# Metody eksperymentalne
# w fizyce wysokich energii

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## Wykład XI

- Systemy wyzwalania i zbierania danych

# Level-1 trigger

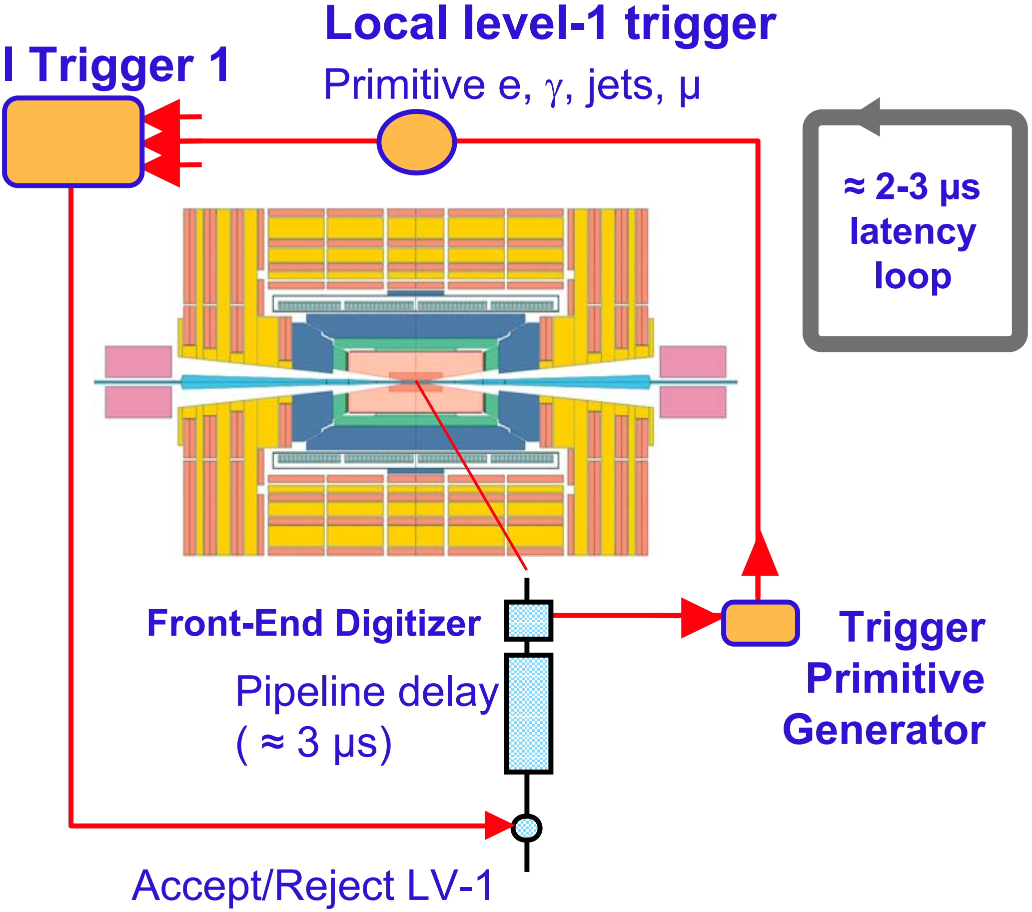
Najważniejsza i najtrudniejsza część układu wyzwalania
* bardzo mało czasu na podjęcie decyzji
* możliwe tylko najprostsze operacje na danych:
    - dodawanie
    - mnożenie
    - adresowanie pamięci (!)
        => jedyny sposób na wykonanie bardziej złożonych operacji to policzyć wcześniej wszystkie możliwości i zapisac w LUT (Look-Up Table)

* musimy wprowadzać uproszczenia
    (ograniczenie strumienia danych => przestrzeni adresowej)
* musimy się pogodzić z dużymi błędami

* najważniejsza jest efektywność (czystość zapewnimy potem)

# Level-1 Trigger: decision loop

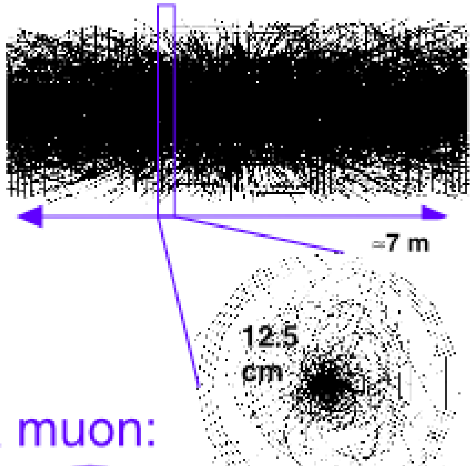
- Synchronous 40 MHz digital system
  - Typical: 160 MHz internal pipeline
  - Latencies:
    - Readout + processing: < 1μs
    - Signal collection & distribution: ≈ 2μs
- At Lvl-1: process only calo+μ info



# ATLAS and CMS Strategy

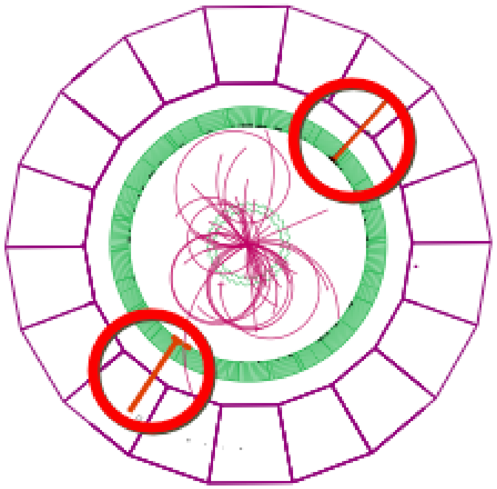
## Level-1 : only calorimeters & muons ....

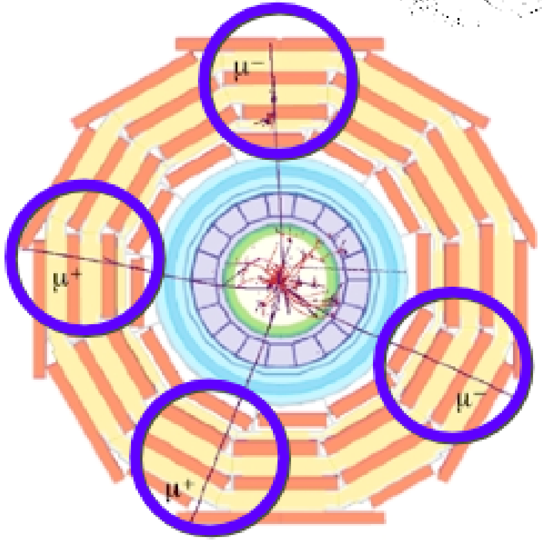
Compare to Central tracking at L = $10^{34}$
(50 ns integration, ≈1000 tracks)



Algorithm Complexity
+
huge amount of data

Pattern recognition much easier on calo & muon:





Complexity handled in software on CPUs

# Level-1 trigger

Wykorzystuje tylko niewielką część informacji płynącej z detektora:

- dające możliwość szybkiego odczytu
- niosące najważniejsze informacje
- proste do przetworzenia
  (nie ma możliwości wykonywania skomplikowanych obliczeń, np. dopasowywania toru)

Często odczytujemy tylko podpróbke pomiarów z danego detektora lub sumaryczne wyniki (bez pełnej granulacji)

Pełny przypadek czeka w buforach elektroniki odczytowej na decyzję globalnego układu wyzwalania!

# Pipelined Readout

[ Drawing by Nick Ellis (CERN), 2006 ]

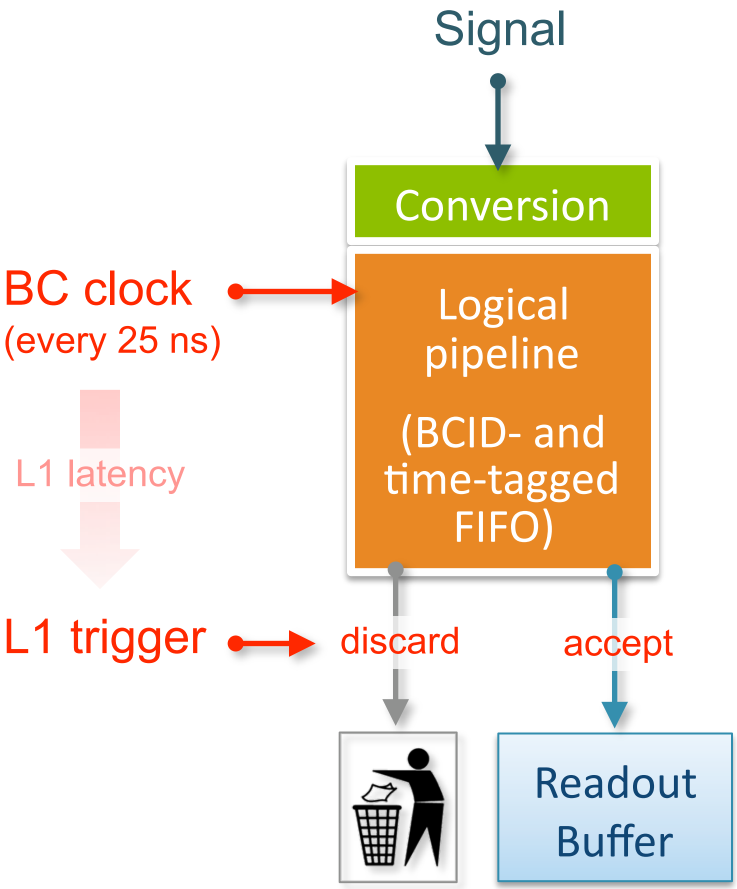
The information from each BC, for each detector element, is retained during the latency of the L1 trigger (few $\mu$s)

The information retained may be in several forms

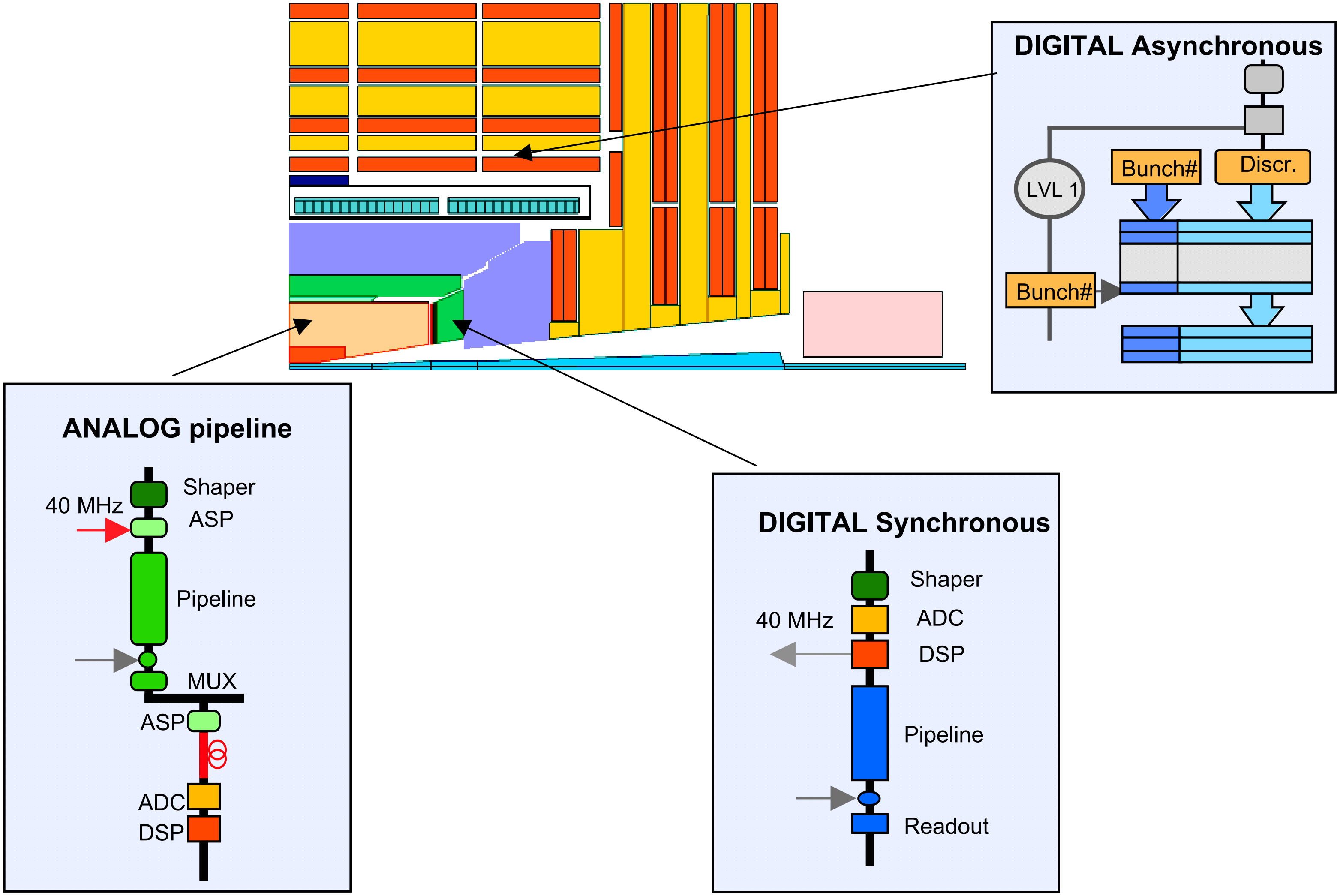
- Analogue level (held on capacitor)
- Digital value (*e.g.* ADC result)
- Binary value (*i.e.* hit / no hit)

Data reaching end of pipeline is either discarded (large majority of events) or accepted by trigger

Pipelined readout already used at HERA and Tevatron, NA48, BABAR, …

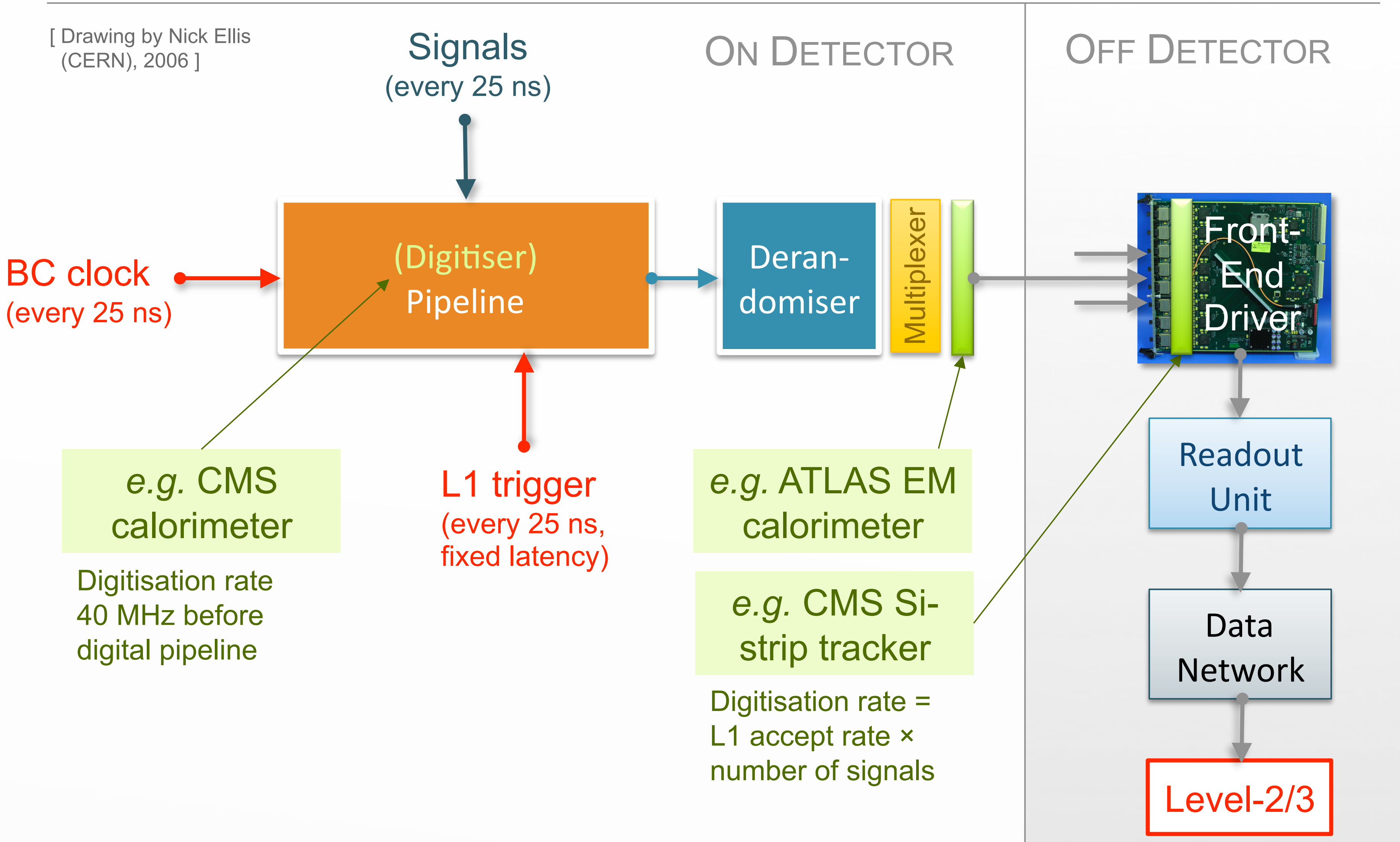


# Detector Readout: front-end types



# Digitisation Options

[ Drawing by Nick Ellis (CERN), 2006 ]



Signals
(every 25 ns)

ON DETECTOR

OFF DETECTOR

BC clock
(every 25 ns)

(Digitiser)
Pipeline

Deran-
domiser

Multiplexer

Front-
End
Driver

Readout
Unit

Data
Network

Level-2/3

L1 trigger
(every 25 ns, fixed latency)

*e.g.* CMS calorimeter

Digitisation rate 40 MHz before digital pipeline

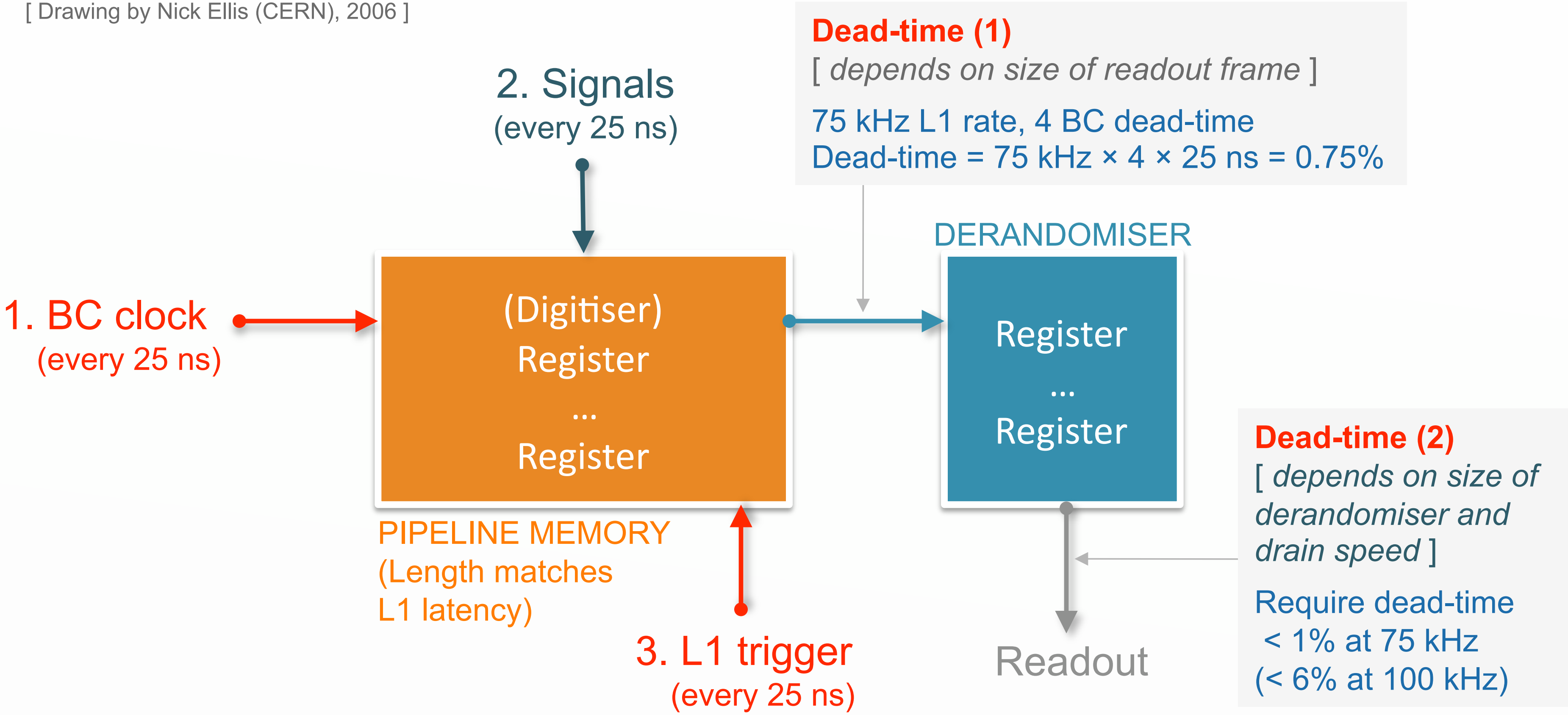
*e.g.* ATLAS EM calorimeter

*e.g.* CMS Si-strip tracker

Digitisation rate = L1 accept rate × number of signals

# Dead-time (here ATLAS)

[ Drawing by Nick Ellis (CERN), 2006 ]



2. Signals
(every 25 ns)

1. BC clock
(every 25 ns)

(Digitiser)
Register
…
Register

PIPELINE MEMORY
(Length matches
L1 latency)

3. L1 trigger
(every 25 ns)

**Dead-time (1)**
[ *depends on size of readout frame* ]

75 kHz L1 rate, 4 BC dead-time
Dead-time = 75 kHz × 4 × 25 ns = 0.75%

DERANDOMISER

Register
…
Register

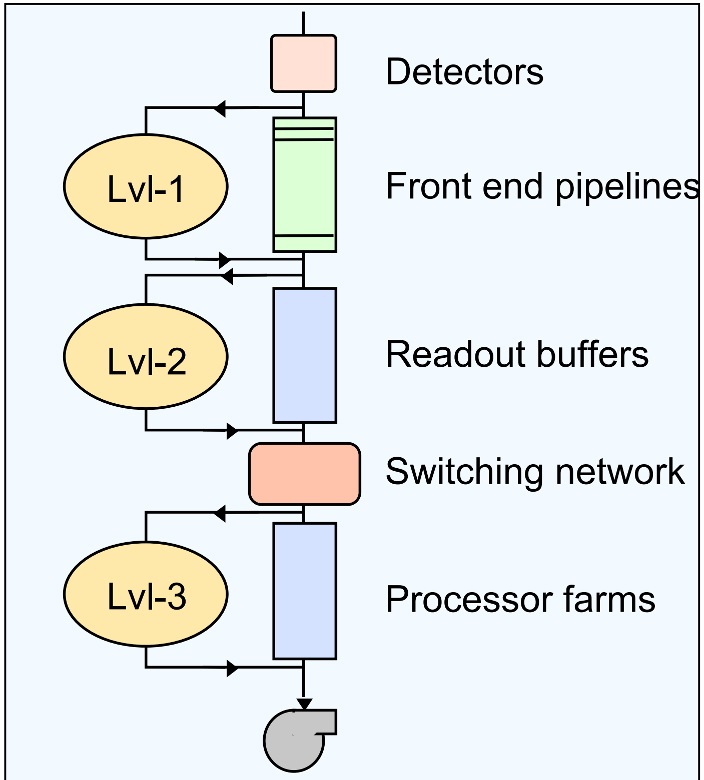
Readout

**Dead-time (2)**
[ *depends on size of derandomiser and drain speed* ]

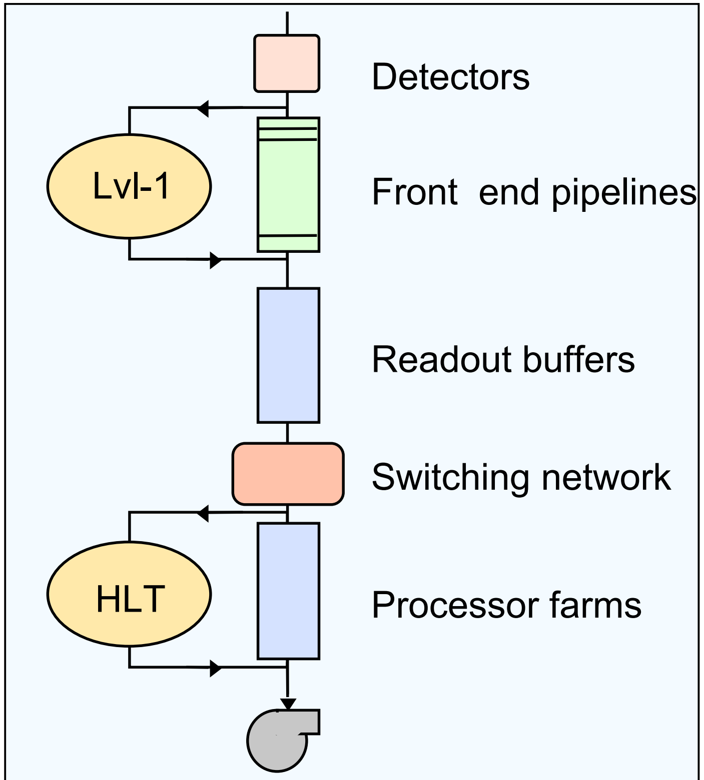
Require dead-time
< 1% at 75 kHz
(< 6% at 100 kHz)

# Online Selection Flow in pp

- Level-1 trigger: reduce 40 MHz to $10^5$ Hz
  - This step is always there
  - Upstream: still need to get to $10^2$ Hz; in 1 or 2 extra steps



“Traditional”: 3 physical levels



CMS: 2 physical levels

# Higher Level Triggers at the LHC

Data are transferred to large buffer memories after a Level-1 accept

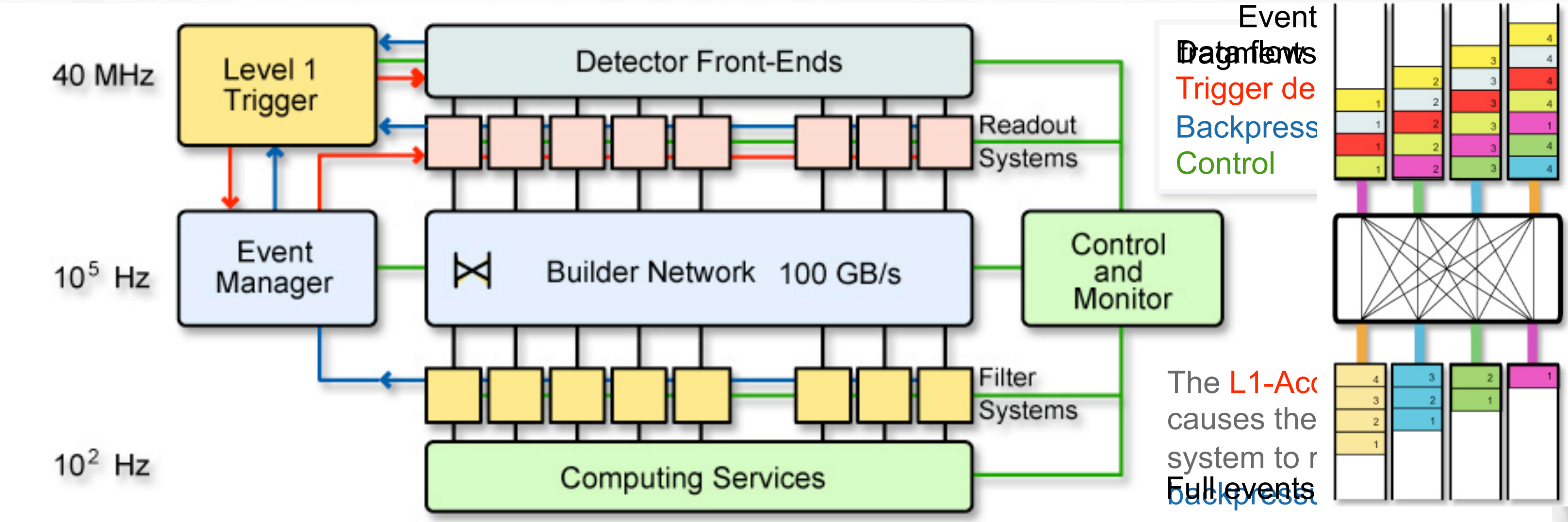
➠ The subsequent stages should not introduce further dead-time

The data rates at the HLT/DAQ input are still massive

- ~1 MB event size at ~100 kHz event rate → 100 GB/s data rate (*i.e.* 800 Gbit/s)

This is far beyond the capacity of the bus-based event building of LEP

- Use network-based event building to avoid bandwidth bottlenecks



**No node in the system sees the full data rate — each Readout System covers only a part of the detector — each Filter System deals with only a fraction of the events**

# HLT and DAQ: Concepts

The massive data rate after L1 poses problems even for network-based event building — different solutions have been adopted to address this

In CMS, the event building is factorized into a number of slices each of which sees only a fraction of the rate

- Requires large total network bandwidth (→ cost), but avoids need for a very large single network switch

In ATLAS, the Region-of-Interest (RoI) mechanism is used to access the data selectively – only move data needed for Level-2 processing

- Reduces by a substantial factor the amount of data that needs to be moved from the readout systems to the processors
- Implies relatively complicated mechanisms to serve the data selectively to the Level-2 trigger processors → more complex software

# Level-2 trigger

Mimo redukcji częstości zdarzeń czas wciąż jest ograniczeniem.
Nie ma szans na pełną, globalną analizę przypadku...

