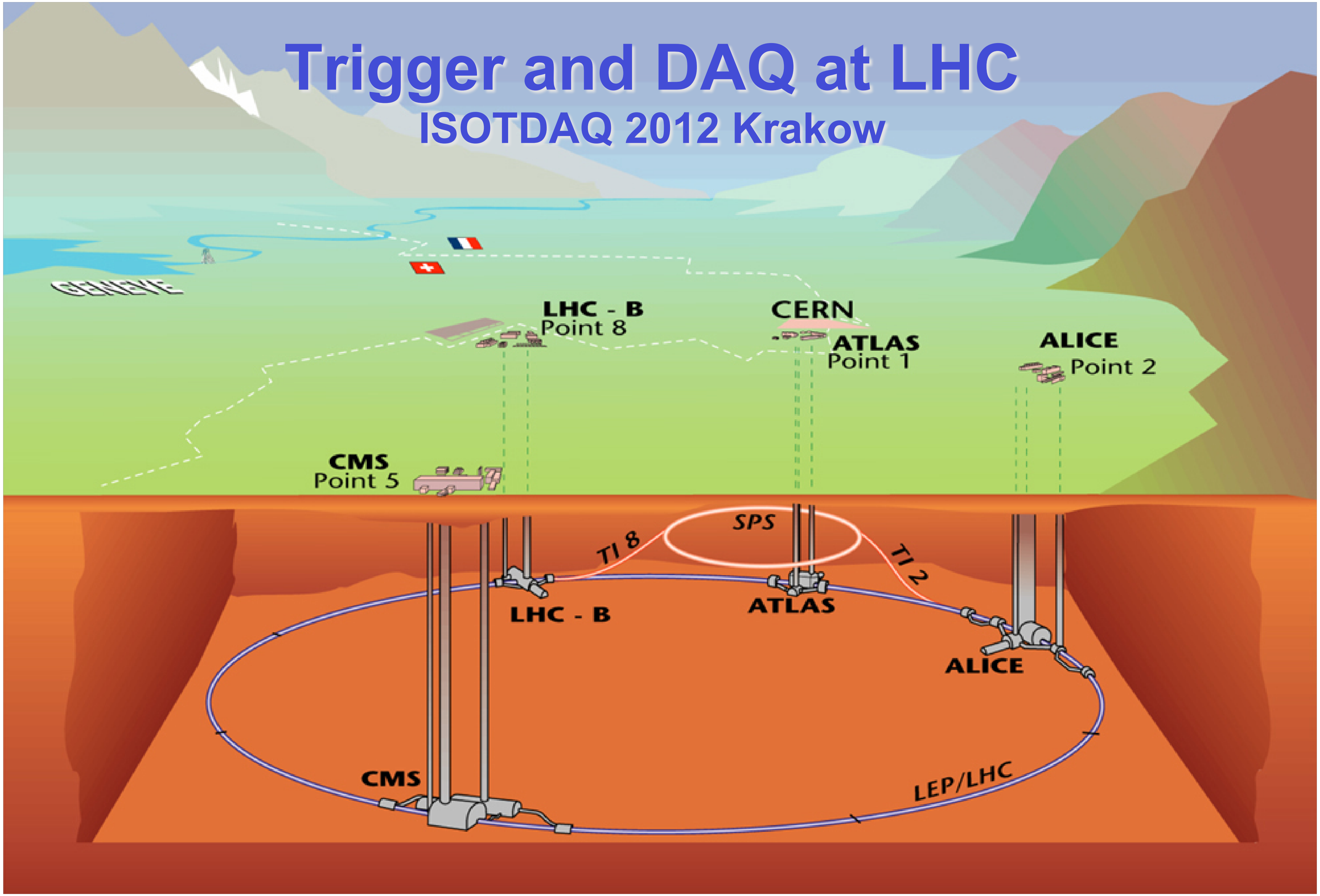
Trigger and DAQ at LHC

ISOTDAQ 2012 Krakow



C.Schwick

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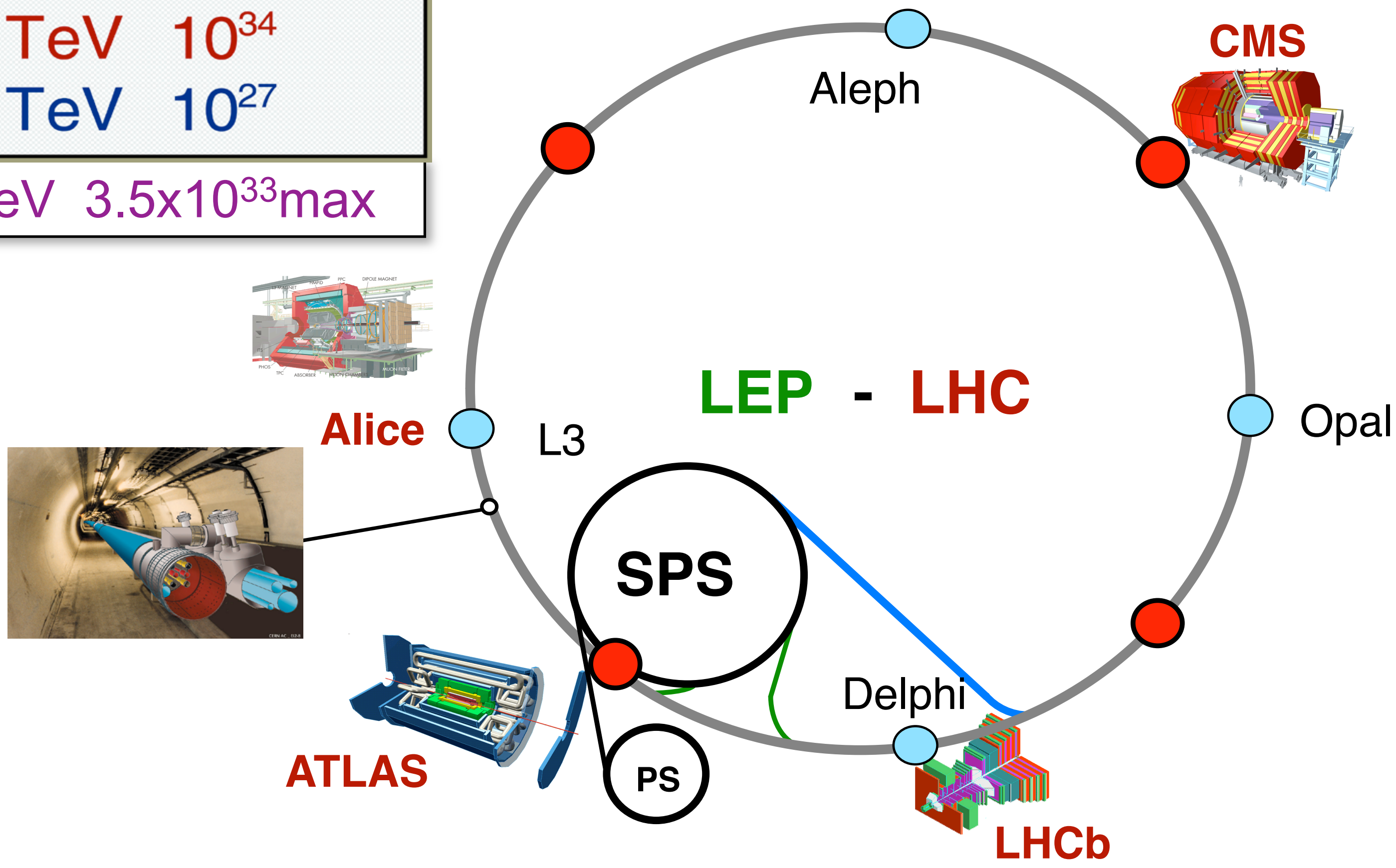
Acknowledgement

Thanks to many of my colleagues in ALICE, ATLAS, CMS, LHCB for the help they gave me while preparing these lectures; and in particular to Sergio Cittolin who provided me with many slides (probably those you will like most are from him!)

Introduction: LHC and the Experiments

LHC: a "discovery" machine

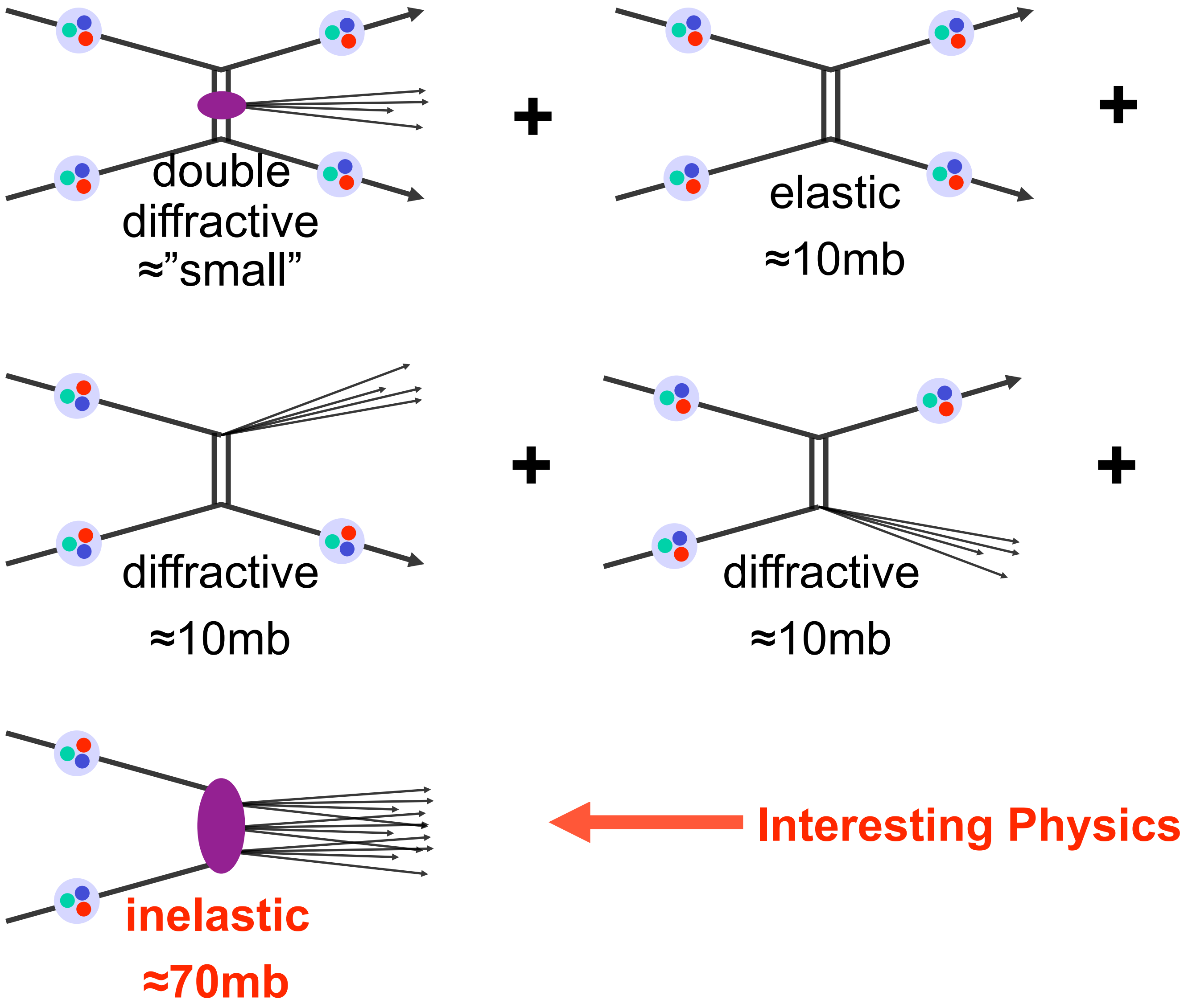
	Beams	Energy		Luminosity
LEP	e^+e^-	200	GeV	$10^{32}\ cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	$P_b\ P_b$	1312TeV		10^{27}
LHC_{2011}	p p	7	TeV	$3.5x10^{33}$max



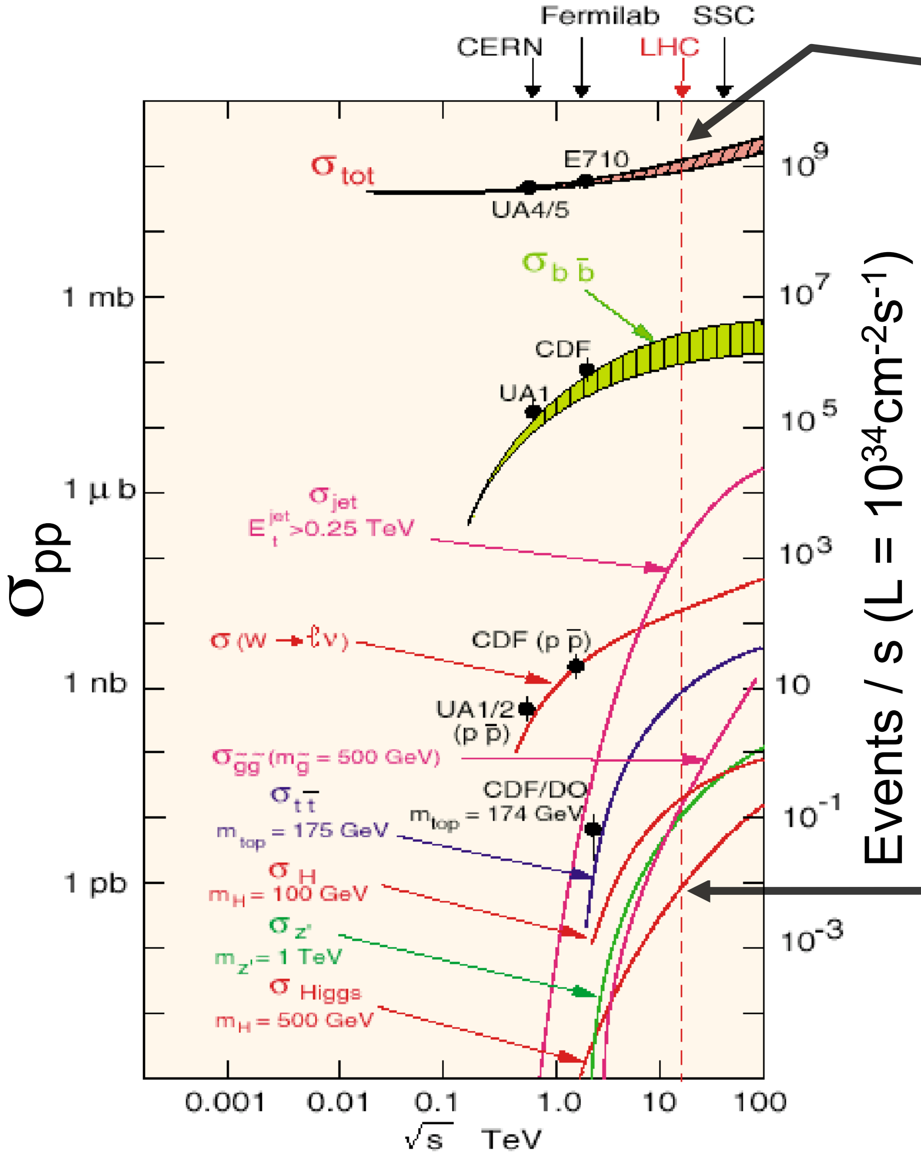
p-p interactions at LHC

σ_{tot} =

≈100mb



Interesting Physics at LHC



$\sigma_{tot} \approx 100$ mb

1 : 100 000 000 000

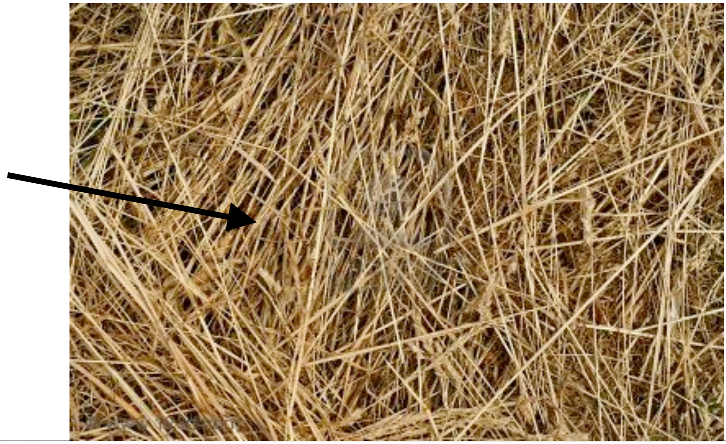
$\sigma_{H(500GeV)} \approx 1$ pb

a needle in the haystack

Is the Higgs a needle in the hay stack ?

- Hay halm:
  - 500mm length; 2mm ⃠
    → 3000mm^3

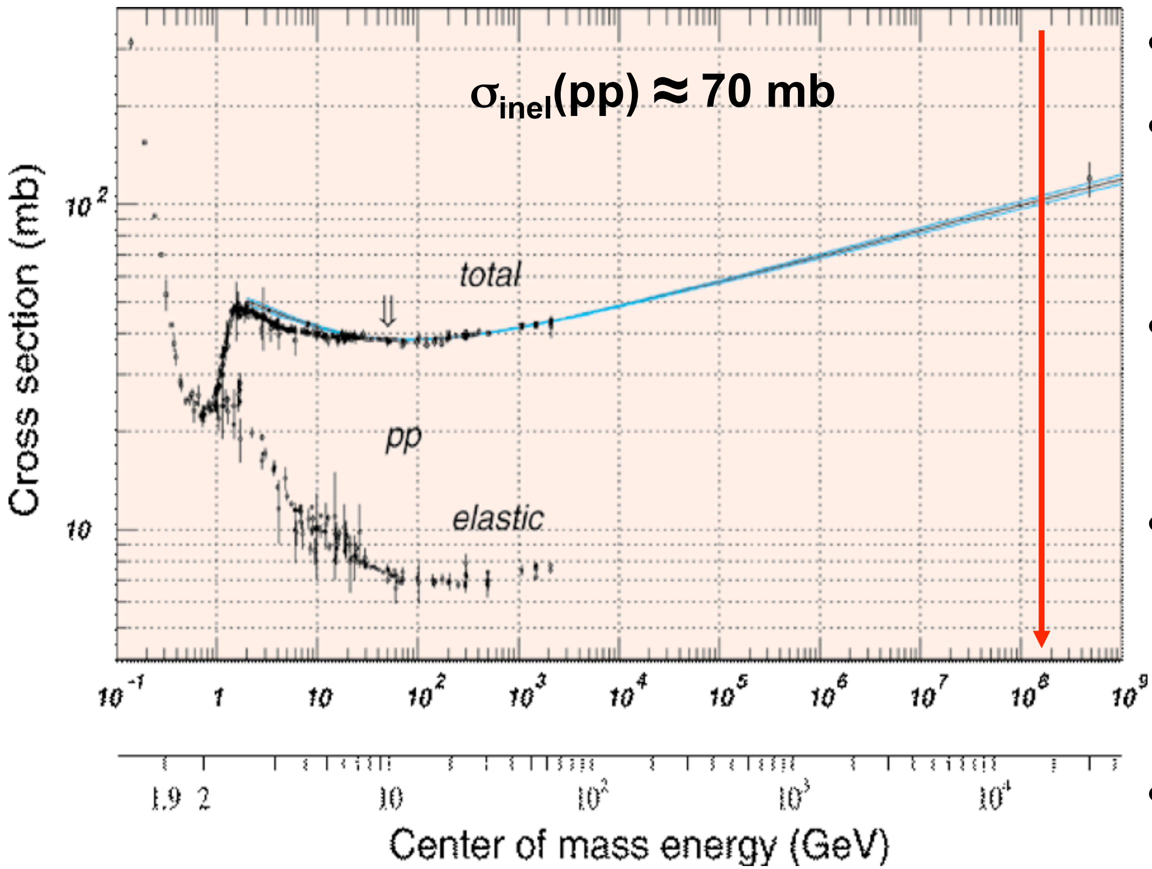
- Needle
  - 50 mm length, 0.3mm ⃠
    → 50 mm^3
  - 60 needles are one hay halm



- Putting it all together
  - Assume hay packing density of 10 (…may be optimistic…)
  - $10 \times 10^{11} * 3*10^{-9}$ m^3 / (6*10) =

