The CMS Trigger

Alex Tapper

- Motivation and LHC challenges
- The CMS detector and trigger
- Commissioning progress
- Towards Super-LHC

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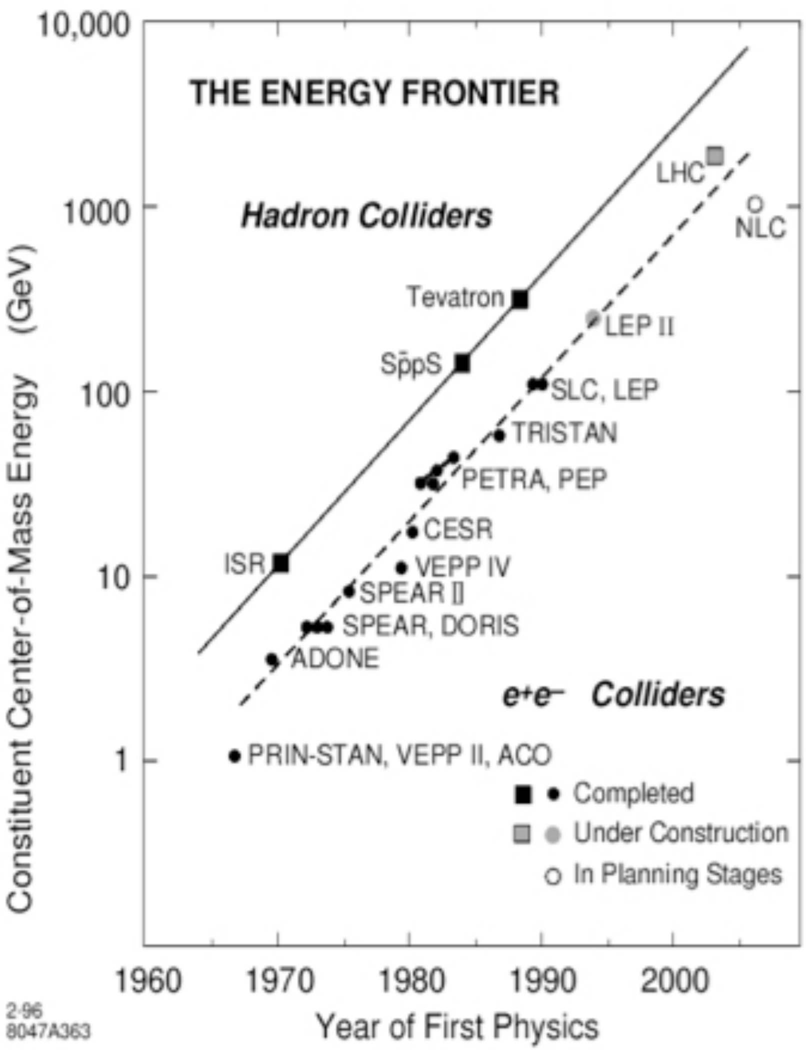
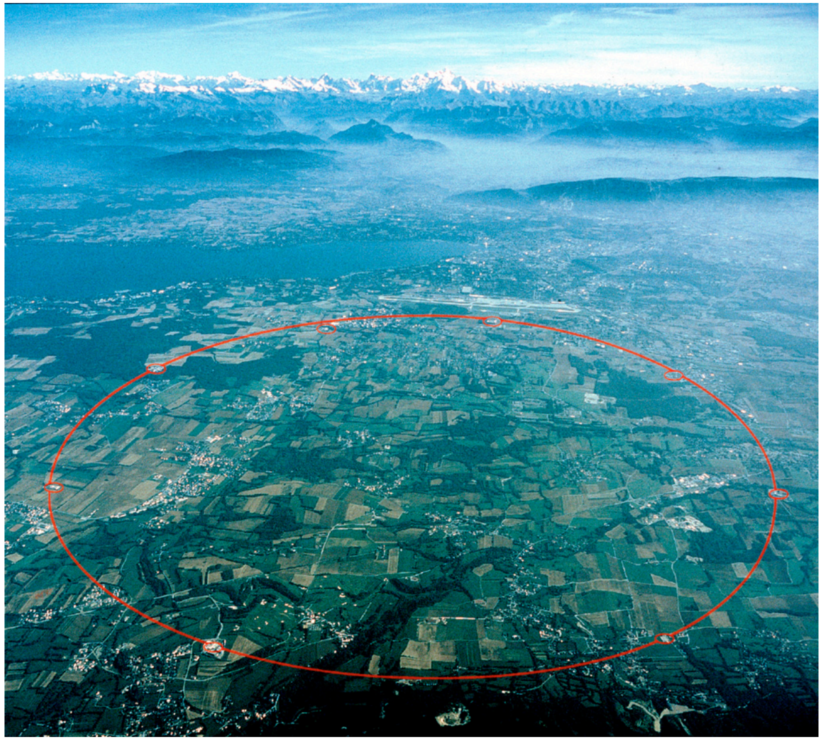
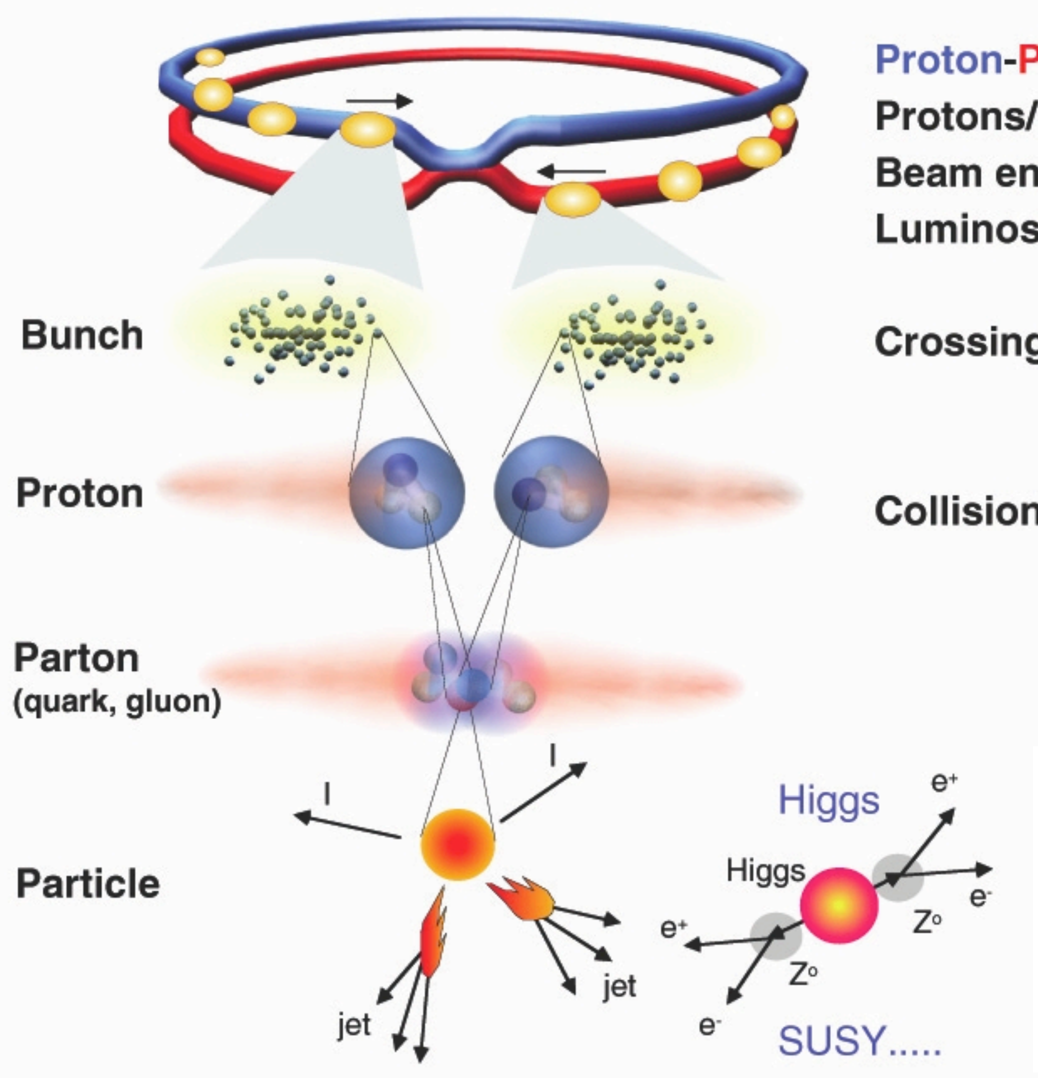
The Large Hadron Collider





$\sqrt{s}$=14 TeV

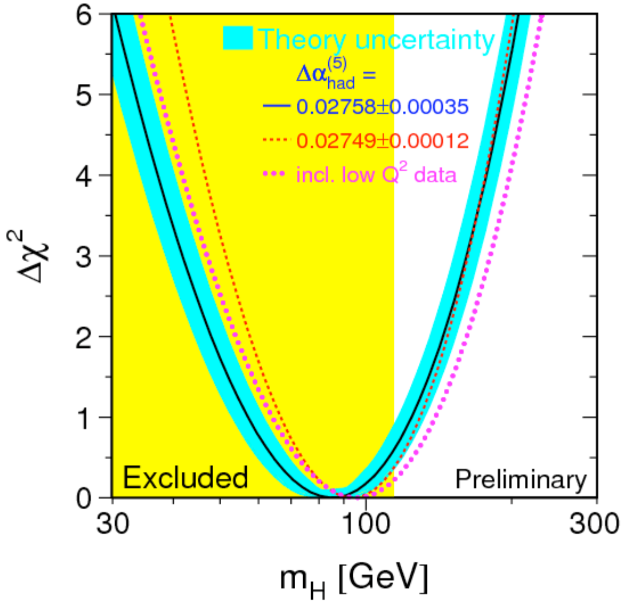
The Large Hadron Collider

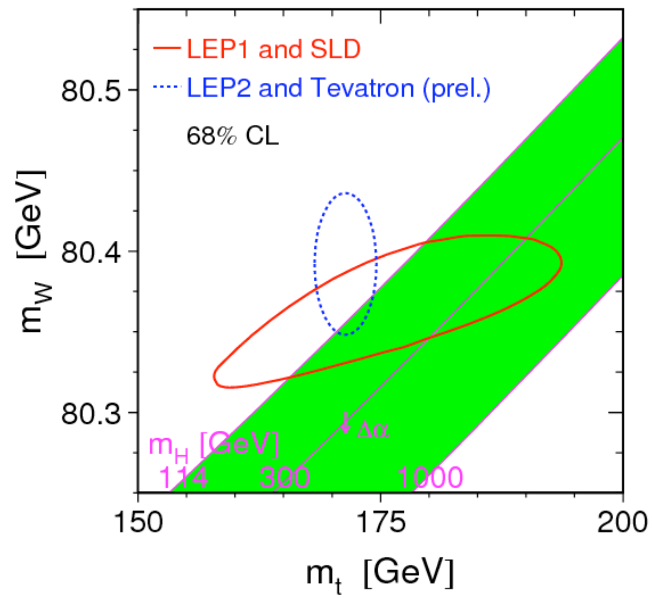


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

Motivation

- Use Higgs as an example to illustrate search requirements





- Electroweak fits give likely mass range for discovery of Higgs
- Something must happen by ~1 TeV or WW scattering becomes divergent

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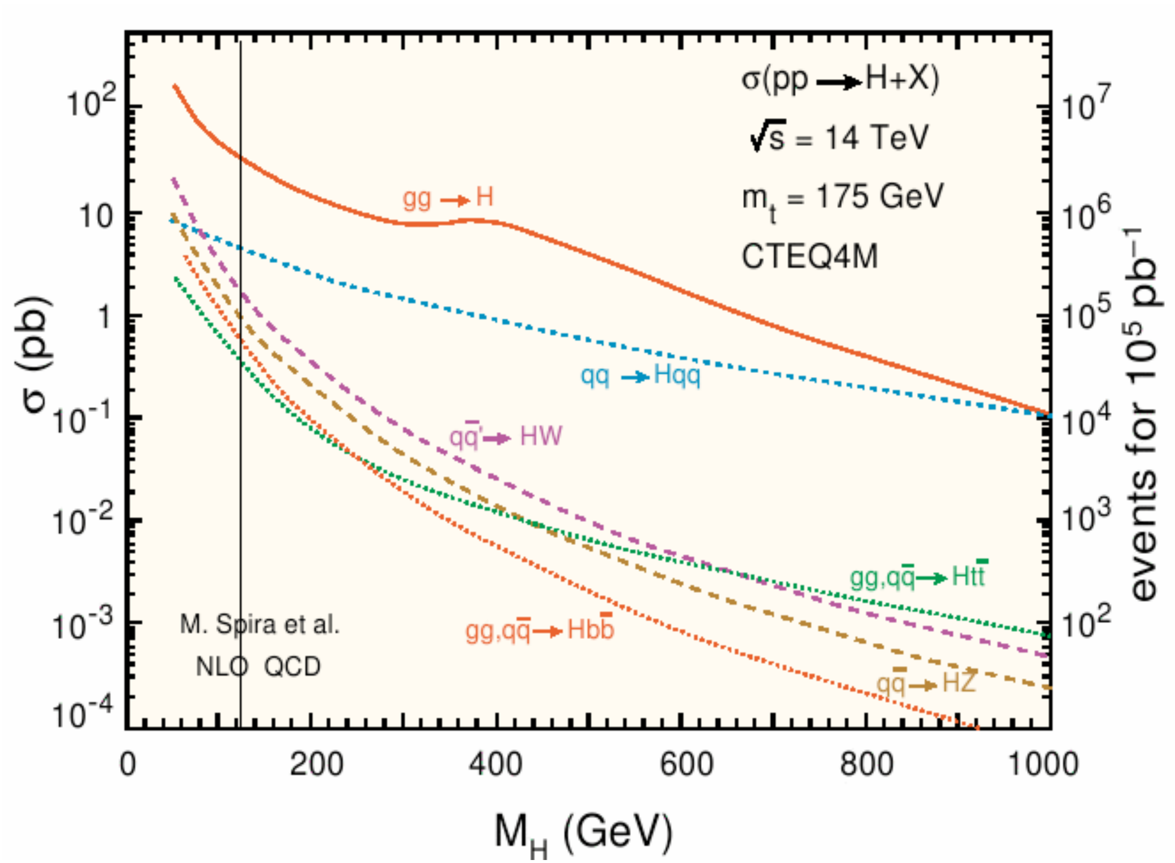
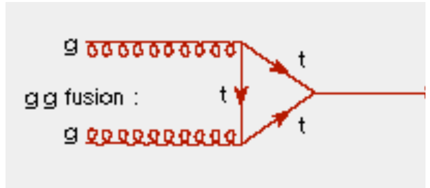
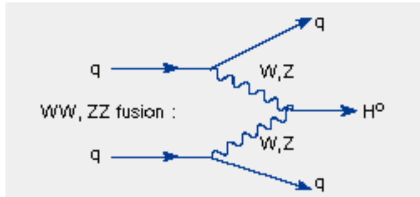
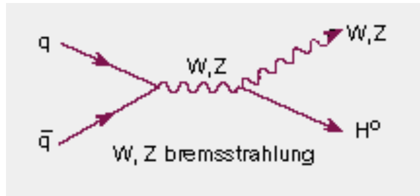
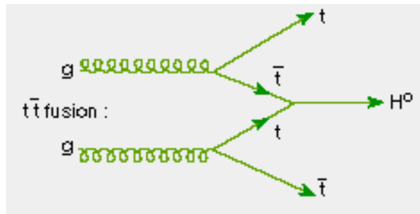
Higgs production at the LHC





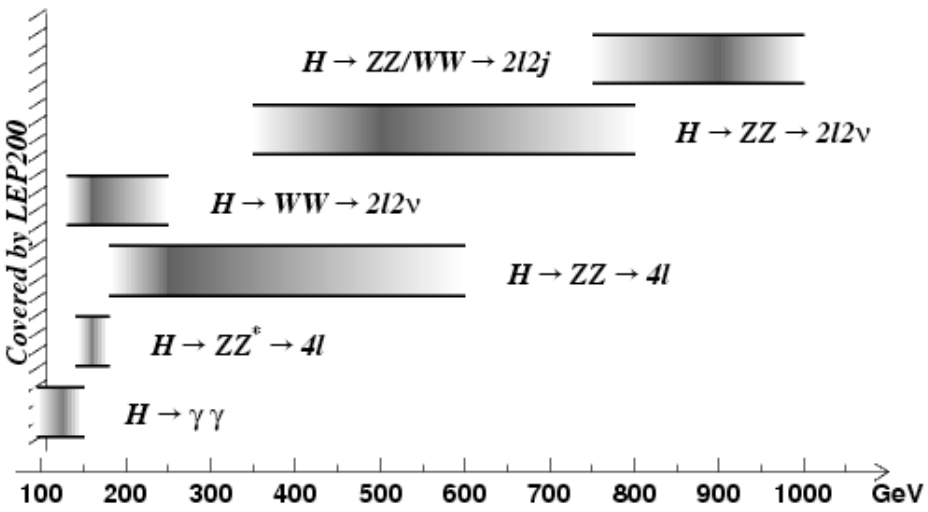


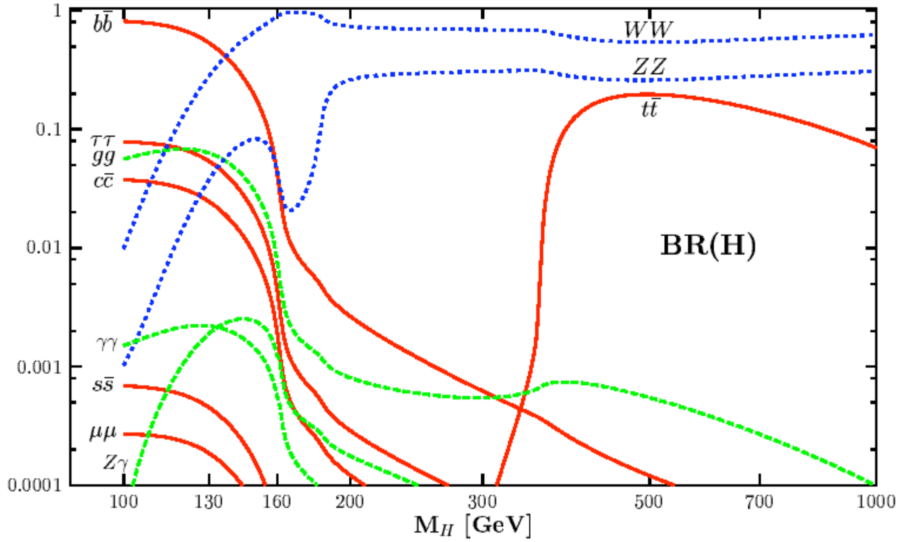




Higgs decay at the LHC

- For low mass Higgs, best choice of decay channel is H→γγ
- Higher mass Higgs can be searched for using WW and ZZ channels
- Decay to b quarks very challenging
- Decays to τ very interesting for Higgs parameters





