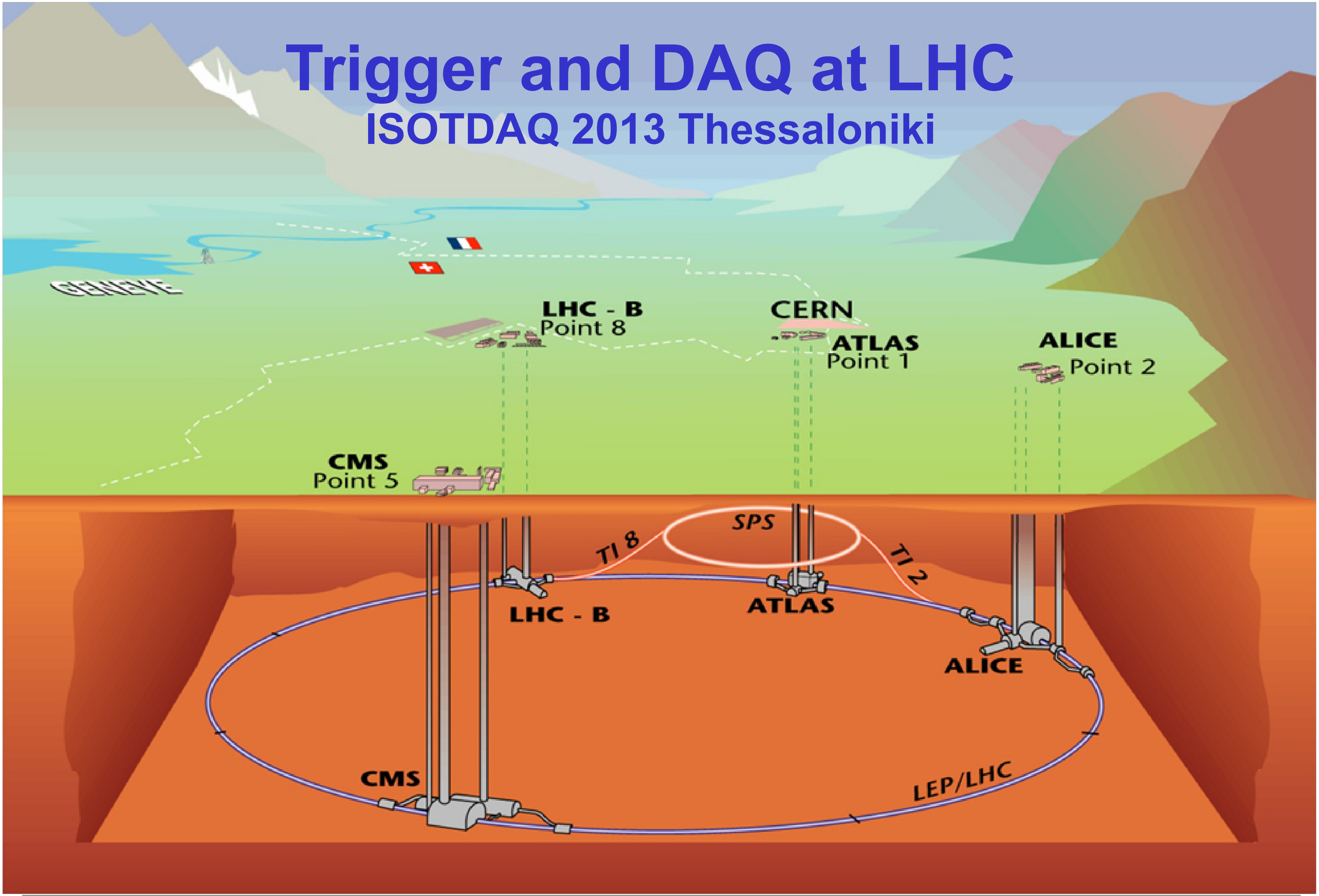
Trigger and DAQ at LHC

ISOTDAQ 2013 Thessaloniki



C.Schwick

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  - Muon and Calorimeter triggers (CMS and ATLAS)
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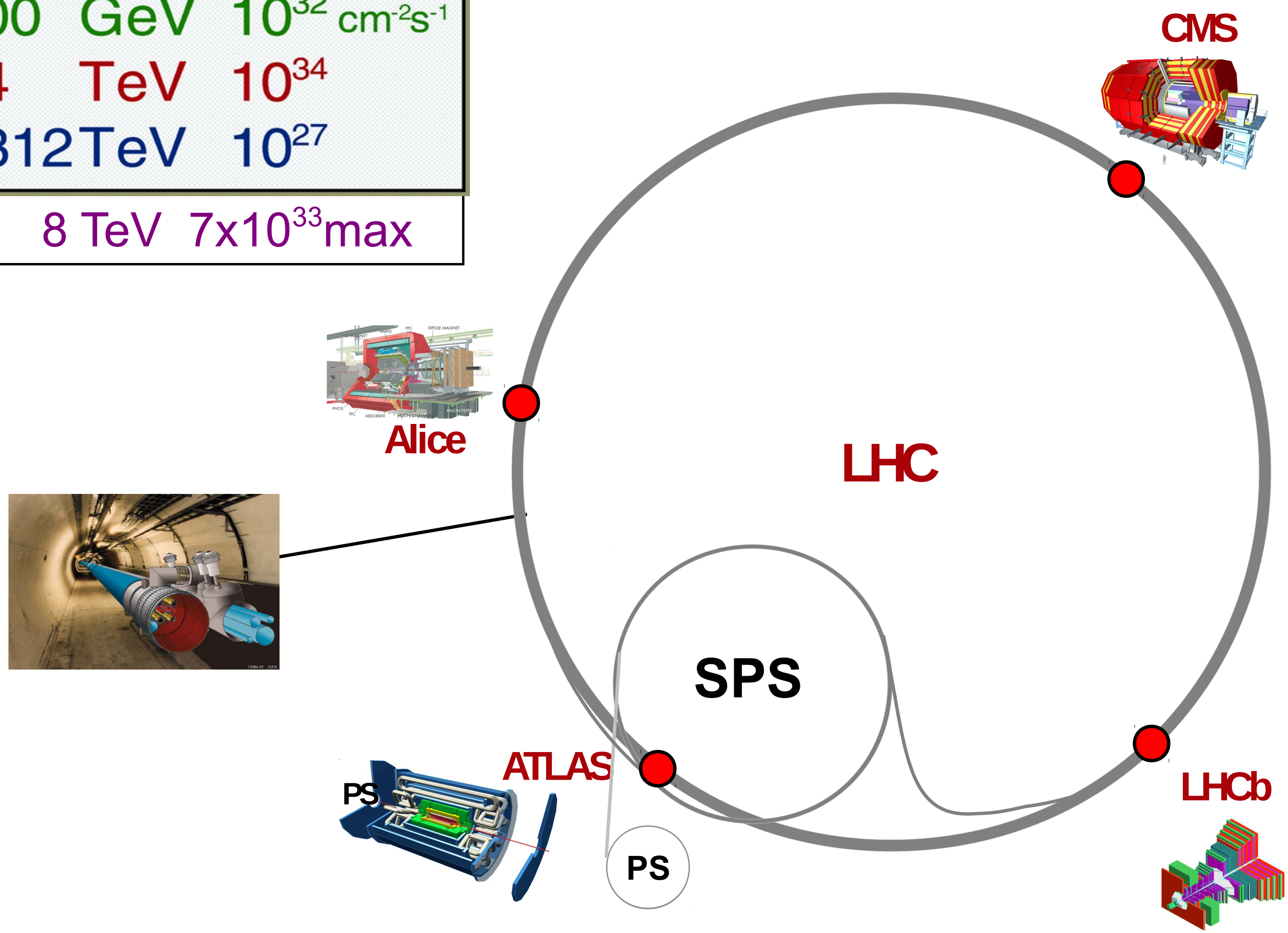
  - Ongoing and future upgrades
- **Part2: Readout Links, Dataflow, and Event Building**
  - Data Readout (Interface to DAQ)
  - Data Flow of the 4 LHC experiments
  - Event Building: CMS as an example
  - Software: Some techniques used in online systems
  - Ongling and future upgrades

- **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

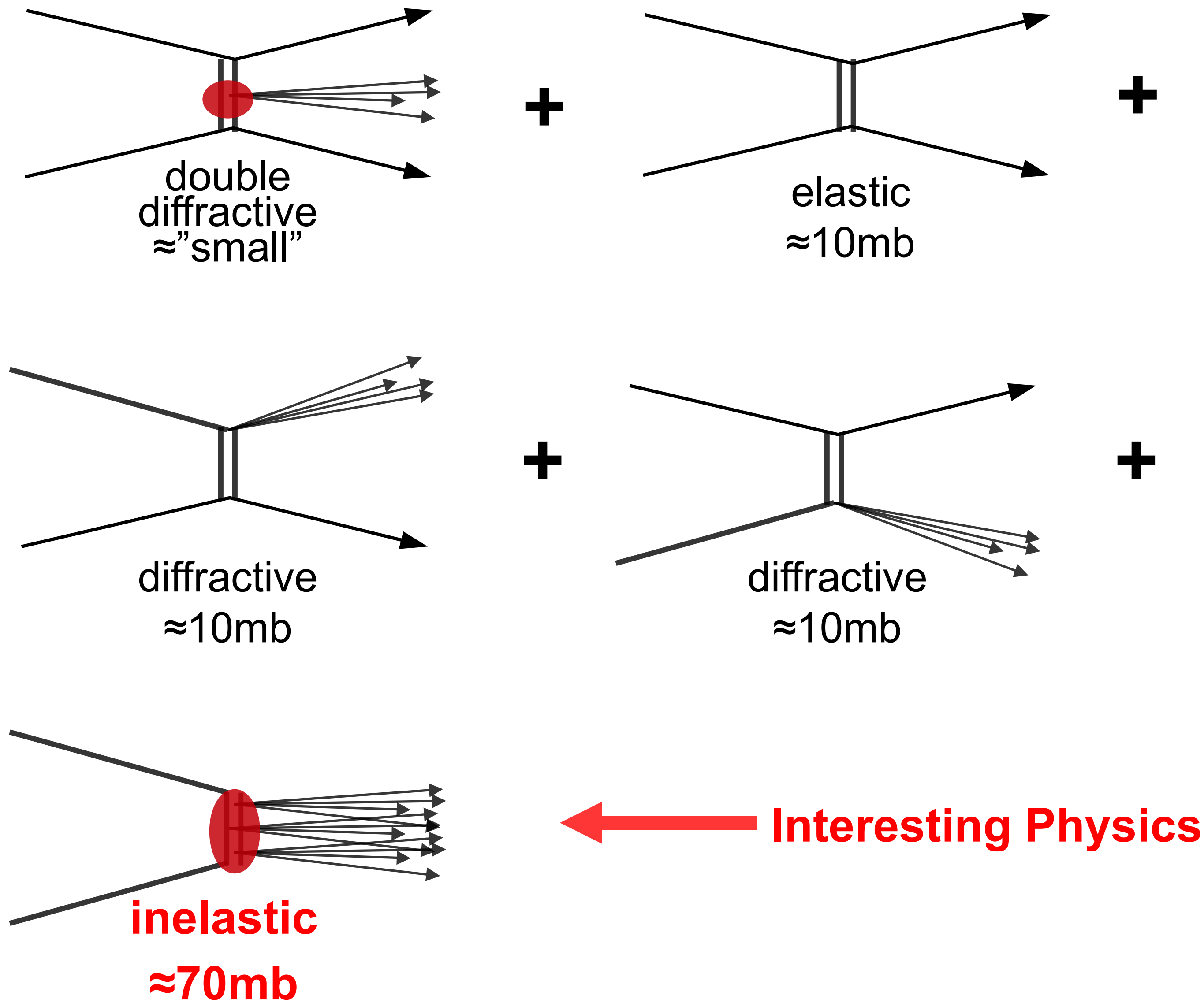
	Beams	Energy	Luminosity
LEP	e^+e^-	200 GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14 TeV	10^{34}
	P_b P_b	1312TeV	10^{27}
LHC2012	pp	8 TeV	$7x10^{33}$max



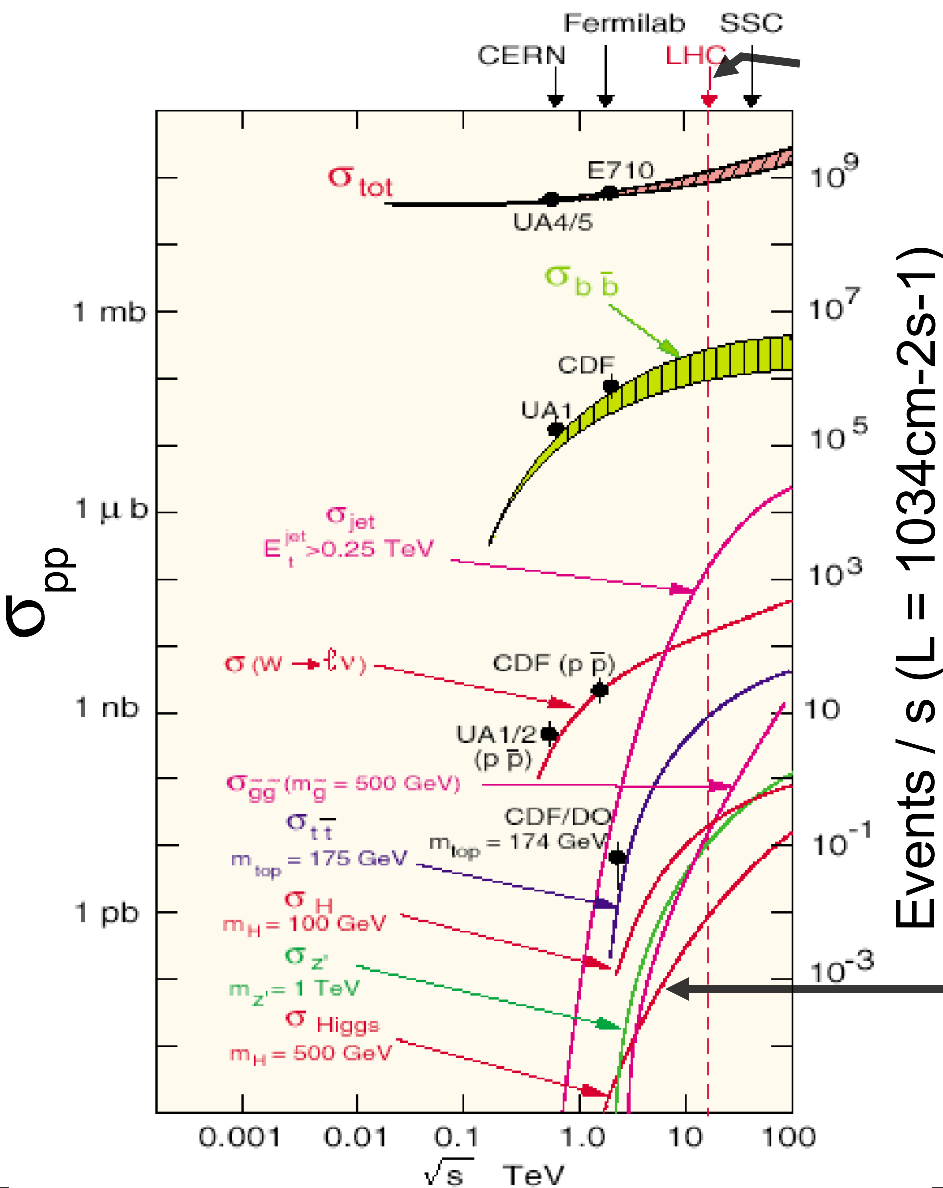
p-p interactions at LHC

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

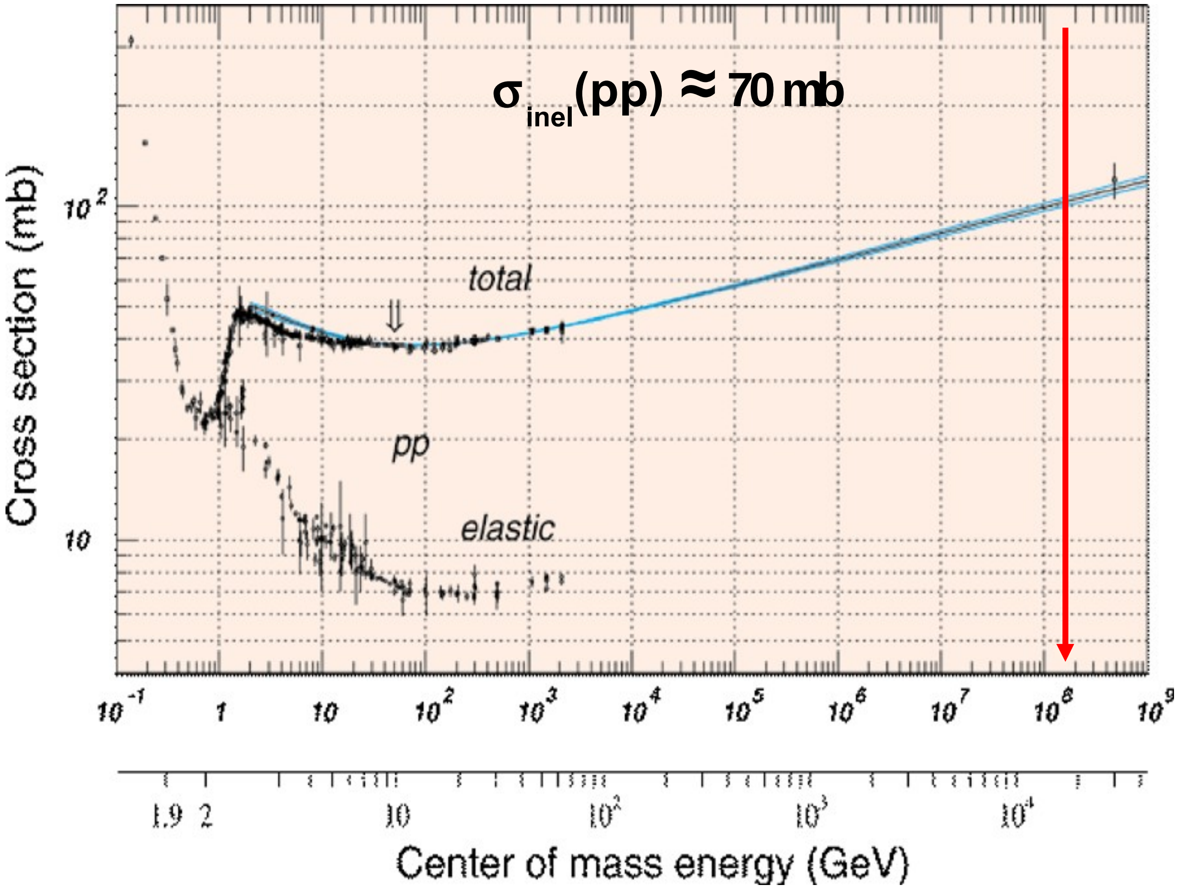
Is the Higgs a needle in the hay stack?

- **Hay halm:**
  - 500mm length, 2mm Ø
    → 3000 mm^3
  -
- **Needle**
  - 50 mm length, 0.3mm Ø
    → 50 mm^3
  - 50 needles are one hay halm
  -

- **Putting it all together**
  - Assume hay packing density of 10
    (...may be optimistic...)
  - 10 x 1011 x 3x109 m^3 / (6x10) =

    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^{8} Hz

Δt = 25ns

events / 25ns = 17.5

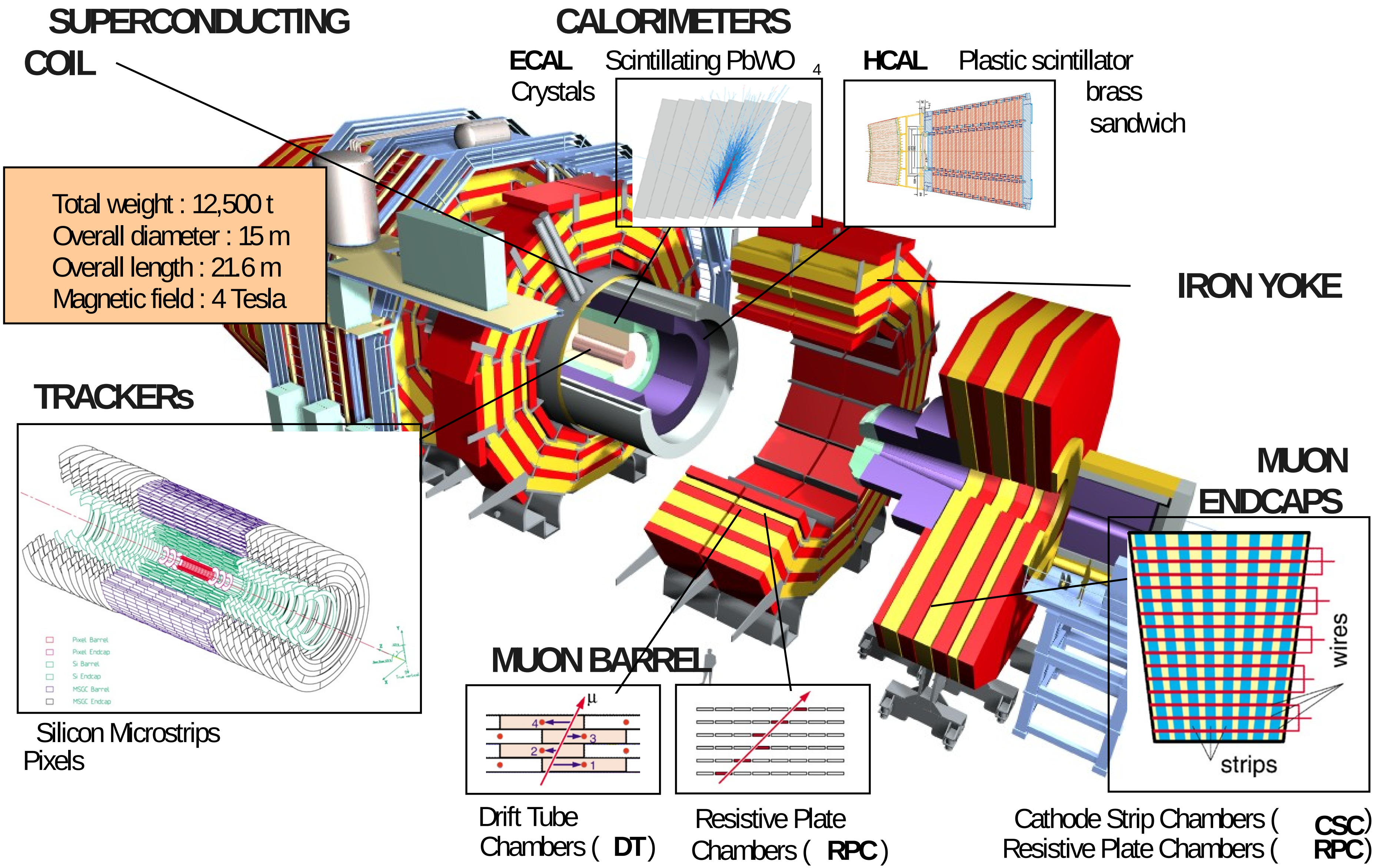
Not all bunches full (2835/3564)

