The Trigger for experiments at the Large Hadron Collider

Aleandro Nisati
INFN Sezione di Roma

Incontri di Fisica delle Alte Energie

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Outline

- The LHC Physics Program
- The requirements to trigger systems for experiments at the LHC
- ATLAS, CMS and LHCb
- Conclusions

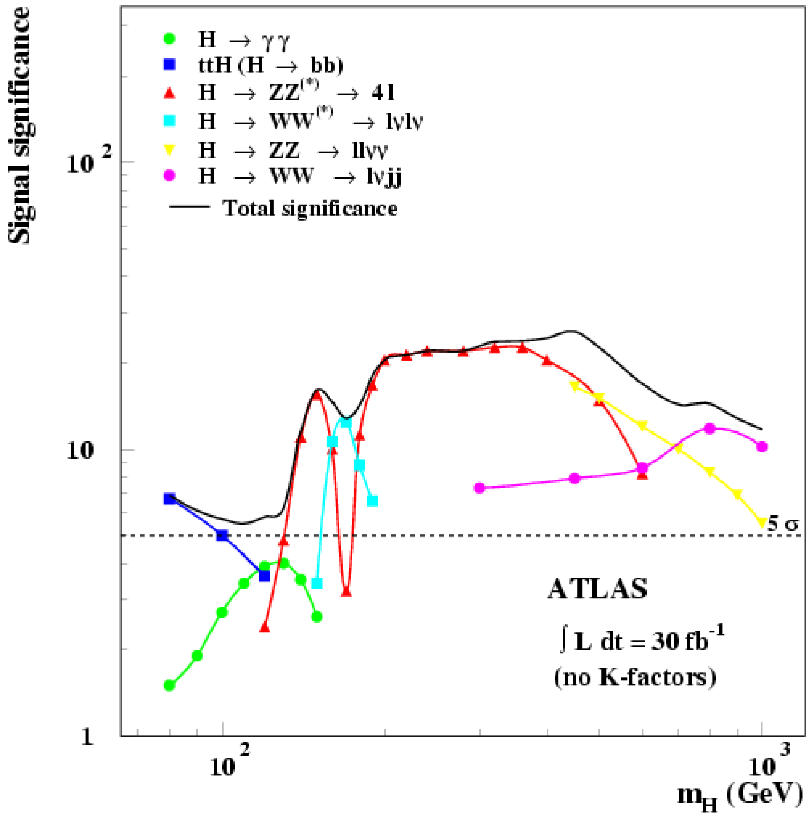
The Large Hadron Collider

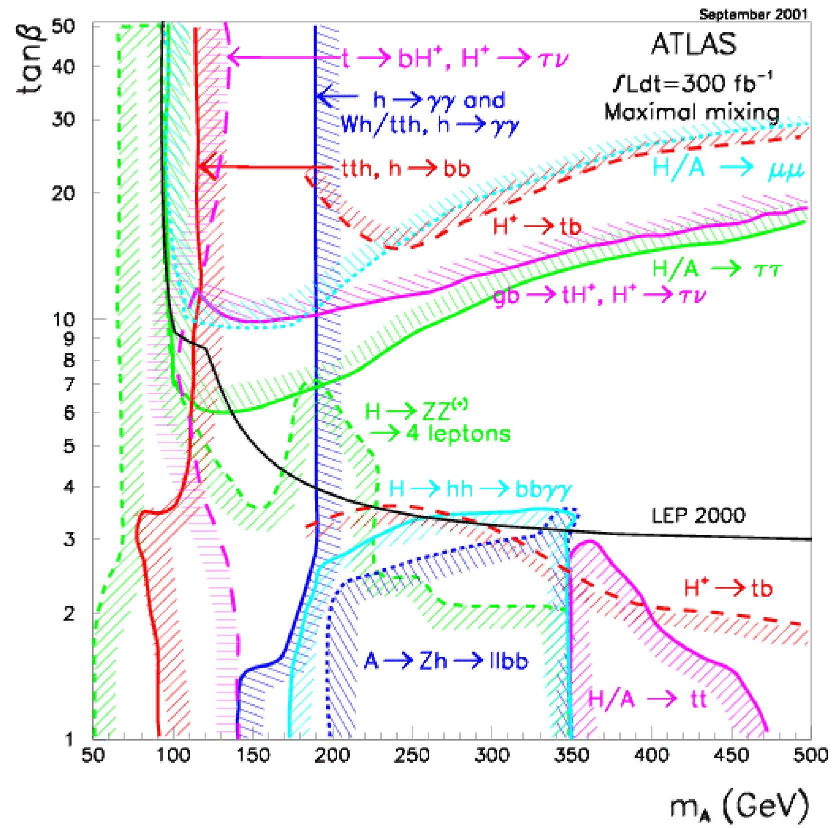
- Proton-proton
  - CM Energy = 14 TeV
  - L=10^{34} cm^{-2} s^{-1} : ATLAS, CMS; (L=2x10^{33} cm^{-2} s^{-1} initial luminosity for about 1.5 years);
  - L=2x10^{32} cm^{-2} s^{-1} : LHCb
  - Bunch Spacing: 25ns
- Lead-Lead
  - CM Energy = 1312 TeV
  - L=10^{29} cm^{-2} s^{-1} : ALICE

The LHC Physics Programme

- Origin of the particle masses: search for the Higgs boson(s);
- SuSy particles;
- Standard Model Physics;
- Origin of the Matter Anti-matter imbalance in the universe: SM CP-violation not sufficient; least tested aspect of the SM
- NEW PHYSICS beyond the SM

Electroweak symmetry breaking

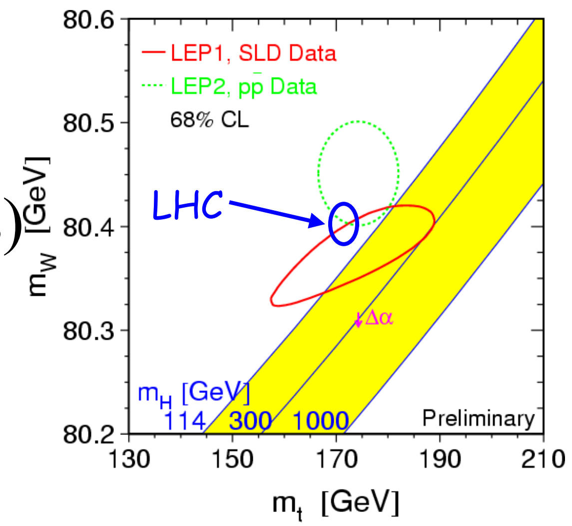




- Standard Model Higgs
  - Cover the full mass range with at least two decay modes
  - Relevant final states: **$\gamma\gamma$, $t\bar{t}b\bar{b}$, 4l, lνlν, ll$\nu\nu$, lljj** (l=e,μ)
- MSSM Higgs bosons
  - Additional final states relevant for H/A and $H^{\pm}$: **$\tau\tau$, $\mu\mu$, $\tau\nu$, tb**

Standard Model … and beyond

- Precision measurements with 10-30 fb^{-1}
  - LHC is a factory for W, Z, top, …
    - δm_{top}~1 GeV, δm_W~15 MeV
  - Triple gauge boson couplings (boson pairs)
    - Probing the symmetry breaking mechanism
  - Indirect information / constraints on new physics (consistency test)
    - Higgs mass to better than 20% (indirect)



- Plenty of possibilities for direct observation of signals for physics beyond the Standard Model
    - and measurements of parameters !
  - Supersymmetry
  - Large extra dimensions
  - Compositeness
  - New (heavy) gauge bosons
  - And many more model predictions …   PLUS: the unforeseen (?)

B-Physics

Hadron Collider: complement physics reach of B-factories;

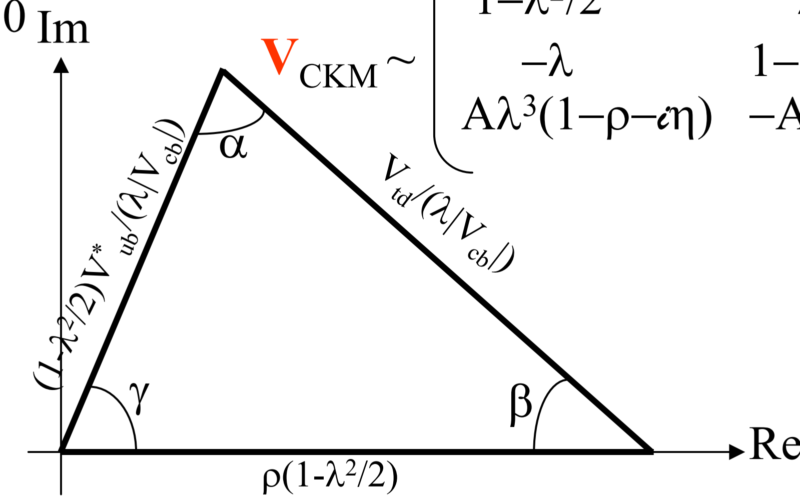
Introducing complex phase into the three-generation mass CKM matrix generates CP and T violation in weak interaction---> (too) small in SM
==> So far, only observed in K mesons (1964)

Supersymmetry, left-right symmetric model, leptoquark, …all extensions have strong influence.

AIM: Measure flavor parameters as accurately as possible

Ex: Unitarity conditions ($V^{+}_{CKM} V_{CKM} = 1$)

$$V_{ud}V_{ub} + V_{cd}V_{cb} + V_{td}V_{tb} = 0$$



Wolfenstein parametrization:

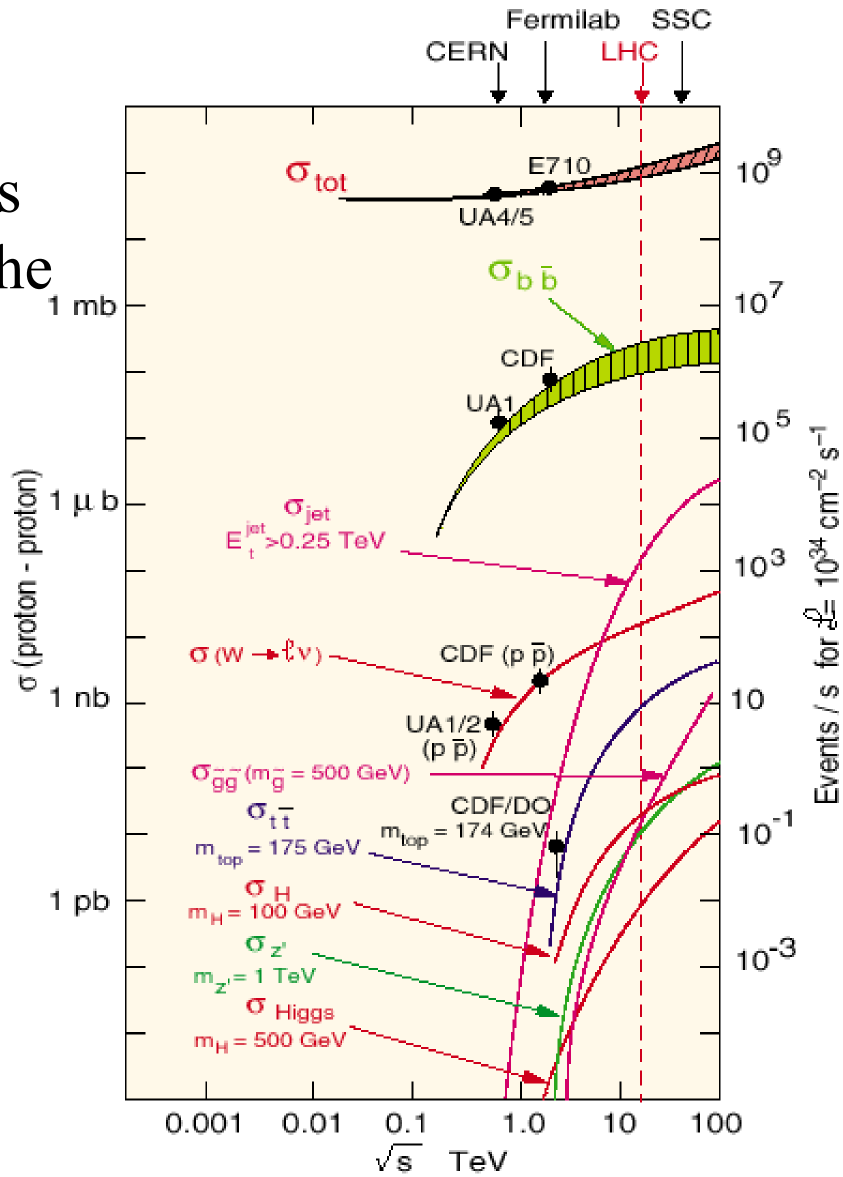
$$\mathbf{V}_{CKM} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

B-Physics (cont'd)

