Technology and R&D
Summary and Next Steps

ECFA HL-LHC Workshop
Aix-Les Bains, October 1-3, 2013
Burkhard Schmidt, CERN

General Remarks

- It is not possible to summarize all the on-going R&D here – only some aspects. Focus will be on Technology R&D, not on system aspects.

- To address the enormous challenges of operating particle detectors in the High Luminosity LHC environment, **collaborative efforts across the experiments are important**, in particular in the early phases of the projects.
- ➢ Synergies

Common R&D facilities:

- Test beam and irradiation facilities are important to carry out the R&D program and to qualify the technologies under consideration.

General Remarks

SYSTEMS	R&D COLLABORATIONS AND GROUPS
Tracking Systems	RD 50 collaboration (rad. hard semiconductors) Cooling: PH-DT and ext. collaborators
Calorimetry	RD52 collaboration (Dual-Readout Calorimetry) CALICE collaboration (Calo. for linear coll.)
Muon Systems	RD 51 collaboration Micro-Pattern Gas Detectors Technologies
Electronics and Readout Systems	Common Electronics Projects, ACES RD 53 collaboration (Dev. of Pixel Readout IC)
Trigger/DAQ/ Offline/ Computing	TDAQ teams of the experiments PH-SFT group and ext. collaborators

Tracking Systems

Tracking System Upgrades

Upgrades	Area	Baseline sensor type
ALICE ITS	12 m^2	CMOS
LHCb VELO	0.15 m^2	tbd
LHCb UT	5 m^2	n-in-p
ATLAS Strips	193 m^2	n-in-p
CMS Strips	218 m^2	n-in-p
ATLAS Pixels	8.2 m^2	tbd
CMS Pixels	4.6 m^2	tbd

Main goal of tracker upgrades:
Achieve enhanced radiation tolerance and improved performance.

ALICE and LHCb:

- New trackers have to cope with much higher event rates.

ATLAS and CMS Outer Trackers:

- Large procurement (2×~200 m^2) with the same timeline
  - Difficult to find vendors with suitable production capacity and quality
  - Possibility of production on 8" wafers needs to be explored
- ➢ Requires dedicated R&D – and may bring substantial financial saving

ATLAS and CMS pixels:

- **Radiation** will increase to > 10^{16} neq cm^{-2}
  - common activities to develop radiation hard sensors within the RD50 collaboration
  - Operational requirements more demanding
- High pile-up requires enhanced functionalities

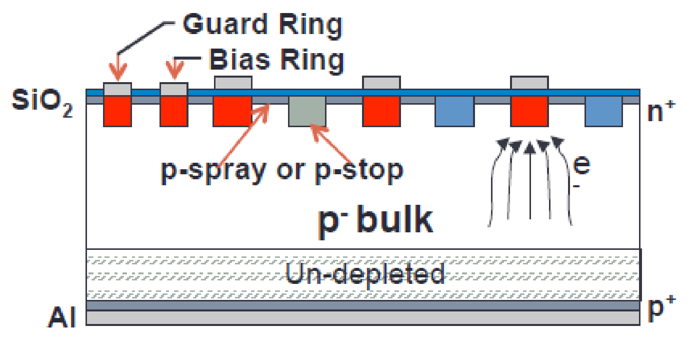
Sensor R&D: Planar Sensors

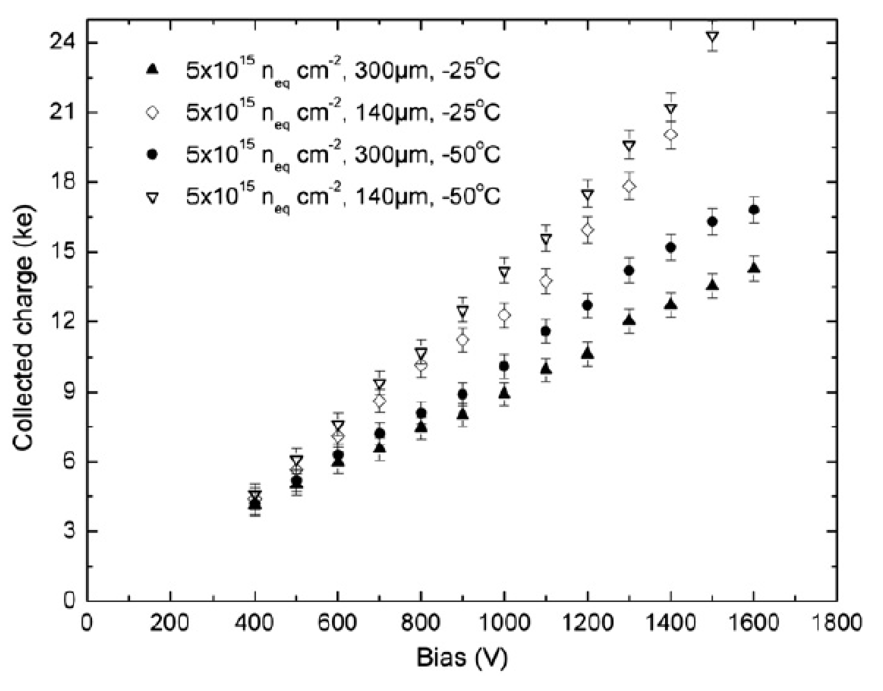
Petra Riedler

Planar sensor R&D:

- Improved radiation hardness
  - Use of **n-in-p sensors**, which deplete from the segmented side. Under-depleted operation possible.
  - Optimization of **sensor thickness** to reduce leakage current (and material) (LHCb VELO 200µm sensors)
  - Optimization of design, e.g. bias structures, isolation

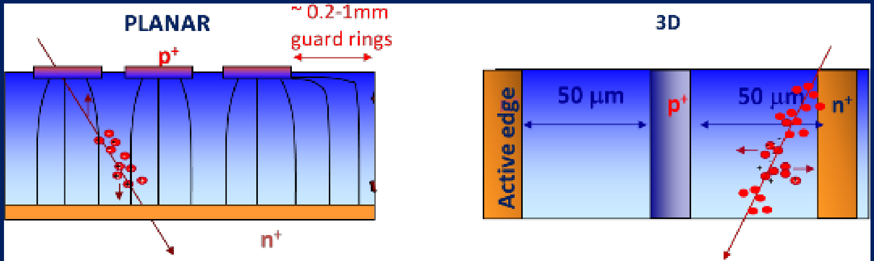
- Development of slim-edge and edgeless sensors
  - Reduced edge allows for better overlap with less material
  - Several techniques under study





Sensor R&D: 3D sensors

Both electrode types are processed inside the detector bulk



- Max. drift and depletion distance set by electrode spacing
- Allows reduced collection time and depletion voltage