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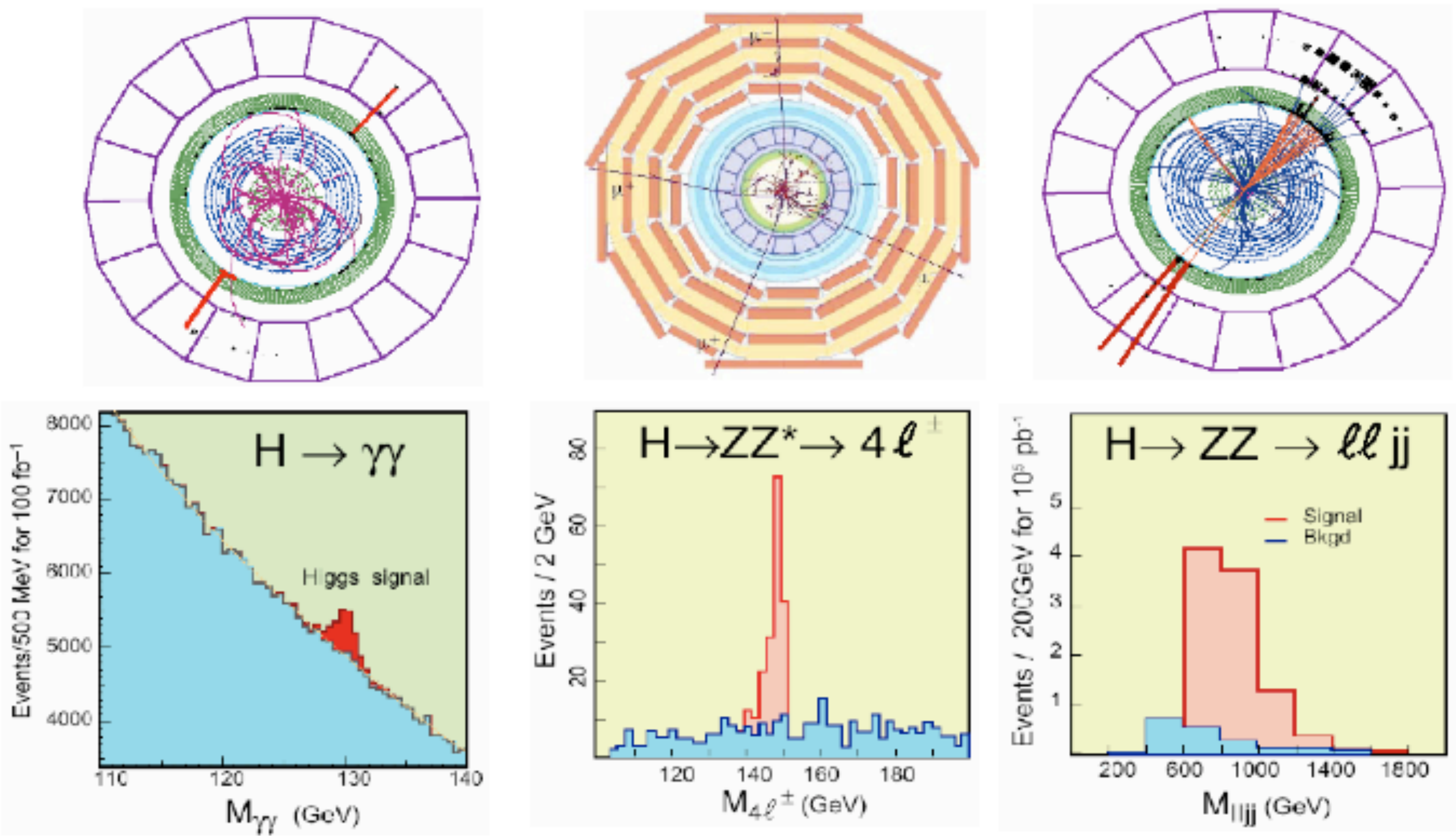
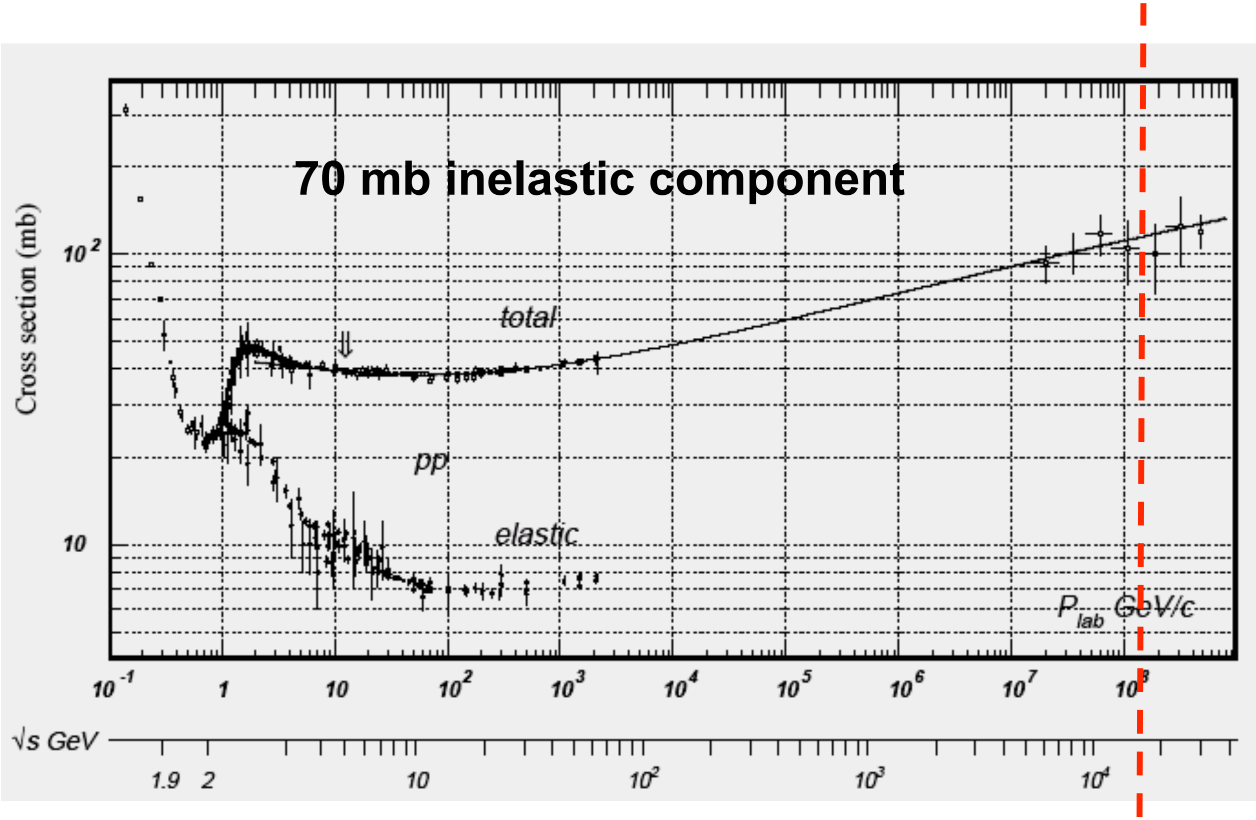
Higgs decay at CMS



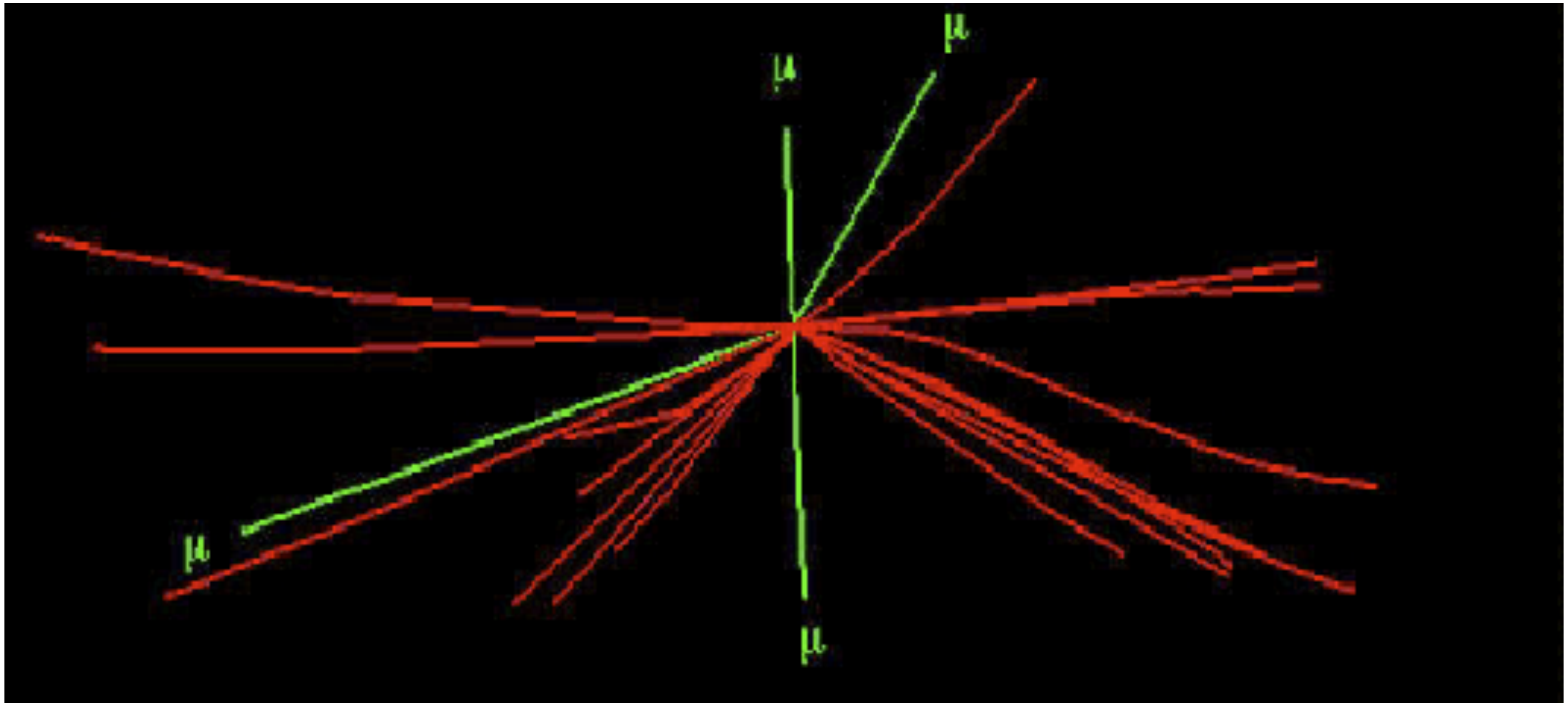
LHC challenges: data rate



- $L = 10^{34}\ cm^{-2}\ s^{-1} = 10^{7}\ mb^{-1}$ Hz
- $\sigma_{inel}(pp) \approx 70$ mb
  → **Event Rate = 7 x 10^8 Hz**
- Δt = 25 ns = 25 x $10^{-9}\ Hz^{-1}$
  → **Events/25ns =7 x 2.5 = 17.5**
- Not all bunches full (2835/3564)
  → **Events/crossing = 22**

- At full LHC luminosity we have 22 events superimposed on any discovery signal
- 10^9 events per second x typical event size of 1-2 Mbytes > 1TByte/sec
- Enormous data rate. Need super-fast algorithms to select interesting events while suppressing less interesting events

LHC trigger challenges - pile-up



Higgs -> 4μ

- We want to select this type of event
  for example Higgs to 4 muons

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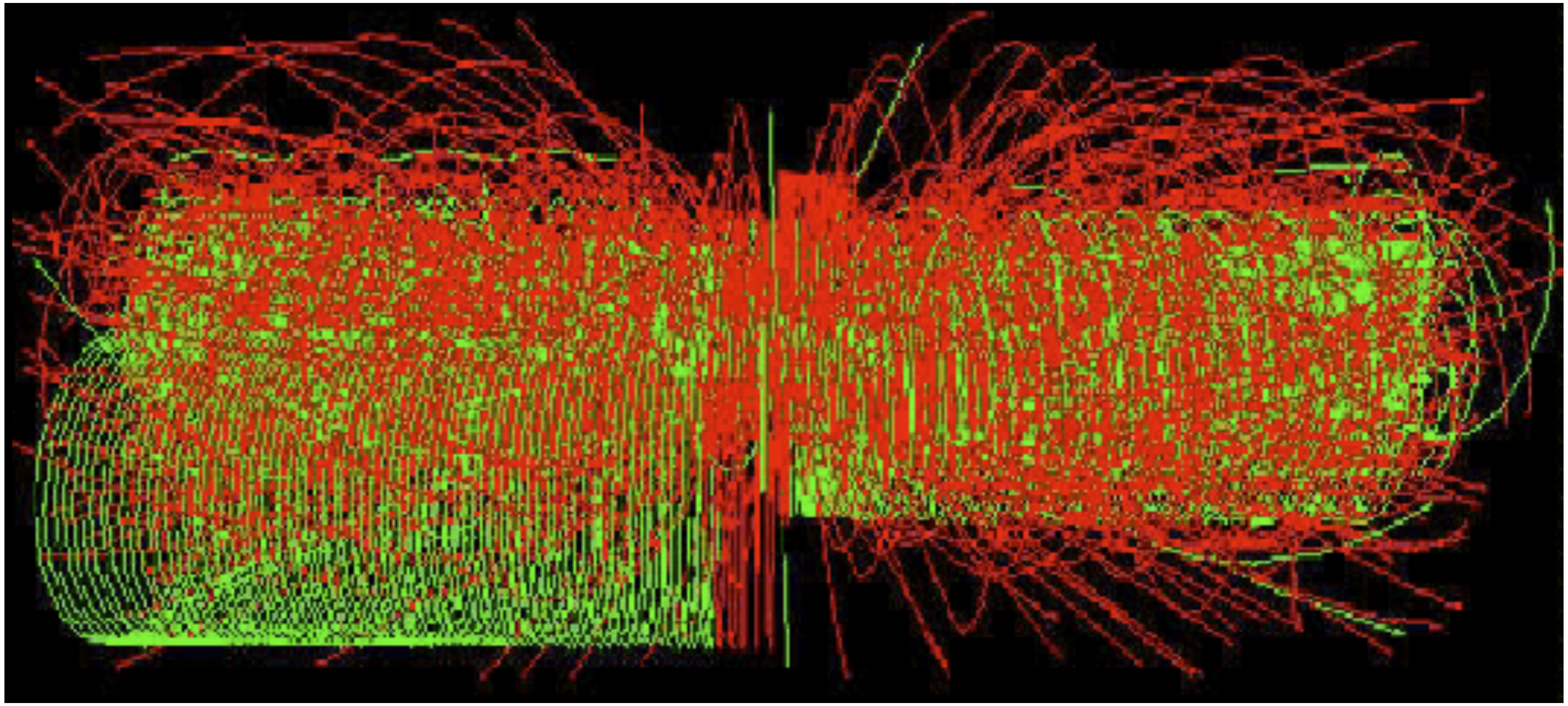
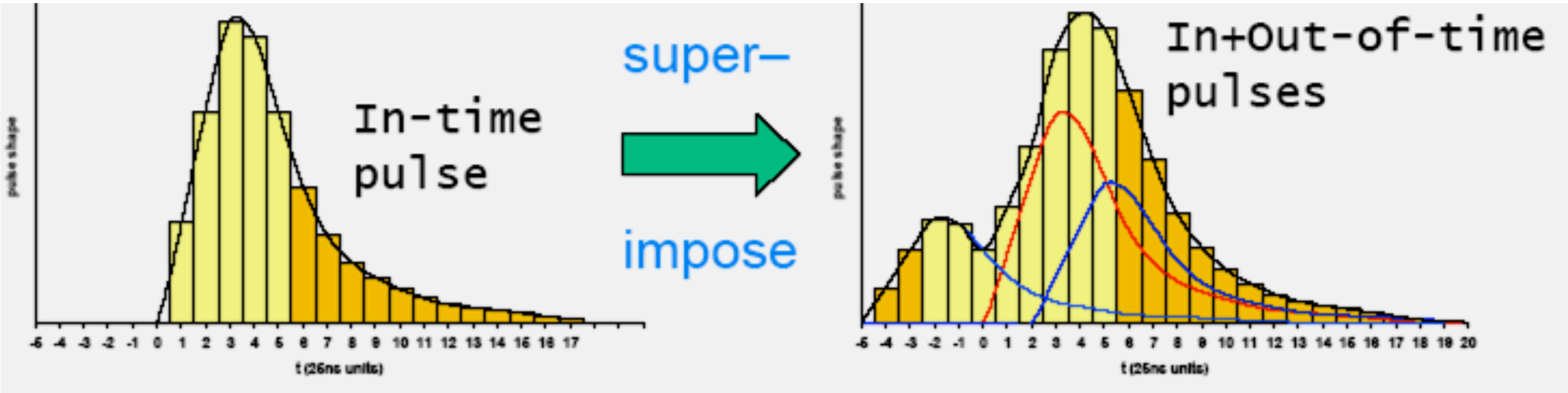
LHC trigger challenges - pile-up