Częstym podejściem jest sprawdzenie decyzji Level-1 trigger, czyli powtórzenie tych samych/podobnych cięć w oparciu o pełniejszą informację z detektora (lepsza granulacja, kalibracja itp.)

Wciąż uproszczone algorytmy, działające na poziomie pojedynczych detektorów.

Lokalnie możliwe łączenie informacji z różnych detektorów.

Czasami dodajemy cięcia, na które nie było czasu na pierwszym poziomie (redukcja tła).

# Selective Readout Concepts

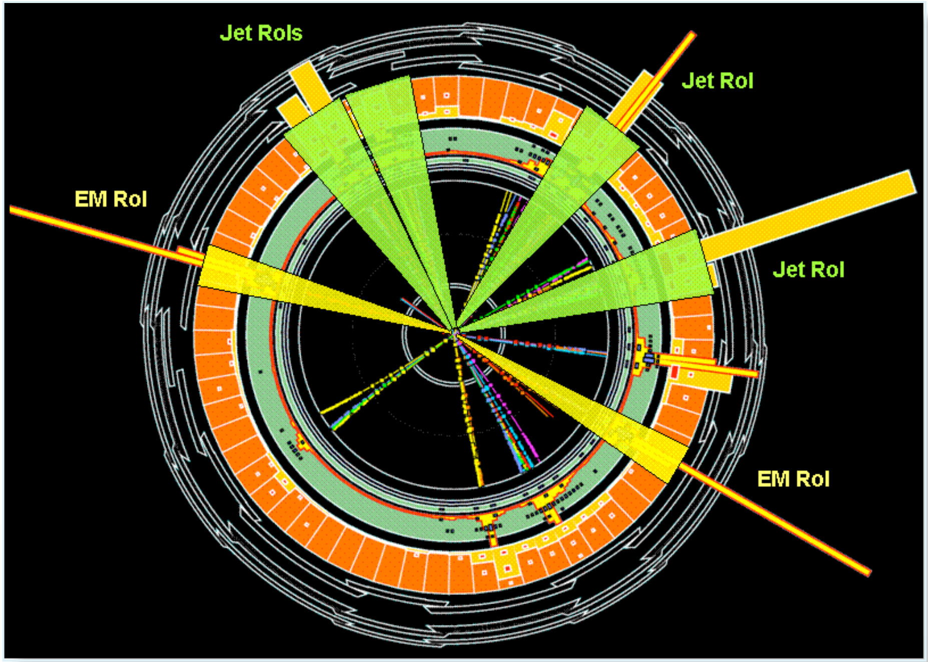
Two concepts are used to select data subsets from the readout systems

*Region-of-Interest* concept (ATLAS, LHCb):

- L1 indicates the geographical location of candidate objects, *e.g.* EM clusters
- L2 only accesses data from RoIs, small fraction of total data

*Sequential-selection* concept (ATLAS, CMS):

- Data are accessed by L2 initially only from a subset of detectors (*e.g.* muon systems and calorimeters)
- Many events rejected without accessing, *e.g.*, inner detector



# RoI Mechanism

**LVL1 triggers on high $p_T$ objects**

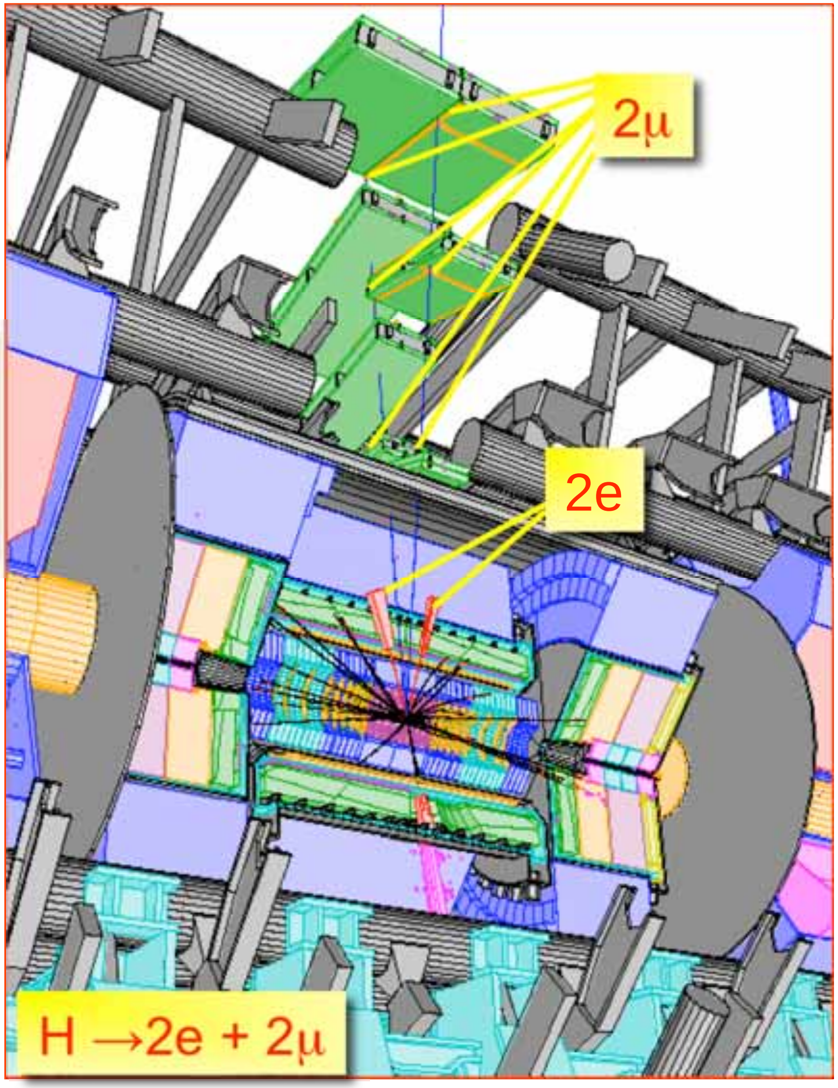
- **Caloriemeter cells and muon chambers to find e/γ/τ-jet-μ candidates above thresholds**

LVL2 uses Regions of Interest as identified by Level-1

- Local data reconstruction, analysis, and sub-detector matching of RoI data

The total amount of RoI data is minimal

- ~2% of the Level-1 throughput but it has to be extracted from the rest at 75 kHz



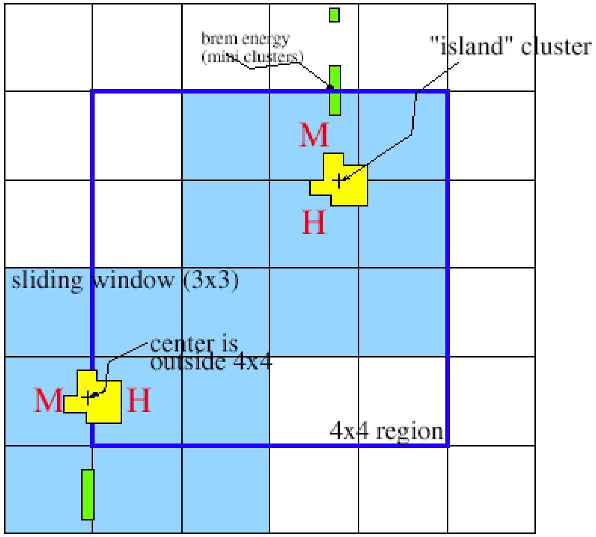
# Example: electron selection (I)

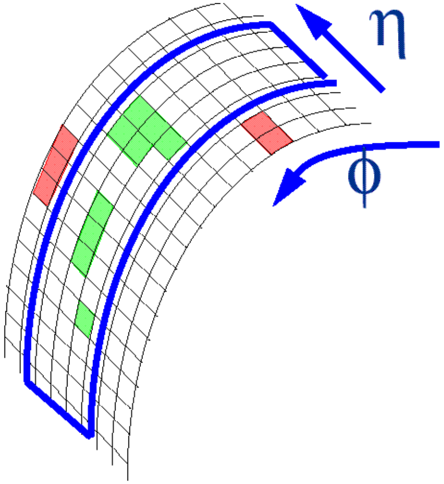
- “Level-2” electron:
  - 1-tower margin around 4x4 area found by Lvl-1 trigger
  - Apply “clustering”
  - Accept clusters if H/EM < 0.05
  - Select highest $E_T$ cluster

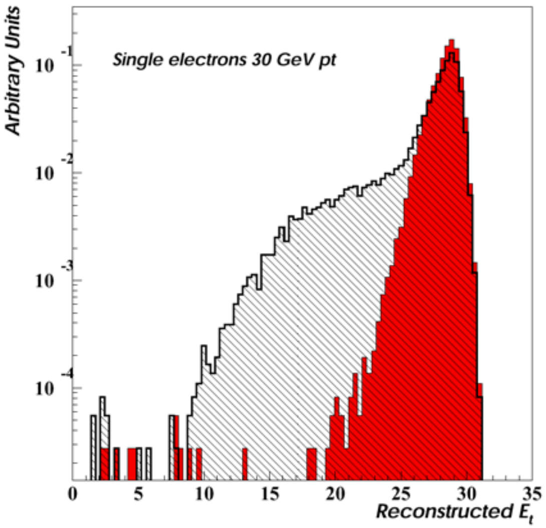
- Brem recovery:
  - Seed cluster with $E_T > E_T^{min}$
  - Road in $\phi$ around seed
  - Collect all clusters in road

  → “supercluster”

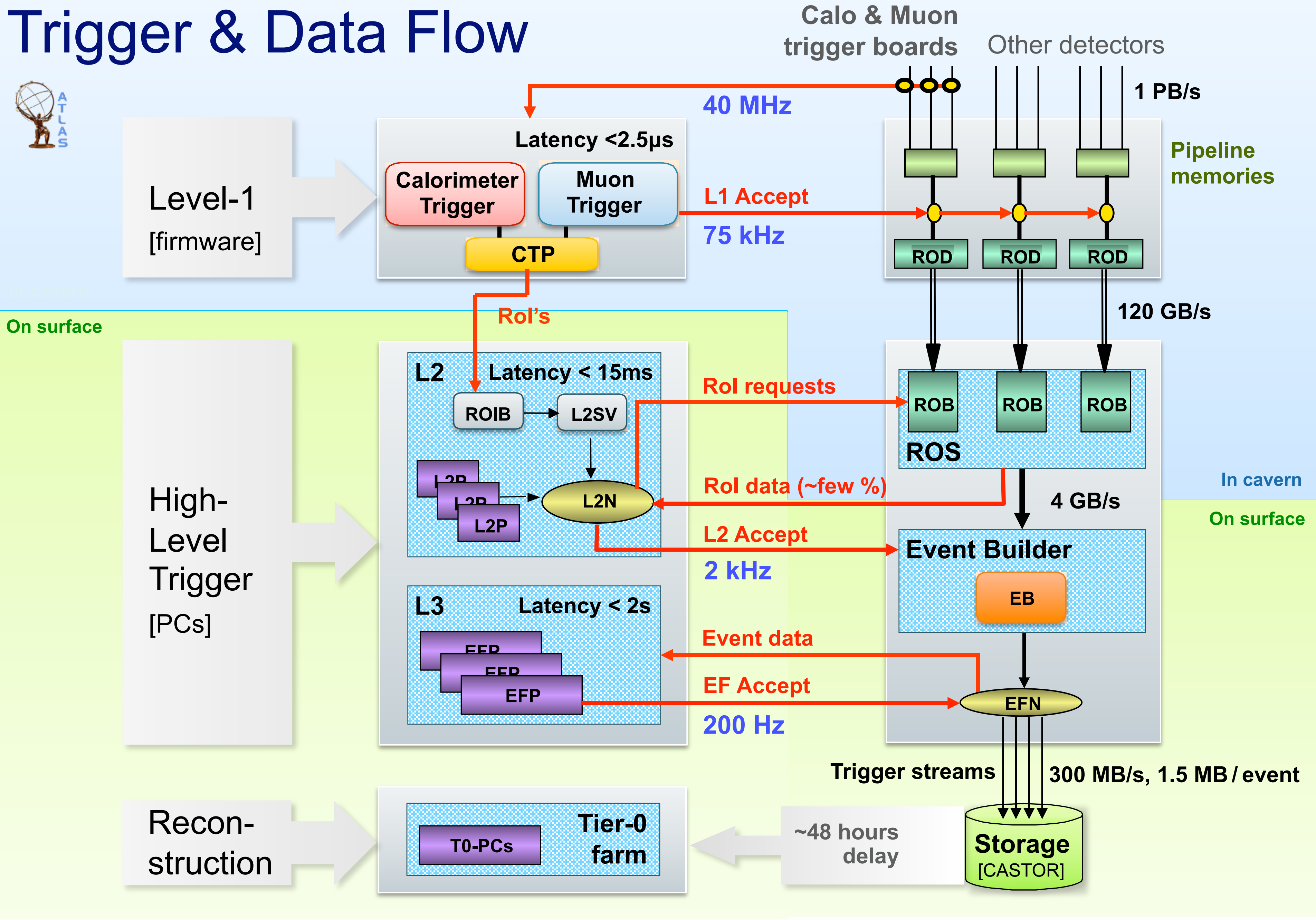
  and add all energy in road:







# Trigger & Data Flow



Calo & Muon trigger boards

Other detectors

1 PB/s

40 MHz

Pipeline memories

Level-1 [firmware]

Latency <2.5μs

Calorimeter Trigger

Muon Trigger

CTP

L1 Accept

75 kHz

ROD

ROD

ROD

120 GB/s

In cavern

On surface

RoI's

High-Level Trigger [PCs]

L2

Latency < 15ms

ROIB

L2SV

L2P

L2P

L2P

L2N

RoI requests

ROB

ROB

ROB

ROS

RoI data (~few %)

4 GB/s

In cavern

On surface

L2 Accept

2 kHz

Event Builder

EB

L3

Latency < 2s

EFP

EFP

EFP

Event data

EF Accept

200 Hz

EFN

Trigger streams

300 MB/s, 1.5 MB / event

Recon-struction

T0-PCs

Tier-0 farm

~48 hours delay

Storage [CASTOR]

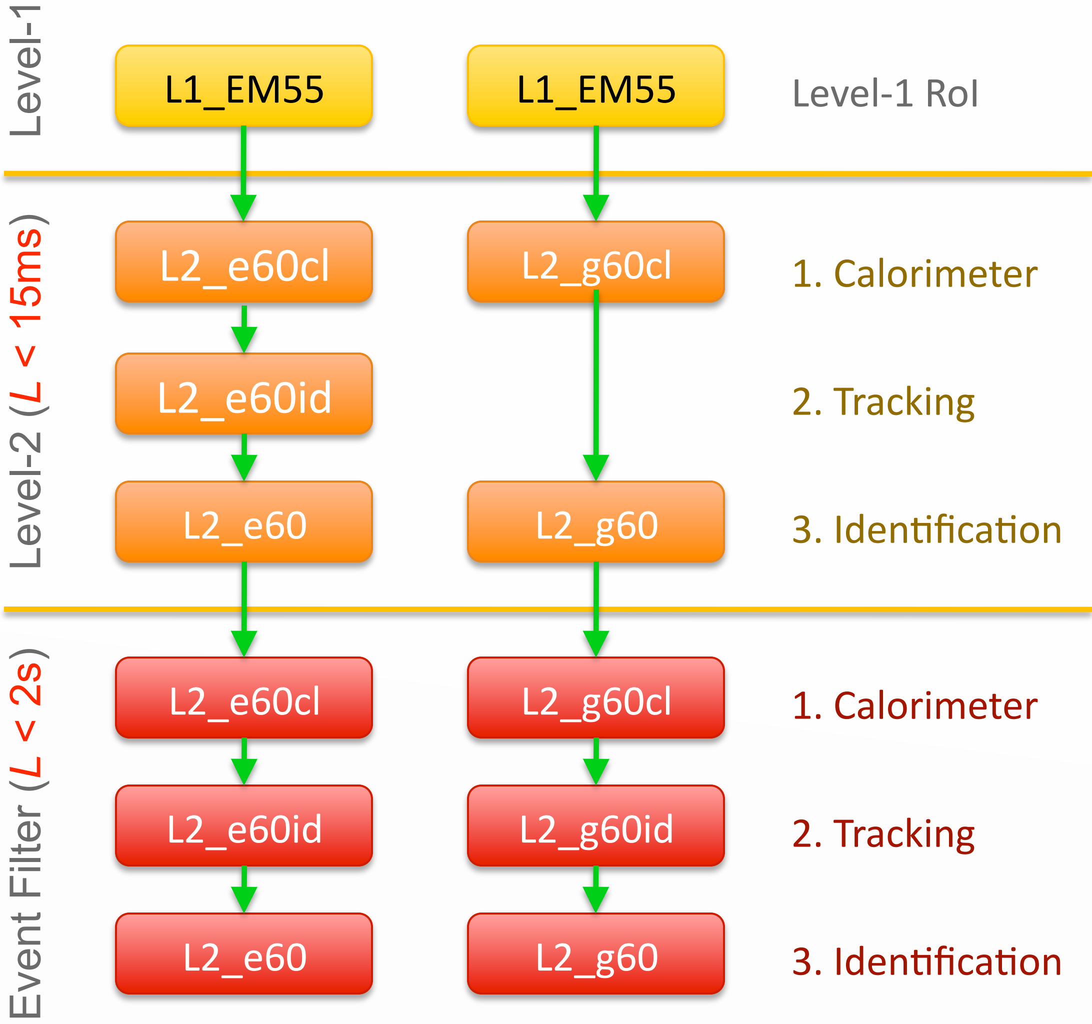
# HLT Trigger Lines

## Example for "e60" and "g60" signature chains in ATLAS

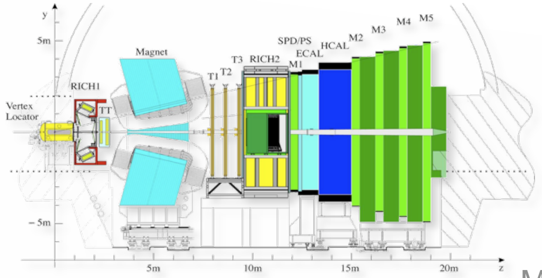
The early reject algorithm benefits from separating HLT algorithms into steps

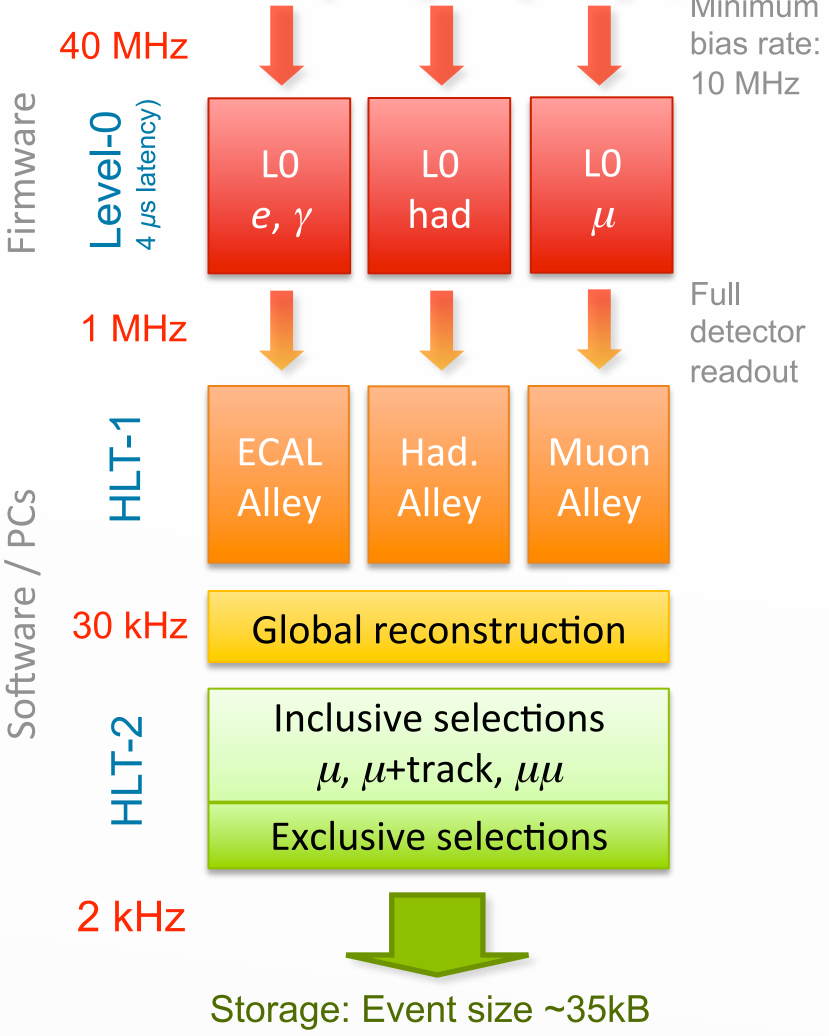
- Each one requesting additional detector data or performing reconstruction, followed by a hypothesis algorithm
- As soon as one steps is unsuccessful, the trigger line is stopped

Compare to full event reconstruction $O$(10s) per event



# LHCb Trigger





40 MHz

Minimum bias rate: 10 MHz

Firmware

Level-0
4 $\mu s$ latency)

L0 $e, \gamma$

L0 had

L0 $\mu$

1 MHz

Full detector readout

Software / PCs

HLT-1

ECAL Alley

Had. Alley

Muon Alley

30 kHz

Global reconstruction

HLT-2

Inclusive selections
$\mu$, $\mu$+track, $\mu\mu$

Exclusive selections

2 kHz

Storage: Event size ~35kB

## Level-0 Firmware Trigger

**Search for high-$p_T$ $\mu$, e, $\gamma$, $h$ candidates, veto pile-up**

### Calorimeter Trigger:

- Energy in 2x2 cell clusters
- PID from ECAL / HCAL energy / PS and SPD information

### Muon Trigger:

- Straight line search in M2-M5
- Look for compatible hits in M1 (before calorimeters)
- $p_T$ from a look-up table

---

## High-Level Trigger

### HLT-1:

- RoIs around L0 candidate (*alleys*)
- Confirm L0 candidate on tracker, VELO

### HLT-2:

- Search for all tracks using VELO segments as seeds
- Inclusive selection based on few tracks
- Exclusive selection of ~100 final states

# Higher Level Trigger

Na ostatnim poziomie mamy już dość czasu na pełną rekonstrukcję. Zakładając, że dysponujemy odpowiednią liczbą CPU...

Możemy przeanalizować wszystkie dane, łącząc informacje z różnych detektorów (podejście globalne).

