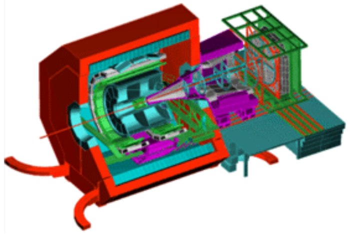
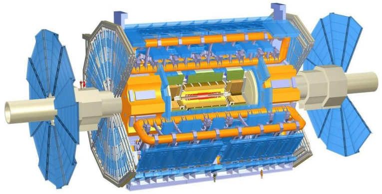
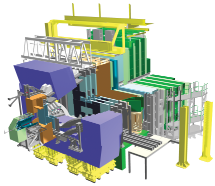


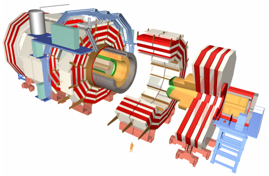


The Upgrade Programme of the LHC Detectors

CERN Academic Training Lectures 2/3

Werner Riegler, CERN





Outline

Lecture 1: Overview of experiment and machine goals,
some overall numbers and facts

Lecture 2: LHCb and CMS upgrade plans,
with excursion into DAQ/Trigger and photon detectors

Lecture 3: ALICE and ATLAS upgrade plans,
with excursions into Silicon and Micropattern Gas Detectors

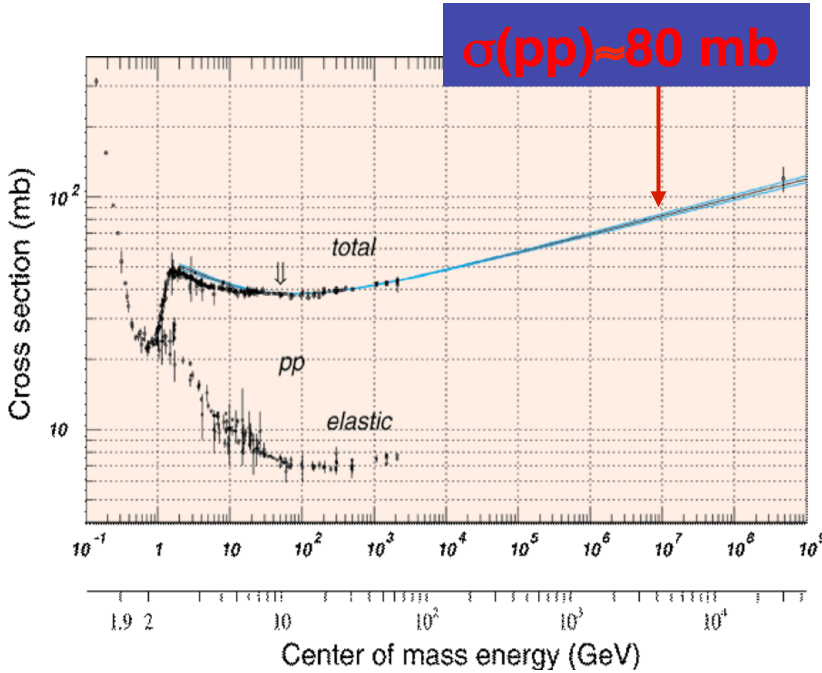
Bonus: Brainstorming on detectors for a FHC (100TeV)

Excursion to DAQ and Trigger Systems

The Challenge at LHC

– **Interactions/s:**
  Lum = 10^{34} cm^{-2}s^{-1}
  σ(pp) = 80 mb
  Interaction Rate, R = 8×10^8 Hz

– **Events/beam crossing:**
  Δt = 25 ns
  Pileup = Interactions/crossing = 20



04/02/2014

Triggering

There is no way to write all data to tape ! (today)

There is no way even to send all data into a computer farm for processing and event selection !

We must inspect the detector information with a hardware layer based on ‚simple' signals and provide a first decision on whether to keep the event or throw it out.

ATLAS/CMS → 40MHz to 100kHz with first Trigger Level.

Detector data not all promptly available → Selection function is highly complex and is evaluated by successive approximations, the so called Trigger Levels.

First Trigger Level is based on 'simple' signals like Calorimeter Energy or Muon Momentum.

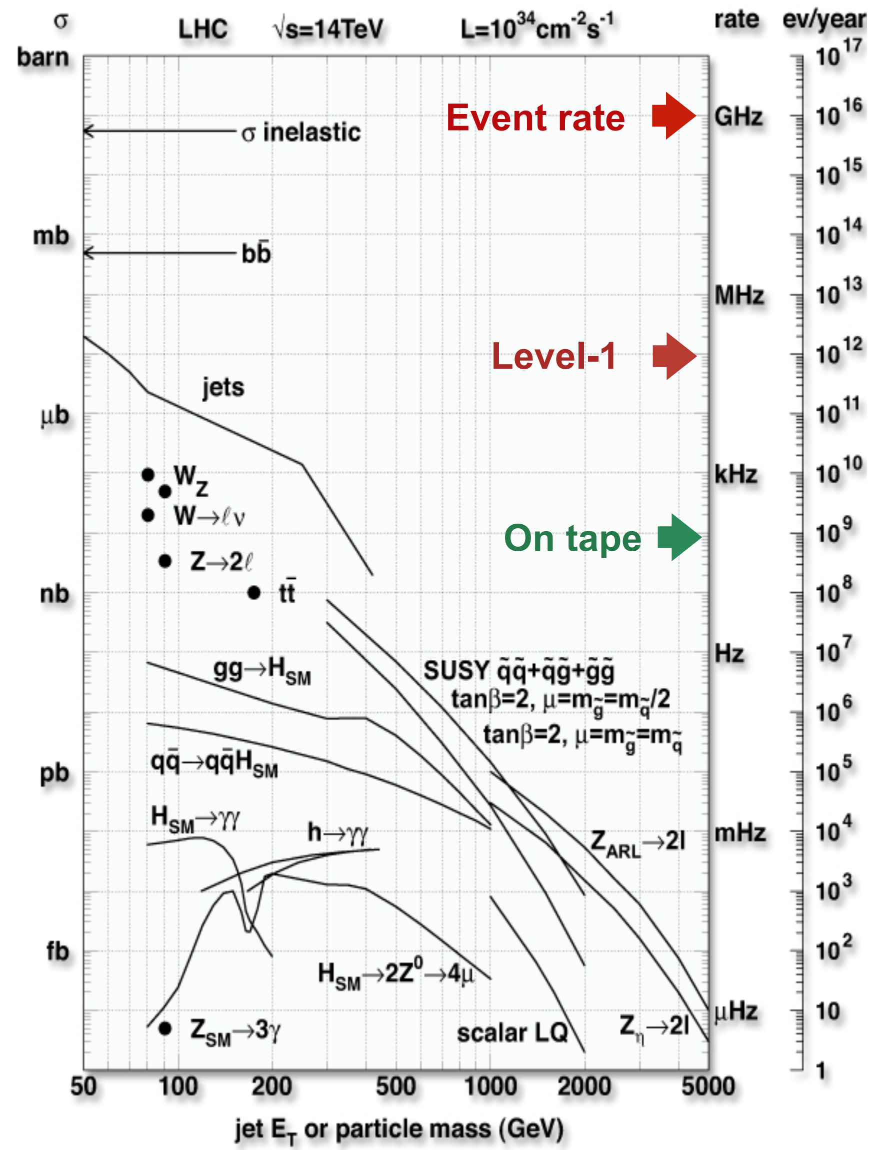
More sophisticated triggering strategies are needed for HL-LHC, i.e. very possibly track triggering at first trigger level !

Selectivity: the Physics

- **Cross sections of physics processes vary over many orders of magnitude**
  - Inelastic: 10^9 Hz
  - $W \rightarrow \ell\nu$: 10^2 Hz
  - t t production: 10 Hz
  - Higgs (125 GeV/c^2): 0.1 Hz

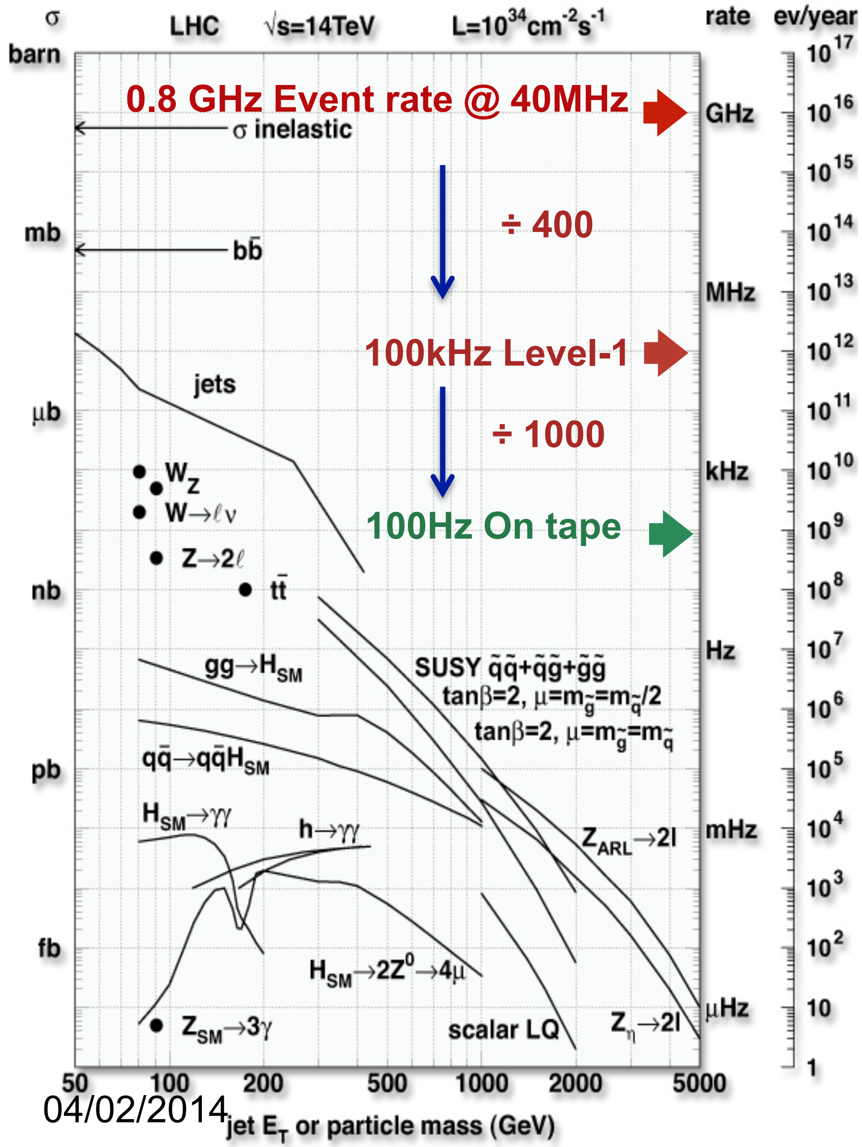
- **QCD background**
  - Jet E_T ~250 GeV: rate = 1 kHz
  - Jet fluctuations → electron bkg
  - Decays of K, π, b → muon bkg

- **Selection needed: $1{:}10^{10-11}$**
  - Before branching fractions...