Higgs -> 4μ **+30 MinBias**

- We want to select this type of event
  for example Higgs to 4 muons which has this superimposed on it……
- Sophisticated algorithms necessary

LHC trigger challenges - pile-up



- In-time pile up: Same crossing different interactions
- New events come every 25 nsec → 7.5 m separation
- Out-of-time pile up: Due to events from different crossings
- Need a to identify the bunch crossing that a given event comes from

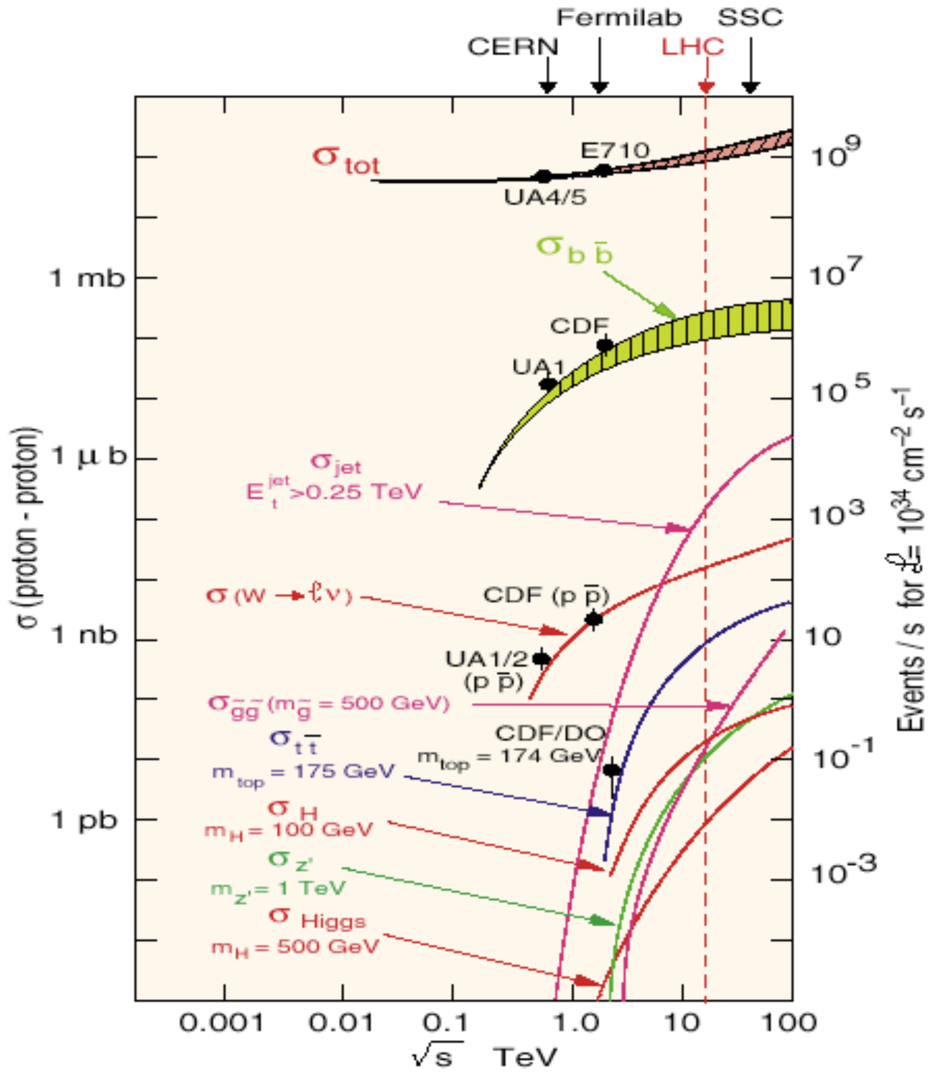
LHC challenges: needle in a haystack

QCD cross sections are orders of magnitude larger than electroweak or any exotic channels

Event rates:

- Inelastic: 10^9 Hz
- $W \to l\nu$: 100 Hz
- t-tbar:10 Hz
- H(100 GeV): 0.1 Hz
- H(600 GeV): 0.01 Hz

⇒ Need to select events at the $1:10^{11}$ level



Challenges

- Enormous data rate: 10^9 Hz ⇒ more than 1TByte/s
- Minimum bias in-time pile-up ⇒ 22 events per bunch crossing
- Out-of-time pile-up ⇒ events from different bunch crossings overlayed
- Tiny cross sections for Higgs and new physics ⇒ selection $1:10^{11}$
- All online ⇒ can't go back and fix it. Events are lost forever!

From the trigger TDR

High efficiency for hard scattering physics at the LHC

- Processes like
  - top decays, $H \rightarrow \gamma\gamma$, $H \rightarrow 4l$, W-W, SUSY...
- Need to efficiently reconstruct decay products from intermediate W and Z bosons
  - Sets scale for single lepton triggers from W decay $P_T > 40$ GeV
- For $H \rightarrow \gamma\gamma$
  - Sets scale for di-photon trigger of $P_T > 20$, 15 GeV
- Benchmark is that muon and isolated electron must have efficiency > 50% for W decays

From the trigger TDR

Requirements

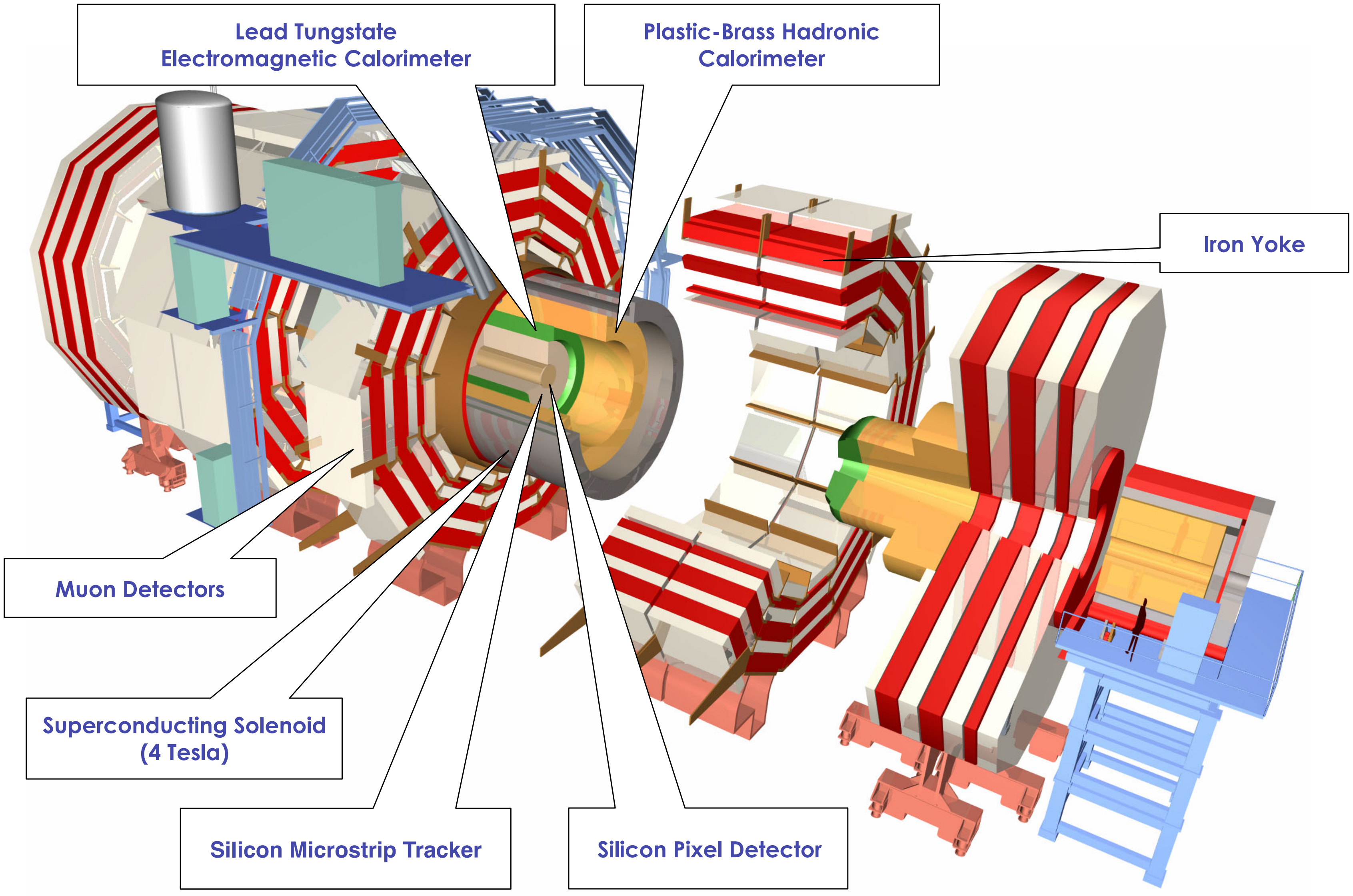
- Leptons and jets $|\eta|<2.5$ with high efficiency above some P_T threshold
- Single lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>40$ GeV
- Di-lepton triggers with high efficiency (>95%) $|\eta|<2.5$ $P_T>20$, 15 GeV
- Di-photons similar to di-leptons
- Jets continuous over $|\eta|<5$ for single and multi-jet topologies. High efficiency required for high-E_T jets
- Missing E_T with threshold around 100 GeV

Backgrounds

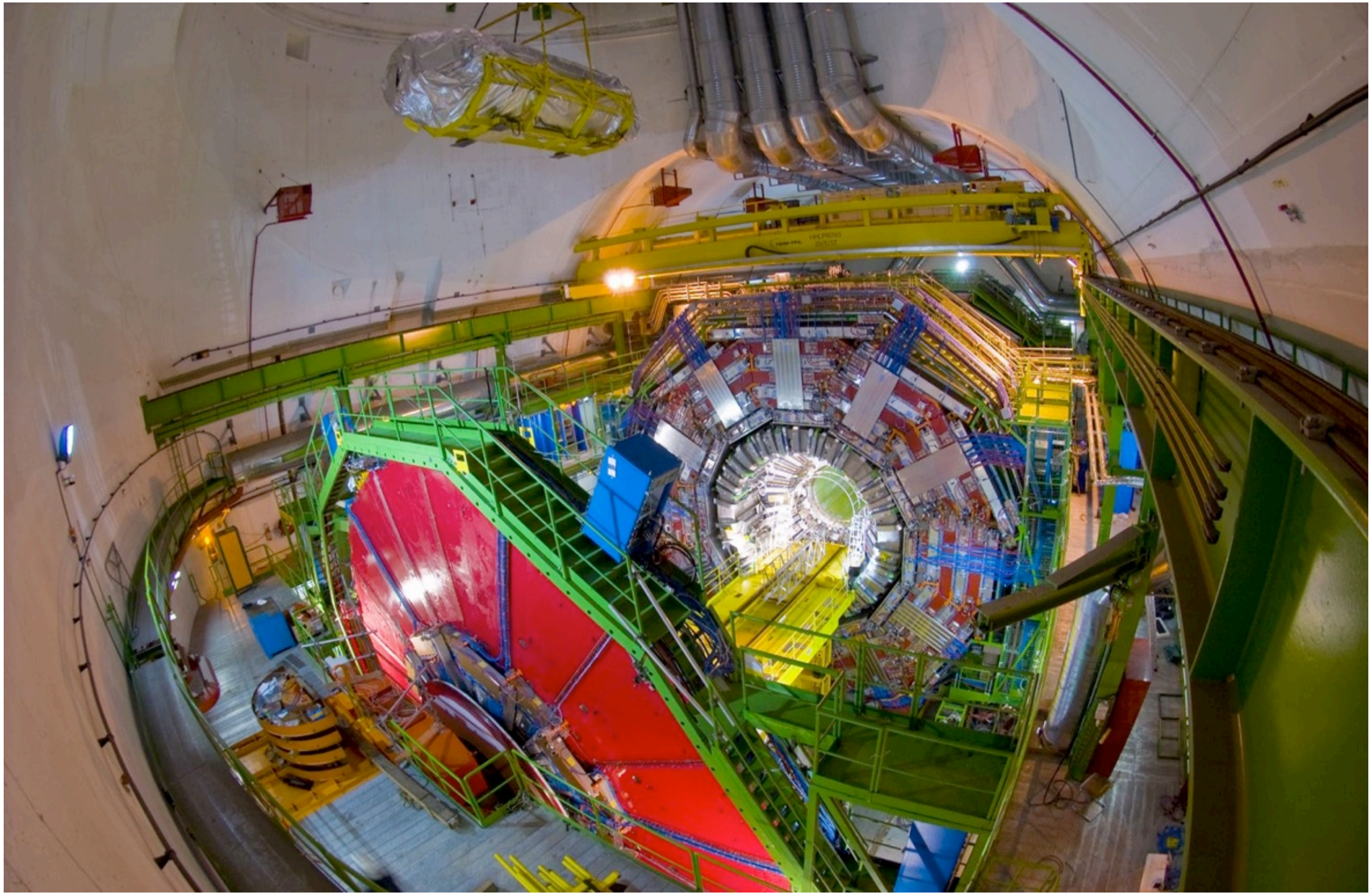
What drives the rate for each type of trigger?

- Electrons and photons
  - High-E_T π^0 from jet fragmentation and direct photon processes
- Muons
  - Mis-measurement of low P_T muons
  - Hadronic decays
  - Punch through from jets
- Jets
  - Mis-measurement of low E_T QCD jets
- Tau
  - Narrow QCD jets fake hadronic tau decays
- Missing E_T
  - All sorts of mis-measurement, machine backgrounds etc.