Haystack of 50 m^3

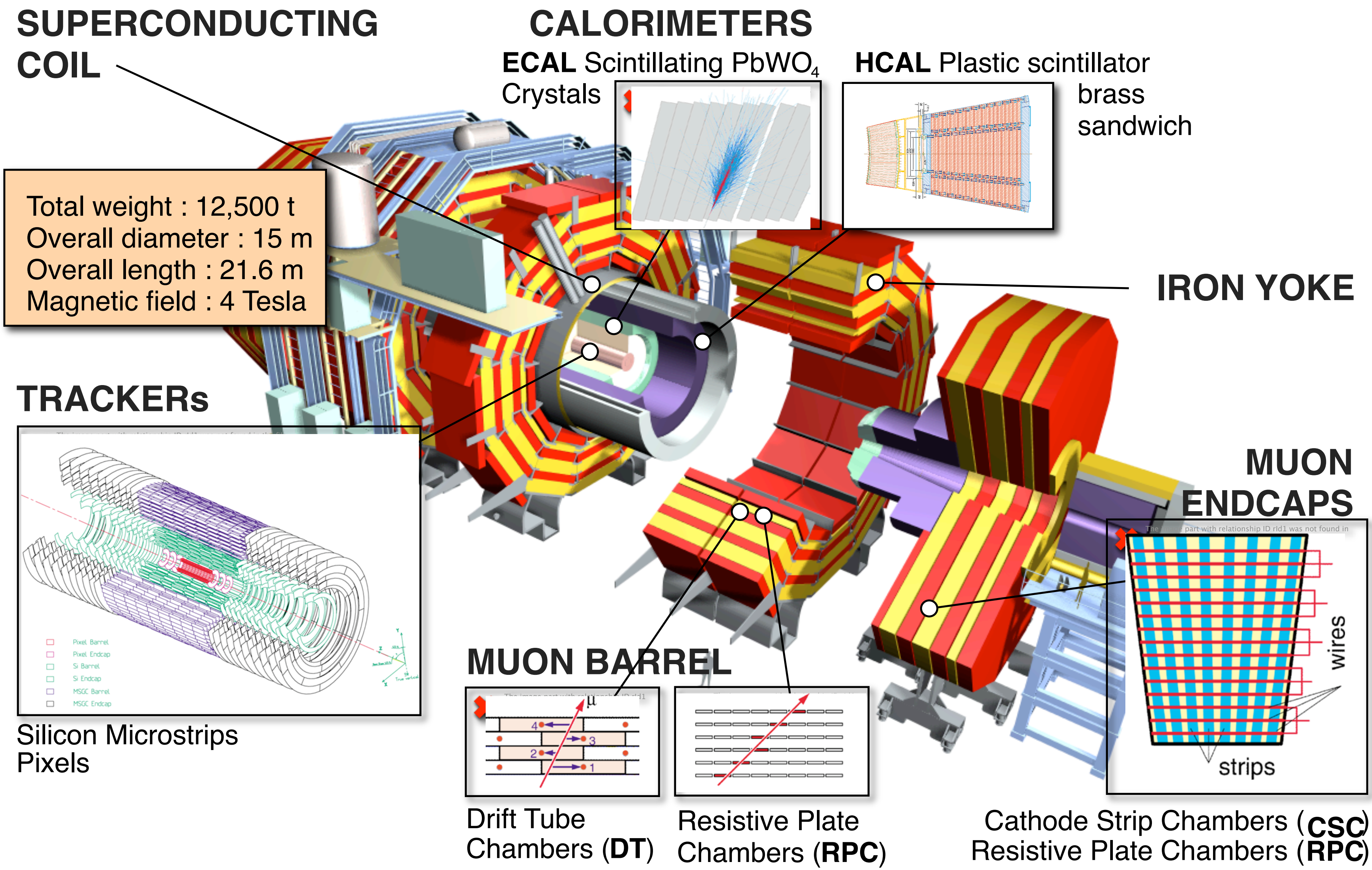
LHC: experimental environment



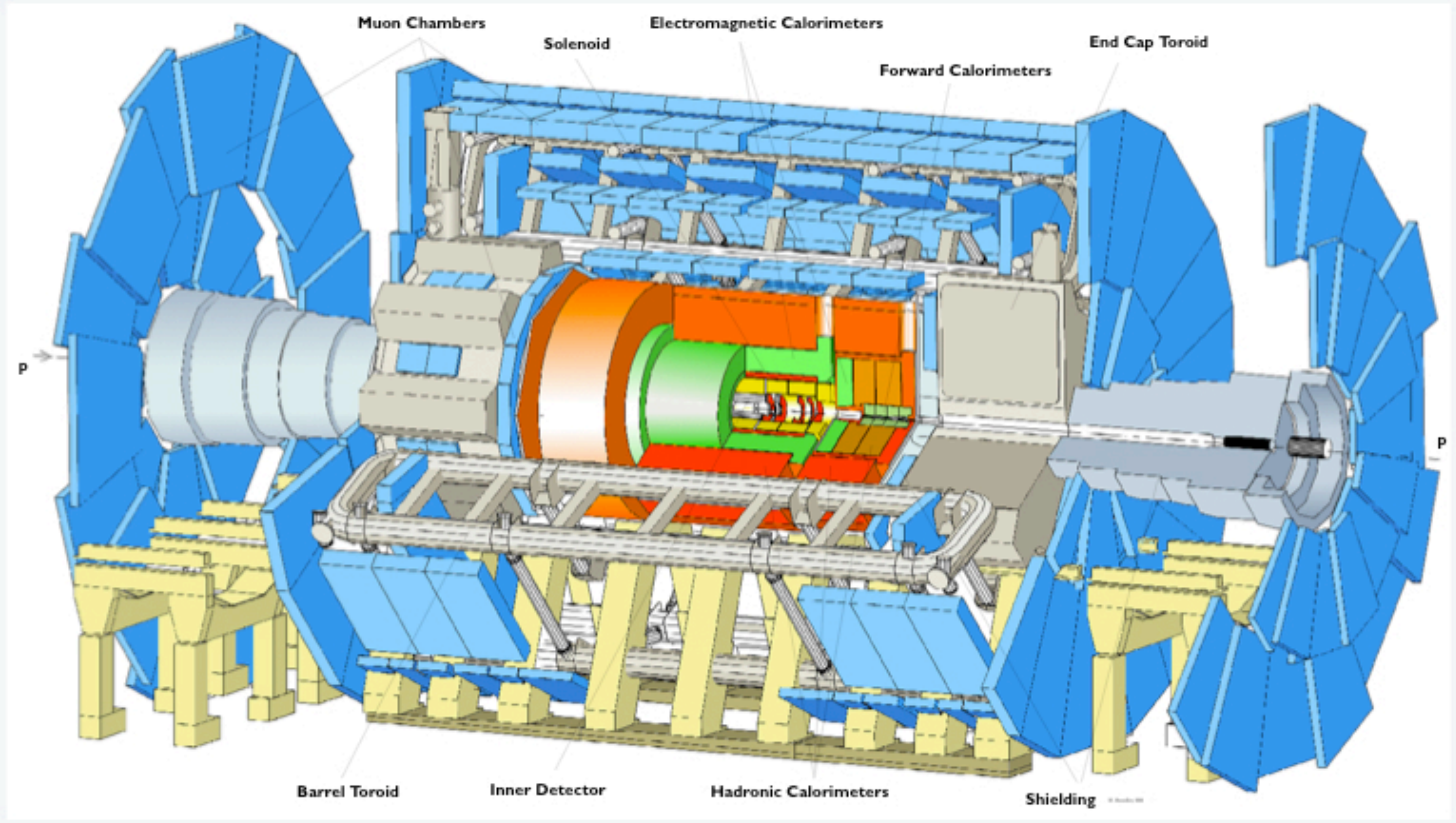
- $L = 10^{34} cm^{-2} s^{-1}$
- $\sigma_{inel}(pp) \approx 70$mb
  event rate = 7 x 10^8Hz
- Δt = 25ns
  events / 25ns = 17.5
- Not all bunches full (2835/3564)
  events/crossing = 23
- **2012 LHC will run at 50ns pile up will be twice as high as for 25 ns (at constant Lumi)**

The 4 largest LHC experiments

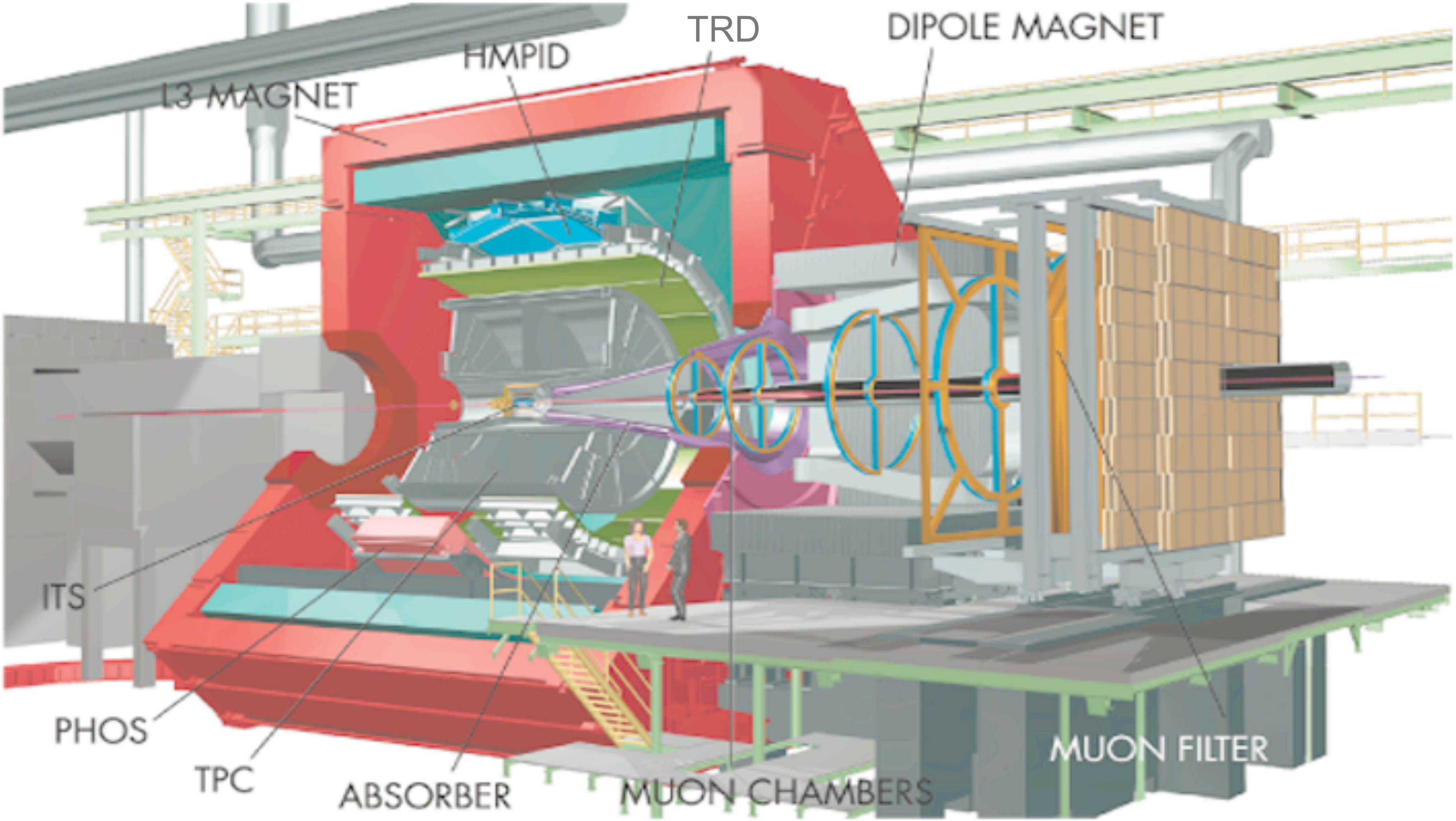
CMS : study pp and heavy ion collisions



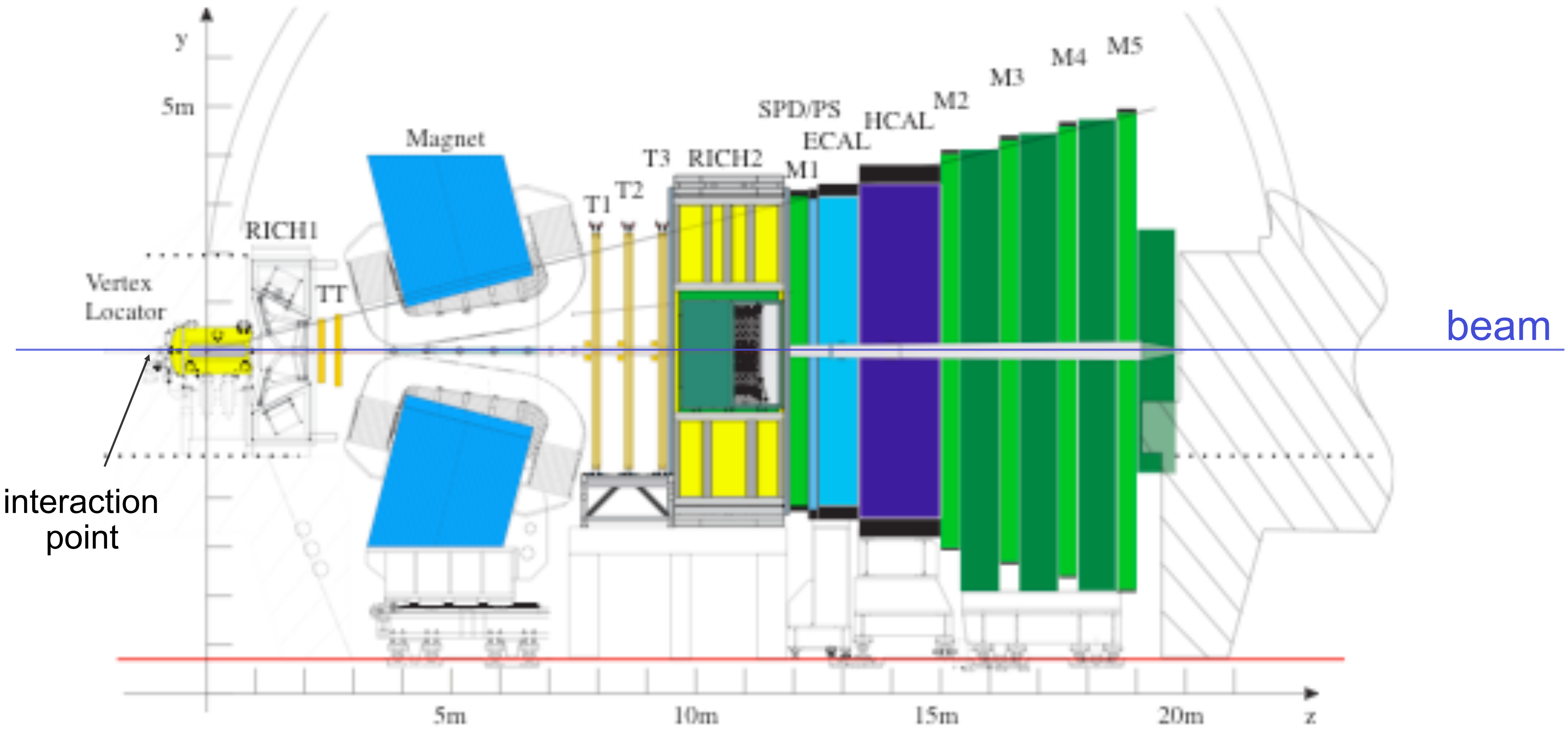
Atlas : study pp and heavy ion collisions



ALICE : study heavy ion collisions

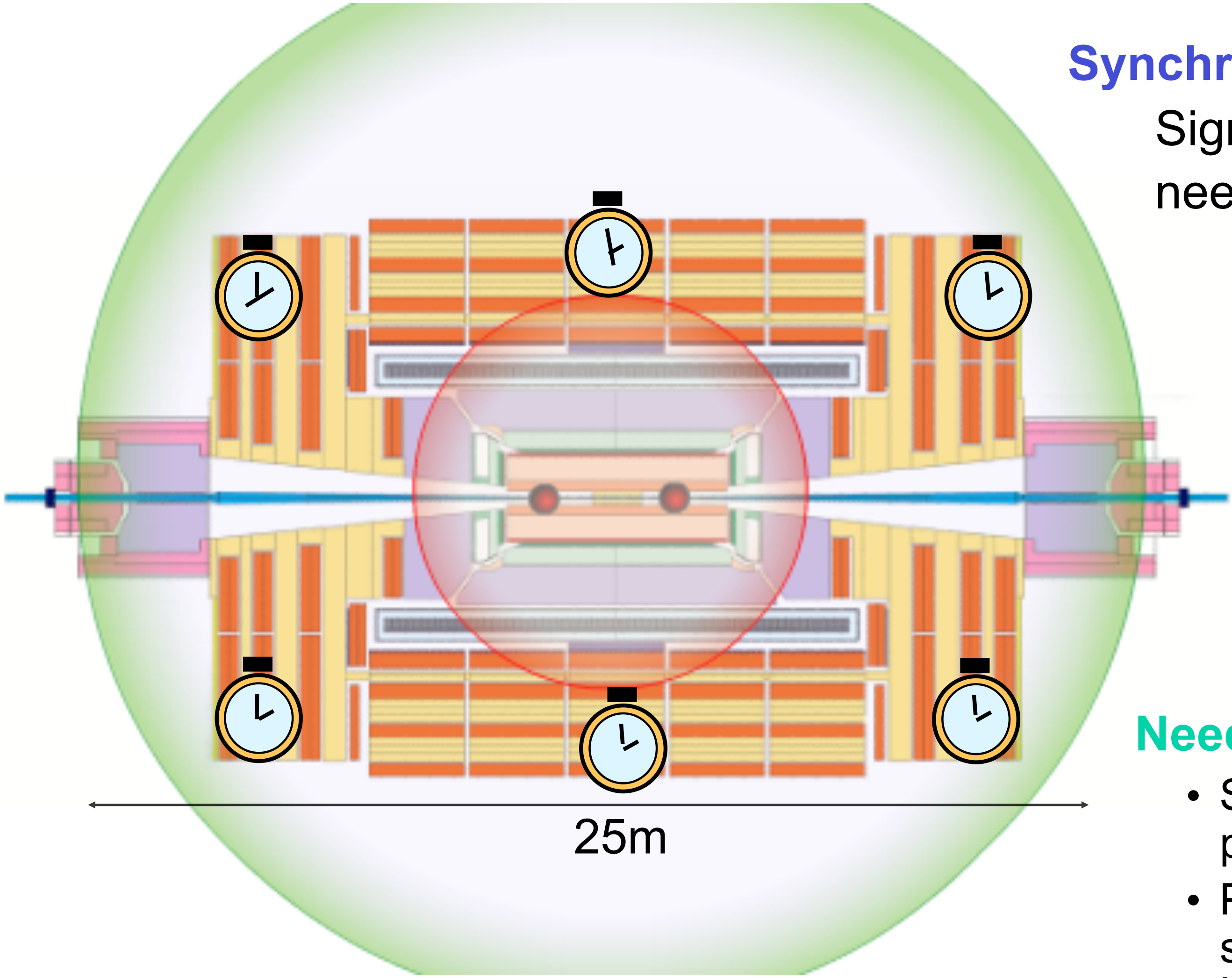


LHCb : study of B-decays (CP)



Timing and Synchronization

Issue: synchronization



Synchronization:

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

But:

Particle TOF >> 25ns

(25 ns == 7.5m)

Cable delay >> 25ns

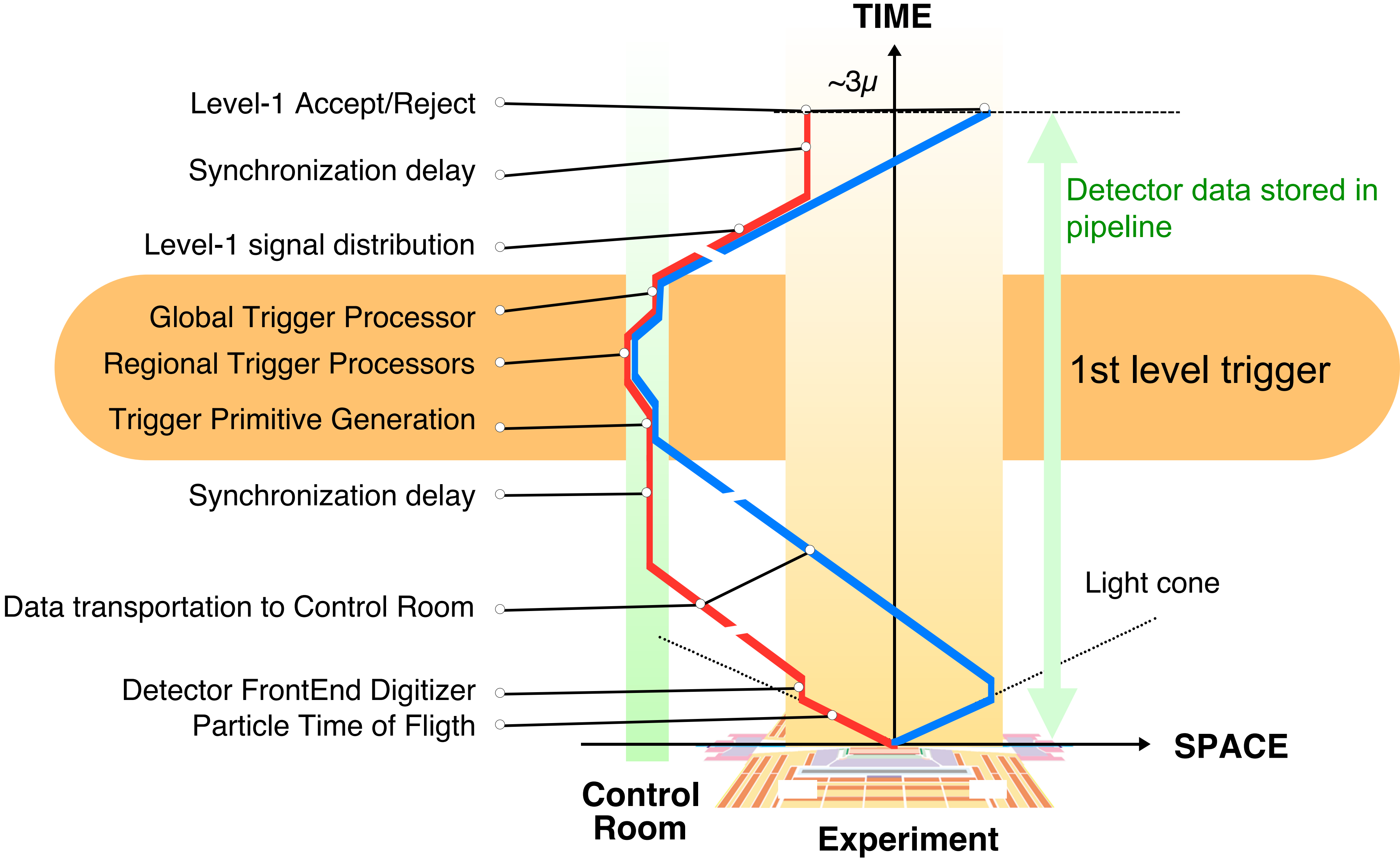
($V_{signal} \approx 1/3$ c)

Electronic delays

Need to:

- Synchronize signals with programmable delays.
- Provide tools to perform synchronization (TDCs, pulsers, LHC beam with few buckets filled…)