P. Sphicas – 2006 CERN summer student lectures

LHC to HL-HLC



ATLAS/CMS plans for L=5x10^{34}

4 GHz Event Rate @ 40MHz

÷ 40

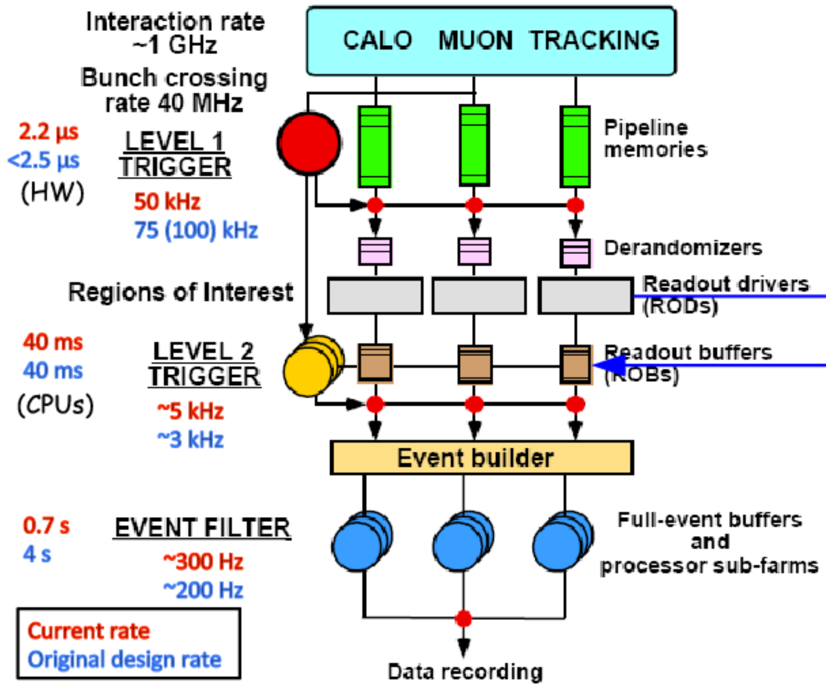
0.5-1 MHz Level-1 Rate

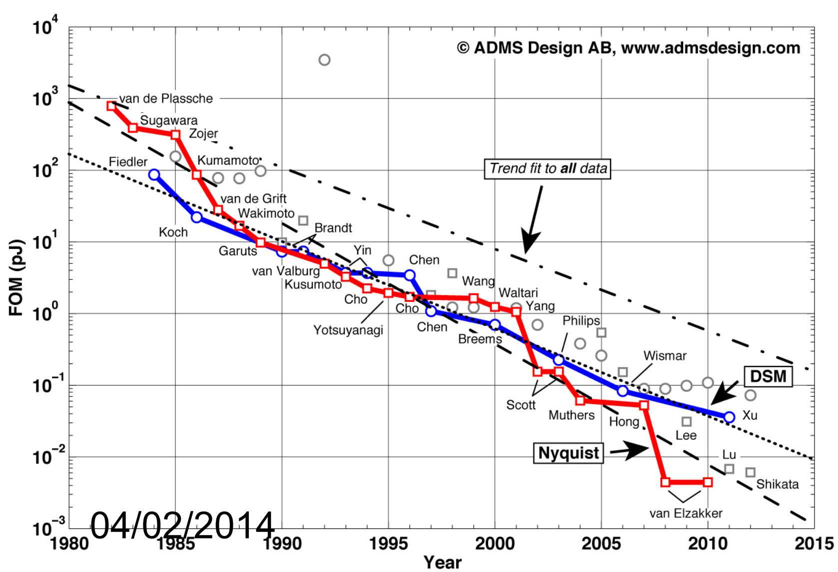
÷ 100

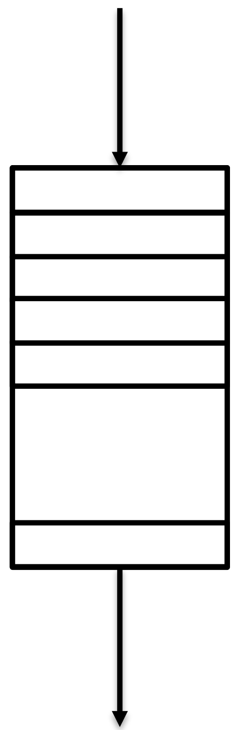
5-10kHz Rate to Tape

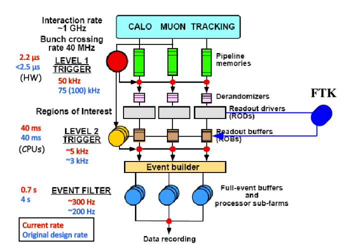
Increase in computing power, according to Moores Law doubling every 2 years, and related increase in storage capacity, makes it possible !

Triggering









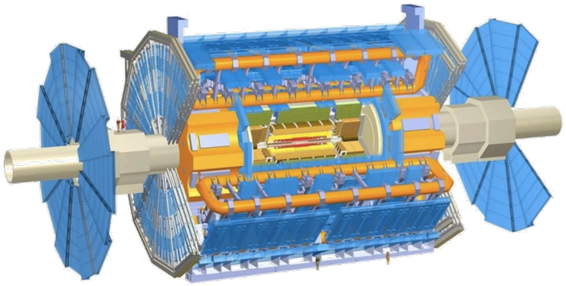
Pipeline Memories, e.g. ATLAS Liquid Argon Calorimeter:

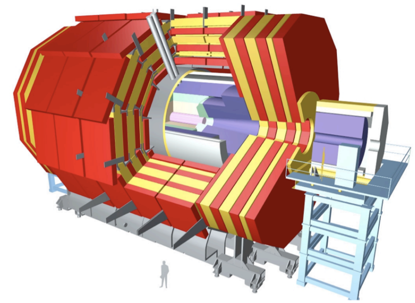
Analog pipeline i.e. Switch Capacitor Array (SCA)

Up to now, full Digitization was not possible at 40MHz 10bit in 2005 due to excessive power consumption.

The power consumption of ADCs has however desreased dramatically over the last years i.e. for the LHC experiment upgrades, 40MHz digitization will be possible !

ATLAS & CMS @ Run 4

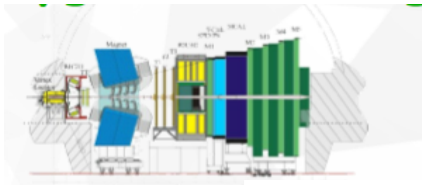




40 MHz

ATLAS		CMS
Level 1	0.5-1 MHz	Level 1
HLT		HLT
5-10 kHz (2MB/event)		10 kHz (4MB/event)
Storage		Storage
10-20 GB/s	← PEAK OUTPUT →	40 GB/s

LHCb & ALICE @ Run 3



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

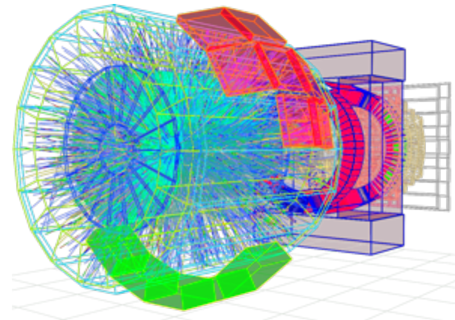
5-40 MHz

HLT: event recon.

20 kHz (0.1 MB/event)

Storage

2 GB/s



50 kHz

Reconstruction + Compression

50 kHz (1.5 MB/event)

Storage

75 GB/s

← PEAK OUTPUT →

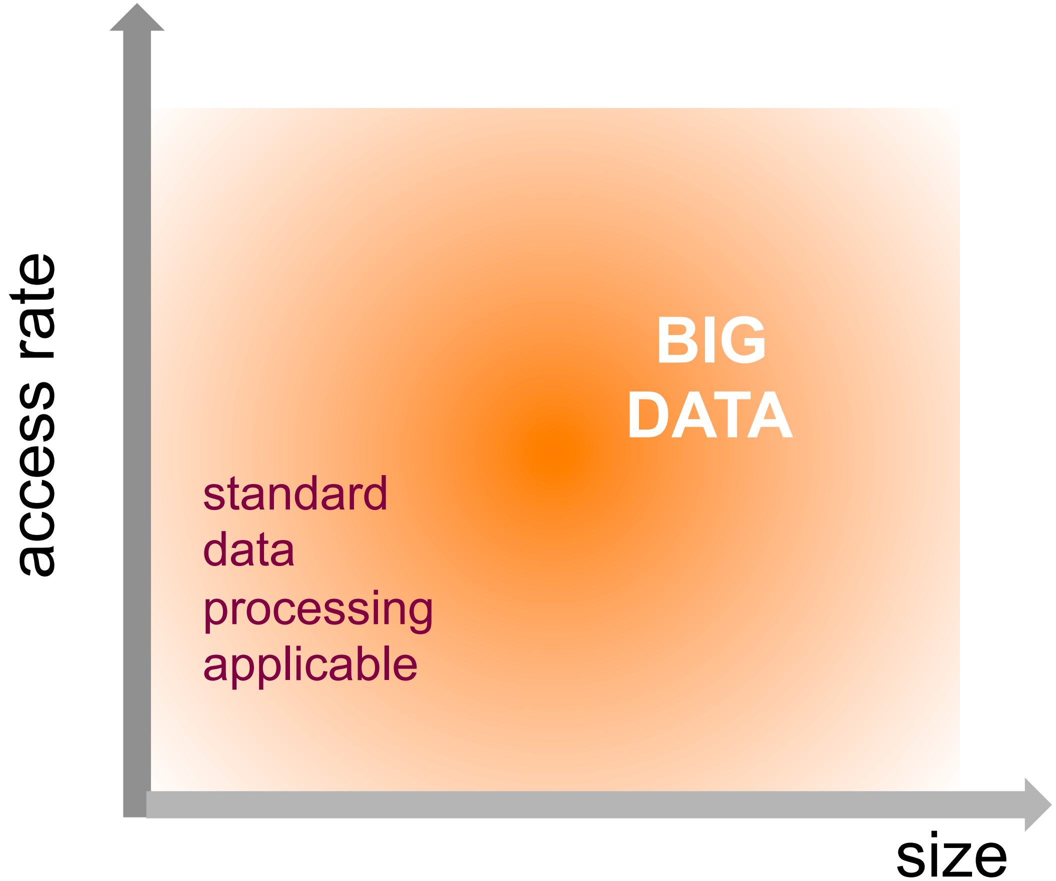
Moore‘s Law

http://www.livescience.com/23074-future-computers.html

If the doubling of computing power every two years continues to hold, "then by 2030 whatever technology we're using will be sufficiently small that we can fit all the computing power that's in a human brain into a physical volume the size of a brain," explained Peter Denning, distinguished professor of computer science at the Naval Postgraduate School and an expert on innovation in computing. "Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