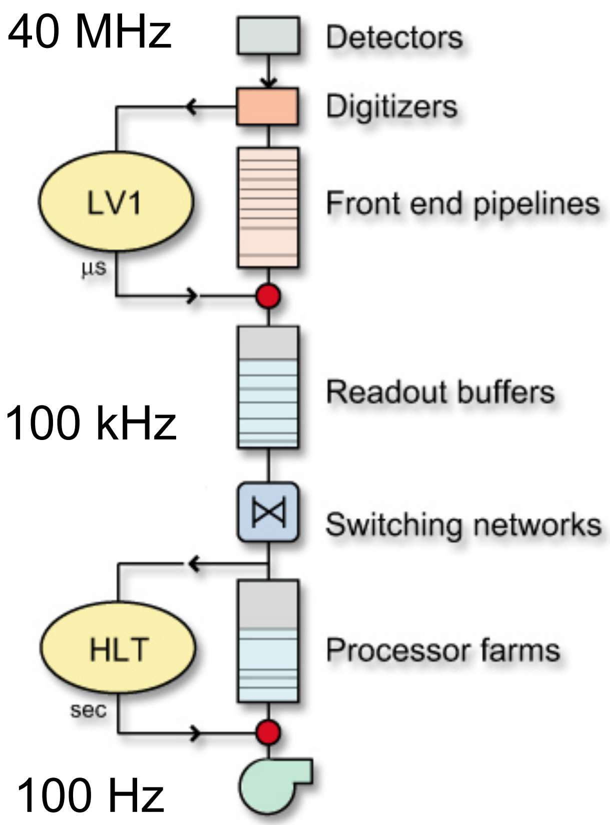
The CMS detector

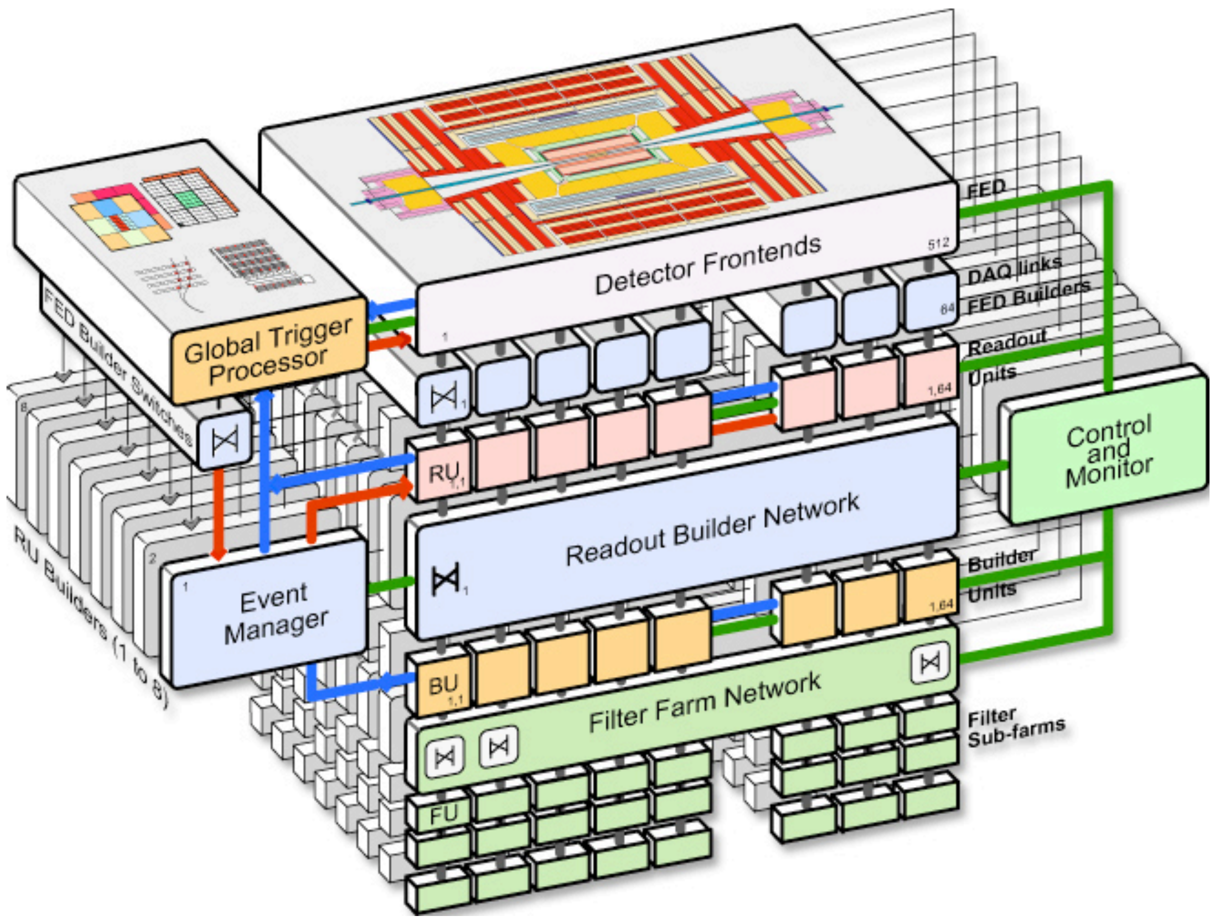


The CMS Detector

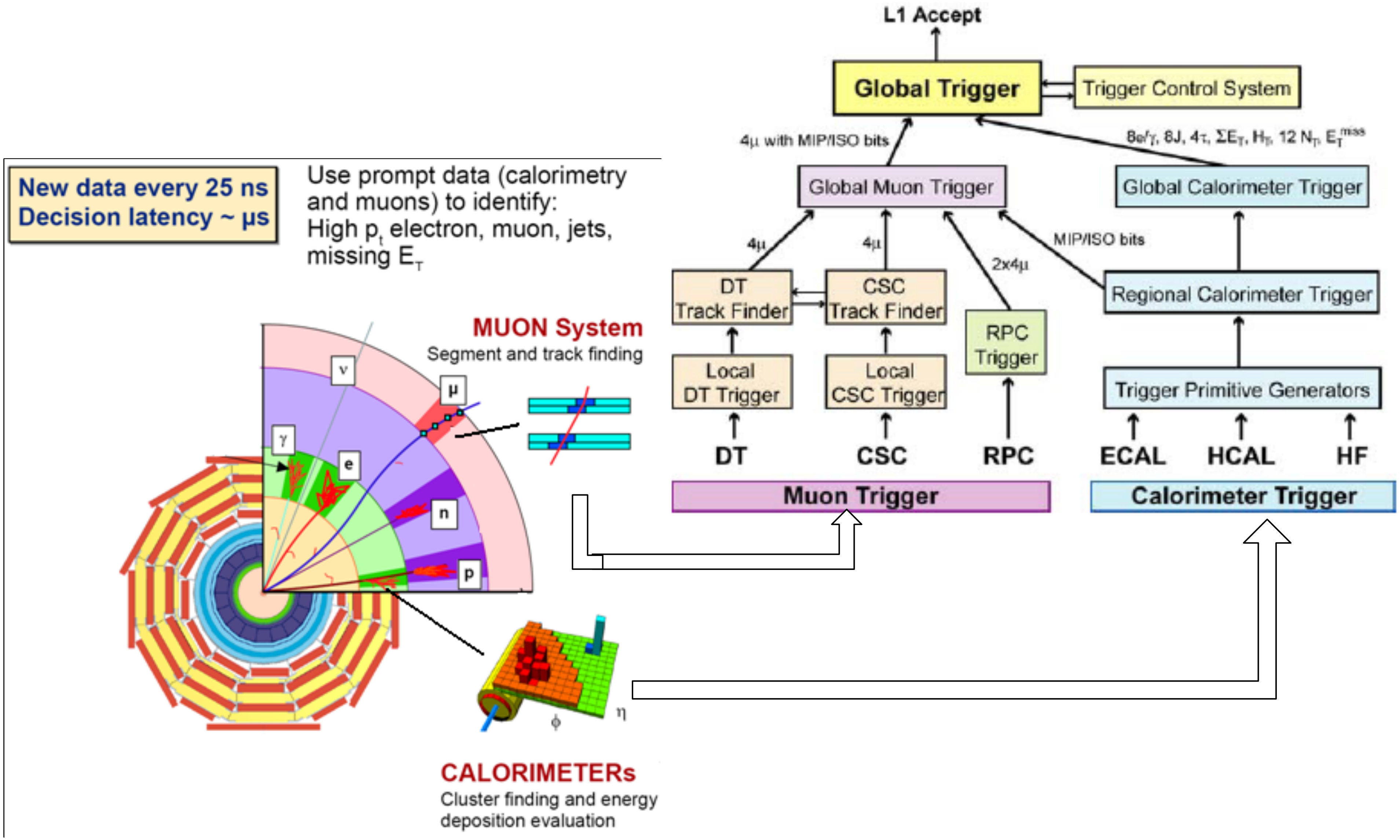


CMS trigger and DAQ





CMS Level 1 Trigger



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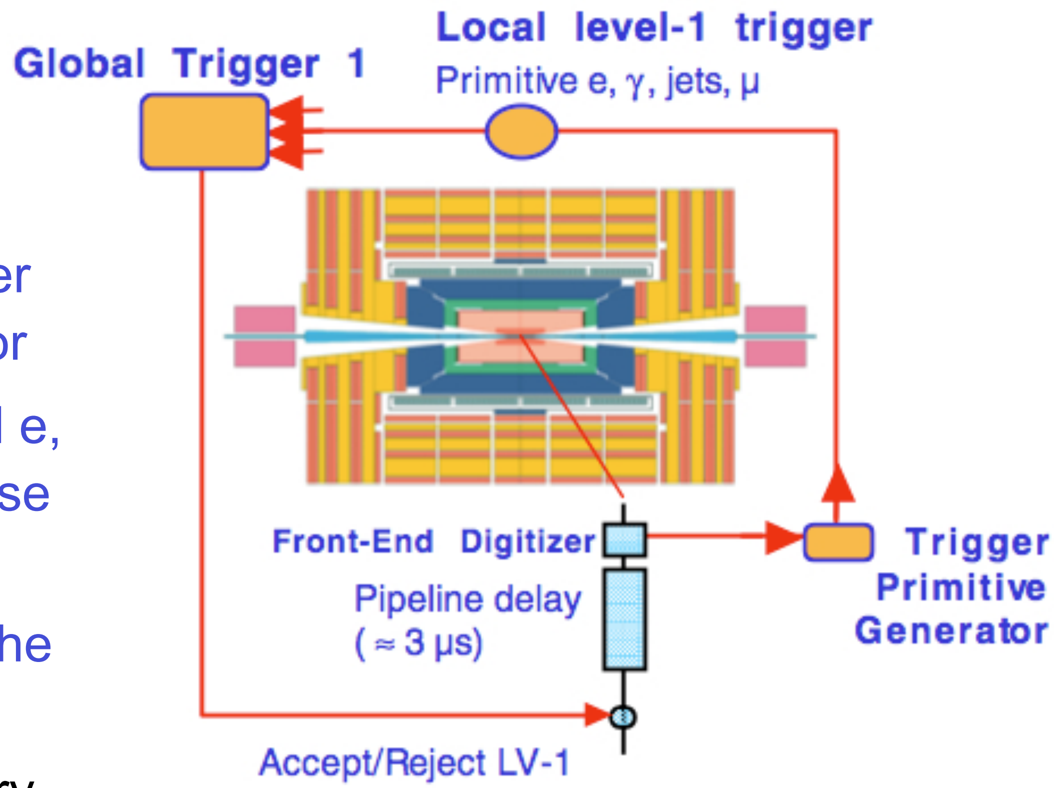
The CMS Level 1 Trigger

- Detector data stored in front-end pipelines
  - Pipelines deep enough for 128 bunch crossings (3.2μs)
- Trigger decision derived from trigger primitives generated on the detector
- Trigger systems search for isolated e, γ, μ, jets and compute the transverse and missing energy of the event
- Event selection algorithms run on the global triggers
  - Must give a trigger decision every 25ns.



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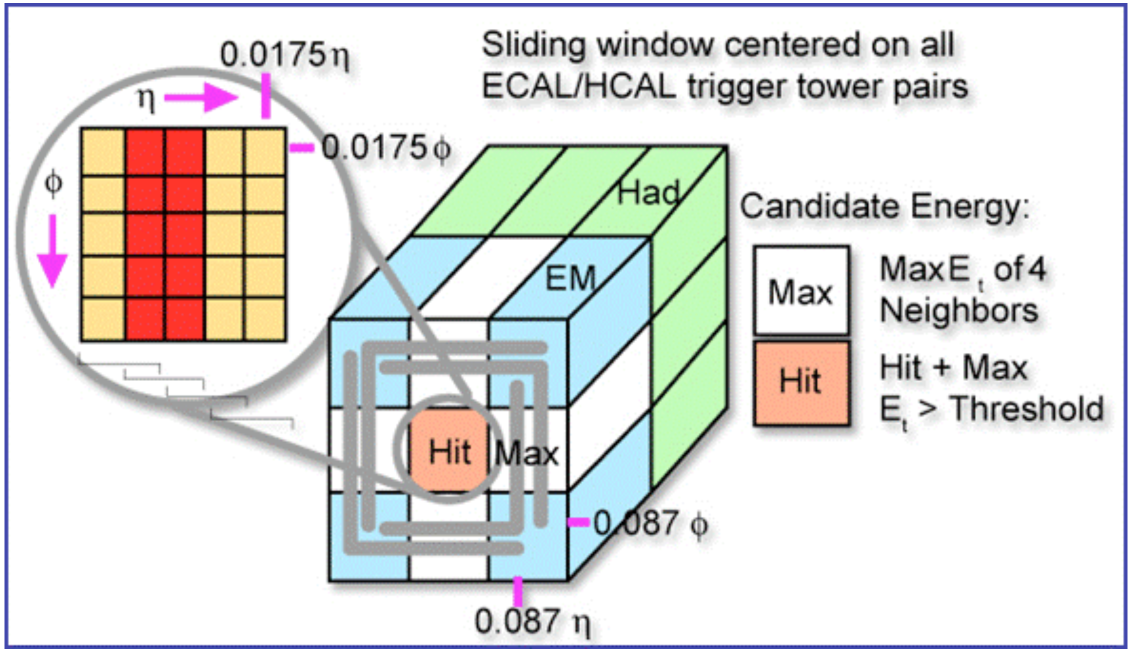
Electron trigger algorithm

- Trigger tower is 5x5 $PbWO_4$ crystals
- Sliding window of 3x3 trigger towers to find local maxima
- Electron ID requirements
  - Large fraction of E_T deposited in 5x2 crystal region (>90%) and HCAL/ECAL veto (<5%) in central trigger tower
  - Greater than threshold E_T in central + maximum neighbouring trigger tower
  - Isolation criterion: at least one "quiet corner" (towers<1.5 GeV) and vetos for all towers



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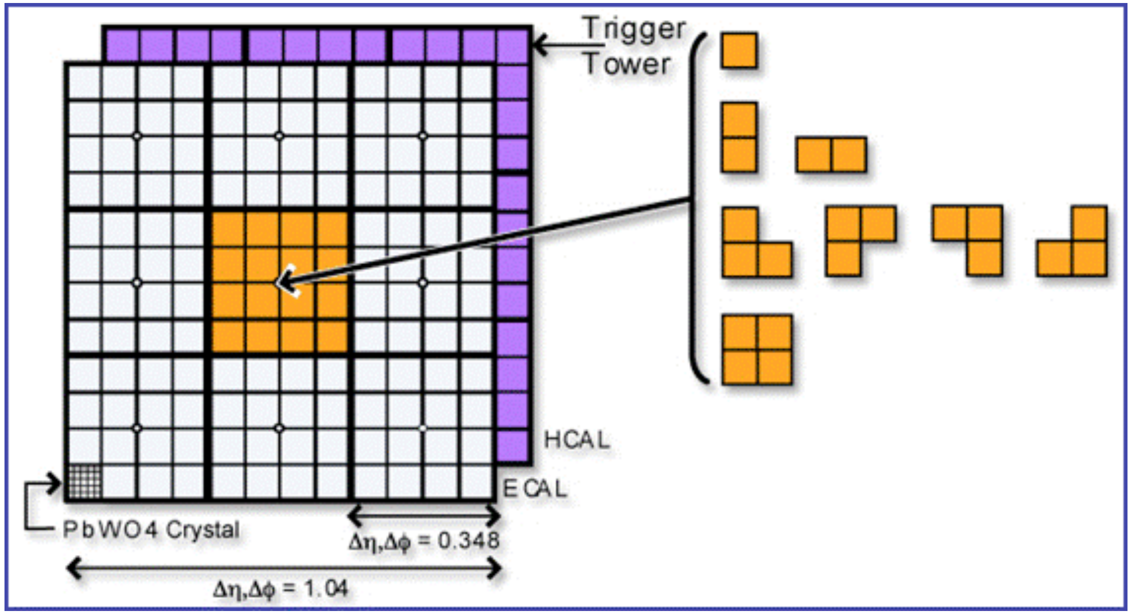
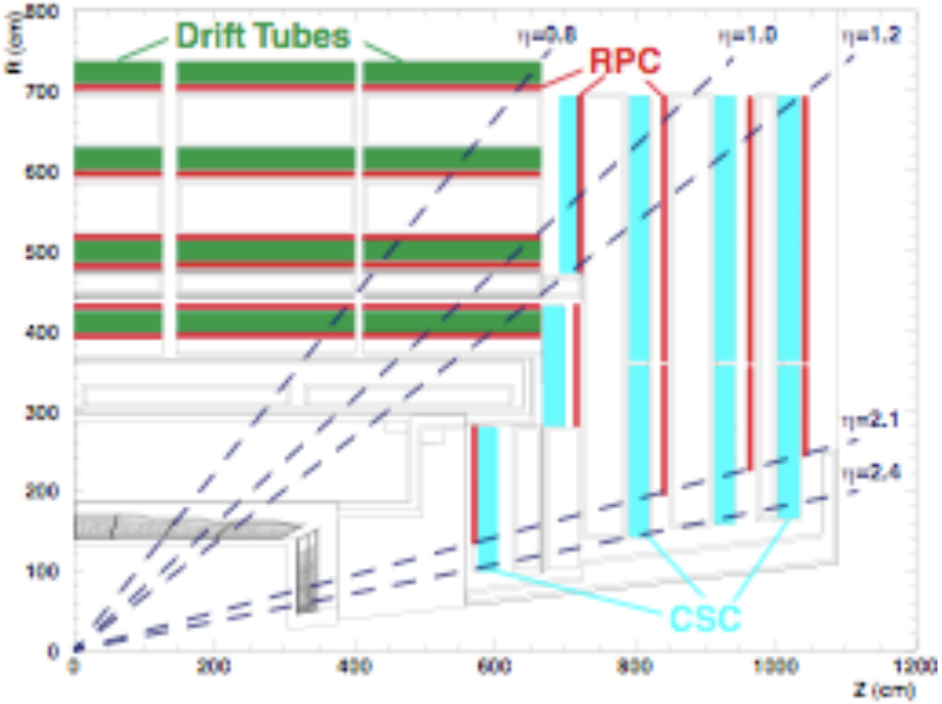
Jet trigger algorithm

- Trigger region is 4x4 trigger towers (20x20 $PbWO_4$ crystals in ECAL)
- Sliding window of 3x3 regions to find local maxima: cone (square) jet algorithm
- Sum all E_T in 3x3 region window
- Tau veto bit set if none of patterns are found in region (trigger tower E_T>3 GeV)
- Jet is marked as tau-jet if tau veto is not set for all 9 regions



L1 muon trigger

- Combination of three technologies
  - Drift tubes
  - Cathode strip chambers
  - Resistive plate chambers
    - For triggering only
  - Redundant
  - Complementary technologies
  - Geometric overlap



- Tracks from different systems combined in the Global Muon Trigger
  - Combination uses optimal information from each system and is less sensitive to backgrounds, noise, etc.