events/crossing = 23

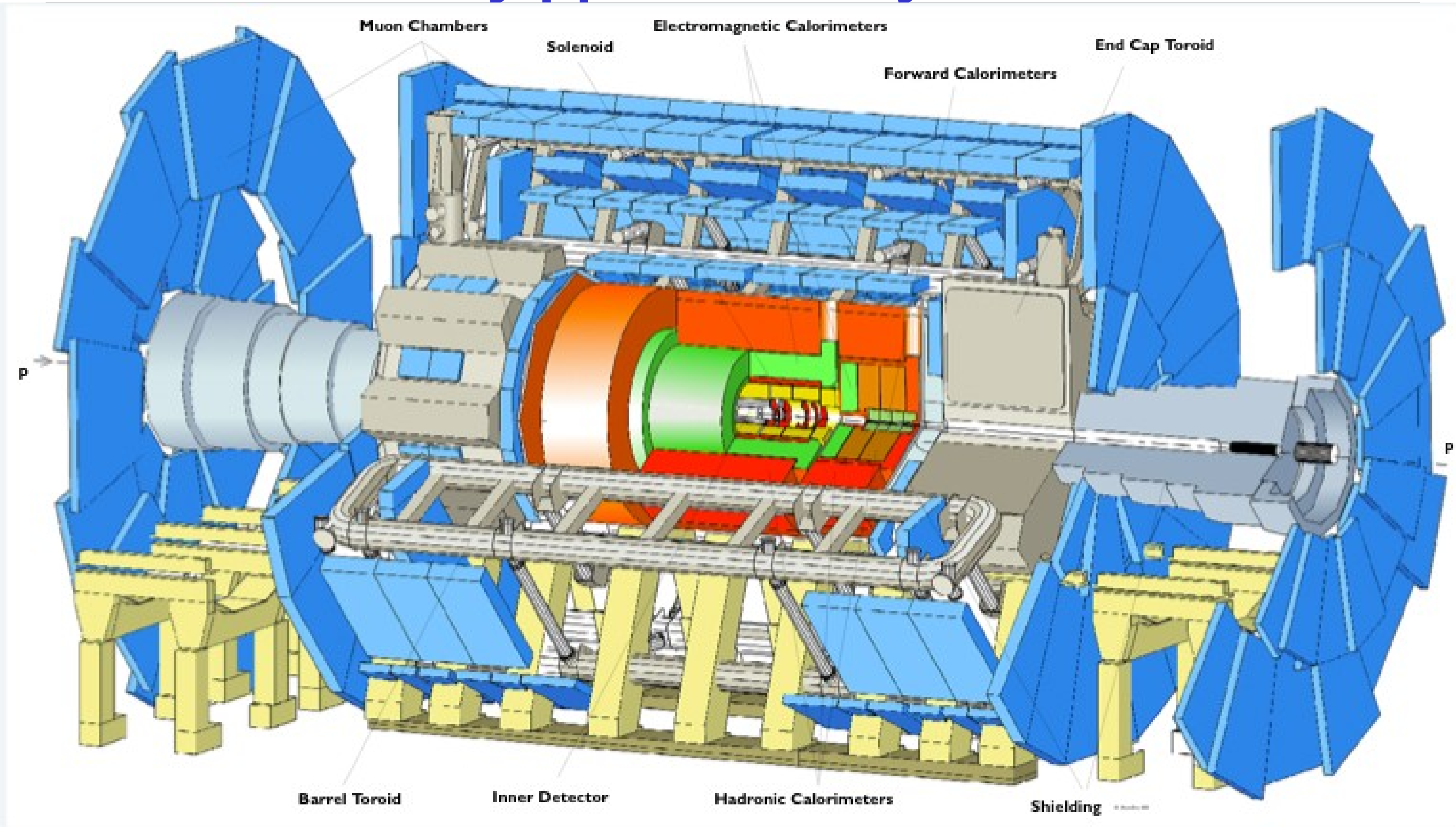
2012 LHC will run at 50ns pile up will be twice as high as for 25 ns (at constant Lumi)

The 4 largest LHC experiments

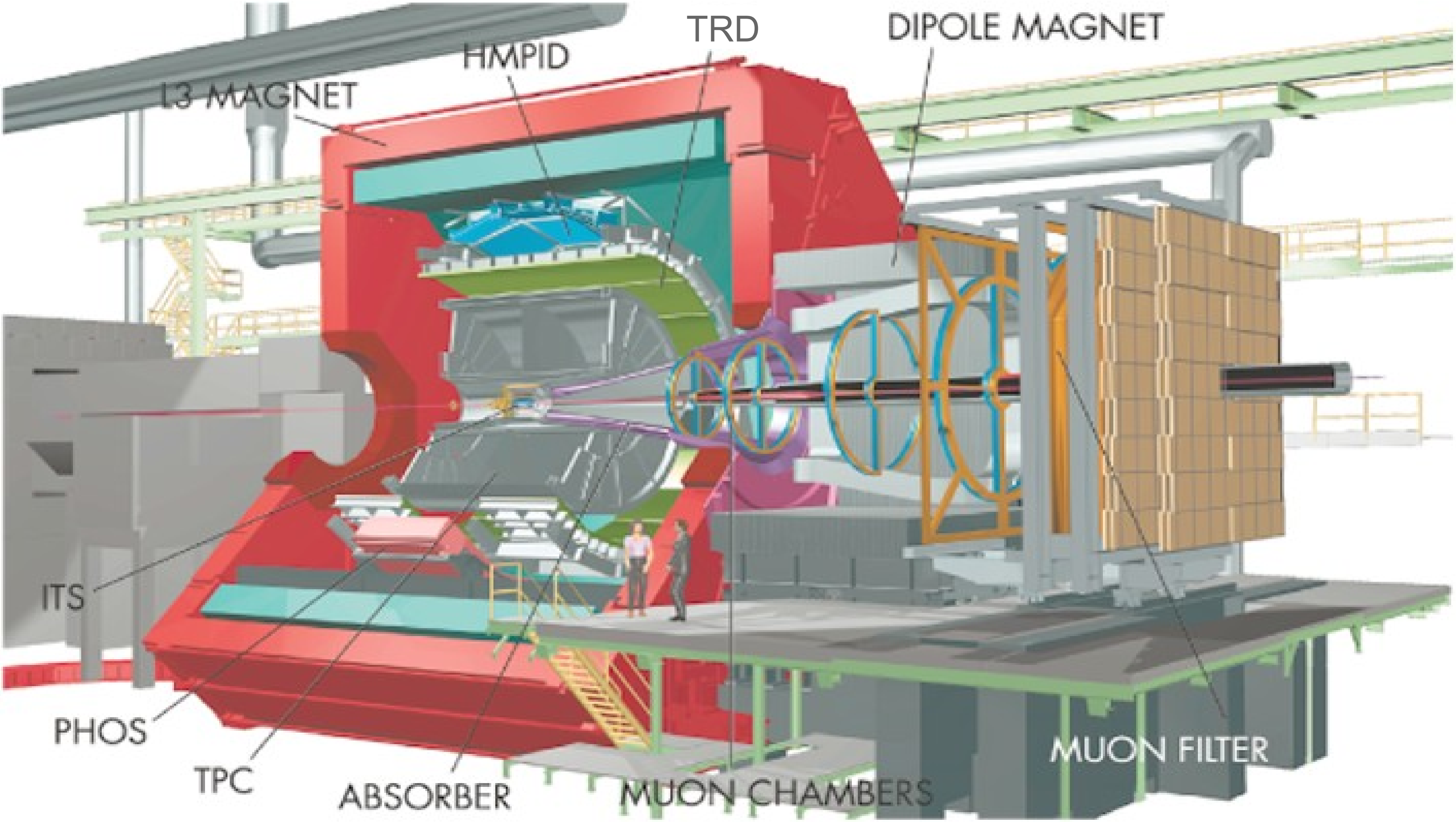
CMS : study pp and heavy ion collisions



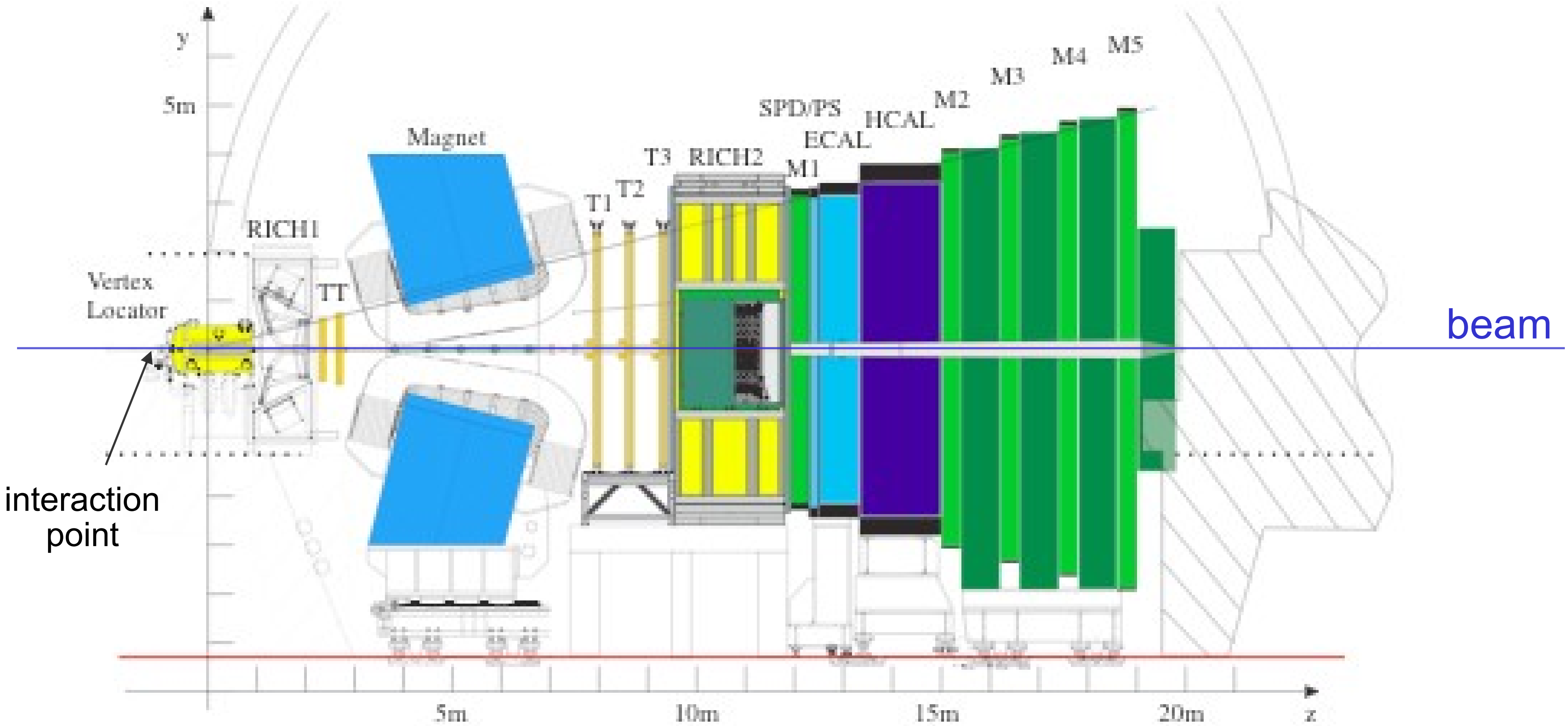
Atlas : study pp and heavy ion collisions



ALICE : study heavy ion collisions

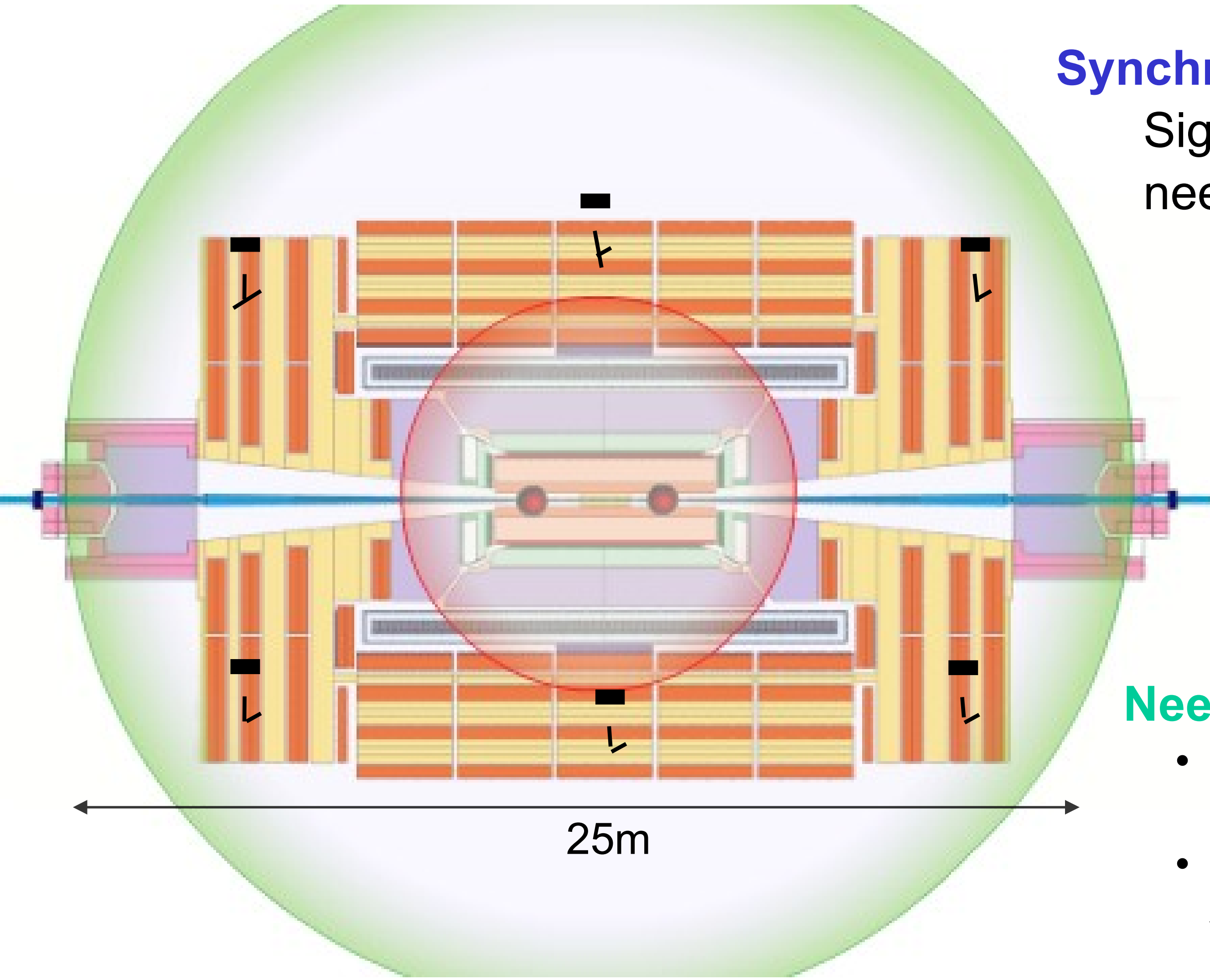


LHCb : study of B-decays (~~CP~~)



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

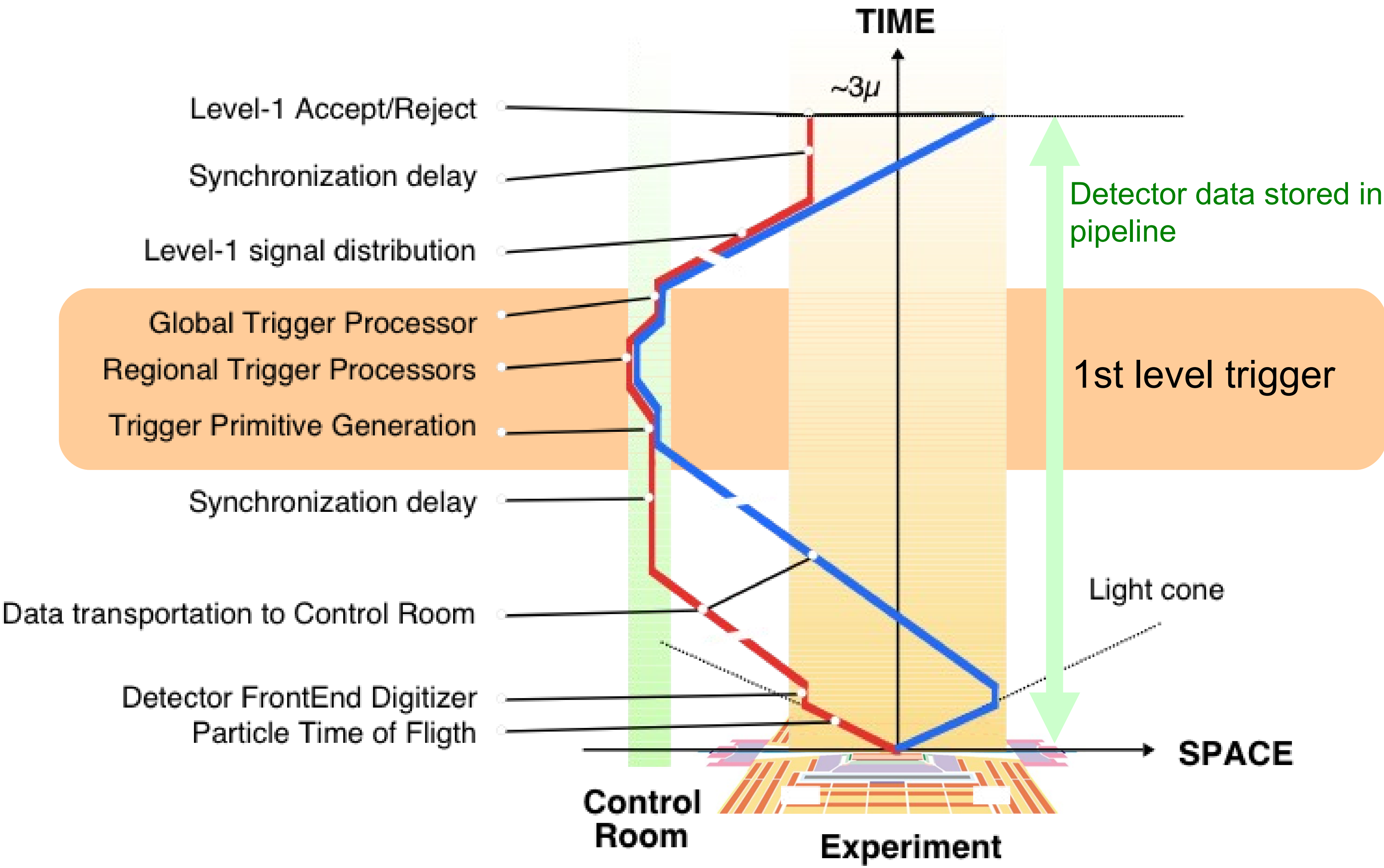
($v_{signal} \approx 1/3$ c)

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

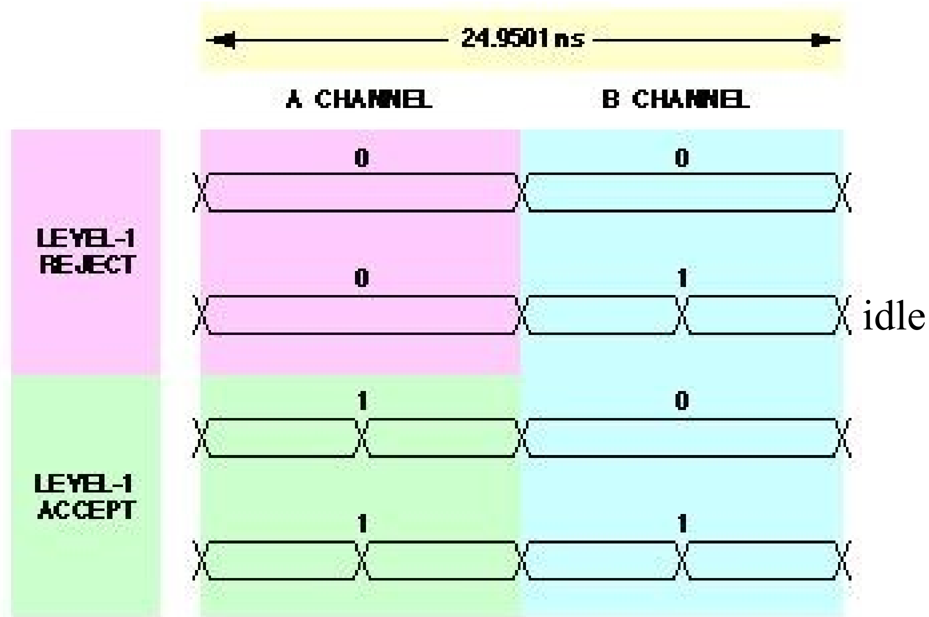


Distribution of Trigger signals

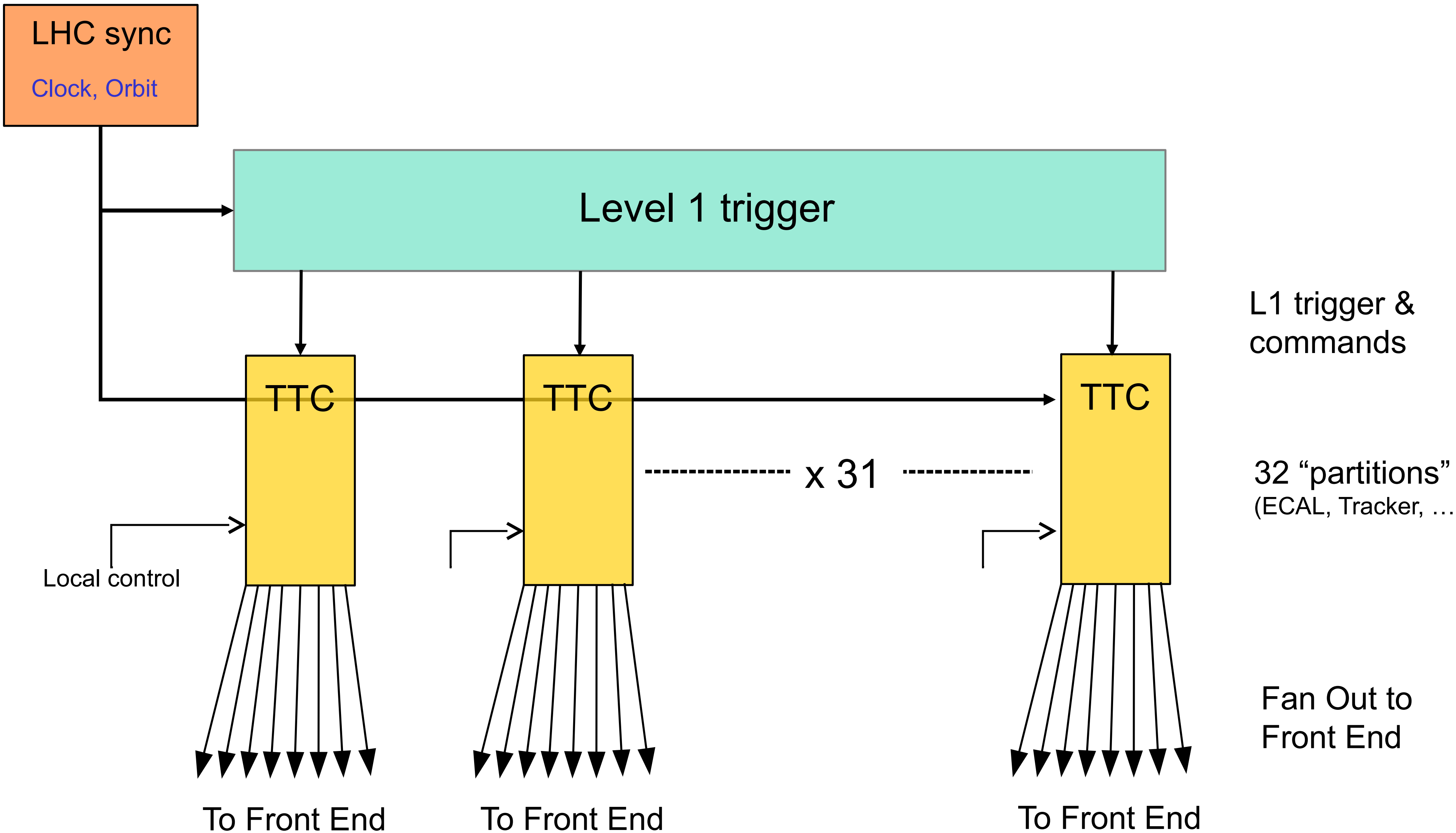
- **The L1 trigger decision needs to be distributed to the front end electronics**
  - Triggers the readout of pipeline
  - Needs to allow to determine the Bunch Crossing of the interaction
    - Timing needs to be precise (low jitter, much below 1ns)
    - Signal needs to be synchronized to LHC clock
- **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/fBX	22μs (later 11μs)	2.7 ns	25 ns
Lvl1 Trig.	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)