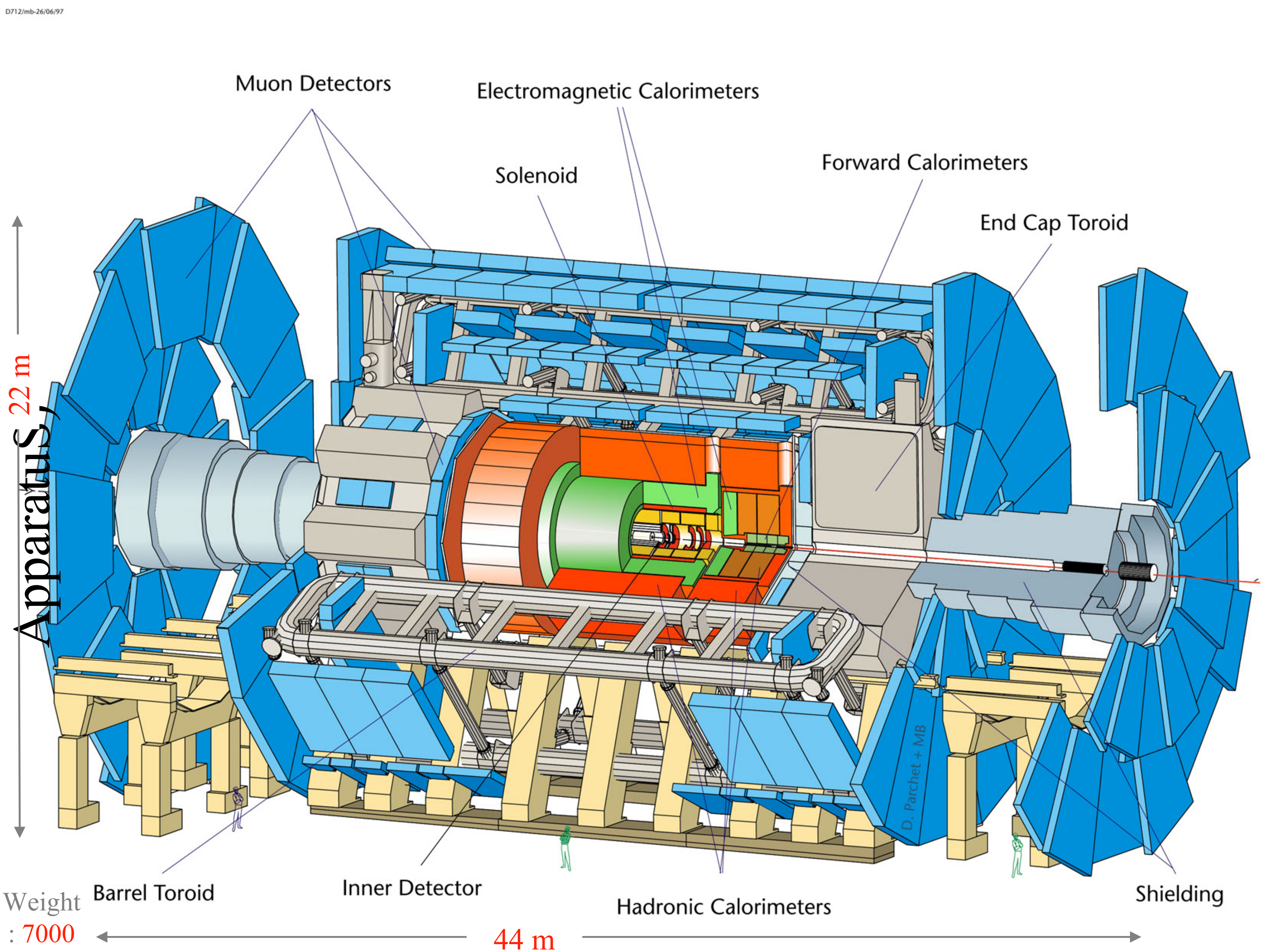
- B^0_d - B^0_d and B^0_s - B^0_s oscillations
- Rare b-decays: important to test SM predictions → New Physics!

Proton-proton interactions

- High event rate: 1 GHz; the rate of these "minimum-bias" events is such that can have an impact on the Trigger system; example: the muon Trigger of ATLAS and CMS;
- LHC is a heavy-flavor factory:
  - bb cross-section: 500 μb;
  - tt cross-section: 1 nb;
- LHC is a vector-bosons factory
- The event rate is huge and this has implications to the trigger/daq System

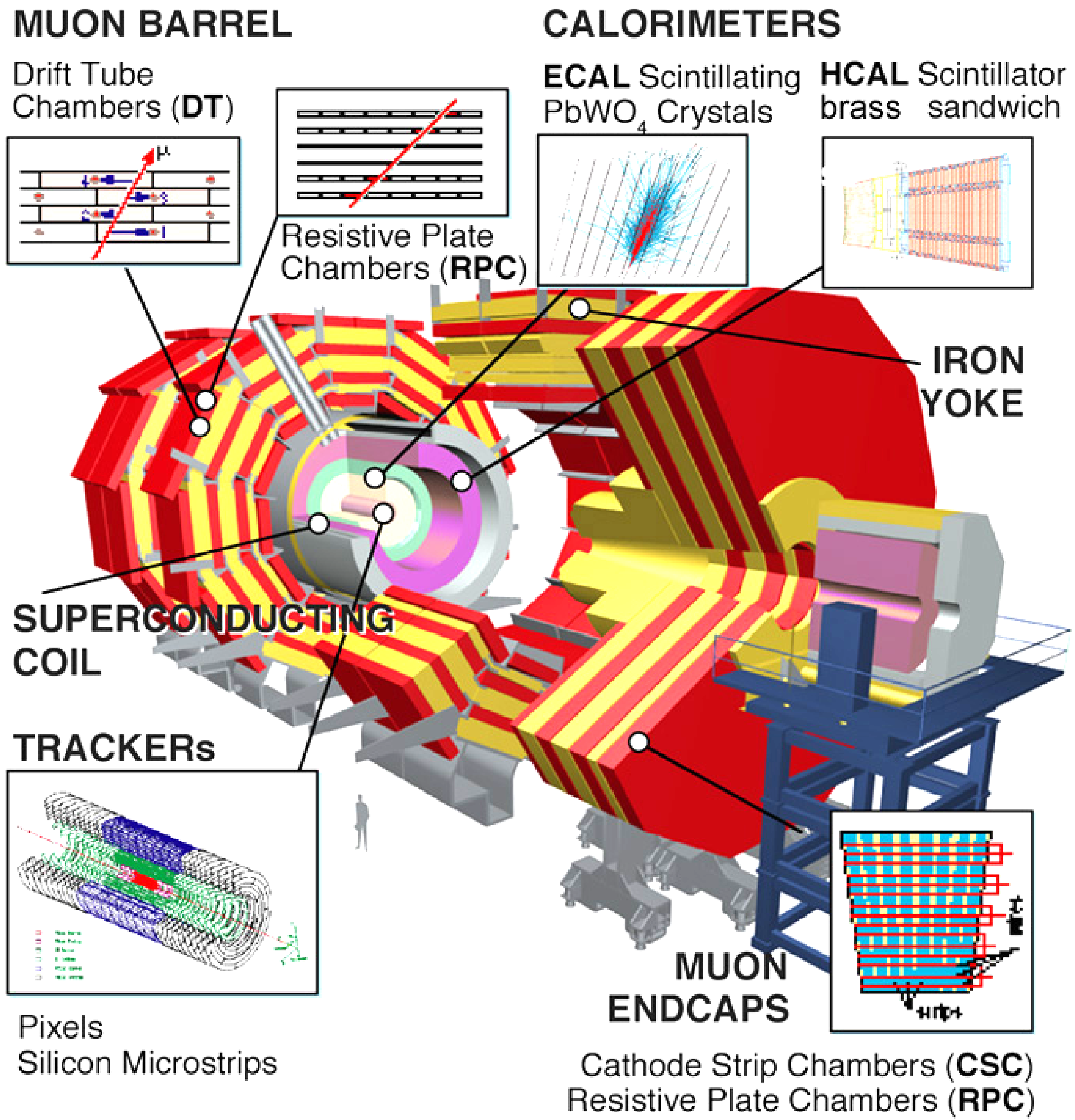


ATLAS (A Toroidal Lhc ApparatuS)



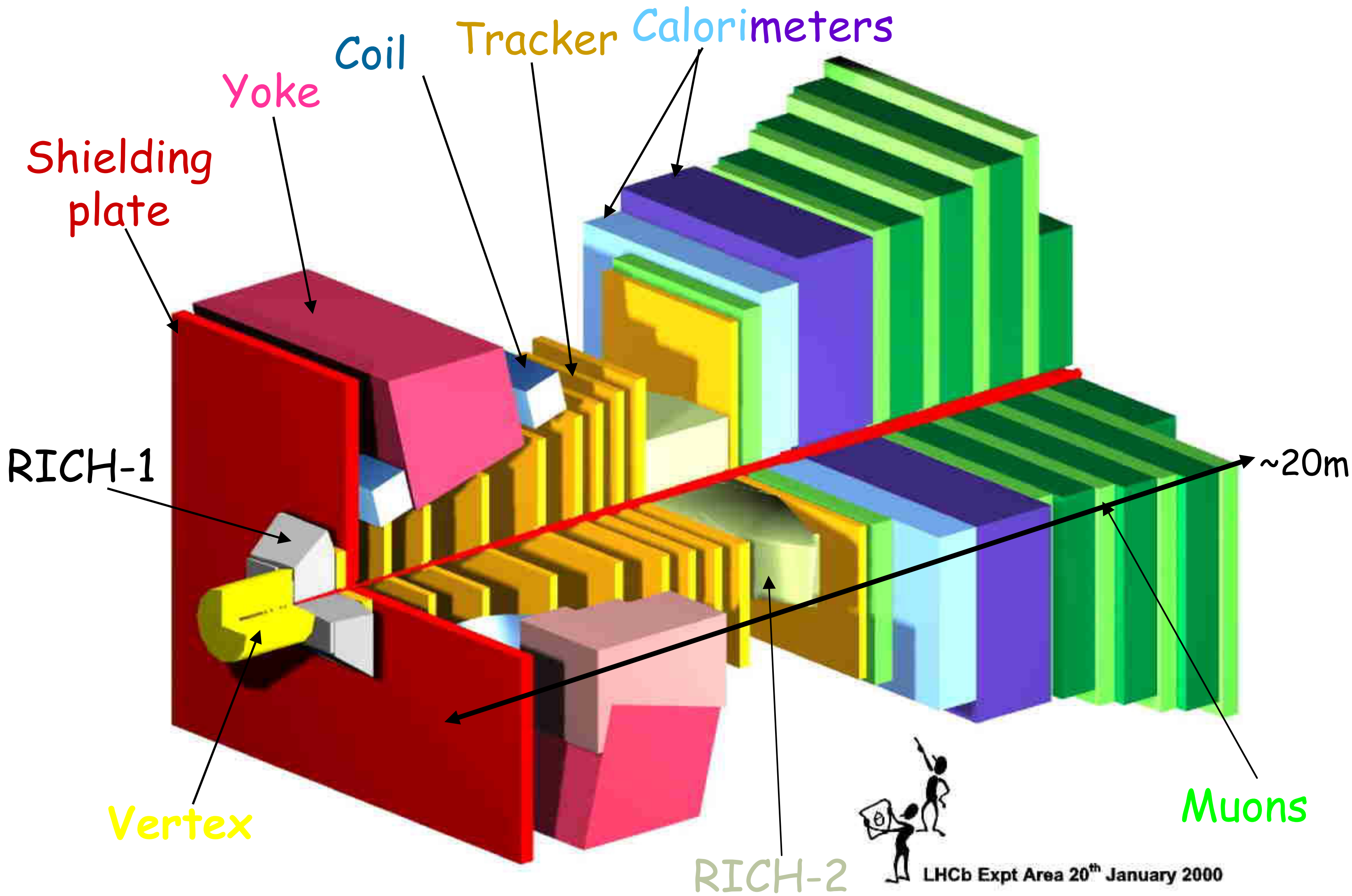
Weight : 7000 t

CMS (Compact Muon Solenoid)



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

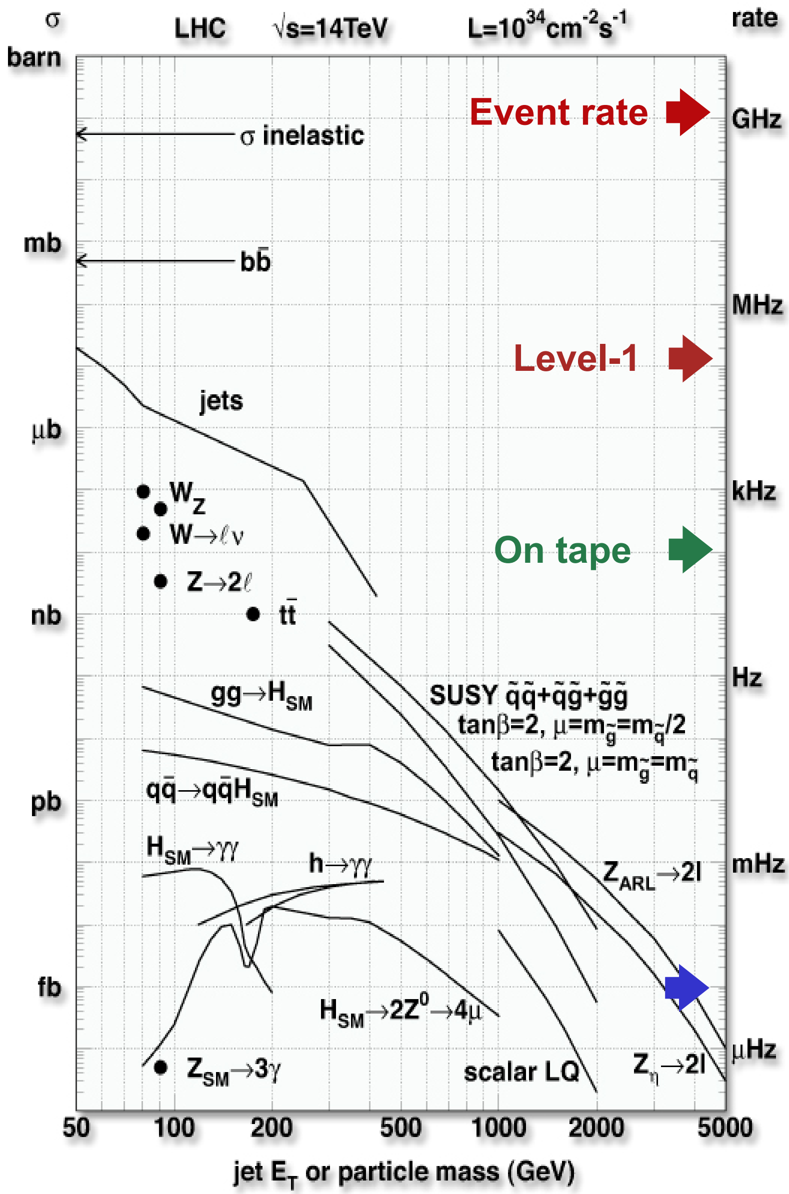
LHCb Detector

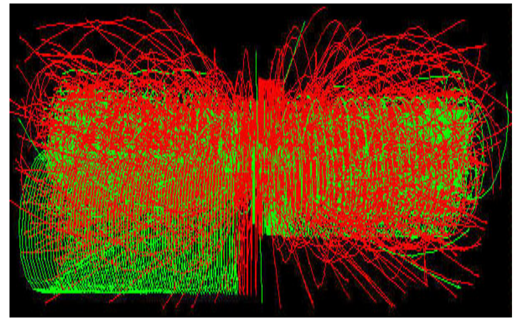


General trigger requirements

- The role of the **trigger** is to make the online selection of particle collisions potentially containing interesting physics
- Need **high efficiency** for selecting processes of interest for physics analysis
  - Efficiency should be precisely known
  - Selection should not have biases that affect physics results
- Need **large reduction of rate** from unwanted high-rate processes (capabilities of DAQ and also offline computers)
  - Instrumental background
  - High-rate physics processes that are not relevant for analysis
- System must be **affordable**
  - Limits complexity of algorithms that can be used
- Not easy to achieve all the above simultaneously!

