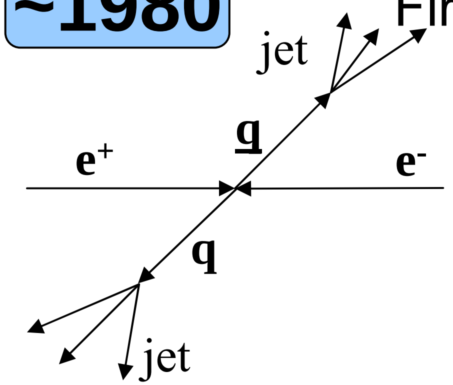
Idea (early 90ies):

- Combine energy measurement from the calorimeter with the momentum measurement from the tracking
- To not double count the energy: energy deposited in the calorimeter by the tracks has to be masked

- First algorithms developed by Aleph: clean e+/e- environment
- Algorithms also developed by H1 for inclusive measurements, successfully adapted by CDF:
  - extrapolate track to the inner surface of the calorimeter and apply a cone or a cylindrical mask to the calorimeter cells behind the track
  - maximize between the energy in the mask and the track momentum

Energy flow history

~1980

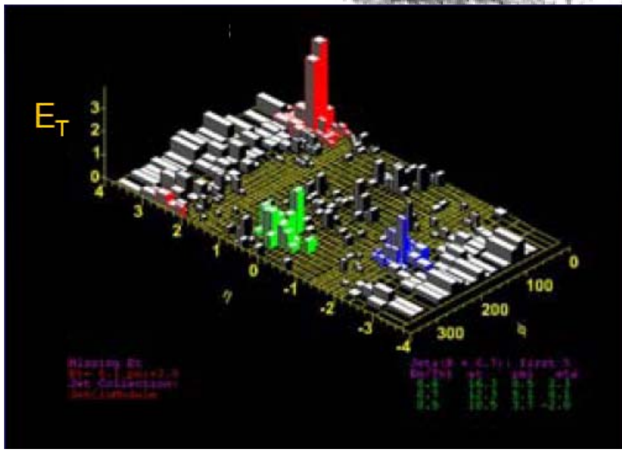


First observation of quark Jets

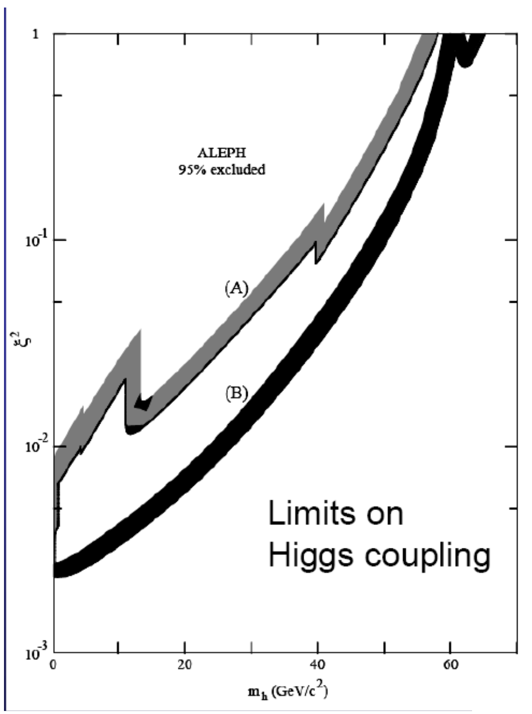
UA1, UA2 @ SppS, CERN
JADE @ PETRA collider, DESY

Traditional Jet measurement:
use the calorimeter alone

→ example of CDF life event



Discovery of new physics requires higher resolution



First application of Energy Flow Algorithm

ALEPH detector searching for Higgs

1990

Use tracker information to improve jet energy resolution

Particle Flow Algorithms

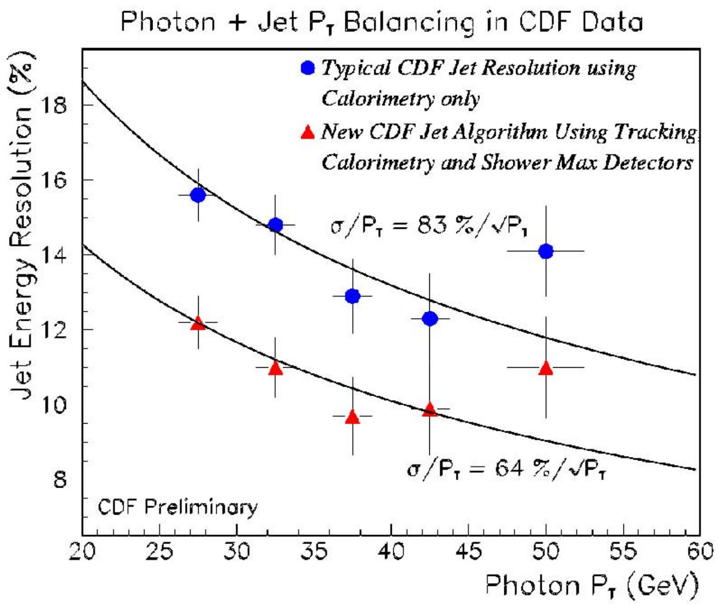
Does the method work ?

Test on existing detectors

ALEPH, CDF, ZEUS, …

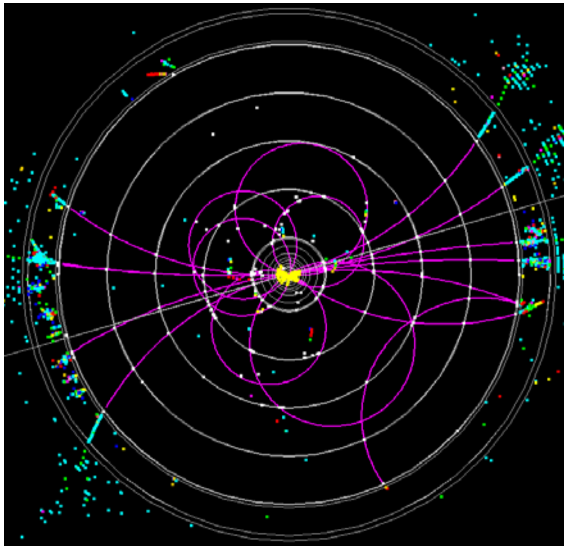
→Significantly improved resolution

YES ! But that is not enough …



Goal of the Linear Collider

Design a detector optimized for Particle Flow application



Physics motivation

ILC / CLIC

- *Need to measure 4-vectors of jets with excellent precision.*
  Physics program relies heavily on final states with (several) bosons: W,Z,H
  Necessary to reconstruct W,Z through their hadronic decay modes.

  Hadronic energy resolution very important for this multi-jet spectroscopy.

- *The same argument can also be made for SLHC.*
  For example, study of multi-boson couplings is statistics limited
  if one only would consider leptonically decaying W,Z.

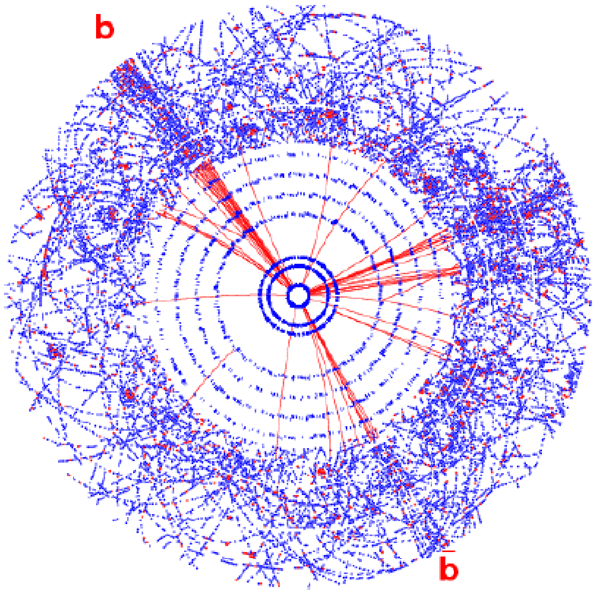
  → *SLHC physics program might benefit from improved hadron calorimetry*

- *The issue of* $H^{o} \rightarrow \gamma\gamma$ *will presumably be settled during LHC running.*
  Therefore, it is conceivable to replace the calorimeter system by one
  with strongly improved hadronic performance for SLHC era.

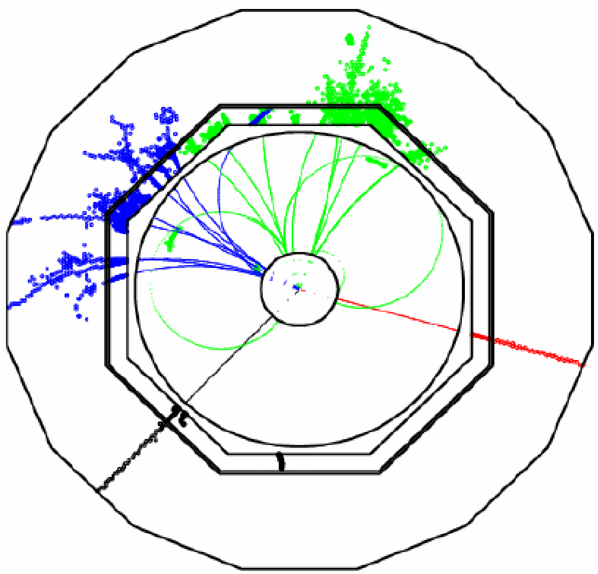
Physics motivation II

★ Electron-positron colliders provide clean environment for precision physics

The LHC $pp \to H + X$



The ILC $e^+e^- \to HZ$



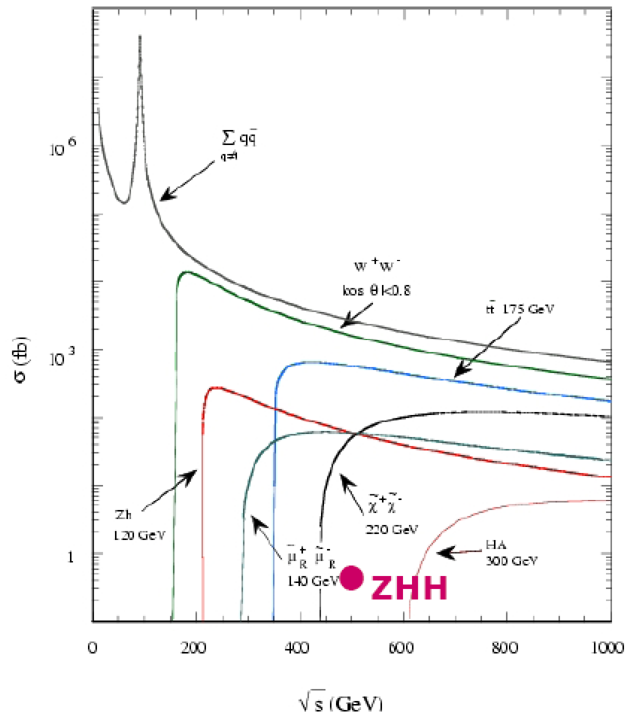
★ At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see $H \to b\bar{b}$ and $Z \to \mu^+\mu^-$ and nothing else…

ILC physics & calorimetry

ILC PHYSICS:

Precision Studies/Measurements

- ★ Higgs sector
- ★ SUSY particle spectrum (if there)
- ★ SM particles (e.g. W-boson, top)
- ★ and much more...



Physics characterised by:

★High Multiplicity final states
often 6/8 jets

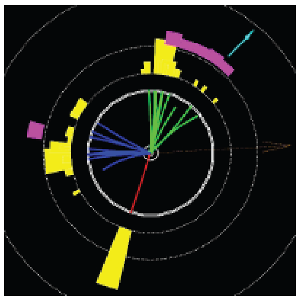
★Small cross-sections
e.g. $\sigma(e^+e^- \rightarrow ZHH) = 0.3$ fb

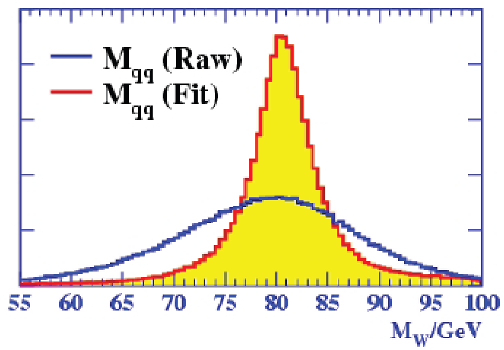
★Require High Luminosity – i.e. the ILC
★Detector optimized for precision measurements in difficult multi-jet environment

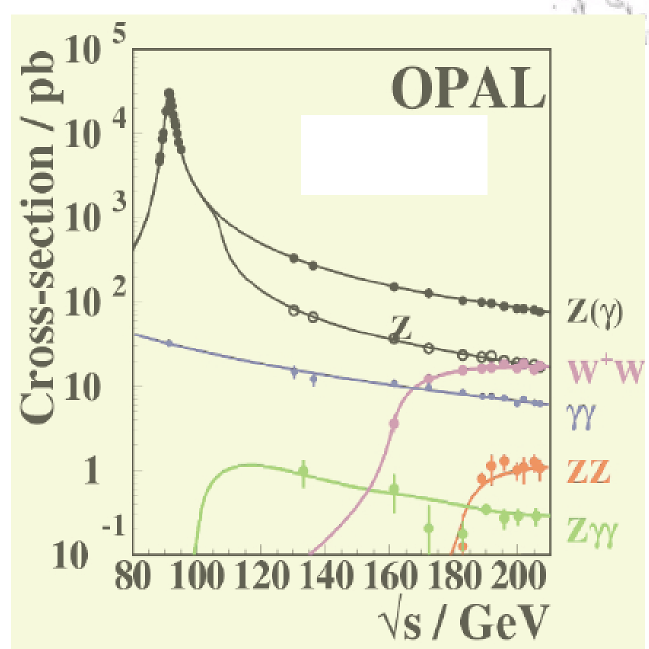
Compare with LEP

★ $e^+e^- \to Z$ and $e^+e^- \to W^+W^-$ dominate
backgrounds not too problematic

★ Kinematic fits used for mass reco.
good jet energy resolution not vital







At the ILC:

★ Backgrounds dominate 'interesting' physics

★ Kinematic fitting much less useful: Beamsstrahlung + final states with > 1 neutrino

- Physics performance depends critically on the detector performance (not true at LEP)
- Places stringent requirements on the ILC detector

Calorimetry at ILC

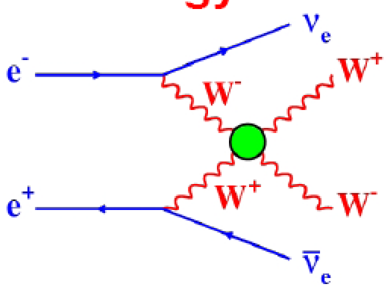
Jet energy resolution:

THIS IS HARD !

Best at LEP (ALEPH):
$\sigma_E/E = 0.6(1+|\cos\theta_{Jet}|)/\sqrt{E(GeV)}$

ILC GOAL:
$\sigma_E/E = 0.3/\sqrt{E(GeV)}$

★ **Jet energy resolution directly impacts physics sensitivity**

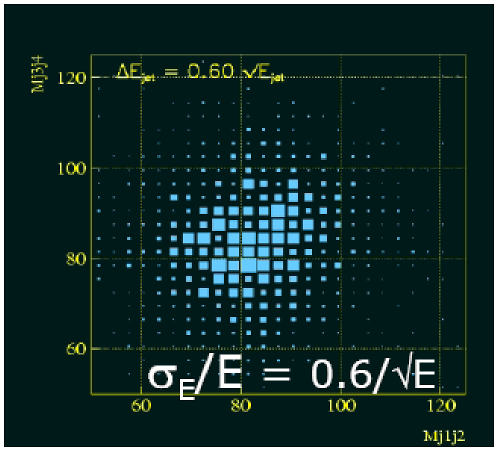


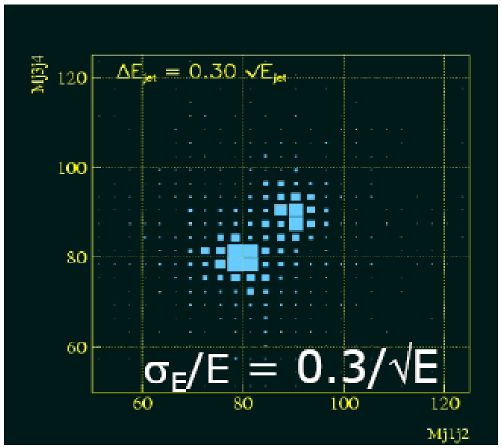
Often-quoted Example:

If the Higgs mechanism is not responsible for EWSB then QGC processes important

$e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$, $e^+e^- \rightarrow \nu\nu ZZ \rightarrow \nu\nu qqqq$

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states





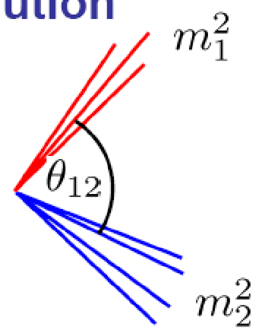
★ **EQUALLY applicable to any final states where want to separate $W \rightarrow qq$ and $Z \rightarrow qq$!**

Calorimetry goal

★ Aim for jet energy resolution giving di-jet mass resolution similar to Gauge boson widths

★ For a pair of jets have:

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_{12})$$



★ For di-jet mass resolution of order $\Gamma_{W/Z}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027$$

⇨ $$\sigma_{E_j}/E_j < 3.8\%$$

+ term due to θ_{12} uncertainty

★ Assuming a single jet energy resolution of normal form

$$\sigma_E/E = \alpha(E)/\sqrt{E(\mathrm{GeV})}$$

⇨ $$\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\mathrm{GeV})}$$

⇨ $$\alpha(E_j) < 0.027\sqrt{E_{jj}(\mathrm{GeV})}$$

E_{jj}/GeV	$\alpha(E_{jj})$
100	< 27 %
200	< 38 %

★ Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

★ Want $\sigma_E/E \sim 30\%/\sqrt{E(GeV)}$

or probably more correctly $\sigma_E/E \sim 3.8\ \%$

★ Very hard (may not be possible) to achieve this with a traditional approach to calorimetry

Limited by typical HCAL resolution of $> 50\%/\sqrt{E(GeV)}$

➡ a new approach to calorimetry

Particle Flow paradigm

reconstruct every particle in the event

How?