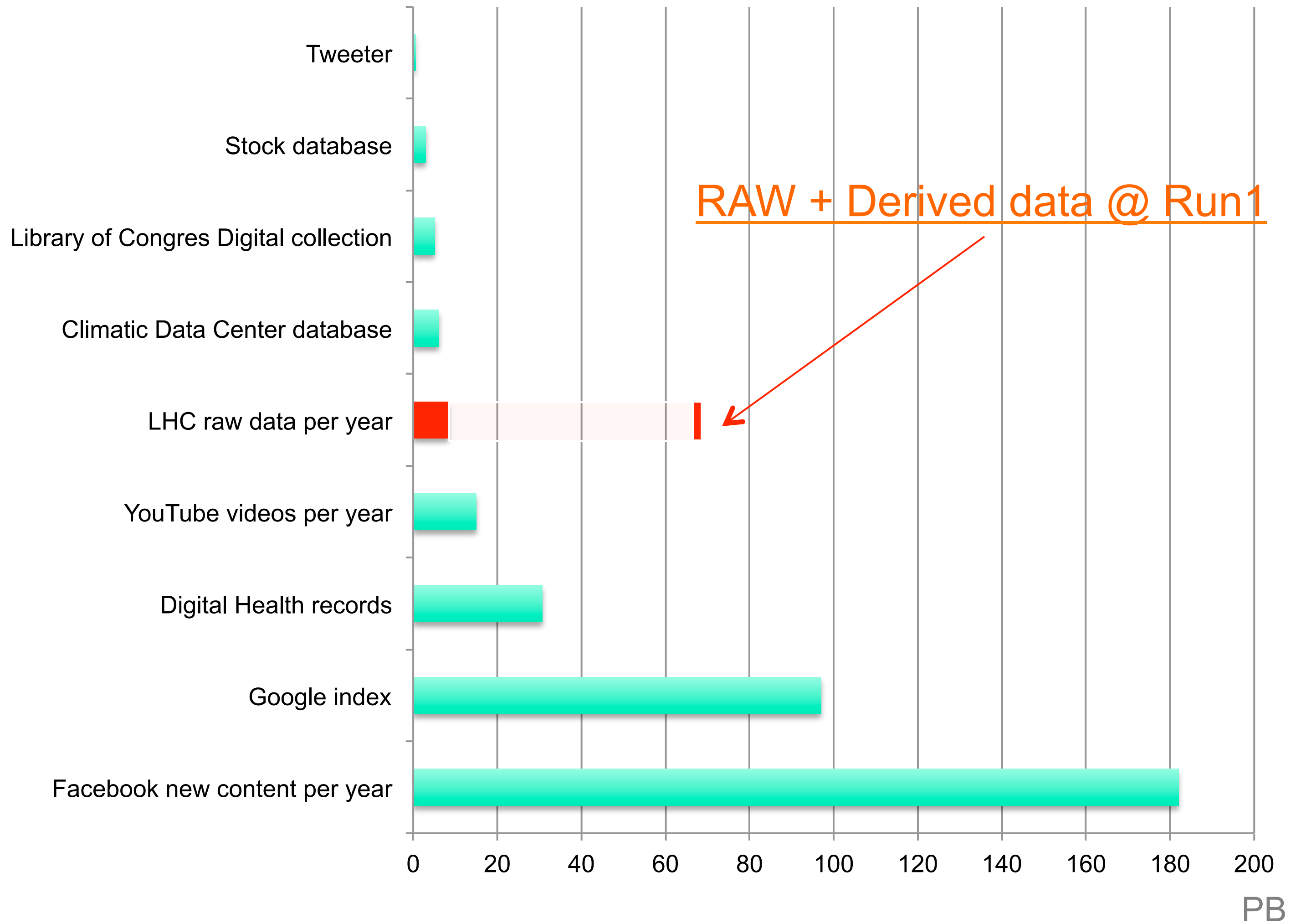
→ Computers will anyway by themselves figure out what to do with the data very soon.

Big Data

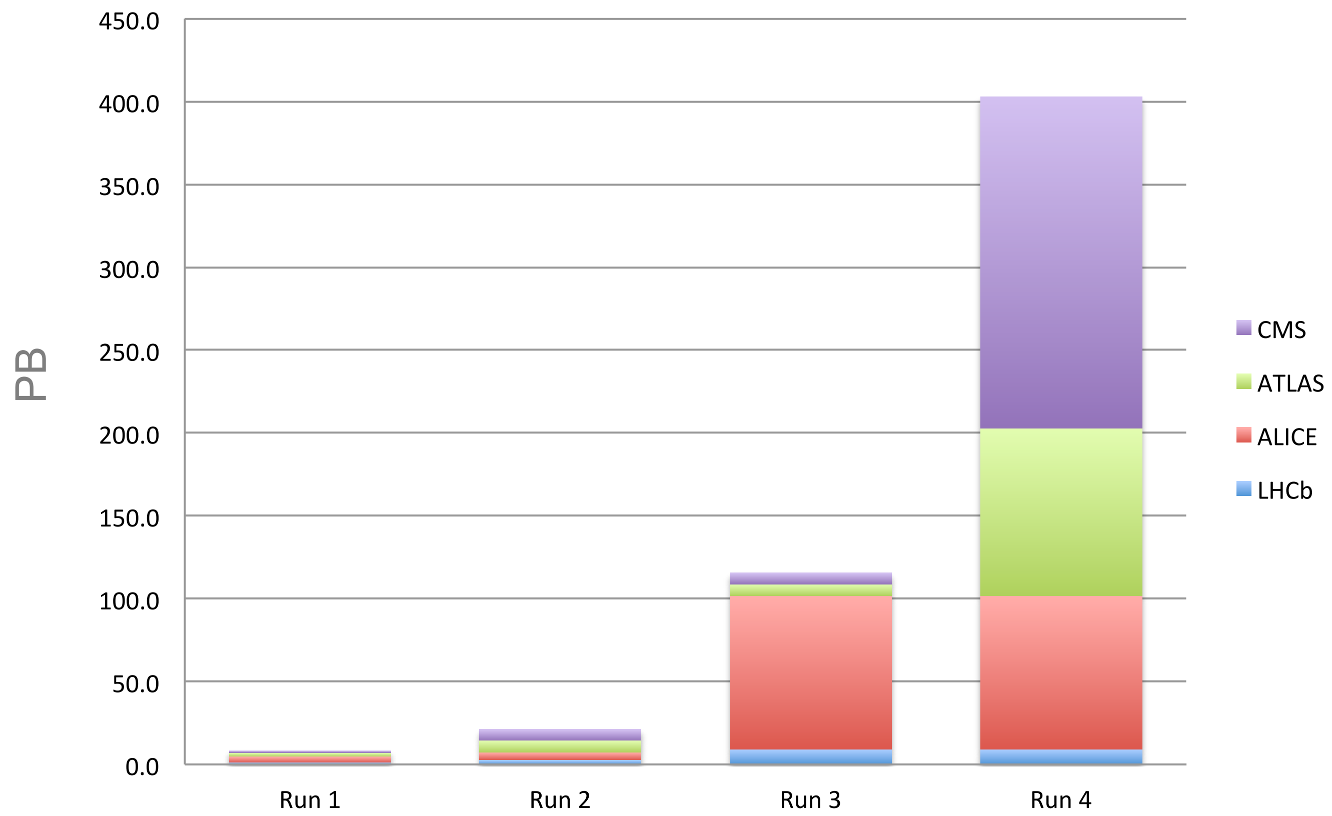


"Data that exceeds the boundaries and sizes of normal processing capabilities, forcing you to take a non-traditional approach"

How do we score today?



Data: Outlook for HL-LHC



- Very rough estimate of a new RAW data per year of running using a simple extrapolation of current data volume scaled by the output rates.
  - To be added: derived data (ESD, AOD), simulation, user data…

Exabyte Scale

- **We are heading towards Exabyte scale**

Scales

We have to learn new vocabulary for HL-LHC era:

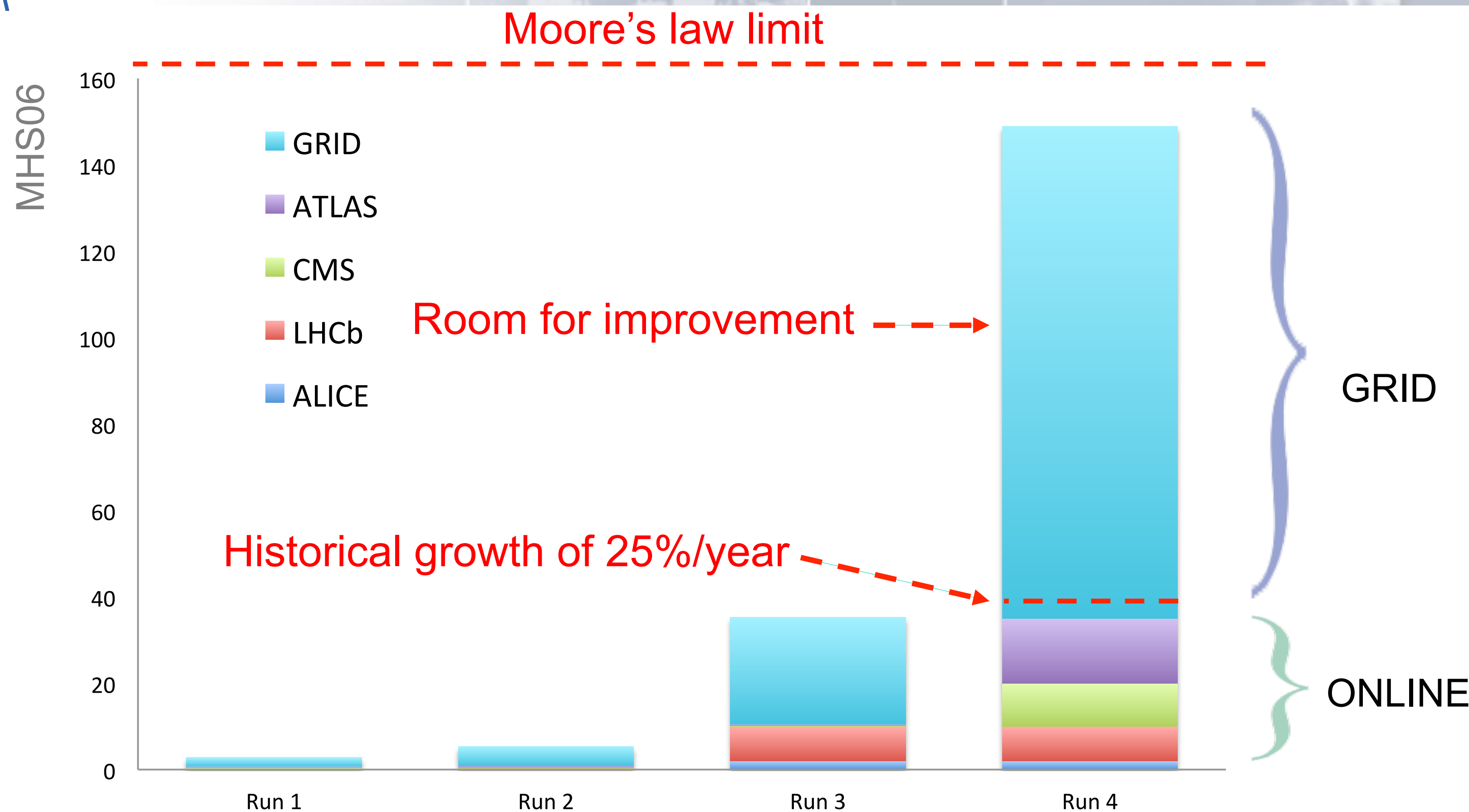
3000 fb^{-1} = 1 $attobarn^{-1}$ atto = 10^{-18}

