Trigger in ATLAS and CMS

Christos Leonidopoulos
CERN-PH

On behalf of the ATLAS and CMS collaborations

LHC New Physics Signatures Workshop
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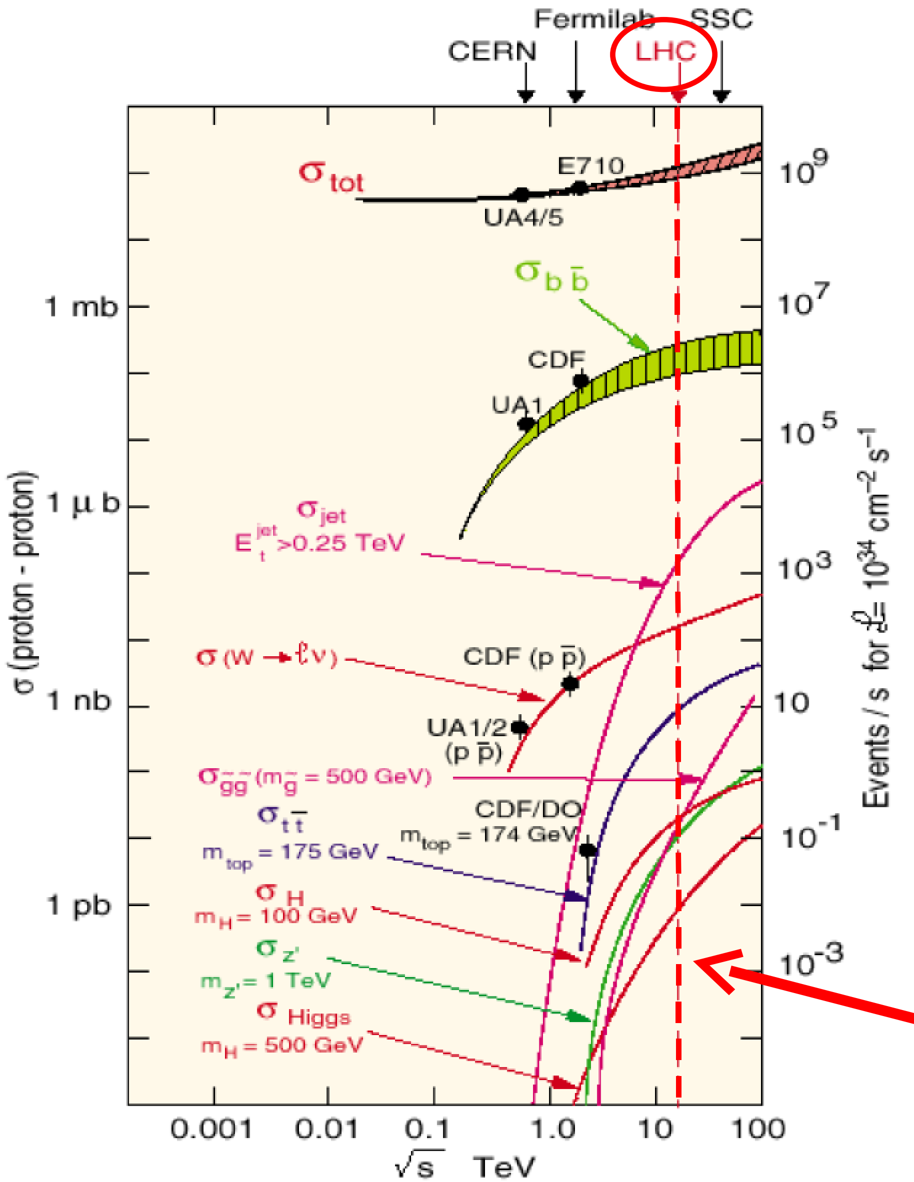
What are we trying to do?

- Find the most interesting physics signals at LHC
- Store them for off-line processing

What do we expect to see?



$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Process	(nb)	Production rates (Hz)
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
H(100 GeV)	0.05	0.1
Z'(1 TeV)	0.05	0.1
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.1
H(500 GeV)	10^{-3}	10^{-2}

You are here

What is the problem?

1) We don’t keep all these events ➔ Selection
2) Old Physics happens more often than New Physics
3) New Physics buried under a ton of Old Physics

We don’t keep all these events

- How many do we keep? About 150-200 Hz

- Why only so few? Not enough resources!

  200 Hz at 1-2 MB/event ➔ Up to 25 GB per minute

  Up to 4´000´000 GB of storage needed per year

  Plus: about 30 secs to reconstruct every event off-line

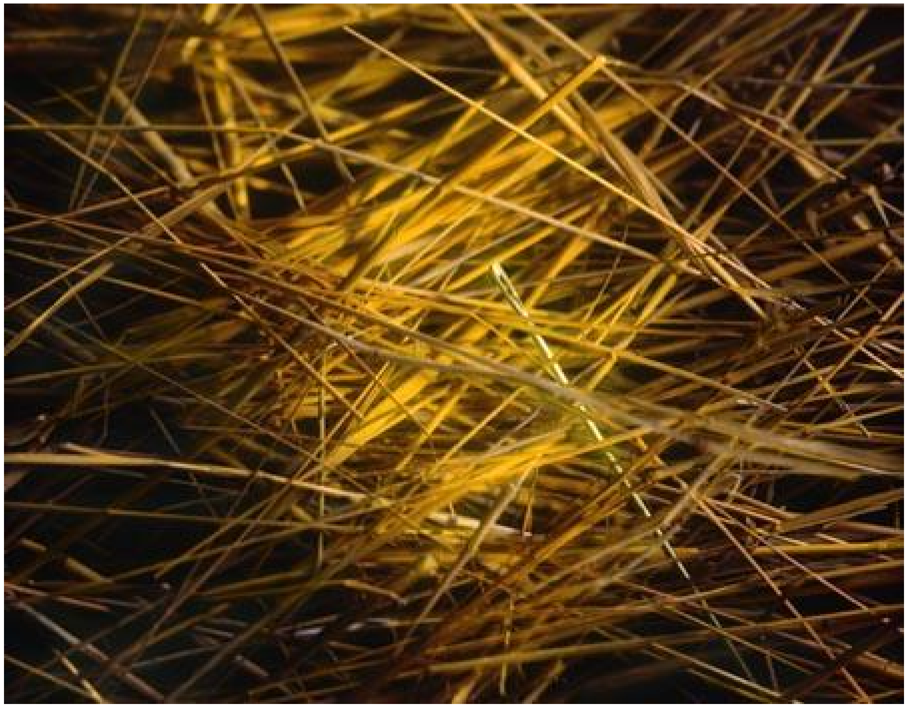
- “Interesting” physics occurs at ~10, 1 or < 1 Hz

  We are only interested in a (tiny) fraction of all events

  We *don’t* really want to keep all these events

Old Physics: more likely than New Physics

$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



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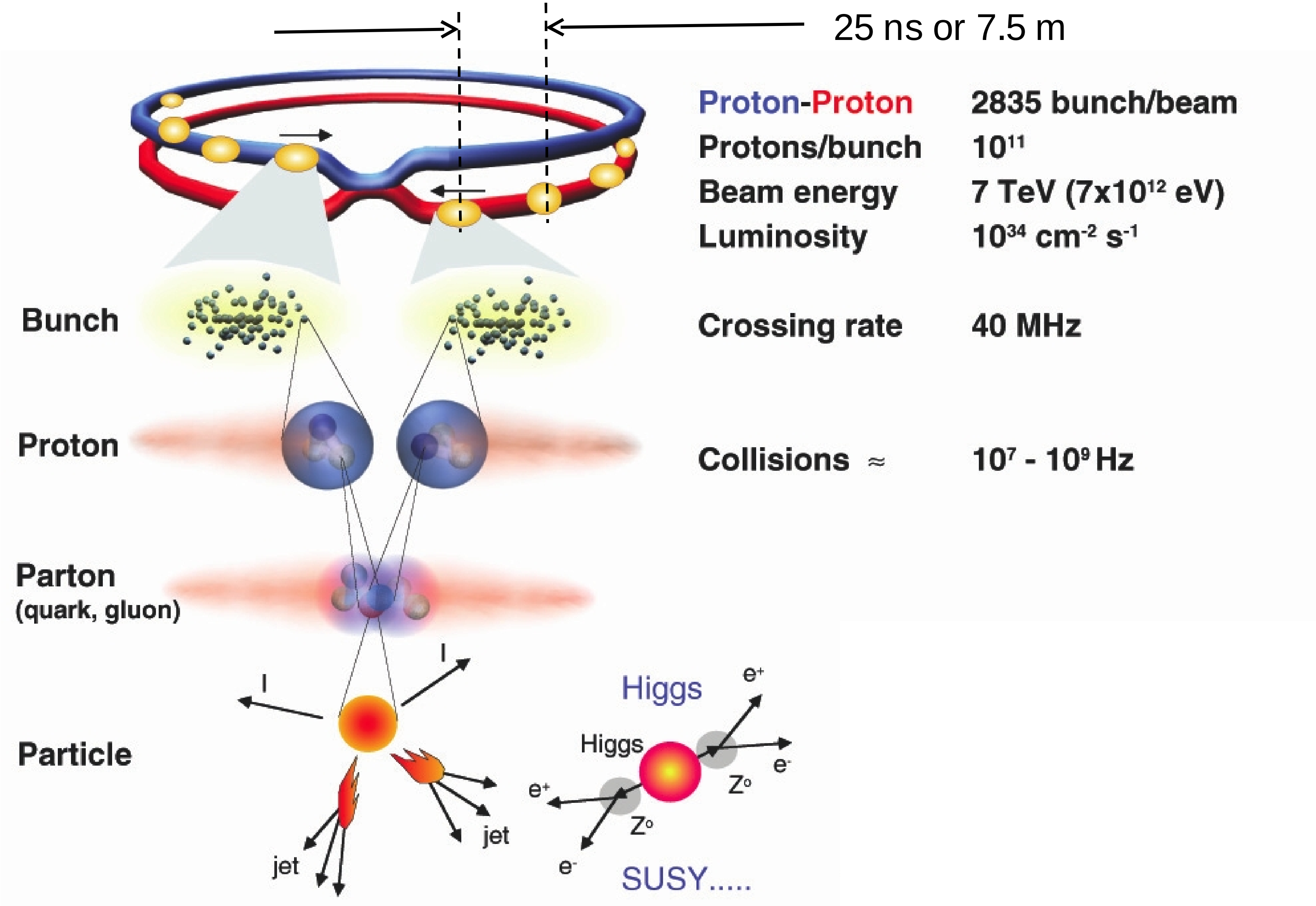
It is challenging (to say the least)
to find these rare exciting events

