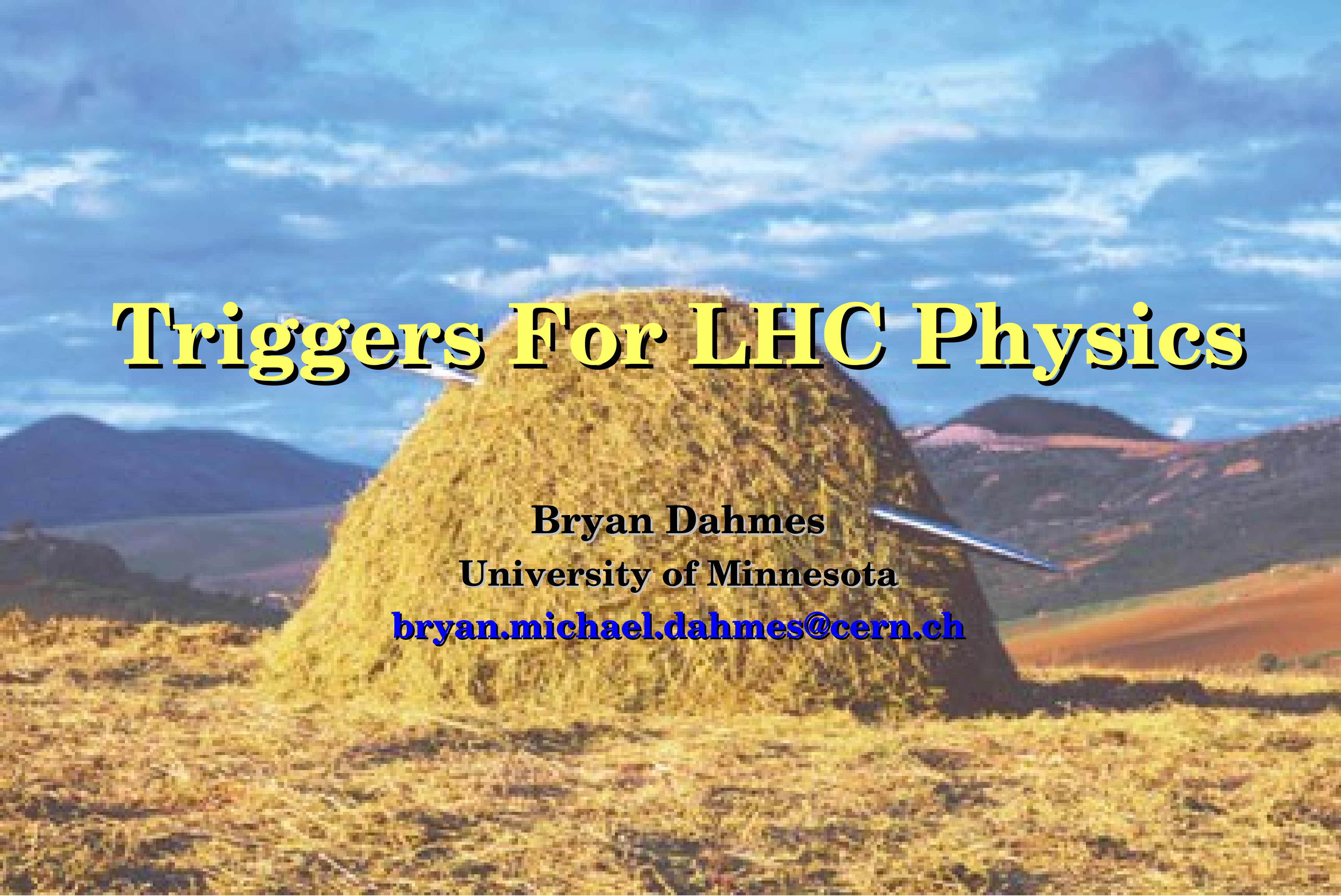

Triggers For LHC Physics

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Introduction

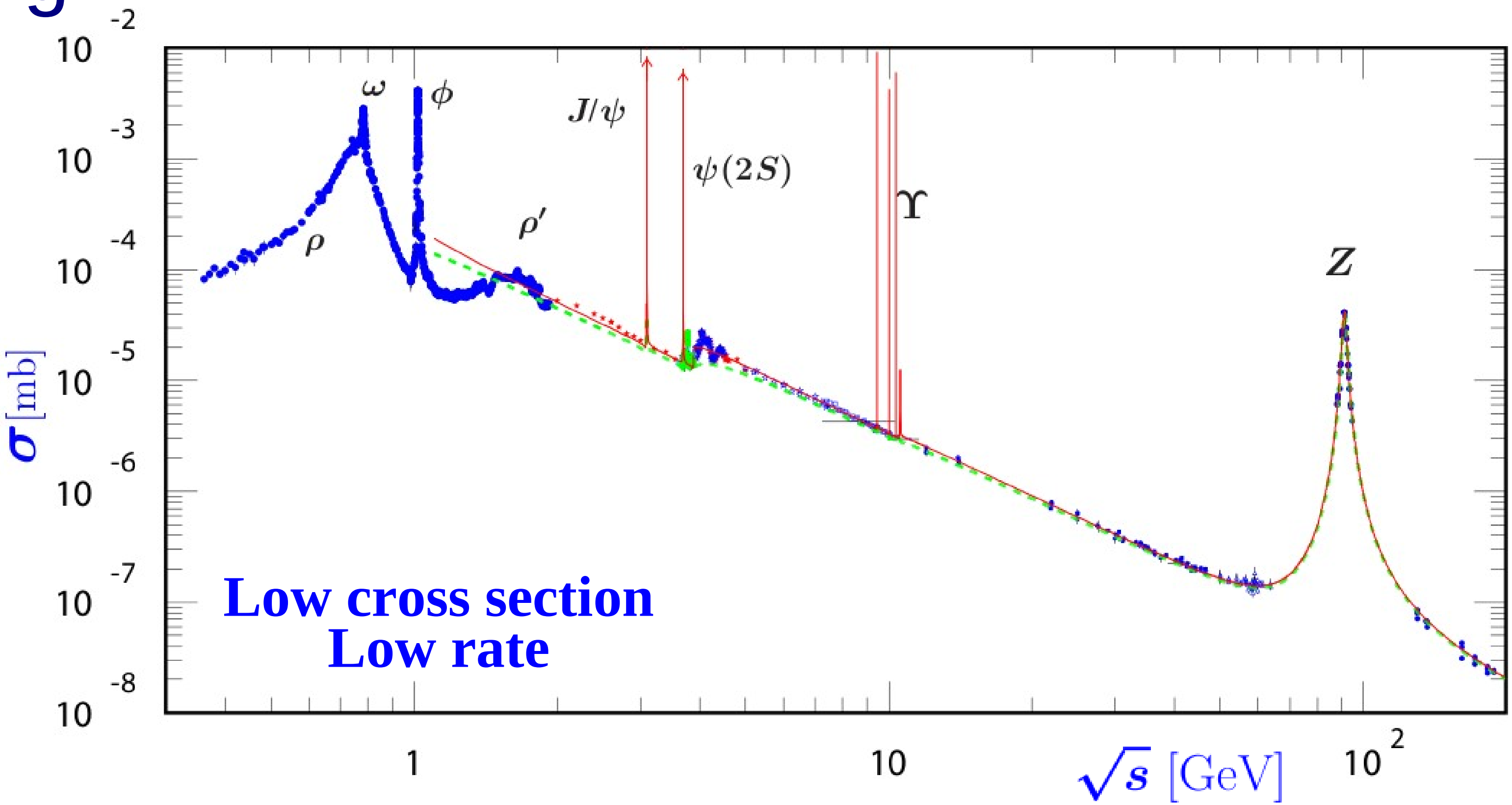
- Some terminology
- Motivation: Why do we need a trigger?
    - Using LHC physics to set the scale
- Explanation of the Trigger components
    - Level 1 (L1) and High Level Trigger (HLT)
    - Features of ATLAS and CMS trigger system
- How a trigger interfaces with an analysis
    - Building a trigger and discussion of strategy
- Other fun (i.e. examples) with triggers

Terminology

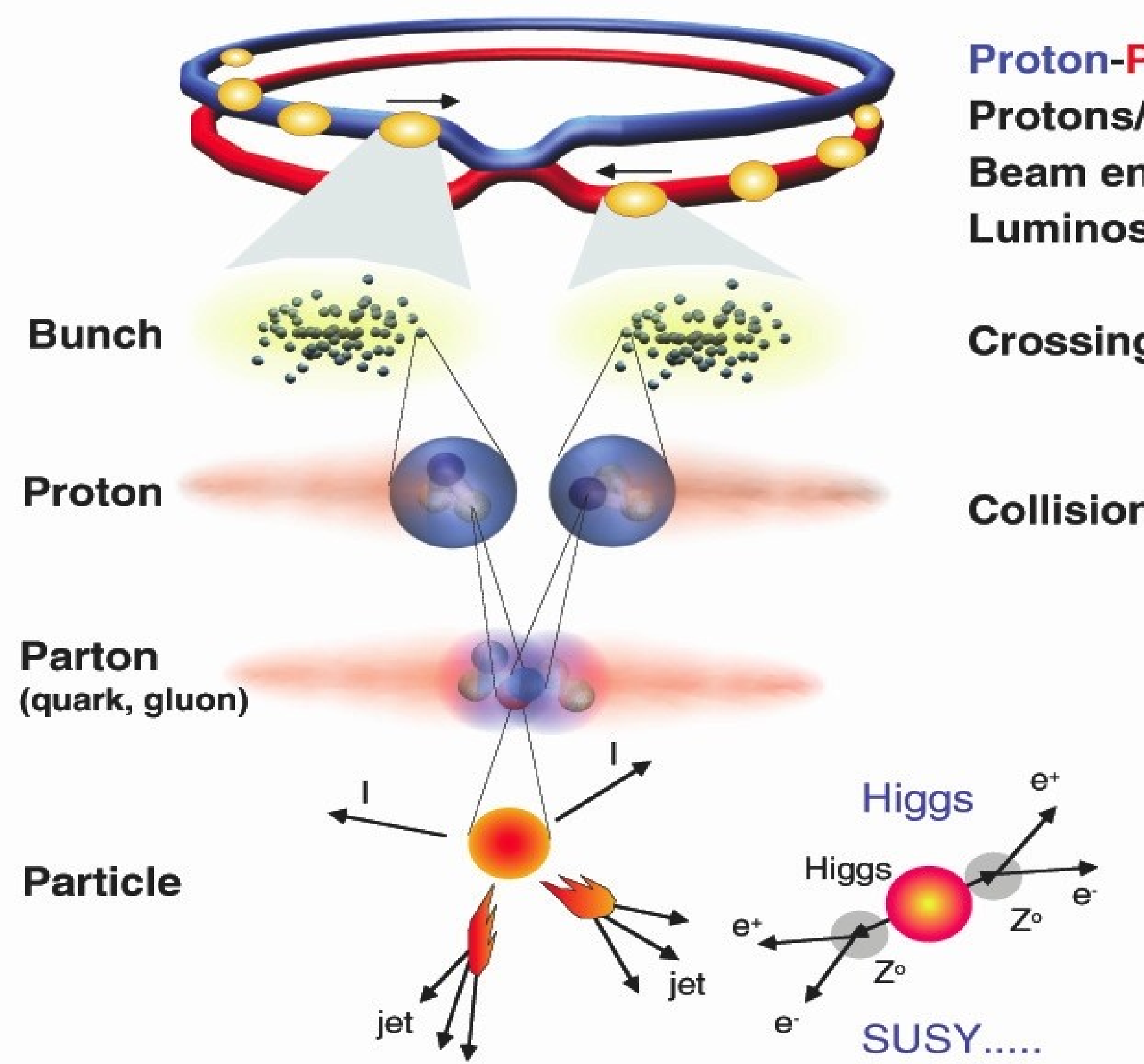
- Data is collected online
  - Collision data recorded by the detectors
- Physicists analyze this data offline
  - Optimizing selection, estimating/modeling background, establishing limits, discovering New Physics, etc.
- The LHC delivers a lot of data, which we need to first select online
- The trigger is a fast online filter that selects the useful events for offline analysis

Why Do We Need a Trigger?

- Save the most interesting events for later
- Simple trigger in e^+e^- colliders: Take (nearly) everything



A Few LHC Facts



Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz **20 MHz**
Collisions ≈	10^7 - 10^9 Hz

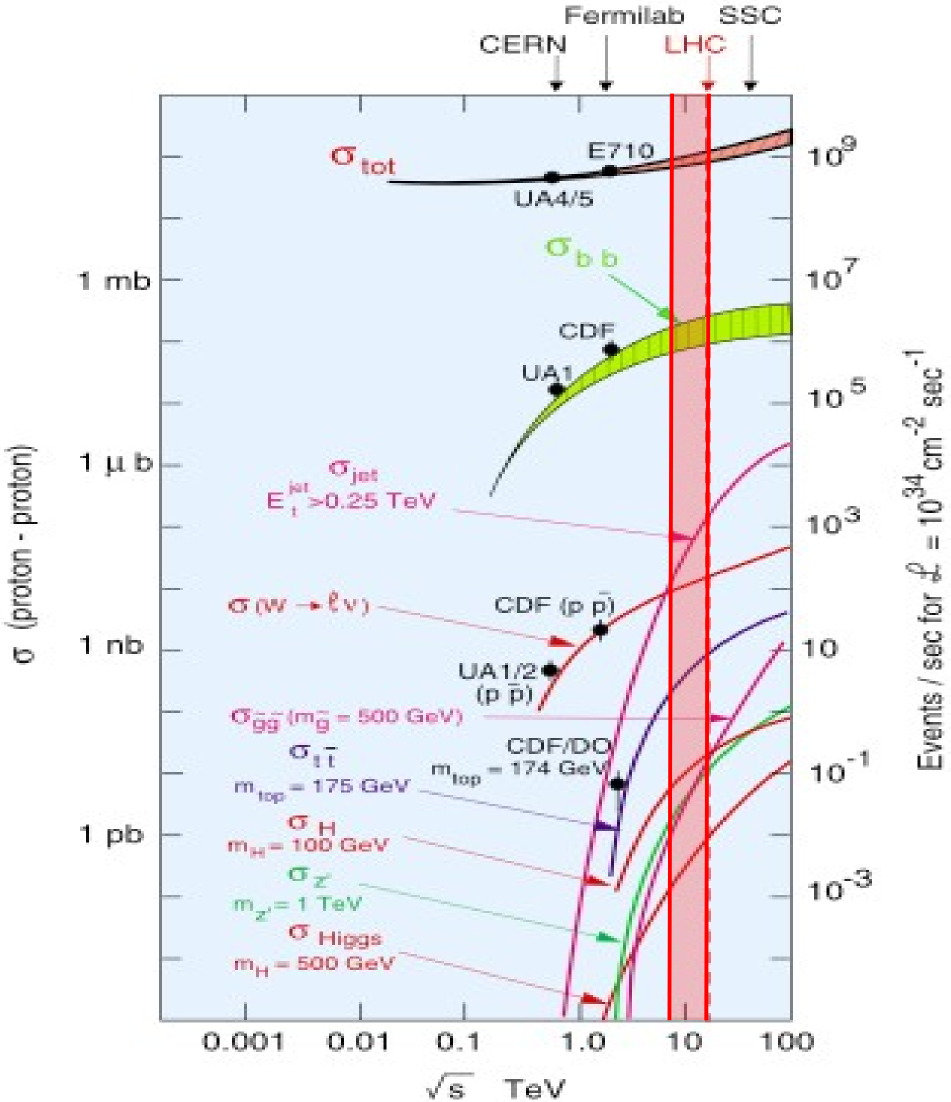
25 nsec (design) between proton bunches

Multiple collisions per crossing

The LHC: Setting the Scale

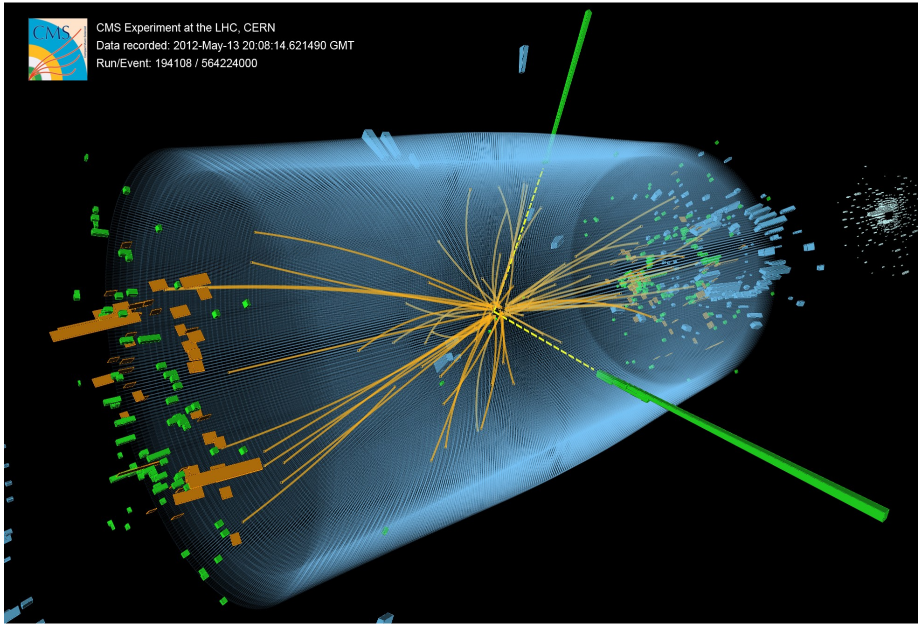
14 TeV, 10^{34} cm^{-2} sec^{-1}

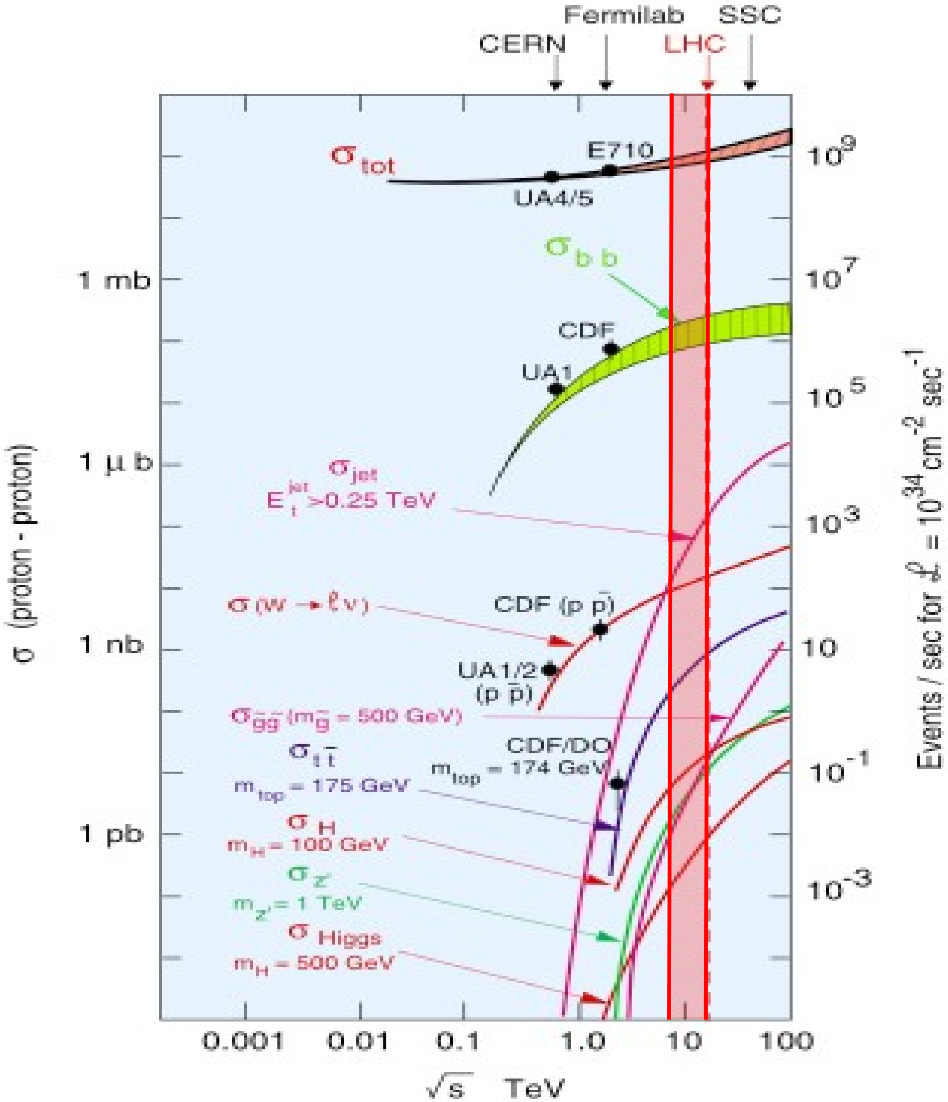
Process	σ (nb)	Production rates (Hz)
Inelastic	10^8	10^9
bb	5×10^5	5×10^6
W → ℓν	15	150
Z → ℓℓ	2	20
tt	1	10
Z' (1 TeV)	0.05	0.5
gg (1 TeV)	0.05	0.5



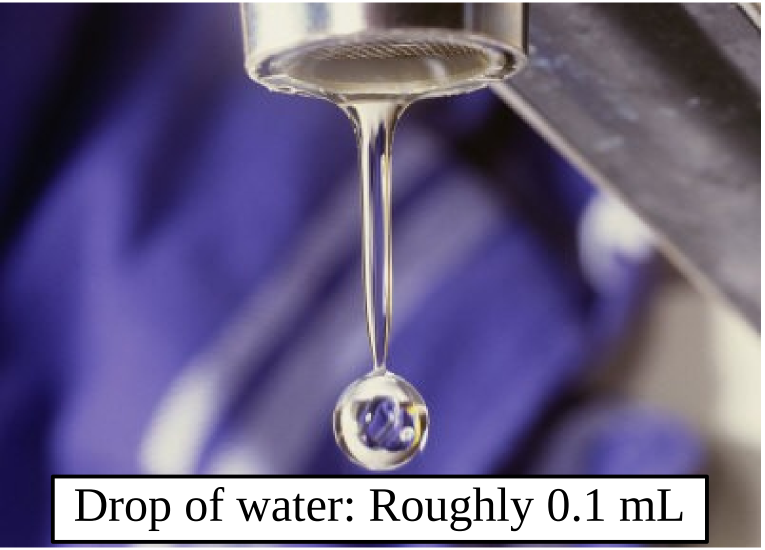
New Physics Rate

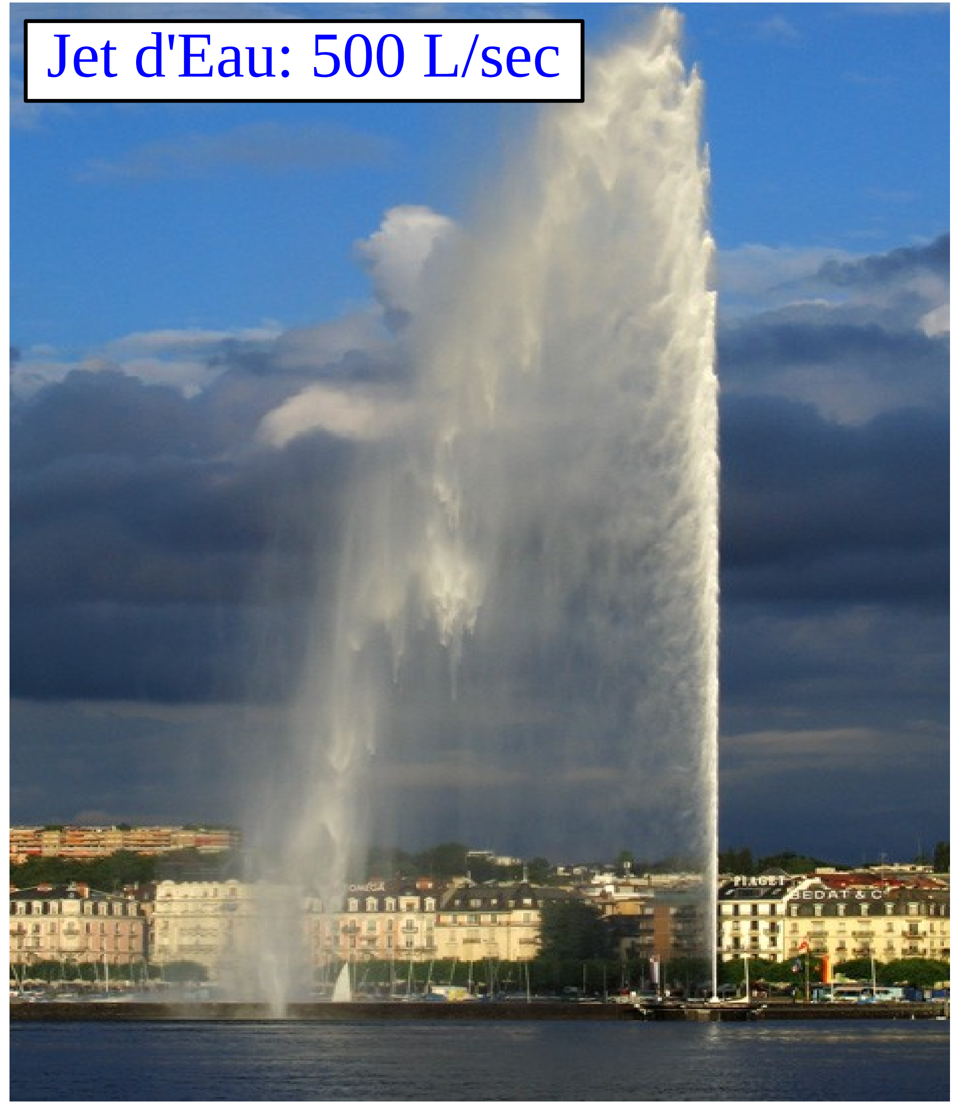
Roughly one light (125 GeV) Higgs for every 10,000,000,000 pp interactions





Perspective





1 in 10,000,000,000:

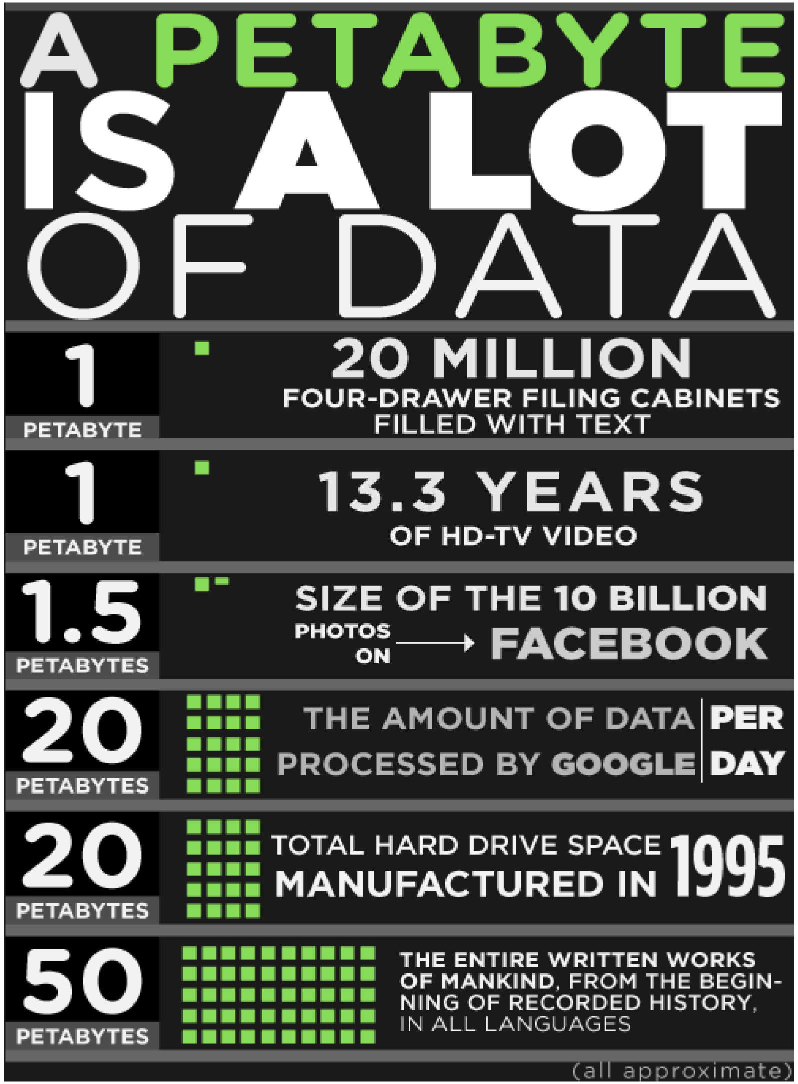
Like looking for a single drop of water from the Jet d'Eau over 30 minutes

Keeping Events

- "New Physics" is rare, and thus buried under lots of "uninteresting" events
- Do we really want to keep every event?
  - This would be the only way to be sure we don't miss anything
- No, for (at least) two reasons
  - We would mostly be saving "background" events
  - But also...