➢ Potentially the option with highest radiation hardness

- Production time and complexity to be investigated for larger scale production

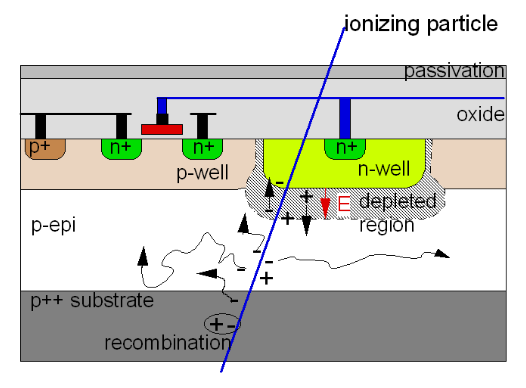
- Could be the optimal choice for inner regions of ATLAS and CMS pixel detectors

- Used in ATLAS IBL

Sensor R&D : MAPS on CMOS process

Combine sensor and electronics in one chip

- \+ No interconnection needed
- \+ Small cell size – high granularity
- \+ Very low material budget
- \- Limited radiation tolerance < 10^{13} n_{eq} cm^{-2}
- \- Readout time ~100 µs (rolling shutter architecture)
- \- Fake hit rate due to diffusion of charge carriers

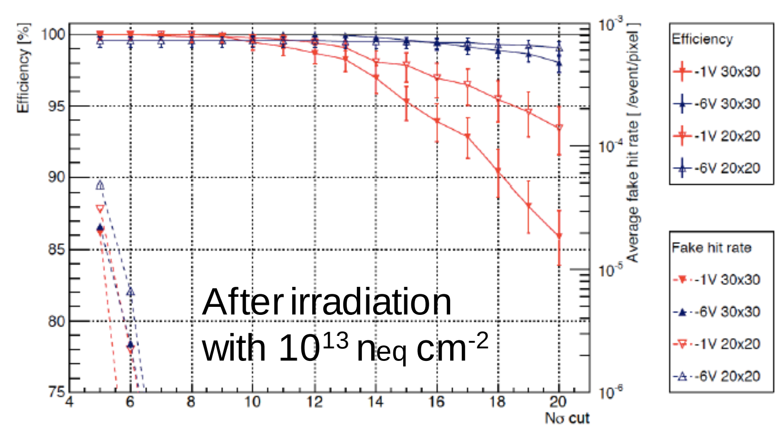


Critical issues have been addressed for ALICE ITS upgrade

- monolithic pixels have been chosen as baseline

Ongoing R&D :

- Moving to smaller CMOS node to improve radiation tolerance
- Optimization of architectures –
  higher speed: < 1 µs
- CMOS process with deep p-well shielding of the collection diode for more complex electronics
  → Reduce fake hit rate

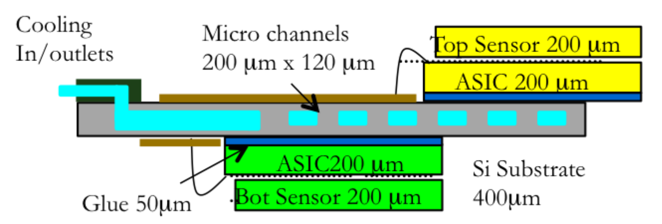


Thermal management

Bart Verlaat

- Thermal management is of unprecedented importance and difficulty in the HL-LHC trackers
- On-detector thermal management requires novel materials and solutions to achieve better performance and higher radiation tolerance
  - "known solutions" need to be re-qualified
  - Novel solutions for small areas: micro-channel cooling, very compact
- CO_2 cooling is the chosen technology
  - Positive experience with LHCb VELO;
  - ATLAS IBL and CMS Pixel systems under construction
  - Large step forward needed for the ATLAS/CMS phase-2 trackers

LHCb VELO upgrade



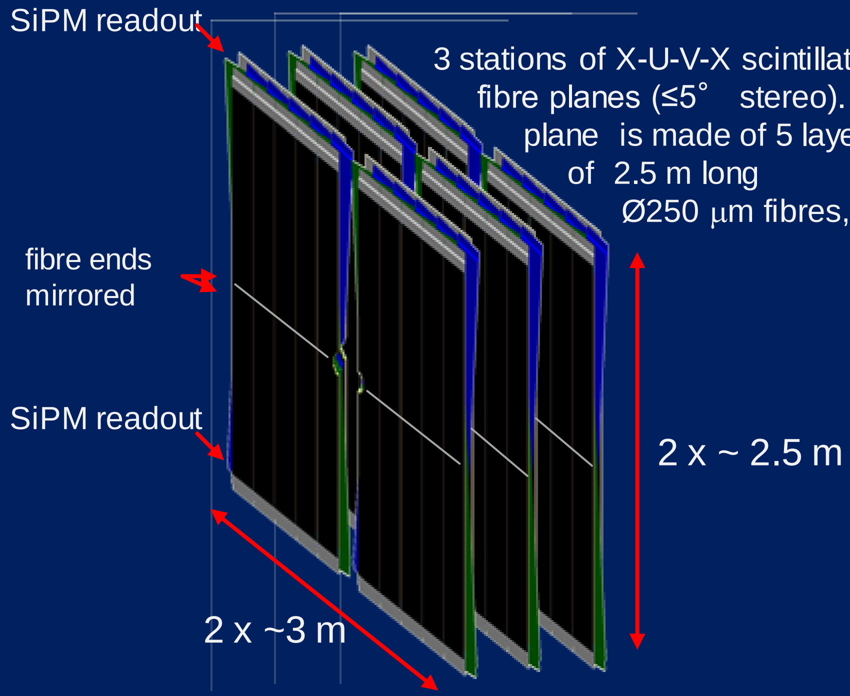
	Temp [°C]	Cooling power [kW]
LHCb VELO	-25	1
CMS pixels	-30	15
ATLAS/CMS Trackers	-40	100

- Centralized development for the cooling plants is a must; organization already in place, centered at CERN in PH-DT.
  - Vigorous R&D effort needed for the development of small CO_2 pumps
  - Development of a compact mobile CO_2 cooler (like Traci)

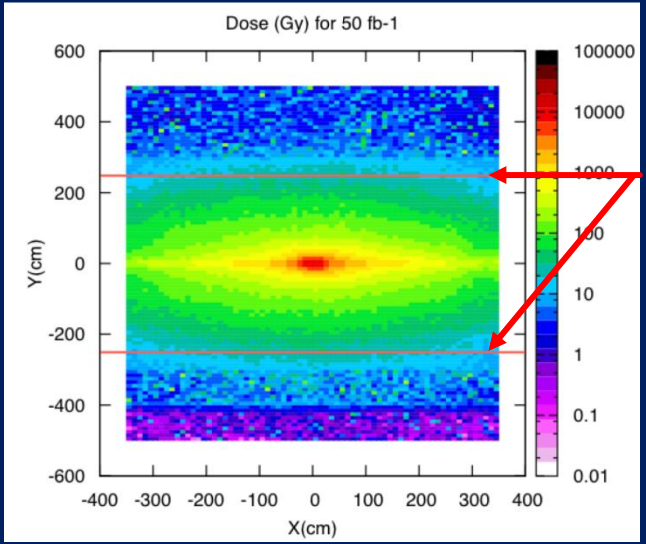
Scintillating fibre tracker R&D

Large scale SciFi tracker for LHCb

C. Joram

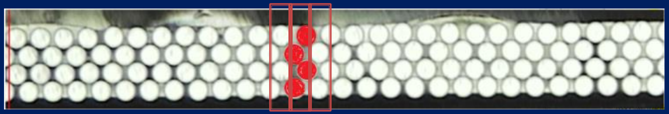


3 stations of X-U-V-X scintillating fibre planes (≤5° stereo). Every plane is made of 5 layers of 2.5 m long Ø250 μm fibres,.