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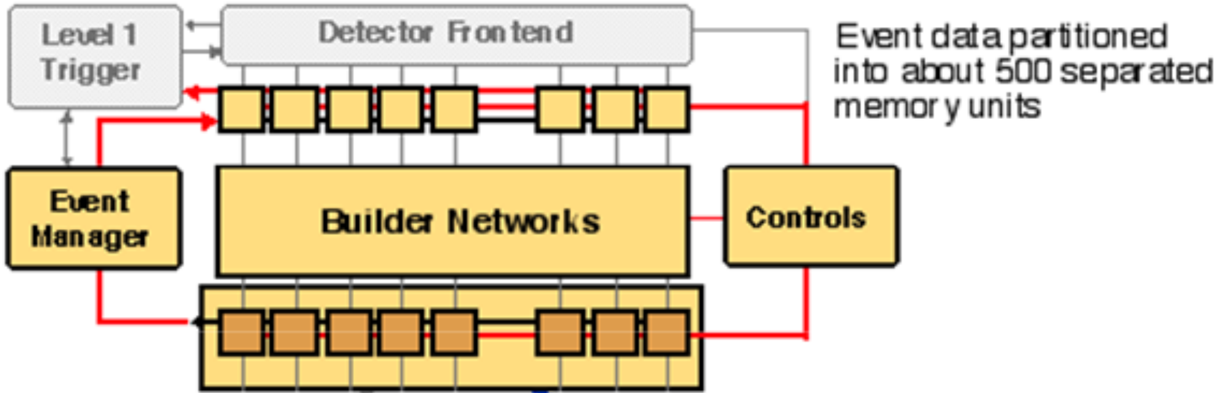
CMS High Level Trigger

L1 Input rate ≈ 40 MHz
L1 latency: 3.2 μs
L1 Output rate: 100 kHz



L2 and L3 merged into
High Level Trigger (HLT)

100kHz input rate
~2000 CPUs
~40 ms average per event

The HLT accesses full full granularity event information seeded by L1 objects

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Status and commissioning

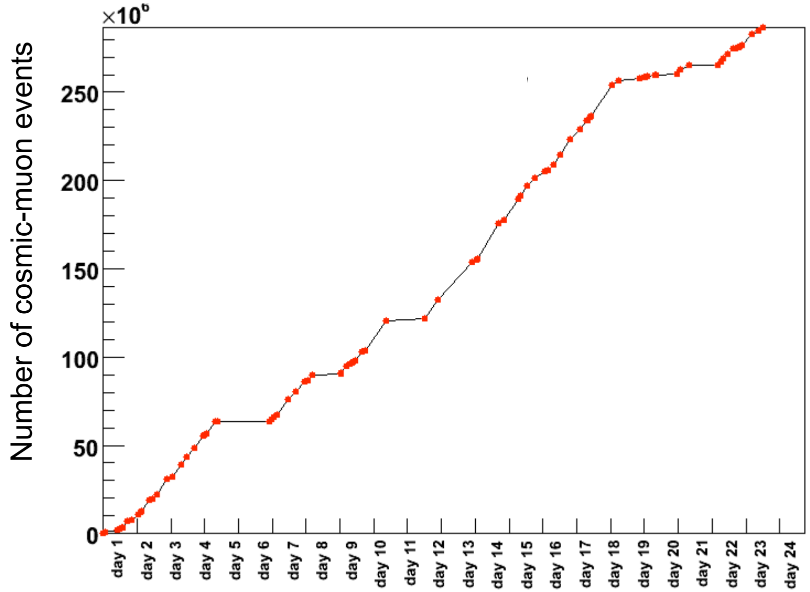
Three stages of commissioning planned:

- Pattern tests
  - Simple patterns to verify cabling map
  - Full Monte Carlo simulated events loaded into hardware. Compare to what is expected by software (C++) emulator.
- Cosmic tests
  - Run with cosmic-ray muons triggered by muon system or calorimeters
  - Compare to what is expected by emulator (comparison run online in DQM stream)
- ~~First running~~
  - ~~Single beam (beam-gas and beam-halo) events~~
  - ~~First collision data!~~

Cosmic Run at Four Tesla

- Aims:
  - Run CMS for 4 weeks continuously to further gain operational experience
  - Study effects of B field on detector components
  - Collect 300M cosmic events with tracking detectors and field
  - Aim for 70% efficiency

- Outcome:
  - Ran 4 weeks continuously
  - 370M cosmic events collected in total



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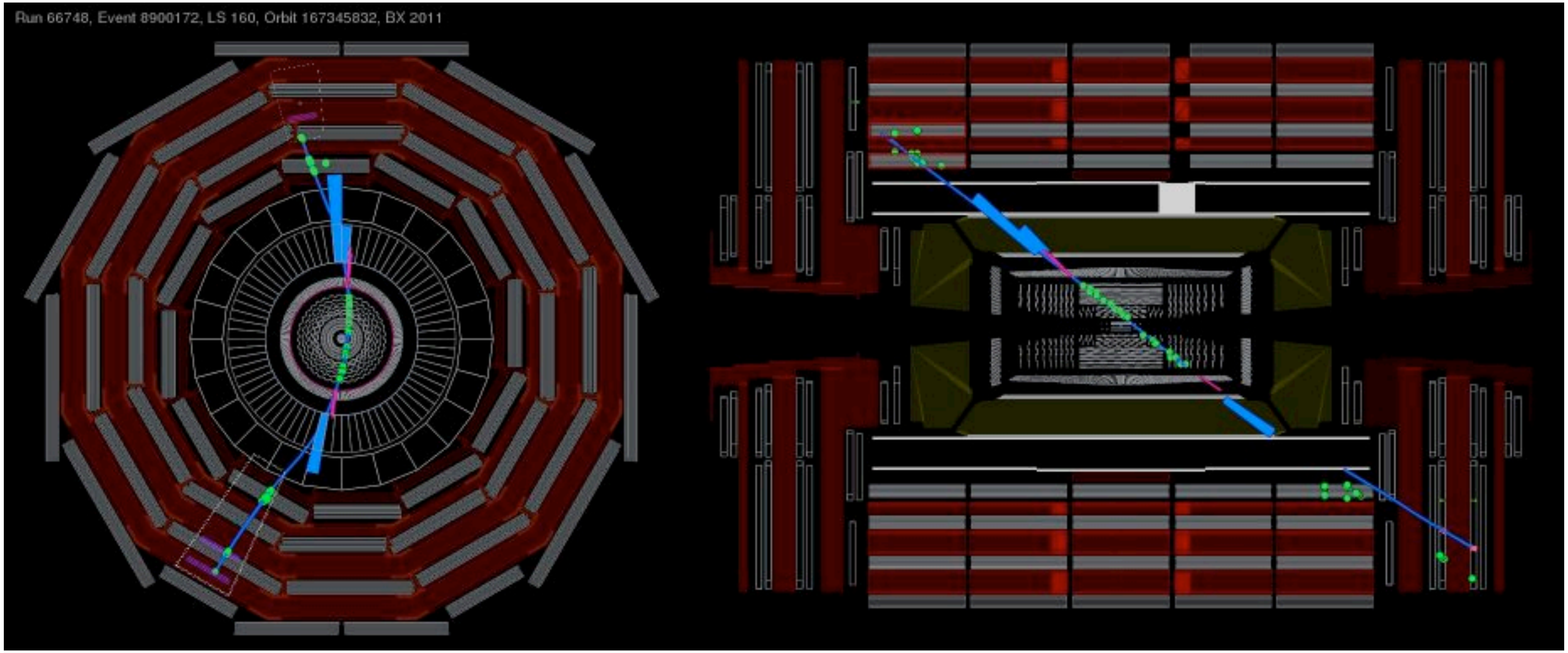
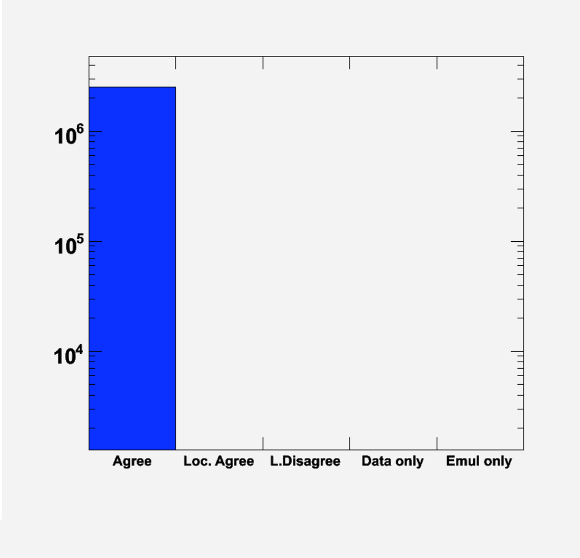
Cosmic muon run



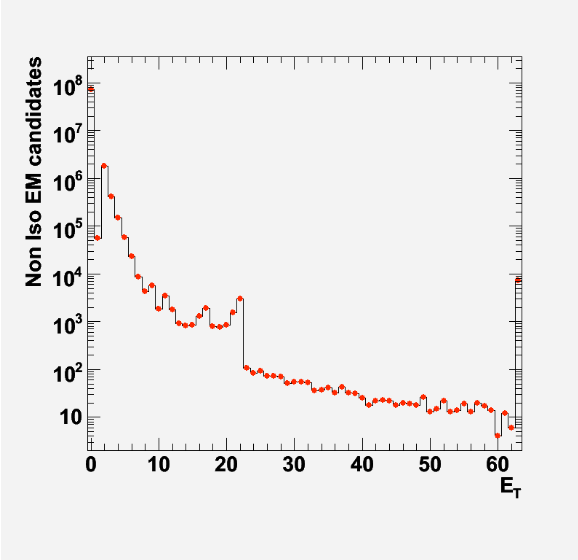
ECAL in magenta, HCAL in blue, tracker and muon hits in green

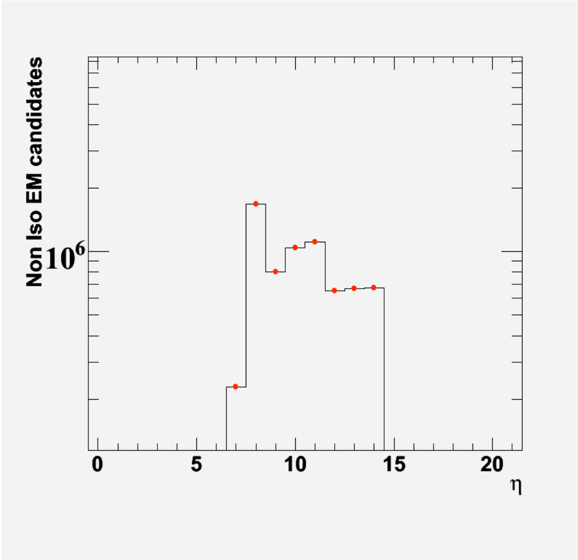
Cosmic muon running

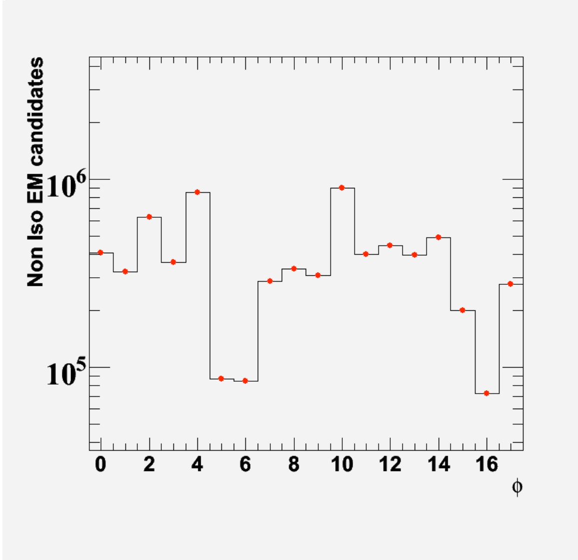
- Electrons



- Trigger hardware
- Trigger emulator



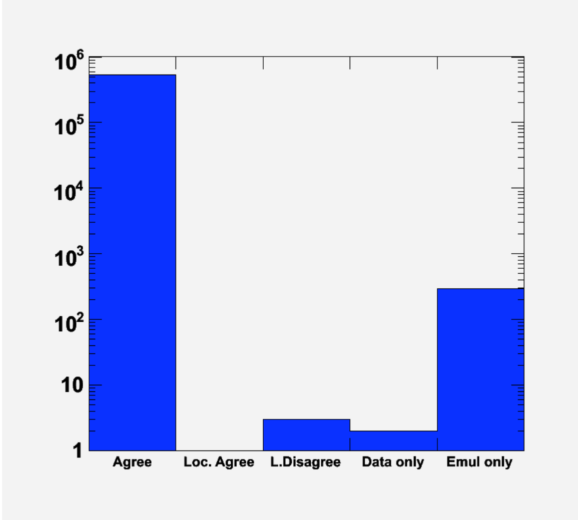


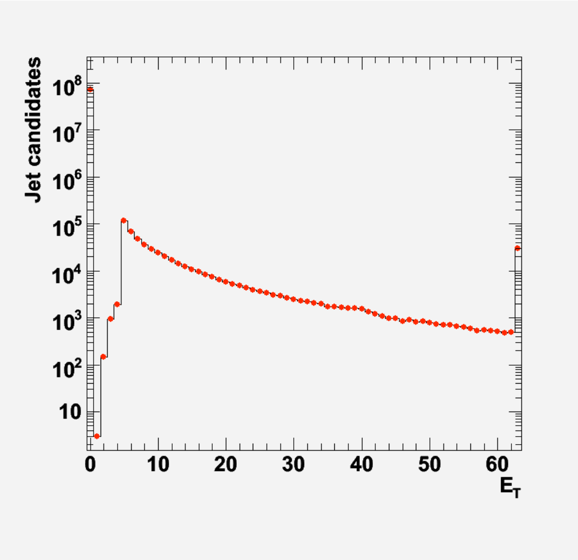


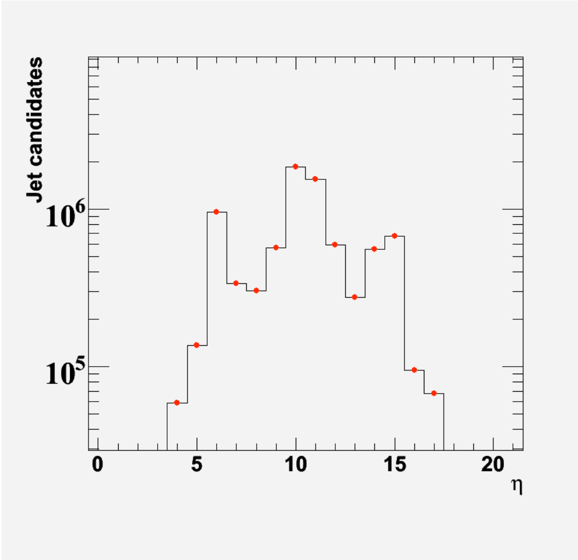
Cosmic muon running

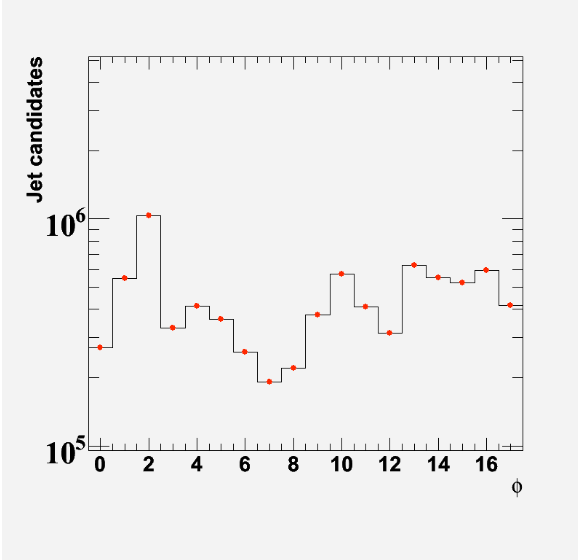
- Central jets (|η| < 3)

• Trigger hardware
- Trigger emulator









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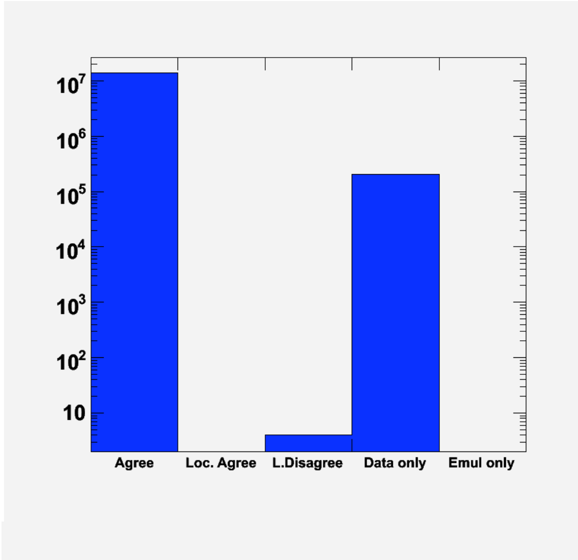
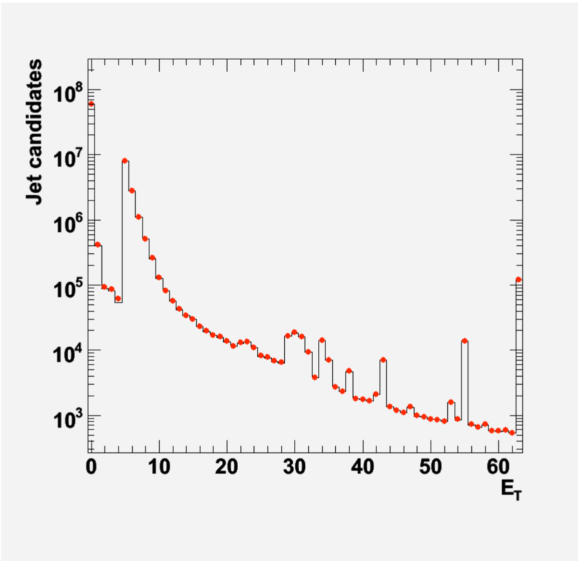
Cosmic muon running

