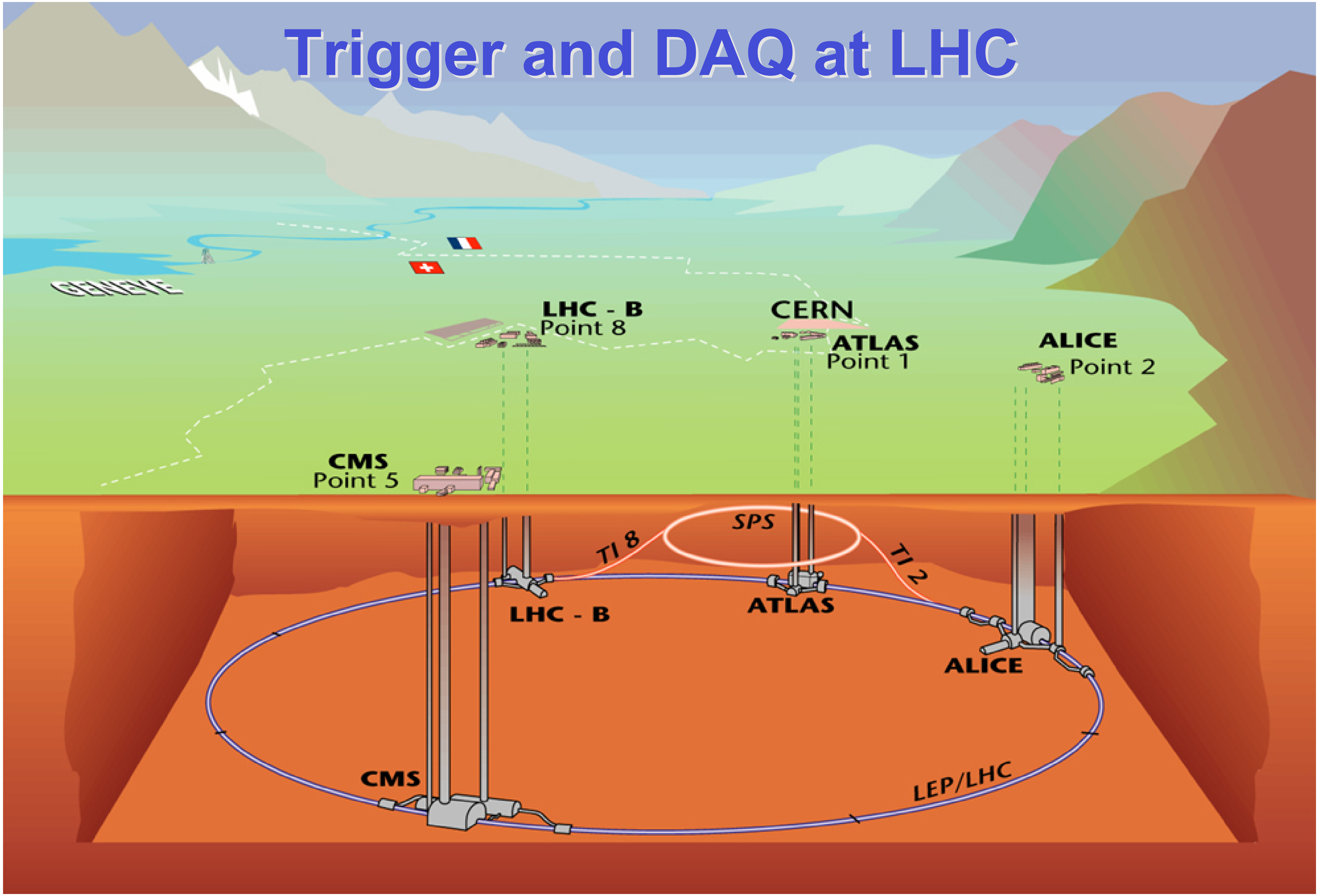
Trigger and DAQ at LHC



C.Schwick

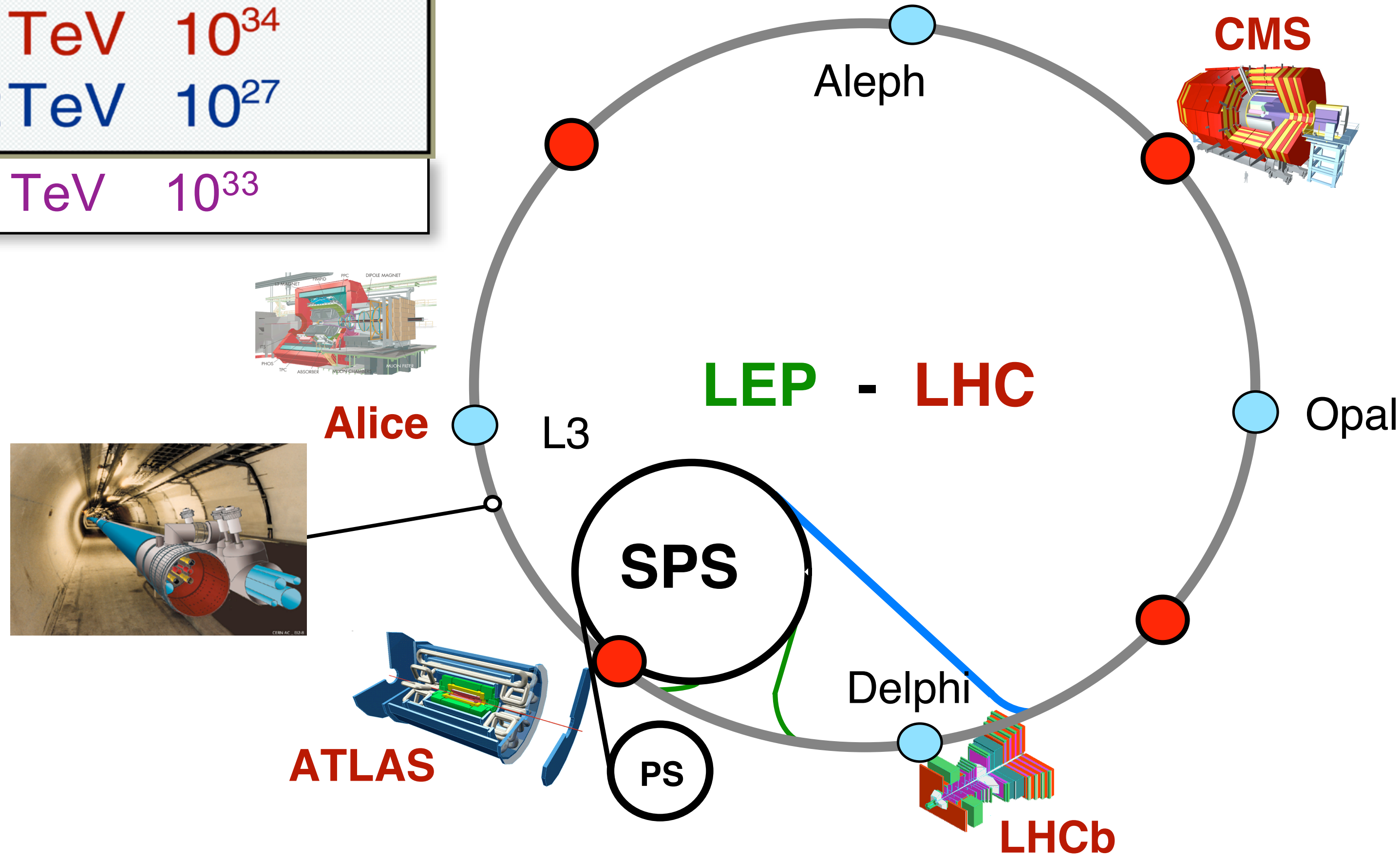
Contents

Thanks to my colleagues of ALICE, ATLAS, CMS, LHCB for the help they gave me during the preparation of these lectures.

Introduction: LHC and the Experiments

LHC: a “discovery” machine

	Beams	Energy		Luminosity
LEP	e^+e^-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	P_b P_b	1312	TeV	10^{27}
$LHC_{startup}$	p p	14	TeV	10^{33}



p-p interactions at LHC

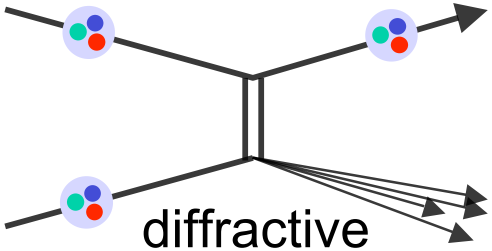
σ_{tot} =

≈100mb

diffractive

≈10mb

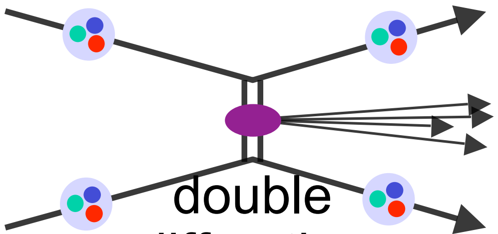
\+



diffractive

≈10mb

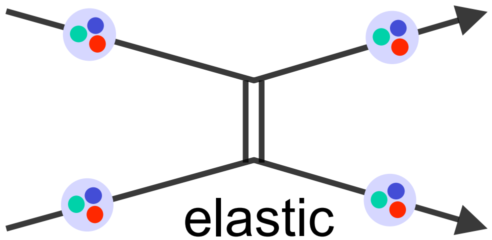
\+



double diffractive

≈"small"

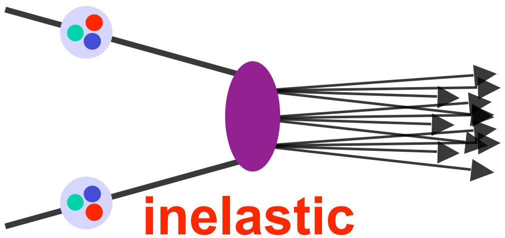
\+



elastic

≈10mb

\+

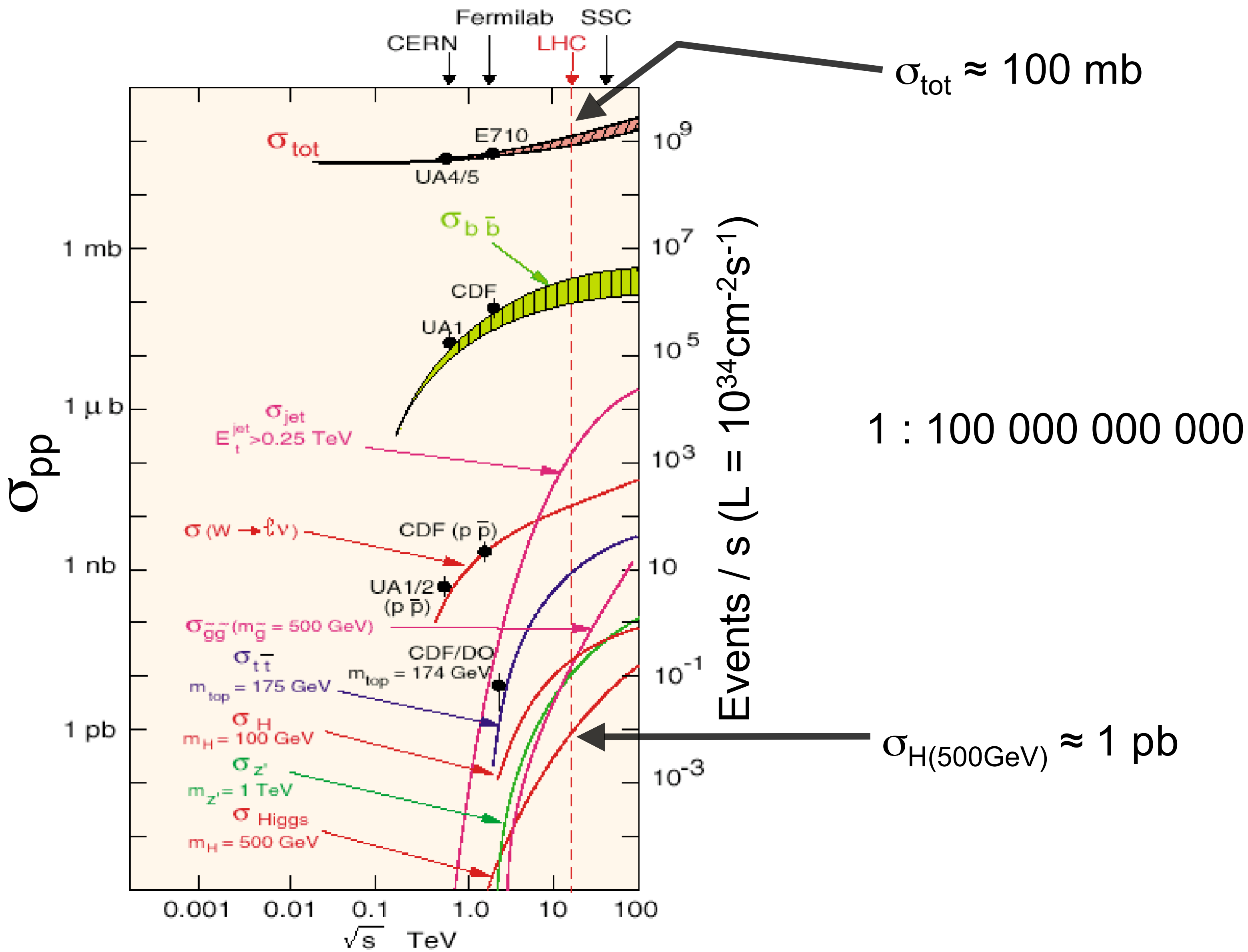


inelastic

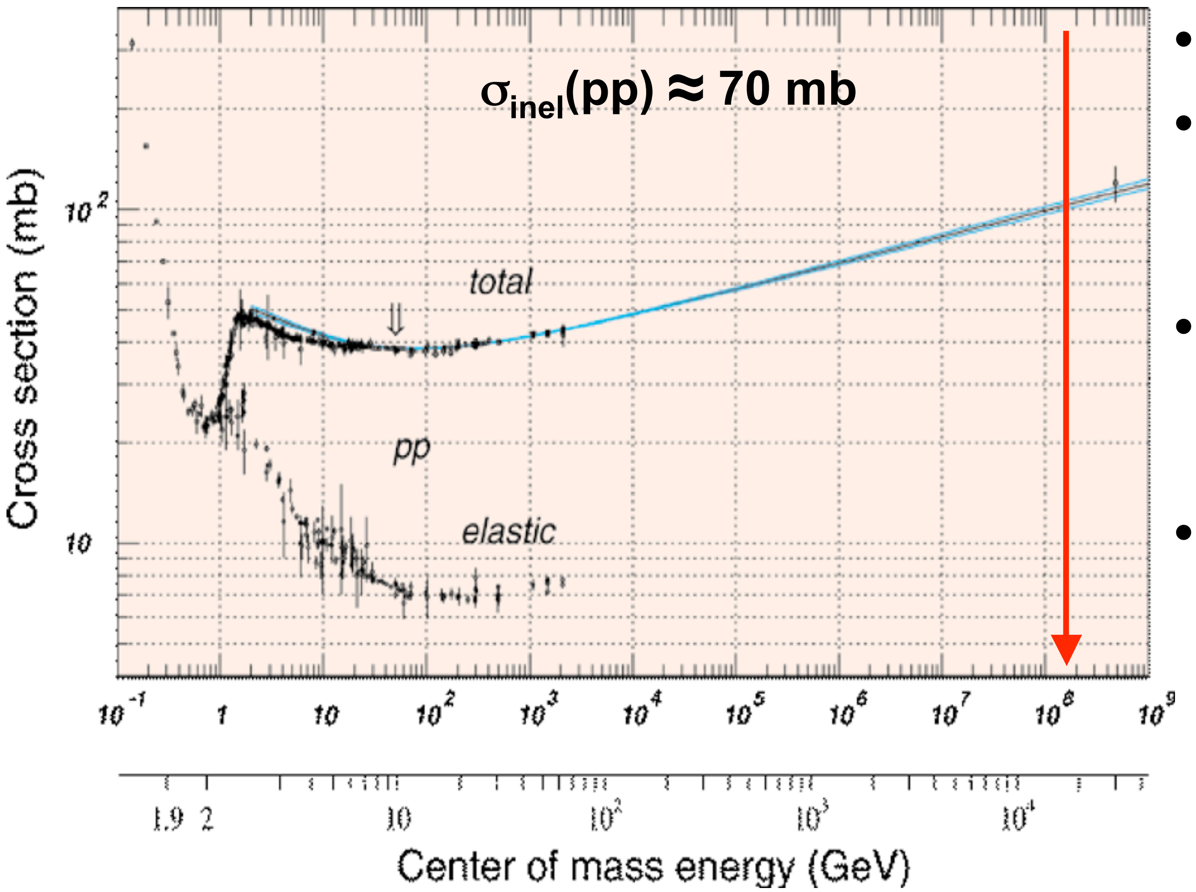
≈70mb

← **Interesting Physics**

Interesting Physics at LHC

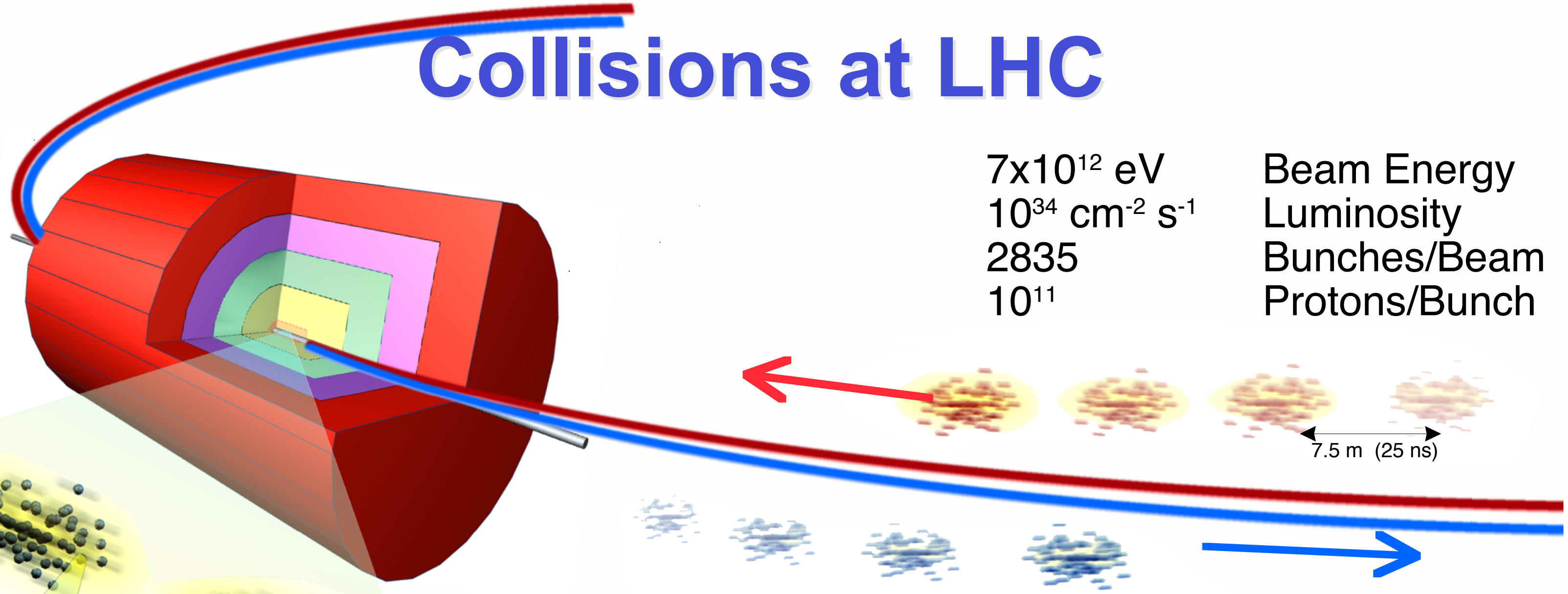


LHC: experimental environment



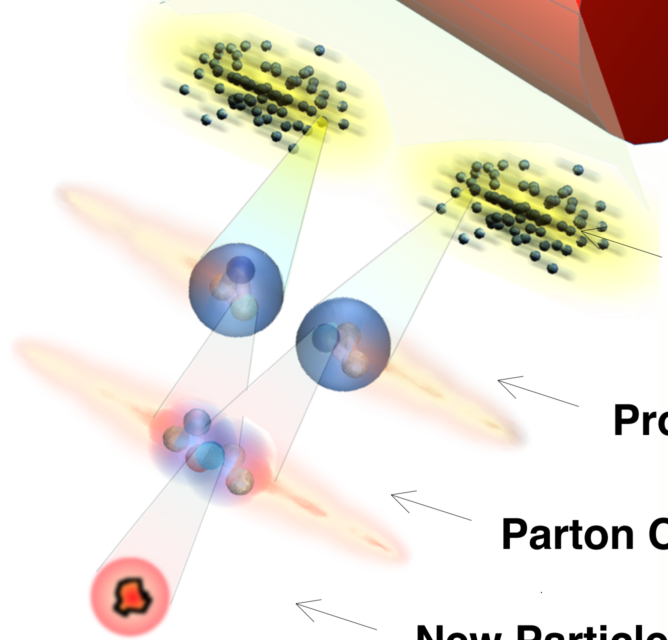
- $L = 10^{34} cm^{-2} s^{-1}$
- $\sigma_{inel}(pp) \approx 70$mb
  event rate = 7 x 10^8Hz
- Δt = 25ns
  events / 25ns = 17.5
- Not all bunches full (2835/3564)
  events/crossing = 23