1000 petabyte = 1 exabyte exa = 10^{18}

We have to cover 36 orders of magnitude in our day to day communication !

We compete with inflation theorists ...

CPU: Online + Offline



- Very rough estimate of new CPU requirements for online and offline processing per year of data taking using a simple extrapolation of current requirements scaled by the number of events.
- Little headroom left, we must work on improving the **performance**.

How to improve the performance?

- Clock frequency
- Vectors
- Instruction Pipelining
- Instruction Level Parallelism (ILP)
- Hardware threading
- Multi-core
- Multi-socket
- Multi-node

Very little gain to be expected and no action to be taken

Potential gain in throughput and in time-to-finish

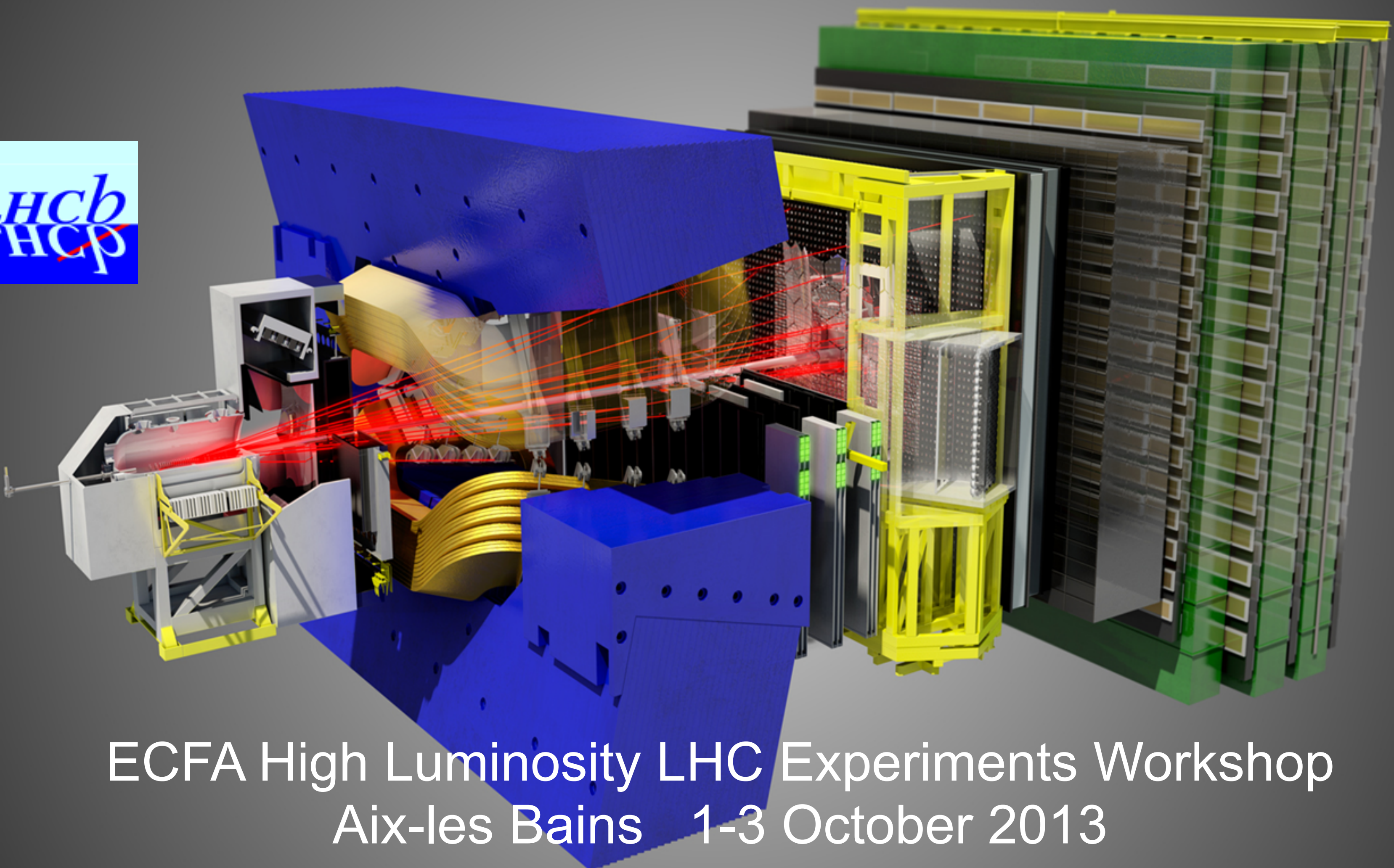
Gain in memory footprint and time-to-finish but not in throughput

Running independent jobs per core (as we do now) is optimal solution for High Throughput Computing applications

Improving the algorithms is the only way to reclaim factors in performance!

The LHCb Experiment Upgrade

The LHCb Upgrade Program



ECFA High Luminosity LHC Experiments Workshop
Aix-les Bains 1-3 October 2013

Andreas Schopper on behalf of LHCb

Motivation

LHCb is a high precision experiment devoted to the search for New Physics (NP) beyond the Standard Model (SM) by

- ➢ studying CP violation and rare decays in the b and c-quark sectors
- ➢ searching for deviations from the SM due to virtual contributions of new heavy particles in loop diagrams
- ➢ being sensitive to new particles above the TeV scale not accessible to direct searches

Past and running experiments have shown that:

- ✓ flavour changing processes are consistent with the CKM mechanism
- ✓ large sources of flavour symmetry breaking are excluded at the TeV scale
- ✓ the flavour structure of the NP, if it exists, would be very peculiar at the TeV scale (MFV)

However:

- ➢ measurable deviations from the standard model are still expected, but should be small
- ➢ need to go to very high precision measurements to probe the most clean observables

→ LHCb upgrade essential to increase statistical precision significantly

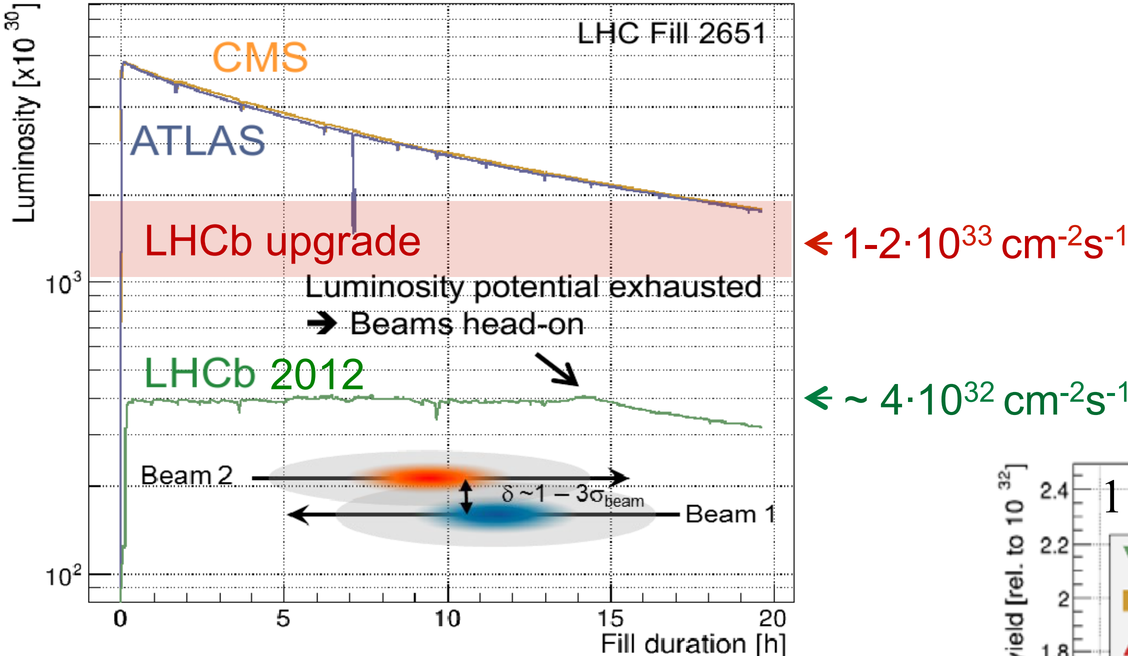
LHCb statistical sensitivity to flavour observables

Expected statistical uncertainties before and after the upgrade, compared to theory

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\,A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\,K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