p-p collisions at LHC





ATLAS / CMS

Event Rates:	$\sim10^9$ Hz
Event size:	~1 MB
Level-1 Output	100 kHz
Mass storage	10^2 Hz
Event Selection:	$\sim1/10^{13}$

LHCb

Event Rates:	$\sim2\ 10^7$ Hz
Event size:	~0.25 MB
Mass storage	200 Hz

Selection signatures

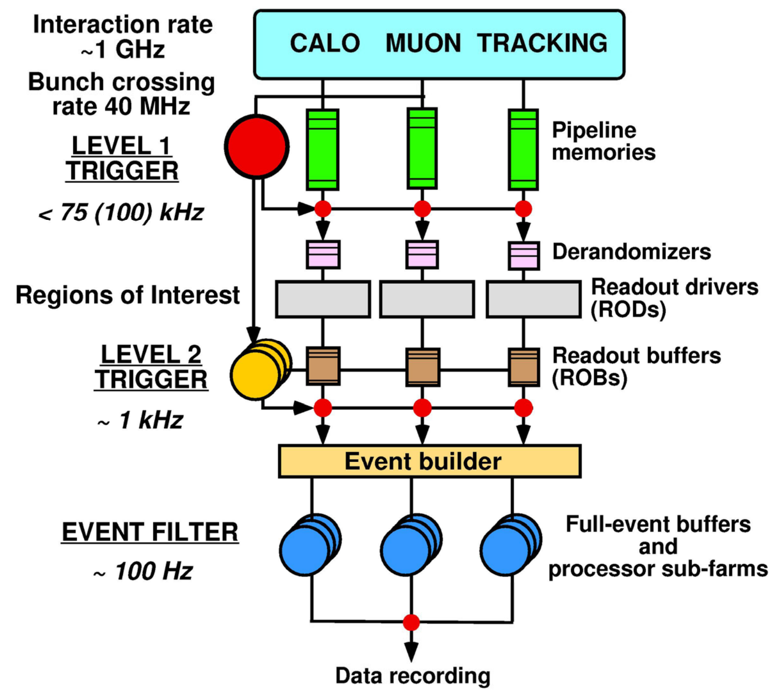
Object	Examples of physics coverage
Electrons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Photons	Higgs (SM, MSSM), extra dimensions, SUSY
Muons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W, top
Jets	SUSY, compositeness, resonances
Jet+missing E_T	SUSY, leptoquarks
Tau+missing E_T	Extended Higgs models (e.g. MSSM), SUSY

- Standard Model processes mandatory to
  - Understand background processes for discoveries and measurements
    - production of Wbb, ttbb, vector boson pairs, …
  - Understand detector performance (esp. during the first year(s))
    - Calibration / energy scale: $Z \rightarrow ee/\mu\mu$, $W \rightarrow jj$, $W \rightarrow e\nu$, $W \rightarrow \tau\nu$, Z+jet, $J/\psi \rightarrow \mu\mu$
  - Get this information from data !

Why do we need *multi-level* triggers?

- Multi-level triggers provide:
  - Rapid rejection of high-rate backgrounds without incurring (much) dead-time
    - **Fast first-level trigger (custom electronics)**
      - Needs high efficiency, but rejection power can be *comparatively* modest
      - Short latency is essential since information from all (up to $O(10^8)$) detector channels needs to be buffered (often on detector) pending result
  - High overall rejection power to reduce output to mass storage to affordable rate: **one or more "High" Trigger Levels**:
    - Progressive reduction in rate after each stage of selection allows use of more and more complex algorithms at affordable cost
    - Final stages of selection, running on computer farms, can use comparatively very complex (and hence slow) algorithms to achieve the required overall rejection power

Exp.	No of Levels
ATLAS	3
CMS	2
LHCb	3
ALICE	4



Example: ATLAS

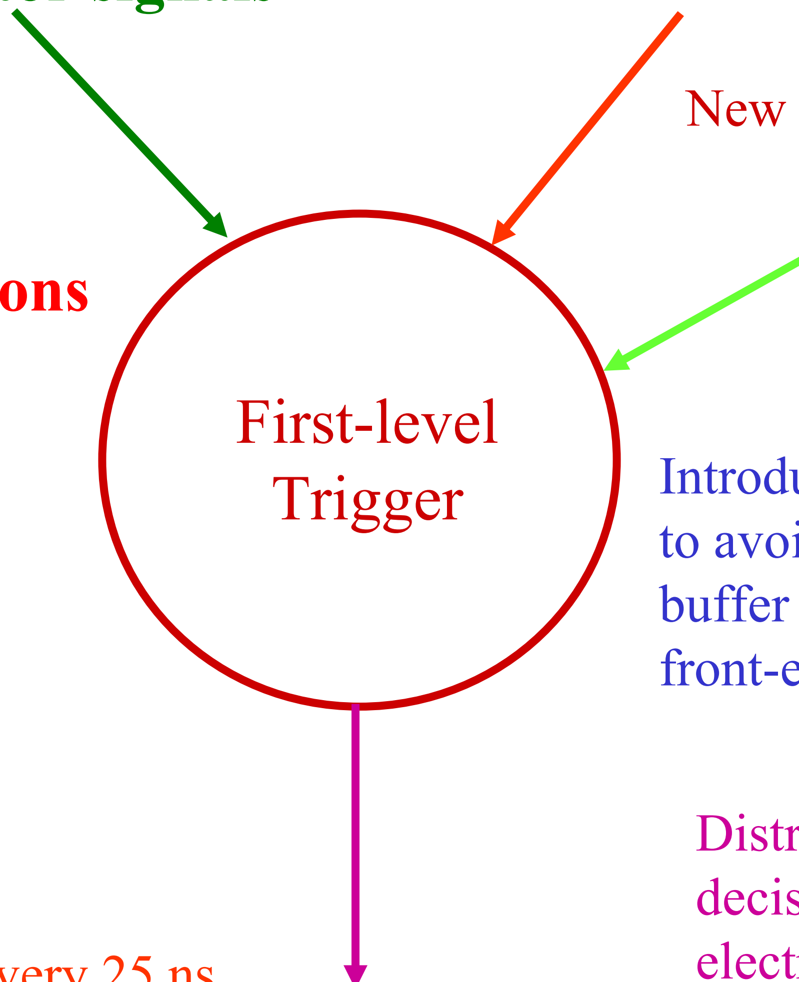
FIRST-LEVEL TRIGGER OVERVIEW

Muon detector signals

Calorimeter signals

New data every 25 ns

BUSY signals



Search for **high-p_T:**

1. **muons**
2. **electrons/photons**
3. **taus/hadrons**
4. **jets**

Calculate:

- ΣE_T
- **missing E_T**

Form trigger decision for each BC based on combinations of above

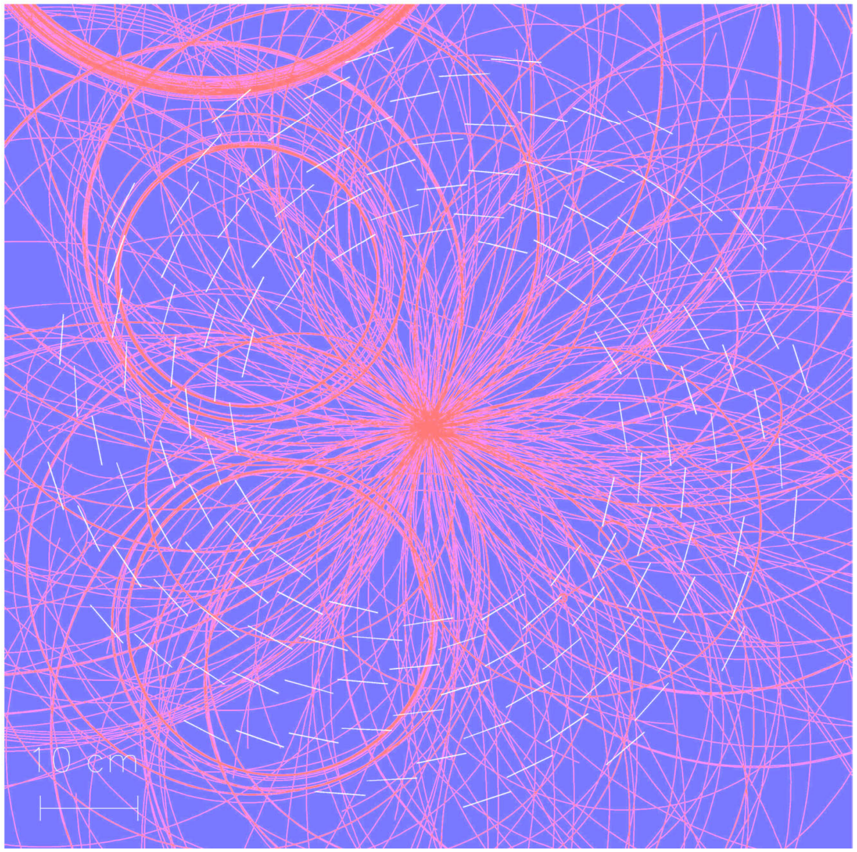
Introduce deadtime to avoid data loss or buffer overflow in front-end electronics