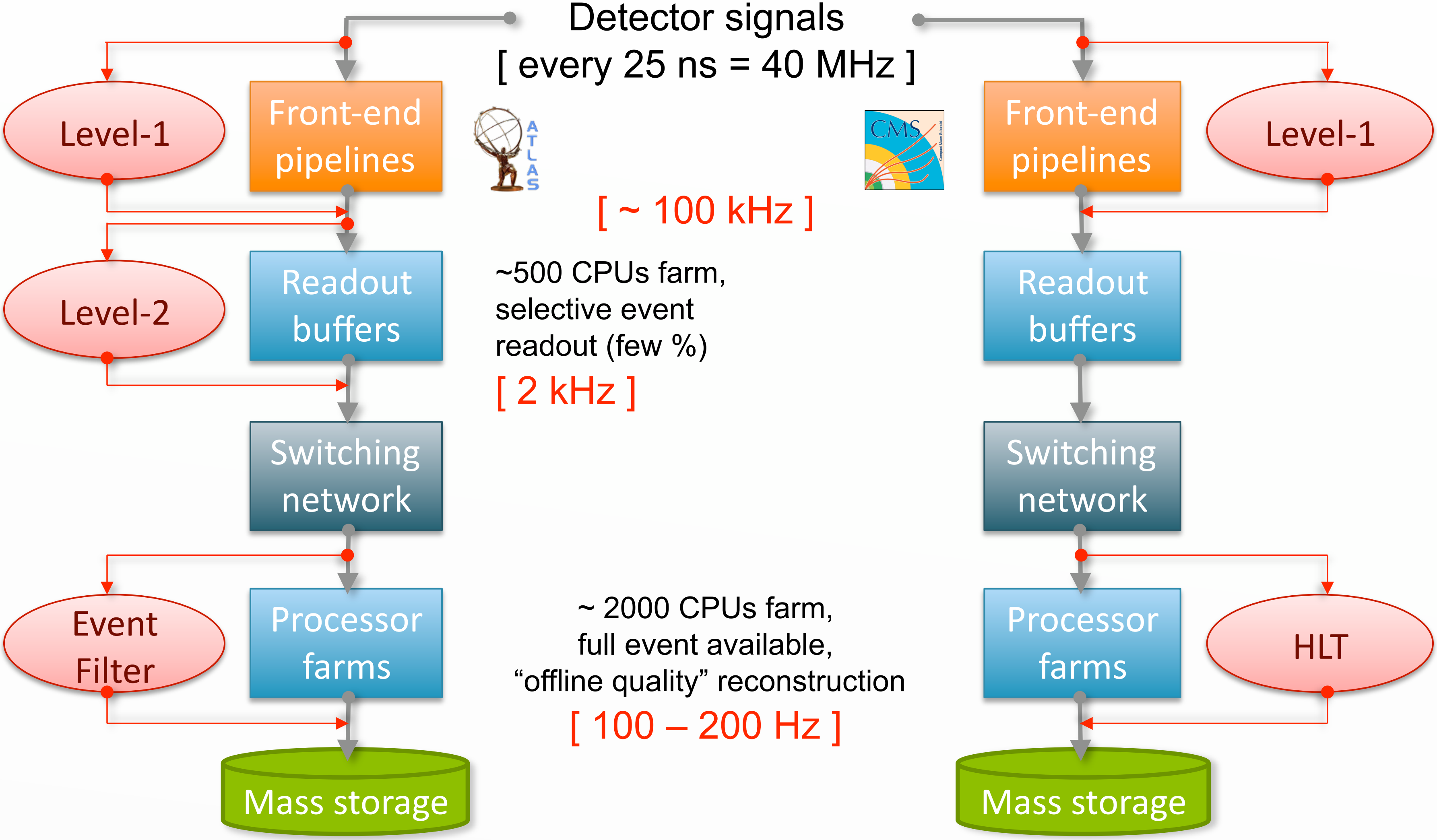
Korzystamy z pełnych kodów rekonstrukcji przypadków, wciąż przybliżone mogą być jednak parametry (kalibracja, alignment).

ale

Zanim przypadki zostaną przeanalizowane na poziomie HLT, dane z poszczególnych detektorów muszą zostać zsynchronizowane i połączone w przypadki.

Trzeba to zrobić nie hamując przepływu danych !

# ATLAS and CMS HLT Concepts



Detector signals
[ every 25 ns = 40 MHz ]

[ ~ 100 kHz ]

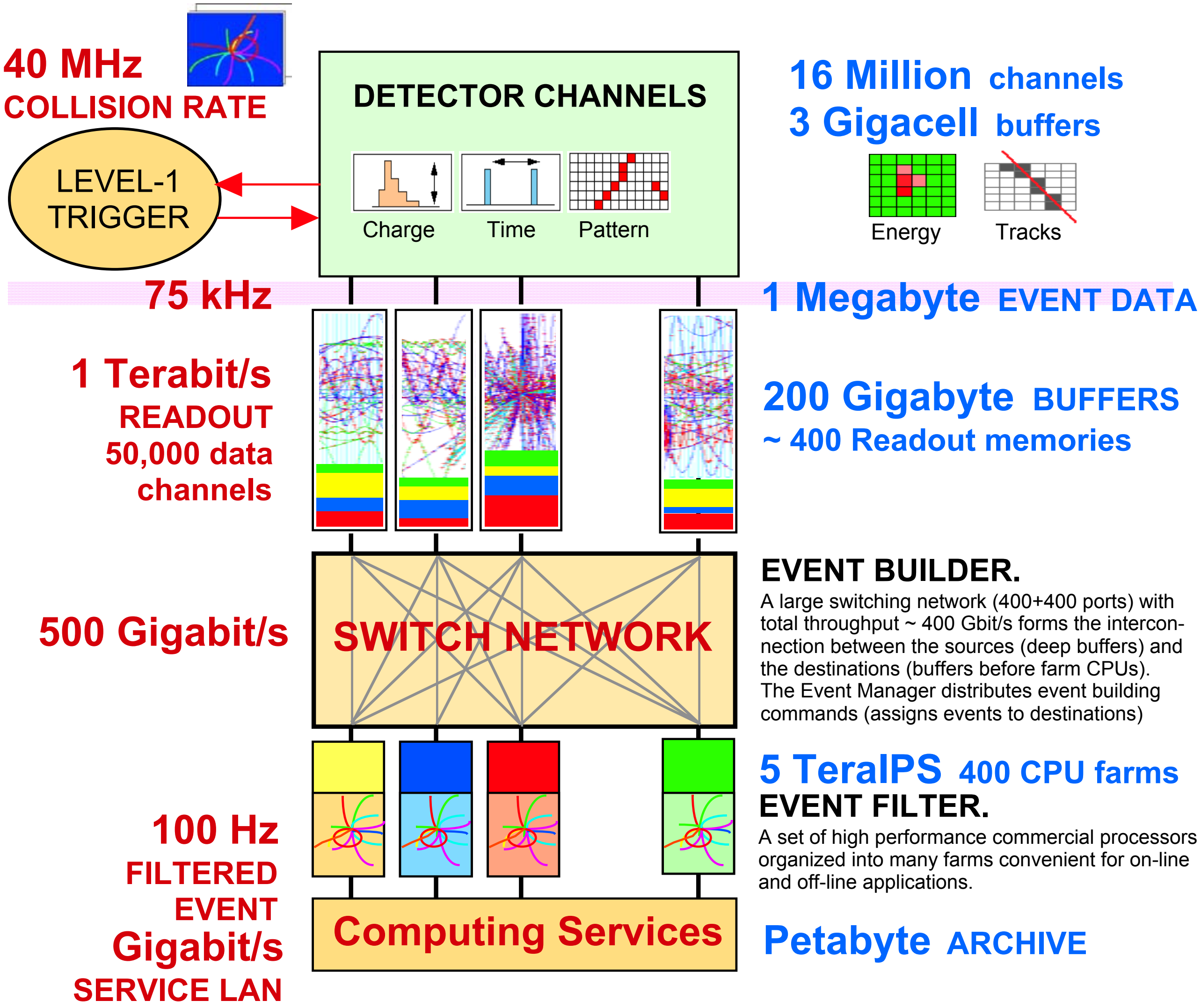
~500 CPUs farm,
selective event
readout (few %)

[ 2 kHz ]

~ 2000 CPUs farm,
full event available,
“offline quality” reconstruction

[ 100 – 200 Hz ]

# Online Selection Flow in pp (II)



**40 MHz**
**COLLISION RATE**

LEVEL-1 TRIGGER

**DETECTOR CHANNELS**

Charge Time Pattern

**16 Million channels**
**3 Gigacell buffers**

Energy Tracks

**75 kHz**

**1 Megabyte EVENT DATA**

**1 Terabit/s**
**READOUT**
**50,000 data channels**

**200 Gigabyte BUFFERS**
**~ 400 Readout memories**

**500 Gigabit/s**

**SWITCH NETWORK**

**EVENT BUILDER.**
A large switching network (400+400 ports) with total throughput ~ 400 Gbit/s forms the interconnection between the sources (deep buffers) and the destinations (buffers before farm CPUs). The Event Manager distributes event building commands (assigns events to destinations)

**5 TeraIPS 400 CPU farms**

**EVENT FILTER.**
A set of high performance commercial processors organized into many farms convenient for on-line and off-line applications.

**100 Hz**
**FILTERED EVENT**

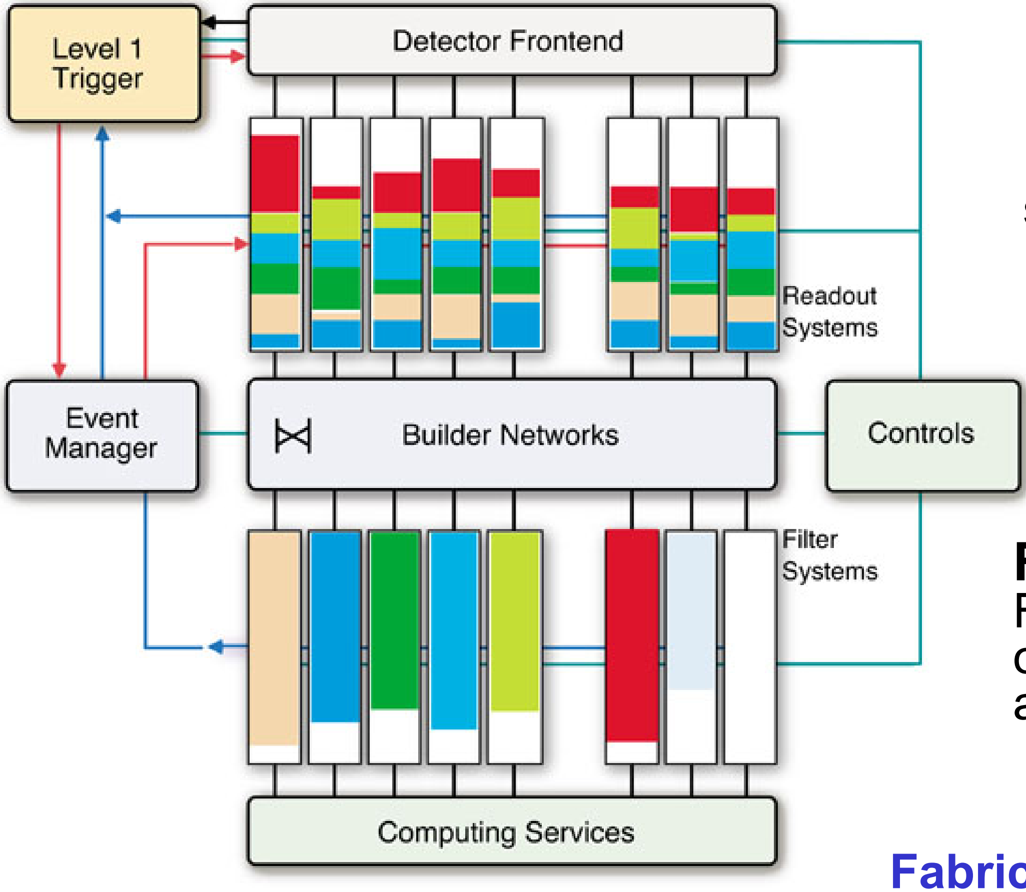
**Gigabit/s**
**SERVICE LAN**

**Computing Services**

**Petabyte ARCHIVE**

# Event Building

- Form full-event-data buffers from fragments in the readout. Must interconnect data sources/destinations.



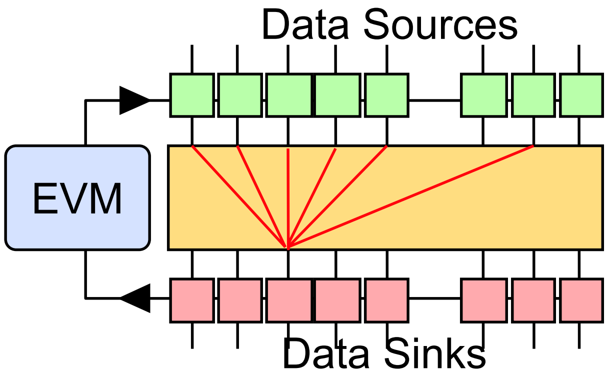
**Event fragments :**
Event data fragments are stored in separated physical memory systems

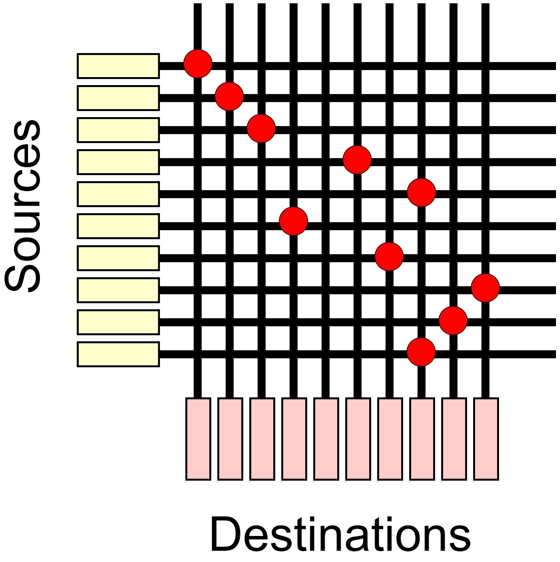
**Full events :**
Full event data are stored into one physical memory system associated to a processing unit

**Hardware:**
**Fabric of switches** for builder networks
**PC motherboards** for data Source/Destination nodes

# Event Building via a Switch

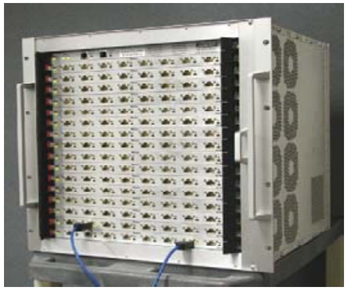
- Three major issues:
  - Link utilization
  - The bottleneck on the outputs
  - The large number of ports needed
- Space-division: crossbar
  - Simultaneous transfers between any arbitrary set of inputs and outputs
    - Can be both self-routing and arbiter-based (determine connectivity between S's and D's for each cycle); the faster the fabric, the smaller the arbitration complexity
    - Does not solve Output Contention issue
    - Need *Traffic Shaping*



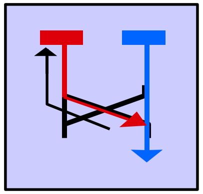


# Switching technologies

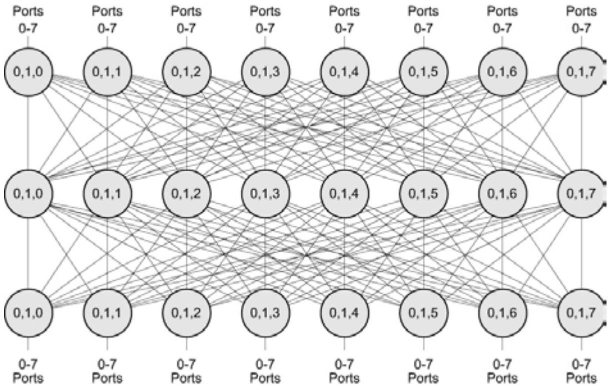
## Myricom: Myrinet 2000



- Switch: **Clos-128 @ 2.5** Gb/s ports
- **NIC**: M3S-PCI64B-2 (**LANai9**)
- **Custom Firmware**

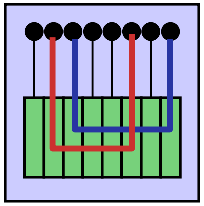


**wormhole data**
transport with flow
control at all stages

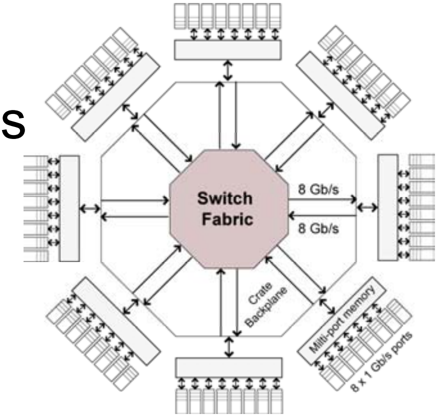


## Gigabit Ethernet

- Switch: Foundry **FastIron64 @ 1.2** Gb/s ports
- **NIC**: **Alteon** (running standard firmware)



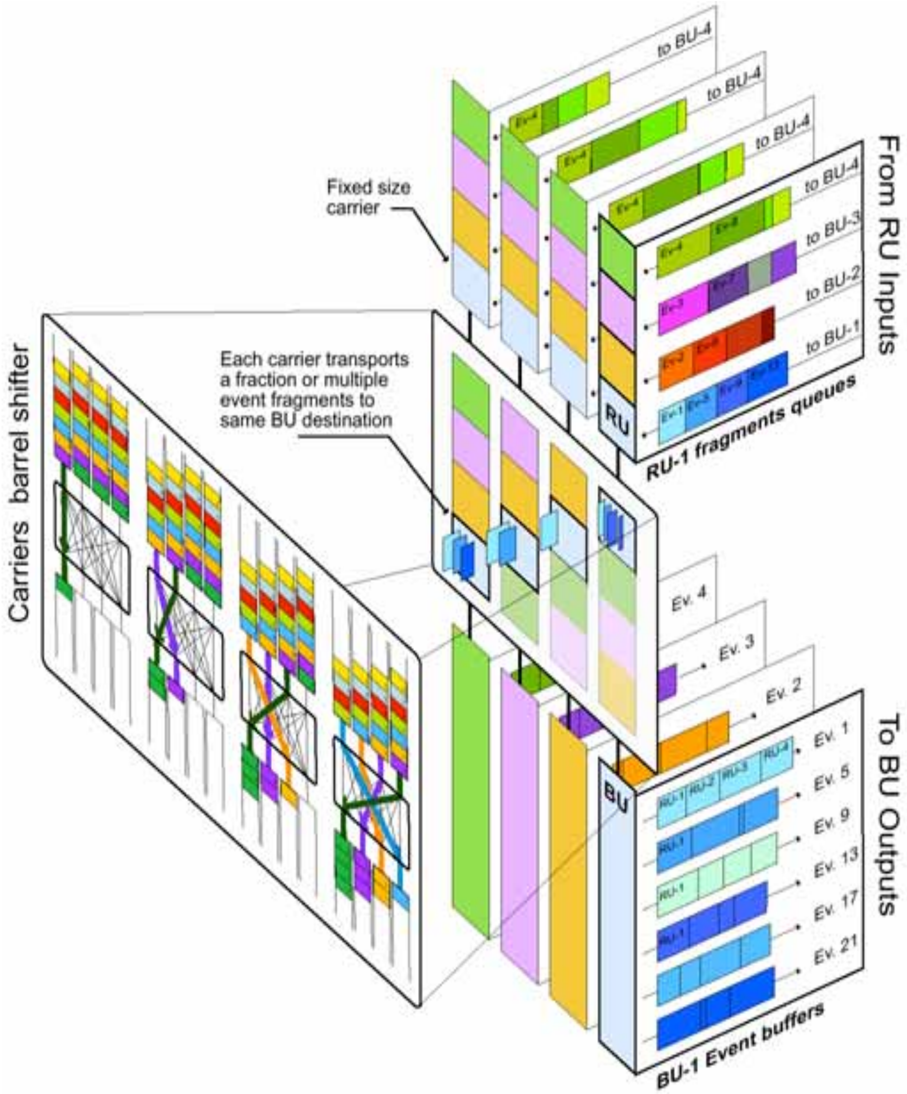
**Implementation:**
Multi-port memory system R/W bandwidth greater than sum of all port speeds
**Packet switching**
Contention resolved by Output buffer.
Packets can be lost.



## Infiniband

- 2.5 Gb/s demo products. First tests completed recently.

# Myrinet Barrel-Shifter



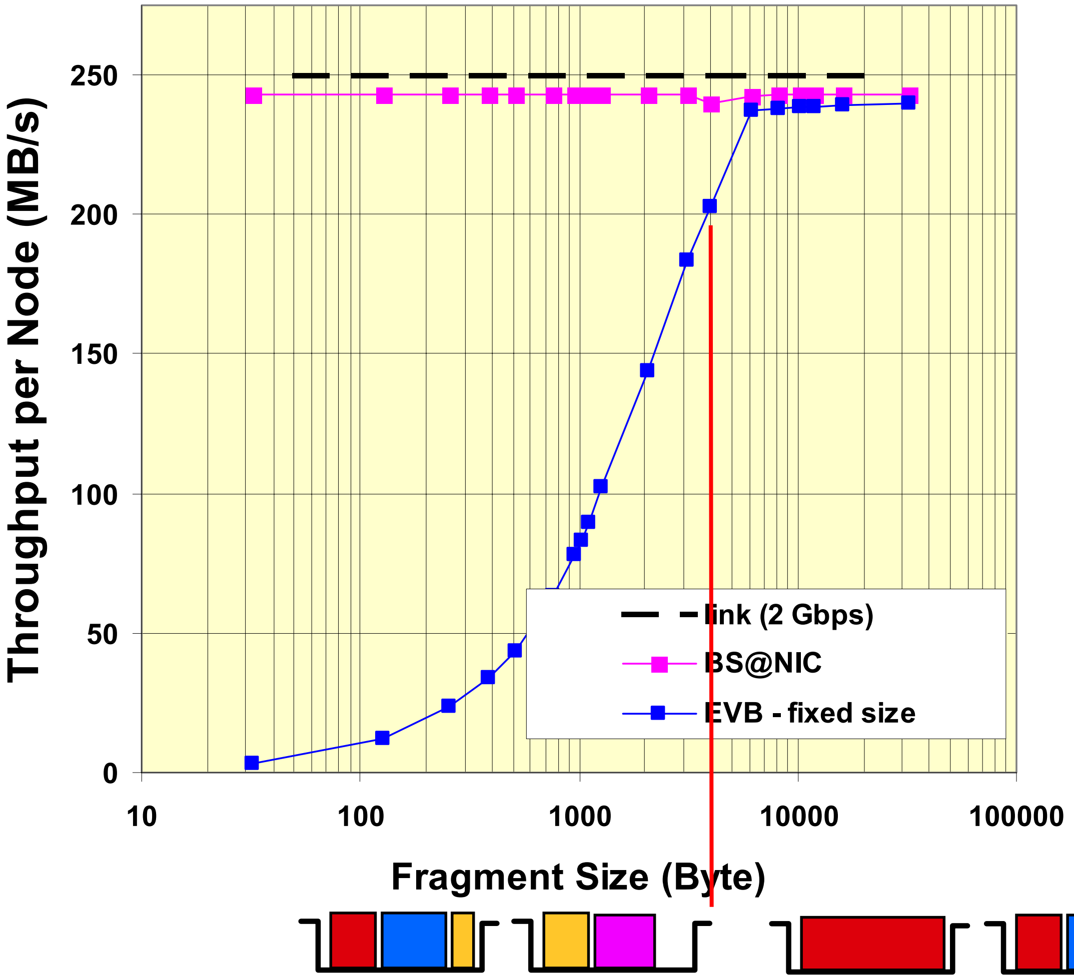
BS **implemented in firmware**

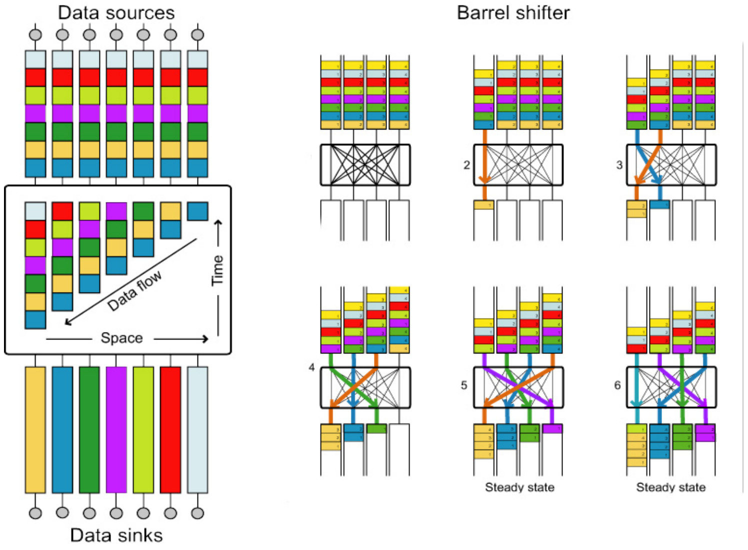
- Each source has message queue per destination
- Sources divide messages into fixed size packets (carriers) and cycle through all destinations
- Messages can span more than one packet and a packet can contain data of more than one message
- No external synchronization (relies on Myrinet back pressure by HW flow control)

zero-copy, **OS-bypass**

**principle works** for multi stage switches

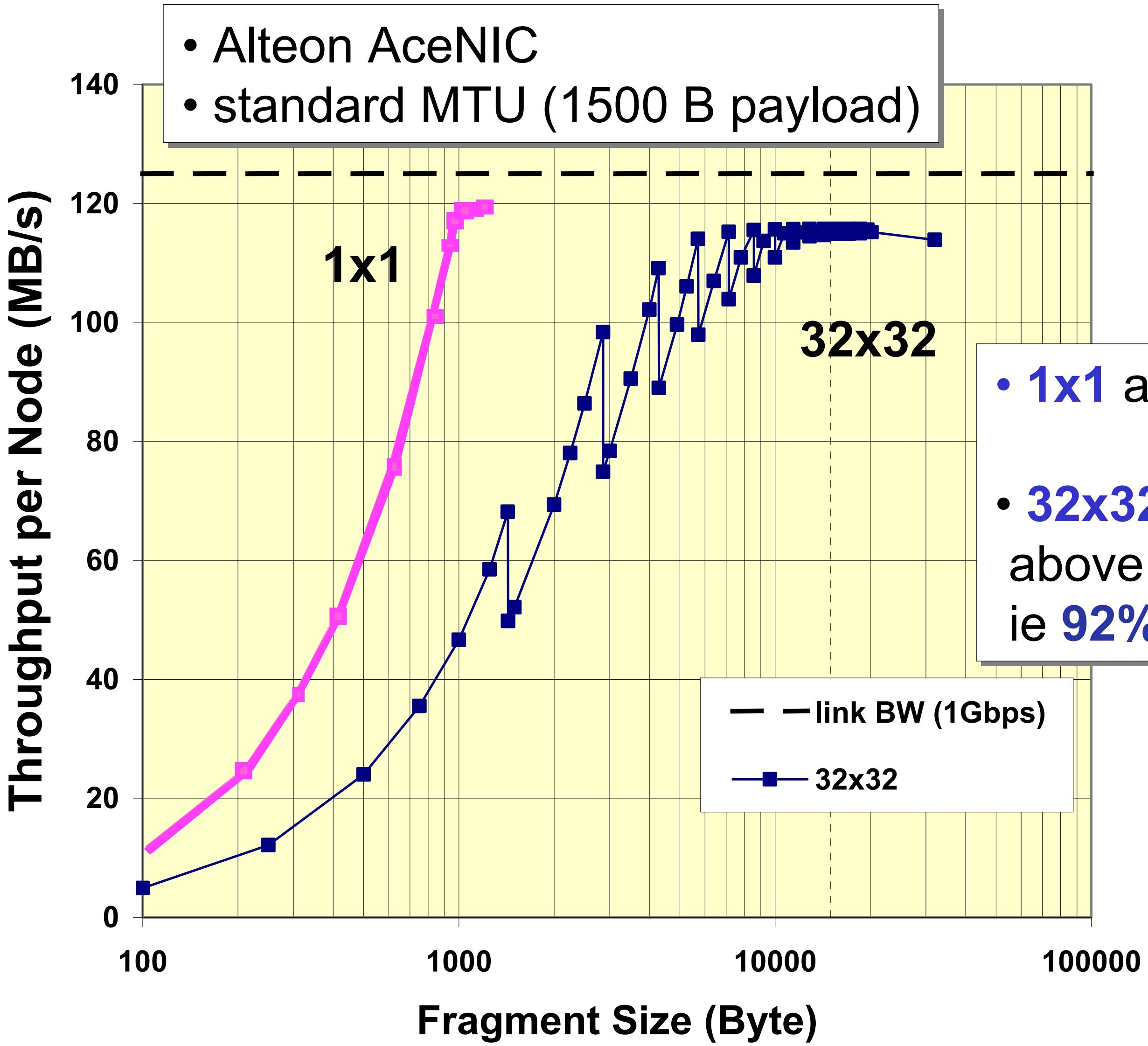
# A Myrinet-based 32x32 EVB





- Fixed-size event fragments
  below 4k: Fragment < BS carrier
  above 4k: Fragment > BS carrier
- Throughput at **234 MB/s**
  = **94% of link Bandwidth**