Keeping Events

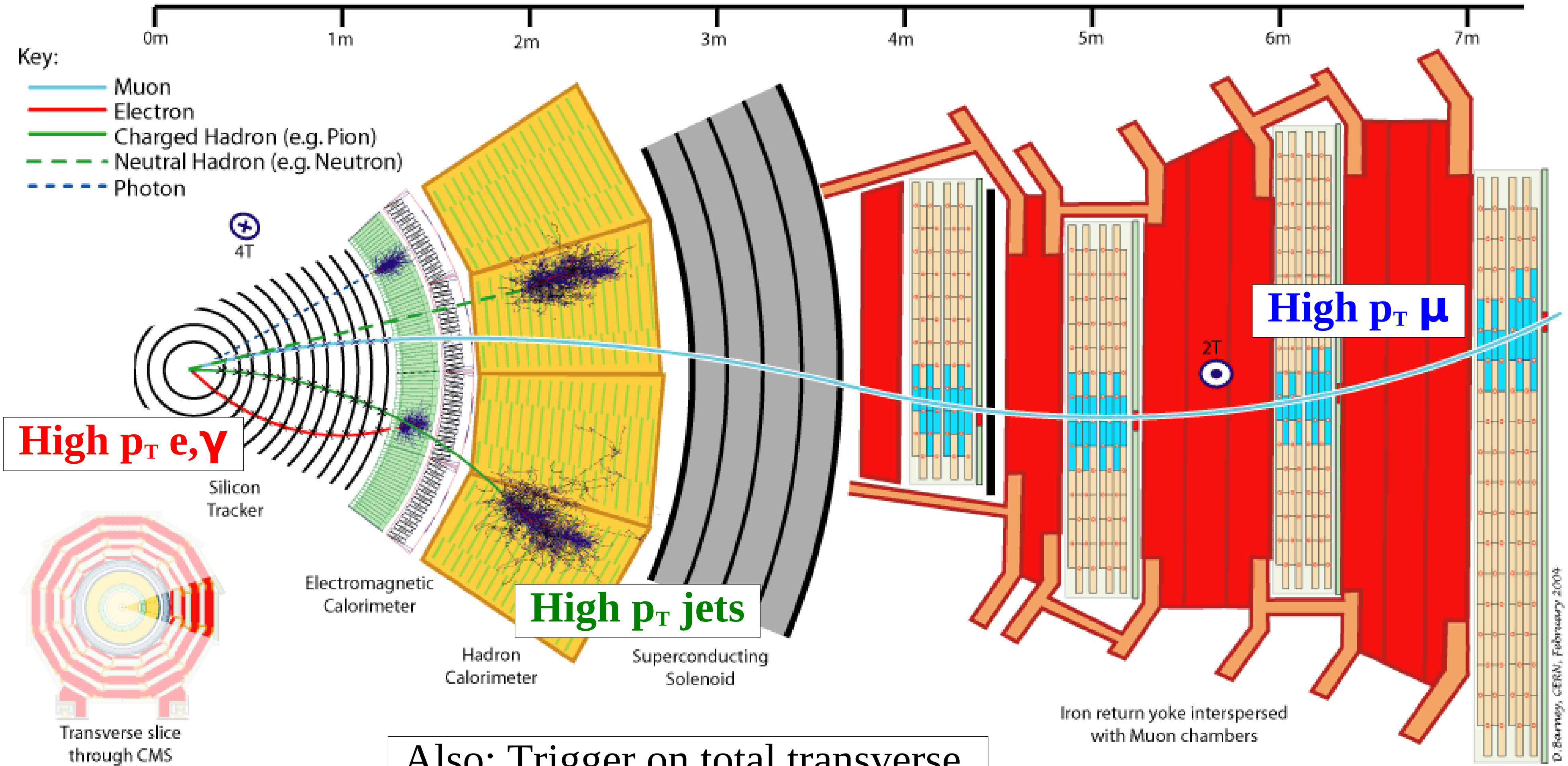
- We can't save everything!
  - Event size: about 1 MB
  - Event reconstruction time:
    - 30 sec – 1 minute
  - At a data rate of O(100 Hz)...
    - O(100) MB/sec
    - O(few) PB/year per experiment
  - Keeping every event
    - O(100000) PB/year
    - Too big to store, reconstruct, analyze



Trigger = Rejection

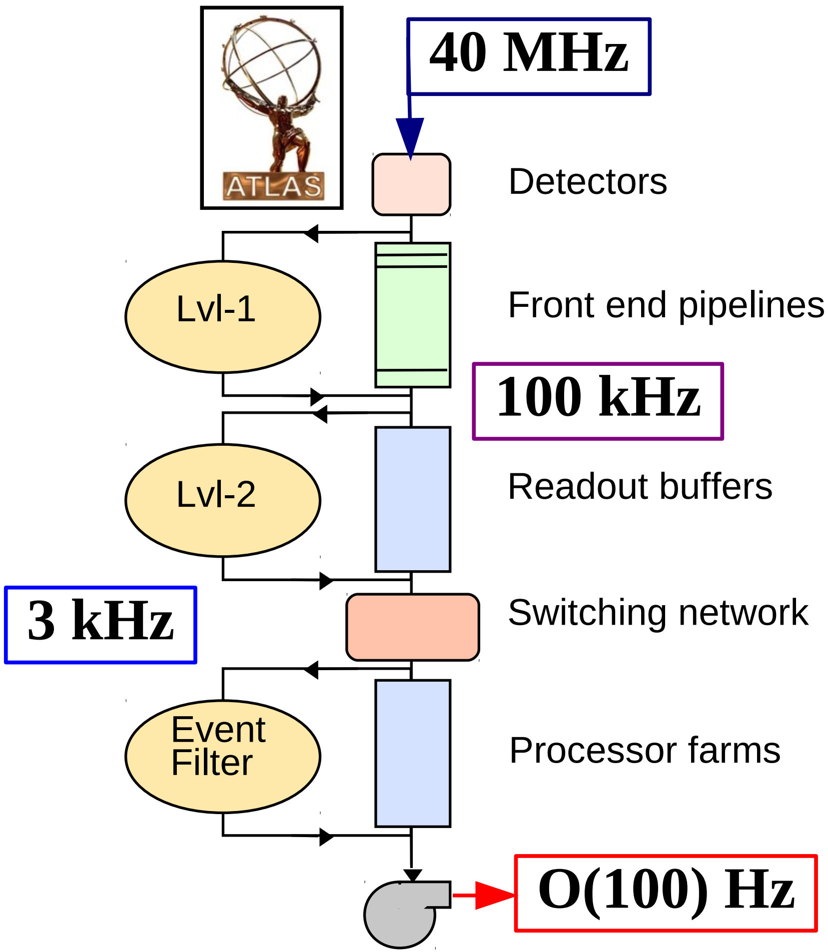
- Problem: We must analyze AND REJECT most LHC collisions prior to storage
- Solution: Trigger
  - Fast processing
  - High rejection factor: $10^4 – 10^5$
  - High efficiency for interesting physics
    - If events fail the trigger, we don't save them!
  - Flexible
  - Affordable
  - Redundant

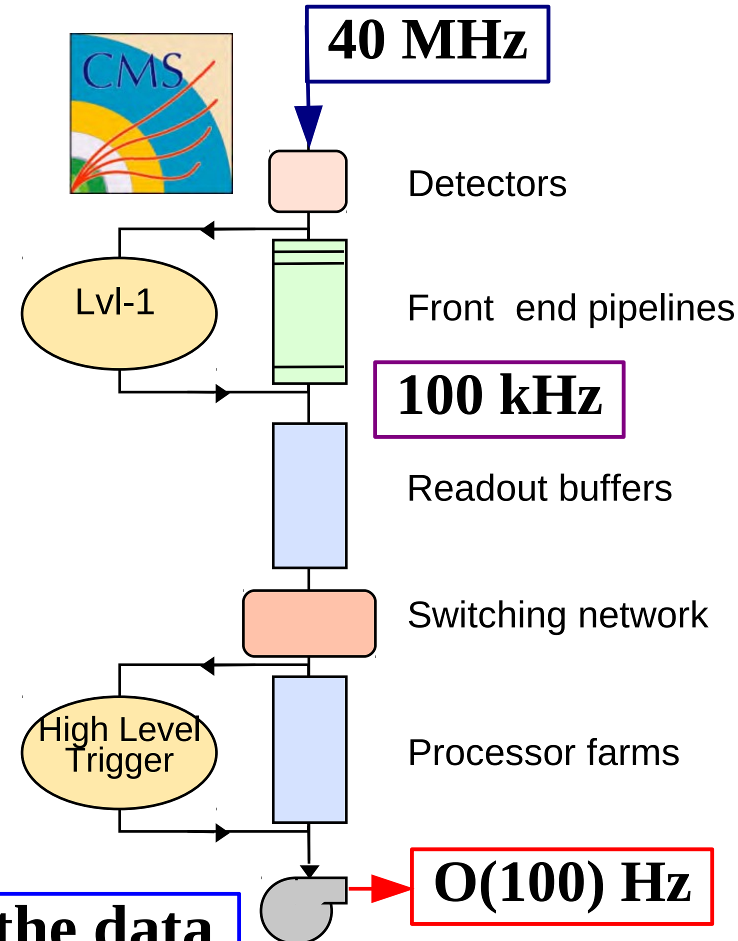
Trigger Signatures



Also: Trigger on total transverse (or missing transverse) energy

Trigger Setup





Reduce the data volume in stages

Trigger Setup

- Level 1: Custom hardware and firmware
  - Reduces the rate from 40 MHz to 100 kHz
  - Advantage: speed
- Level 2: Computing farm (software)
  - Further reduces the rate to a few kHz
  - Reconstruct a region surrounding the L1 trigger object
  - Advantage: Further rejection, still relatively fast
- Level 3: Computing farm (software)
  - Store events passing final selection for offline analysis
  - Advantage: The best reconstruction

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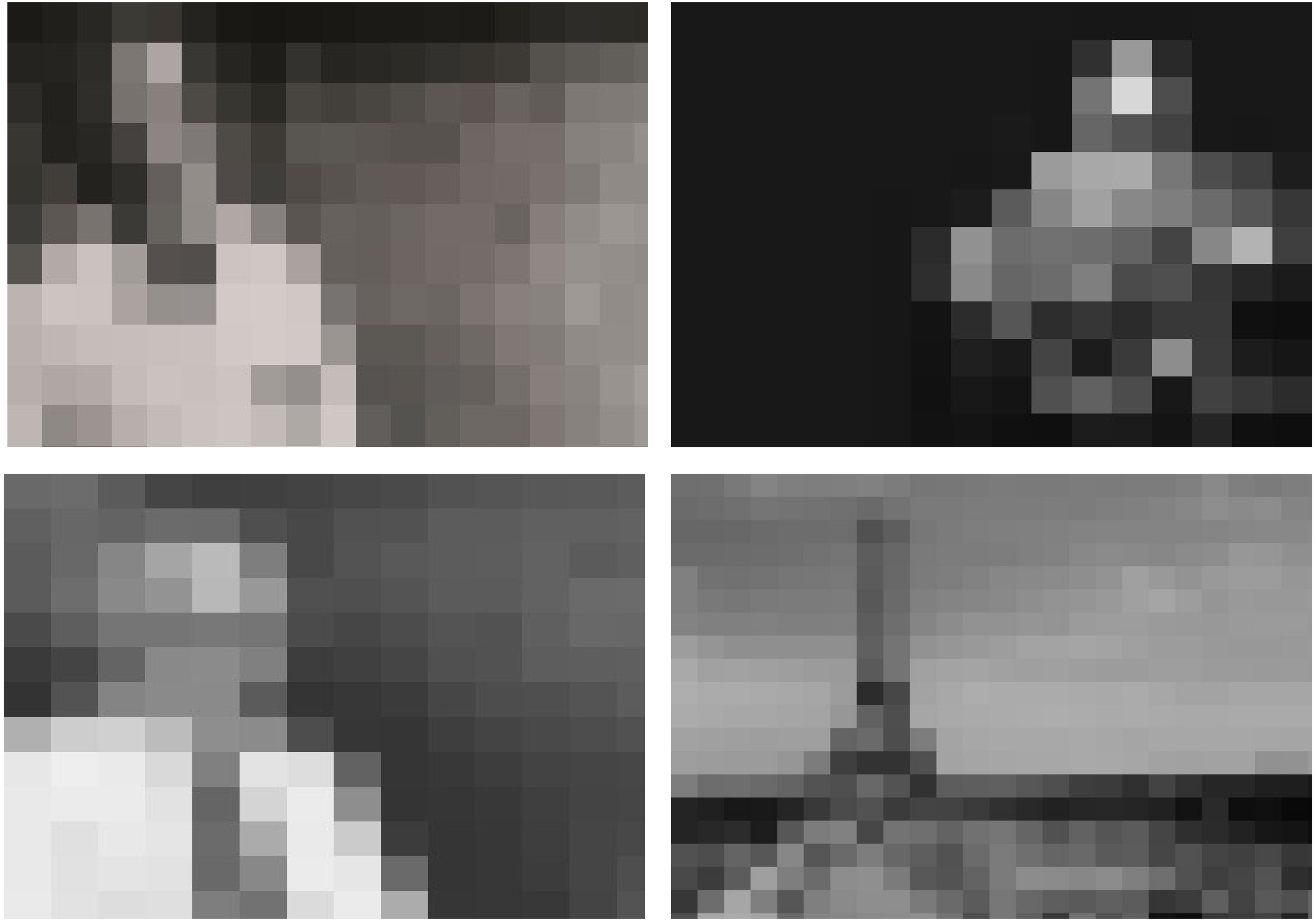
High Level Trigger

Trigger Example: Higgs

Higgs Selection using the Trigger



Level 1:

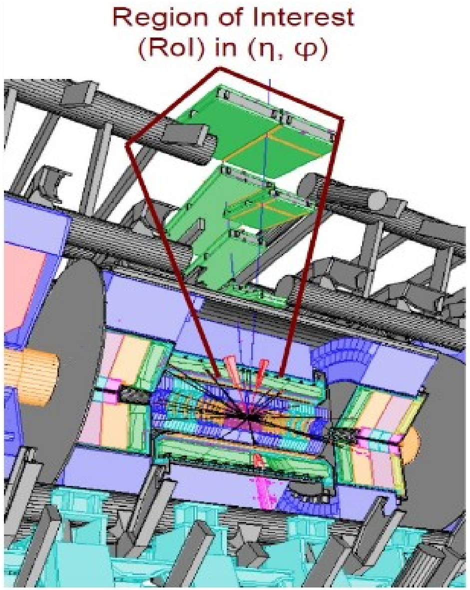
Not all information available, coarse granularity

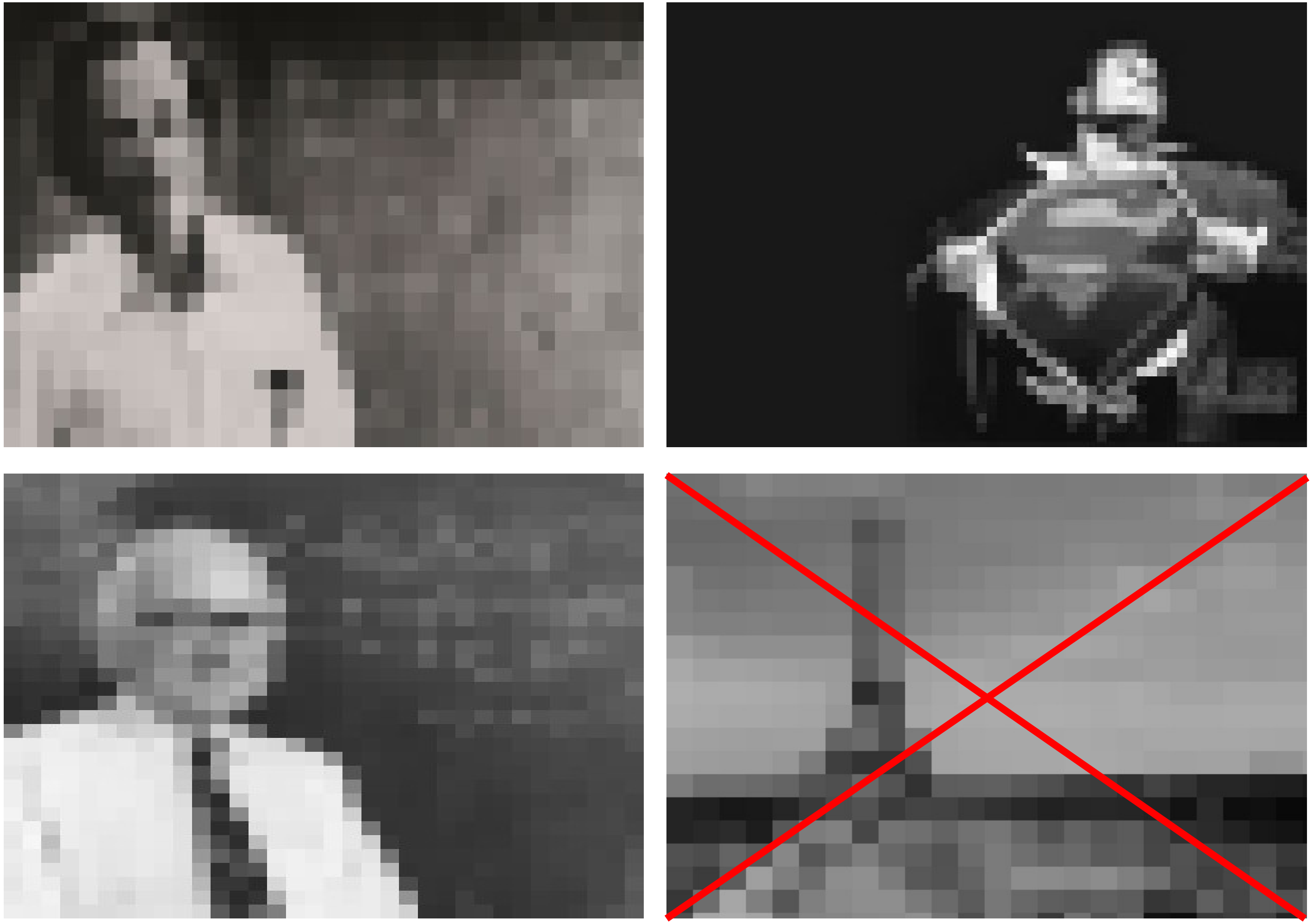
Trigger Example: Higgs

Higgs Selection using the Trigger

Level 2:

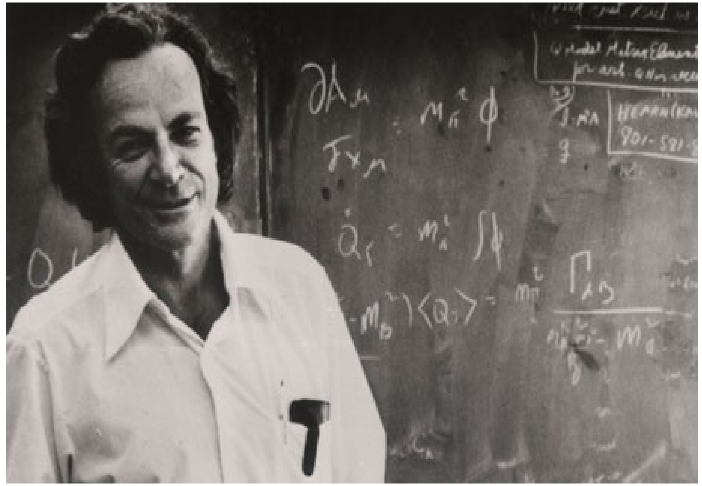
Improved reconstruction techniques, improved ability to reject events

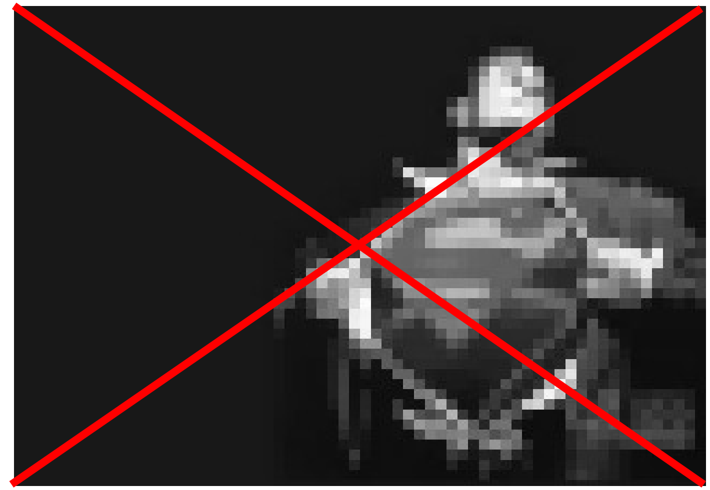




Trigger Example: Higgs

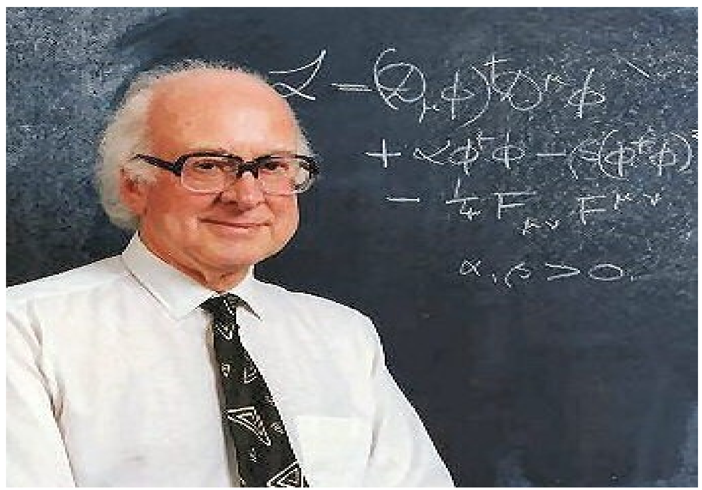
Higgs Selection using the Trigger

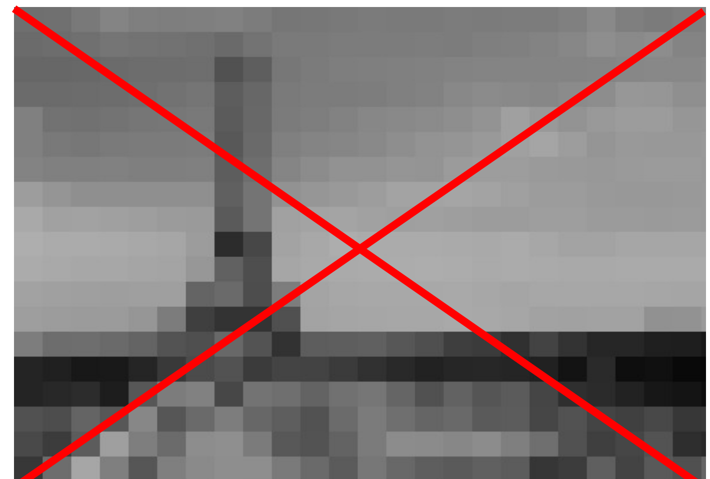




Level 3:

High quality reconstruction algorithms using information from all detectors

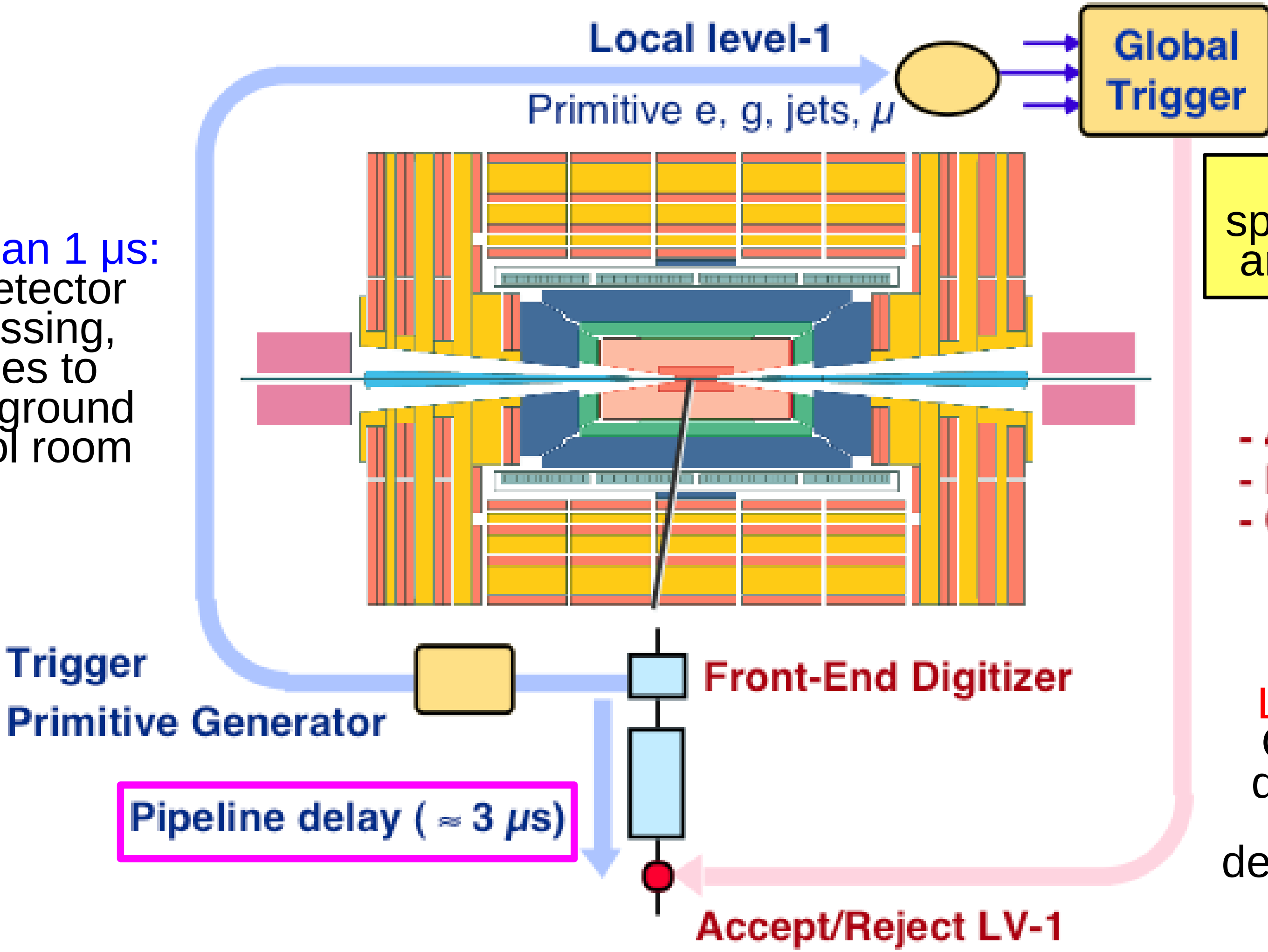




L1 Trigger

- Custom electronics designed to make very fast decisions
  - Application-Specified Integrated Circuits (ASICs)
  - Field Programmable Gate Arrays (FPGAs)
    - Possible to change algorithms after installation
- Must be able to cope with input rate of 40 MHz
  - Otherwise trigger wasting time (and money) as new events keep arriving
  - Event buffering is expensive, too
- L1 Trigger: Pipeline
  - Process many events at once
  - Parallel processing of different inputs as much as possible

L1 Trigger Latency



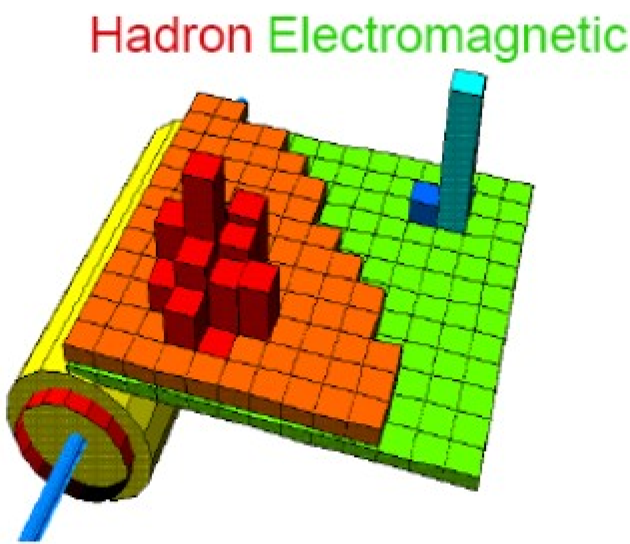
Less than 1 µs:
On-detector processing, cables to underground control room

Roughly 1 µs
spent on Processing and Decision Logic

- 40 MHz Clock
- Level-1 Accept
- Controls

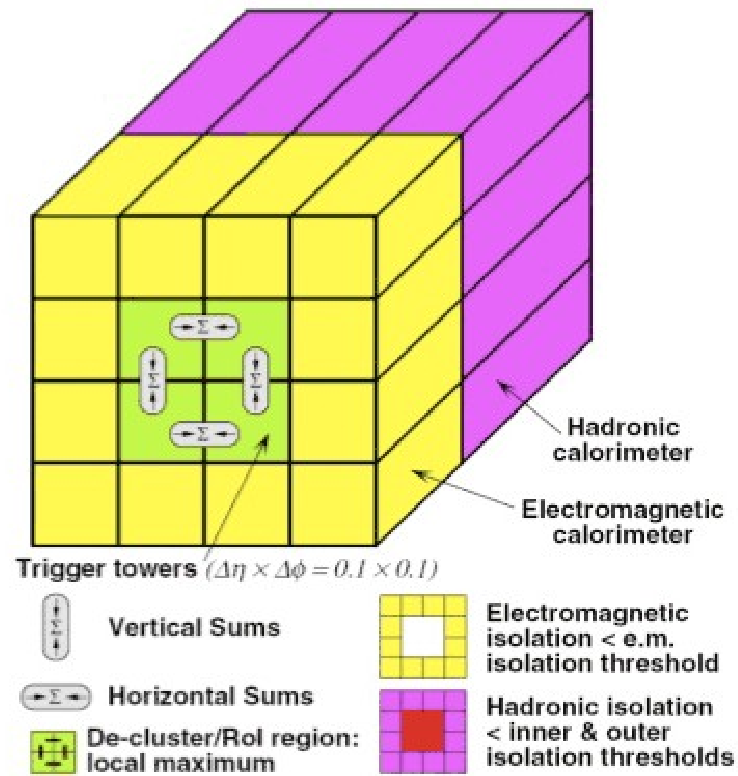
Less than 1 µs:
Cables back to detector in hall, distribution to detector front-ends

L1 Calorimeter Trigger



Signatures for several physics objects

- Electrons, photons (EM only)
- Jets, τ leptons (EM+Had)
- Sum E_T, missing E_T



Example: ATLAS e/γ trigger

- Sum energy in calorimeter cells into towers
- Search in 4x4 tower overlapping, sliding window
- Cluster: local maximum within the window