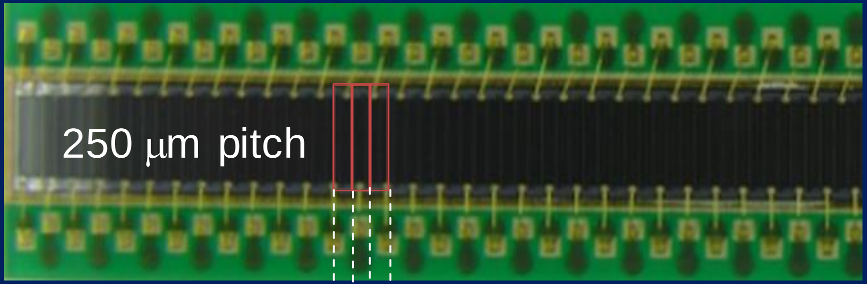


SiPM location

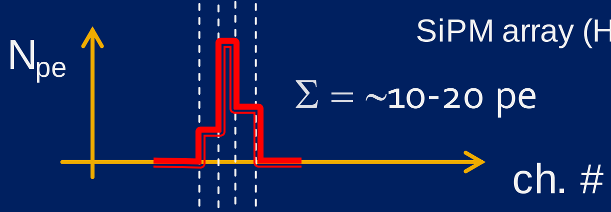
$F_n = 6{\cdot}10^{11}\ \mathrm{cm}^{-2}$



4 layer proto mat



SiPM array (HPK)



Challenges

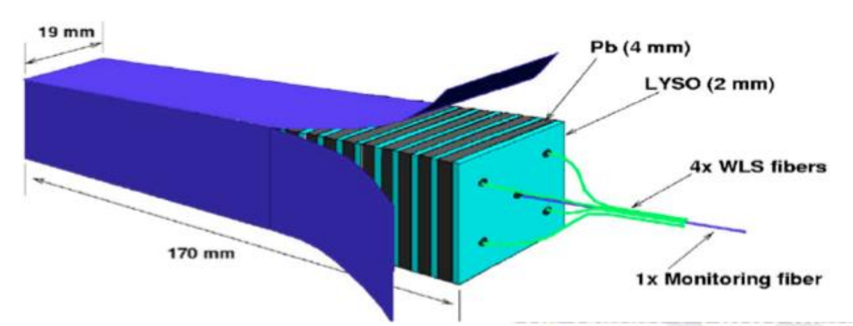
- Large size – high precision
- O(10’000 km) of fibres
- Operation of SiPM at -40° C

Calorimeters

Sampling Calorimeter R&D

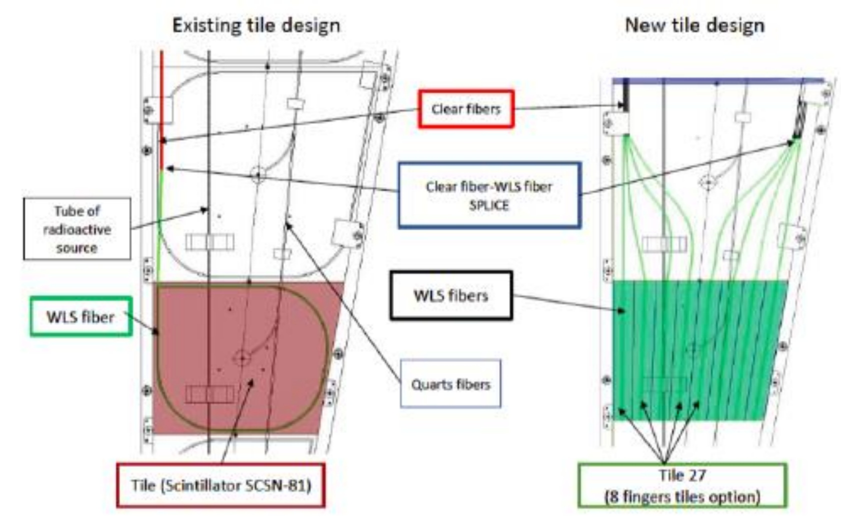
Pawel
De Barbaro

- Development of a radiation tolerant Crystal sampling calorimeter
(to replace CMS EC ECAL $PbWO_4$ crystals)
  - E.g. Shashlik configuration, using wavelength shifting fibers (WLS) in quartz capillaries with a short light path in scintillator and WLS
  - ➢ reduced sensitivity to radiation



- **Ongoing R&D**:
  - rad-tolerant crystal scintillators (LYSO, YSO, Cerium Fluoride)
  - WLS fibres in quartz capillaries
  - rad-tolerant photo-detectors (e.g. GaInP)

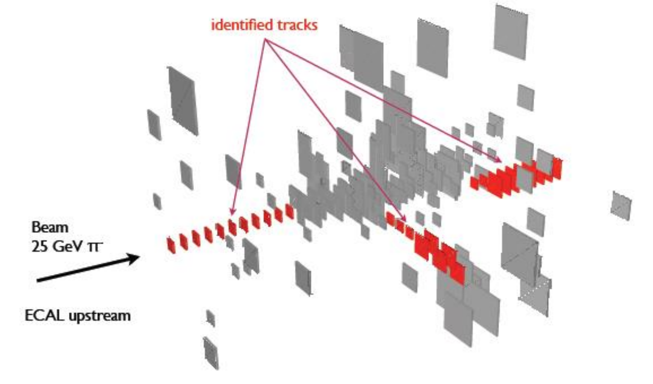
- Development of radiation tolerant Plastic/Scint. calorimeter
(to replace CMS EC HCAL)
  - Change layout of tile calorimeter using WLS fibres within scintillator to shorten the light path length



- **Ongoing R&D:**
  - rad-tolerant version of scintillator material (yellow emitting 3HF)
  - WLS fibres with quartz capillaries

Integrated ECAL/HCAL R&D

- High granularity Particle flow / Imaging Gas Calorimetry (CALICE)
  - high segmentation (transv.and longit.) to measure shower topology



- **Challenges and R&D:**
  - high rate capability of gas detectors
  - large number of channels (~ 10^7)
  - compact and inexpensive electronics, low power 40 MHz ADC, cooling
  - development of high speed data links (10 Gbps) to transport large volumes of data

- Dual ReadOut with Cerenkov/Scint. sampling detector (DREAM, RD52)
- **Ongoing R&D:**
  - **Quartz fibers:**
    - Cerenkov radiator for Dual Readout
    - Doped Quartz fibers for scintillation signal in Dual Readout Calorimeter
  - **Crystal fibers:**
    - doped inorganic crystal fibers, e.g. LuAG for scintillation light detection
    - Undoped LuAG for Cerenkov light detection


CFCAL is a brass absorber with 9 LuAG fibers

Calorimeter Electronics Upgrade

Arno Strässner

The common trend is to design a readout architecture where:

- the **data are not buffered** in the front-end, but rather streamed off-detector at 40 MHz
- **fast pre-processors convert raw-data into calibrated information** that feed the trigger system where improved and more complex algorithms are applied.
- Off-detector buffers allow for a much **higher trigger latency** or purely software-based triggers.