Collisions at LHC



7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

7 TeV Proton Proton
colliding beams

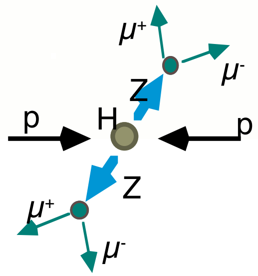


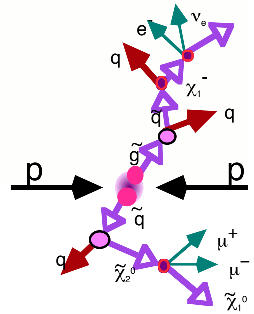
Bunch Crossing **$4\ 10^{7}$ Hz**

Proton Collisions **10^{9} Hz**

Parton Collisions

New Particle Production **10^{-5} Hz**
(Higgs, SUSY, ...) **$\sigma \approx 0.001$pb**





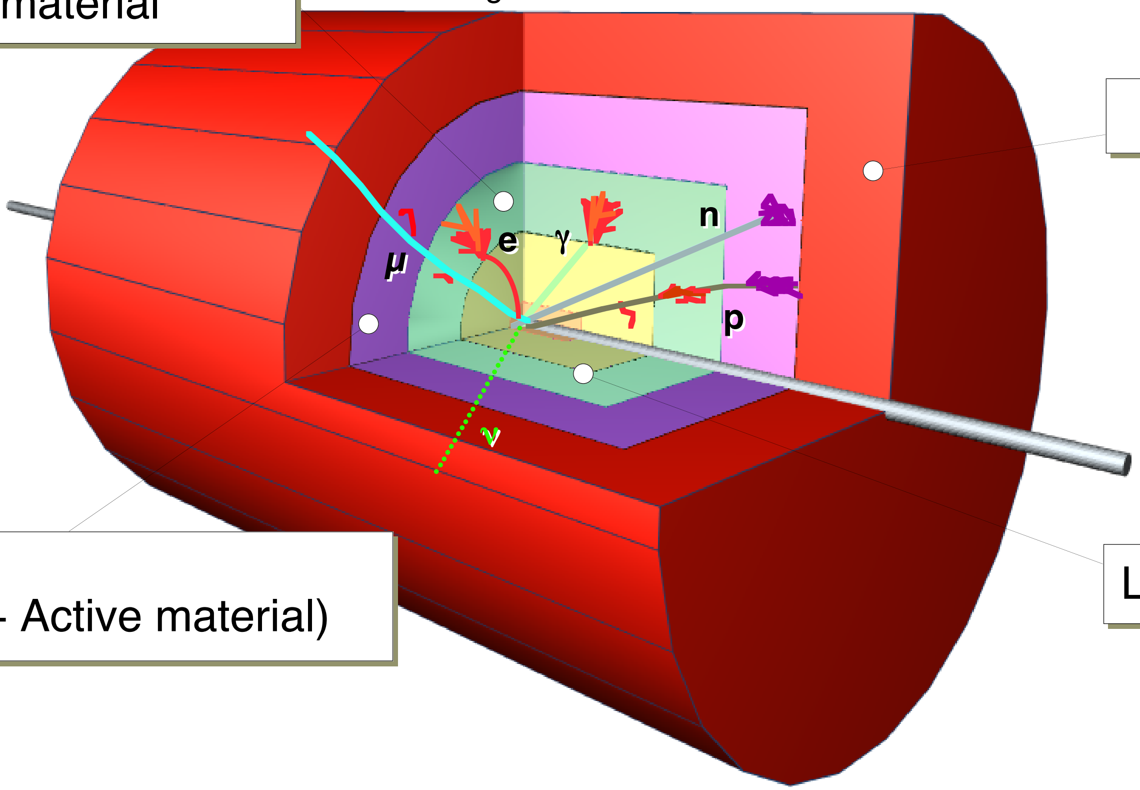
Selection of 1 event in 10,000,000,000,000

LHC Detector: main principle

Materials with high number of protons + Active material

Hermetic calorimetry
• Missing Et measurements

Electromagnetic and Hadron calorimeters
• Particle identification (e, γ Jets, Missing E_T)
• Energy measurement



Heavy materials

Muon detector
• μ identification

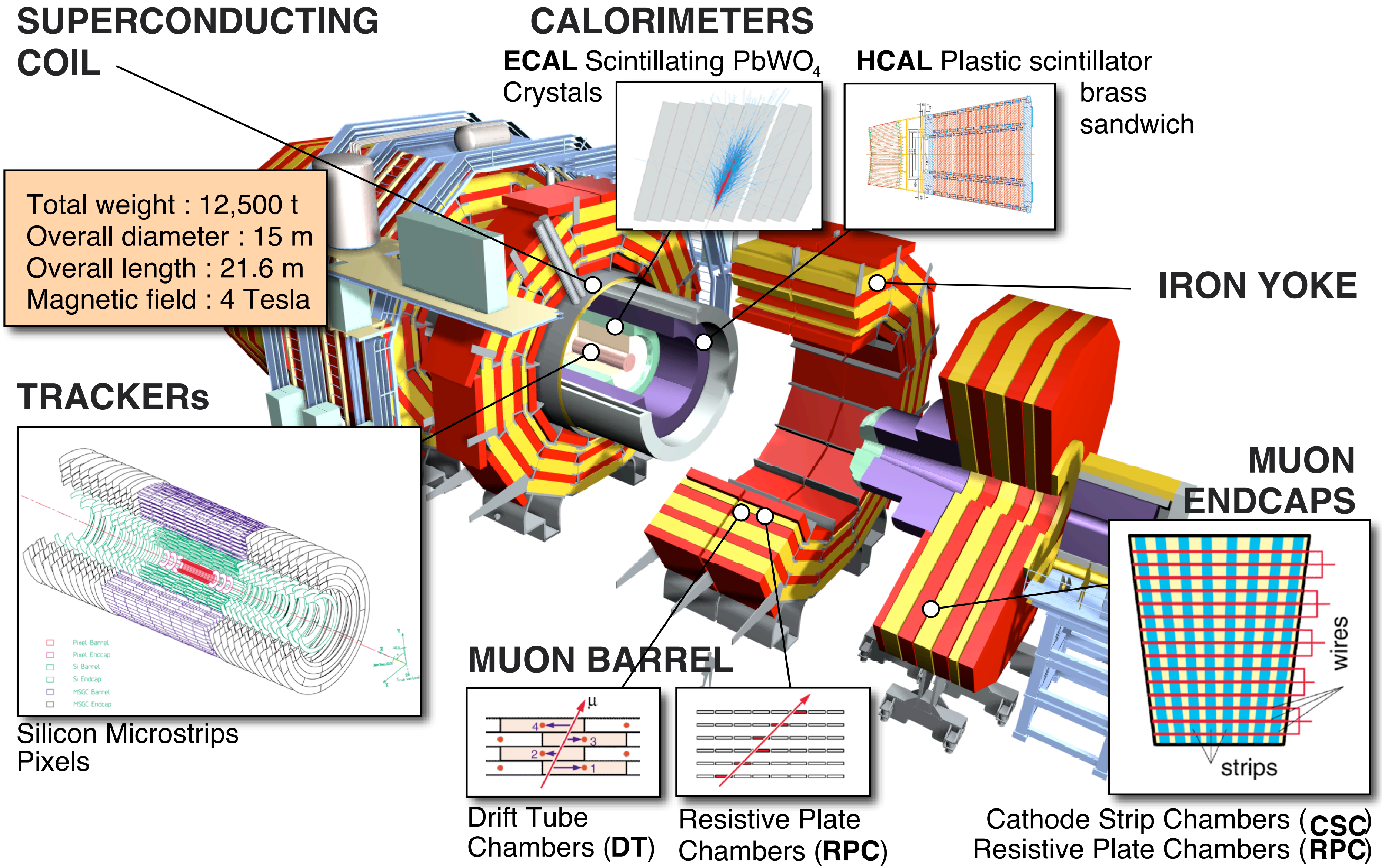
Heavy materials
(Iron or Copper + Active material)

Light materials

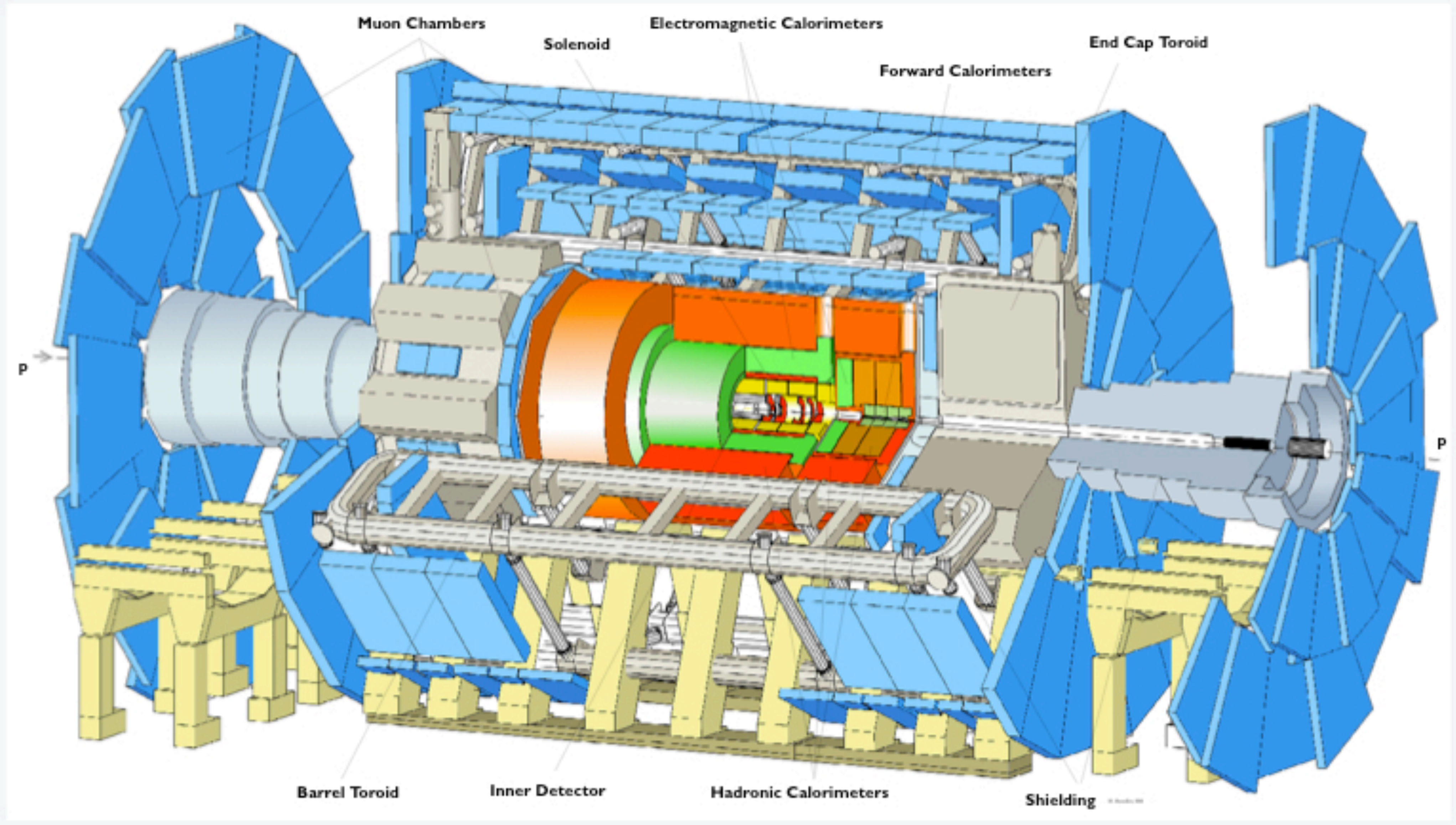
Central detector
• Tracking, p_T, MIP
• Em. shower position
• Topology
• Vertex

Each layer identifies and enables the measurement of the momentum or energy of the particles produced in a collision