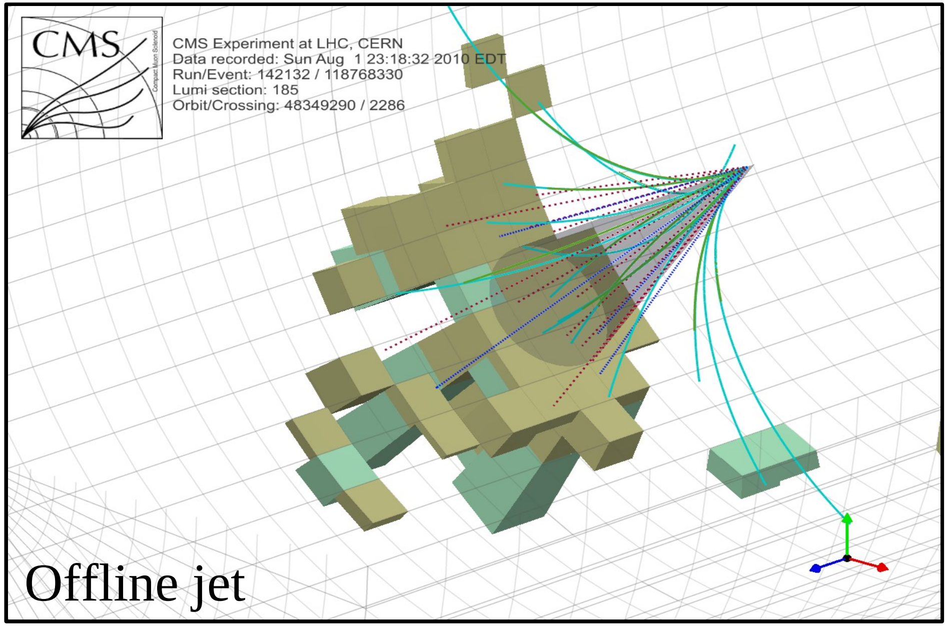
L1 Calorimeter Trigger

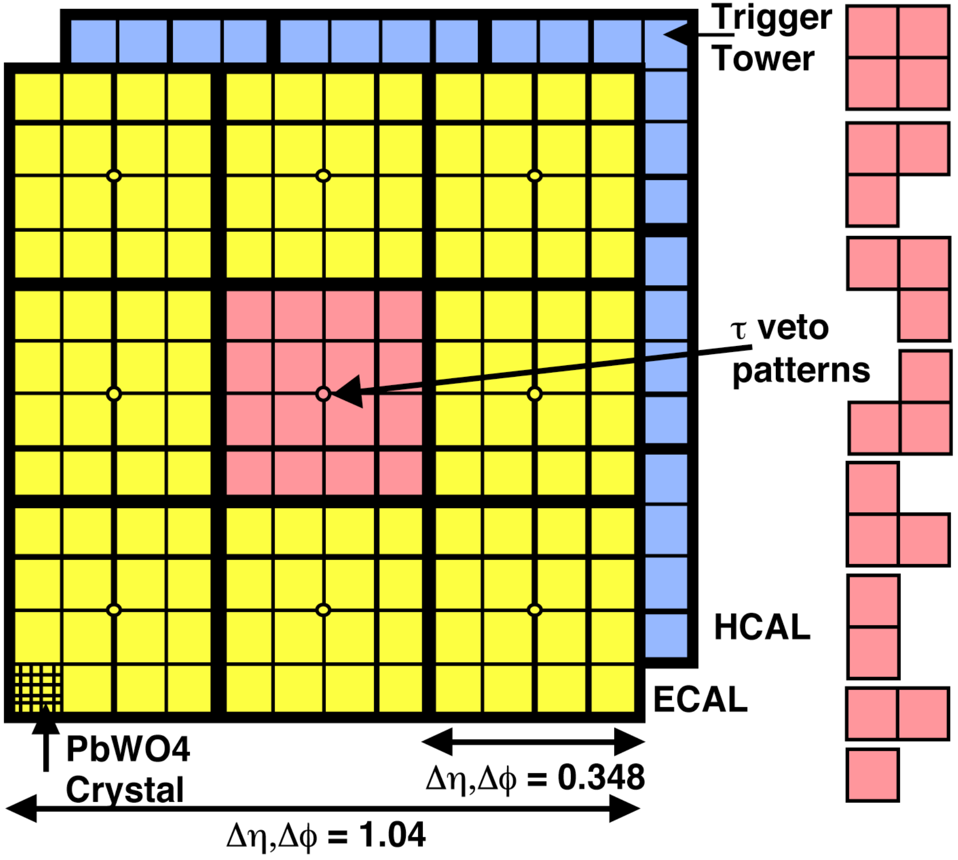
L1 Jets (CMS)

- Search in large 12x12 region
- Centering the L1 jet: highest E_T 4x4 region

L1 Tau (CMS)

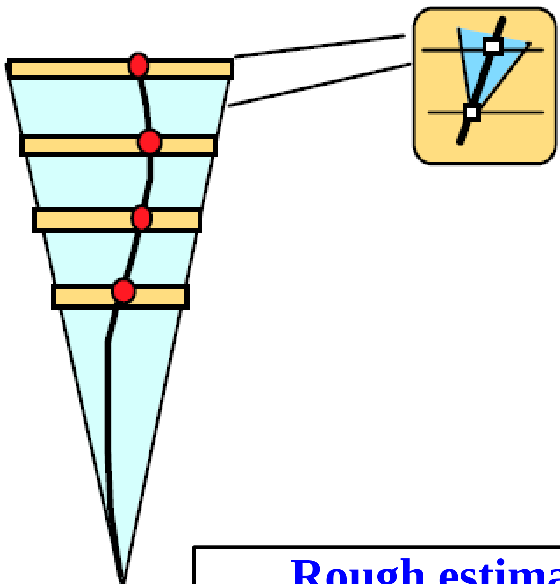
- Search in a narrow 2x2 region
- Jet = τ if no τ veto set

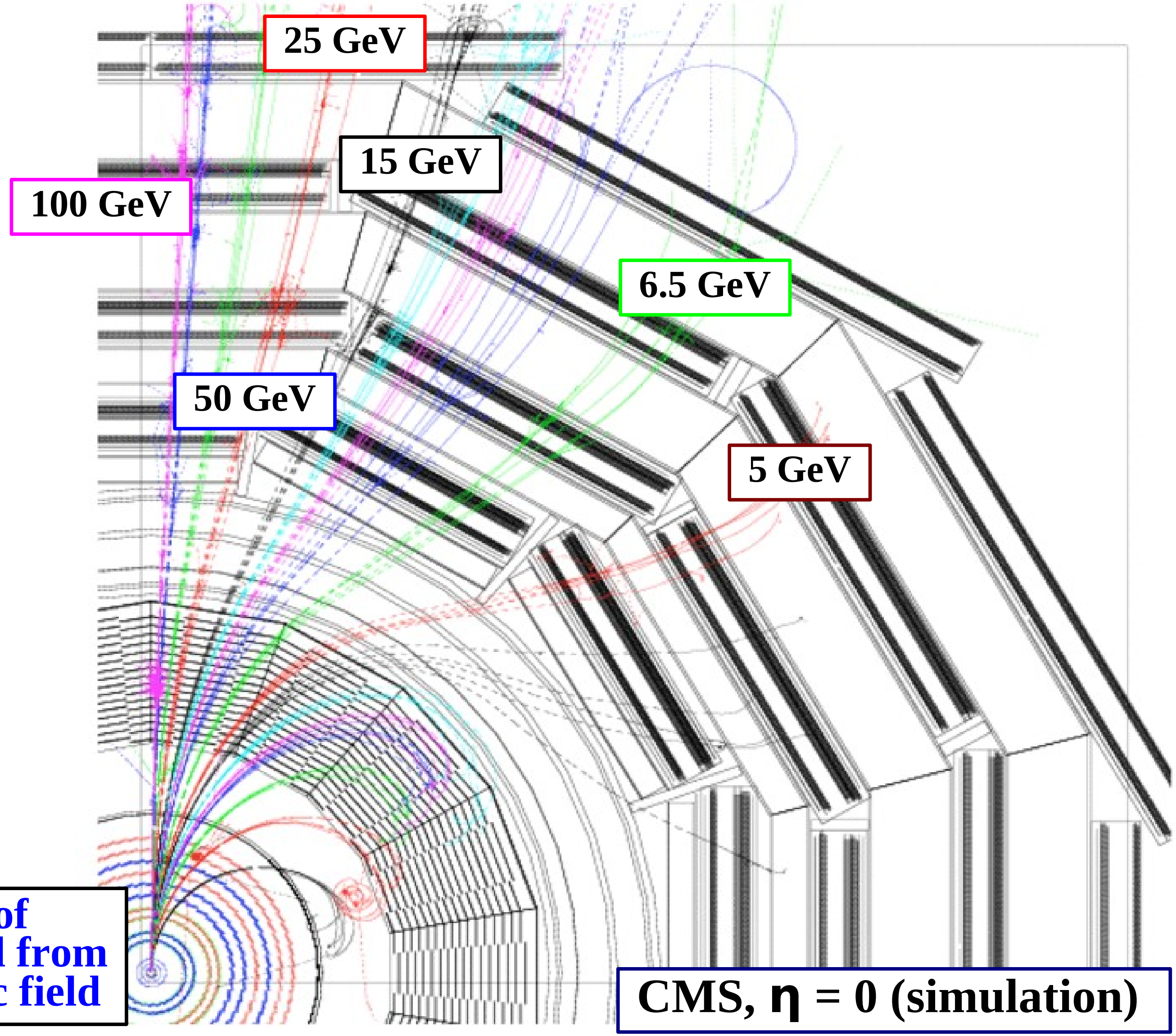




L1 Muon Trigger

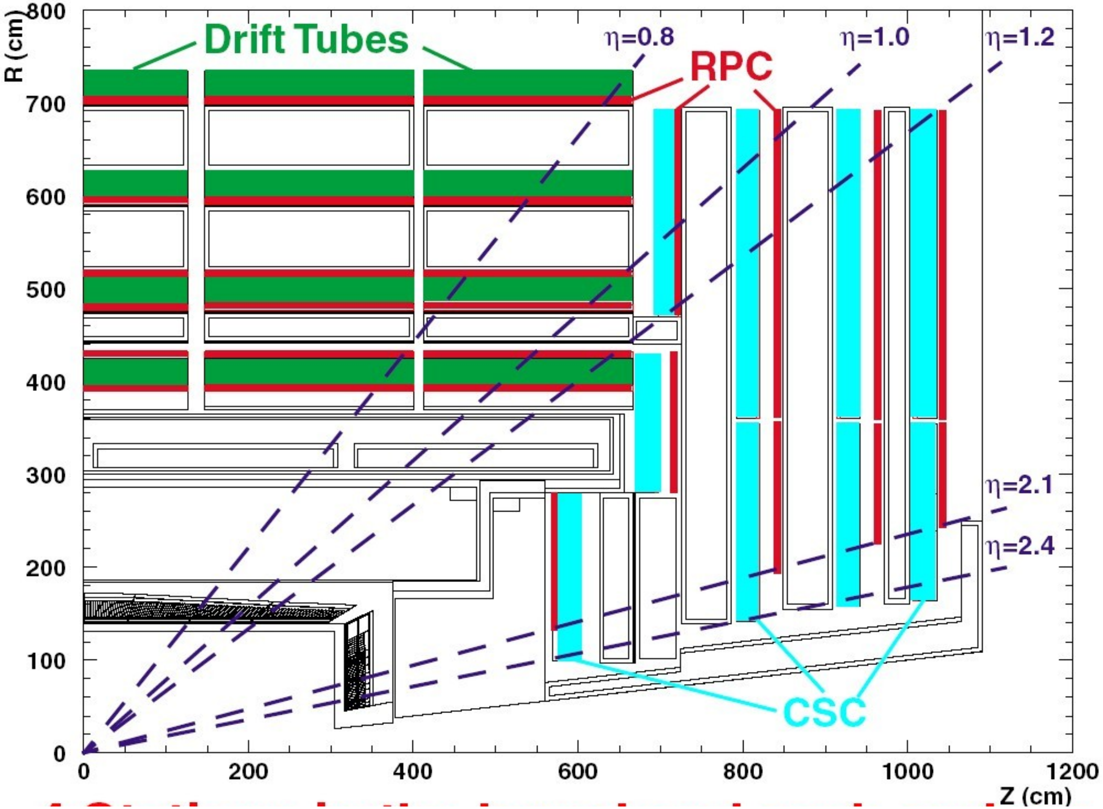
Curved p_T-dependent muon path requires fast pattern recognition



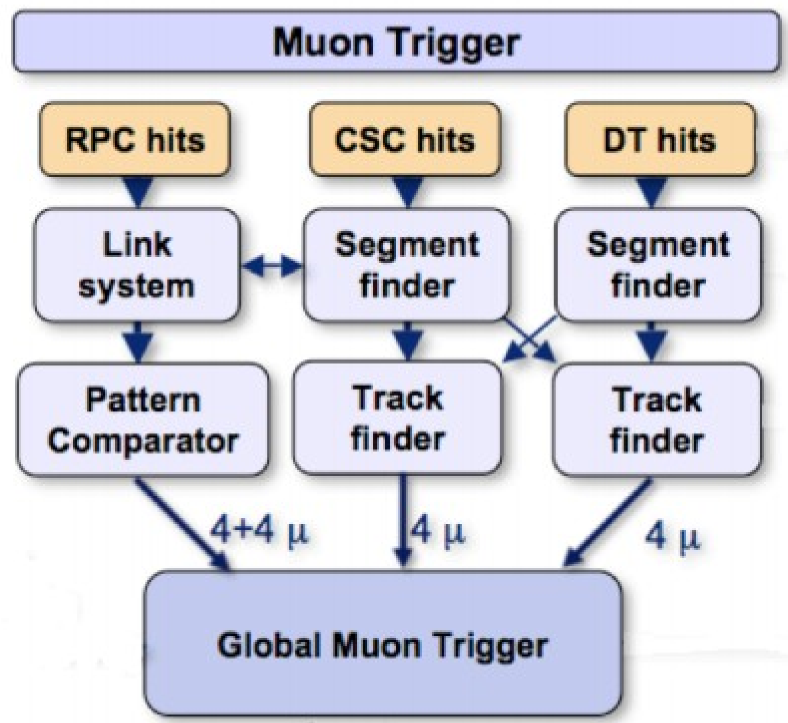


Rough estimate of muon p_T determined from bending in magnetic field

L1 Muon Trigger



CMS Muon Trigger selects best four candidates per bunch crossing

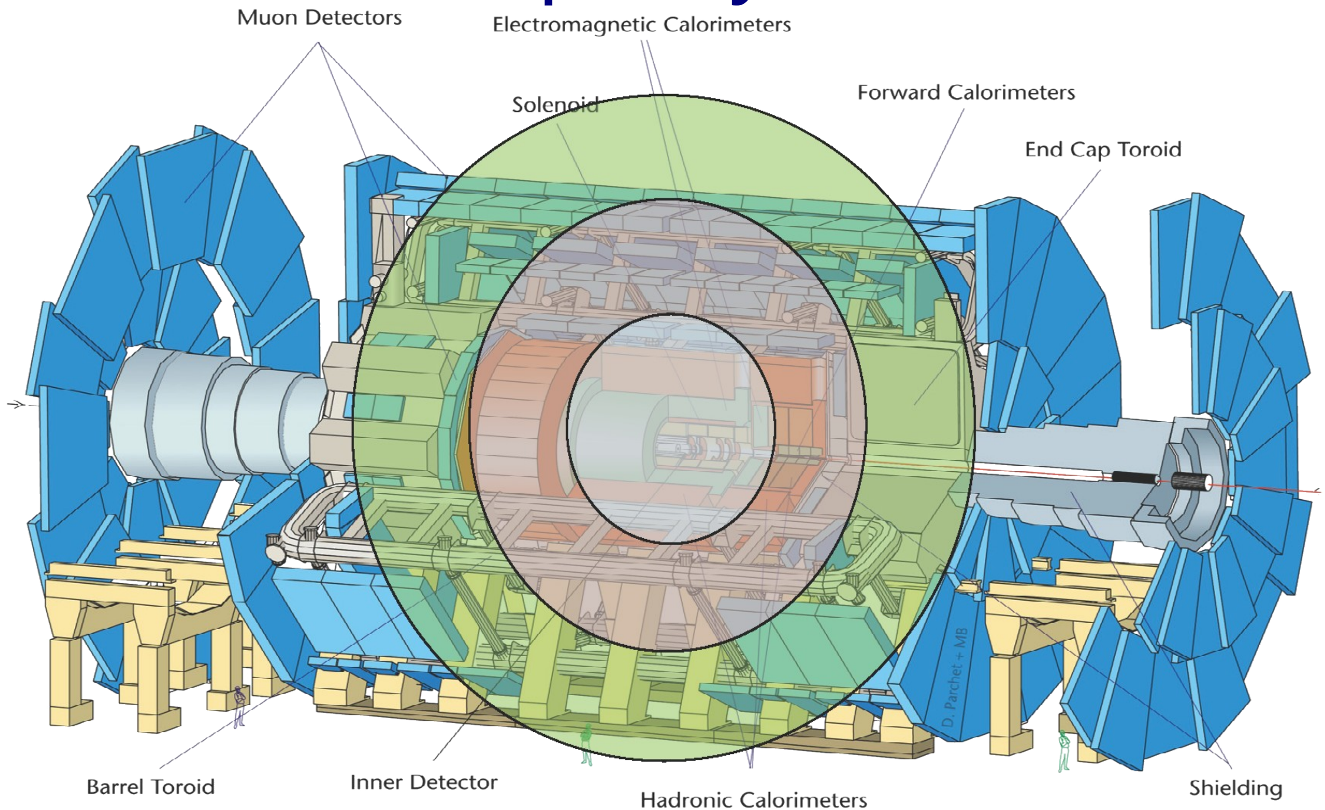


Putting Everything Together

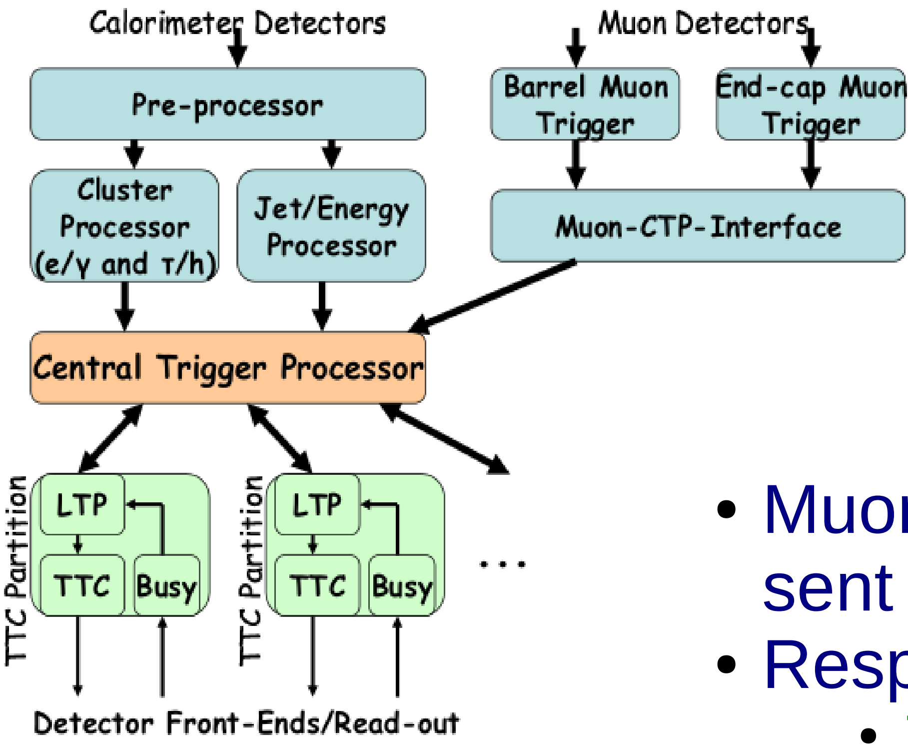
- We still need a global decision
  - We have the information, does the event pass?
- Decision needs to be made quickly

Large Detectors

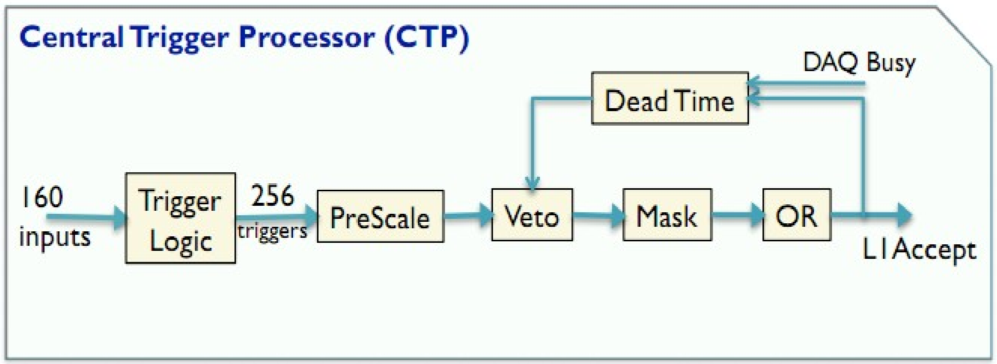
Small time/space (25 nsec, 7.5 m) between collisions



Central/Global Trigger



ATLAS Central Trigger

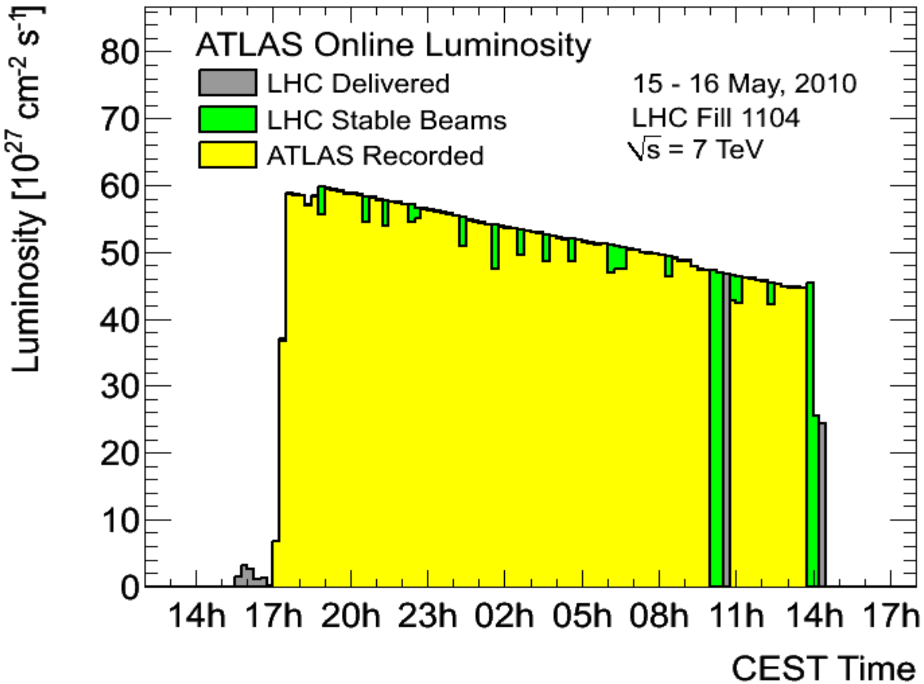


- Muon and Calorimeter L1 outputs sent to L1 Central/Global Trigger
- Responsibilities of CTP/GT
  - Time-synchronize inputs
  - Combine inputs, apply trigger logic
  - Apply prescales
  - Busy (deadtime) logic
  - Issue L1 decision

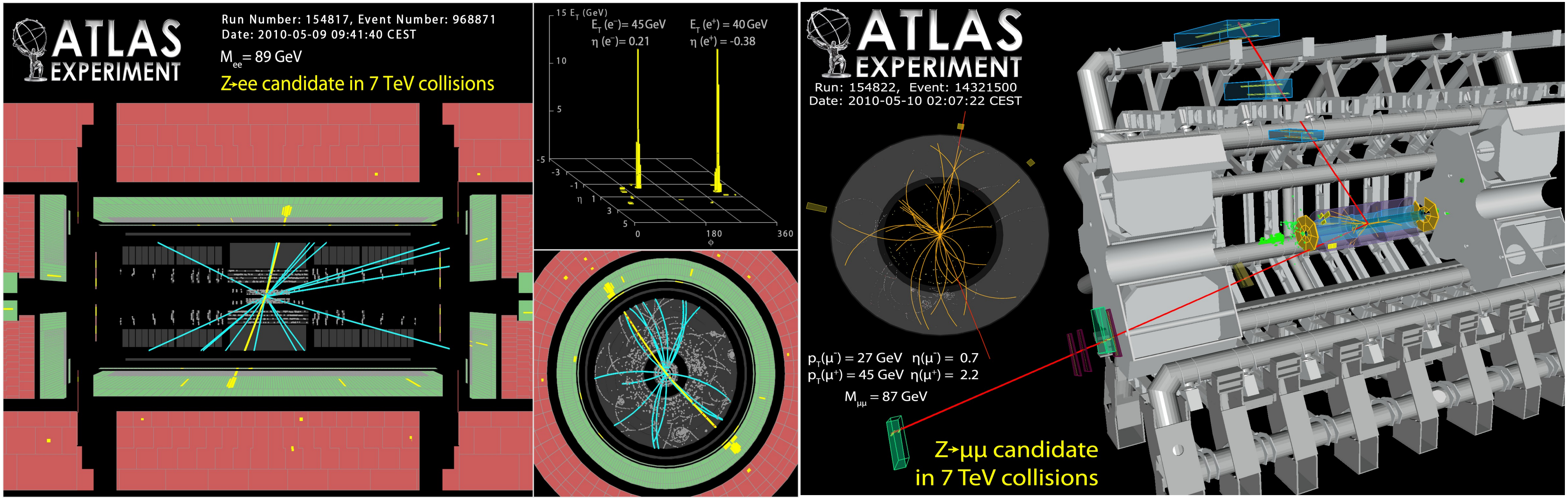
Dead Time

- Sending information from detector to DAQ takes time
  - Too many events at once can clog the system, prevent new data from being analyzed
- L1 trigger rules control the flow of data
  - Dead time in short time window surrounding an event accepted by L1
  - Prevent too many triggers in longer time periods
  - Inefficiency at the percent level, but unbiased

Example of deadtime due to detector readout issues



L1 Track Trigger?...Not Yet



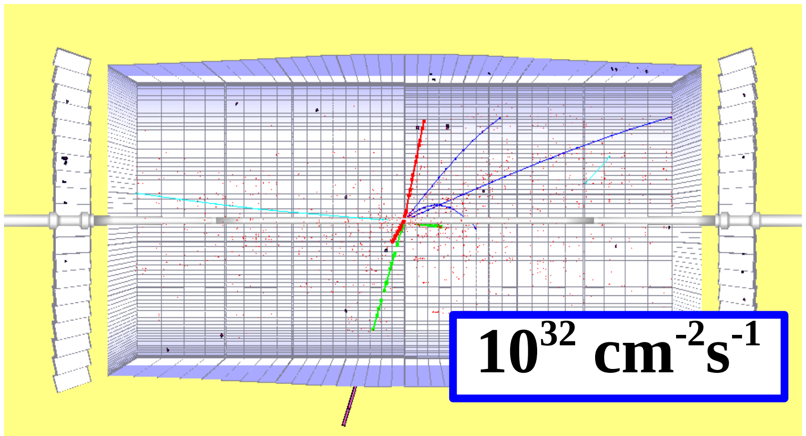
- L1 triggers use muon systems and calorimeters
  - Many thousands of channels, fast pattern recognition
- Tracking detectors
  - (Tens of) Millions of channels, complicated track reconstruction
  - Transmitting all data at 40 MHz prohibitive
- LHC experiments currently run without tracking at L1
  - Tracking at L1 expected for SLHC upgrades

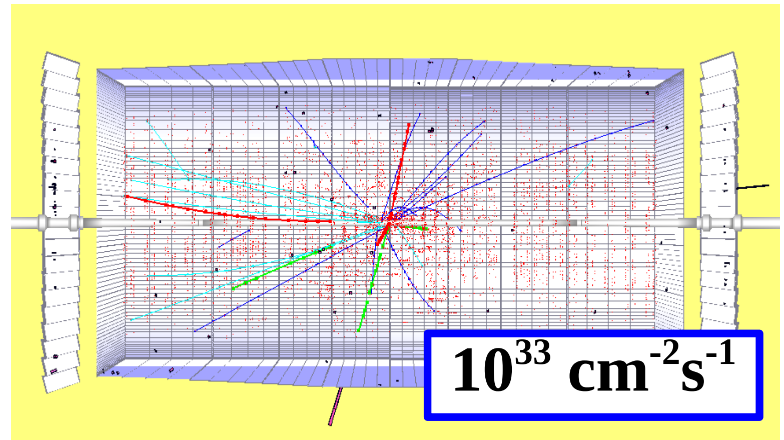
Reaching for More Physics

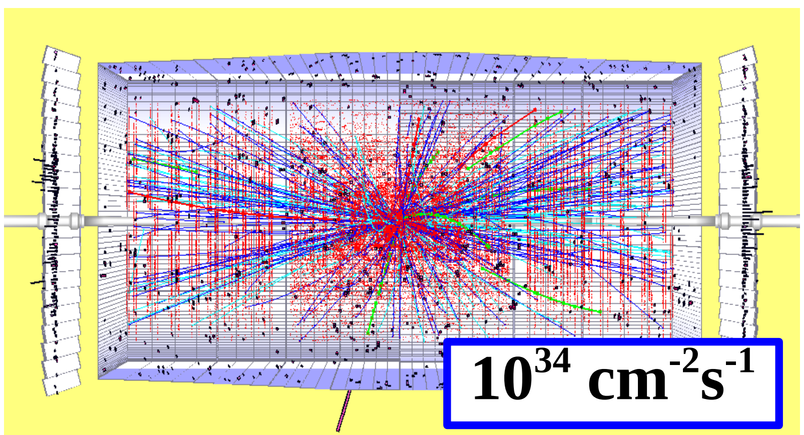
- Problem: We know that the rate of interesting physics is low
  - Otherwise, we would have found it (i.e. more than the Higgs) already!
  - We need to produce many more collisions to quantify the new physics, whatever it looks like
- Solution: Increase the collision rate
  - More bunches (50→25 nsec spacing)
  - More protons per bunch, tighter bunches
  - More crossings, more collisions per crossing
  - Sustained collision intensity throughout an LHC fill
- These extra collisions produce...