Distribute first-level trigger decision to front-end electronics

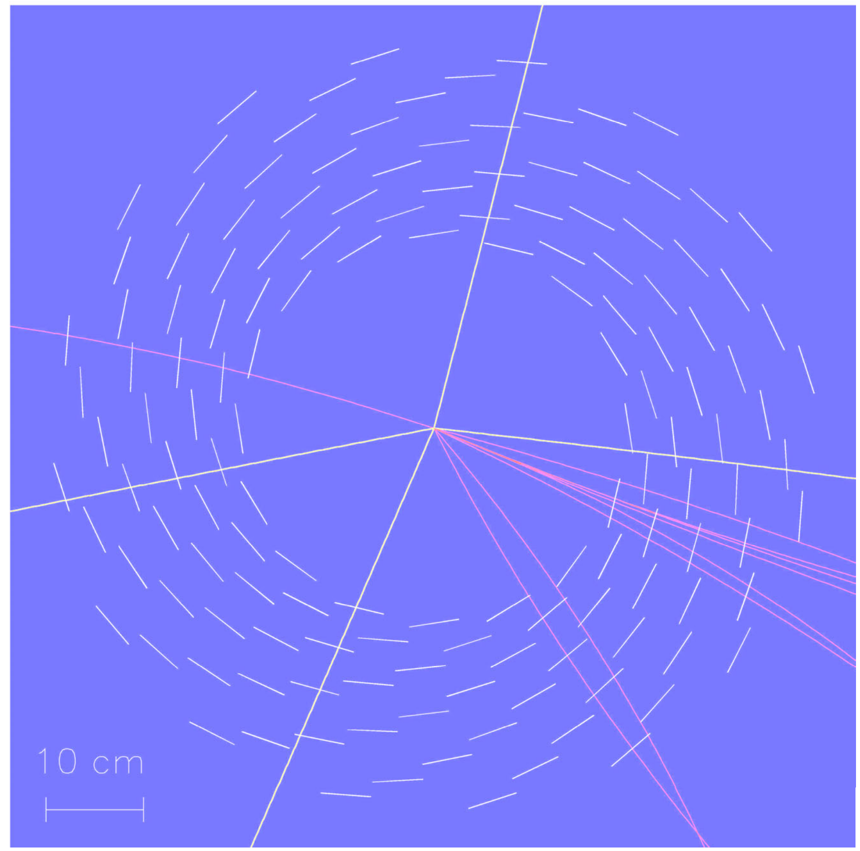
Decision every 25 ns
Latency ~few μs

Yes/No

Effect of p_T cut in minimum-bias events



All tracks



$p_T > 2$ GeV

Simulated $H \rightarrow 4\mu$ event + 17 minimum-bias events

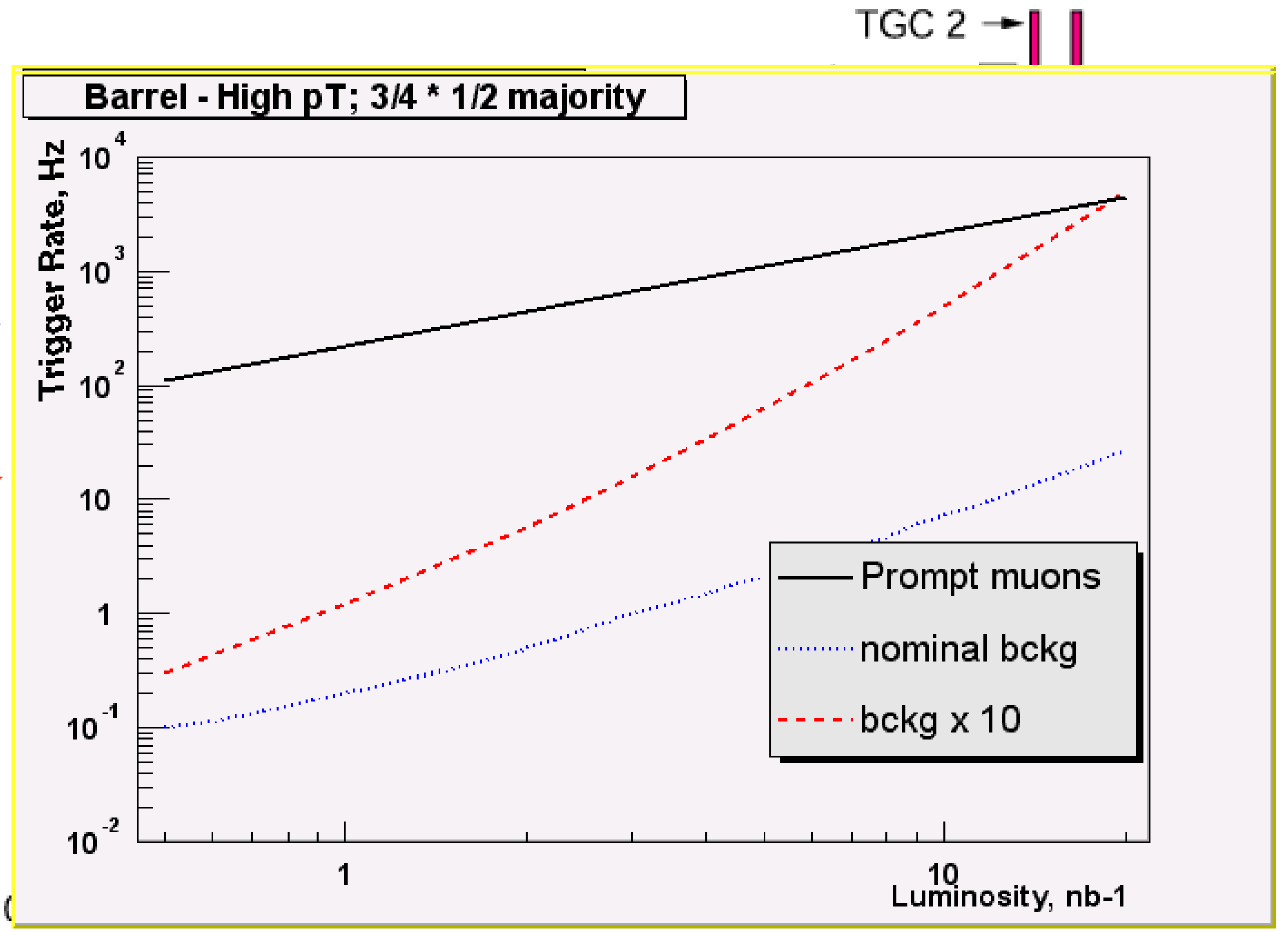
Level-1 Trigger: ATLAS and CMS

- In contrast to the particles produced in typical pp collisions (typical hadron $p_T \sim 1$ GeV), the products of new physics are expected to have large transverse momentum, p_T
  - E.g. if they were produced in the decay of new heavy particles such as the Higgs boson; e.g. $m \sim 100$ GeV $\Rightarrow p_T \sim 50$ GeV
- Typical examples of first-level trigger thresholds for LHC design luminosity are:
  - Single muon $p_T > 20$ GeV (rate ~ 10 kHz)
    - Pair of muons each with $p_T > 6$ GeV (rate ~ 1 kHz)
  - Single e/γ $p_T > 30$ GeV (rate ~ 10-20 kHz)
    - Pair of e/γ each with $p_T > 20$ GeV (rate ~ 5 kHz)
  - Single jet $p_T > 300$ GeV (rate ~ 200 Hz)
    - Jet $p_T > 100$ GeV and missing-$p_T > 100$ GeV (rate ~ 500 Hz)
    - Four or more jets $p_T > 100$ GeV (rate ~ 200 Hz)

The LVL1 Muon Trigger

- Wide p_T-threshold range
- Safe Bunch Crossing Identification
-Strong rejection of fake muons (induced by noise and physics background)

→ Fast and high redundancy system

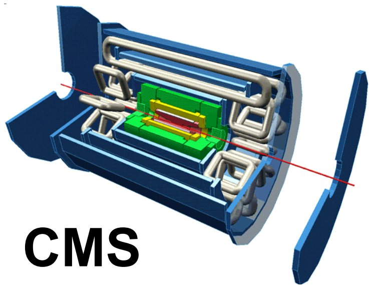


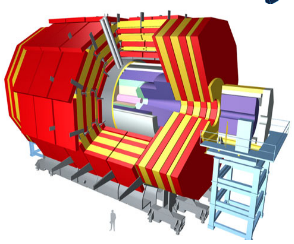
LHCb

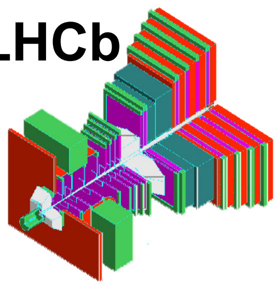
- The LHCb experiment, which is dedicated to studying B-physics, faces similar challenges to ATLAS and CMS
  - It will operate at a relatively low luminosity (~2×10^{32} $cm^{-2}s^{-1}$), giving an overall pp interaction rate of ~20 MHz
    - Chosen to maximise the rate of single-interaction bunch crossings
  - However, to be sensitive to the B-hadron decays of interest, the trigger must work with comparatively ***very low p_T thresholds***
    - The first-level ("level-0") trigger will search for muons, electrons/photons and hadrons with p_T > 1 GeV, 2.5 GeV and 3.4 GeV respectively
  - **Level-0 output rate up to ~1 MHz**
  - Higher-level triggers must search for displaced vertices and **specific B decay modes** that are of interest for the physics analysis
    - Aim to record event rate of only ~200 Hz

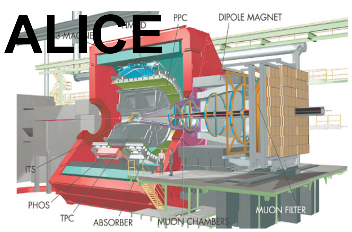
LHC LVL1 trigger

	No.Levels Trigger		**First Level** Rate (Hz)	**Event** (relevant for FE electronics) Size (Byte)
ATLAS	**3**		**10^5**	**10^6**
CMS	**2**		**10^5**	**10^6**
LHCb	**3**	**LV-0**	**10^6**	**$2x10^5$**
ALICE	**4**	Pp-Pp	**500**	**$5x10^7$**
		p-p	**10^3**	**$2x10^6$**