Over energy range up to ~100 GeV

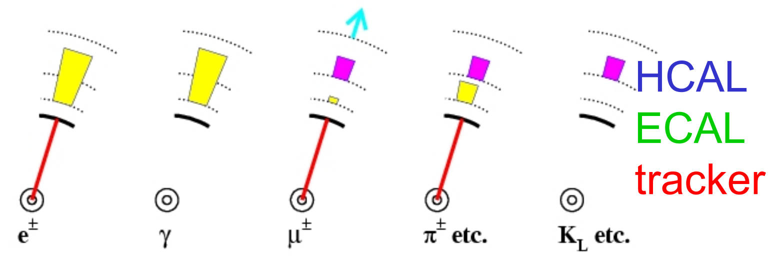
Tracker is superior to calorimeter →

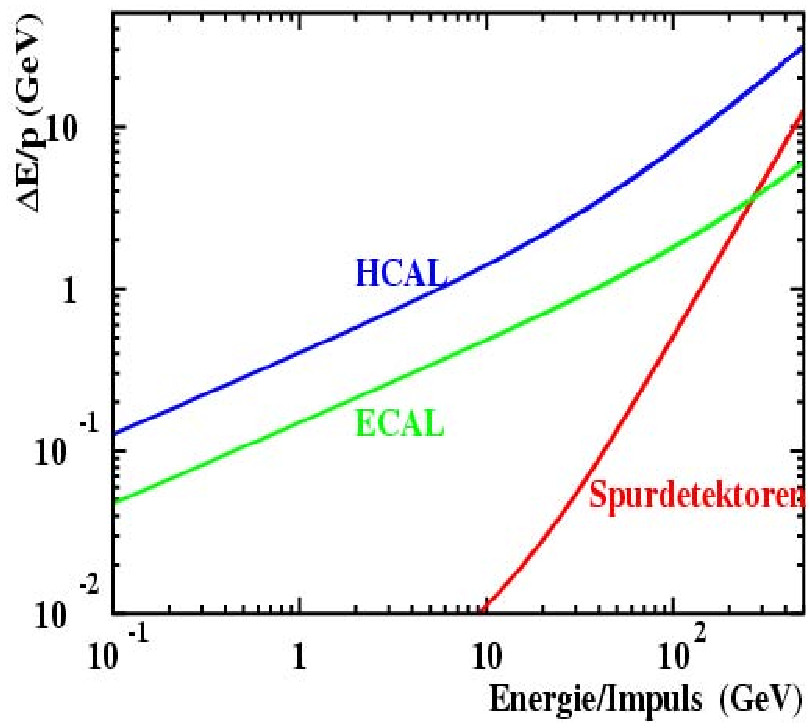
Use tracker to reconstruct charge objects, $e^{\pm}, \mu^{\pm}, h^{\pm}$ (<65%> of E jet)

Use ECAL for γ reconstruction (<25%>)

(ECAL+) HCAL for h^0 reconstruction (<10%>)

→ The "sum" gives the Jet energy

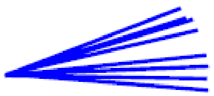




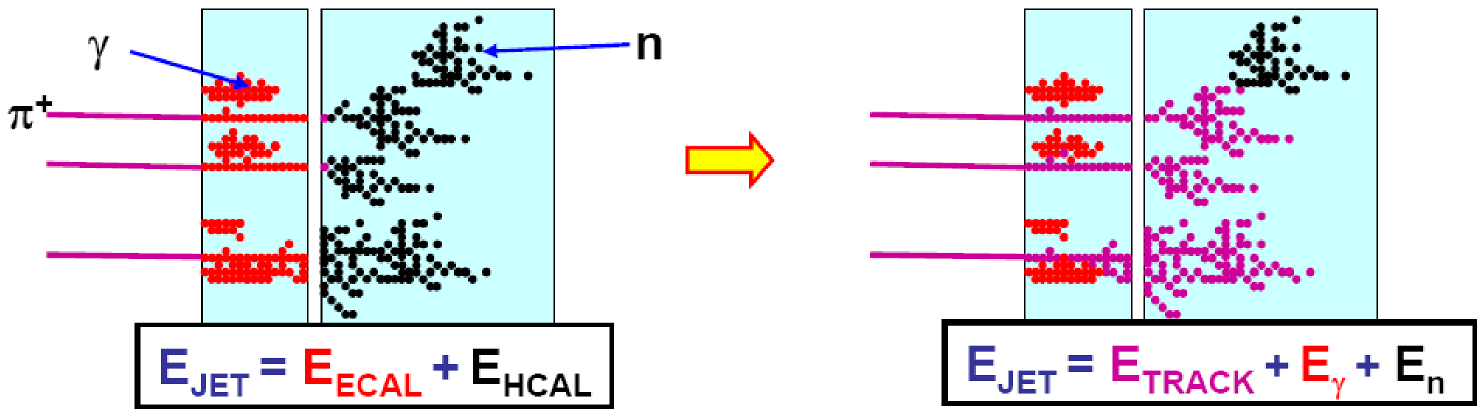
* HCAL E resolution dominates jet resolution

Particle flow paradigm II

- In a typical jet :
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)



- Traditional calorimetric approach:
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically “poor” HCAL resolution limits jet energy resolution



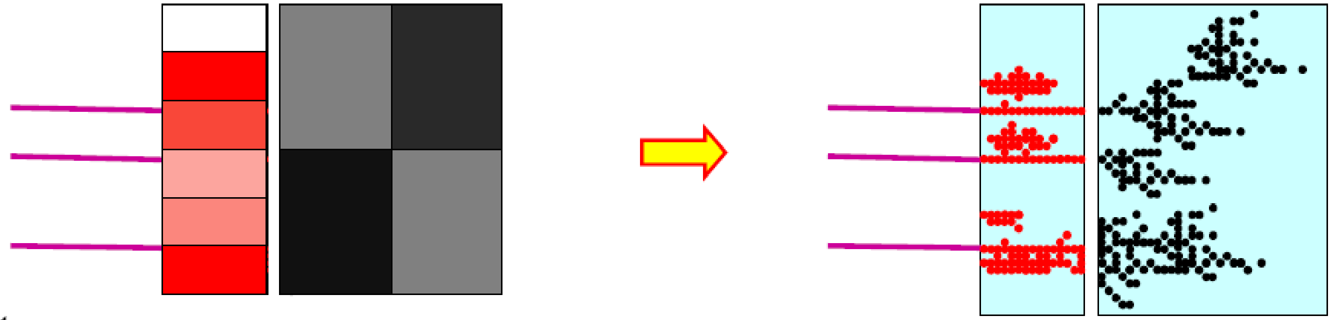
- Particle Flow Calorimetry paradigm:
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_{\mathrm{E}}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⟹ much improved resolution

Particle flow calorimetry

Hardware:

★Need to be able to resolve energy deposits from different particles

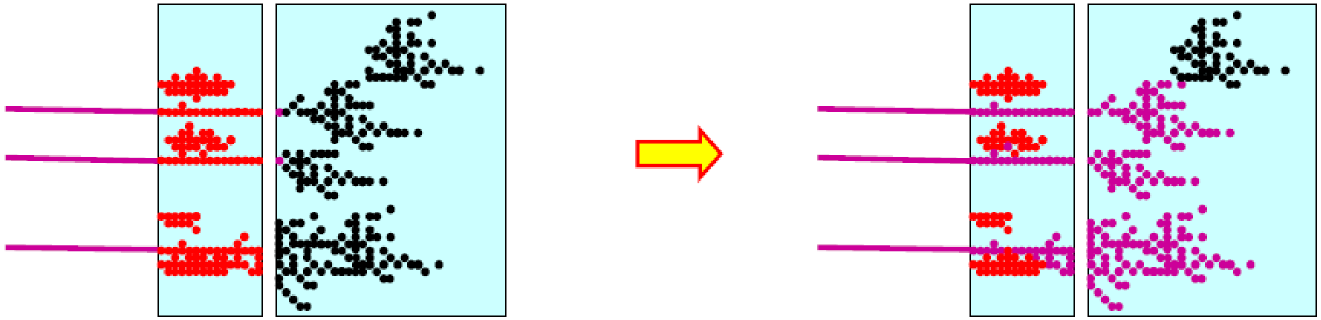
→ Highly granular detectors (as studied in CALICE)



Software:

★Need to be able to identify energy deposits from each individual particle !

→ Sophisticated reconstruction software



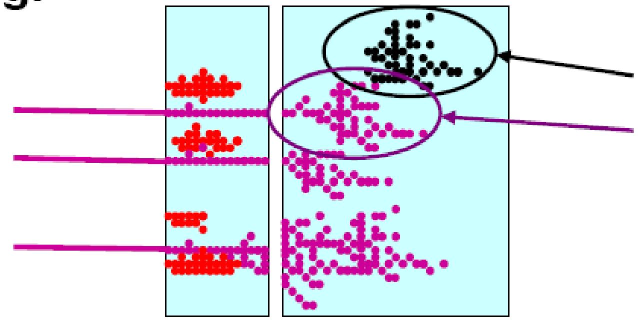
★Particle Flow Calorimetry = HARDWARE + SOFTWARE

Particle flow reconstruction (PFA)

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles

e.g.



If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

- ★ PFA performance depends on detailed reconstruction
- ★ Relatively new, still developing ideas (not just software)
- ★ Studies need to be based on a sophisticated detector simulations

Reconstruction overview

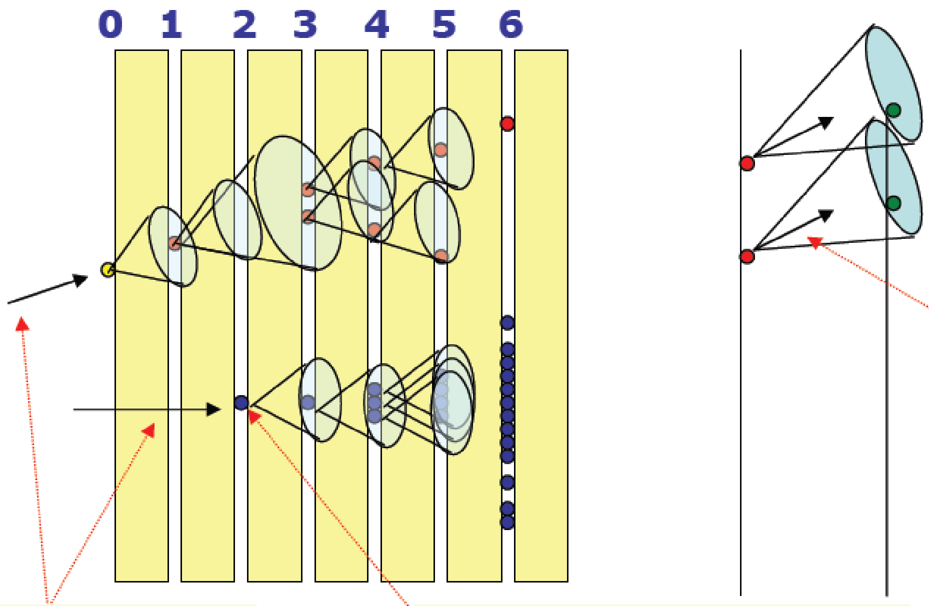
PFA: several steps + iterative process

i. Preparation
ii. Loose clustering in ECAL and HCAL
iii. Topological linking of clearly associated clusters
iv. Courser grouping of clusters
v. Iterative reclustering
vi. Photon Identification/Recovery
vii. Fragment removal
viii. Formation of final Particle Flow Objects (reconstructed particles)

Includes analysis of all detector components… we discuss only some aspects relevant to calorimeters

ECAL/HCAL clustering

- ★ Start at inner layers and work outward
- ★ Tracks can be used to “seed” clusters
- ★ Associate hits with existing Clusters
- ★ If no association made form new Cluster
- ★ Simple cone based algorithm



Initial cluster direction

Unmatched hits seeds new cluster

Simple cone algorithm based on current direction + additional N pixels

Cones based on either:
initial PC direction or
current PC direction

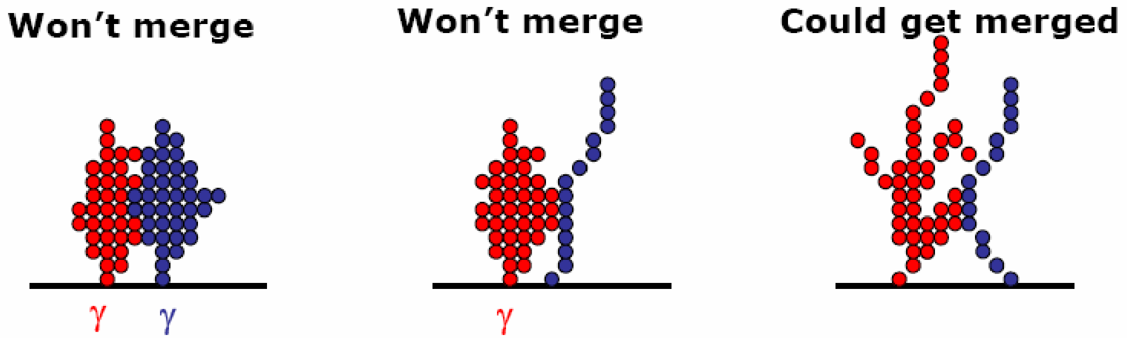
Parameters:
- cone angle
- additional pixels

Topological cluster association

- By design, clustering errs on side of caution
  i.e. clusters tend to be split
- Philosophy: easier to put things together than split them up
- Clusters are then associated together in two stages:
  - 1) Tight cluster association – clear topologies
  - 2) Loose cluster association – fix what's been missed

Photon ID

- Photon ID plays important role
- Simple "cut-based" photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone

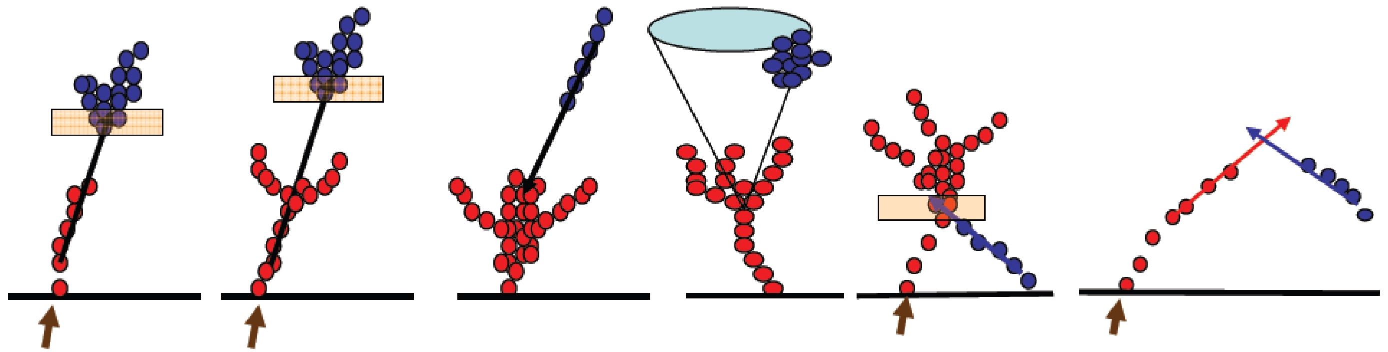


Cluster topological association II

★ Clusters associated using a number of topological rules

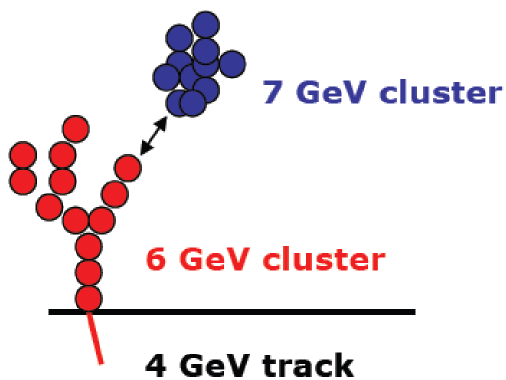
Clear Associations:

- Join clusters which are clearly associated making use of high granularity + tracking capability: very few mistakes



Less clear associations:

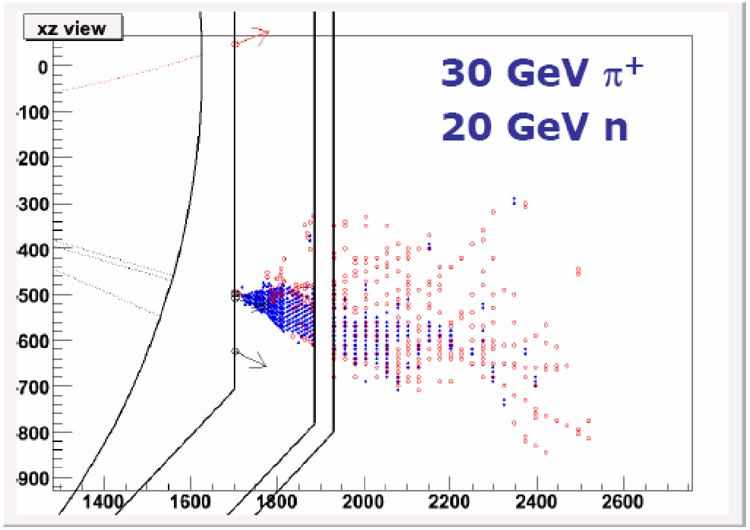
e.g. Proximity



Use E/p consistency to veto clear mistakes

Iterative re-clustering

- Upto this point, in most cases performance is good – but some difficult cases…



- **At some point hit** the limit of "pure" particle flow
  - just can't resolve neutral hadron in hadronic shower

The ONLY(?) way to address this is "statistically"

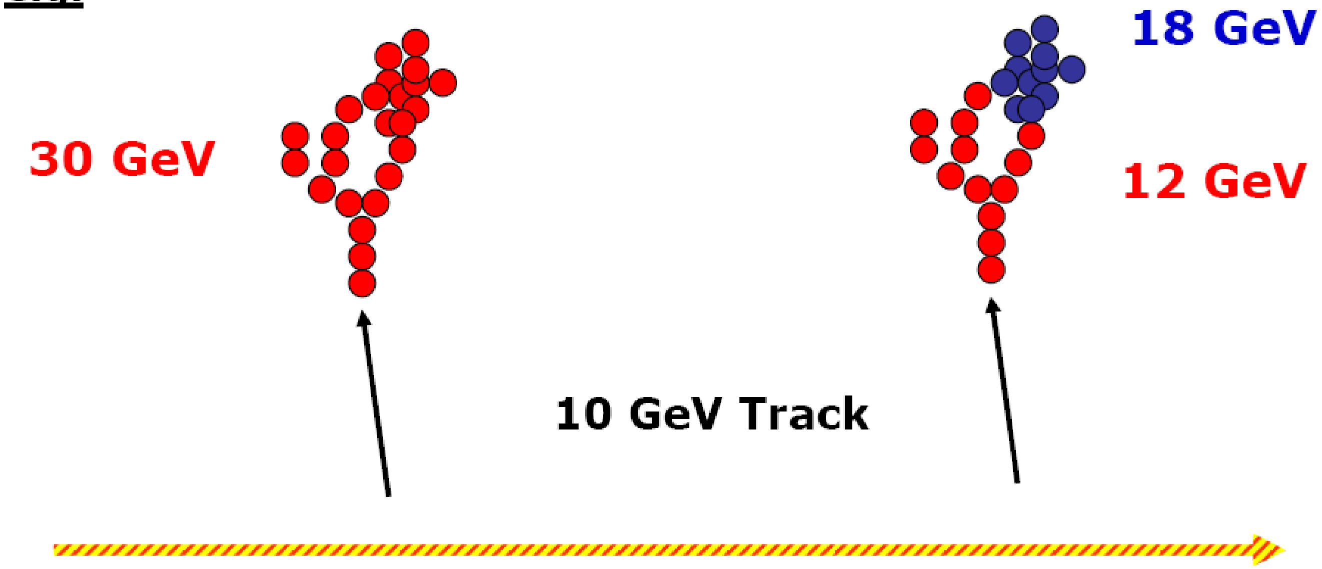
→

e.g. if have 30 GeV track pointing to 20 GeV cluster
SOMETHING IS WRONG

Iterative re-clustering II

★ If track momentum and cluster energy inconsistent : **RECLUSTER**

e.g.