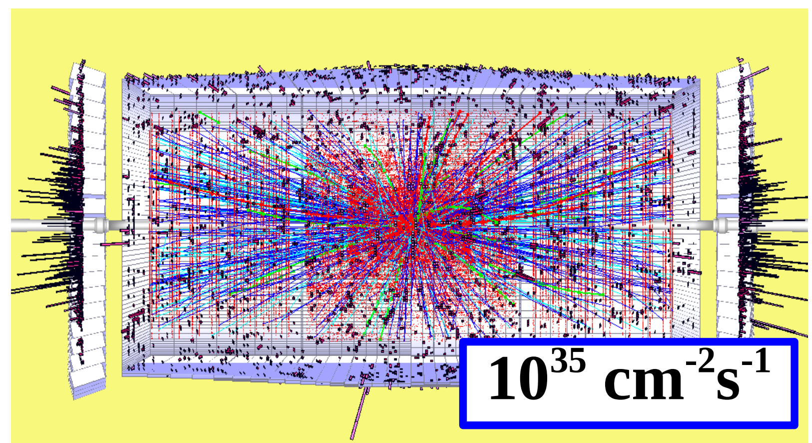
Pileup

CMS Simulation: 300 GeV H→ZZ→eeμμ at various instantaneous luminosities



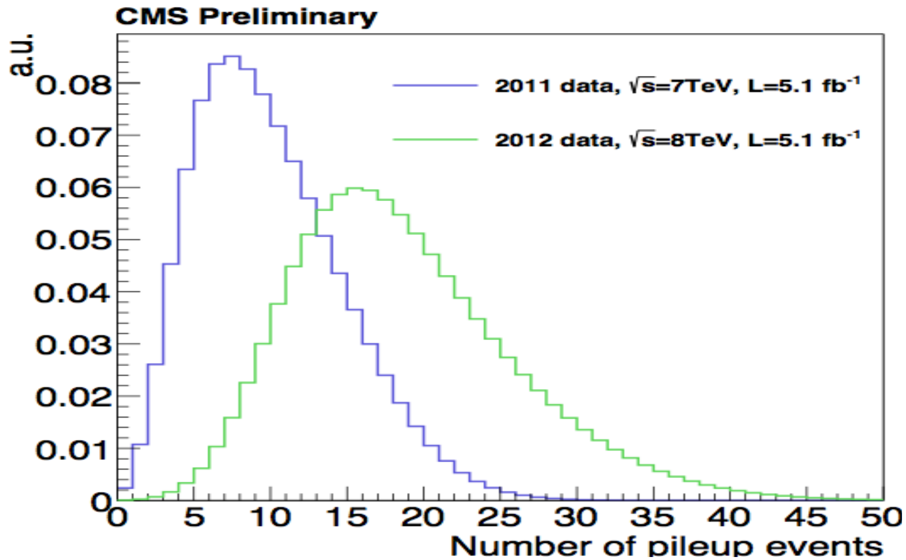


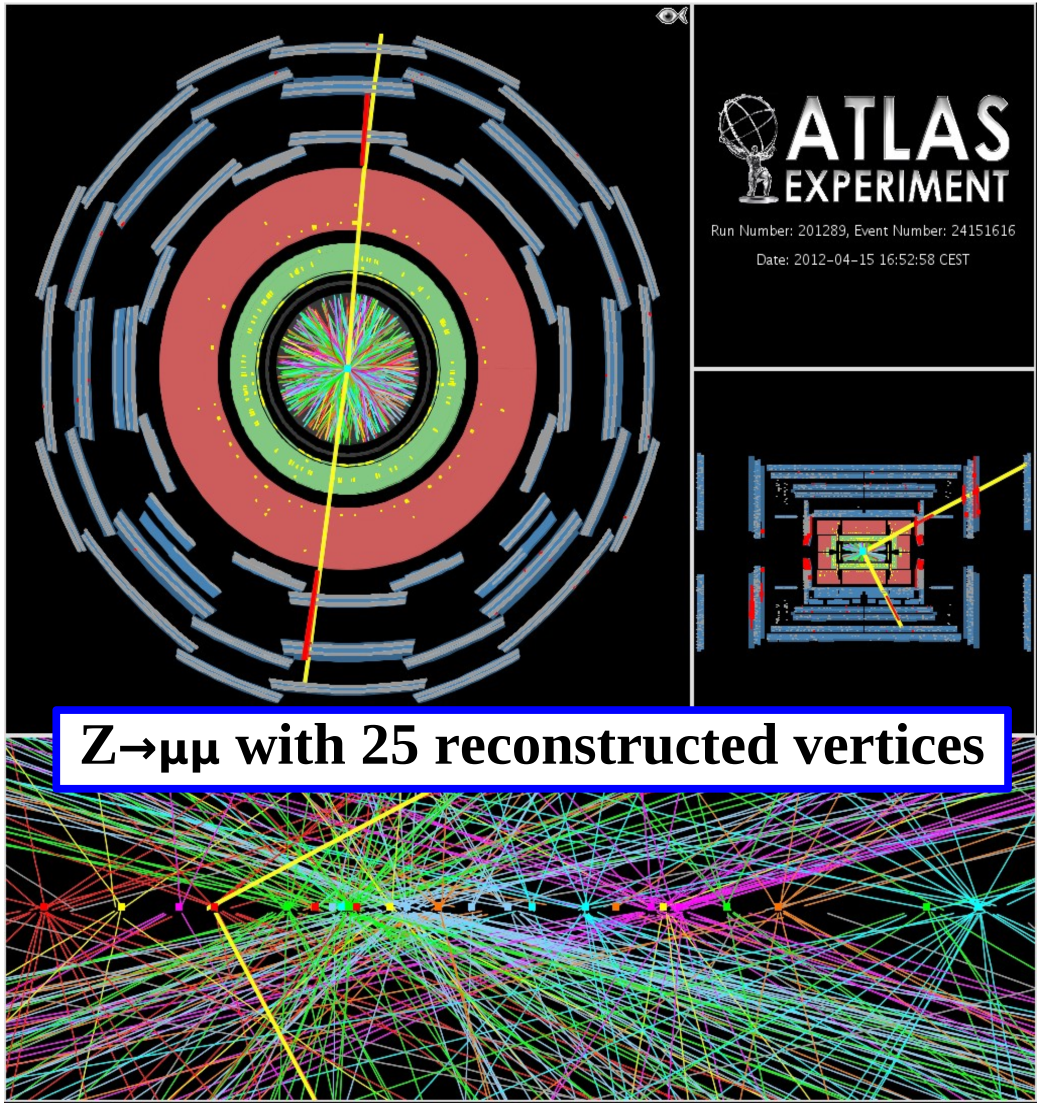




Pileup

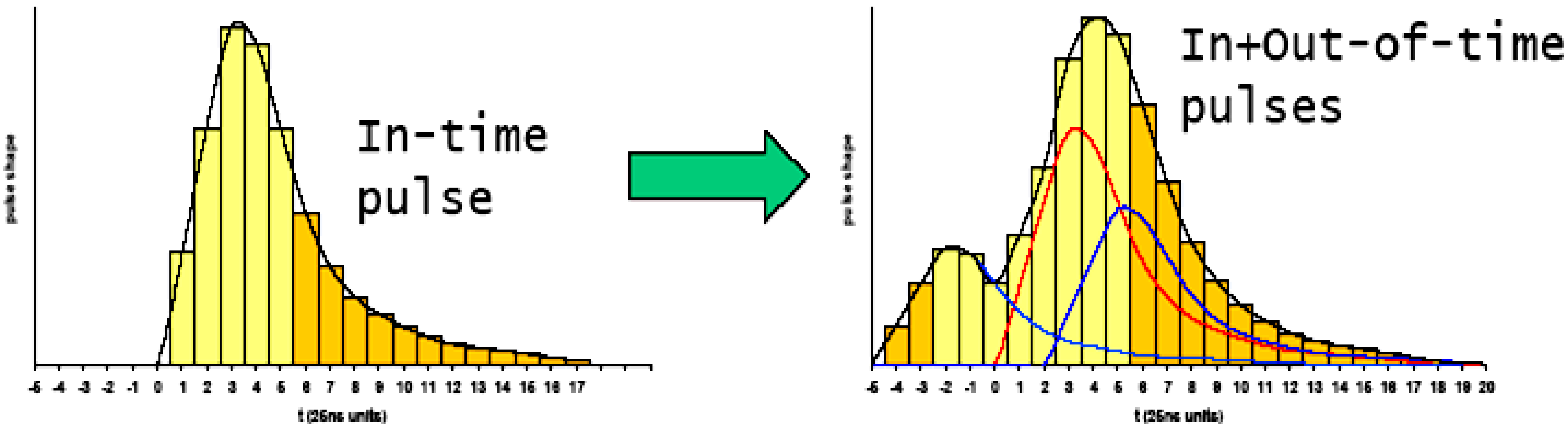
- LHC Design:
  20 collisions per crossing
- 7 to 8 TeV: 5-20 collisions per crossing on average
- Multiple pp collisions per crossing produce lots of low-energy background tracks
    - Tracks from interesting process should still be isolated





L1 Trigger at High(er) Collision Rate

- L1 Trigger must cope with high collision rate
  - Tighten trigger requirements to reject extra background
  - Trade-off: Possible loss of signal efficiency
- Multiple collisions per crossing impacts the L1 trigger
- All this was “known” already, as part of the LHC detector design
  - SLHC: New challenges

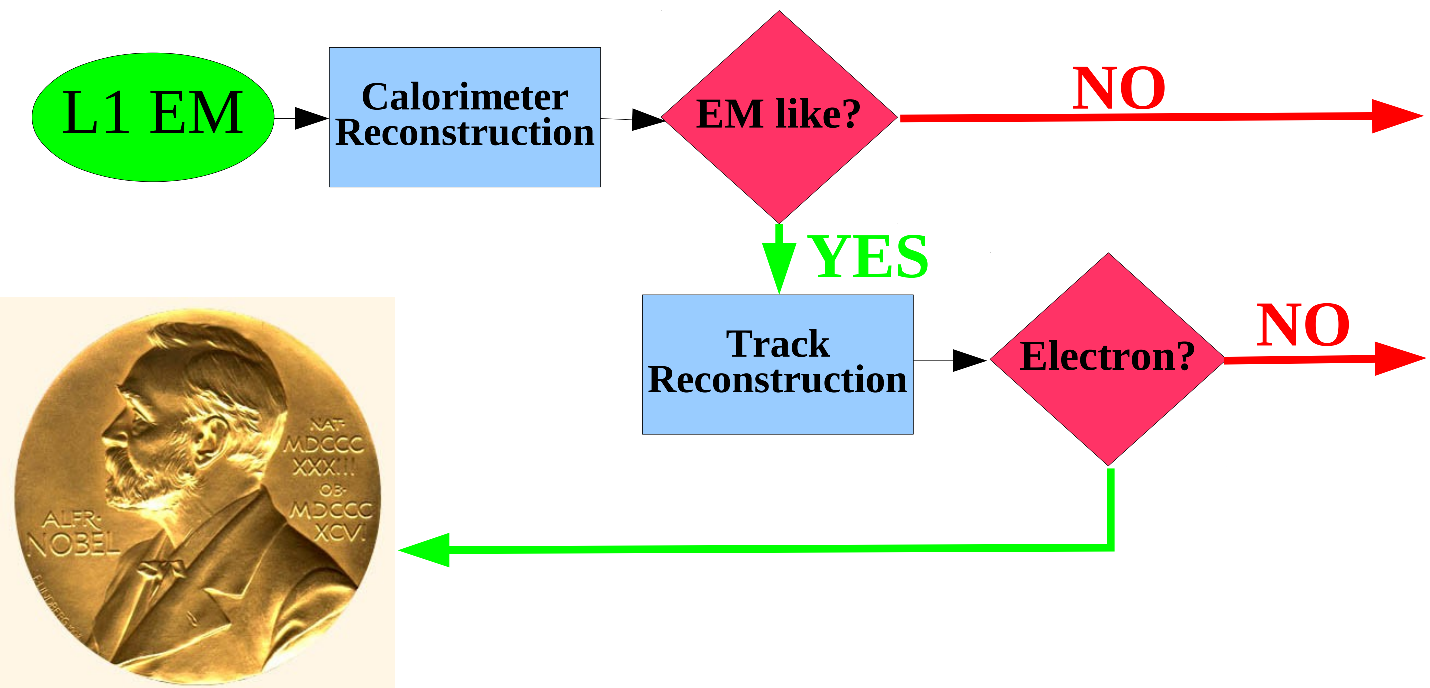


Higher Level Triggering

- From L1 we expect a large rate (up to 100 kHz) of events that “might be interesting”
- These events are not kept yet (rate too high for storage), but sent to the HLT for additional filtering
  - Massive commercial computer farm
  - ATLAS: L2 and L3 handled by separate computing farms
    - Roughly 17k CPUs that can be freely assigned to either
  - CMS: Single computing farm (roughly 13k CPUs)
- Parallel processing, each CPU processes individual event
- Resources are still limited
  - Offline: Full reconstruction takes seconds (minutes)
  - Online latency: milliseconds (input rate dependent)

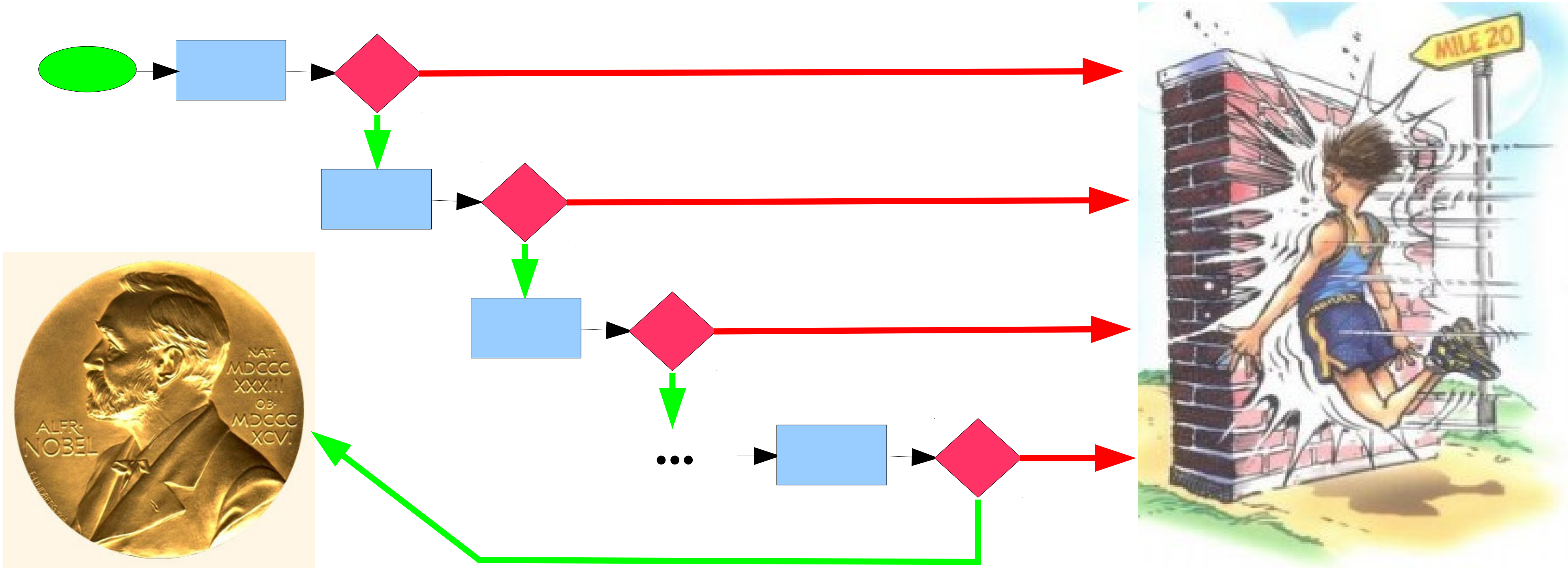
Making a Fast HLT

- HLT is composed of hundreds of trigger algorithms
  - Software design, so no strict limit on the number of algorithms
  - Each designed with a specific physics signature in mind
- Algorithm speed enhanced by various checkpoints
  - Opportunity to reject early and save processing time



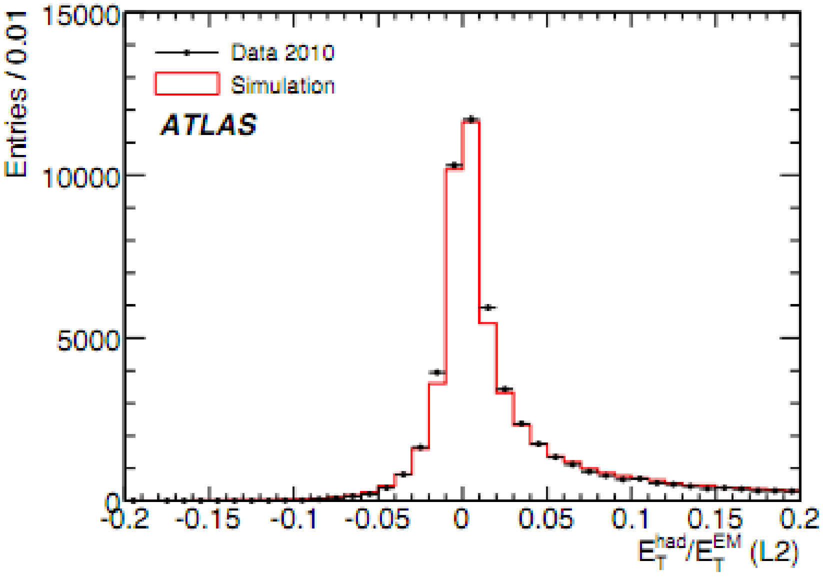
Making a Fast HLT

- All algorithms ("trigger paths") are executed in parallel
  - Every trigger path is run to completion (i.e. we get yes/no)
  - The time to process an event depends mostly on the slowest running trigger path
- Multiple checkpoints speed up processing
  - Run more complicated, slower, operations on fewer events



Example: HLT Electrons

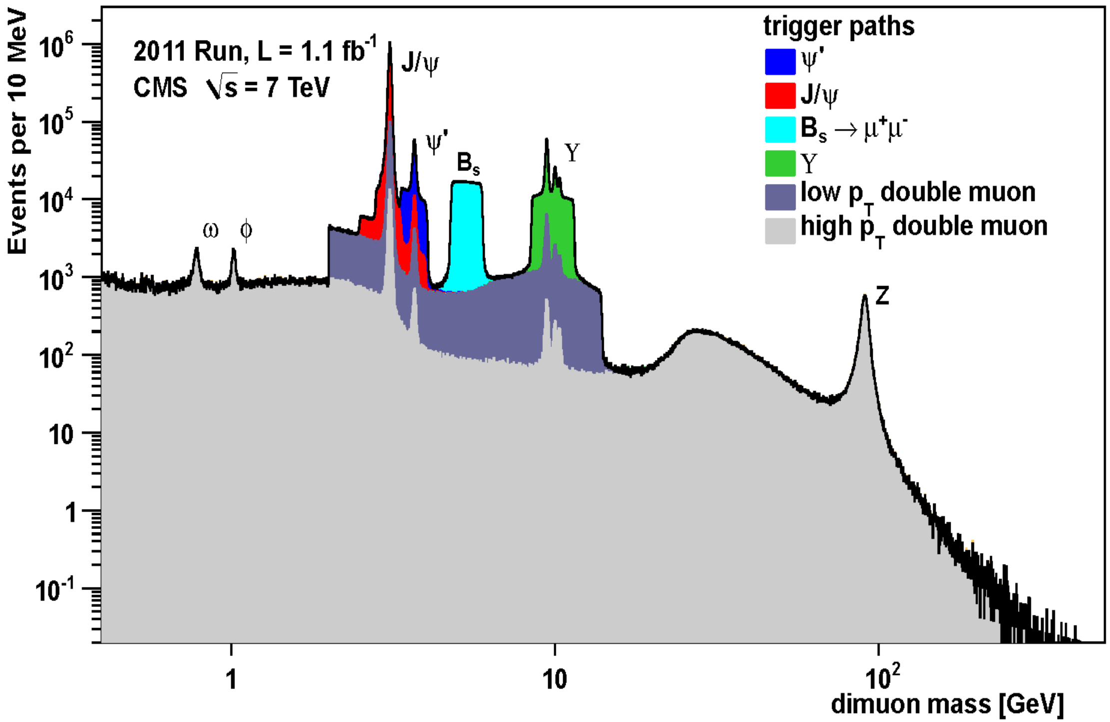
- Start from L1 e/γ seed with sufficient E_T
- Reconstruct the cluster in EM Calorimeter
  - Is there enough energy to continue?
  - Does the cluster shape look like that of an electron/photon?
  - Make sure the cluster is not a hadron (check Hadronic Calorimeter)
  - Is the candidate isolated in the calorimeters?
- Electrons
  - Is there a track matched to the cluster?
  - Is the electron isolated in the tracker?
- Photons
  - Check for tracks pointing to the cluster



Loose description of CMS electron/photon paths, Similar logic in ATLAS

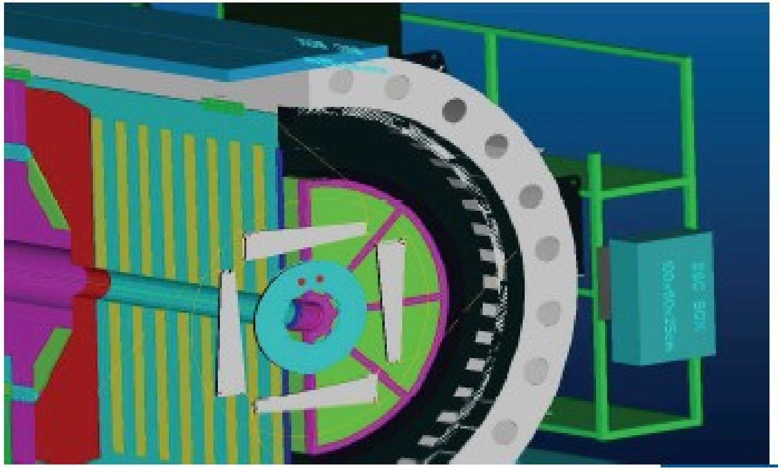
Example: HLT Muons

- Muons in CMS:
  - Starting from L1 muon candidate, refit using the muon system
    - Continue if sufficient p_T
  - Combine tracker hits with muon system to get a better p_T measurement
    - Keep the event if p_T is large enough



- Muons in ATLAS:
  - At Level 2, using detector information from the region of interest, assign muon p_T based on fast look up tables
  - Extrapolate to the collision point and find the associated track
  - Is the muon isolated in the tracker, calorimeters?
  - Refine selection at L3, compute p_T using Tracking information

The Evolution of the Trigger

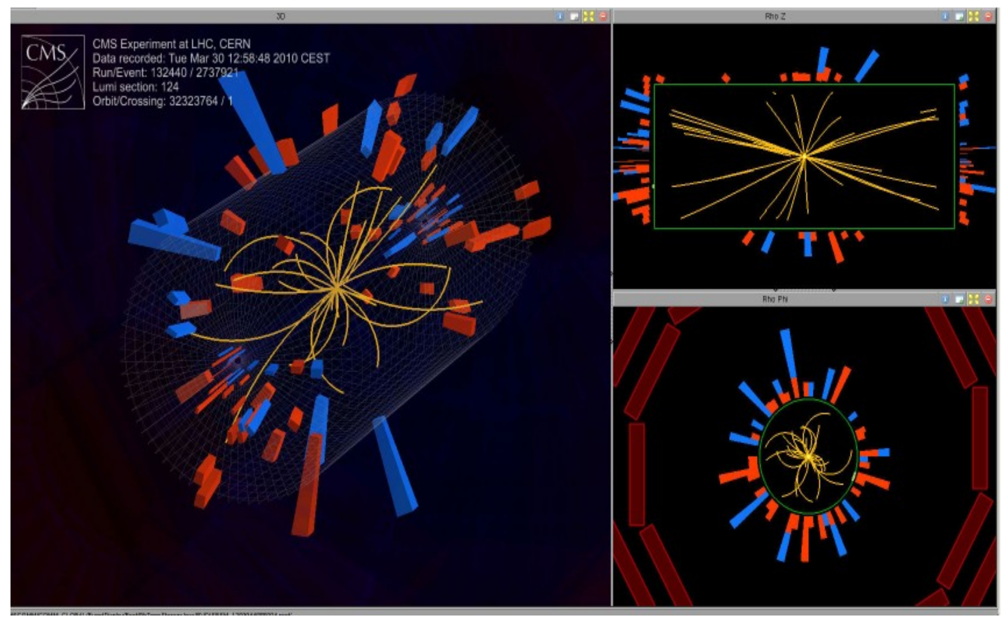


The trigger (L1+HLT) is by design very flexible:

- Should always be able to respond to the present physics demand
- And demands can change quickly!

Example: 2010 LHC running

- First collisions, luminosity of 10^{27} Hz/cm^2
- Initially possible to save nearly every pp collision
- Very simple HLT algorithms
    - Pass-through of L1 triggers
    - And then...



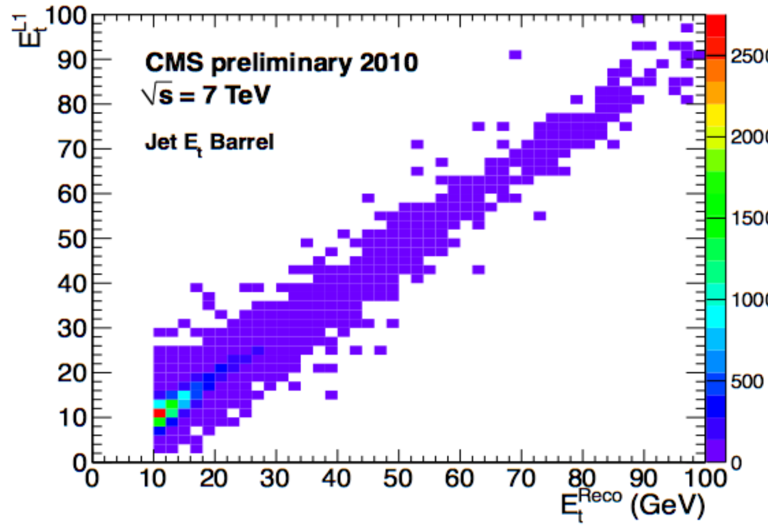
Evolution of the Trigger

- From March-October 2010, instantaneous luminosity increased rapidly to 10^{32}
  - 10^5 increase over roughly six months
- Important to be able to adapt quickly, using tools best suited for the conditions

Increase of ~10^4

HLT Path Structure

The simplest HLT paths:
Pass-through for L1
No additional selection,
no bias with respect to L1



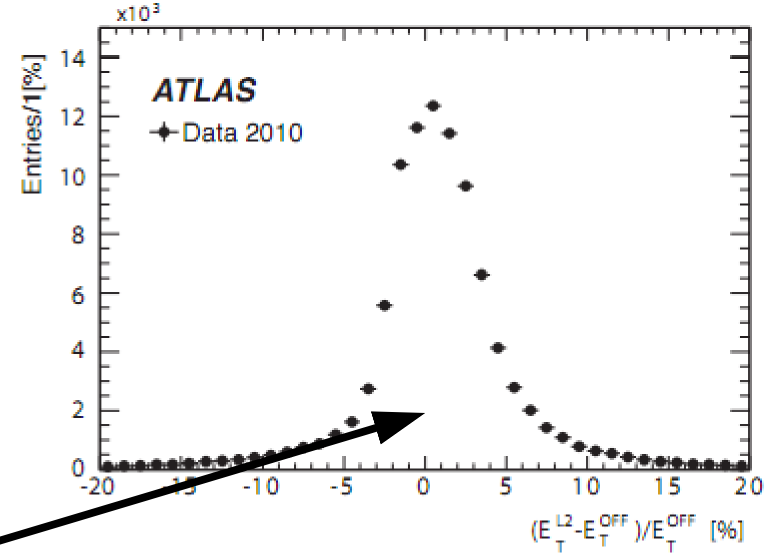
HLT Path Structure

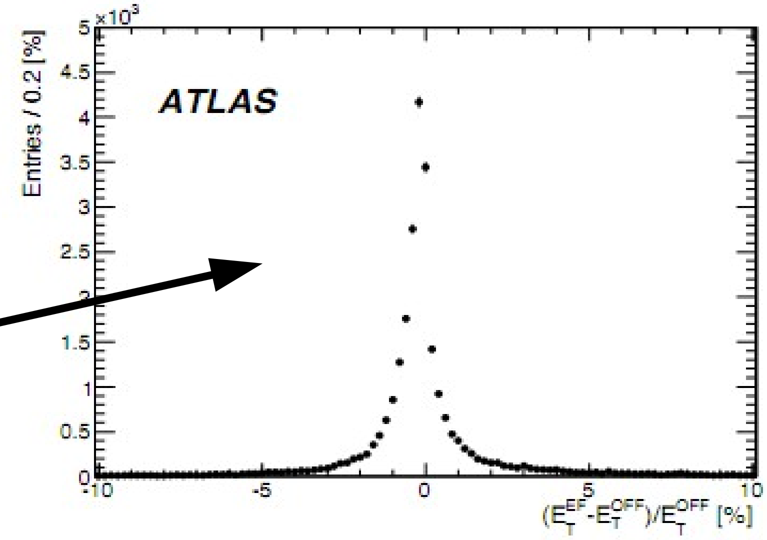
Increased complexity, increased time

The simplest HLT paths: Pass-through for L1
No additional selection,
no bias with respect to L1

Next Level: Confirm L1 object using higher granularity detector information
Fast reconstruction techniques,
improved resolution