Custom pre-amp, signal shaping and delay ASIC: re-prototyped in cost-effective IHP technology

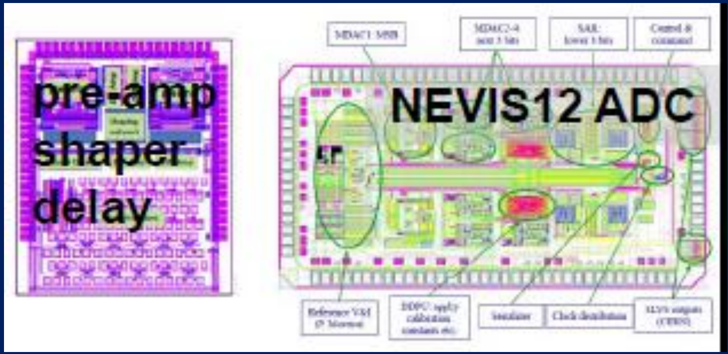
Custom ADC developments:

NEVIS / PEALL12-bit ADC, IBM 130nm CMOS

Key enabling technologies:

- On-detector front-end electronics with sufficient resolution and large dynamic range (~16-bit)
  - COTS vs. ASIC development.
  - If ASIC – what technology should be used
  - ➢ across the experiments at least 5-6 developments using different processes
  - ➢ **Try to identify synergies across the experiments**

Example: ATLAS LAr Calorimeter



Muon Systems

GEM Detector R&D

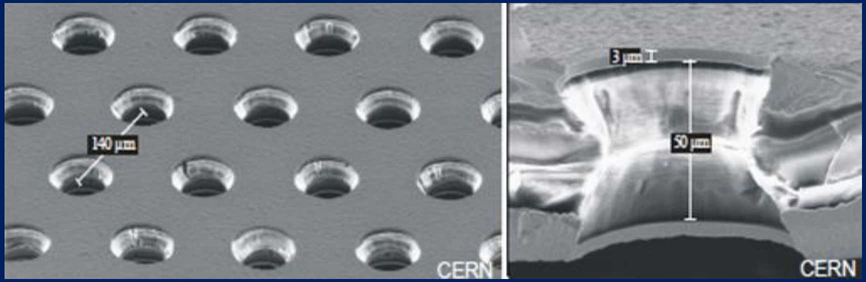
Marcello Abrescia

- Triple GEM detectors have been used successfully in LHCb (after ~10 years of R&D)

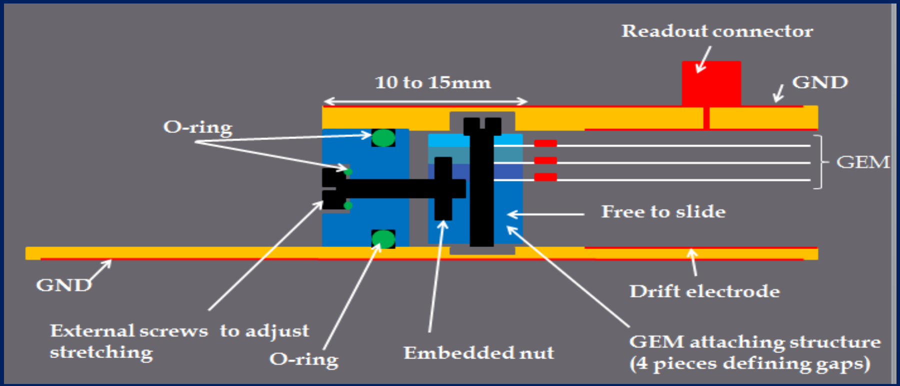
- Main challenge now :
  - build large systems (CMS and ALICE)
  - larger foils, made with single sided etching technique
- ➢ Industrialize production

Ongoing R&D:

- Performance studies
  - time and space resolution
- Longevity
  - ageing tests at GIF and GIF++
- Stretching of foils without spacers
  - Allows reopening of chambers



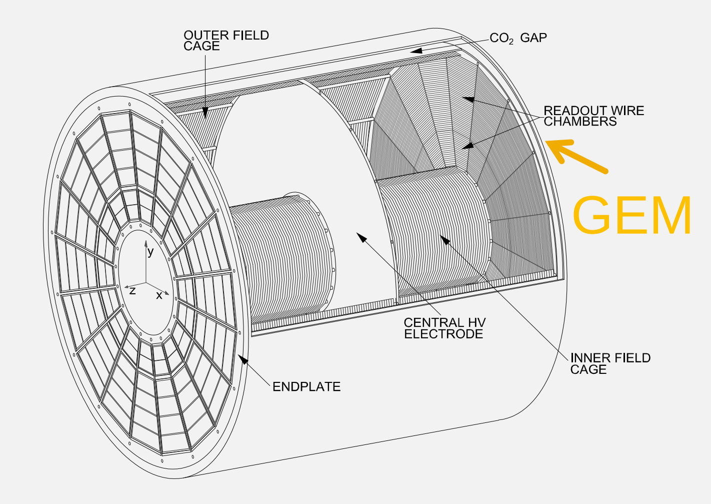
	Detector surface	Foil Area
LHCb Muon system (now)	0.6 m²	4 m²
ALICE TPC	32 m²	130 m²
CMS Muon system	335 m²	1100 m²



New GEM detector applications

ALICE TPC:

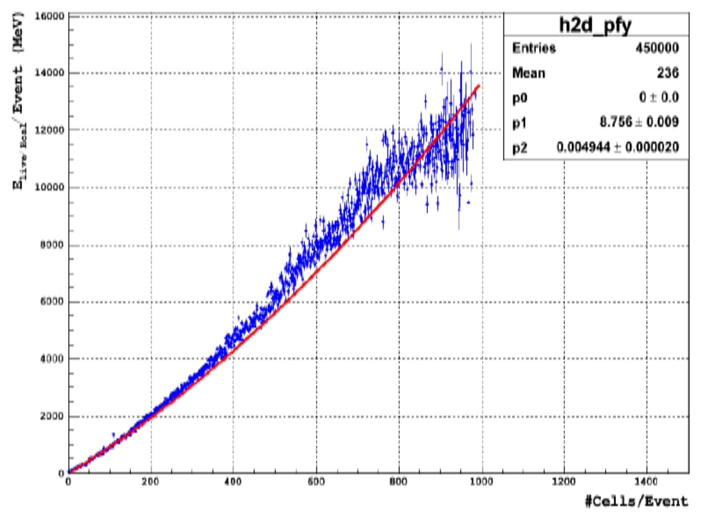
- Replace wire chambers with quadruple-GEMs
- MWPC not compatible with 50 kHz operation because of ion backflow in the field cage
- Choice of quadruple-GEM detectors to minimize ion backflow (< 1 %)