Signal path during trigger

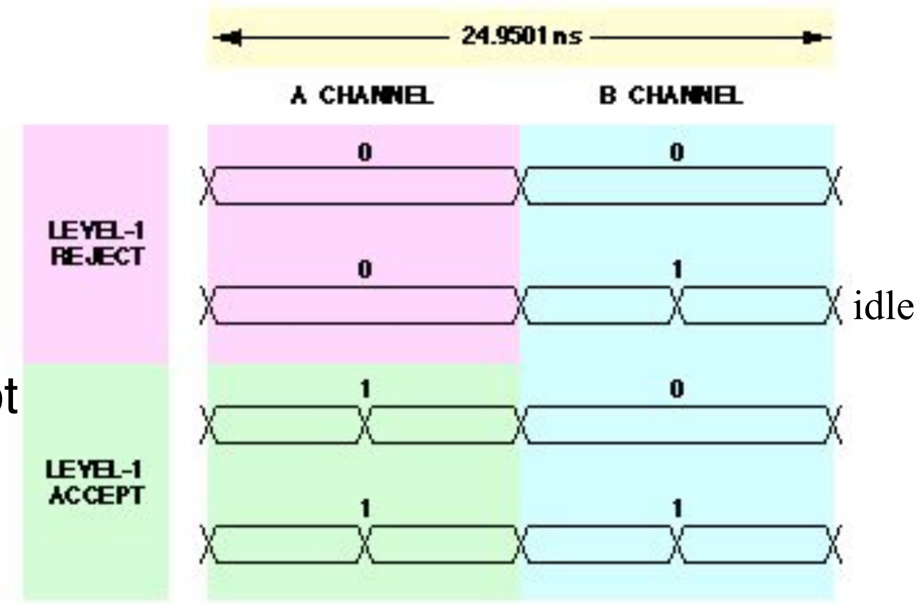


Distribution of Trigger signals

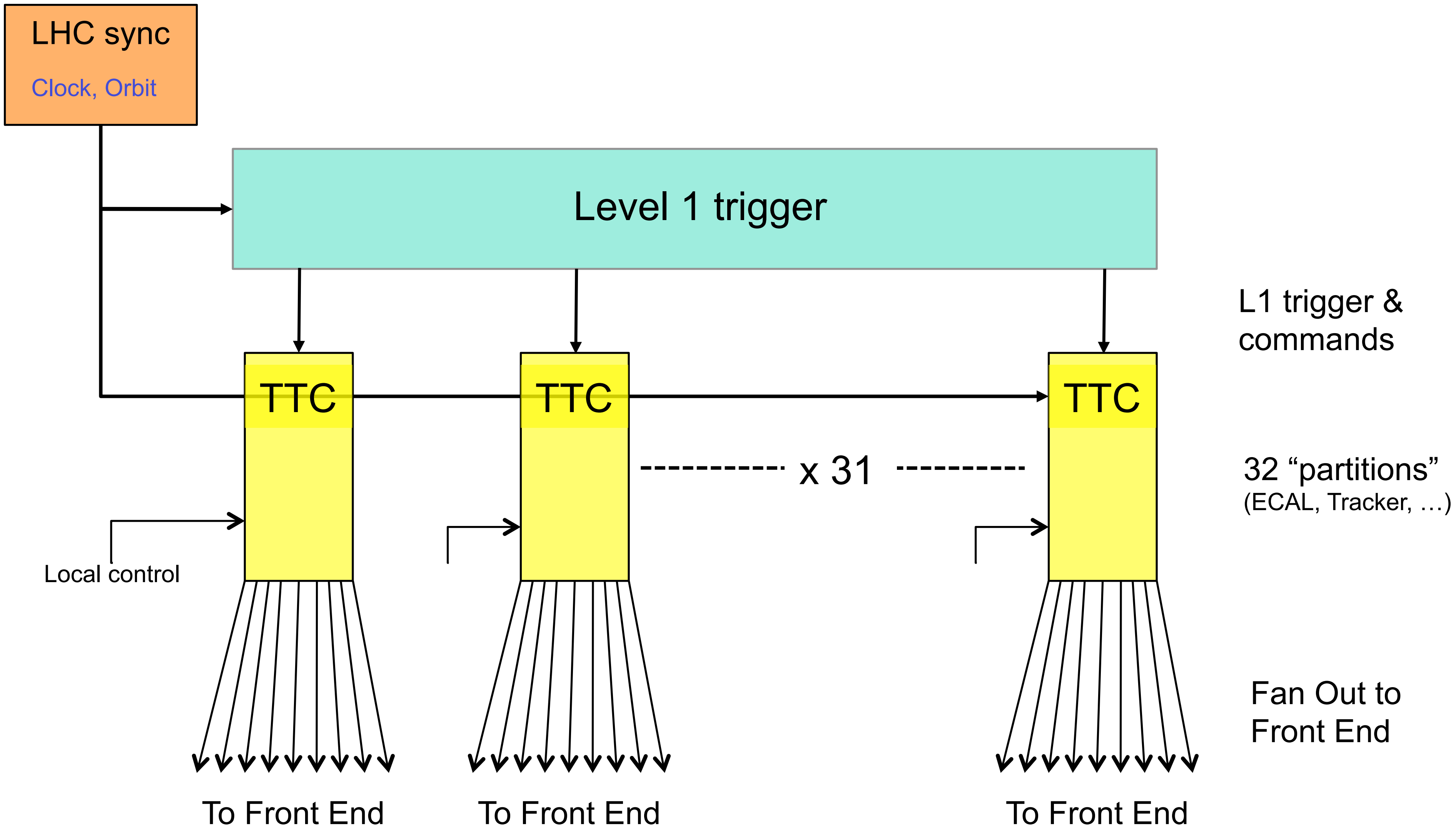
- The L1 trigger decision needs to be distributed to the front end electronics
  - Triggers the readout of pipeline
  - Needs to allow to determine the Bunch Crossing of the interaction
    - Timing needs to be precise (low jitter, much below 1ns)
    - Signal needs to be synchronized to LHC clock
- In addition some commands need to be distributed:
    - always synchronous to LHC clock; e.g.
      - To do calibration in LHC gap (empty LHC buckets)
      - Broadcast reset and resynchronization commands
- Used by all experiments: TTC (Trigger Timing and Control)

TTC encoding: 2 Channels

- Channel A:
  - One bit every 25ns
  - constant latency required
    - Used to read out pipelines
  - 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
    - Serves special sub-system purposes



Trigger, Timing, Control at LHC



First Level Trigger

Three very different real world examples

	LEP	DaΦne	LHC
physics	e+ / e-	e+ / e-	p / p
Event size	O(100 kB)	O(5 kB)	O(1MB) (CMS & ATLAS)
$1/f_{BX}$	22us (later 11us)	2.7 ns	25 ns
Lvl1 Operation	Decision between 2 bunch crossings	Continuously running; trigger readout on activity	Synchronous to 40Mhz base clock; decision with 3us latency; pipeline
trigger rate	O(10Hz)	50kHz	100kHz (1MHz LHCb)

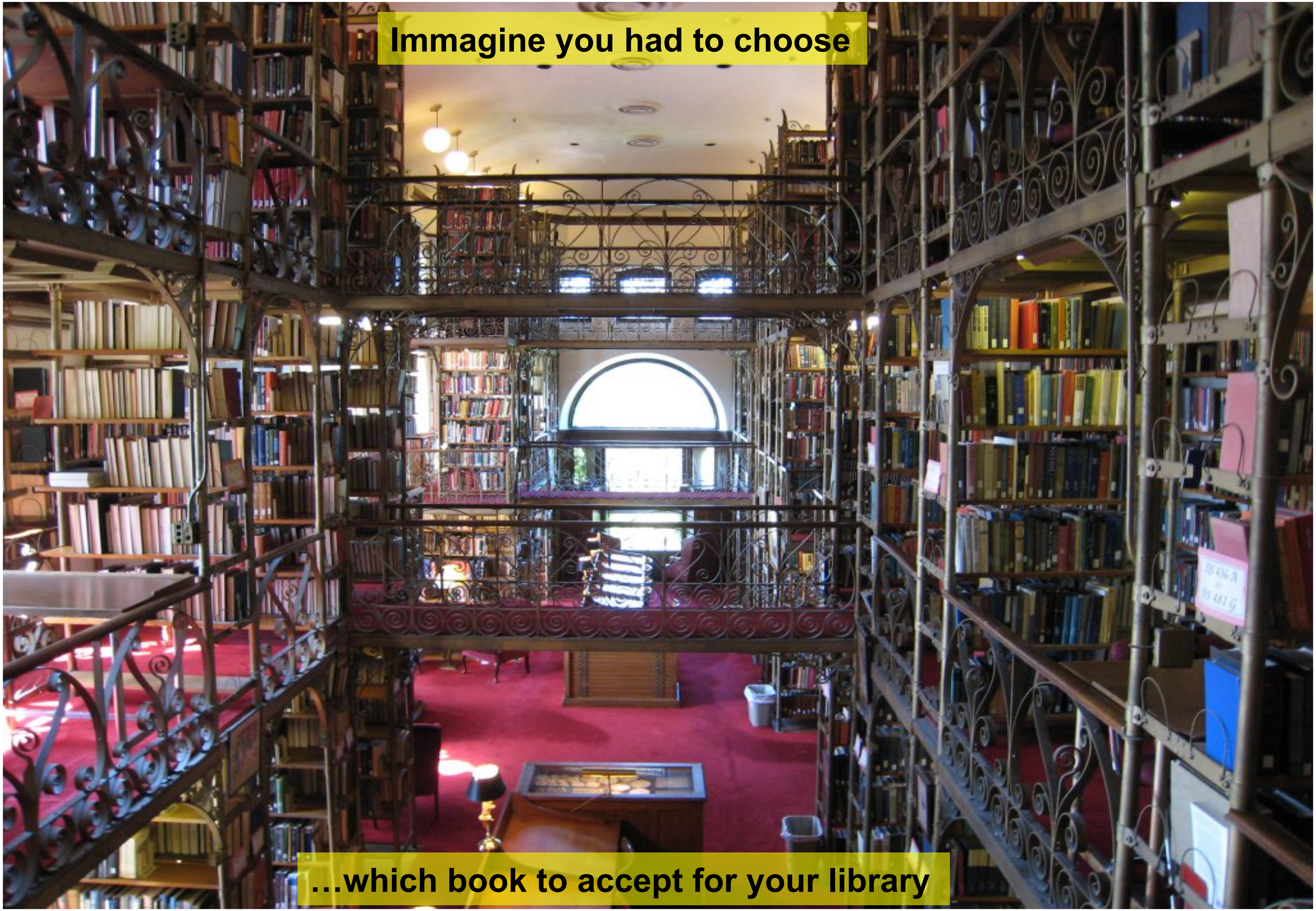


Immagine you had to choose
…which book to accept for your library

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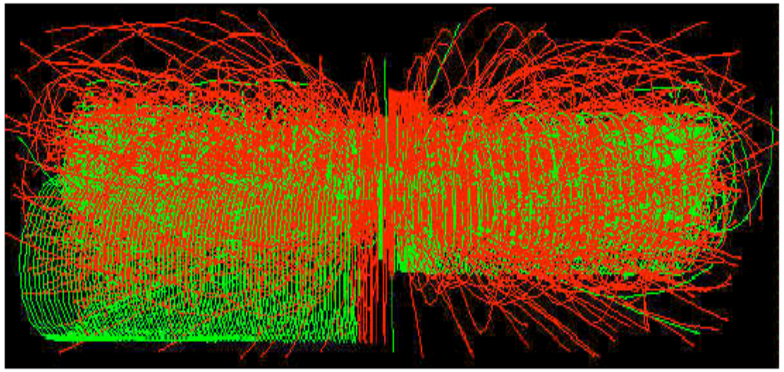
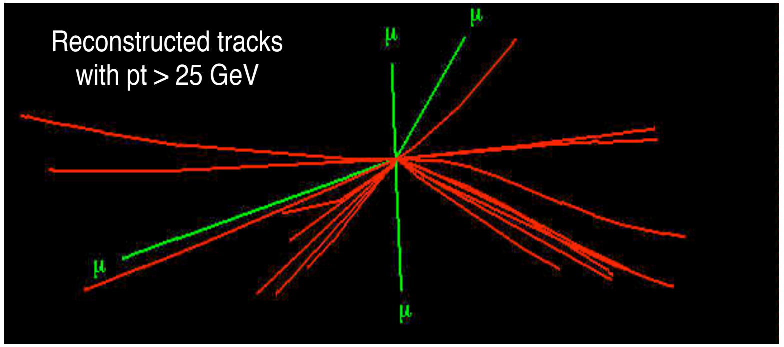
"Typical event"

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





Prepare an "event - TOC"

- Data must be available fast (I.e. shortly after the interaction)
  - Some sub-detectors are build for triggering purposes
- Prepare data with low resolution and low latency in sub-detectors

Therefore for ATLAS and CMS:

- Use only calorimeter and muon data

Track reconstruction for trigger would have been too complex with available technology.

But there are upgrade plans…

First Level Trigger of ATLAS and CMS

Triggering at LHC

- The trigger dilemma:
  - Achieve **highest efficiency for interesting events**
  - Keep **trigger rate as low as possible (high purity)**
    - 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 1st level 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

  – Transverse Momentum of muons
    - 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)

Boundary conditions for level 1

- Max trigger rate
  - DAQ systems of CMS/ATLAS designed for approx. 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 was designed to fire with ≈ 35 kHz
  - Security margin 3 for unforeseen situations like noise, dirty beam conditions, unexpected detector behaviour
- Trigger design needs to be flexible
  - need many handles to adjust the rates.

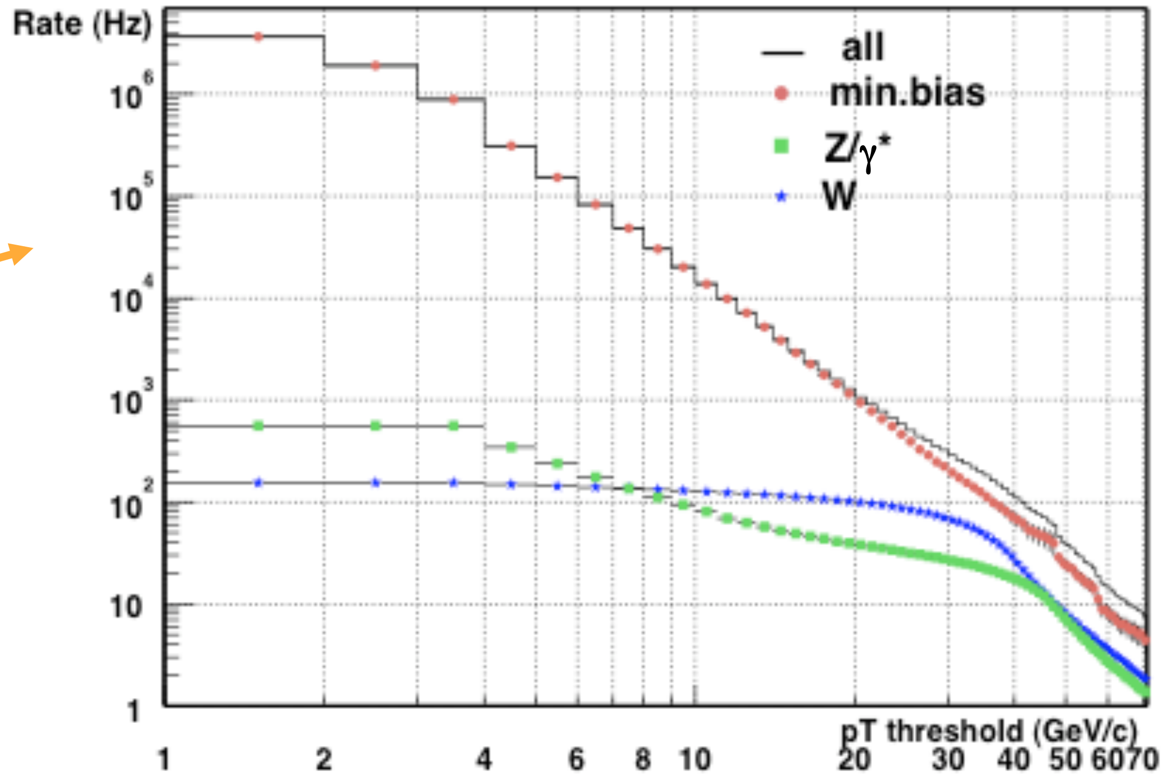
Triggering at LHC : example Muons

- Minimum bias events in pp:
  - Minimum bias: decays of quarks e.g. pions (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

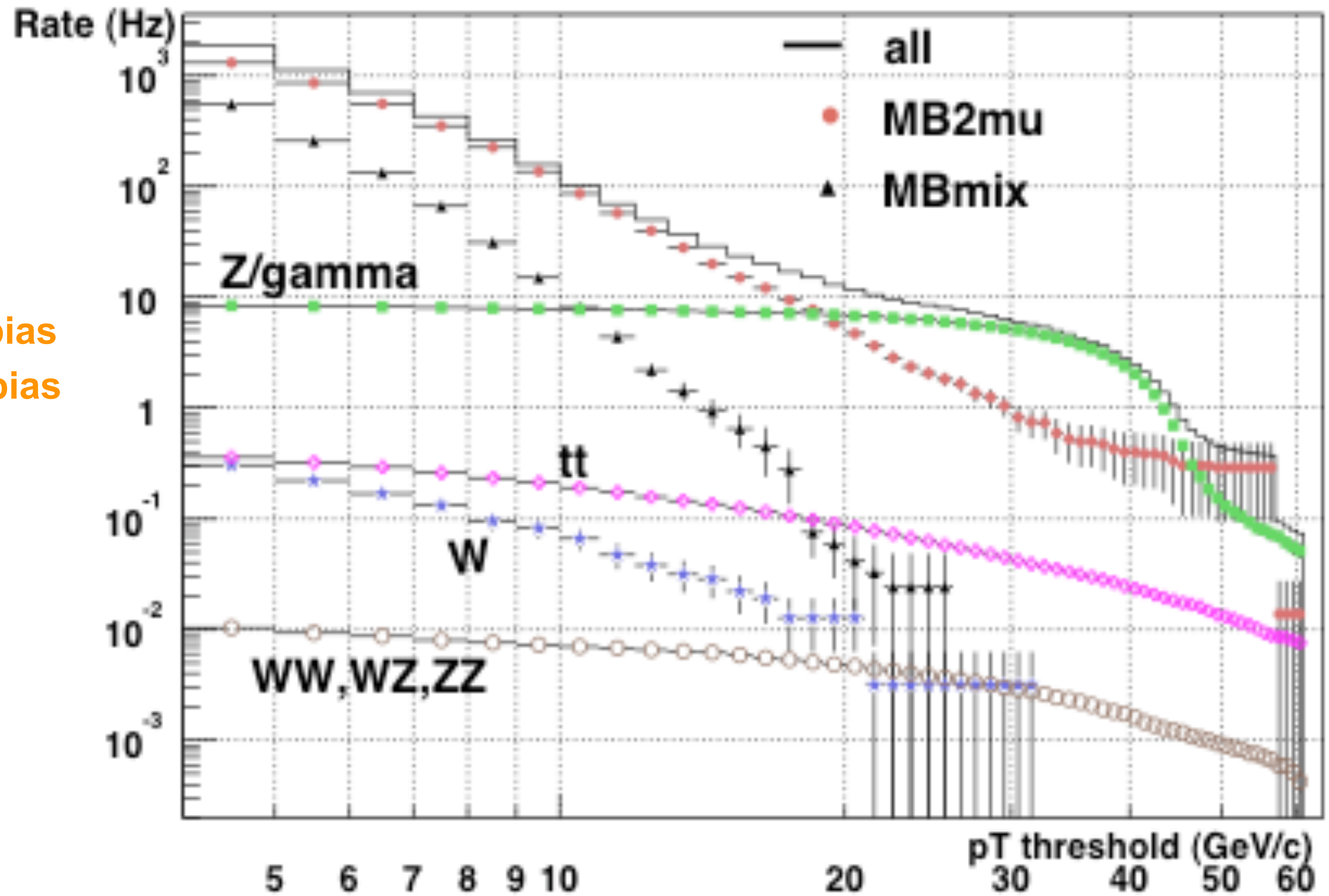
- Interesting events: contains (almost) always 2 objects to trigger on

Example muon pairs :

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

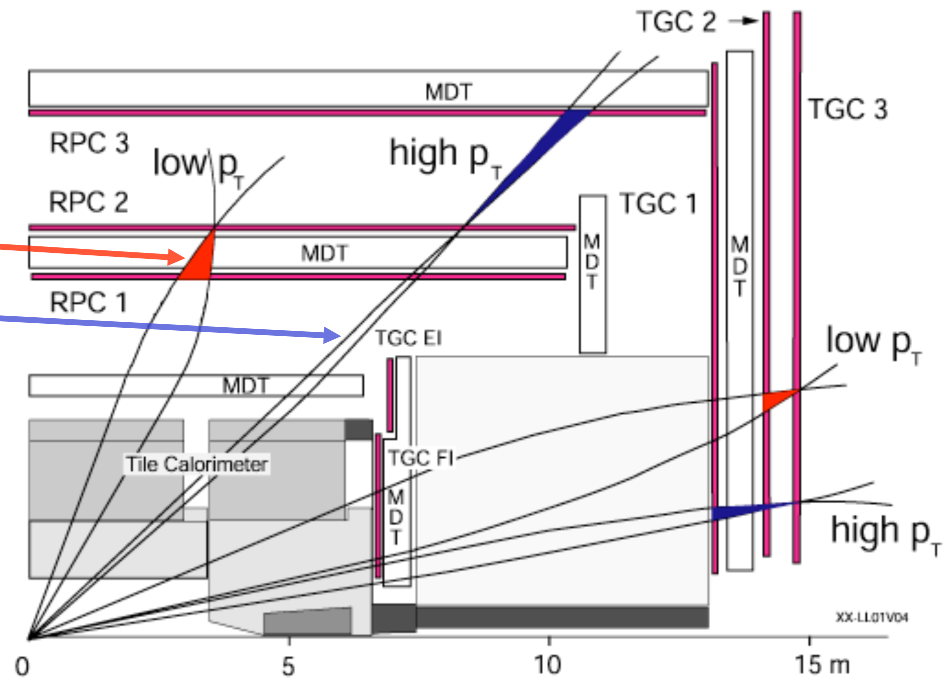
Threshold ≈ 10 GeV
Rate ≈ 100Hz

L = 10^{34}



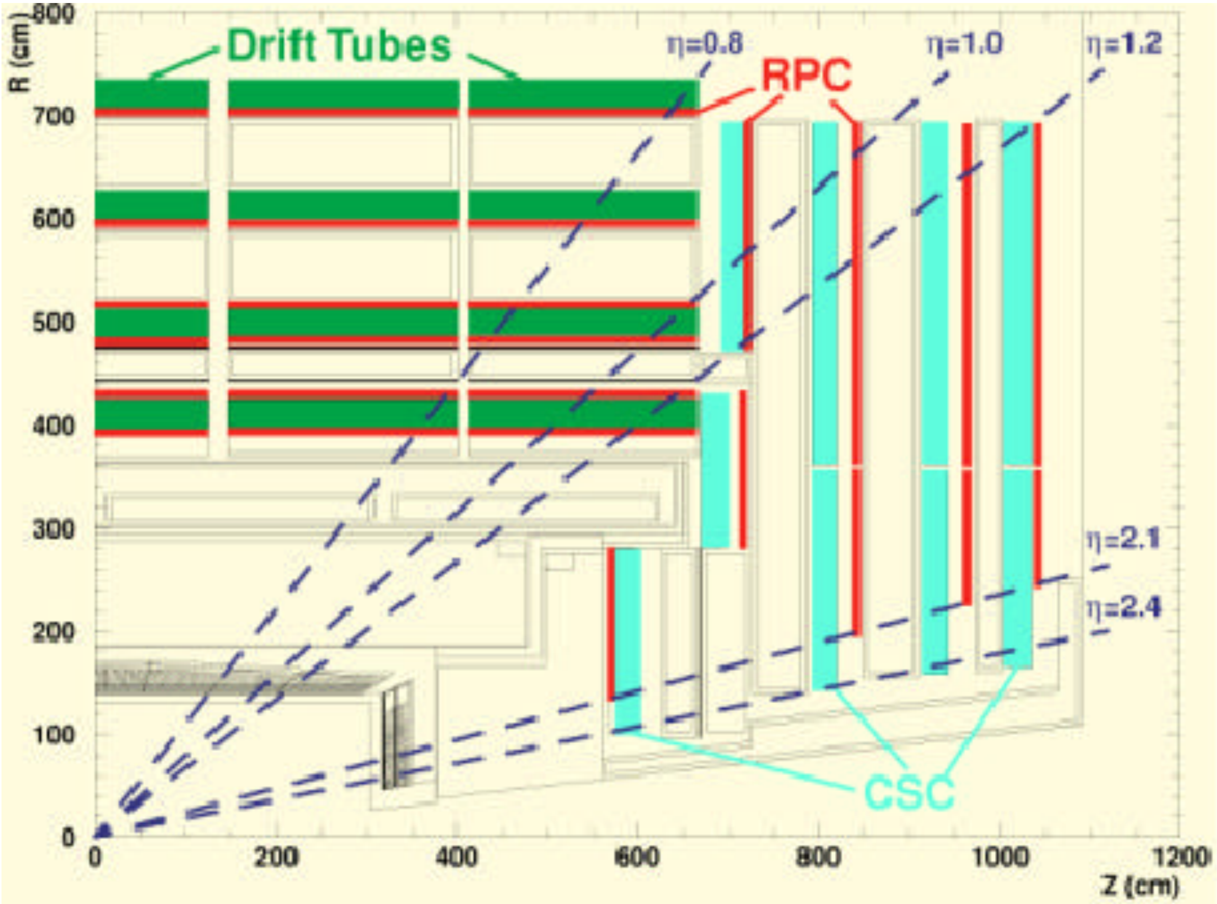
How to trigger on Muons

- 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)