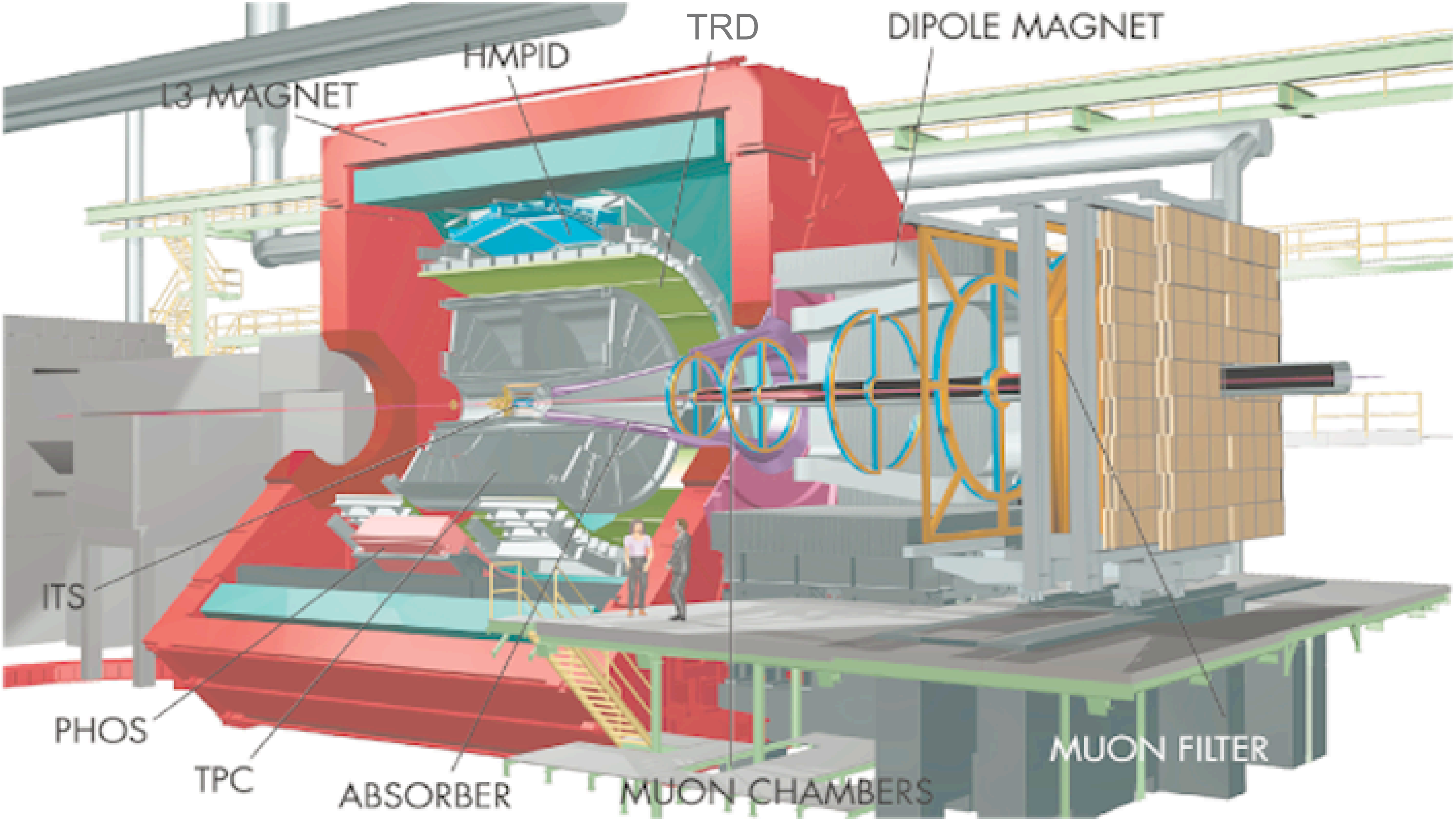
CMS : study of pp



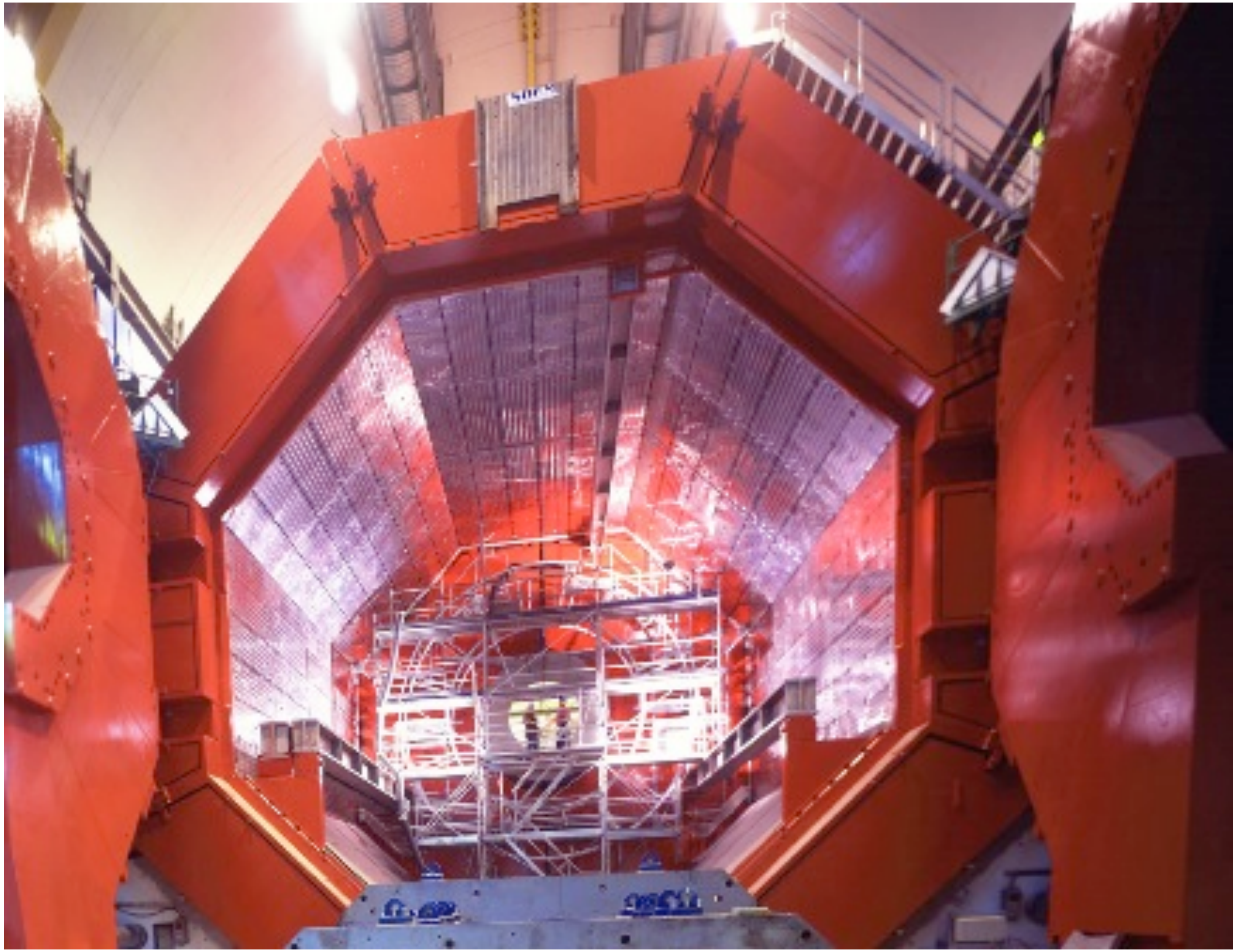
Atlas : study of pp



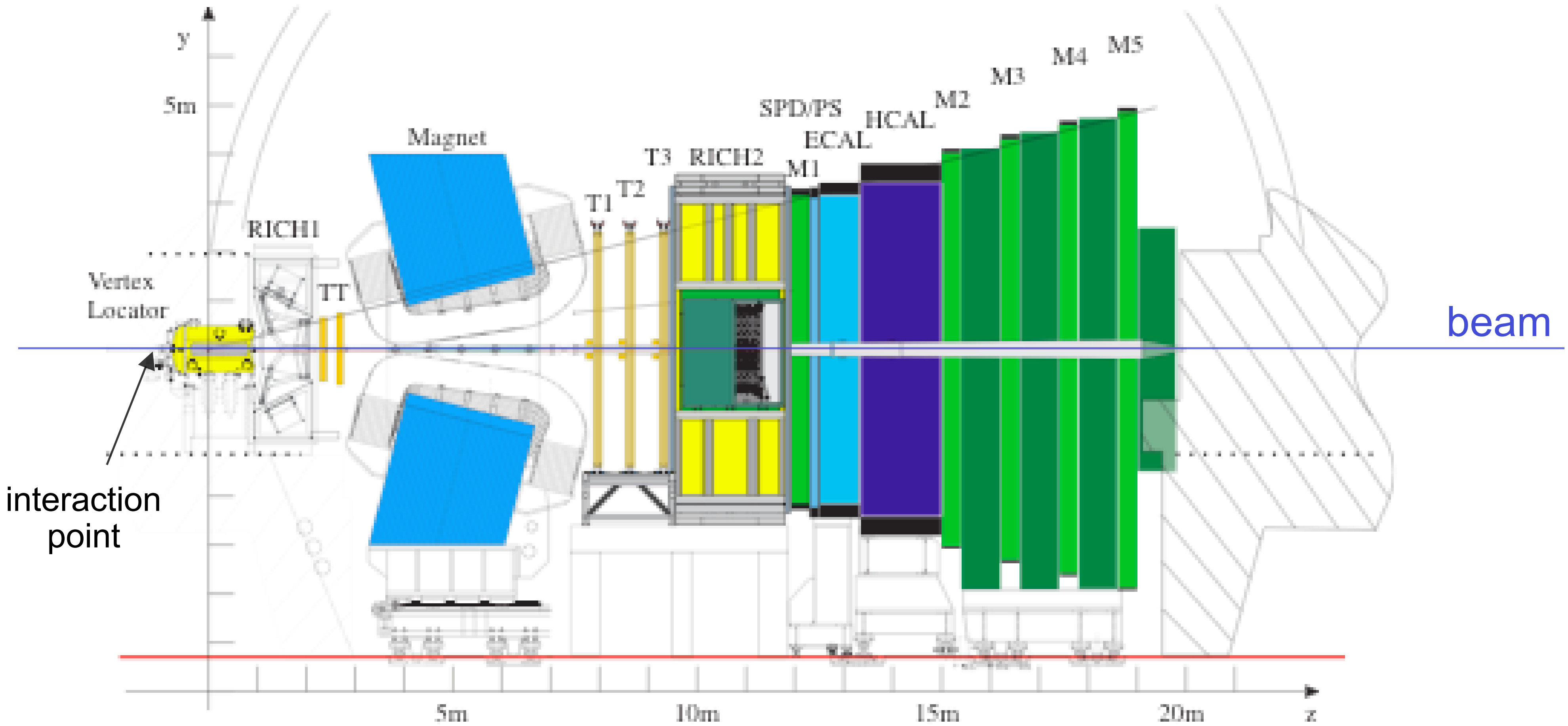
ALICE : study of heavy ion collisions



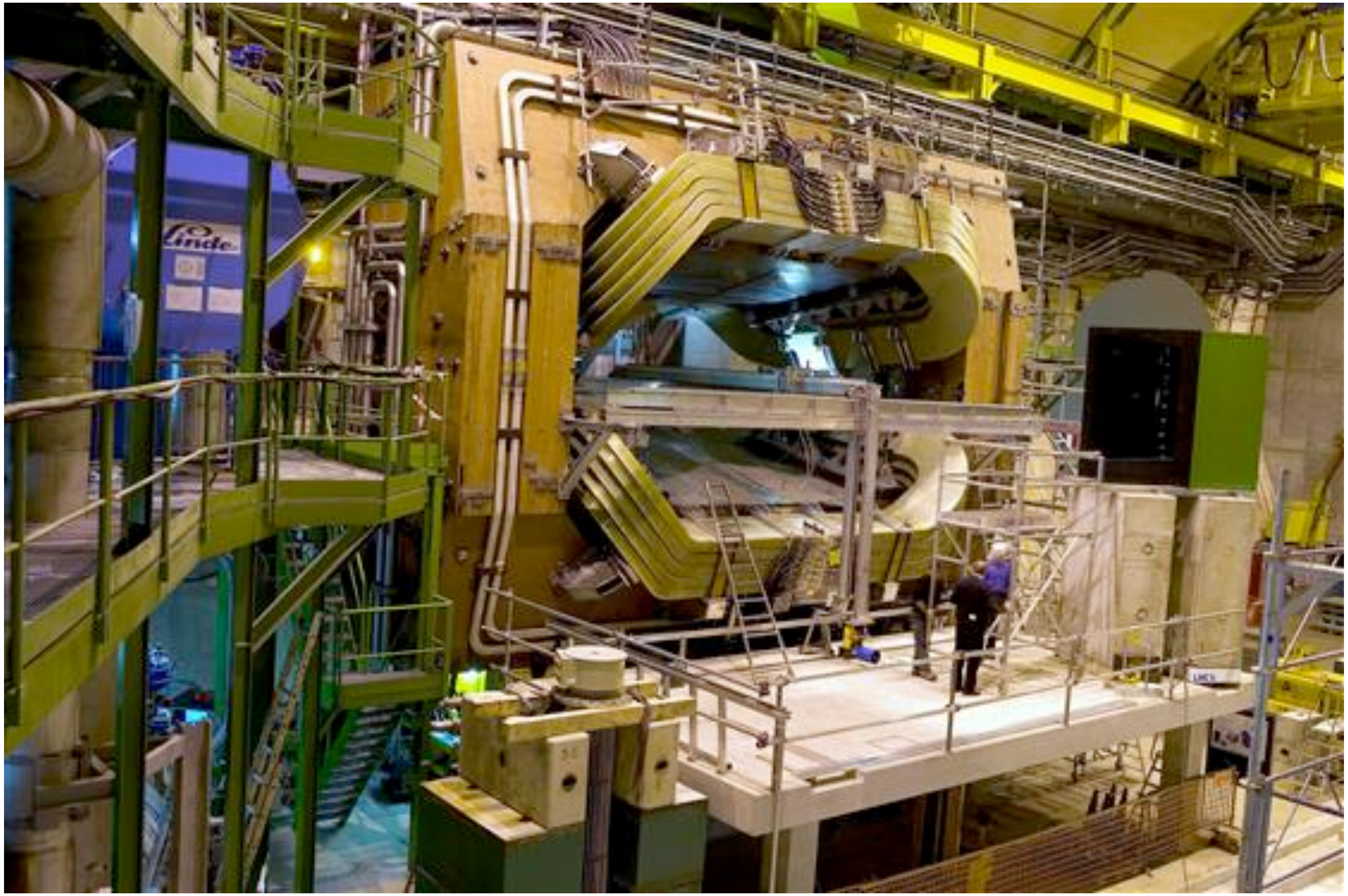
ALICE: Magnet



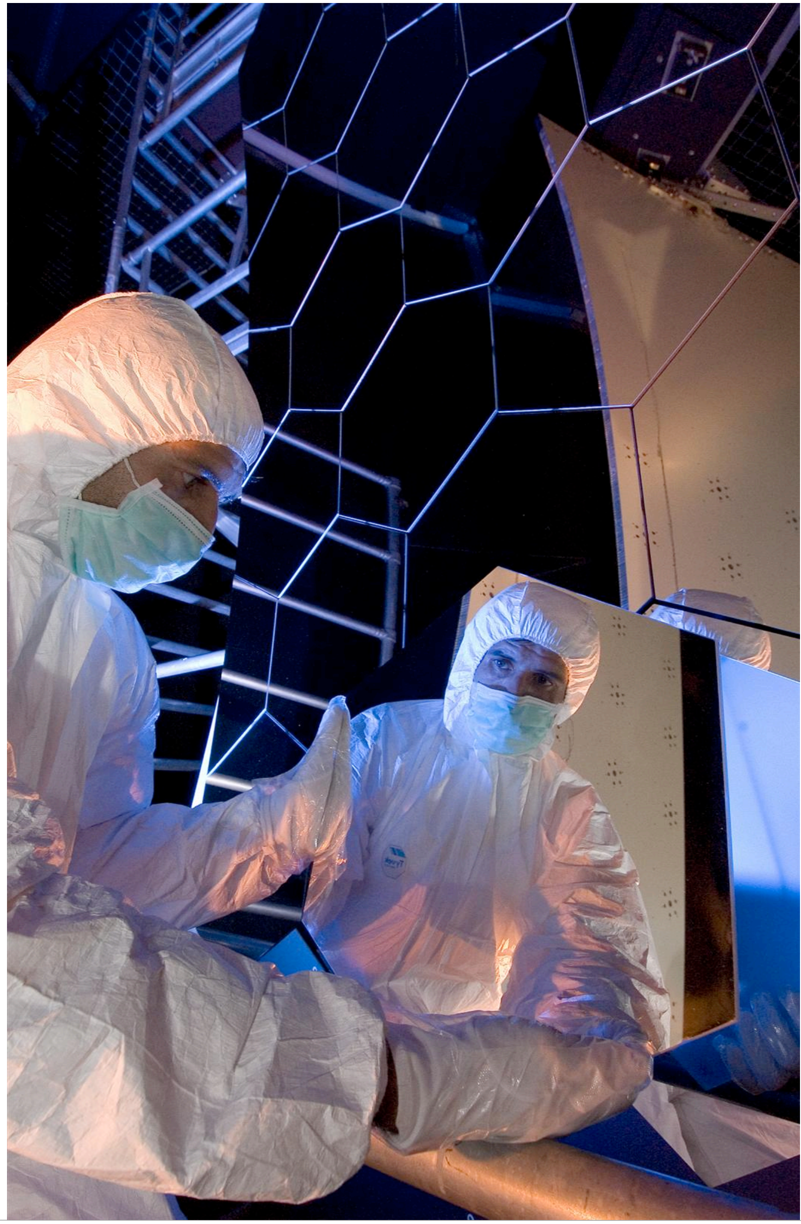
LHCb : study of B-decays (CP̸)



LHCb: Dipole put in place



LHCb: Rhich Mirror



First Level Trigger

Why choosing? I want it all !!!

Every 25ns interactions occur and produce 1MB data

- 40 Mhz * 1 MB = 40 TB/sec (200 harddisks per second)
- Would need 40000 Gigabit Ethernet links to transfer this amount of data
- Assuming you need 300ms to analyze and event, a computer would need 140 days to analyze 1 second of data.

Compare LEP (e+/e-):

Essentially triggering on any (significant) activity in the detector: Trigger rates around 20Hz

The 1st level trigger at LHC experiments

Requirement:

Do not introduce (a lot of) dead-time

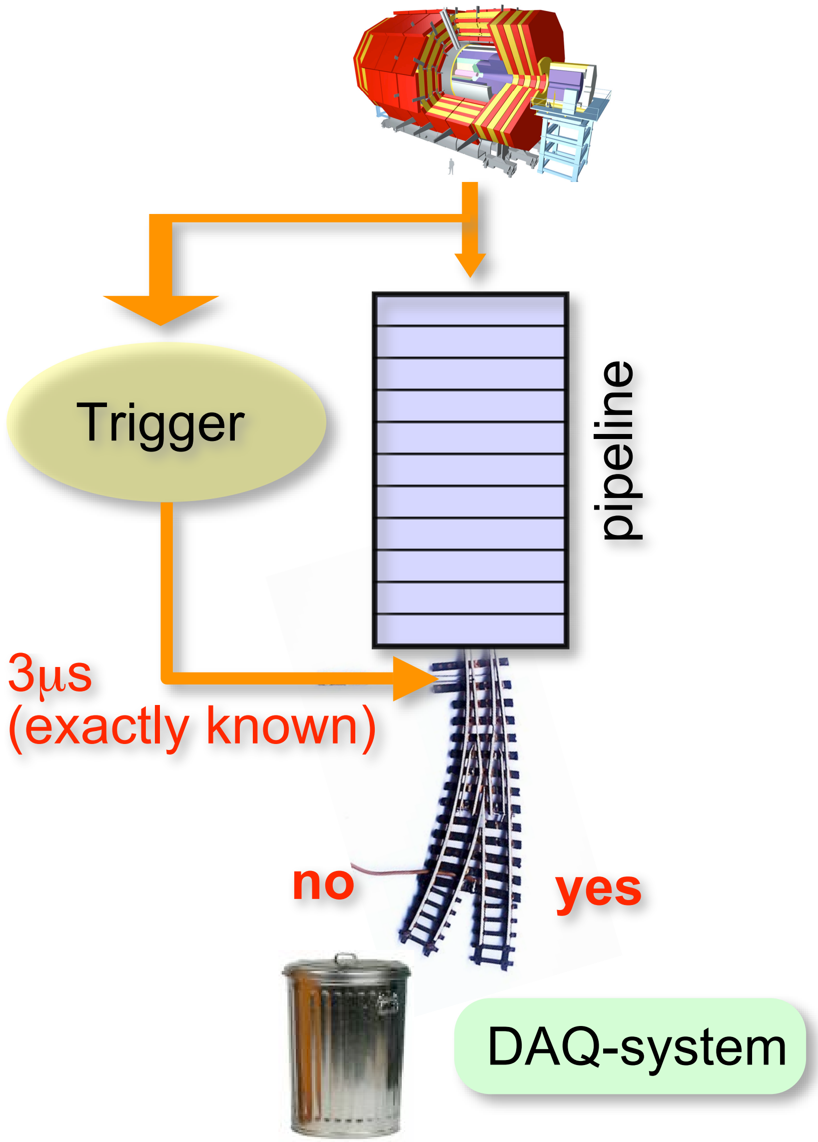
- O(1%) is tolerated
- Introduced by trigger rules :
  not more than n triggers in m BX
- Needed by FE electronics

Need to implement pipelines

- Need to store data of all BX for latency of 1st level trigger
- Typical : 10^7 channels / detector
  some GB pipeline memory
- Also the trigger itself is "pipelined"

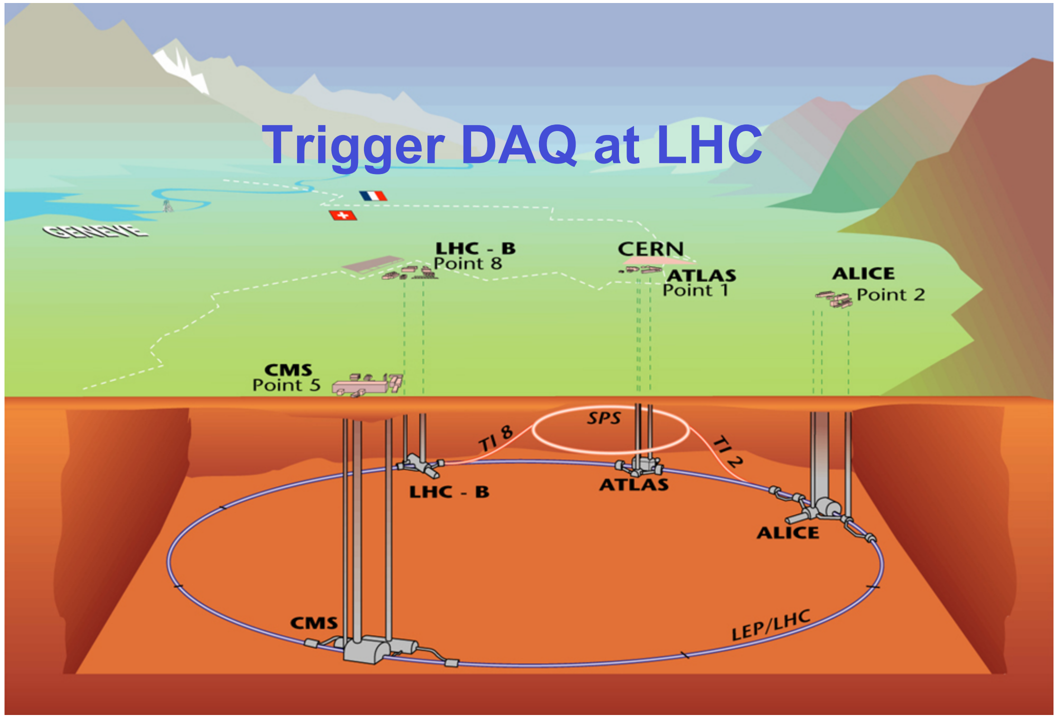
Trigger must have low latency (2-3 μs)

- Otherwise pipelines would have to be very long



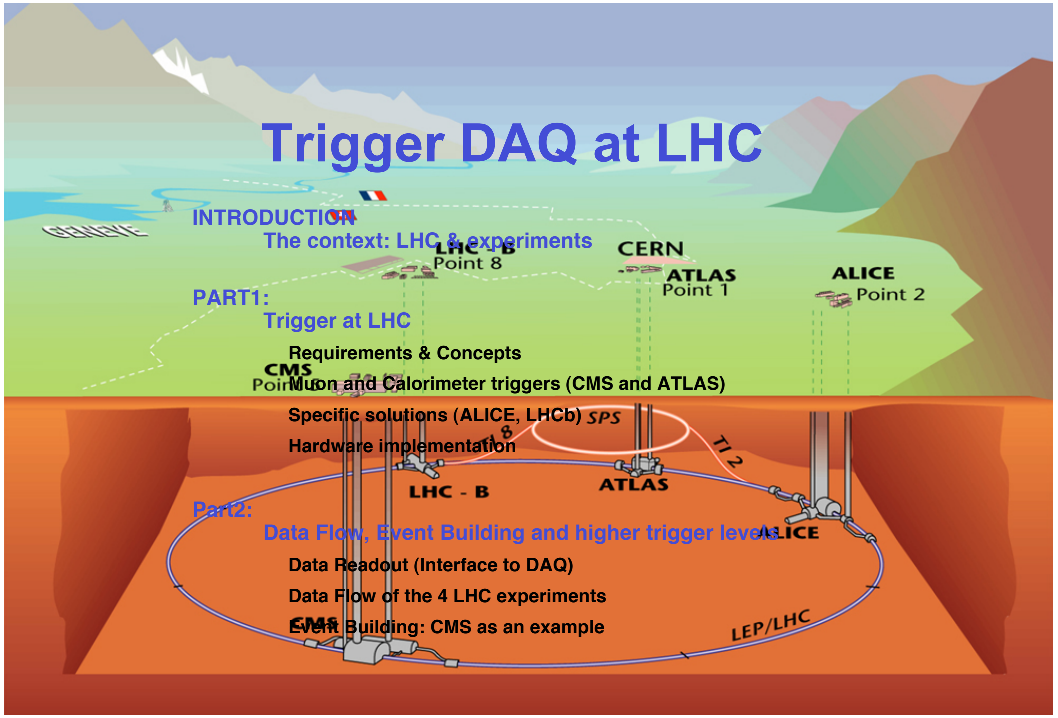
Imagine you had to choose…

How to decide ?



Imagine you had to choose…

How to decide ?



Look at
Table of Contents

“Typical event”

No track reconstruction for trigger (2-3μs) possible with today’s electronics

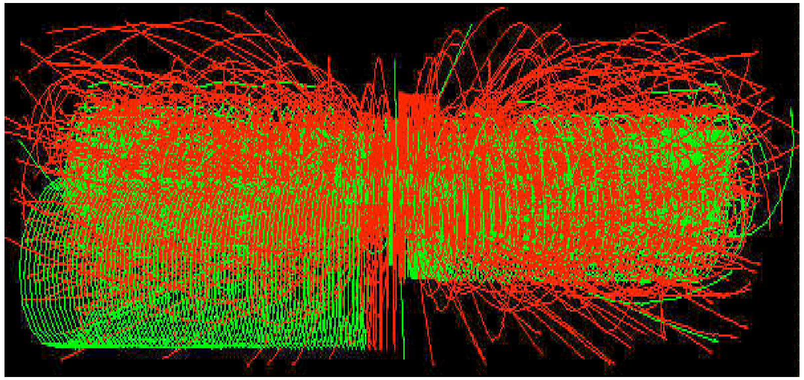
Prepare an “event - TOC”

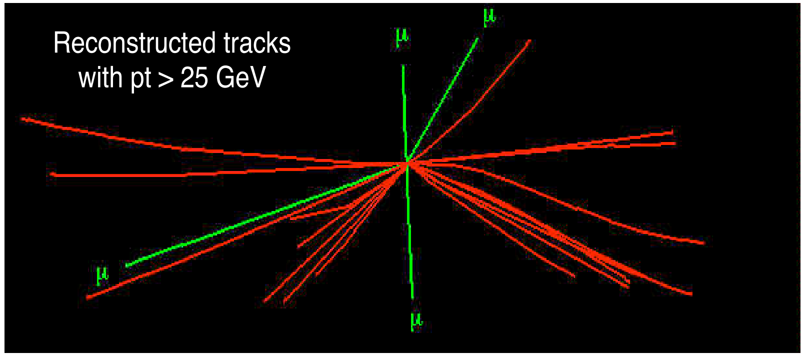
- Data must be available fast (I.e. shortly after the interaction)
- Use dedicated sub-detectors
- Prepare data with low resolution and low latency in sub-detectors

Therefore at LHC:

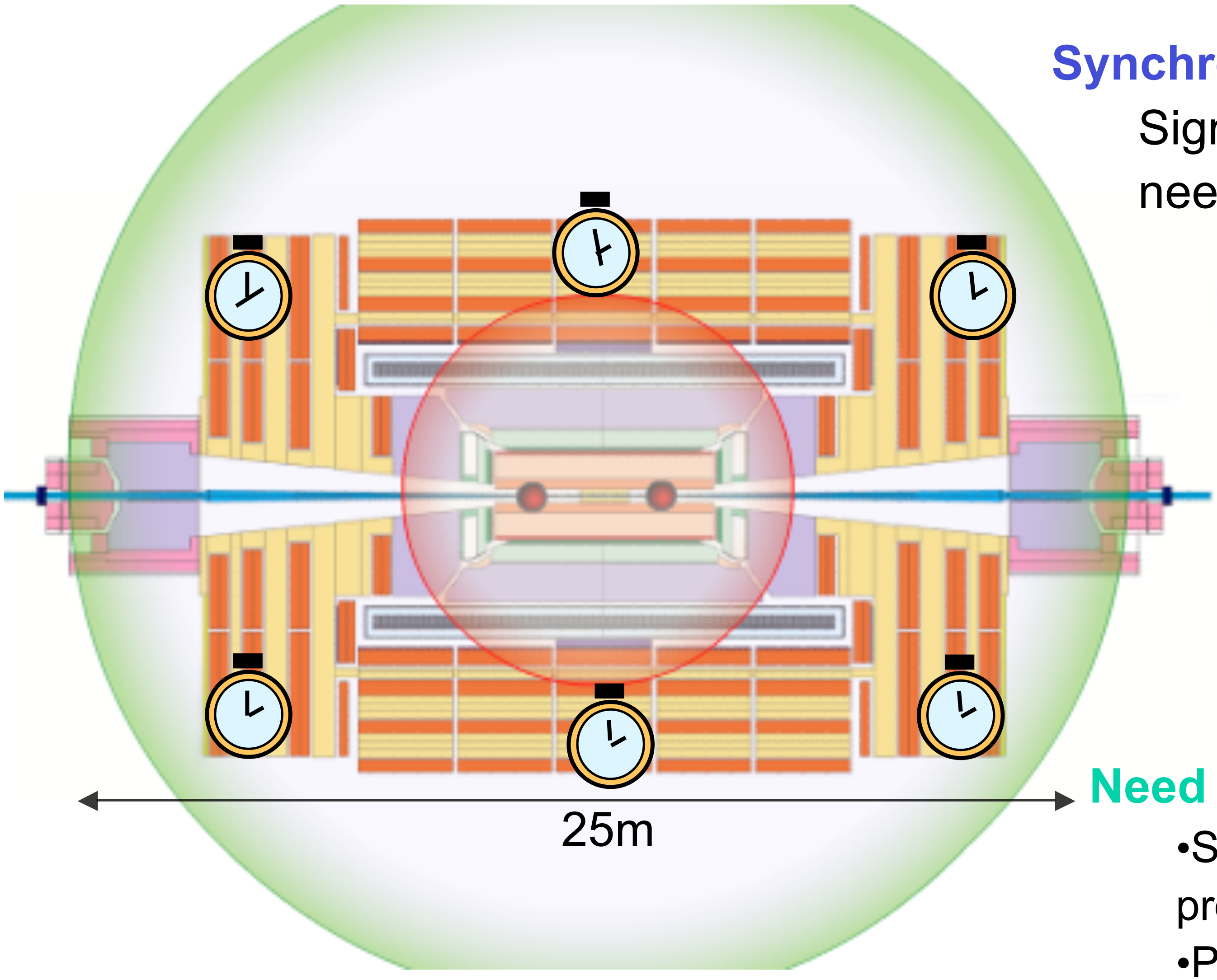
- Use only calorimeter and muon data

$H \to Z^0 Z^0 \to 4\mu$





Issue: synchronization



Synchronization:

Signals/Data from the same BX need to be processed together

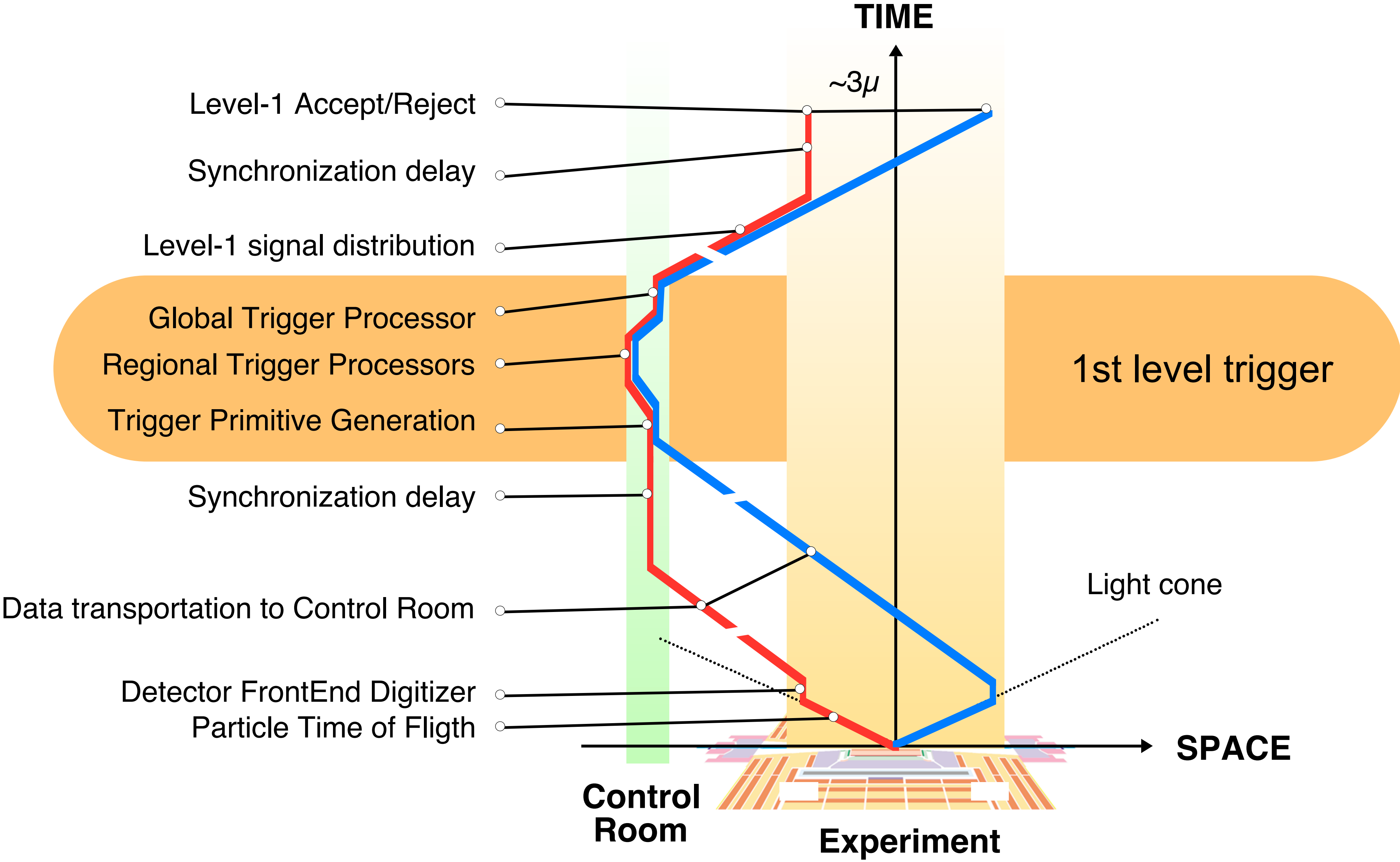
But:

Particle TOF >> 25ns
Cable delay >> 25ns
Electronic delays

Need to:

- Synchronize signals with programmable delays.
- Provide tools to perform synchronization (TDCs, pulsers…)

Signal path during trigger



Triggering at LHC

- The trigger dilemma:
  - Achieve **highest efficiency for interesting events**
  - Keep **trigger rate as low as possible**
    - Most of the interactions (called minimum bias events) are not interesting
    - DAQ system has limited capacity

- Need to study event properties
  - Find differences between minimum bias events and interesting events
  - Use these to do the trigger selection

Triggering wrongly is dangerous:

Once you throw away data in the trigger it is lost for ever

- Offline you can only study events which the trigger has accepted!
- Important: must determine the trigger efficiency (which enters in the formulas for the physics quantities you want to measure)
- A small rate of events is taken “at random” in order to verify the trigger algorithms (“what would the trigger have done with this event”)
- Redundancy in the trigger system is used to measure inefficiencies

Triggering at LHC : what info can be used

- Measurements with Calorimeters and Muon chamber system
  - Momentum
    - Measurement of muon p_t in magnetic field
    - p_t is the interesting quantity:
      - Total p_t is 0 before parton collision (p_t conservation)
      - High p_t is indication of hard scattering process (i.e. decay of heavy particle)
      - Detectors can measure precisely p_t
  - Energy
    - Electromagnetic energy for electrons and photons
    - Hadronic energy for jet measurements, jet counting, tau identification
    - Like for momentum measurement: E_t is the interesting quantity
    - Missing E_t can be determined (important for new physics)

Trade off: trigger thresholds versus trigger rate

The lower the thresholds the higher the trigger efficiency (good for physics)

The lower the thresholds the higher the trigger rate (conflict with DAQ system)

First Level Trigger of ATLAS and CMS

CMS and ATLAS: 1st level trigger

- Max trigger rate
  - DAQ systems designed for max 100 kHz
    - Assumes average event size of 1-1.5 MB.
  - Trigger rate estimation
    - Difficult task since depends on lots of unknown quantities:
      - Physics processes are not known at this energy (extrapolation from lower energy experiments)
      - Beam quality
      - Noise conditions
- Trigger is designed to fire with ≈ 35 kHz -> security factor 3
- Trigger design needs to be flexible so that there are many handles to adjust the rates.

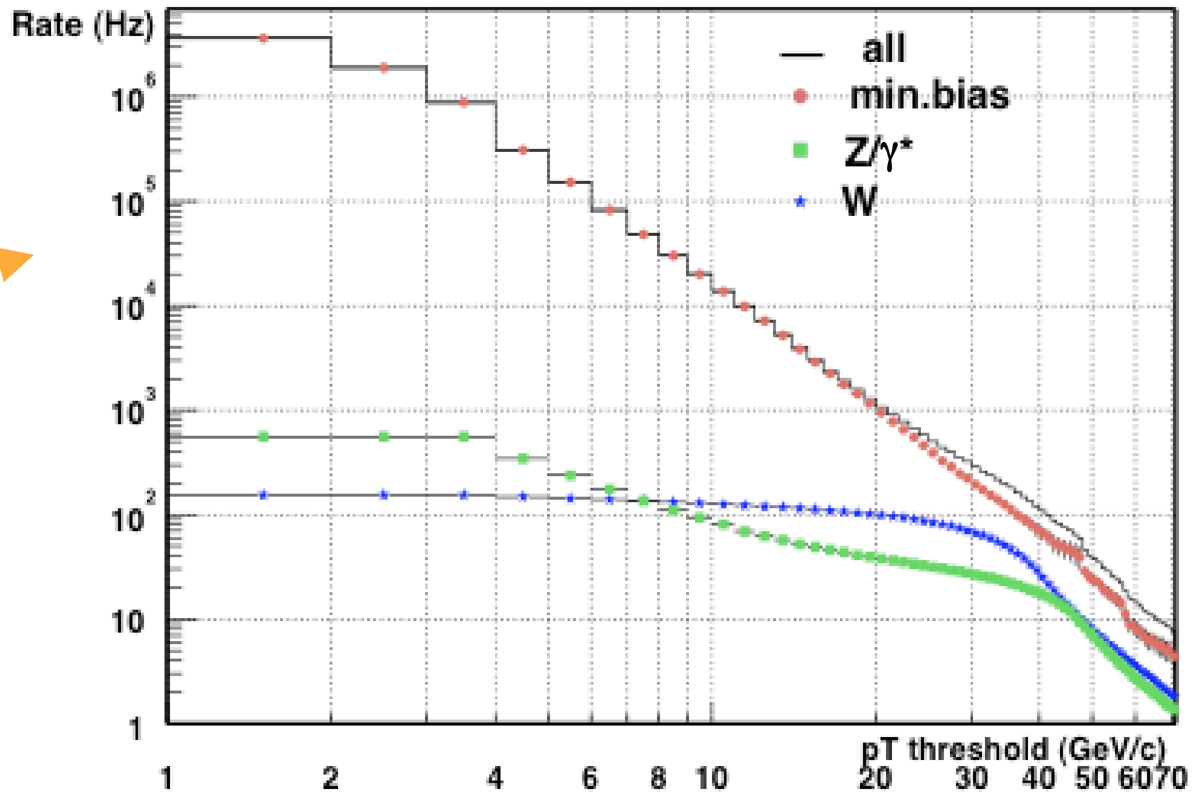
Triggering at LHC : example Muons

- Minimum bias events in pp:
  - Minimum bias: decays of quarks (SM)
- "Interesting" events
  - Often W/Z as decay products

Example: single muons min. bias vs W/Z decays

Threshold ≈ 10 GeV
Rate ≈ 20 kHz

L = 10^{34}



Cont'ed: triggering on Muons

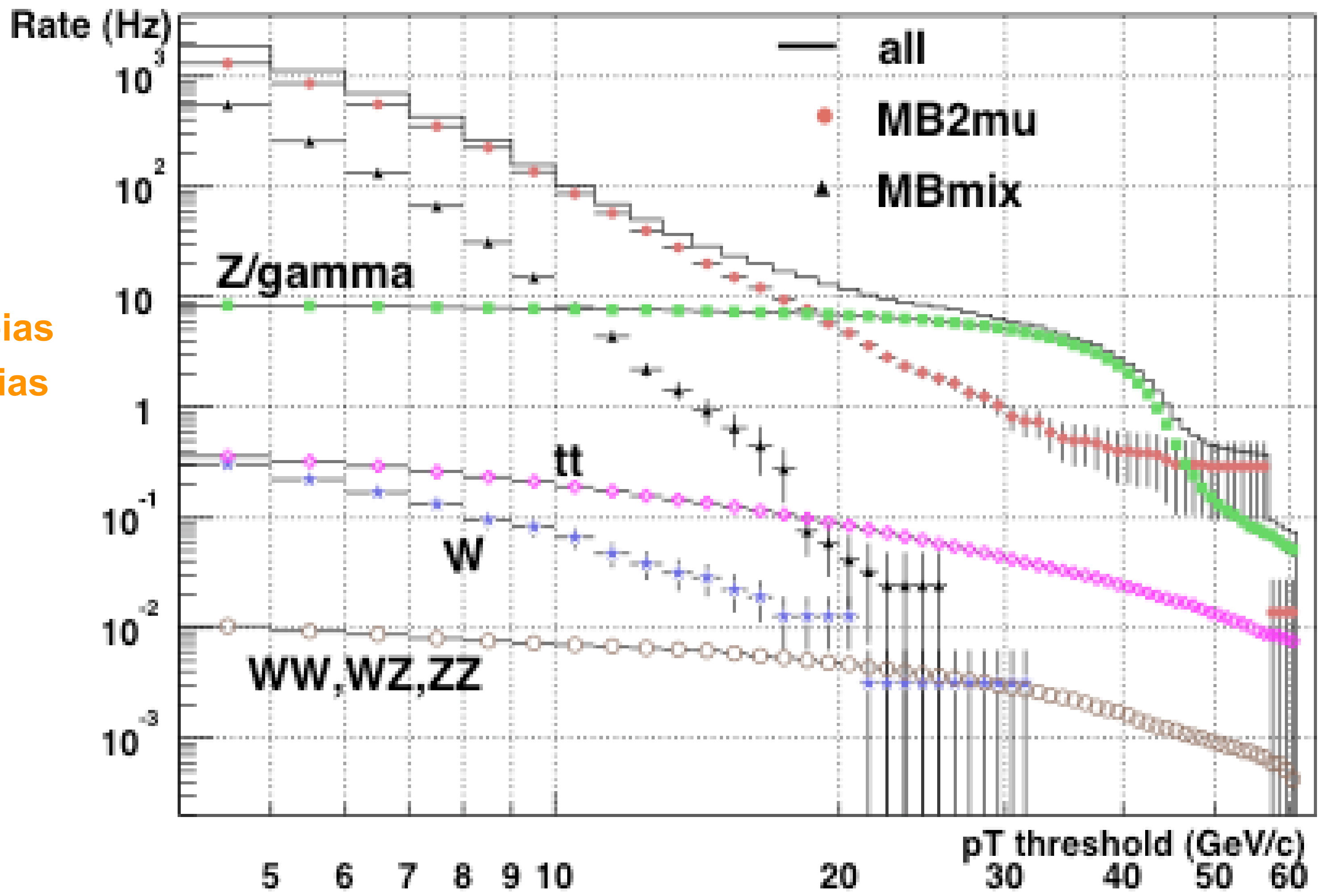
- Interesting events: contains (almost) always 2 objects to trigger on

L = 10^{34}

Example muon pairs :

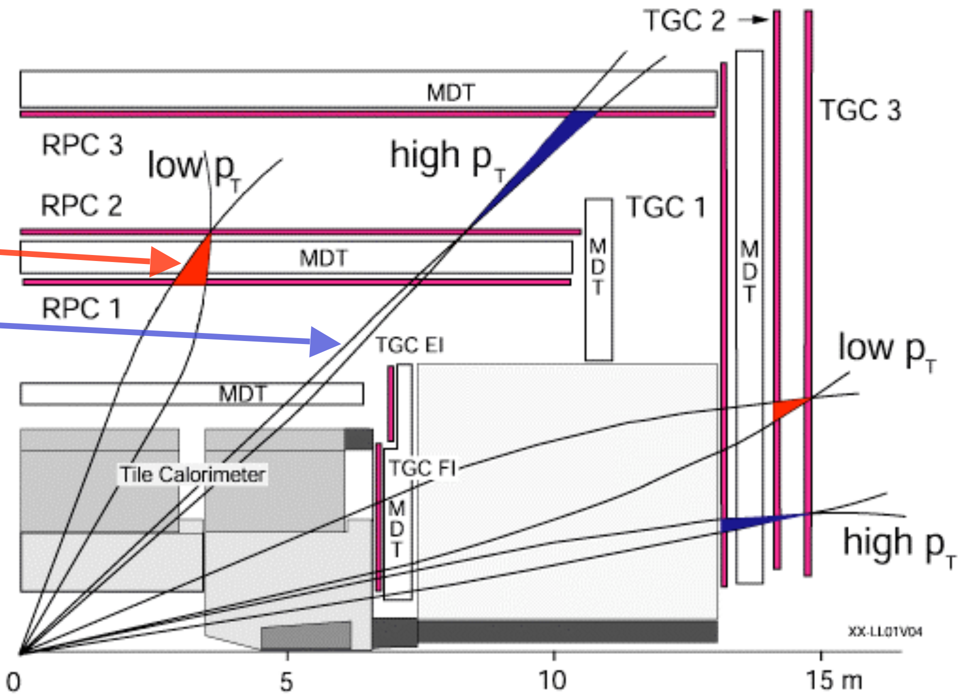
MB2mu : 2μ from min bias
Mbmix :1μ from min bias

Threshold ≈ 10 GeV
Rate ≈ 100Hz



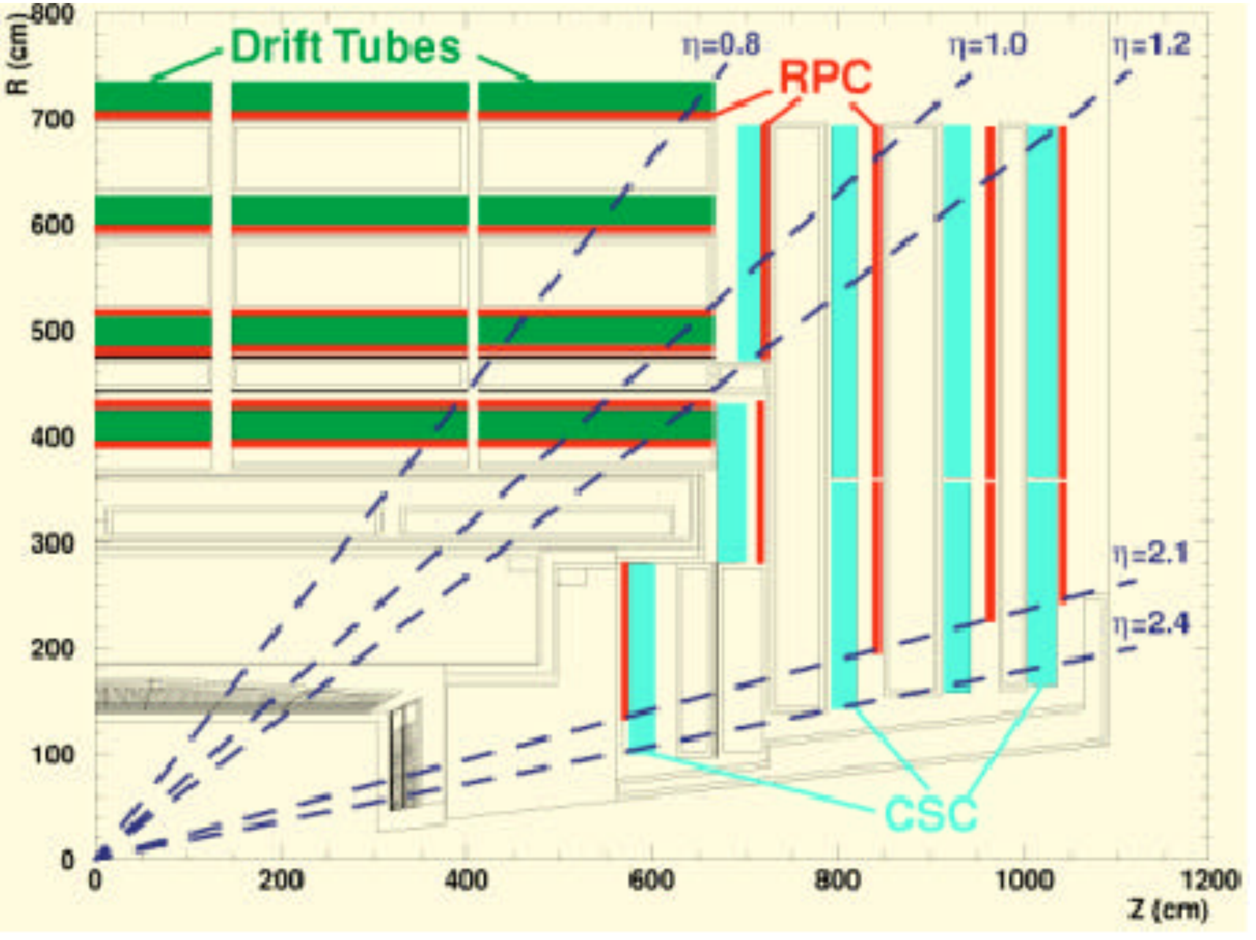
How to trigger on Muons

- Example ATLAS muon trigger
  - Three muon detectors:
    - Muon Drift Tubes (MDT) : high precision, too slow for level 1 trigger
    - Resistive Plate Chambers (RPC) : 1st level trigger barrel
    - Thin Gap Chambers (TGC) : 1st level trigger endcap
  - Measure p_t by forming coincidences in various layers:
    - Low p_t : 2 layers
    - High p_t: 3 layers
  - "Coincidence matrix"
    - Implemented with ASIC (Application Specific Integrated Circuit)