GEMs for calorimetry:

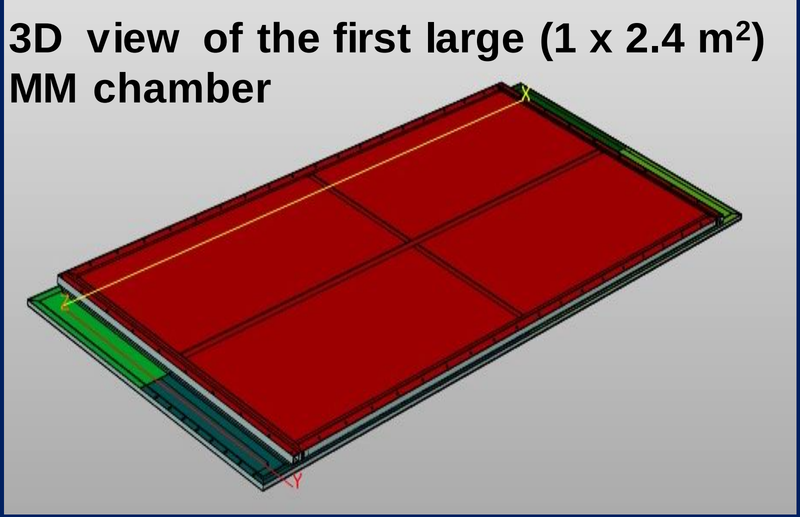
- Digital calorimetry approach:
  - Cell is either ON or OFF
- High granularity for charged particle tracking
  - 1x1 cm^2 cells proposed
- Requires development of Particle Flow algorithm

➢ Good correlation between particle energy and numbers of cells hits



Micromega Detector R&D

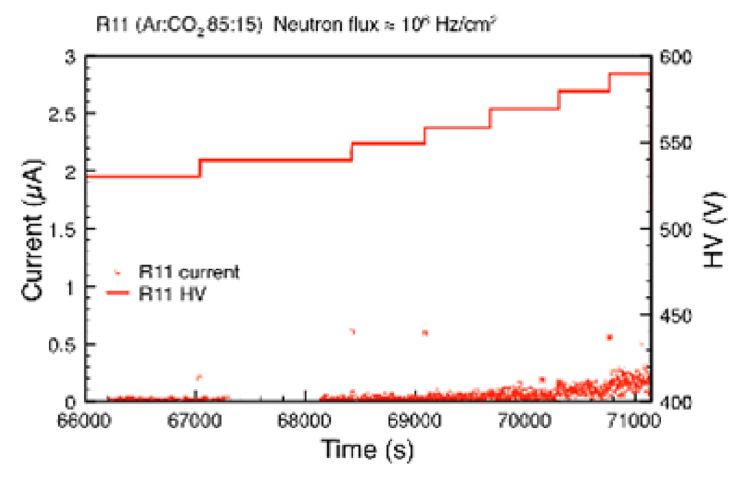
- Micromegas have been chosen as precision measurement and trigger detectors of the New Small Wheels of ATLAS
- ➢ First large system based on Micromegas
  - Detector dimensions: 1.5–2.5 m²
  - A total of ~1200 m² of detection layers
  - 'Floating mesh' technique used for chamber construction



3D view of the first large (1 x 2.4 m²) MM chamber

Breakthroughs and on-going R&D:

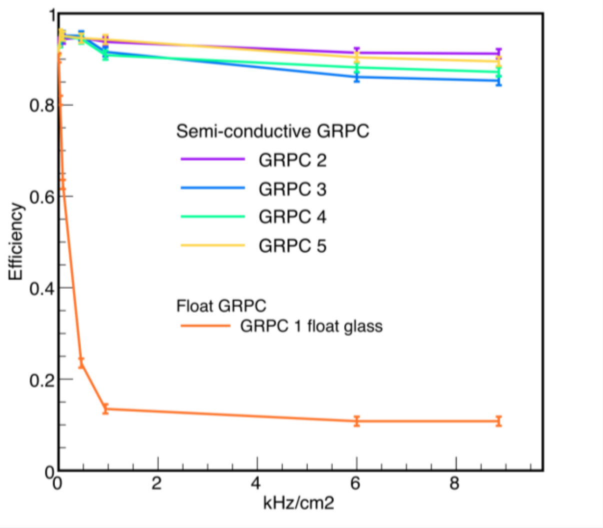
- Resistive strips to reduce discharges
- µTPC operation mode to get good spatial resolution for inclined tracks



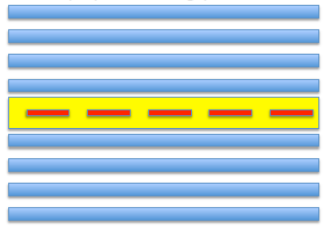
R&D to Improve RPC (iRPC)

Main goal: Improve rate capability

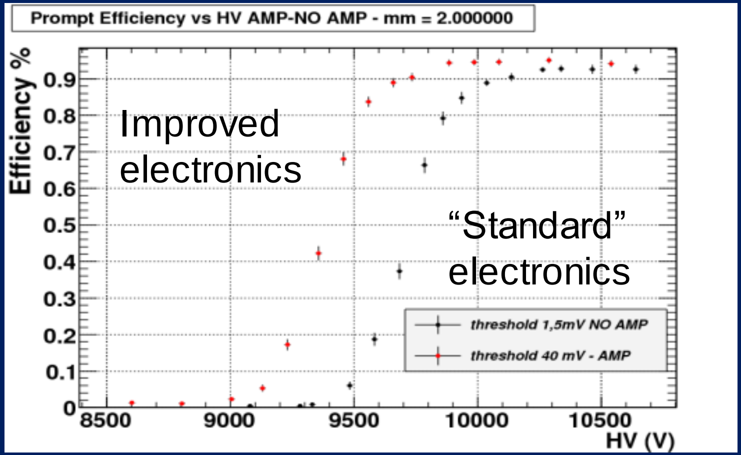
- Reduce the electrode resistivity
  - “low” resisitivity (10^{10} Ωcm) glass (lowest resistivity usable 10^{7}Ωcm)
  - ➢ Needs important R&D on electrode materials



- Change the detector configuration
  - Go to ‘double-triple gap’ option
    - Improves the ratio: *induced signal/charge in the gap*
    - Rate capability ~ 30 kHz/cm^2
    - Time resolution 20-30 ps



- Change the operating conditions
  - reduces the charge/avalanche,
  - part of the needed amplification transferred from gas to FE electronics
  - ➢ Needs an improved detector shielding against electronic noise



Electronics

IC designs and HD interconnects

A. Marchioro
J. Christiansen

On-detector electronics 100% custom made with highly specialized complex ASICs that **must work reliably in unprecedented hostile radiation environments for many years**.