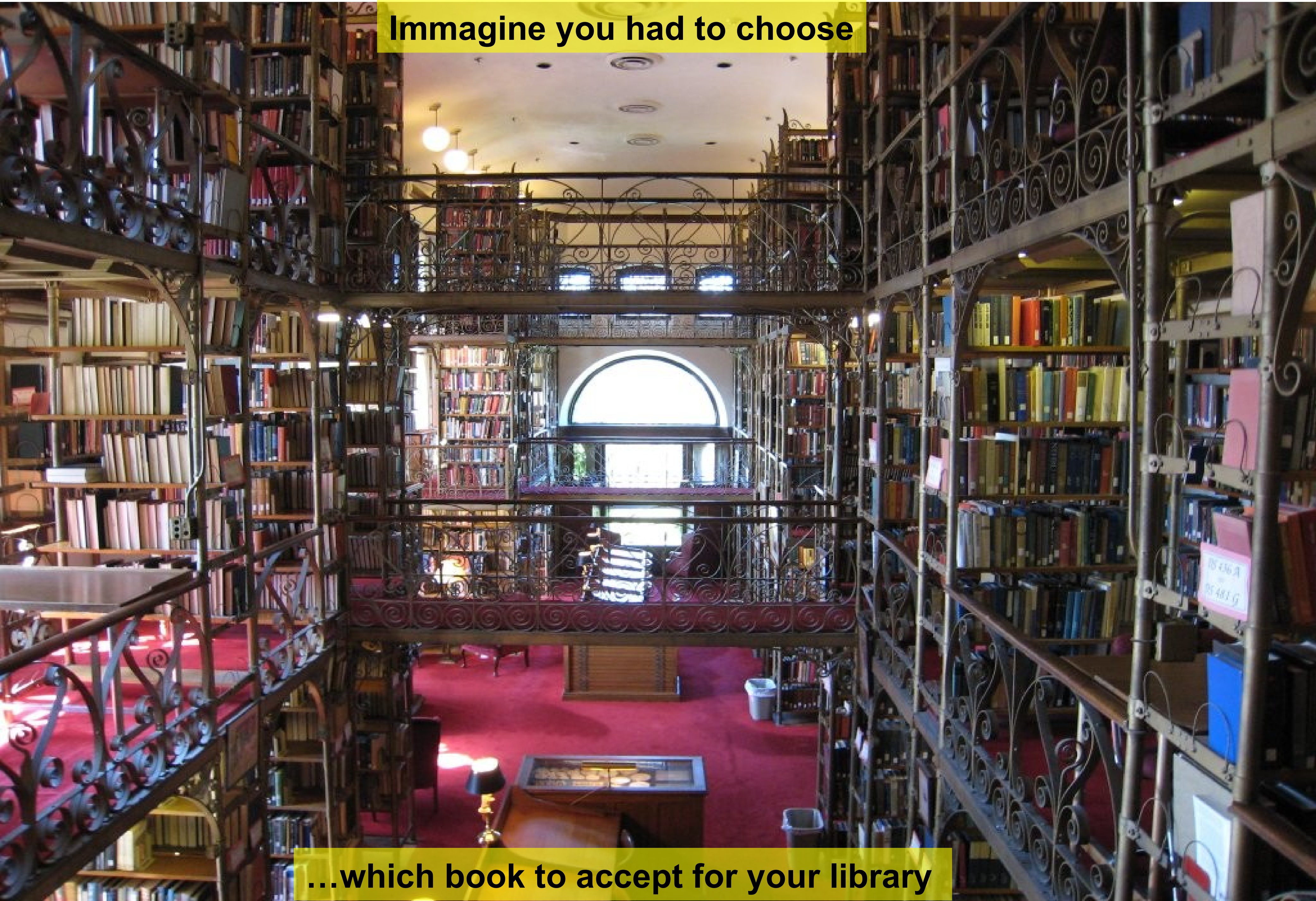


Immagine you had to choose
…which book to accept for your library

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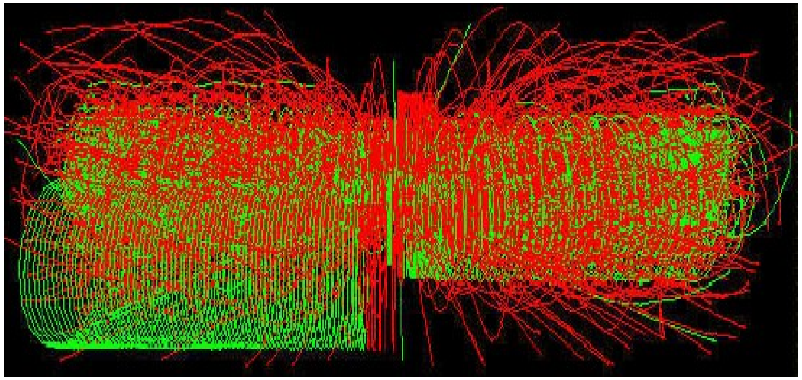
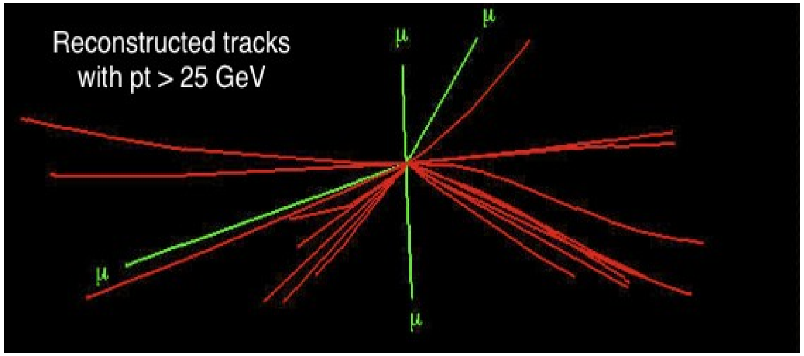
"Typical event"

H -> Z0Z0 -> 4μ





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

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 behavior

- **Trigger design needs to be flexible**
  - need many handles to adjust the rates.

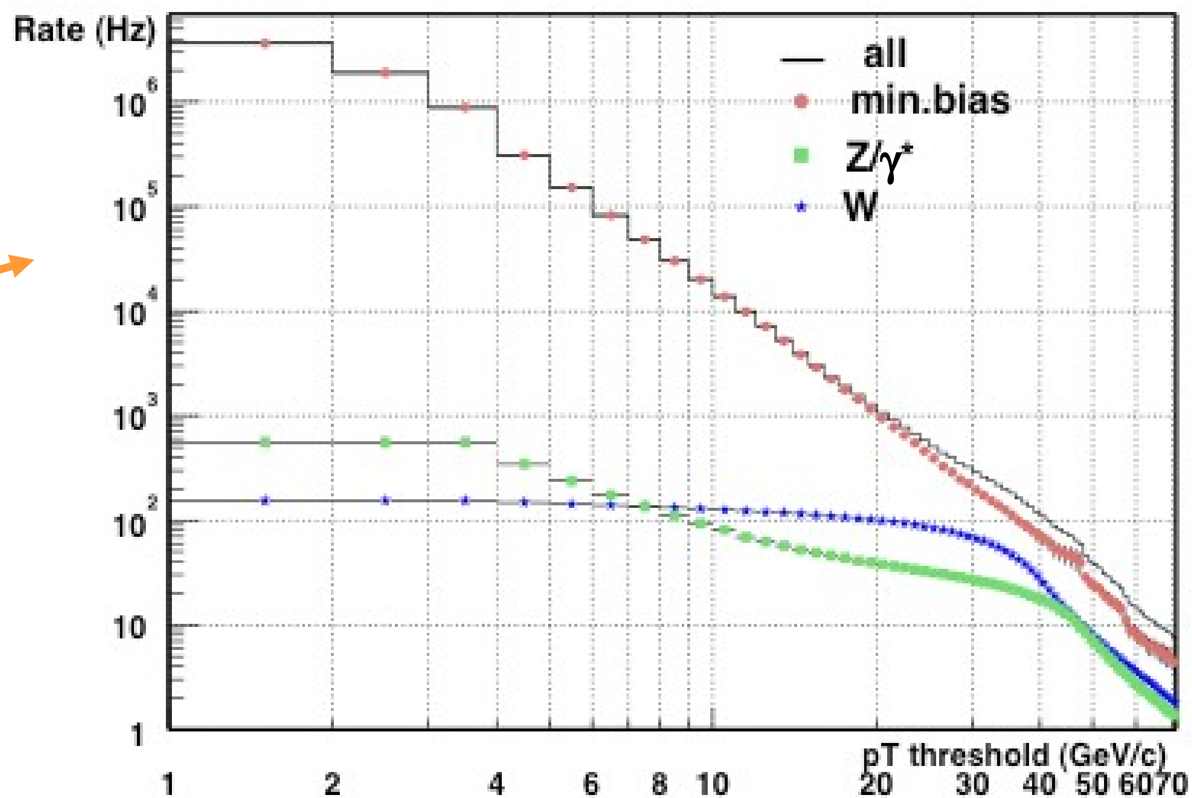
Triggering at LHC : example Muons

- **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

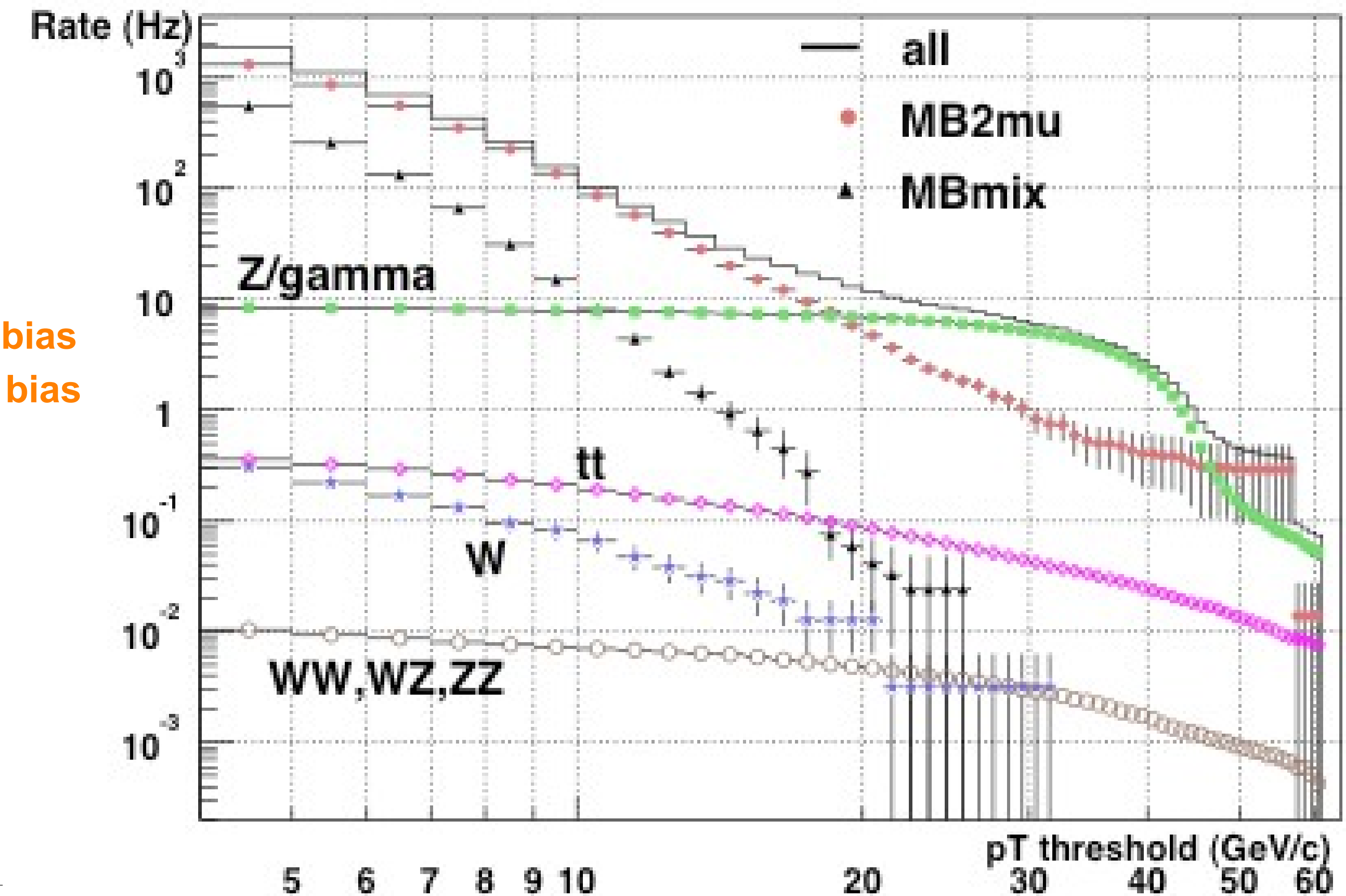
- **Interesting events: contains (almost) always 2 objects to trigger on**

L = 10^{34}

Example muon pairs :

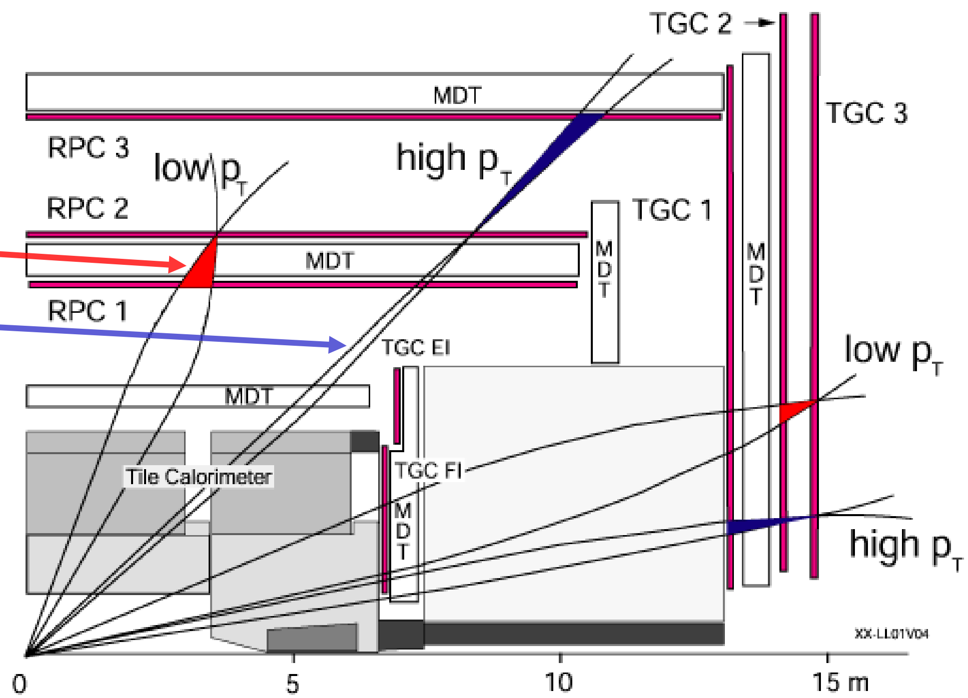
MB2mu : 2μ from min bias
Mbmix : 1μ from min bias

Threshold ≈ 10 GeV
Rate ≈ 100Hz



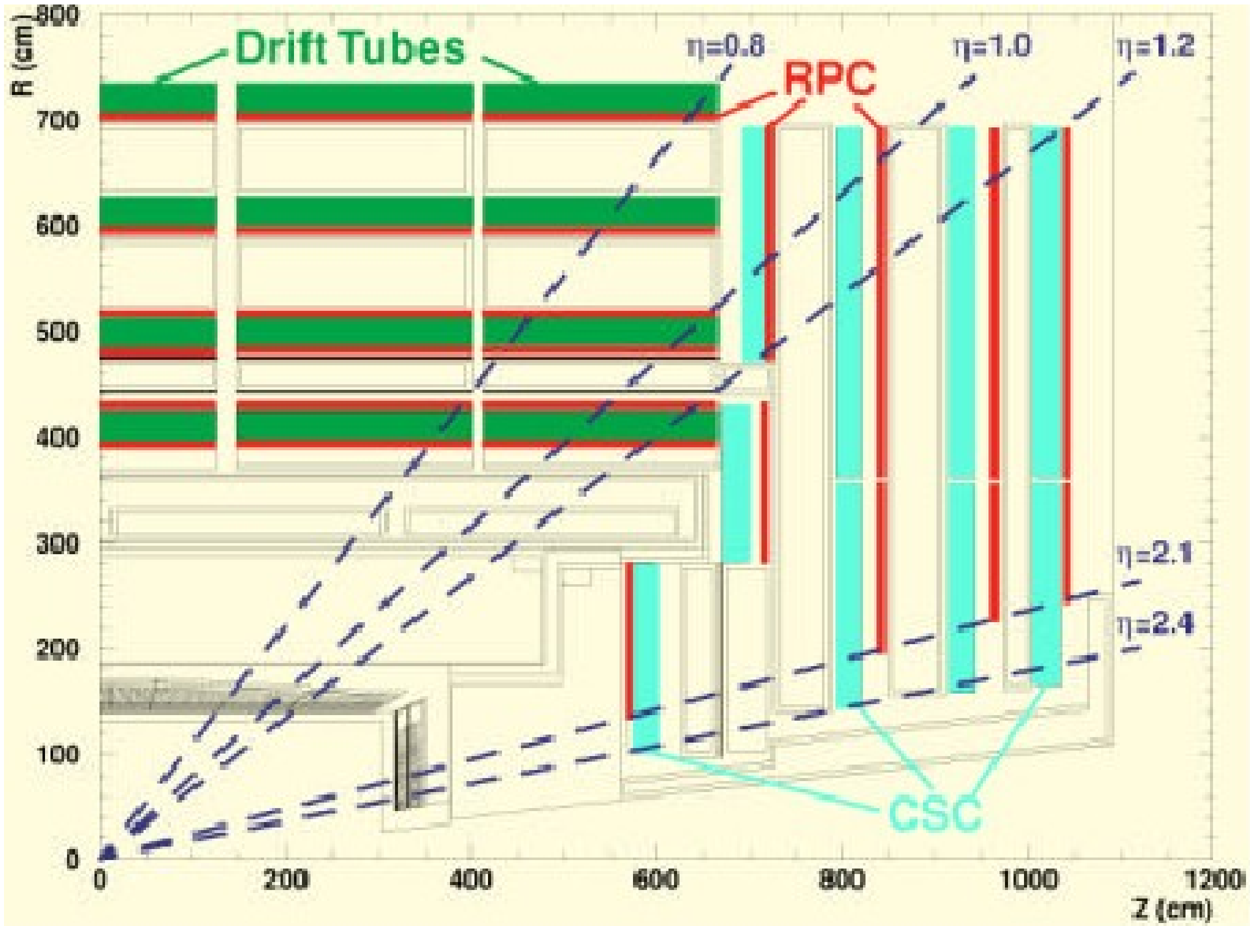
How to trigger on Muons

- **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)

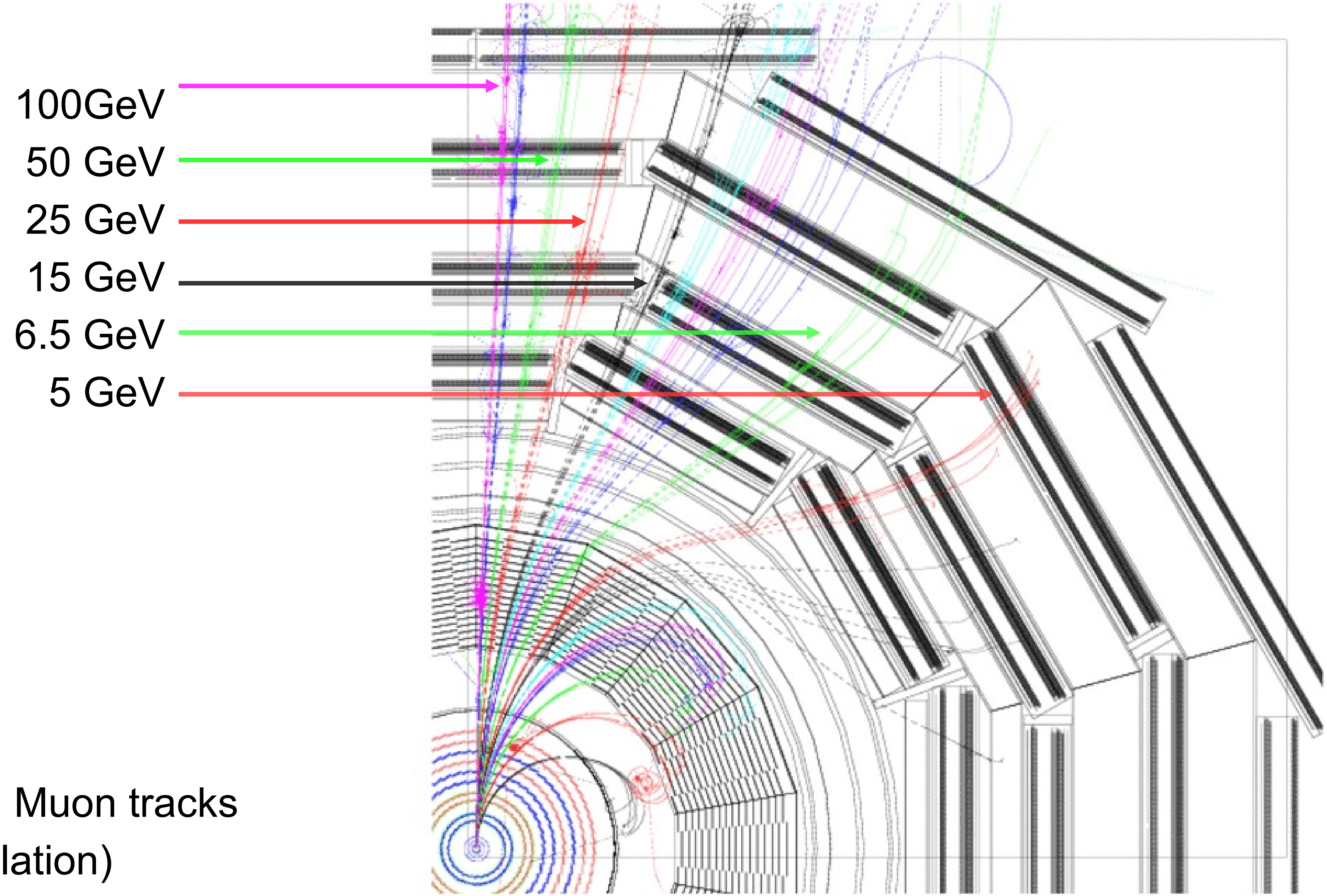


How to trigger on Muons

The CMS muon system



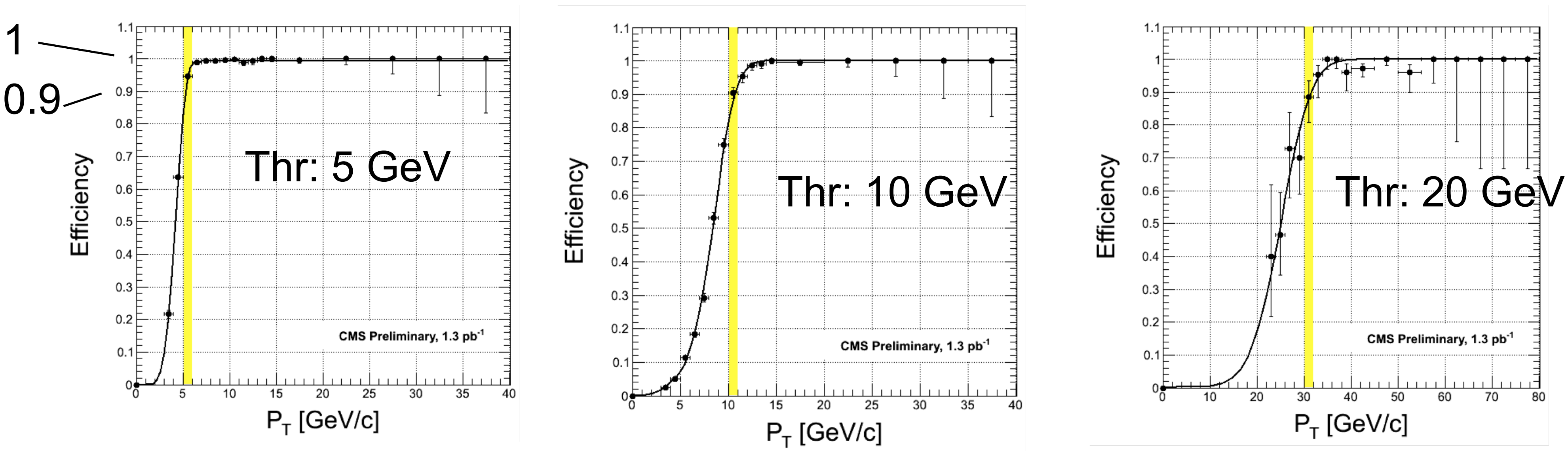
How good does it work?