LHC reference numbers



New Physics buried under Old Physics

- Interaction rate:

$$R = \mathcal{L} \times \sigma_{\rm tot} = 10^{34}\ {\rm cm}^{-2}{\rm s}^{-1} \times 80\ {\rm mb}^{(*)} \sim 0.8\ {\rm GHz}$$

(*) Total inelastic cross section (±20%)

- Distance between bunch crossings:

$$\Delta t = 25\ {\rm ns\ (or\ 7.5\ m)}$$

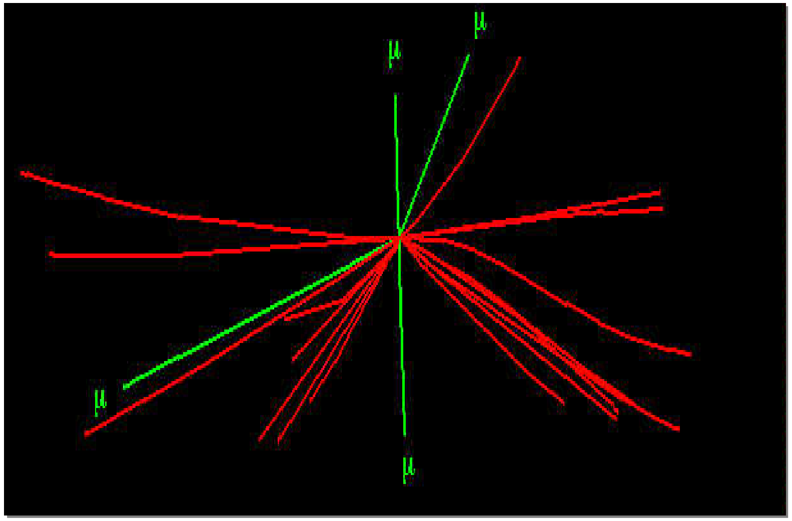
- Non-empty bunch crossings:

$$2835\ {\rm out\ of}\ 3564\ ({\rm or}\ \epsilon = 79.5\%\ )$$

- Average # of interactions per (non-empty) crossing:

$$\bar{n} = R \times \Delta t / \epsilon \sim 25$$

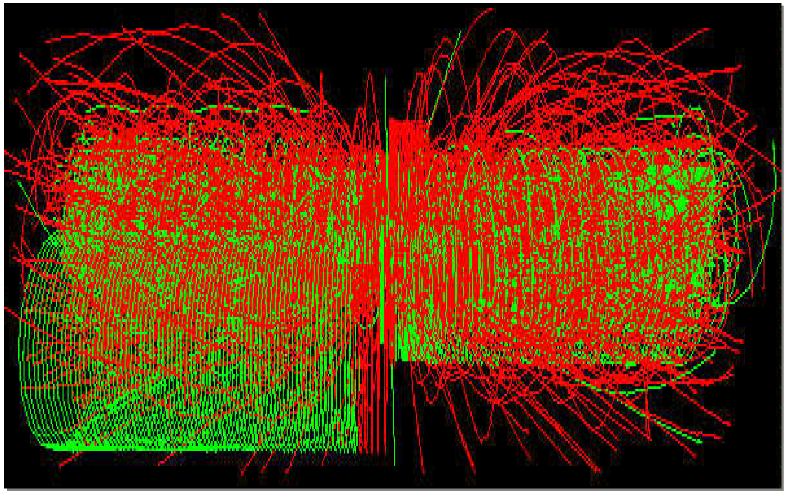
New Physics buried under Old Physics



For every exciting interaction…

$$H \rightarrow ZZ \rightarrow 4\mu$$

Reconstructed tracks with p_T > 25 GeV



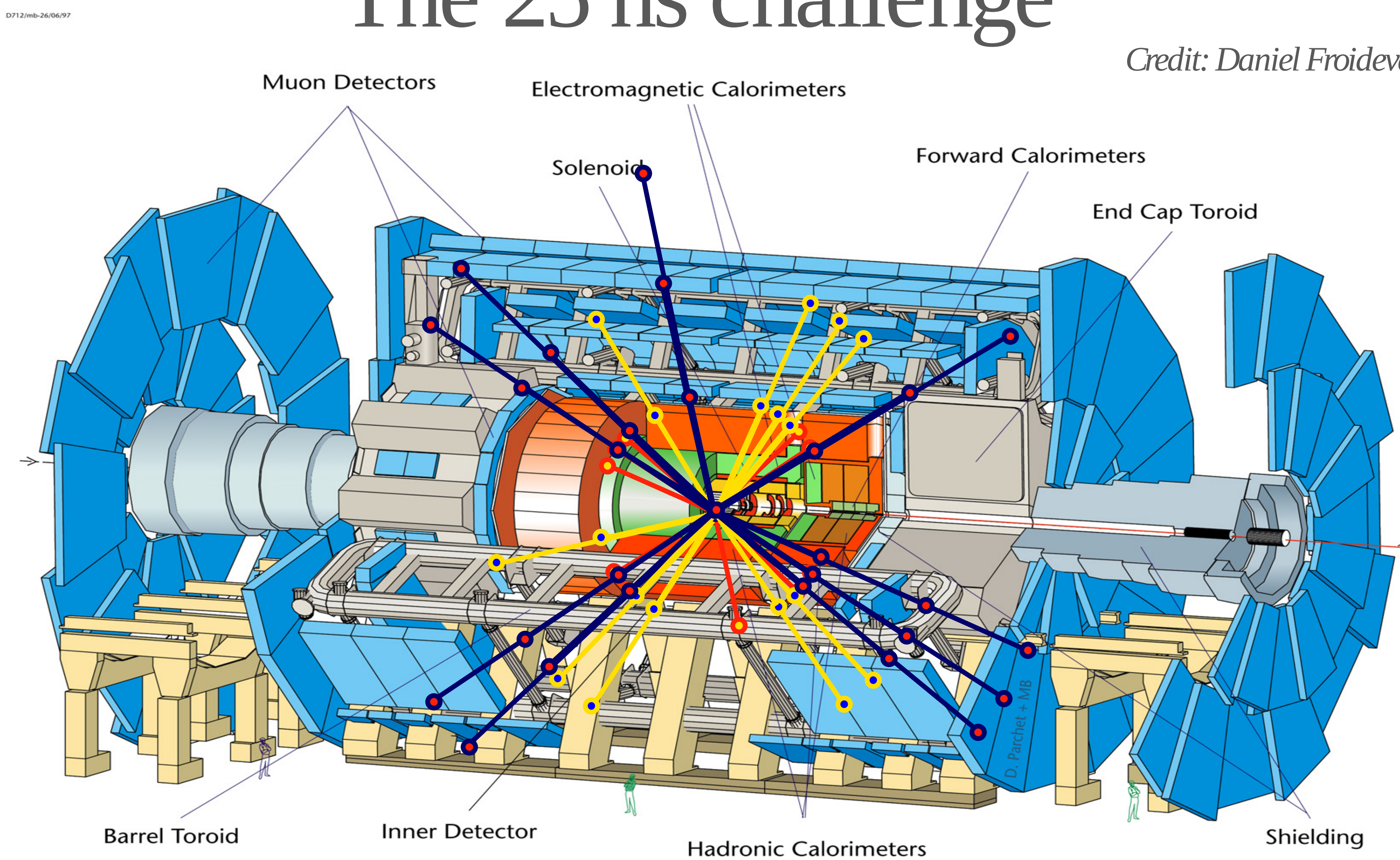
…expect 25 non-exciting *overlaid* interactions (at ~1000 tracks per event)