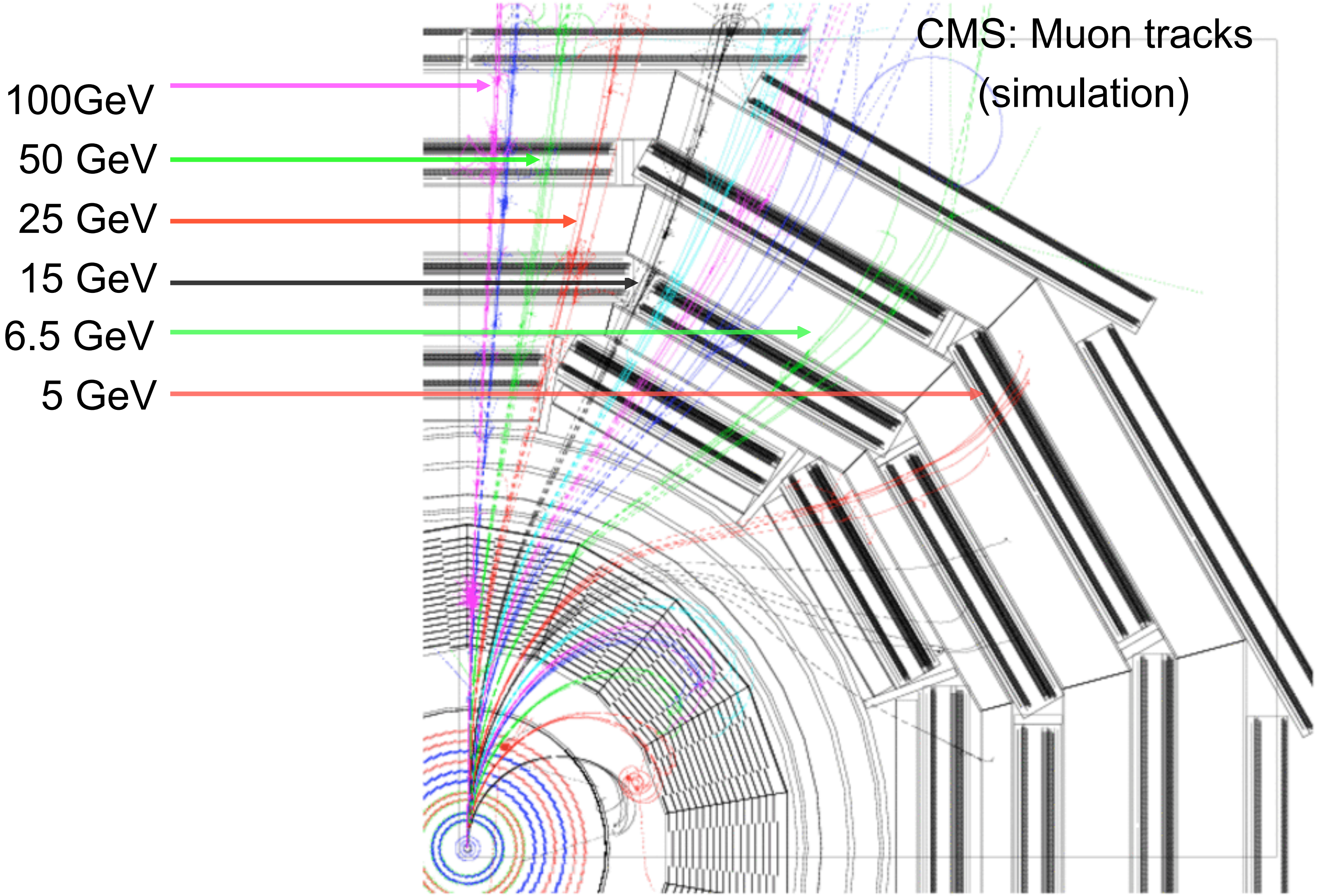


How to trigger on Muons

- The CMS muon system



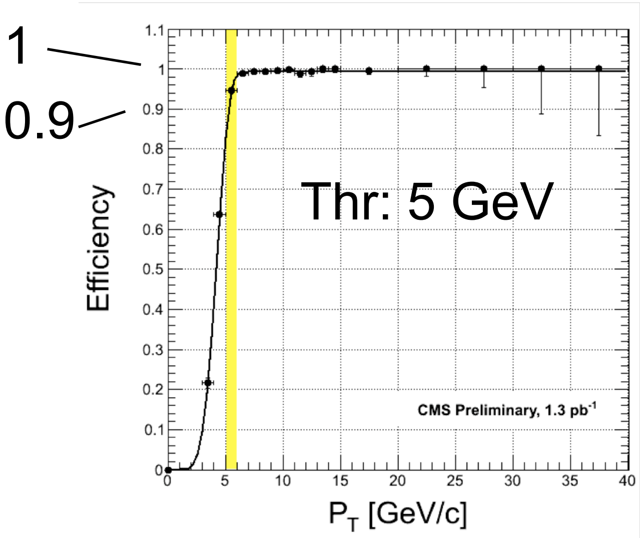
How good does it work?

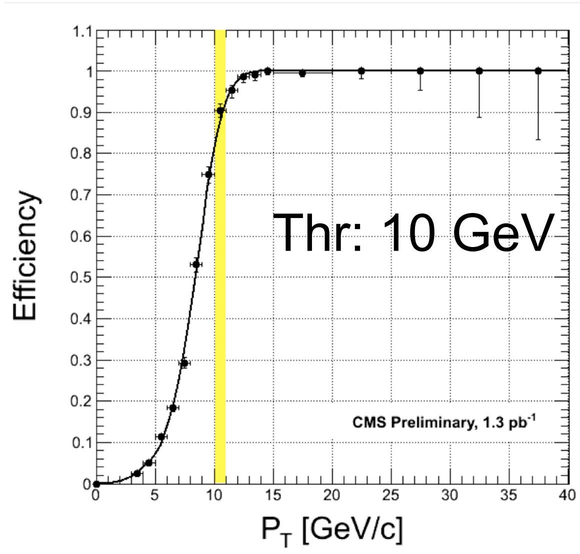


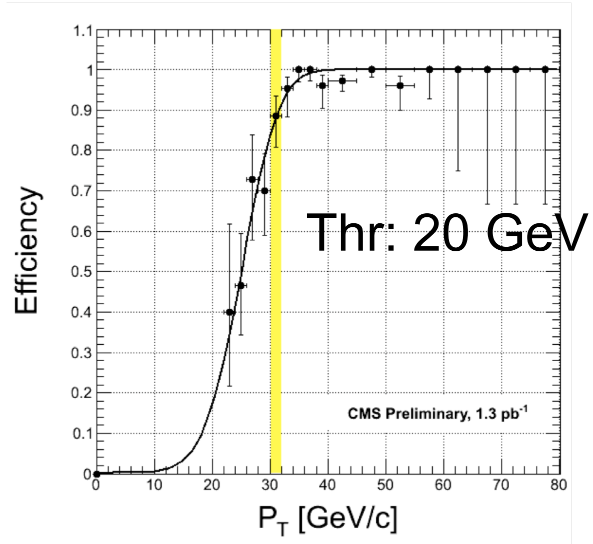
CMS: Muon tracks
(simulation)

Performance of CMS muon trigger

- Efficiency turn-on curves



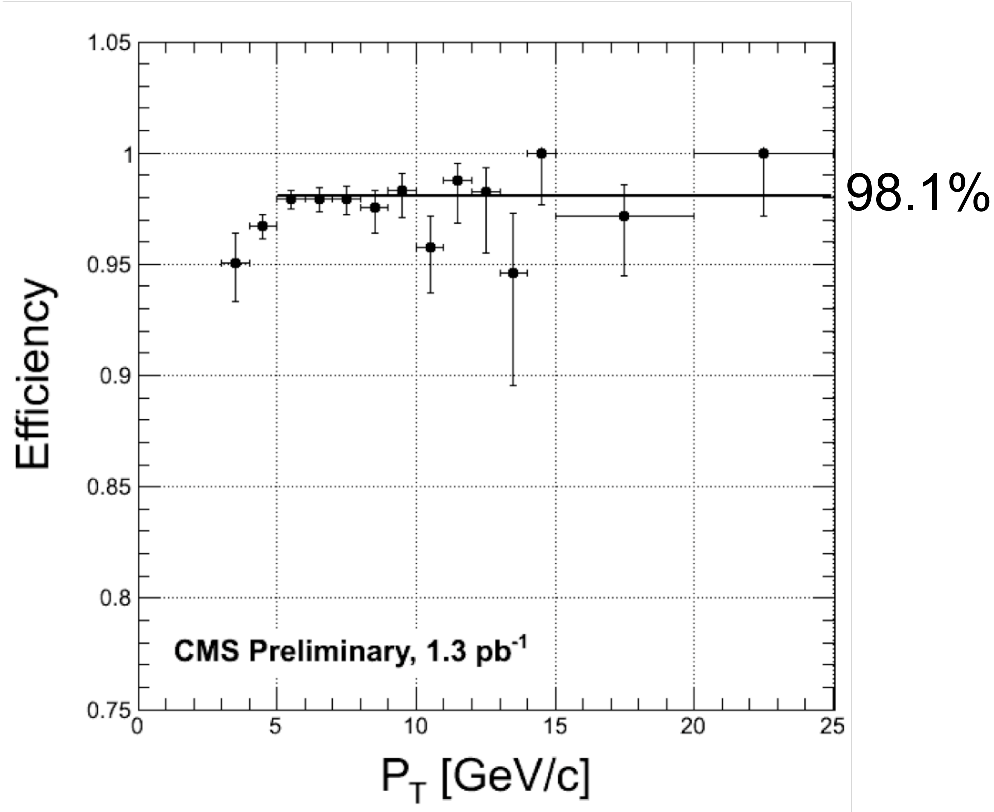




  - From Data with events: J/ψ -> μμ and Z -> μμ
  - "Real" p_t vs. efficiency for imposed trigger threshold
  - For an imposed threshold x the efficiency for muons with p_t = x GeV is larger 90% (…as foreseen).

Muon Track Finding Efficiency (CMS DT)

- Technique tag & probe
  - J/Ψ -> μμ,
  - one μ satisfied trigger, the other used to measure efficiency
  - Inefficiency understood hardware problem



Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)

L = 10^{34}

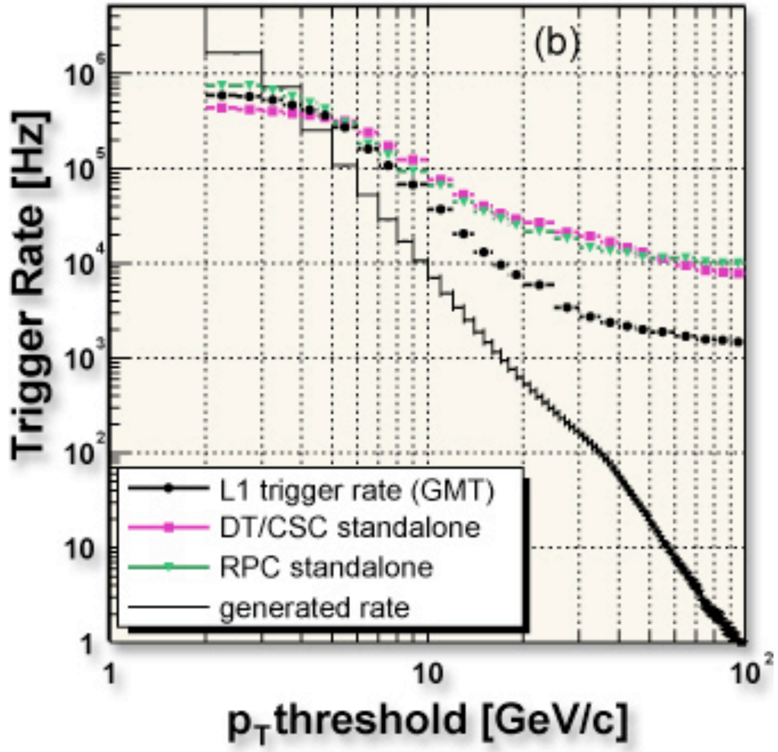
Redundancy allows to impose tight quality cuts (i.e. number of hits required for each muon, …)

this improves purity

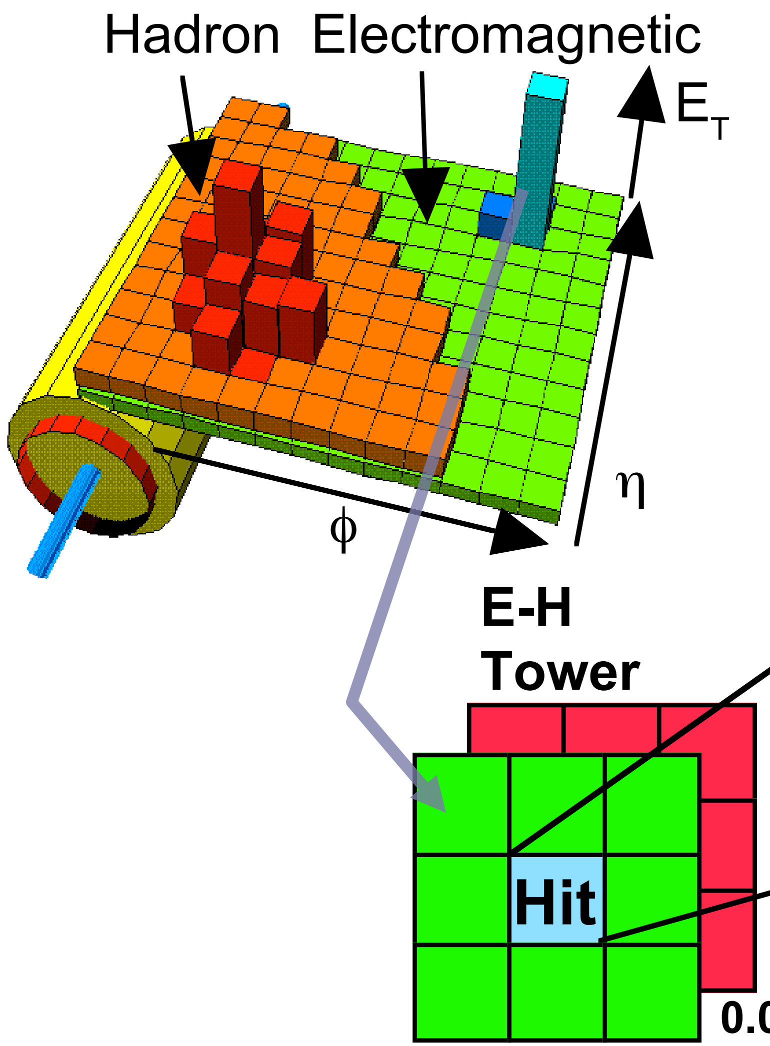
p_t > 20GeV:

≈ 600 Hz generated,

≈ 8 kHz trigger rate



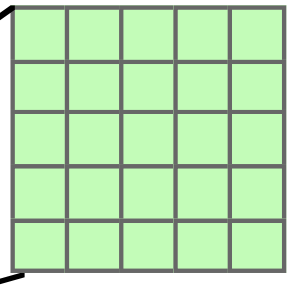
Calorimeter Trigger: example CMS



Divide Calorimeter into towers

Match towers between ECAL and HCAL

Trigger Tower = 5x5 EM towers



0.087 φ

0.0145 η

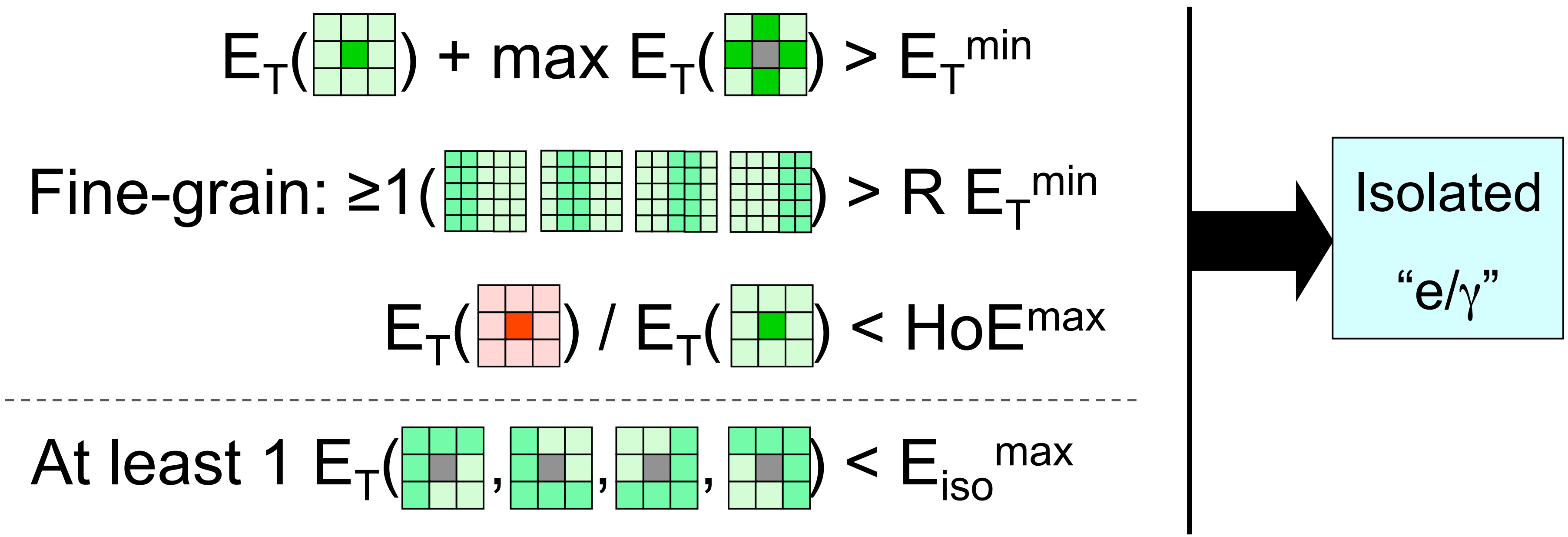
0.0145 η

72 φ x 54 η x 2 = 7776 towers

Algorithm to identify e/γ

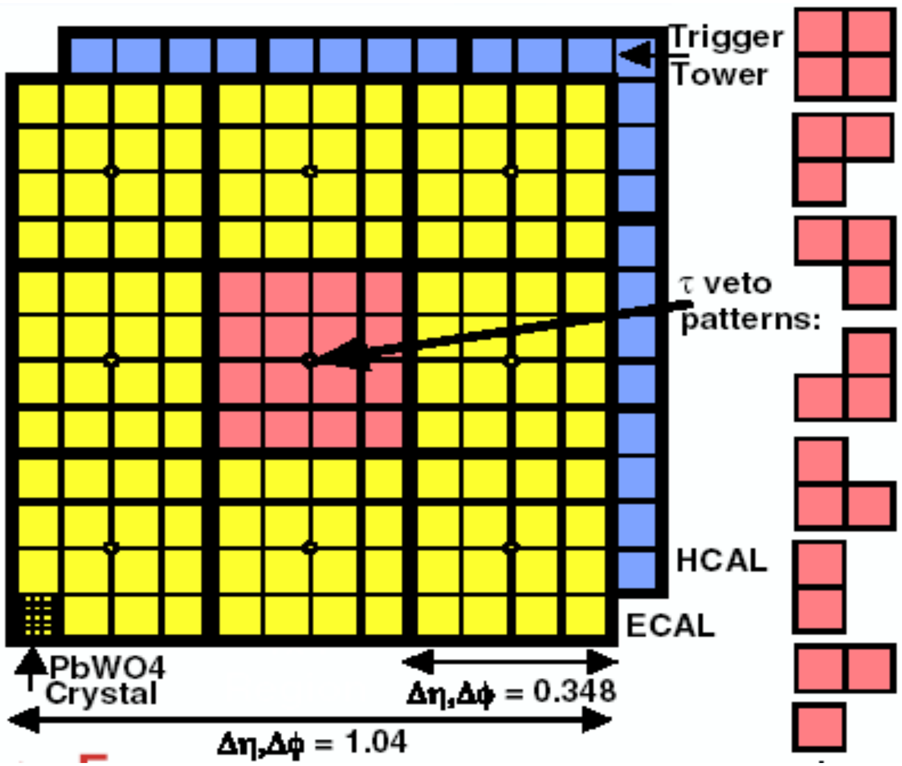
Characteristics of isolated e/γ:

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



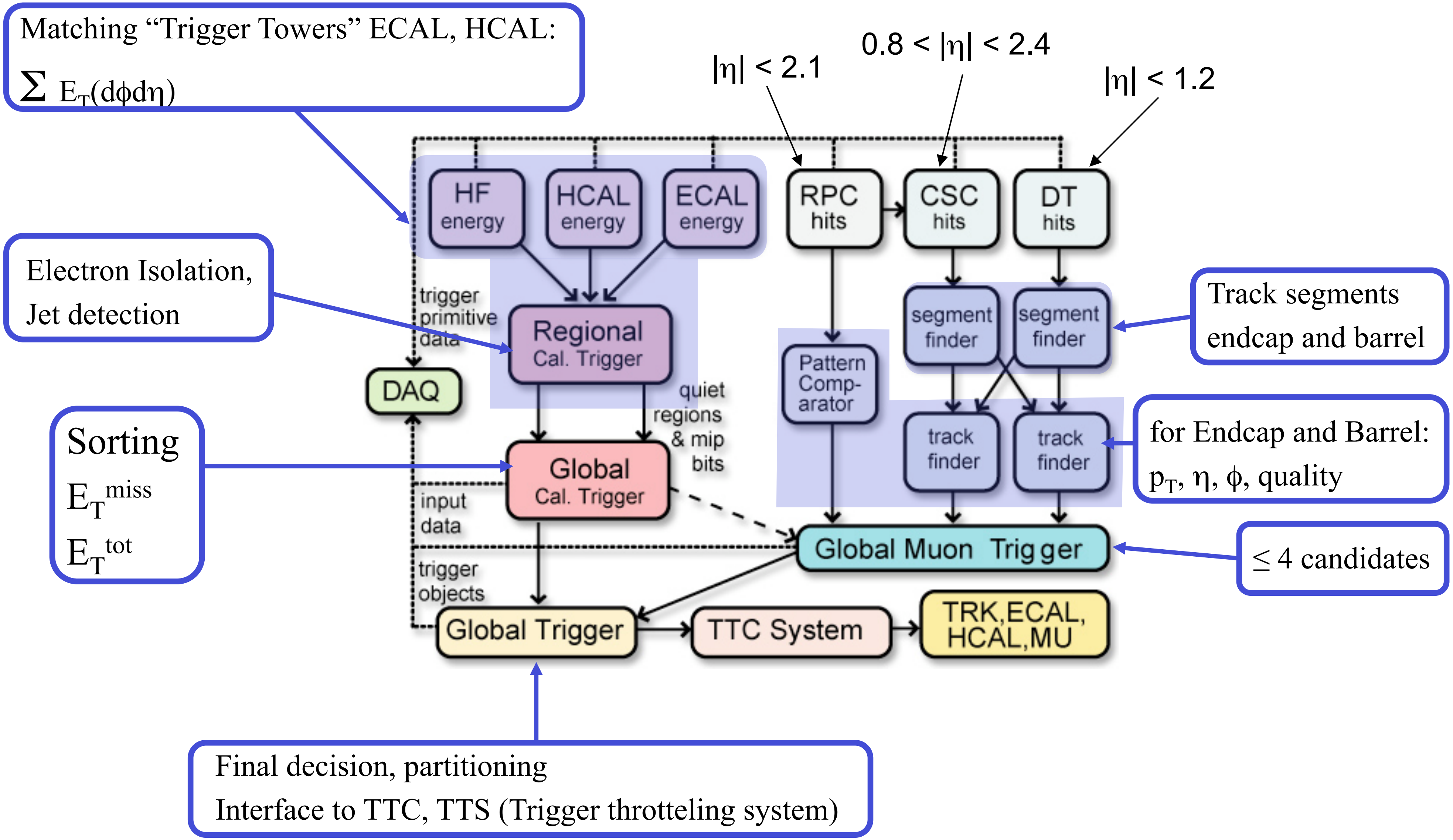
Calorimeter Trigger: jets and Taus

- 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

Trigger Architecture: CMS



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)

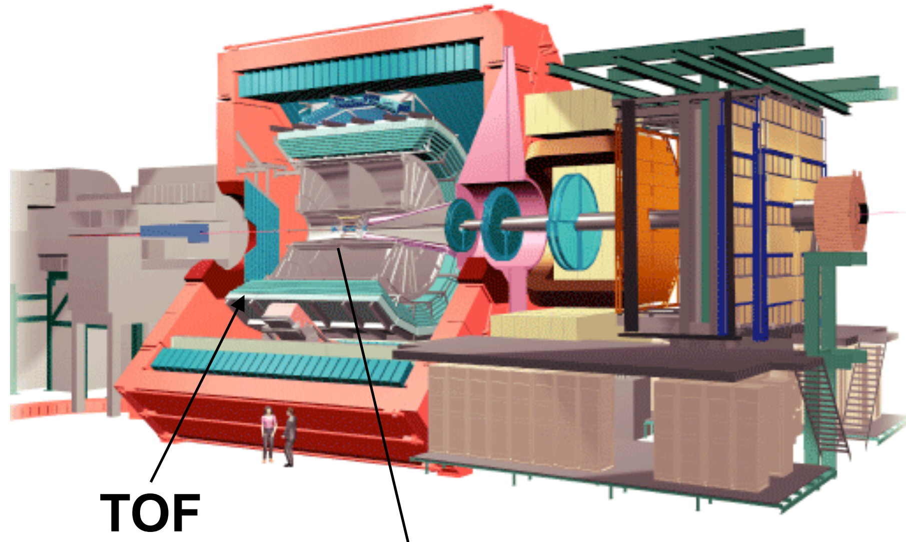
    Example:

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”**
	⋮		

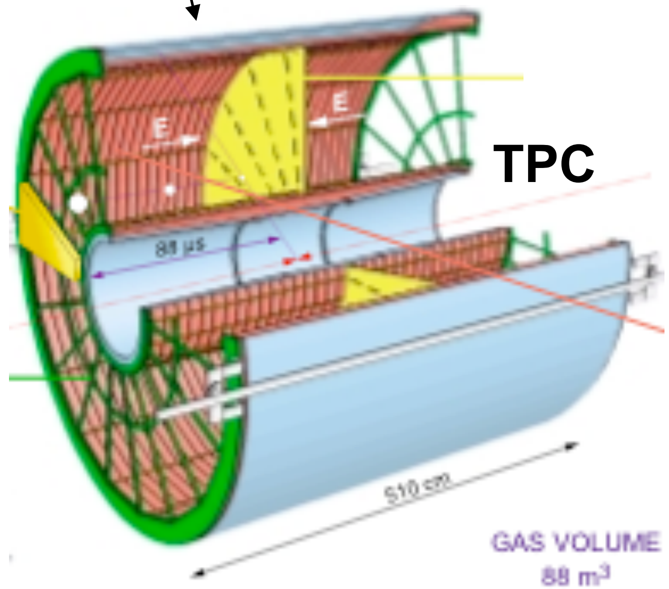
Specific solutions for specific needs: ALICE and LHCb

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**



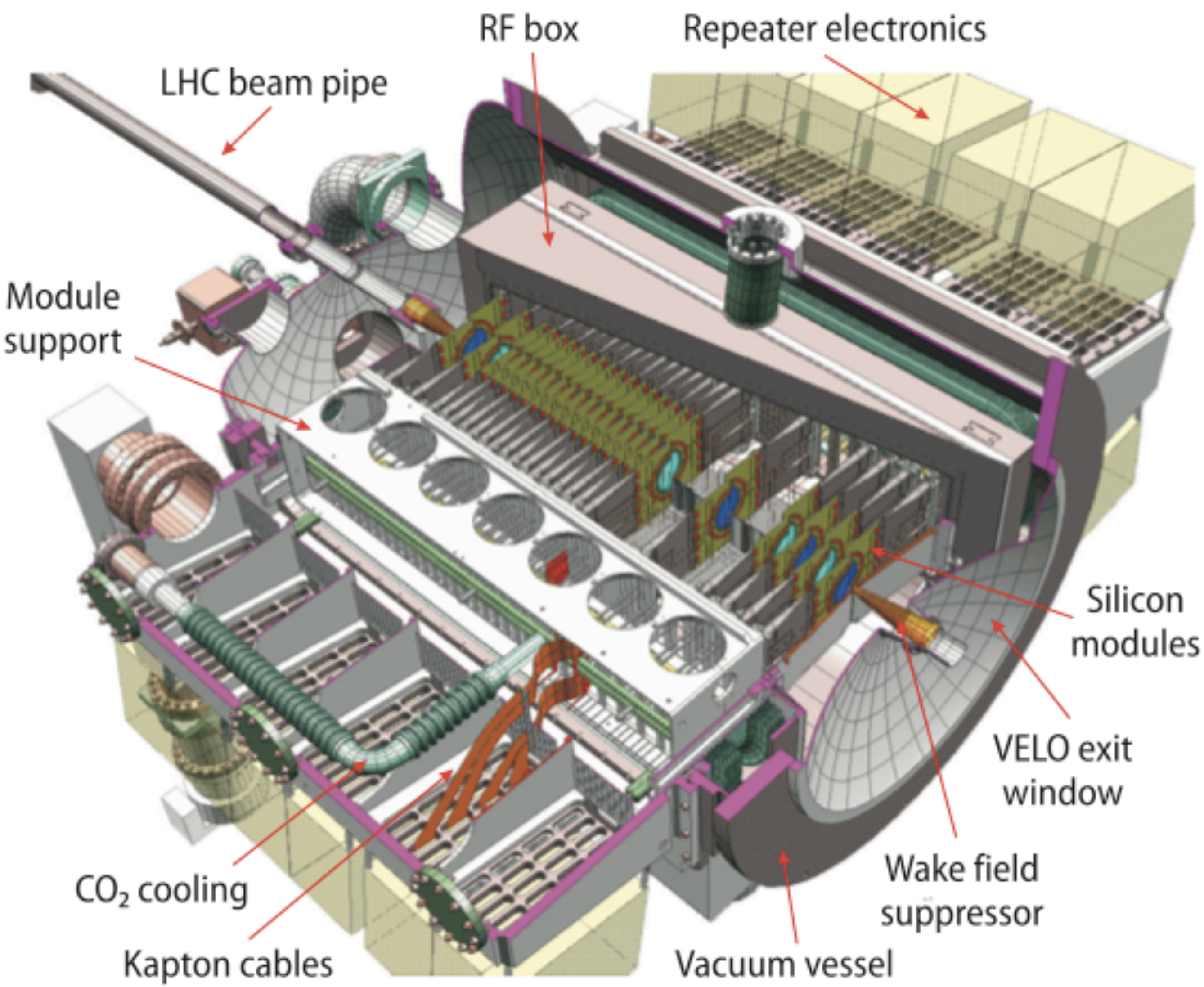
- ALICE uses a TPC for tracking
  - TPC drift time: 88μs
  - In Pb-Pb collisions only one interaction at a time can be tolerated (otherwise: too many tracks in TPC)
  - Need pile-up protection:
    - Makes sure there is only one event at a time in TPC (need to wait for TPC drift time)
  - **L2 : latency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



ALICE: optimizing efficiency

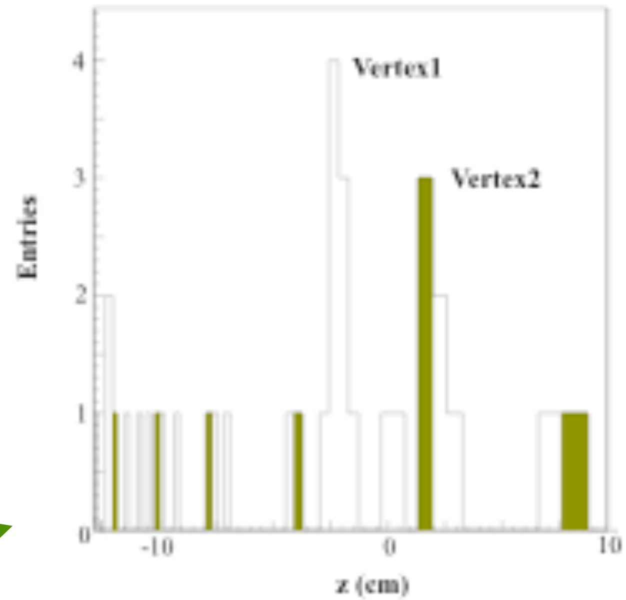
- Specific property of ALICE:
  - Some sub-detectors need a long time to be read out after LVL2 trigger (e.g. Si drift detector: 260μs)
  - But: Some interesting physics events need only a subset of detectors to be read out.
- Concept of **Trigger clusters**:
  - Trigger cluster: group of sub-detectors
    - 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

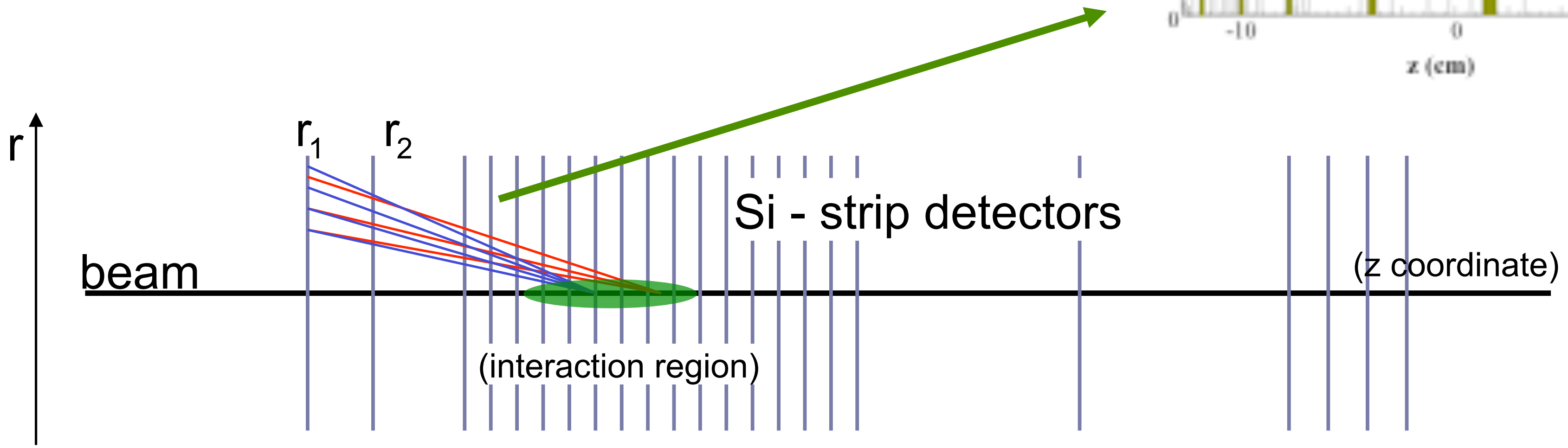
LHCb: VELO (Vertex Locator)



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



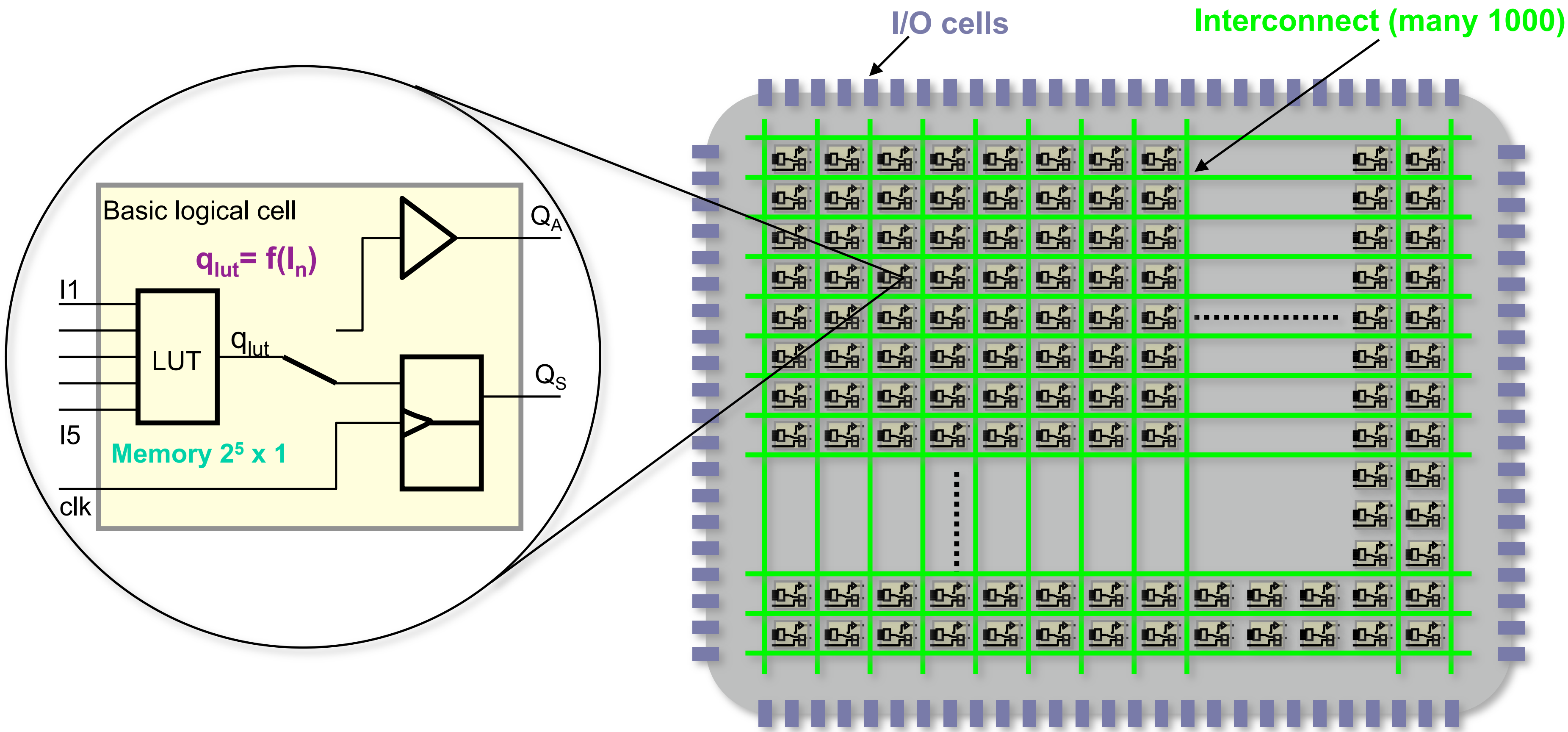


Trigger implementation

First level trigger: Implementation

- Custom Electronics design based on **FPGAs and ASICs**
- **FPGA** : Field Programmable Gate Array

- Concept: Put together a lot of pretty stupid units to end up with a very intelligent device
  (This concept is not universally valid: c.f. political parlaments, …)



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
  - Coincidence matrix in Muon Trigger of ATLAS

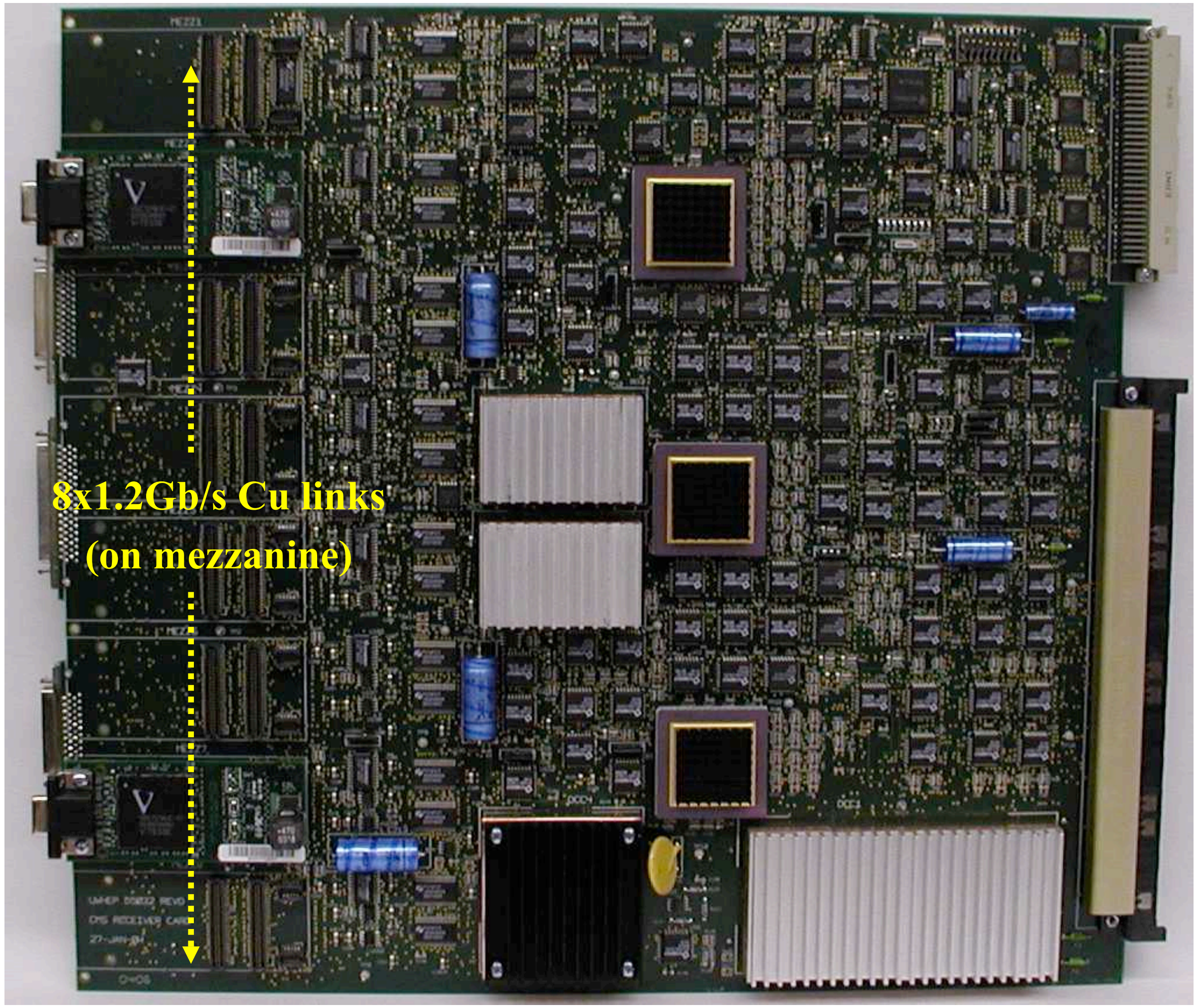
Trigger implementation (III)

- Key characteristics of Trigger Electronic boards
  - 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 high speed links
    - Backplane parallel busses for in-crate connections
    - LVDS links for short (O(10m)) inter-crate connections (LVDS: Low Voltage Differential Signaling)