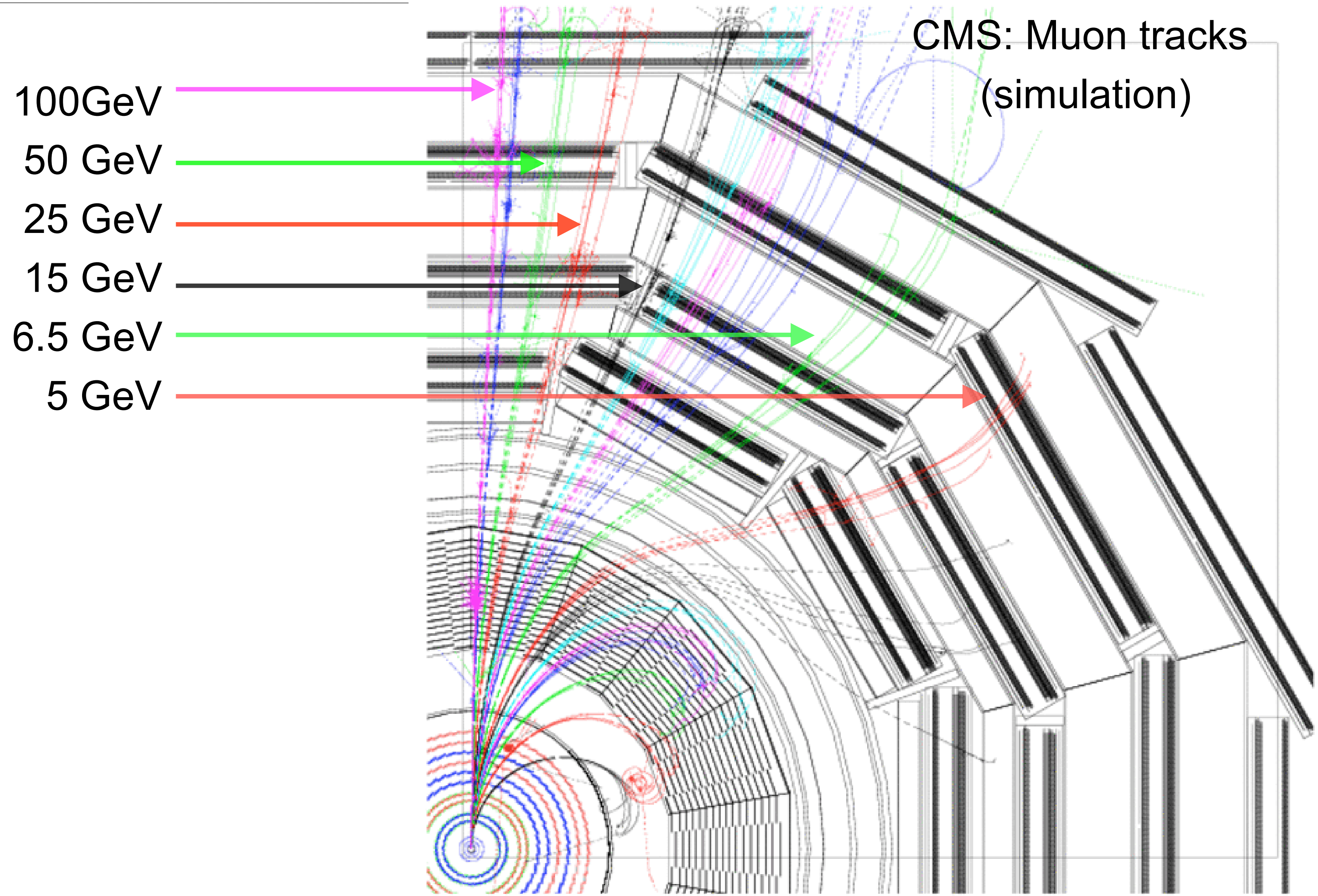


How to trigger on Muons

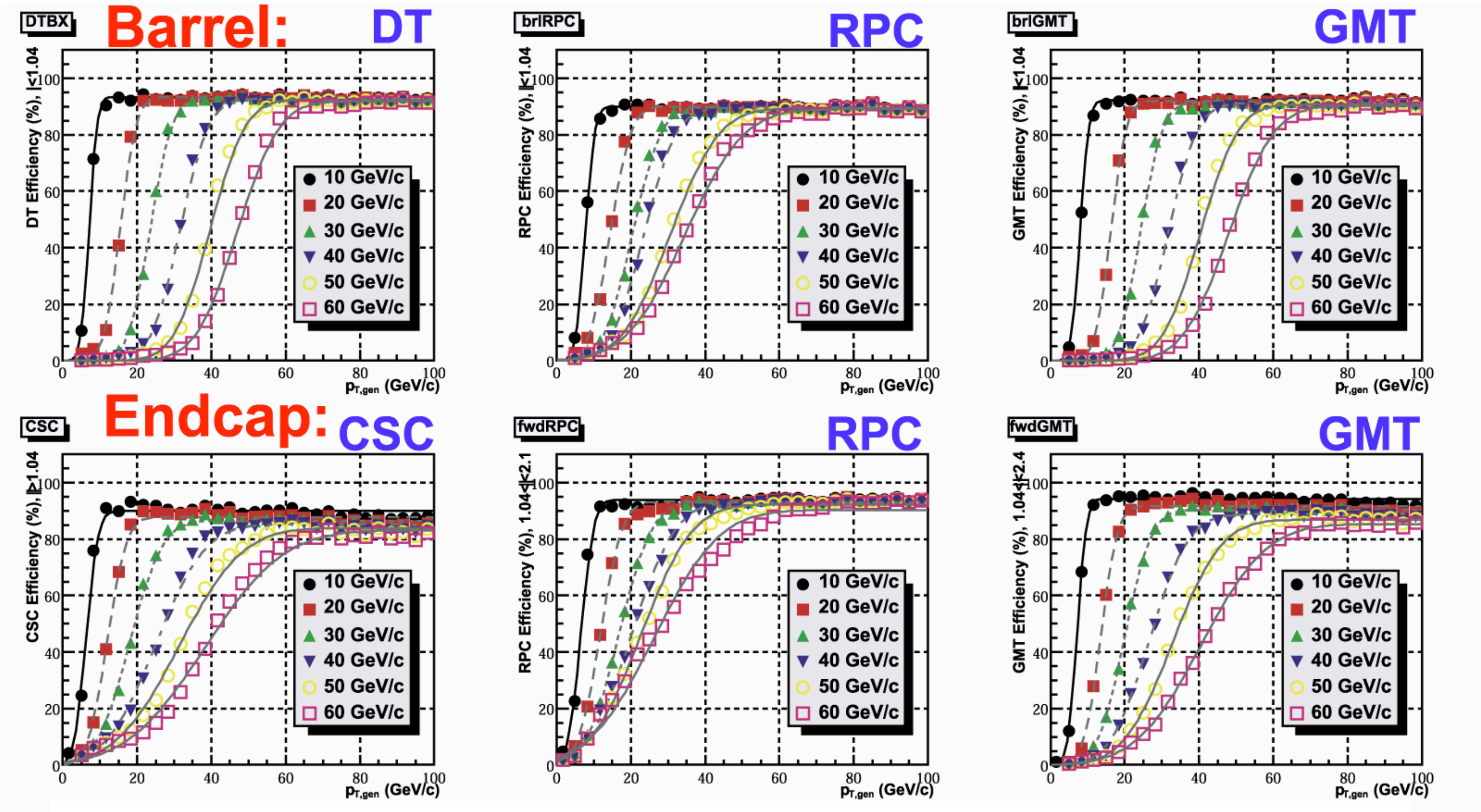
- The CMS muon system



How good does it work?

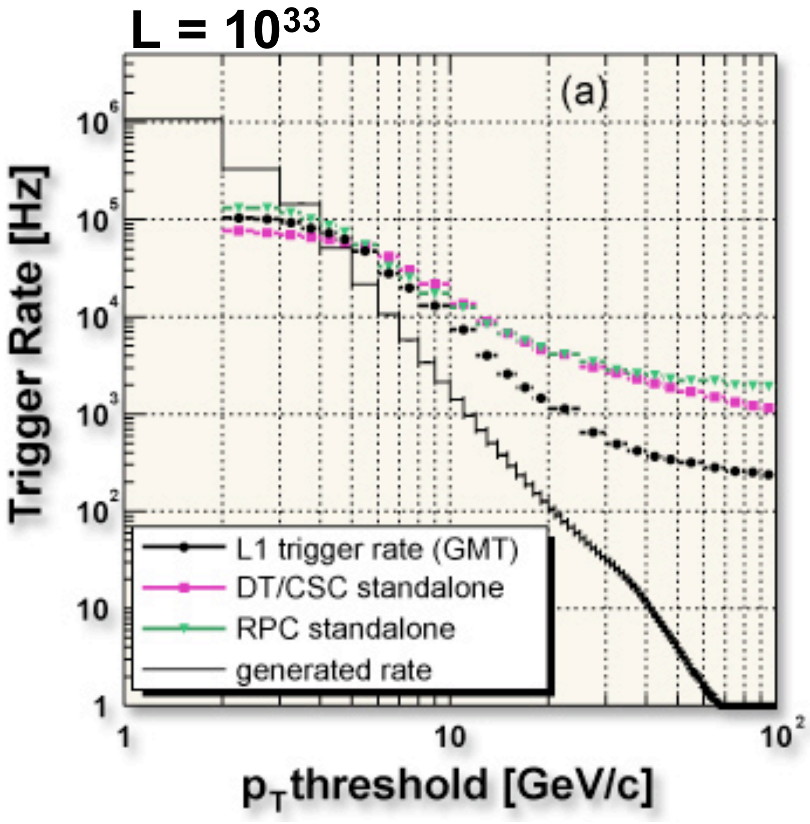


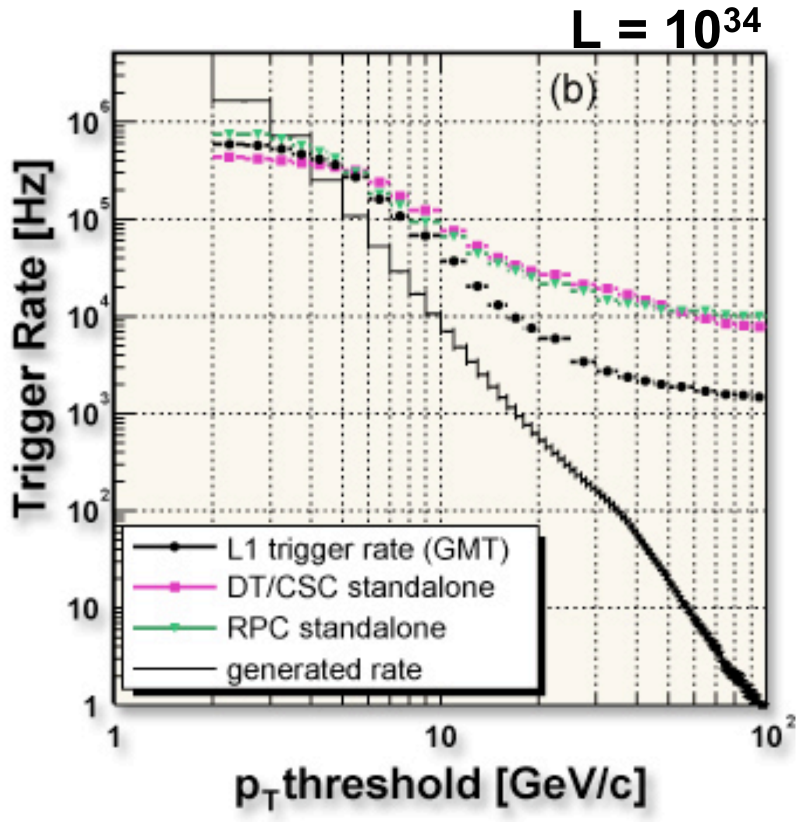
CMS Muon Trigger: Efficiency



Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)





p_t > 20GeV:

≈ 100 Hz generated,

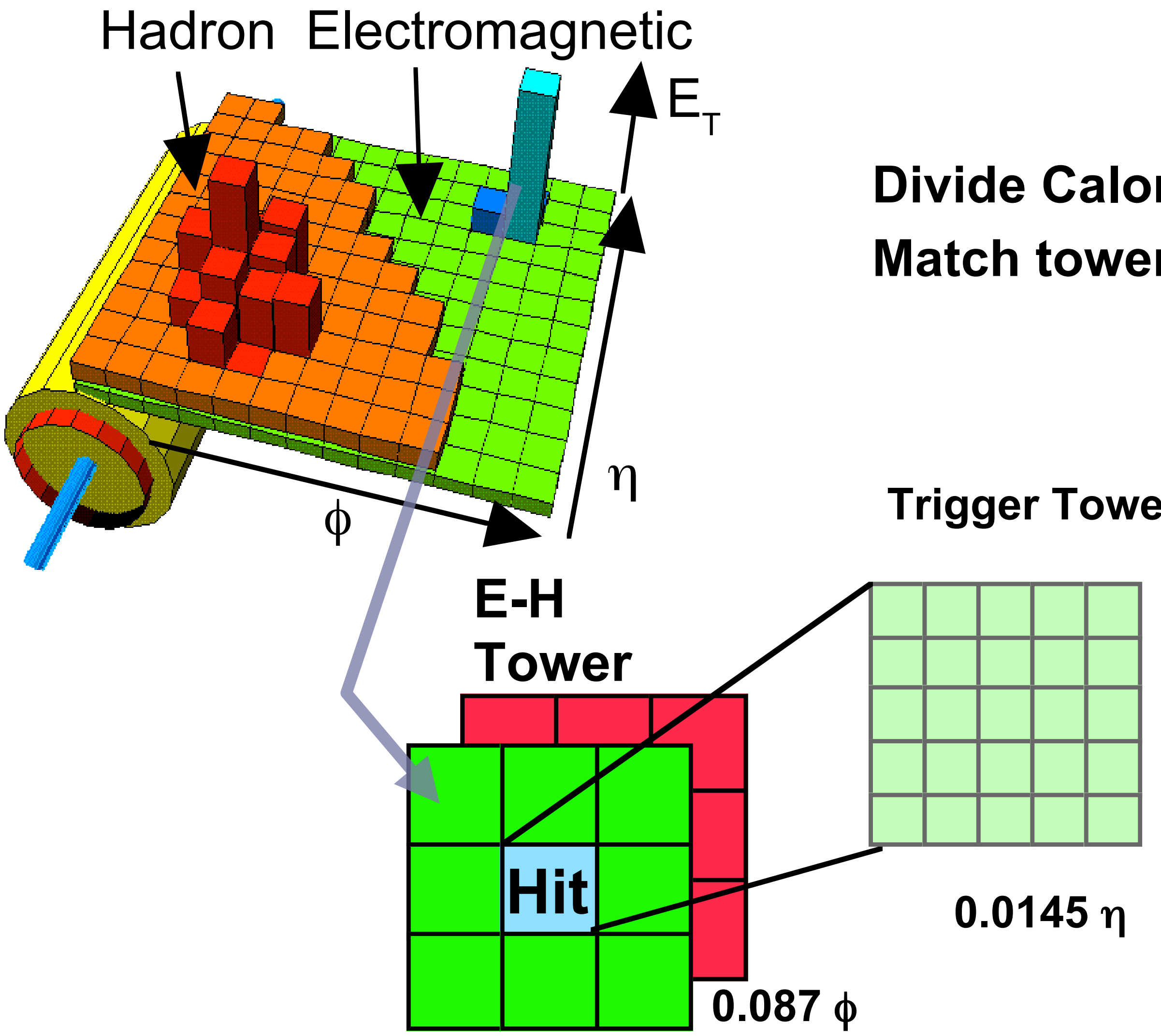
≈ 1 kHz trigger rate

p_t > 20GeV:

≈ 600 Hz generated,

≈ 8 kHz trigger rate

Calorimeter Trigger: example CMS



Divide Calorimeter into towers

Match towers between ECAL and HCAL

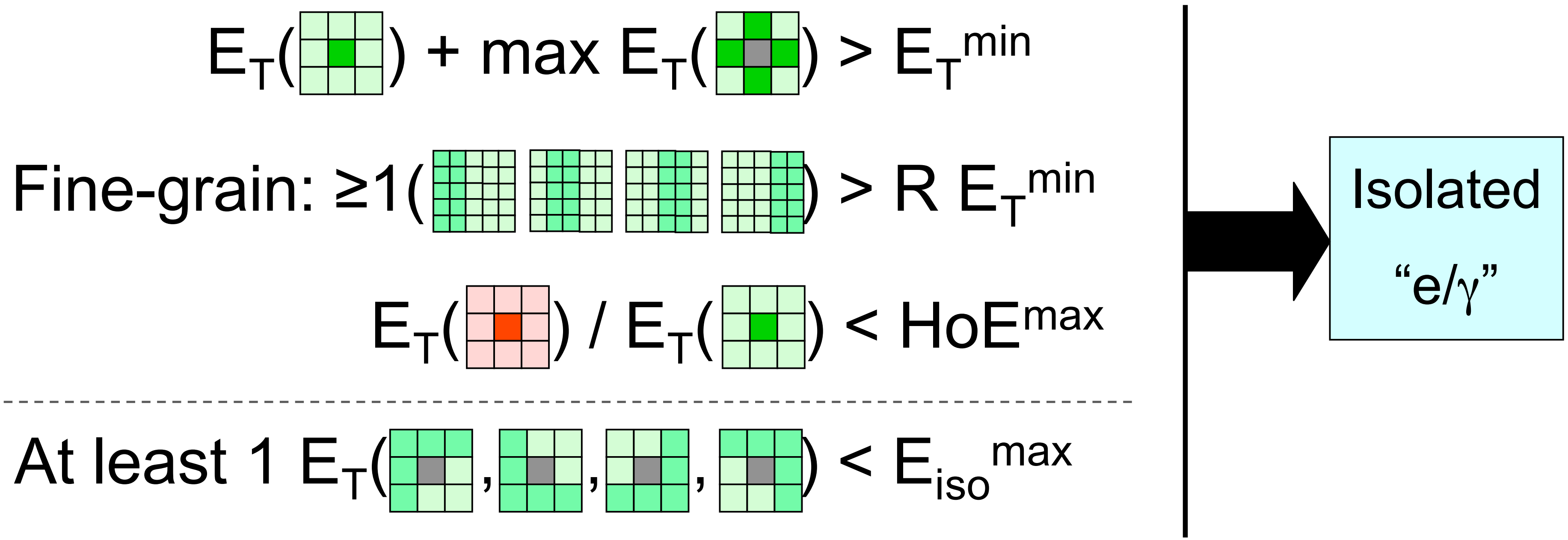
Trigger Tower = 5x5 EM towers

72 ϕ x 54 η x 2
= 7776 towers

Algorithm to identify e/γ

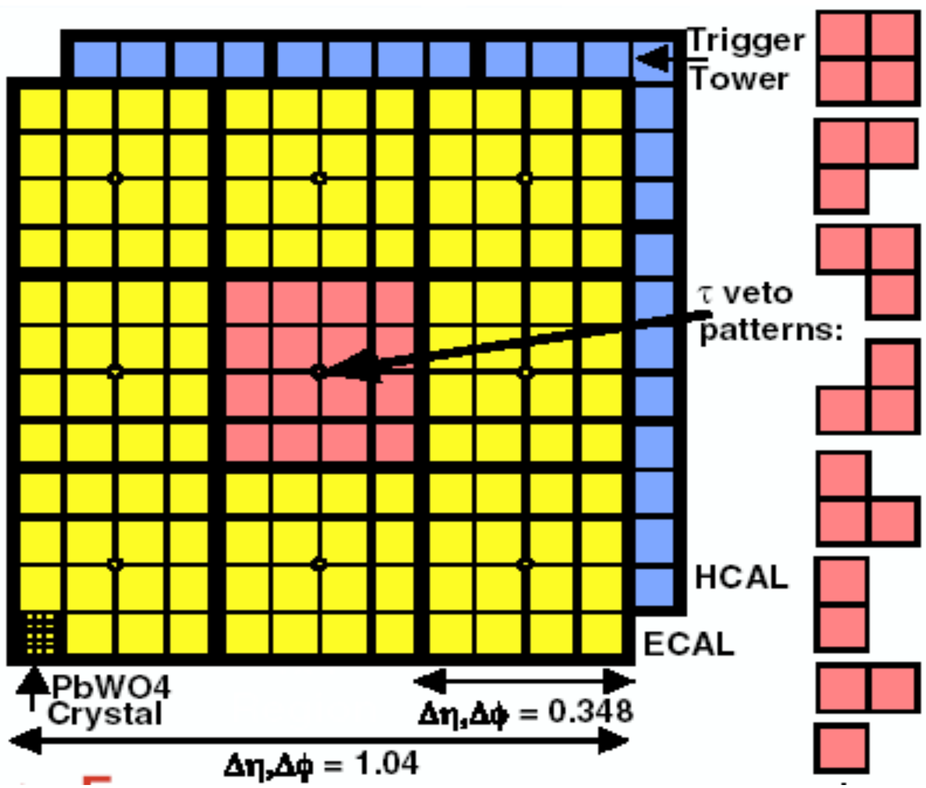
Characteristics of isolated e/γ:

- energy is locally concentrated (opposed to jets)
- energy is located in **ECAL**, not in **HCAL**