Reconstructed tracks with p_T > 2 GeV

Pileup: serious problem at LHC at high luminosities

The 25 ns challenge

Credit: Daniel Froidevaux



Interactions every 25 ns …

In 25 ns particles travel 7.5 m

Cable length ~100 meters …

In 25 ns signals travel 5 m

What are we trying to do? (v.2)

- Select the most interesting physics signals at LHC

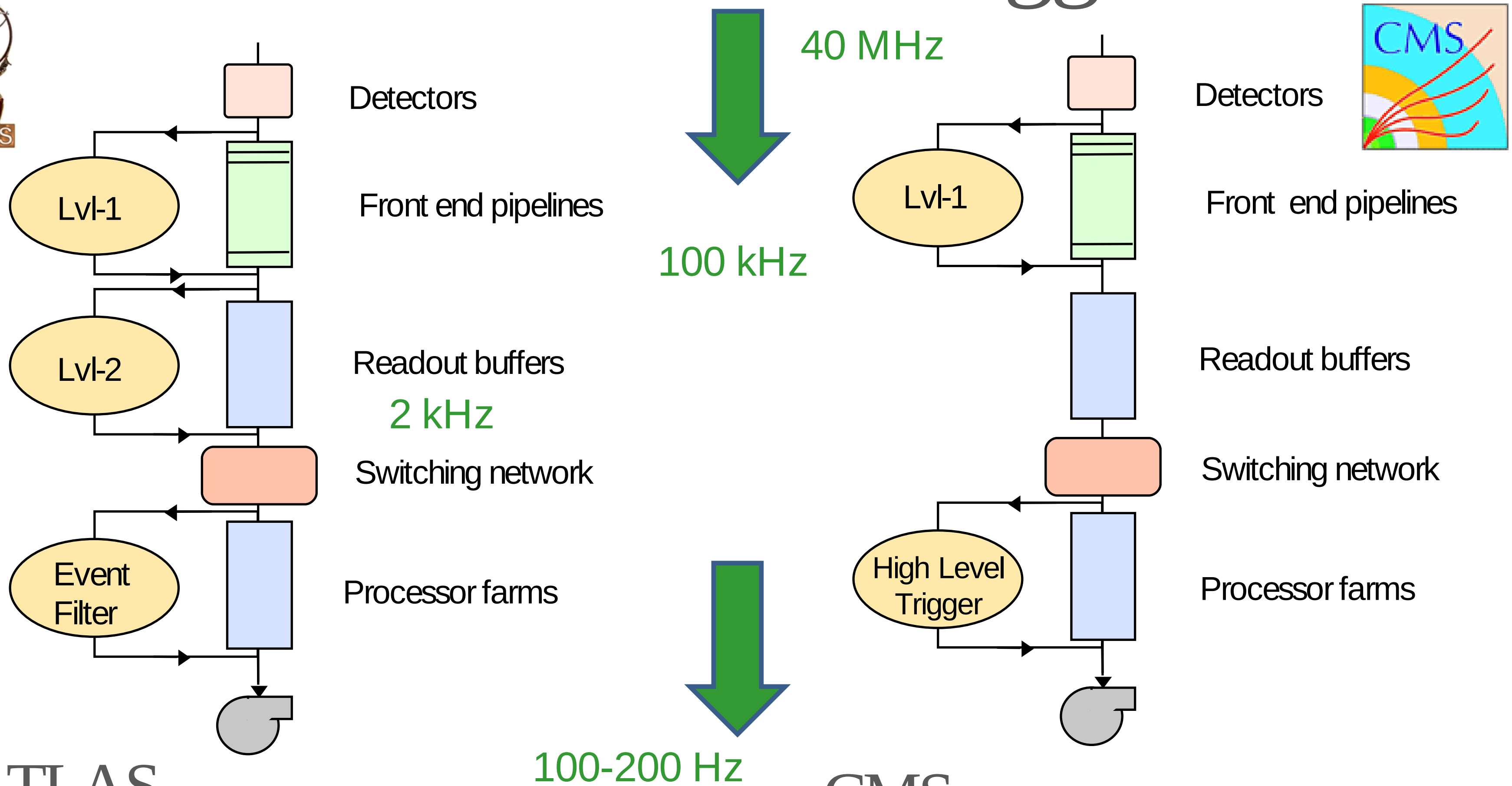
  150-200 Hz out of ~ 1 GHz of “noise” (selection: 10^{-7})

- In real time
- Store them for off-line processing

Background is a Disease

Meet the Cure

ATLAS and CMS triggers



<u>ATLAS</u>

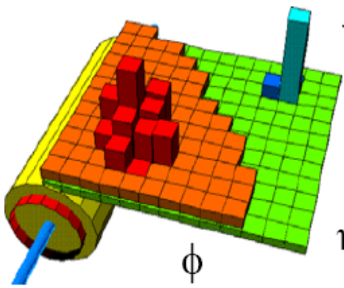
- 3 levels (traditional design)
- L1: hardware, firmware
- L2 + EvF: high-level software

<u>CMS</u>

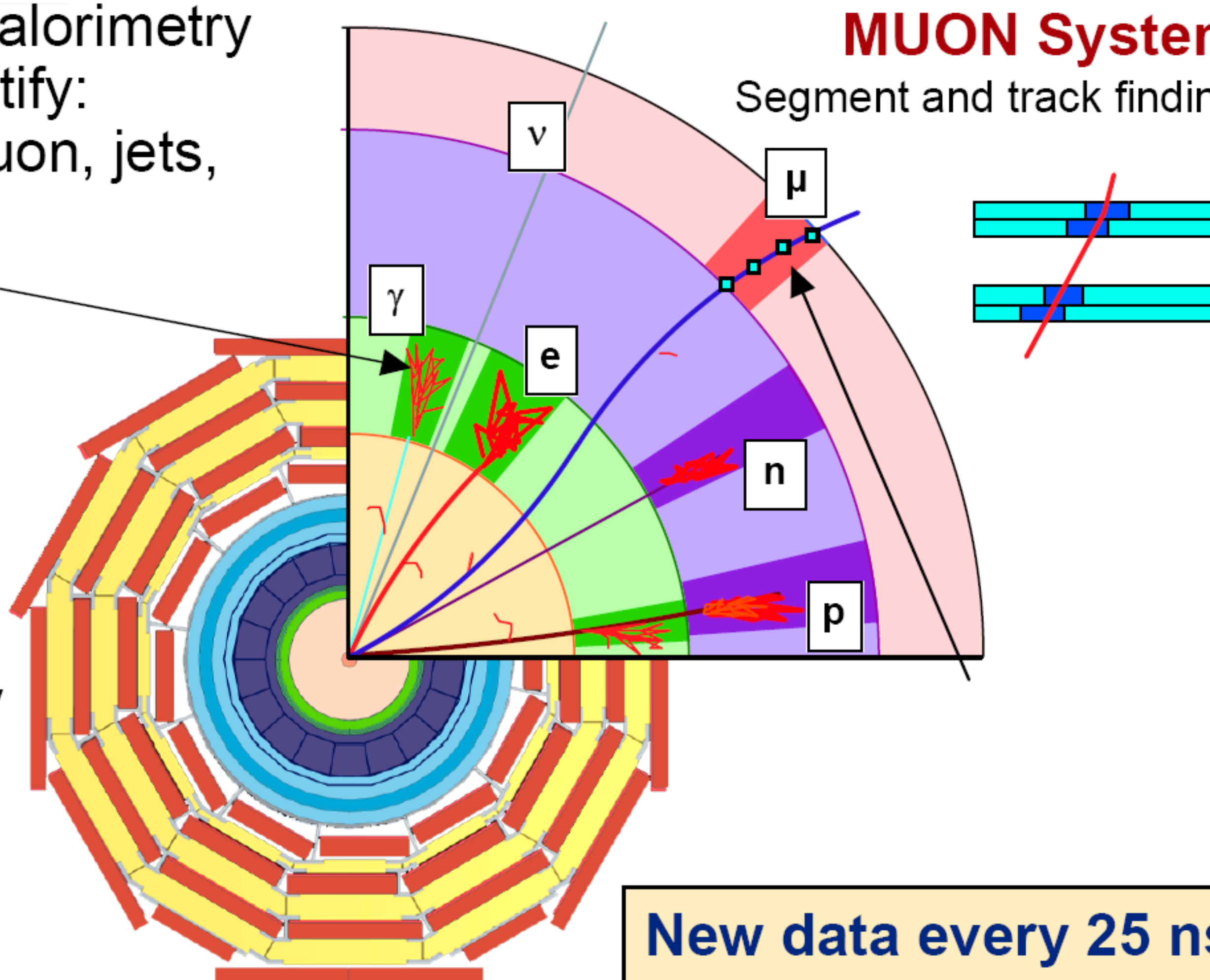
- L2, L3: merged into HLT
- L1: hardware, firmware
- HLT: high-level software

