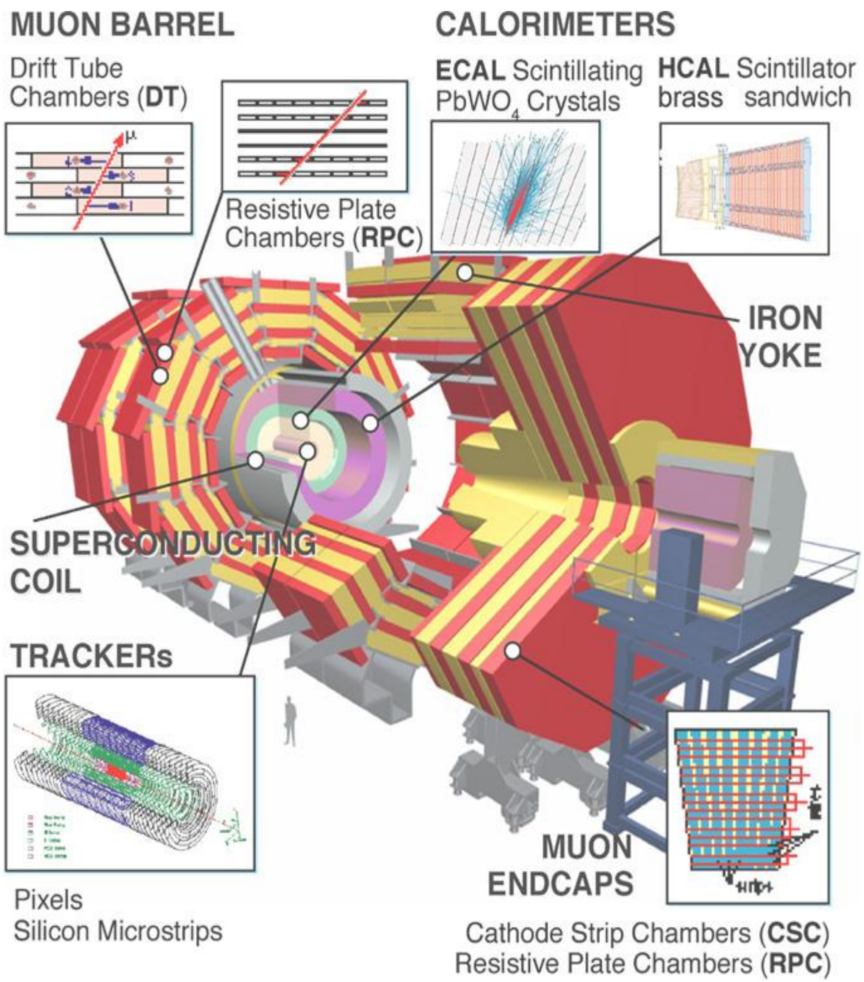
Operational Experience with the CMS Data Acquisition System

Hannes Sakulin, CERN/PH

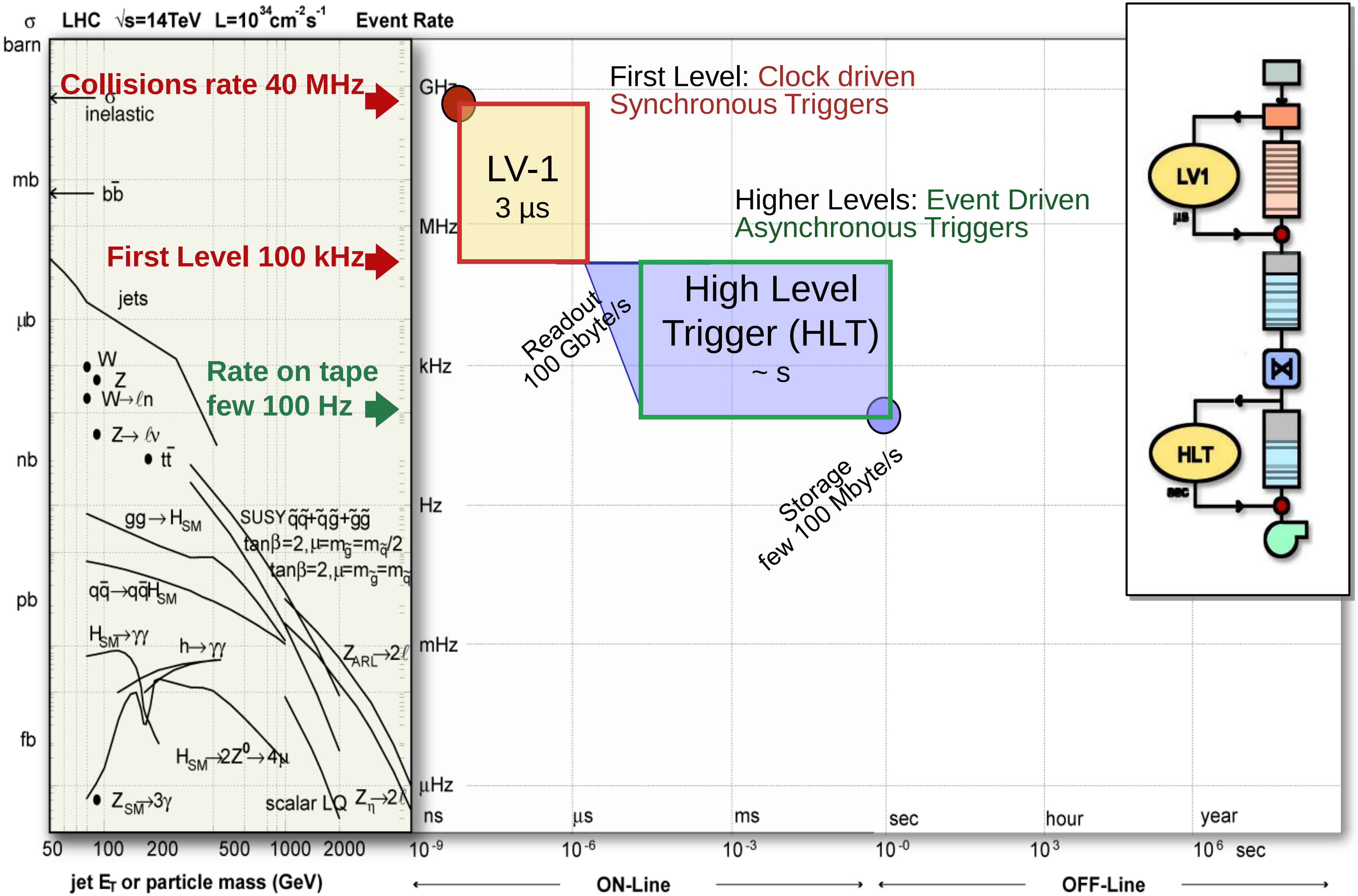
on behalf of the CMS DAQ group

Compact Muon Solenoid

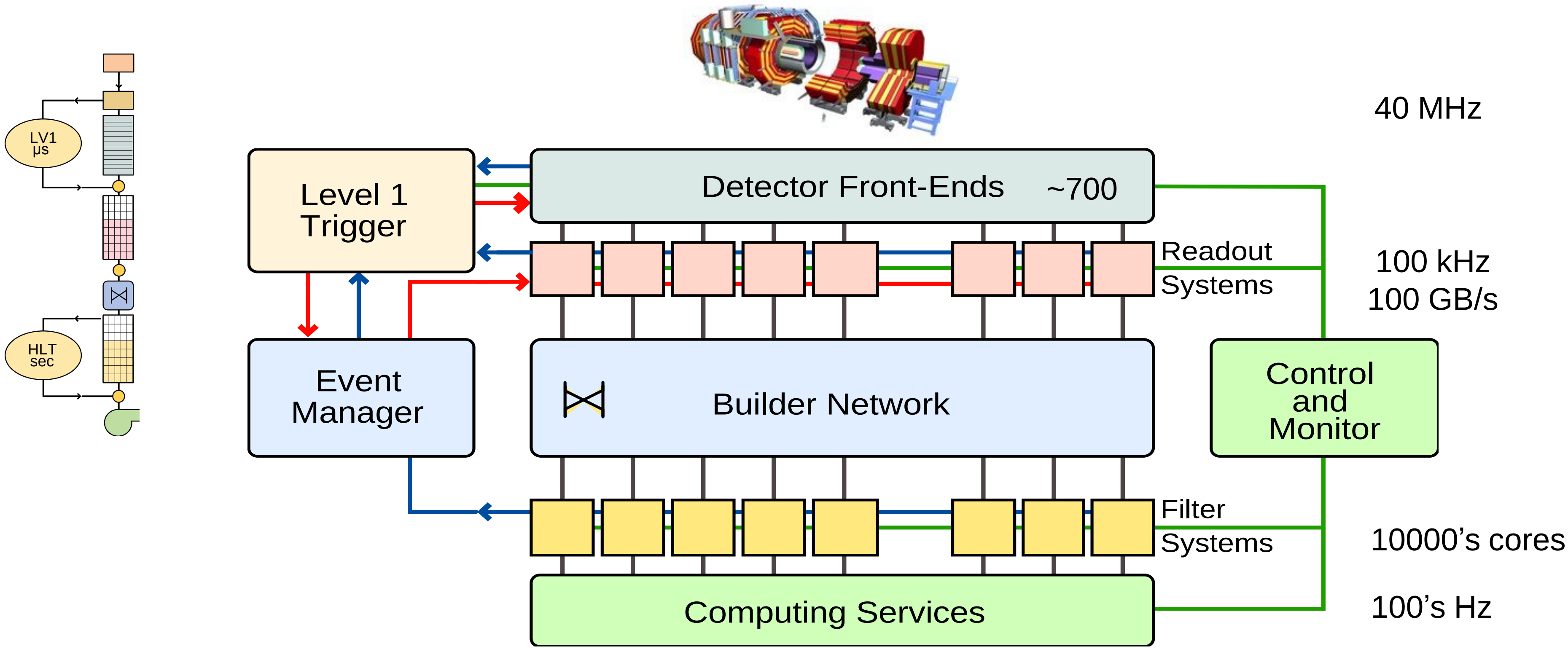


- General purpose detector at the LHC
- 55 million readout channels
  - Event size of 1MB
- Proton physics
  - At 7 TeV in 2010/11
  - At 8 TeV in 2012
- Heavy Ion physics
  - In 2010 & 2011

Two-level trigger concept

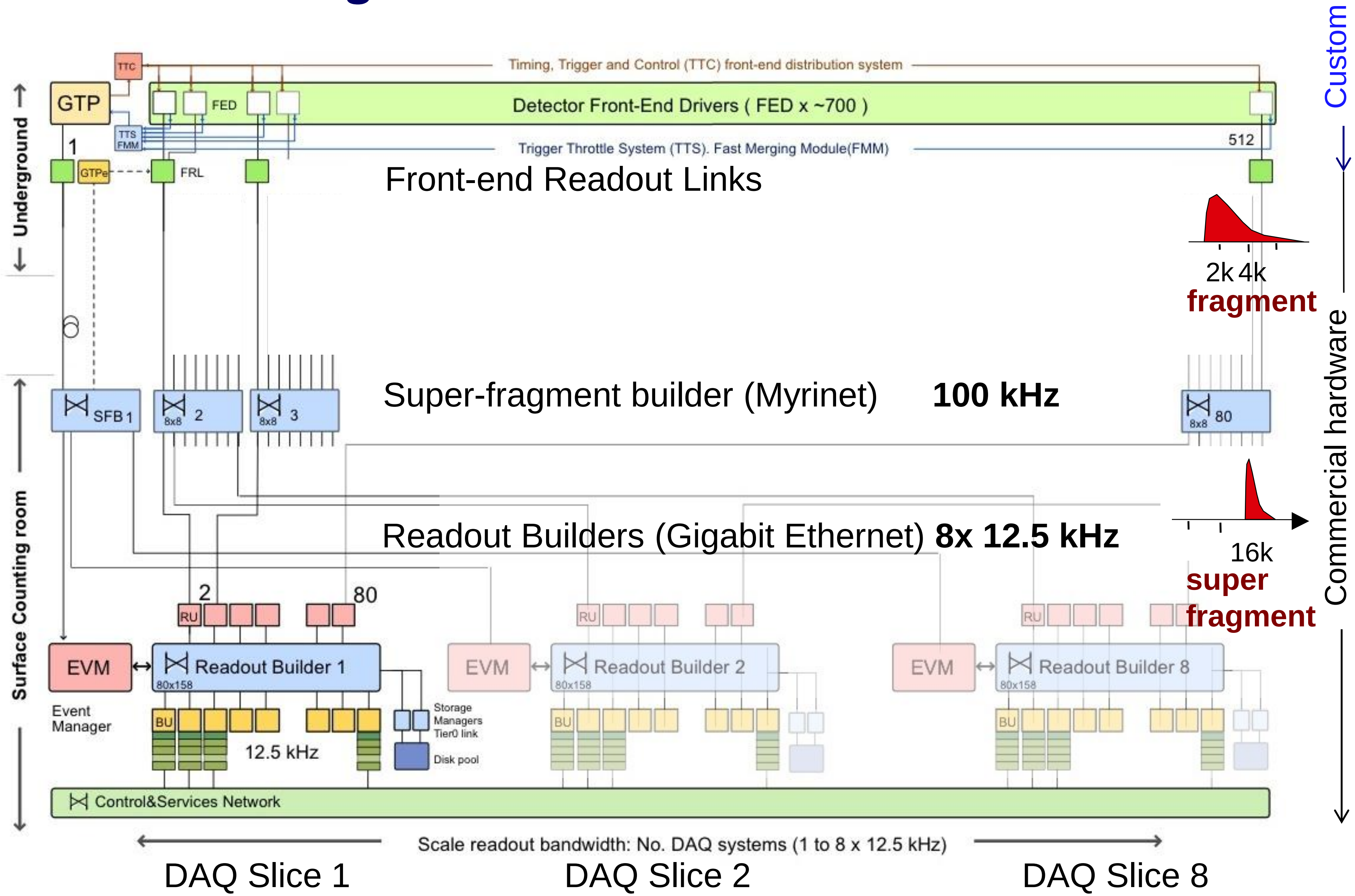


CMS DAQ requirements

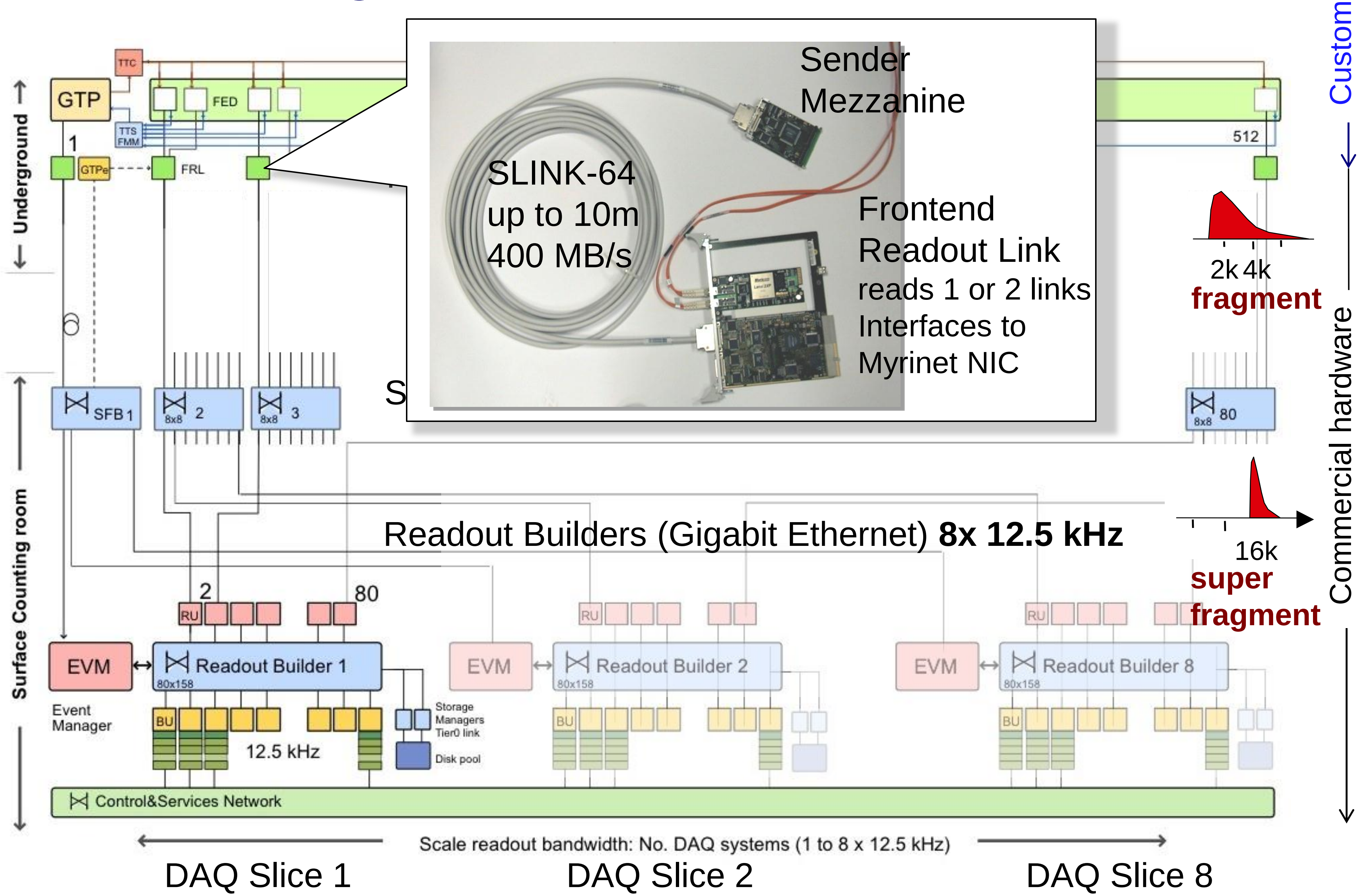


- Read out 700 detector front-ends (max. average fragment size 2 kB)
- Build complete events at 100 kHz (L1 trigger rate)
- Make them available to a filter farm of O(10000) cores
- Store 100's of Hz to disk (10's of TB/day)
- Scalable system employing commercial components wherever possible
  - Proprietary / Commercial: Front-Ends, VME, PCI, PC servers, networks, Protocols, OS