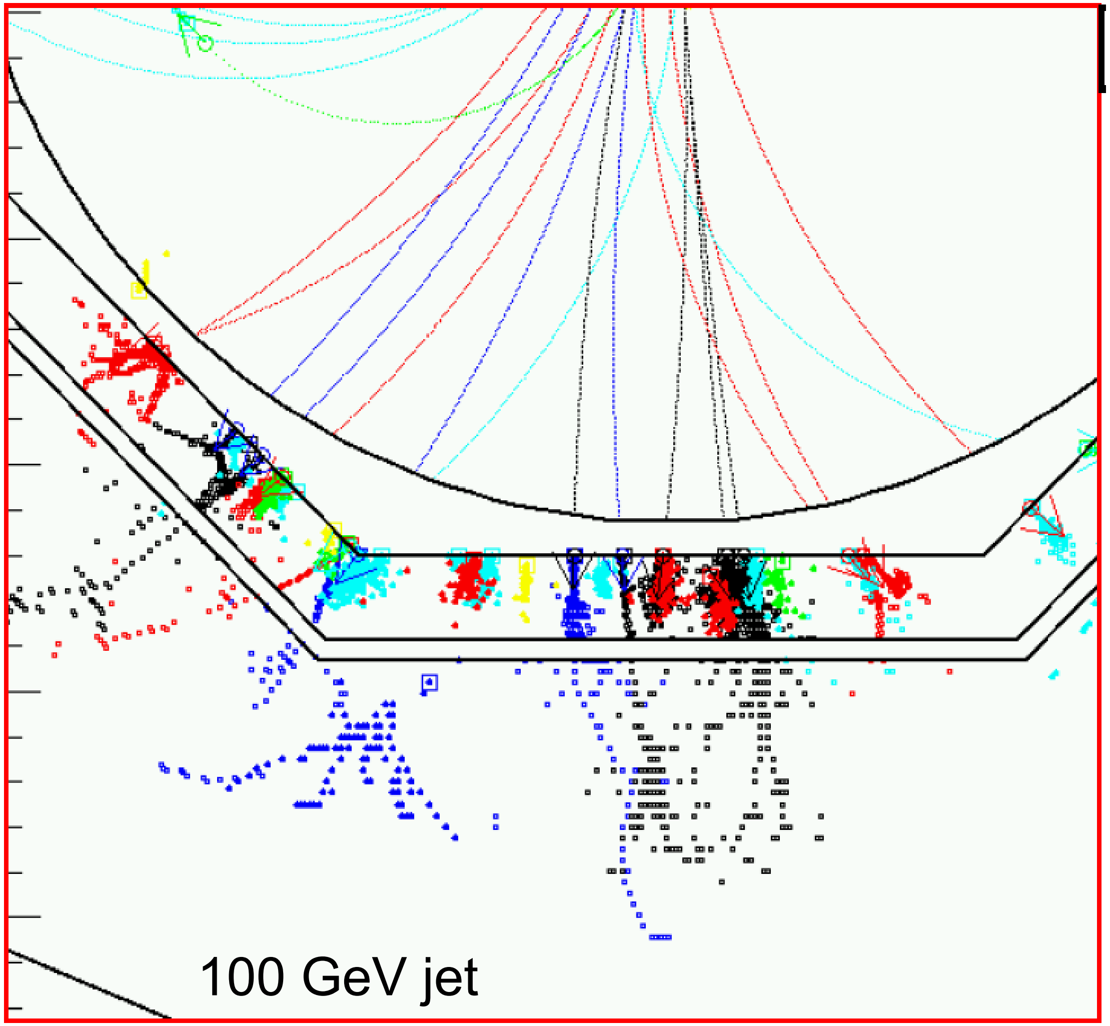


Change clustering parameters until cluster splits and get sensible track-cluster match

NOTE: NOT FULL PFA as clustering driven by track momentum

This is very important for higher energy jets

The outcome of PFA



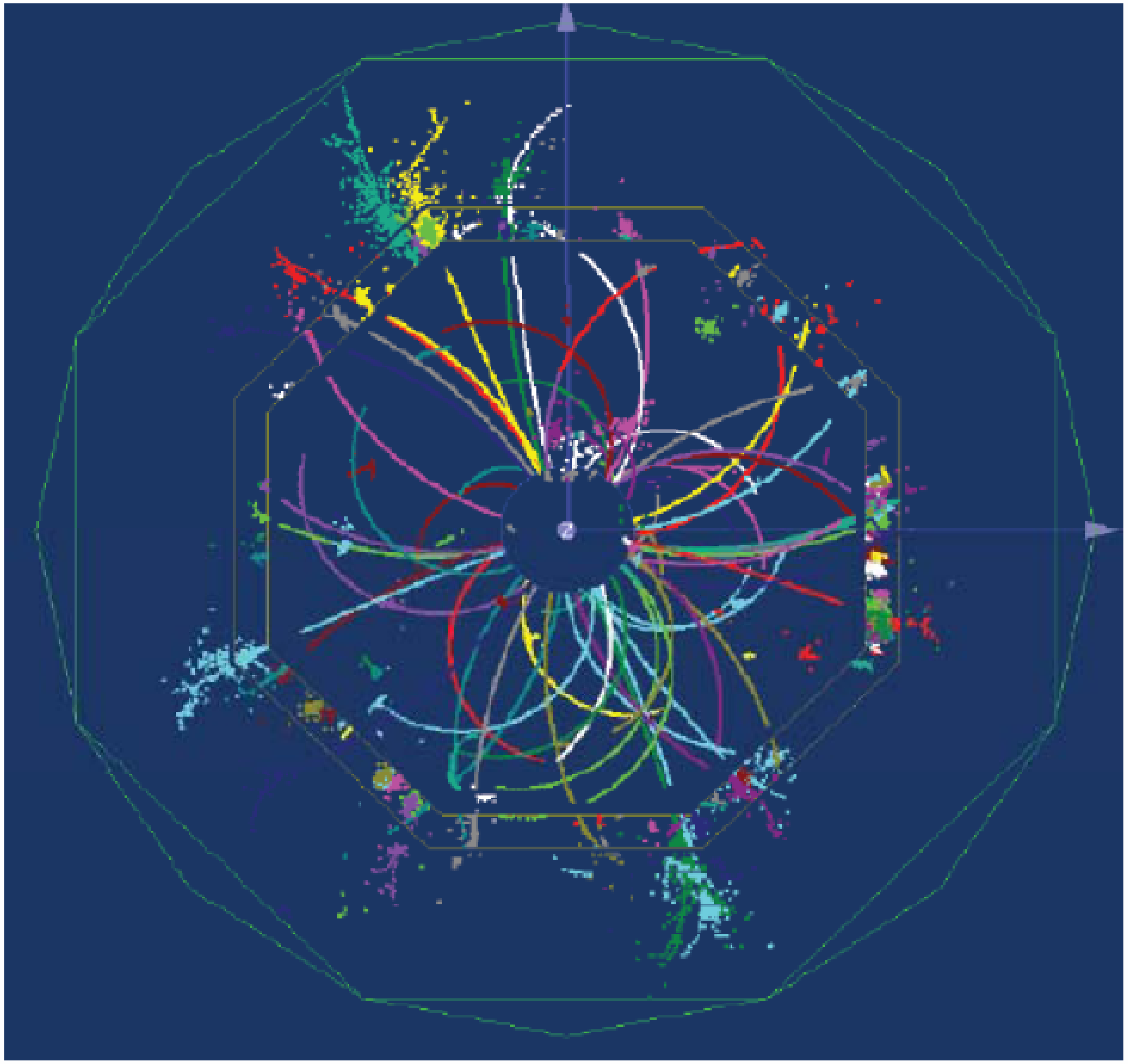
PFlow at work

Simulated event

$$e^+e^- \to t\bar{t}$$

color-encoding according to track-cluster association based on PFA

Stochastic term of 30% could be reached for the jet energy resolution

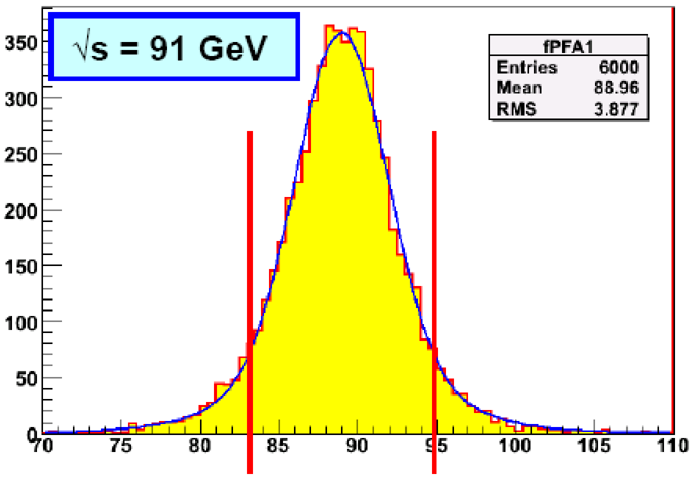


Performance

Figures of Merit:

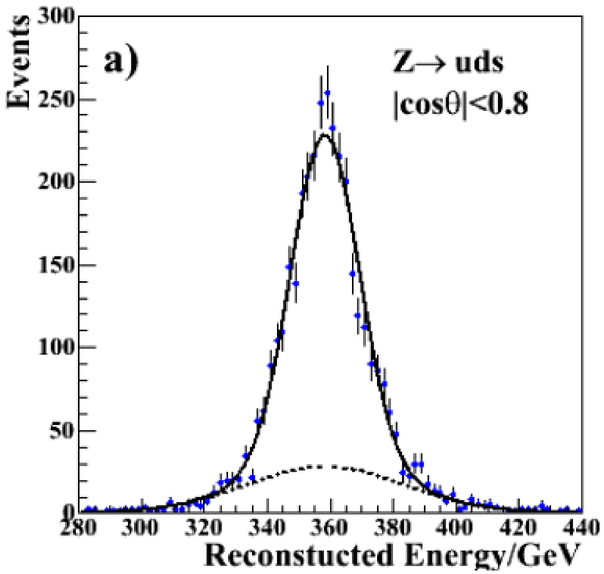
rms_{90}

- Find smallest region containing 90 % of events
- Determine rms in this region



σ_{75}

- Fit sum of two Gaussians with same mean. The narrower one is constrained to contain 75% of events
- Quote σ of narrow Gaussian



It is found that $rms_{90} \approx \sigma_{75}$

Performance / detector study

Performance (LDC00)

rms90 PandoraPFA v02-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.235	3.5 %
100 GeV	0.306	3.1 %
180 GeV	0.427	3.2 %
250 GeV	0.565	3.6 %

NOTE: studies based on ILD detector concept are "work-in-progress"

- Tesla TDR detector model
- Full simulation
- Full reconstruction

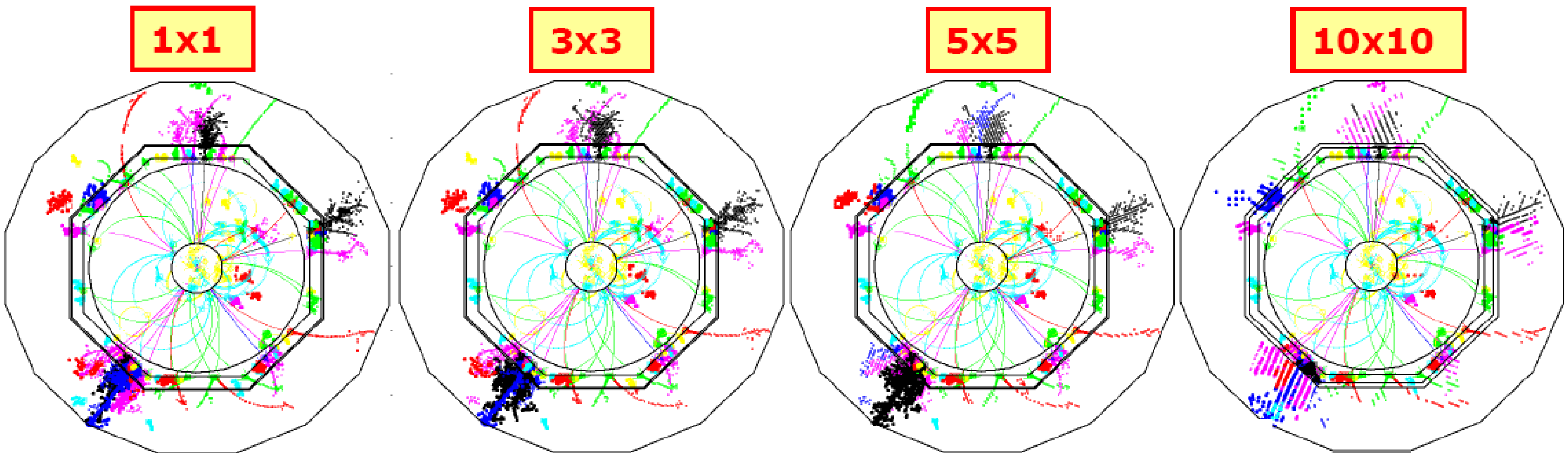
In simulation

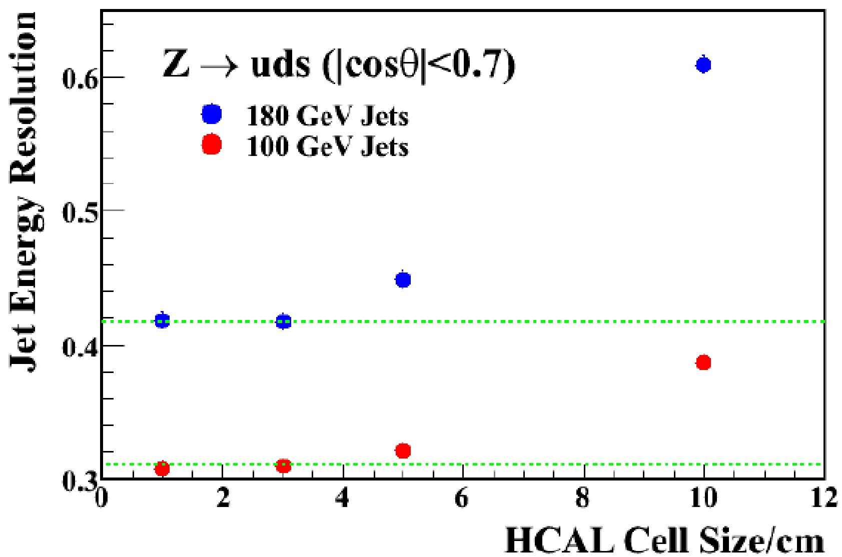
★ Particle flow can achieve ILC goal of $\sigma_E/E_j < 3.8\ \%$
★ For lower energy jets Particle Flow gives **unprecedented** levels of performance, e.g. @ 45 GeV : 3.5% c.f. ~10% (ALEPH)
★ "Calorimetric" performance (α) degrades for higher energy jets
★ + current code is not perfect - can do better

PARTICLE FLOW CALORIMETRY WORKS !

Effect of granularity on PFlow

Degrading the HCAL granularity kills PFlow !!!

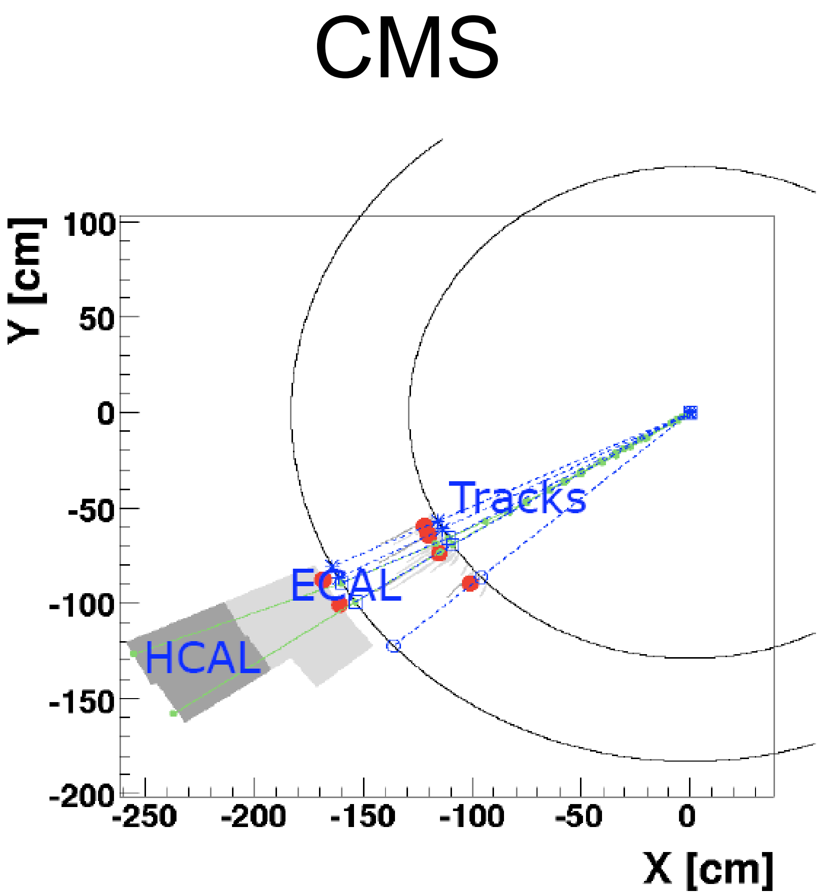


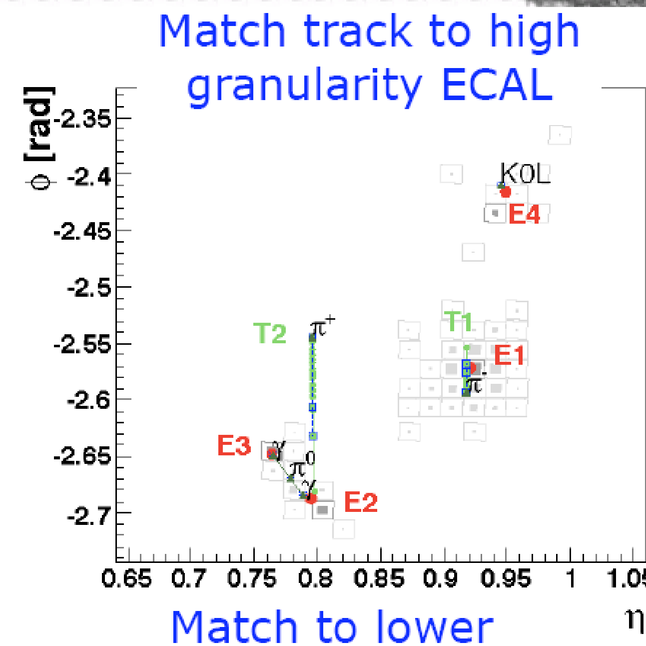


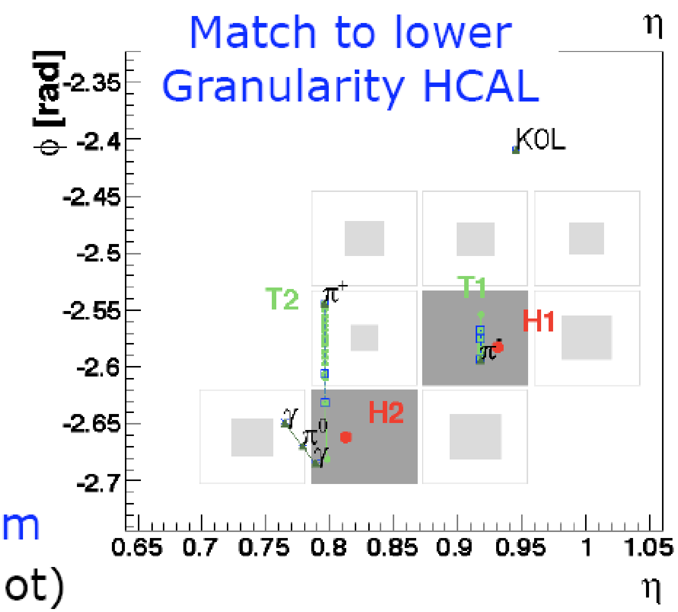
"Preliminary Conclusions"