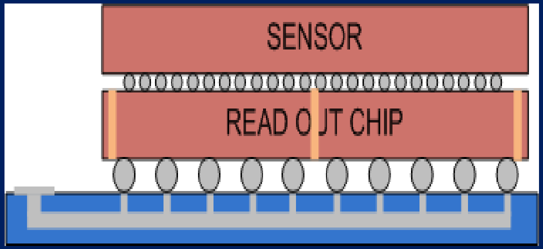
- ASICs in 130 nm – good progress already, but still a lot of work ahead
- ASICs in 65 nm new for HEP – huge amount of work, including special radiation qualification for extreme conditions (ATLAS/CMS pixels)
- ➢ Must be a collaborative effort – **RD53 established**

new "Moore's Law" on documentation volume seen from the 14th floor at Fermilab perspective

Increased channel densities makes High Density Interconnect (HDI) technologies increasingly critical

- High density interconnects:
  - hybrid substrates, bump-bonding, Through Silicon Vias (TSV)…
- Investigate and qualify vendors with suitable products, interested in our volumes and budgets
- ➢ Often project-specific. Share information and experience.

Use of TSV



Power Distribution R&D

Peter Phillips

- Two main power strategies being explored for the HL-LHC
  - Serial Powering
  - DC-DC Buck converters
- In addition
  - Switched capacitor DC-DC

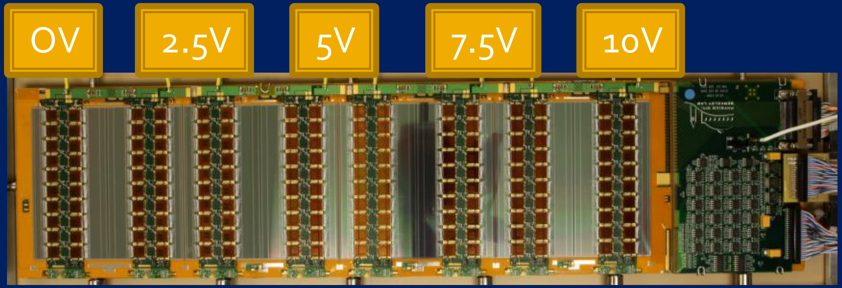
➢ Necessary to continue work on all

Overall efficiencies of > 80% can be obtained

- Continued support is needed to deliver suitable parts in time
  - Bulk supplies
  - Evaluation of larger Serially Powered systems
  - Low mass DC-DC Buck Converters *with increased radiation tolerance*
  - Identification of "HV" switch transistors for sensor bias applications

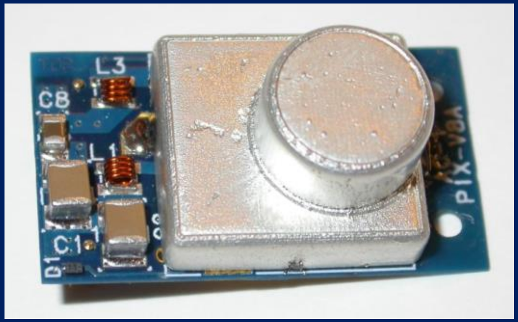
- Example Serial Powering:

ATLAS Strip staves



- Ex. DC-DC buck converter

CMS Pixel upgrade

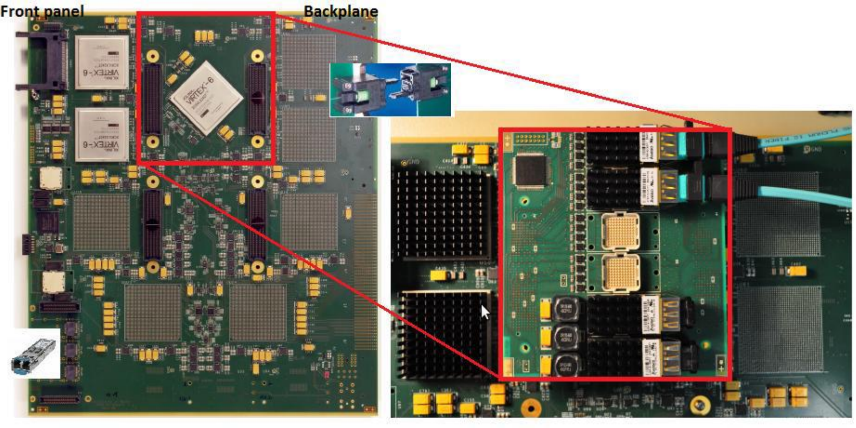


Modular Electronics

Jean-Pierre Cachemiche

- xTCA and its sub-standards:
  - ATCA (2002): ATLAS, LHCb, ILC, …
  - µTCA (2006): CMS, XFEL
  - ➢ favoured candidate as successor of VME
  - ➢ Tight roadmap to define and test common developments

Example: ATLAS Calorimeter Trigger Topological Processor Card



Next steps:

- Manpower and tools needed to develop common solutions and support them
- Raising the competence of developers community will take time
- Many coordinating actions already started, but lots to be done
- xTCA Interest Group should play a major role

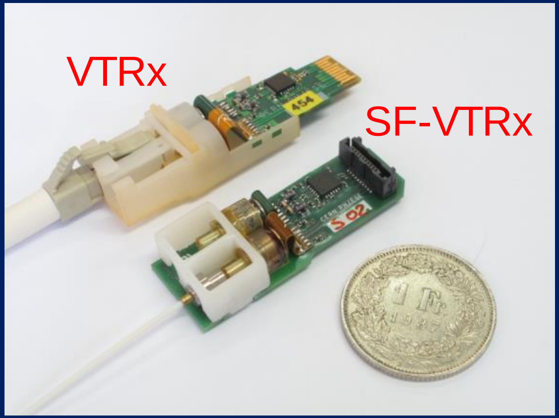
- Alternatively development of high bandwidth system based on **PCIx cards in "commodity" PCs** to interface detector specific front-end to DAQ systems on a switched-network.

High speed Link R&D

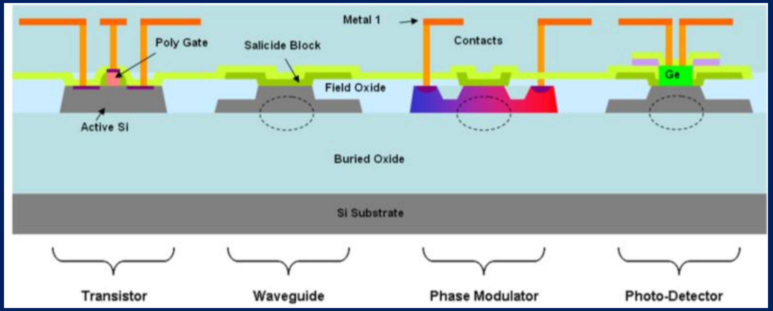
Francois Vasey

- High speed links (≳10 Gbps) are the umbilical cords of the experiments
- Meeting the HL-LHC challenge requires:
  - Qualifying new technologies and components
  - Designing electronics, interconnects, packages and perhaps even optoelectronics
  - Maintaining expertise, tools and facilities
  - Investing heavily with a few selected industrial partners
- The community is healthy, but small and fragmented. Manpower is the bottleneck.
- Development time remains very long (~6y) in comparison to industry.
- ➢ HL-LHC environment is unique and requires specific R&D and qualification procedures.