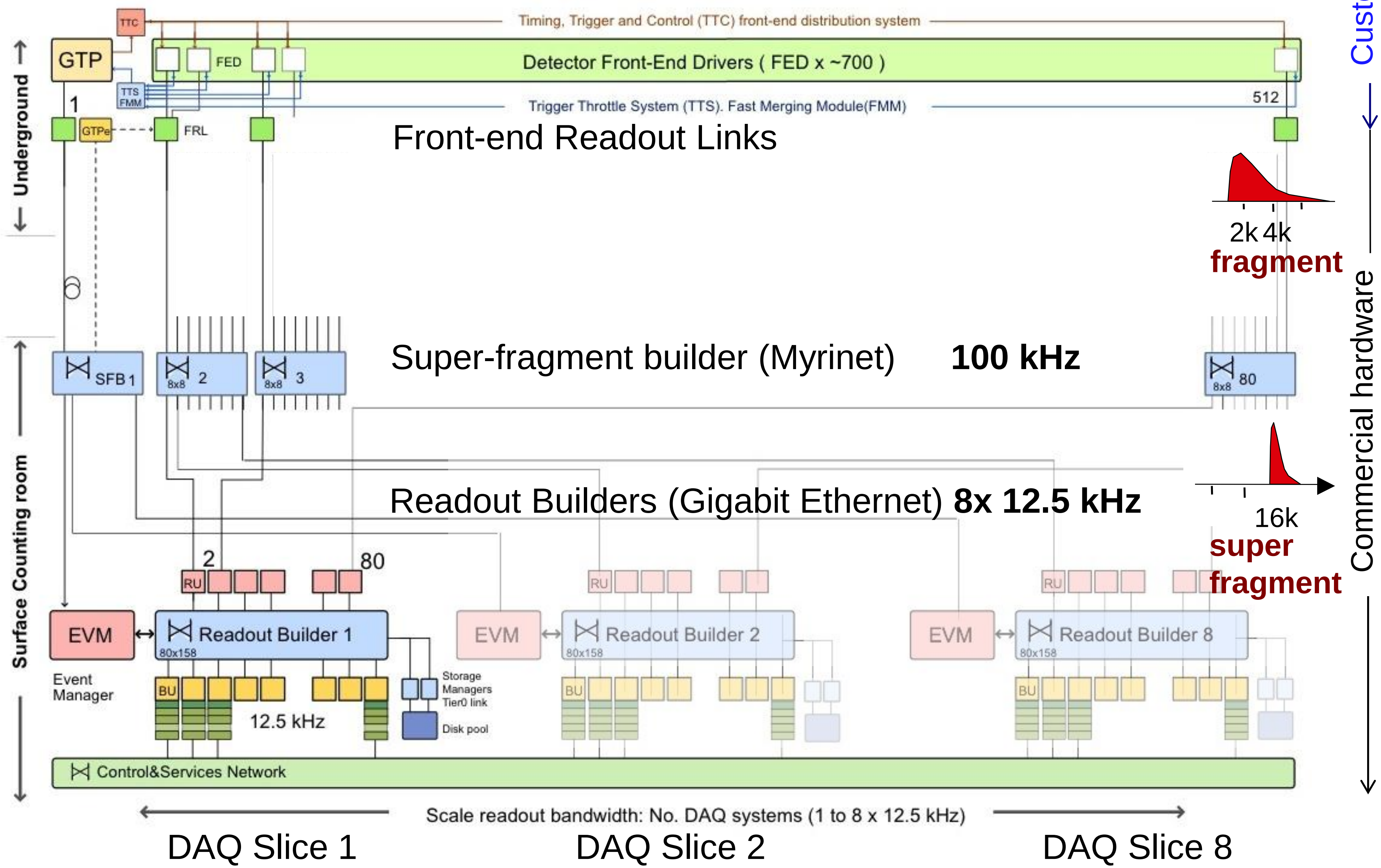
CMS two-stage event builder



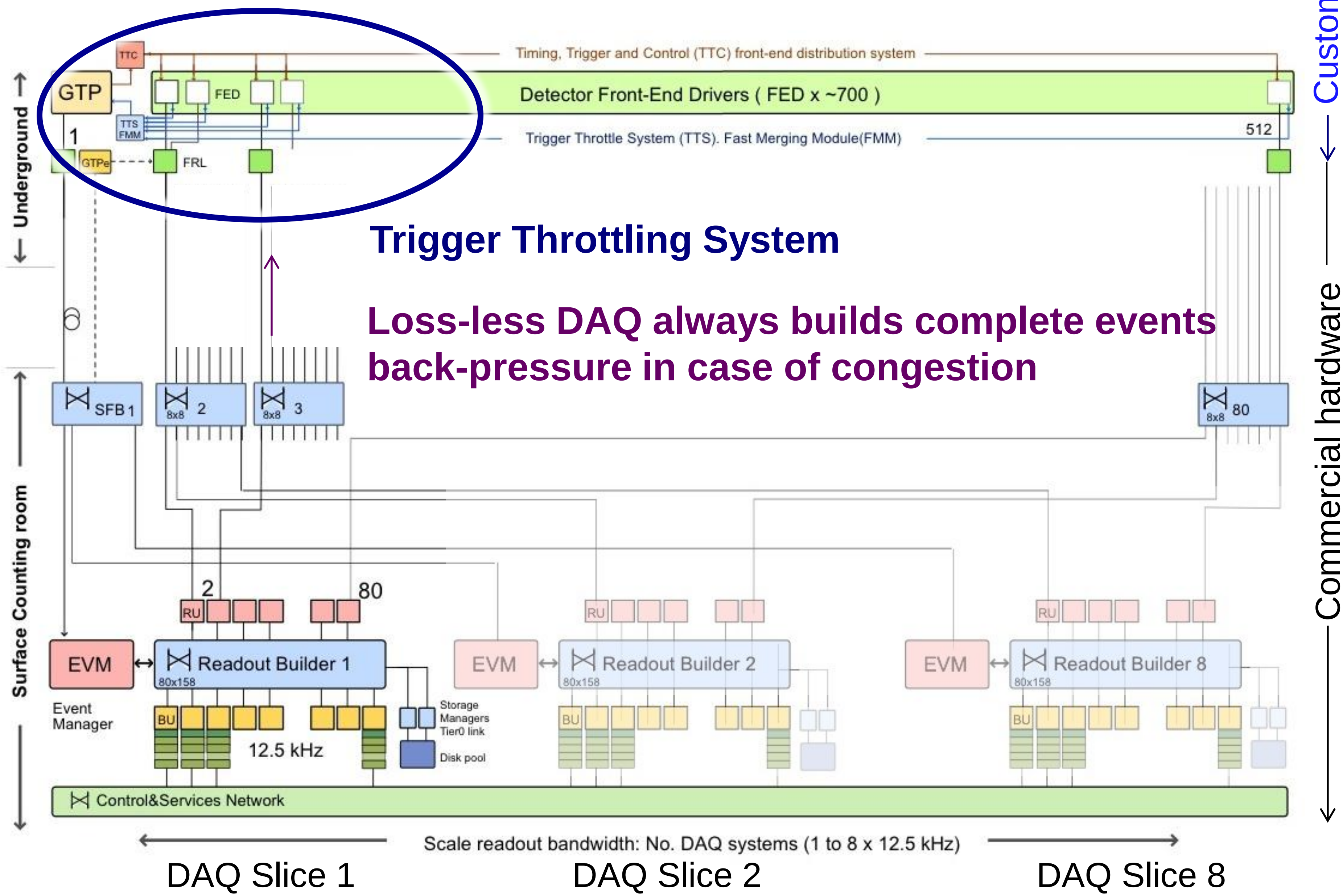
CMS two-stage event builder



CMS two-stage event builder



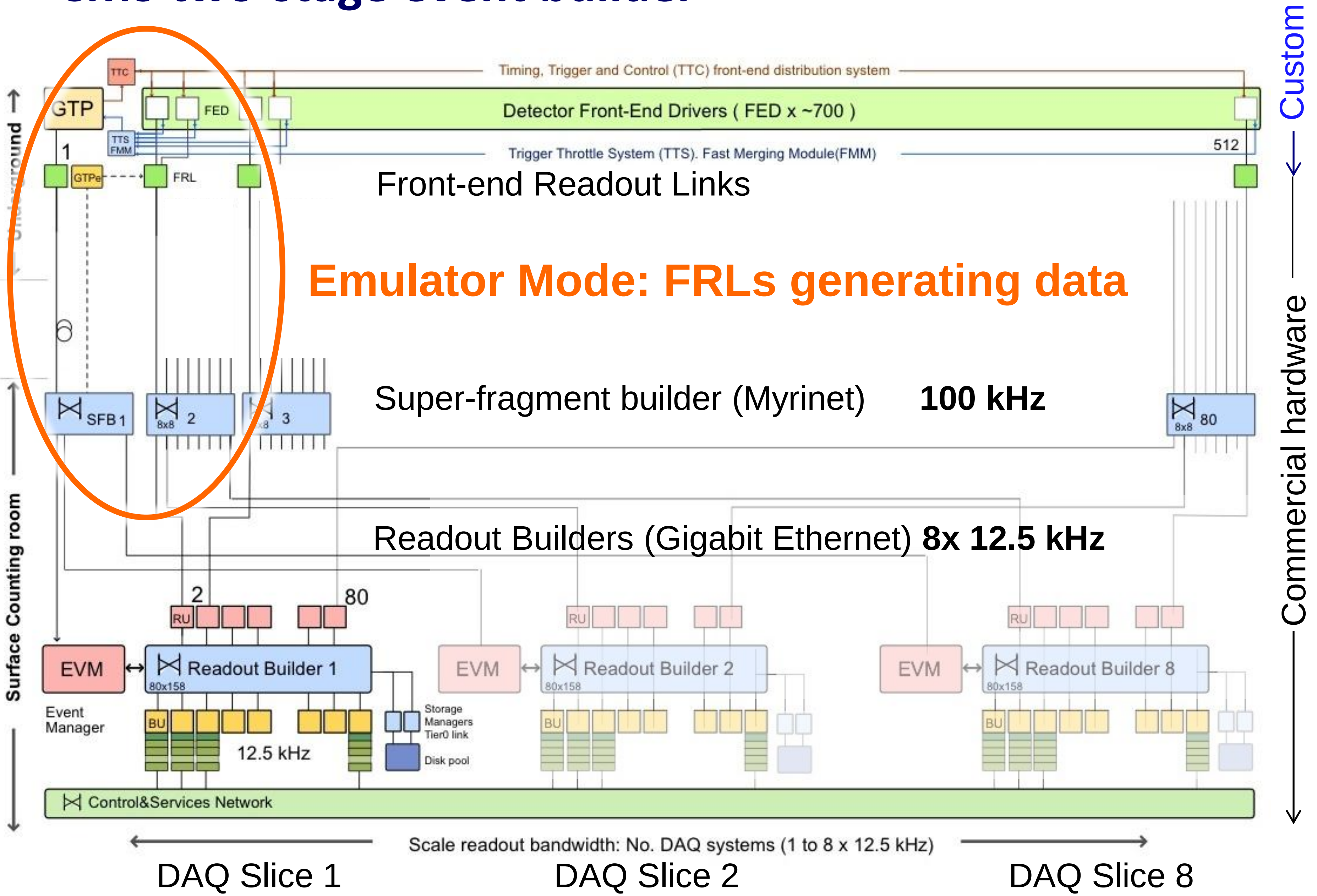
CMS two-stage event builder



Trigger Throttling System

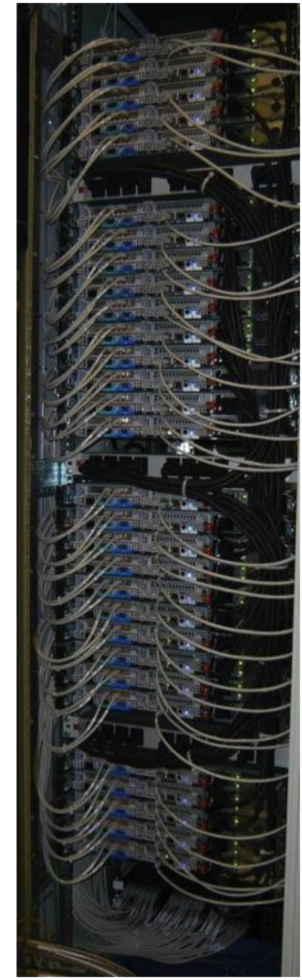
Loss-less DAQ always builds complete events back-pressure in case of congestion

CMS two-stage event builder



Installed hardware

- Custom compact PCI Modules
  - 512 Frontend Readout Links
  - 60 Fast merging modules (trigger throttling)
- Myrinet Switches
  - 12 clos-256 enclosures
  - 1536 2.5 Gb/s links underground to surface
- “Readout Unit” PC nodes
  - 640 times dual 4-core E5130 (2007)
  - Each node has 3 links to GbE switch
- Gbe Switches
  - 8 times F10 E1200 routers
  - In total ~4000 ports (1 Gb/s)
- Event builder–output + HLT nodes (“BU-FU”)
  - Currently ~13000 cores, 26 TB RAM
  - Extensible – see later
- Storage Manager
  - 16 PCs
  - Storage Area Network (NexSan SataBeasts), 300 TB
  - 2.1 GB/s write speed (2.6 GB/s w/o Tier0-Transfers)



CMS DAQ Software

Run Control System – Java, Web Technologies

Defines the control structure

GUI in a web browser

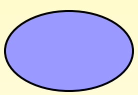
HTML, CSS, JavaScript, AJAX

Run Control Web Application

Apache Tomcat Servlet Container

Java Server Pages, Tag Libraries,

Web Services (WSDL, Axis, SOAP)

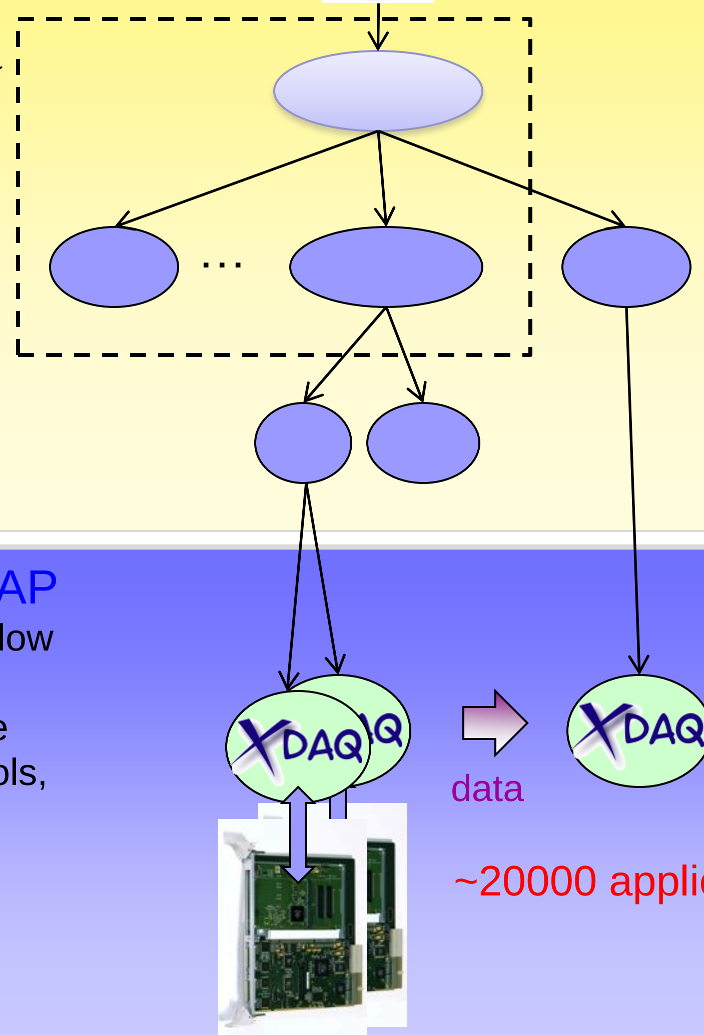


Function Manager

Node in the Run Control Tree

defines a State Machine & parameters

User function managers dynamically loaded into the web application



XDAQ Framework – C++, XML, SOAP

XDAQ applications control hardware and data flow

XDAQ is the framework of CMS online software

It provides Hardware Access, Transport Protocols, Services etc.