- 3x3 cm^2 cell size
- No advantage → 1x1 cm^2
  - physics ?
  - algorithm artefact ?
- 5x5 cm^2 degrades PFA
  - Does not exclude coarser granularity deep in HCAL

Particle Flow @ LHC



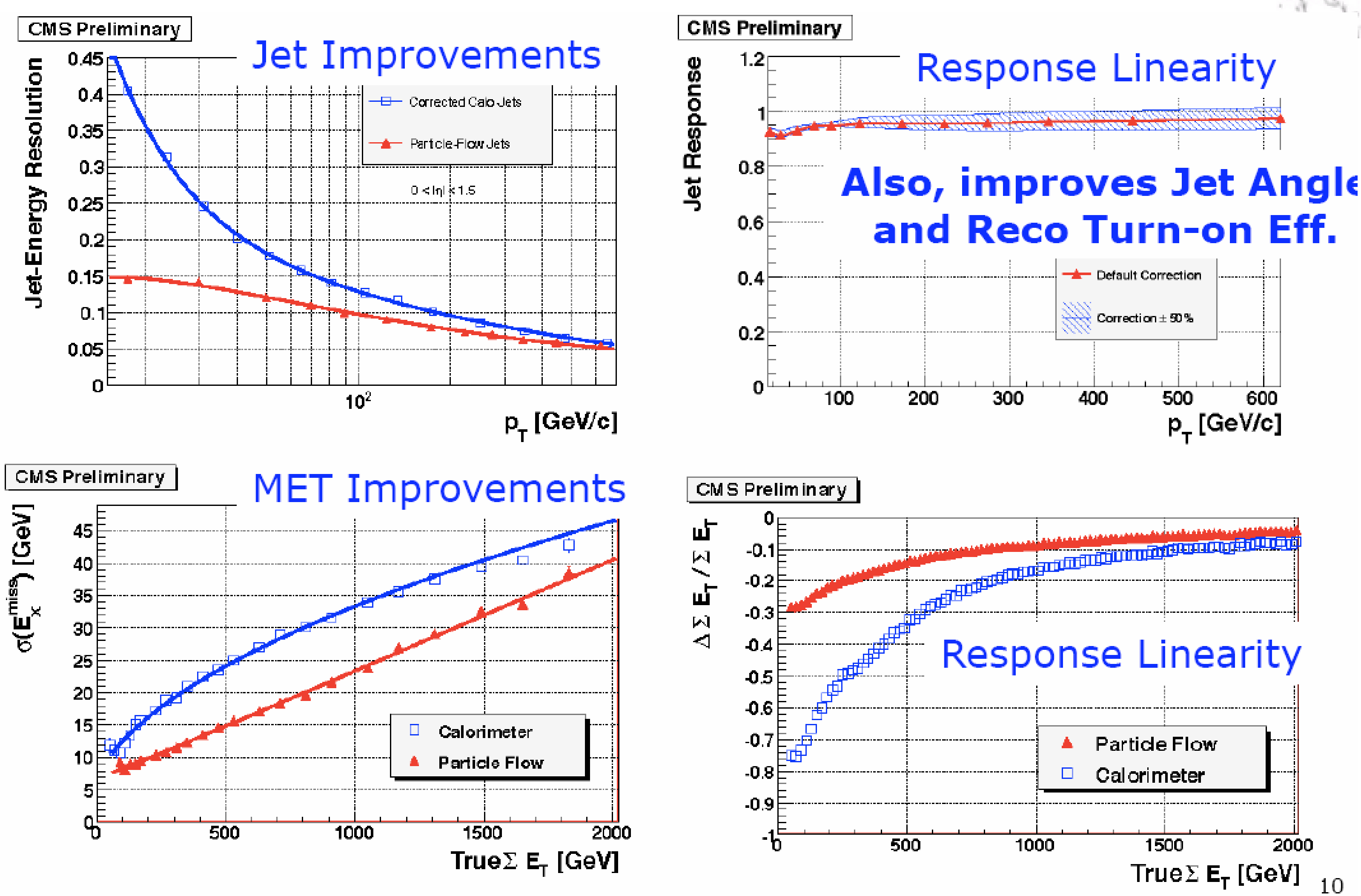




1) Leverage High Precision Tracking
2) And High Resolution ECAL EM-Showers
3) Match and Discard Charged Hadron Showers Replacing with Track Momentum

(Courtesy of P. Janot)

PFlow improvements at CMS



Conclusions on PFlow

Particle flow is a concept to improve the jet energy resolution of a HEP detector

It is based on:

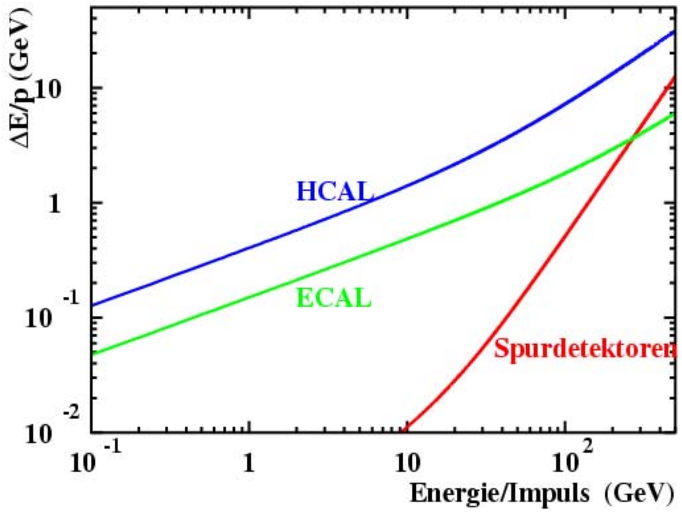
proper detector design (high granular calorimeter!!!)

+ sophisticated reconstruction software

PFlow techniques have been shown to improve jet E resolution in existing detectors, but the full benefit can only be seen on the future generation of PFlow designed detectors

Issues:

- At which energy does Pflow break down?
- Is there anything better?



Dual readout calorimetry

Alternative approach to the problem of improving hadronic / jet energy resolution:

- measure the shower components in each event ➔ access the source of fluctuations:
  - measuring f_{em} in each event removes the EM fluctuations
  - ideally one wants to measure also f_n which is proportional to the binding energy to remove fluctuations in the invisible energy

- Example: The DREAM calorimeter as a test of this approach

Measure the EM shower content

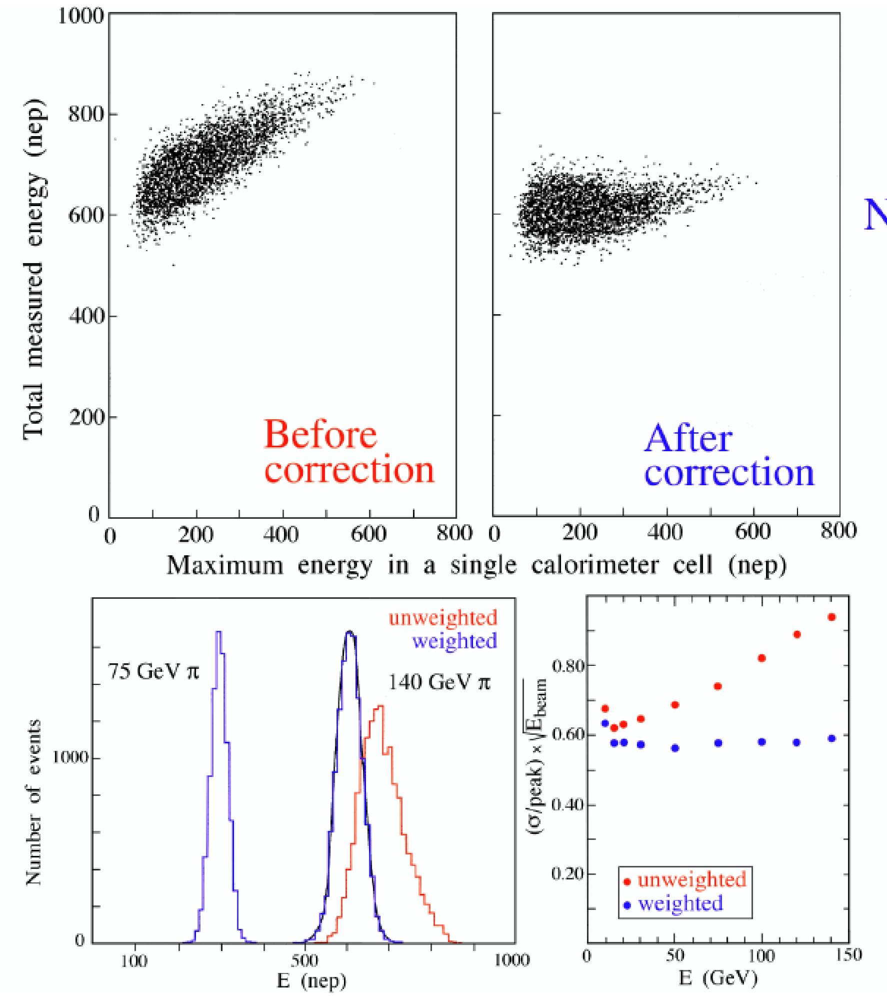
Measure f_{em} event-by-event

Pioneered by WA1 around 1980 ➔

- Used characteristics of energy deposit profile to disentangle em/non-em shower components

Works better as energy increases

Does *not* work for jets (collection of γ and π showering simultaneously in the same area)



The Dual REAdout Method principle

Use Cerenkov light !!!

Quartz fibers are only sensitive to em shower component !

- Production of Cerenkov light ⇒ Signal dominated by em component
- ~80% of non-em energy deposited by non-relativistic particles
  ⇒ e/h=5 (CMS-HF)
  ⇒ lateral profile of hadronic showers
- Hadronic component mainly spallation protons E_k ~ few hundred MeV
  ⇒ non-relativistic ⇒ no Cerenkov light
- Electron and positrons emit Cerenkov light up to a portion of MeV

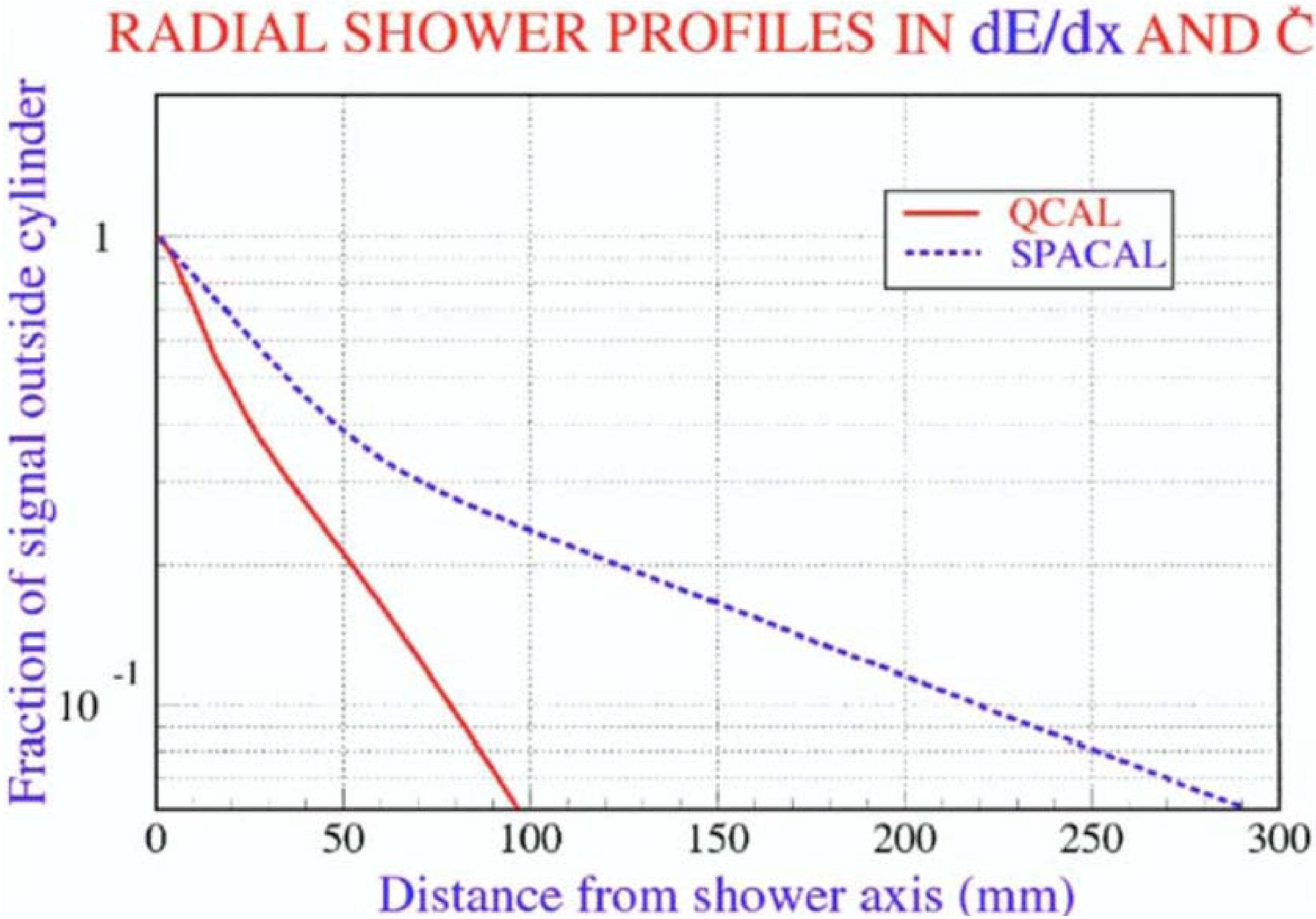
Use dual-readout system:

- Regular readout (scintillator, LAr, ...) measures visible energy
- Quartz fibers measure em shower component E_{em}

➔ Combining both results makes it possible to determine f_{em} and the energy E of the showering hadron

➔ Eliminates dominant source of fluctuations

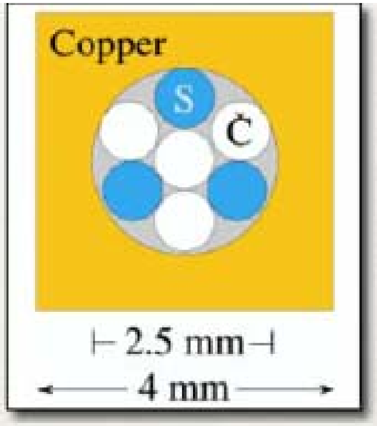
Quartz fiber calorimetry



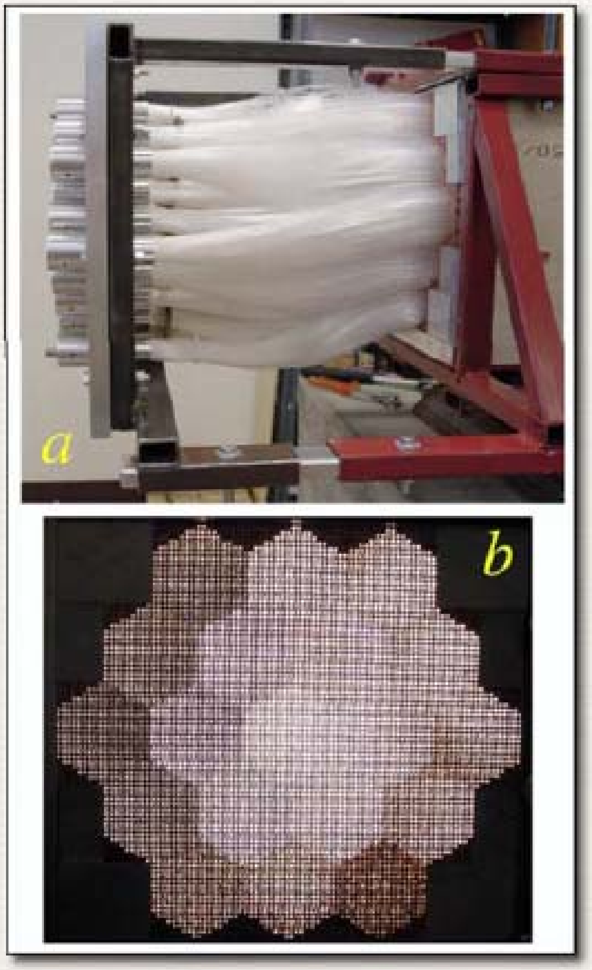
Radial shower profile in SPACAL (scintillatior fibers) and QCAL (quartz fiber)

The DREAM prototype

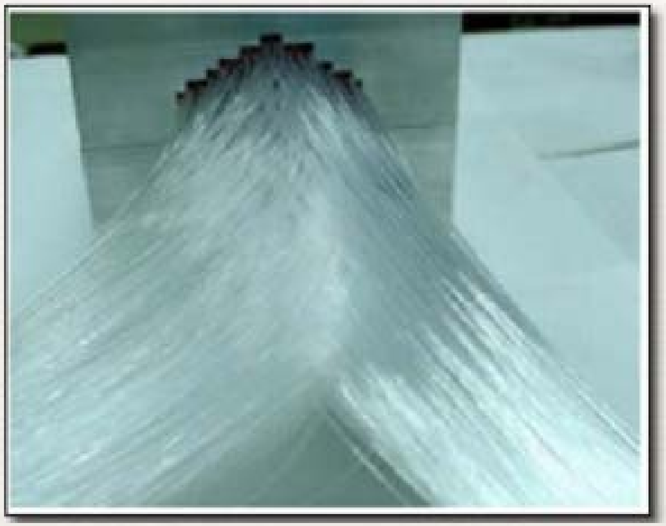
Basic structure:
$4x4\ mm^2$ Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov



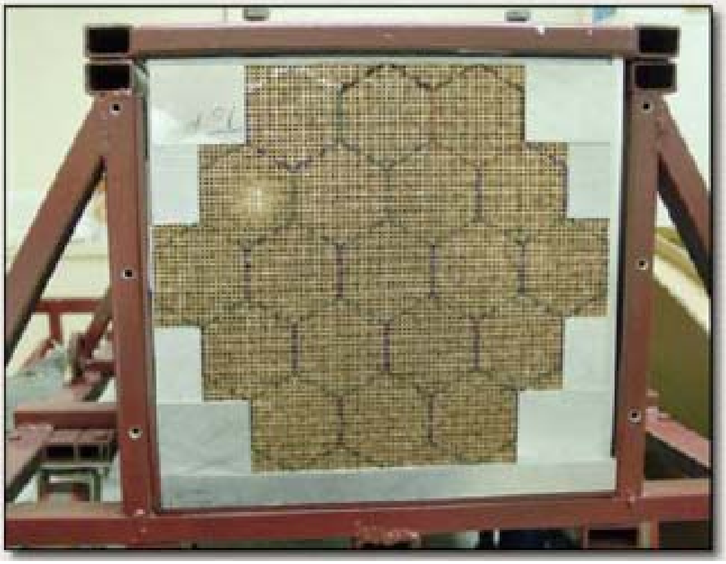
DREAM prototype:
5580 rods, 35910 fibers, 2 m long ($10\ \lambda_{int}$)
16.2 cm effective radius ($0.81\ \lambda_{int}$, $8.0\ \rho_M$)
1030 Kg
$X_0 = 20.10$ mm, $\rho_M = 20.35$ mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm ($1.82\ \rho_M$)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings