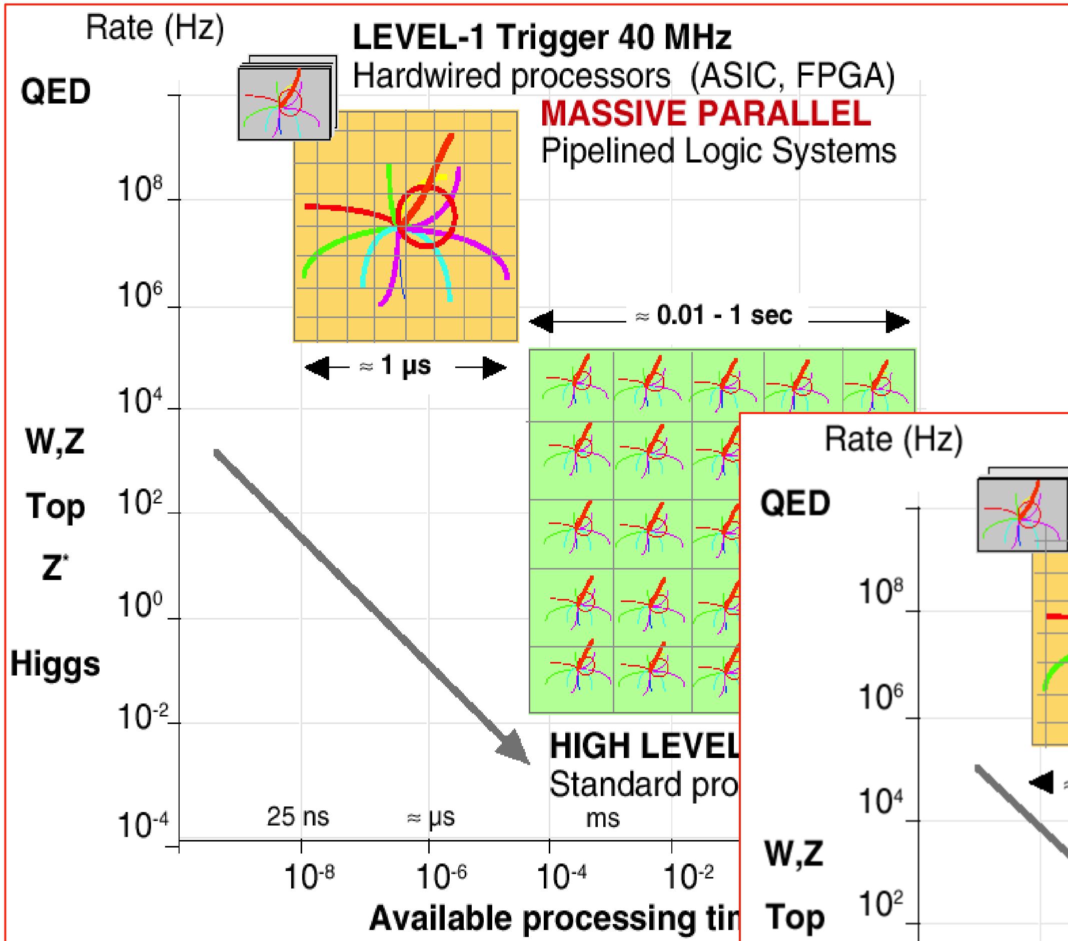


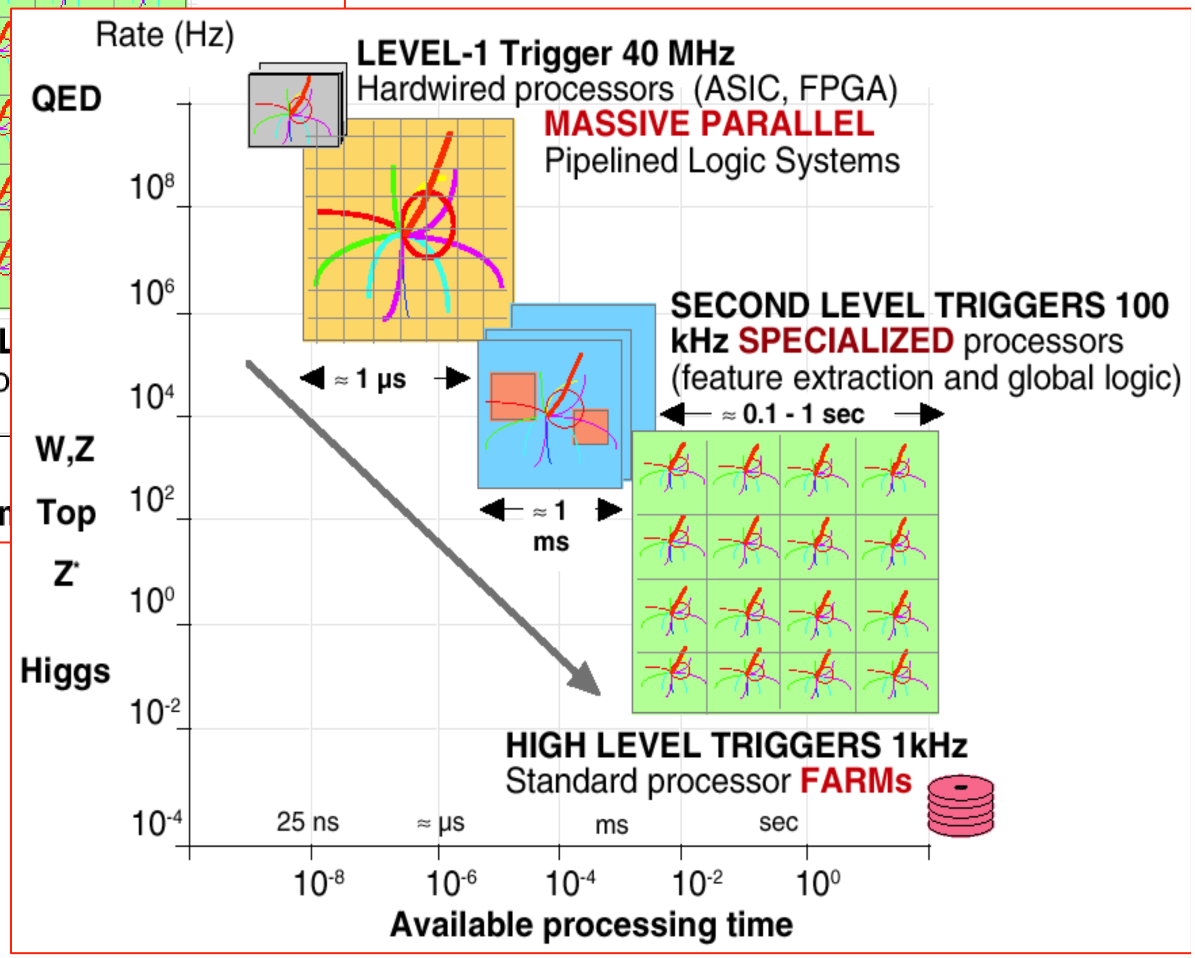






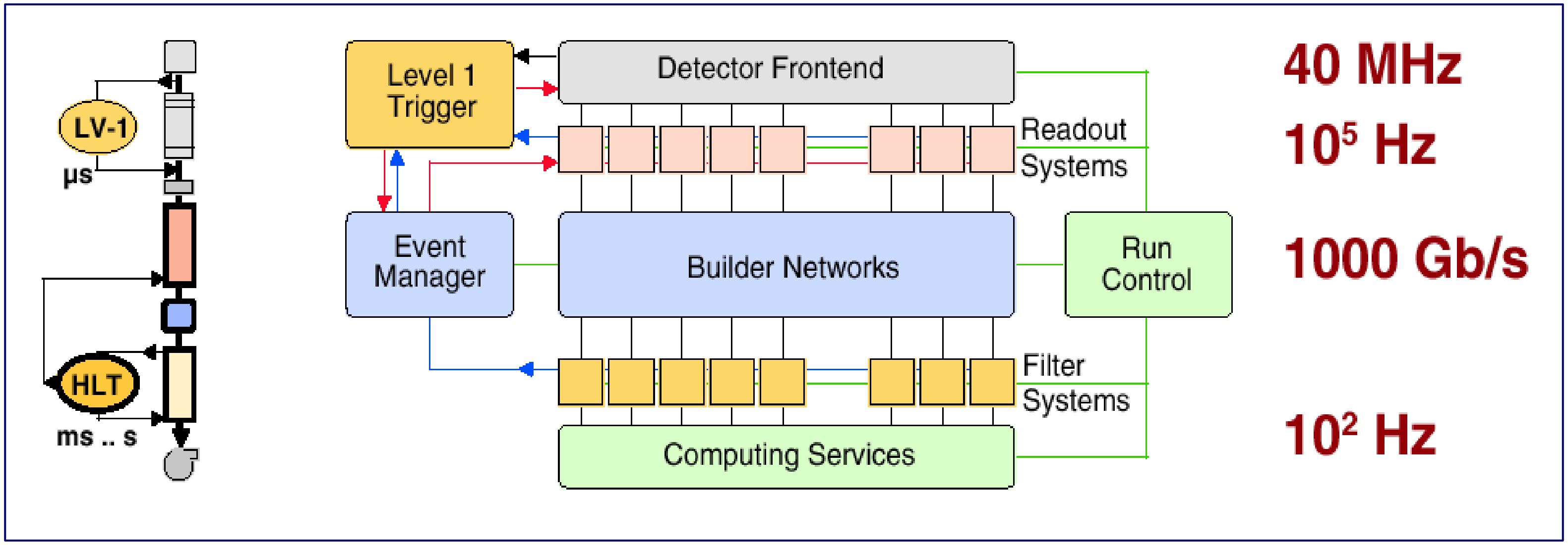
Online Selection: 2 …

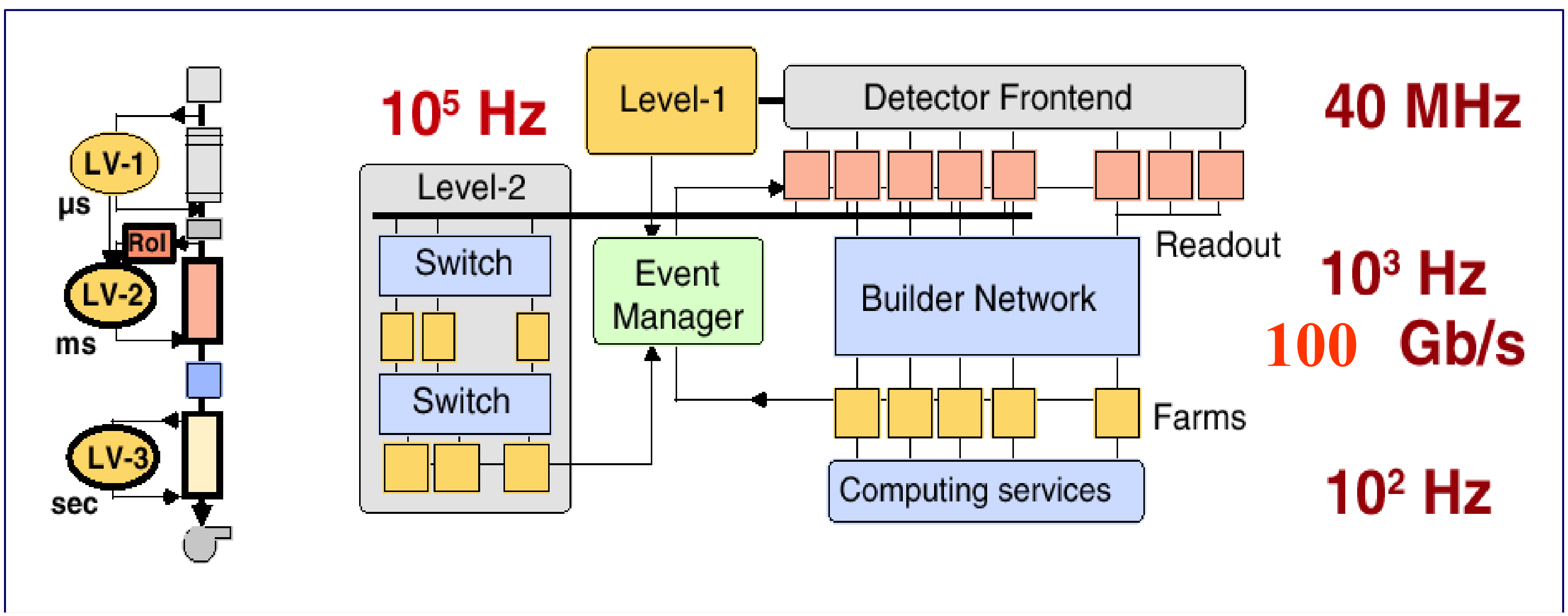




… or 3 steps?

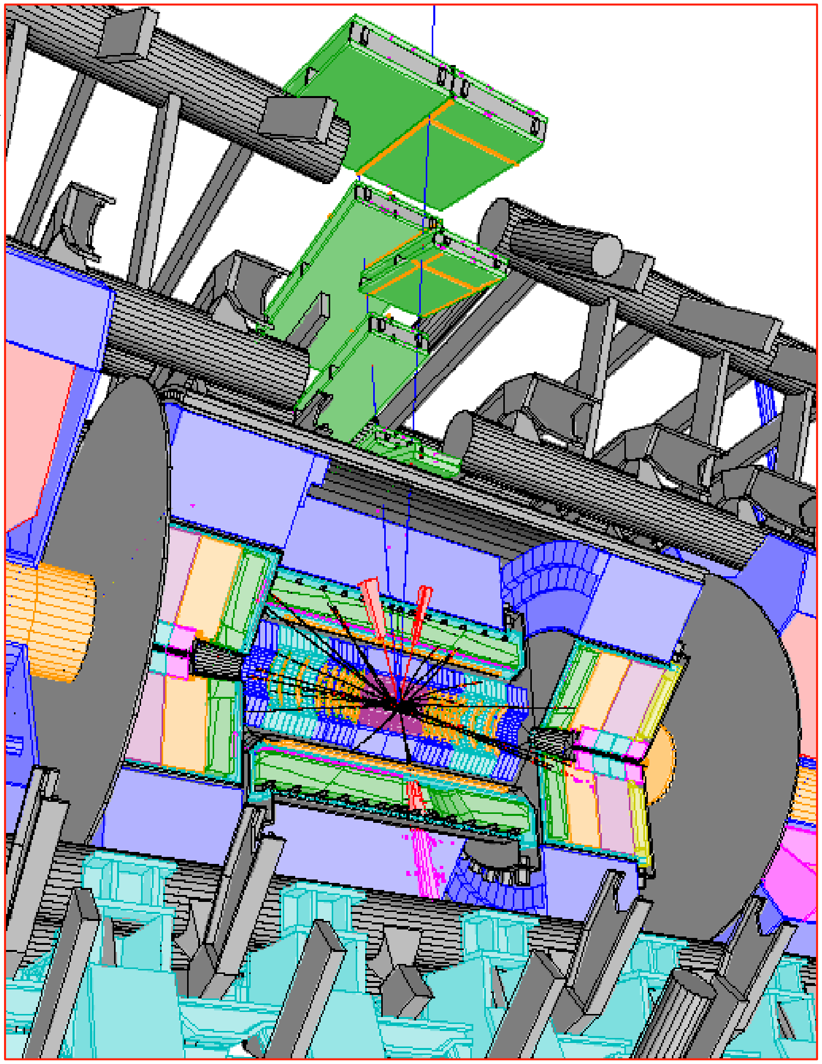
2 or 3 trigger levels?





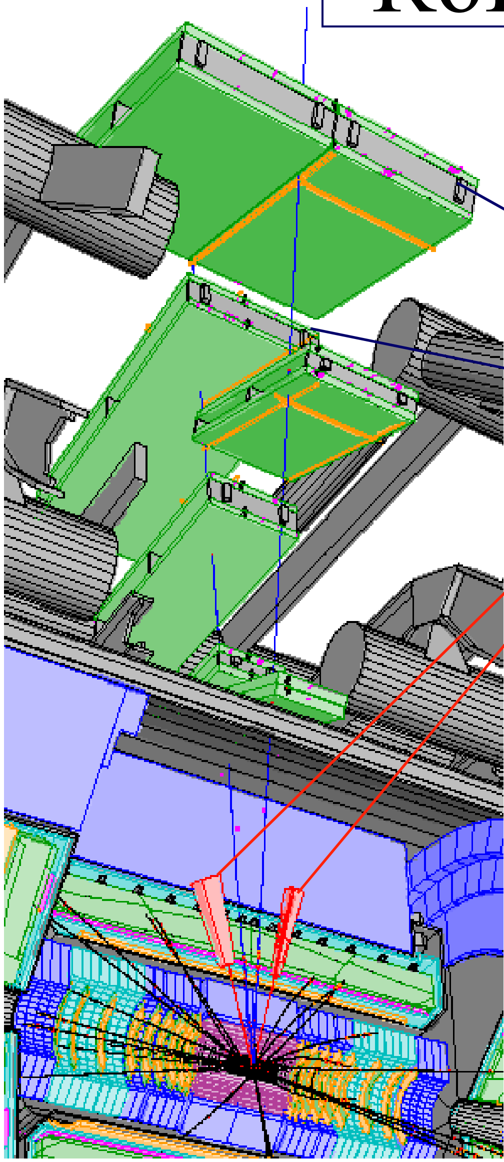
ATLAS: the Region of Interest - Why?