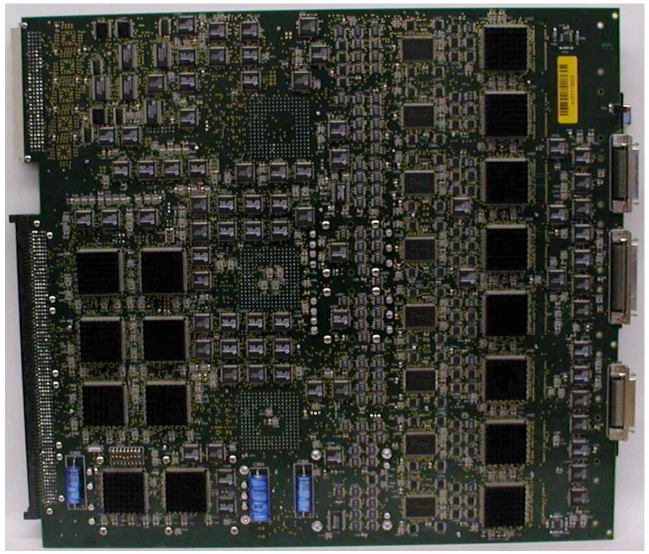
CMS: Regional Calorimeter Trigger

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:

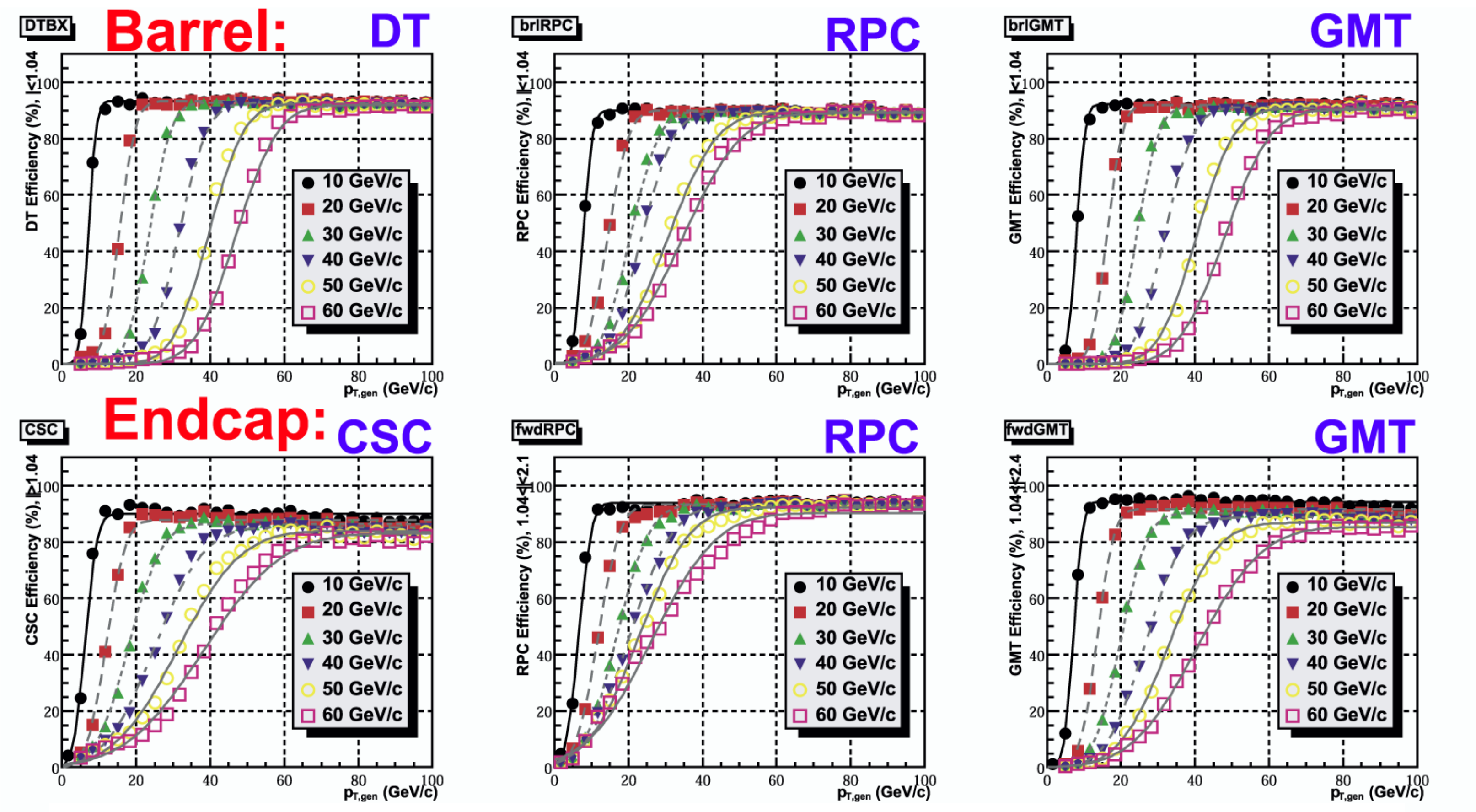


Trg. Implementation: Interconnectivity

You might guess that todays modern technology (serial links, uTCA,…) offers some room for improvement in a future upgrade project…

Extra slides: Lvl1 trigger

CMS Muon Trigger: Efficiency



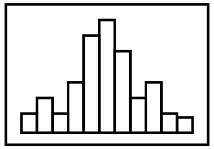
Challenges in the start up year of LHC

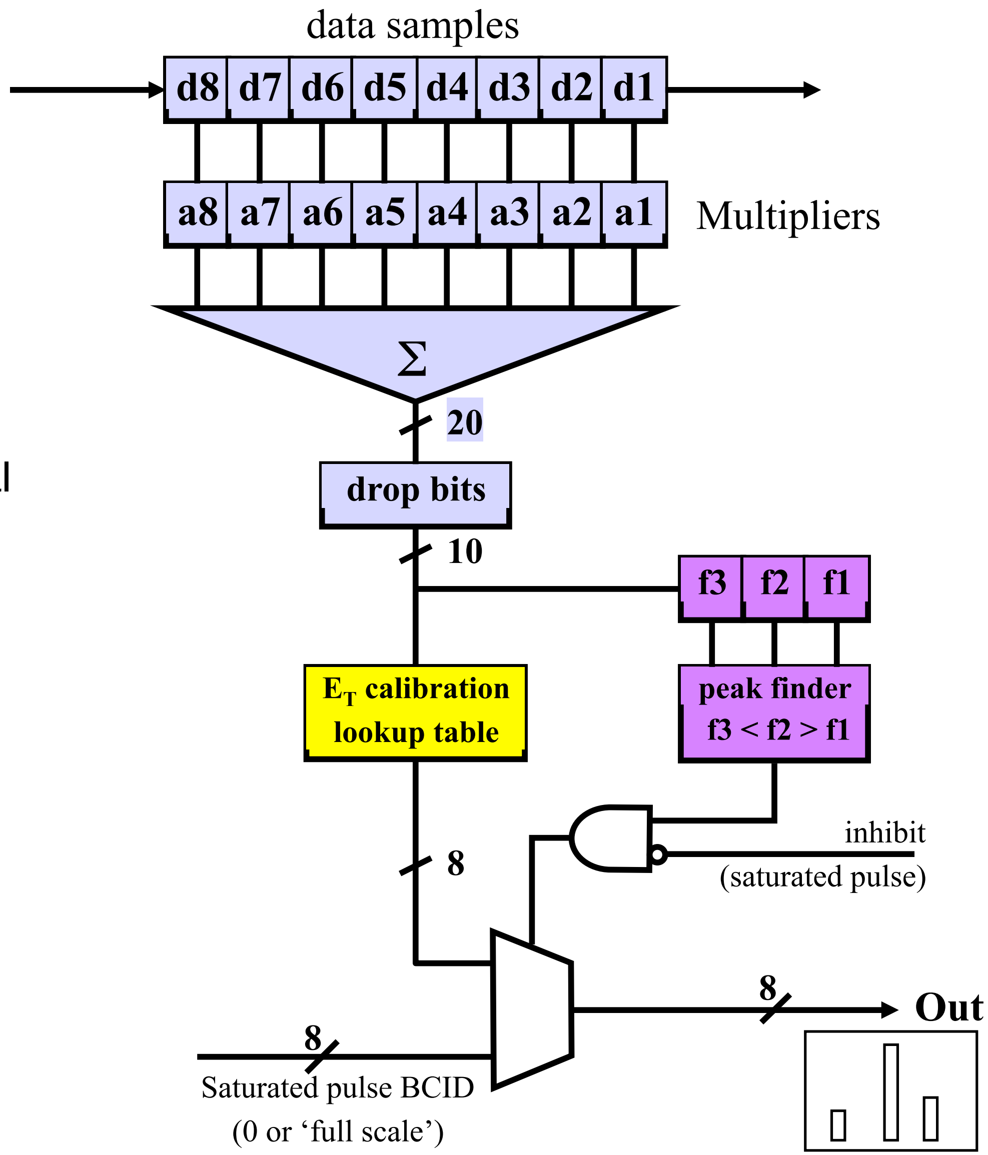
- Peak luminosity changed by more then 5 orders of magnitude!
  - From : **10^{27} → 2 x 10^{32}**
  - In every Luminosity step experiments wanted to take "as much data as possible"
    - NOT to discover new physics… but
    - Understand the detector with known physics
      - See example above tag & probe with J/ψ
      - Learn step by step coping with pile-up
  - Trigger menu design was a challenge
    - L1 menus had to be synchronized with higher level triggers
    - CPU power in HLT farms limited
    - Processing power in the Tier0 center became a limiting factor

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

ATLAS Calorimeter: BX & E_T

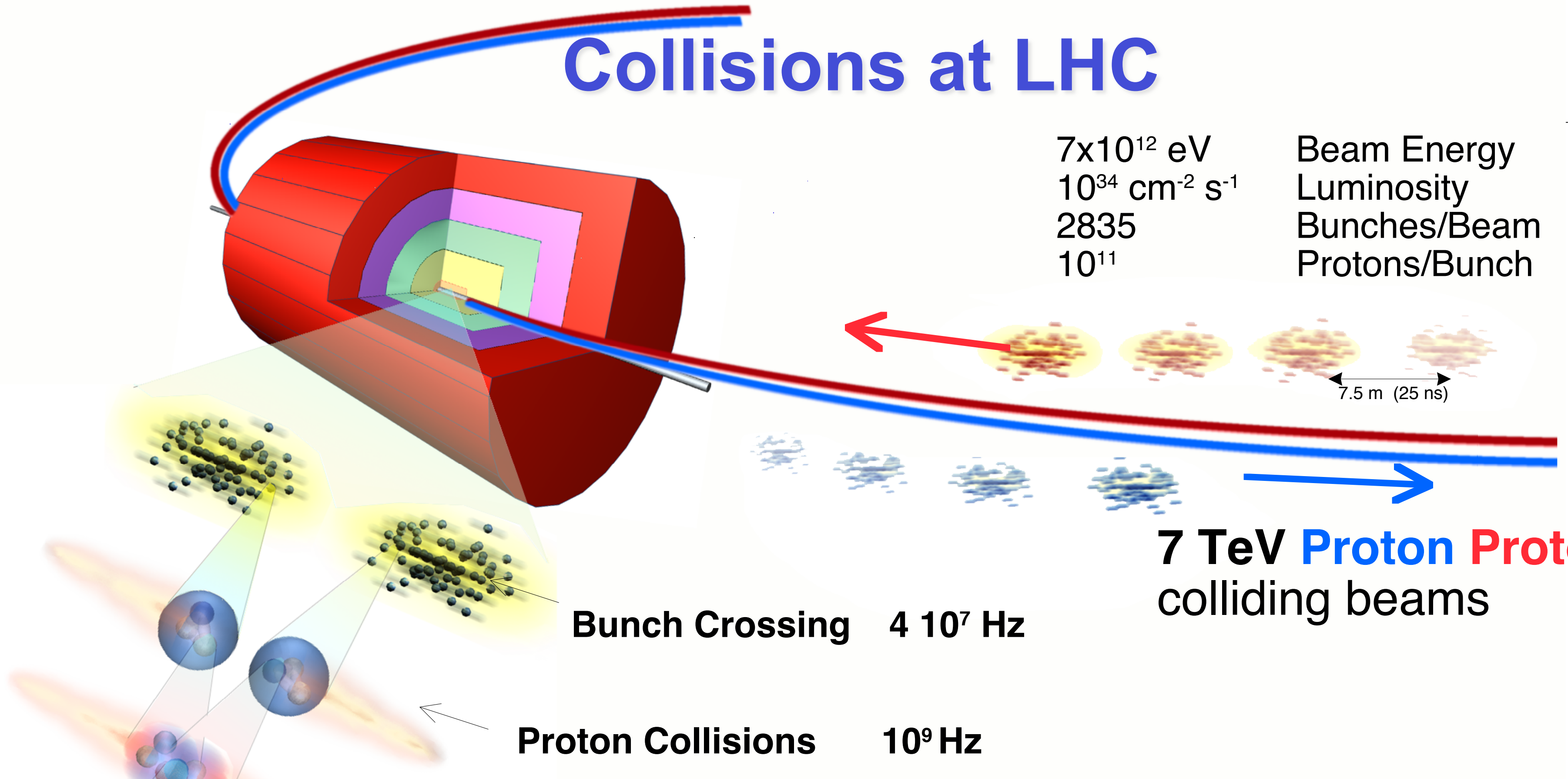




- Signals length >> 25ns
  - Need to "integrate" over several BXs
  - Signals of subsequent BXs might overlap
- FIR filter
  (digital filter: Finite Impulse Response)
  - Multipliers optimized for particular signal shape
- LUT to get calibrated E_T
  - Lookup Table is a memory:
    - Input: Address of 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