XDAQ Application

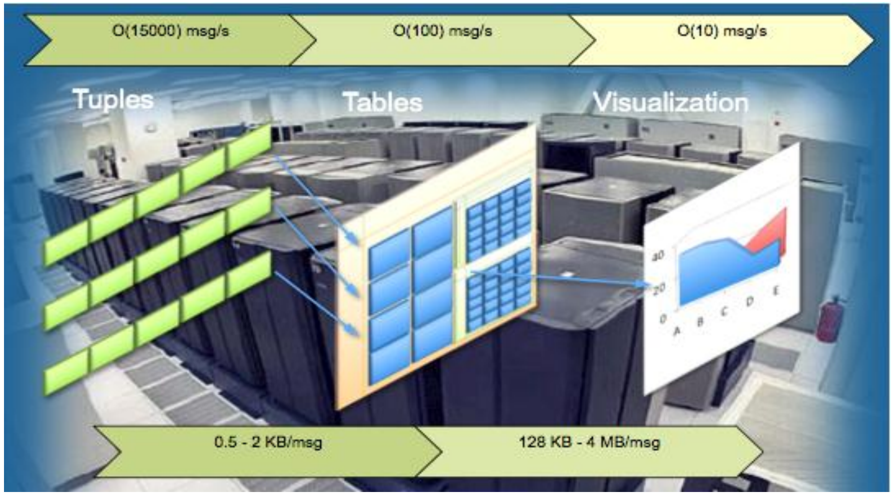
~20000 applications to control

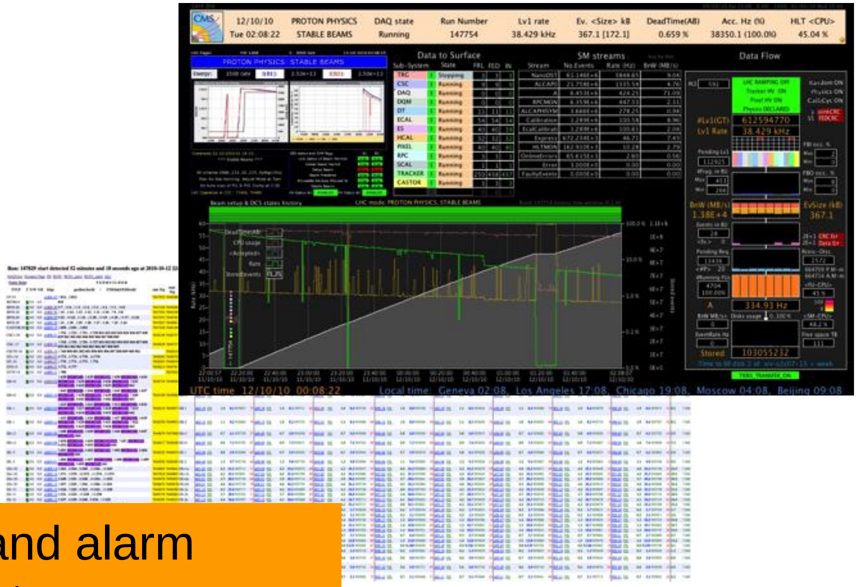
Top level control Web - GUI

- GUI is a web-page
- Top level is Global state machine, aware of LHC states, eg stable beams
- Trigger configuration and clock source (LHC/local)
- Control of individual sub-systems for fast recovery
- Cross-checks and warnings to help the DAQ shifter

Monitoring

- Monitoring tuples and error messages
  - O(2000) PCs
  - O(20000) applications
- Collect and aggregate
  - Hierarchy of collectors
  - Load balancing
  - Latency ~seconds
- Access service for
  - Error reporting GUI
  - Visualization applications
  - DAQ Doctor ("expert system")

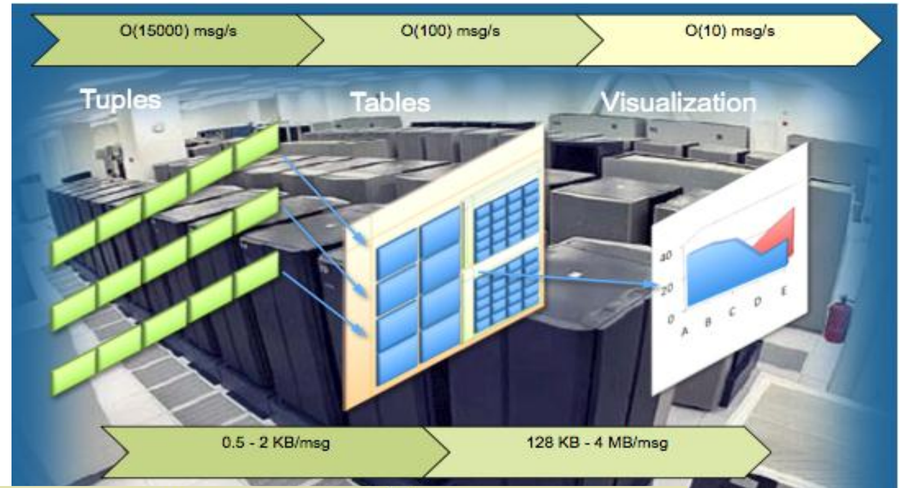


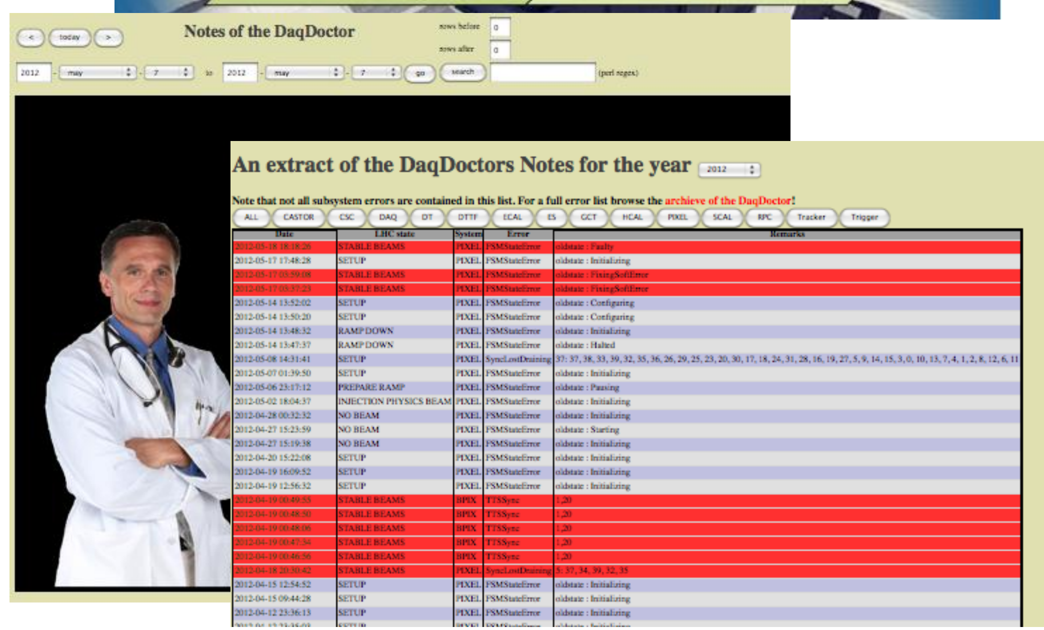


Poster #139 / session 2: Distributed error and alarm processing in the CMS data acquisition system

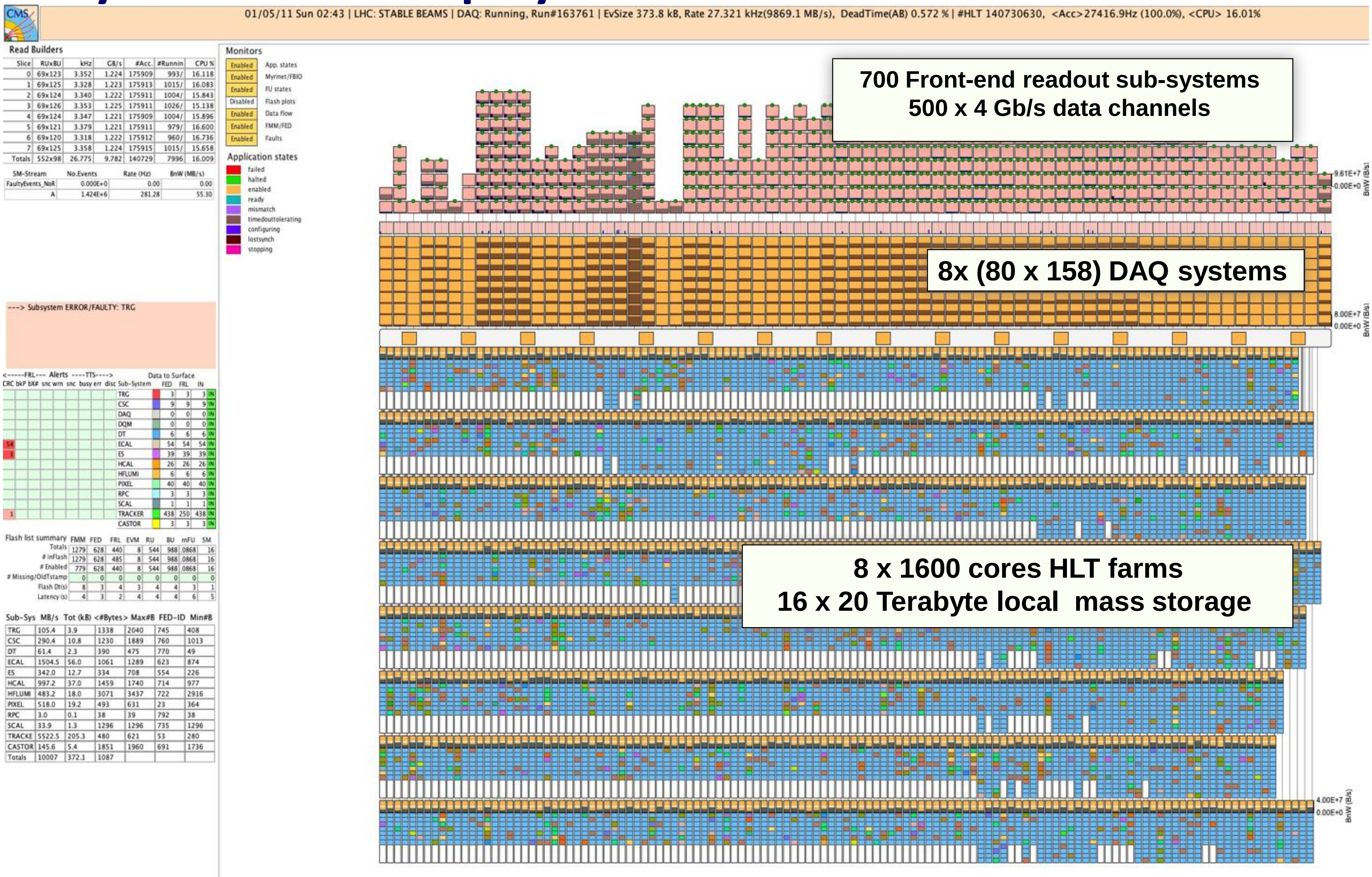
The DAQ doctor

- Constantly analyzes monitoring information
- Detects abnormal situations
  - Warns the shift crew with Text & Audio alerts
  - Gives recovery instructions
  - Now also creates new DAQ configurations
  - Dumps diagnostic info for post-mortem analysis
- All diagnostic information is archived & categorized by sub-system

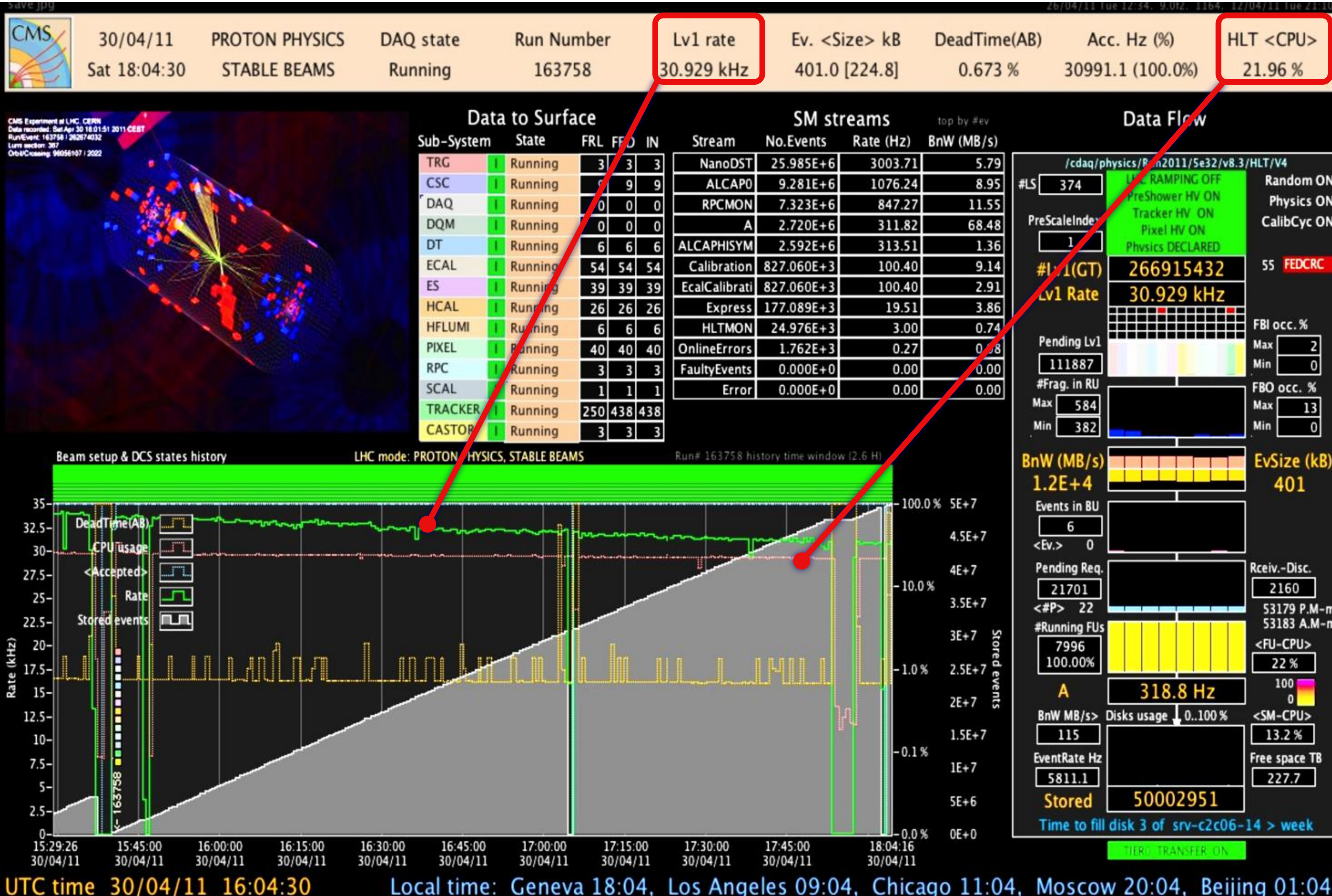




System status display

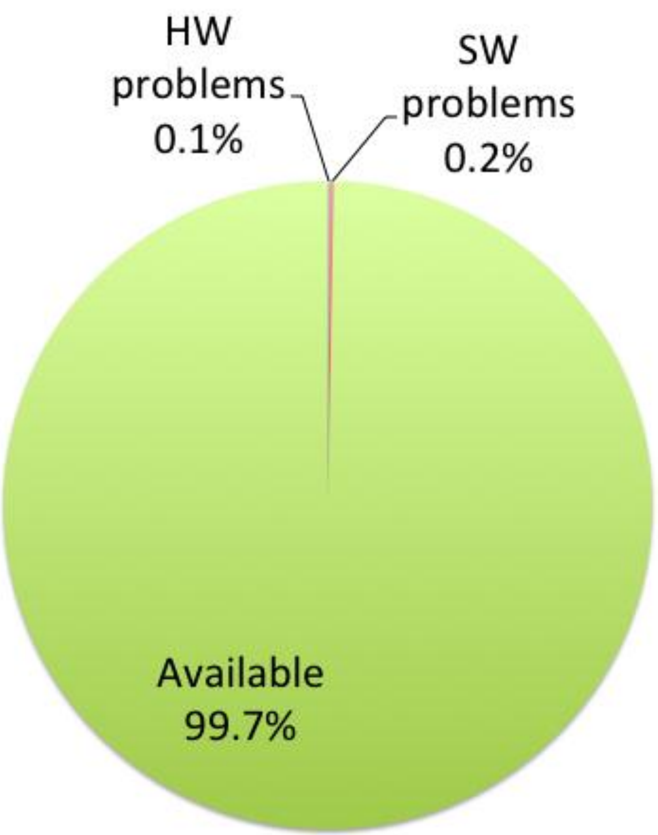


Data acquisition in operation




Operational Efficiency
CMS control room, Cessy, France …

CMS Central DAQ efficiency, 2011 - pp



CMS central DAQ availability during stable beams: 99.7 %

CDAQ down time : < 4 hours

Luminosity lost: ~ 0.5% of delivered

Central DAQ Down times

- Software (24 down times, 3 hours)
  - Due to surfacing and newly introduced bugs
    - Often related to features that were added to the original design
  - Usually fixed as soon as identified
- Hardware (8 down times, 1 hour)
  - 1 Broken Myrinet link
  - 1 Broken Gigabit-ethernet switch line card
  - 1 Broken control network switch
  - 203 PC failures