CMS: Muon tracks
(simulation)

Performance of CMS muon trigger

- **Efficiency turn-on curves**



- From Data with events: $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$
- “Real” pt vs. efficiency for imposed trigger threshold
- For an imposed threshold x the efficiency for muons with pt = x GeV is larger 90% (…as foreseen).

Redundancy in the CMS Muon trigger

Generated Muons versus trigger rate (simulation)

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

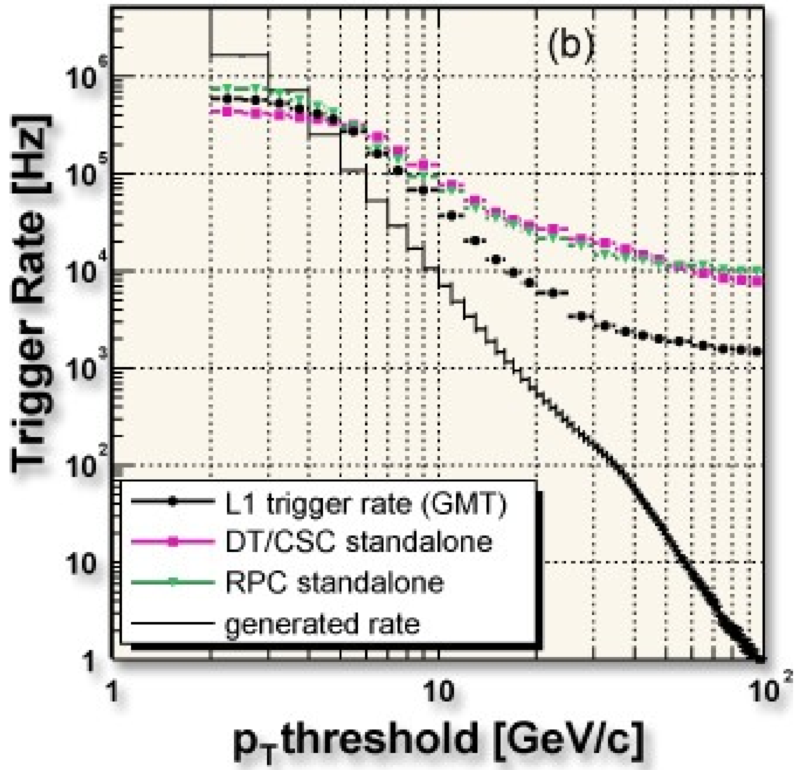
this improves purity

p_t > 20GeV:

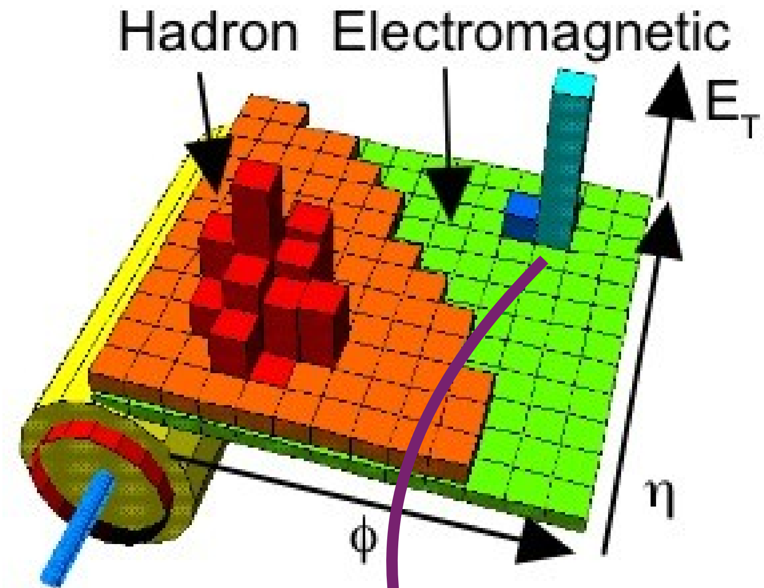
≈ 600 Hz generated,

≈ 8 kHz trigger rate

L = 10^{34}

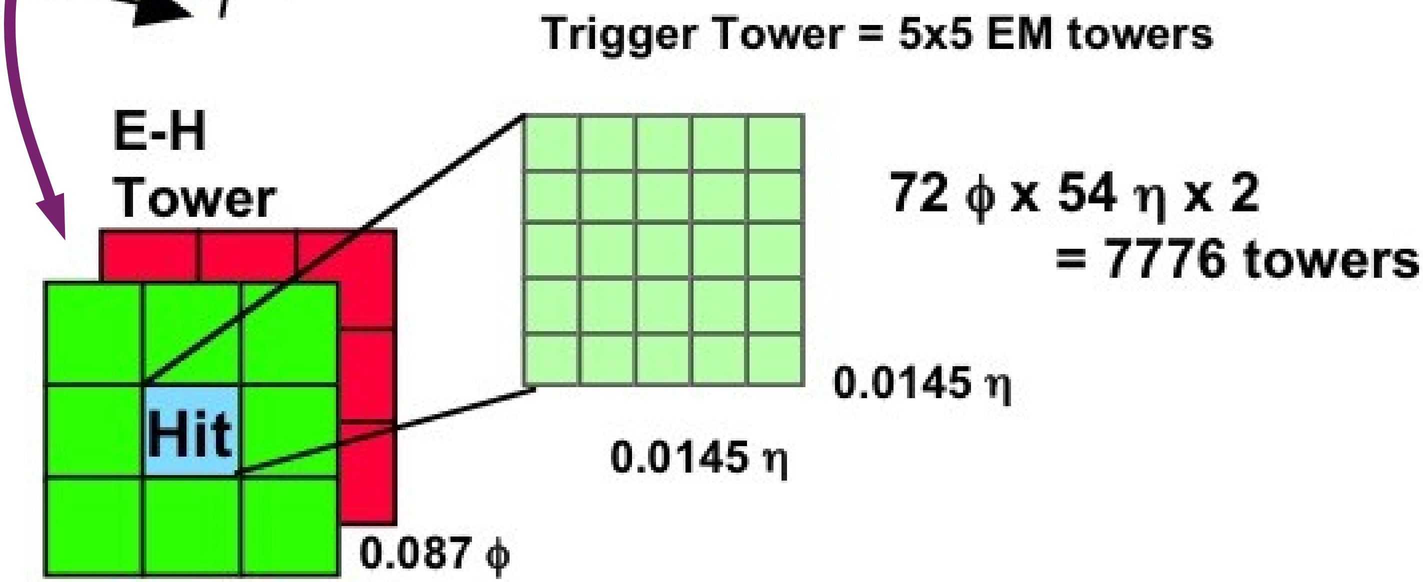


Calorimeter Trigger: example CMS



Divide Calorimeter into towers

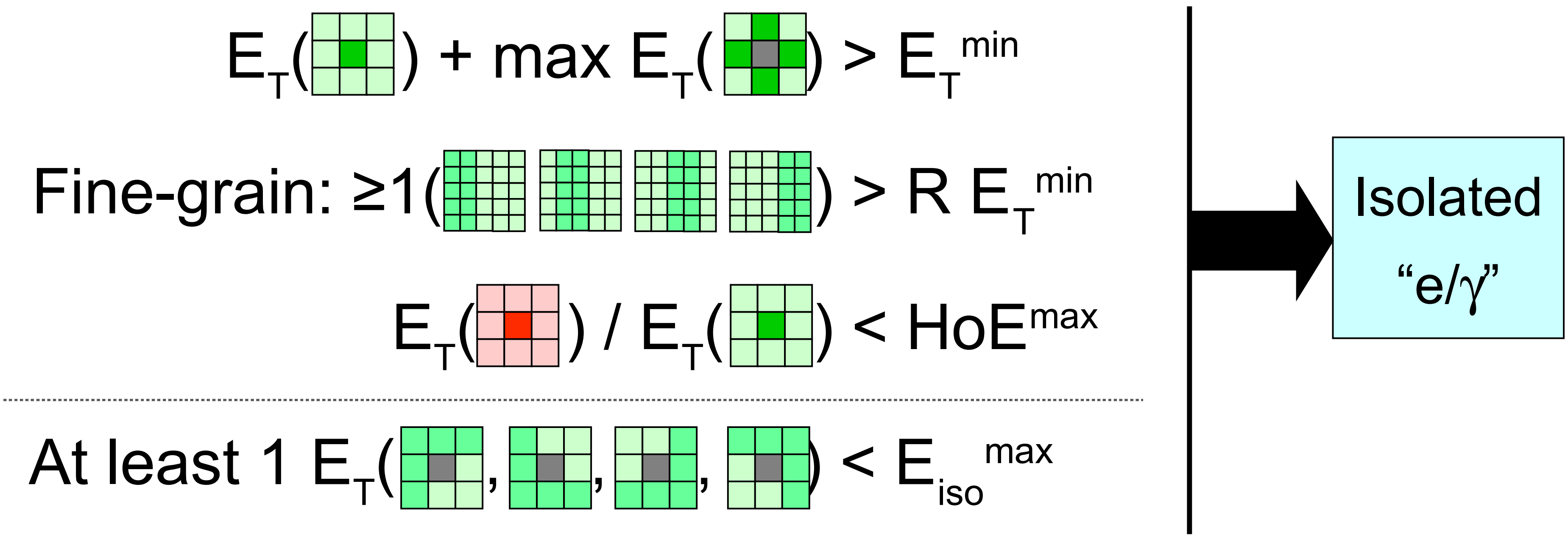
Match towers between ECAL and HCAL



Algorithm to identify e/γ

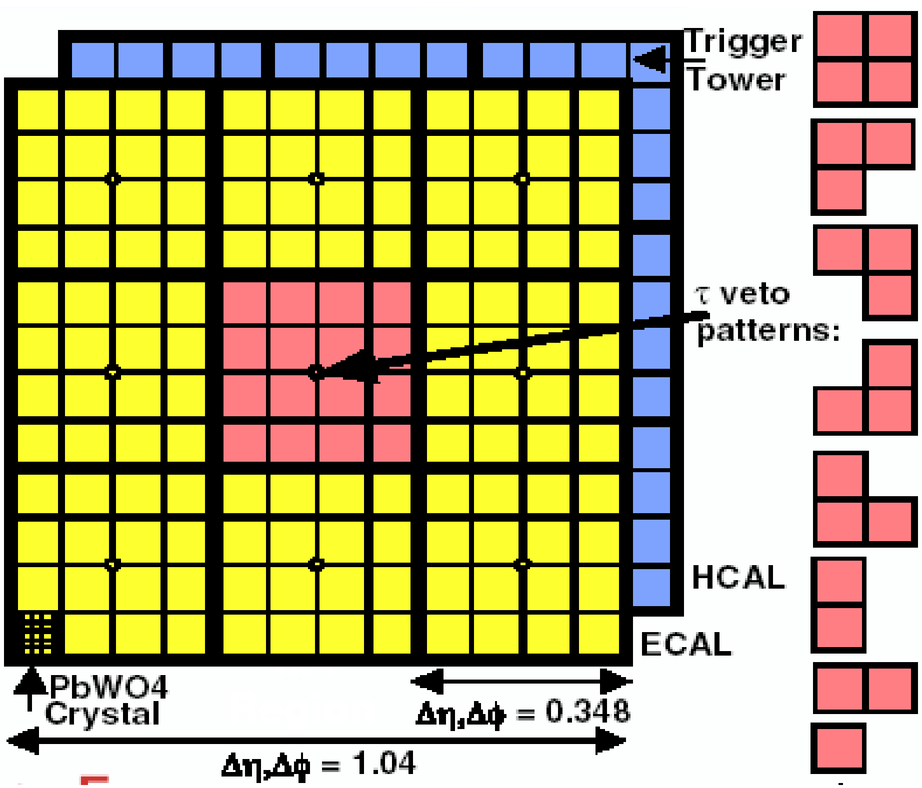
Characteristics of isolated e/γ:

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



Calorimeter Trigger: jets and Taus

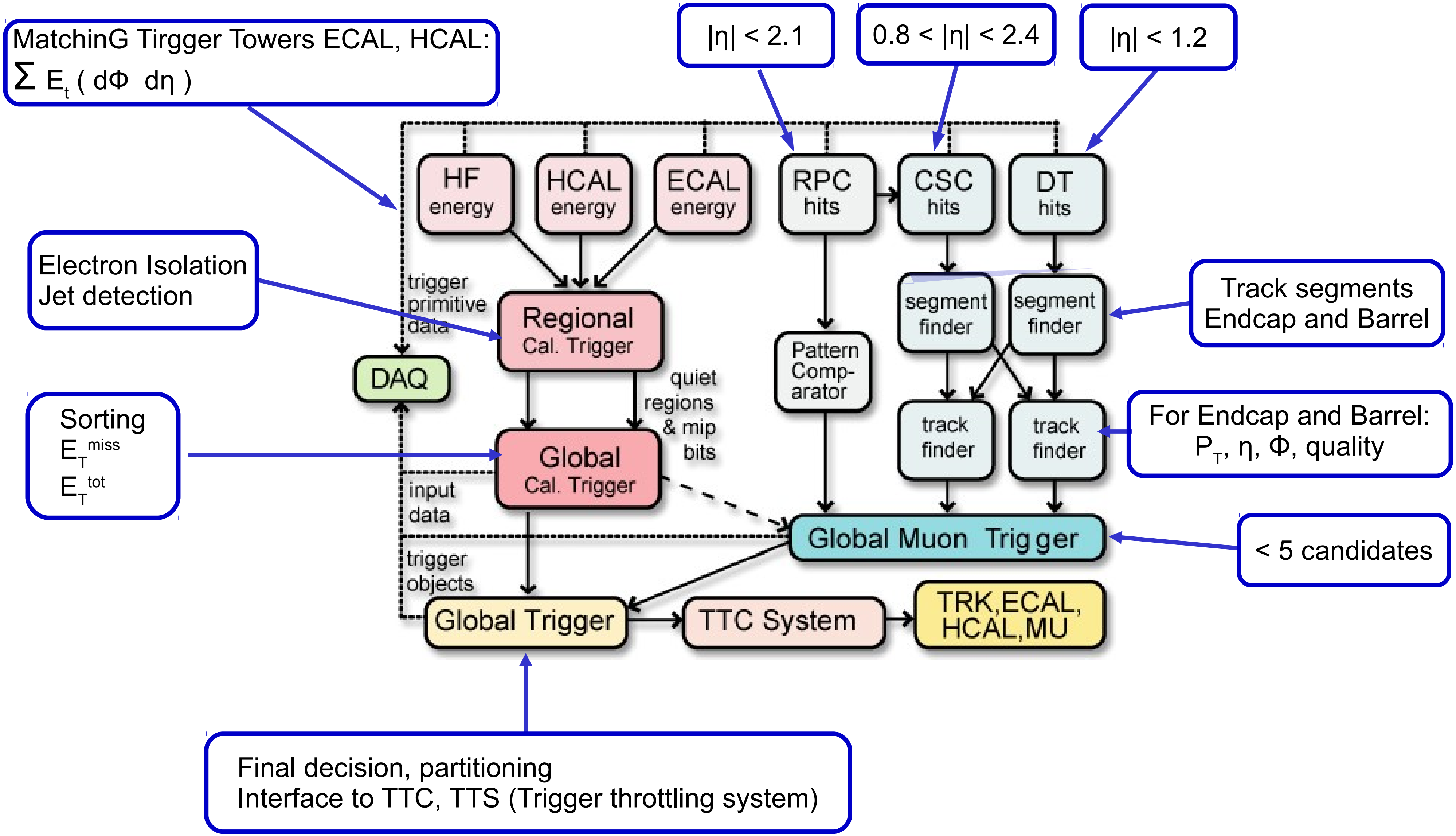
- **Algorithms to trigger on jets and tau:**
  - based on clusters 4x4 towers
  - Sliding window of 3x3 clusters



- **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

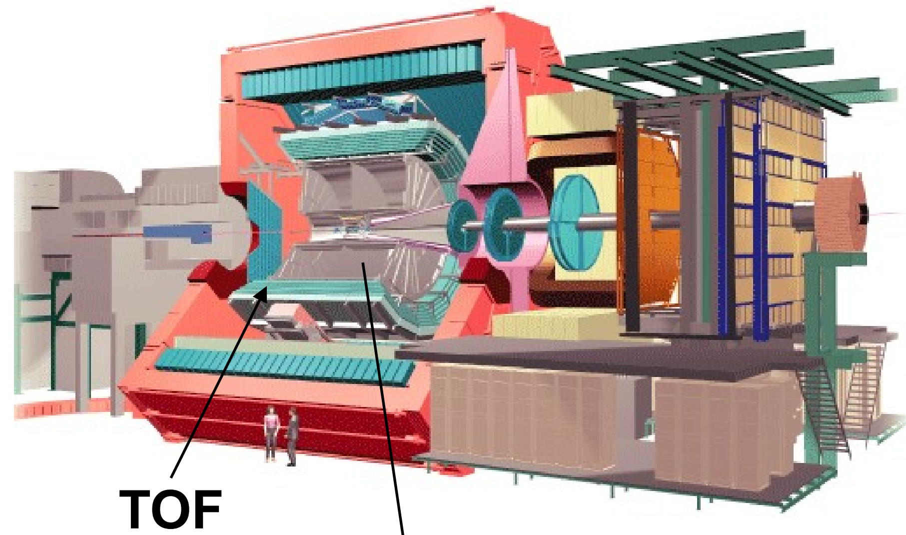
- **Forms final decision**
  - Programmable “Trigger Menu”
  - Logical “OR” of various trigger conditions
    - In Jargon these trigger conditions are called “triggers” themselves. The individual triggers may be downscaled (only take every 5th) Example:

1 μ	with Et > 20 GeV	**or**	“single muon trigger”
2 μ	with Et > 6 GeV	**or**	“di - muon trigger”
1 e/γ	with Et > 25 GeV	**or**	“single electron trigger”
2 e/γ	with Et > 15 GeV	**or**	“di - electron trigger”
	⋮		

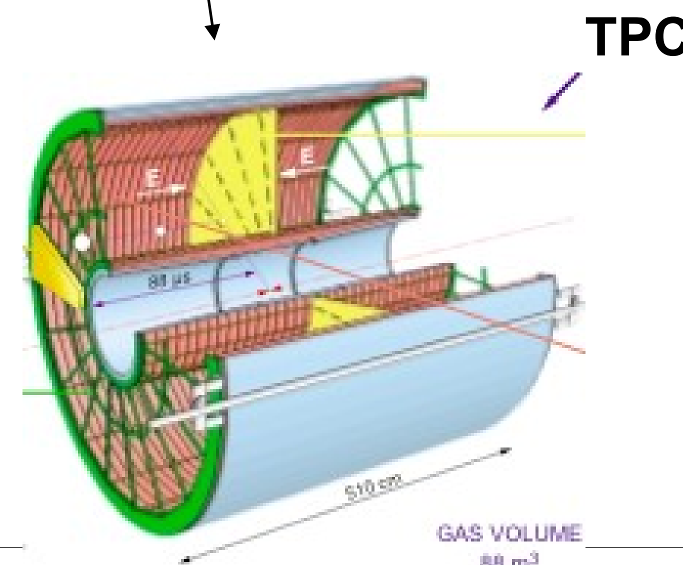
Specific solutions for specific needs: ALICE and LHCb

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 time in TPC (need to wait for TPC drift time)
  - **L2 : latency 88μs**



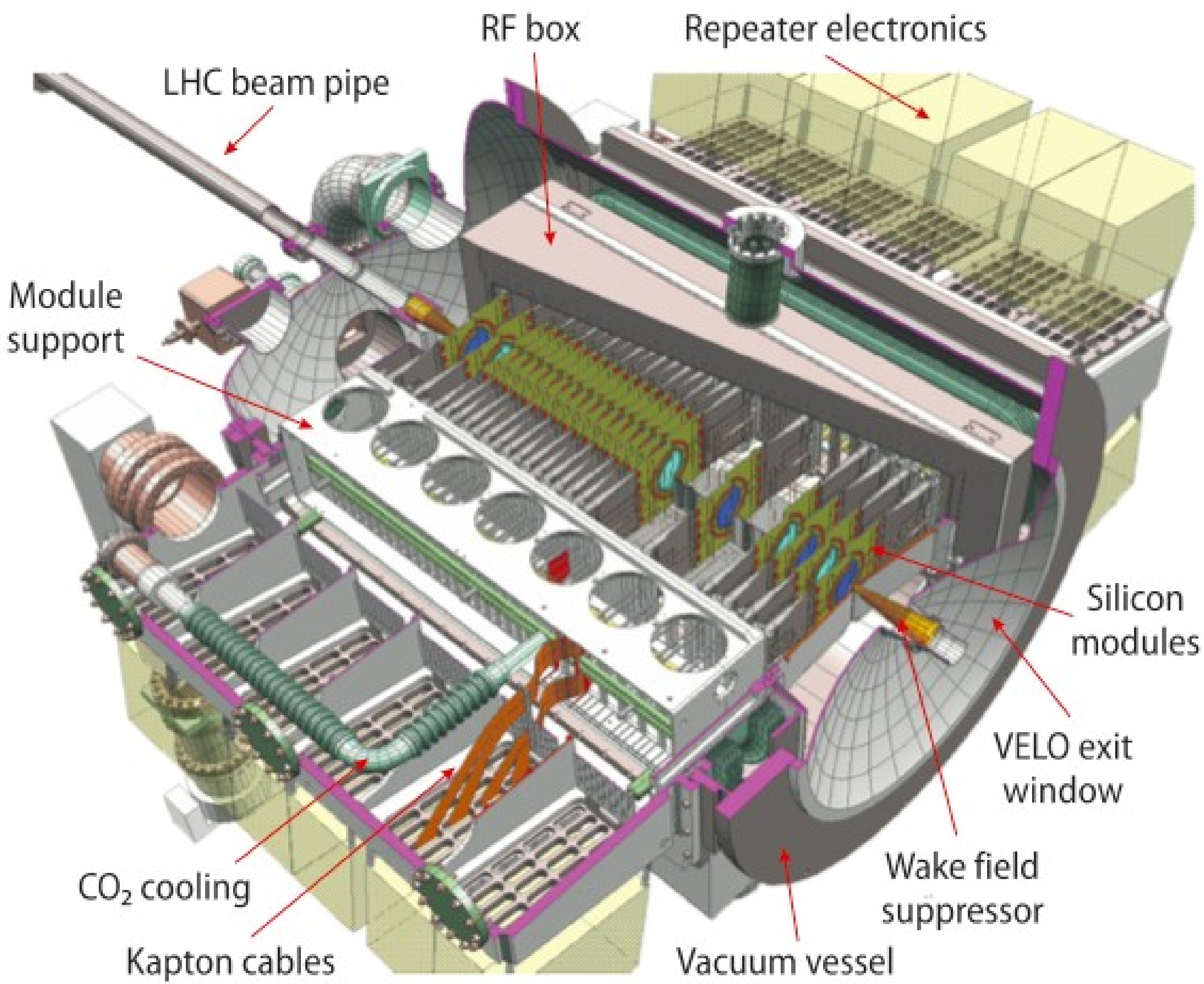
ALICE: optimizing efficiency

- **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 due to readout: triggers for not-busy clusters can be accepted.