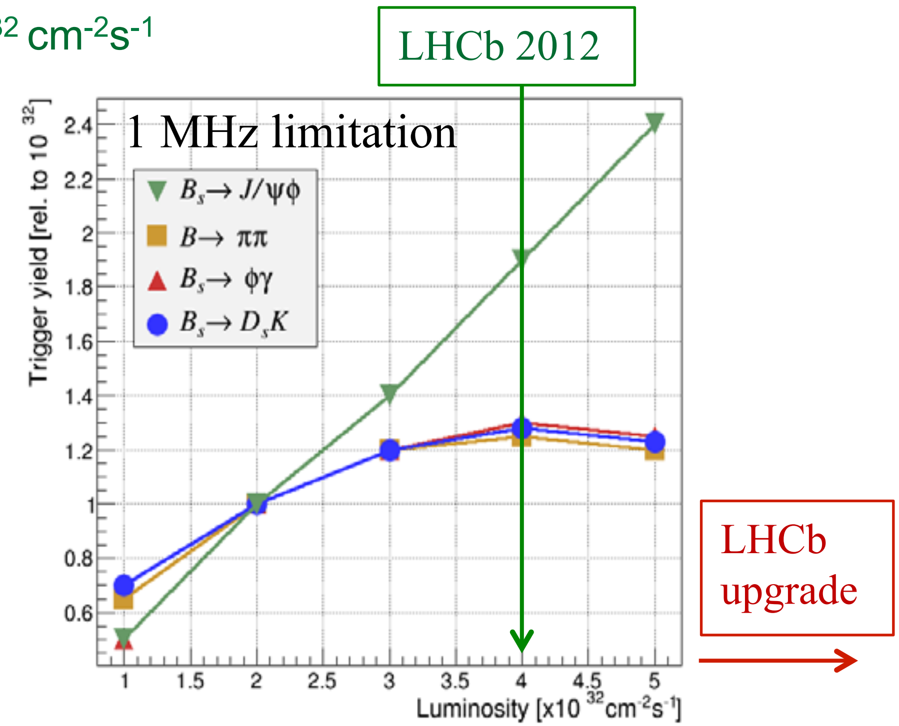
How to increase LHCb statistics significantly

2012 running conditions



LHCb up to LS2

- running at levelled luminosity of ~ $4\cdot10^{32}$ cm^{-2}s^{-1}, pile-up~1
- first level hardware trigger running at ~1 MHz
- record ~3-5 kHz



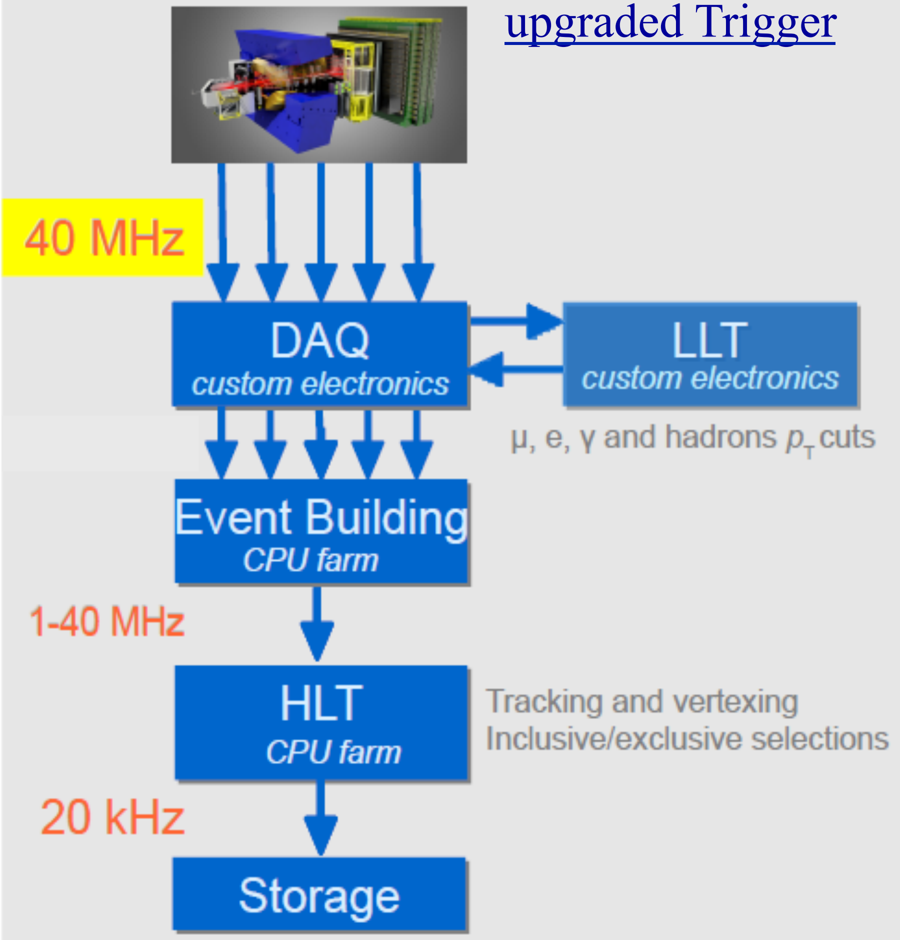
LHCb upgrade

- increase luminosity to a levelled $1\text{-}2\cdot10^{33}$ cm^{-2}s^{-1}, pile-up~5
- run fully flexible & efficient software trigger up to 40 MHz
- record ~20 kHz

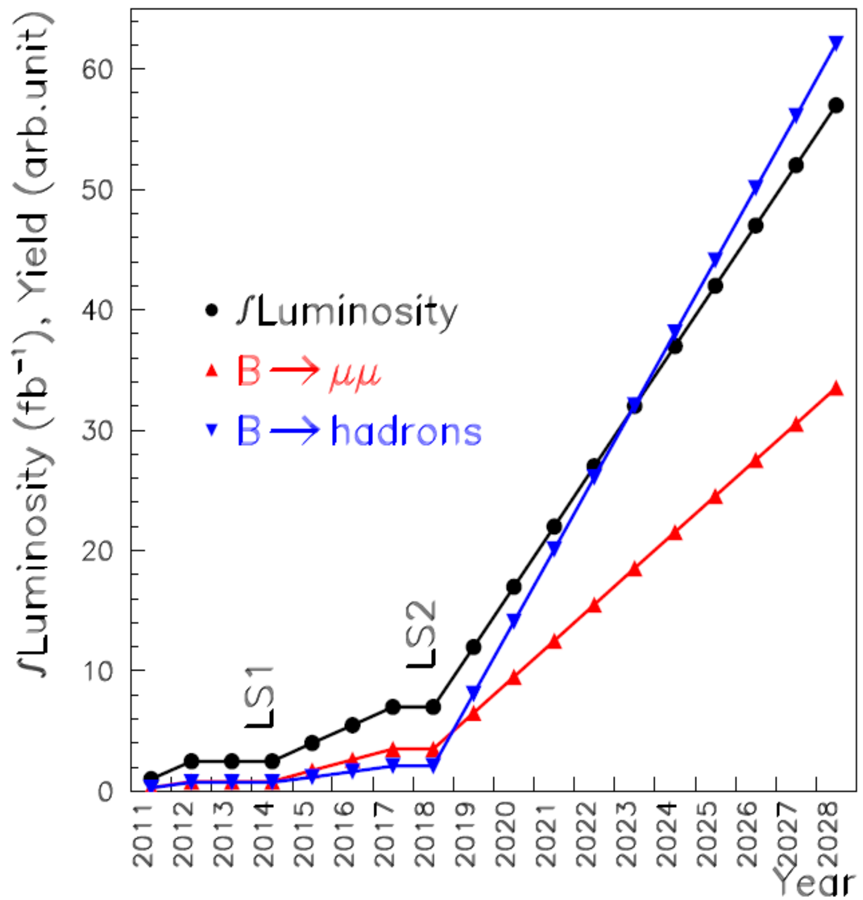
Trigger upgrade

run an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing → increase luminosity and signal yields

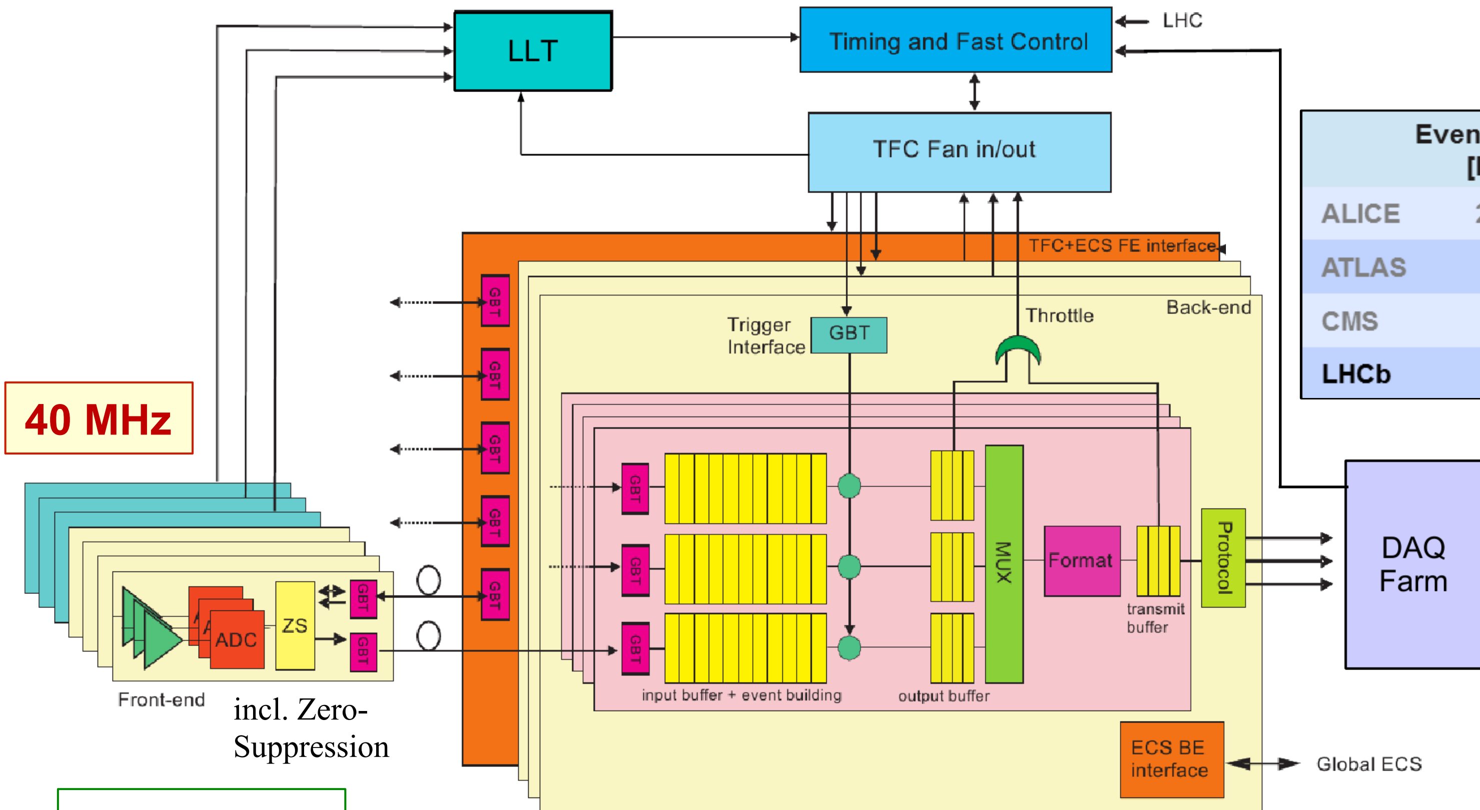
upgraded Trigger



effect on luminosity and signal yields



40 MHz architecture overview



see N.Neufeld talk

	Event-size [kB]	Rate [kHz]	Bandwidth [Gb/s]	Year
ALICE	20 000	50	8 000	2019
ATLAS	4 000	200	6 400	2022
CMS	4 000	1000	32 000	2022
LHCb	**100**	**40 000**	**32 000**	**2019**