# Gigabit Ethernet-based 32x32 EVB



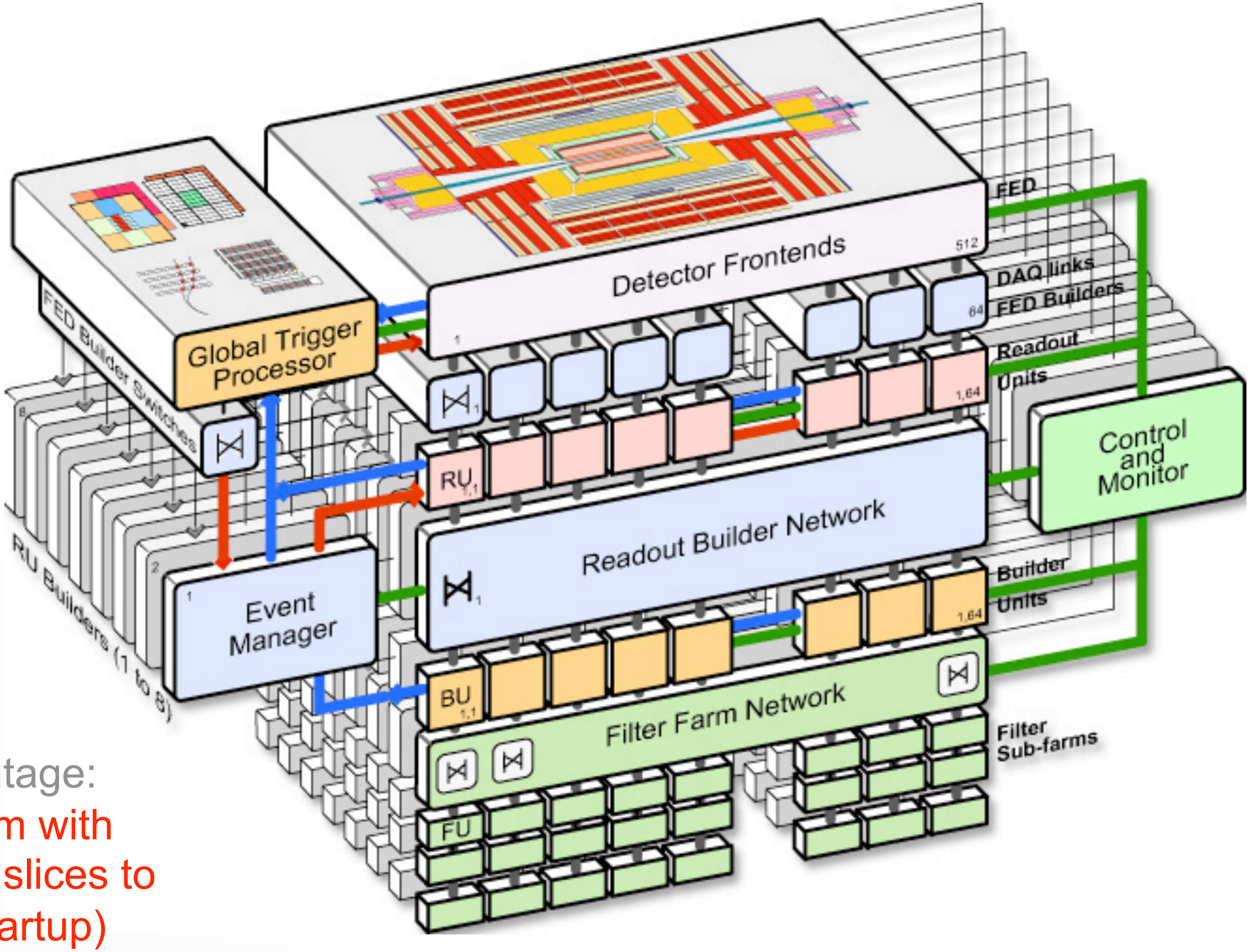
- Alteon AceNIC
- standard MTU (1500 B payload)

- **1x1** asymptotically to 125 MB/s

- **32x32** saw tooth due to MTU above **10k**: plateau of 115 MB/s ie **92%** of link speed (1Gbps)

# CMS Slicing Concept – 3D Event Builder

Eight slices:
each slice sees
only 1/8th of
the events

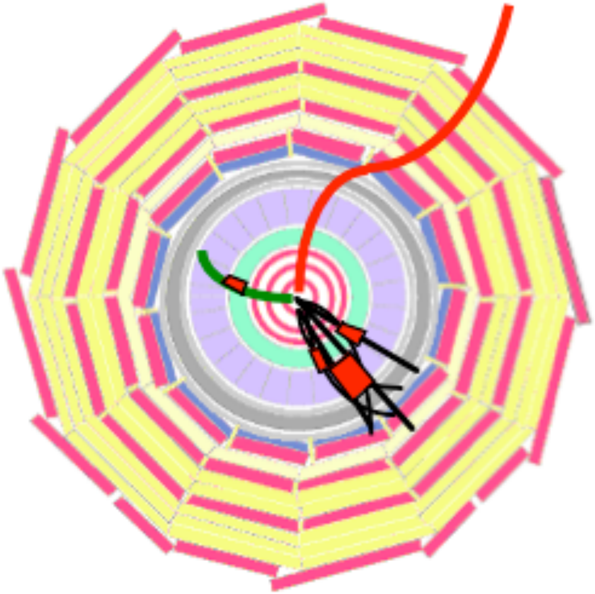


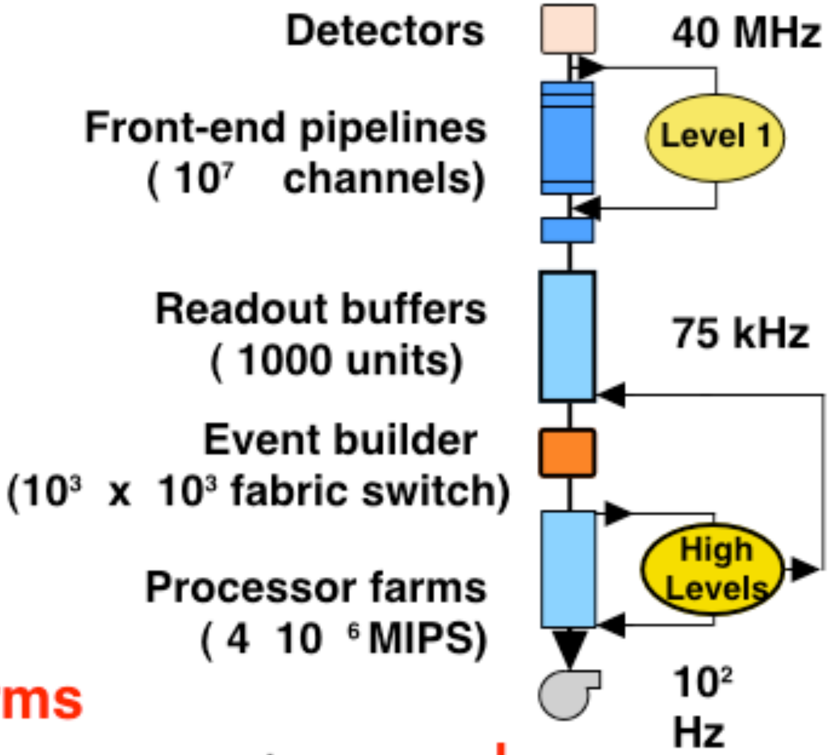
Additional advantage:
extensible system with
rising funding (4 slices to
be installed at startup)

# HLT requirements and operation

- Strategy/design guidelines
  - Use offline software as much as possible
    - Ease of maintenance, but also understanding of the detector
- Boundary conditions:
  - Code runs in a single processor, which analyzes one event at a time
  - HLT (or Level-3) has access to full event data (full granularity and resolution)
  - Only limitations:
    - CPU time
    - Output selection rate (~$10^2$ Hz)
    - Precision of calibration constants
- Main requirements:
  - Satisfy physics program (see later): high efficiency
  - Selection must be inclusive (to discover the unpredicted as well)
  - Must not require precise knowledge of calibration/run conditions
  - Efficiency must be measurable from data alone
  - All algorithms/processors must be monitored closely

# High Level Trigger Strategy





Detectors

40 MHz

Front-end pipelines
( $10^7$ channels)

Level 1

Readout buffers
( 1000 units)

75 kHz

Event builder
($10^3$ x $10^3$ fabric switch)

High Levels

Processor farms
( 4 10 $^6$ MIPS)

$10^2$
Hz

**High level triggers. CPU farms**

- Finer granularity precise measurement
- Clean particle signature ($\pi^0$-$\gamma$, isolation, ...)
- Kinematics. Effective mass cuts and topology
- Track reco and matching, b,$\tau$-jet tagging
- Full event reconstruction and analysis

**Successive improvements : background event filtering, physics selection**

# Physics, Signatures and Triggers

**Some physics and their experimental signatures:**

- Higgs
  - $\gamma\gamma$, bbar, WW, ZZ (peak)
- Supersymmetry
  - multi-leptons or same-sign lepton pairs
  - jets and Missing $E_T$
- Z′
  - di-electron, di-muon (peak)
- W′
  - electron or muon and Missing $E_T$
- Large Extra dimensions
  - jet + Missing $E_T$ (mono-jet)
  - di-fermion, di-boson
- Compositeness
  - di-jet (hi mass tail)
  - lepton and jet (LeptoQuark)

**Corresponding "primary" triggers:**

- di-photon
- di-electron
- di-muon
- di-jet
  - with b-tagging

- Inclusive leptons, either:
  - higher threshold
  - Isolation cut
  - Pre-scale applied

- Missing $E_T$ .
  - Jet(s)
  - leptons

- "mixed" or "composite" triggers
  - …

# High-Level Trigger Menu

Illustrative HLT menu for LHC at $2\times10^{33}$ cm$^{-2}$s$^{-1}$ luminosity (CMS)

Refinement of Level-1 selection criteria and additional signatures

| Signature | Approximate rate |
|---|---|
| ≥ 1 μ > 19 GeV or ≥ 2 μ > 7 GeV | 29 Hz |
| ≥ 1 γ > 80 GeV or ≥ 2 γ > 40, 25 GeV | 9 Hz |
| ≥ 1 e > 29 GeV or ≥ 2 e > 17 GeV | 34 Hz |
| ≥ 1 τ > 86 GeV or ≥ 2 τ > 59 GeV | 4 Hz |
| ≥ 1 jet ≥ 180 GeV and $E_{T,\mathrm{miss}}$ > 123 GeV | 5 Hz |
| ≥ 1 jet > 657 GeV or ≥ 3 jets > 247 GeV or 4 jets > 113 GeV | 9 Hz |
| Others (e/γ-jet, b-jets, etc.) | 7 Hz |

Total of ~ 100 Hz (large uncertainties), large fraction of interesting physics

- Need to balance physics coverage against offline computing cost

# HLT Efficiency for Physics

Expected CMS results for HLT menu at $2\times10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity

| Channel | Efficiency (in detector accept.) |
|---|---|
| $W \to e\nu$ | 67 % (fid: 60 %) |
| $W \to \mu\nu$ | 69 % (fid: 50 %) |
| $tt \to \mu+X$ | 72 % |
| $H(115\ \text{GeV}) \to \gamma\gamma$ | 77 % |
| $H(160\ \text{GeV}) \to WW^* \to 2\mu$ | 92 % |
| $H(150\ \text{GeV}) \to ZZ^* \to 4\mu$ | 92 % |
| $A/H(200\ \text{GeV}) \to 2\tau$ | 45 % |
| $H^+(200 – 400\ \text{GeV}) \to \tau\nu$ | 58 % |
| SUSY (≈ 0.5 TeV squarks/gluinos) | ≈ 60 % |

LHCb also expects good (fiducial) efficiencies for primary physics modes

- 40% (total) for $B_s \to D_s^+\pi^-$, 70% for $B_s \to J/\psi(\mu\mu)\phi$, 40% for $B \to K^*\gamma$
- 1 billion fully contained (decay-unbiased) *B* mesons for 2 $\mathrm{fb}^{-1}$ from inclusive trigger

# Start with L1 Trigger Objects

## Electrons, Photons, τ-jets, Jets, Missing $E_T$, Muons

- HLT refines L1 objects (no volunteers)

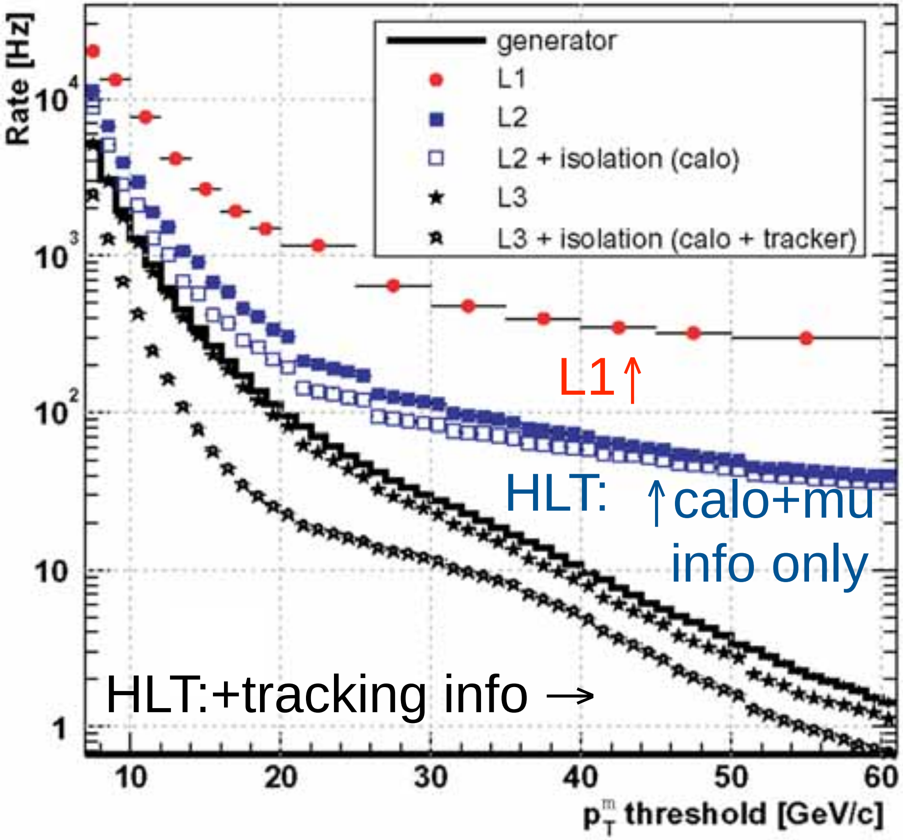
## Goal

- Keep L1T thresholds for electro-weak symmetry breaking physics
- However, reduce the dominant QCD background
  - From 100 kHz down to 100 Hz nominally

## QCD background reduction

- Fake reduction: e±, γ, τ
- Improved resolution and isolation: μ
- Exploit event topology: Jets
- Association with other objects: Missing $E_T$
- Sophisticated algorithms necessary
  - Full reconstruction of the objects
  - Due to time constraints we avoid full reconstruction of the event - L1 seeded reconstruction of the objects only
  - Full reconstruction only for the HLT passed events

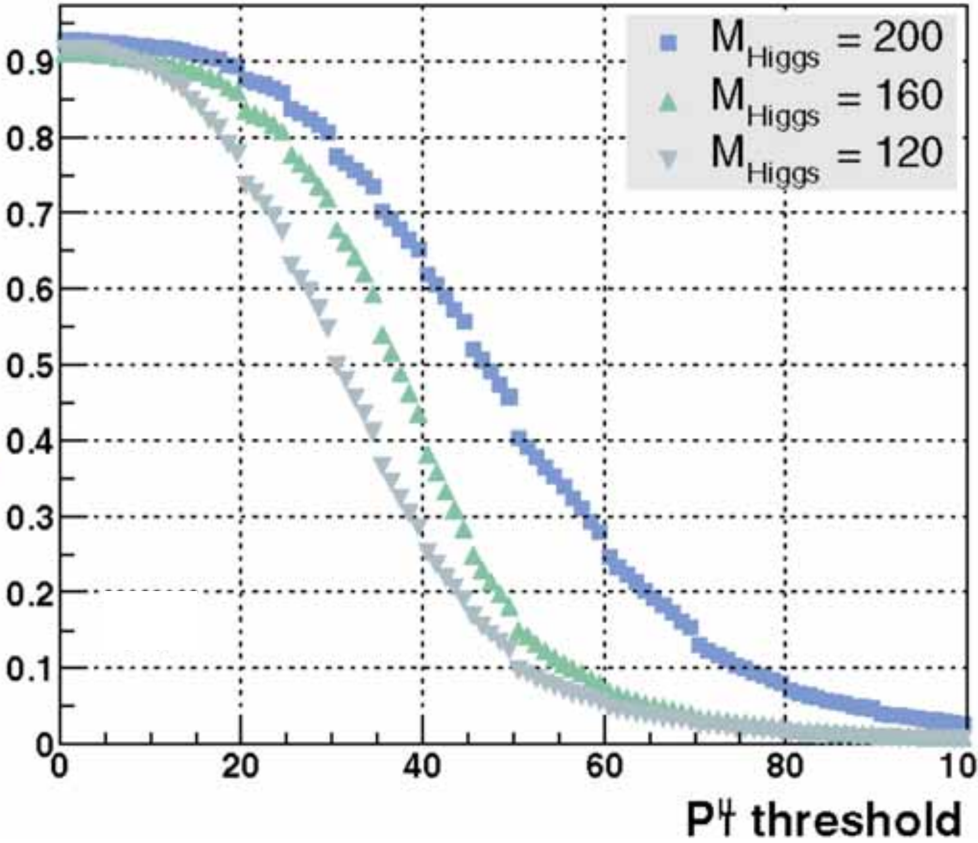
# Muon Higher Level Trigger



L1↑

HLT: ↑calo+mu info only

HLT:+tracking info →

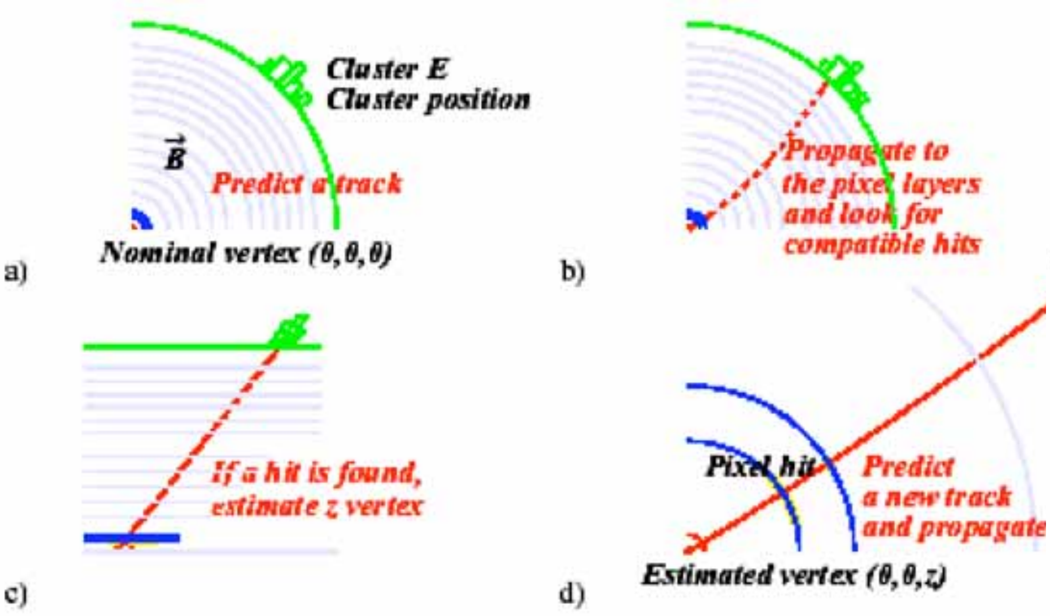


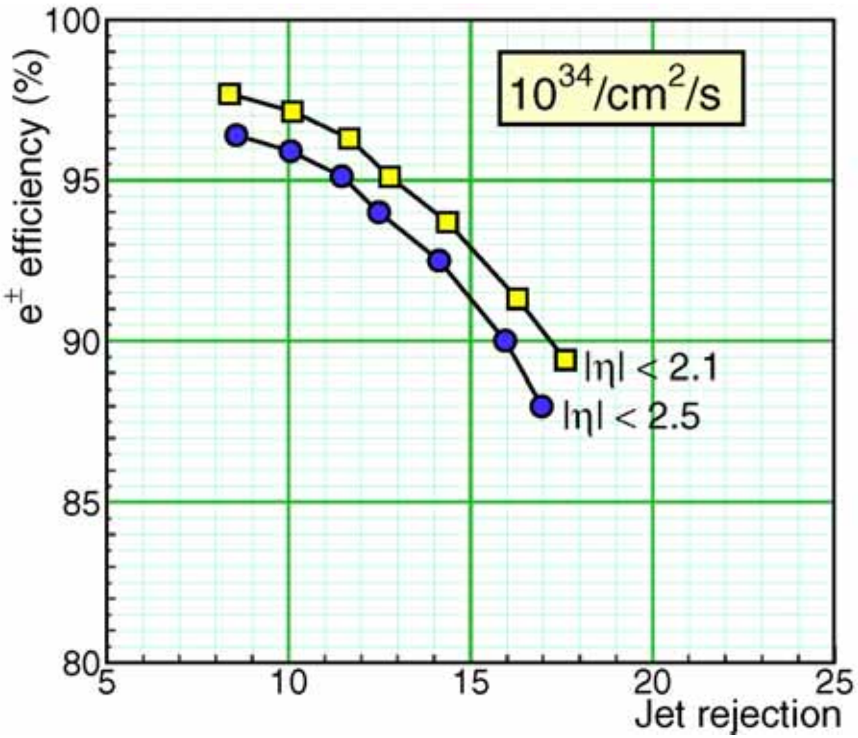
**Trigger rates vs. muon $p_T$ threshold through levels of HLT processing at $L = 2 \times 10^{33}$**

**Efficiency for Higgs selection vs. muon $p_T$ threshold for different Higgs masses**

# CMS tracking for electron trigger

## Present CMS electron HLT

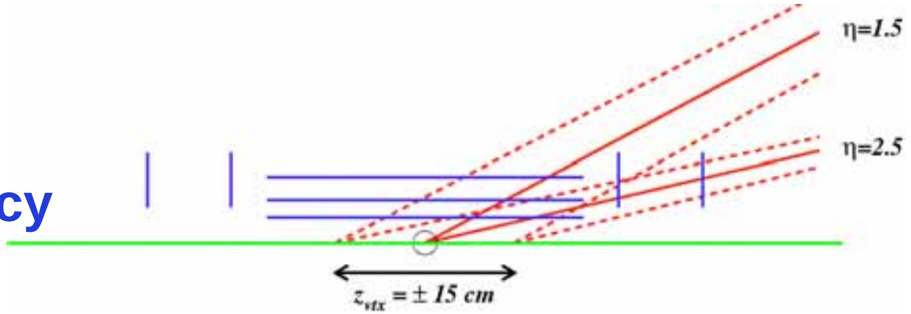




## Factor of 10 rate reduction

## γ: only tracker handle: isolation

- **Need knowledge of vertex location to avoid loss of efficiency**



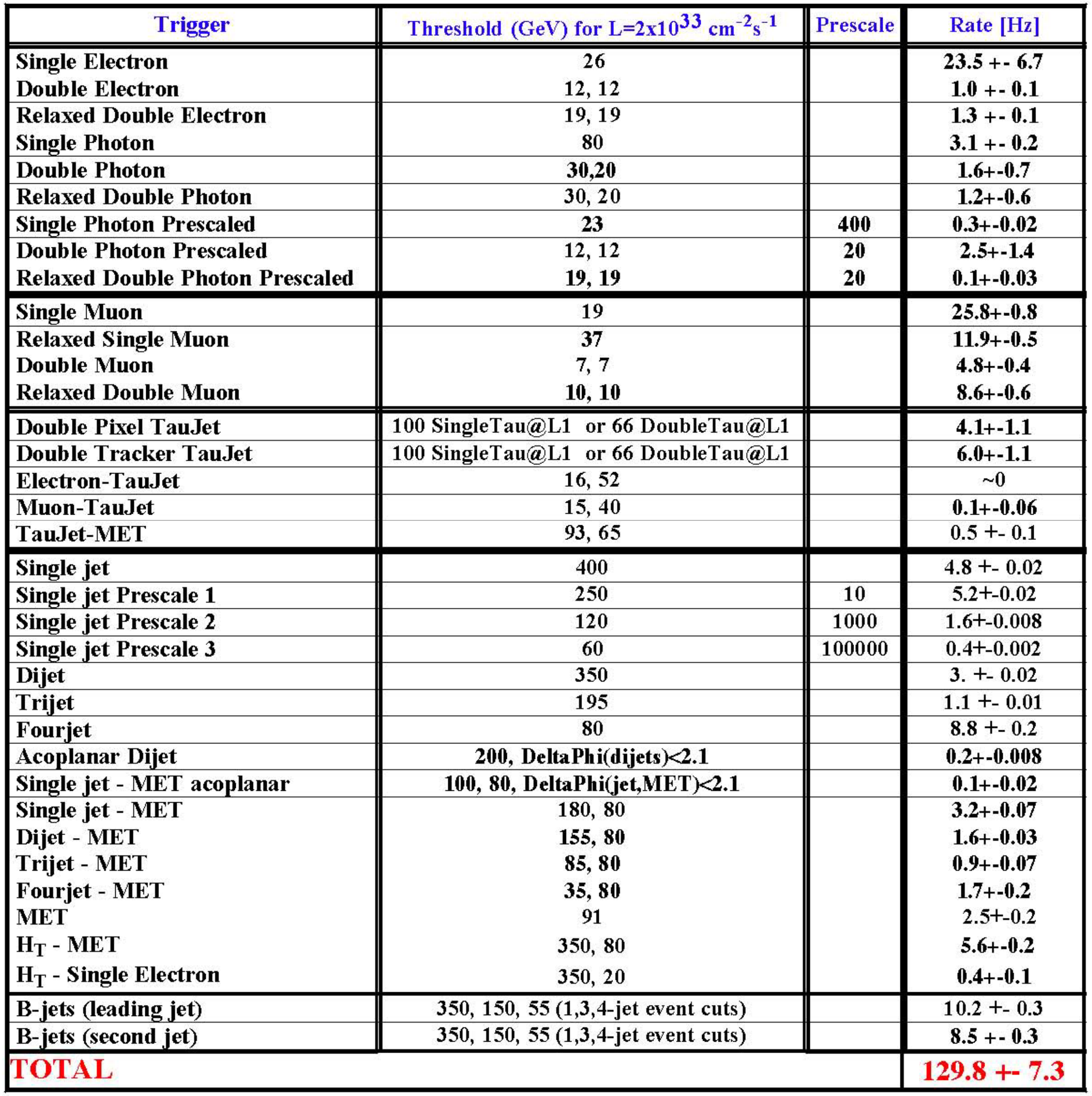
# Pre-requisites, Volunteers

- Pre-Requisite:
  - Only muons that have a L1 accept are pursued in the HLT.
  - Moreover, only that region may be even looked-at (reconstructed).