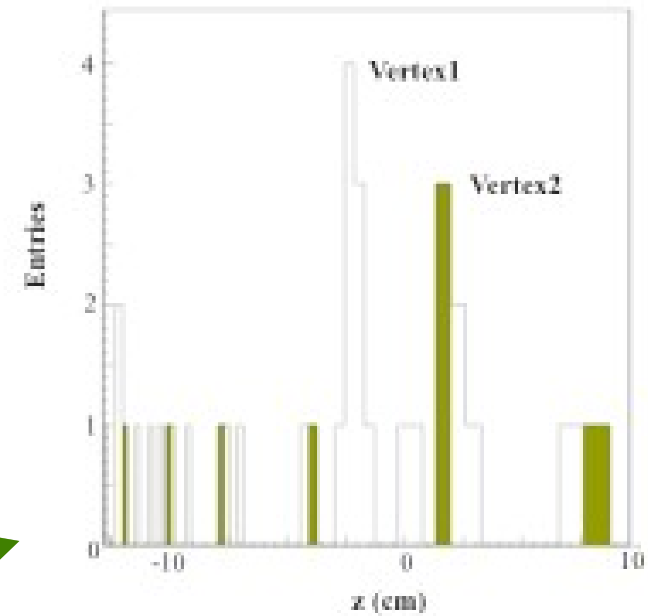
- **Triggers with "rare" classification:**
  - In general at LHC: stop the trigger if readout buffer almost full
  - ALICE:
    - "rare" triggers fire rarely and contain potentially interesting events.
    - when buffers get "almost-full" accept only "rare" triggers

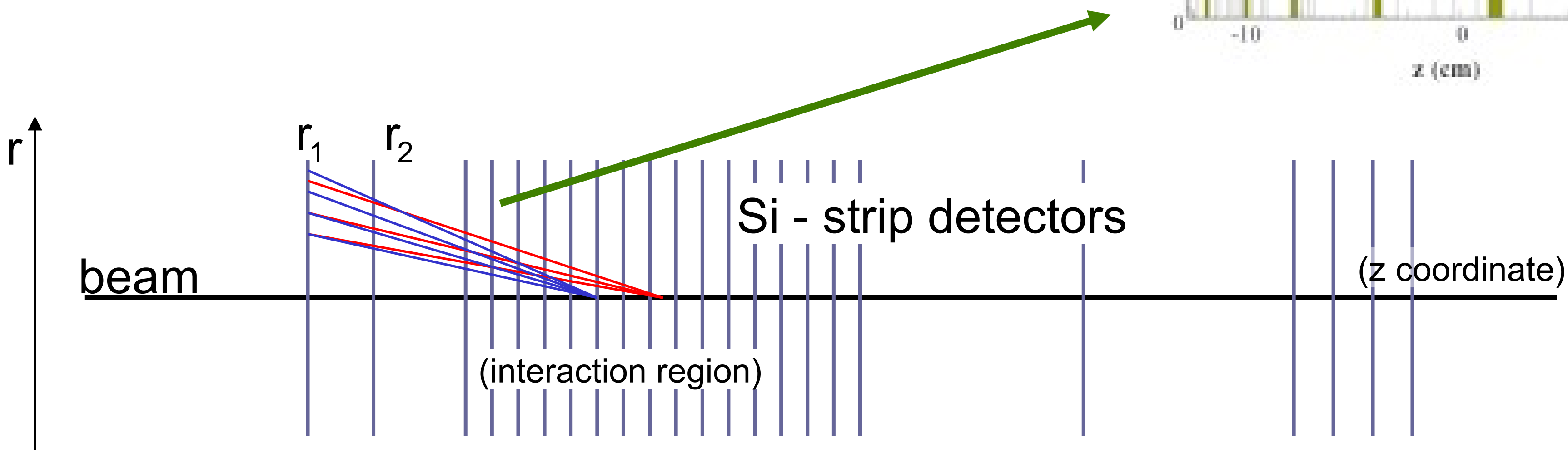
LHCb: VELO (Vertex Locator)



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



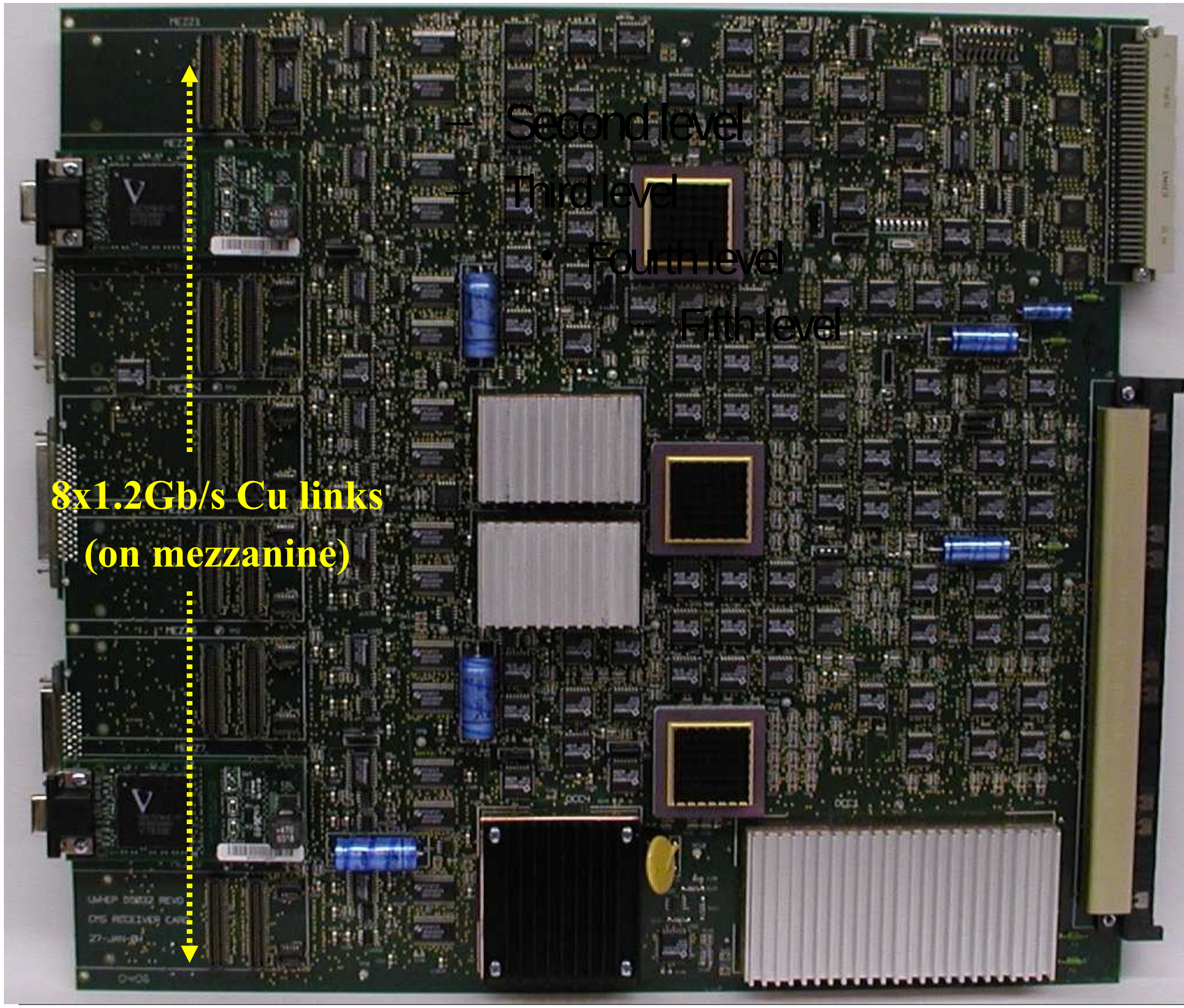


Trigger implementation

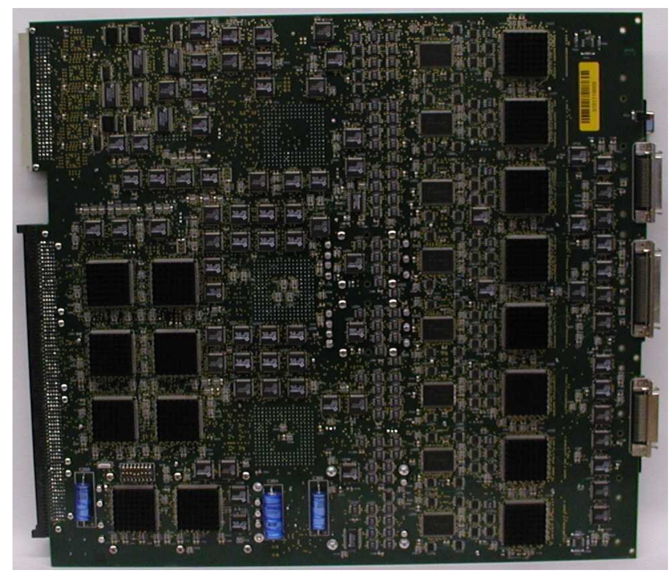
CMS: Regional Calorimeter Trigger

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

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



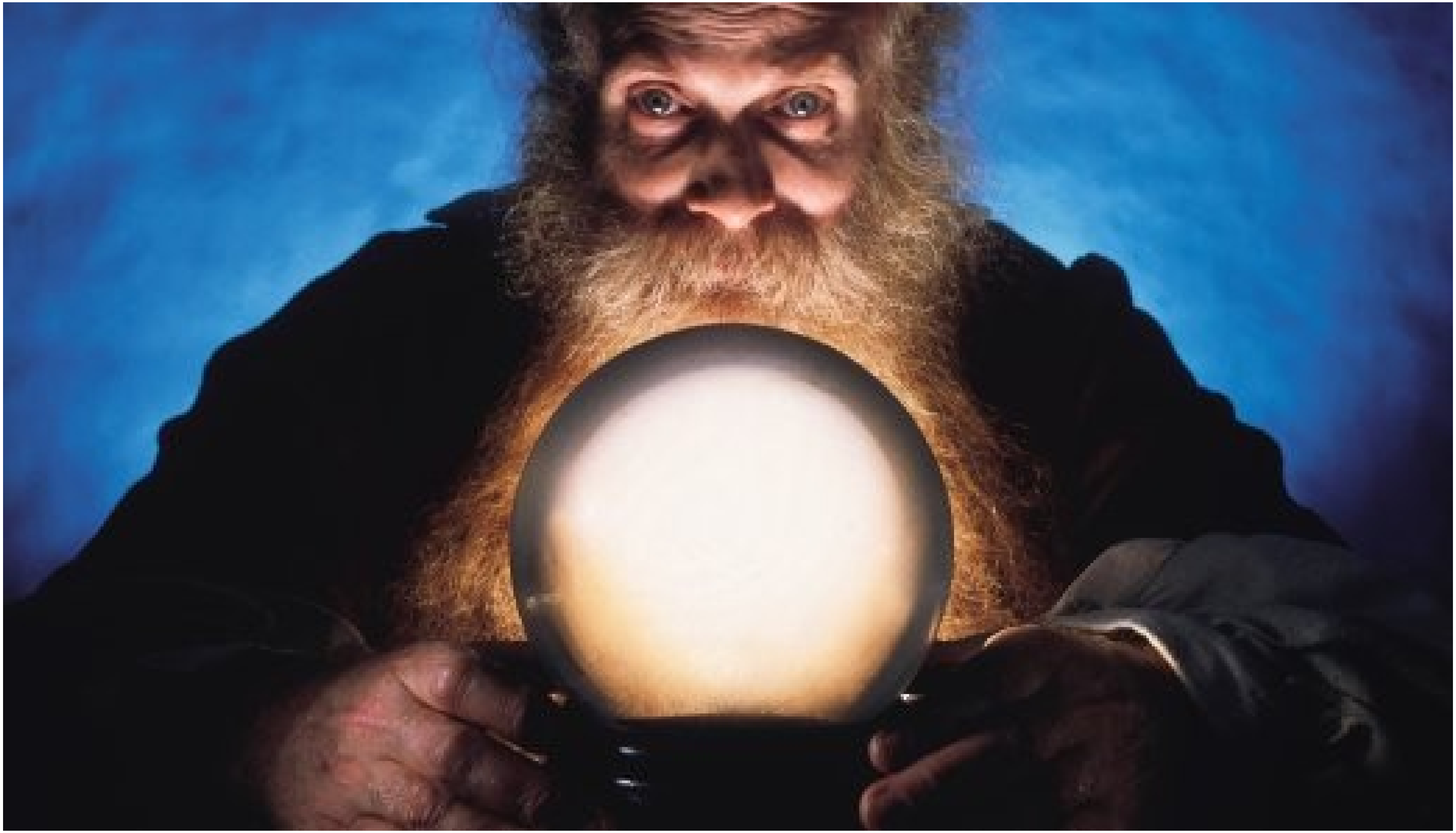
“solder” - side of the same card:



Trg. Implementation: Interconnectivity

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

??? What does the future bring us ???



Trigger upgrades: Introduction

- **LHC plans to upgrade the accelerater in the next 2 years**
  - Energy will go from 8 TeV to 14 TeV
  - Peak Luminosity from $7x10^{33}$ to approx. $2x10^{34}$
  - Not yet clear if 25ns or 50ns bunch spacing
    - Remember the relation between this and Pileup
  - **Pileup might increase well above 50**
    - The experiments were constructed for a pileup around 23

BX spacing [ns]	Beam current [$x10^{11}$ e]	Emittance [μm]	Peak Lumi [x $10^{34}cm^{-2}s^{-1}$]	Pileup
25	1.15	3.5	0.92	21
25	1.15	1.9	1.6	43
50	1.6	2.3	0.9-1.7	40-76
50	1.6	1.6	2.2	108

Trigger updates: Introduction

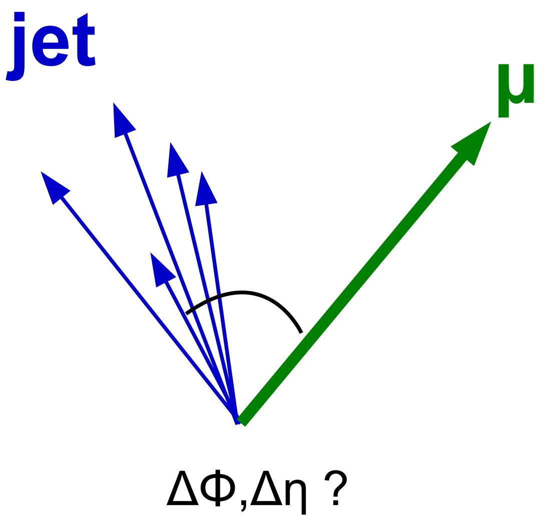
- **The high pileup degrades the performance of current trigger algorithms**
  - If nothing is done the rates exceed by far 100 kHz

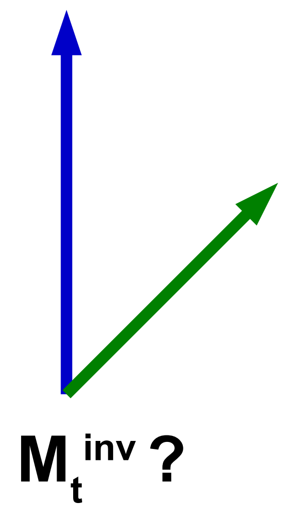
- **The new “Higgs-like” boson is relatively light (125GeV)**
  - The future physics program foresees to investigate this boson with enhanced precision.
    - This means trigger **efficiencies need to stay** at least as good as they are.
    - **Trigger thresholds cannot be increased** without “cutting into the physics”

- **The experiments need to find ways to**
  cope with the higher pileup without loosing efficiency for physics
- **General solutions:**
  - Increase resolution for trigger object: Energy, Momentum, Spacial
    - Finer grain input data to trigger
      - More input data to the trigger
      - Enhance detectors in critical high multiplicity regions (forward region)
  - More complex algorithms
    - To be implemented in modern FPGAs
    - e.g. topological triggers, calculation of invariant mass, subtraction of pileup, ...
  - Include tracking in Lvl1 Trigger

Atlas Trigger Upgrade

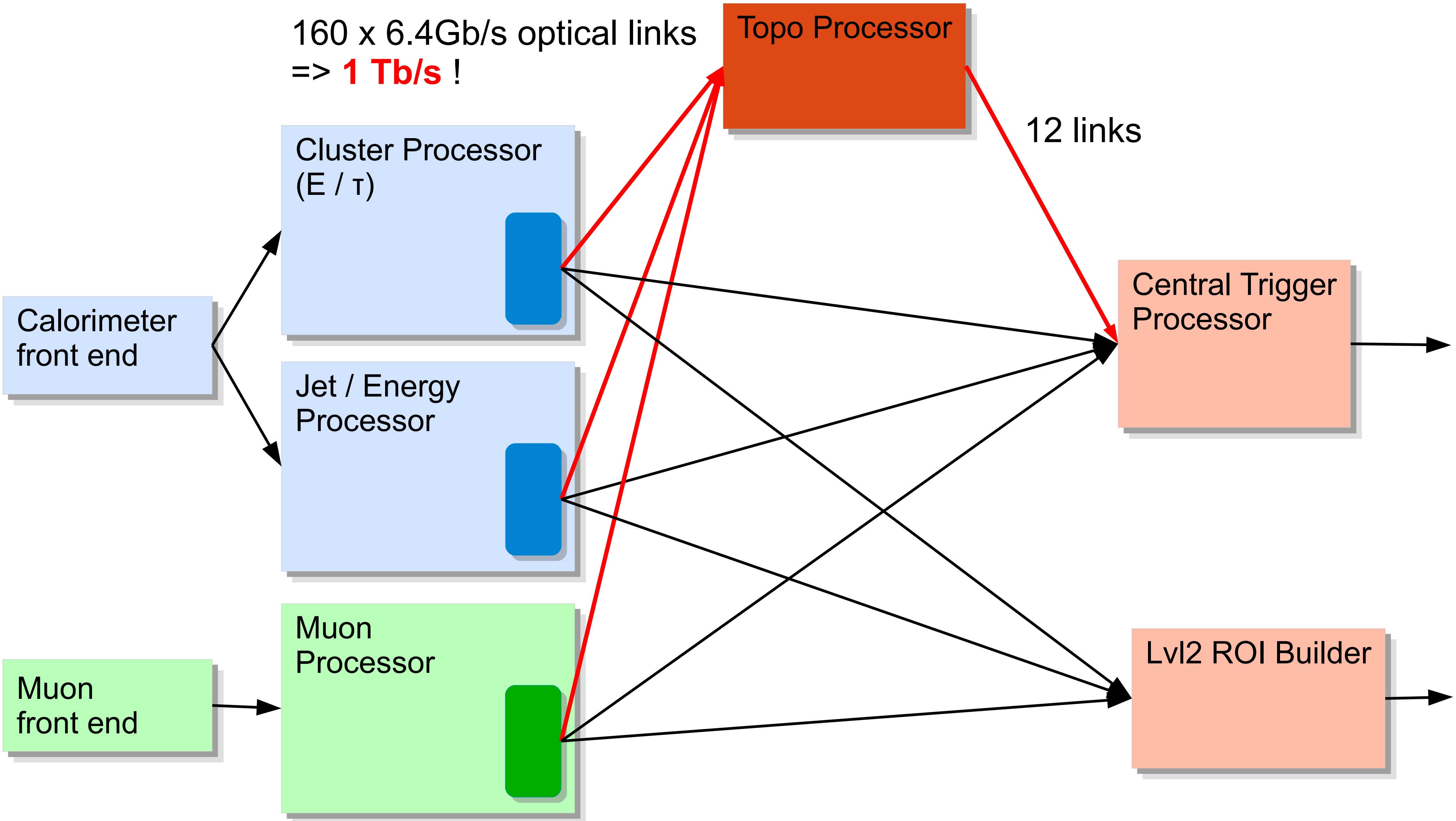
- **Keep trigger rates under control by using topology**
  - Use Trigger primitives of Lvl2: ROIs
  - Send them to dedicate topology processor based on powerful FPGAs
  - Calculate invariant masses, determine topologies like “back to back”, measure rapidity gaps, ...





Need to process topological information at Lvl1

Topological Trigger: Concept



Atlas Topological Trigger

- **Nothing comes for free...: Latency**
  - Front-end pipelines are expensive resources: **Latency budget is tight**.
  - The Topology Processor is an **additional Processing Step** in Front of the Central Trigger Processor: It “eats” from the Latency Budget.