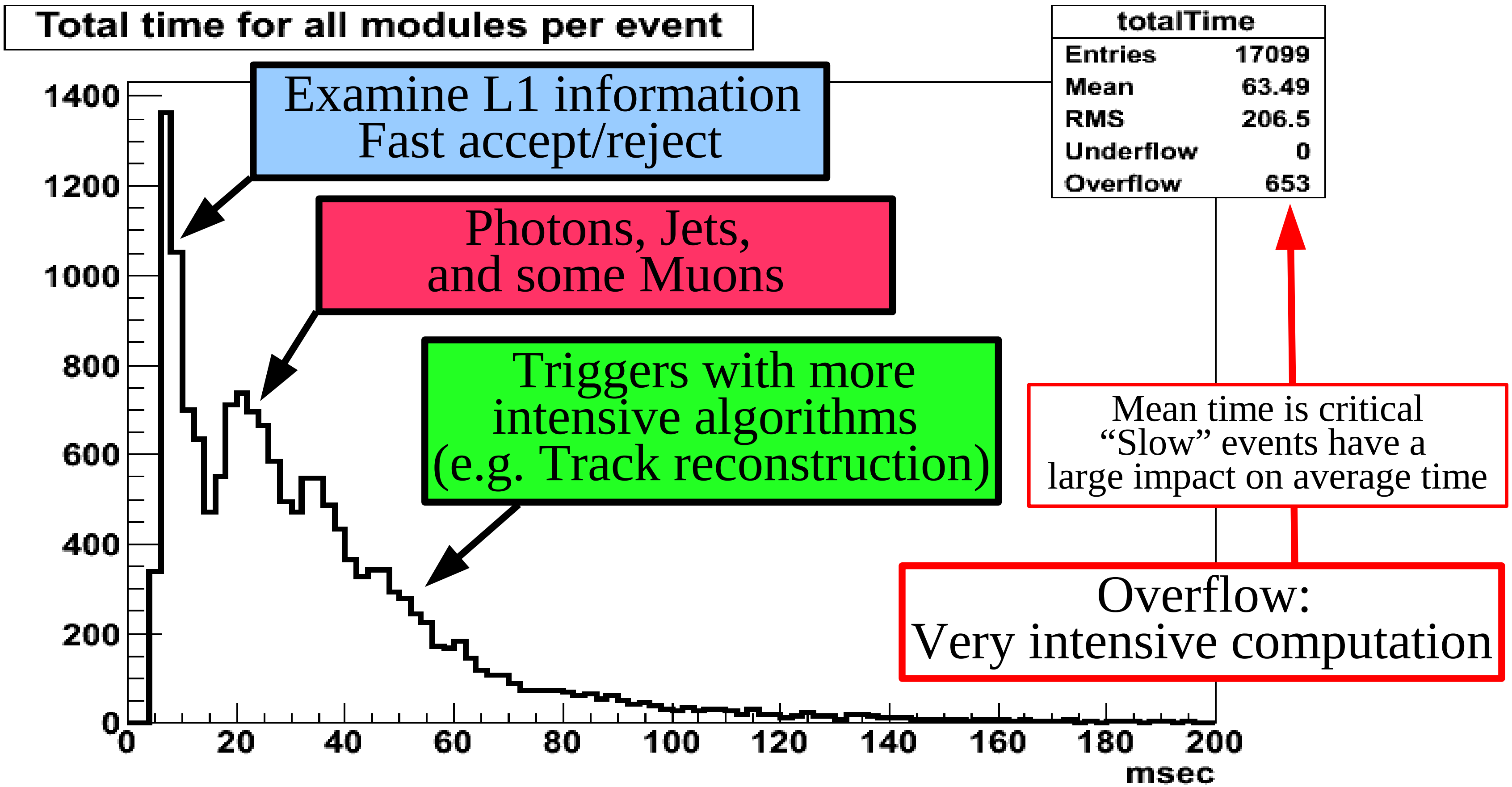
Continue adding complexity
Improve quality of trigger object,
approaching offline quality





HLT Timing

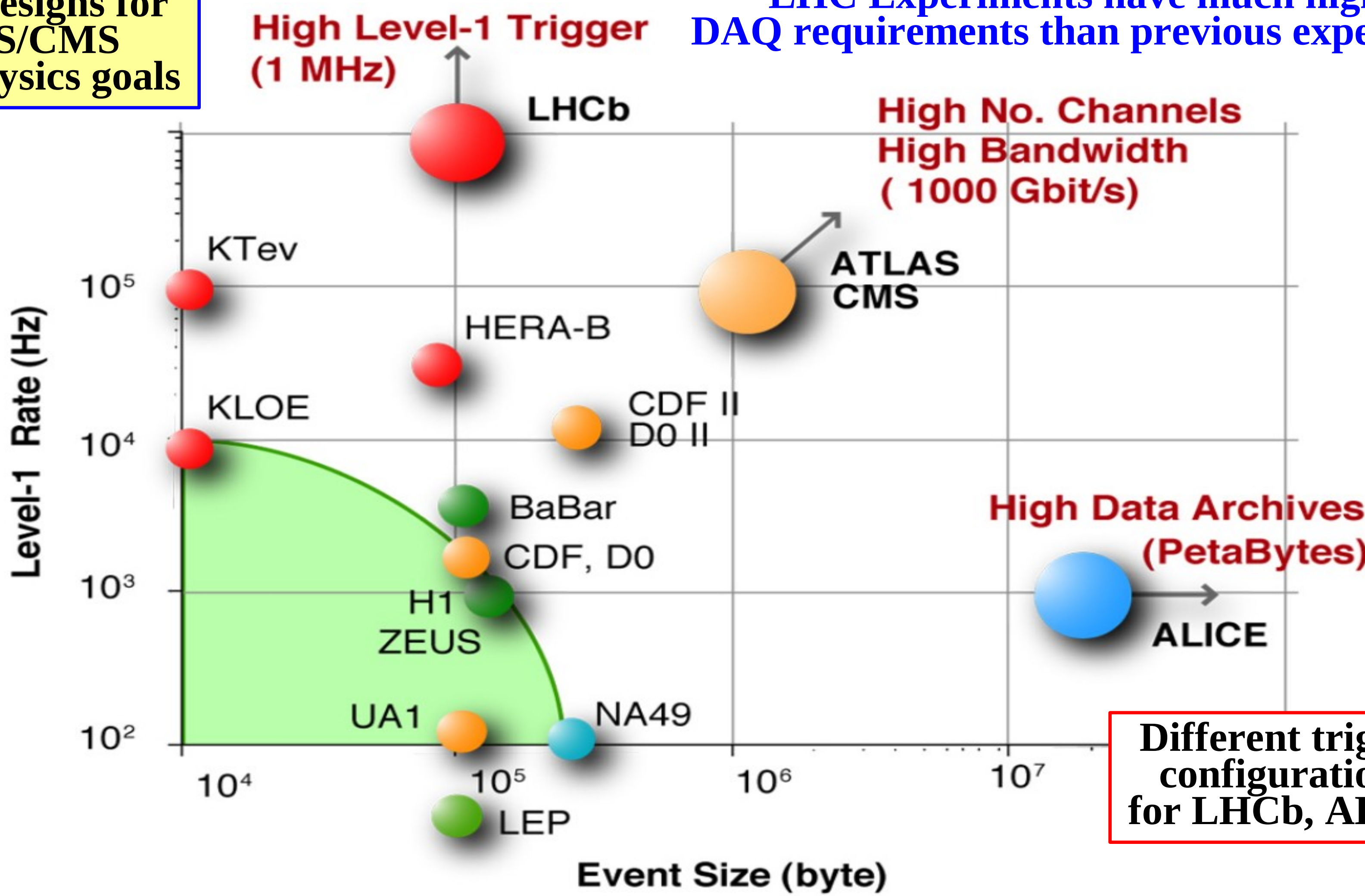
Expected CMS HLT CPU Performance at 2x10^{32} Hz/cm^2
Sample: Minimum Bias L1-skim



Trigger and DAQ

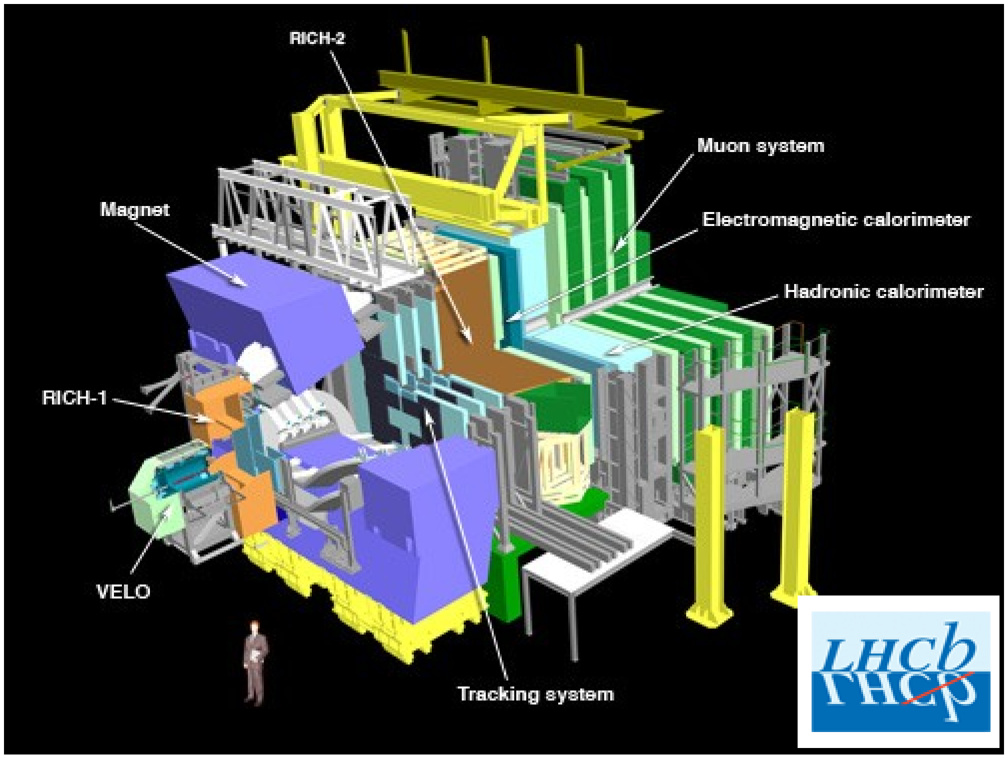
Trigger designs for ATLAS/CMS reflect physics goals

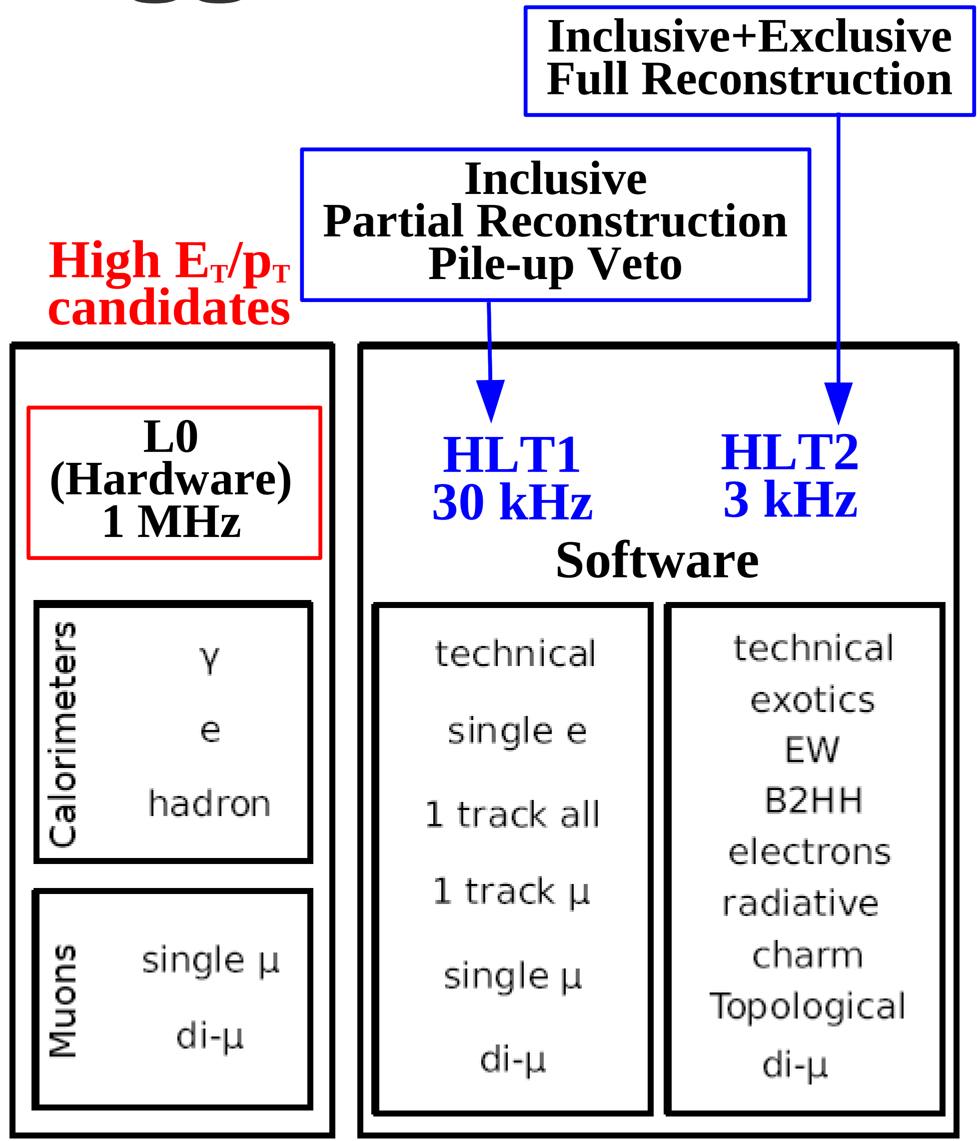
LHC Experiments have much higher DAQ requirements than previous experiments



Different trigger configurations for LHCb, ALICE

LHCb Trigger

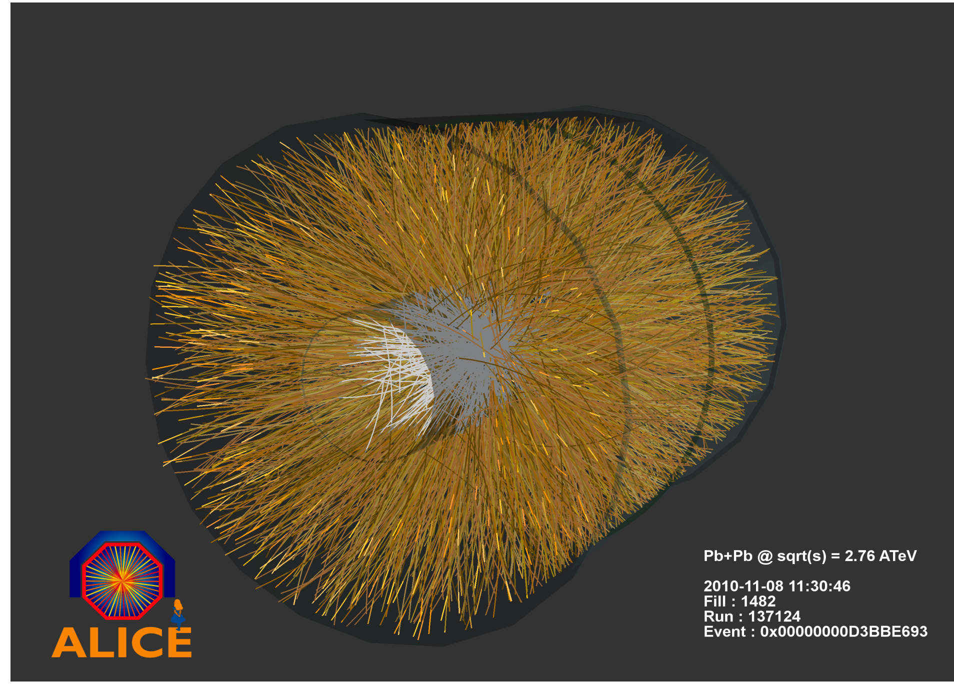


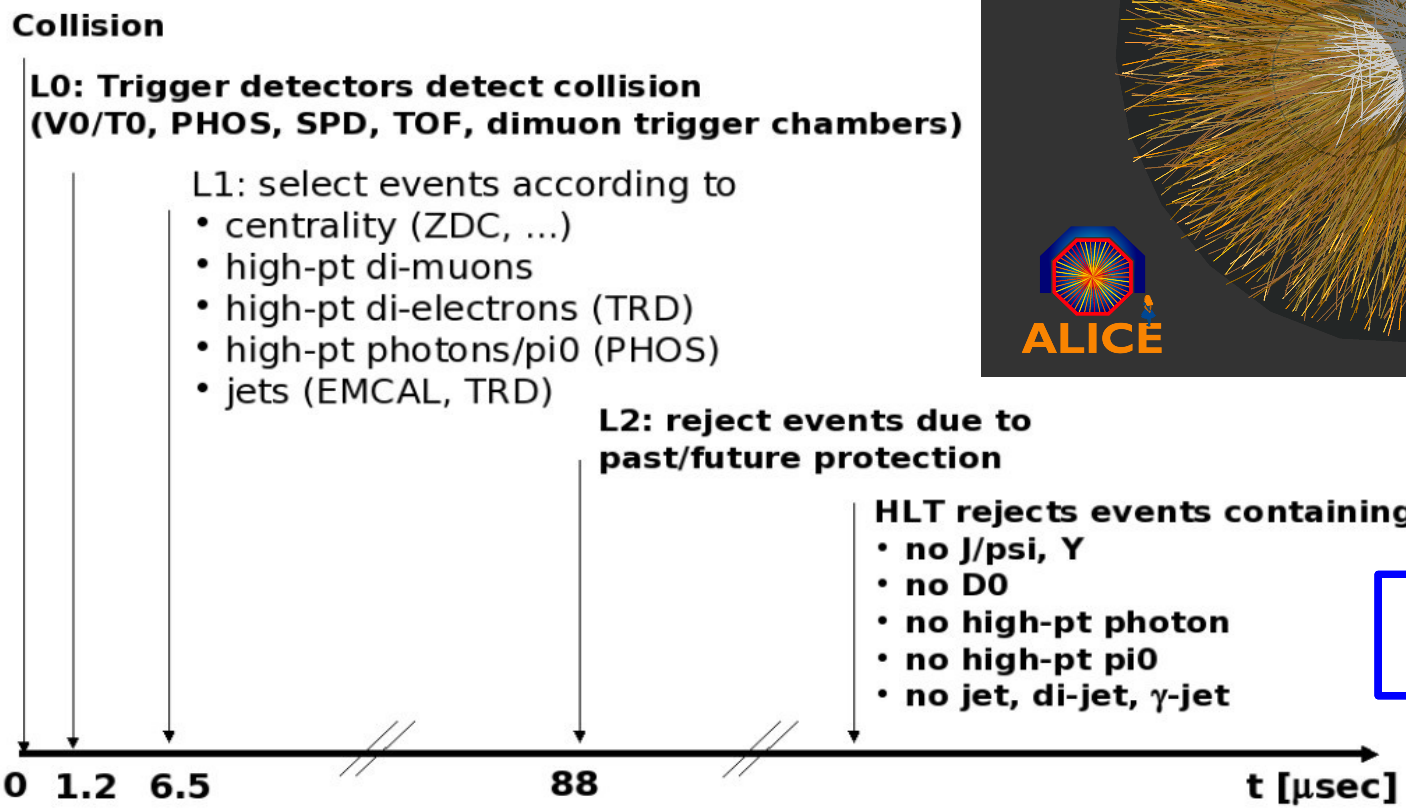


ALICE Central Trigger Processor

Unique ALICE constraints

- Low rate of Pb-Pb collisions
- Very large events
- Slow tracking detector (TPC)





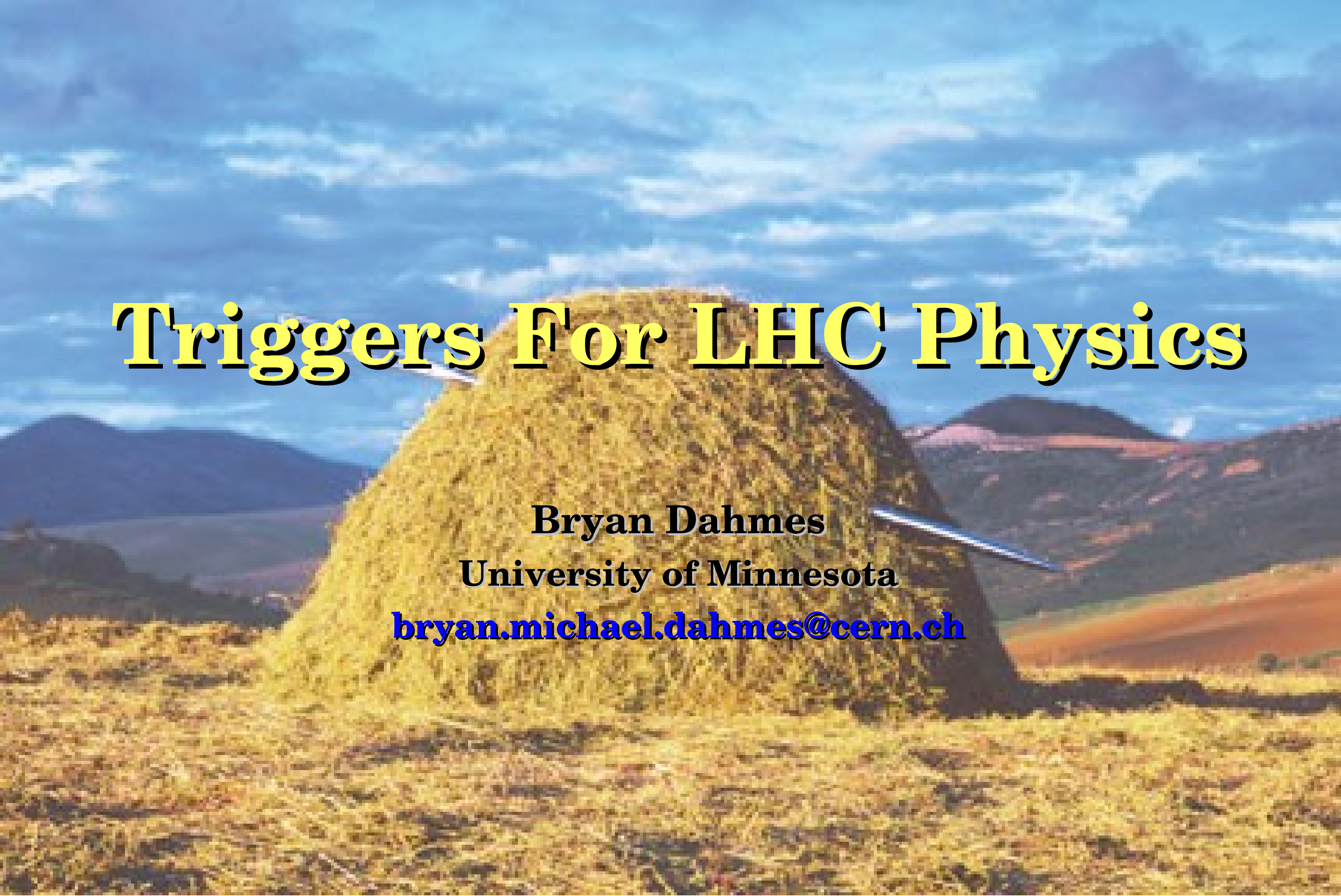
Three levels of hardware triggers

Trigger/DAQ Comparison

	ATLAS	CMS	LHCb	ALICE
"L1" Latency [μs]	2.5	3.2	4	1.2/6/88
Max "L1" output rate [kHz]	75	100	1000	~2
Frontend readout bandwidth [GBytes/s]	120	100	40	25
Max HLT avg. latency [ms] (upgrade with luminosity)	L2: 40 EF: 1000	50 (in 2010)	20	
Event building bandwidth [GBytes/s]	4	100	40	25
Trigger output rate [Hz]	~200	~300	~2000	~50
Output bandwidth [MBytes/s]	300	300	100	1200
Event size [MBytes]	1.5	1	0.035	Up to 20

Summary

- Very challenging to design a trigger setup for LHC conditions
  - Very high rate of collisions
  - High rejection rates, “interesting physics” efficiency, and speed required
- Custom hardware at first level partially reduces the rate
  - Coarse granularity, but very fast
- Parallel computing (massive commercial computing farm) complicated data analysis online
- Trigger stages cooperate to reject uninteresting data quickly



Triggers For LHC Physics

Bryan Dahmes
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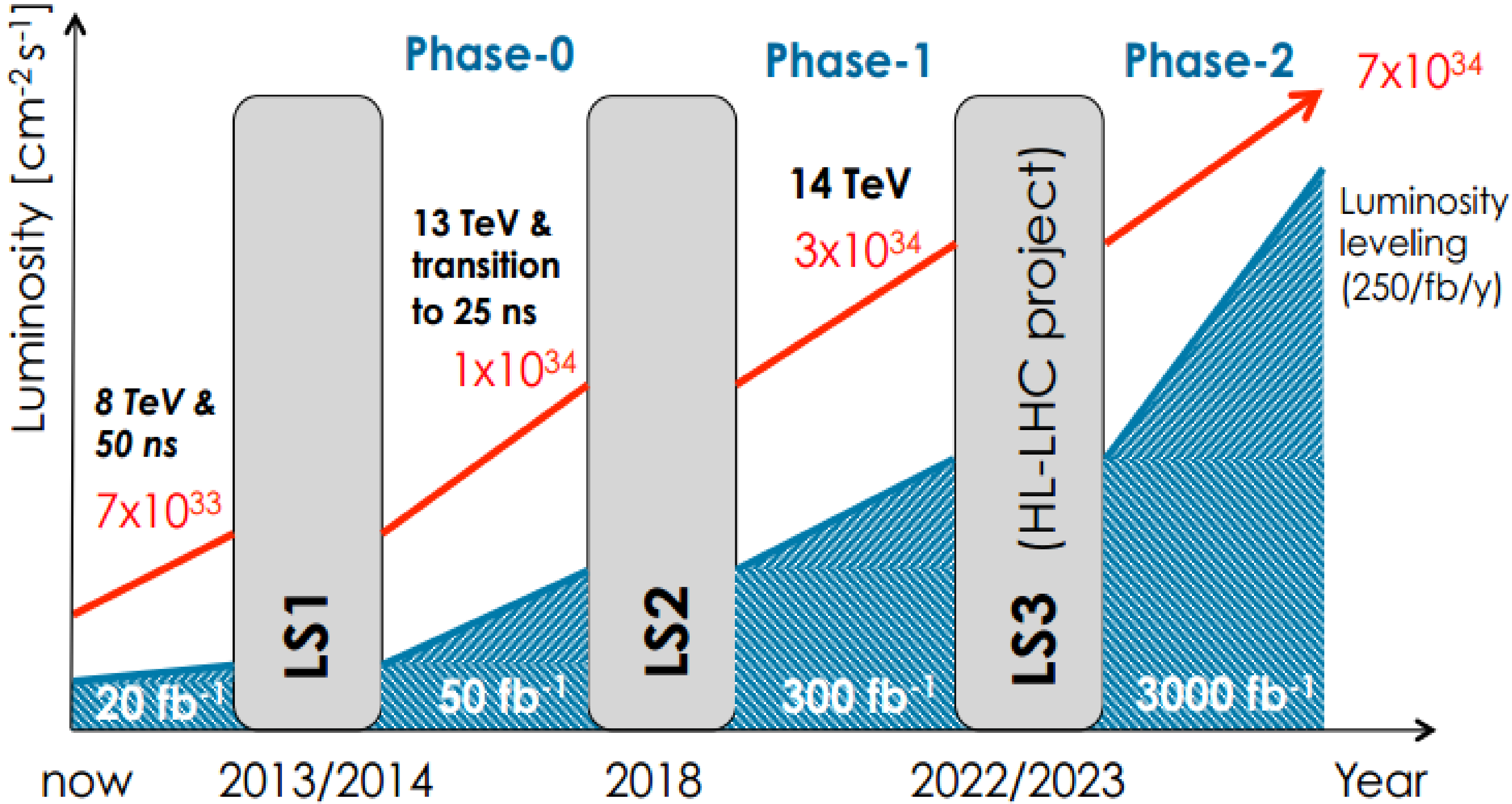
Reminder

- Very challenging to design a trigger setup for LHC conditions
    - Very high rate of collisions
    - Require high rejection rates, “interesting physics” efficiency...
    - ...and speed!
- Custom hardware at first level partially reduces the rate
    - Coarse granularity, but very fast
- Parallel computing (massive commercial computing farm) allows complicated data analysis online
- Trigger stages (L1 through HLT) cooperate to reject uninteresting data quickly

Preview

- What will happen today
  - Overview of trigger strategy, and how a good understanding of the trigger is important for analysis
  - Some examples of the trigger in action

LHC Upgrade Plans



High luminosity era on the way...massive increase in number of pileup collisions from O(20) "today" to O(100-200) in Phase 2

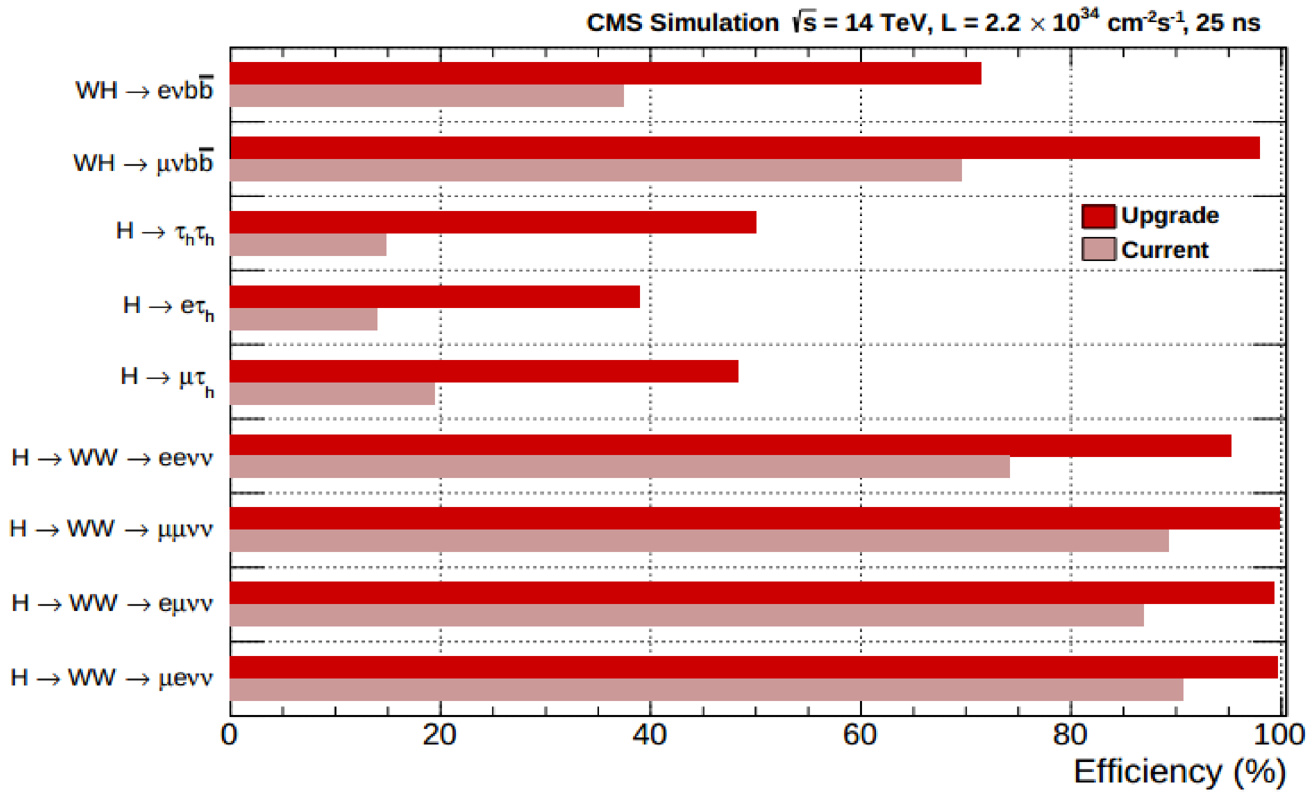
Motivations for Trigger Upgrade

- Rate of “interesting physics” increases with increasing instantaneous luminosity
  - Need to maintain sensitivity to Standard Model (+Higgs!) scale physics
  - Raising trigger p_T thresholds kill interesting physics
- Higher instantaneous luminosity comes with higher pileup
  - More low p_T particles from extra pp collisions, more tracks and calorimeter energy deposits
  - Reduces effectiveness of isolation algorithms at L1 and HLT
  - More likely to lose good leptons, harder to reconstruct jets and missing energy

Trigger Upgrade Plans

- Improve isolation, resolution of trigger objects at Level 1
- Increase complexity by moving some software (HLT) selection to Level 1

Example:
CMS trigger upgrade plans for Phase I and impact on Higgs physics



Long-Term Upgrade Plans

- Over 100 pileup collisions per event expected in Phase 2
  - Expect a very different collision environment than what we have seen
- Proposals for Trigger upgrades
  - Add tracking trigger for Level 1
    - Requires increased L1 latency to ~20 μsec
  - Increase L1 output bandwidth
  - Split hardware trigger in two: Add a Level 0
    - Low latency, large accept rate
- Will need to replace detector Front End Electronics
  - Electronics will have been damaged by radiation
- Plans are in development now
  - Primary motivator: how upgrades maintain **or improve** physics potential

Trigger Interface with Analysis

- As far as the data is concerned, the trigger is the first step towards publication
- But the order is a bit backward for physicists
- Why?