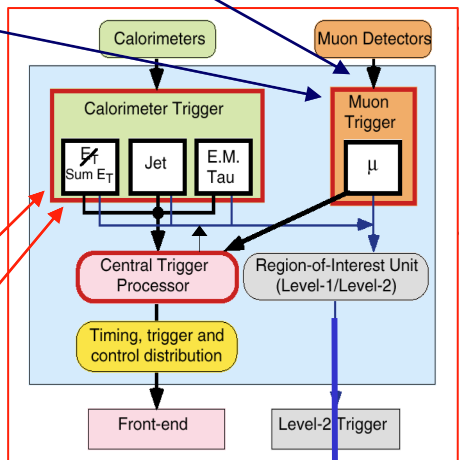
- The Level-1 selection is dominated by local signatures
  - Based on coarse granularity (calo, mu trig chamb), **w/out access to inner tracking**
  - Important further rejection can be gained with local analysis of full detector data



- The geographical addresses of interesting signatures identified by the LVL1 (Regions of Interest)
  - Allow access to local data of each relevant detector
  - Sequentially
- Typically, there are less than 2 RoIs per event accepted by LVL1
  - <RoIs/ev> = ~1.6
- The resulting total amount of RoI data is minimal
  - a few % of the Level-1 throughput

RoI mechanism - Implementation





4 RoI
η–φ addresses

- There is a simple correspondence

  ROI region <-> ROB number(s)
  (for each detector)

  for each RoI the list of ROBs with the corresponding data from each detector is quickly identified (LVL2 processors)

  This mechanism provides a powerful and economic way to add an important rejection factor before full Event Building

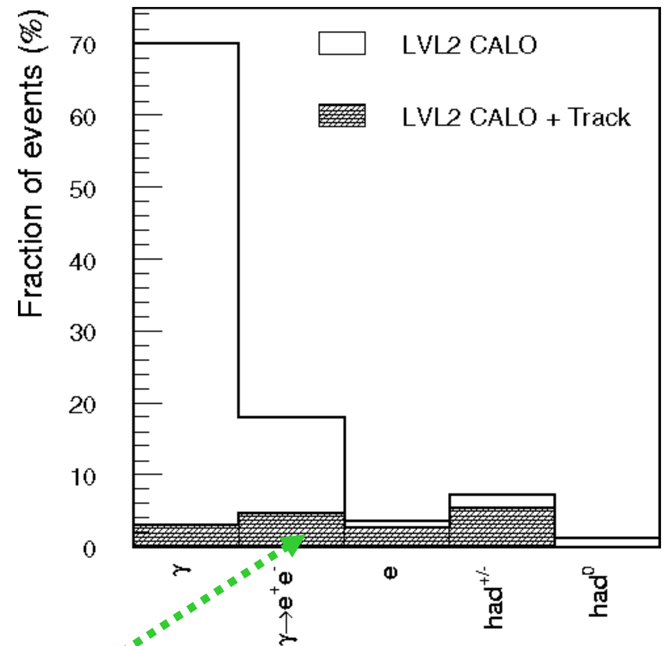
--> the ATLAS RoI-based Level-2 trigger

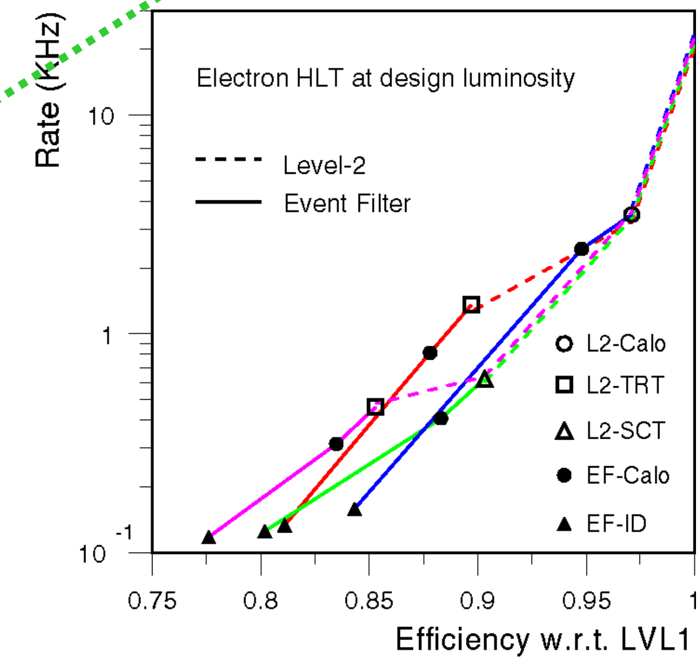
… ~ one order of magnitude smaller ReadOut network …
… at the cost of a higher control traffic …

Note that this example is atypical; the average number of RoIs/ev is ~1.6

ATLAS LVL2: selection of electrons

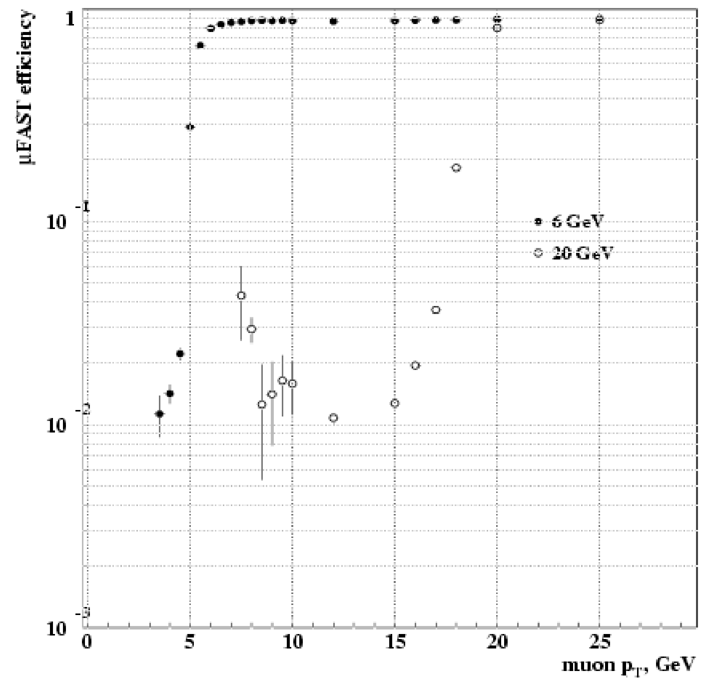
- LVL1 rate of isolated electrons with $E_T > 30$ GeV @ nominal luminosity: **22 kHz;**
- LVL2 rate isolated electrons with $E_T >$ 30 GeV @ nominal luminosity: **0.41 kHz;**
  - Detailed shower shape analysis
    - Similar to photons, but looser cuts
  - Track search in Inner Detector
    - Rejects large fraction of neutrals
  - Matching track – calorimeter cluster
  - Bremsstrahlung recovery
- **Rate reduction > 50**
- **Present algorithm latency: ~ 1ms (2 GHz processor)**

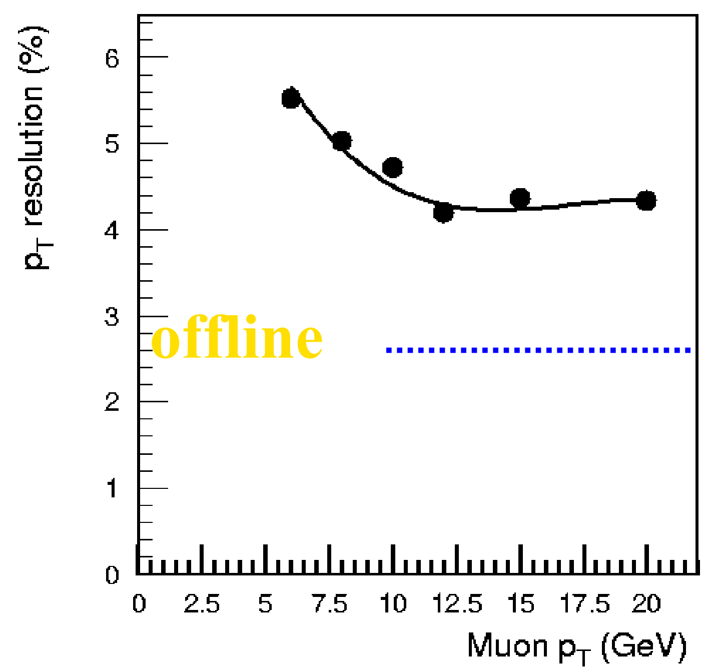




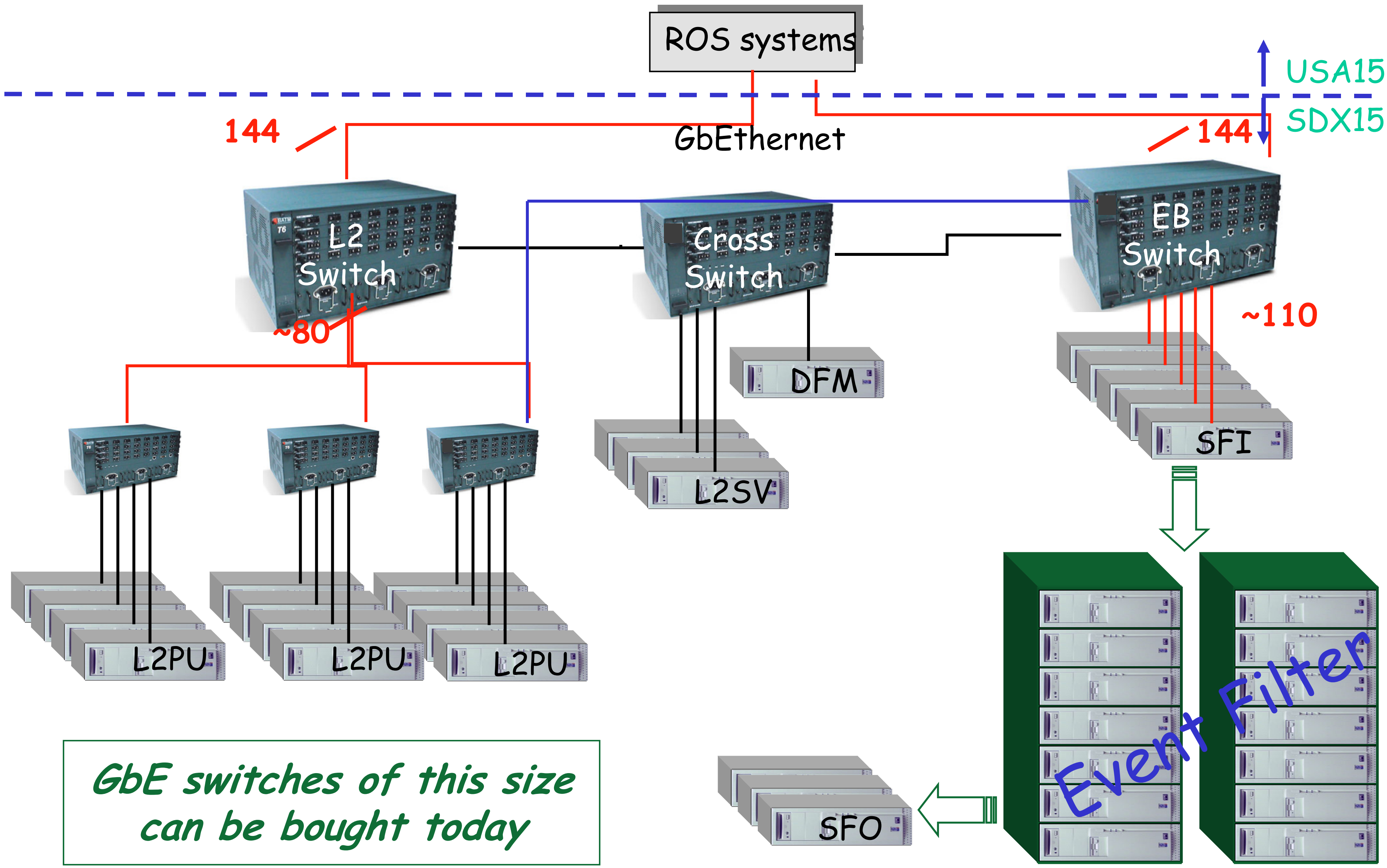
ATLAS LVL2: selection of muons

- Algorithm (*μFast*) steps:
  - Pattern recognition in MDT chambers (no drift time)
  - Trajectory fit to determine super-points (including drift time)
  - Calculate sagitta and determine p_T using LUT
- Rate of muons with p_T>20 GeV/c reduced by a **factor of 10**
- Present latency: about 2 ms