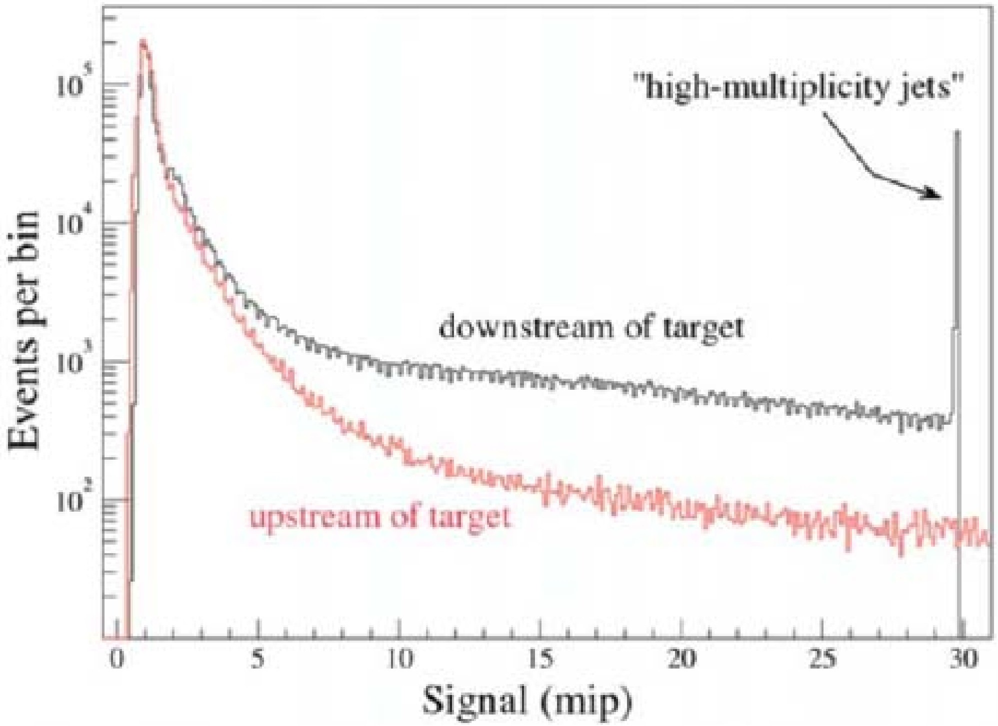
The DREAM prototype



DREAM prototype:
tested at the CERN H4 beam line
Data samples:
π from 20 to 300 GeV
"Jets" from 50 to 330 GeV
"Jets" mimicked by π interaction on 10 cm polyethylene target in front of the detector



Making “jets” at test beams



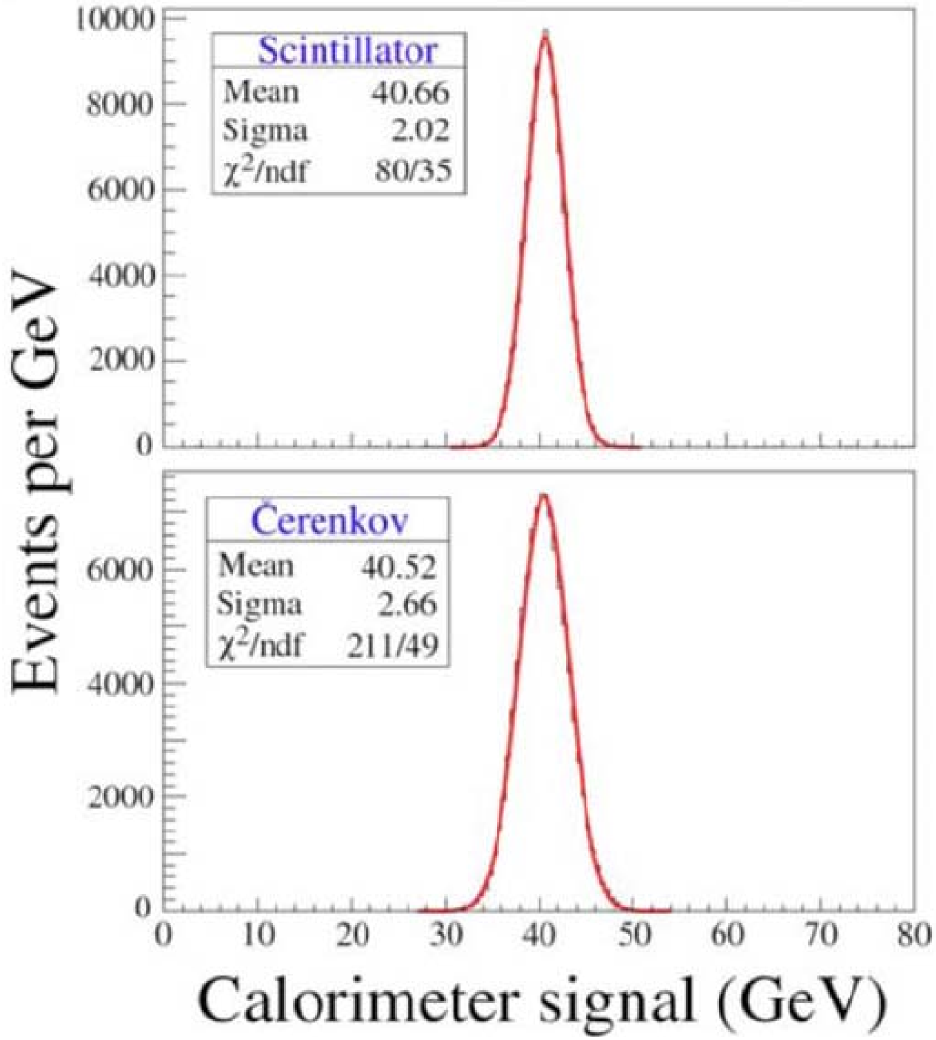
"JET" Measurements

Calibration with 40 GeV electrons

• Tilt 2° respect to the beam direction to avoid channelling effects

• Modest energy resolution for electrons (scintillator signal):

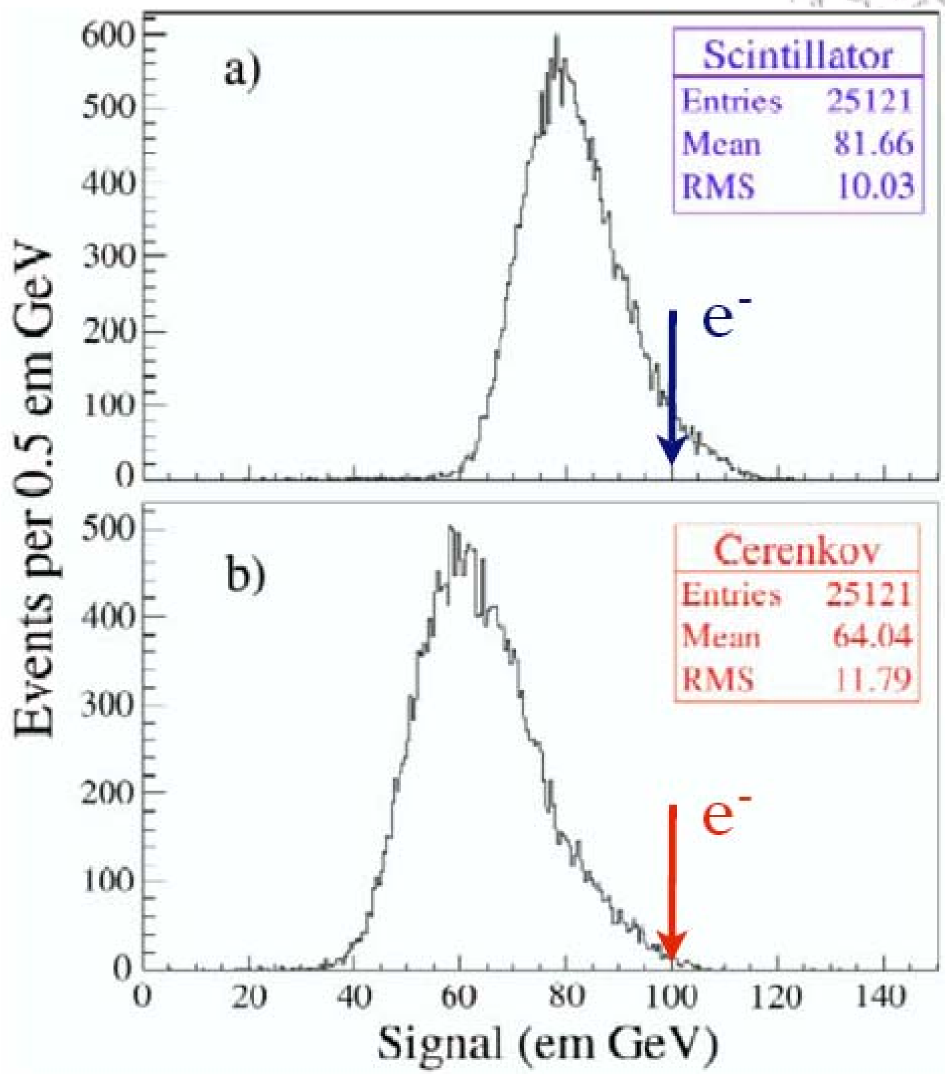
$\sigma/E = 20.5\%/\sqrt{E} + 1.5\%$



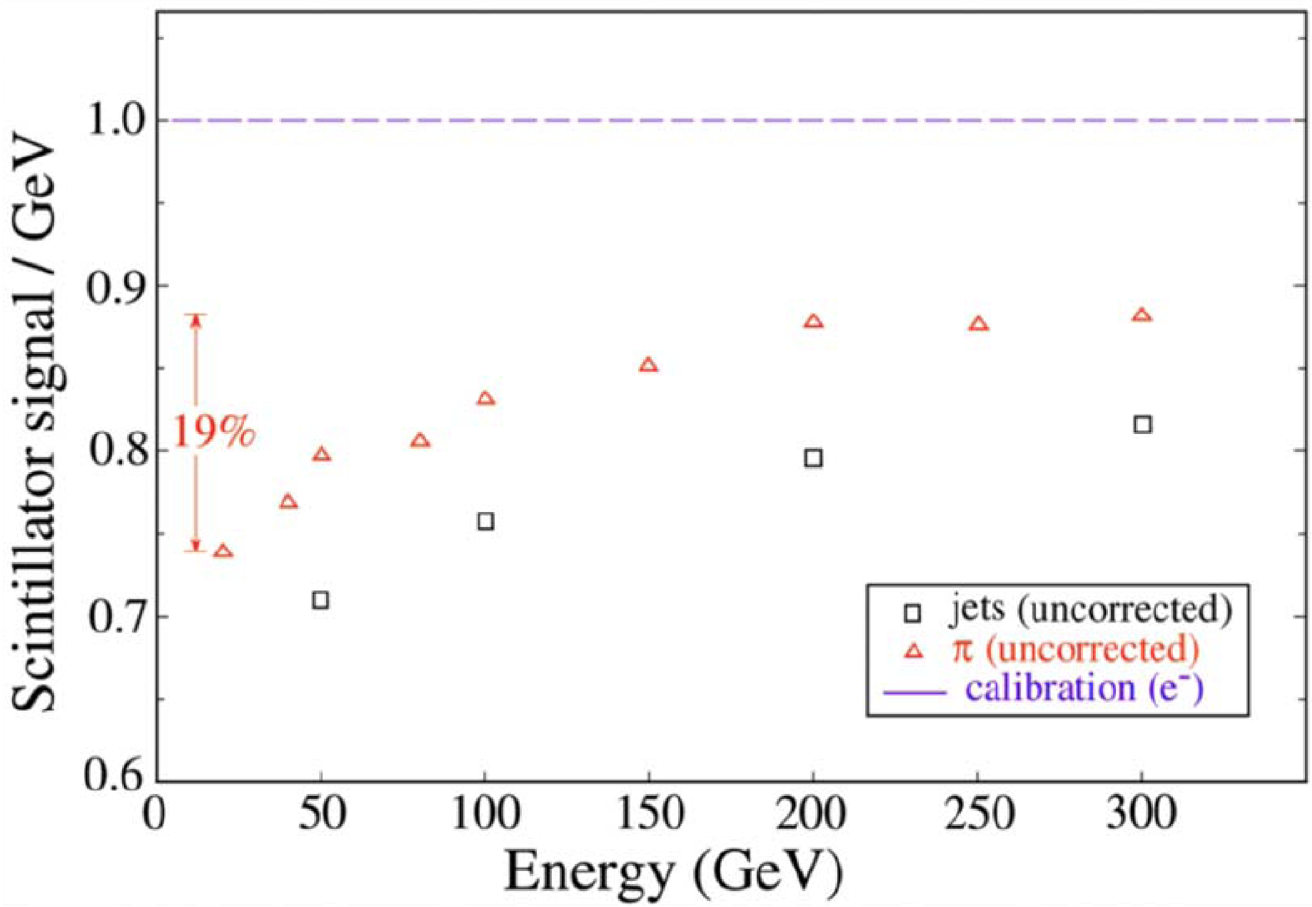
100 GeV single pions (raw signal)

Signal distribution:

- Asymmetric, broad, smaller signal than for e-
- Typical tails feature of a non-compensating calorimeter



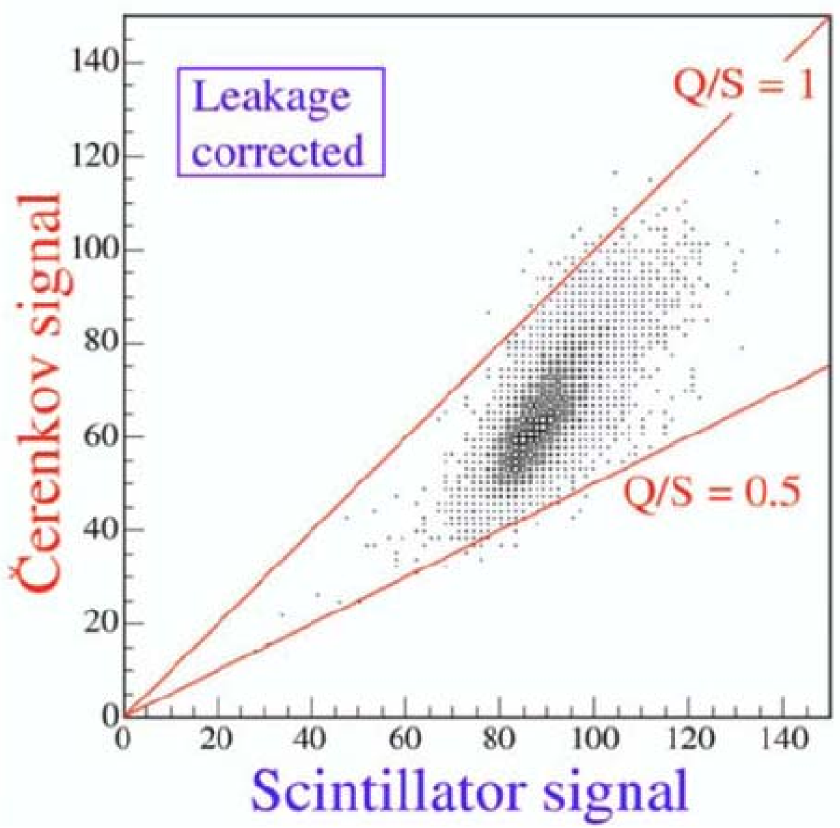
Hadronic response non-linearity



Hadron response is < 1 and ~20% non-linear

Similar non-linearity for jets

How to determine f_{em} and E



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

e.g. If $e/h = 1.3$ (S), 4.7 (Q)

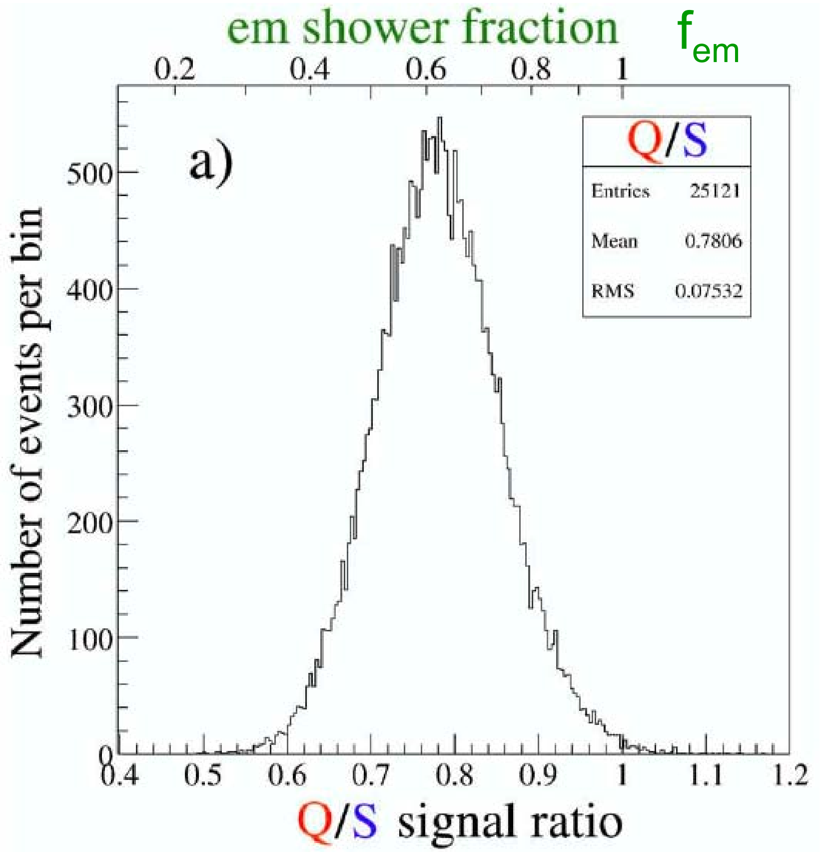
$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

Q/S<1 ➔ ~25% of the scintillator signal from pion showers is caused by non-relativistic particles, typically protons from spallation or elastic neutron scattering

Relation between Q/S ratio and f_{em}



f_{em} strongly correlated to Q/S

~60% of a 100 GeV pion shower is carried by em components

➔ use f_{em} extracted from the Q/S method to correct non-compensation effects in the scintillator response

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

1/(e/h) for quartz and scintillator

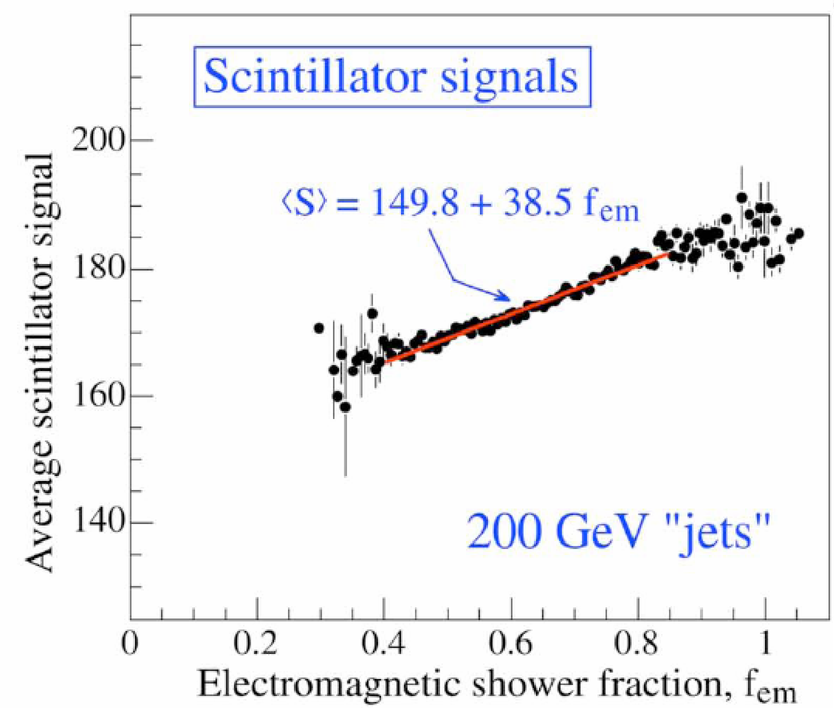
Non-compensation correction

Calorimeter response: $R = S/E_{beam}$

$$R(f_{em}) = f_{em} + \frac{1}{e/h}[1 - f_{em}],$$

e/h = 1.3 from fit to scintillator ➔

(in the same way one gets
e/h = 4.7 for quartz)