Trigger Interface with Analysis

- Physicists start with an analysis idea
  - Determine what you want to look for (i.e. where you want to go)
  - Then figure out how to select the data
- There is little point in trying to do an analysis if every “interesting” event fails the trigger
- Want to build a trigger that has loose requirements that you tighten up offline
- Design a trigger to meet analysis goals, but...

Competing for Data

- There are hundreds to thousands of physicists on an LHC collaboration
  - All are competing for the same resources
  - Only O(100) Hz of collision data available
    - At L = 10^{34}, this is roughly the rate of $W \to \ell\nu$ production!
- How do you make sure your (very important) data is kept for later analysis?
  - Need to meet physics needs with limited bandwidth
- Cutting at the trigger level throws away data forever
  - Potential bias to events that you analyze
  - Loss of interesting data

"The Trigger does not determine which Physics Model is right, only which Physics Model is left"

Trigger Menus

Triggers are created for a specific analysis,
but the Physics Goals of the experiment determine
where the events can be most useful

Trigger Menus: All triggers used to collect data for a given run period

At present, roughly 500 triggers in each menu for ATLAS/CMS

Breakdown of sample CMS trigger menus

$L = 8 \times 10^{29}$ Hz/cm^2
Rate ~ 200-300 Hz (*)

Jets, MET, Tau: 15%
Electrons: 25%
Muons: 25%
"Support" Triggers: 50%

Early-Mid 2010

$L = 2 \times 10^{32}$ Hz/cm^2
Rate ~ 300-500 Hz

Jets, MET: 30%
b, Tau: 15%
Electrons: 25%
Muons: 30%
"Support" Triggers: 10%

End 2010

$L = 2 \times 10^{33}$ Hz/cm^2
Rate ~ 200-300 Hz

Jets, etc.: 20%
Tau: 5%
Electrons: 20%
Muons: 20%
Cross Triggers: 20%
"Support" Triggers: 5%

2011

(*) **Numbers and fractions approximate, and do not account for trigger overlap**

Trigger Menus

(Unprescaled) Object	Trigger Threshold (GeV)	Rate (Hz)	Physics
Single Muon	40	21	Searches
Single Isolated muon	24	43	Standard Model
Double muon	(17, 8) [13, 8 for parked data]	20 [30]	Standard Model / Higgs
Single Electron	80	8	Searches
Single Isolated Electron	27	59	Standard Model
Double Electron	(17, 8)	8	Standard Model / Higgs
Single Photon	150	5	Searches
Double Photon	(36, 22)	7	Higgs
Muon + Ele x-trigger	(17, 8), (5, 5, 8), (8, 8, 8)	3	Standard Model / Higgs
Single PFJet	320	9	Standard Model
QuadJet	80 [50 for parked data]	8[100]	Standard Model /Searches
Six Jet	(6 x 45), (4 x 60, 2 x 20)	3	Searches
MET	120	4	Searches
HT	750	6	Searches

Object breakdown for LHC Run 1 instantaneous luminosities of (nearly 7 x 10^{33} $s^{-1}cm^{-2}$ at the start of a fill)

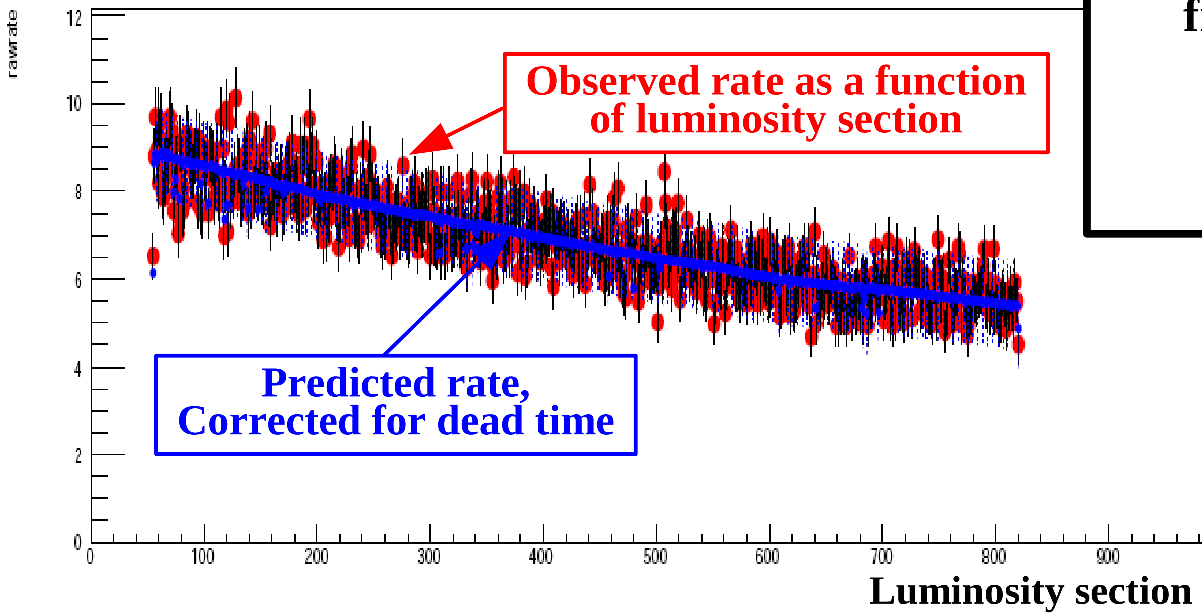
Trigger Menus

	Offline Selection	Trigger Selection L1	 EF	L1 Peak (kHz) $L_{peak} = 7\times10^{33}$	EF Ave (Hz) $L_{ave} = 5\times10^{33}$
Single leptons	Single muon p_T > 25 GeV	15 GeV	24 GeV	8	45
	Single electron p_T > 25 GeV	18 GeV	24 GeV	17	70
Two leptons	2 muons p_T >15 2 muons p_T > 20,10 GeV	2x10 GeV 15 GeV	2 x 13 GeV 18,8 GeV	1 8	5 8
	2 electrons, each p_T > 15 GeV	2x10 GeV	2x12 GeV	6	8
	2 taus p_T > 45, 30GeV	15,11 GeV	29,20 GeV	12	12
Two photons	2 photons, each p_T > 25 GeV 2 loose photons, p_T > 40,30 GeV	2 x10 GeV 12,16 GeV	2 x 20 GeV 35, 25 GeV	6 6	10 7
Single jet	Jet p_T > 360 GeV	75 GeV	360 GeV	2	5
MET	MET > 120 GeV	40 GeV	80 GeV	2	17
Multi-jets	5 jets, each p_T > 55 GeV	4x15 GeV	5x55 GeV	1	8
b-jets	b + 3 other jets p_T > 45 GeV	4x15 GeV	4x45 GeV+btag	1	4
TOTAL				**<75**	**~400 (mean)**

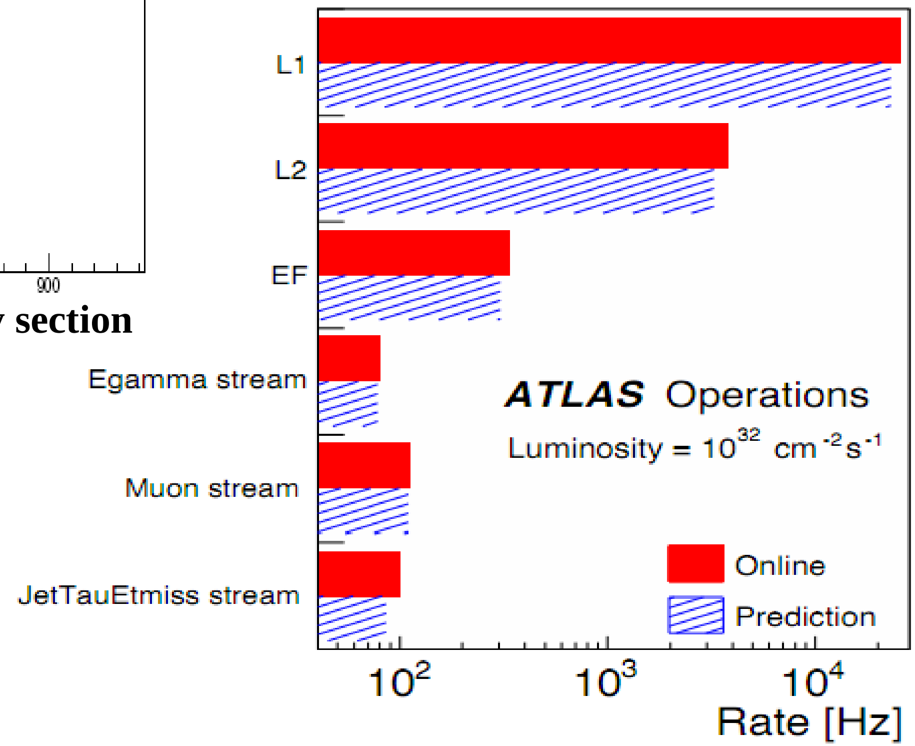
Object breakdown for LHC Run 1 instantaneous luminosities of (nearly 7 x 10^{33} $s^{-1}cm^{-2}$ at the start of a fill)

Menu Forecasting

CMS Double Electron Trigger



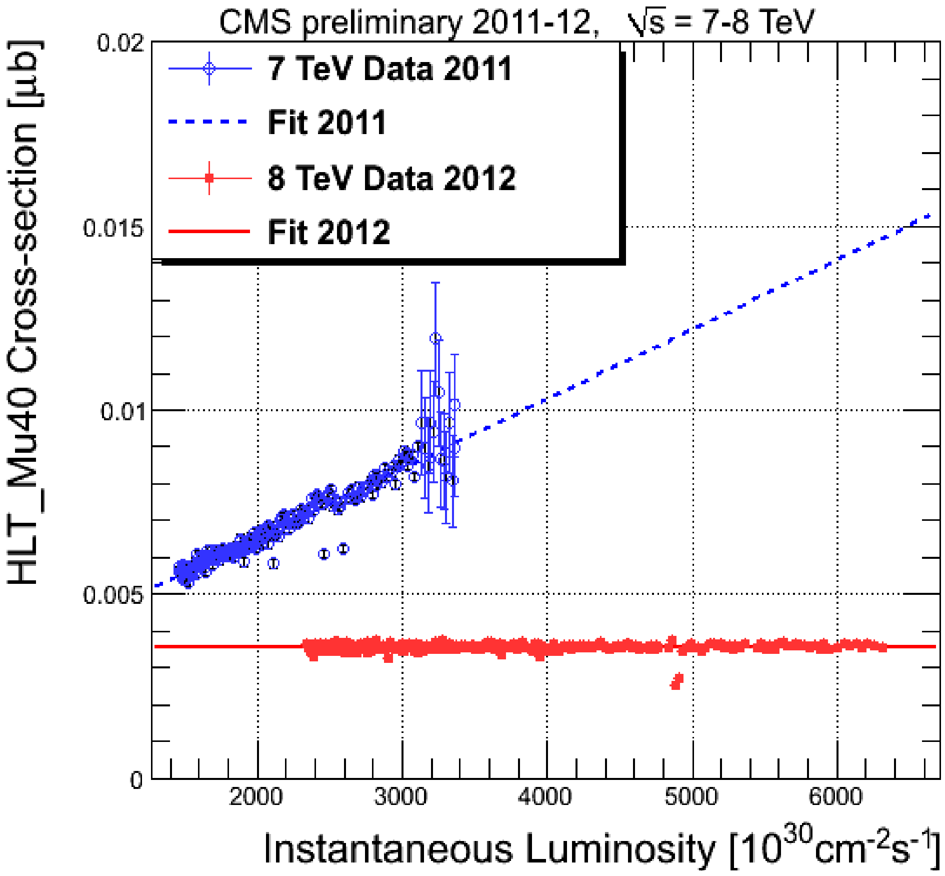
Trigger rates for new menus determined from large minimum bias samples
Linear extrapolation based on increased luminosity
Some trigger rates also affected by pileup



We must predict the trigger menu behavior at each new step up in instantaneous luminosity

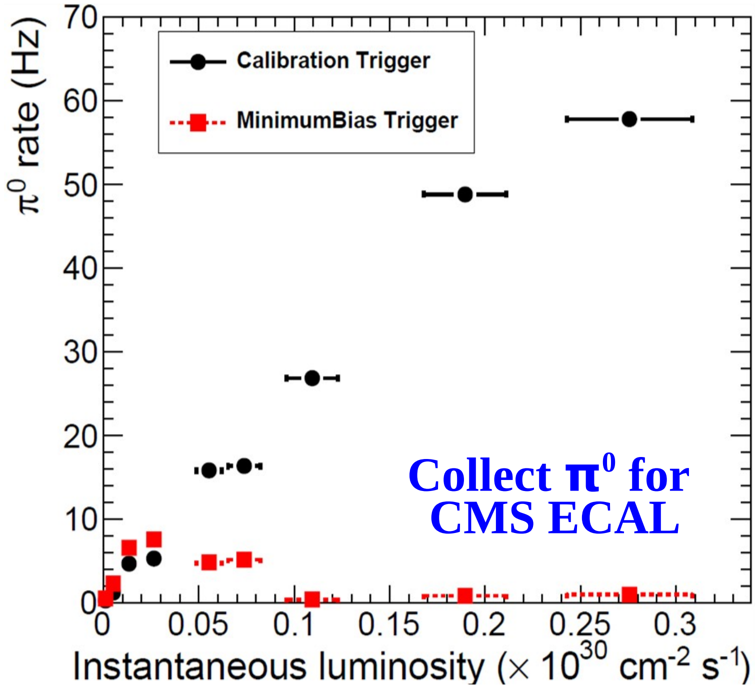
Pileup

- Some triggers can be very sensitive to pileup
  - Low thresholds
  - Loose requirements
- Increasing requirements or improving the trigger algorithms can stabilize trigger performance

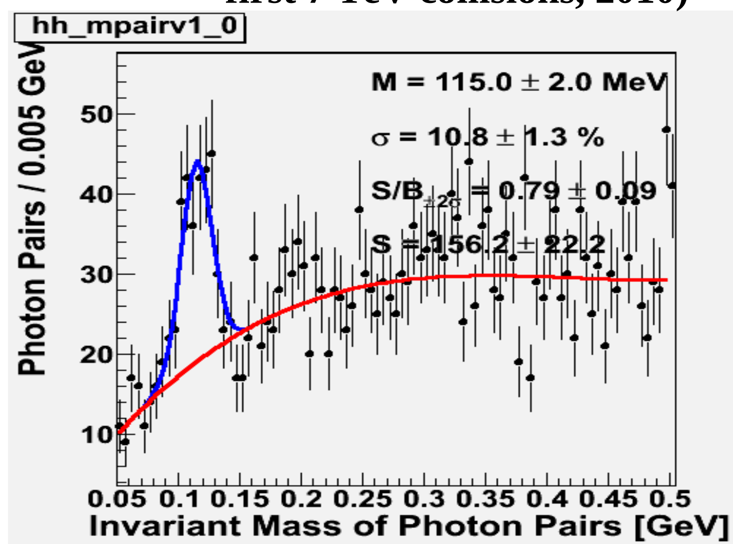


Calibration Triggers

- Additional triggers used for detector calibration
- Calibration triggers in CMS
  - Save only small portion of detector information
  - Allows O(kHz) output rate



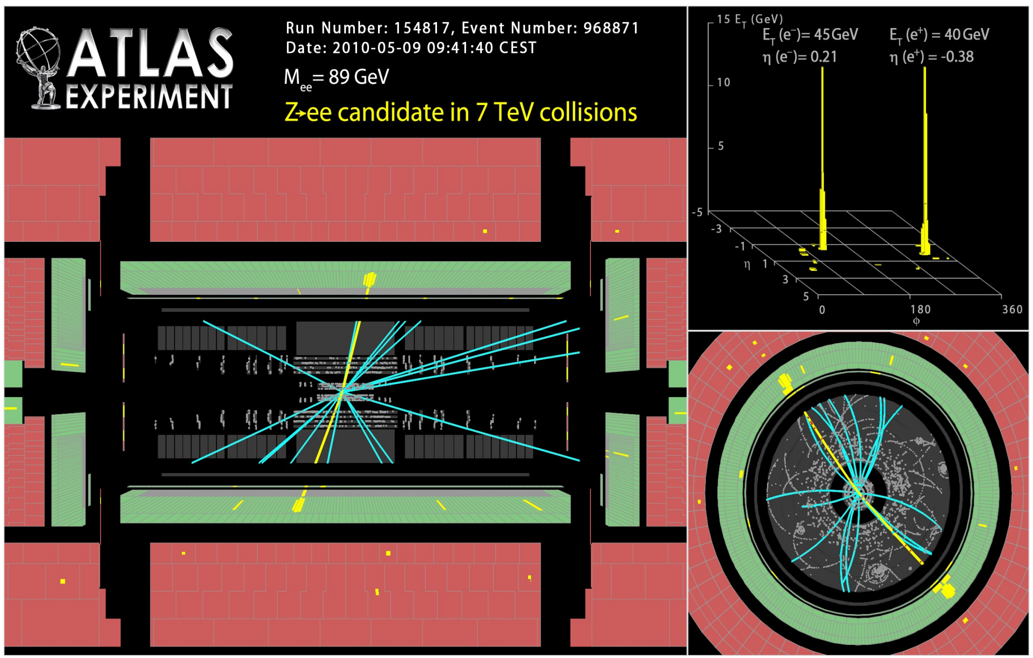
Fast reconstruction of π^0 peak (using 200 seconds of data from first 7 TeV collisions, 2010)

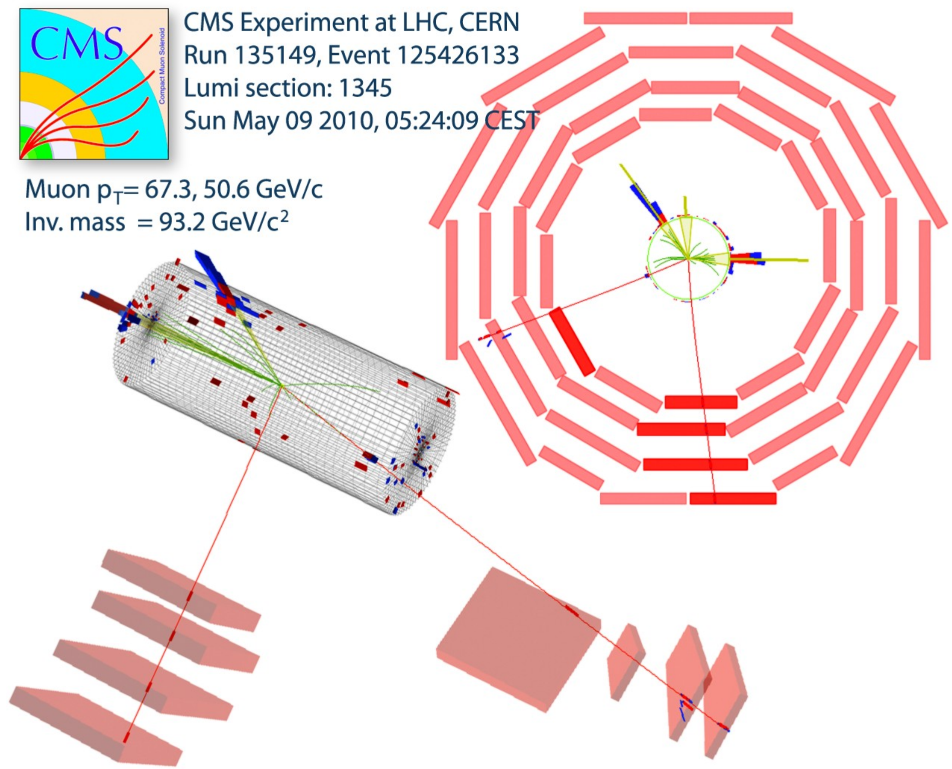


Similar techniques employed by ATLAS

Building a Trigger

- Imagine you need events with a Z boson
  - Standard Model, Higgs→ZZ, useful for Z' searches, ...
- How do you collect these events online?





Trigger Strategy

- Isolated high p_T leptons are rarely produced in a typical pp collision
  - Every Z decay has two of them!
  - So, construct a trigger that requires high p_T leptons
- General strategy for building a trigger
  - The simpler, the better
  - Be as inclusive as possible
  - Robust design
  - Redundancy

Understanding Triggers

- Simple triggers are
  - Easier to commission
  - Easier to debug
  - Easier to understand
- If possible, create a new (tighter) trigger from an older (more inclusive) trigger
  - At high rate, or limited bandwidth, more inclusive triggers tend to be prescaled

Trigger Strategy

- Simple
- Inclusive
- Robust design
- Redundancy

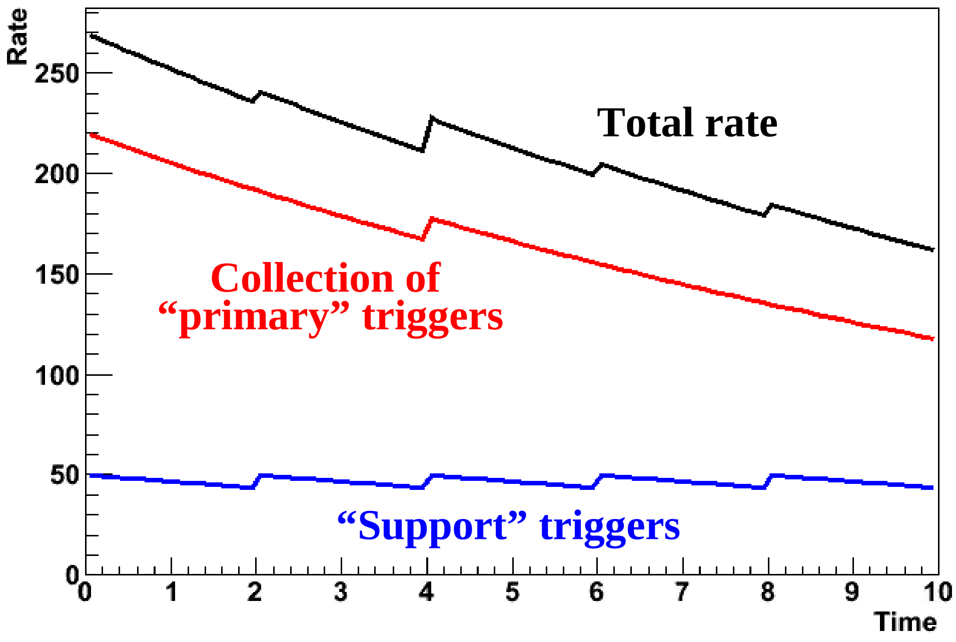
Aside: Prescaling Triggers

- Triggers start out as loose as possible
  - Low p_T thresholds
  - Minimum requirements
- Bandwidth needs change, loose triggers become tighter or get prescaled
  - Looser triggers may still be useful for efficiency, calibration, analysis support, etc.
- Prescaling
  - Take 1 out of every N events
    - ATLAS prescaler allows you to take x out of every N events (with x not necessarily 1)
  - Usually used to deliver a small fraction of the nominal trigger rate
    - O(1 Hz) or less is typical

Support triggers typically provide
Samples of low E_T events
Events passing looser requirements

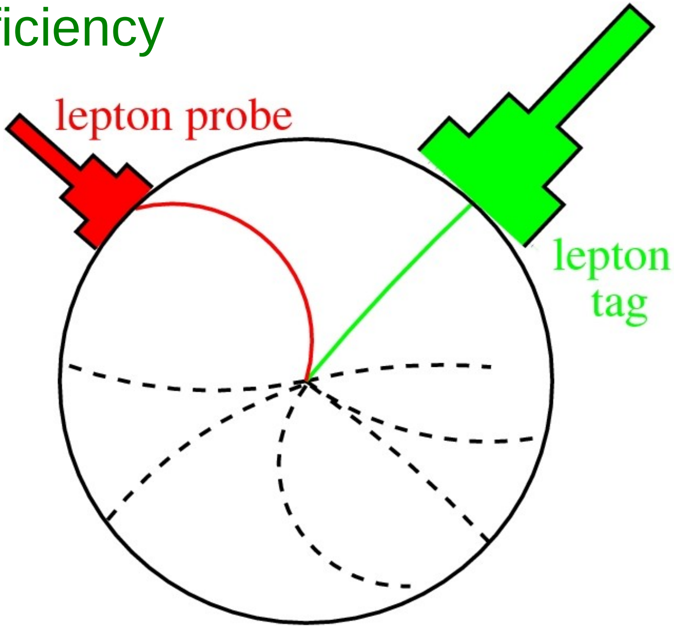
Prescale early to reduce processing time

Simulated rate evolution for an LHC Fill



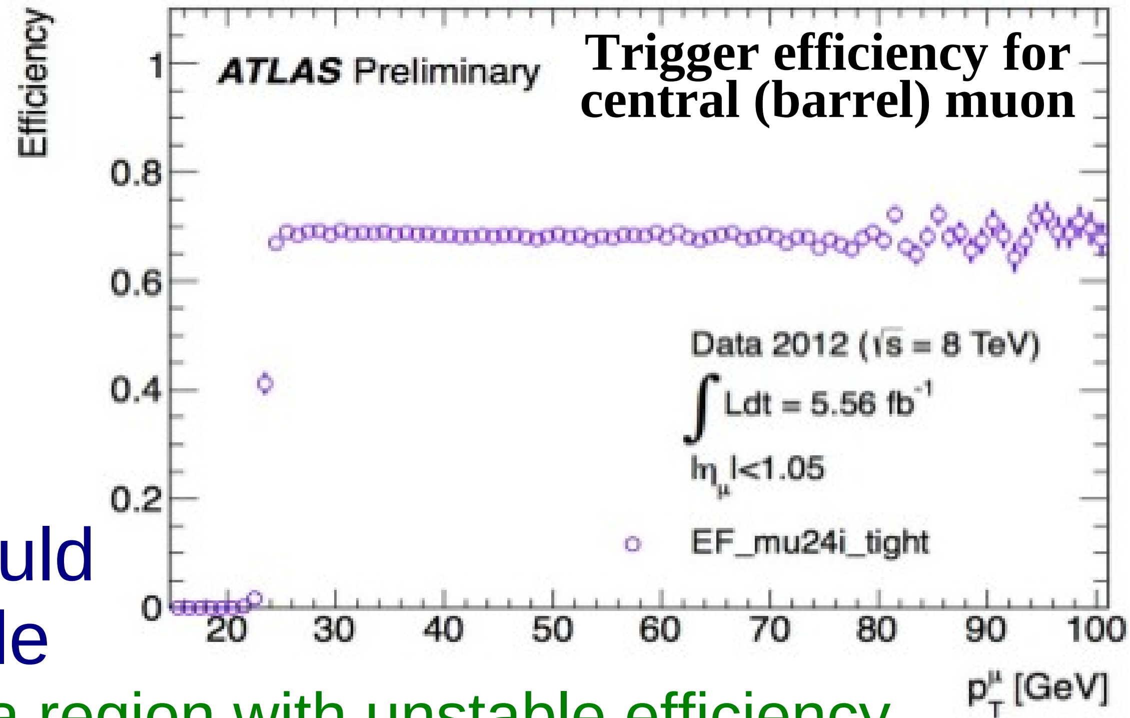
Trigger Efficiency

- In order to determine a cross section, you need to know your selection efficiency
  - Detector acceptance
  - Reconstruction efficiency
  - Trigger efficiency
- Your trigger is used to collect your data
  - You cannot blindly use your data to study efficiency
- Need an unbiased measurement of trigger efficiency
  - Random sample of pp collisions
  - Events collected by an orthogonal trigger
  - Use events collected by a looser (prescaled) trigger
  - Tag-and-Probe sample

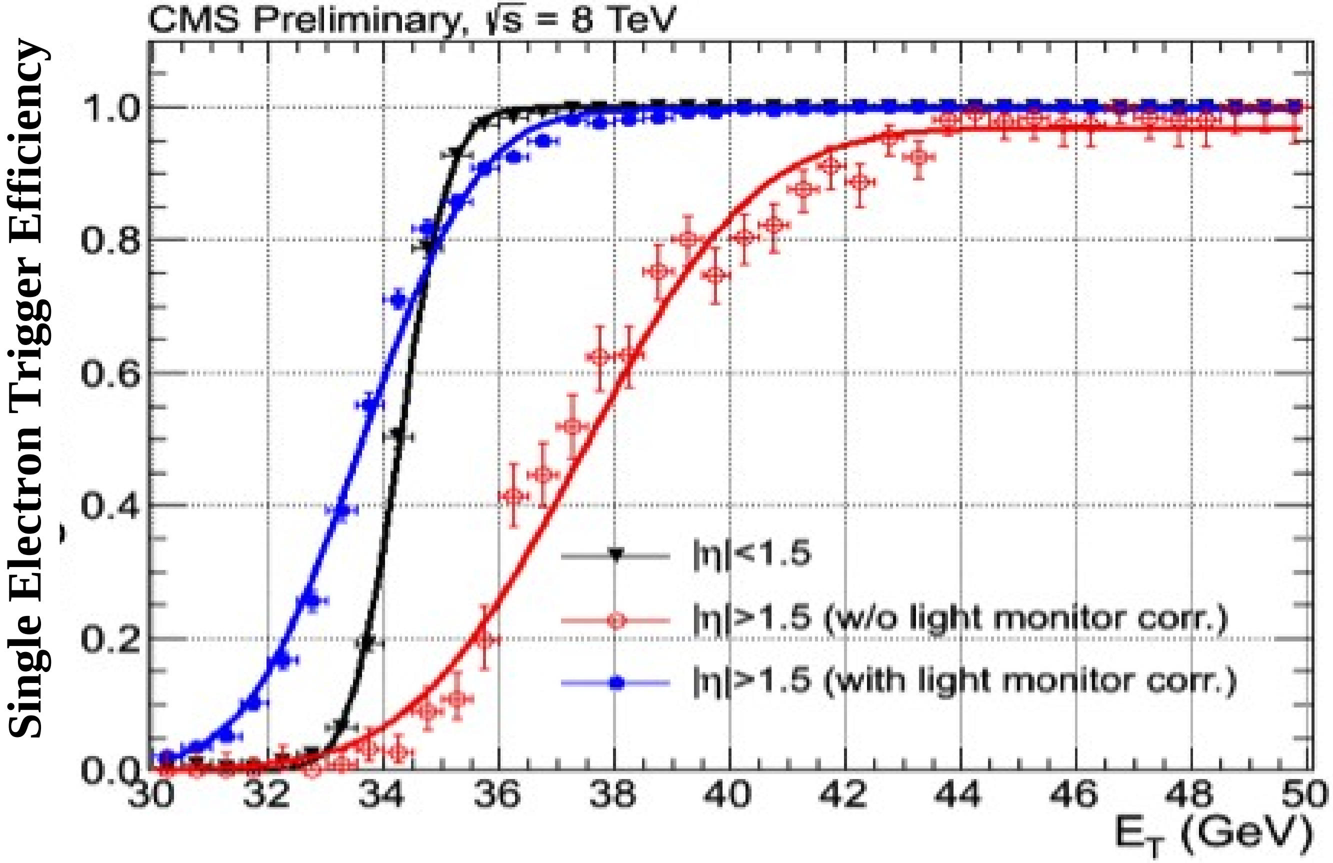


Trigger Efficiency

- Trigger efficiency is usually measured as a function of p_T and/or detector position
- We often speak of a trigger "turn-on" curve
- The turn-on curve should be as sharp as possible
    - Prevents working in a region with unstable efficiency
- Even when flat, the efficiency may not be 100%
    - Important to consider in the analysis



CMS Electron Trigger Turn-On



Adjust trigger conditions to account for a changing detector
Increased luminosity, increased light loss in CMS EM calorimeter

Online Selection Evolution

- Initially, we started with a single lepton trigger
  - Efficiency for Z events was very high
  - Take our (hypothetical) single muon trigger as an example
    - Let's say we estimated the muon efficiency to be 90% using tag and probe techniques
    - Our trigger efficiency for $Z \rightarrow \mu\mu$ should be...