- Volunteer:
  - A muon “found” in the HLT, without a corresponding L1 accept
    - Possible Convention: such cannot be the cause of a trigger decision (CDF/CMS)
  - Cannot happen if only “seeded” (on L1 muon track) reconstruction is pursued in HLT
  - Can happen if global reconstruction is performed.

  - Very useful in understanding trigger efficiencies (more later).

# HLT Trigger Table - Example (CMS)



| Trigger | Threshold (GeV) for $L=2x10^{33}$ $cm^{-2}s^{-1}$ | Prescale | Rate [Hz] |
|---|---|---|---|
| **Single Electron** | 26 | | 23.5 +- 6.7 |
| **Double Electron** | 12, 12 | | 1.0 +- 0.1 |
| **Relaxed Double Electron** | 19, 19 | | 1.3 +- 0.1 |
| **Single Photon** | 80 | | 3.1 +- 0.2 |
| **Double Photon** | 30,20 | | 1.6+-0.7 |
| **Relaxed Double Photon** | 30, 20 | | 1.2+-0.6 |
| **Single Photon Prescaled** | 23 | 400 | 0.3+-0.02 |
| **Double Photon Prescaled** | 12, 12 | 20 | 2.5+-1.4 |
| **Relaxed Double Photon Prescaled** | 19, 19 | 20 | 0.1+-0.03 |
| **Single Muon** | 19 | | 25.8+-0.8 |
| **Relaxed Single Muon** | 37 | | 11.9+-0.5 |
| **Double Muon** | 7, 7 | | 4.8+-0.4 |
| **Relaxed Double Muon** | 10, 10 | | 8.6+-0.6 |
| **Double Pixel TauJet** | 100 SingleTau@L1 or 66 DoubleTau@L1 | | 4.1+-1.1 |
| **Double Tracker TauJet** | 100 SingleTau@L1 or 66 DoubleTau@L1 | | 6.0+-1.1 |
| **Electron-TauJet** | 16, 52 | | ~0 |
| **Muon-TauJet** | 15, 40 | | 0.1+-0.06 |
| **TauJet-MET** | 93, 65 | | 0.5 +- 0.1 |
| **Single jet** | 400 | | 4.8 +- 0.02 |
| **Single jet Prescale 1** | 250 | 10 | 5.2+-0.02 |
| **Single jet Prescale 2** | 120 | 1000 | 1.6+-0.008 |
| **Single jet Prescale 3** | 60 | 100000 | 0.4+-0.002 |
| **Dijet** | 350 | | 3. +- 0.02 |
| **Trijet** | 195 | | 1.1 +- 0.01 |
| **Fourjet** | 80 | | 8.8 +- 0.2 |
| **Acoplanar Dijet** | 200, DeltaPhi(dijets)<2.1 | | 0.2+-0.008 |
| **Single jet - MET acoplanar** | 100, 80, DeltaPhi(jet,MET)<2.1 | | 0.1+-0.02 |
| **Single jet - MET** | 180, 80 | | 3.2+-0.07 |
| **Dijet - MET** | 155, 80 | | 1.6+-0.03 |
| **Trijet - MET** | 85, 80 | | 0.9+-0.07 |
| **Fourjet - MET** | 35, 80 | | 1.7+-0.2 |
| **MET** | 91 | | 2.5+-0.2 |
| **$H_T$ - MET** | 350, 80 | | 5.6+-0.2 |
| **$H_T$ - Single Electron** | 350, 20 | | 0.4+-0.1 |
| **B-jets (leading jet)** | 350, 150, 55 (1,3,4-jet event cuts) | | 10.2 +- 0.3 |
| **B-jets (second jet)** | 350, 150, 55 (1,3,4-jet event cuts) | | 8.5 +- 0.3 |
| **TOTAL** | | | **129.8 +- 7.3** |

Electron, photon

muon

~60%

tau

jets

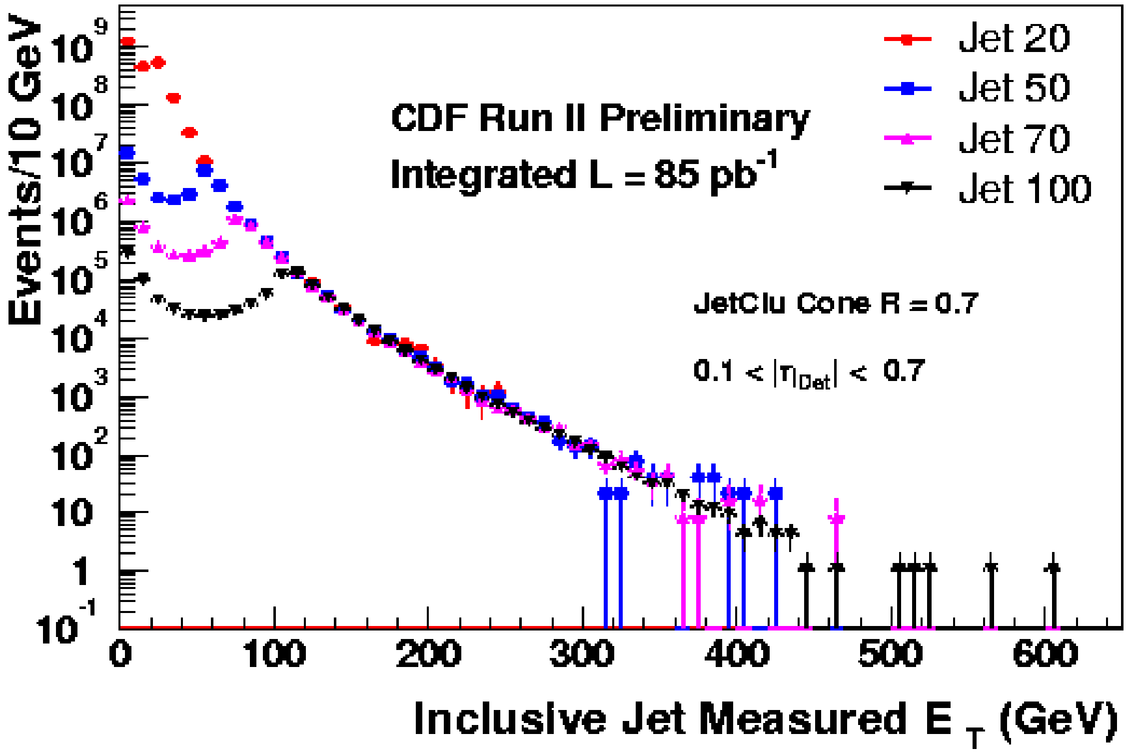
jets,met, HT

# Pre-scales

- Inclusive jet triggers - rate too high to take them all

Sample

- Lower threshold -- higher pre-scale
- Lower threshold at lower trigger level
  - "sharp" cut at HLT
- "assemble" spectrum



- Fancy:

  dynamic prescales

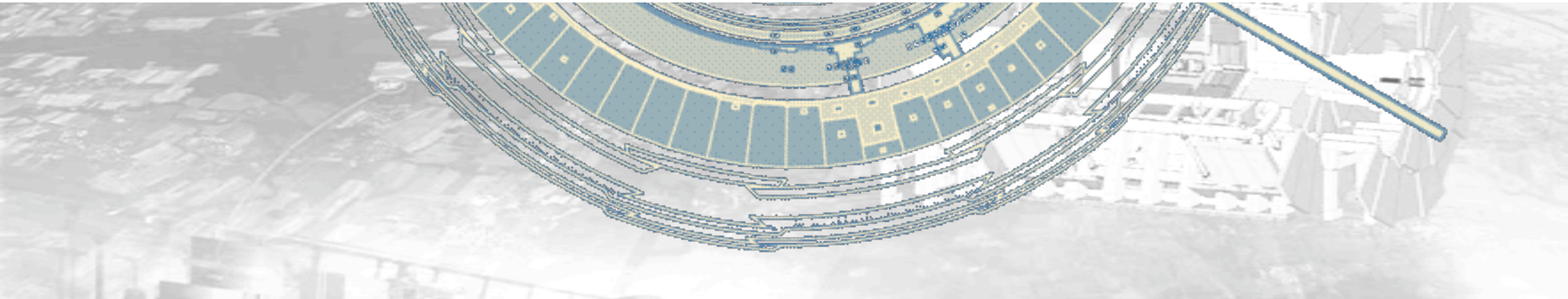
# Trigger Efficiencies (from Data)

The knowledge of the trigger efficiency is required for most LHC analyses

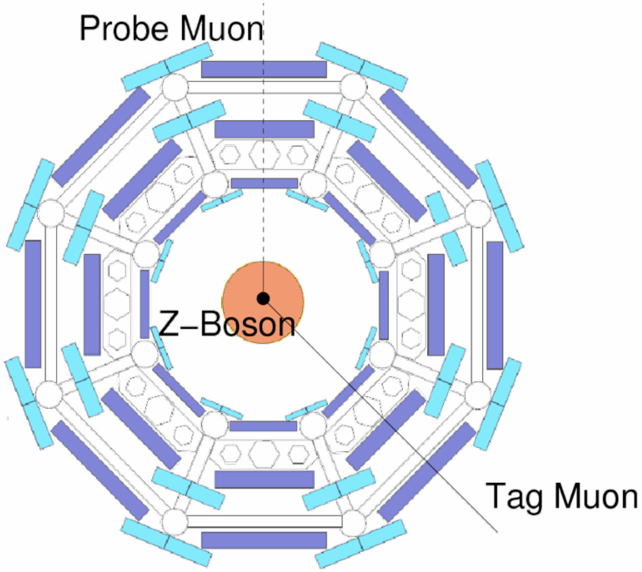
- Corrections to be applied for cross section measurements
- But also kinematic measurements (masses, spin, *CP* asymmetries) require the correction of trigger inefficiencies

Don’t trust Monte Carlo simulation – use data driven methods !

- Tag-and-probe method using known resonances, in particular $Z \rightarrow ee, \mu\mu, \tau\tau$
- Orthogonal triggers
- Bootstrapping methods
- Reference measurements



# Tag-and-Probe Method



**Example:** muon trigger efficiency with $Z \rightarrow \mu\mu$

**Tag muon**:

- event triggered by tag muon
- isolated ID-MS muon with $p_T > 20$ GeV

**Probe muon** (unbiased with respect to tag selection):

- require inner detector track ($\mu$ candidate)
- $m(\mu\mu) \sim M_Z$ (91 GeV)
- count how often the probe muon has been triggered in the muon system

With sufficient statistics the efficiency can be evaluated in bins of $p_T$, $\eta$ ,$\phi$

Usually, the result has to be corrected for combinatorial background under the $Z$ peak

The Tag-and-Probe Method is very flexible, many versions of the same idea exist

Simplest case (ignoring backgrounds), just compare rates of $Z \rightarrow ee$ for two triggers:

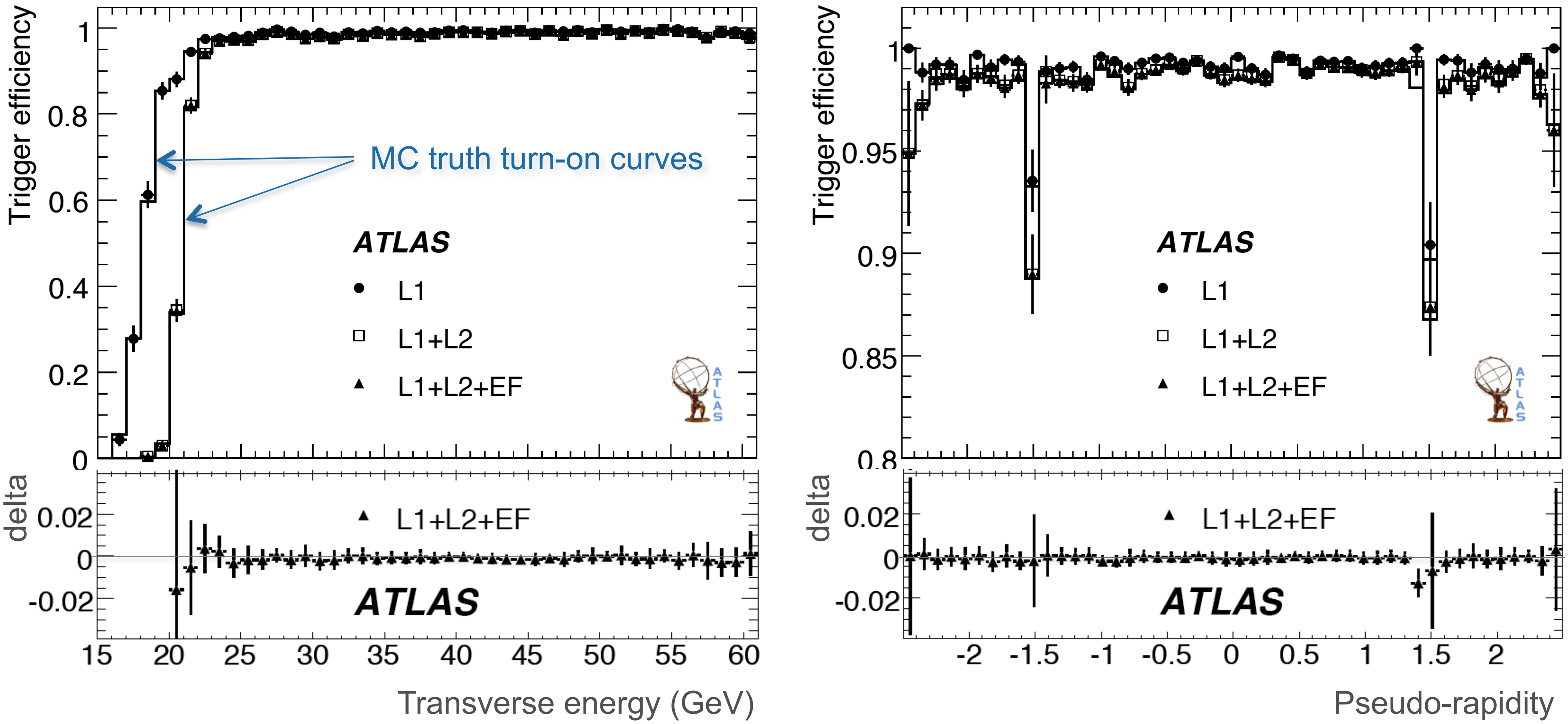
- **e15** ($N_1$ observed events) and **2e15** ($N_2$)
- $\varepsilon$ = e15 efficiency

⇨

$$\left.\begin{aligned} N_2 &= \varepsilon^2 \cdot N_{\text{prod}} \\ N_1 &= \left(2\varepsilon - \varepsilon^2\right) \cdot N_{\text{prod}} \end{aligned}\right\} \Rightarrow \varepsilon = \frac{2N_2}{N_1 + N_2}$$

# Simulated $Z\rightarrow ee$ tag-and-probe results for the "e20" trigger signature

- Trigger efficiencies with respect to tight offline electron selection
- Signal statistics corresponds to 100 pb$^{-1}$ (background neglected)



# Combining Triggers

**Issue**: how to combine data samples collected by several triggers in a physics analysis analysis (*e.g.*, cross section measurement) ?

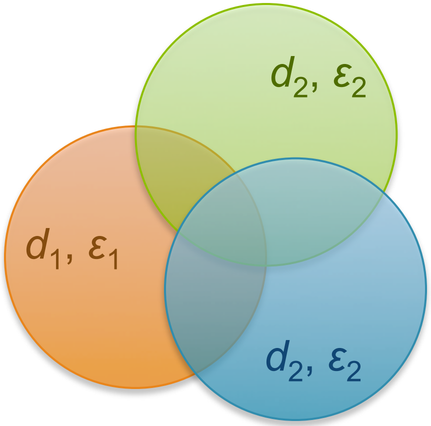
- Limited bandwidth → rate **prescaling** by factor: *d*
- Limited resources → reduced **efficiency** (with respect to **offline** selection): *ε*

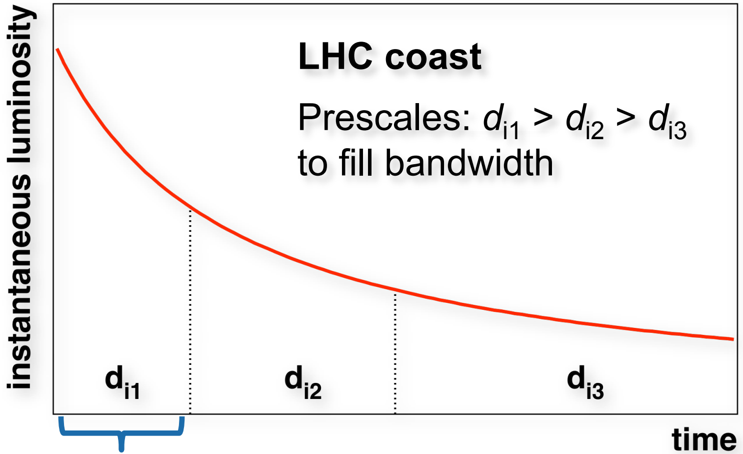
Goal: $\sigma = \dfrac{N_{\text{prod}}}{\mathcal{L}}$

However, only $N_{\text{rec}} < N_{\text{prod}}$ events recorded

➠ Fortunately, knowing $d$ and $\varepsilon$, one finds: $N_{\text{prod}} = N_{\text{rec}}\, d / \varepsilon$

**But** – what if several trigger lines overlap, or if $d_{ik}$ and $\varepsilon_{ik}$ (for trigger line $i$ and run $k$) depend on *time* ?



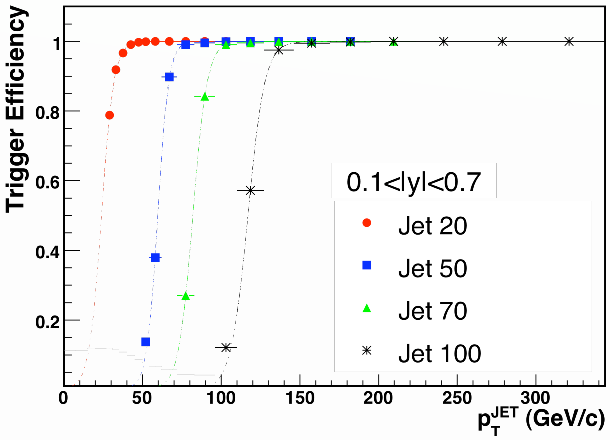


Denote "run" in the following

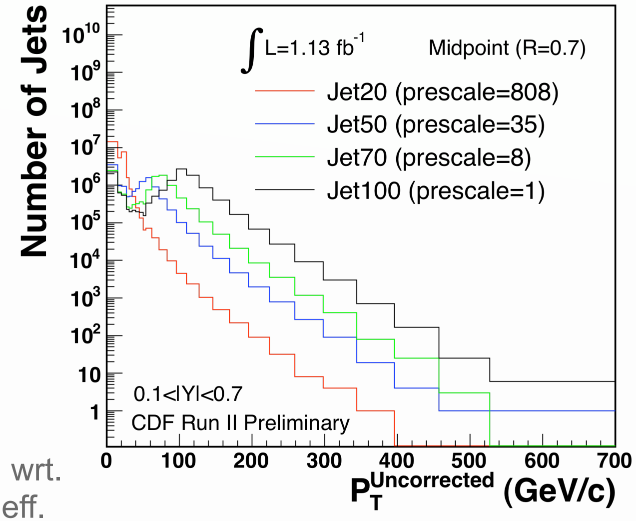
# Why Do We Need to Combine Triggers ?

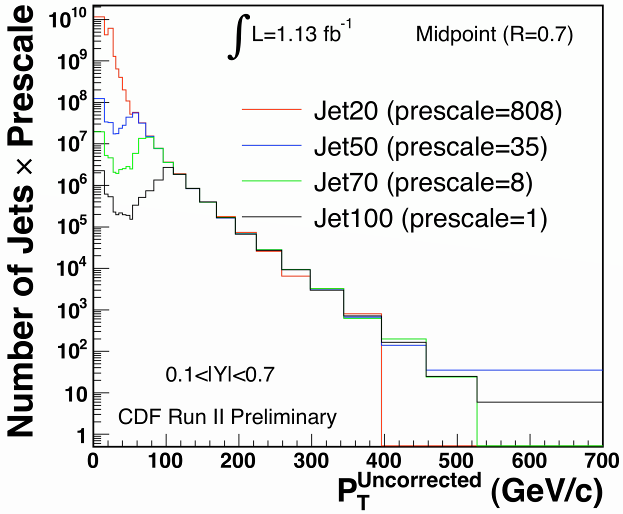
Cover different phase space regions, detectors with maximum statistics

- **Different sub-detectors** (*e.g.* di-muon analysis with one $\mu$ in barrel and one in endcap)
- **Different signals** (*e.g.* use jets *or* electron triggers)
- **Different energies** (*e.g.* combine trigger lines with different $p_T$ thresholds)


Turn-on curves for jet triggers

Trigger efficiencies are usually determined wrt. offline selection: important to know trigger eff. to be able to improve in future runs!


Observed numbers of jets


Corrected for prescales

# The Goal is…

…to calculate the weights $w(j)$ for each event $j$, such that: $N_{\text{prod}} = \sum_{j=1}^{N_{\text{rec}}} w(j)$

Simplest approach for single trigger: $w_k(j) = d_k / \varepsilon_k$ for (stable-$d$) run $k$

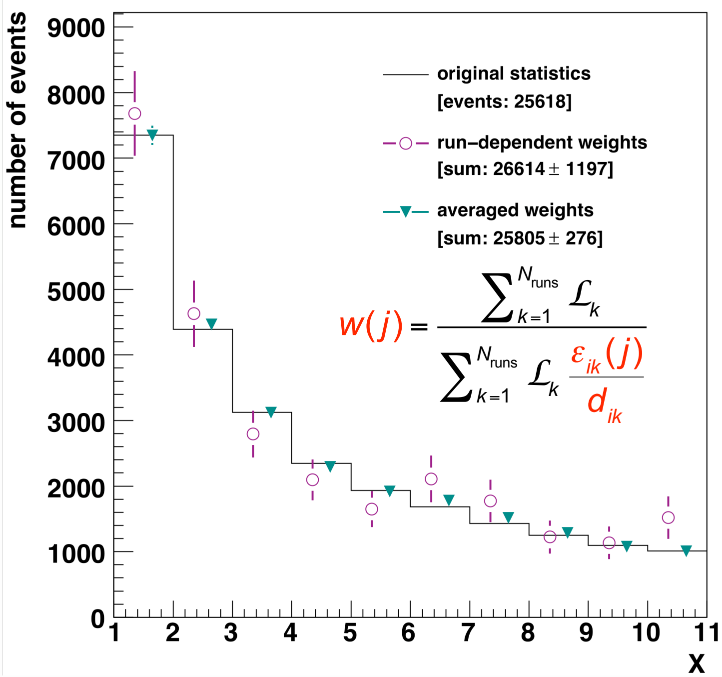
- In case of stable conditions compute **average** $w(j)$ over **all runs**, instead of individual $w_k(j)$ per run, even if prescales and efficiencies vary between runs → smaller error !

**Toy example** (single trigger line):

- 10 runs with $d$ = 1…5 – good LHC conditions
- 10 runs with $d$ =100 – huge beam backgrounds
- 1000–1500 events per run

**Averaged weights always better than or equal to run-wise weights !**

Note that averaging requires that the definition of the trigger line did not change between the runs !



$$w(j) = \frac{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k}{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k \frac{\varepsilon_{ik}(j)}{d_{ik}}}$$

# Combining Triggers

Consider combination of triggers for single trigger level

Distinguish three methods, with rising complexity

1. ***Division method*** *(basic)*
   - Divide phase space into distinct regions with only one trigger line per region
   - Choose the region providing largest statistics for analysis
   - Determine trigger efficiency for this region
2. ***Exclusion method*** *(better)*
   - Divide data sample according to trigger lines and prescale factors
3. ***Inclusion method*** *(Rolls Royce)*
   - A combined weight based on all considered trigger lines is determined for the entire event sample …

For simple final states, or measurements not limited by statistics, the *Division Method* can be a straightforward choice.