Only 1 hour of down time due to HW ?
=> Resilience

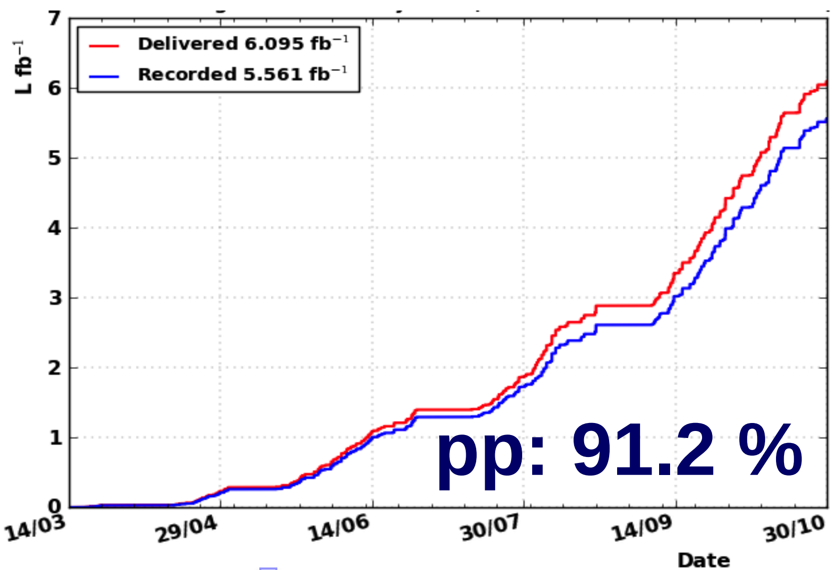
Resilience features of CMS DAQ

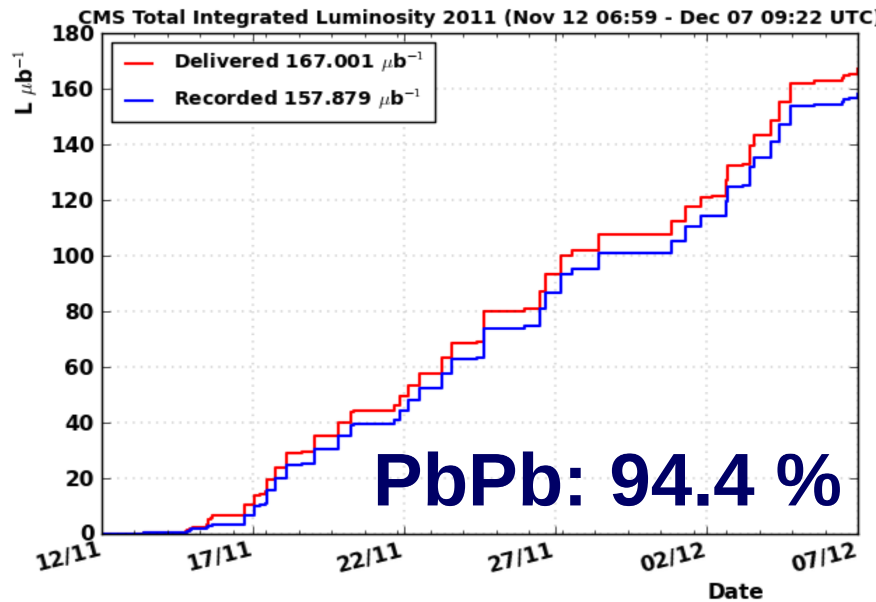
- **Automatic restart** of crashed Event Filter processes during an ongoing run
- **Tolerance** against crashed processes & machines
  - Data flow applications / machines
    Builder & Filter Units, Storage Manager
    run continues with reduced throughput
  - Applications controlling custom hardware
    run continues with degraded monitoring
- **Slice Masking**: fast workaround for single points of failure in a DAQ Slice (Readout Units, GbE switches, etc.)
  - mask the slice and continue with 7/8th of capacity
  - requires stop/start of the run

Resilience features of CMS DAQ (2)

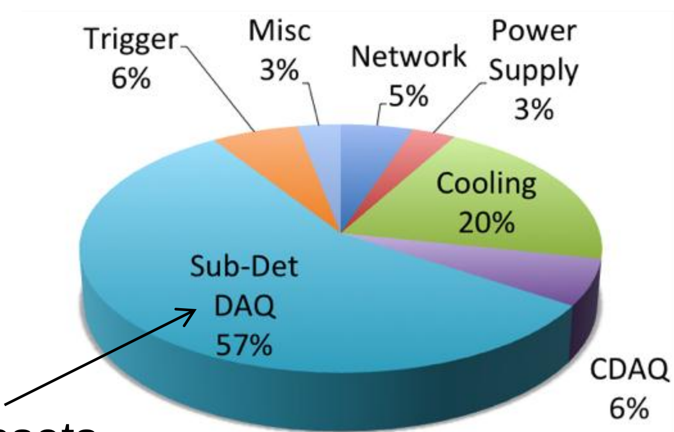
- **Fast Configuration Change**
  - Mask a broken machine (except those controlling custom hardware)
  - Mask a rail in one leg of the Myrinet Super-Fragment Builder
  - Use only 1 out of 2 racks of Storage Managers
- **Tool: CMS DAQ Configurator**
  - Until mid 2010: Several tools needed, manual bookkeeping
    new configuration in ~10 minutes
  - mid 2010 - 2011: One-Step tool with blacklist database
    new configuration in ~2 minutes
  - Since 2012: One-Step tool automatically launched by DAQ Doctor
    new configuration in ~ 40 seconds
- **Configuration change requires a run stop/start**

Over-all CMS data taking efficiency 2011





pp



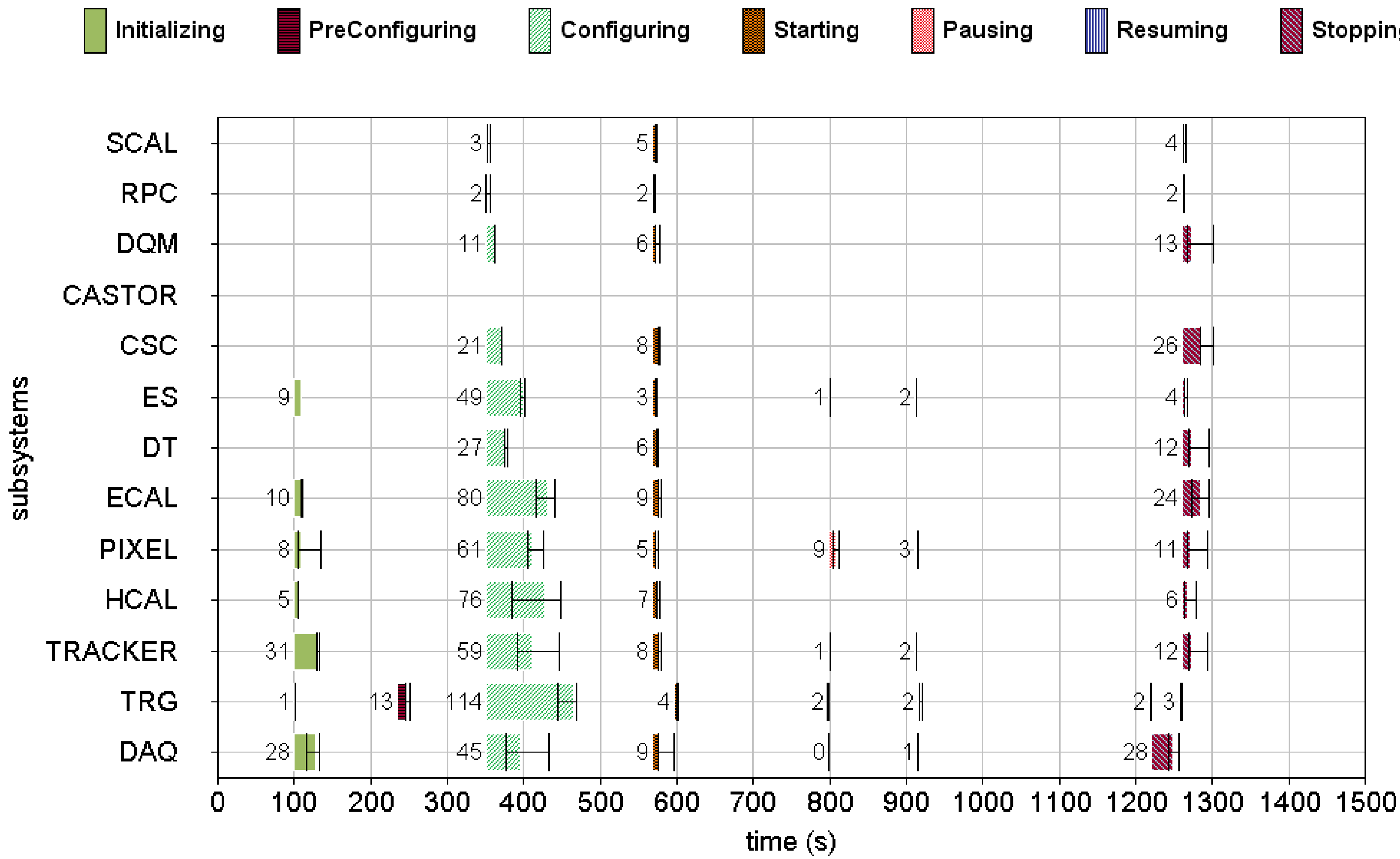
In part due to Single-Event upsets

Lumi lost in down times (pp)

New: Automatic Recovery from Single Event Upsets

- Frequent sub-detector DAQ failures due to Single-Event upsets observed towards the end of 2011 with increasing instantaneous luminosity
- Recovery typically needed re-configuration of the system
- New in 2012: Automatic Single-event-upset Recovery Mechanism
  - Coordinated by top-level run control
  - Sub-detector detects SEU problem and notifies top-level run control
  - Top-level Run Control
    - Invokes a recovery transition
      - On the requesting sub-system
      - Other sub-systems may do preventive actions in the shadow

Impacting over-all efficiency: startup time



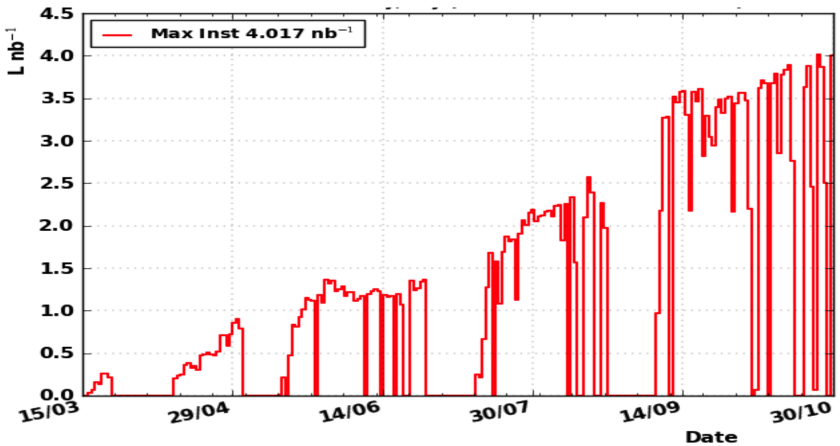
During stable beams, Apr 13 – May 2, 2012

- Start of data taking session (starts all software): < 3 minutes
- Run stop & start: 1 min 15 seconds

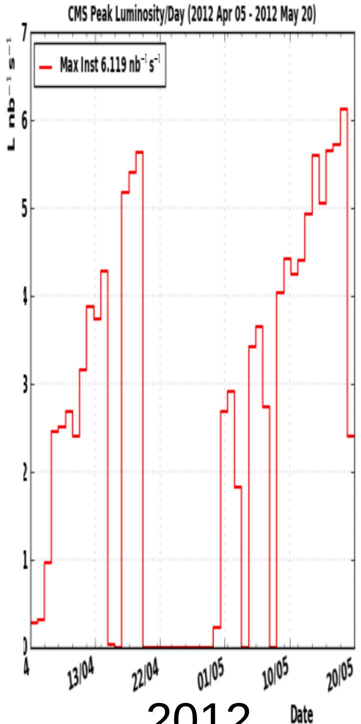
Evolution of operating conditions

Evolution of operating conditions

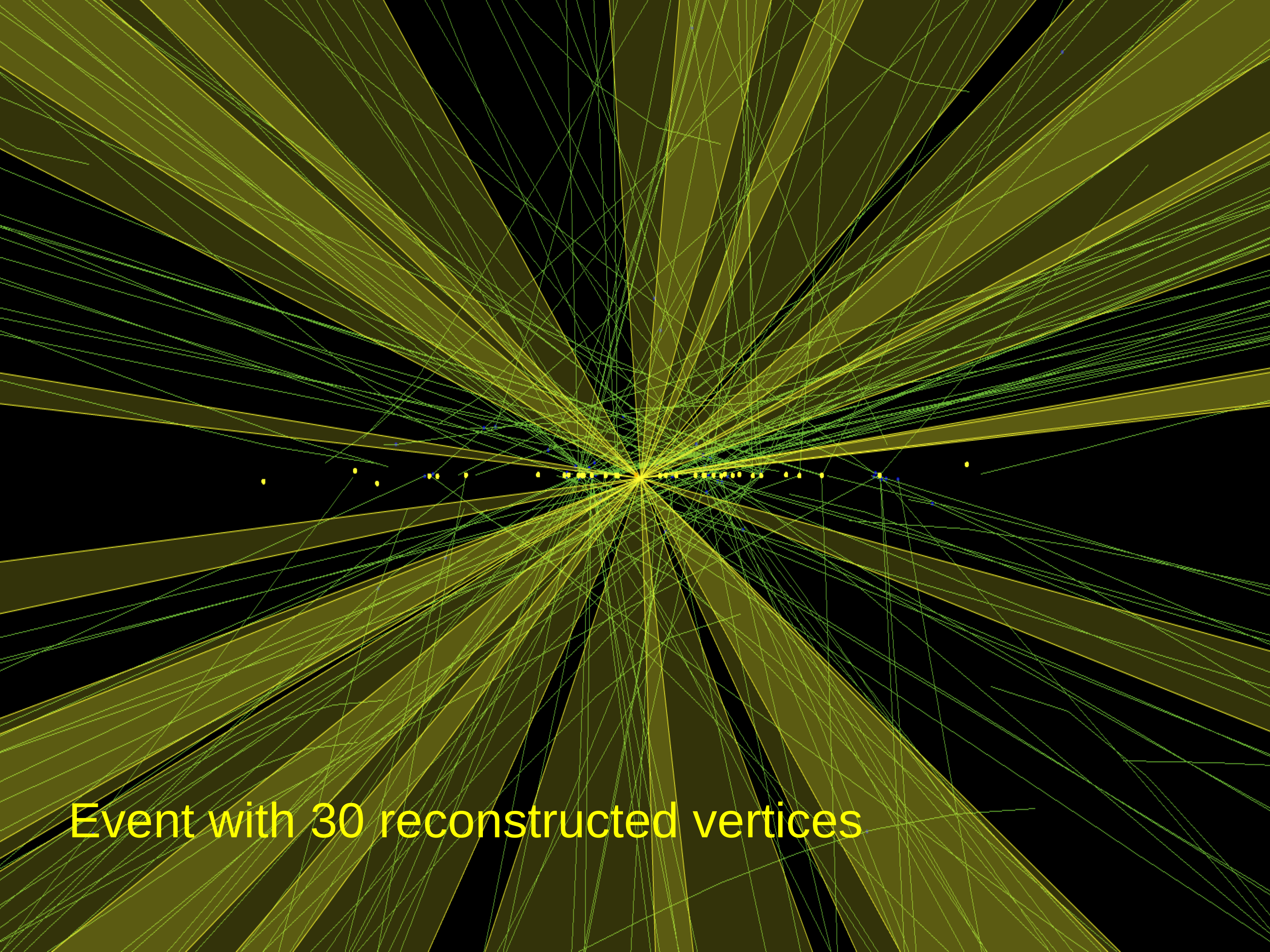
- Design
  - L = 10^{34} / cm^2s, 25 ns bunch spacing, 14 TeV
  - Pile-up of 20
  - DAQ at 100 kHz
- 2012
  - L = $7x10^{33}$ / cm^2s (expected), **50 ns bunch spacing**, 8 TeV
  - Pile-up of 35 **(~2x design)**
  - DAQ at 100 kHz



2011

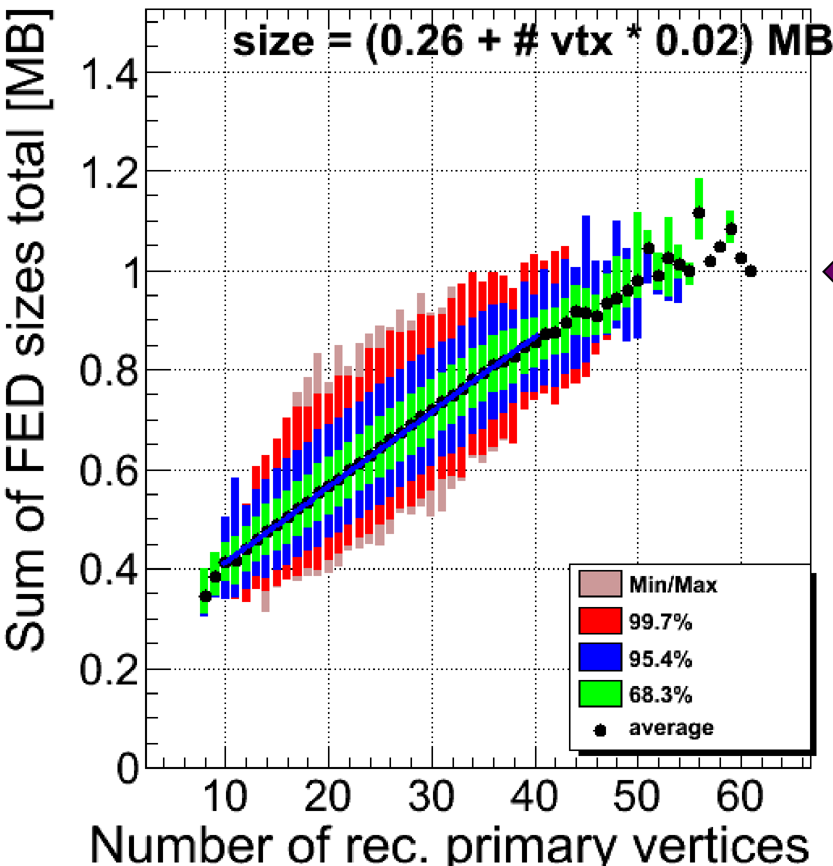


2012


Event with 30 reconstructed vertices

Can we handle the event size?