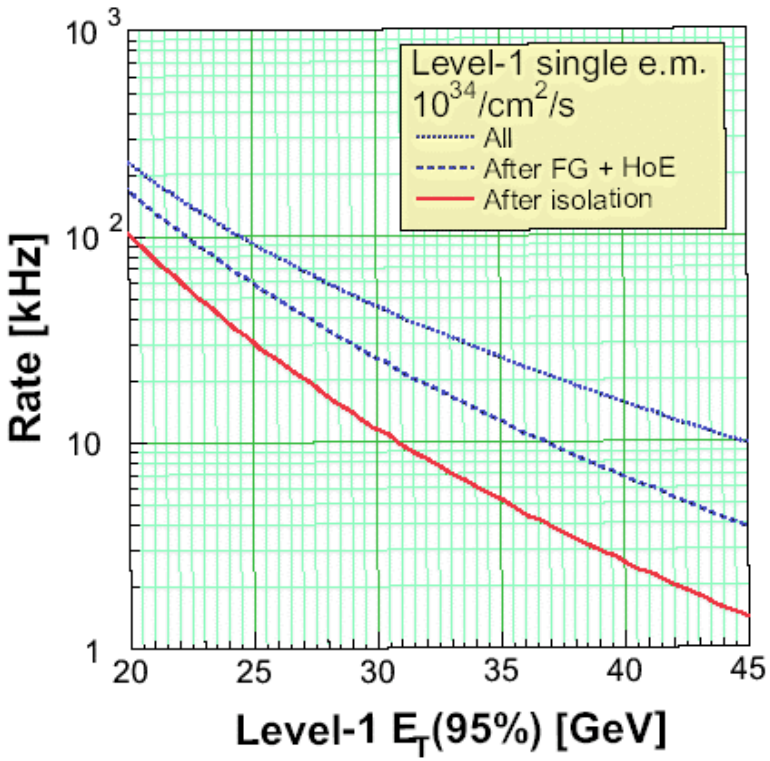
Calorimeter Trigger: jets and Taus

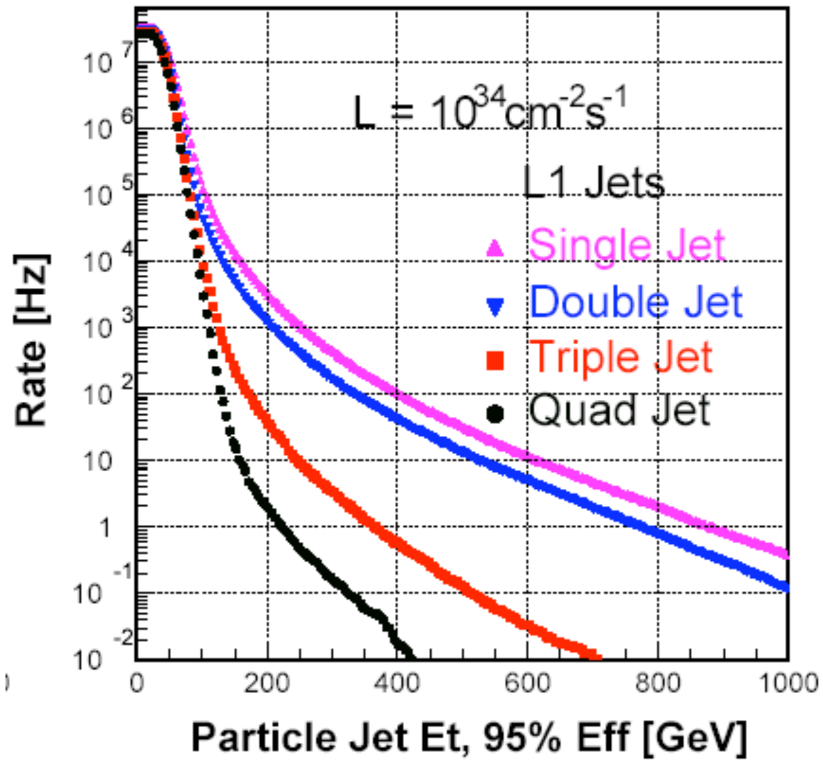
- Algorithms to trigger on jets and tau:
  - based on clusters 4x4 towers
  - Sliding window of 3x3 clusters



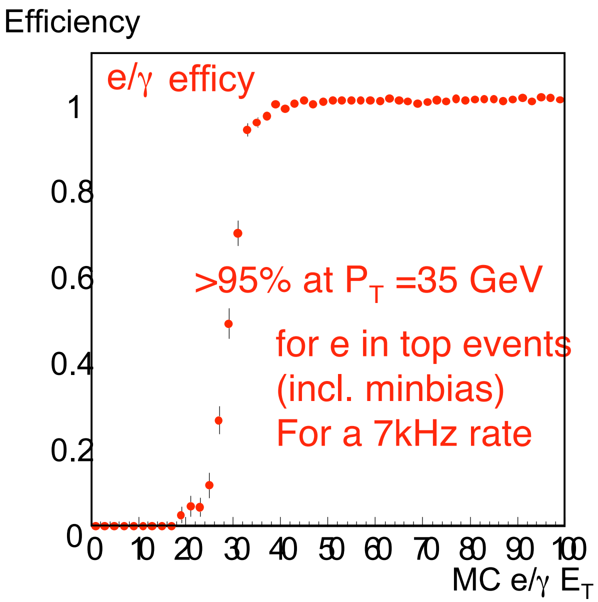
- **Jet trigger : work in large 3x3 region:**
  - $E_t^{central} > E_T^{threshold}$
  - $E_t^{central} > E_T^{neighbours}$
- **Tau trigger: work first in 4x4 regions**
  - Find localized small jets:
    If energy not confined in 2x2 tower pattern -> set Tau veto
  - Tau trigger: No Tau veto in all 9 clusters

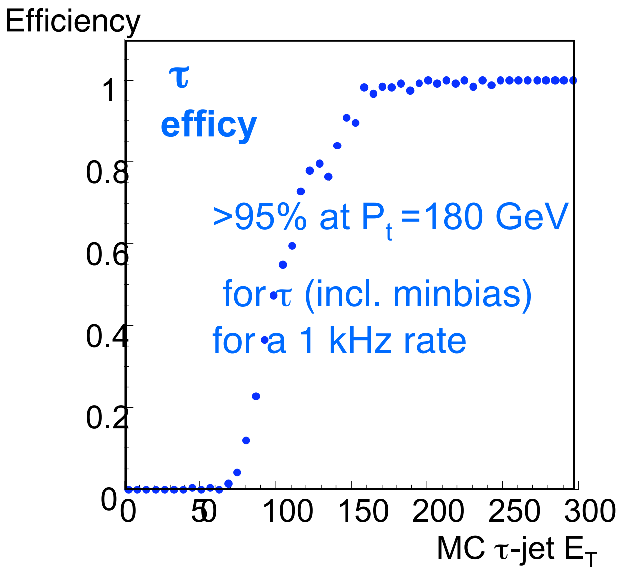
Calorimeter trigger: rates

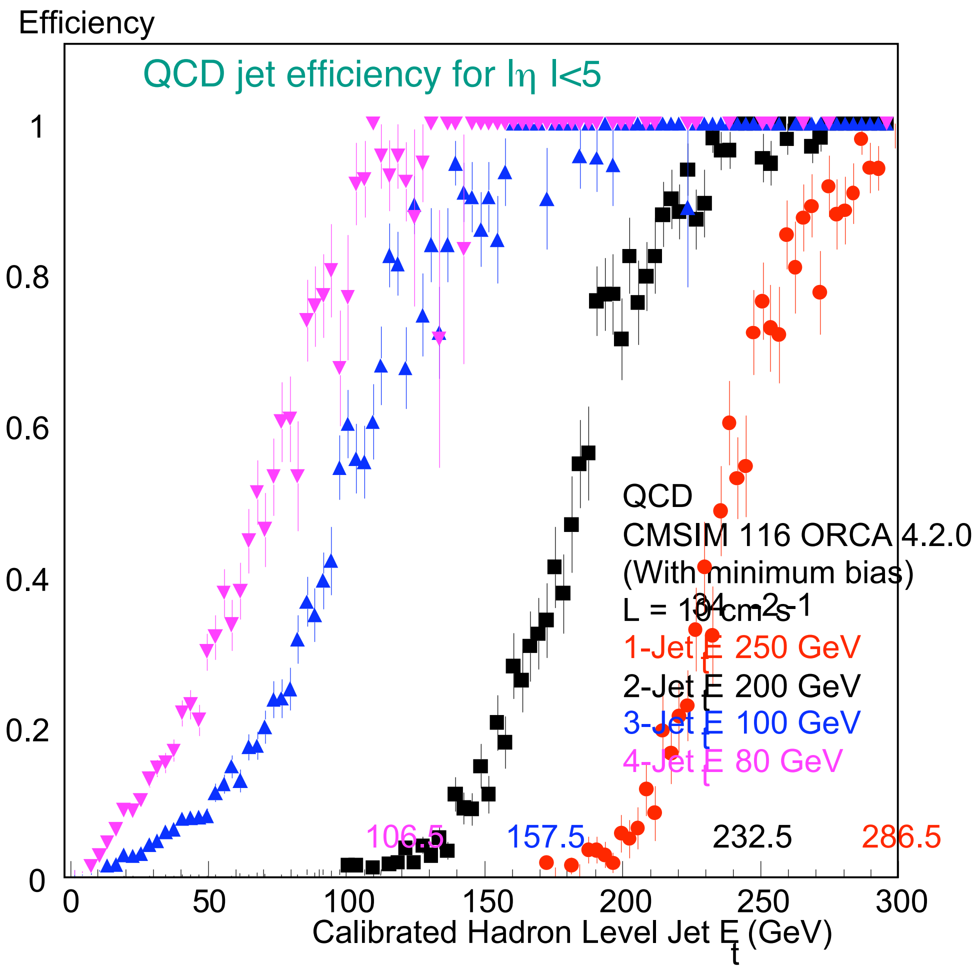




Calorimeter trigger: rates







>95% at P_T =286, 232, 157, 106 GeV for individual 1,2,3,4 jet triggers (incl. minbias) (~0.5 kHz rate each totaling ~2 kHz)

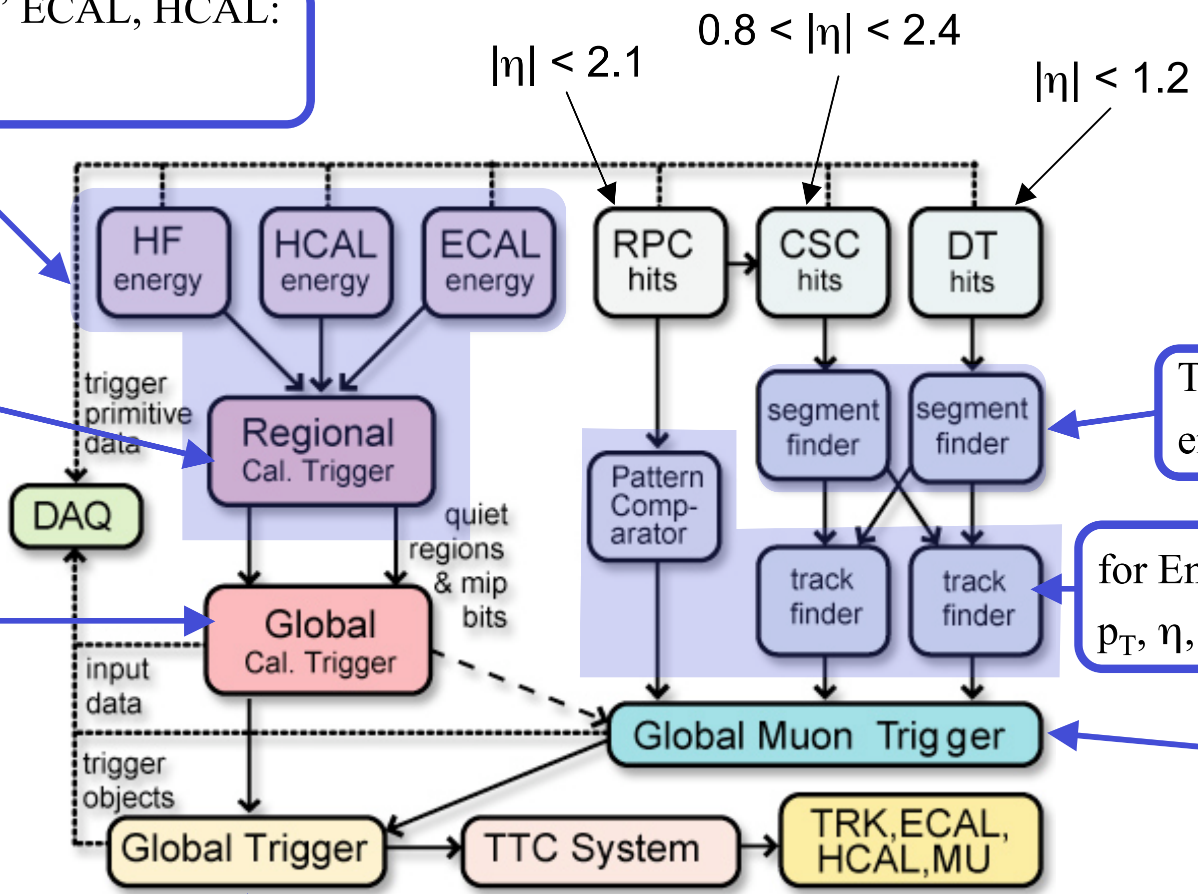
Trigger Architecture: CMS

Matching “Trigger Towers” ECAL, HCAL:

Σ $E_T(d\phi d\eta)$

Electron Isolation,
Jet detection

Sorting
E_T^{miss}
E_T^{tot}



Track segments endcap and barrel

for Endcap and Barrel:
p_T, η, ϕ, quality

$\leq$ 4 candidates

Final decision, partitioning
Interface to TTC, TTS (Trigger throtteling system)

Global Trigger

- Forms final decision
  - Programmable "Trigger Menu"
  - Logical "OR" of various trigger conditions

    In Jargon these trigger conditions are called "triggers" themselves.

    The individual triggers may be downscaled (only take every 5th)

    Example:

1 μ with	$E_t > 20$ GeV	or	"single muon trigger"
2 μ with	$E_t > 6$ GeV	or	"di muon trigger"
1 e/γ with	$E_t > 25$ GeV	or	"single electron trigger"
2 e/γ with	$E_t > 15$ GeV	or	"di electron trigger"

⋮

Level-1 trigger "cocktail" (low/high lumi)

Low Luminosity

Total Rate: 50 kHz
Factor 3 safety,
allocate 16 kHz

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate(kHz)
1e/γ, 2e/γ	29, 17	4.3	4.3
1μ, 2μ	14, 3	3.6	7.9
1τ, 2τ	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet & Miss-E_T	88 & 46	2.3	14.3
e & jet	21 & 45	0.8	15.1
Min-bias		0.9	**16.0**

High Luminosity

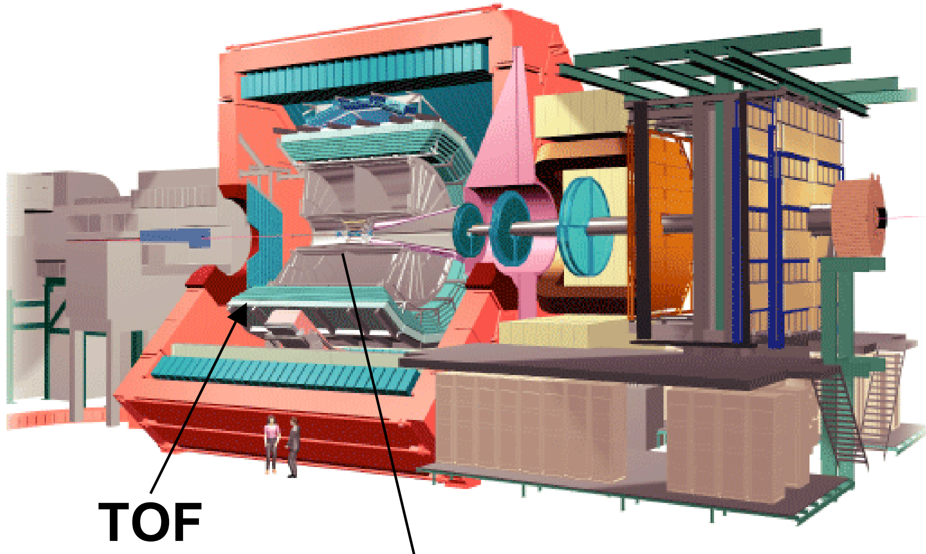
Total Rate: 100 kHz
Factor 3 safety,
allocate 33.5 kHz

Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/γ, 2e/ γ	34, 19	9.4	9.4
1μ, 2μ	20, 5	7.9	17.3
1τ, 2τ	101, 67	8.9	25.0
1-jet	250	1.0	25.6
3-jets, 4-jets	110, 95	2.0	26.7
Jet & Miss-E_T	113 & 70	4.5	30.4
e & jet	25 & 52	1.3	31.7
μ & jet	15 & 40	0.8	32.5
Min-bias		1.0	**33.5**

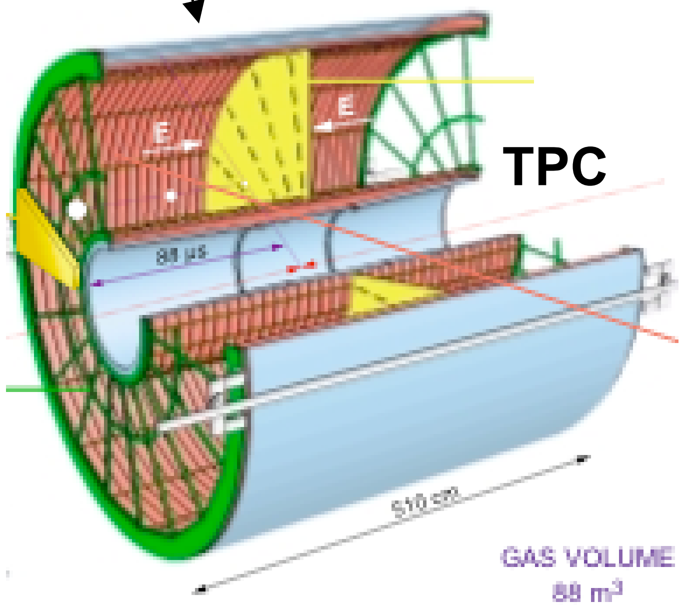
Specific solutions for specific needs: ALICE and LHCb

ALICE: 3 hardware trigger levels

- Some sub-detectors e.g. TOF (Time Of Flight) need very early strobe (1.2 μs after interaction)
  - Not all subdetectors can deliver trigger signals so fast
  - ➡ Split 1st level trigger into :
  - **L0 : latency 1.2 μs**
  - **L1 : latency 6.5 μs**



- ALICE uses a TPC for tracking
  - TPC drift time: 88μs
  - In Pb-Pb collisions only one interaction at a time can be tolerated (otherwise: too many tracks in TPC)
  - Need pile-up protection:
    - Makes sure there is only one event at a time in TPC (need to wait for TPC drift time)
  - **L2 : latency 88μs**



ALICE: optimizing efficiency

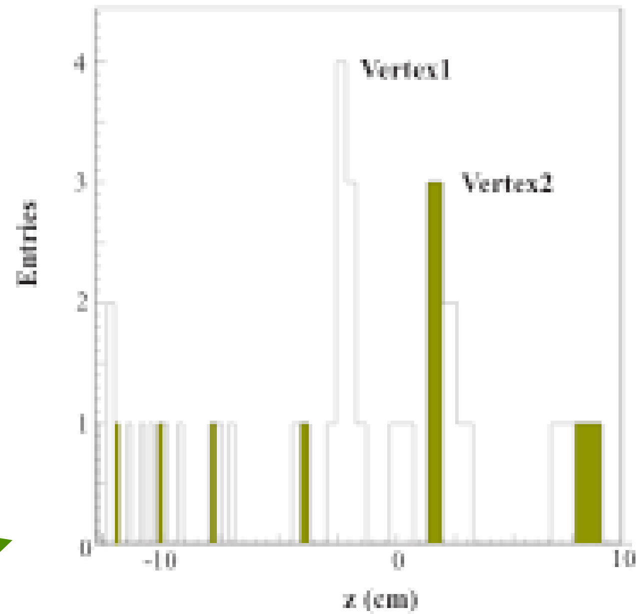
- ALICE requirement:
  - Some sub-detectors need a long time to be read out after LVL2 trigger (e.g. Si drift detector: 260μs)
  - But: Some interesting physics events need only a subset of detectors to be read out.

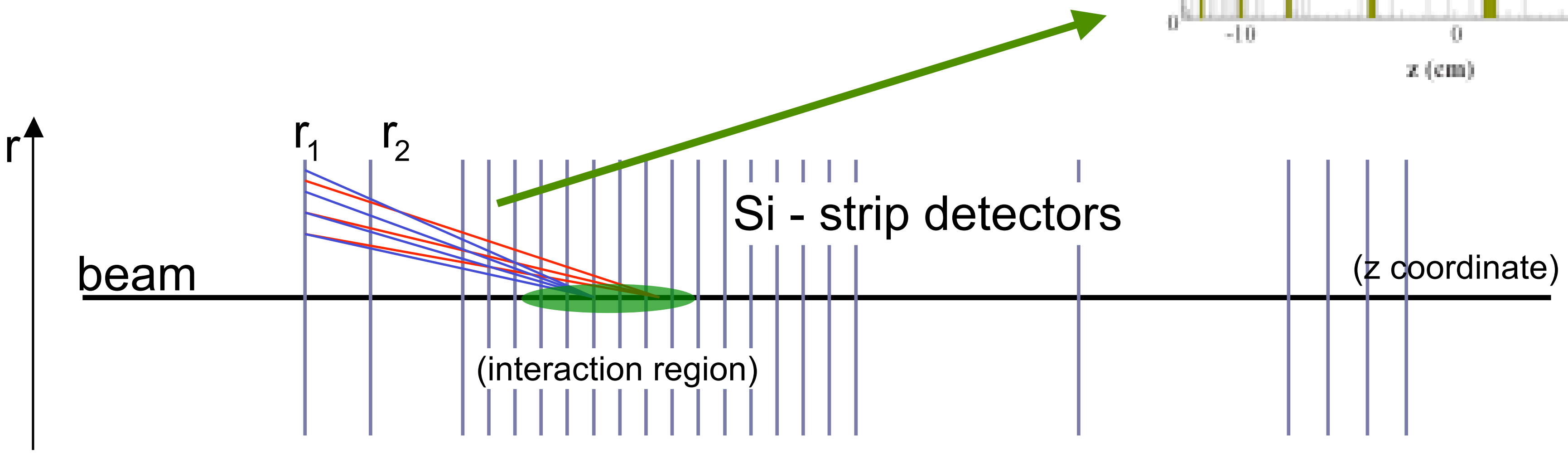
- Concept of **Trigger clusters**:
  - Trigger cluster: group of sub-detectors
    - one sub-detector can be member of several clusters
  - Every trigger is associated to one Trigger Clusters
  - Even if some sub-detectors are busy with readout triggers for not-busy clusters can be accepted.