- Shrinking of GBT package size to smaller footprint



- Exploratory Project on Si-photonics for HEP applications



Trigger / DAQ / Offline / Computing

Technology Trends TDAQ and Computing

Niko Neufeld

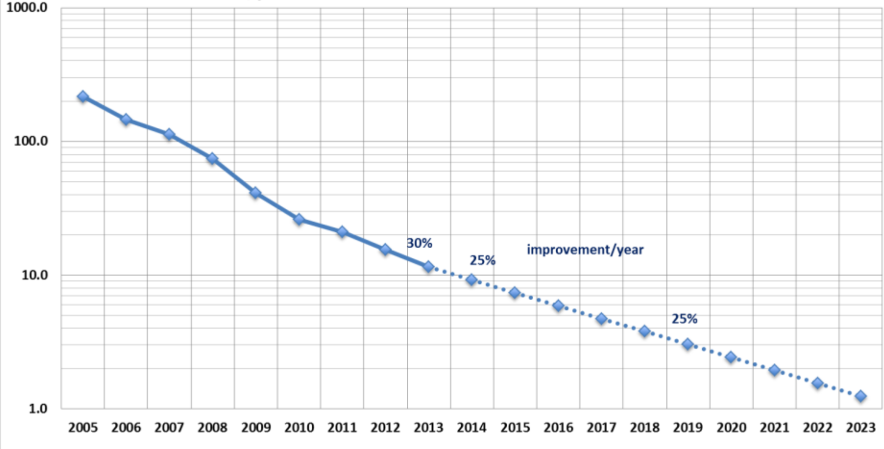
HEP profit from industrial developments

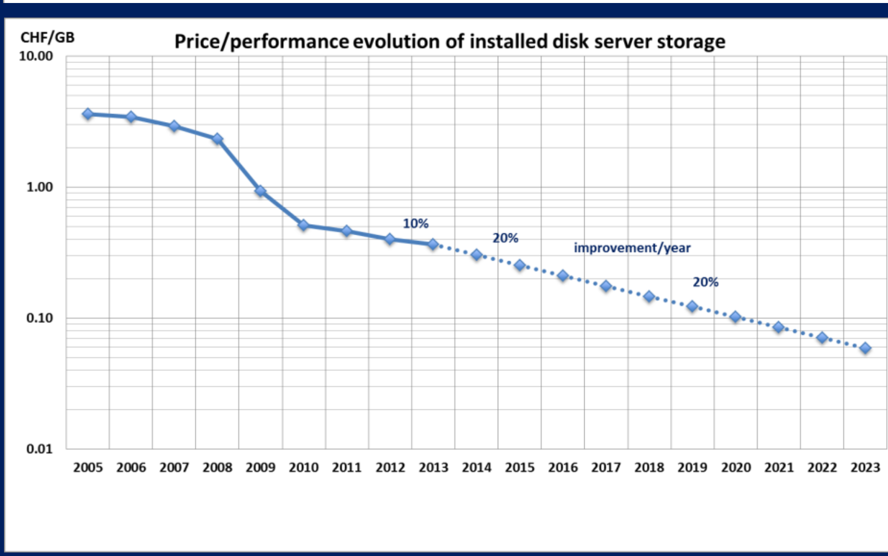
- We expect current performance rates (and price performance improvements) will hold at least until 2020
  - 25% performance improvement per year in computing at constant cost.

  → **Only if our efficiency in using the resources remains constant as well!**
  - Local area network and link technology show a similar trend as processors.
  - 20% price-drop per year at constant capacity expected for disk-storage.

- Far beyond LS2 the technical challenges for further evolution seem daunting.

➢ Nevertheless, the proven ingenuity and creativity of IT justifies cautious optimism.



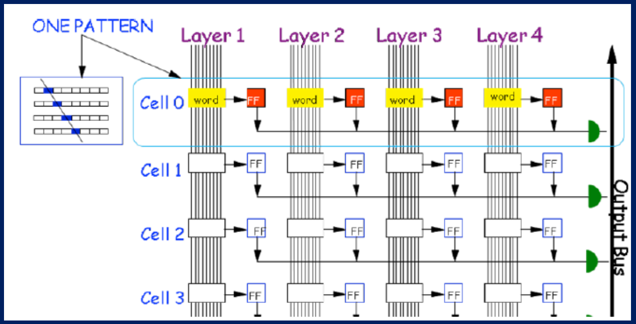


Trigger Developments

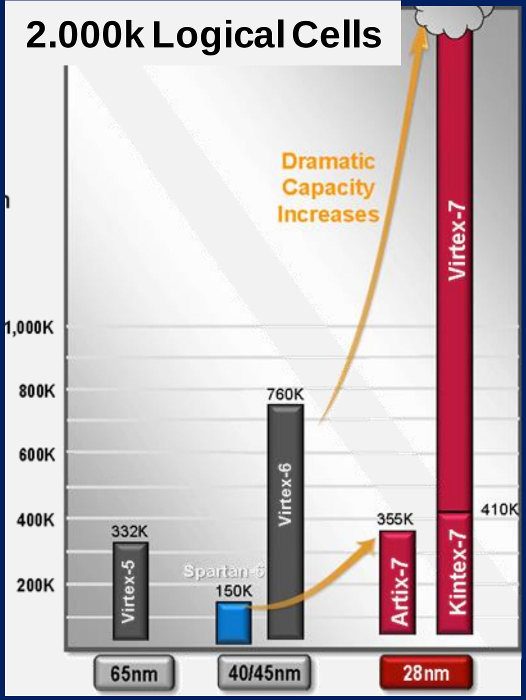
Wesley Smith

- Tracking Triggers
  - ATLAS: L1 trigger at 500KHz within 20 µs; ‘pull path’
  - CMS: L1 trigger at 40MHz within 10-20µs; ‘push path’
- Challenges:
  - Complex pattern recognition over very large channel counts with short latency and no dead time (clock/event pipelined).
  - ➢ Highly challenging connectivity and processing problem
- Tools:

Associative memories for pattern matching



1. Pattern Recognition **Associative Memory** (PRAM)
   - Match and majority logic to associate hits in different detector layers to a set of pre-determined hit patterns
   - highly flexible/configurable
   - Pattern recognition finishes soon after hits arrive
   - Challenges:
     - Increase pattern density by 2 orders of magnitude
     - Increase speed x 3 (latency)
     - Use 3D architecture: Vertically Integrated Pattern Recognition AM - VIPRAM
2. FPGAs:
   - Challenges:
     - Latest generation FPGAs create complex placement issues
     - Designs must be heavily floor-planned similar to ASIC layout
     - Embedded Processors, moving tasks from FPGA to SW design



Trends in HLT & DAQ

Wesley Smith

- Event building architectures for cost effective large bandwidth networks are required
    - Profit from progress in PC evolution PC server architecture