Particle-id at Level-1

Use prompt data (calorimetry and muons) to identify:
High p_t electron, muon, jets, missing E_T

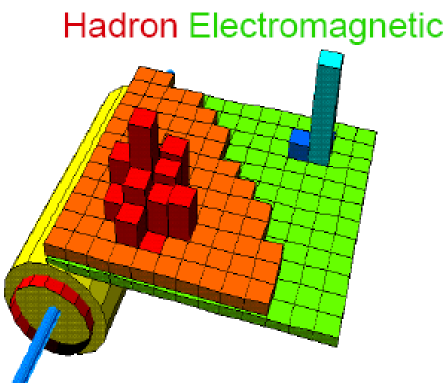


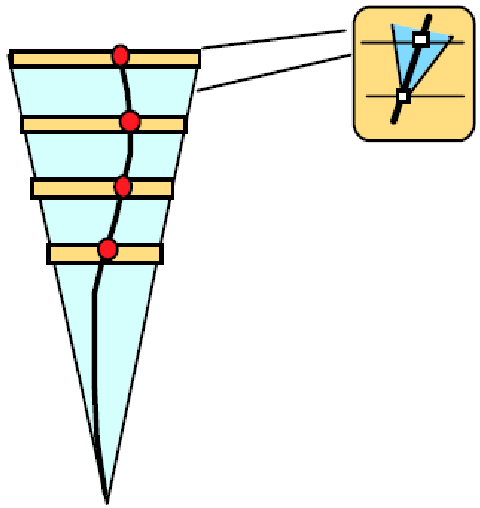
CALORIMETERs
Cluster finding and energy deposition evaluation



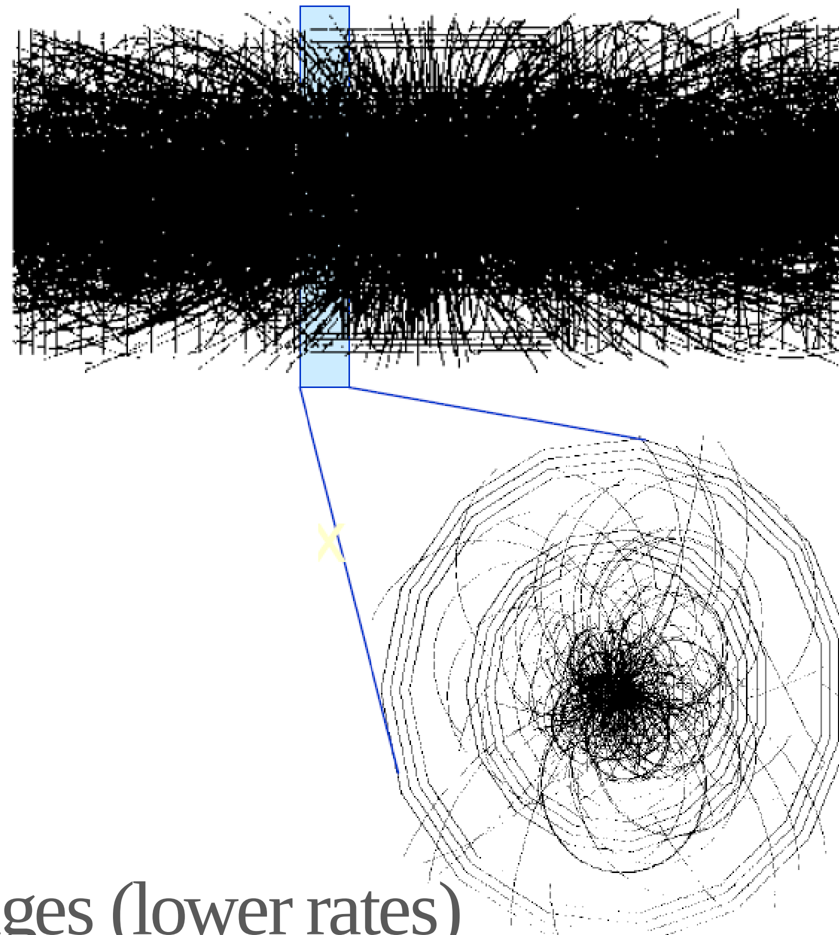
New data every 25 ns
Decision latency ~ μs

Why not use tracker info at Level-1?





Thoughts of including tracker info at L1 for SLHC



Calorimeter, muon detectors:

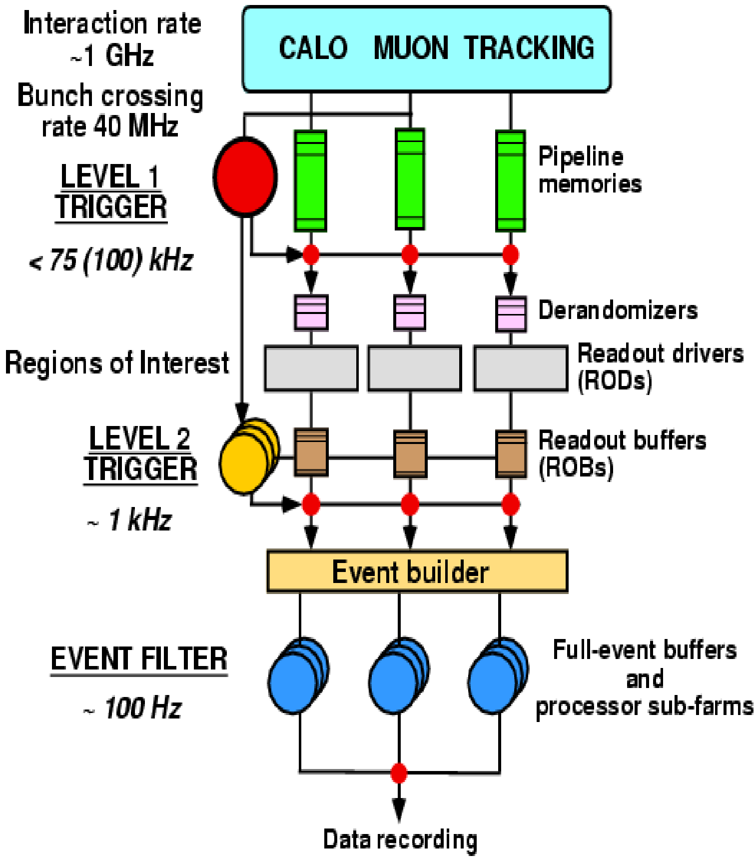
- Thousands of channels
- Patter recognition fast

Tracking, vertexing detectors:

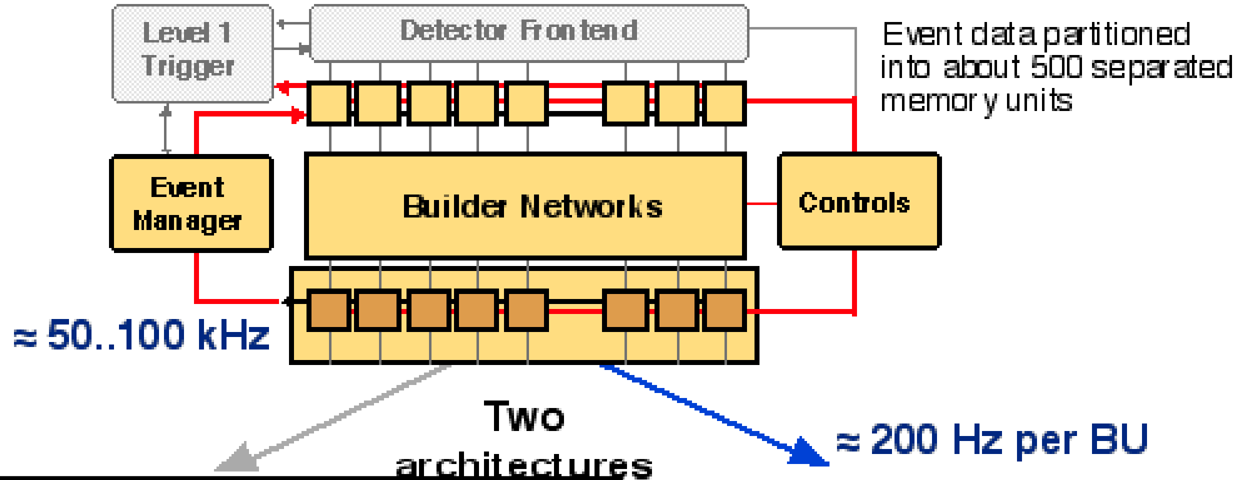
- Millions of channels
- Patter recognition slow
- Reserved for later triggering stages (lower rates)