Online Selection Evolution

- Initially, we started with a single lepton trigger
  - Efficiency for Z events was very high
  - Take our (hypothetical) single muon trigger as an example
    - Let's say we estimated the muon efficiency to be 90% using tag and probe techniques
    - Our trigger efficiency for $Z \rightarrow \mu\mu$ should be...**99%**

81%	**9%+9%=18%**	**1%**
Probability that both muons triggered the event	Probability that only one muon triggered the event	Probability that neither muon triggered the event

Online Selection Evolution

- By using minimal (simple) trigger strategies, we have nearly 100% efficiency in our selection
- By making our trigger more complicated by adding a second muon (or electron), our efficiency drops
  - Must account for such effects in the analysis

81%	**9%+9%=18%**	**1%**
Probability that both muons triggered the event	Probability that only one muon triggered the event	Probability that neither muon triggered the event

Back to Our Trigger Design...

- So, we wish to collect events with Z decays online
  - What should we do?
- Easiest solution: Use single lepton triggers
  - Two leptons (electrons or muons) from the Z as either could trigger the event
  - If you choose a double lepton trigger, you are insisting online that both leptons pass trigger requirements
    - Best to wait until you must do this
    - Determined by LHC conditions, physics goals

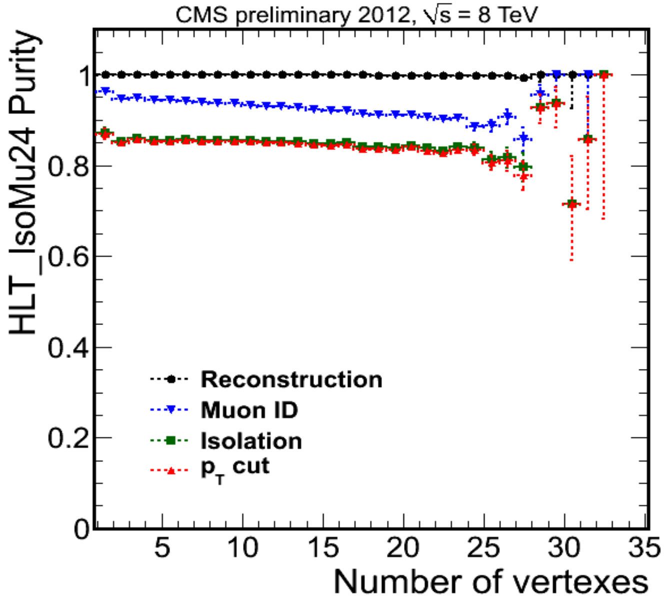
Trigger Strategy

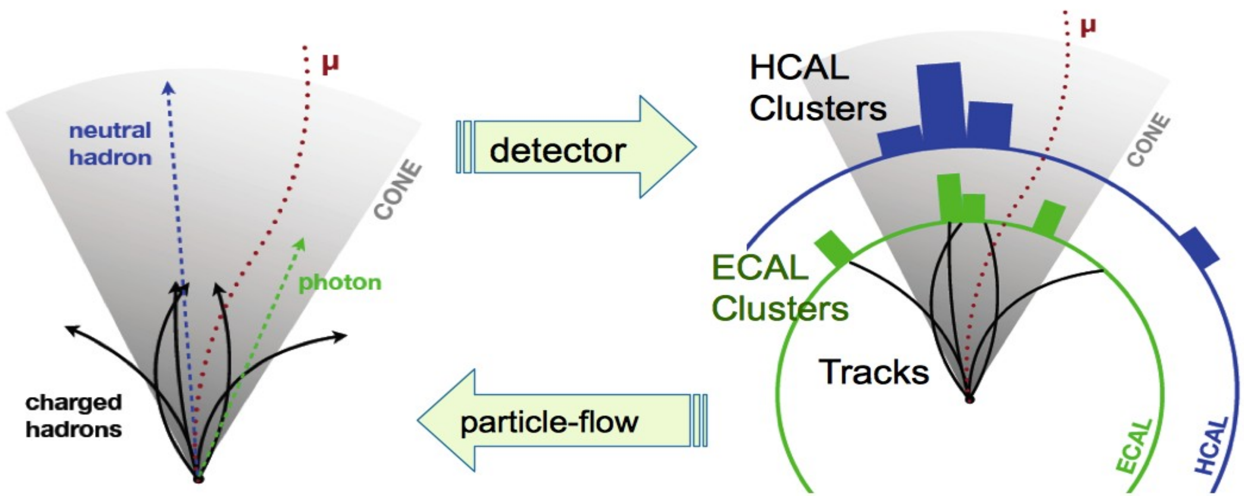
- Simple
- Inclusive
- Robust design
- Redundancy

What is done online cannot be undone...

When Simple is no Longer Possible

- LHC increases luminosity
  - Initially by adding more colliding bunches
  - Once maximum number of bunches reached, increase number of protons per bunch
    - Busier events as mean number of collisions per crossing increases
- Control the trigger rate by increasing signal purity





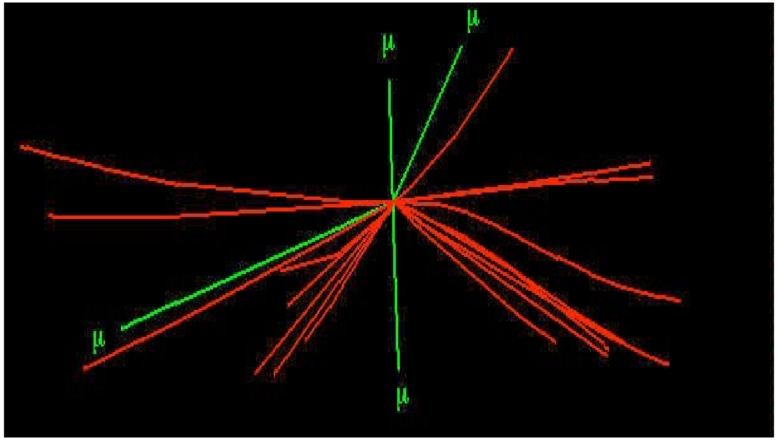
Be Inclusive

- What happens if your trigger has a large rate?
  - Remember, we can only save O(100) events/second
- Possible solution: Get Help!
- Hopefully many physics analyses (besides yours) could use the same trigger
  - Likely we are not the only group looking for lepton triggers
    - Standard Model: Z, W, top
    - SUSY
    - Exotic signatures
    - ...
- A trigger is easier to keep if most of the collaboration is using it

Trigger Strategy
- Simple
- Inclusive
- Robust design
- Redundancy

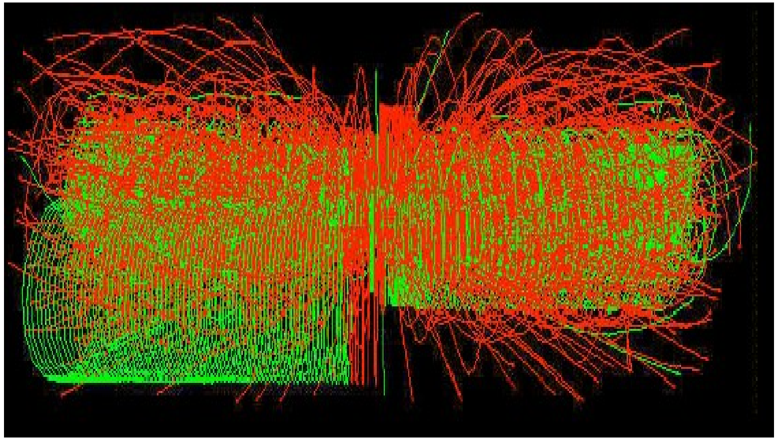
Robust Design

Don't design your trigger expecting this...



- Your trigger is going online, so it should run on every kind of event
- Prepare for “real life”, which includes pathological events
- Minimize (to ZERO) the number of crashes due to trigger design

...when life might look like this



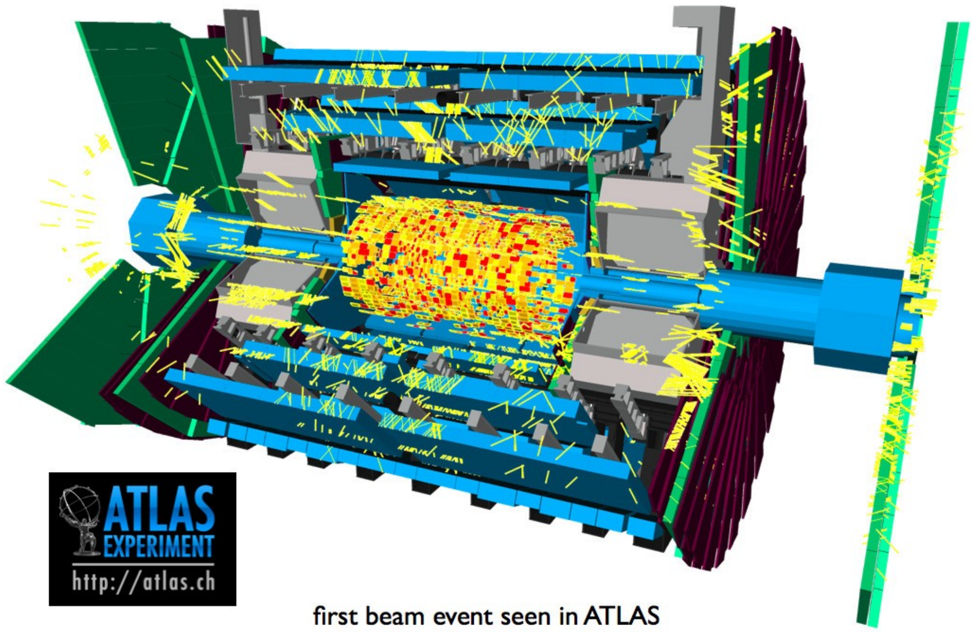
H→ZZ→4μ (and 25 pileup events), with and without p_T > 25 GeV track requirement

Trigger Strategy

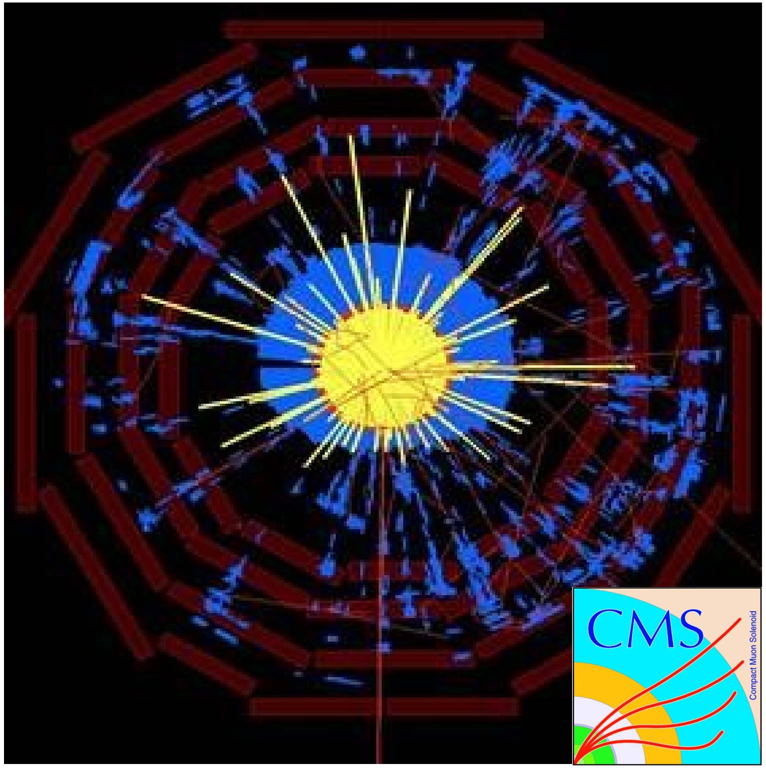
- Simple
- Inclusive
- Robust design
- Redundancy

Aside: Splash Event

Extraordinarily busy detector can cause strange behavior in trigger algorithms
Including timeouts and crashes



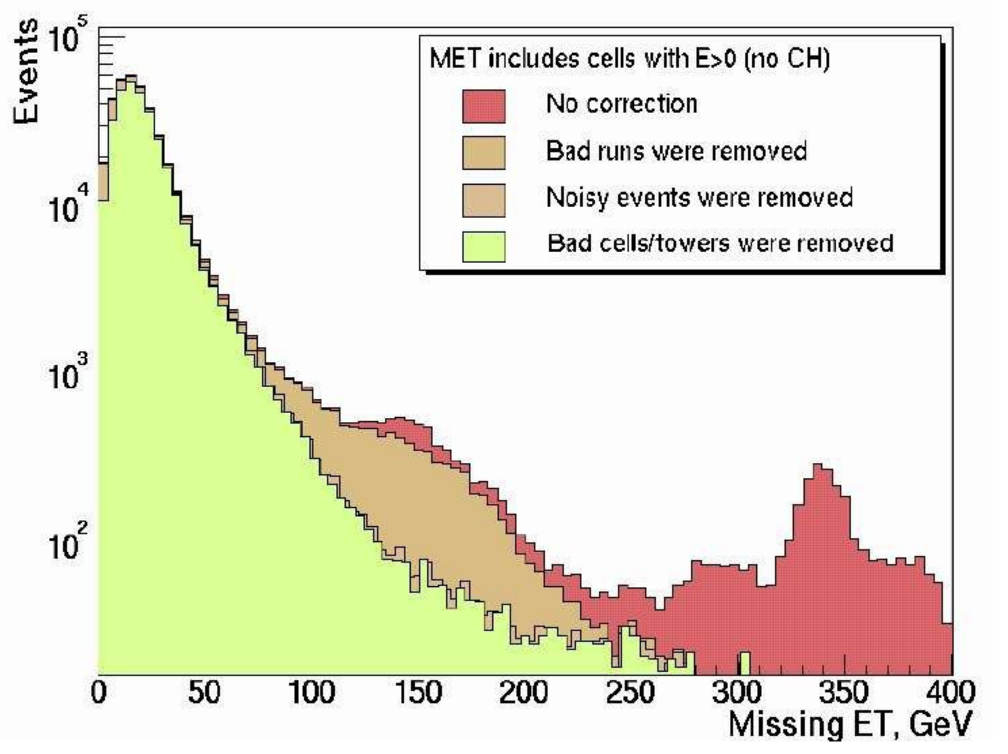
first beam event seen in ATLAS



"Splash" events produce
a very busy detector these events
are for commissioning purposes
(and nice pictures) only

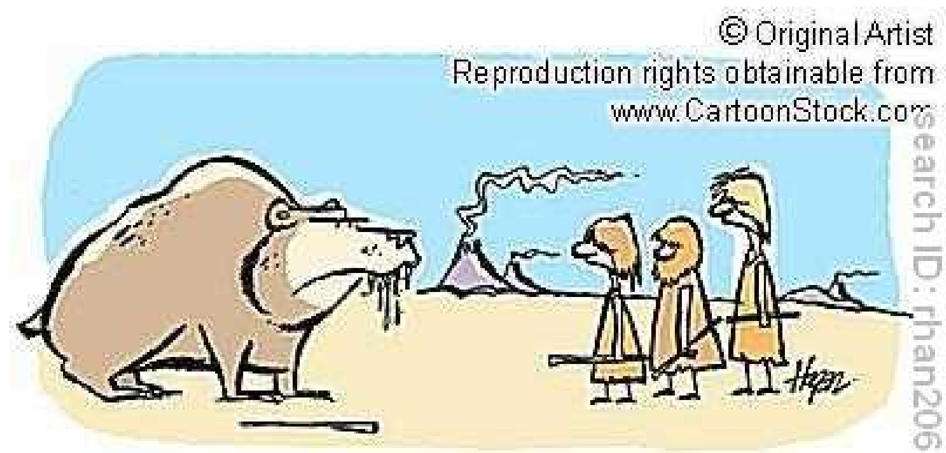
Example: Missing E_T at D0

- Missing transverse energy is a signature of many New Physics signatures
  - Attractive as a trigger idea
- It is also very susceptible to detector problems or beam conditions
  - Dangerous as the sole trigger option for an analysis



Redundancy

- It is very useful if your analysis can be selected using more than one trigger
  - Will help understand any potential trigger bias
  - If one trigger has problems (detector or LHC conditions leading to higher rate), you can still get your data
- Try to introduce tighter triggers online before they are necessary
  - Allows triggers to collect data before they are strictly necessary
  - Provides consistency for physics analysis, opportunity to study new trigger on existing data



If anyone's got a Plan B, now would be a good time

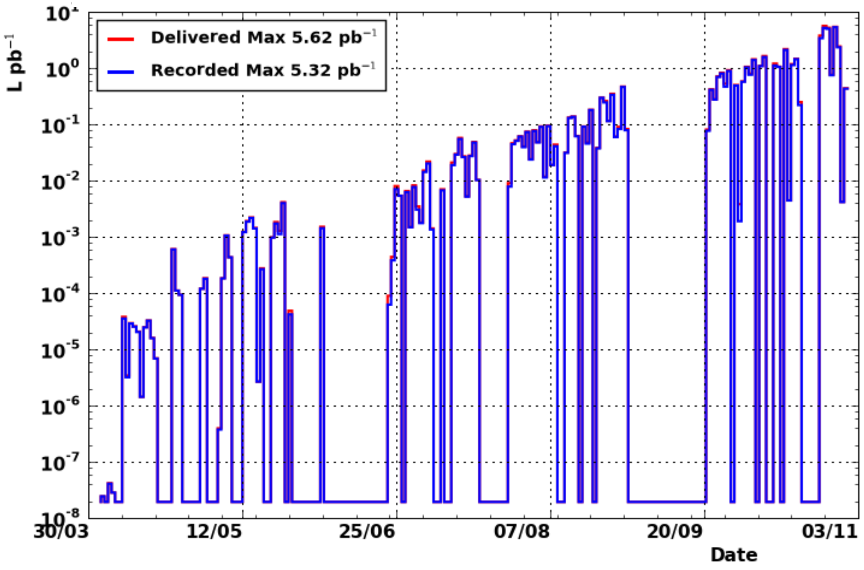
Trigger Strategy

- Simple
- Inclusive
- Robust design
- Redundancy

Summary: Z Trigger

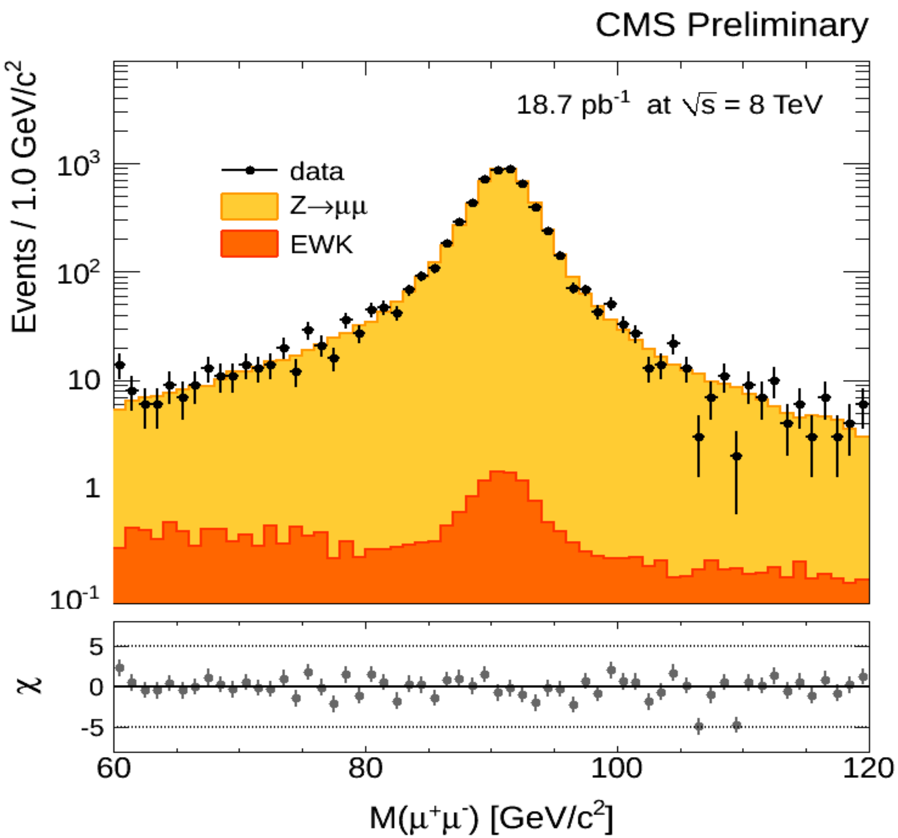
- Trigger strategy with a concrete example
- Collecting Z events using single electron, single muon triggers
  - High p_T, isolated leptons are rare in pp collisions
    - Much of the physics (and hence the detectors) designed around this fact
  - Lots of consumers in the community, so we can use a “common” trigger
  - (Let's assume that the trigger has been robustly tested and is working without problems online)
- We have back-up (redundant) triggers in place and ready for higher luminosity
  - Single electron/muon triggers with tighter requirements
  - Double electron, double muon triggers also ready

CMS Integrated Luminosity per day, 2010

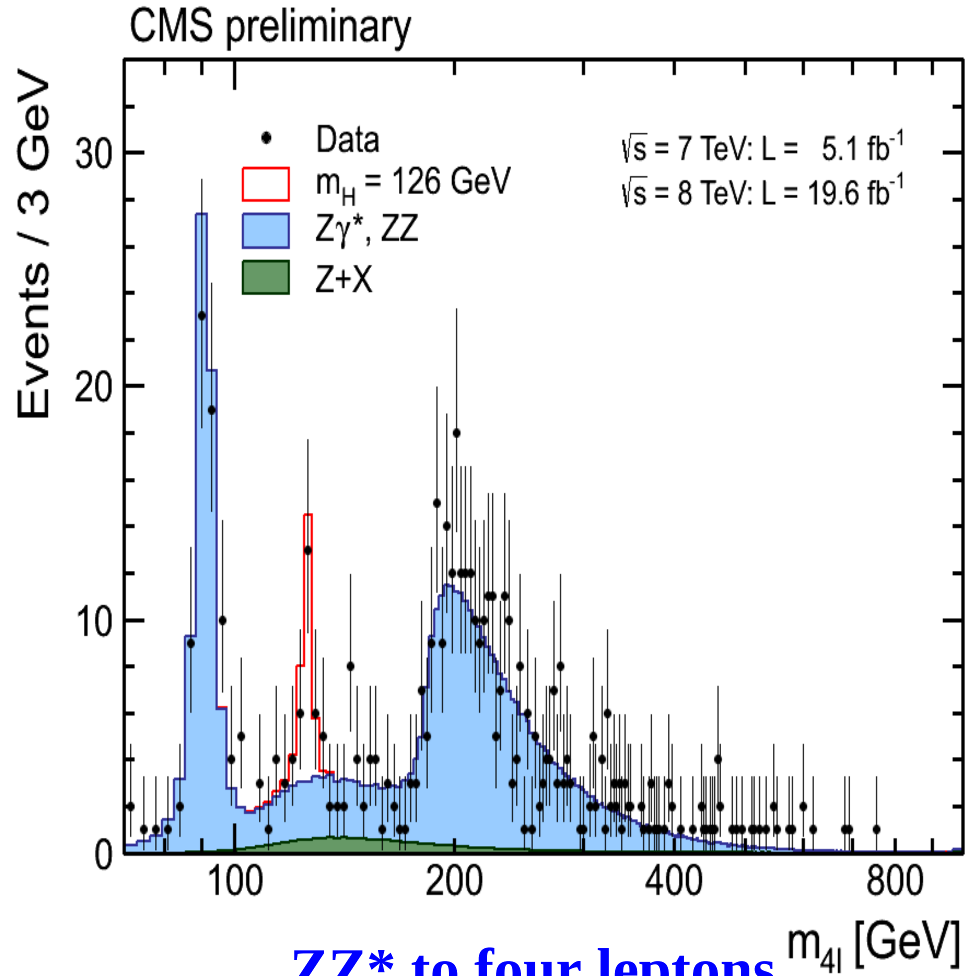


And Now…the Analysis

Once you have the data, analysis awaits!



W/Z cross section measurement at 8 TeV (CMS, SMP-12-011)



ZZ* to four leptons 2011/12 data (CMS, HIG-13-002)

Moving Forward

- You should always look ahead, even when working with the data you have
  - Always more to explore, additional properties to investigate
- The LHC is constantly improving
  - Higher instantaneous luminosity, so rate of W, Z, H, ... production constantly increasing
- Very likely that our first trigger idea is now obsolete
  - Improvements in software will increase efficiency
  - Additional filters in trigger path increase purity
    - But these filters reduce efficiency
  - Is it time to move to double electron/muon triggers?

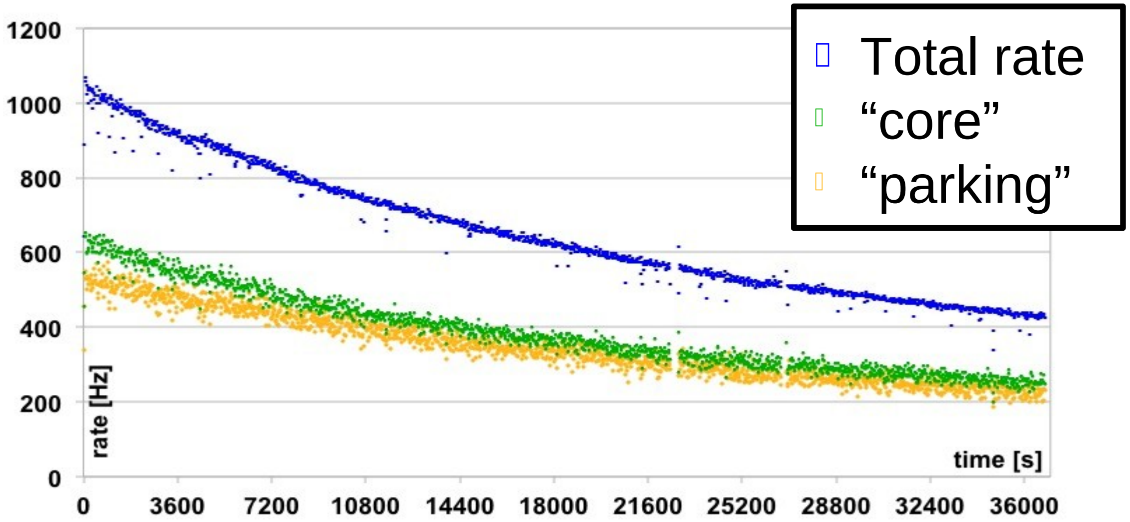
Most Important: How do our trigger choices impact the analysis, and how do we adapt?