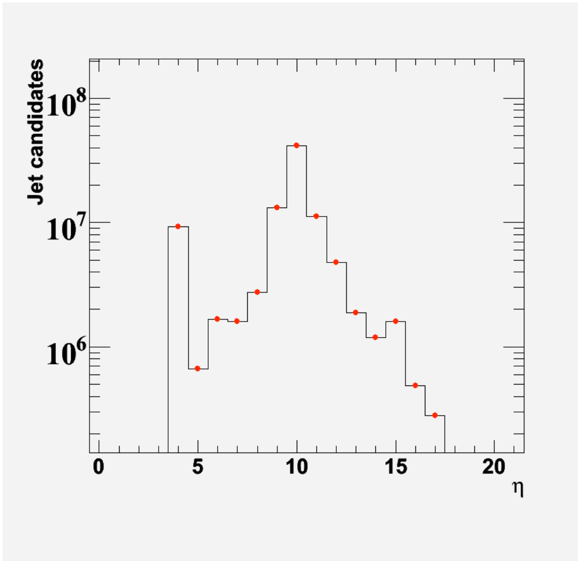
- Tau jets ($|\eta| < 3$)

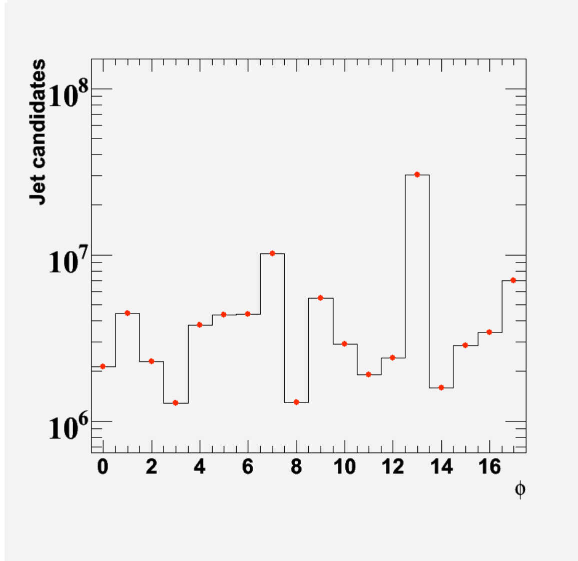


- Trigger hardware

\- Trigger emulator







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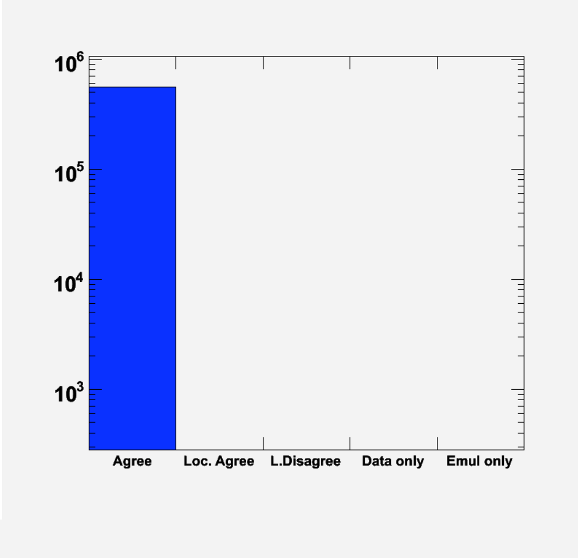
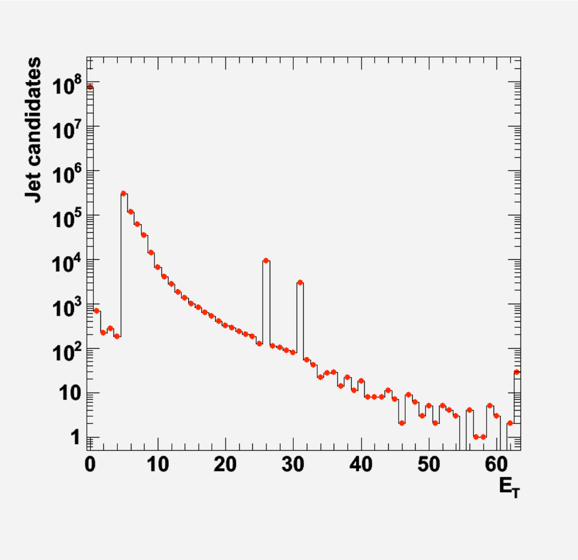
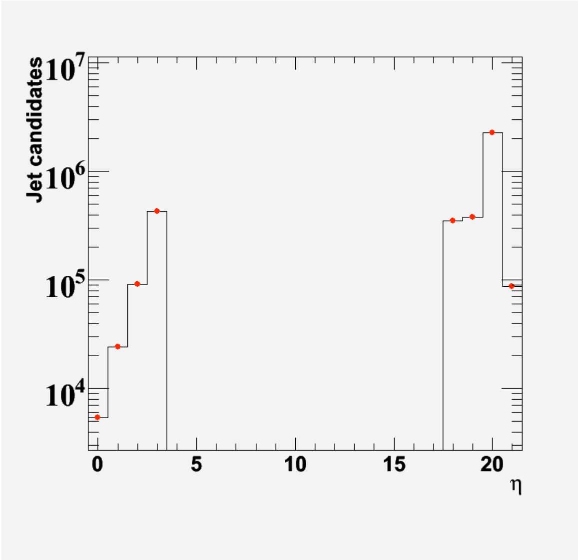
Cosmic muon running

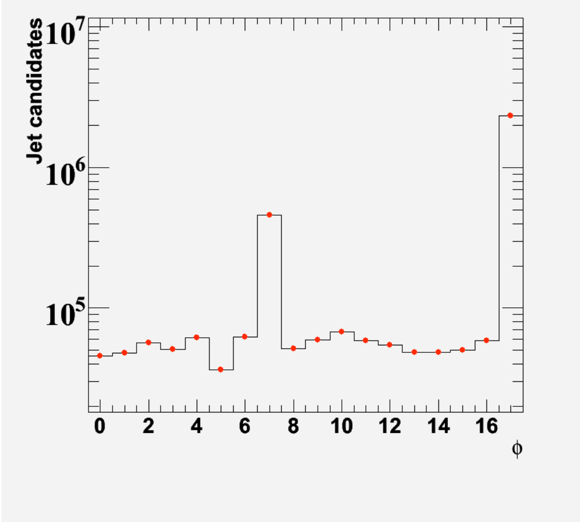
- Forward jets (3 < |η| < 5)



- • Trigger hardware
- \- Trigger emulator







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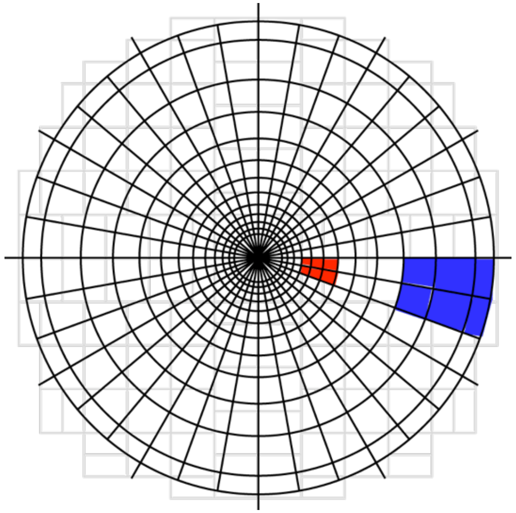
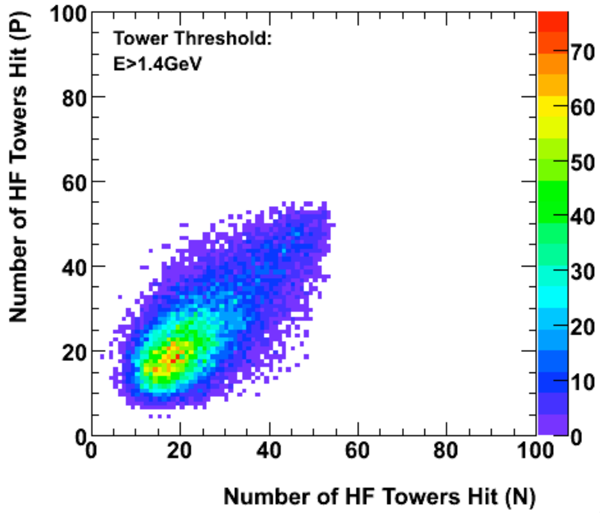
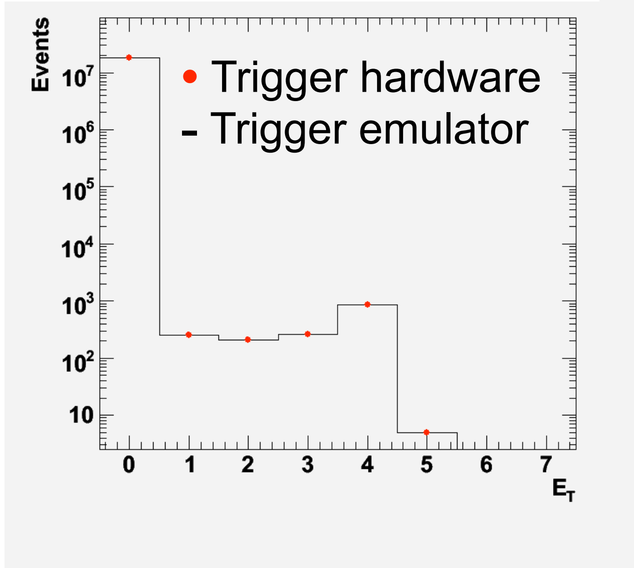
Cosmic muon running





- New idea for triggering low P_T events in early running
  - Consider inner two rings of trigger towers in the forward calorimeter
  - Make E_T sums and count towers over E threshold
  - Make coincidence in +/- η



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Splash event

- 2x10^9 protons on collimator ~150 m upstream of CMS
  - > 80% of channels fired ⇒ 100 - 1000 TeV
  - timed in beam monitor, muon and HCAL triggers

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Sep 10th – first multiple orbits

orbit signals

BPTX

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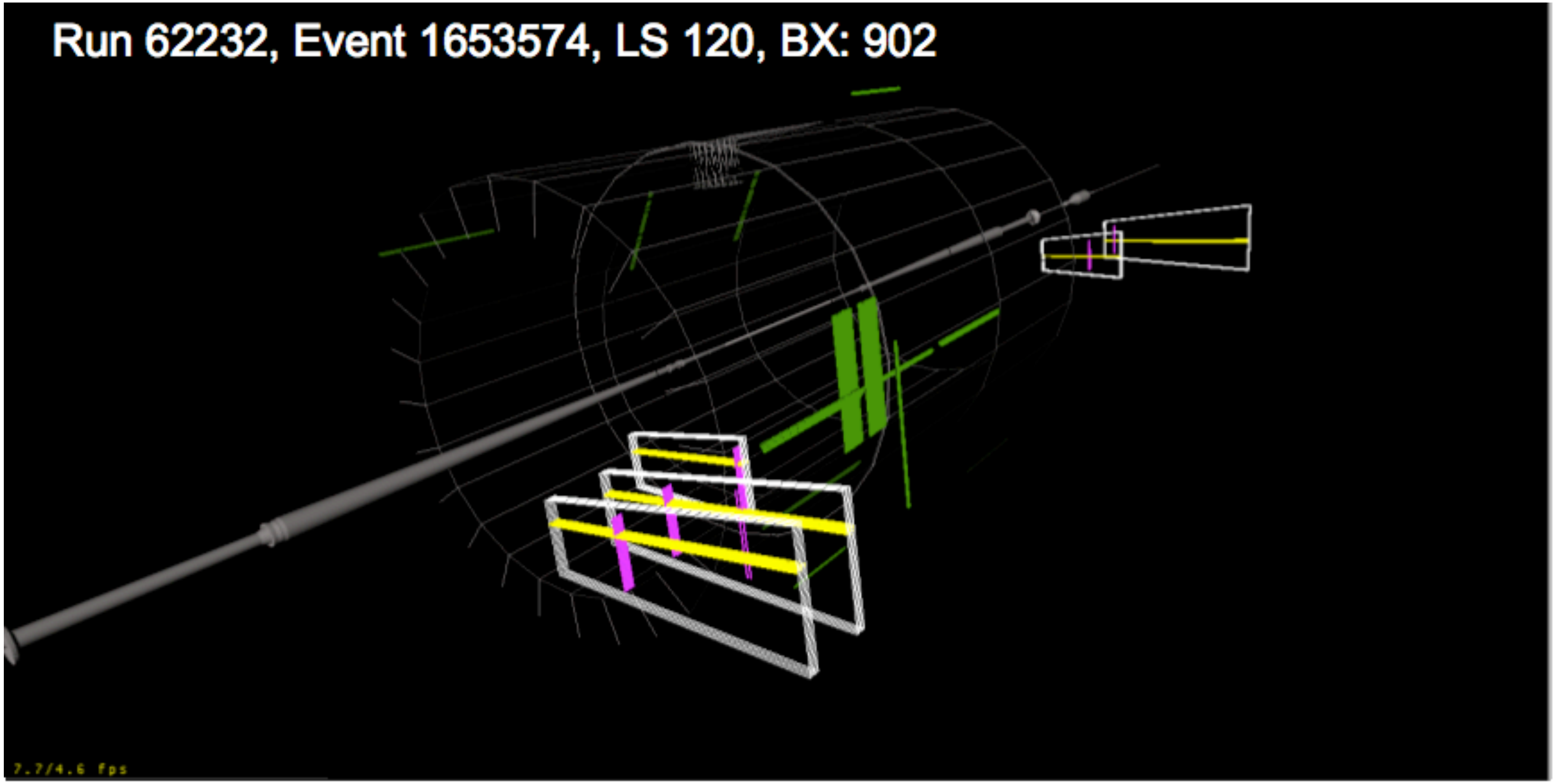
Halo Muon Event



Happy people (for now…)

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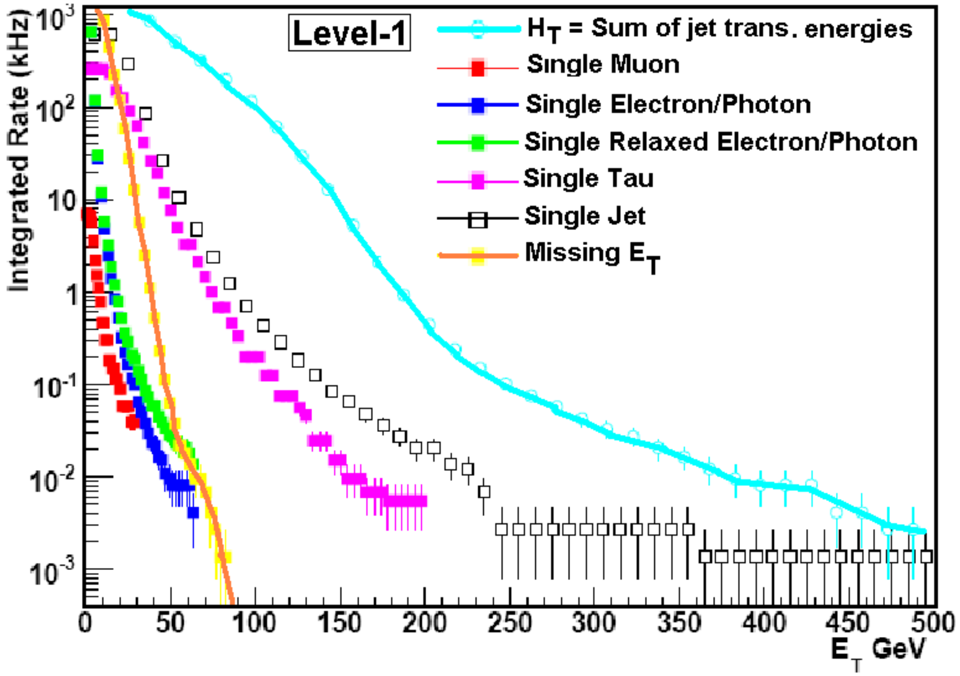
LHC Start-up luminosity

- Start-up schedule from 2008 → 2009 not significantly different
- For trigger note
  - Huge range in luminosity and min bias rate
  - Significant pile-up due to small number of bunches
  - Each step lasts ~1 week

Bunches	Protons/bunch	Luminosity	Pile-up	Min bias rate
1 x 1	1×10^{10}	1×10^{27}	Low	55 Hz
43 x 43	3×10^{10}	3.8×10^{29}	0.06	20 kHz
43 x 43	3×10^{10}	1.7×10^{30}	0.28	60 kHz
43 x 43	4×10^{10}	6.1×10^{30}	0.99	200 kHz
156 x 156	4×10^{10}	1.1×10^{31}	0.50	400 kHz
156 x 156	9×10^{10}	5.6×10^{31}	2.3	2 MHz
156 x 156	9×10^{10}	1.1×10^{32}	5.0	4 MHz

L1 trigger rates and tables

M. Felcini, Novosibirsk 2008.



Design tables for 17kHz L1 output rate
1/3 actual initial capability of 50 kHz

How do we allocate bandwidth between the different triggers?