	Event size [kB]	L1 Rate [kHz]	Bandwidth [Gb/s]	Year [CE]
ALICE	20000	50	8000	2019
ATLAS	4000	>200	6400	2022
CMS	4000	<1000	32000	2022
LHCb	100	40000	32000	2019

Tools:

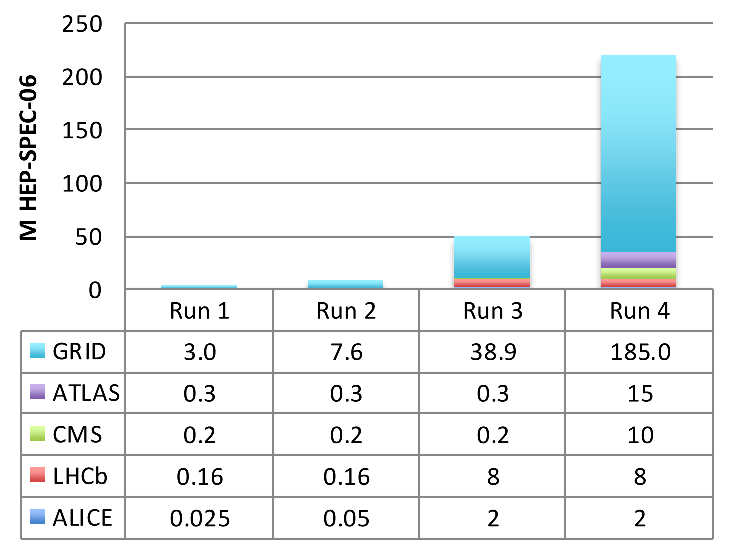
- HLT Specialized Track Processing
    - Various options, e.g. GPU.
        - Depends on resources available, CPU and link speed
- Use of New Processors in HLT
    - ARM, Nvidia Tesla (GPU), Xeon Phi…
- HLT on the Cloud
    - e.g. share resources between HLT & Tier-O
- Merging of HLT & offline software development

Trends in Computing

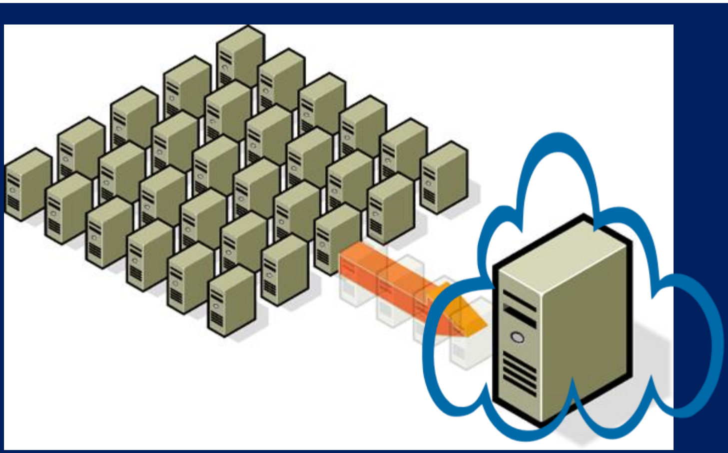
Predrag Buncic

- Resources needed for Computing at the HL-LHC are large – but not unprecedented.
- Development of the WLCG was a great success.
- Experiments are proposing to build very large computing **online facilities** that could be potentially used for **offline computing.**
- Virtualization and Clouds may help
  - reducing the complexity of the Grid middleware
  - fully utilizing resources.

➢ Cloud federation may be a way to build our next Grid



	Run 1	Run 2	Run 3	Run 4
🟦 GRID	3.0	7.6	38.9	185.0
🟪 ATLAS	0.3	0.3	0.3	15
🟩 CMS	0.2	0.2	0.2	10
🟥 LHCb	0.16	0.16	8	8
🟦 ALICE	0.025	0.05	2	2



Virtualization is the key technology behind the Cloud

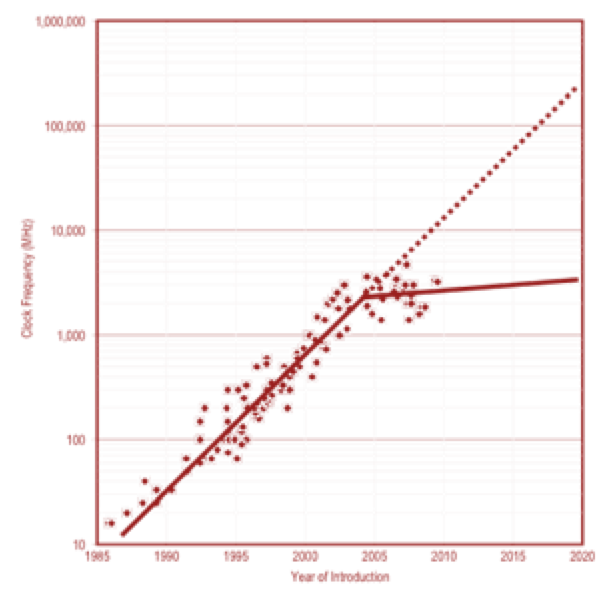
Software Trends

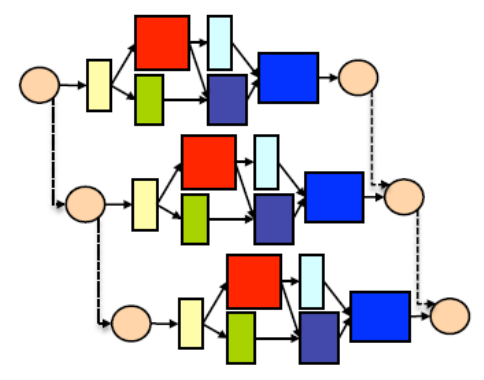
David Rousseau

- Future evolution of processors: many cores with less memory per core, more sophisticated processor instructions (micro-parallelism),
  - Parallel framework to distribute algorithms to cores
  - Optimization of software to use high level processor instructions
- LHC experiments software has more than 15 million lines of code, written by more than 3000 people
- a whole community to embark, starting essentially now

→ **Revisiting code is a good opportunity to share effort and software.**

- We can do much more: http://concurrency.web.cern.ch





Concurrent event-processing

Final Remarks

- The radiation environment in which the experiments have to operate reliably poses an always greater challenge.
- Work in the R&D collaborations has been very beneficial for the advancement of many detector technologies.
- More R&D is needed in relation to the gas mixtures for Muon Systems to reduce or even avoid the use of green house gases.
- Emphasis has to be more on more on overall system/experiment aspects.
- Technologies for ASIC design are increasingly complicated to use. Significant R&D manpower and resources are needed at an early stage.
- There is an increasing integration of the sensors and its electronics in the case of Tracking Systems. In this context the integration of cooling should be considered further for pixel detectors.
- Technology choices should be made not too late in order to bring conceptual studies to the level of a technical design report and to realize the projects in the time available.
- The challenges in terms of computing and software design should not be underestimated. More common developments across the experiments are desirable.

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