Collisions at LHC

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



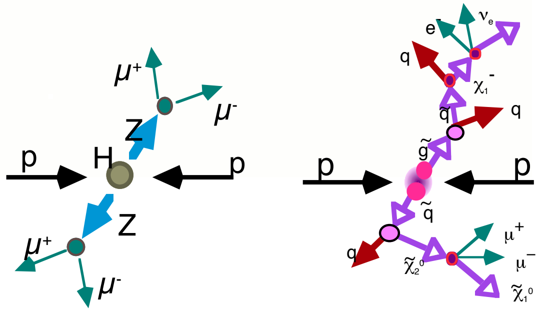
7 TeV Proton Proton
colliding beams

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

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

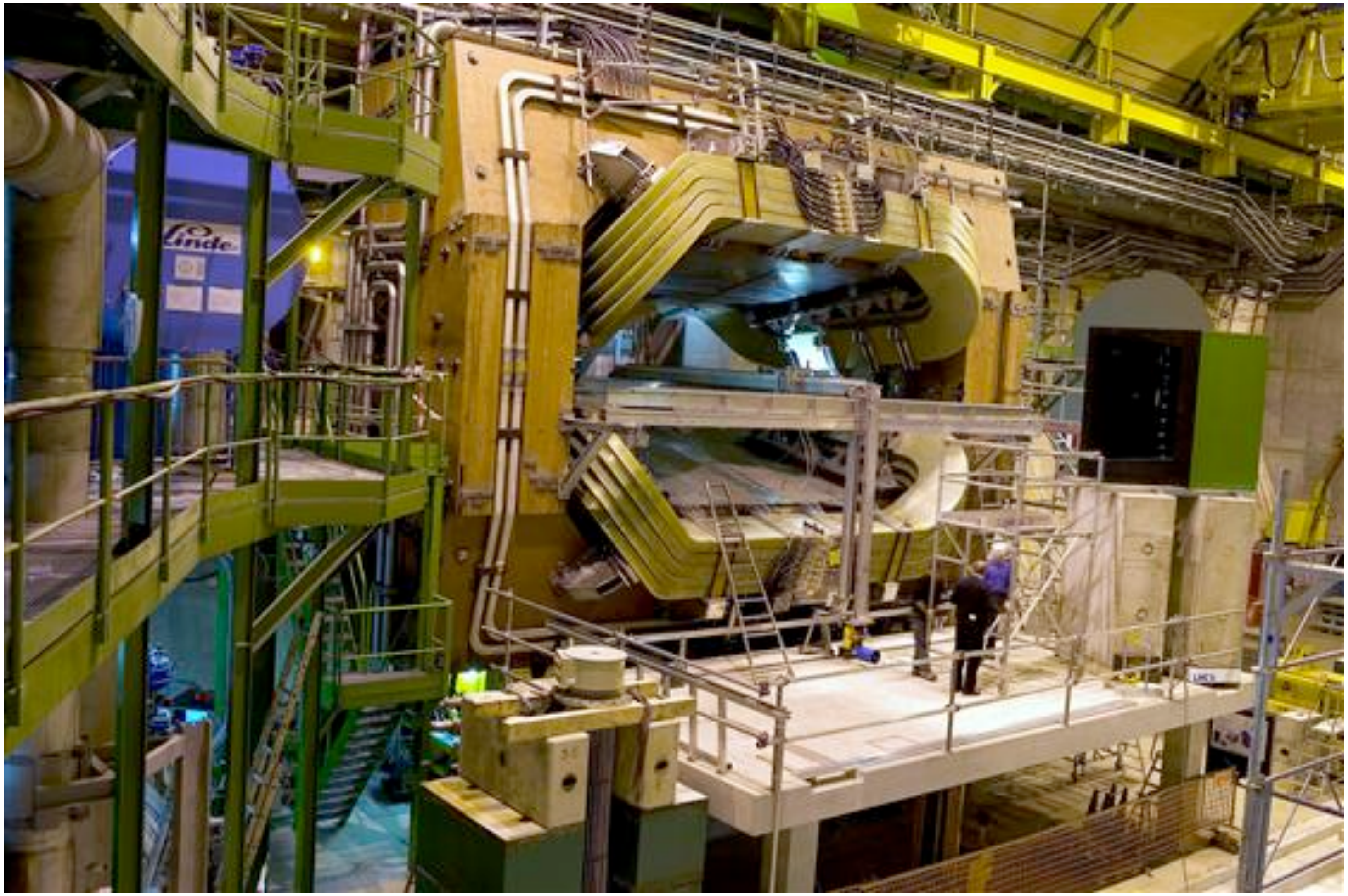
Parton Collisions

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

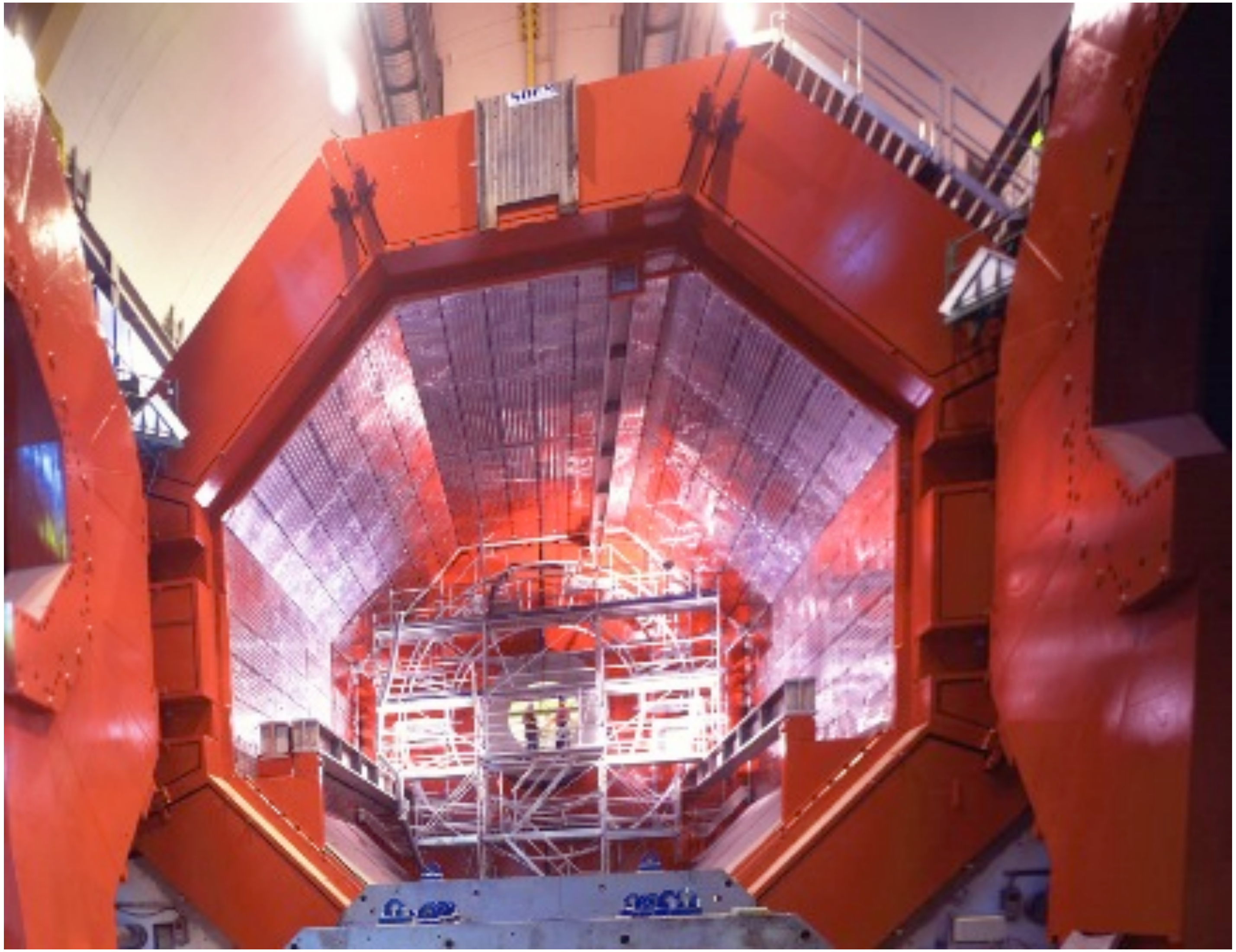


Selection of 1 event in 10,000,000,000,000

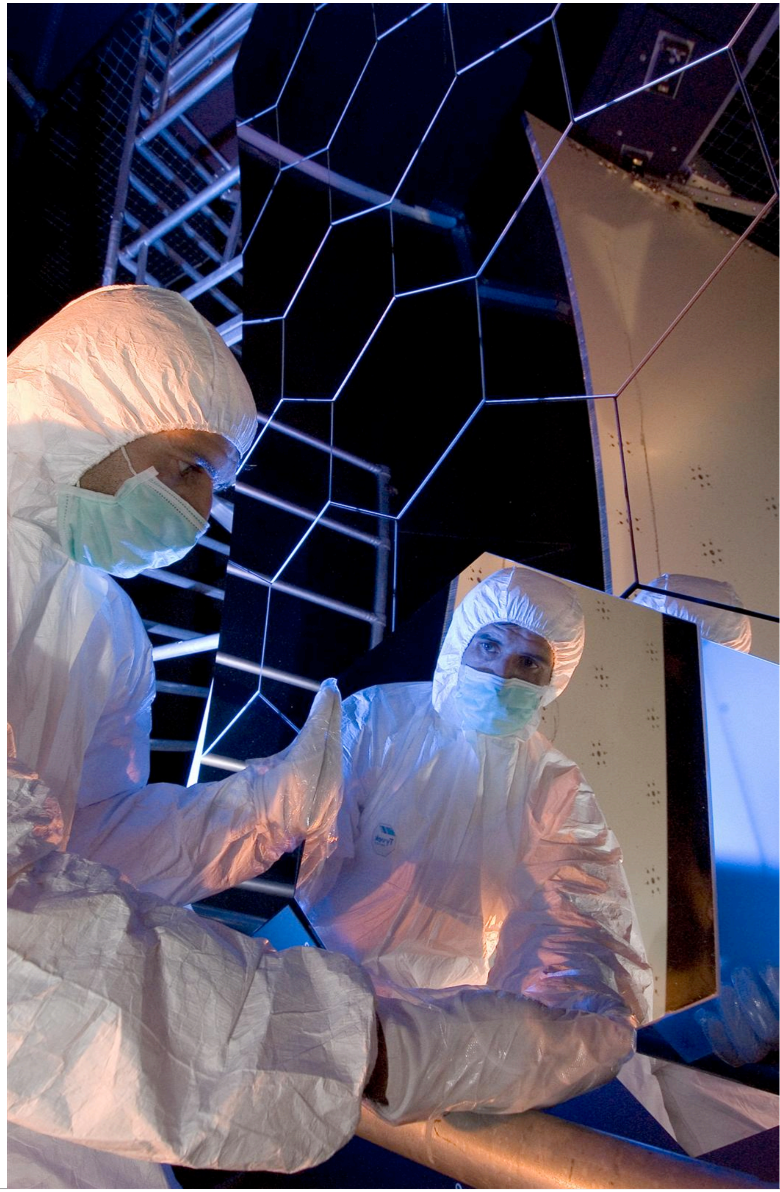
LHCb: Dipole put in place



ALICE: Magnet



LHCb: Rhich Mirror



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

Low Luminosity

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

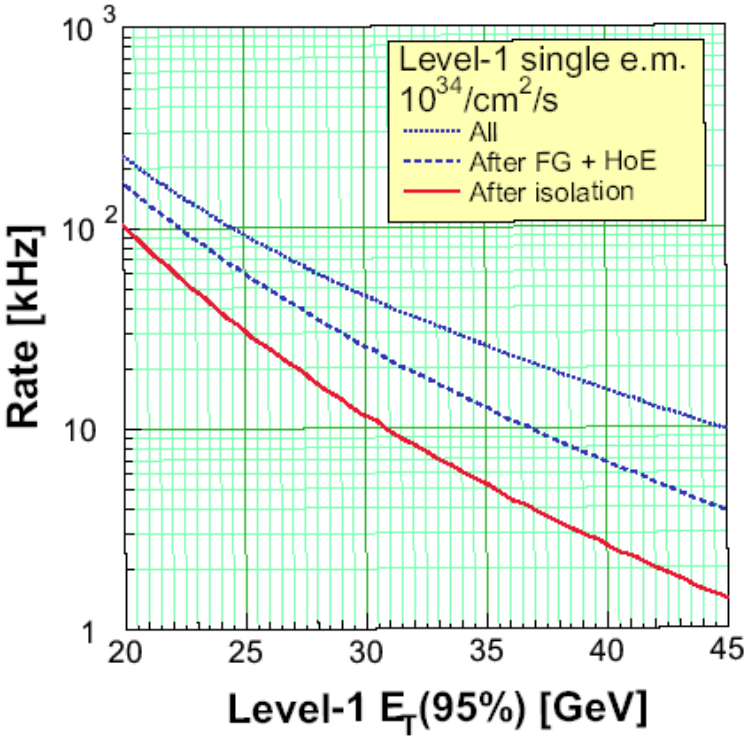
Trigger	Threshold (ε=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate(kHz)
1e/γ, 2e/γ	29, 17	4.3	4.3
1μ, 2μ	14, 3	3.6	7.9
1τ, 2τ	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet & Miss-E_T	88 & 46	2.3	14.3
e & jet	21 & 45	0.8	15.1
Min-bias		0.9	**16.0**

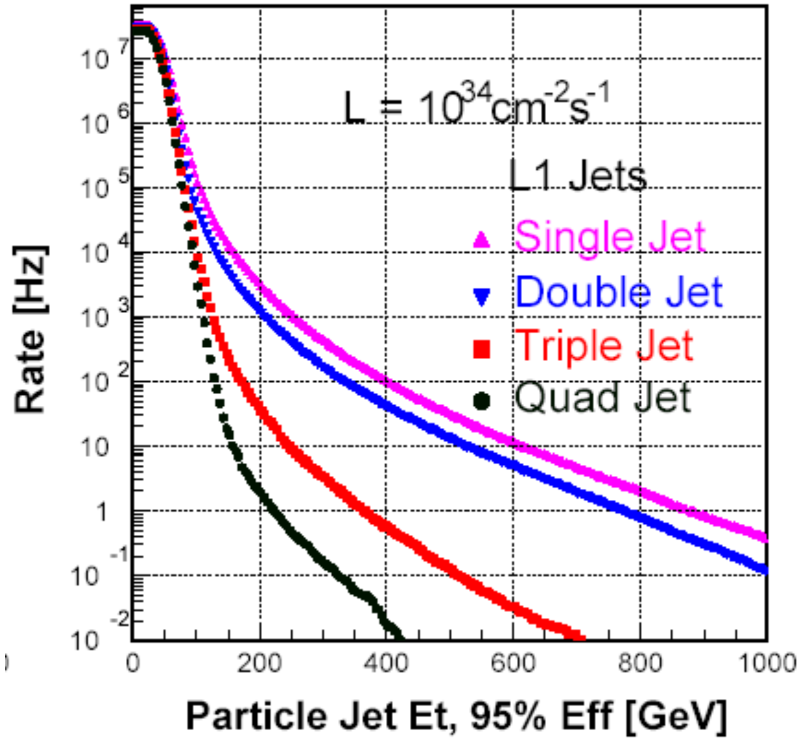
High Luminosity

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**

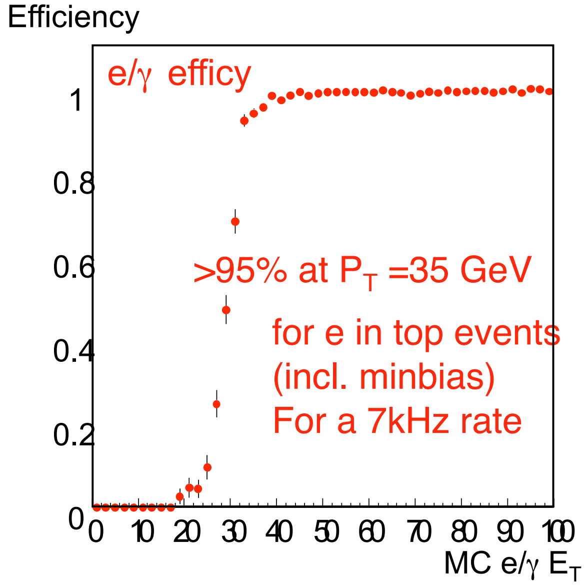
Calorimeter trigger: rates

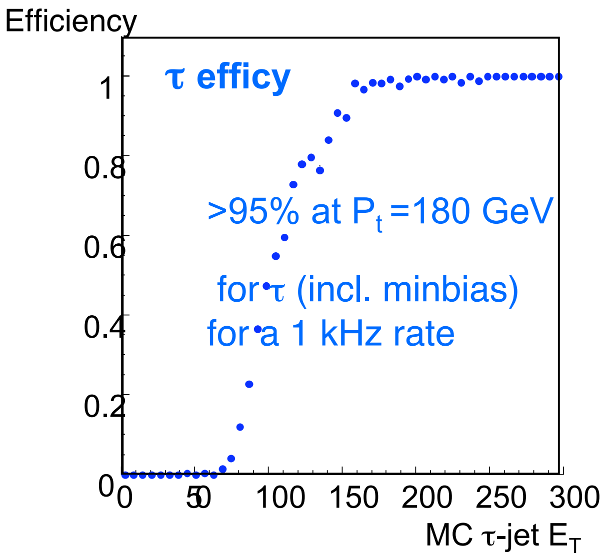


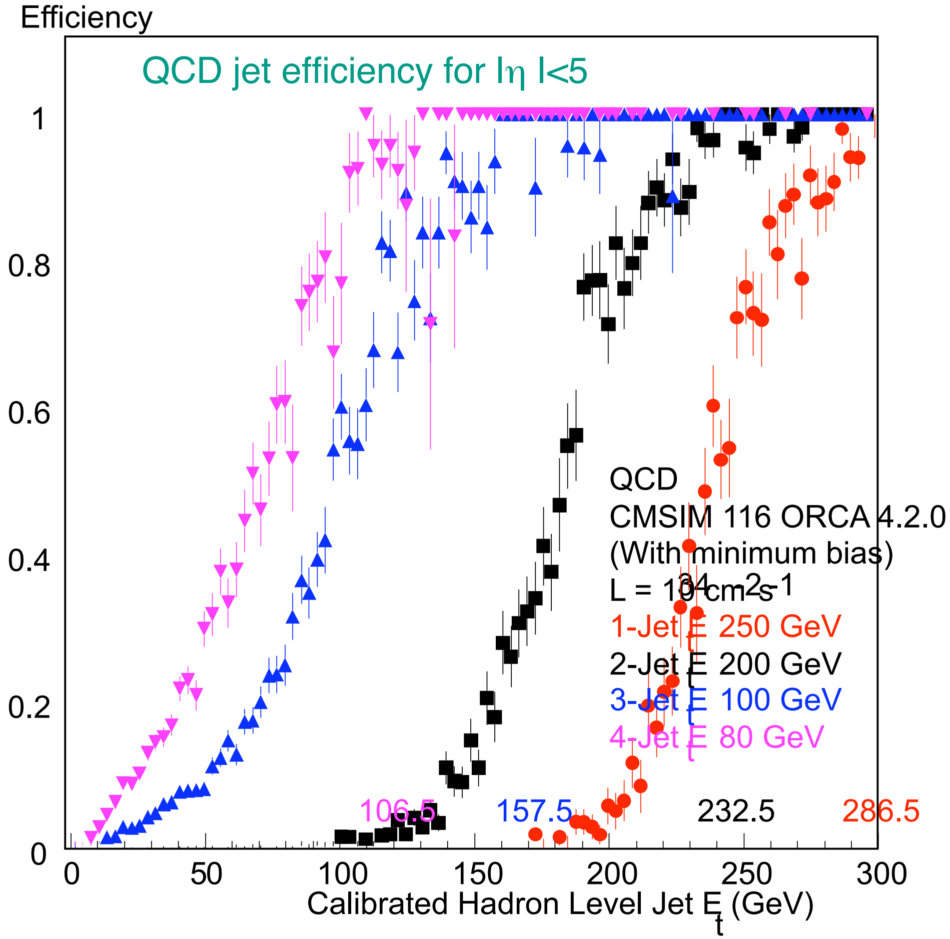


- Simulation

Calorimeter trigger: rates (Simulation)







>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)

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

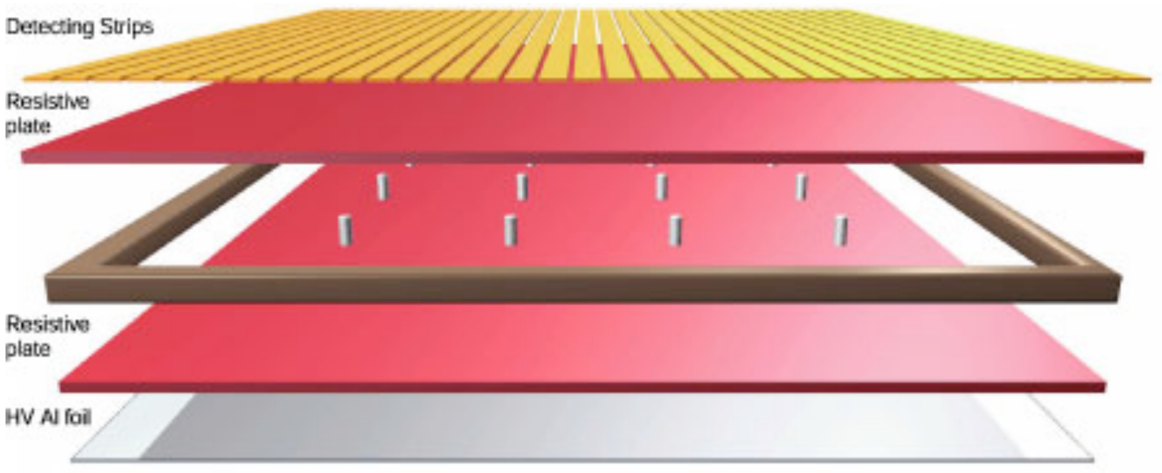
- B-physics
  - Trigger on leptons
  - In particular: muons (trigger thresholds can be lower than for electrons)

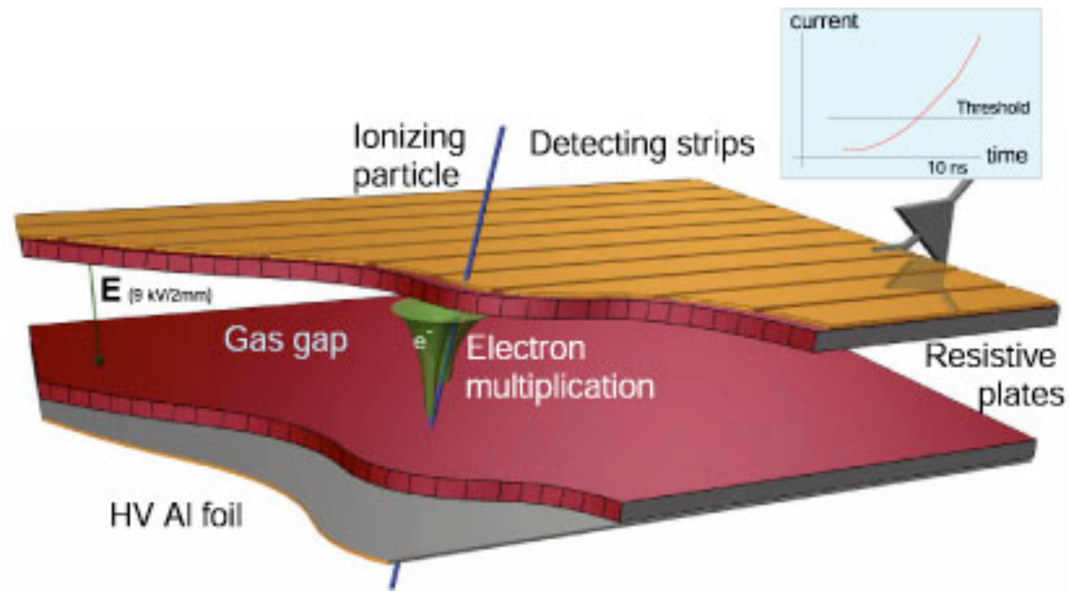
- t-quark physics
  - Trigger on pairs of leptons.

LHCb

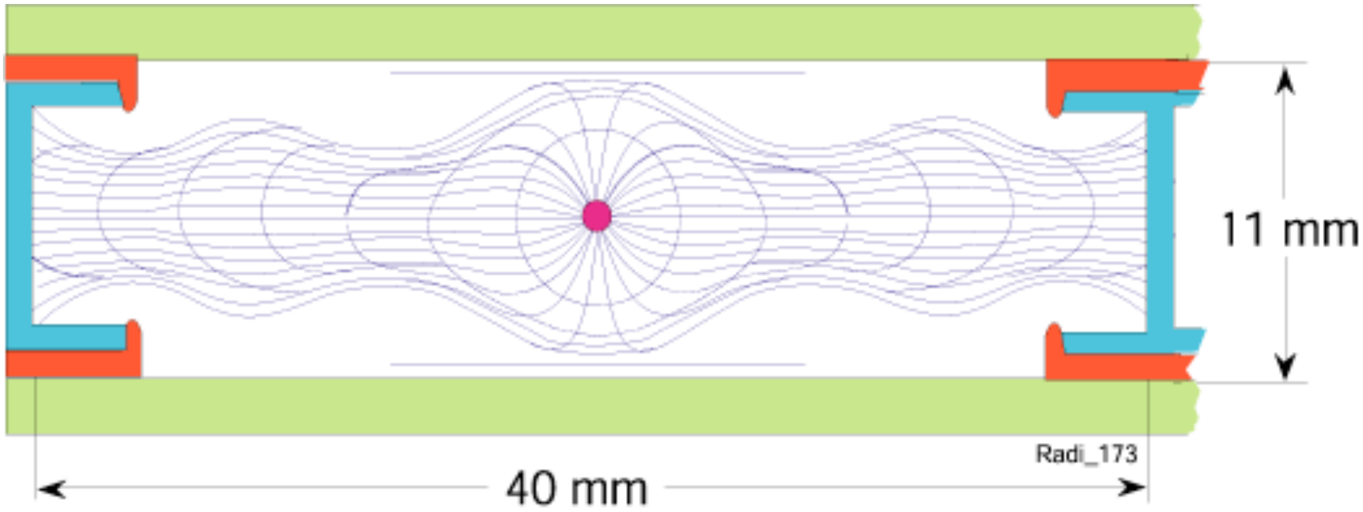
- Operate at L = 2 x 10^{32} $cm^{-2}s^{-1}$: 10 MHz event rate
- Lvl0: 2-4 us latency, 1MHz output
  - Pile-up veto, calorimeter, muon
- Pile up veto
  - Can only tolerate one interaction per bunch crossing since otherwise always a displaced vertex would be found by trigger

CMS RPCs

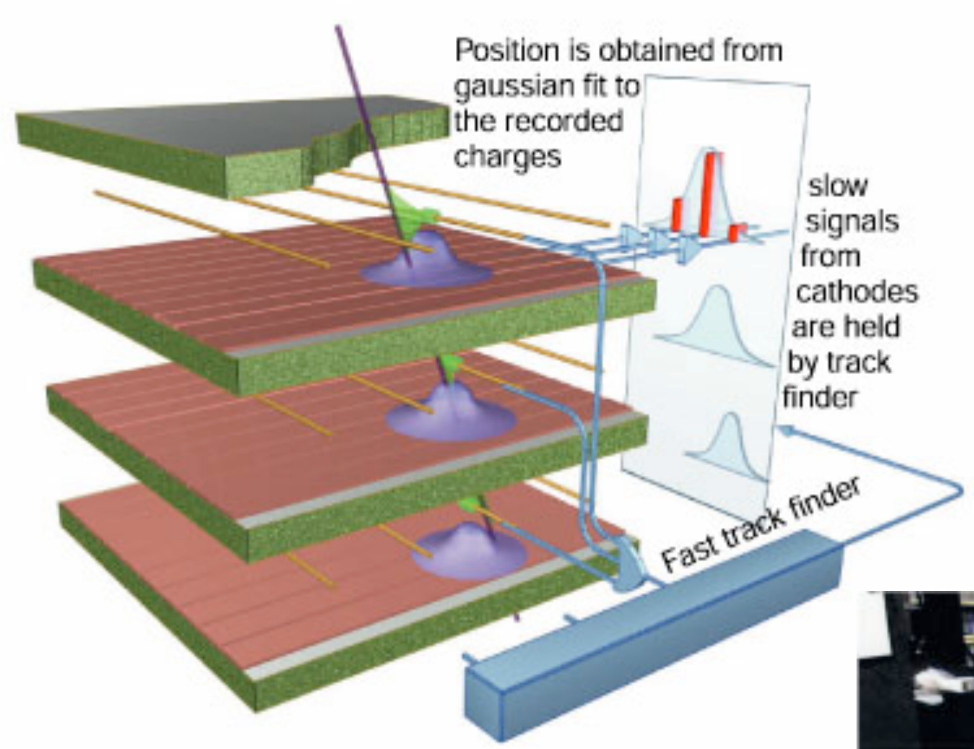

Detecting Strips
Resistive plate
Resistive plate
HV Al foil

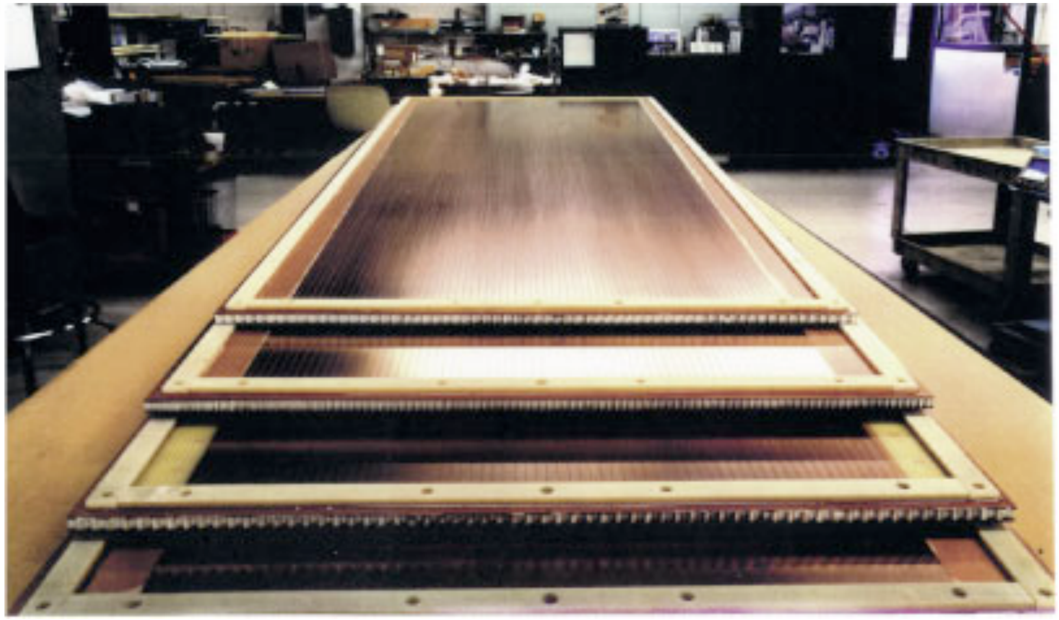

current
Threshold
time
10 ns
Ionizing particle
Detecting strips
E (9 kV/2mm)
Gas gap
e-
Electron multiplication
Resistive plates
HV Al foil