# Exclusion Method (assuming FETC)

Need to first introduce concept of *fully efficient trigger combinations (FETC)*

- ➠ **“OR”** of the combination of trigger lines has **$\varepsilon = 1$** with respect to offline selection
- Example: $s_1 = \{N_{\text{tracks}} > 2\}$, $s_2 = \{N_{\text{tracks}} < 4\}$ → $\{s_1 \,||\, s_2\}$ is fully efficient

Split data sample according to trigger lines and prescale factors

- Choose the trigger line $i^*$ with the smallest $d_{i^*k}$ for which the ”raw trigger” passed
- The raw trigger of a line is the trigger response before prescale
- Event weight then given by: $w_k(j) = d_{i^*k}\, a_{i*}(j)$ , where “actual trigger” $a_{i*}(j) = 1$ (0) if event passed (did not pass) trigger line $i^*$ after applying prescale
- Again, instead of computing $w_k(j)$ per run $k$, compute average weight over runs $w'_{i^*}$, giving the event weight: $w(j) = w'_{i^*}\, a_{i*}(j)$

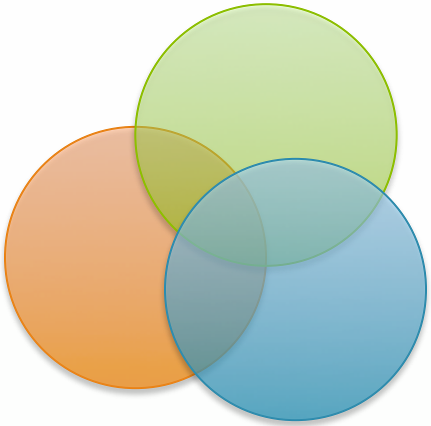
$$w'_i = \frac{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k}{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k \big/ d_{ik}}$$

Sufficient for many statistically non-critical analysis

[ *e.g.* used for inclusive measurements of structure functions at low $Q^2$ by H1 ]

# Inclusion Method

Determine combined weight based on all considered trigger lines



Use *all events* passing *at least* one trigger

- Probability to trigger event:

$$P_k(j) = 1 - \prod_{i=1}^{N_{\text{lines}}} \left( 1 - \frac{r_i(j)}{d_{ik}} \right)$$

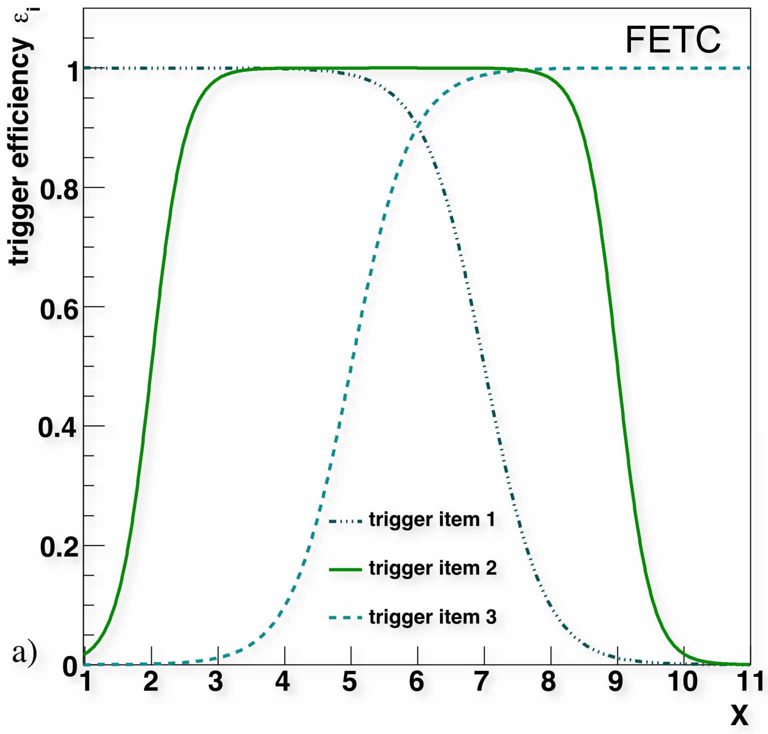
- Run-wise weight: $w_k(j) = 1 / P_k(j)$, or better run-averaged: $w(j) = \frac{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k}{\sum_{k=1}^{N_{\text{runs}}} \mathcal{L}_k P_k(j)}$
- Note: assumes independent application of prescales !

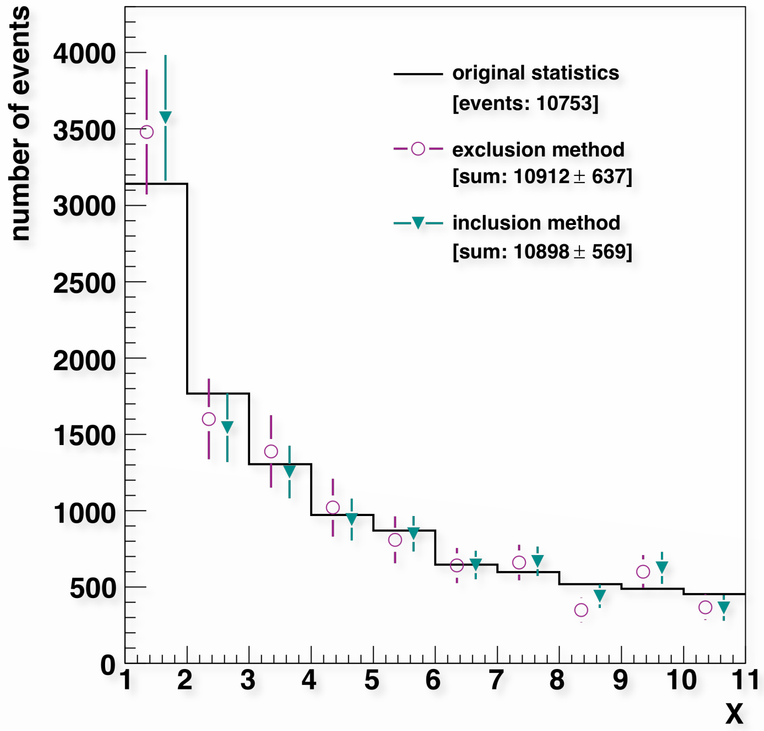
Optimum correction in presence of prescaled triggers that significantly overlap (unless equivalent to exclusion method)

# Comparison between Methods

Toy Monte Carlo example:

- 20 runs with varying luminosity, 500–600 events per run





Similar performance for many practical cases …

# Recommendations for Trigger Operation

[ From: arXiv:0901.4118 ]

Include all trigger bits in event record. *Raw bits must not be omitted*

- For efficiency determination
- For FETC methods

Provide *all bits* from *all levels*

- Compute all HLT trigger bits when event has been accepted

Do not use the actual decision at lower levels as input to higher levels

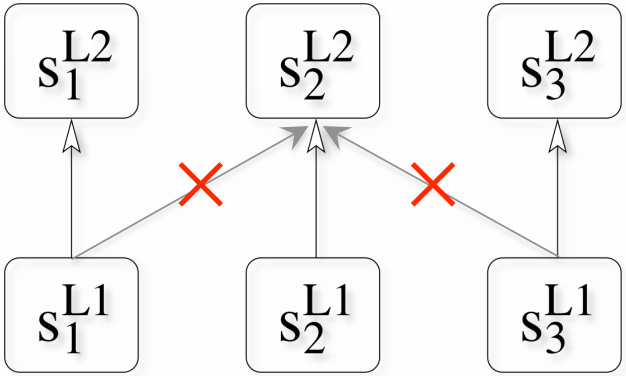
- Correlates triggers and invalidates FETC

Avoid overlaps between trigger lines

- Correlates trigger lines

Keep trigger definitions simple and stable !

- Simplifies efficiency calculations
- allows to average over runs !



# Układ wyzwalania

Powinien zapewnić zebranie/zapisanie

*  możliwie największej liczby przypadków "sygnału",
np. poszukiwanych procesów "nowej fizyki", produkcji bozonu Higgsa

*  możliwie różnorodnych topologii tych przypadków
różne kanały produkcji i/lub rozpadu, różne zakresy kinematyczne
=> konieczne dla weryfikcji modeli, dopasowania parametrów

* odpowiedniej (minimalizacja błędów) liczby przypadków dla:
- synchronizacji detektora
- kalibracji detektora
- pozycjonowania detektora
- pomiaru procesów tła
- pomiaru procesów dających wkład do modeli (np. PDF)
- pomiaru procesów pozwalających na wyznaczenie świetlności

## Układ wyzwalania

Aby zgromadzić wszystkie potrzebne informacje wykorzytujemy całą gamę wmożliwych triggerów:

- przypadki fizyczne (wybrane na podstawie kryteriów LV1/HLT)
- przypadki "minimum bias" ("cokolwiek w detektorze")
  weryfikacja algorytmów selekcji
- przypadki losowe: przypadkowe przecięcie z wiązką
  ocena tła wiązki
  przypadkowe przecięcie bez wiązki
  ocena poziomu szumów, pile-up
- przypadki kalibracyjne (różnego typu)
  w zależności od typu detektora może to być impuls lasera, impuls ładunku, pomiar sygnału przy wydłużonej bramce...
- przypadki "środowiskowe"
  każdy detektor odsyła istotne informacje o swoim działaniu
- przypadki testowe (różnego rodzaju)
  każdy detektor wykonuje zadaną procedurę
  (np. generacja pseudo danych)

# ECAL Calibration and Alignment

- Goal: approximately 0.5% constant term

$$E = G \times F \times \sum C_i A_i$$

- G = overall gain
- F = correction function depending on type of particle, position, energy and cluster algorithm used
- $C_i$ = intercalibration constant
- $A_i$ = signal amplitude (ADC) in channel i

# ECAL Calibration and Alignment

- **During construction, often possible to calibrate with radioactive sources (e.g. $^{60}$Co), pulsers and so on.**
  - Design mechanical tolerances for resolution goal.

- **Test beams used to get overall gain factor.**
  - Test beam conditions (material in front of calorimeter often different, electronics used may not be final, cables almost certainly not final.
  - Understand response as function of position

- **Cosmic ray muons can be useful.**

# CMS ECAL Calibration & Monitoring

## ➢ECAL Calibration (Resolution : ‘Constant Term of the Resolution Formula’) :

**Raw (uncalibrated) Supermodule : 6%-10% ‘Resolution’**
Spread among channels before calibration

**Beam Test Precalibration : 2 % ‘Resolution’**
With a ‘fast’ calibration
**‘Lab Precalibration’ : 4 % ‘Resolution’**

**In-Situ Physics Calibration : 0.5 % ‘Resolution’**
Timescale for calibration : Weeks

## ➢ECAL Monitoring (Monitor Stability and Measure Radiation Effects) :

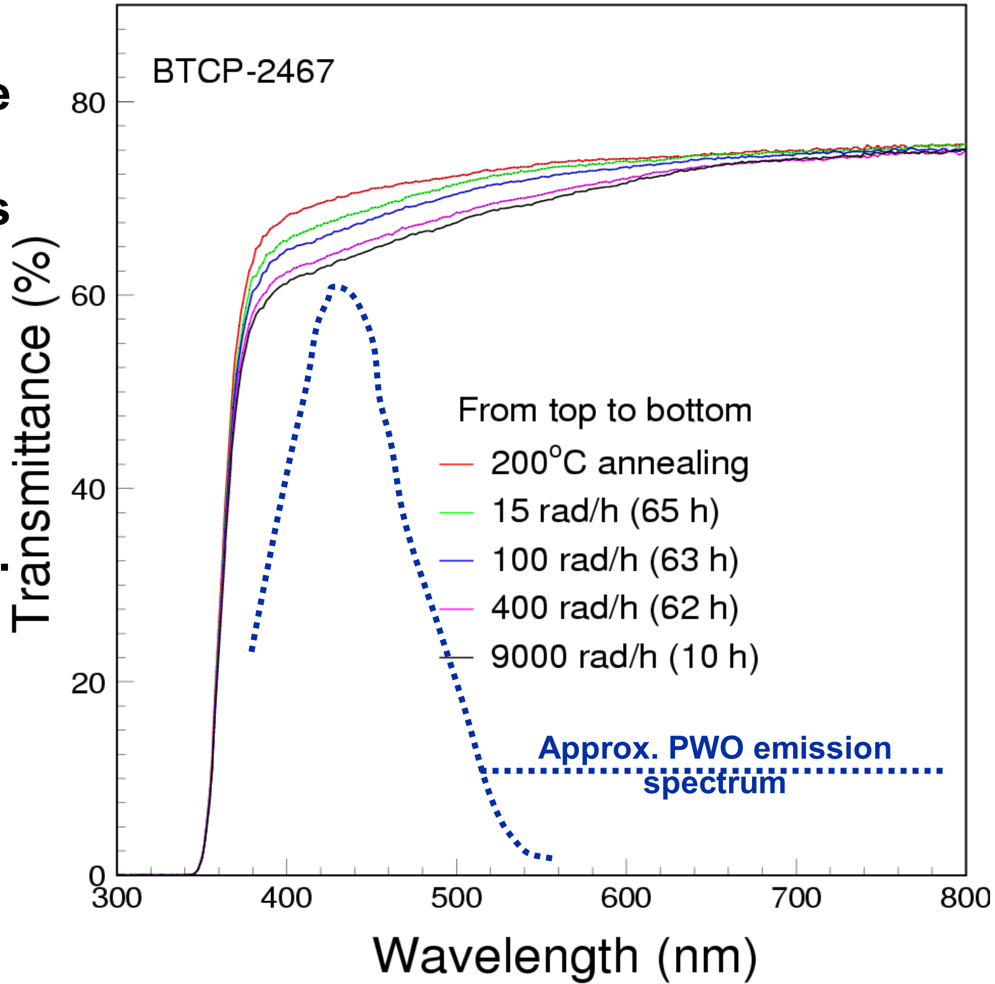
**ECAL Stability (<< 0.5%) ,**
**Monitored with Laser Monitoring System**

**Transparency Loss Correction,**
**Signal Change under Irradiation ~5%**
**Measured with Laser Monitoring System**

# CMS: Radiation Effects PWO Transparency

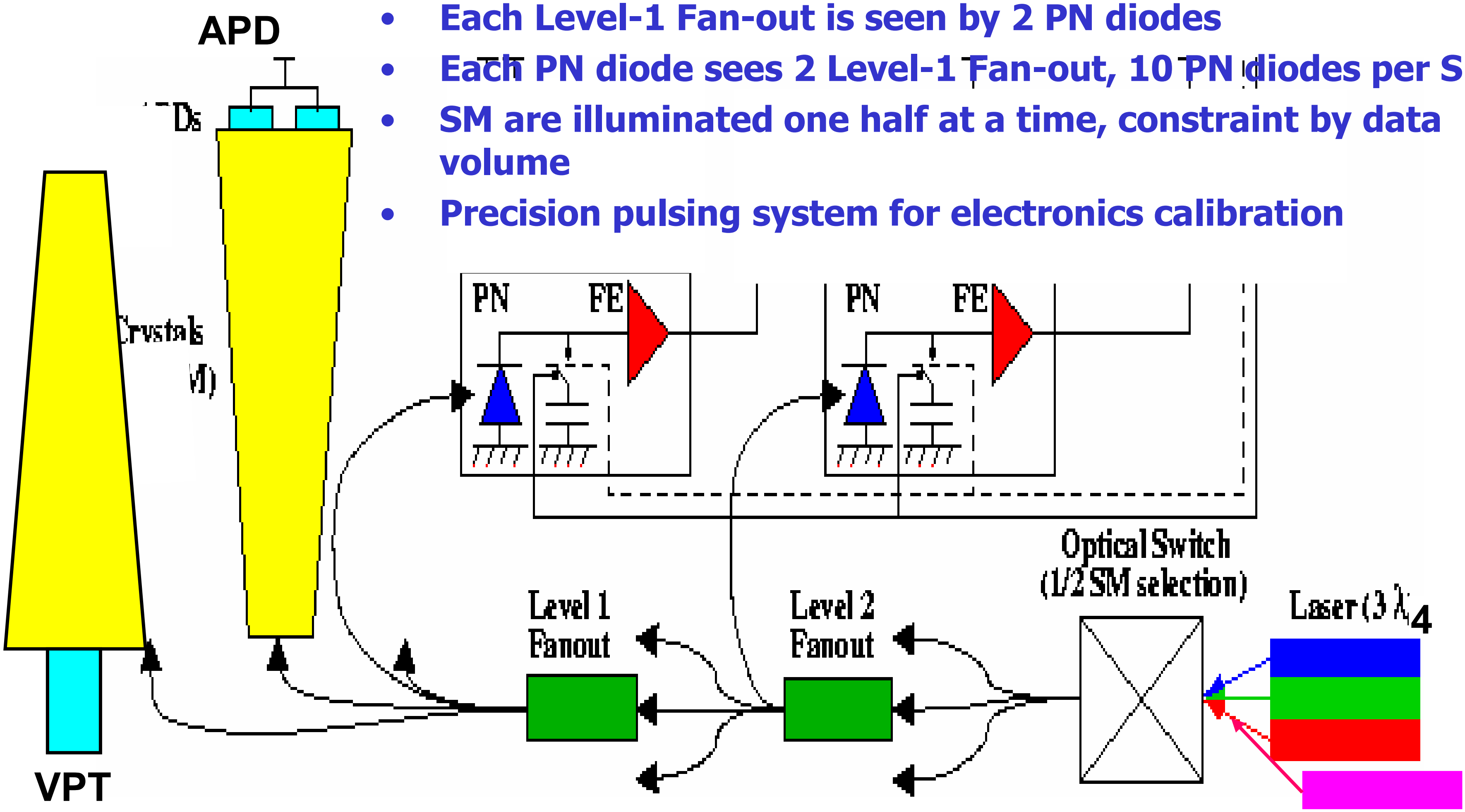
- Radiation reduces transparency in the blue, where PWO emission spectrum peaks
- Effect is dose rate dependent.
- Monitoring relative change of PWO transparency with pulsed laser light.

**For CMS barrel (15 rad/hour) :**
**Transparency change at a level of ~5%.**



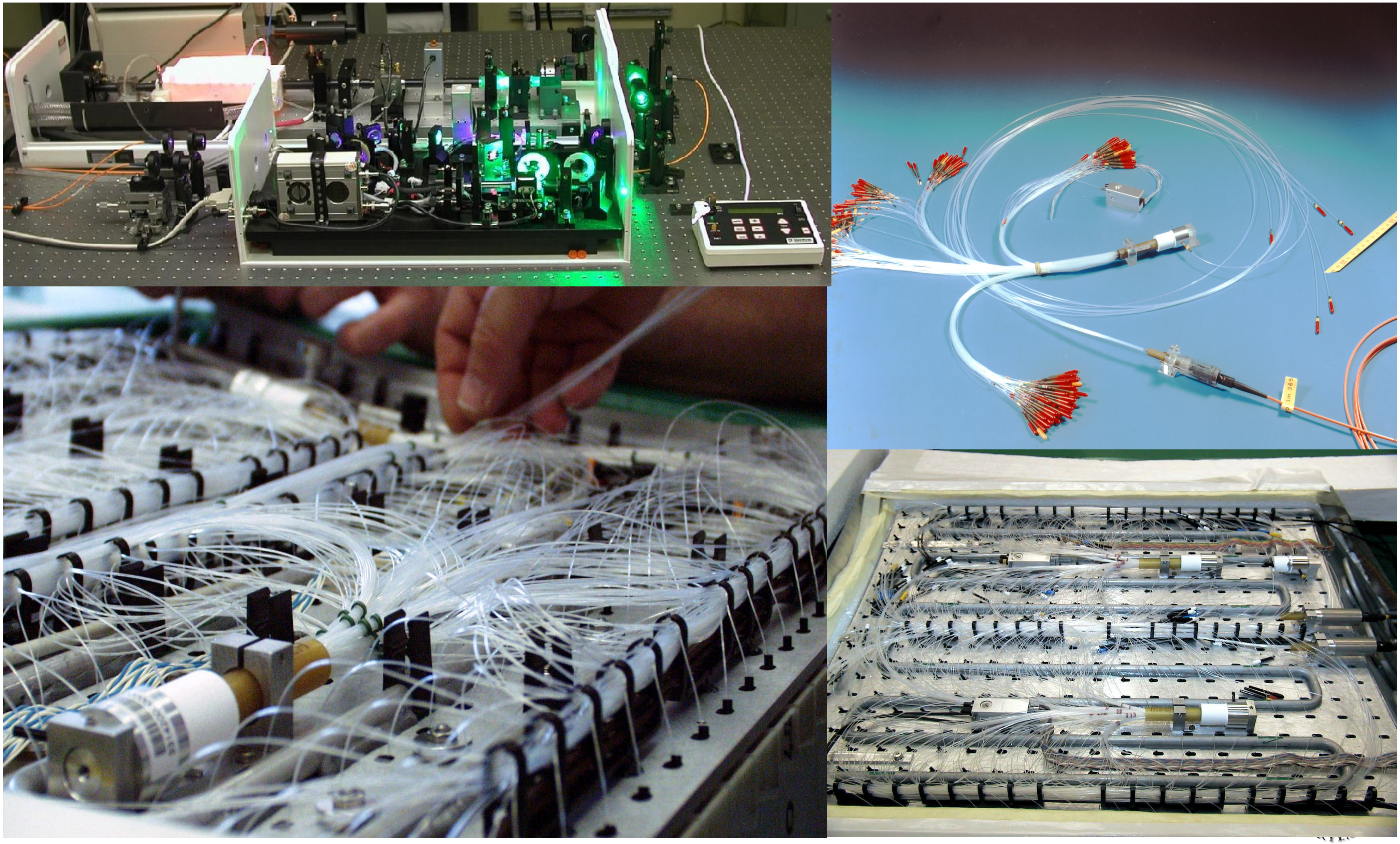
# ECAL Laser Monitoring System

- Very stable PN-diodes used as reference system
- Each Level-1 Fan-out is seen by 2 PN diodes
- Each PN diode sees 2 Level-1 Fan-out, 10 PN diodes per SM
- SM are illuminated one half at a time, constraint by data volume
- Precision pulsing system for electronics calibration



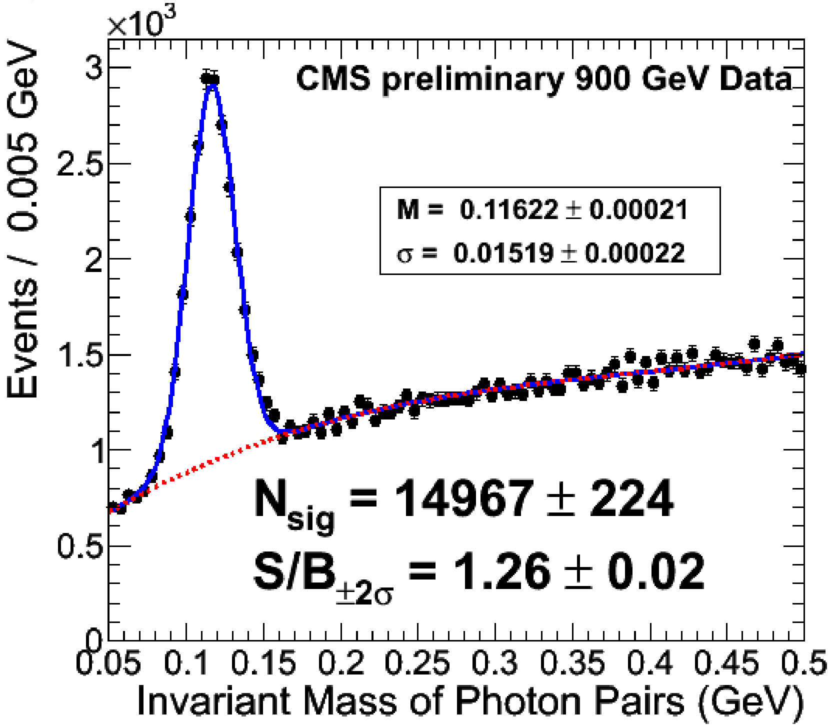
⇒Transparency of each crystal is measured with a precision of <0.1% every 20 minutes