ATLAS High Level Trigger

- L2 and L3 (Event Filter) form High Level Trigger (HLT)
- L2 (~500 CPUs) accesses ~10% of event info (full granularity) seeded by L1 objects
- Event Filter (~2000 CPUs) accesses full event using "off-line quality" algorithms
- Custom L2-steering system
- L1: 2.5   s, L2: 40 ms, L3: 4s



CMS High Level Trigger



- L2 and L3 merged into High Level Trigger (HLT)
- HLT (~2000 CPUs) accesses full event info (full granularity) seeded by L1 objects using “off-line quality” algorithms
- L1: 3.2   s, HLT: 40 ms

Farm of processors

ONE event, ONE processor

- High latency (larger buffers)
- Simpler I/O
- Sequential programming

ATLAS *vs.* CMS Triggers

- More traditional, safer design
- Concrete steps & requirements for each of Level-2, Level-3 steps of selection
- Accesses fraction of event at L2 (small throughput)
- But: Custom controls and separate farms for L2, L3

- More flexibility

  Full event info (and offline reconstruction) as early as L2

  HLT: continuous software environment in single farm
- But:

  Large data throughput (and switching network) needed

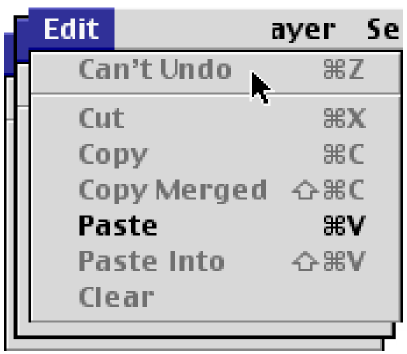
  Risky design decision (at the time)

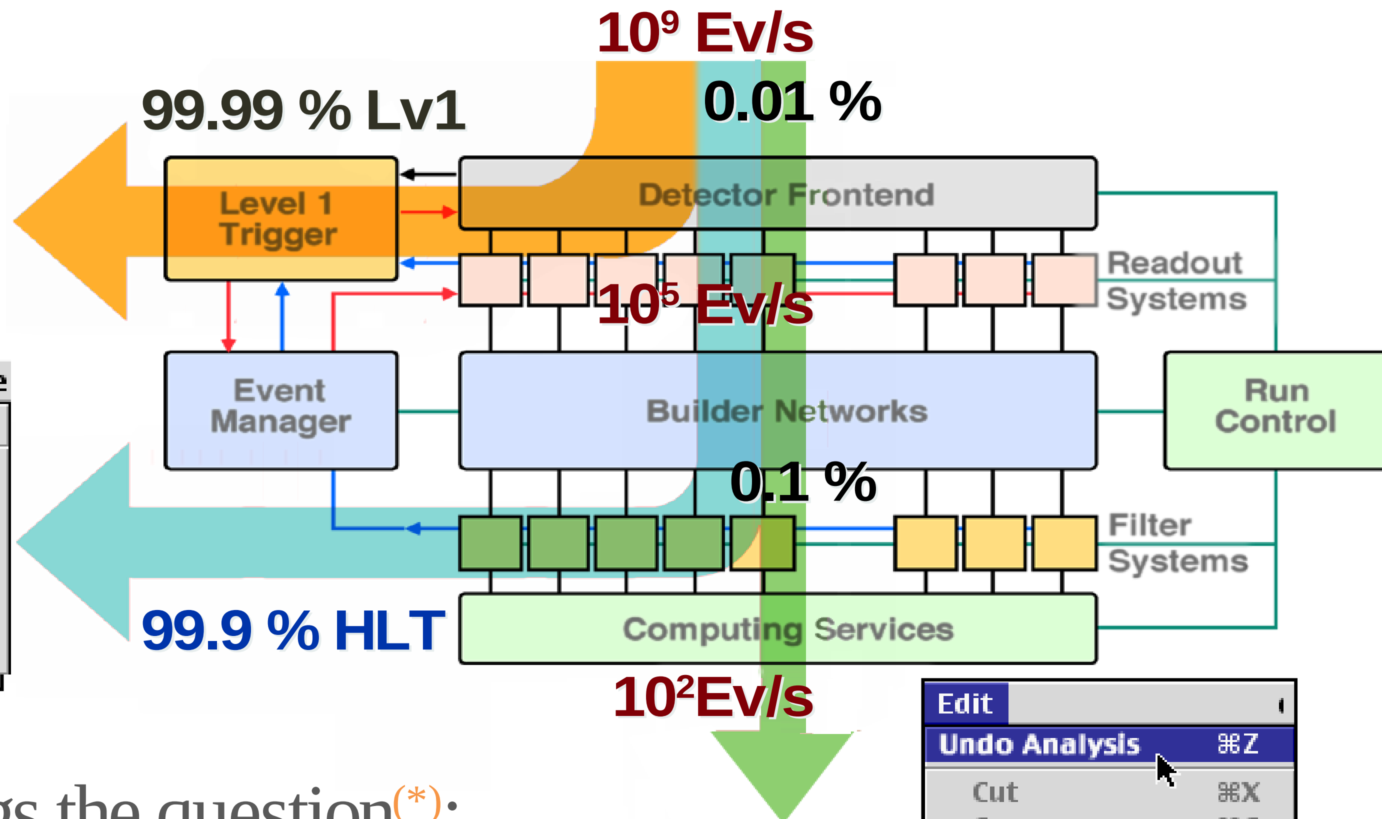
ATLAS *vs*. CMS Triggers

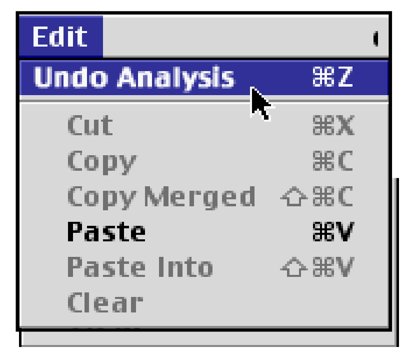
Overall:

- Very similar performances
- Trigger bandwidth determined by detectors and physics programs, not trigger design
- Systems still differ (two farms vs. single farm at HLT) so: commissioning and debugging also different

Trigger: A tricky business







Which begs the question(*):

Will your favorite new physics signal be included in the small fraction of selected events? (unexpected signatures always a worry)

(*) LHC upgrade: 1B CHF, CMS+ATLAS detectors: 1.2B CHF

What are we trying to do? (v.3)

- Select the most interesting physics signals at LHC

  150-200 Hz out of ~ 1 GHz of “noise” (selection: 10^{-7})
- In real time
- Store them for off-line processing
- Don’t screw up

What to avoid

- Killing the interesting physics altogether
- Biasing the selected event samples:
  - Uncertainties in topologies of rejected events
  - Introduction of large systematic errors

arXiv:hep-ex/0502042v3 9 Feb 2007

Reduction of the Statistical Power Per Event Due ... Measurements

Abstract

A cut on the max... the number of event... decreases the statist... parameter cut in the ... to technical limitations, has the same effect. In this note we describe and quantify the consequences of such a cut on lifetime measurements. We

The small loss of events due to a moderate upper lifetime cut is accompanied by a large loss of information, because not only a few events outside the allowed time window are lost, but also the information that there were only a few. This can have dramatic effects on the precision of the measurement. As shown

How to build good triggers

Ask old people

Learn from previous experiments

How to build good triggers

- No single silver bullet
- Using common sense (and trigger studies)

General strategies

- As simple as possible
- As inclusive as possible
- Robustness
- Redundancy

Simplicity

- Construct triggers with simple conditions
- Simple triggers easier to
    - commission
    - debug
    - understand

General strategies

- **As simple as possible**
- As inclusive as possible
- Robustness
- Redundancy

Be inclusive

- Better to have one trigger covering similar analyses
- Even better: covering other, unrelated analyses
- Should be able to discover the unexpected as well

Strong social aspects, often ignored

- Competition inside experiment

  One (wo)man's signal is another (wo)man's background

  It's best for your analysis to rely on a popular trigger

- Inertia: people get used to "old" triggers
- Safety: people tend to ignore "new" triggers