For **single object triggers**:
- Muon rates are low
- Electron rates are high at low E_T
- Jet rates are high also at high E_T

For **double object triggers** (not shown here) rates are one to more orders of magnitude lower than for single object triggers: allow to keep low thresholds at small bandwidth cost.

Trigger class	Allowed Rate
Muon (single or double)	**2 kHz**
Electron/photon (single or double)	**3 kHz**
Jets or Total Transverse Energy	**6 kHz**
Tau jets	**3 kHz**
Combination of triggering objects	**3 kHz**
Total Level-1 output rate	**17 kHz**

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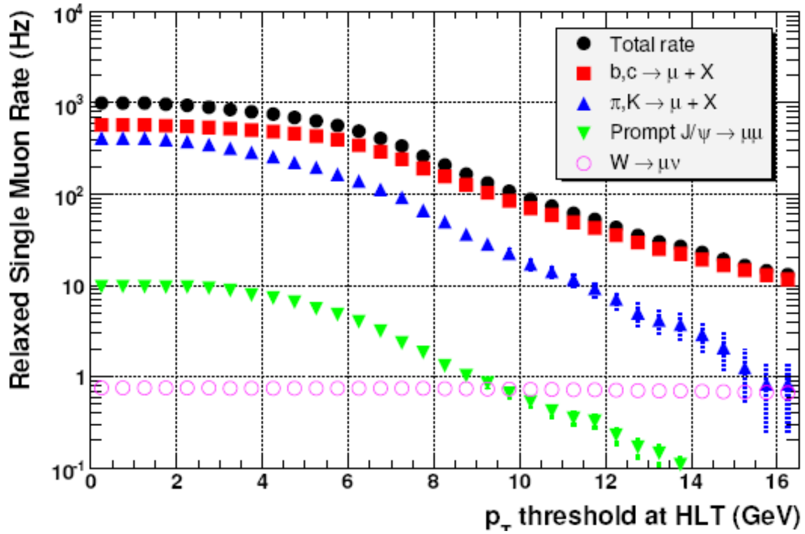
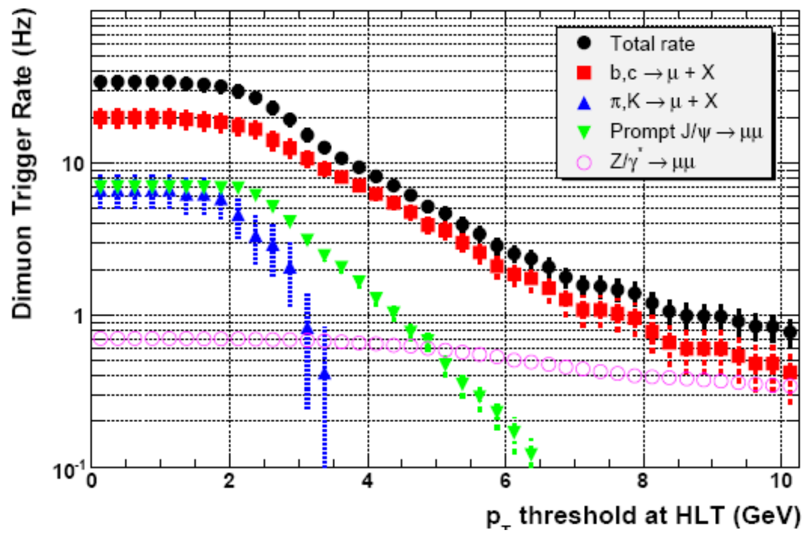
HLT rates and tables





M. Felcini, Novosibirsk 2008.

Design HLT tables for 150 Hz HLT output rate
50% of actual initial capability of 300 Hz

Share bandwidth according to detector and physics priorities at the given luminosity

Examples of **muon and electron (next page) triggers rates and tables** at **L=$10^{32}s^{-1}cm^{-2}$:**

At this luminosity set **muon trigger thresholds** as **low as possible** (detector and physics studies) Allow **1/3 of total bandwidth for muon triggers**

Muon HLT table -Total rate: 30 Hz

Trigger	Threshold (GeV)	Note
1μ	16	
1μ	11	isolation
2μ	3	

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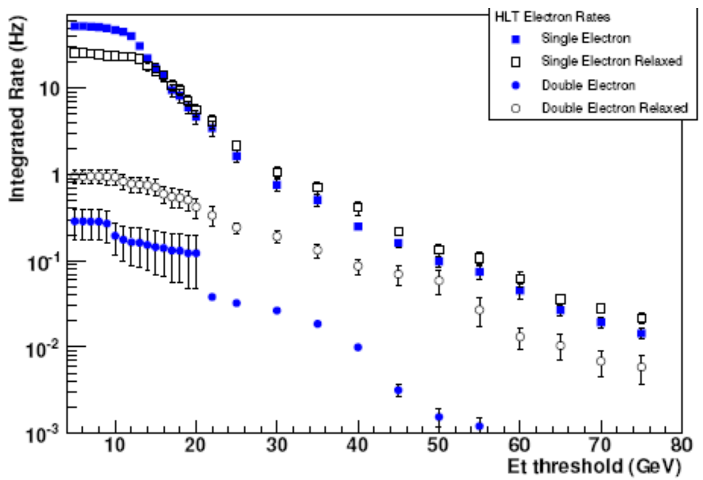
HLT rates and tables

M. Felcini, Novosibirsk 2008.



Electrons/Photons HLT table
Total rate: 30 Hz

Trigger	Threshold	Notes
1e	17	
1e	15	isolation
2e	12	
2e	10	isolation
1γ	40	
1γ	30	isolation
2γ	20	
2γ	20	isolation
High-E_T EM	80	looser
Very high-E_T EM	200	looser

Overview of bandwidth sharing among the different trigger classes a $L=10^{32}s^{-1}cm^{-2}$

Trigger class	Allowed Rate
Muon (single or double)	50 Hz
Electron/photon (single or double)	30 Hz
Single jet or multi-jet or Missing Transverse Energy (MET)	30 Hz
Tau and b-jets	20 Hz
Combination of triggering objects	20 Hz
Total HLT output rate	**150 Hz**

CMS schedule

- Midweek global runs
  - Run two days a week, 24 hours a day with all detector components
- Cosmic-muon Runs
  - Run in June with magnetic field off
  - Run in July with 4T magnetic field
- Final preparations
  - Move to beam mode two weeks before circulating beam
- CMS ready for LHC beam!

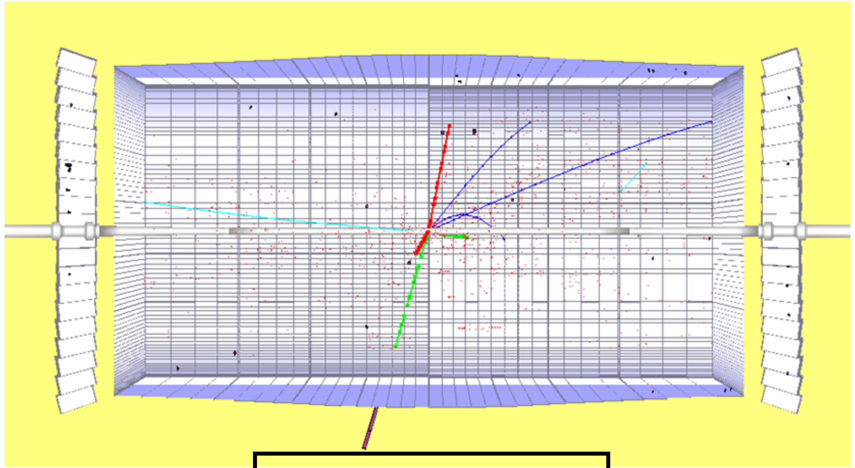
Super LHC

- Luminosity $10^{34} \rightarrow 10^{35}$ $cm^{-2}s^{-1}$ (phase II after 10 years of LHC)
- 20 MHz bunch crossing rate
- 400 events per bunch crossing
  - factor of 20 higher than LHC

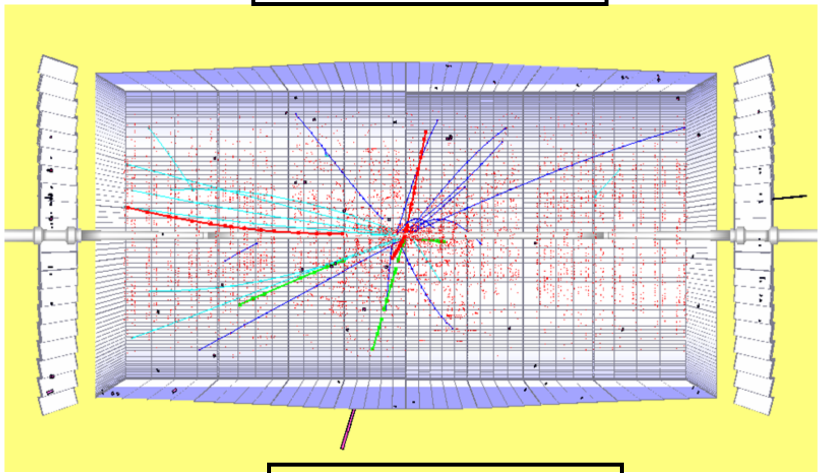
- Effect on the trigger
  - Degraded performance of algorithms
    - Electrons: for fixed efficiency, reduced rejection from isolation
    - Muons: increased background rates from accidental coincidences
    - Jets: increased pileup

What does it look like?

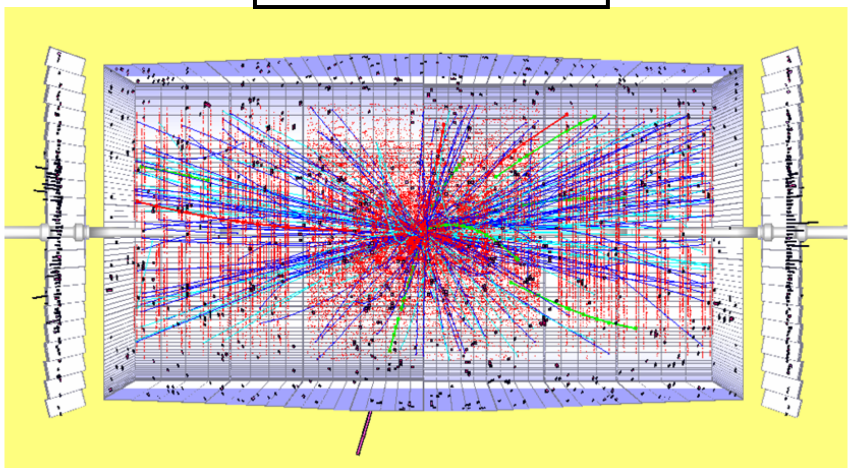
10^{32} cm^{-2}s^{-1}



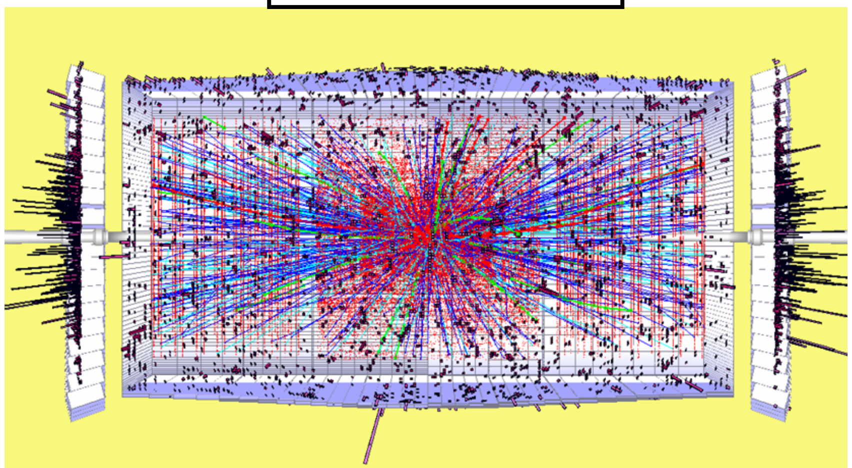
10^{33} cm^{-2}s^{-1}



10^{34} cm^{-2}s^{-1}



10^{35} cm^{-2}s^{-1}



Super LHC

- Luminosity $10^{34} \rightarrow 10^{35}$ $cm^{-2}s^{-1}$ (phase II after 10 years of LHC)
- 20 MHz bunch crossing rate
- 400 events per bunch crossing
  - factor of 20 higher than LHC

- Plan
  - Keep L1 output rate at 100 kHz
  - Increase L1 accept latency to 6.4 μs
  - Improve L1 calo trigger objects
  - Raise E_T thresholds on electron, photon, muon and jet triggers
  - Less inclusive triggers than at LHC (for EWSB studies for example)
  - Calibration triggers with low thresholds and high prescales (W,Z,t)

Super LHC

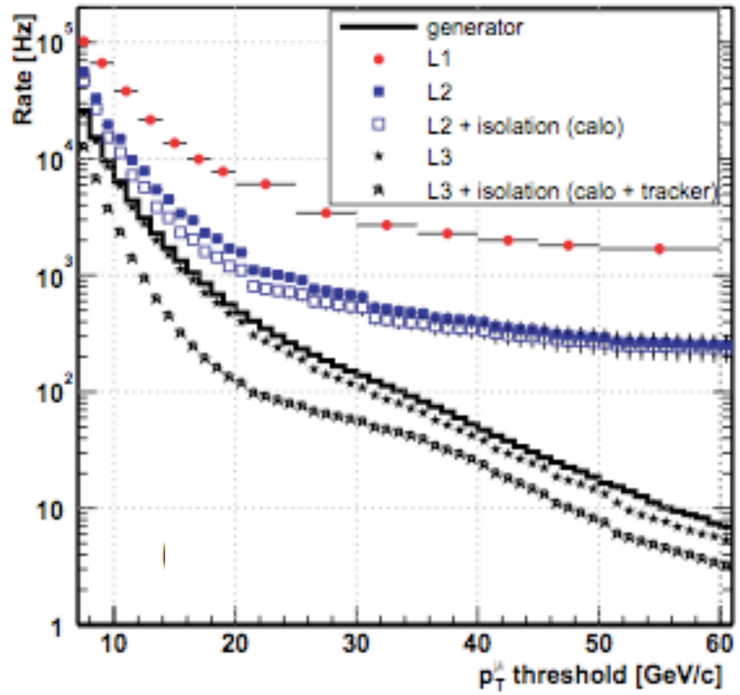
- Raise thresholds to keep rate constant
  - Single muon P_T>30 GeV
  - Single electron(photon) P_T>55 GeV
  - Di-electron(photon) P_T>30 GeV (or 45 and 25 GeV)
  - Di-muon P_T>20 GeV
  - Jet E_T>150 GeV and MET>80 GeV
  - Jet E_T>350 GeV
  - MET>150 GeV

F. Gianotti et al., Physics Potential and Experimental Challeges of the LHC Luminosity Upgrade, hep-ph/0204087.

- Thresholds not tolerable (and wouldn't work for CMS)
  - Scale set much lower by W, Z (and H?) masses
  - Need a different solution
    - Look at how rate is reduced at the Higher Level Trigger for ideas....