Can we handle the event size ?



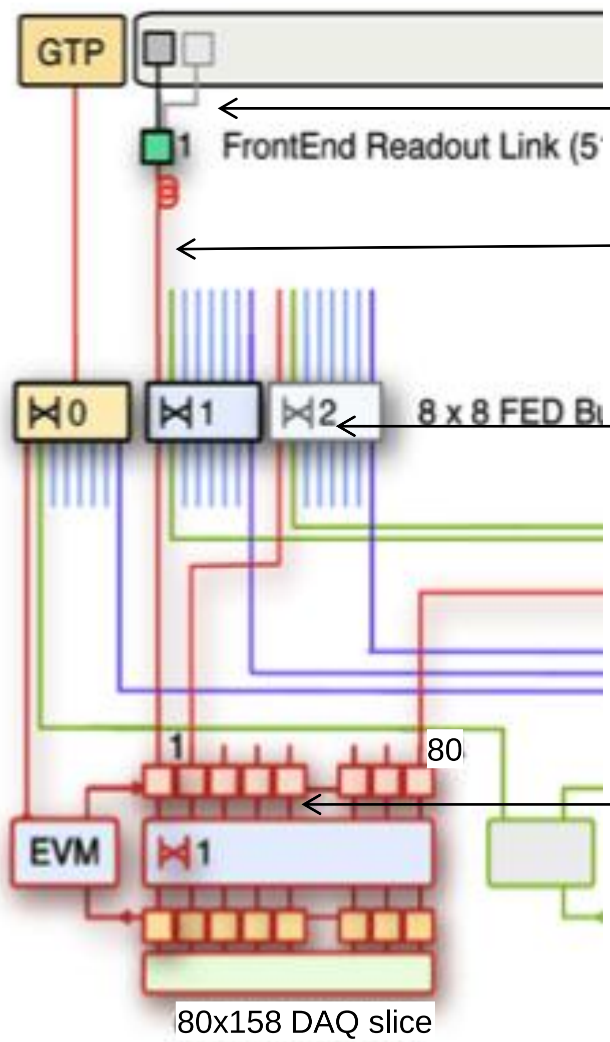
CMS design event size: 1 MB

- Globally yes, but have to look at individual Inputs & Super-fragment builders

High pile-up fill
Run 179827

Expected 2012
30 primary vertices corresponding to pile-up of 35

Bandwidth at various stages



SLINK: **400 MB/s** (64b @ 50 MHz)

✔ No problem

Myrinet link: **500 MB/s** (2 rails of 2.5 Gbit/s)

✔ No problem

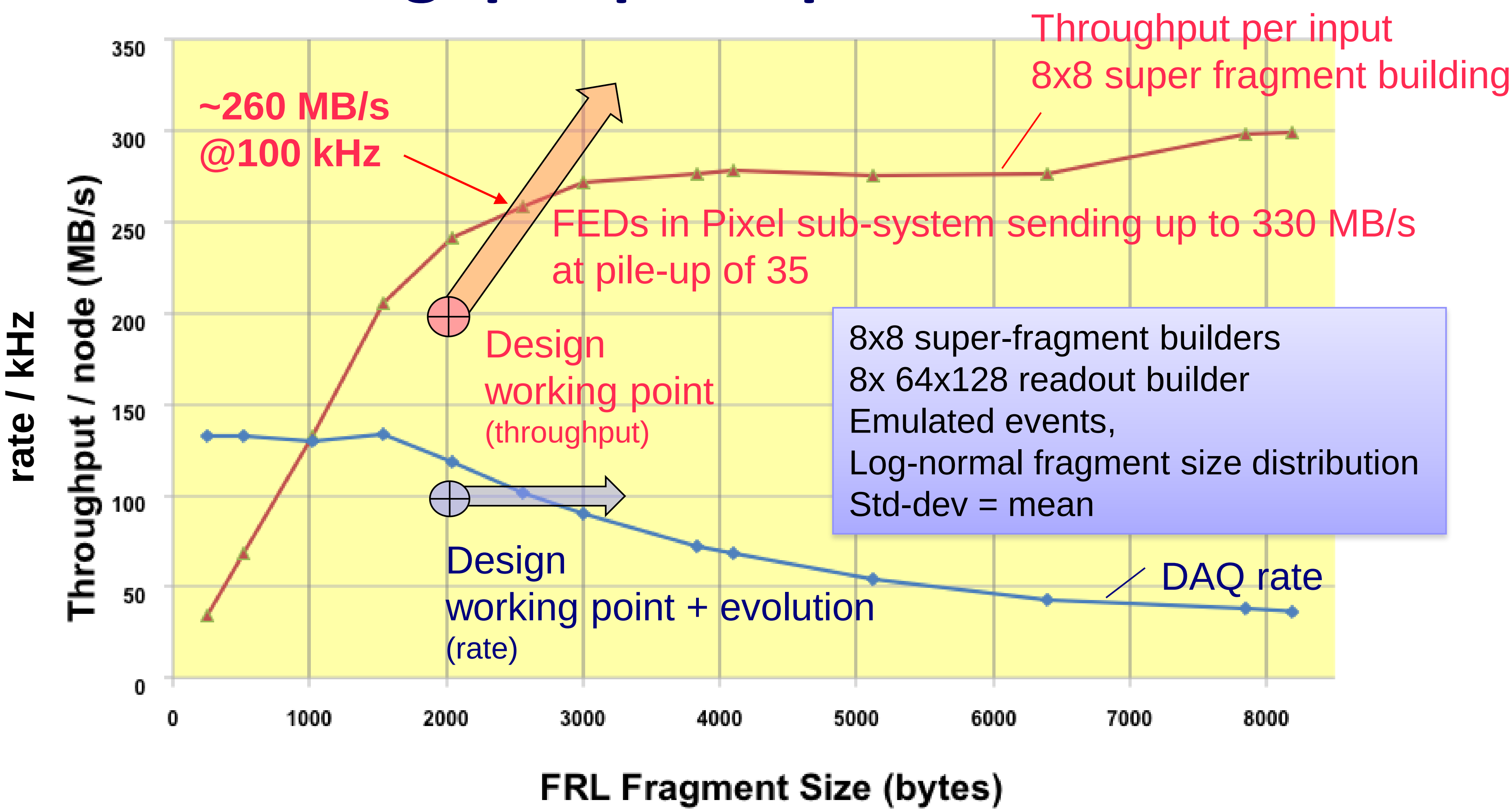
Myrinet Cross-bar switch: **~260 MB/s**
Wormhole-routed
No buffering in switch
Head-of line blocking reduces throughput by up to 50% when no traffic-shaping applied

Some Super-Fragment Builders critcal

Gigabit Ethernet: 3 rails: **375 MB/s**
Ethernet switches have internal buffer shared memory – no HOL blocking

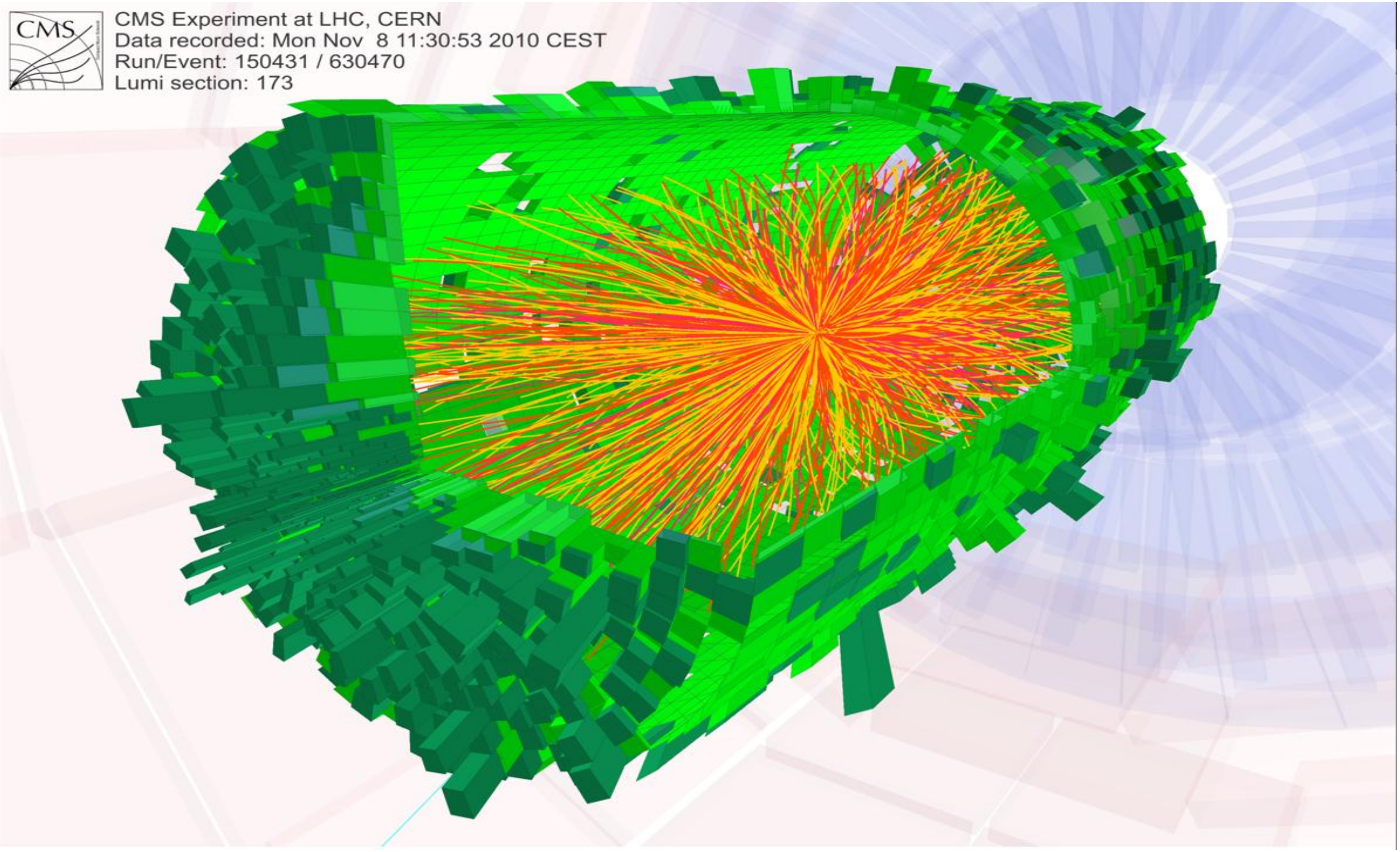
✔ No problem

DAQ throughput per input



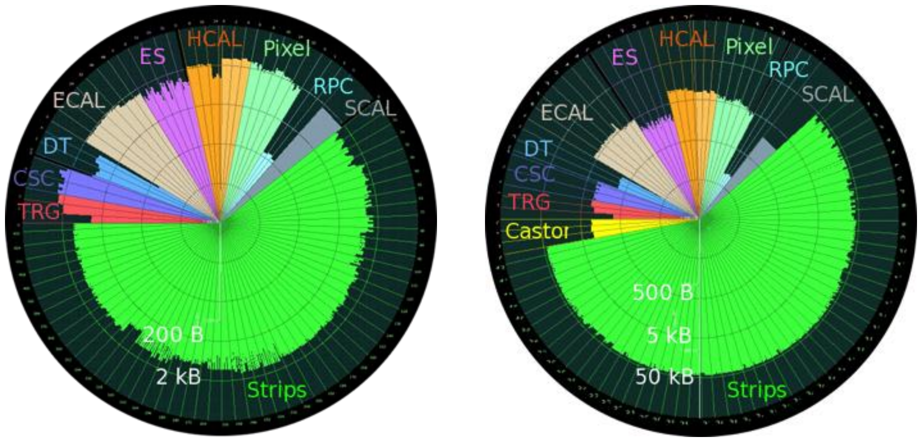
- **32 inputs (Pixel sub-system) may exceed available throughput at pile-up of 35**
  - ✓ Solution: super-fragment builders with fewer than 8 inputs for pixel
    combine some smaller super-fragment builders,

Throughput in Heavy-Ion Operation


CMS Experiment at LHC, CERN
Data recorded: Mon Nov 8 11:30:53 2010 CEST
Run/Event: 150431 / 630470
Lumi section: 173

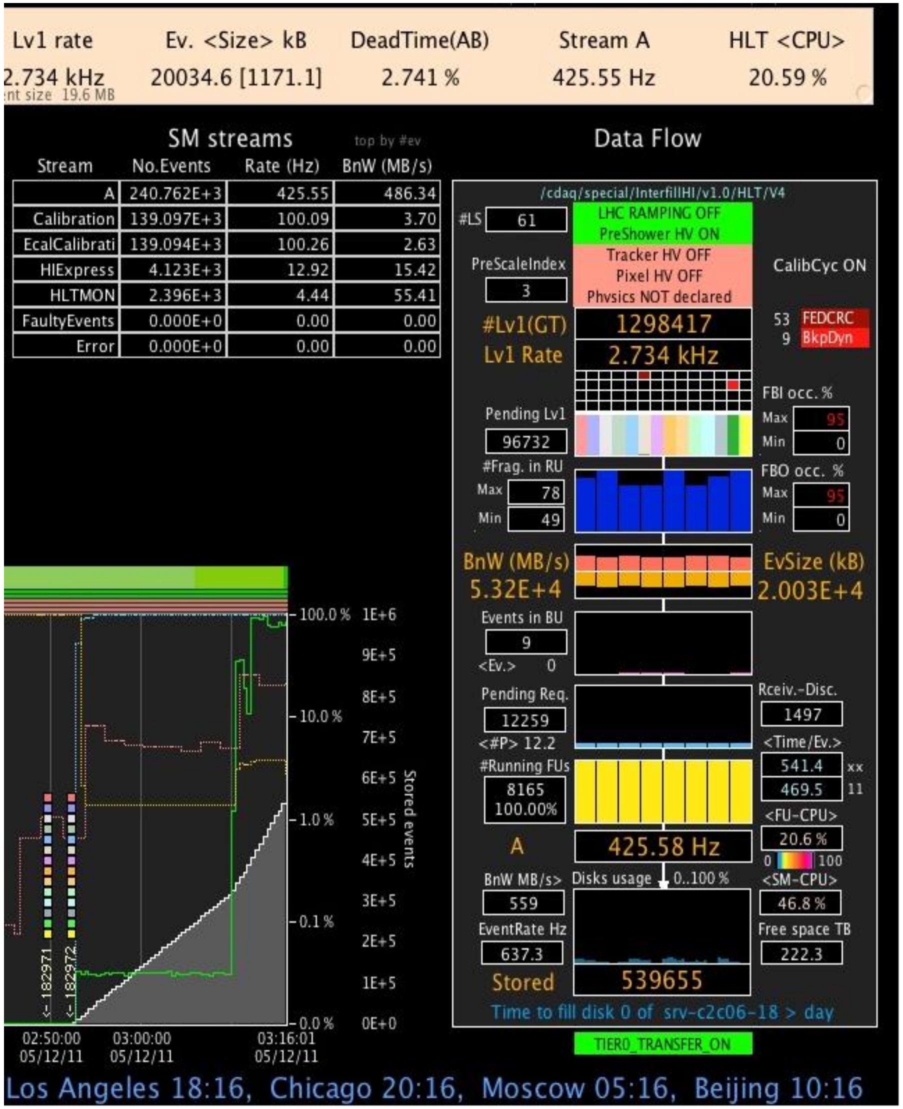
Proton physics – Ion physics

	Proton physics	Ion Physics
Zero suppression for Si-strip tracker	**In FED (hardware)**	In HLT farm (software)
Fragment size	**2 kB**	50 kB (**100 kB** after merging)
Event size	1 MB	20 MB
Max trigger rate	100 kHz	3.5 kHz
Max. DAQ throughput per input (8x8 super-fragment building)*	260 MB/s	350 MB/s (DAQ settings tuned for large fragments)