- **ATLAS has some latency contingency**
  - Around **12 BC** contingency in the L1 latency budget can be used for the topology processor
    - This limits the complexity and number of calculations which can be done

Does it make sense to upgrade LHCb ?

- **LHCb is a high statistics experiment**
  - LHCb is doing high precision measurements which are limited by statistics
  - To significantly improve the physics results of LHCb one should increase the statistics by a **factor of 10**

- **Where can LHCb gain a factor of 10 in statistics**
  - Currently LHCb takes data with 4×10^{32}
    - Beams are on purpose separated a bit in LHCb to achieve reduce the Luminosity to this value
  - **Upgraded Lumi by factor of 5** to approx. 10^{33}

Does it make sense to upgrade LHCb ?

- **Gain another factor of 2 in B → π π**
  - Currently the efficiency of this channel is about 50% due to inefficiency in the first level trigger.
  - To gain back the 50% lost efficiency: **plan to run without Hardware Trigger**.
    - This means to construct a DAQ system with effectively 30MHz event rate.
    - Events at the luminosity of 10^{33} are expected to have 100kB
    - **This results in a 30 Tb/s Event Builder!**

  - As an emergency brake the Lvl0 Trigger will be kept and can be switched on.

Therefore...

Yes, it DOES make sense to upgrade LHCb

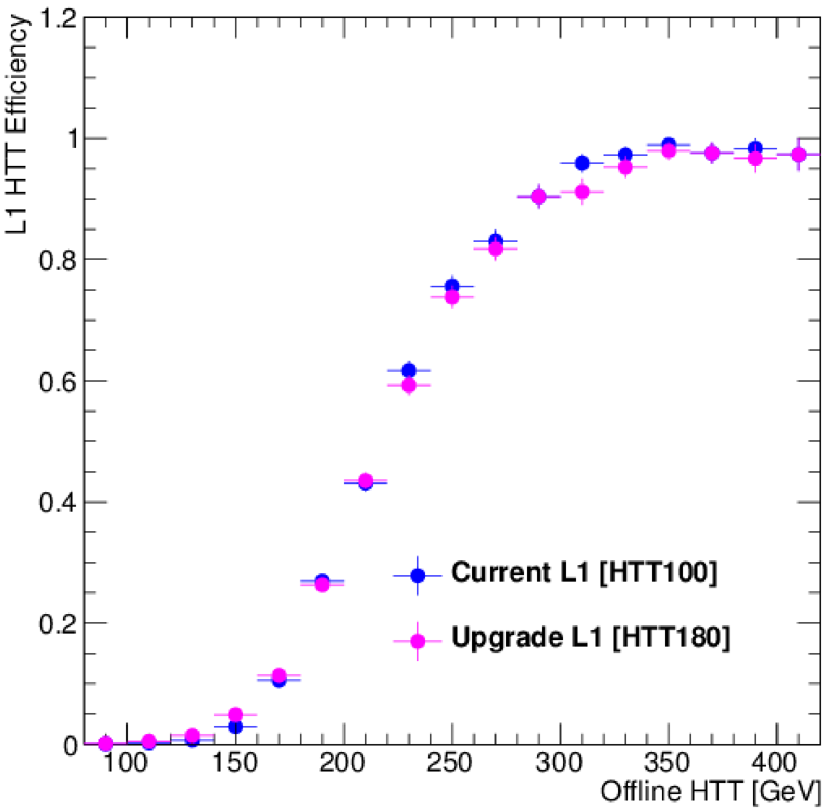
Calorimeter Trigger of CMS

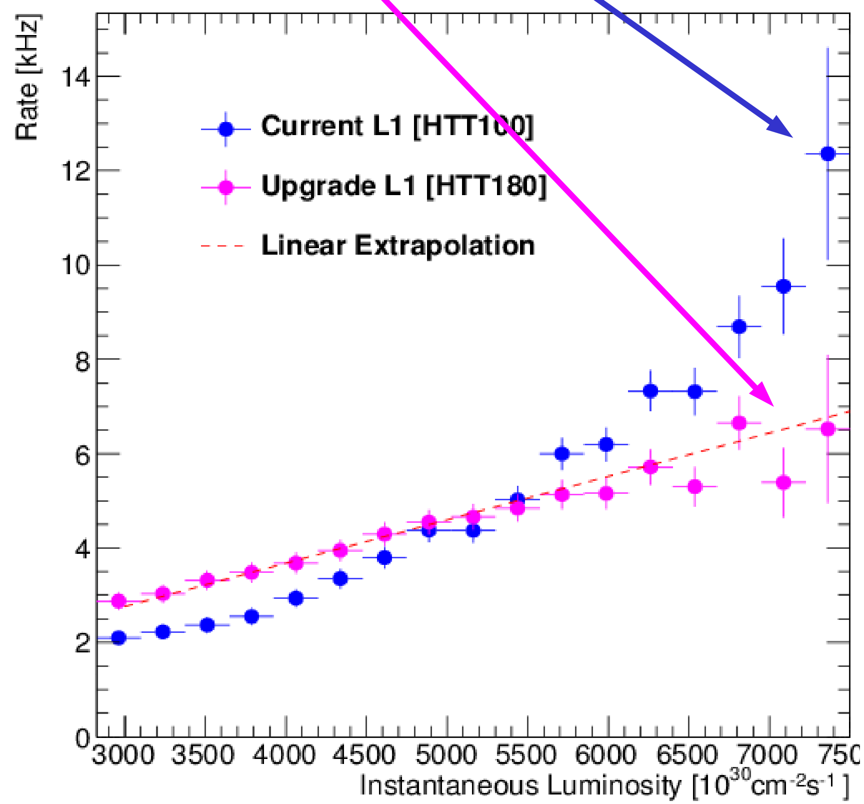
- **Upgrade of the Calorimeter Trigger electronics will bring improvements in various area**

  - Make use of full granularity of trigger primitives available.
    - (The current trigger is not able to exploit this)
  - The resulting better spacial resolution will allow to improve significantly the τ-trigger.
    - τ-triggers are based on finding small jets requiring good resolution

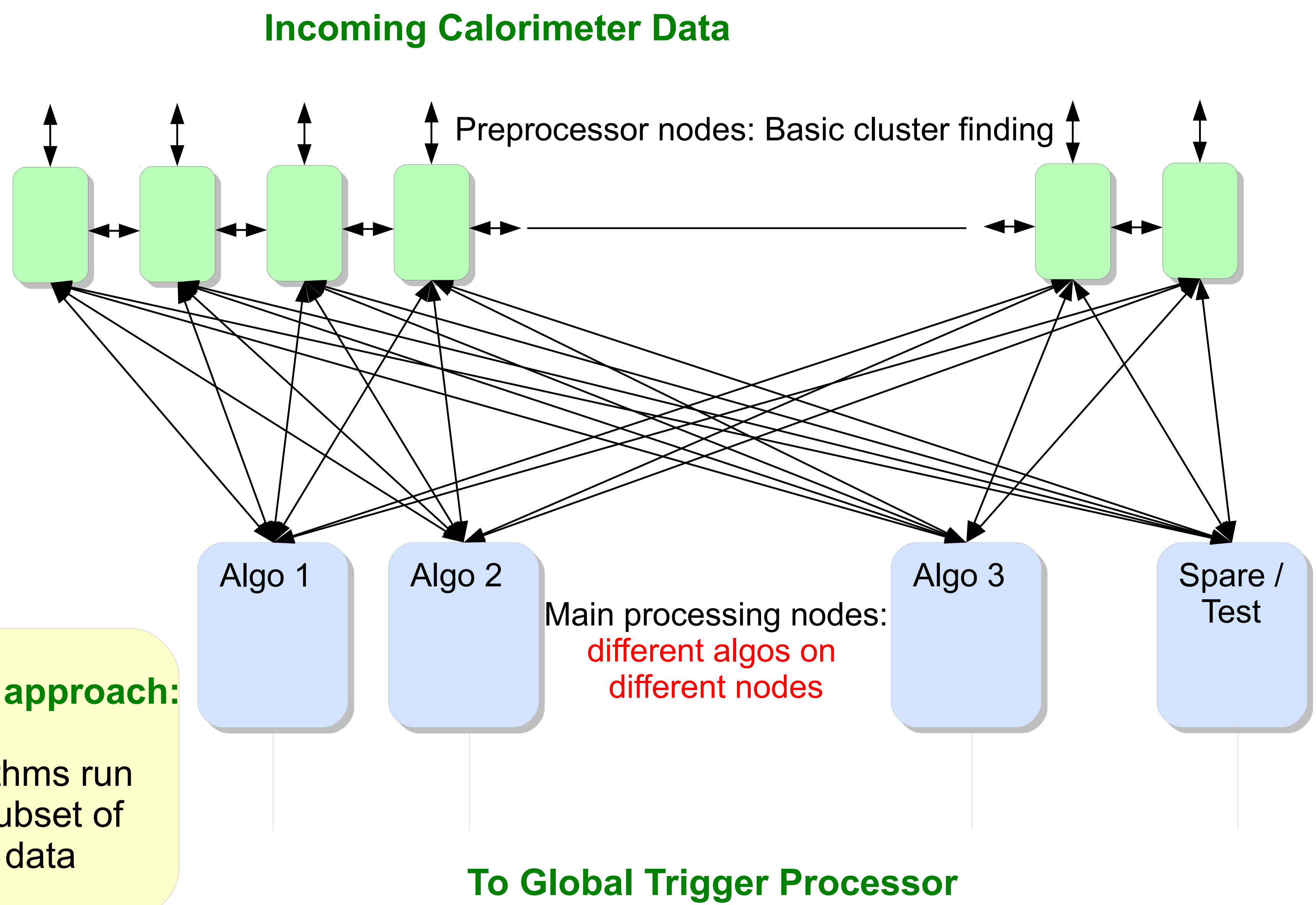
Calorimeter Trigger of CMS

- **More Complex Trigger Algos: Event by Event Pileup subtraction**
  - HTT : trigger on total transverse Jet Energy: At high pileup the rate of this trigger grows exponentially in the current system
  - With Pileup subtraction the trigger rate increases linearly with moderate slope





Upgrade of CMS Calorimeter Trigger: Variant 1

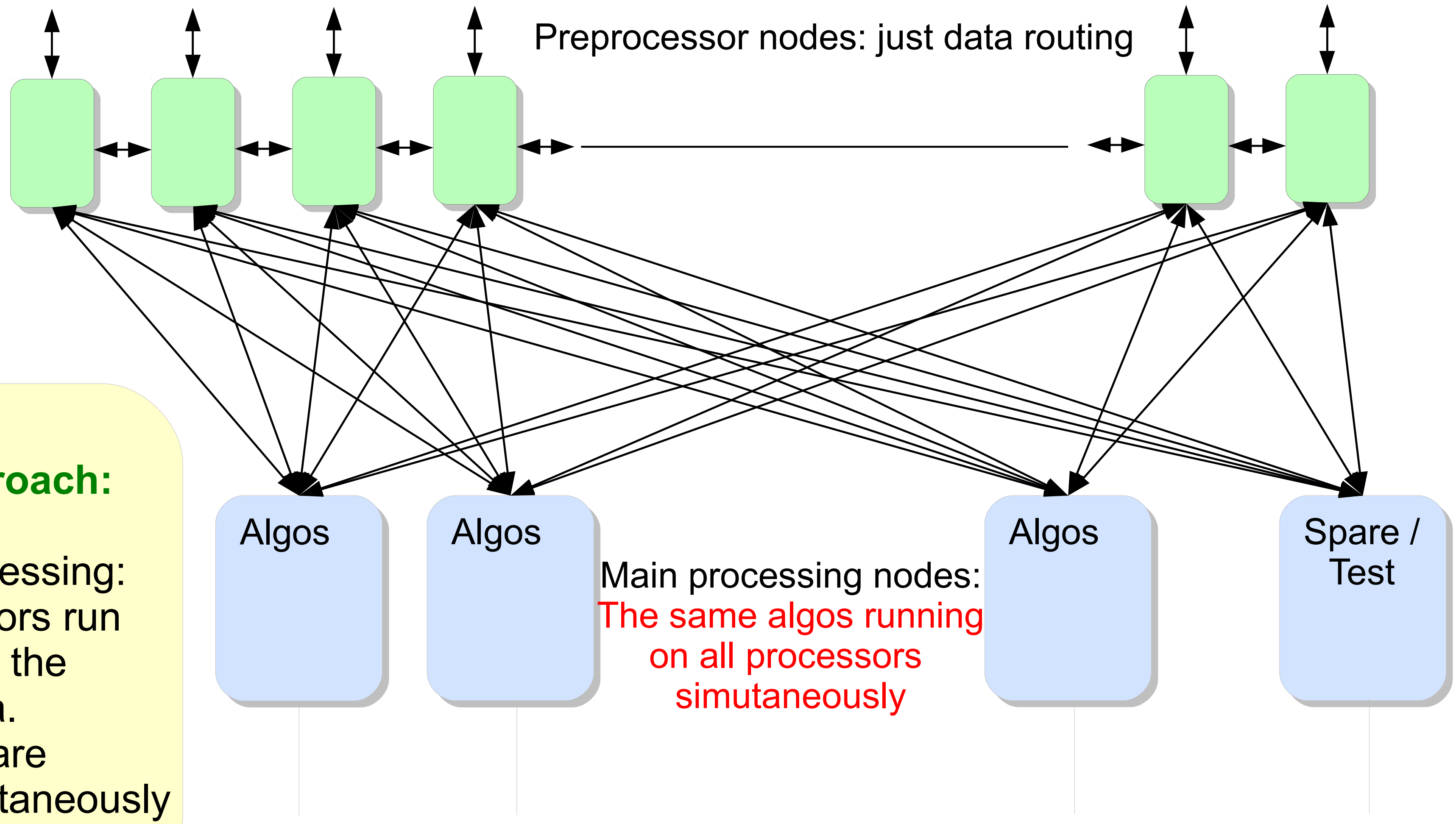


Conventional approach:

Specific Algorithms run on a specific subset of pre-processed data

CMS Calorimeter Trigger: Time Sliced

Incoming Calorimeter Data



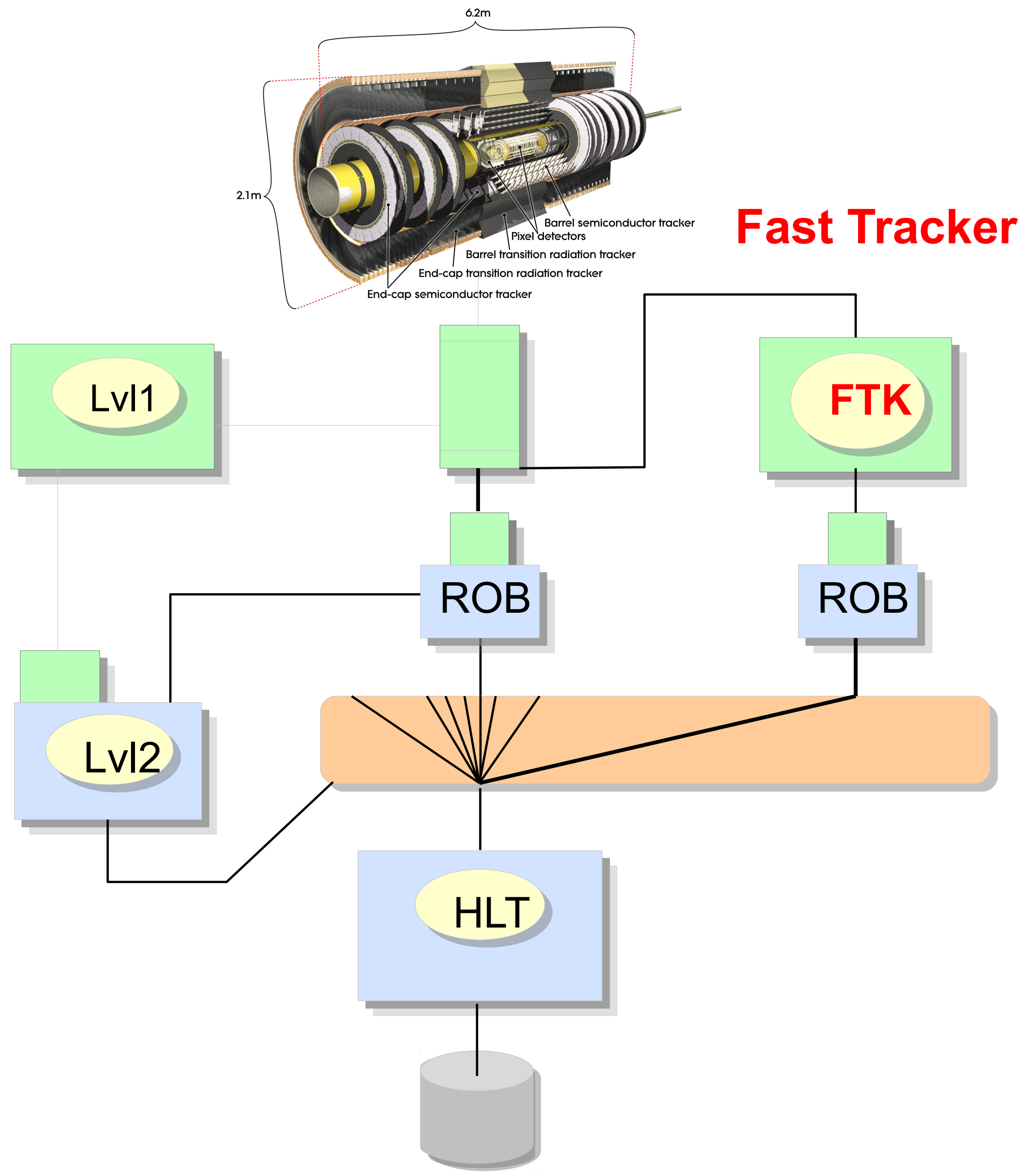
To Global Trigger Processor

Innovative approach:

Time sliced processing:
Several processors run all algorithms on the entire event data.
Several Events are processed simultaneously

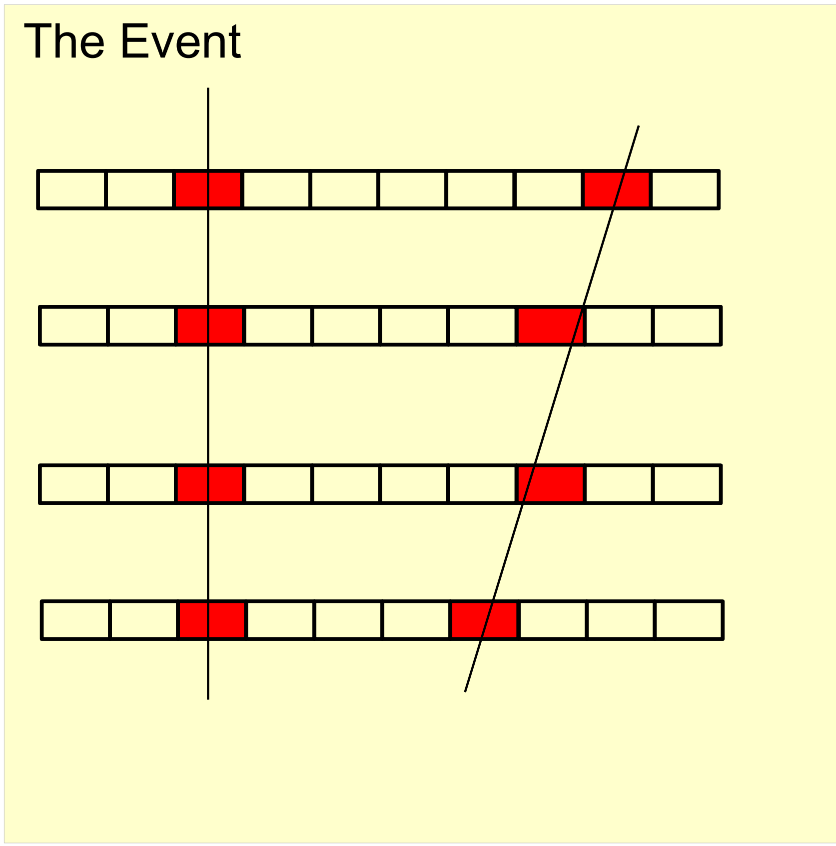
Atlas: First step to a Hw-Track Trigger

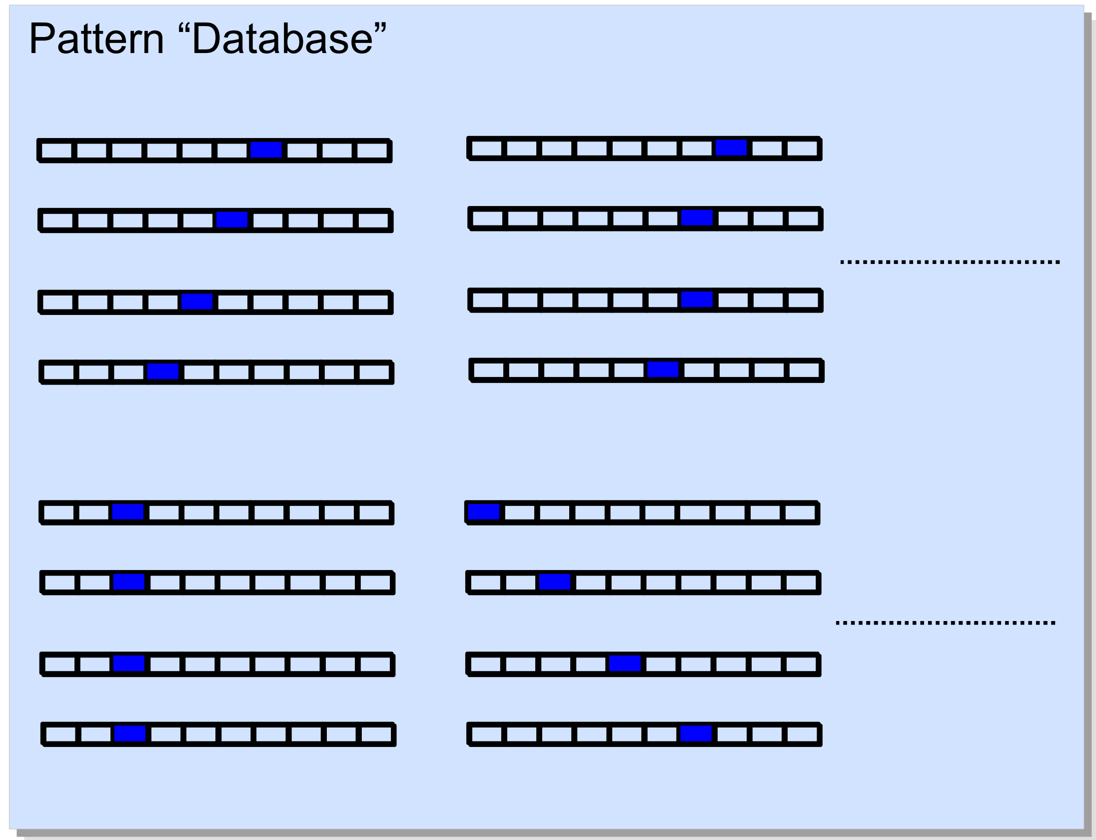
- **Track-finding is CPU intensive**
  - Especially in high pileup events the events the resources needed to do track-finding increase exponentially
- **Idea: Special highly parallel hardware processors should find tracks**
  - The output of the processor will be available at Lvl2 / Filter
  - The CPU time saved by not having to do tracking can be used for other trigger algorithms.