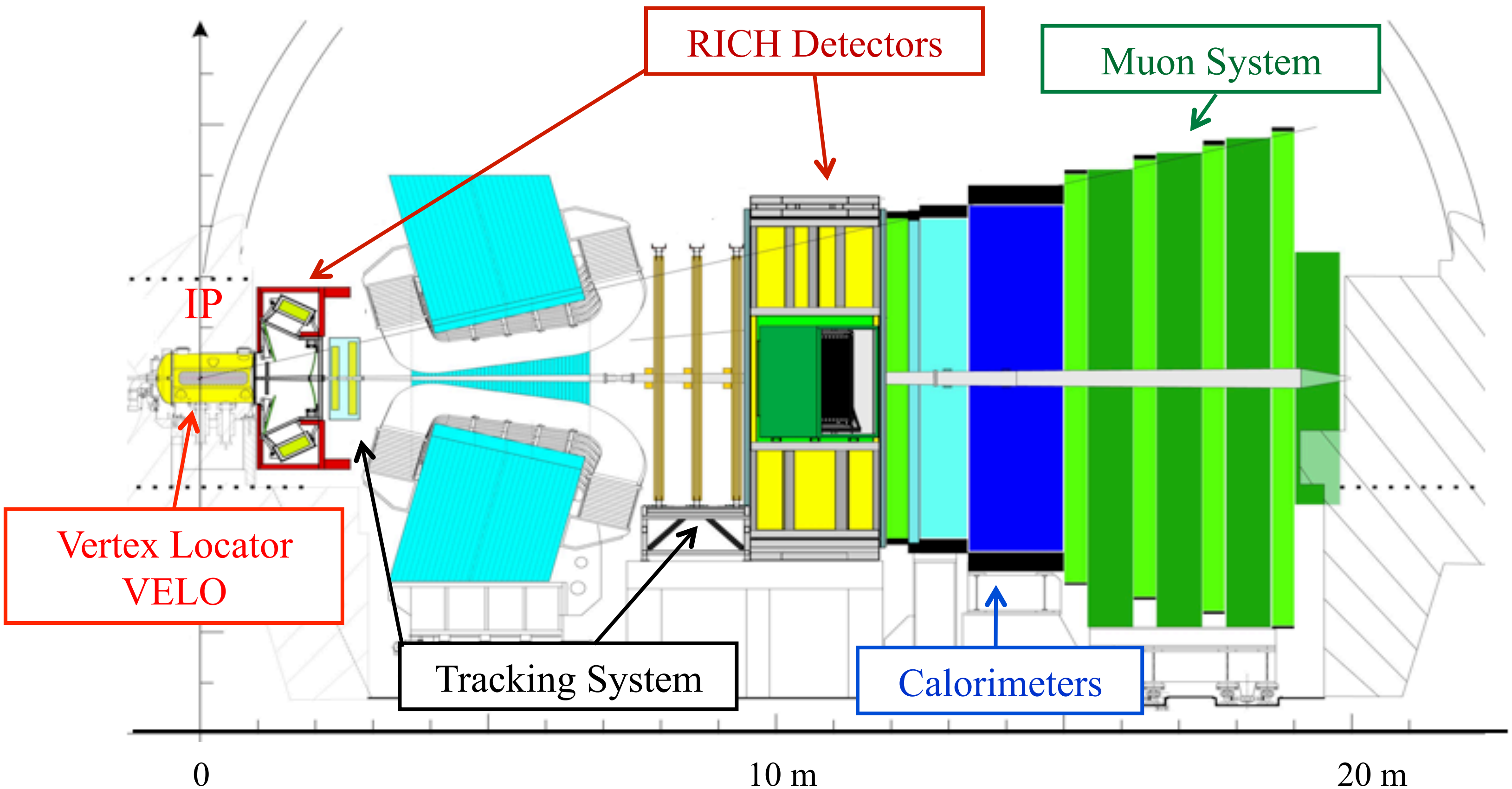
20 KHz

individual sub-systems Front-End electronics → optical link via GBT → common Back-End readout boards TELL40 [or PCI express] → event building & HLT

underground — ~300m — on surface

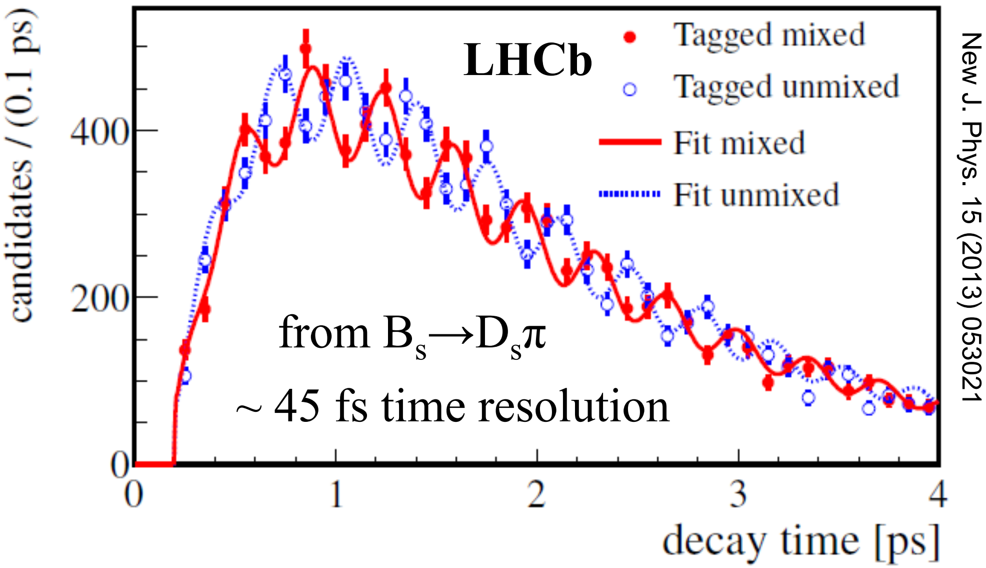
Detector upgrade to 40 MHz readout

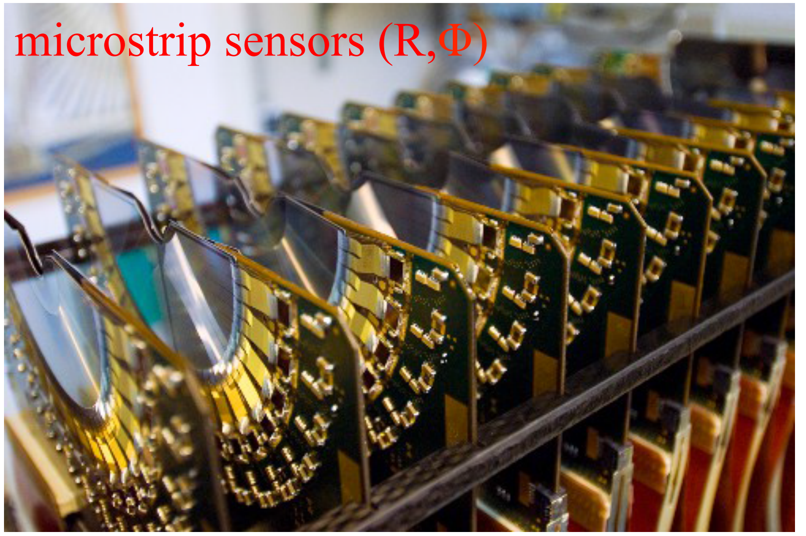
- ✓ upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- ✓ replace complete sub-systems with embedded FE electronics
- ✓ adapt sub-systems to increased occupancies due to higher luminosity
- ➢ keep excellent performance of sub-systems with 5 times higher luminosity and 40 MHz R/O