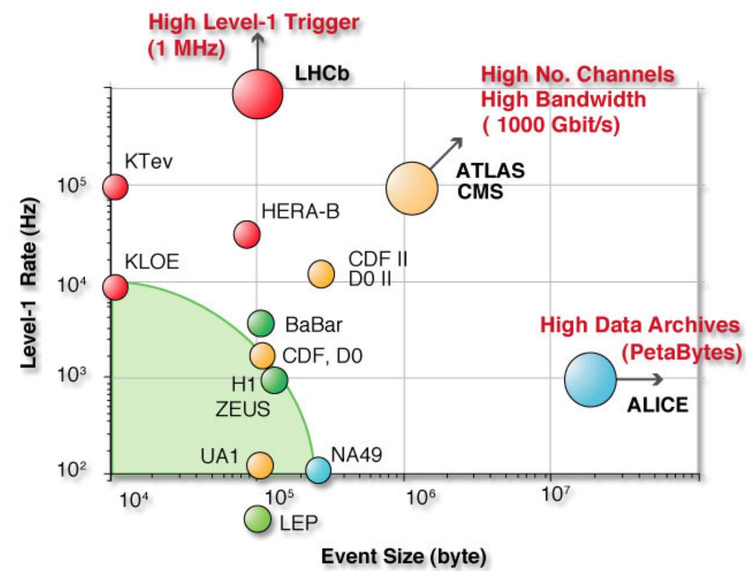
ATLAS Trigger/DAQ Final-Initial System

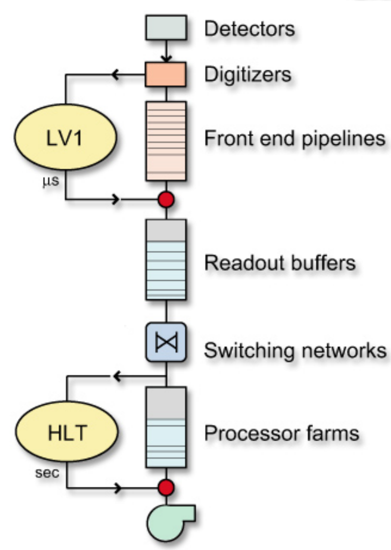


GbE switches of this size can be bought today

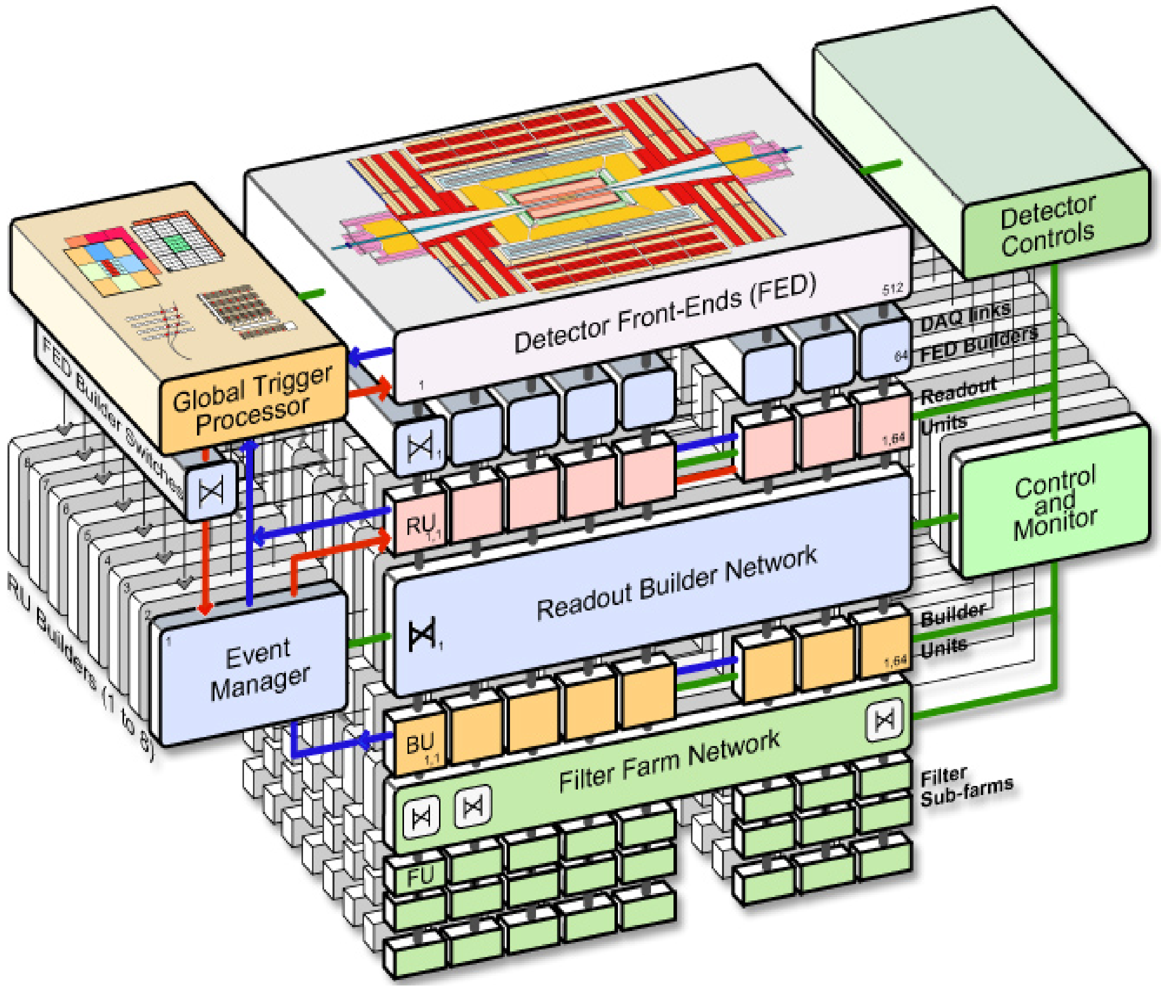
The CMS High-Level Trigger

- Formidable task:
  - Bunch crossing rate → permanent storage rate for events with size ~1MB
  - 40MHz → O(10^2)Hz
- CMS design:
  - Beyond Level-1 there is a High Level Trigger running on a single processor farm





CMS DAQ staging and scaling: 8 x (64x64)



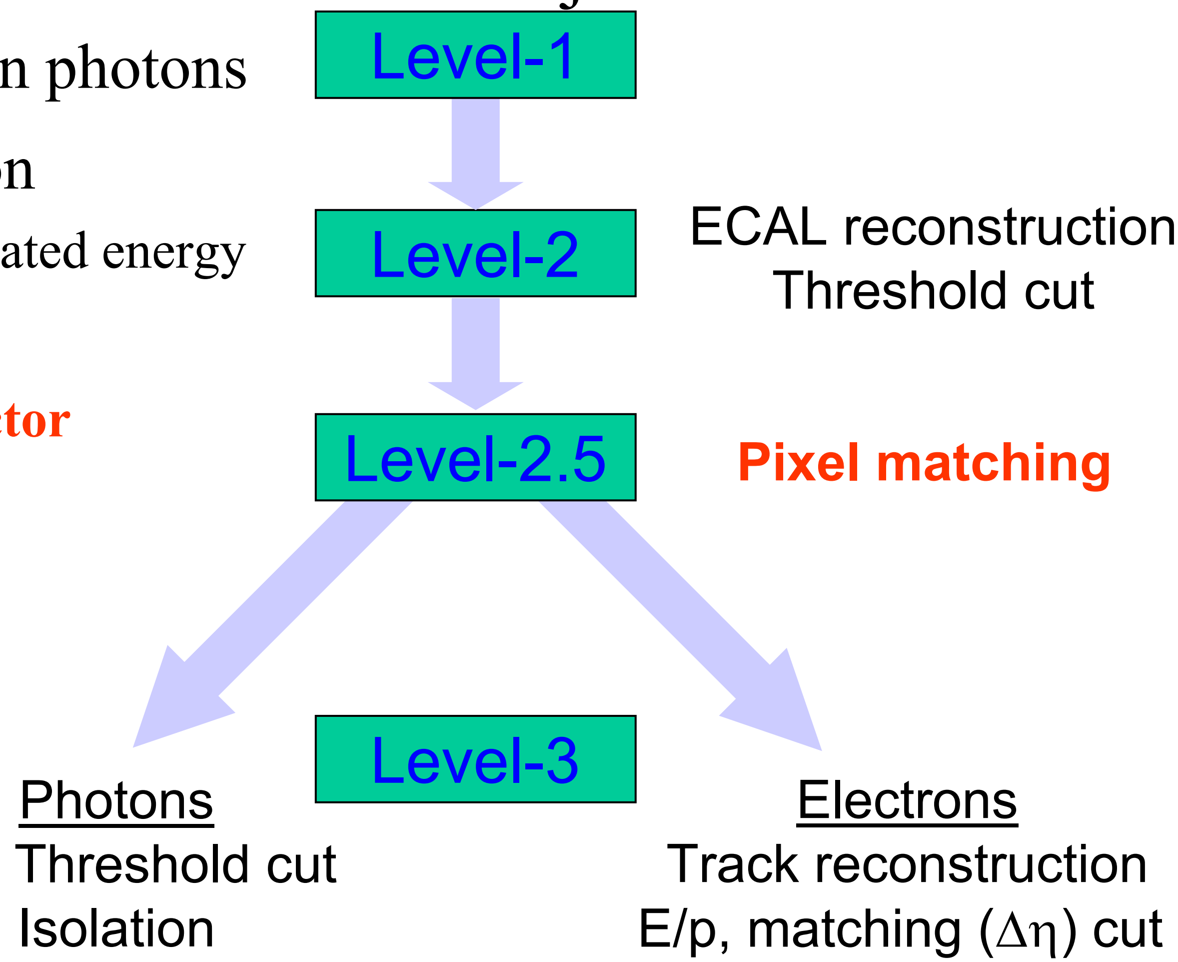
8 x (12.5 kHz DAQ units)

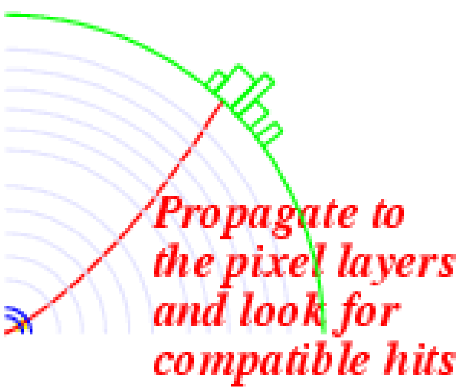
CMS High-Level Trigger

- Runs on CPU farm
- Code as close as possible to offline reconstruction code
  - Ease of maintenance
  - Able to include major improvements in offline reconstruction
- Selection must meet CMS physics goals
  - Output rate to permanent storage limited to $O(10^2)$Hz
- Reconstruction on demand
  - Reject as soon as possible
  - Hence trigger "Levels":
    - Level-2: use calorimeter and muon detectors
    - Level-2.5: also use tracker pixel detectors
    - Level-3: includes use of full information, including tracker
  - And "regional reconstruction": e.g. tracks in a given road or region

CMS HLT selection: electrons and photons

- Issue is electron reconstruction and rejection
- Higher E_T threshold on photons
- Electron reconstruction
  - key is recovery of radiated energy
- Electron rejection
  - **key tool is pixel detector**





CMS HLT Summary: $2x10^{33}$ $cm^{-2}s^{-1}$

Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cuml. rate (Hz)
Inclusive electron	29	33	33
Di-electron	17	1	34
Inclusive photon	80	4	38
Di-photon	40, 25	5	43
Inclusive muon	19	25	68
Di-muon	7	4	72
Inclusive tau-jet	86	3	75
Di-tau-jet	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jet OR 4-jet	657, 247, 113	9	89
Electron * jet	19 * 45	2	90
Inclusive b-jet	237	5	95
Calibration etc		10	105
TOTAL			105

CMS HLT performance - signal efficiency

Channel	Efficiency (for fiducial objects)
$H(115\ GeV) \to \gamma\gamma$	77%
$H(160\ GeV) \to WW^* \to 2\mu$	92%
$H(150\ GeV) \to ZZ \to 4\mu$	98%
$A/H(200\ GeV) \to 2\tau$	45%
SUSY (~0.5 TeV sparticles)	~60%
With R_P-violation	~20%
$W \to e\nu$	67%
$W \to \mu\nu$	69%
$Top \to \mu X$	72%