How to build a Hardware Tracker

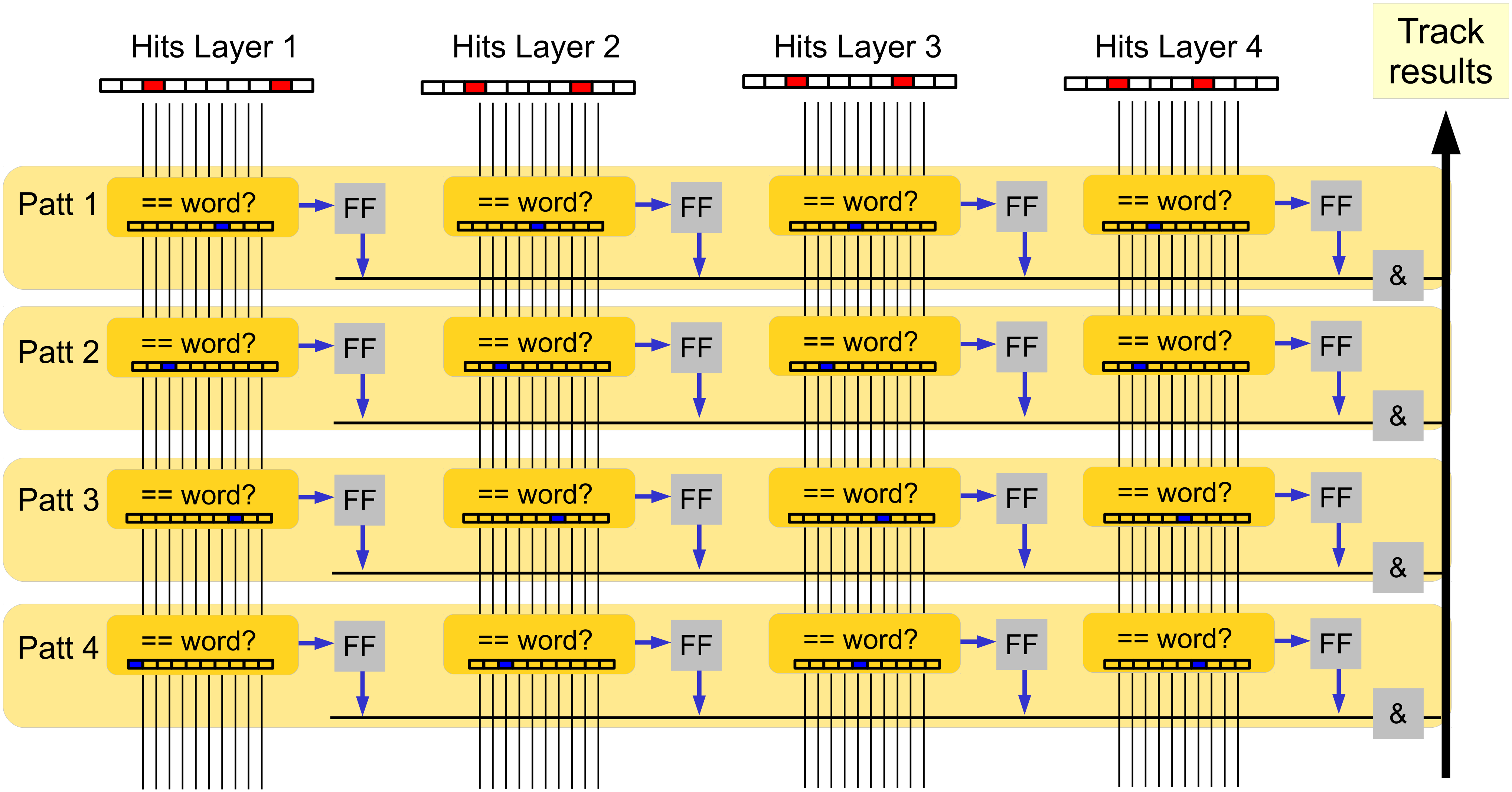
- **Compare the Event Hit Pattern with many Stored patterns**
  - The comparision with all patterns has to be done in parallel!





Implementation of Hardware Track Trigger

Principle of a CAM: Content Addressable Memory



Conclusion

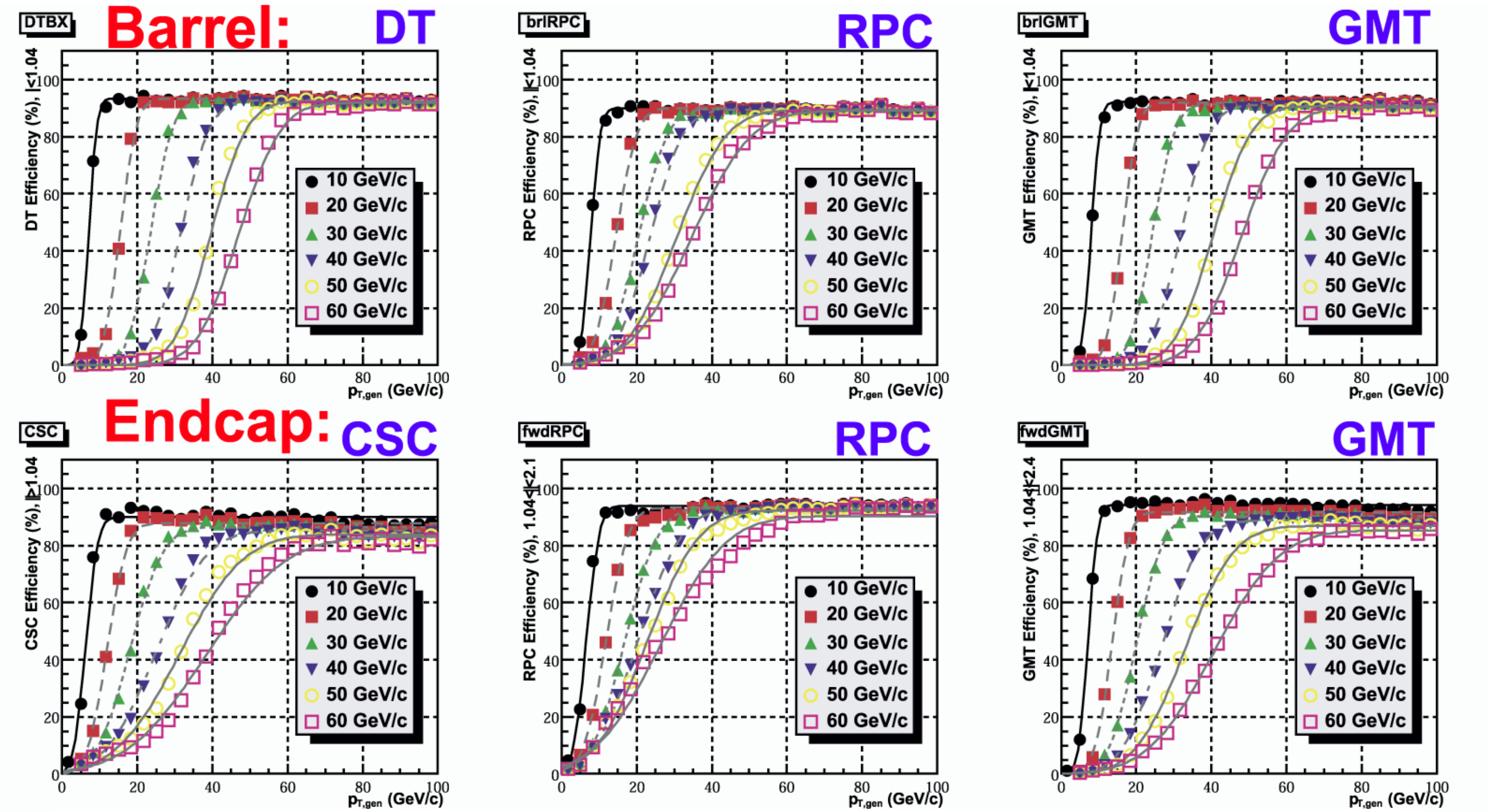
- **The concepts and techniques you learned in this school are widely applied in the LHC experiments.**

- **The design for the trigger of the LHC experiments is driven by**
  - Physics needs
  - Conditions of the accelerator
  - Compromises wrt budget

- **An exciting upgrade program has started in order to meet the experimental challenges after upgrade of the accelerator**

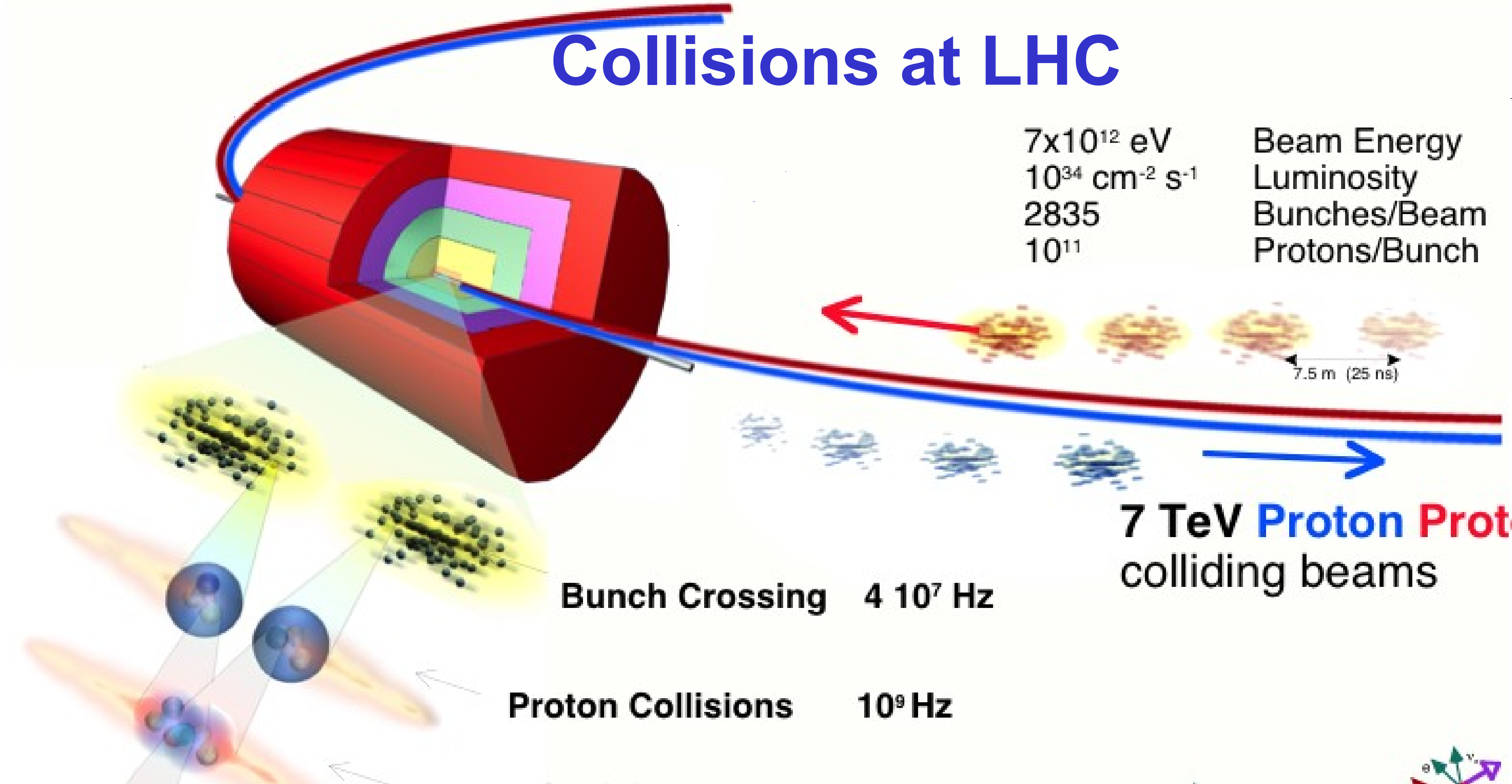
Extra slides: Lvl1 trigger

CMS Muon Trigger: Efficiency



Collisions at LHC

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



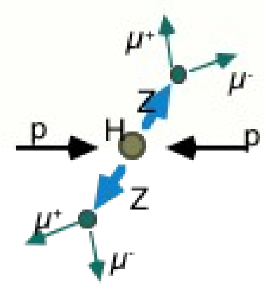
7 TeV Proton Proton
colliding beams

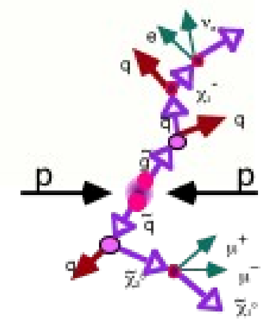
Bunch Crossing **$4\ 10^{7}$ Hz**

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

Level-1 trigger “cocktail” (low/high lumi)

Low Luminosity

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

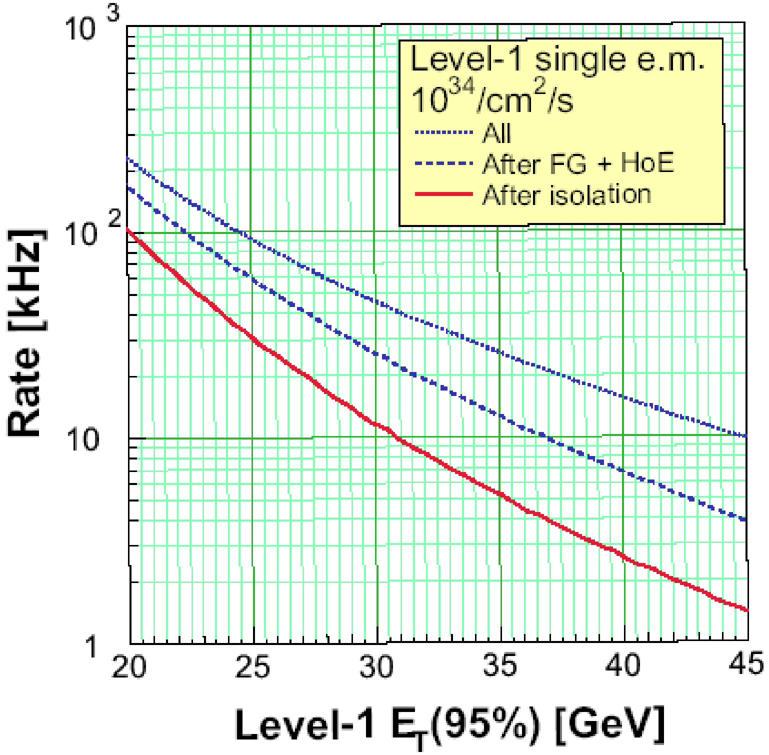
Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate(kHz)
1e/g, 2e/g	29, 17	4.3	4.3
1m, 2m	14, 3	3.6	7.9
1t, 2t	86, 59	3.2	10.9
1-jet	177	1.0	11.4
3-jets, 4-jets	86, 70	2.0	12.5
Jet & Miss-ET	88 & 46	2.3	14.3
e & jet	21 & 45	0.8	15.1
Min-bias		0.9	16.0

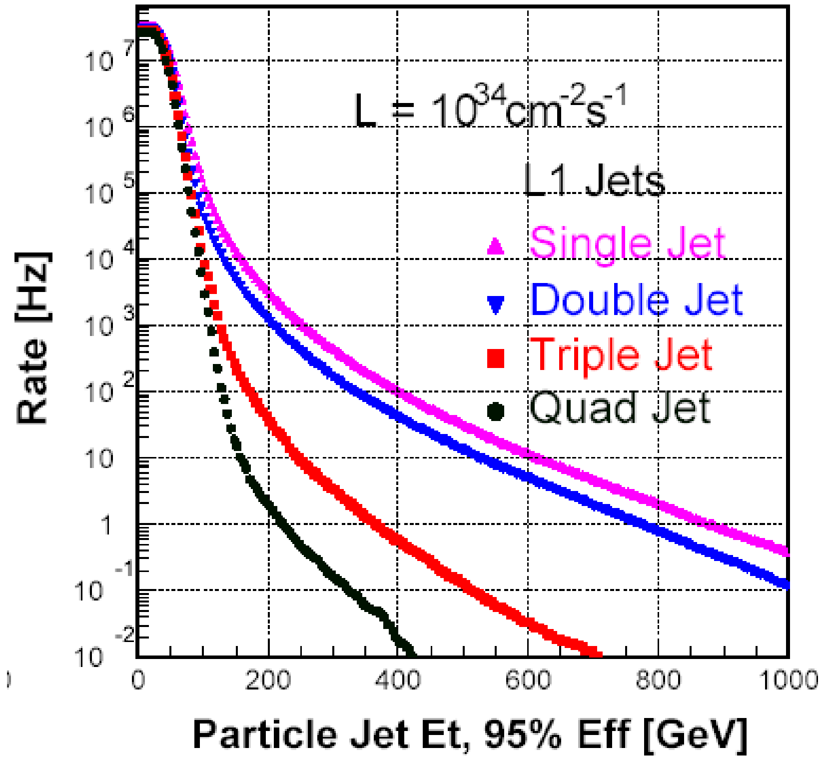
High Luminosity

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

Trigger	Threshold (e=90-95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/g, 2e/ g	34, 19	9.4	9.4
1m, 2m	20, 5	7.9	17.3
1t, 2t	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-ET	113 & 70	4.5	30.4
e & jet	25 & 52	1.3	31.7
m & jet	15 & 40	0.8	32.5
Min-bias		1.0	33.5

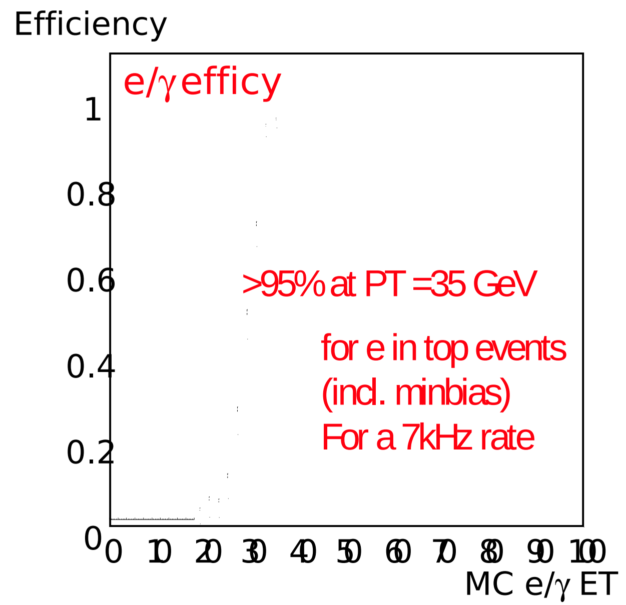
Calorimeter trigger: rates

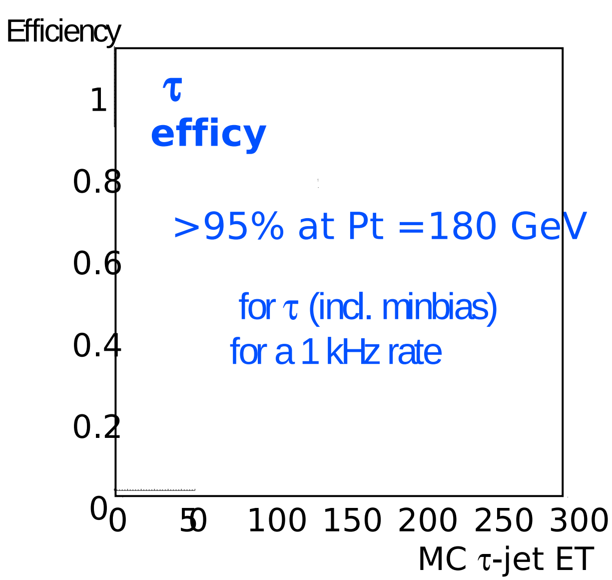


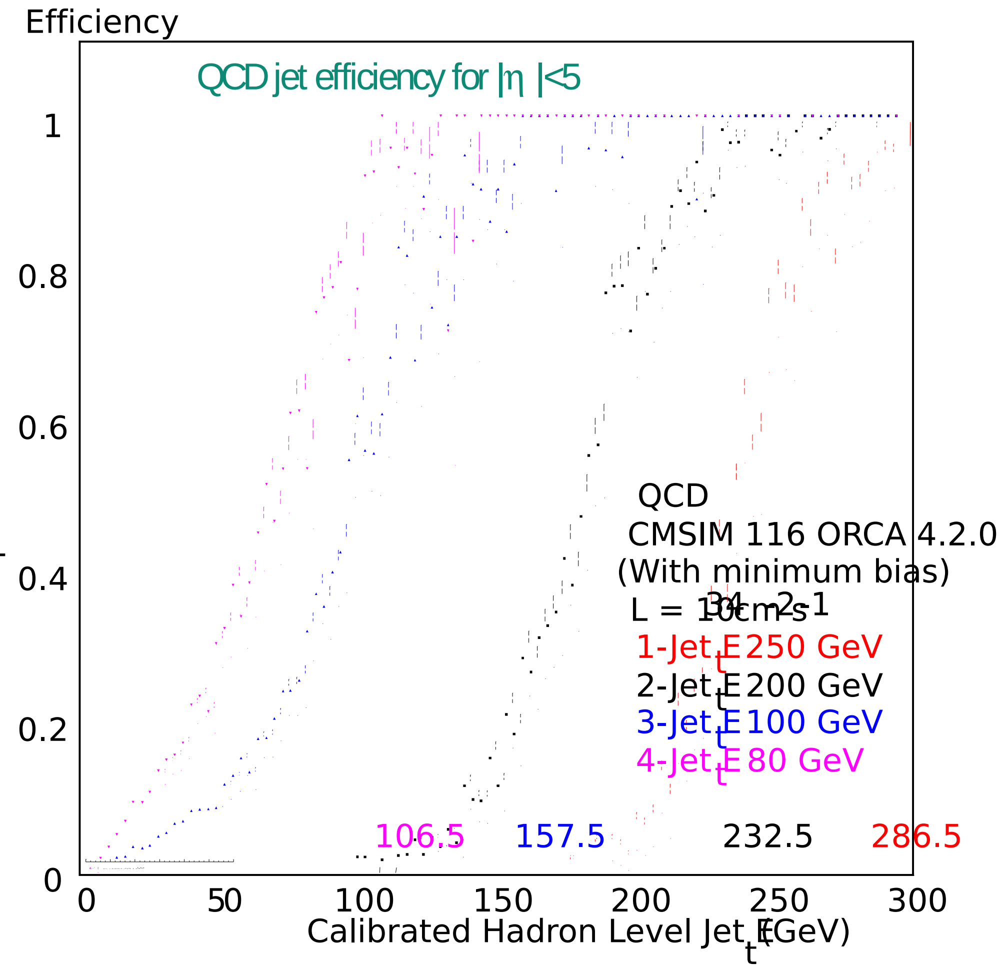


- Simulation

Calorimeter trigger: rates (Simulation)







>95% at PT =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 -> ㄹㅅ ㄹㅅ H -> ZZ* -> 4l
  - Trigger on electromagnetic clusters, lepton-pairs
  - If Higgs is heavier other channels will be used to detect it
  - H -> ZZ -> llㄷ ㄷ
  - H -> WW -> lㄷ jj
  - H -> ZZ -> lljj
  - Need to trigger on lepton pairs, jets and missing energies

- **Supersymmetry**
  - Neutralinos and Gravitinos generate events with missing Etmiss
  - Squarks decay into multiple jets
  - Higgs might decay into 2 taus (which decay into narrow jets)

Trigger at LHC startup: L=1033cm-2s-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.