CMS DTs

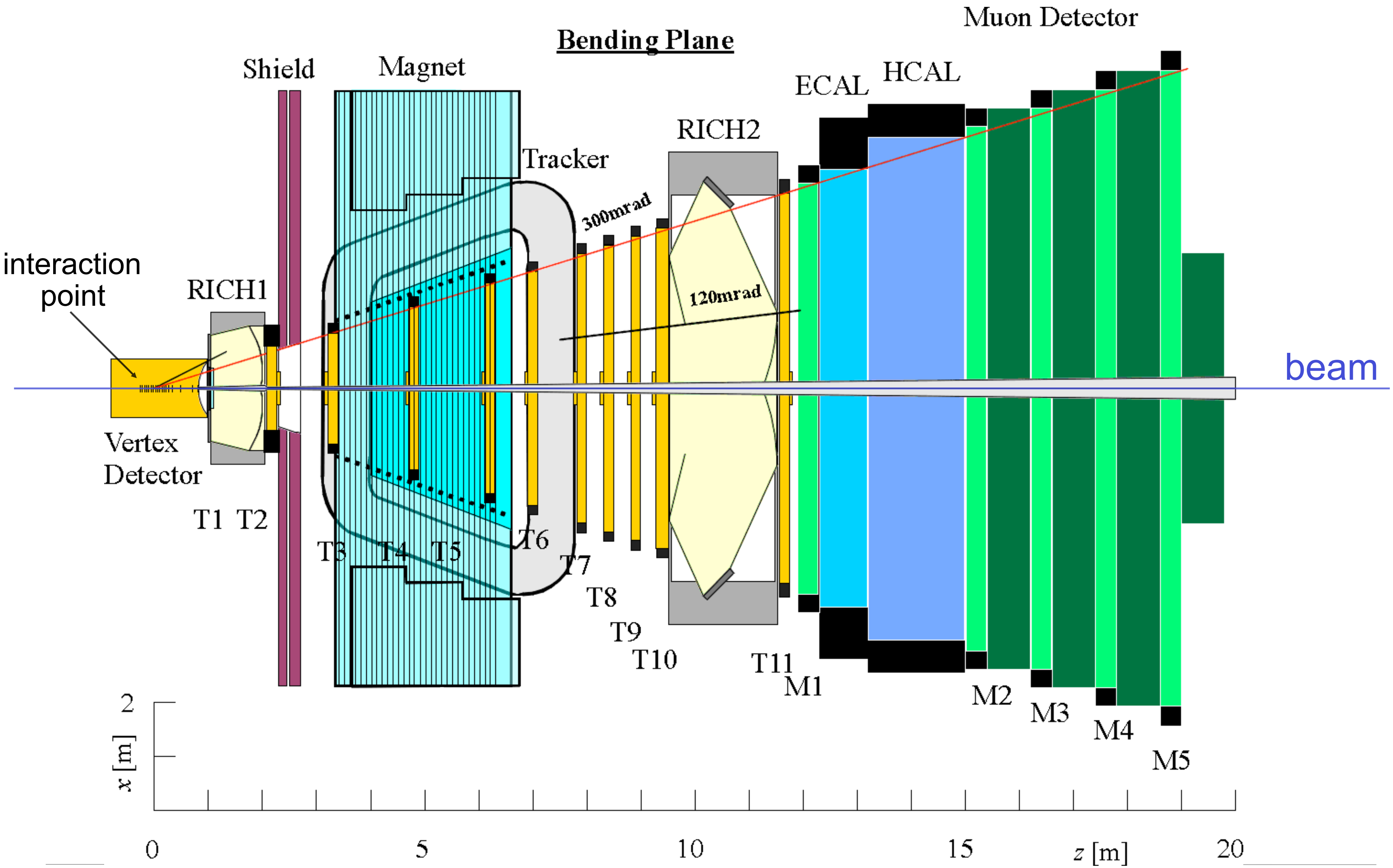


CMS CSCs

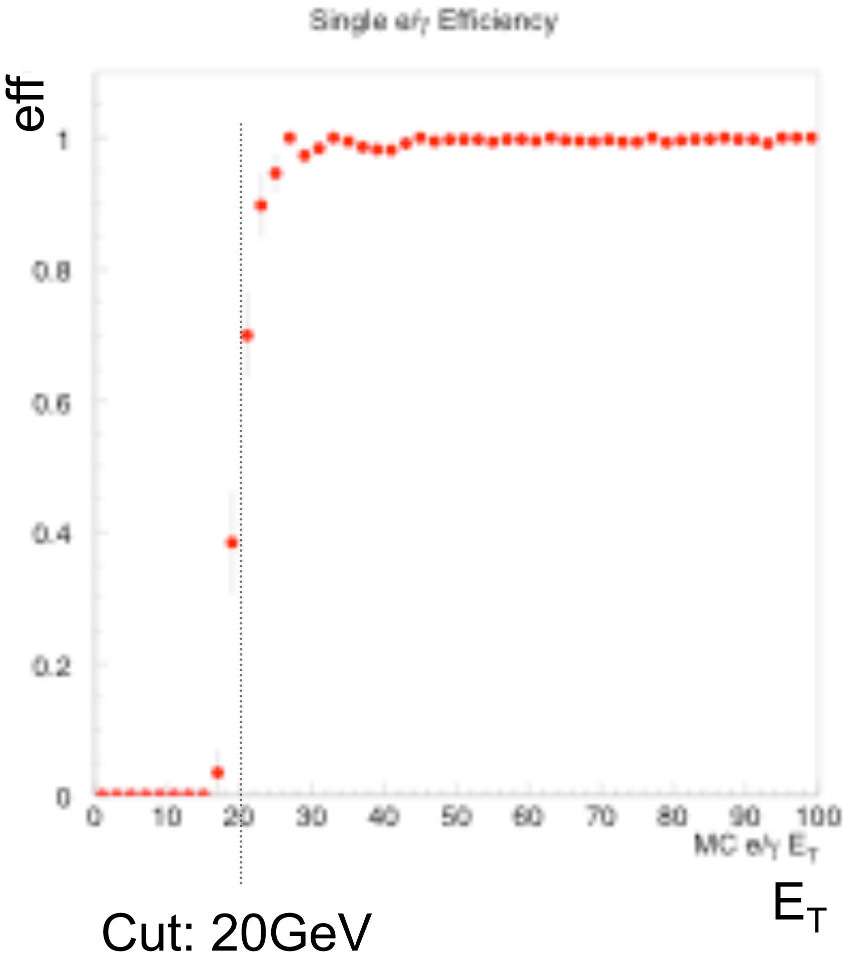

Position is obtained from gaussian fit to the recorded charges
slow signals from cathodes are held by track finder
Fast track finder

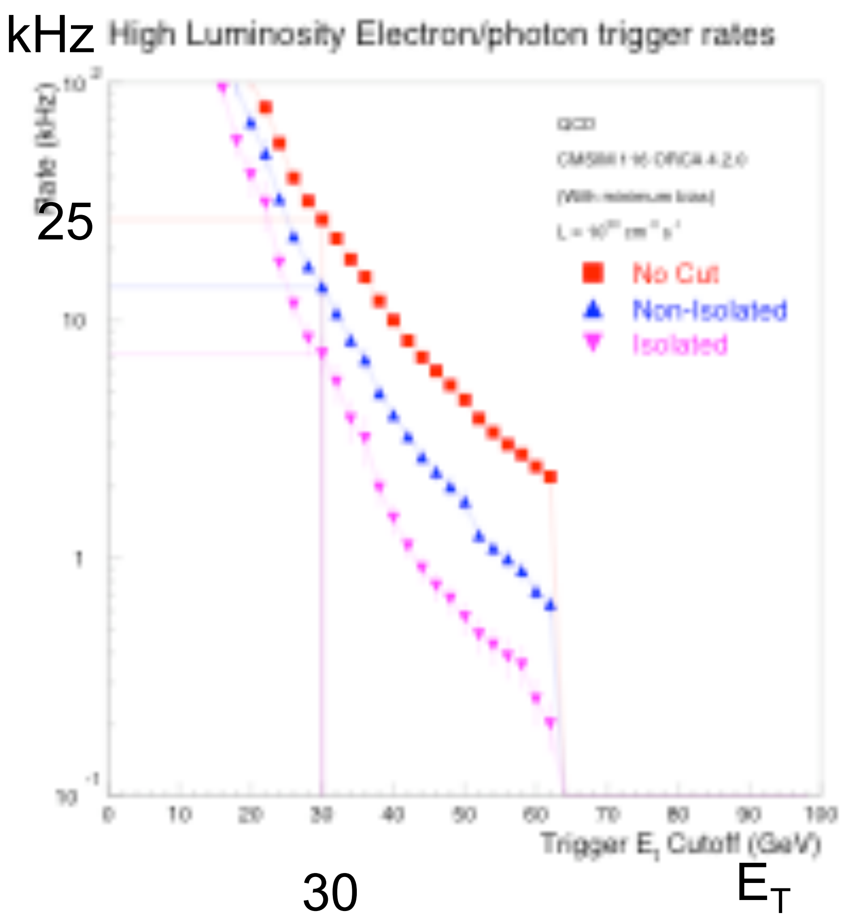


LHCb : study of B-decays (CP̸)

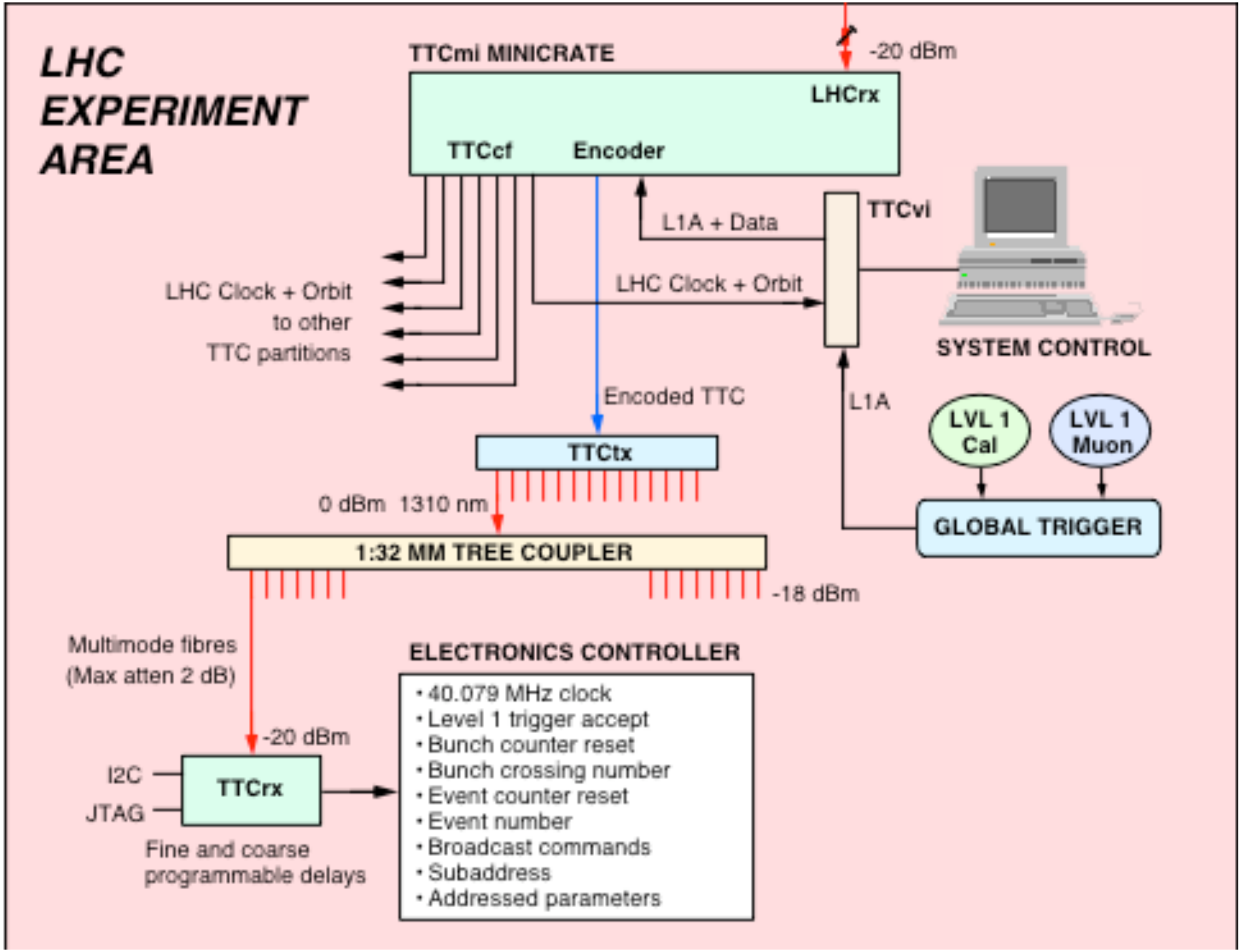


CMS isolated e/γ performance





Trigger distribution: TTC system



The 1st level trigger at LHC experiments

Requirement:

Do not introduce (a lot of) dead-time

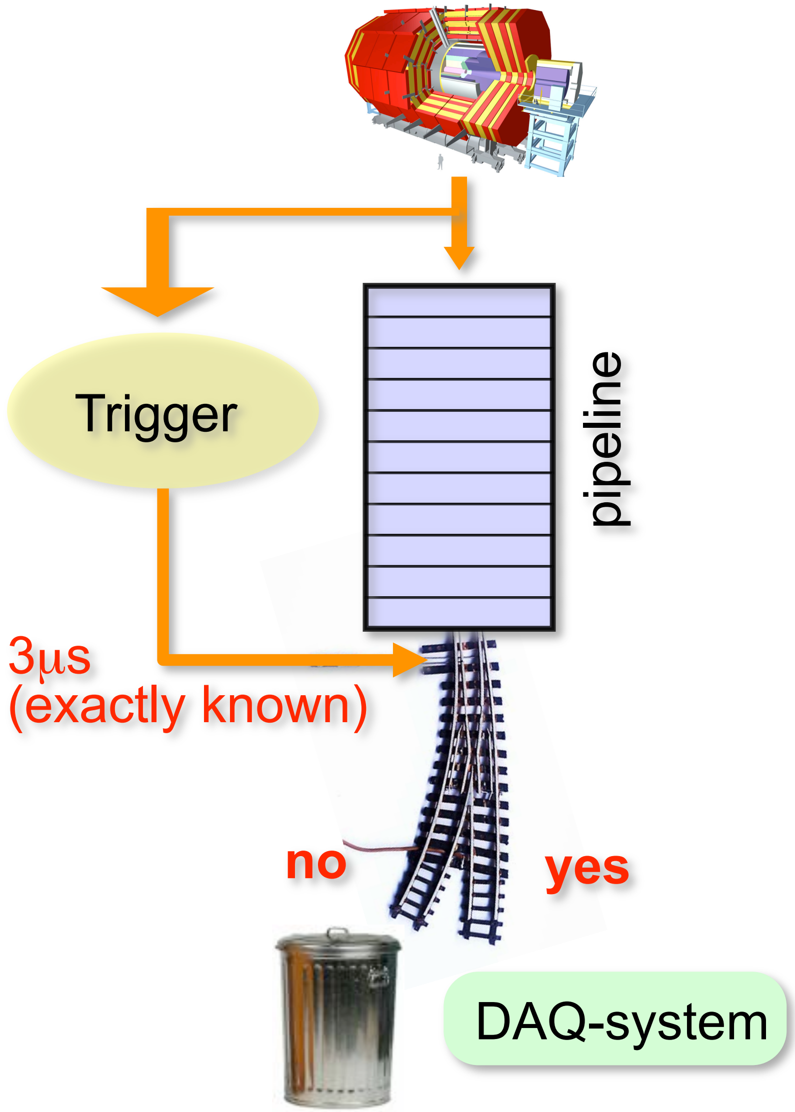
- O(1%) is tolerated
- Introduced by trigger rules :
  not more than n triggers in m BX
- Needed by FE electronics

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
  and derandomizer buffers
- Also the trigger itself is "pipelined"

Trigger must have low latency (2-3 μs)

- Otherwise pipelines would have to be very long

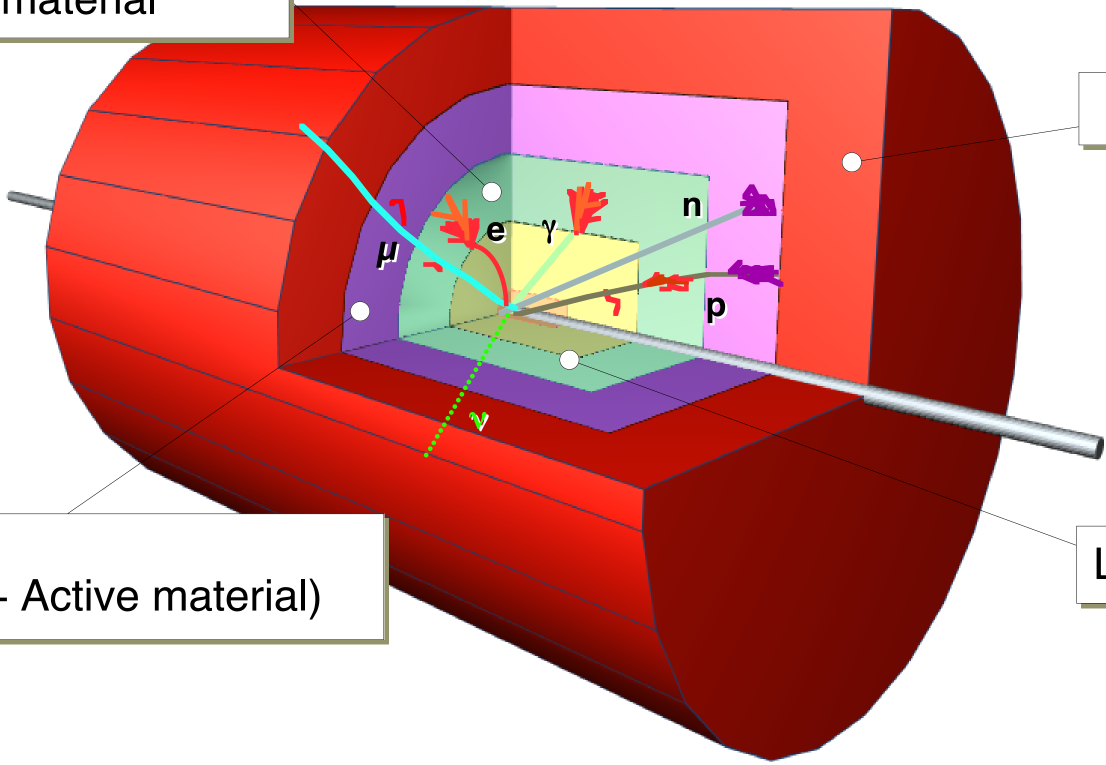


LHC Detector: main principle

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)

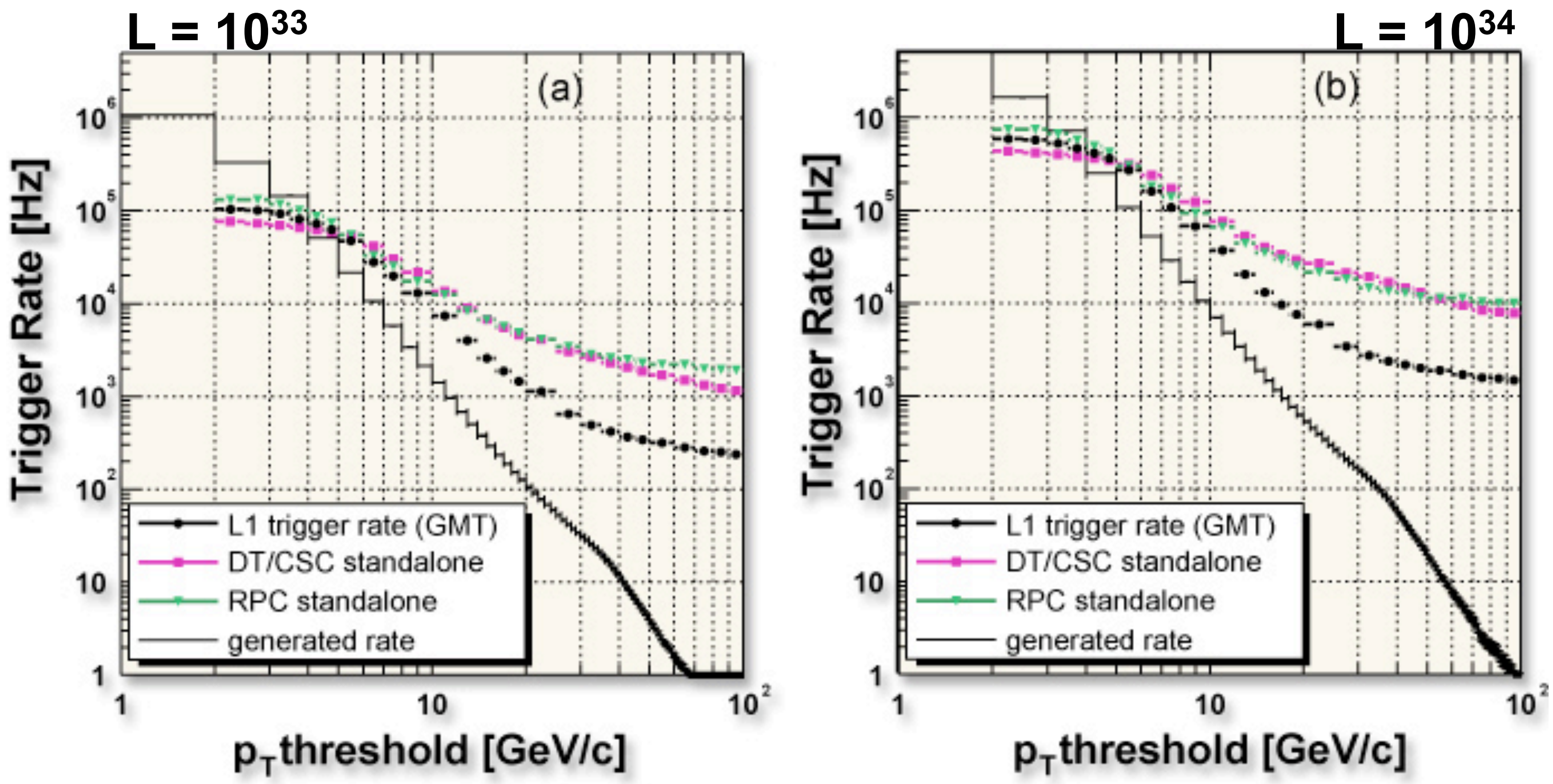
Light materials

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

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