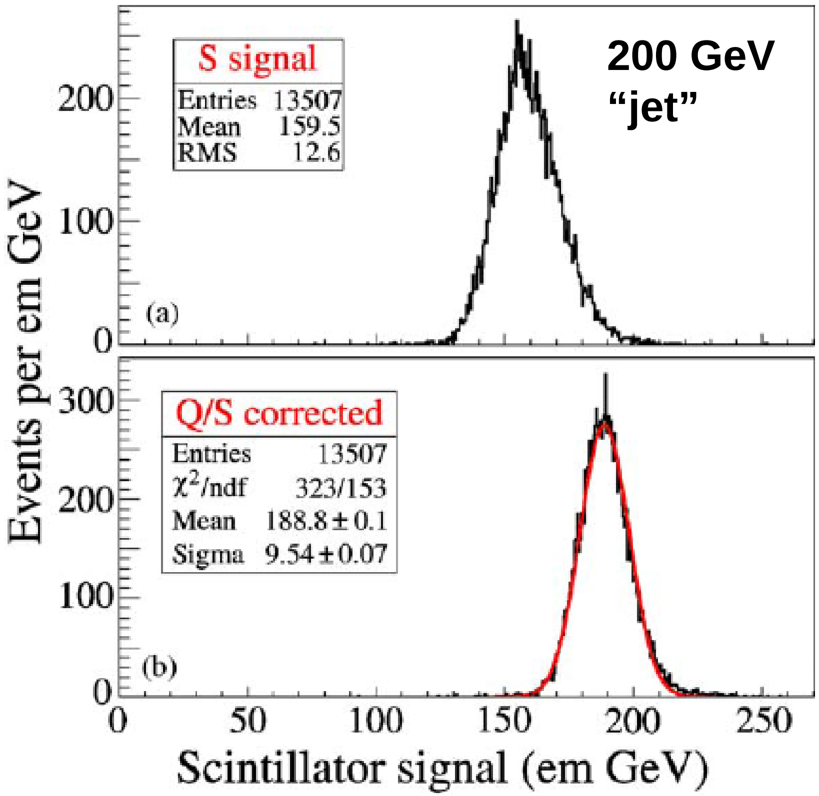


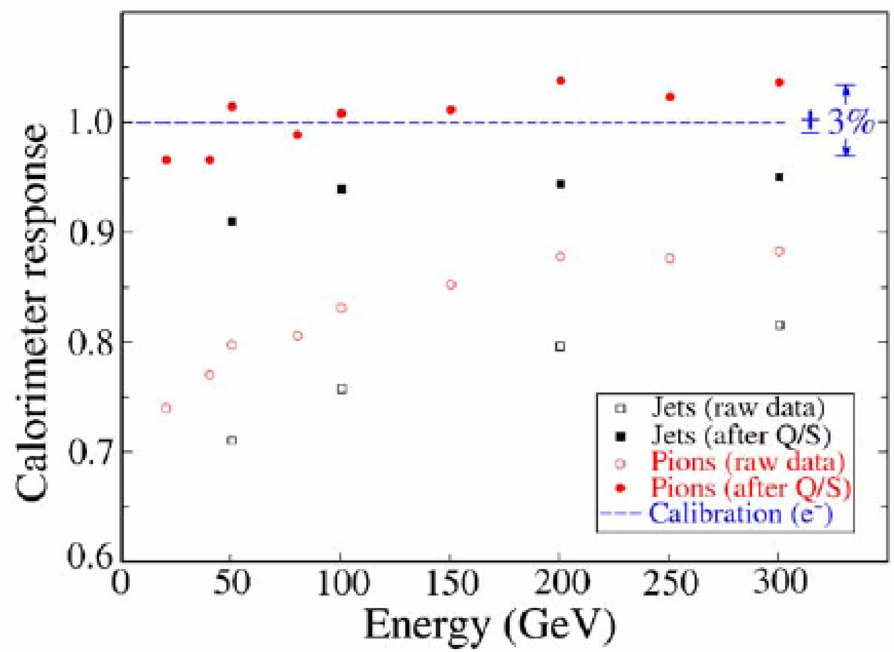
$$R(f_{em}) = p_0 + p_1 f_{em}$$

$$S_{corr} = S_{meas}\left[\frac{1 + p_1/p_0}{1 + fem \cdot p_1/p_0}\right], \quad with \quad \frac{p_1}{p_0} = (e/h)_s - 1$$

Reconstructed hadron energy

Scintillator signal before correction ➔ asymmetry due to non-compensation

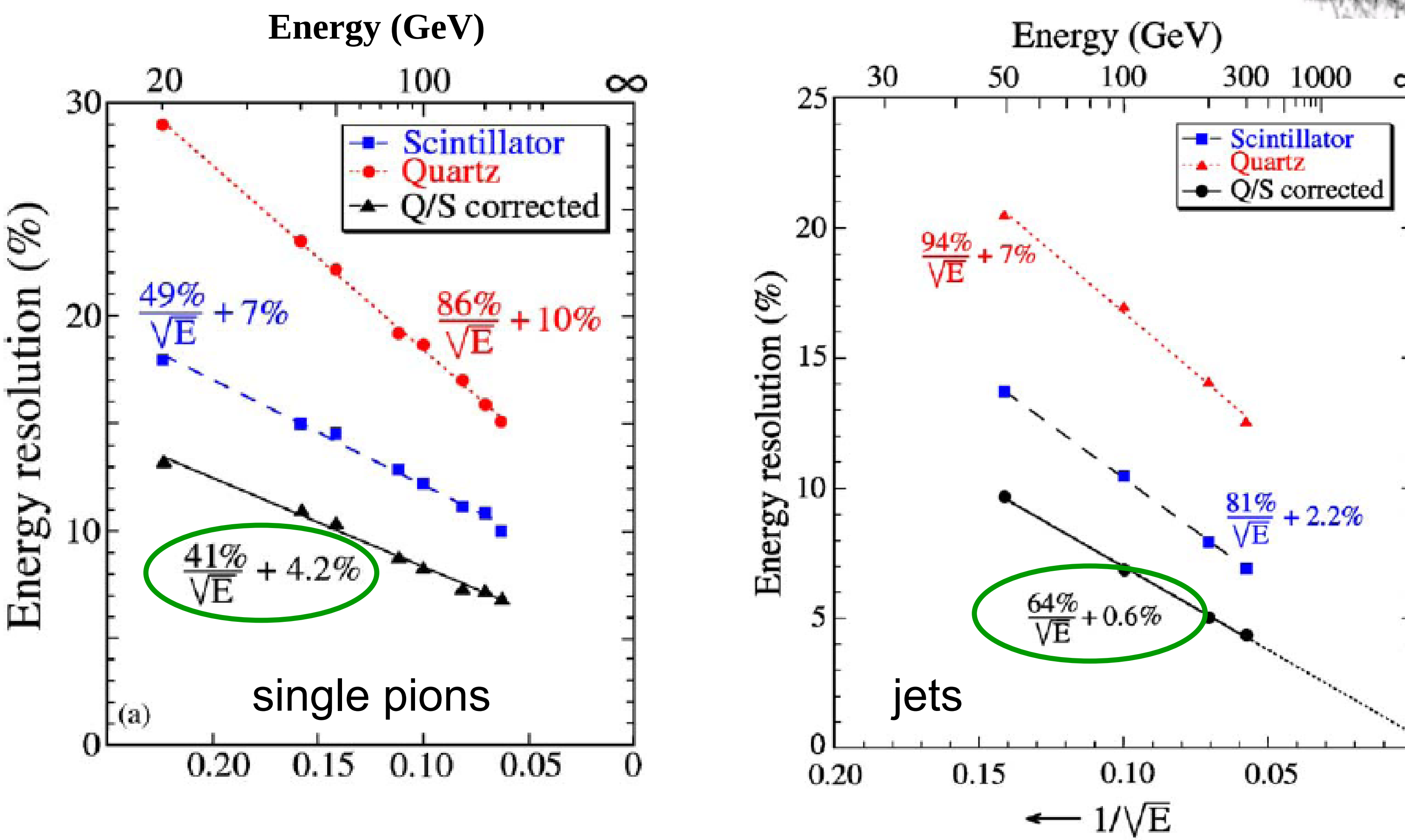




After Q/S method correction
➔ good Gaussian signal

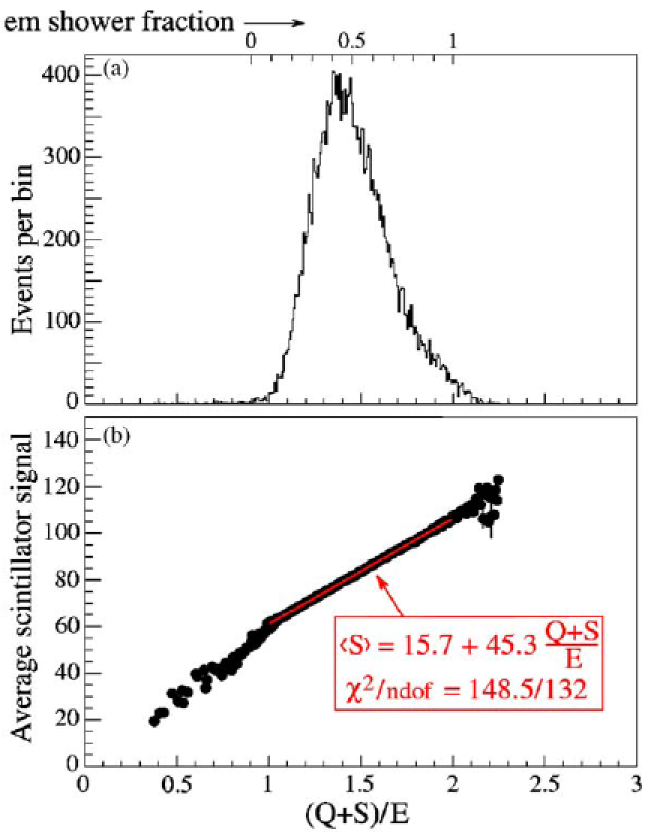
Recovered linearity of response to pions and "jets"

Energy resolution

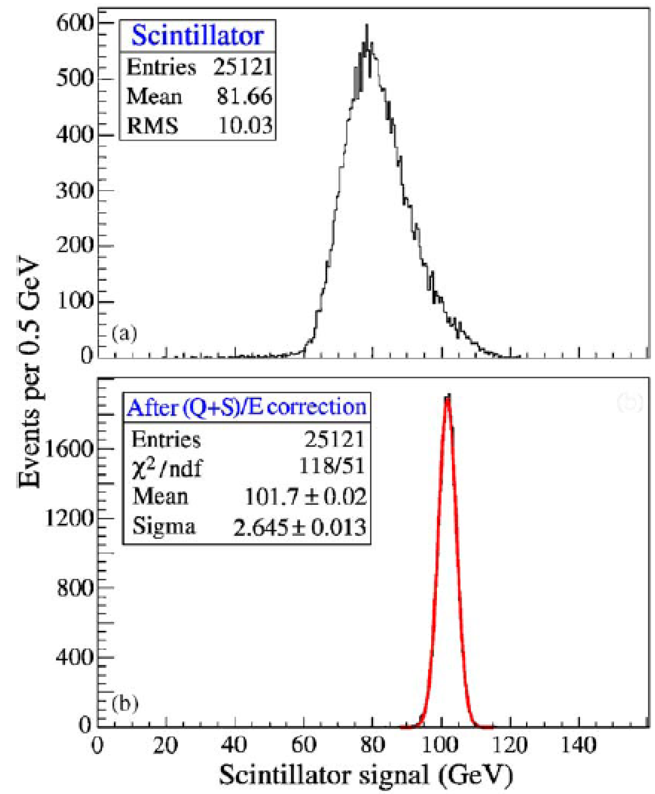


Significant improvement in energy resolution especially for jets

Alternative calibration method



apply correction



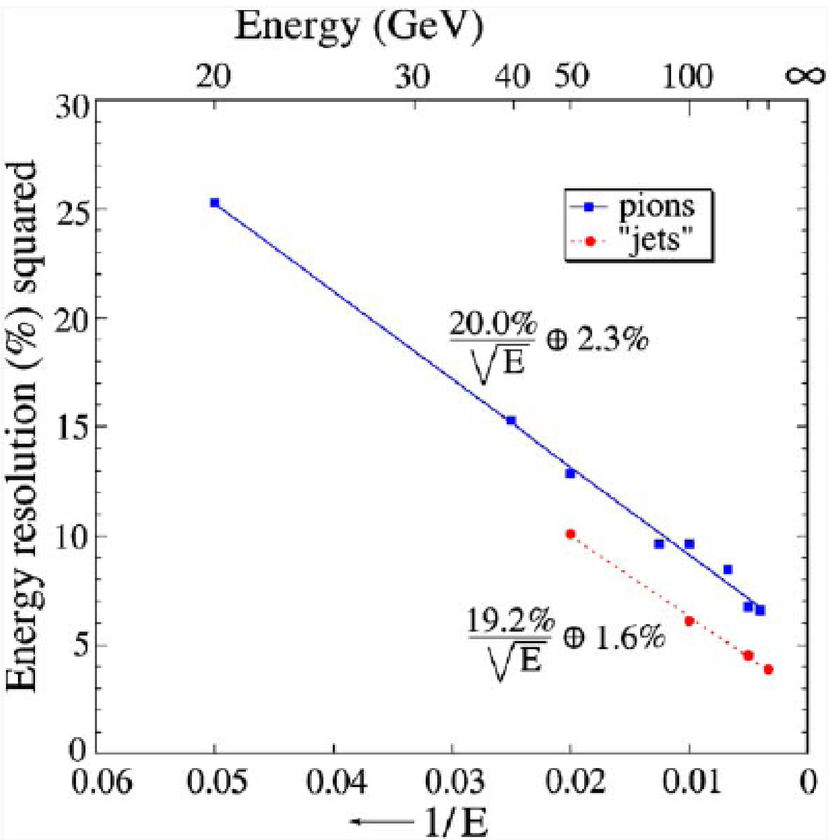
Determine f_{em} from the relation:

$$\frac{(Q+S)}{E} = 0.91 + 1.09\, f_{em}$$

$$\left(\frac{S}{E}\right)_{corr} = \left(\frac{S}{E}\right)_{meas} + 0.453\,\frac{(Q+S)}{E}$$

where E is the beam energy

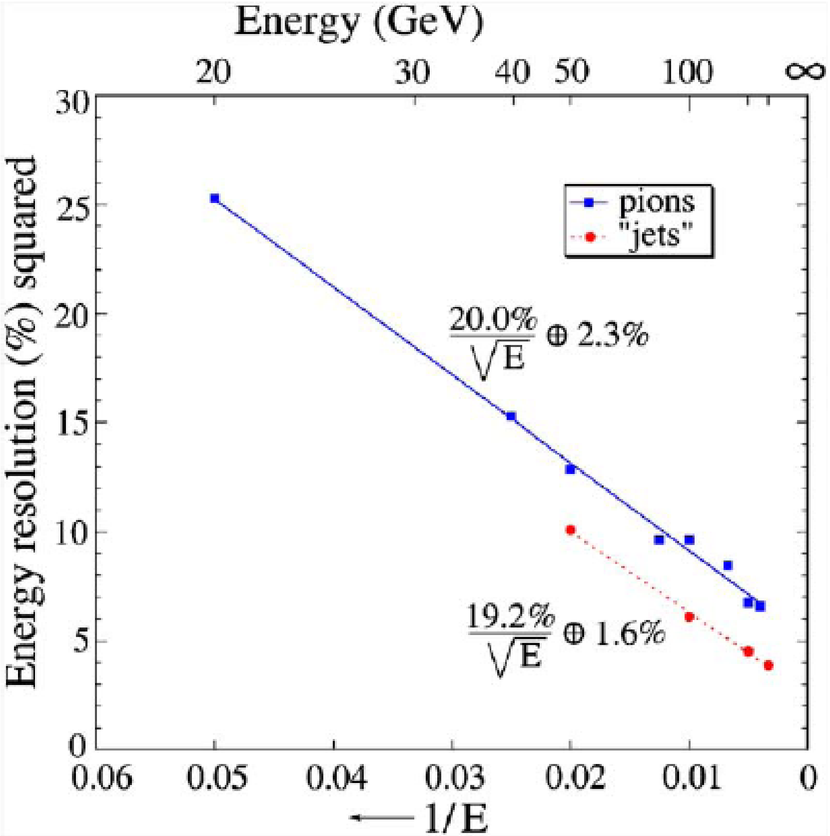
Obtained resolution with (Q+S)/E method



Significant improvements w.r.t. Q/S method for both "jets" (64%→19%) and pions (41%→20%)

➔so where is the "trick"?

Obtained resolution with (Q+S)/E method



Significant improvements w.r.t. Q/S method for both "jets" (64%→19%) and pions (41%→19%)

➔so where is the "trick"?

$$\frac{(Q+S)}{E} = 0.91 + 1.09\, f_{em}$$

where E is the beam energy

➔makes use of the beam energy not known in real experiment

always careful at what assumptions you make during analysis!!!