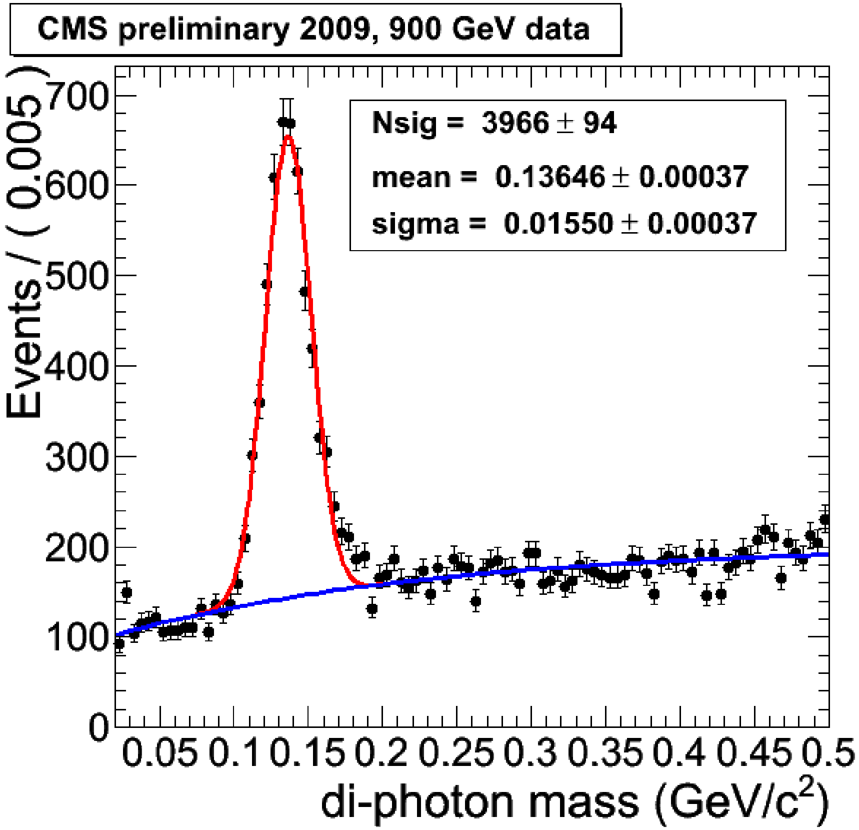
# ECAL Laser Monitoring System



# First Di-photon Distribution in CMS

**First shown on Thur 27th Nov, Today's distributions shown below**



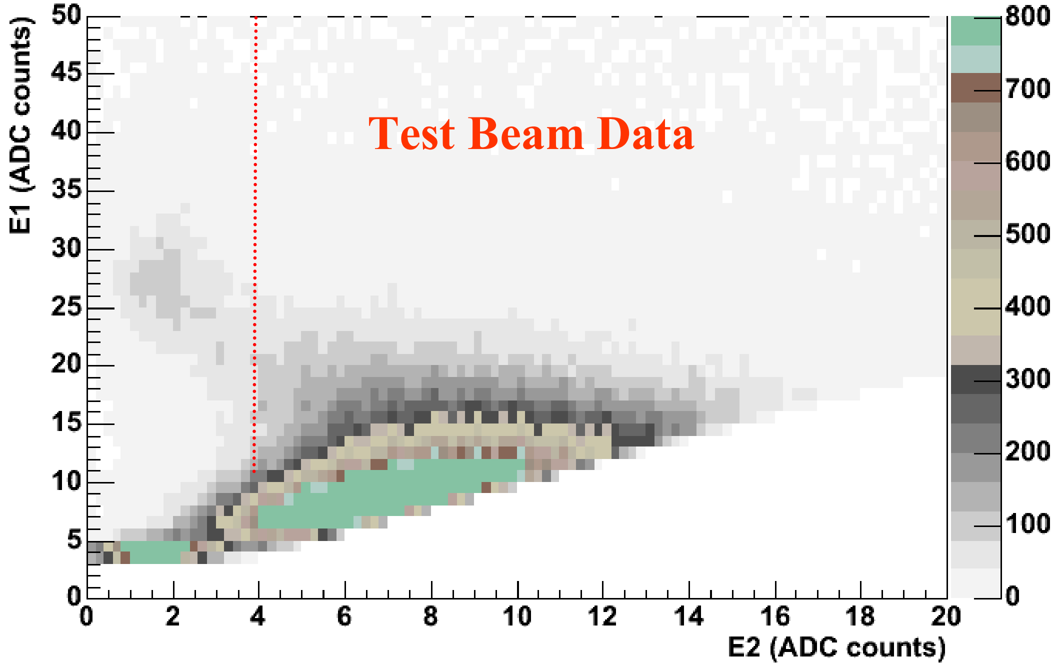


- **Data and MC comparison (uncorrected distributions)**
- Almost identical S/B, mass and width compatible
- M($\pi^0$) is low in both data and MC - Mostly due to the readout threshold (100 MeV/Crystal) and conversions

**Using "out of the box" corrections**

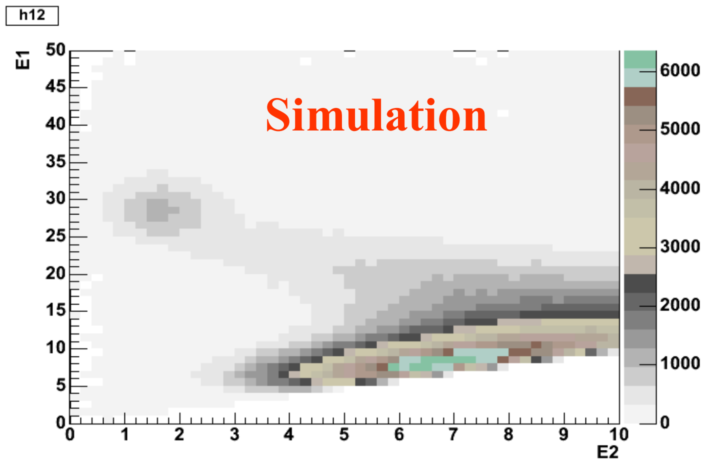
# Cosmic Muon Calibration

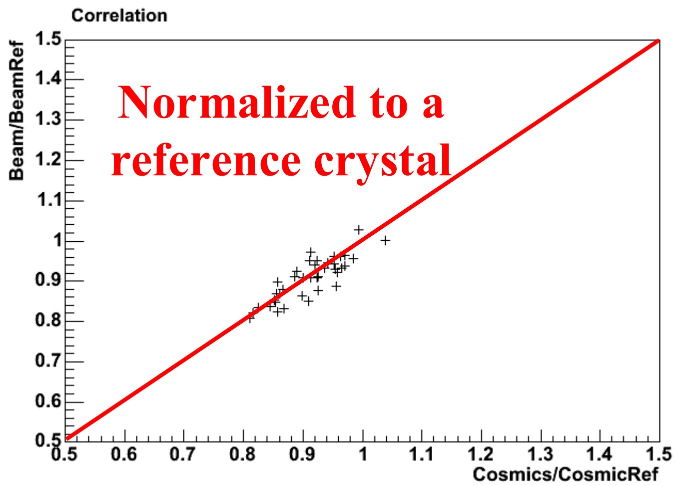
For APD gain (50) cosmic muons are hidden in the noise.
Run at higher gain (200).



**E1 is the highest energy deposit (maximum sample)**

**E2 is the second highest energy deposit in the 3x3 matrix (evaluated at the same sample as E1 )**

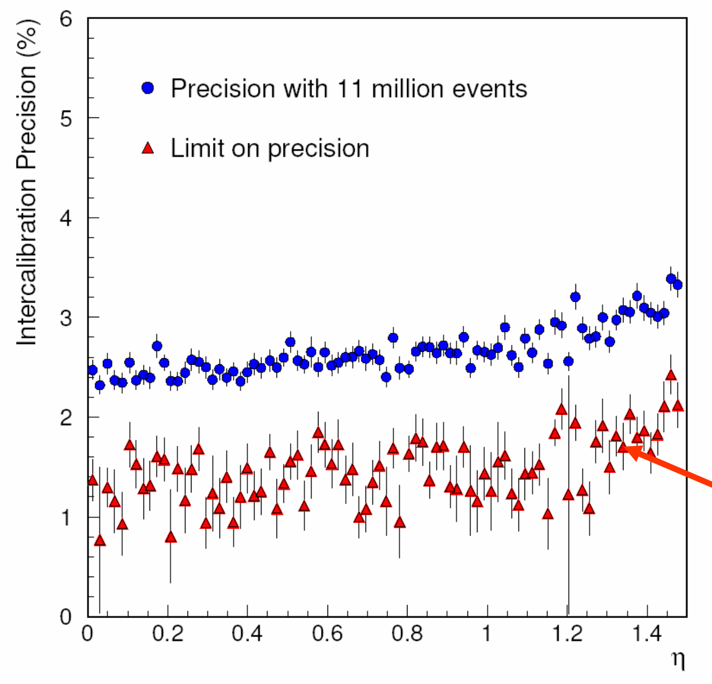




**Relative calibration ~ 2% achievable.**

# CMS In-situ : φ-uniformity method

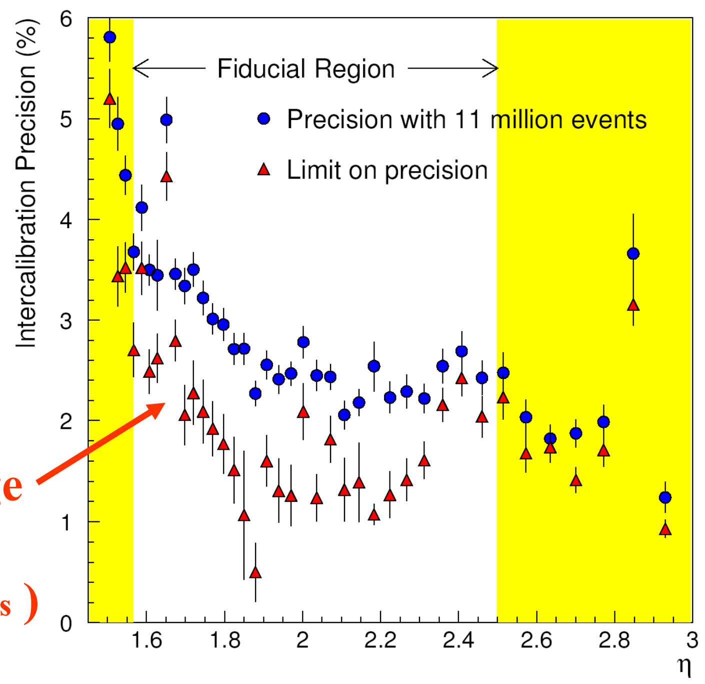
### *BARREL*



11 million

Level-1 jet trigger events

### *ENDCAPS*



**Precision limits assuming no knowledge of tracker material**

**(~10h , 1kHz L-1 single jet triggers )**

***Idea***: φ-uniformity of deposited energy in crystals at constant η

***Limitations*** : non-uniformities in φ

- in-homogeneity of tracker material
- geometrical asymmetries

***Used***: Min-bias / Level-1 jet trigger events

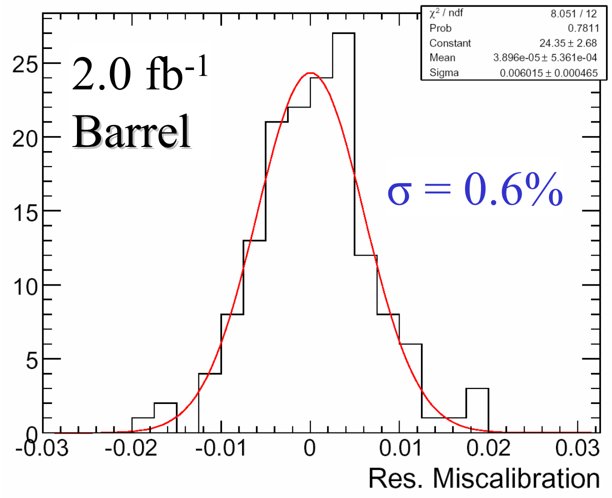
***Method***: Compare $<E_T>_{CRYSTAL}$ with $<E_T>_{RING}$ .

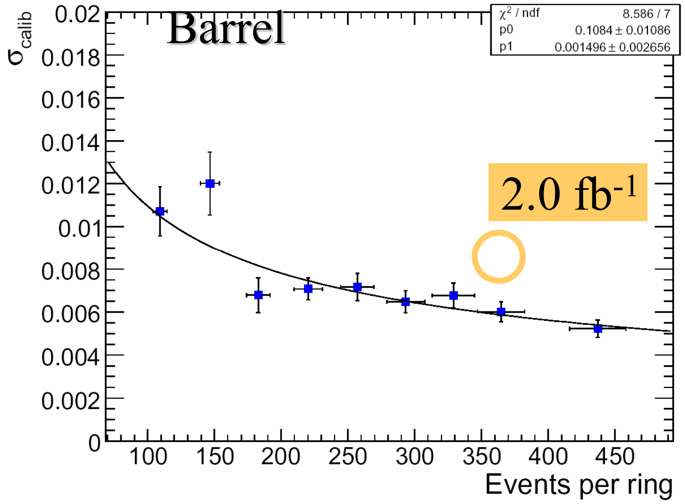
***Inter-calibration of η rings:***

$Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-\gamma$ , isolated electrons

Nick Hadley

# CMS In-situ: using Z→$e^+e^-$





Method:

Z mass constraint

Use cases:

- Inter-calibrate crystals in ECAL regions
- Inter-calibrate ECAL regions (i.e.rings in φ-symmetry method)
- Set the absolute energy scale
- Tune algorithmic corrections for electron reconstruction

Events Selection: Low brem electrons.

Algorithm:

Iterative (~10-15), constants are obtained from the peak of $\varepsilon^i$ distribution.

$$\bar{\epsilon}^i = \frac{1}{2}\cdot\left[\left(\frac{M^i_{inv}}{M_Z}\right)^2 - 1\right]$$

Results:

Assuming 5% mis-calibration between the rings and 2% mis-calibration between the crystals within a ring

↓ *Statistics:* ***2.0 fb$^{-1}$***

**0.6%** ring inter-calibration precision

# CMS In-situ: using isolated electrons

**Target**: 0.5% calibration precession

**Method**: E / P <width minimization>

ECAL

$$E = \sum^{5x5} c_i E_i$$

TRACKER

electron momentum

**Sources**: $W \to e\nu$ (10Hz HLT @ $2x10^{33}cm^{-2}s^{-1}$ ),
$Z \to e^+e^-$ ( 2Hz HLT @ $2x10^{33}cm^{-2}s^{-1}$ ),
$J/\Psi \to e^+e^-$, $b/c \to e$, …

**Event Selection**:

We need a narrow E/P ⇒ Low brem $e^{\pm}$

Variables related to electron bremsstrahlung :

ECAL ($S_{3x3}/S_{5x5}$)

TRACKER (track valid hits, $\chi^2$/n.d.f., $P_{out}/P_{in}$)

Efficiency after HLT: 20-40% Barrel ,
10-30% Endcaps

Background: S/B~8
(isol. electrons from W/QCD)
Part of it might be useful ($b/c \to e$).

**Calibration Constants extraction Techniques**:

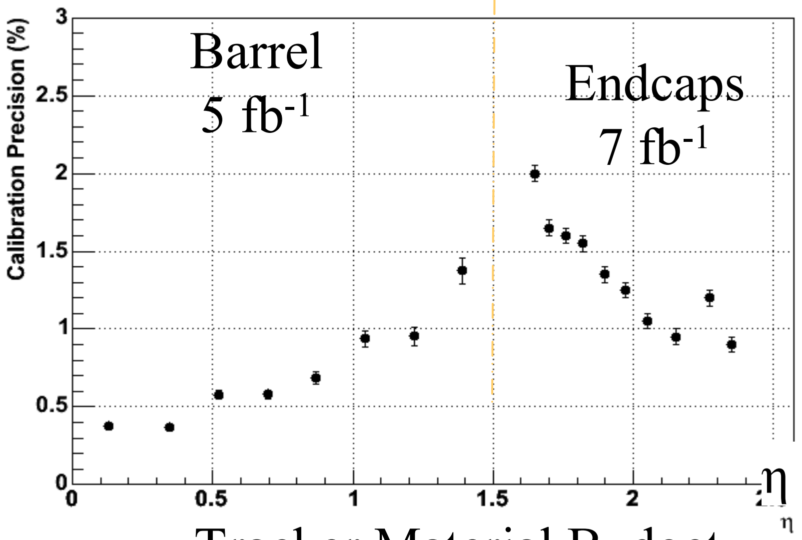
- L3/LEP iterative (~20 iterations),
- matrix inversion

**Calibration Steps**

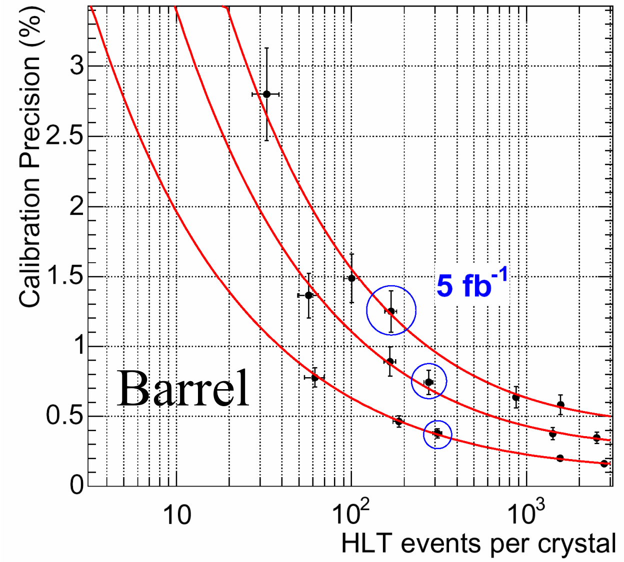
- Calibrate crystals in small η-φ regions
- Calibrate regions between themselves using tighter electron selection, $Z \to e^+e^-$ , $Z \to \mu^+\mu^-\gamma$

# In-situ:  using isolated electrons

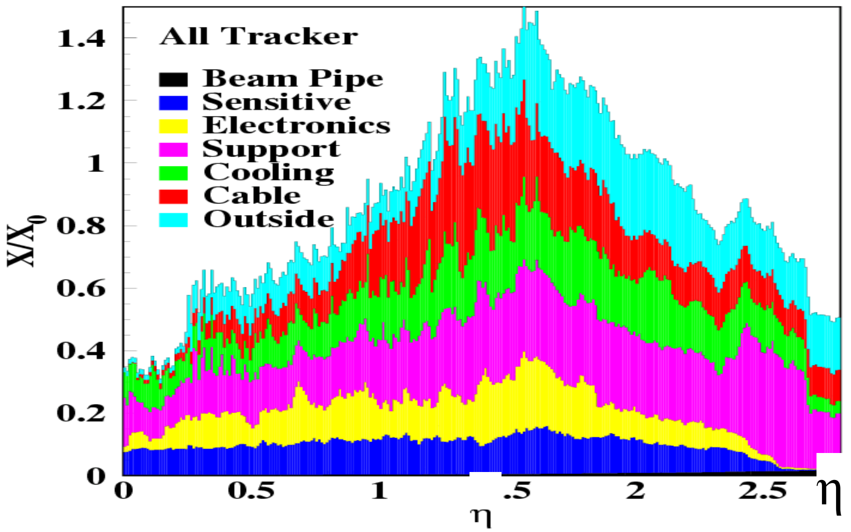
Calibration Precision versus η



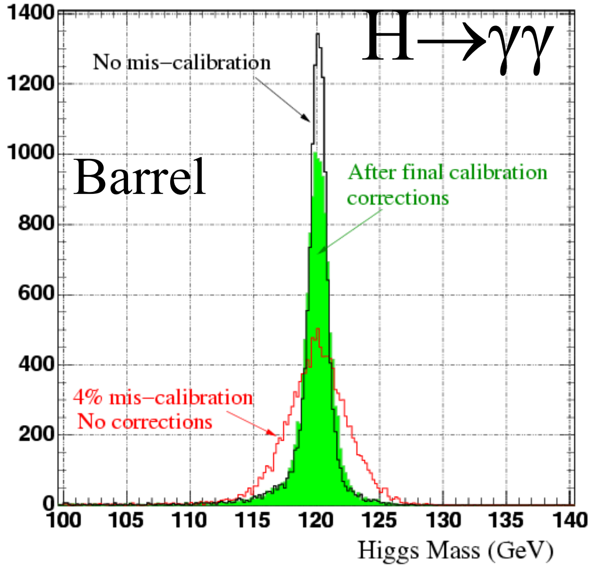
Precision versus Statistics



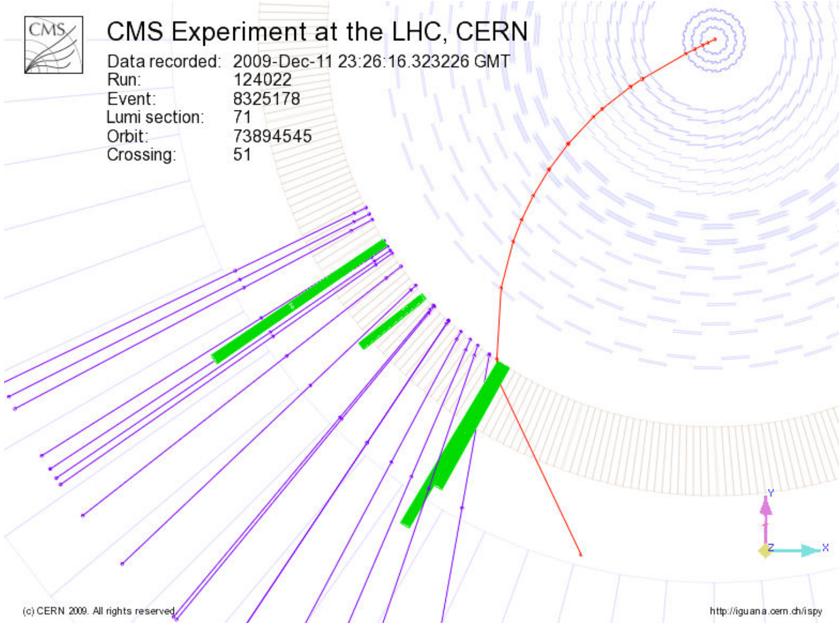
Tracker Material Budget

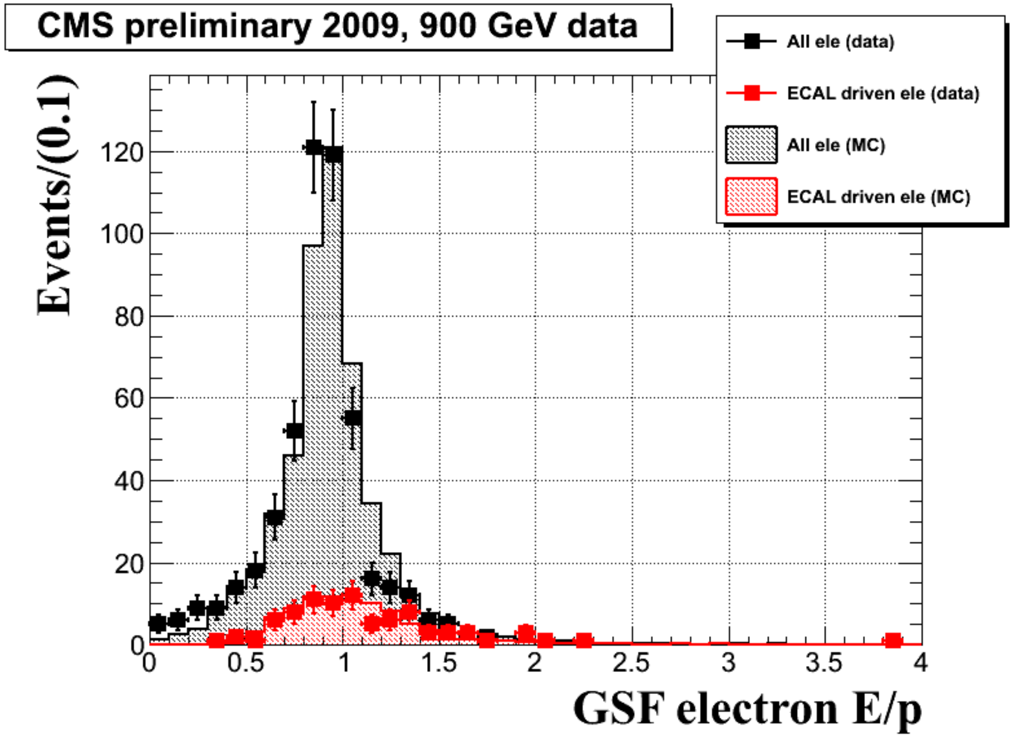


Higgs Boson Mass Resolution



# Reconstruction of Electrons





2.5 GeV electron with bremstrahlung

# Alignment Strategy

- **Applies to tracking detectors including muon chambers.**
  - Then use tracks to align calorimeters as trackers measure position better (usually) than calorimeters

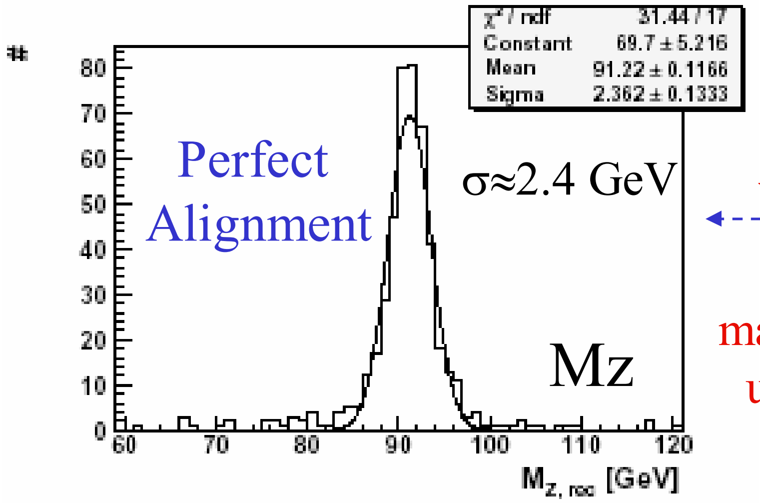
- **Typically 3 step process**
  1. Measure element (e.g. wire, pixel) position during construction of subdetector using coordinate measuring machines and similar devices.
  2. Measure relative position of subdetectors after assembly using surveying techniques such as lasers.
     - Only works for detectors you can see.
  3. Track based alignment

# Alignment Concept & Typical Numbers

| | Muon | Tracker | |
|---|---|---|---|
| | | Strip | Pixel |
| Assembly: | O(mm) | 0.1-0.5mm | 50-100 μm |
| + | | | |
| Hardware Alignment: | ~<100μm | <100μm | 50-100 μm (no HA foreseen) |
| + | | | |
| Track Based Alignment | ~100μm (perhaps below) | ~10μm | ~5 μm |
| Remarks: | Hardware Alignment will provide the operational alignment level. Track based alignment will be a cross check and eventually a completion | Hardware Alignment will insure pattern recognition. Track Based Alignment must provide the final alignment | Only Track based Alignment. Nothing else! |

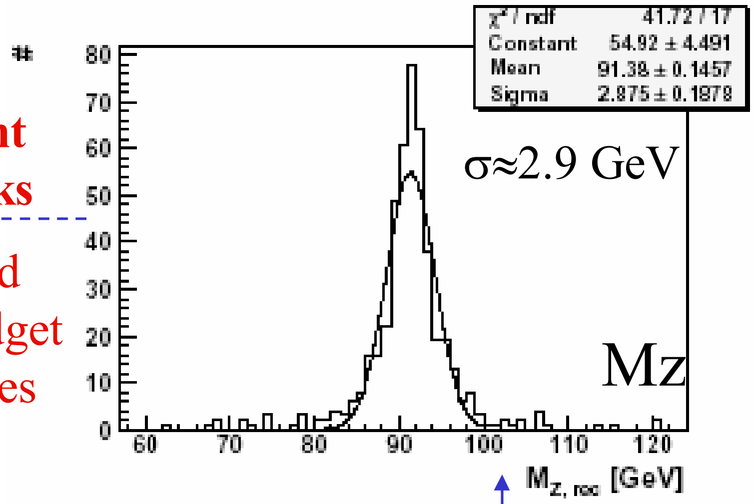
# Mis-Alignment: Impact on Physics (important for Z′, LED)