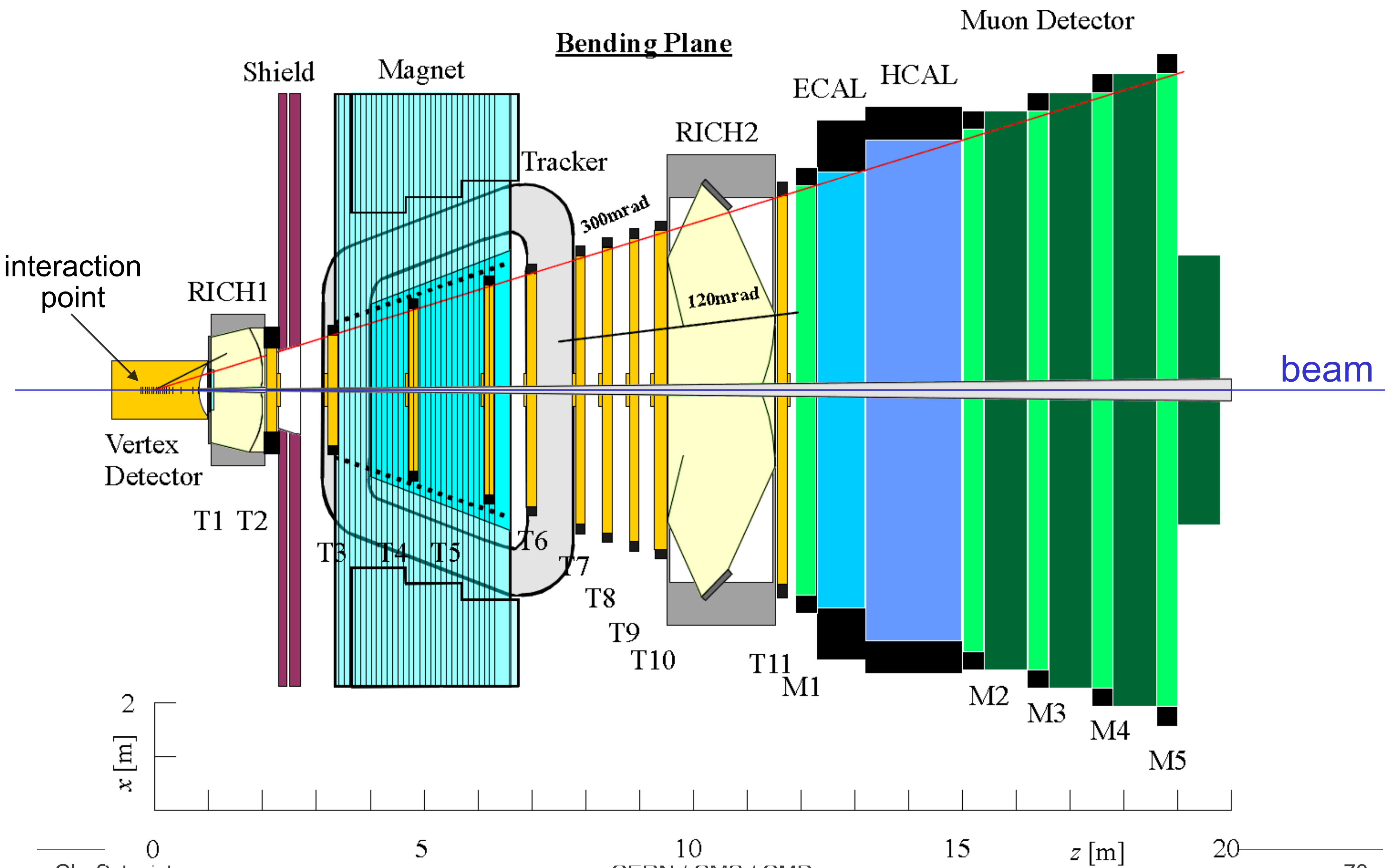
LHCb

- **Operate at L = 2 x 1032 cm-2s-1: 10 MHz event rate**

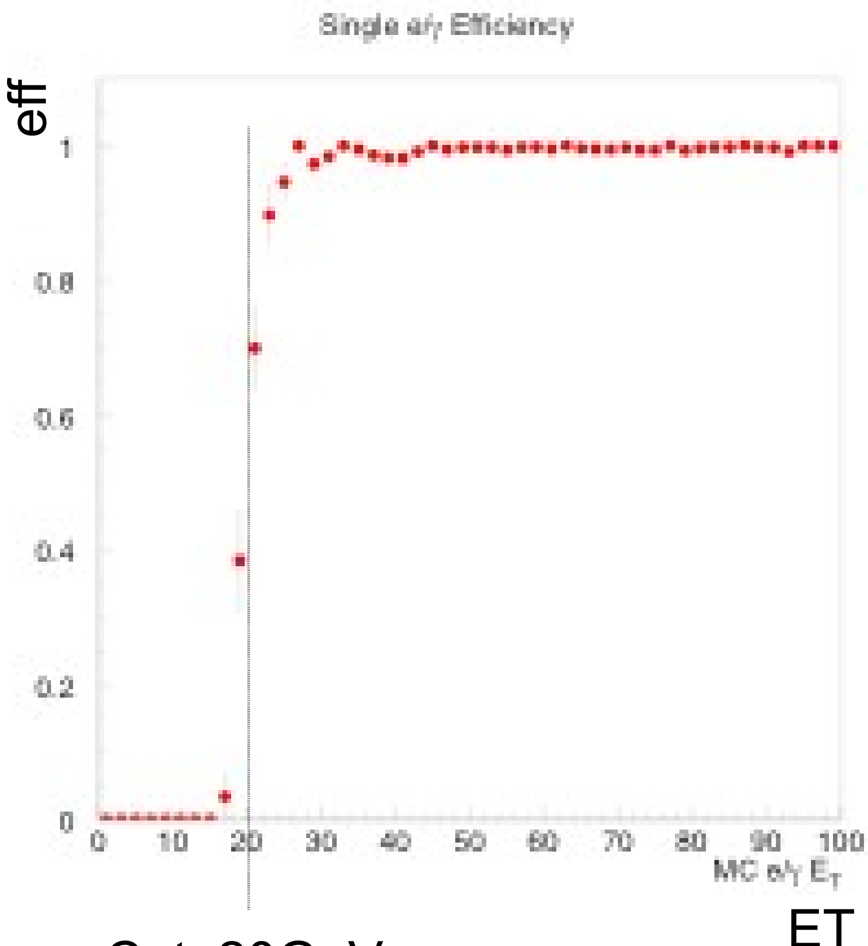
- **Lvl0: 2-4 us latency, 1MHz output**
  - Pile-up veto, calorimeter, muon

- **Pile up veto**
  - Can only tolerate one interaction per bunch crossing since otherwise always a displaced vertex would be found by trigger

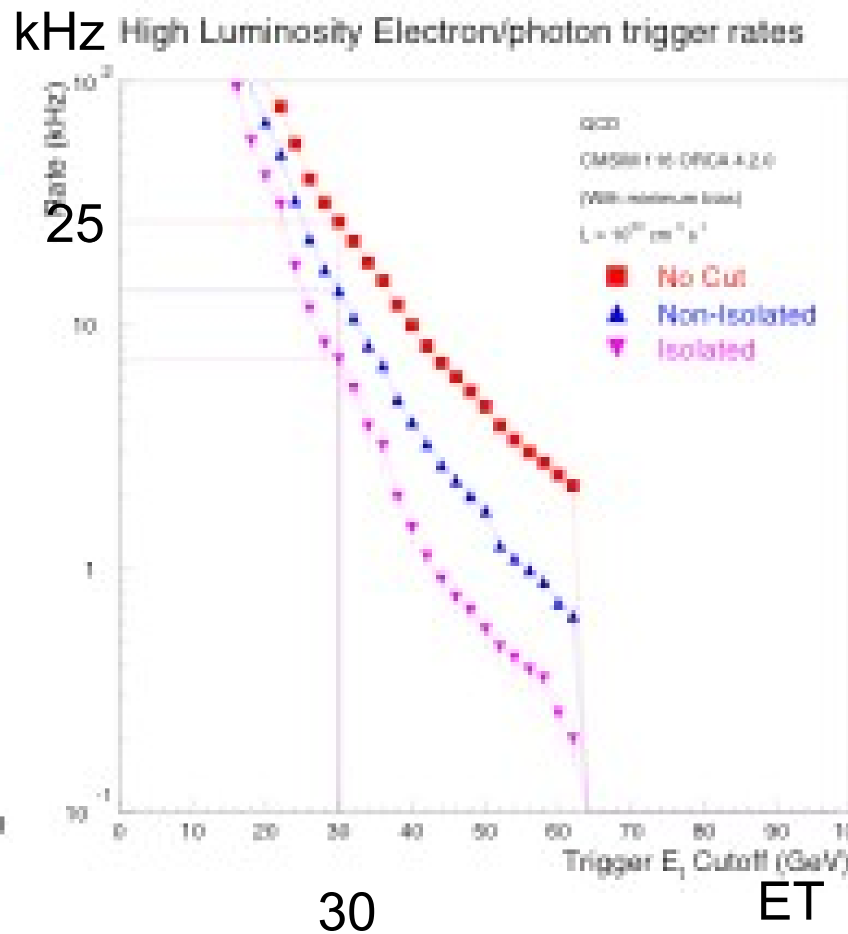
LHCb : study of B-decays (CP)



CMS isolated e/γ performance



Cut: 20GeV



The 1st level trigger at LHC experiments

Requirement:

Do not introduce (a lot of) dead-time

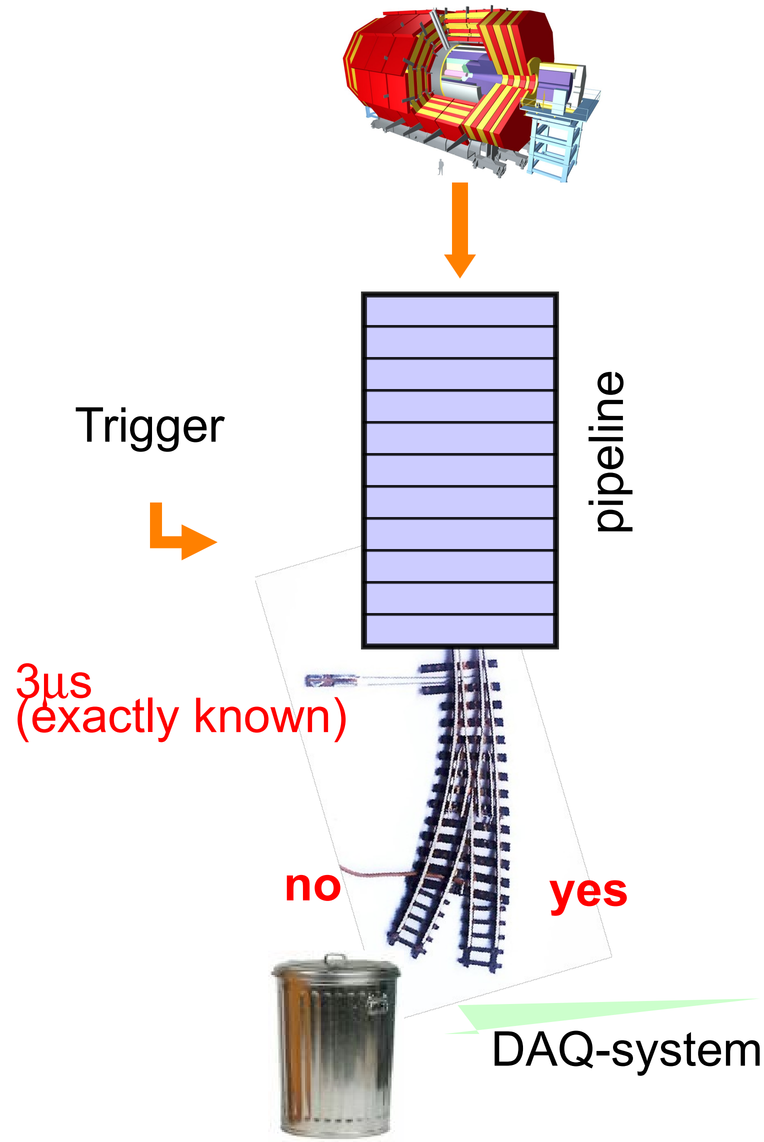
- O(1%) is tolerated
- Introduced by trigger rules :
  not more than n triggers in m BX
- Needed by FE electronics

Need to implement pipelines

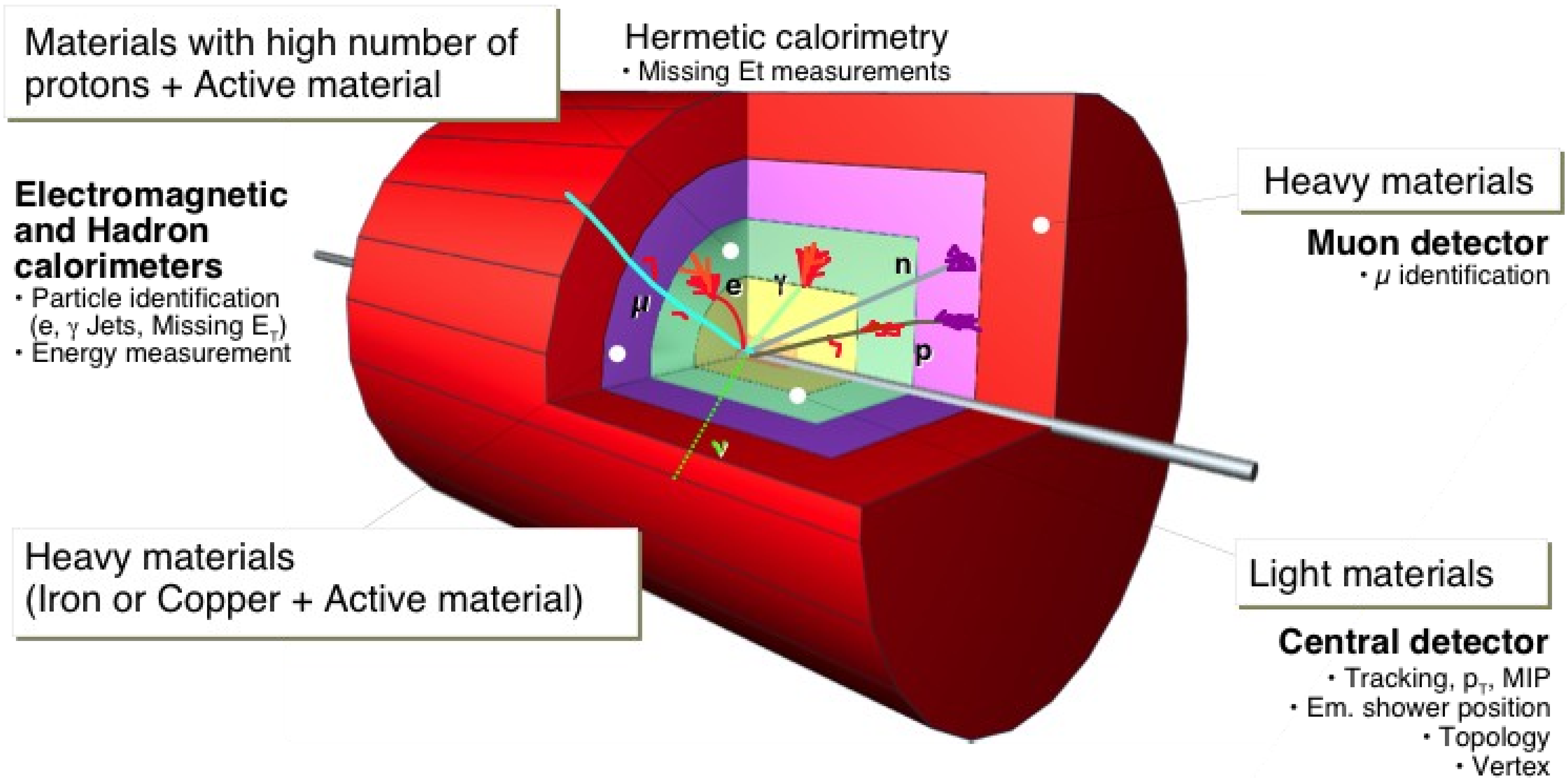
- Need to store data of all BX for latency of 1st level trigger
- Typical : 107 channels / detector
  some GB pipeline memory
    - and derandomizer buffers
- Also the trigger itself is “pipelined”

Trigger must have low latency (2-3 μs)

- Otherwise pipelines would have to be very long



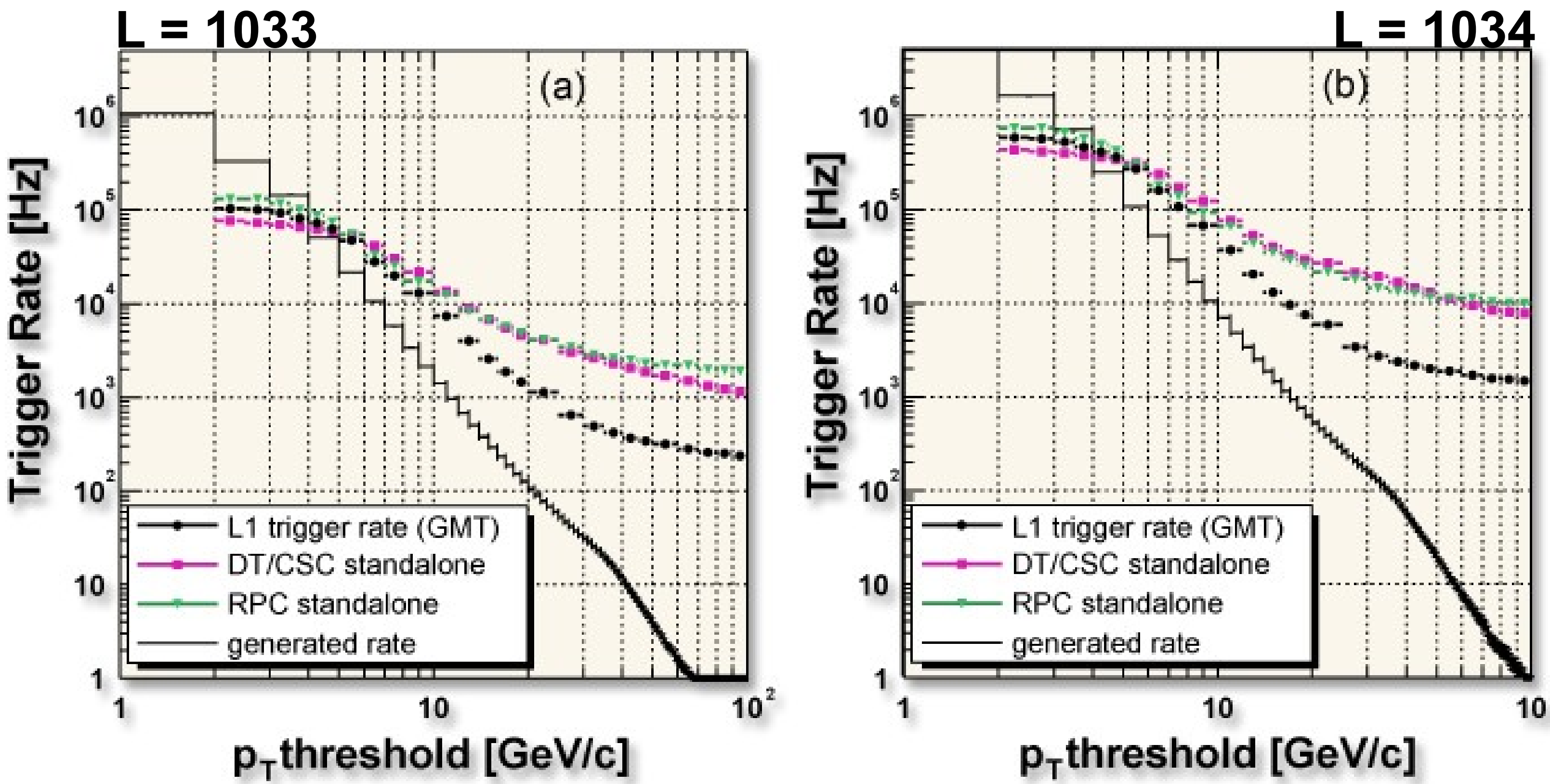
LHC Detector: main principle



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)



pt > 20GeV:

≈ 100 Hz generated,

≈ 1 kHz trigger rate

pt > 20GeV:

≈ 600 Hz generated,

≈ 8 kHz trigger rate

Triggering at LHC : what info can be used

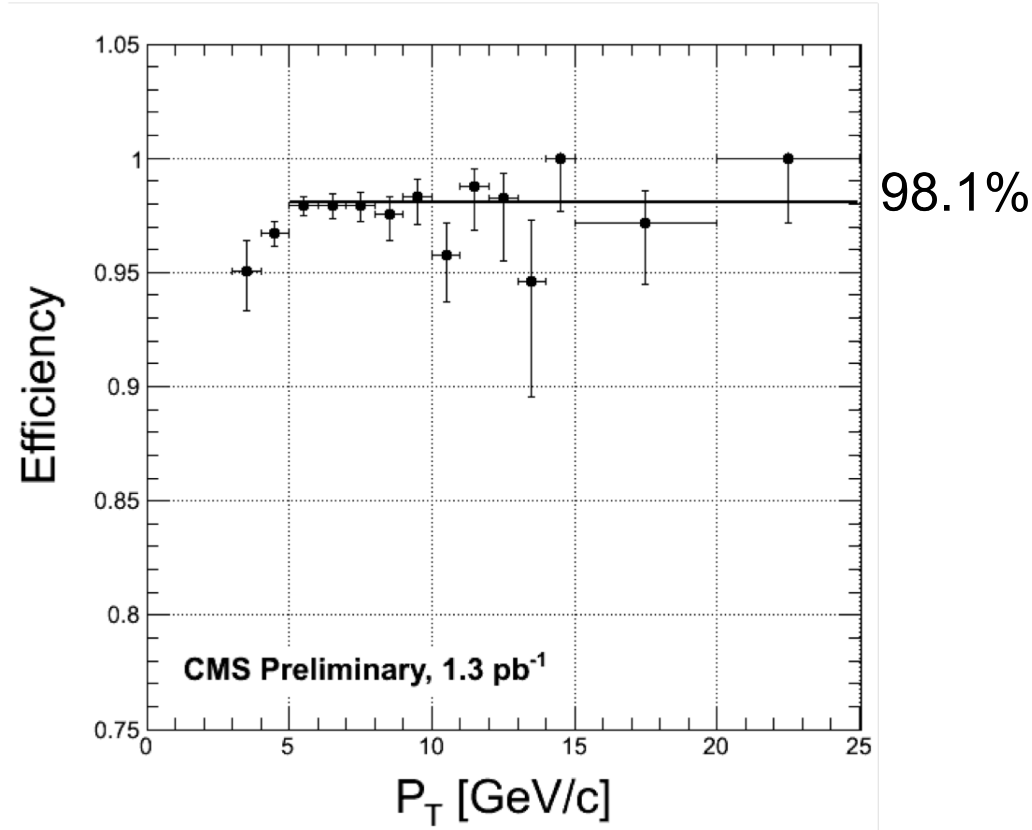
- **Measurements with Calorimeters and Muon chamber system**

- **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 (pt 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)

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



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 ET 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)