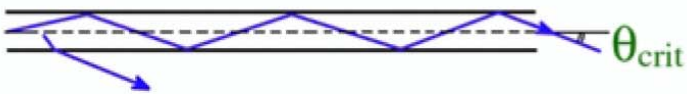
In the DREAM case this investigation was motivated by the large lateral leakage in the DREAM module. The (Q+S)/E only indicates where the limit would be on E resolution. Message: there is still room for improvements w.r.t. the Q/S method results at present if one uses a larger detector

Intermezzo: Cerenkov fiber calorimetry

- *Čerenkov* light is emitted by *relativistic charged* particles ($\beta > 1/n$)
  e.g. quartz ($n = 1.45$): Threshold 0.2 MeV for e, 400 MeV for p

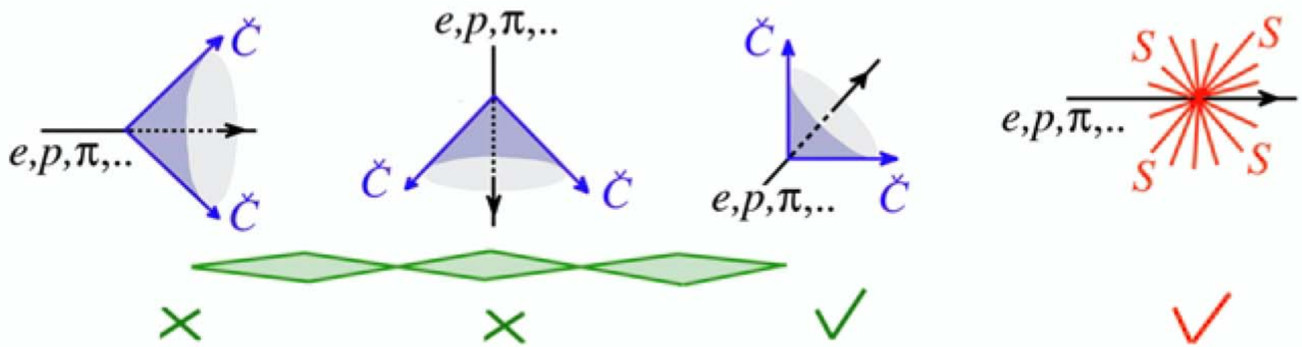
  Light is emitted at angle $\theta = \arccos(\beta n)^{-1}$ (~ 45° for β ~ 1 in quartz)

- *Optical fibers* only trap light emitted within the *numerical aperture*

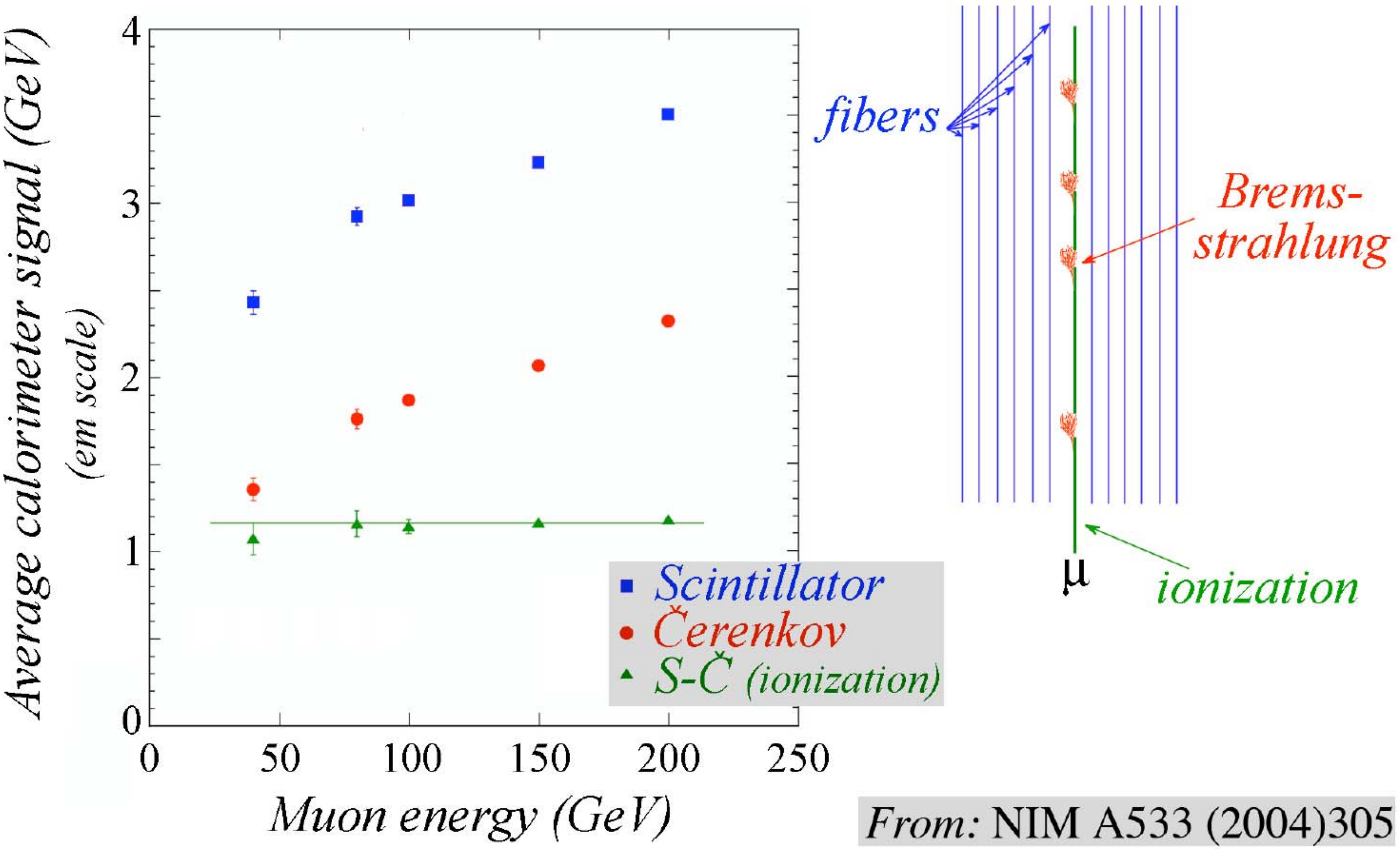


θ_{crit} ~ 20° for quartz fibers

- Comparison of *Čerenkov* light (directional) and *scintillation* light (isotropic) produced in fiber calorimeters is a rich source of information on details of shower development



Muon signal in DREAM calorimeter



From: NIM A533 (2004)305

DREAM conclusions

DREAM offers a powerful technique to improve hadronic calorimeter performance:

- Correct hadronic energy reconstruction, in an instrument calibrated with electrons !
- Linearity for hadrons and jets
- Gaussian response functions
- Energy resolution scales with sqrt(E)
- $\sigma/E < 5\%$ for high-energy “jets”, in a detector with a mass of only 1 ton ! (dominated by fluctuations in shower leakage)

How to improve on DREAM?

- Build a larger detector ➔reduce effects side leakage
- Increase Cerenkov light yield
  - DREAM: 8 p.e./GeV ➔ fluctuations contribute 35%/√E

- No reason why DREAM principle is limited to fiber calorimeters
  - Homogeneous detector ?!

  ⇒ Need to separate the light into its Č, S components
  - Sampling structure with alternating tiles of Č, S materials

Good solution for an ILC/CLIC calorimeter:

- Homogeneous em calorimeter + DREAM
- Highly granular PFlow calorimeter with quartz and scintillator tiles

Cerenkov light in PbWo4 crystals

- Light yield typically 10 p.e./MeV (dependent on T, readout)
- Lead glass 0.5 - 1 p.e./MeV from Cerenkov effect (3 - 5%/$\sqrt{E}$)

  ➔ Expect substantial Č component in PbWO4 signals

- How to detect/isolate Cerenkov component ?
  - Directionality of Cerenkov component
  - Time structure of signals
  - Spectral differences
  - Test doped Pb-glass with red / green scintillator

Dual Readout with homogeneous material

Separation of Scintillation & Cherenkov light can be based on:

- Time structure of the signal
- Spectral difference
- Directionality of Cherenkov component

	Cherenkov	Scintillation
Time response	Prompt	Exponential decay
Light Spectrum	$\propto 1/\lambda^2$	Peak
Directionality	Cone: $\cos\theta_c = 1/\beta n$	Isotropic

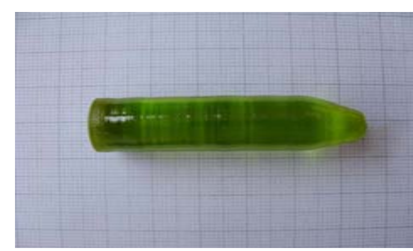
Tests performed at the SPS (CERN) by the DREAM collaboration with 2 kinds of crystals: **$PbW0_4$**, **BGO**

Crystal	LightYield % NaI(Tl)	Decay Time (ns)	Peak wavel.(nm)	Cutoff wavel.(nm)	Refr. Index	Density (g/cm³)
BGO	20	300	480	320	2.15	7.13
PWO	0.3	10	420	350	2.30	8.28

Disadvantages: Much brighter → C/S factor 100 smaller

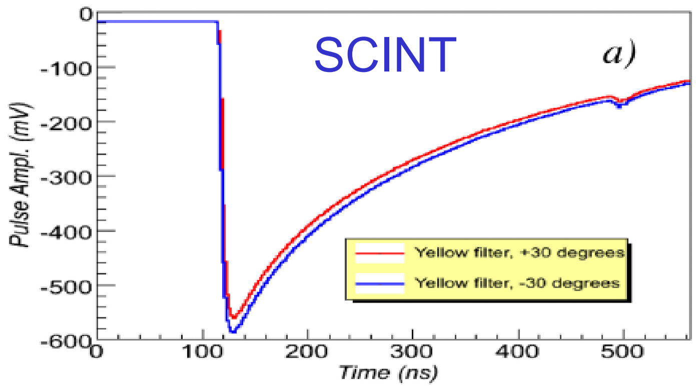
Advantages: Scintillation spectrum peak at 480 nm → use filters Yellow for S, UV for C
Scint Decay time 300 ns (very different from prompt Cherenkov signal)

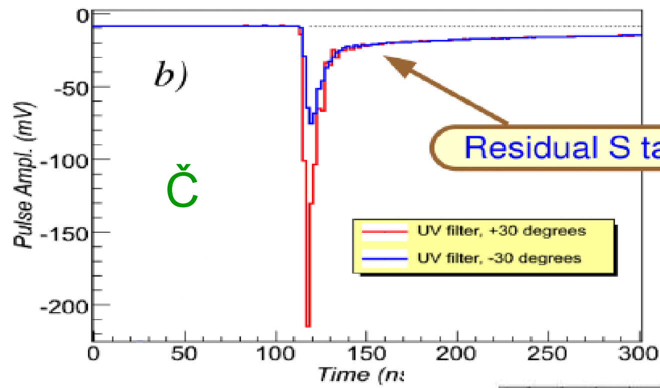
New crystals PbWO4 doped with different concentrations of
→ Praesodymium (peak 630 nm, τ~μs)
→ Molybdenum (500 nm, τ~30 ns) → seems to me more promising



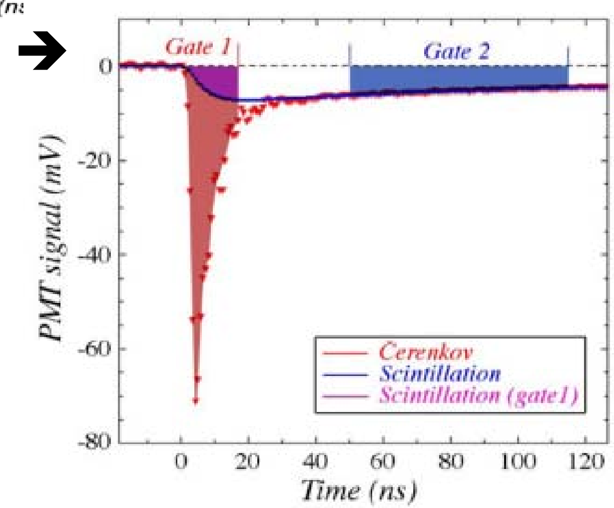
Cherenkov light measurements

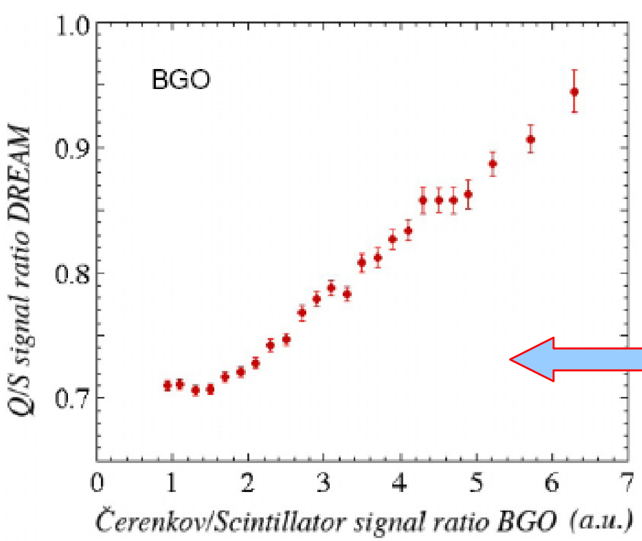
Average Time structure for 50 GeV electrons





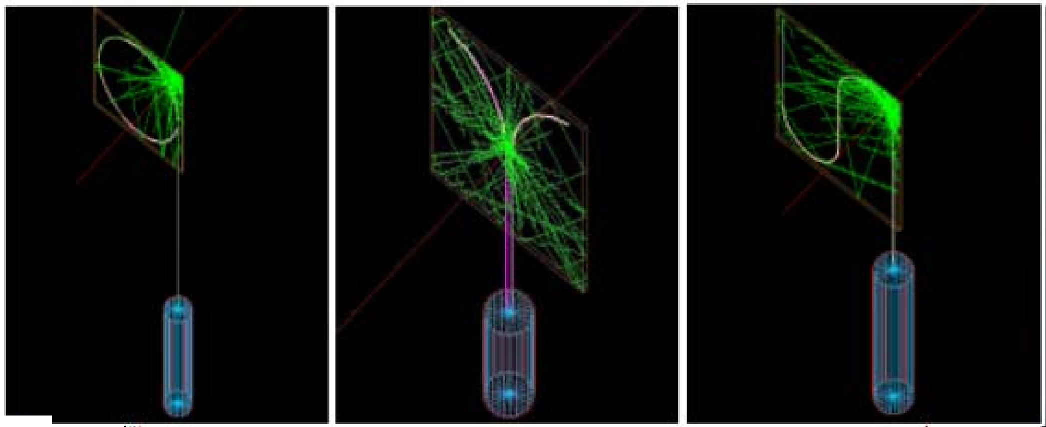
C/S ratio event by event: integrate charge Q1 collected in the Gate1, and Q2 collected in Gate2 ➔

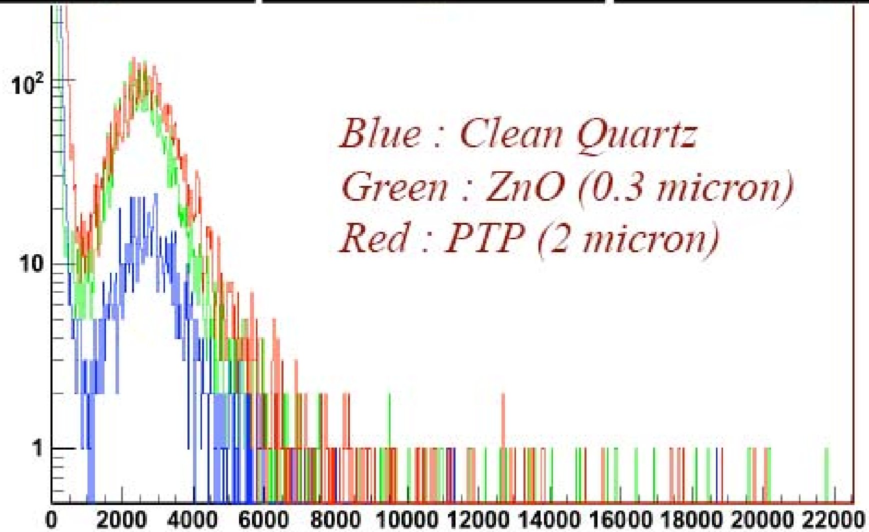




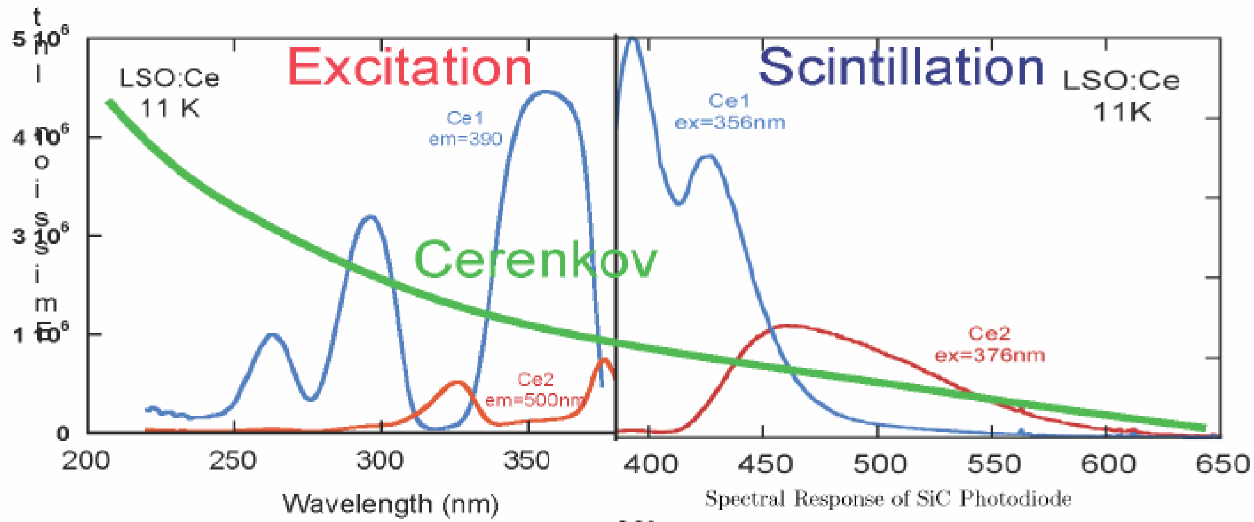
The variable C/S on BGO is able to measure the em component of the shower on the Calorimeter

Quartz plates

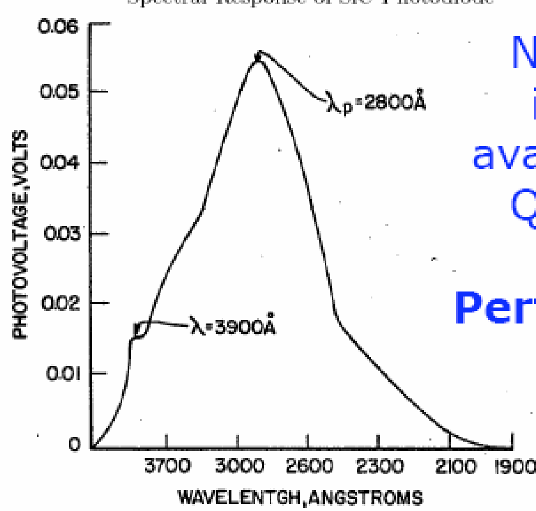




Detecting UV light



Spectral Response of SiC Photodiode



New Developments
in Silicon Carbide
avalanche photodiodes
QE of 60% peaking
at 280nm
Perfect for Cherenkov

Behond DREAM

For ultimate hadron calorimetry (15%/√E)

➔ Measure E_{kin} (neutrons)

- correlated to nuclear binding energy loss (invisible energy)
- can be measured with third type of active material TREAM