*log-normal distributed event size
std-dev = average

DAQ performance at start of 2011 HI fill



2.7 kHz L1 rate

20 MB / event

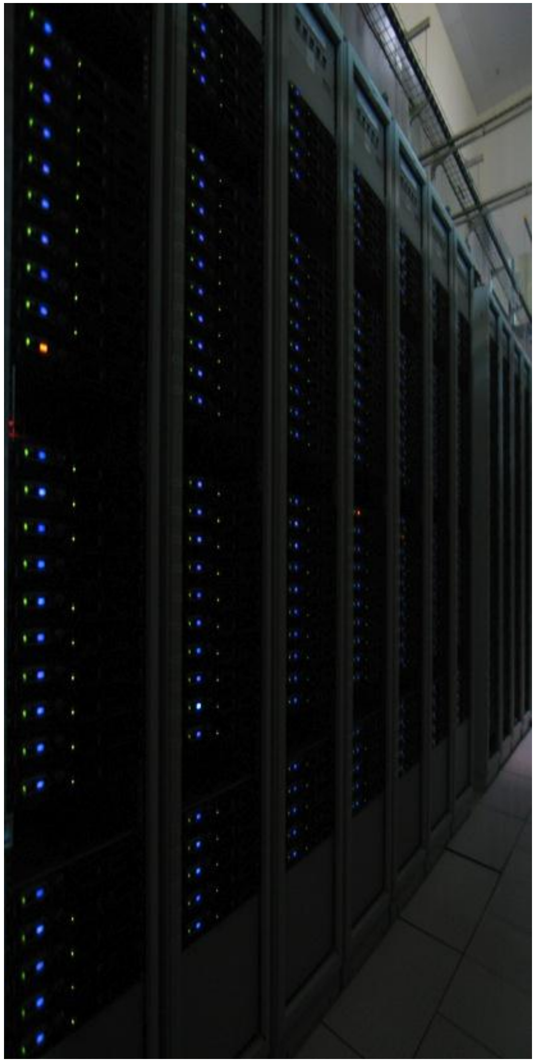
Zero-suppression in HLT farm -> 1MB

560 MB/s to disk

2010 HI run: ZS offline /
ROOT compression in HLT
11 MB / event, 1.8 GB/s to disk

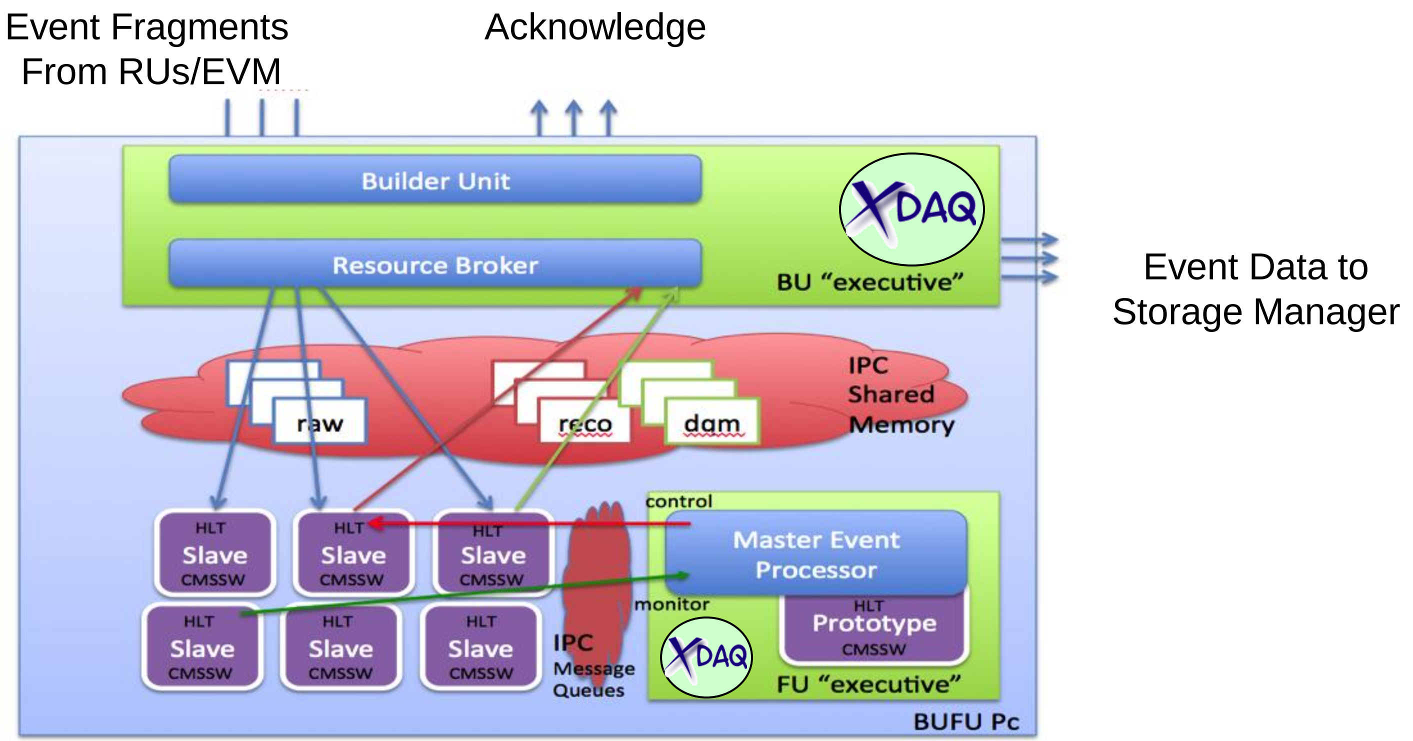
High-Level Trigger

Filter Farm deployment strategy



- High-level trigger based entirely on commodity hardware
- Buy the processing power just in time
  - Better value for money
- Computing requirements evolve with LHC luminosity
  - Higher luminosity requires higher selectivity ➔ more complex algorithms
  - Higher luminosity ➔ more pile-up ➔ more time consuming tracking
- Challenge: increasing number of cores per machine

High-Level Trigger Software



- Trigger algorithms are processed with CMS offline software framework CMSSW
- 1 Process per core / per hyperthread but limited memory available
- Copy On Write: 1) Prototype process loads configuration and conditions
  2) Child processes are forked
- Coupling between XDAQ and CMSSW very tight
  - same compiler, same process

Poster #219 / session 2: The CMS High Level Trigger System: Experience and Future Development

HLT farm evolution

2009:

720x

May 2011 add:

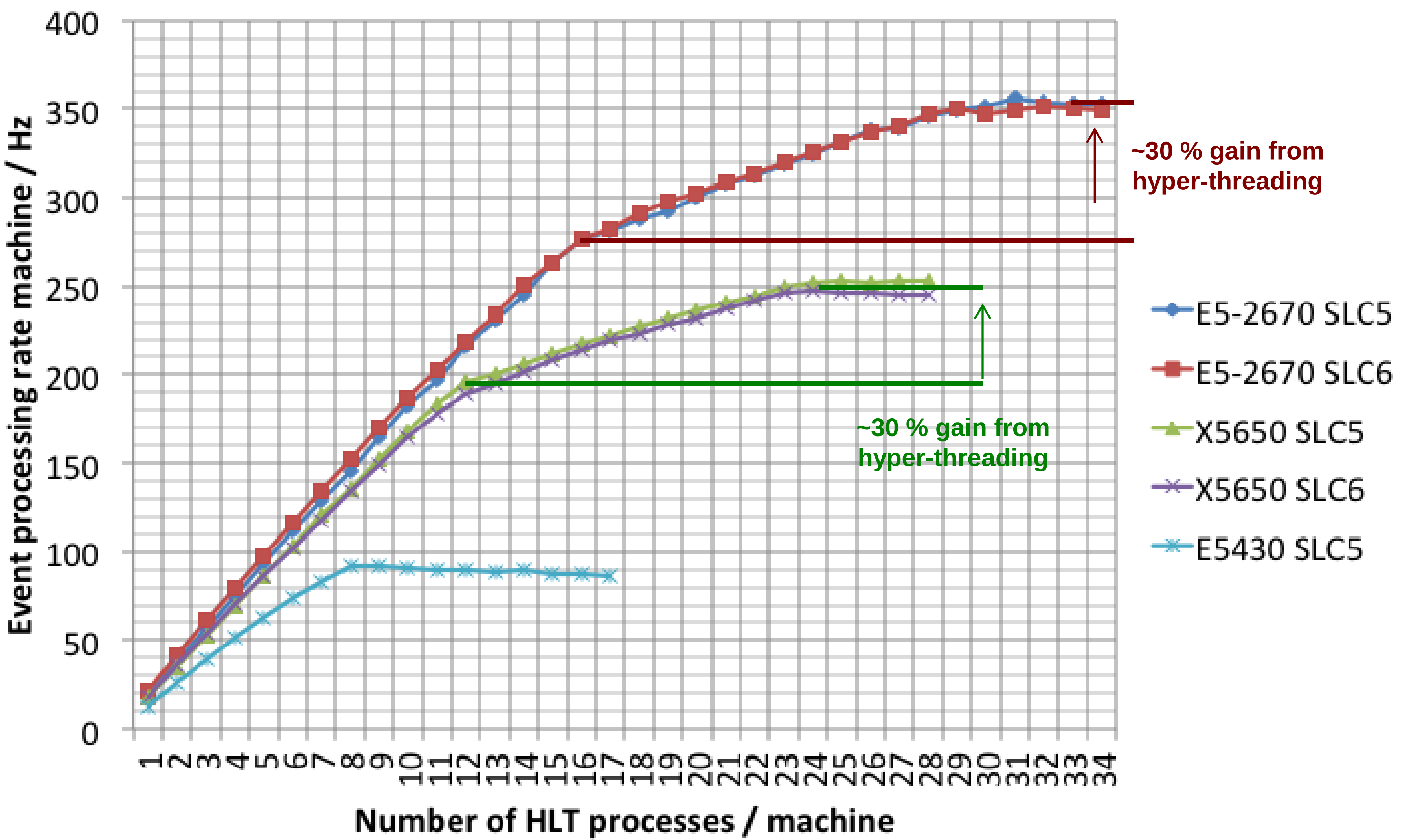
72x

May 2012 add:

64x

	Original HLT System **Dell Power Edge 1950**	**2011 extension** **Dell Power Edge c6100**	**2012 extension** **Dell Power Edge c6220**
Form factor	1 motherboard in 1U box	4 motherboards in 2U box	4 motherboards in 2U box
CPUs per mother-board	2x 4-core Intel **Xeon E5430 Harpertown**, 2.66 GHz, 16GB RAM	2x 6-core Intel **Xeon X5650 Westmere**, 2.66 GHz, hyper-threading, 24 GB RAM	2x 8-core Intel **Xeon E5-2670 Sandy Bridge**, 2.6 GHz, hyper threading, 32 GB RAM
#boxes	720	72 (=288 motherboards)	64 (=256 motherboards)
#cores	5760	3456 (+ hyper-threading)	4096 (+ hyper-threading)
cumulative #cores	5.6k	9.1k	13.2k
cumulative #CMSSW	5k	11k	20k

HLT machine performance with HLT playback



HLT menu for $5x10^{33}/(cm^2s)$, recent data sample & software

HLT farm evolution

2009:

720x

May 2011 add:

72x

May 2012 add:

64x

	Original HLT System Dell Power Edge 1950	**2011 extension Dell Power Edge c6100**	**2012 extension Dell Power Edge c6220**
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#cores	5760	3456 (+ hyper-threading)	4096 (+ hyper-threading)
cumulative #cores	5.6k	9.1k	13.2k
cumulative #CMSSW	5k	11k	20k

Per-event CPU budget @ 100 kHz:

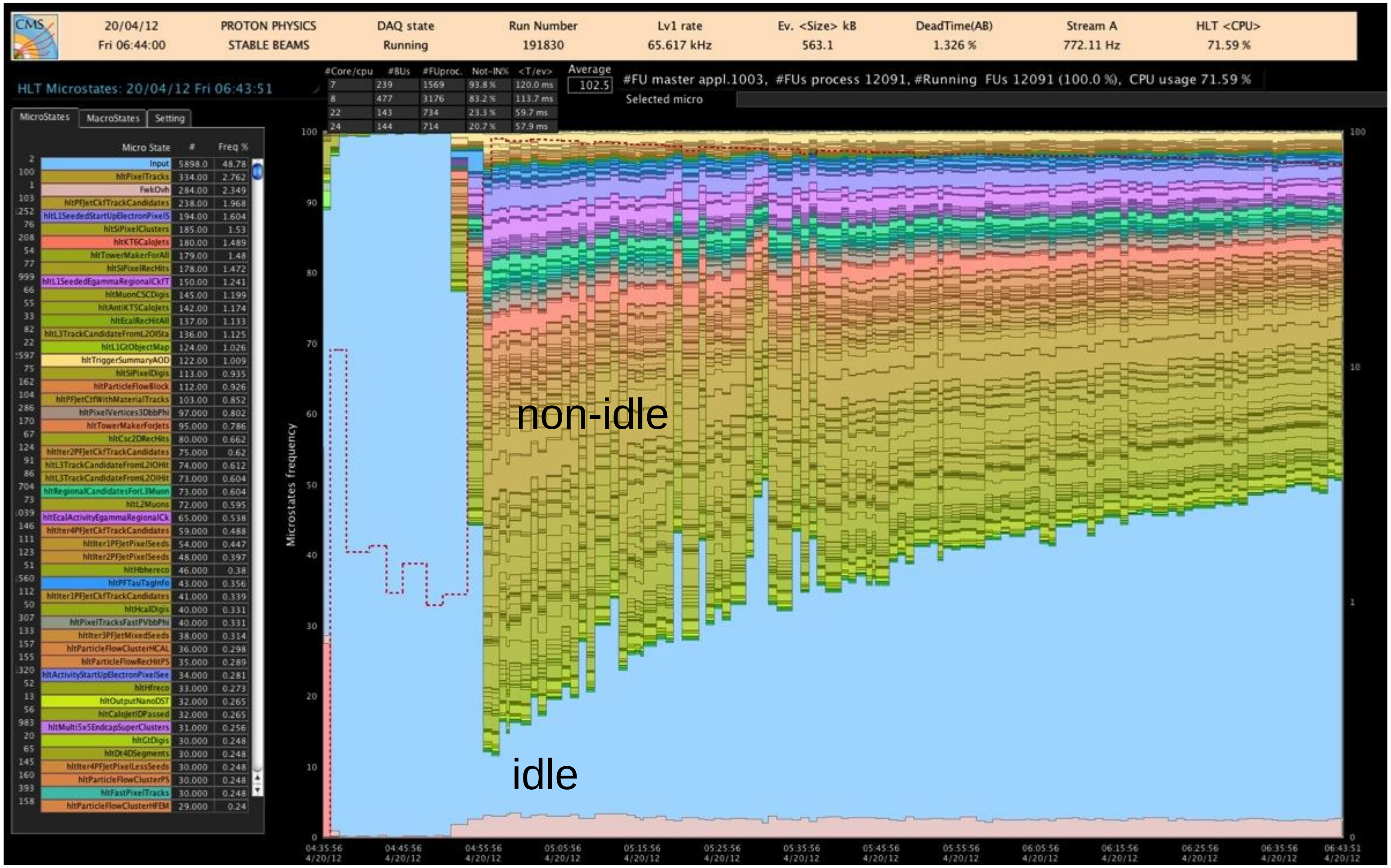
2009: ~50 ms / evt

2011: ~100 ms / evt

2012: ~150 ms / evt

(CPU budgets are on 1 core of an Intel Harpertown)