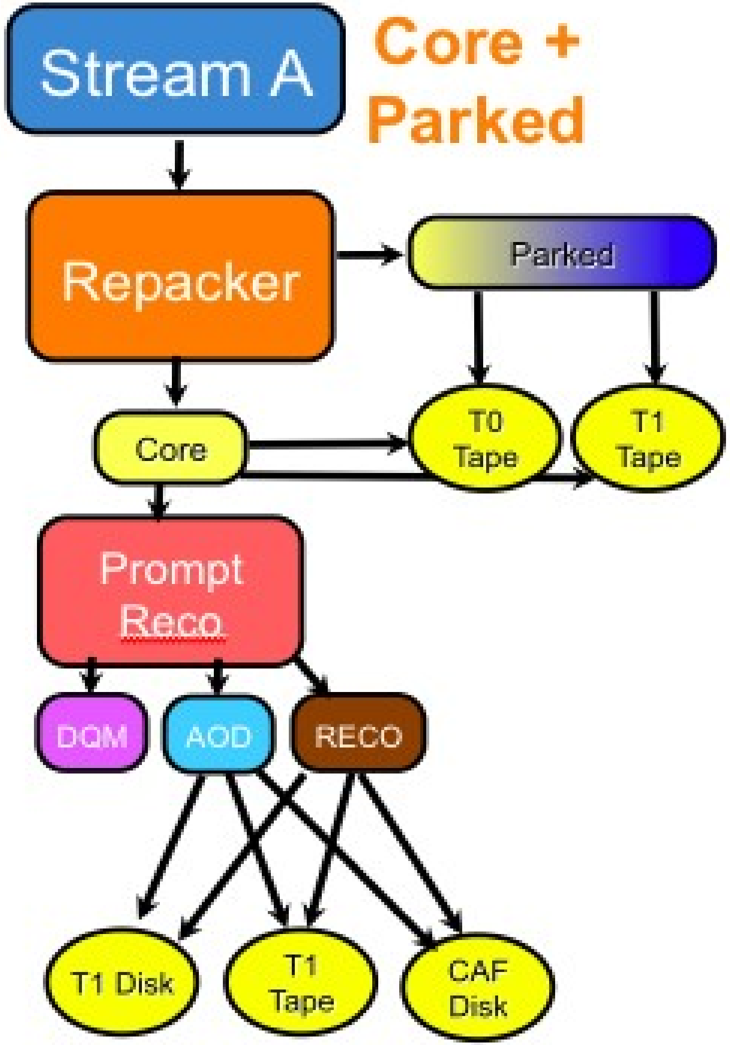
Another Perspective on Evolution

- Great expectations for LHC physics
  - Discovery of new physics phenomena
  - Precision tests of SM at high energy
- Physicists are impatient
  - All want to look at the data NOW, but must "fight" for trigger bandwidth
  - Leads to higher purity triggers
    - More selection applied online
    - Lower rate, higher thresholds
    - Negative impact on physics?

Data Parking

- Data rate limited by offline resources
    - Keep only what we can process
- LHC shutdown in 2013 provided opportunity to save data now, process later
    - Physics with “new” data, even during shutdown



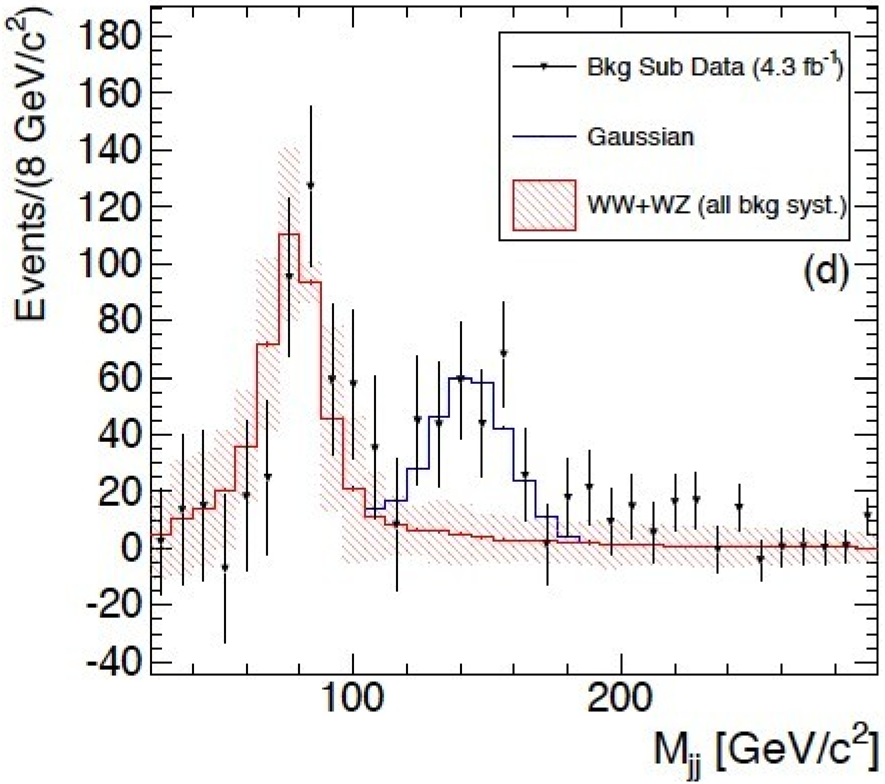


Data Scouting

- Events rejected online by the trigger can never be recovered
  - What if we have the wrong picture of Nature, and are insensitive to New Physics due to our bias?
- Use the trigger to search for something new
  - Keep events with E_T sum for jet objects above 250 GeV
  - Minimize event size to deal with rate
- If you see something interesting
  - Trigger menu is configurable
  - Design a trigger to study strange events

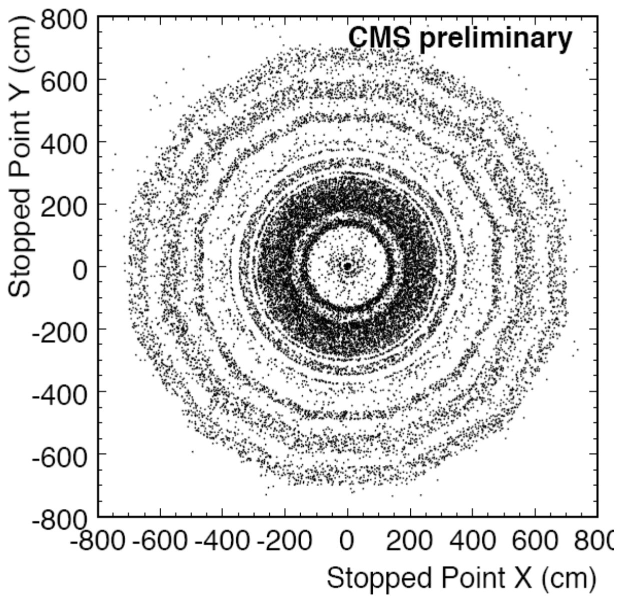
Fun With Triggers

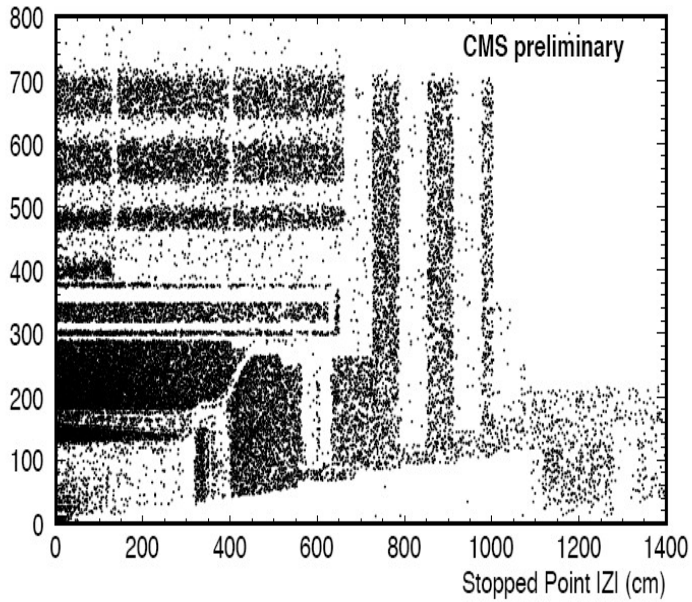
- Some “real world” examples to help illustrate what can be done with triggers
  - Helps illustrate the power and flexibility of the triggers
- Example: The CDF “bump”
  - Excess in dijet mass distribution (CDF) for W+2 jets events
  - CMS trigger menu was adjusted to collect extra events with this signature

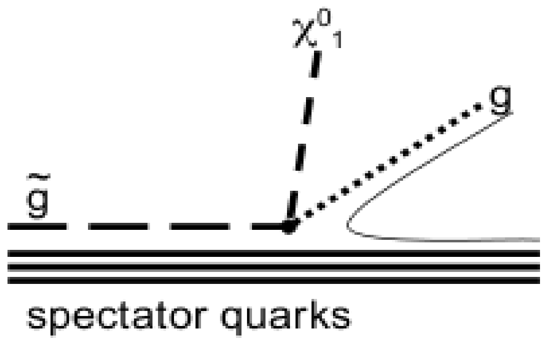


Fun With Triggers: Long-Lived Particles

- Several SM extensions predict particles with long lifetimes
  - One such example (of several): "Split" SUSY, with gluino lighter than squark and decaying via R-parity conserving virtual squark



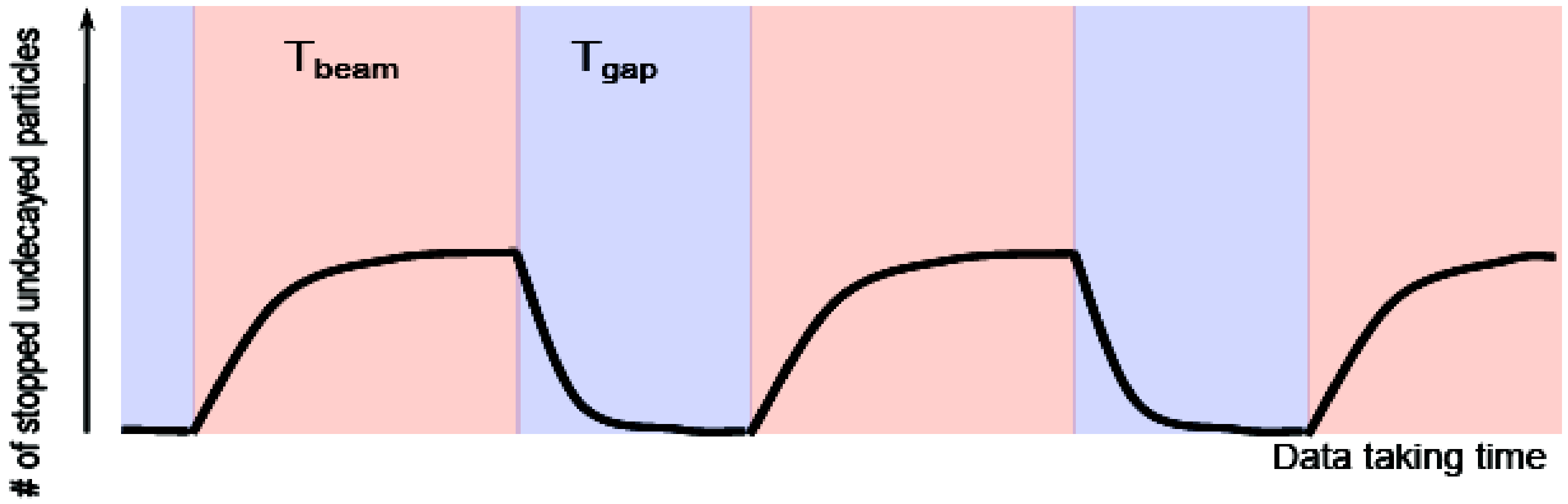




"R-hadrons" become stopped in the detector

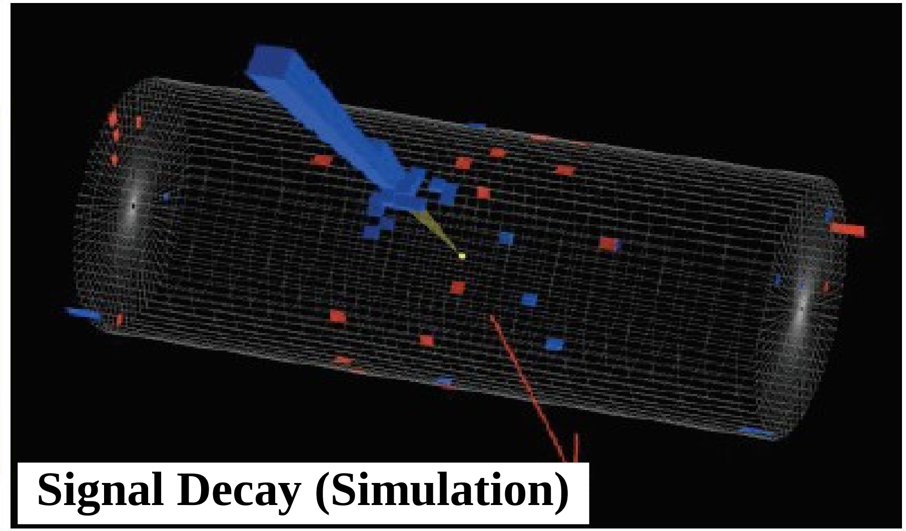
Long-Lived Particles

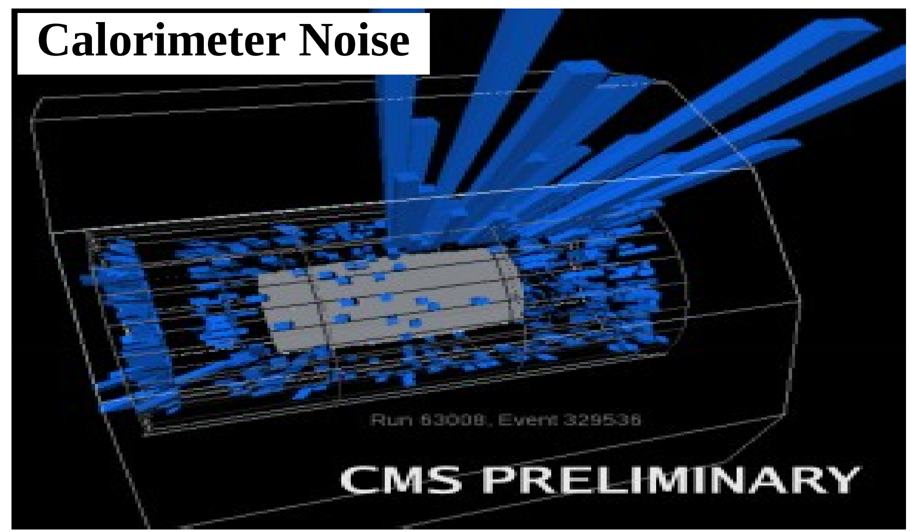
- Long-lived particle decays will be uncorrelated with proton-proton collisions
  - Once stopped, could decay seconds, hours, days later
- Look for decays when CMS should be "quiet"
  - Record data during collision-free periods
  - Backgrounds from detector noise, cosmic rays



Long-Lived Particles

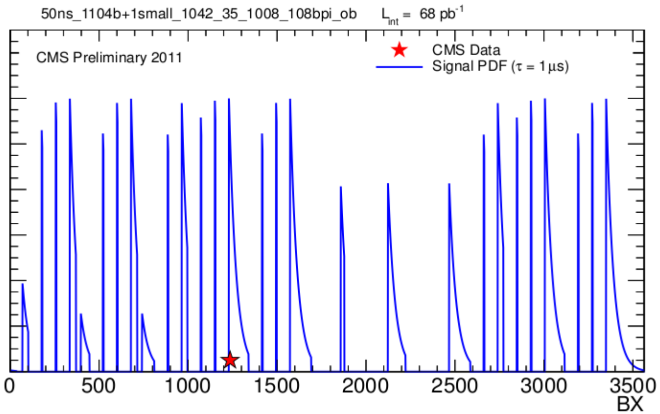
- Trigger on jet-like signature only when no beam in detector
- Also trigger on detector noise, cosmic rays
    - Backgrounds studied prior to first collisions

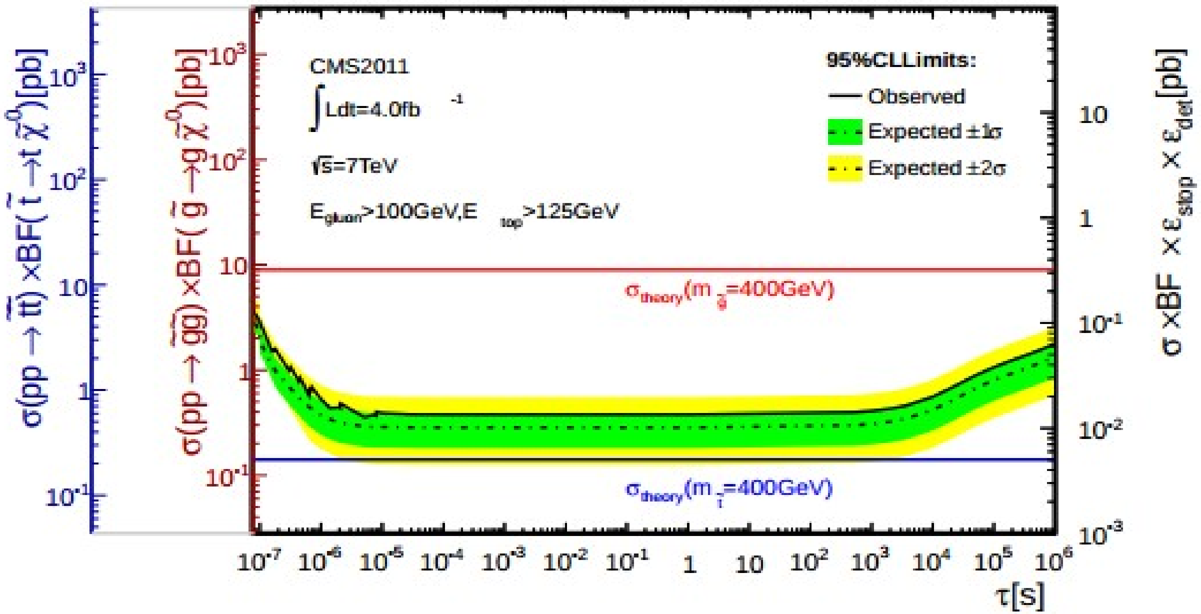

Signal Decay (Simulation)



Calorimeter Noise

Long-Lived Particles





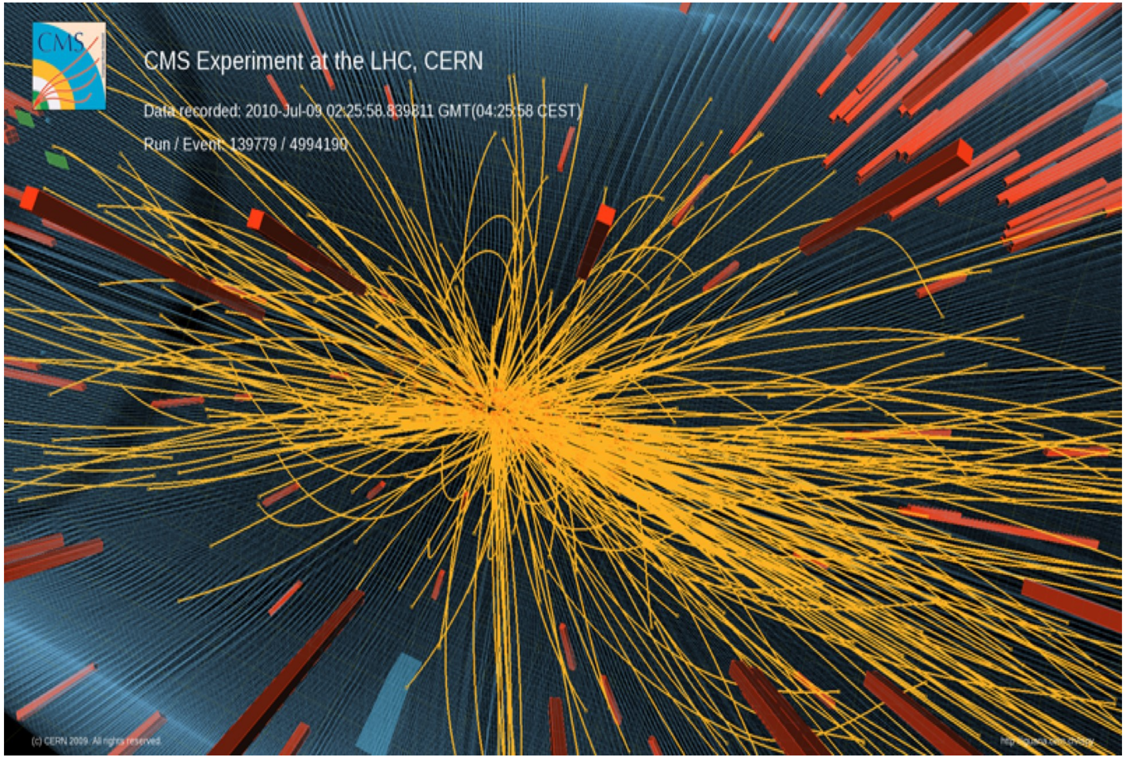
τ	L_{eff} (pb^{-1})	Live time (s)	N_{exp}	N_{obs}
75 ns	19.6	2.06×10^4	0.200 ± 0.056	1
100 ns	57.8	6.17×10^4	0.60 ± 0.17	2
1 μs	508	4.41×10^5	4.3 ± 1.2	7
10 μs	913	8.67×10^5	8.5 ± 2.4	12
100 μs	935	8.86×10^5	8.6 ± 2.4	12
10^3 s	866	8.86×10^5	8.6 ± 2.4	12
10^4 s	636	8.86×10^5	8.6 ± 2.4	12
10^5 s	332	8.86×10^5	8.6 ± 2.4	12
10^6 s	198	8.86×10^5	8.6 ± 2.4	12

Exclusion limits extend over 13 orders of magnitude (~100 nsec to 10^6 sec), depending on mass and model assumptions

CMS EXO-11-020

Fun with Triggers: The "Ridge"

- In early 2010, CMS started collecting a sample of events with high track multiplicity
  - Useful for minimum bias studies
  - Performance studies, looking ahead to high pileup conditions
  - Examine two-particle angular correlations, and compare to those seen in relativistic heavy ion collisions

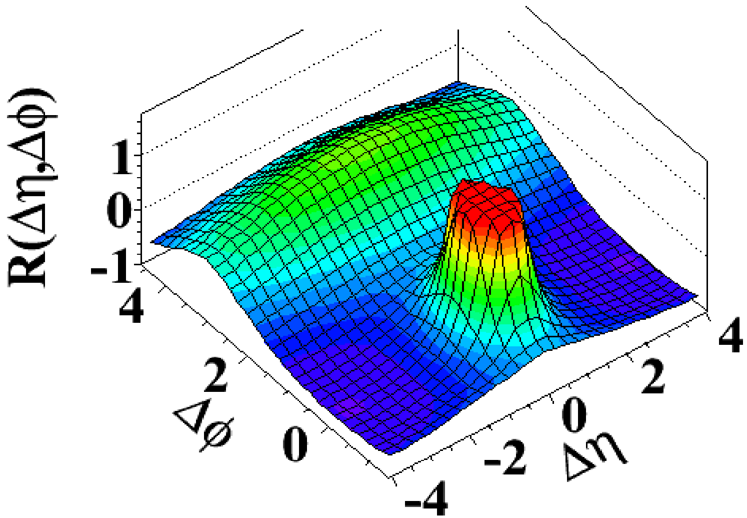


The Ridge

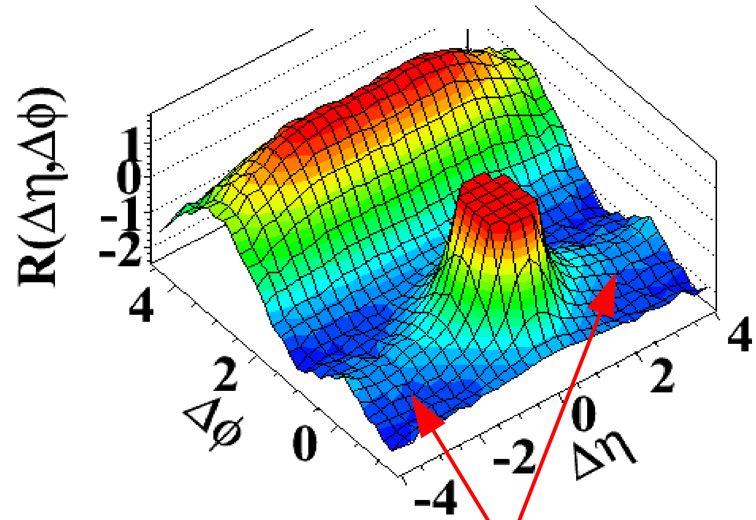
- Design a trigger path to collect these events
  - Level 1: Look for energy (60 GeV)
  - Reconstruct tracks at HLT
  - Keep the events if track multiplicity is high enough
    - Enhanced selection statistics by $O(10^3)$
- During Summer 2010, roughly 1/3 of the total HLT CPU resources were spent on this trigger
  - First time at a hadron collider
  - Highlights the flexibility of the HLT

Results

Minimum Bias events, no multiplicity cut



High Multiplicity events, N(trk) > 110

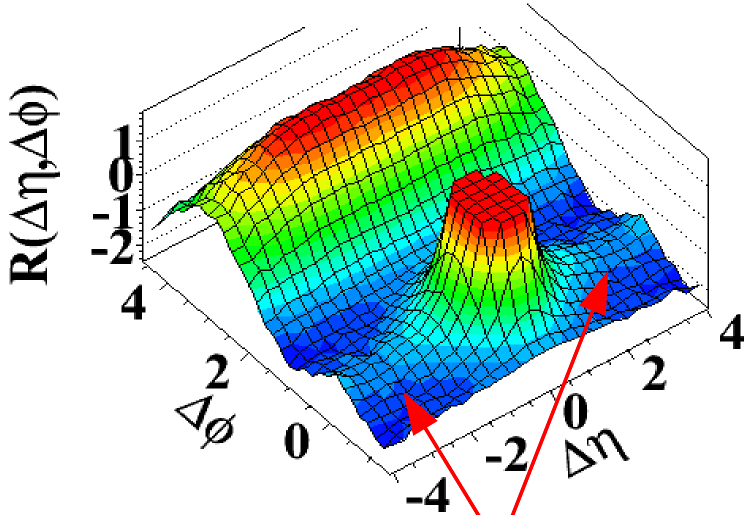


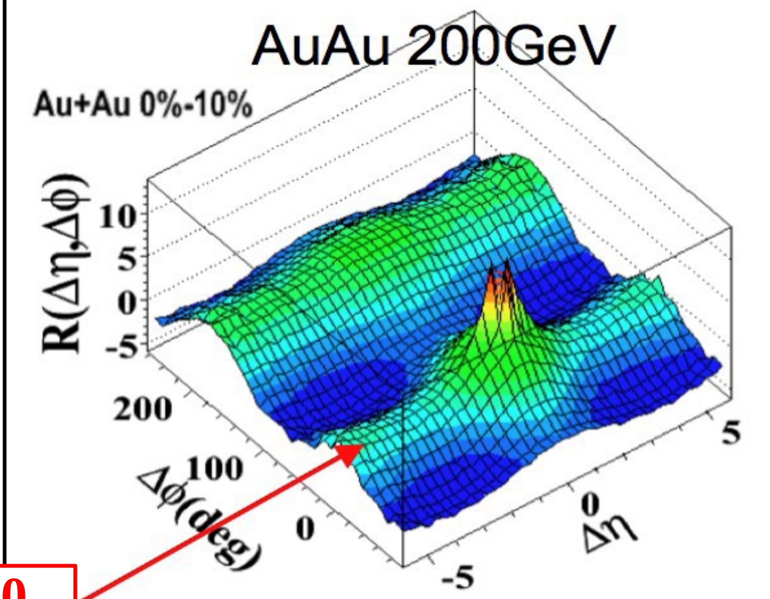
Ridge-like structure at Δφ ~ 0, extending to large Δη (not expected)

First observation of such a long-range, near-side feature in pp collisions

Results

High Multiplicity events, N(trk) > 110





Ridge-like structure at Δφ ~ 0, extending to large Δη

First observation of such a long-range, near-side feature in pp collisions

Summary

- The trigger systems at the LHC experiments are designed to handle a large influx of data, rejecting most uninteresting events quickly while maintaining a high efficiency on interesting events
- Successful trigger operations essential for discovery of New Physics phenomena
- Creating a trigger menu requires balancing the needs of the collaboration in order to record all the most interesting event signatures
- The trigger menu evolves over time, reflecting the current LHC/detector conditions and physics goals
- Challenging work, but very rewarding!

Thanks

Many thanks to those who provided material for these lectures!

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Greg Landsberg, Roel Aaij, David Evans

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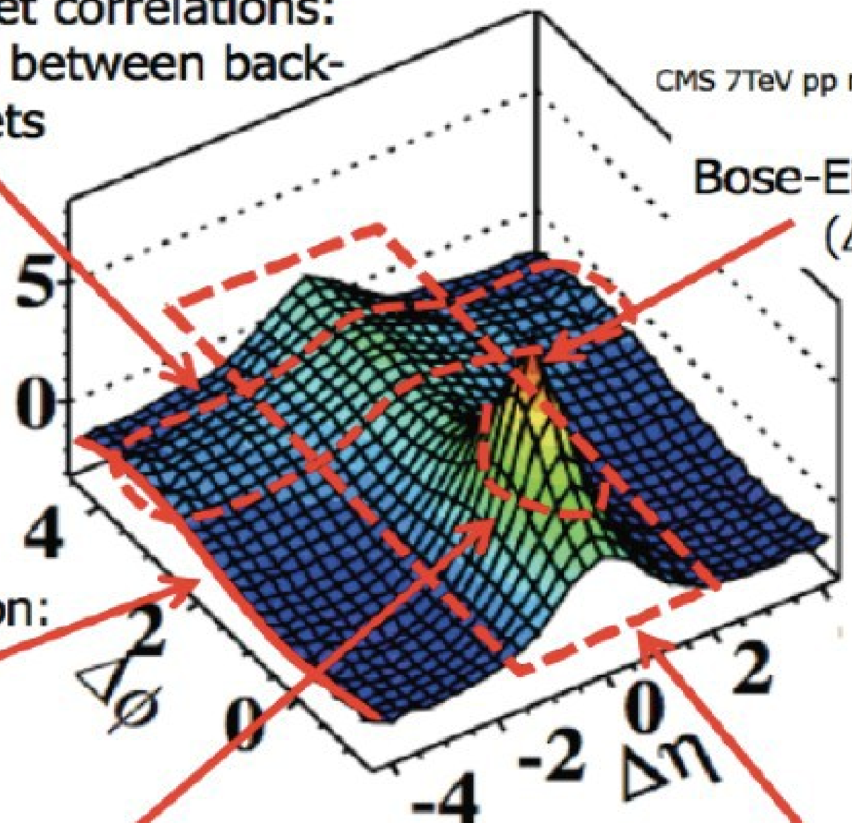
Two-Particle Correlations

"Away-side" ($\Delta\phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets

Bose-Einstein correlations:
$(\Delta\phi, \Delta\eta) \sim (0,0)$



Momentum conservation:
$\sim -\cos(\Delta\phi)$

"Near-side" ($\Delta\phi \sim 0$) jet peak:
Correlation of particles within a single jet

Short-range correlations ($\Delta\eta < 2$):
Resonances, string fragmentation, "clusters"