- Triggers with **“rare” classification**:
  - In general at LHC: stop the trigger if readout buffer almost full
  - ALICE:
    - “rare” triggers fire rarely and contain potentially interesting events.
    - when buffers get “almost-full” accept only “rare” triggers

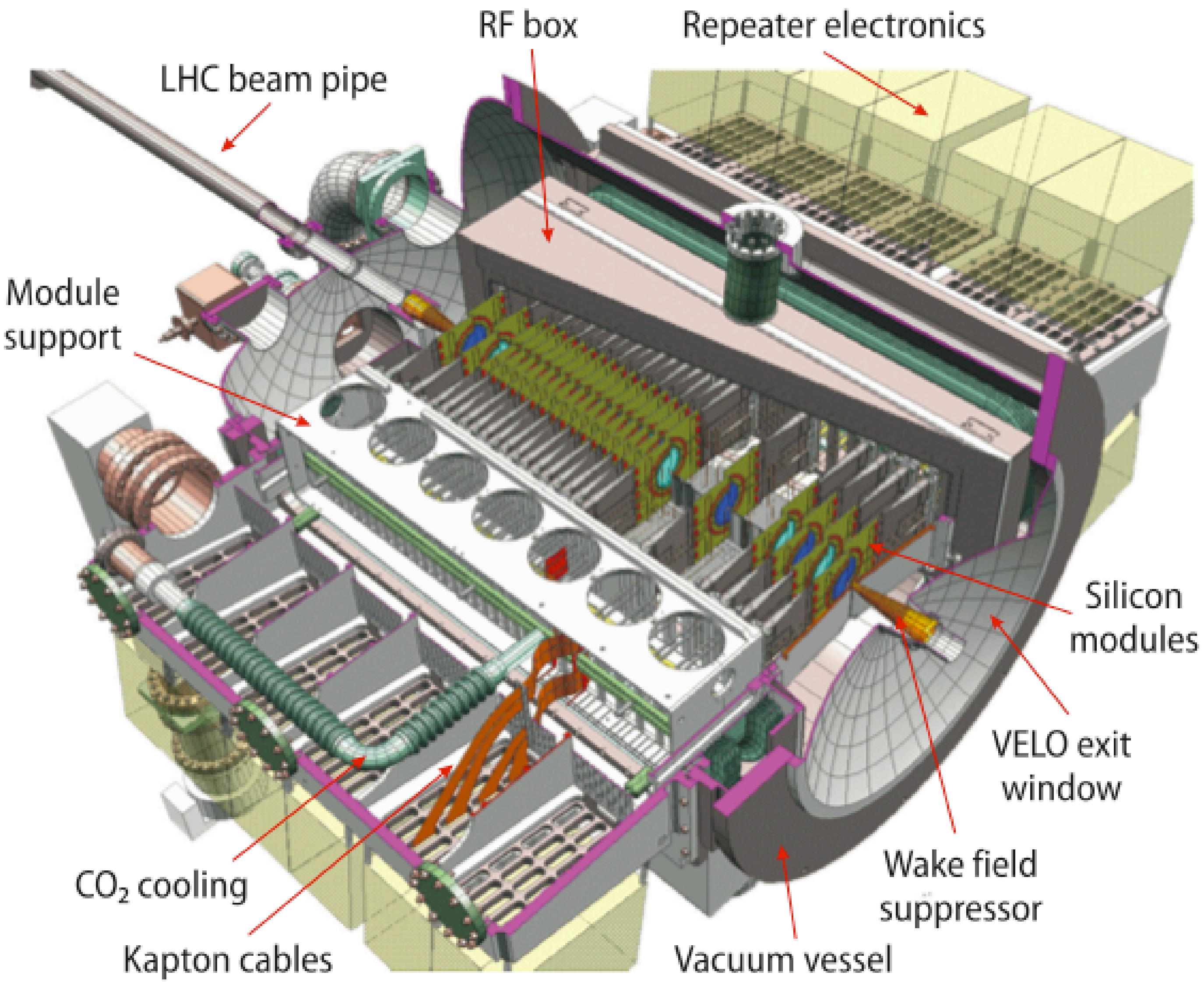
LHCb: pile-up protection

- LHCb needs to identify displaced vertices online
  - This is done in the HLT trigger (see later)
  - This algorithm only works efficiently if there is no pile-up (only one interaction per BX)
  - Pile-up veto implemented with silicon detector: Detect multiple PRIMARY vertices in the opposite hemisphere
  - Vertex position depends on $k=r_1/r_2$





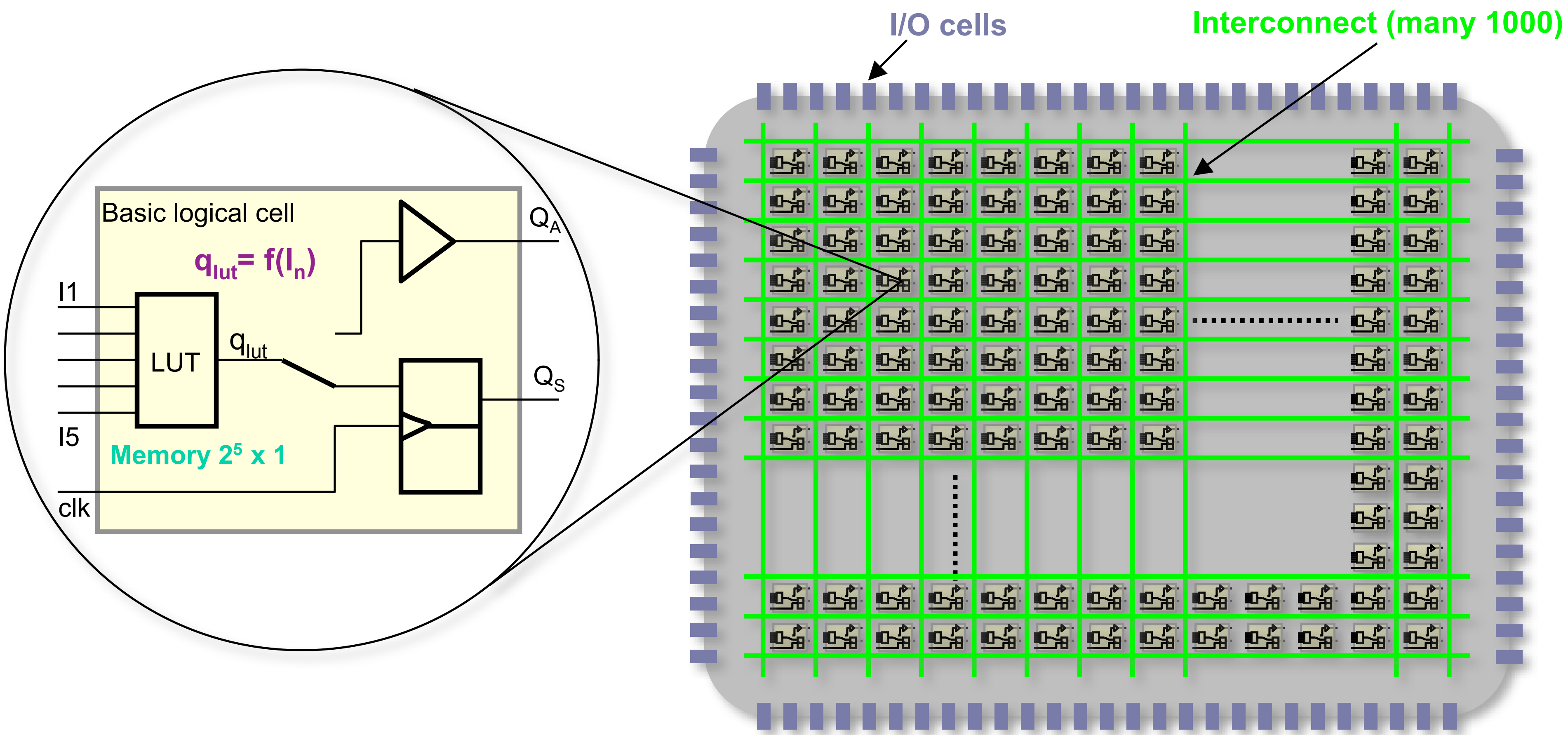
LHCb: VELO (Vertex Locator)



Trigger implementation

First level trigger: Implementation

- Custom Electronics design based on **FPGAs and ASICs**
- **FPGA** : Field Programmable Gate Array
  - Might contain also memory, processors, high speed serial links
  - Development with dedicated (vendor specific) FPGA design software
  - Complex designs like dedicated processors, PCI interfaces, Web-Servers possible in one device

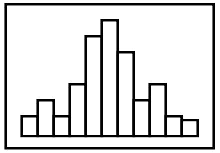


Trigger implementation (II)

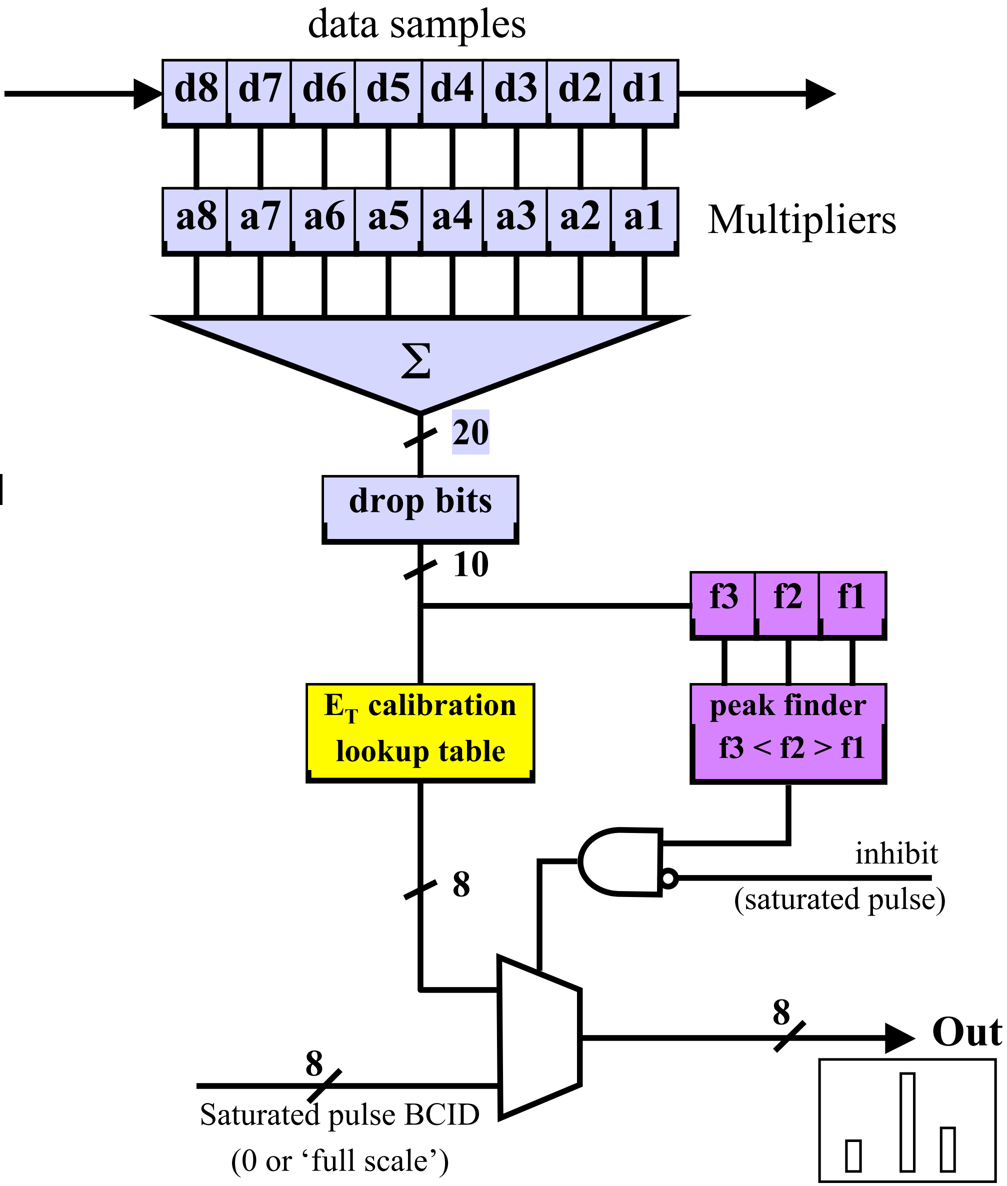
- ASIC (Application Specific Integrated Circuit)
  - Can be produced radiation tolerant (for “on detector” electronics)
  - Can contain “mixed” design: analog and digital electronics
  - Various design methods: from transistor level to high level libraries
  - In some cases more economic (large numbers, or specific functionality)
  - Disadvantages:
    - Higher development “risk” (a development cycle is expensive)
    - Long development cycles than FPGAs
      - No bugs tolerable -> extensive simulation necessary

- Example :
  - ASIC to determine E_T and to identify the Bunch Crossing (BX) from the ATLAS calorimeter signals

ATLAS Calorimeter: BX & E_T



- Signals length >> 25ns
  - Need to “integrate” over several BXs
  - Signals of subsequent BXs might overlap
- FIR filter
  (digital filter: Finite Impulse Response)
  - Multipliers optimized for particular signal shape
- LUT to get calibrated E_T
  - Lookup Table is a memory:
    - Input: Address of memory
    - Output: Data of memory
- Feeds peak-finder to identify BX
- Special handling of very large pulses
  - Potentially interesting physics
  - Takes into account how long the pulse is in saturation



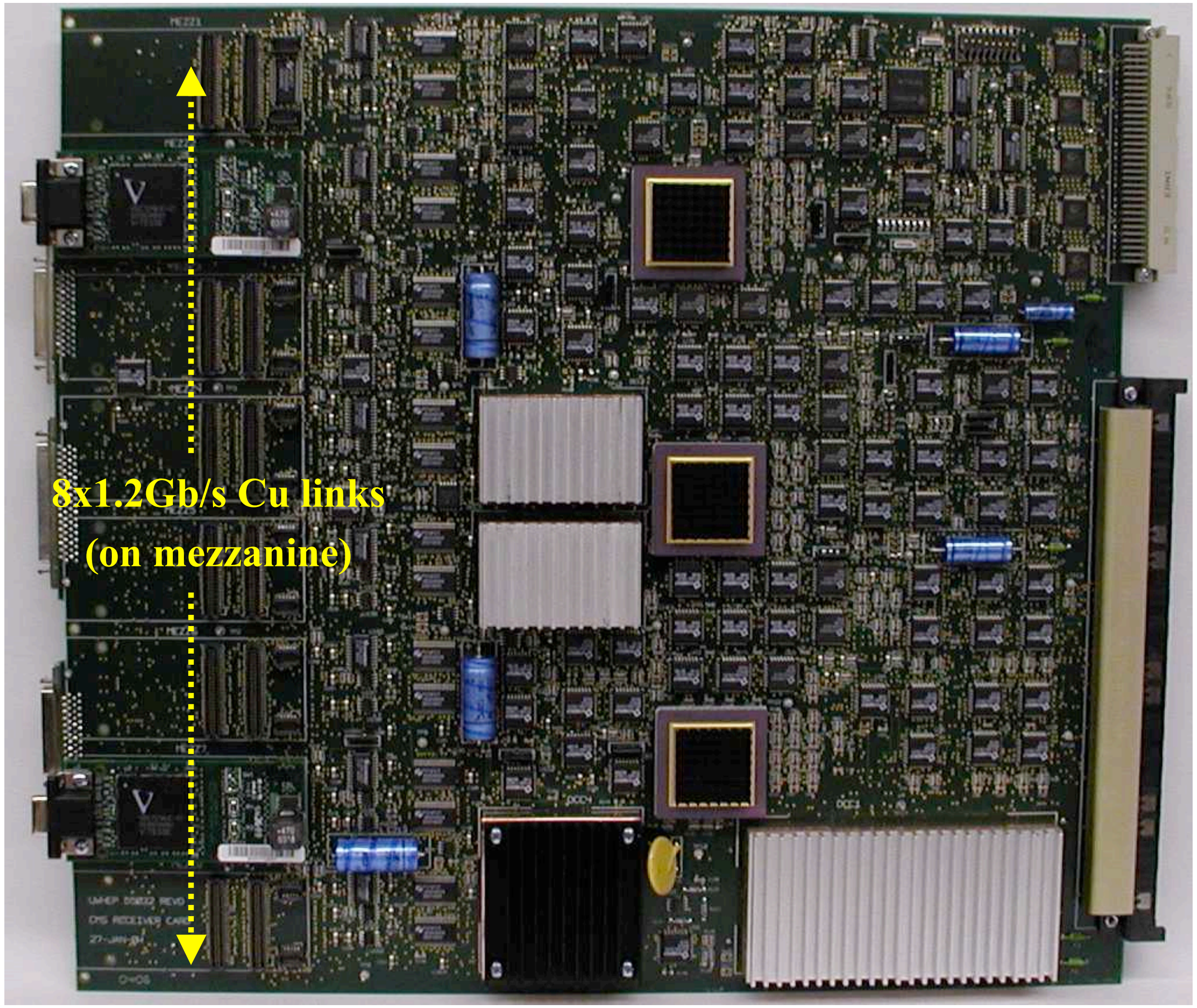
Trigger implementation (III)

- Trigger circuits need extremely high connectivity with low latency
  - Large cards because of large number of IO channels
  - Many identical channels processing data in parallel
    - This keeps latency low
  - Pipelined architecture
    - New data arrives every 25ns
  - Custom links
    - Backplane parallel busses for in-crate connections
    - LVDS links for short (O(10m)) inter-crate connections (LVDS: Low Voltage Differential Signaling)

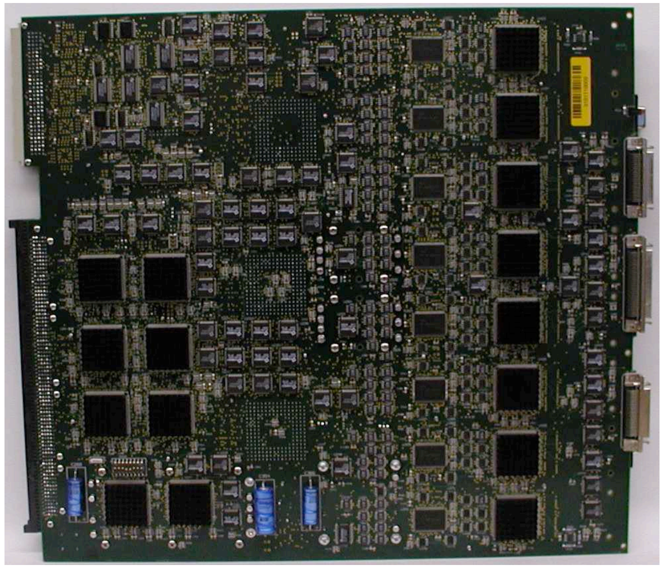
CMS: Regional Calorimeter Trigger

Receives 64 Trigger primitives from (32 ECAL, 32 HCAL)

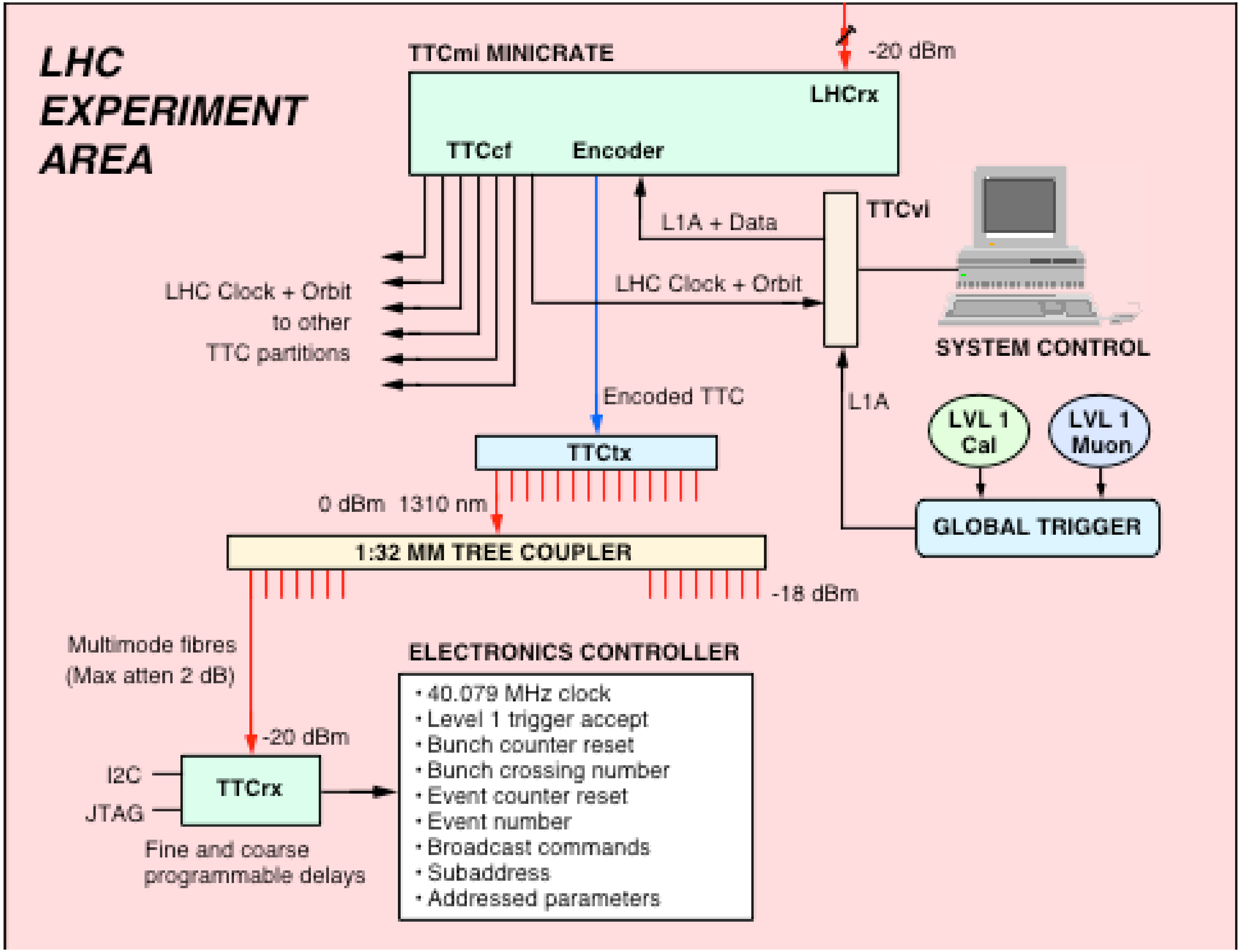
Forms two 4x4 Towers for Jet Trigger and 16 E_T towers for electron identification card