States of HLT nodes at start of a pp fill before extension 2

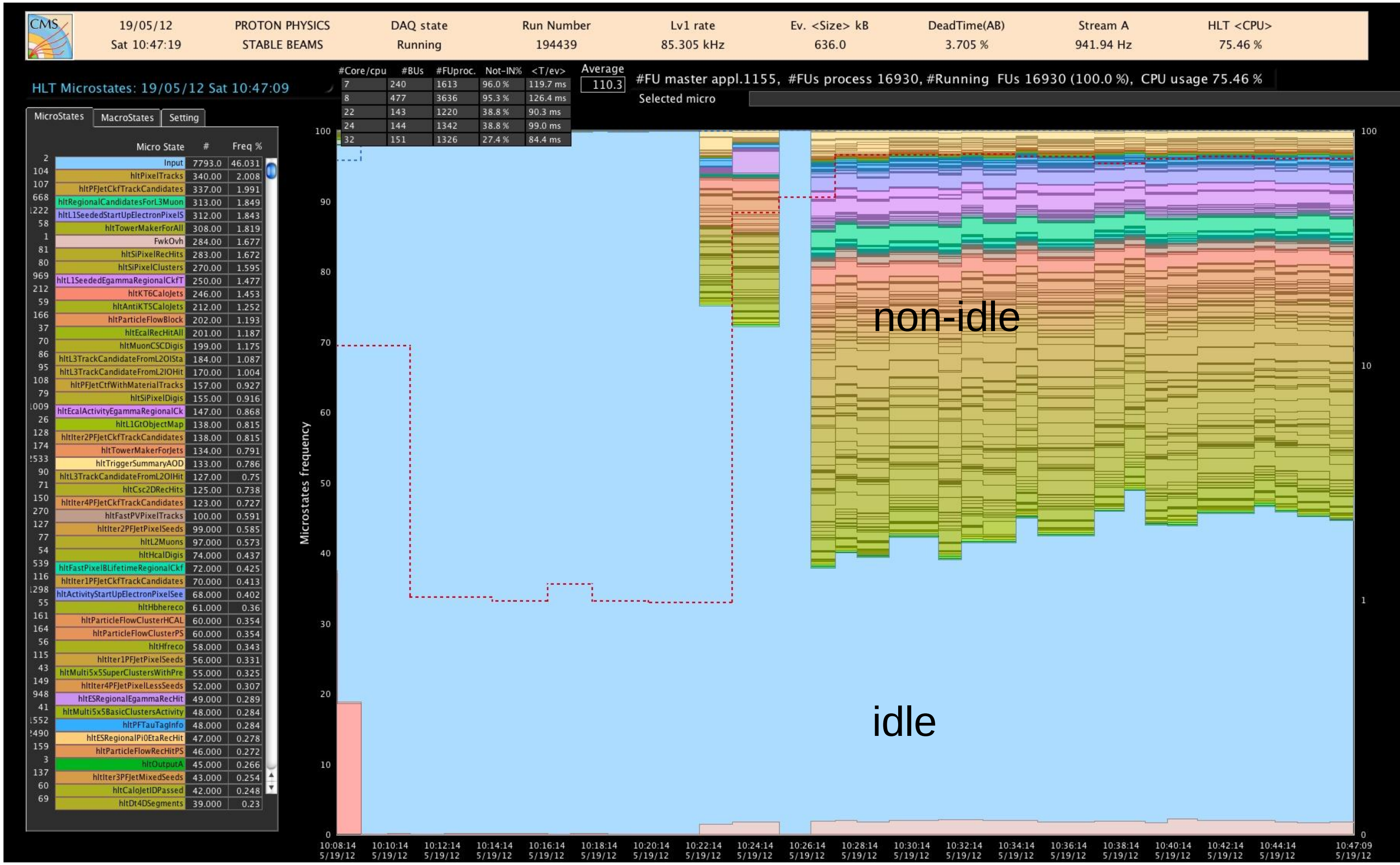


Time into fill

Fill 2536, 20 Apr 2012
$L_{peak} = 6.1 \times 10^{33}/(cm^2 s)$

HLT farm almost fully utilized at start of fill (since September 2011)
Algorithms are tuned for available computing power

HLT states with HLT extension 2



HLT extension-2 in 5 out of 8 DAQ slices

Time into fill →

- Ready for higher instantaneous luminosity and more complex algorithms

Fill 2645, 19 May 2012

$L_{peak} = 6.1 \times 10^{33}/(cm^2 s)$

Summary

- CMS DAQ system building events at 100 kHz in 2 stages
  - 1MB event size, 100 GB/s throughput
- Central DAQ availability 2011: 99.7 %
- Continuous effort to improve CMS over-all efficiency
- Increased data volume due to higher pile-up with 50 ns LHC bunch spacing can be handled
- HLT farm being extended as required
  - reached 13000 cores this month. Ready for higher luminosity.

Beyond 2012: see next talk …

Thank You

Bonus track

Comparison of HLT machines

	Harpertown	Westmere	Sandy Bridge
	Xeon E5430, 2.66 GHz	Xeon X5650, 2.66 GHz	Xeon E5-2670 2.6 GHz
#cores	8 (2x4)	12 (2x6) + HT	16 (2x8) + HT
SPEC int (max)	25	37 (= 25 * 1.5)	52 (= 25 *2.1)
HEP Spec	73	208	386
CPU burner test*	1.0	3.6	5.4
Eg Action 11 test (CPU + memory)	1.0	2.2	3.3
HLT 2011	1.0	2.4	-
HLT playback*	1.0	2.8	3.9

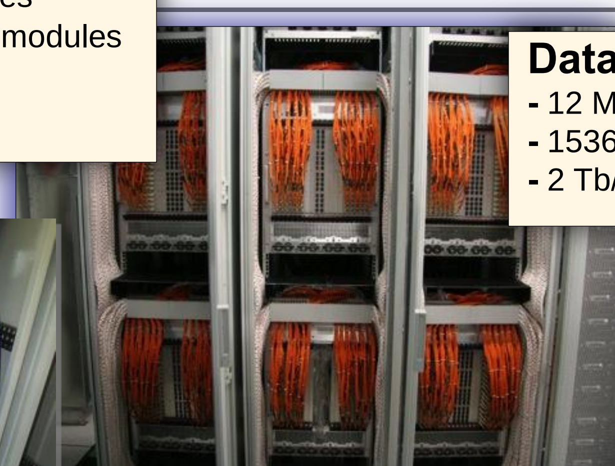
Performance per motherboard

* Does not include event building

CMS DAQ installation

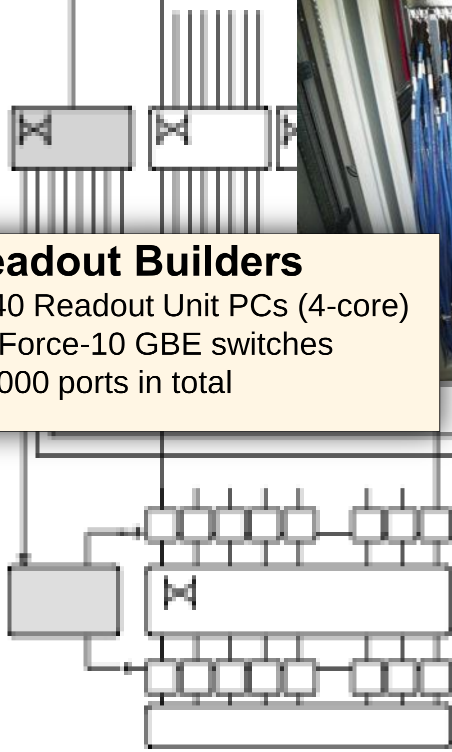
Detector readout.

- 650 Slink/FMM cables
- 500 FRL + 60 FMM modules
- 60 FRL/FMM crates
- 200 DAQ/DCS PCs



Data to surface

- 12 Myrinet switches (clos-256)
- 1536 D2S links (2.5 Gb/s)
- 2 Tb/s total



Readout Builders

- 640 Readout Unit PCs (4-core)
- 8 Force-10 GBE switches
  4000 ports in total

High Level Trigger Farm

- 110 water cooled racks
- Extensible design
- Currently 13000 cores, 26 TB RAM
- Storage to disk at 2.1 GB/s
- 300 TB Mass storage

Experiment control and monitor system and WWW services

Cessy: Master&Command control room

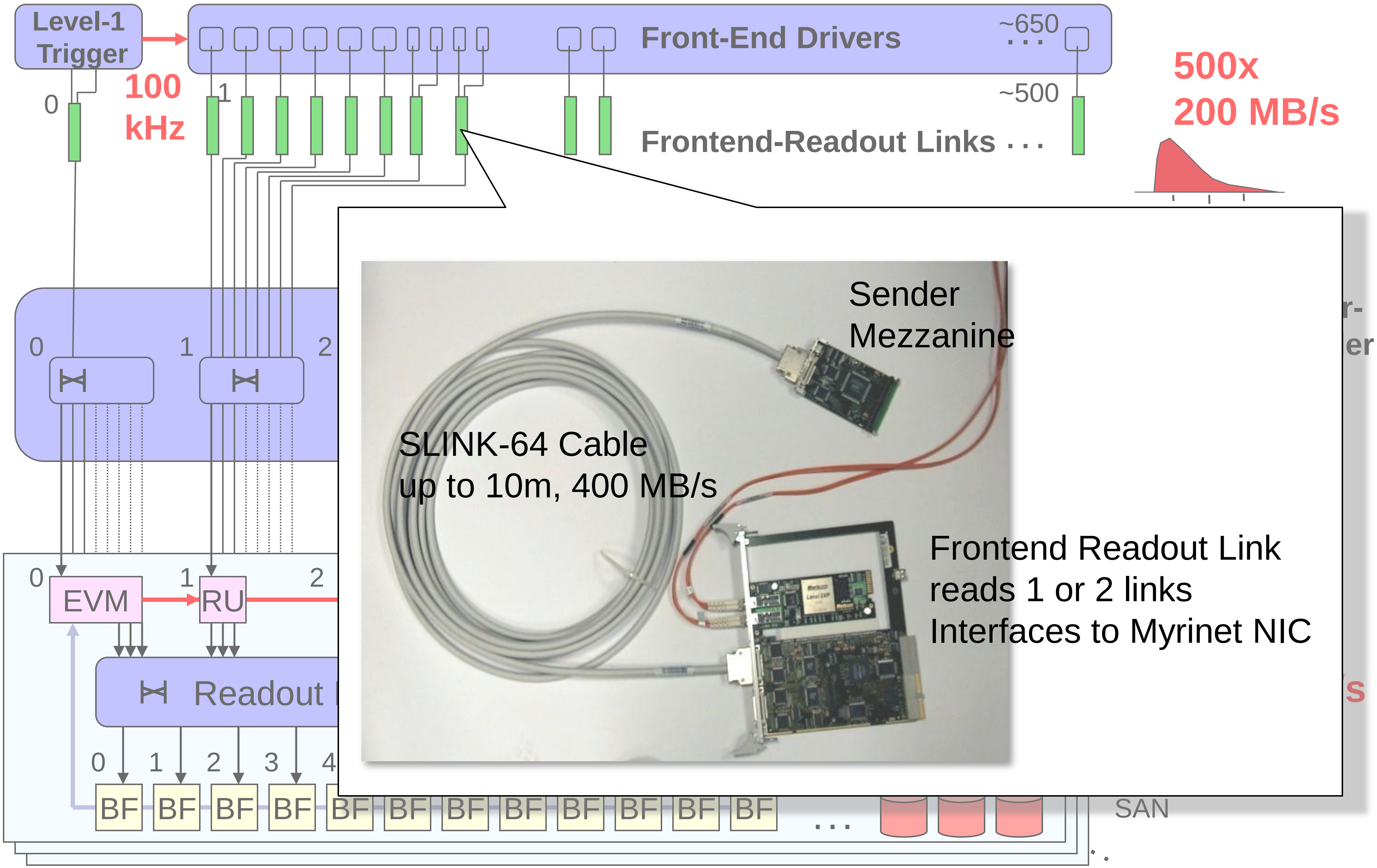
Fermilab: Remote Operations Centre

Meyrin: CMS DQM Centre

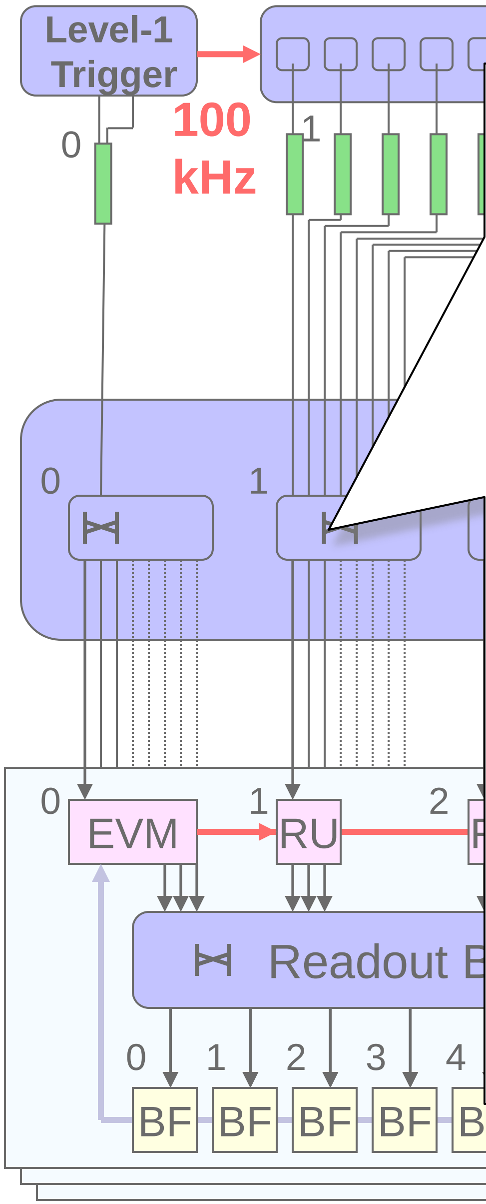
CR: Any Internet access.....

A general and expandable architecture has been deployed for the **experiments' Run control and monitoring** largely based on the emerging Internet technology developed in the field of **WWW services**

Two-stage event building architecture



Two-stage event building architecture

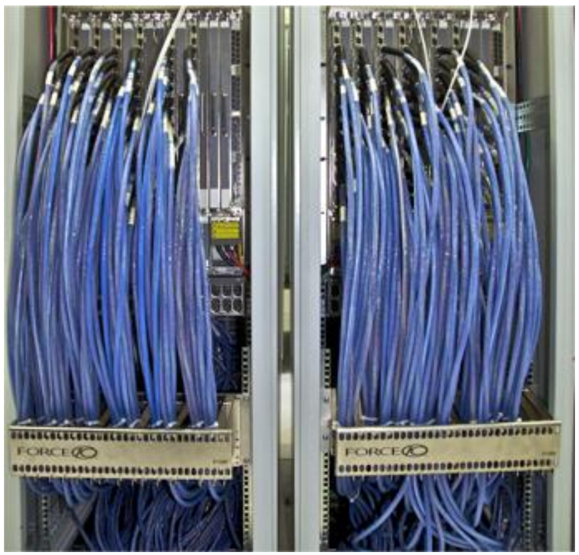


Superfragment builder technology: Myrinet

- Wormhole-routed cross-bar switch
  - 2.5 GB/s / link
  - Low latency
  - No buffering
  - Link level flow control
  - Head-of-line blocking
- NICs
  - Programmable RISC processor
  - Custom protocol
  - LUT-based destination assignment

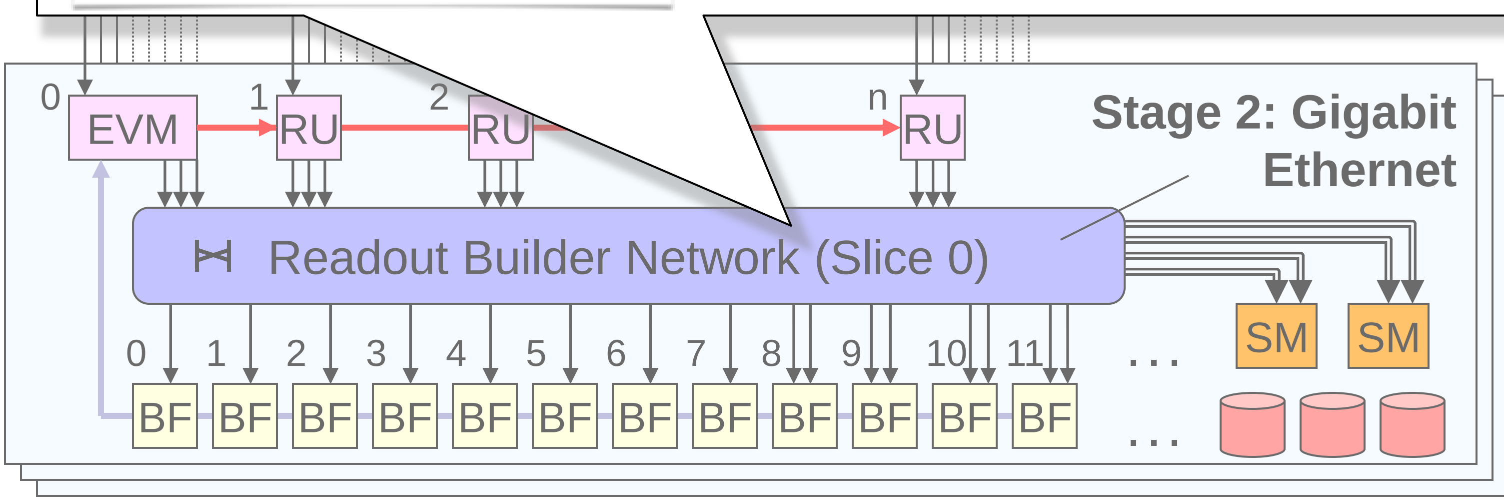
Two-stage event building architecture

Event builder technology: Gigabit ethernet



- Standard 1 Gb/s Ethernet
- 8 switches (by Force-10)
  - 1 per slice
  - 4000 ports in total
- 3 rails per Readout Unit PC
- 1 or 2 rails per Builder/Filter PC according to performance

500x
200 MB/s
4k
8x8 Super-
ment Builder
0 GB / s
16k



8 independent DAQ Slices:
~72 x (90 .. 160)