General strategies

- As simple as possible
- As inclusive as possible
- Robustness
- Redundancy

Your favorite trigger should be deployed online as early as possible

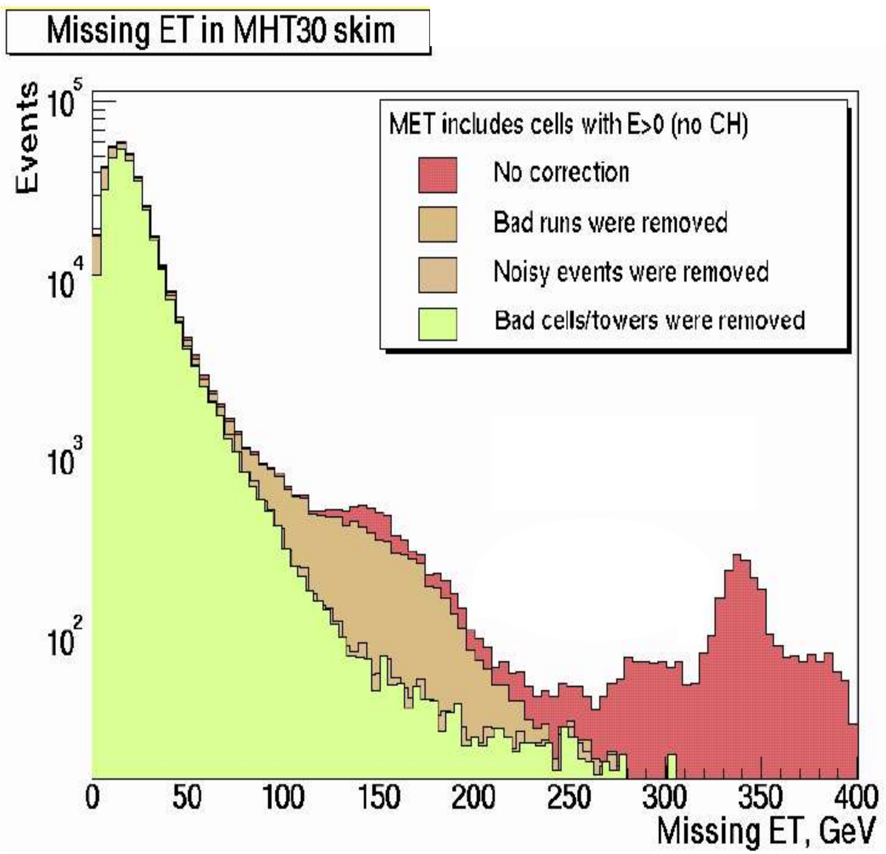
Robustness

- Make sure your trigger can run for *many* events
  - Including pathological events
  - Including events with x10 more hits than MC predicts
- Make sure your trigger is immune
  - To beam conditions, detector problems

Missing E_T : the popular trigger for

- SUSY particles
- Dark matter candidates
- But also: neutrinos (so: *W*s, Higgs, etc)

Missing E_T at DØ



It takes a *long* time to

- Commission the detector for data-taking
- Remove all problematic runs
- Understand noisy environment
- Discover (and remove) problematic channels

Missing E_T :

- Not ideal for startup
- Typically the last trigger to be commissioned

Redundancy

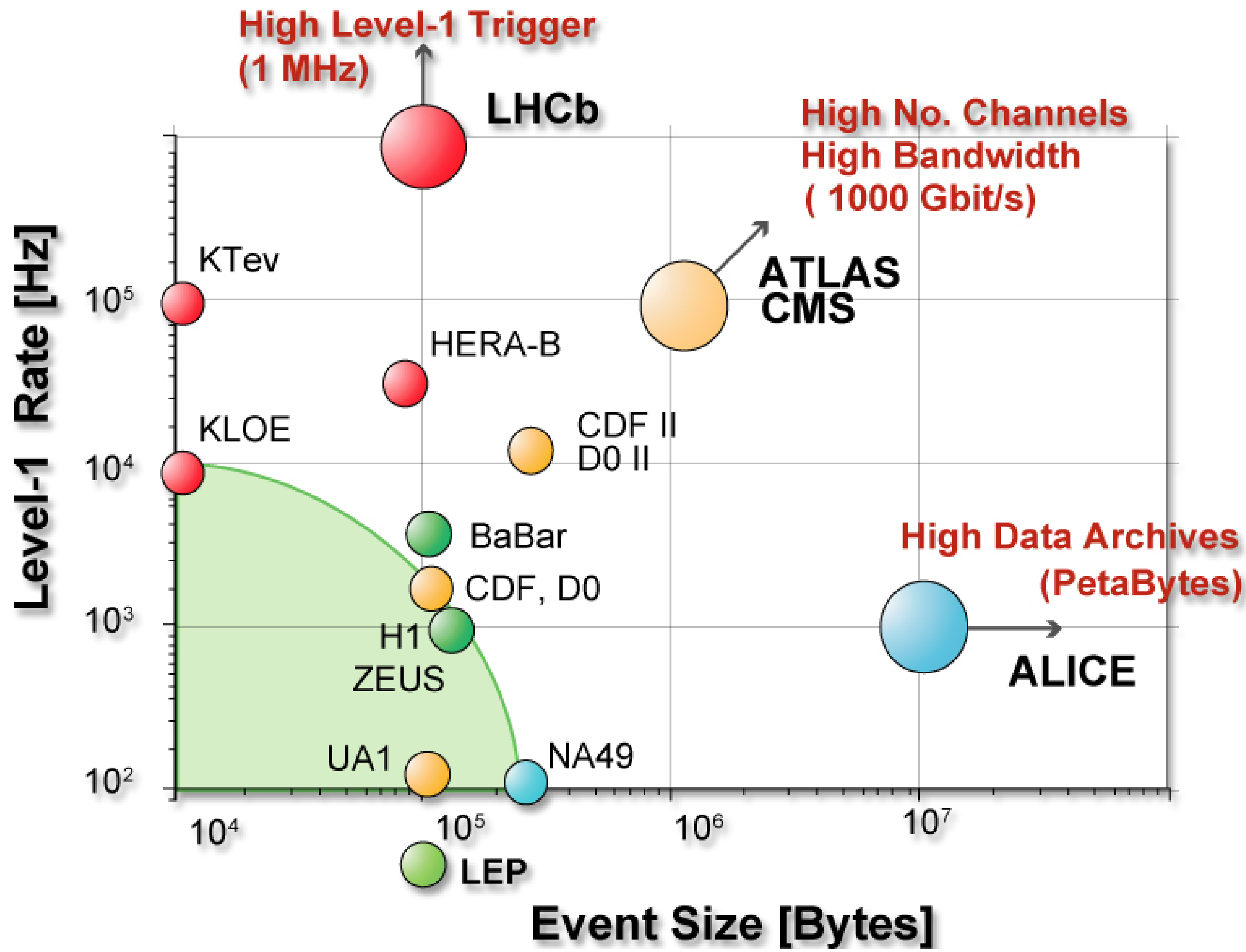
- Make sure your signal can be selected by more than one triggers
    - Helps to understand biases
    - Ensures that if a trigger has problems (rates too high or instability) you still get your events

General strategies

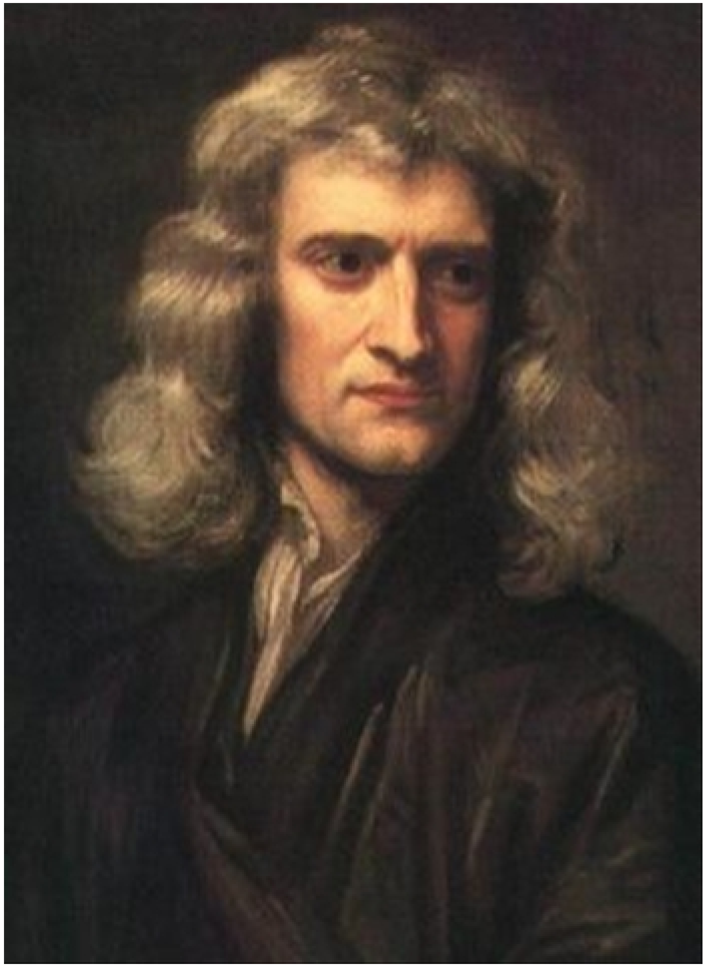
- As simple as possible
- As inclusive as possible
- Robustness
- Redundancy

How is the trigger different at LHC?