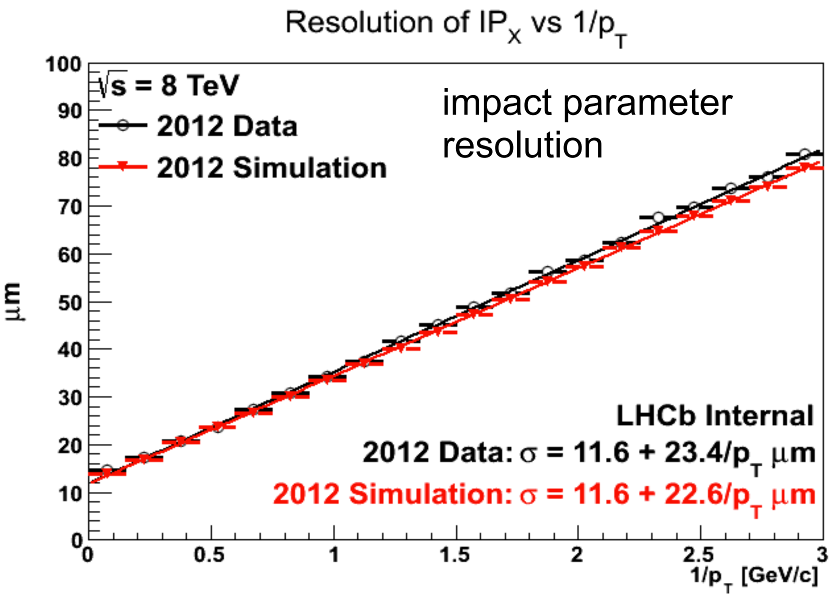


Vertex reconstruction with VELO

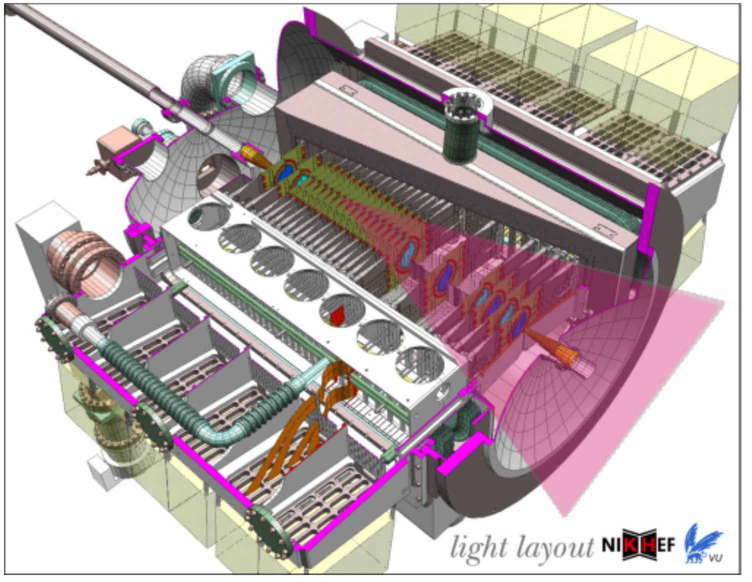
Current detector



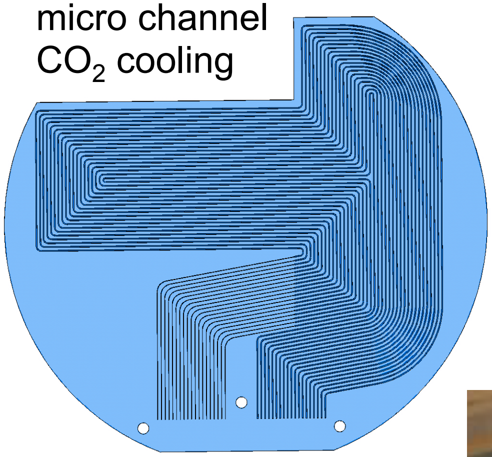


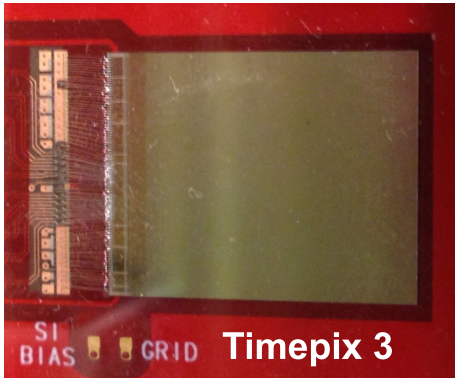


movables halves → 5.5 mm from beam



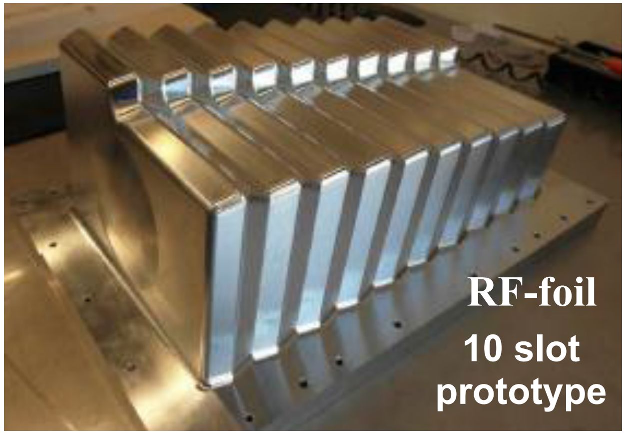
VELO upgrade





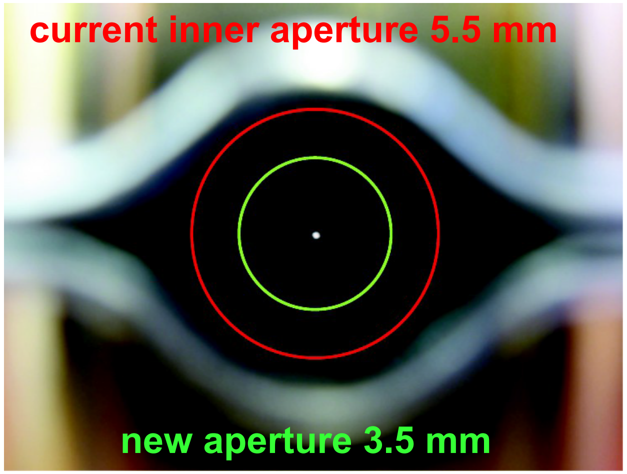
Upgrade challenge:

- ✓ withstand increased radiation (highly non-uniform radiation of up to $8 \cdot 10^{15}\ n_{eq}/cm^2$ for 50 fb^{-1})
- ✓ handle high data volume
- ✓ keep (improve) current performance
  - ➢ lower materiel budget
  - ➢ enlarge acceptance

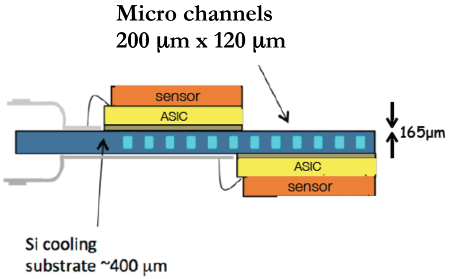


Technical choice :

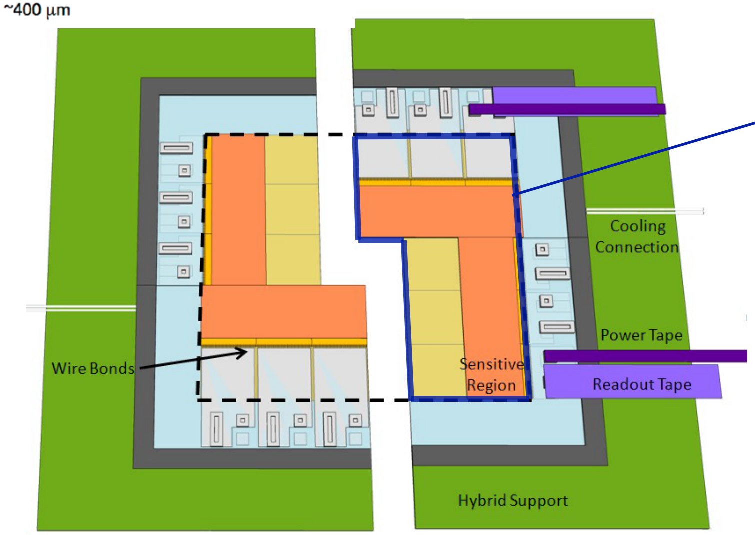
- ✓ 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- ✓ 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - ➢ 130 nm technology to sustain ~400 MRad in 10 years
  - ➢ VELOPIX hit-rate = ~8 x TIMEPIX 3 rate
- ✓ replace RF-foil between detector and beam vacuum
  - ➢ reduce thickness from 300 μm → ~150 μm
- ✓ move closer to the beam
  - ➢ reduce inner aperture from 5.5 mm → 3.5 mm

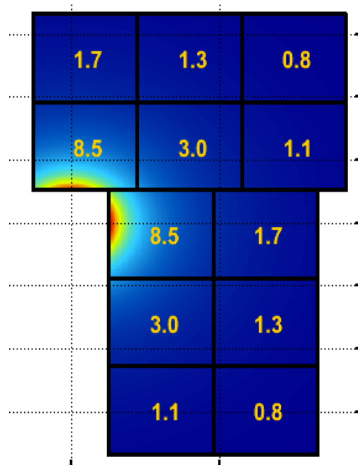


VELO upgrade



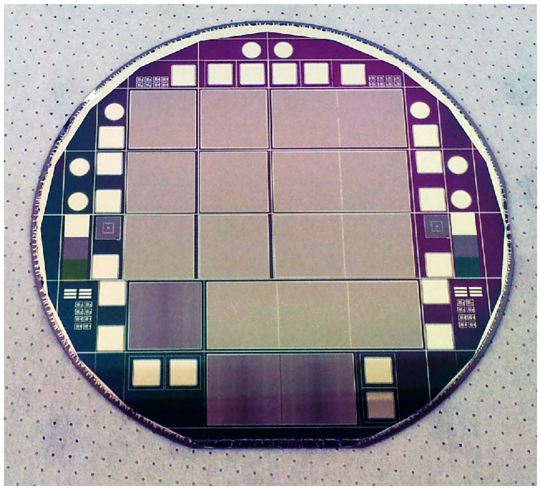
pixel detector with
micro channel cooling