8x 12.5 GB/s

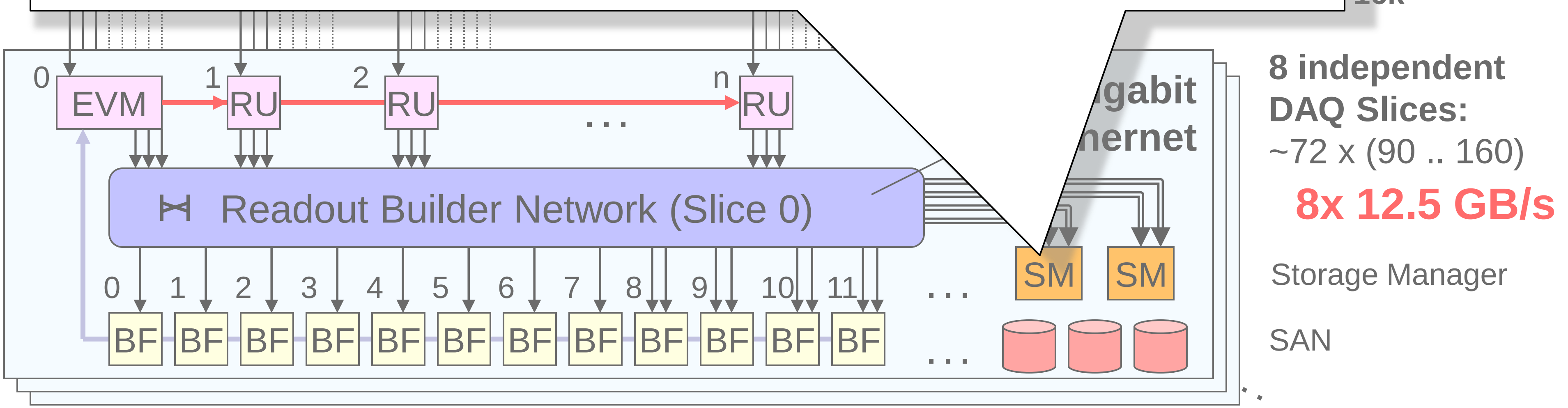
Storage Manager

SAN

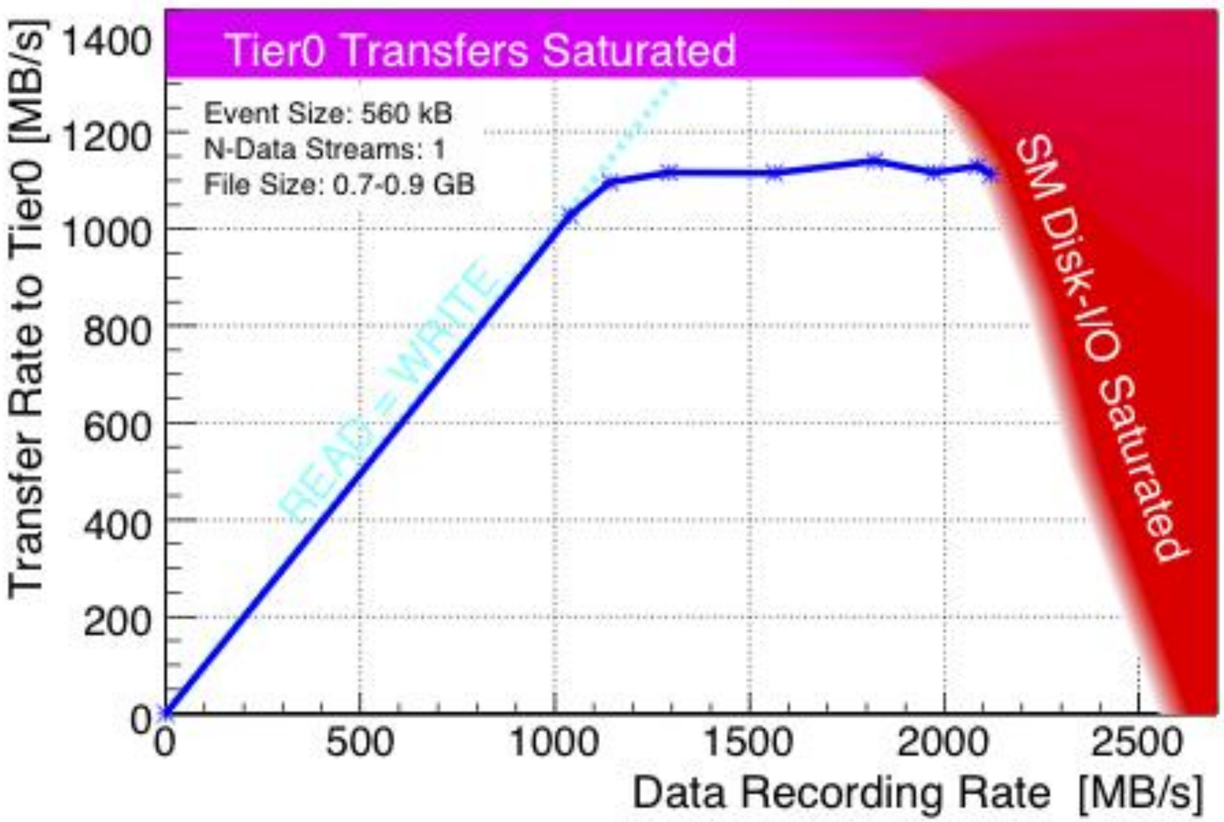
Two-stage event building architecture

Storage Managers

- 2 Storage Manager PCs per slice
- NexSan SataBeasts (RAID-6 disk array) connected through redundant Fibre Channel switches
- Max write speed 2.1 GB/s with simultaneous transfer to Tier-0
  2.6 GB/s w/o transfer
- Local storage 300 TB (several days)

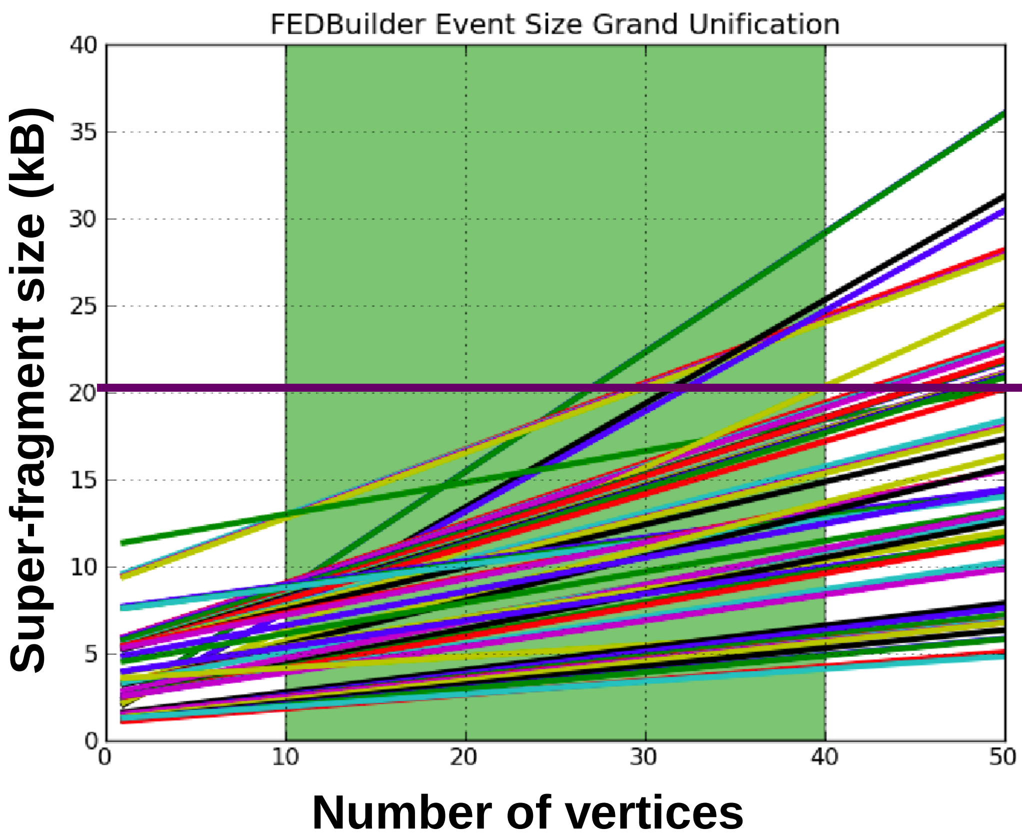


Storage Manager Performance



- Total capacity: 300 TB (several days of data talking)
- HLT compresses event data (root); reduction by factor ~2
- Event data to disk
  - pp; ~200 MB/s, design 600 MB/s
  - Heavy Ions: ~1.4 GB/s (up to 2.8 GB/s w/o transfer)

Super-fragment size in pp runs (n_{vertex})



Super-fragment size at 30 vertices / kB

BPIX s1d06-30 (0.687 kB/vertex)	22.3
BPIX s1d06-29 (0.686 kB/vertex)	22.3
EB- s2d10-03 (0.382 kB/vertex)	20.5
EB+ s2d10-10 (0.373 kB/vertex)	20.4
EB+ s2d10-02 (0.377 kB/vertex)	20.4
EB- s2d10-11 (0.376 kB/vertex)	20.3
BPIX s1d06-29 (0.596 kB/vertex)	19.3
BPIX s1d06-30 (0.576 kB/vertex)	18.9
HF s2d10-07 (0.182 kB/vertex)	16.6

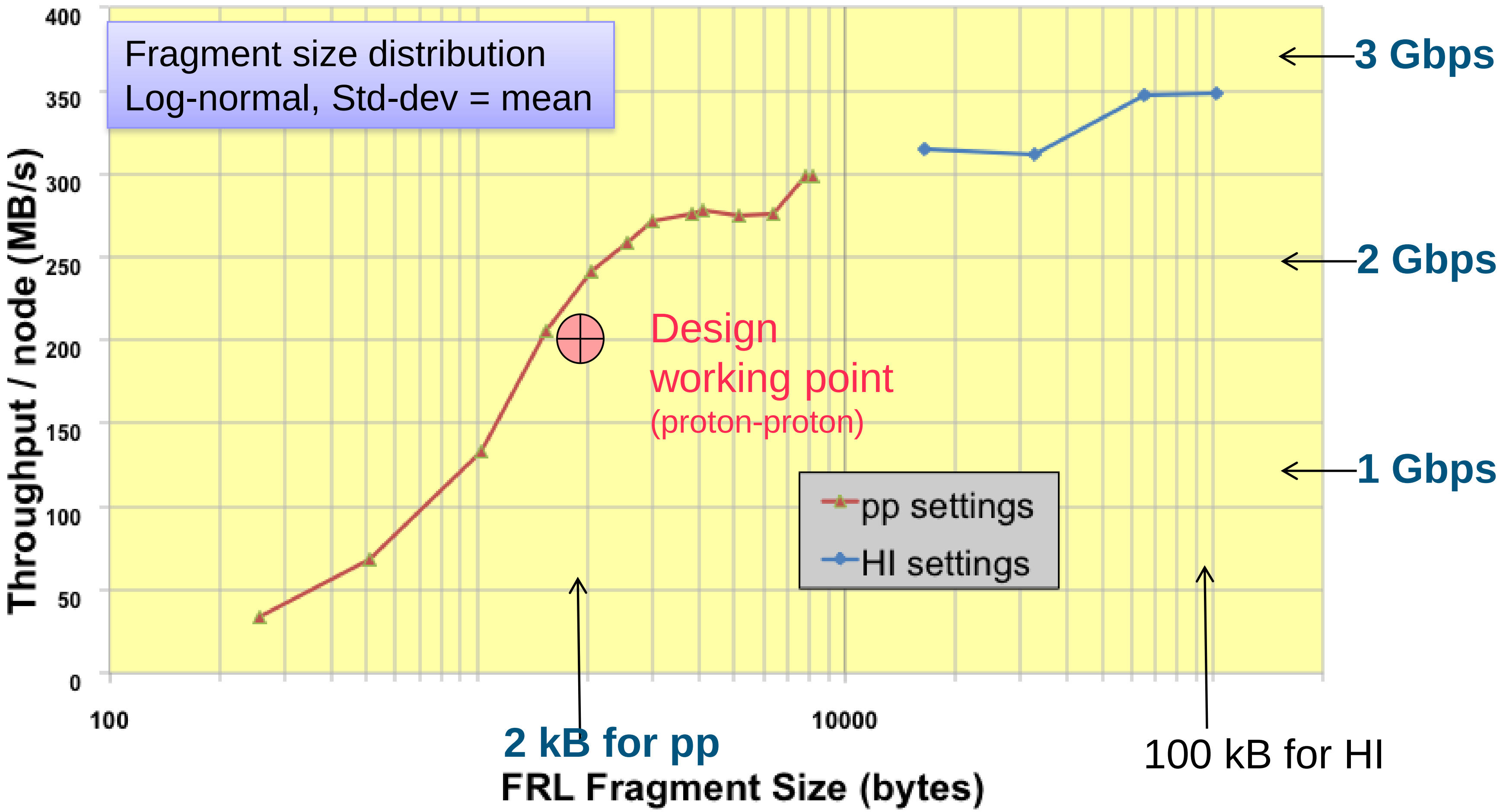
At 100 kHz can take 2.5 kB per FED or 20 kB per super-fragment

expected 2012

- Some super-fragment builders at the limit with 2011 configuration
- ✓ Fixed by re-arrangement of super-fragment composition

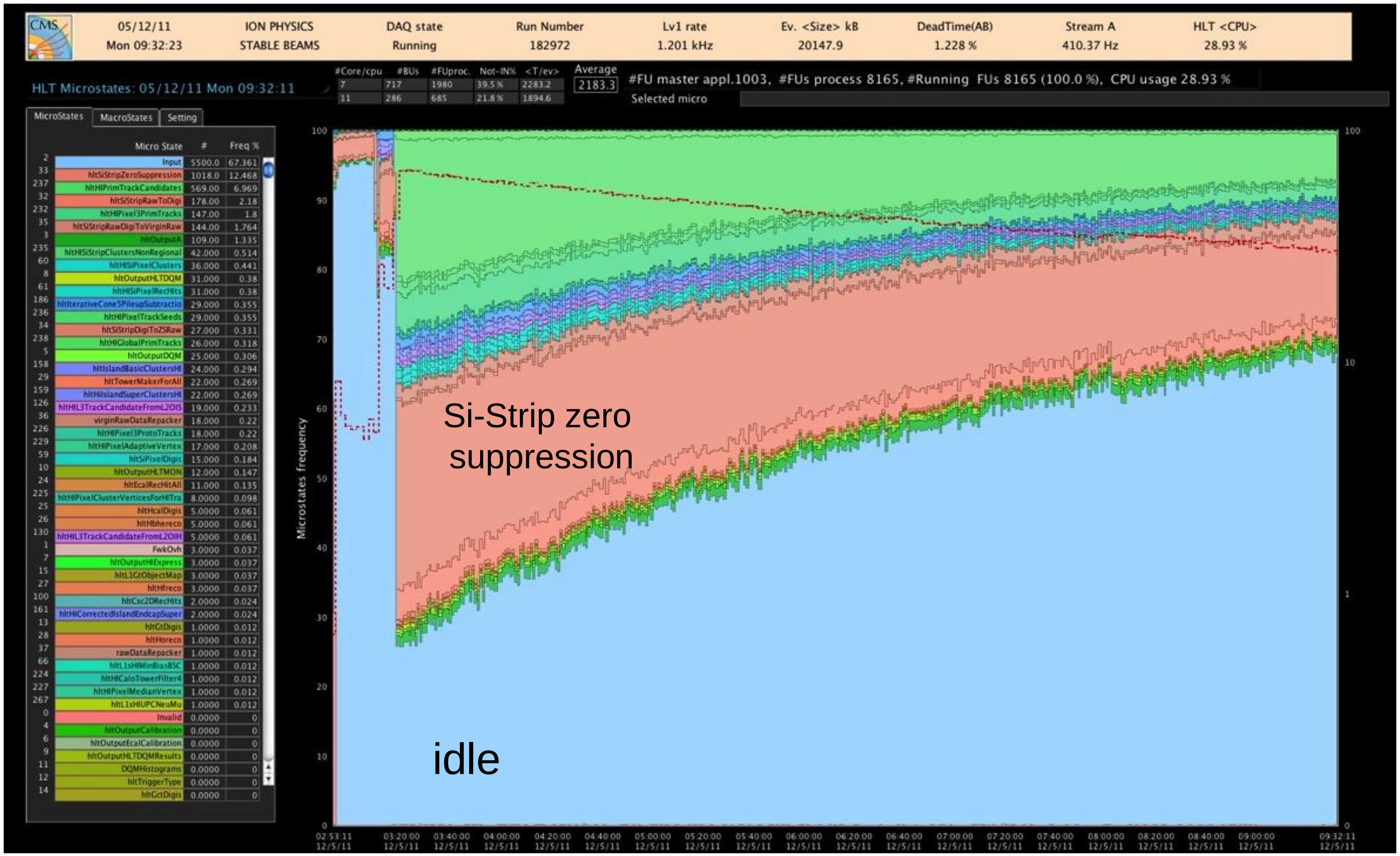
DAQ throughput per input / pp and HI

(generated events)



- DAQ optimized for large fragment sizes: reach 350 MB/s (limited by GBe)
- Max rate at 100 kB/FRL: 3.5 kHz
- Max aggregate EVB throughput: ~150 Gbyte/s (436 x 350 MB/s)

HLT states during 2011 Heavy Ion run



Fill 2343, 05 Dec 2011

Time into fill

- In 2011, Tracker zero-suppression done in HLT farm