Trigger trends



Luminosity, rates, event sizes:
all increased by ~an order of magnitude



"If I have seen further it is by standing on the shoulders of Giants"

Evolution in computing

Advances in

- Networking (Ethernet, Terabit/s networks)
- PC industry (computing power and memory abundance)
- Software standards (Linux, http, XML, C++, Java)

offer affordable, modular, scalable, upgradable solutions

LHC trigger: scalable

The trigger at ATLAS and CMS evolves with luminosity

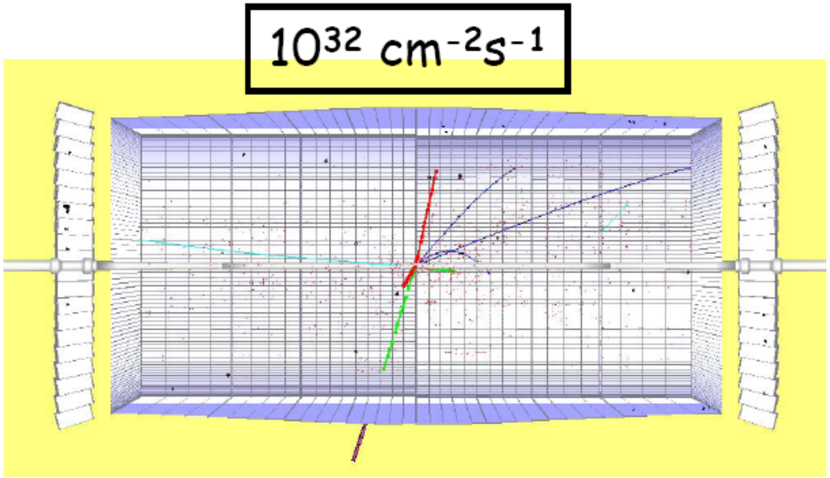
Adjusts to increases in:

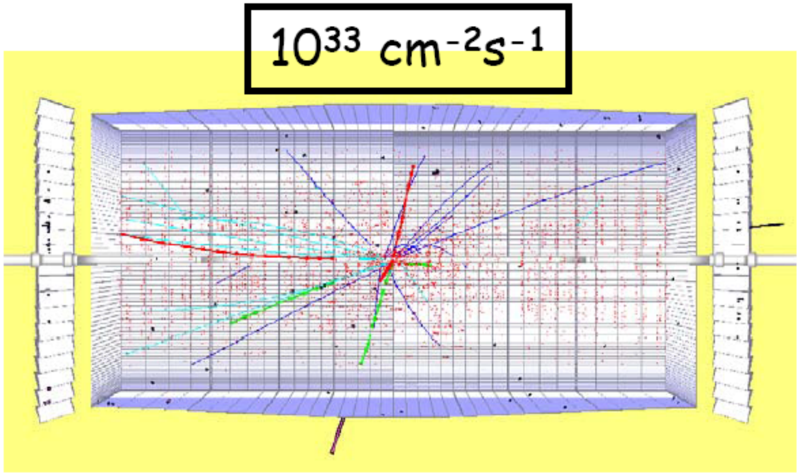
- DAQ capacity (L1 rate)
- CPU-power needed at HLT

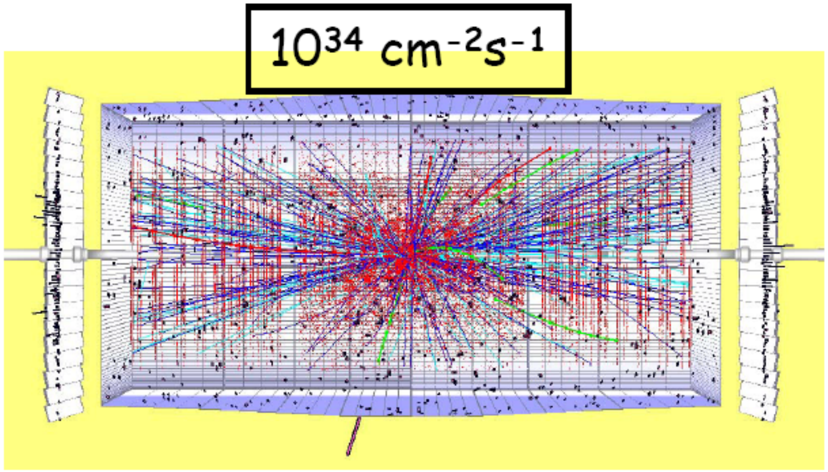
By adding/upgrading PCs as necessary

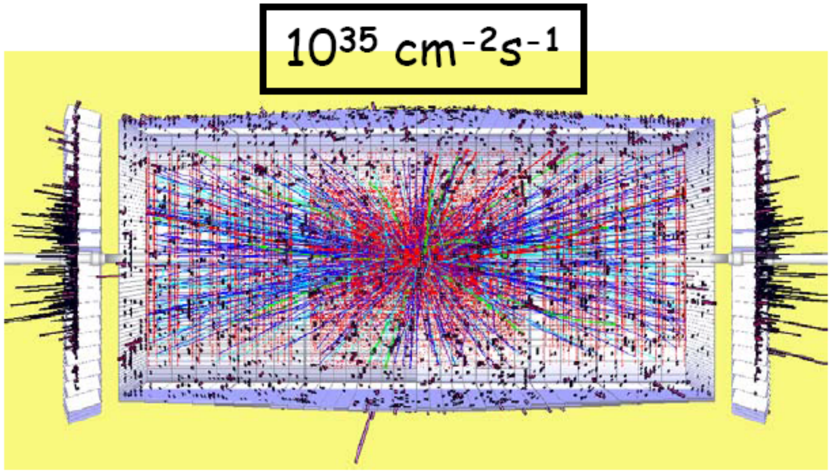
Luminosity effects

$H \to ZZ \to \mu\mu ee$ event with M_H= 300 GeV for different luminosities









LHC trigger at low luminosities

Lower luminosities allow us to trigger

- with lower thresholds, looser requirements

  e.g. no isolation on leptons

- on physics that we cannot trigger on later

  e.g. *B* physics or other low-p_T physics

Building triggers

- *pp* inelastic collisions: mainly hadrons at ~few GeV
  Interesting physics: typically with larger p_T
  Make sure we can still trigger on events
  with many soft particles

- Signatures (event topologies) compatible
  with new (or old but still interesting) physics
  - Simple objects: leptons, jets, photons
  - More advanced objects: taus, b-jets

- Trigger's "sine qua non":
  - High efficiency on signal events

Trigger examples

<u>Nota Bene:</u>

- Impossible to cover all LHC New Physics channels & their triggers
- ATLAS and CMS focusing on early luminosity studies
- Listing only unprescaled "physics" triggers here
  - Ignoring triggers for calibration, monitoring, etc. (~20% of total)

Electrons and photons

ATLAS: Very early luminosity 10^{31} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Electrons rate: 40 Hz – Photons rate: 10 Hz		
1e	10	
2e	5	
1	20	
1	20	isolation
2	10	
3	10	

CMS: Early luminosity 10^{32} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Electrons/Photons – Total rate: 30 Hz		
1e	17	
1e	15	isolation
2e	12	
2e	10	isolation
1	40	
1	30	isolation
2	20	
2	20	isolation
High-E_T EM	80	looser cuts
Very high-E_T EM	200	looser cuts

- Electrons & photons share the same reconstruction code
- Electrons also have an associated track (so: thresholds can be lower)

Muons

ATLAS: Very early luminosity 10^{31} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Muons – Total rate: 25 Hz		
1	6	
1	10	isolation
2	6	

CMS: Early luminosity 10^{32} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Muons – Total rate: 50 Hz		
1	16	
1	11	isolation
2	3	

- Low threshold crucial for *B* physics
- Topological ATLAS trigger (including *B* physics) at 15 Hz

- Muons are typically cleaner than electrons
- Favorite trigger for many channels with even lower thresholds

Physics with leptons and photons

- Higgs discovery (E/W symmetry breaking scale)

  $115 < m_H < 250\ \mathrm{GeV}/c^2$, with $H \to \gamma\gamma, WW^*, ZZ^*$

  $H(120) \to \gamma\gamma:\ E_T^\gamma > 50-60\ \mathrm{GeV}/c^2$

  $H \to WW^*, W \to \ell\nu : p_T^\ell > 30-40\ \mathrm{GeV}$

  $H \to ZZ^*, Z \to \ell\ell : p_T^\ell > 40\ \mathrm{GeV}$

CMS trigger efficiencies (%)

Signal process	Isolated single photon	Relaxed single photon	Isolated double photon	Relaxed double photon
HLT: $H \to \gamma\gamma(m_H$=120 GeV)	80.5	76.8	75.8	75.7
L1*HLT: $H \to \gamma\gamma(m_H$=120 GeV)	78.8	76.8	58.7	72.7