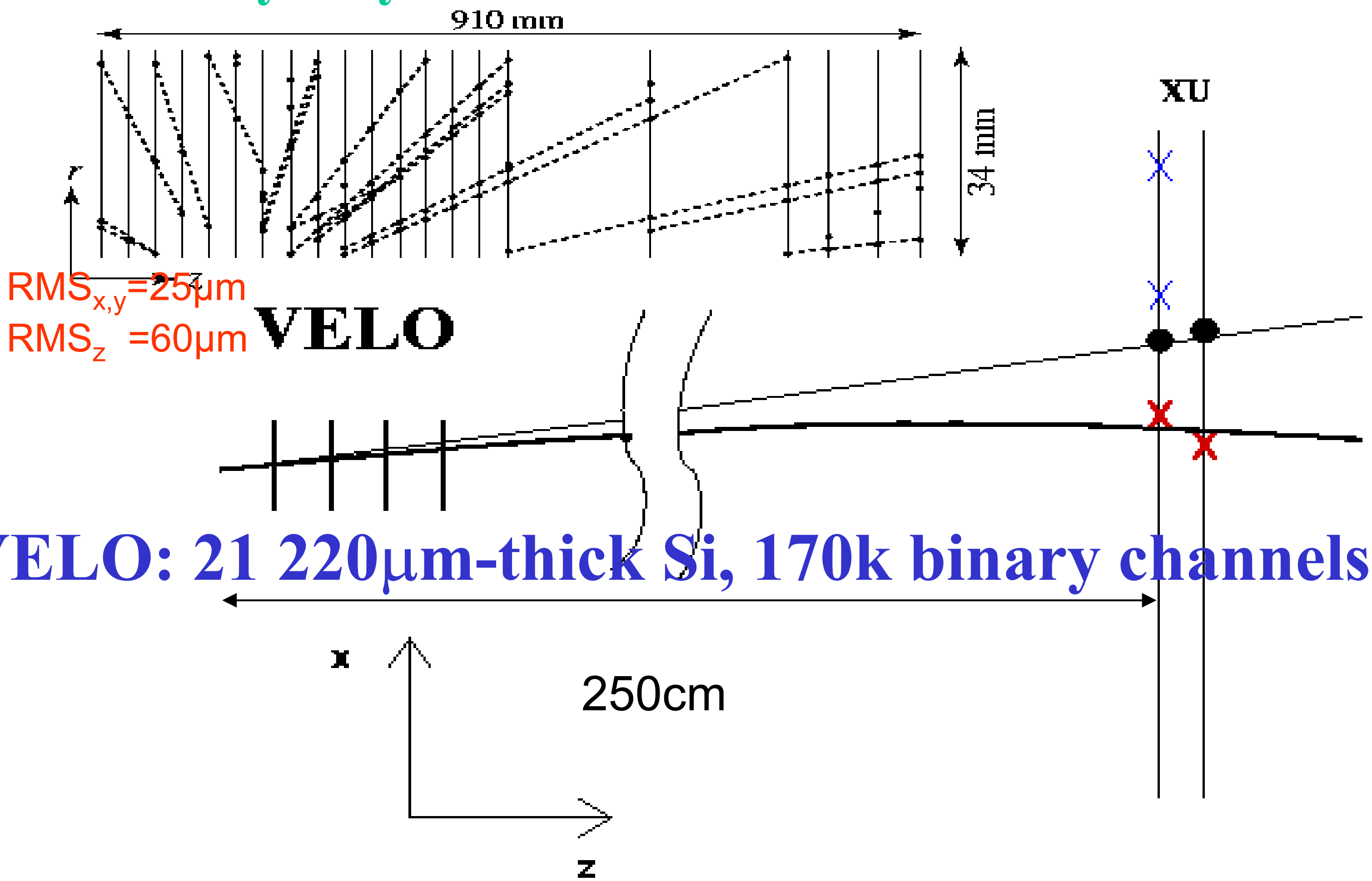
LHCb: L1 Trigger Algorithm

Purpose: find high impact parameter tracks

Estimate the tracks pT

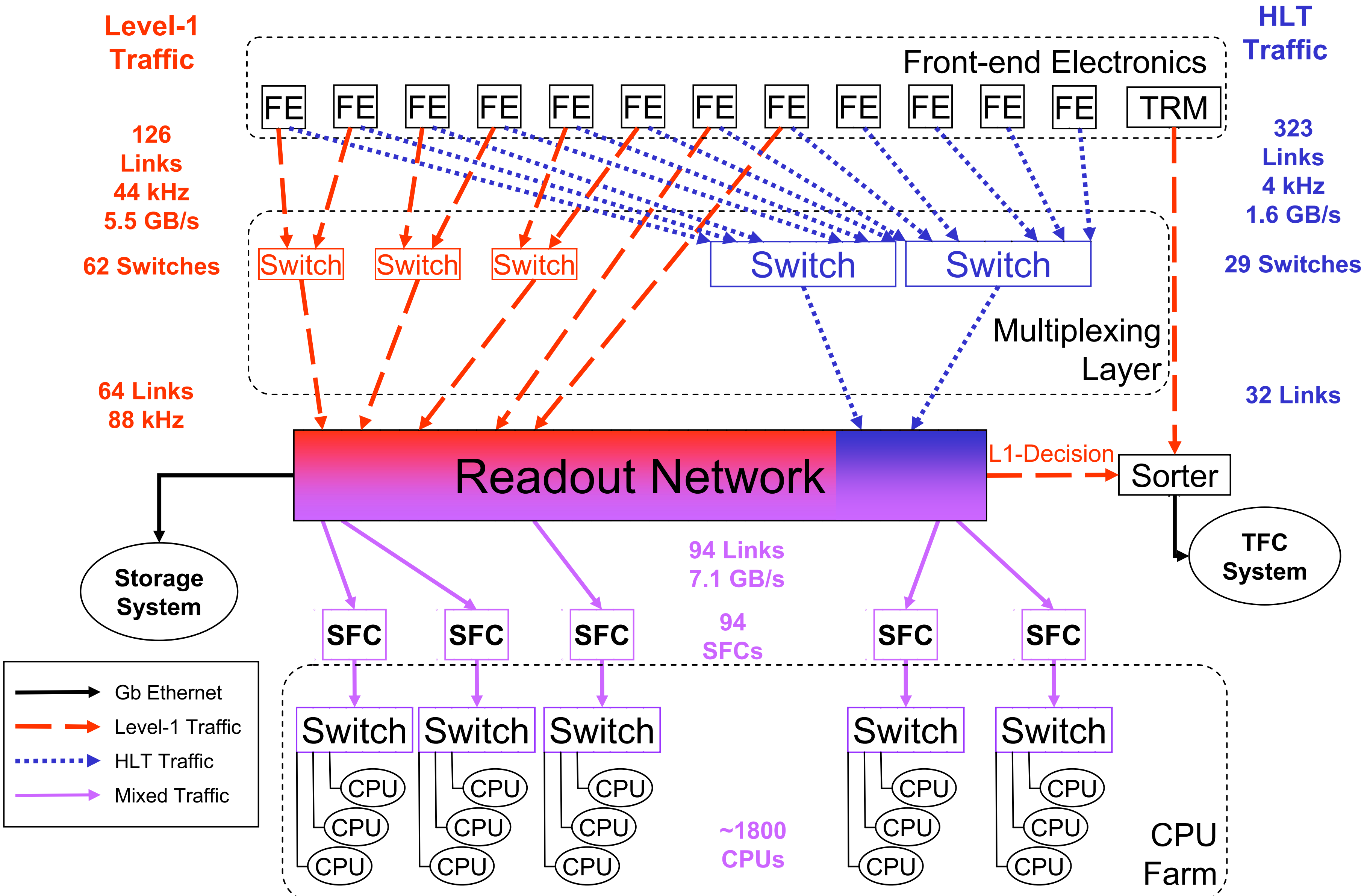
Then 3D matching with L0 objects

Basically only the VELO detector is used at L1



VELO: 21 220µm-thick Si, 170k binary channels forL1

LHCb Architecture for L1 & HLT

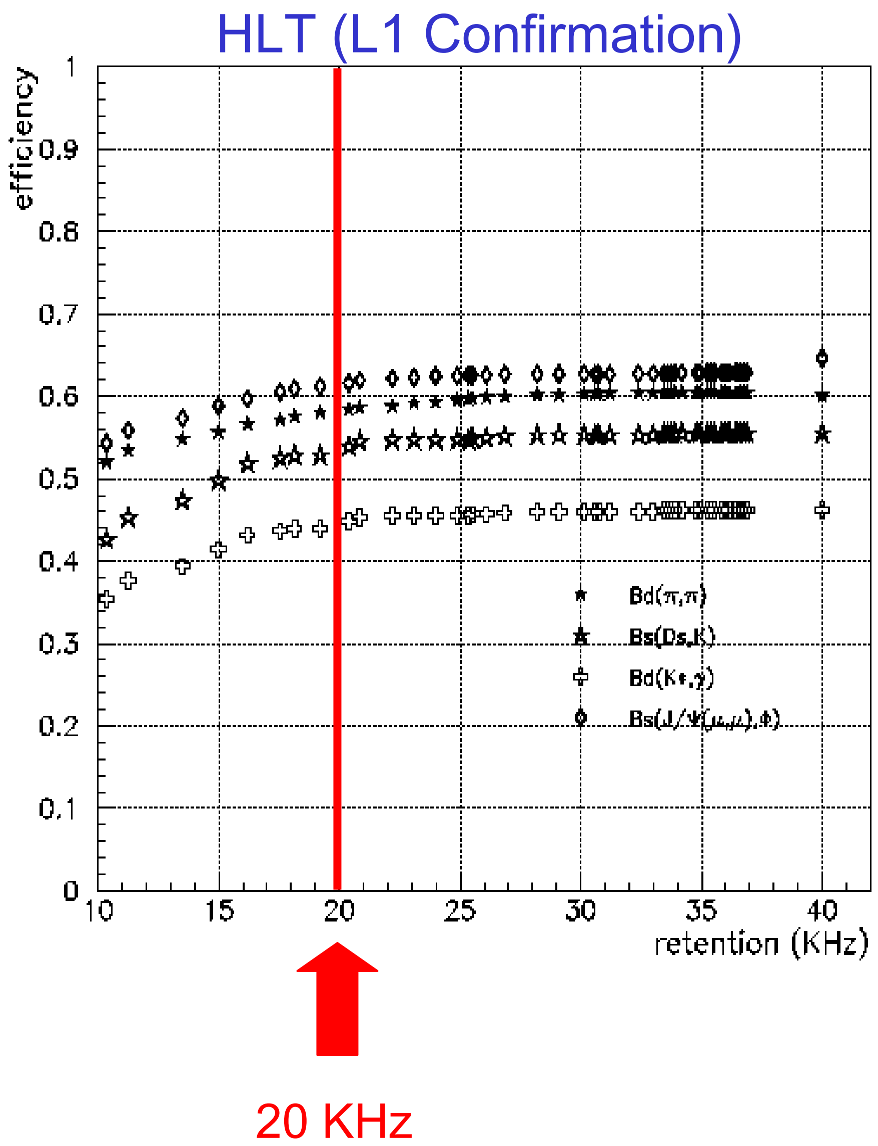


LHCb HLT L1-Confirmation

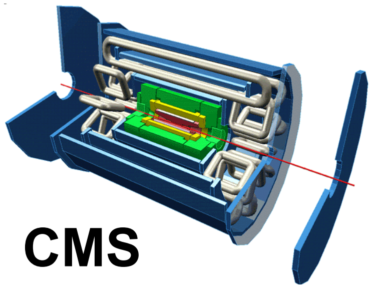
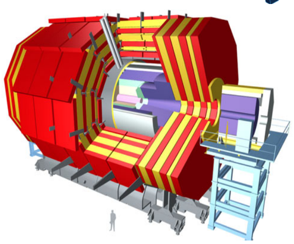
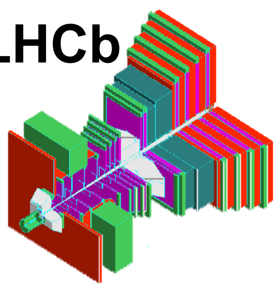
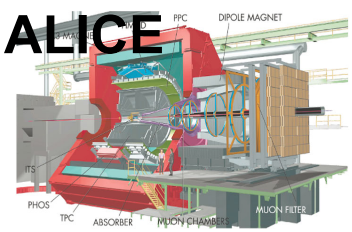
Trigger Enrichment Factors

	bb(%)	cc(%)
Generated	1.1	5.6
Level-0	3.0	10.6
Level-1	9.7	14.2
HLT-L1C	**14.0**	14.7

The 20 KHz of the events after the HLT L1-confirmation is still dominated by light quarks



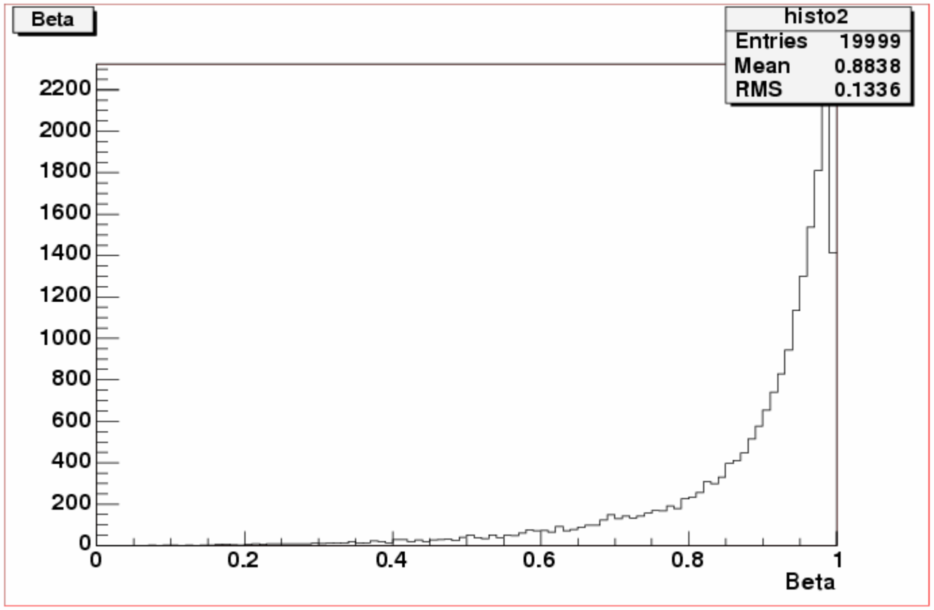
LHC trigger and DAQ summary

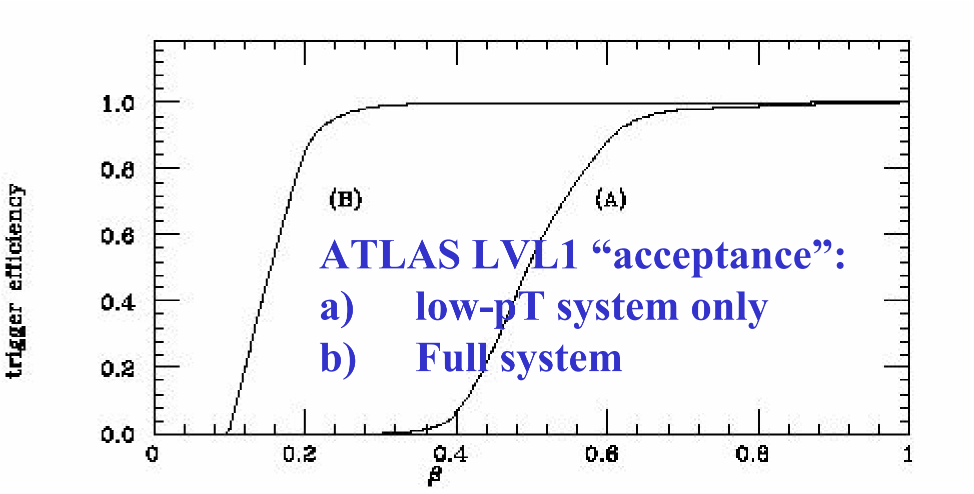
	No.Levels Trigger	**First Level** Rate (Hz)	**Event** Size (Byte)	**Readout** Bandw.(GB/s)	**Filter Out** MB/s (Event/s)
ATLAS	**3**	**10^5** LV-2 **10^3**	**10^6**	**10**	**100** (10^2)
CMS	**2**	**10^5**	**10^6**	**100**	**100** (10^2)
LHCb	**3**	LV-0 **10^6** LV-1 **$4\ 10^4$**	**$2x10^5$**	**4**	**40** ($2x10^2$)
ALICE	**4**	Pp-Pp **500** p-p **10^3**	**$5x10^7$** **$2x10^6$**	**5**	**1250** (10^2) **200** (10^2)

… Do we reject any possible "New Physics" ??

- Just an example: recent SUSY and Extra-Dimensions Models do predict high p_T massive long-lived charged particles produced in Hadron Colliders with speed significantly less than c. Would the ATLAS and CMS trigger systems be capable of catching such an object?



- The LHC trigger systems must have enough flexibility to cope with new possible physics signatures not known today but that could become important during the data-taking of ATLAS and CMS



Conclusions

- The Trigger/DAQ systems of LHC experiments are crucial for the exploitation of the physics program
- Multi-Level selection can handle the high p-p collision rate e rejects events of no physics interest
- High readout data traffic and data storage are required
- System scalability is essential to face staging/deferral scenarios of the LHC detectors
- Trigger systems flexibility important for event selection of unknown physics
- Acknowledgements…

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  - ....