Examples from HLT

- Single muon rate for different P_T thresholds



- L1 rate flattens out at higher P_T
  - Increasing the threshold won't work
- L2 rate shows similar feature
- Need L3 algorithm including tracking to reduce the rate further
  - Reason is that including the tracker information improves the P_T resolution by a factor of 10
  - Main background from low P_T feed-through is reduced

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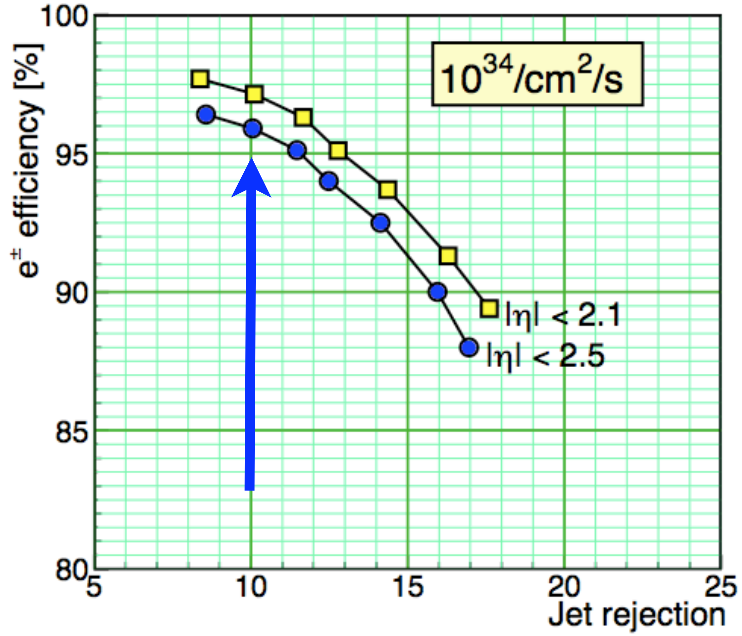
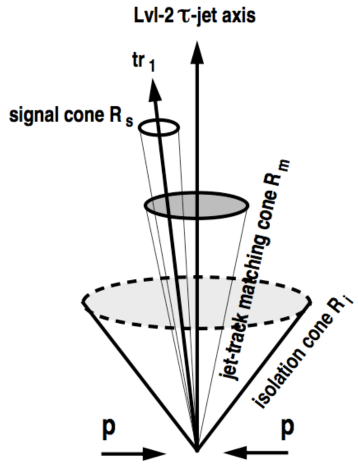
Examples from HLT

- Single electron trigger
  - Match at least two pixel hits to ECAL supercluster
  - High efficiency maintained
  - Large reduction factor in QCD jet background compared to ECAL alone



- τ jet triggers
  - Look for tracks from same vertex inside a signal cone
  - Veto jets based on tracks in a larger cone
  - Yields a factor of 10 rejection for QCD jets



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Super LHC tracking trigger

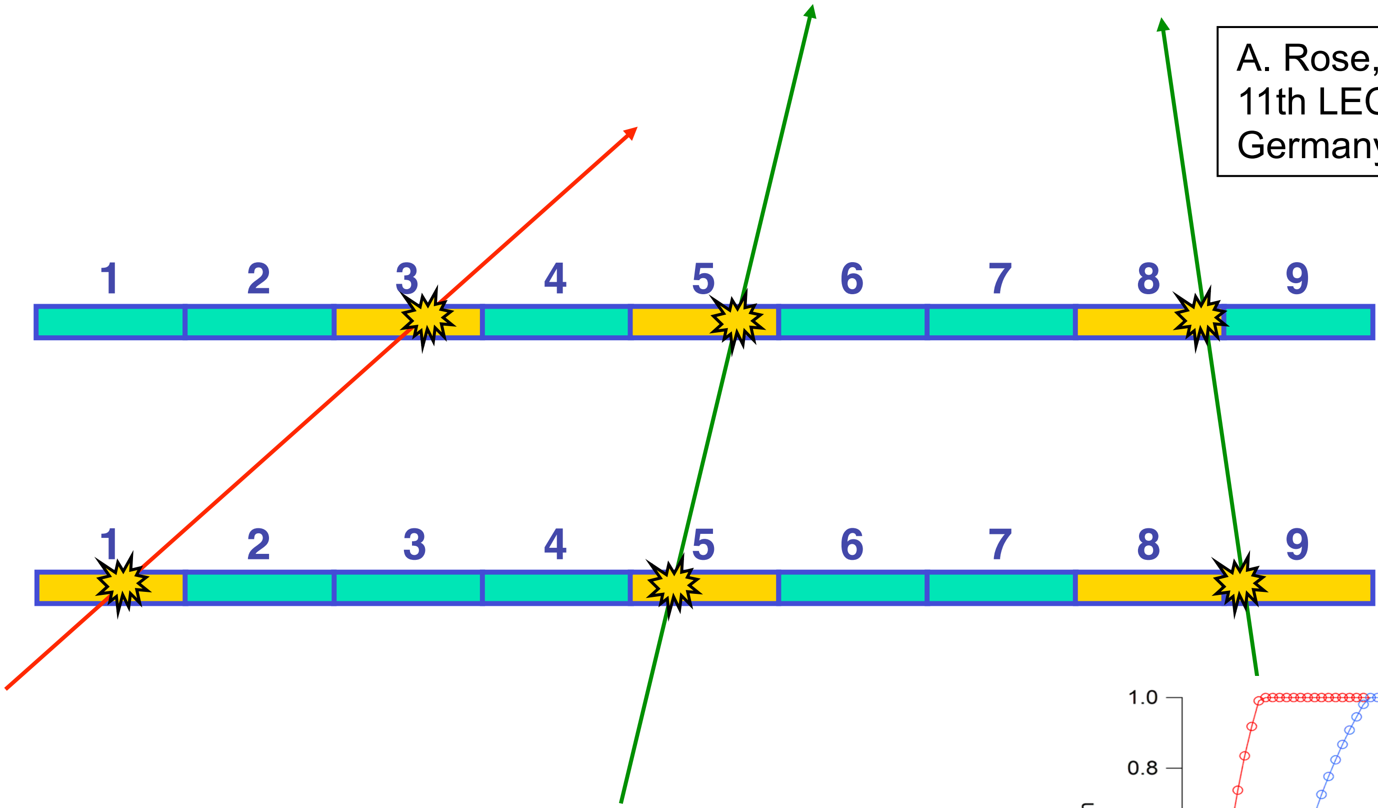
- Clear that as they stand HLT algorithms cannot be implemented at L1

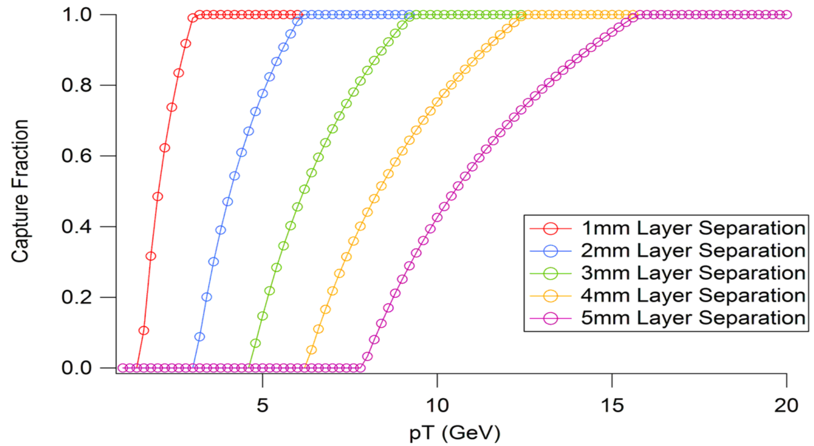
- Motivates need for tracking trigger at L1
  - Tracking information can solve problem with muon rate
  - Tracking information may well control electron rate
    - Does it need to be at small radius to avoid Bremstrahlung problems?
  - Isolation from tracking information may help τ and γ triggers
  - Ability to disentangle event vertices at L1 useful

- Note “tracking information” not complete track fit
  - Any inner and/or outer track stub would likely be a big help

Super LHC tracking trigger

A. Rose, C. Foudas, J. Jones & G. Hall, 11th LECC Workshop, Heidelberg, Germany (2005).





- Pixel spacing and separation of layers gives an implicit min P_T cut on track stubs

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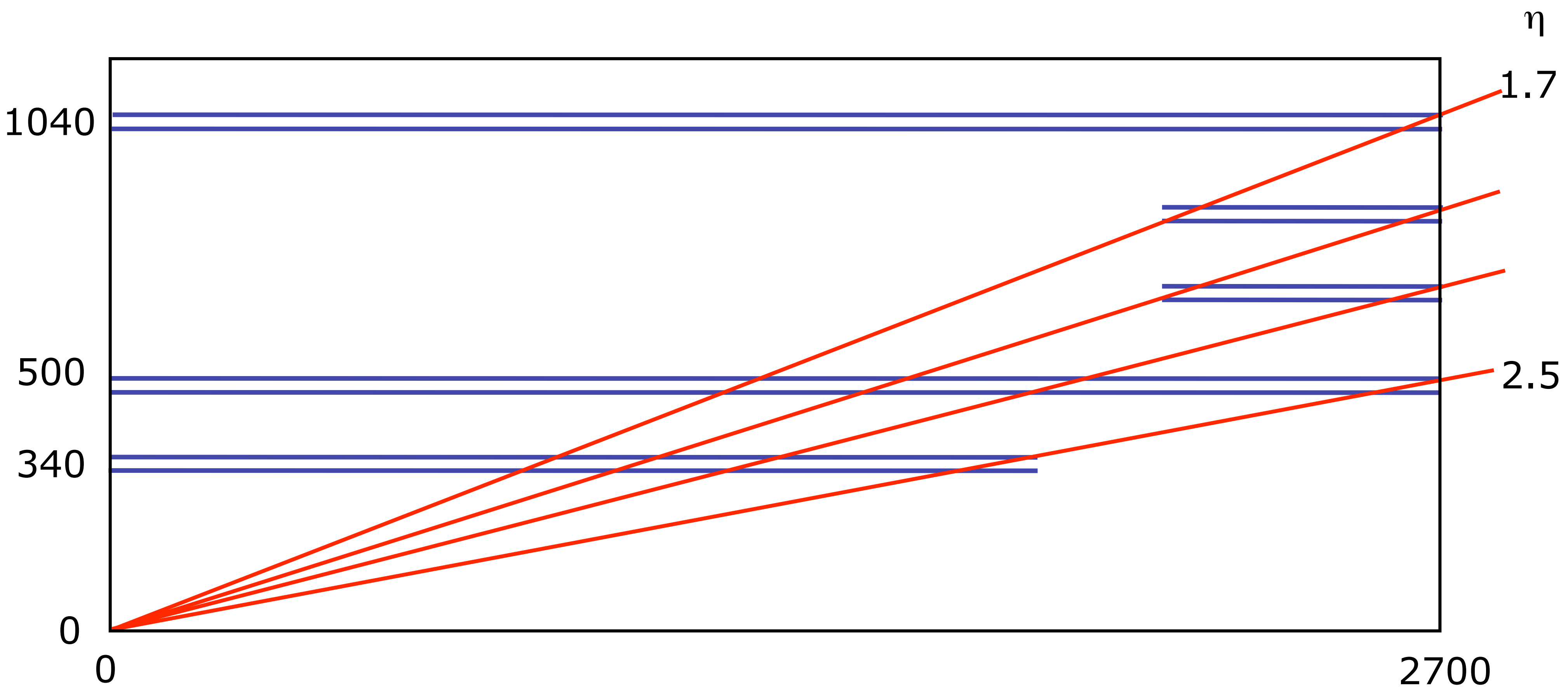
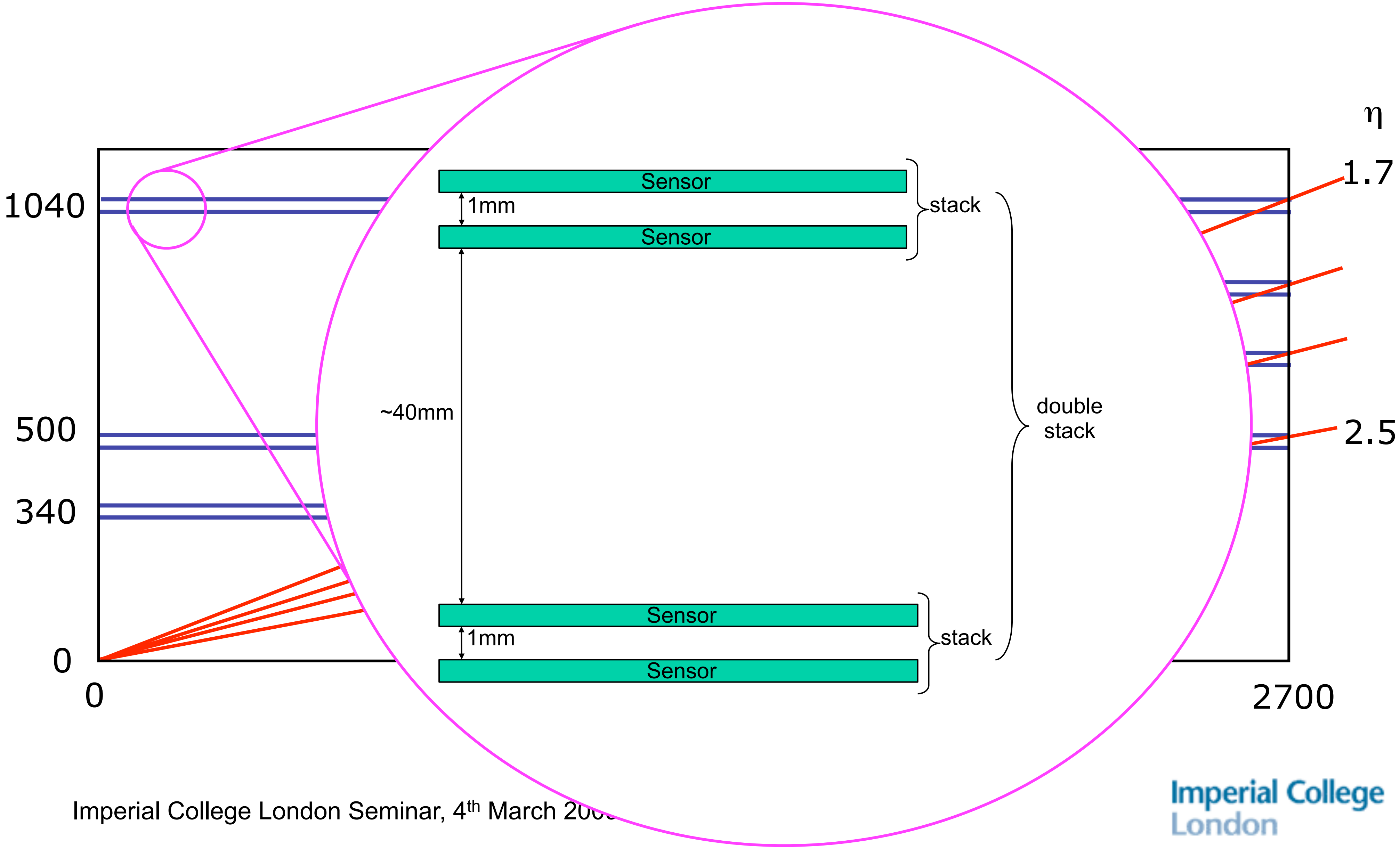
Super LHC tracking trigger

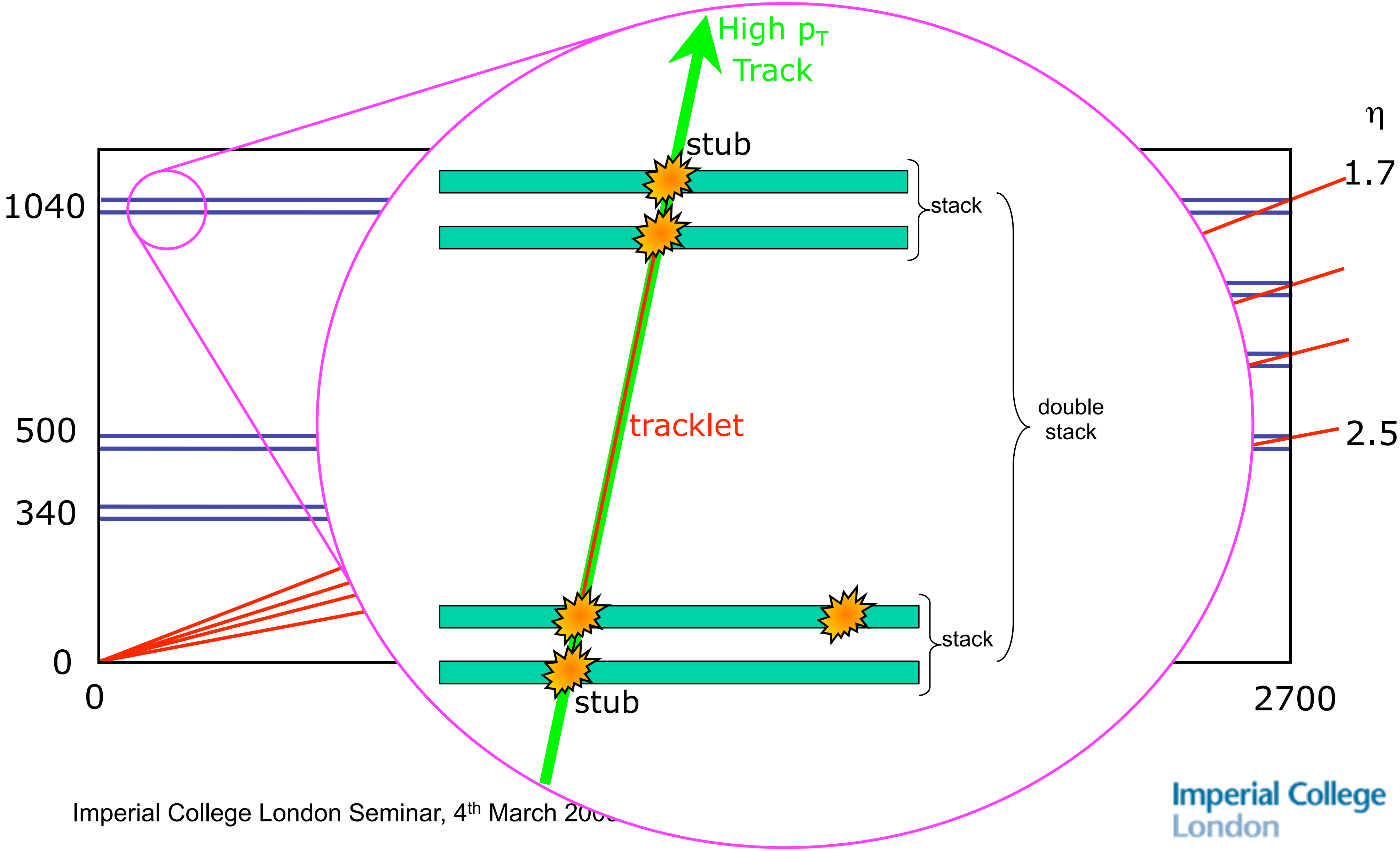
This idea is the basis for further study within CMS



Super LHC tracking trigger



Super LHC tracking trigger



Summary

- The CMS trigger is designed to cope with the very challenging environment of the LHC
- The Level 1 trigger implemented in hardware takes the full 40 MHz bunch-crossing rate and selects 100 KHz for further processing
- The High Level Trigger based on a large cluster of commercial PCs reduced the 100 KHz input rate to around 100 Hz for permanent storage
- The CMS trigger has been commissioned with cosmic-ray muon events and is ready for LHC collisions
- Started to think seriously about Super-LHC upgrade → studies underway