Suggested triggers by ATLAS and CMS adequate for all channels

Physics with leptons and photons

- Randall-Sundrum model searches with dileptons, diphotons (extra dimensions)
- $Z' \to ee, \mu\mu$ (TeV scale: stabilize Higgs sector)

triggers with (one or) two electrons, muons, photons

Increase trigger efficiency by loosening up trigger requirements for large EM deposits

CMS trigger efficiencies (%)

Signal process	single high energy EM	Single very high energy EM
$Z' \to ee$ ($M \geq 200$ GeV)	67	7.0
$Z' \to ee$ ($M \geq 500$ GeV)	91	69
$Z' \to ee$ ($M \geq 1000$ GeV)	94	92
$Z' \to ee$ ($M \geq 2000$ GeV)	90	97
$G \to \gamma\gamma$ ($M \geq 2000$ GeV)	91	97

80 GeV

200 GeV

Physics with leptons

- Rare or forbidden decays

$B_S \to \mu\mu$ dimuon trigger (lowest possible threshold)

$Z \to e\mu, e\tau, \mu\tau$

triggers with combinations of different leptons

Leptonic flavor violation $\tau \to \mu\gamma$

single muon or + triggers

Physics with leptons

- *W´* spin-1 boson, heavy partner of *W*

single-muon trigger

Jets, missing E_T, total E_T

ATLAS: Very early luminosity 10^{31} cm^{-2} s^{-1}

Trigger	Thresh (GeV)
Jets, MET, Total E_T Total rate: 40 Hz	
1j	100
4j	23
MET	70
Sum E_T	340

CMS: Early luminosity 10^{32} cm^{-2} s^{-1}

Total rate: 30 Hz

HLT path	Thresholds (GeV)
Single-Jet	200
Double-Jet	150
Triple-Jet	85
Quad-Jet	60
$\not{E}_T$	65
Acopl. Double-Jet	125
Acopl. Single-Jet + $\not{E}_T$	(100, 60)
Single-Jet + $\not{E}_T$	(180, 60)
Double-Jet + $\not{E}_T$	(125, 60)
Triple-Jet + $\not{E}_T$	(60, 60)
Quad-Jet + $\not{E}_T$	(35, 60)
H_T + $\not{E}_T$	(350, 65)
Single Jet Prescale 10	150
Single Jet Prescale 100	110
Single Jet Prescale 10^4	60
VBF Double-Jet + $\not{E}_T$	(40, 60)
SUSY 2-jet+$\not{E}_T$	(80,20,60)
Acopl. Double-Jet + $\not{E}_T$	(60, 60)

- (Multi-)jets are another favorite trigger for BSM signals
- MET is a difficult trigger to commission (already discussed)
- Total E_T can be used to study biases of jet algorithms

Physics with jets, total E_T

- Black holes

  Events with high-multiplicity, energy deposit

  multi-jet triggers

- Searches for new resonances (SUSY or Exotica)

  multi-jet triggers + MET + total E_T

  or multiple-lepton triggers

- Di-jet mass

  Look for excess compared to SM distribution

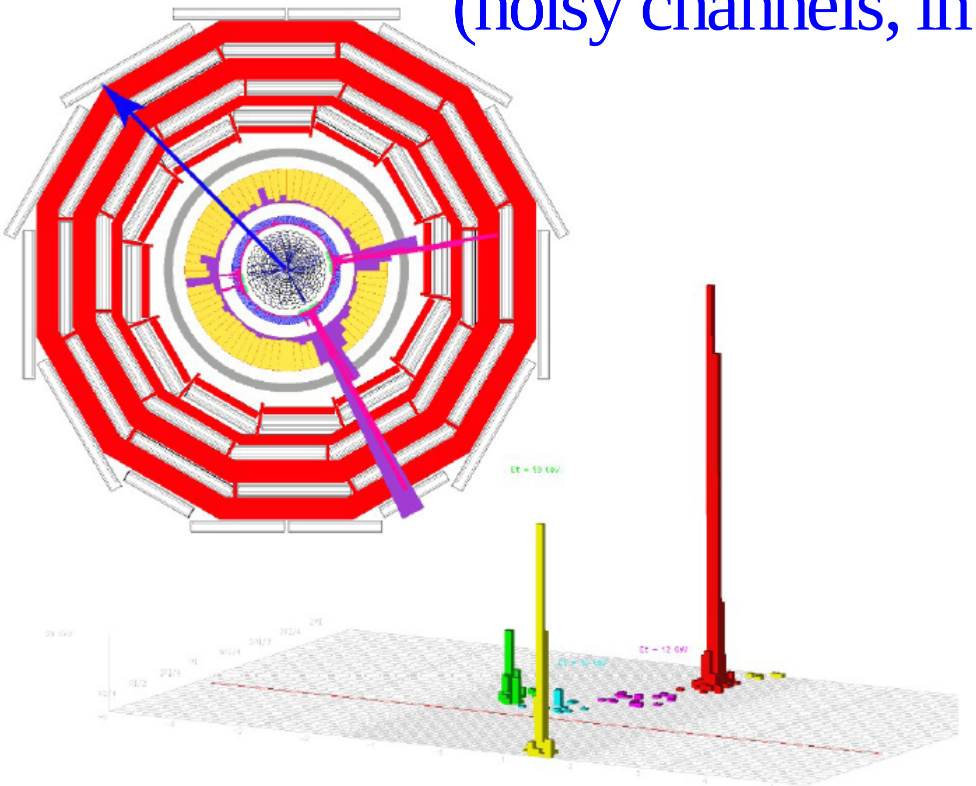
  single- or di-jet triggers

Physics with MET

- Dark matter, lightest supersymmetric particle

MET trigger: will take time to commission

(noisy channels, improper calibration, etc)



Taus, b-jets

ATLAS: Very early luminosity 10^{31} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Taus, b-jets – Total rate: 45 Hz		
1	60	
1	45	isolation
+	45, 40	
+	20, 30	isolation
Plus: + , +e, +jets and b-jets		

CMS: Early luminosity 10^{32} cm^{-2} s^{-1}

Trigger	Thresh (GeV)	Notes
Taus, b-jets – Total rate: 17 Hz		
1	80	
+MET	30, 35	
2	40	
+	20, 15	
+e	20, 12	
Plus: b-jets (displaced vertex or soft)		

Total investment in combined triggers:
ATLAS: 50 Hz (10^{31} cm^{-2} s^{-1}), CMS: 20 Hz (10^{32} cm^{-2} s^{-1})

- Taus and b-jets popular for Higgs (and top) analyses
- More difficult to commission and fine-tune, not suitable for startup

Physics with taus, b-jets

- MSSM Higgs: $h^0, H^0, A^0, H^{\pm}$

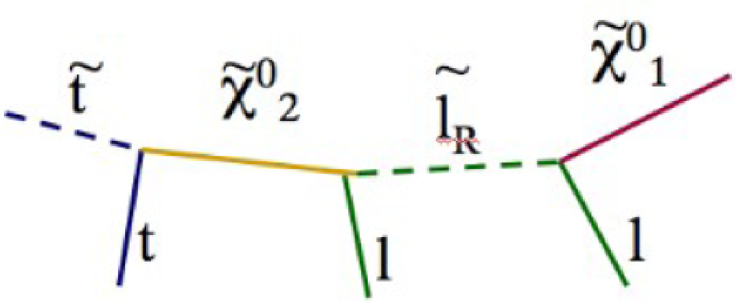
  $H \rightarrow bb, \tau\tau$ b-jet, single- and double-tau triggers

  CMS trigger efficiencies at 10^{32} cm^{-2} s^{-1}

	$H^{\pm} \rightarrow \tau\nu$		QCD
	$M_H = 200\,GeV/c^2$	$M_H = 400\,GeV/c^2$	$\hat{p}_T$ 120-170
Level-2 $\not{E}_T$ cut	59%	81%	6%
Level-2 Jet Reconstruction and Ecal Isolation	81%	85%	53%
Level-2.5 SiStrip Isolation	67%	76%	27%
Level-3 SiStrip Isolation	70%	72%	18%
HLT	23%	38%	0.15%
L1 * HLT	16%	29%	-

- Stop production

  Excess in reconstructed top distributions b-jet triggers



Fit everything into O(100) Hz

- How should the bandwidth be shared among the large number of available triggers?

  A difficult question – many things to consider:

  Are triggers inclusive enough?

  Which triggers are used by what physics analyses?

  What are the experiment's priorities?

Example #1:
"Experiment X has a stronger chance of discovering the Higgs first"

Example #2:
"Rumors are that experiment Y is seeing a bump on channel Z.
We must increase bandwidth of corresponding trigger"

Epilogue

- The trigger is a dynamic creature, made by human beings
    - Bound to imperfections, common sense, inertia and strong personalities
    - Must evolve with time, luminosity increases and better detector understanding
    - It requires dedicated studies by analysis users
- But it remains the single most important item in hadron experiments: what makes the difference between discovering New Physics at LHC or not

Epilogue