**⇒ Use Z→μμ to illustrate the impact of mis-alignment on physics**



**Alignment with tracks**

B field and material budget uncertainties



*First Data Taking*

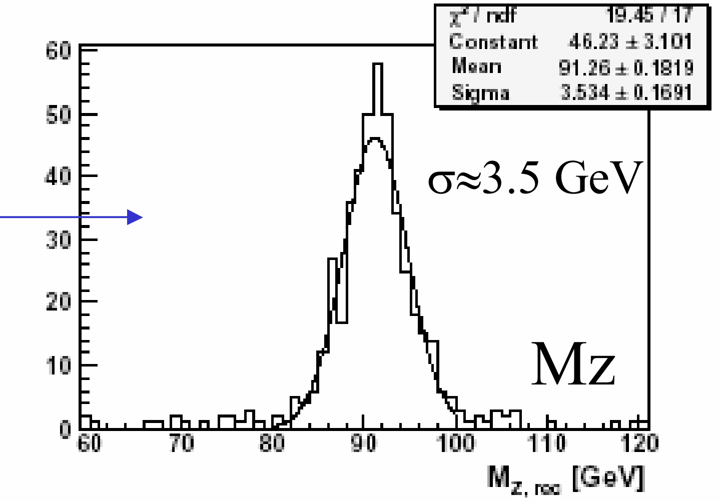
*<1fb$^{-1}$*

*Laser Alignment*

⊗

*Mechanical Constraints*

⇒≈100μm alignment uncertainties



*Long(er) Term:*

*≈>1fb$^{-1}$*

*First results of Alignment with tracks*

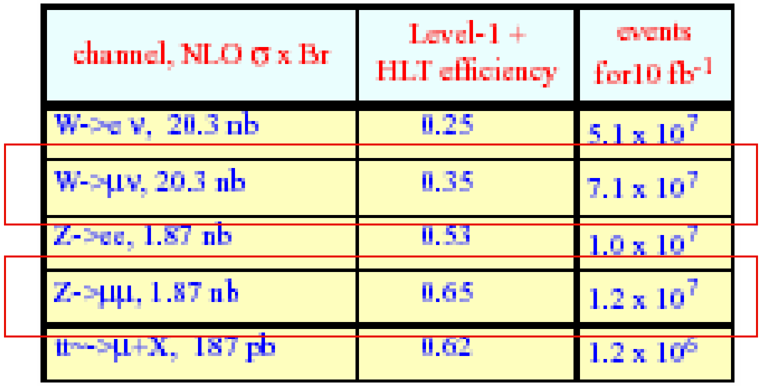
⇒≈20μm alignment uncertainties

# CMS Data Samples for Alignment

***The Golden Alignment Channels:***

$Z\to\mu\mu$ O(20K x 2) per day

$W\to\mu\nu$ O(100K) per day



| channel, NLO $\sigma$ x Br | Level-1 + HLT efficiency | events for10 $fb^{-1}$ |
|---|---|---|
| W->e ν, 20.3 nb | 0.25 | $5.1 \times 10^7$ |
| W->μν, 20.3 nb | 0.35 | $7.1 \times 10^7$ |
| Z->ee, 1.87 nb | 0.53 | $1.0 \times 10^7$ |
| Z->μμ, 1.87 nb | 0.65 | $1.2 \times 10^7$ |
| tt~->μ+X, 187 pb | 0.62 | $1.2 \times 10^6$ |

⇒ Isolated well measured track statistic of one day nominal running should enable us to align all higher lever tracker structures (rod level)

**A dedicated trigger stream for these event types would be very beneficial in order to insure *immediate* access to the data and, thus, a speedy alignment of the tracker!**

## *Bottom Line:*

Isolated high momentum ($p_T$ ~50-100 GeV) muon tracks seem to be the first choice for the alignment

***⇒ Need special stream for these events!***

**Exploit mass constraint:**

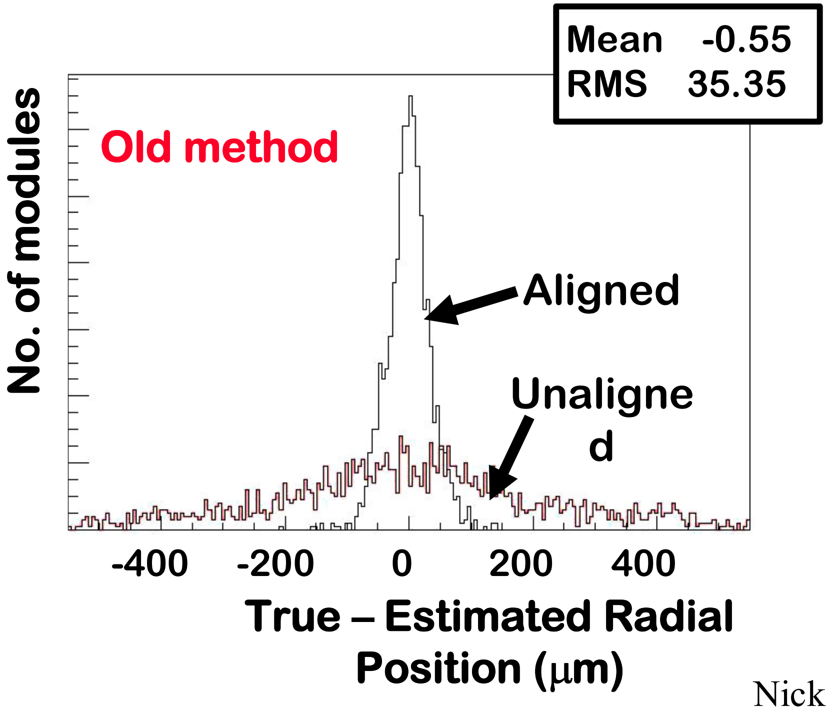
*Properly including the mass constraint for $Z\to\mu\mu$ (or even $J/\phi\to\mu\mu$) will significantly enlarge our capability two align also detectors wrt each other which are not crossed by single collision tracks*

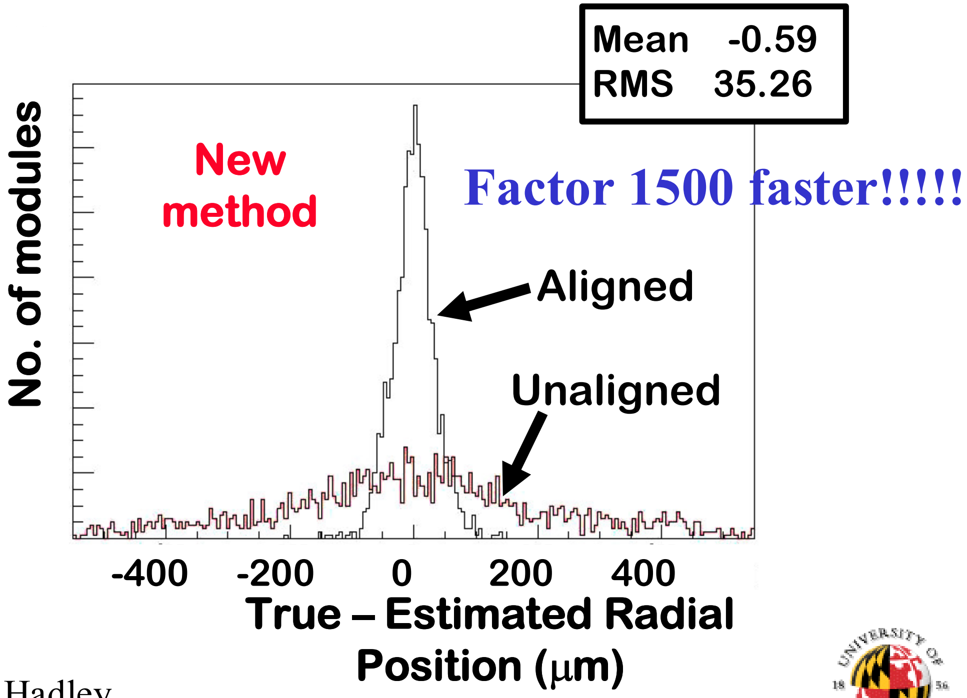
# CMS implementation of Millepede II Algorithm (Millepede see www.desy.de/~blobel)

Original Millepede method solves matrix eqn. A x = B, by inverting huge matrix A.
This can only be done for < 12000 alignment parameters.

New Millepede method instead minimises |A x – B|.
Is expected to work for our 100000 alignment parameters.

Both successfully aligned ~12% of Tracker Modules using 2 million Z $\rightarrow \mu^+ \mu^-$ events.
Results identical, but new method 1500 times faster !



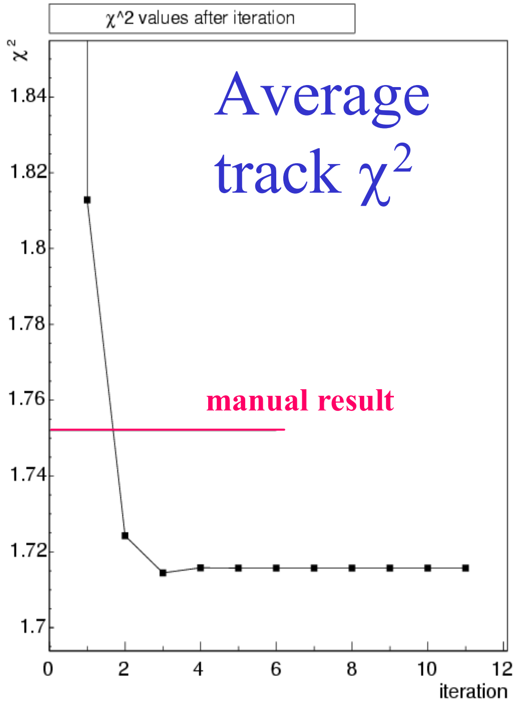


Factor 1500 faster!!!!!

# CMS Hits and Impact Points (HIP) Algorithm

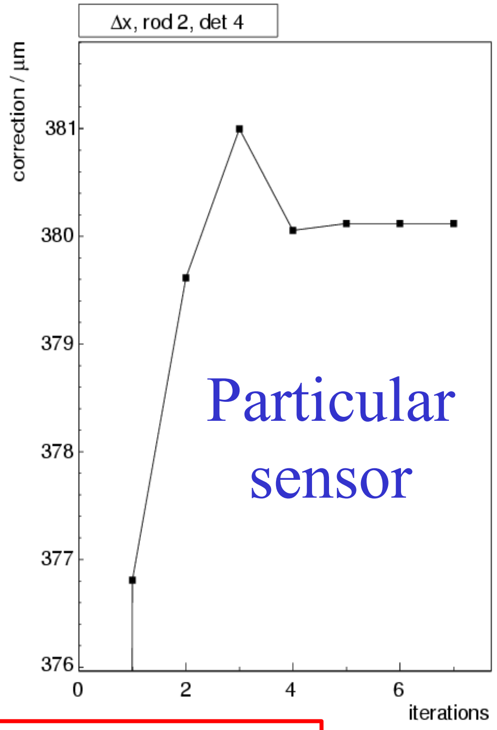
- **Collect a sample of tracks**
- **Align individual sensors independently**
- **Reconstruct tracks and iterate**
- **Low computational cost, 6 x 6 matrix per sensor**
- **Algorithm studied with <u>real data</u>: CRack test beam and cosmic data (8 genuine alignable strip detectors)**
- **Proof of principle for alignment software implementation in CMS software**
- **Larger cosmic data sample expected**

- Tests using testbeam and cosmic data ongoing



Average track $\chi^2$

manual result



Particular sensor

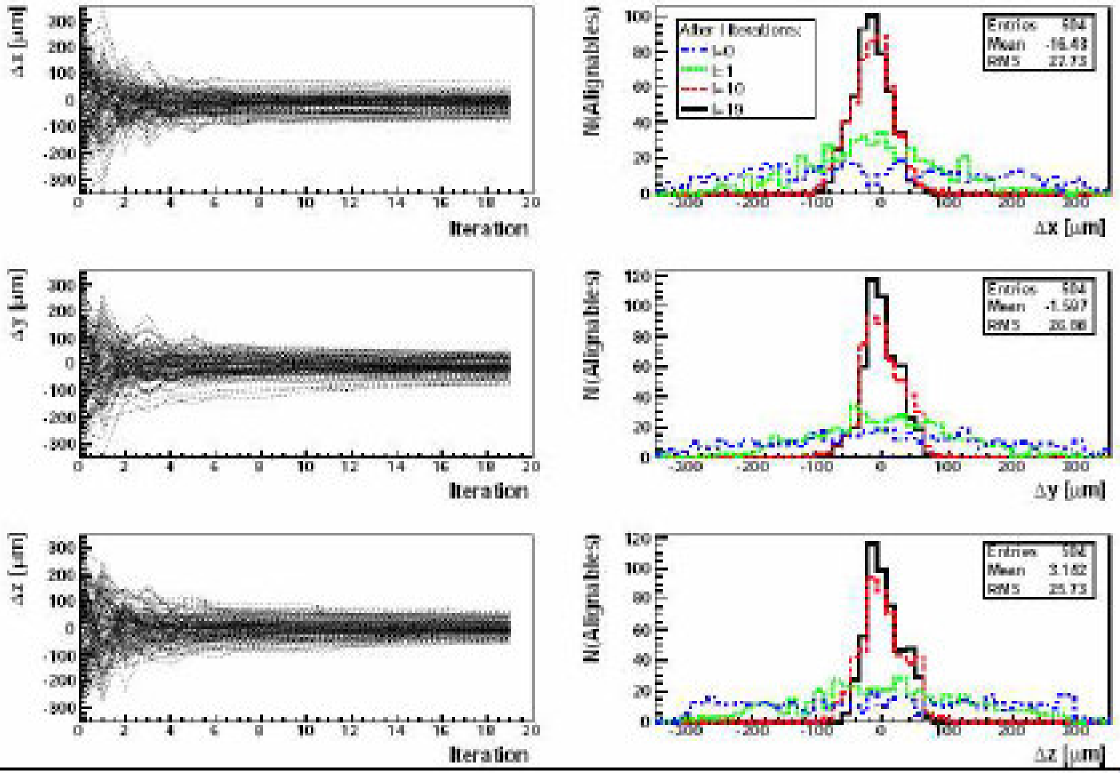
Results from pion test beam data

# CMS HIP Algorithm

- Stand-alone alignment of Pixel Barrel modules
- Track curvature obtained from track-fit of full Tracker (even mis-aligned Tracker)

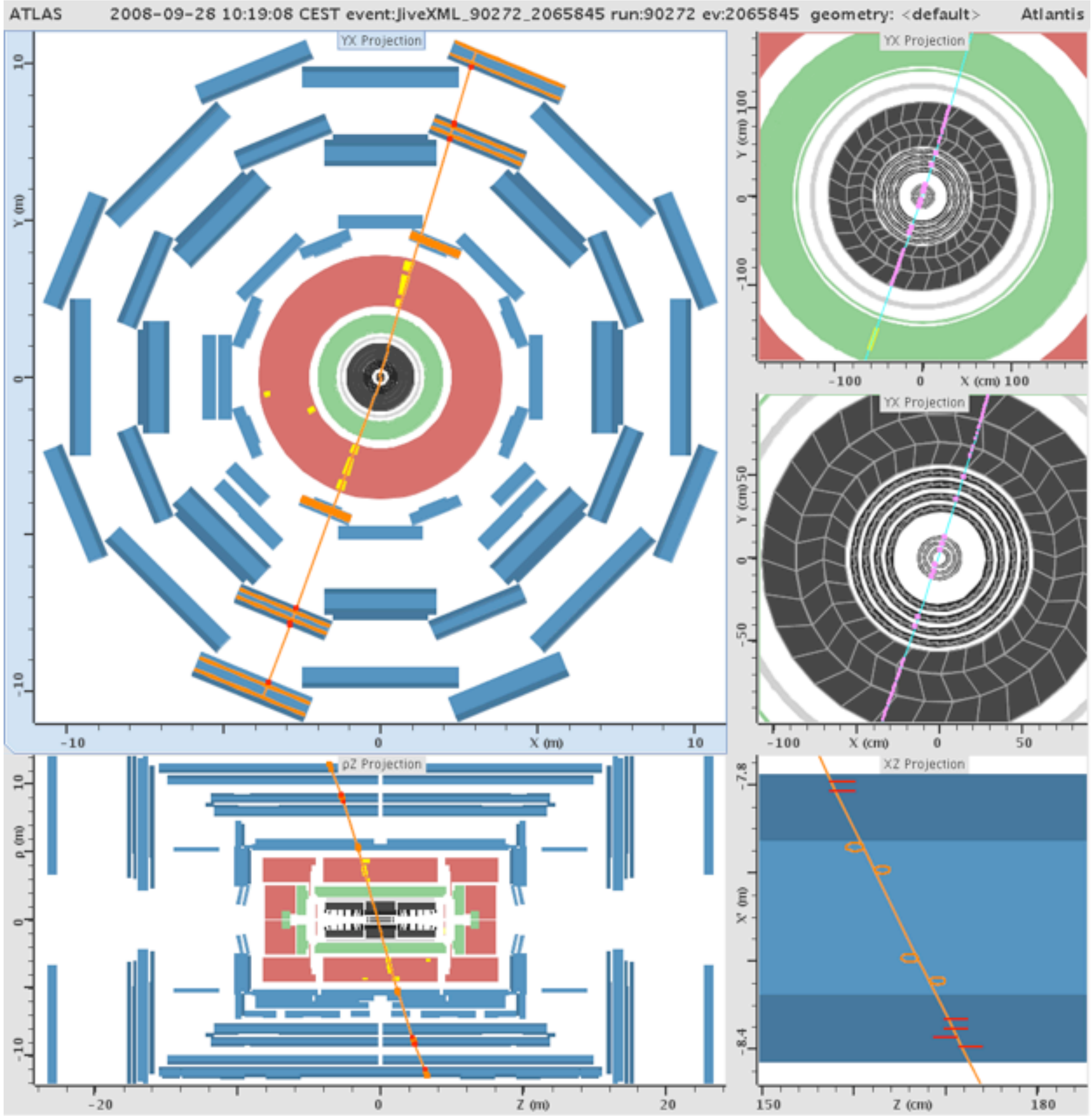
Convergence of estimates

Distribution of local shifts

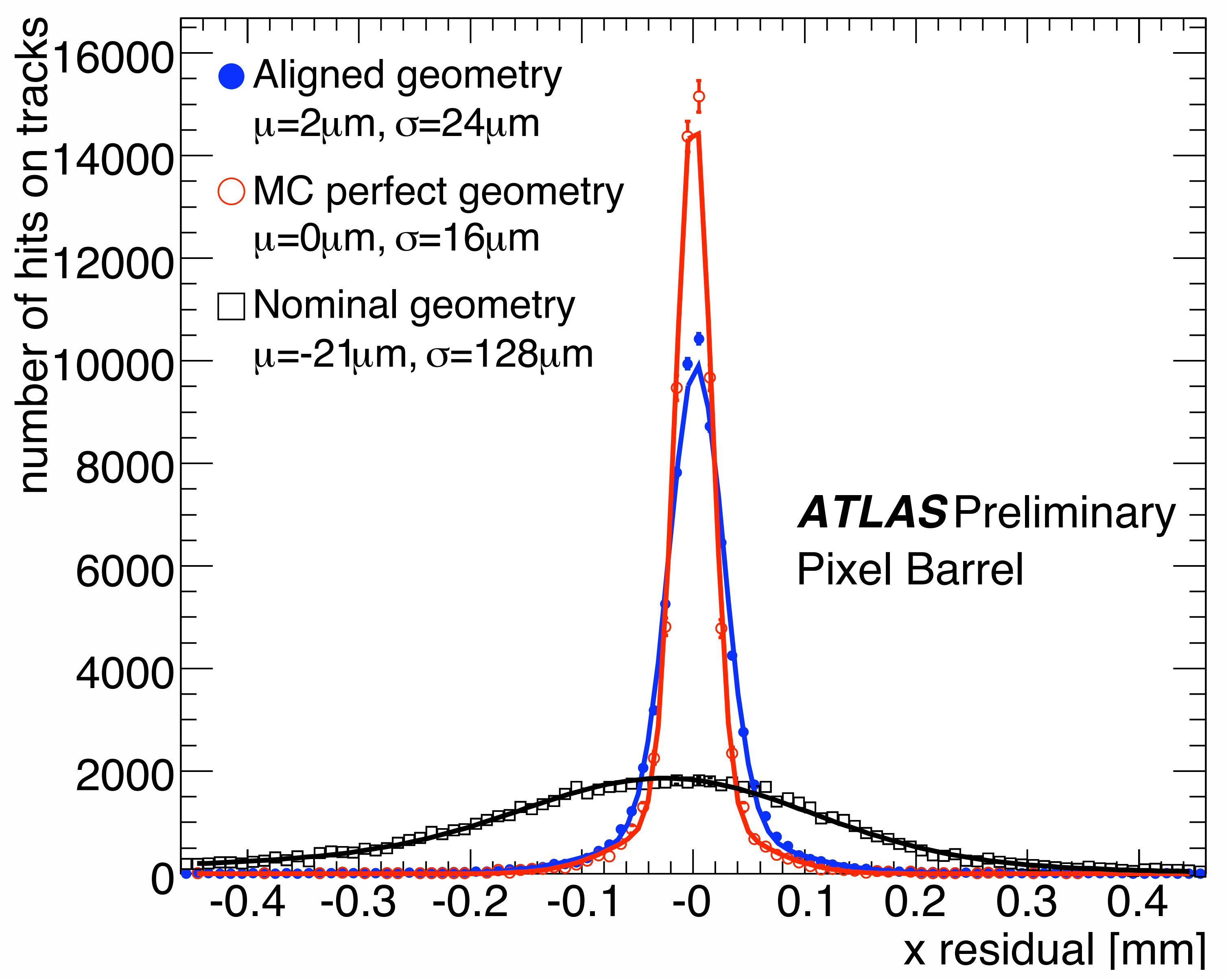


Nick Hadley

# 14. ATLAS Cosmic Event



# 14. ATLAS Pixel Results: Cosmic Rays

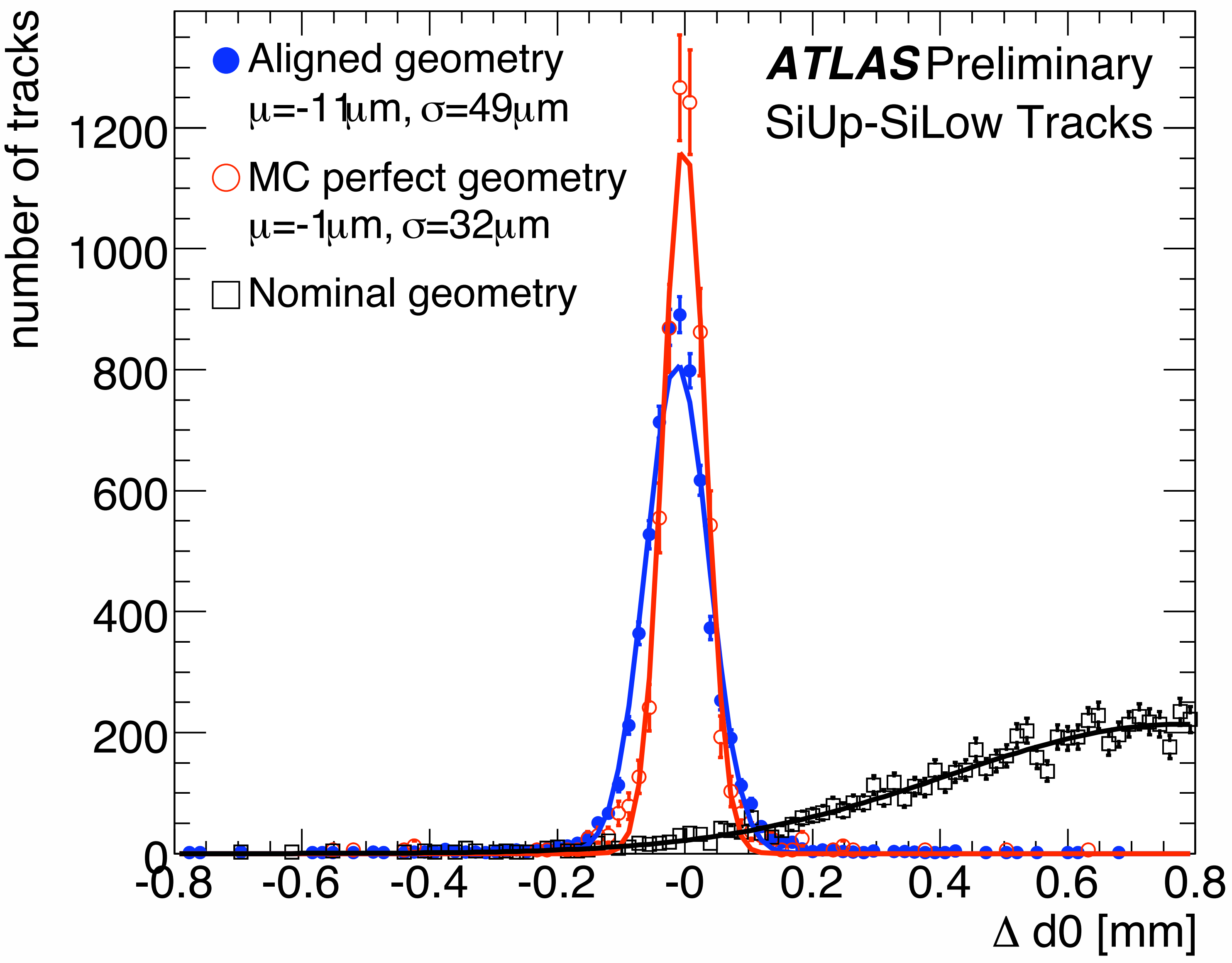


Residual distribution in x, integrated over all hits-on-tracks in the pixel barrel for the nominal geometry and the preliminary aligned geometry.

The residual is defined as the measured hit position minus the expected hit position from the track extrapolation. Shown is the projection onto the local x coordinate, which is the precision coordinate.

Tracks are selected to have pT > 2 GeV, |d0|<50mm, |z0|<400mm (in other words they are required to go through the pixel L0).

# 14. ATLAS ID Results: Cosmic Rays



Cosmic tracks crossing the entire ID leave hits in both the upper and lower halves of the ID.

These tracks can be split near the interaction point and fit separately, resulting in two collision-like tracks that can then be compared.

The plots shows the difference in the d0 track parameter between the two split tracks. Tracks are selected to have pT > 2 GeV, |d0|<50mm, |z0|<400mm (in other words they are required to go through the pixel L0).

Tracks also are required to have a hit in the Pixel B layer, 3 Pixel hits and in total 7 Silicon hits.