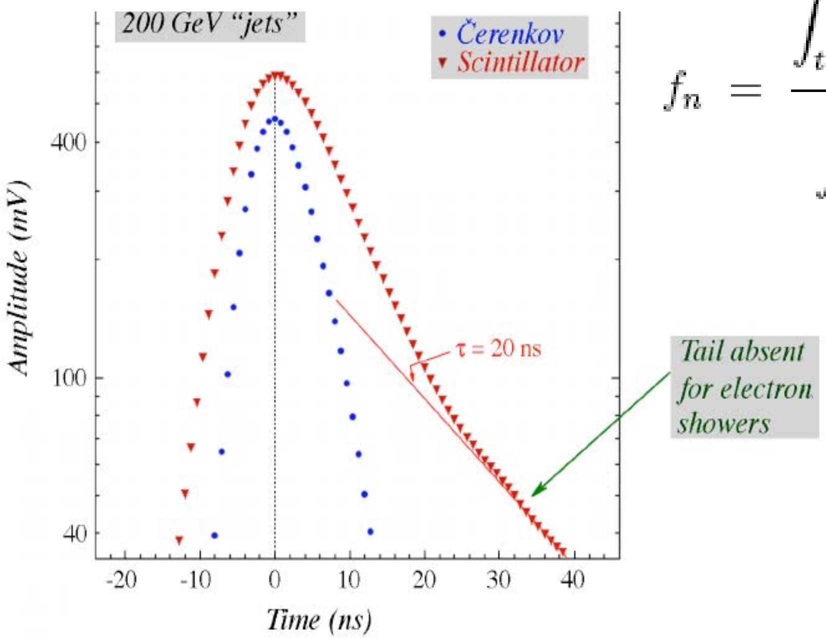
Measure Neutron Fraction

from the time structure of the signal

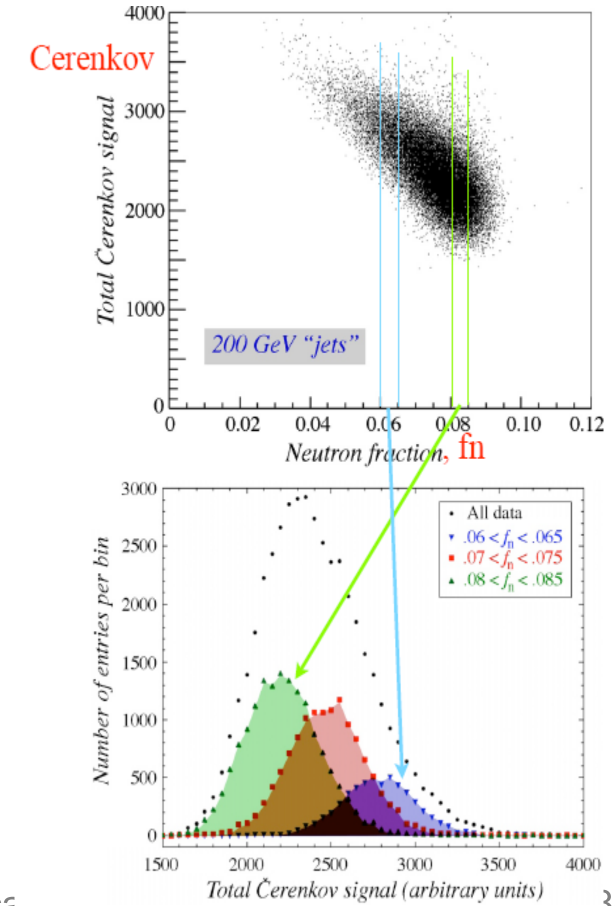
The neutron fraction is correlated to nuclear binding energy (invisible energy) ➔ next large source of fluctuations to attack

Neutron signal (f_n)= integral of scint signal over 20-40 ns

$$f_n = \frac{\int_{t=20\mathrm{ns}}^{40\mathrm{ns}} \sum_{i=2}^{19} S_i}{\int_{t=0}^{\infty} \sum_{i=1}^{19} S_i}$$



f_n anticorrelated with C as aspected



The total C distribution can be decomposed into its constituent parts as a function of f_n

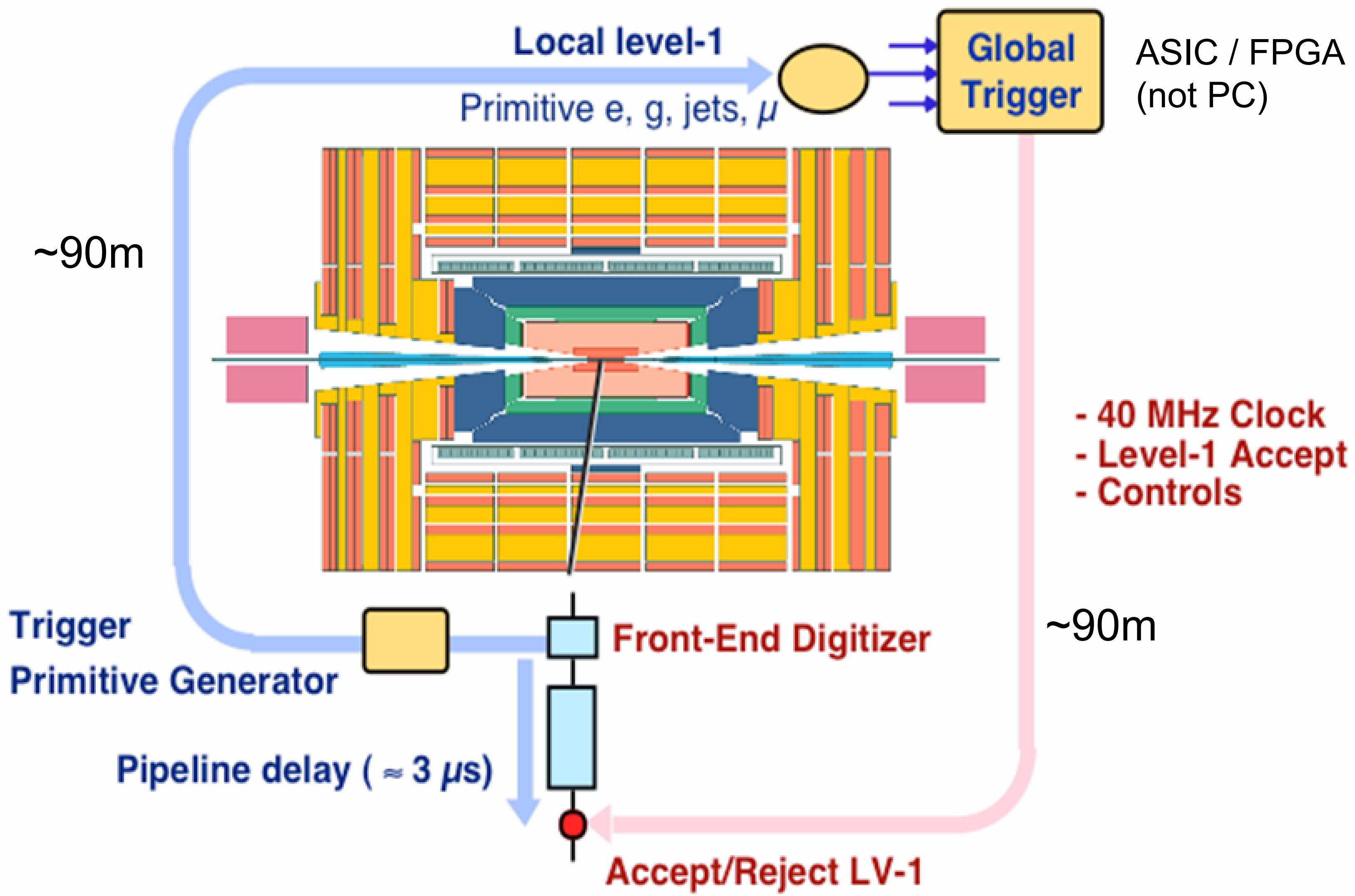
Acknowledgments

These slides are largely based on the work of:

John Hauptman, Greg Landsberg, Wesley H. Smith,
Mark Thompson, Richard Wigmans

backup

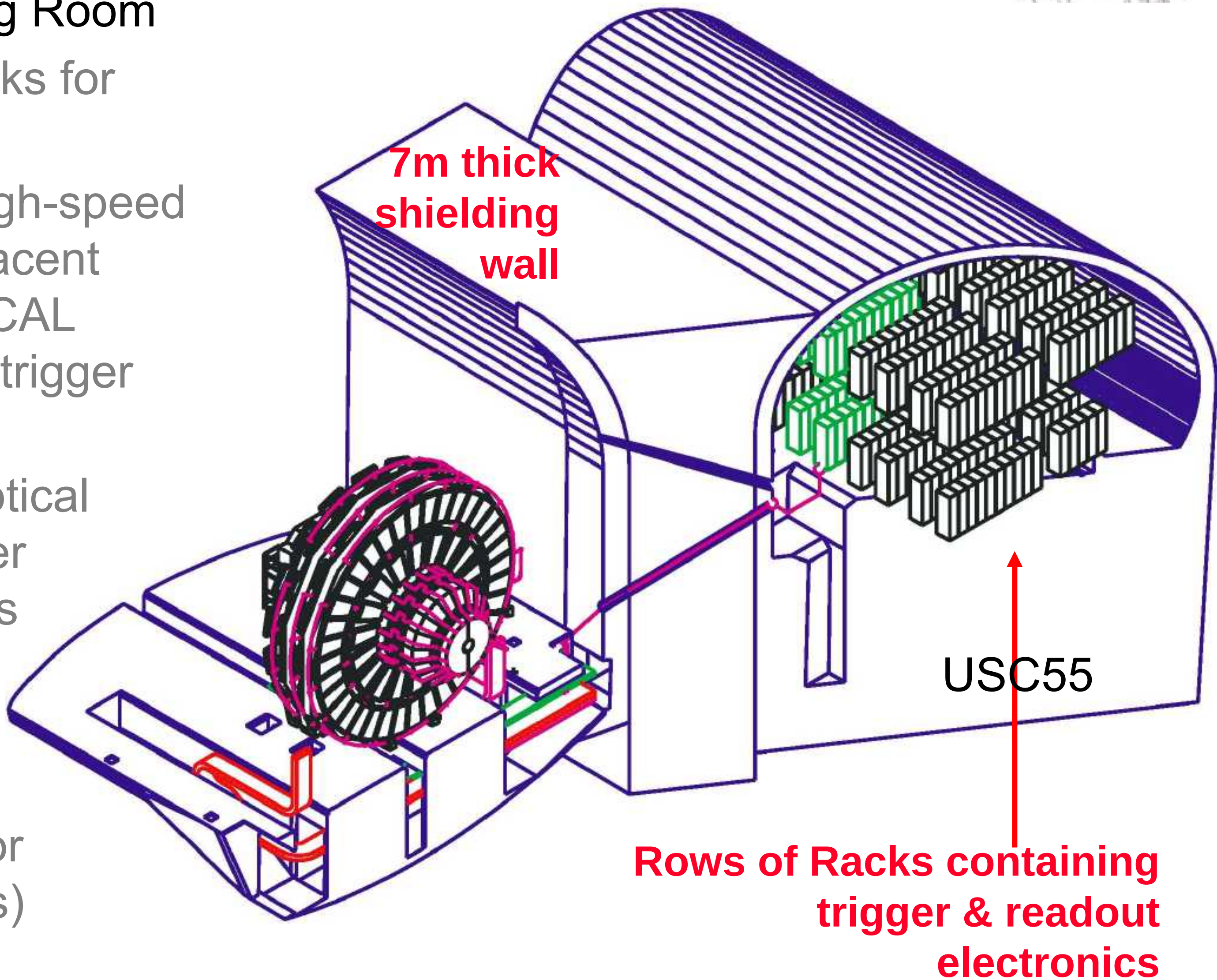
Level 1 Trigger Operation



L1 Trigger Locations

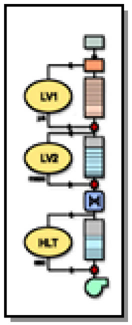
Underground Counting Room

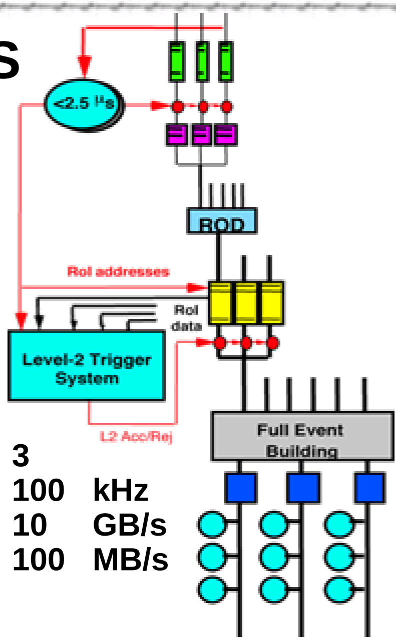
- Central rows of racks for trigger
- Connections via high-speed copper links to adjacent rows of ECAL & HCAL readout racks with trigger primitive circuitry
- Connections via optical fiber to muon trigger primitive generators on the detector
- Optical fibers connected via "tunnels" to detector (~90m fiber lengths)



Trigger & DAQ at LHC

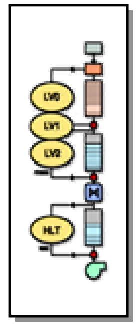
ATLAS

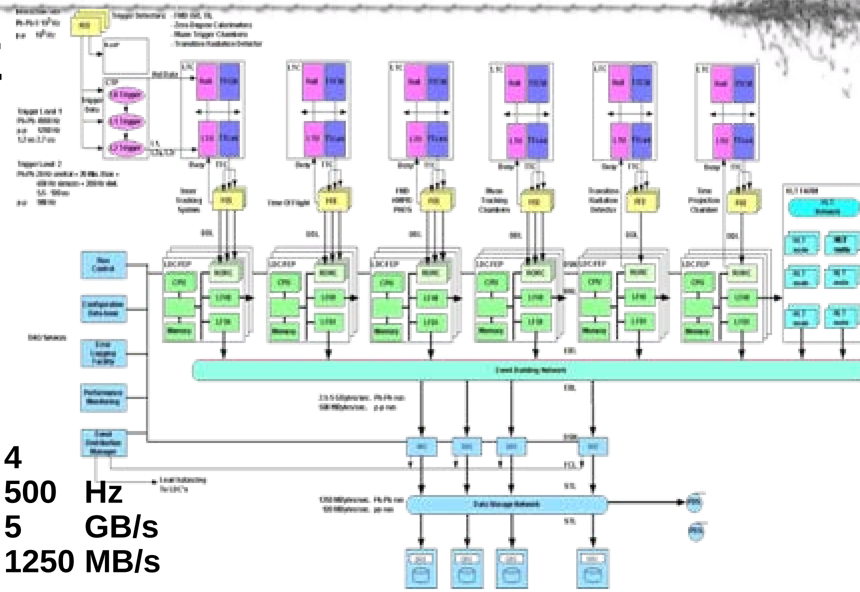




Levels	3	
LV-1 rate	100	kHz
Readout	10	GB/s
Storage	100	MB/s

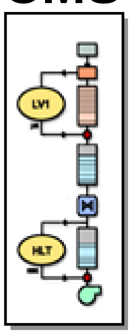
ALICE

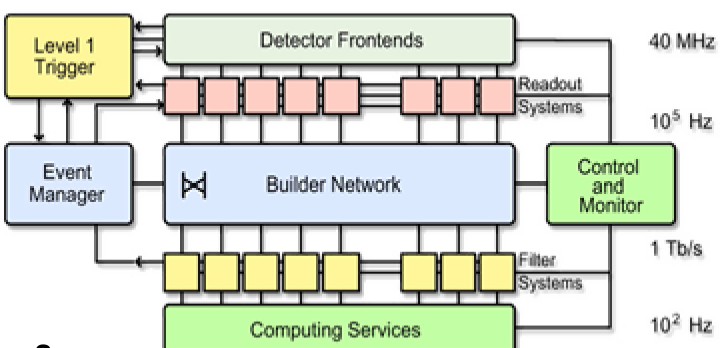




Levels	4	
LV-1 rate	500	Hz
Readout	5	GB/s
Storage	1250	MB/s

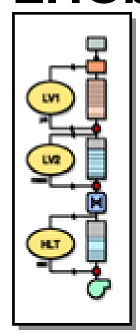
CMS





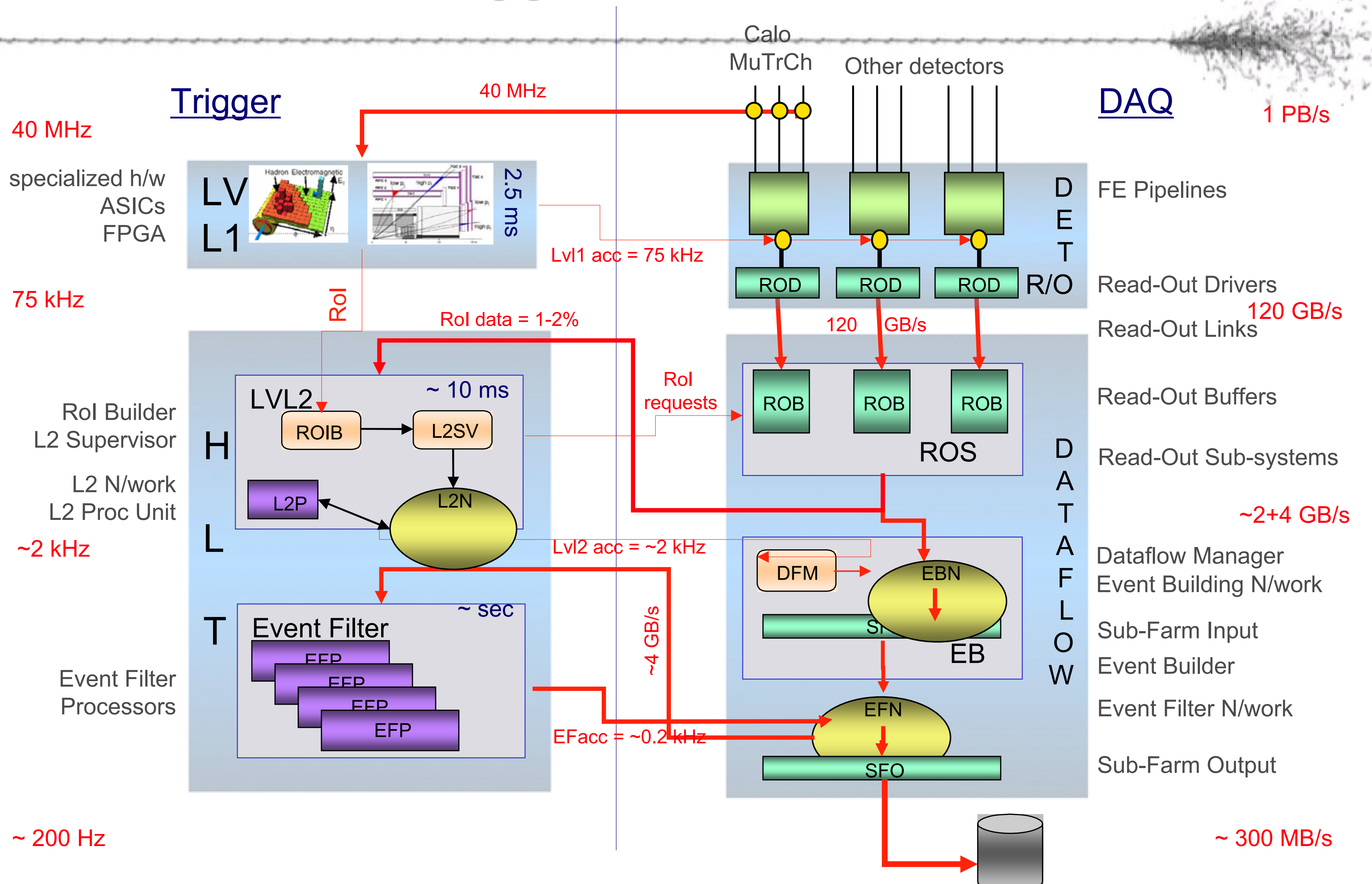
Levels	2	
LV-1 rate	100	kHz
Readout	100	GB/s
Storage	100	MB/s

LHCb



Levels	3	
LV-1 rate	1	MHz
Readout	4	GB/s
Storage	40	MB/s

ATLAS Trigger & DAQ Architecture



ATLAS LVL1 Trigger