"solder" - side of the same card:

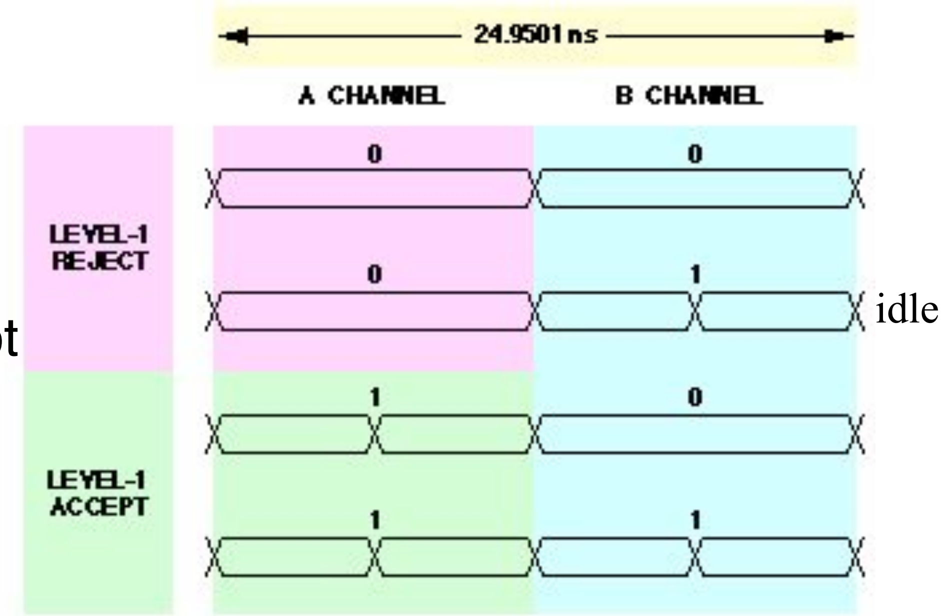


Trigger distribution: TTC system



TTC encoding: 2 Channels

- Channel A:
  - One bit every 25ns
  - low and constant latency
  - For distribution of LVl1-accept
- Channel B:
  - One Bit every 25 ns
  - Synchronous commands
    - Arrive in fixed relation to LHC Orbit signal
  - Asynchronous commands
    - No guaranteed latency or time relation
  - “Short” broadcast-commands (Bunch Counter Reset, LHC-Orbit)
  - “Long” commands with addressing scheme
    - Addressing scheme
    - Can be used for calibration, re-synch, …



Summary

- Trigger design is driven by:
  - Physics requirements
  - Technological (and financial) constraints
  - Compromises have to be found.
- Flexibility and redundancy are important design criterias
  - Allow to react to real life scenarios (beam background, detector noise, …)
  - Allow cross checks to determine efficiencies from data
- ATLAS & CMS have very similar concepts
- Special features for LHCb and ALICE

Extra slides: Lvl1 trigger

Potentially interesting event categories

- Standard Model Higgs
  - If Higgs is light (< 160GeV) : H -> $\gamma\gamma$ H -> ZZ^* -> 4l
    - Trigger on electromagnetic clusters, lepton-pairs
  - If Higgs is heavier other channels will be used to detect it
    - H -> ZZ -> ll$\nu\nu$
    - H -> WW -> lνjj
    - H -> ZZ -> lljj
  - Need to trigger on lepton pairs, jets and missing energies

- Supersymmetry
  - Neutralinos and Gravitinos generate events with missing E_t^{miss}
  - Squarks decay into multiple jets
  - Higgs might decay into 2 taus (which decay into narrow jets)

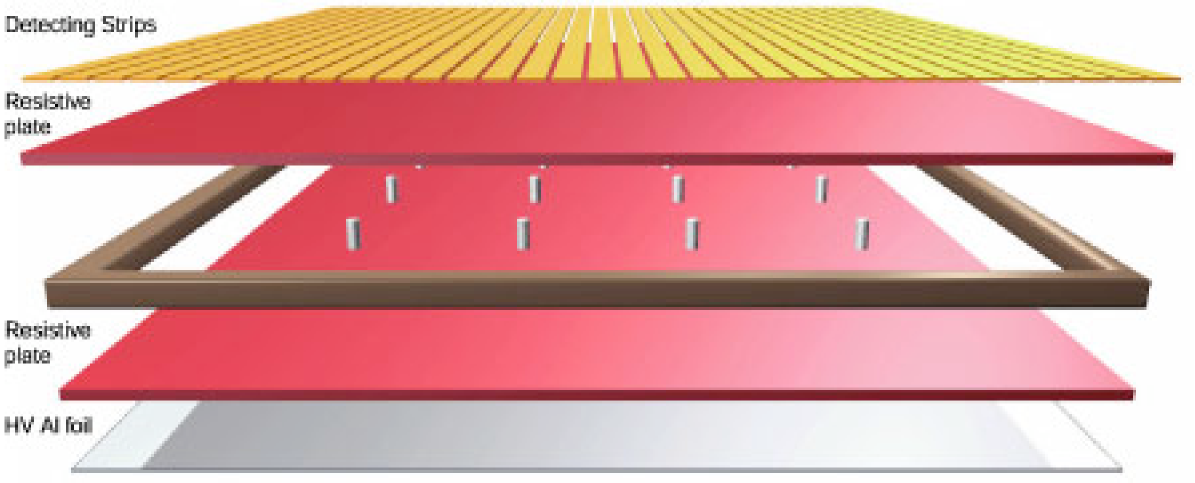
Trigger at LHC startup: $L=10^{33}cm^{-2}s^{-1}$

- LHC startup
  - Factor 10 less pile up O(2) interactions per bunch crossing
  - Much less particles in detector
    - Possible to run with lower trigger thresholds
- B-physics
  - Trigger on leptons
  - In particular: muons (trigger thresholds can be lower than for electrons)
- t-quark physics
  - Trigger on pairs of leptons.

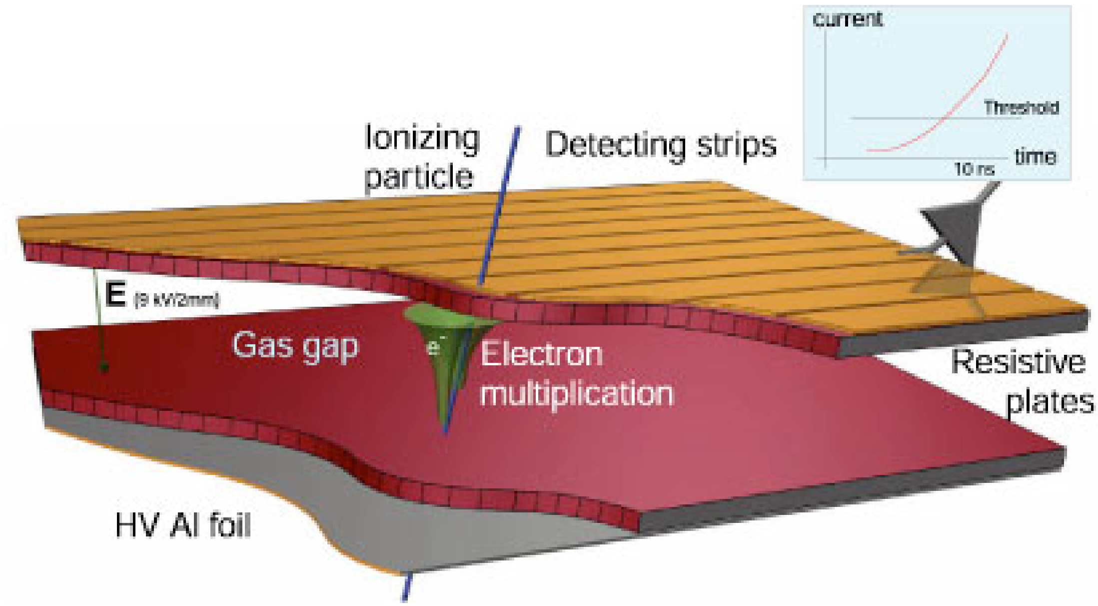
LHCb

- Operate at $L = 2 \times 10^{32}$ $cm^{-2}s^{-1}$: 10 MHz event rate
- Lvl0: 2-4 us latency, 1MHz output
  - Pile-up veto, calorimeter, muon
- Pile up veto
  - Can only tolerate one interaction per bunch crossing since otherwise always a displaced vertex would be found by trigger

CMS RPCs

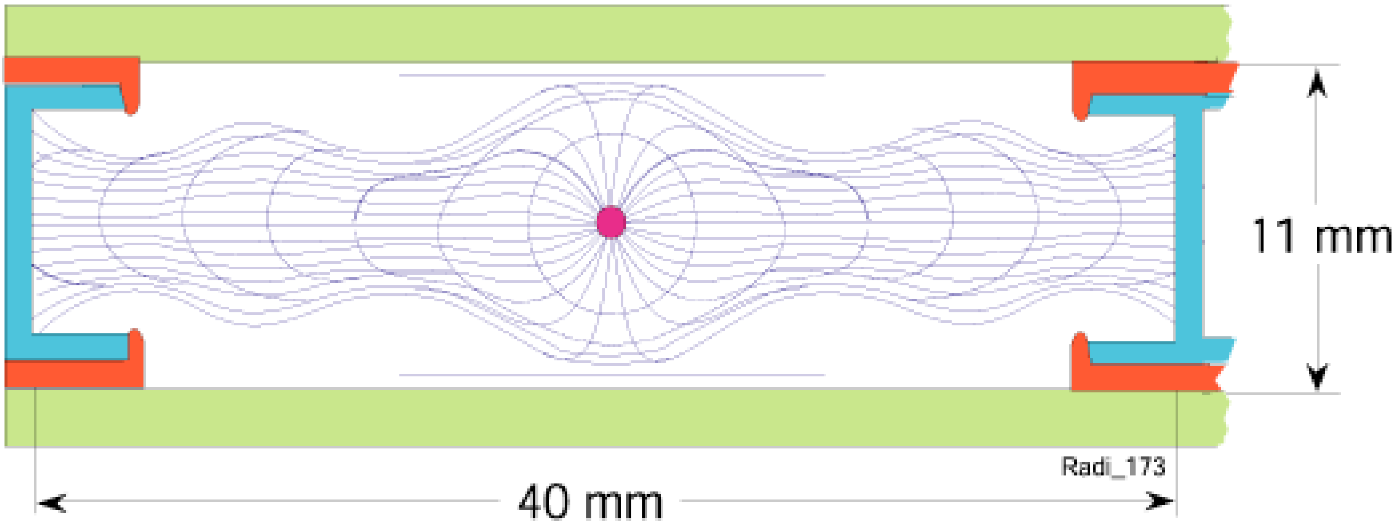


Detecting Strips
Resistive plate
Resistive plate
HV Al foil

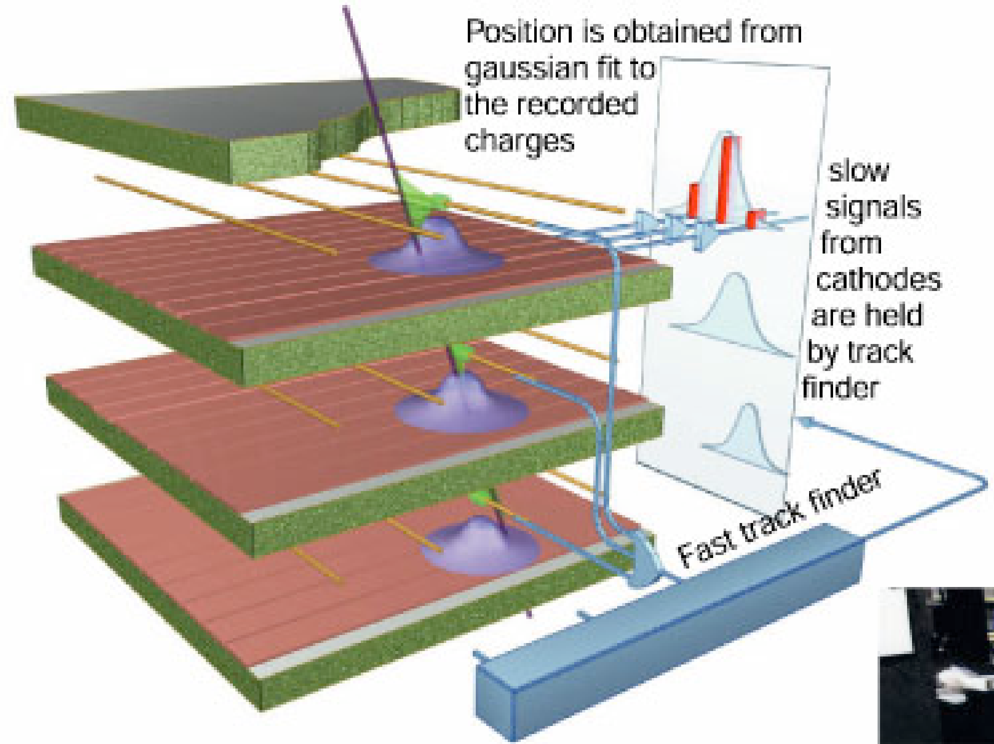


current
Threshold
time
10 ns
Ionizing particle
Detecting strips
E (9 kV/2mm)
Gas gap
e⁻
Electron multiplication
Resistive plates
HV Al foil

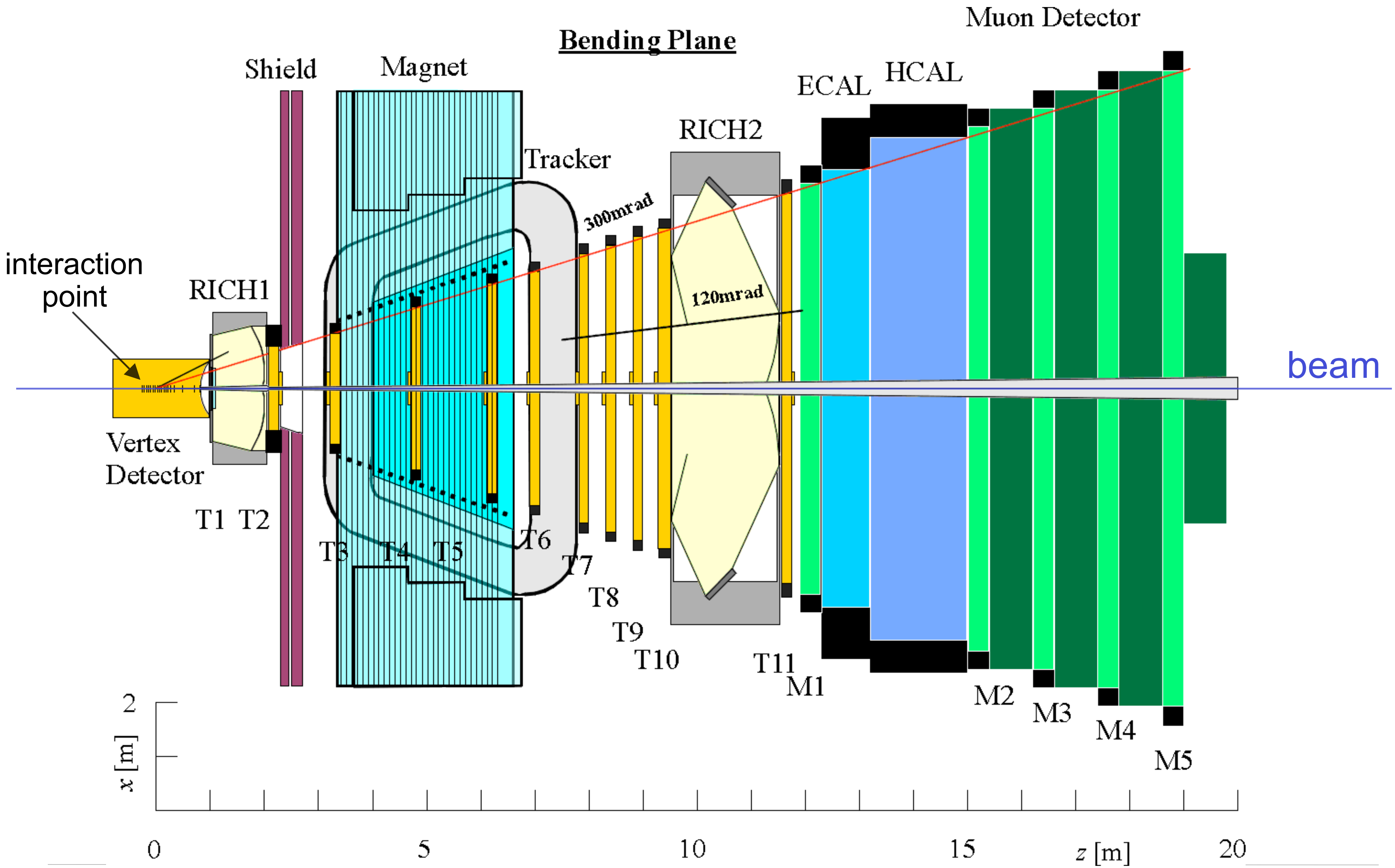
CMS DTs



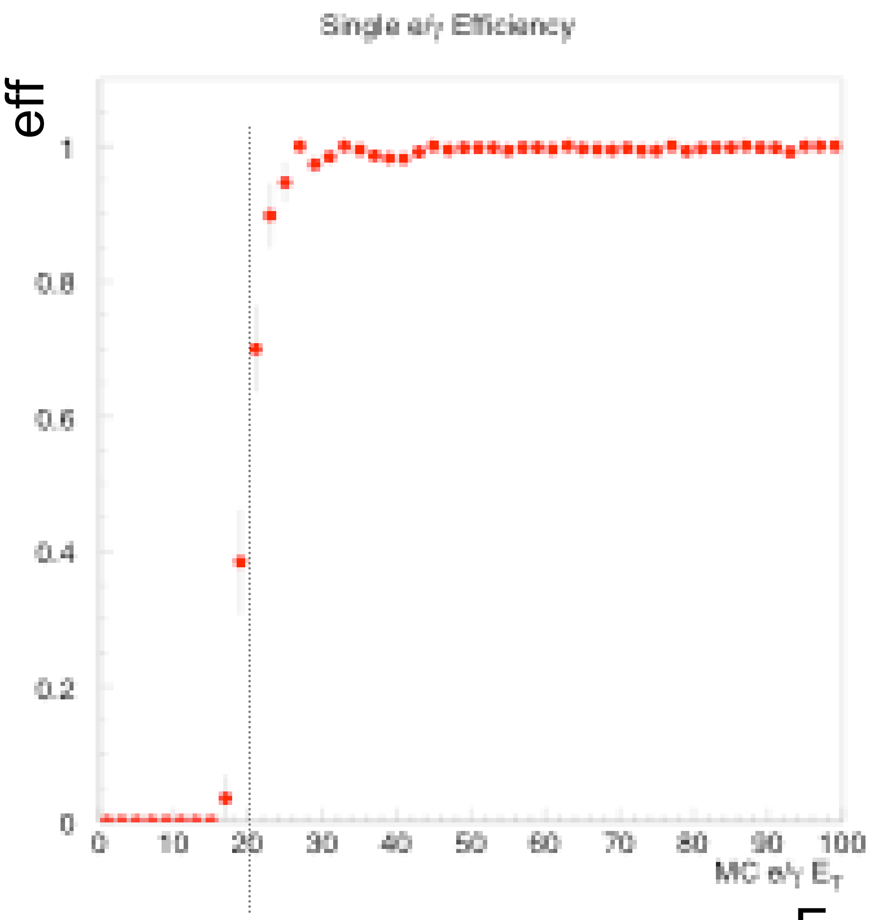
CMS CSCs


Position is obtained from gaussian fit to the recorded charges
slow signals from cathodes are held by track finder
Fast track finder

LHCb : study of B-decays ($\not{C}\not{P}$)



CMS isolated e/γ performance



Cut: 20GeV