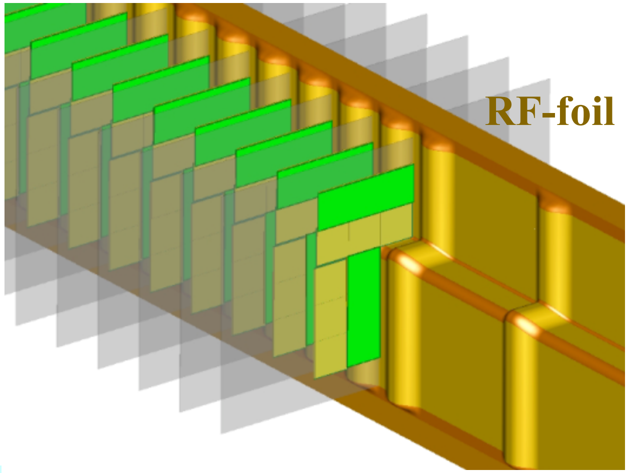


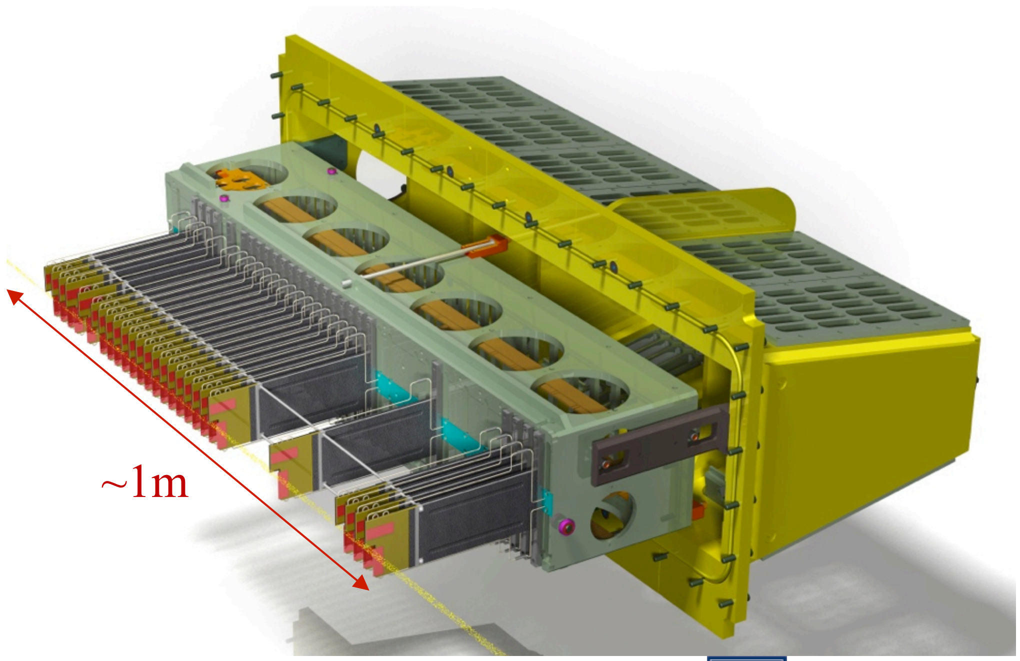


tracks/chip/event
at L=$2{\cdot}10^{33}$ $cm^{-2}s^{-1}$

Prototype pixel sensor

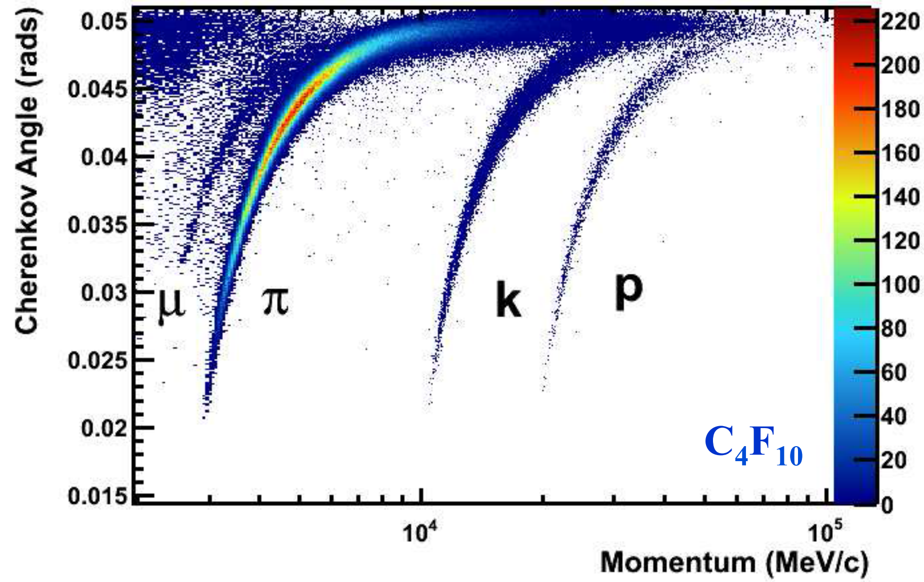




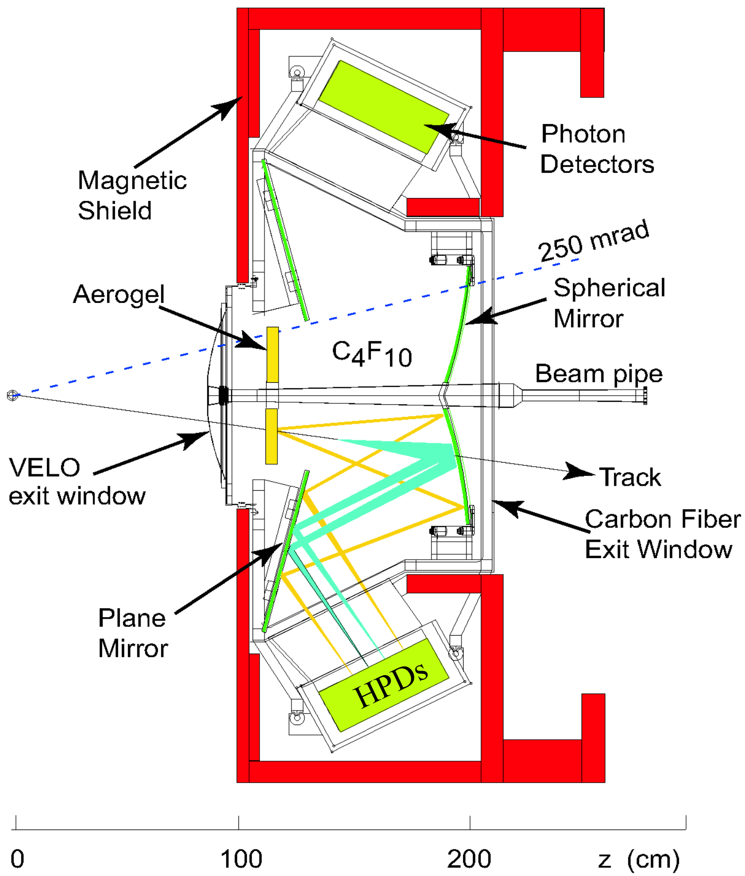


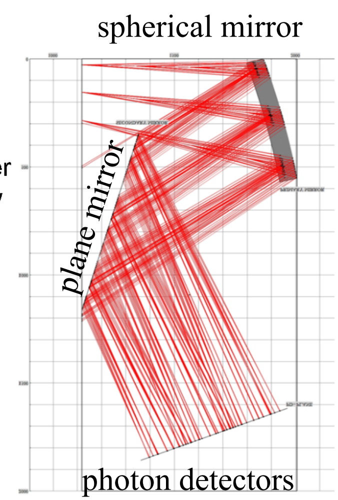
RICH(1) optics

Particles traversing radiator produce Cherenkov light rings on an array of HPDs located outside the acceptance



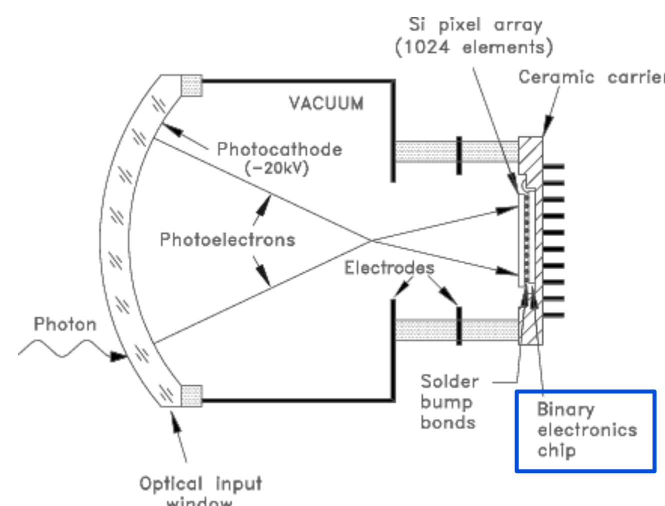
RICH 1





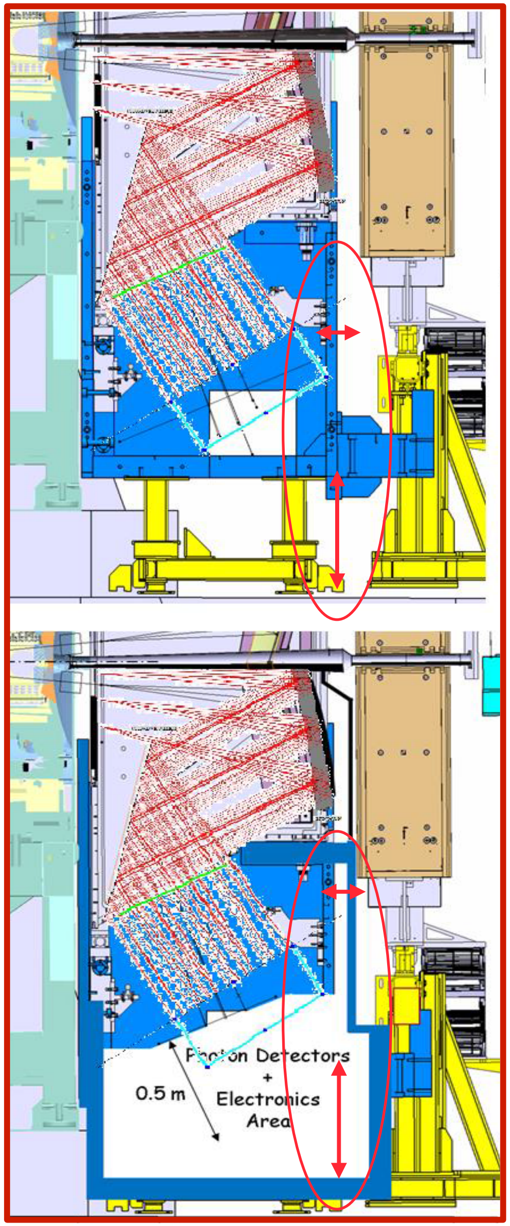
Hybrid Photon Detector

with embedded 1 MHz R/O chip



RICH upgrade

optimise RICH1 optics

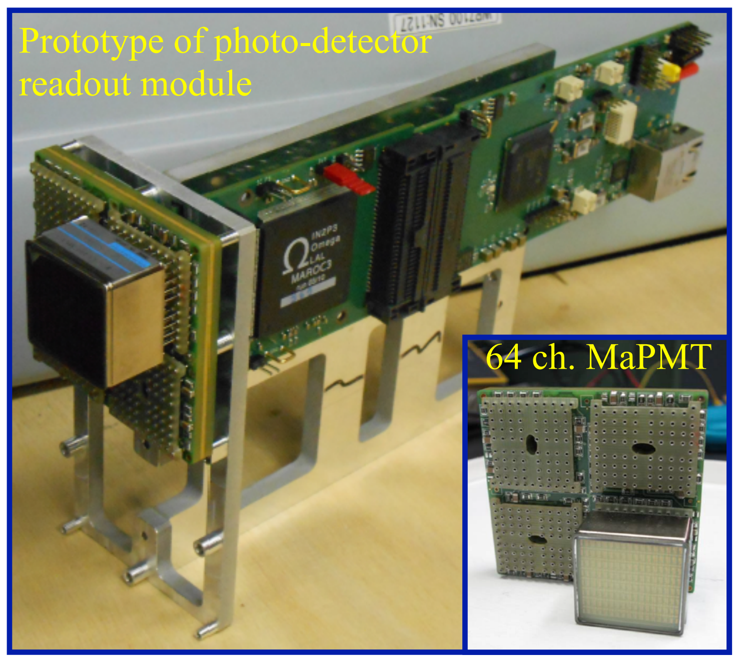


Luminosity of $2 \cdot 10^{33}$ cm^{-2}s^{-1} → adapt to high occupancies

- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

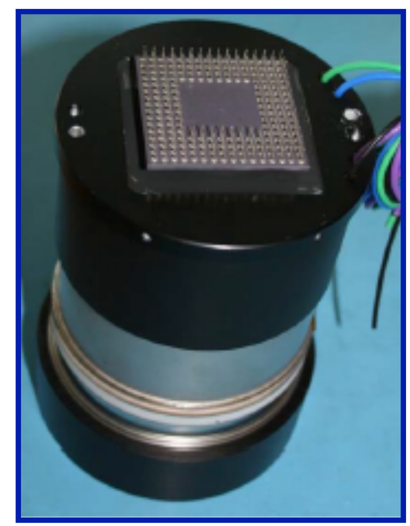
40 MHz readout → replace HPDs due to embedded FE

- 64 ch. multi-anode PMTs (baseline)
- 40 MHz Front-End: Claro or Maroc chip



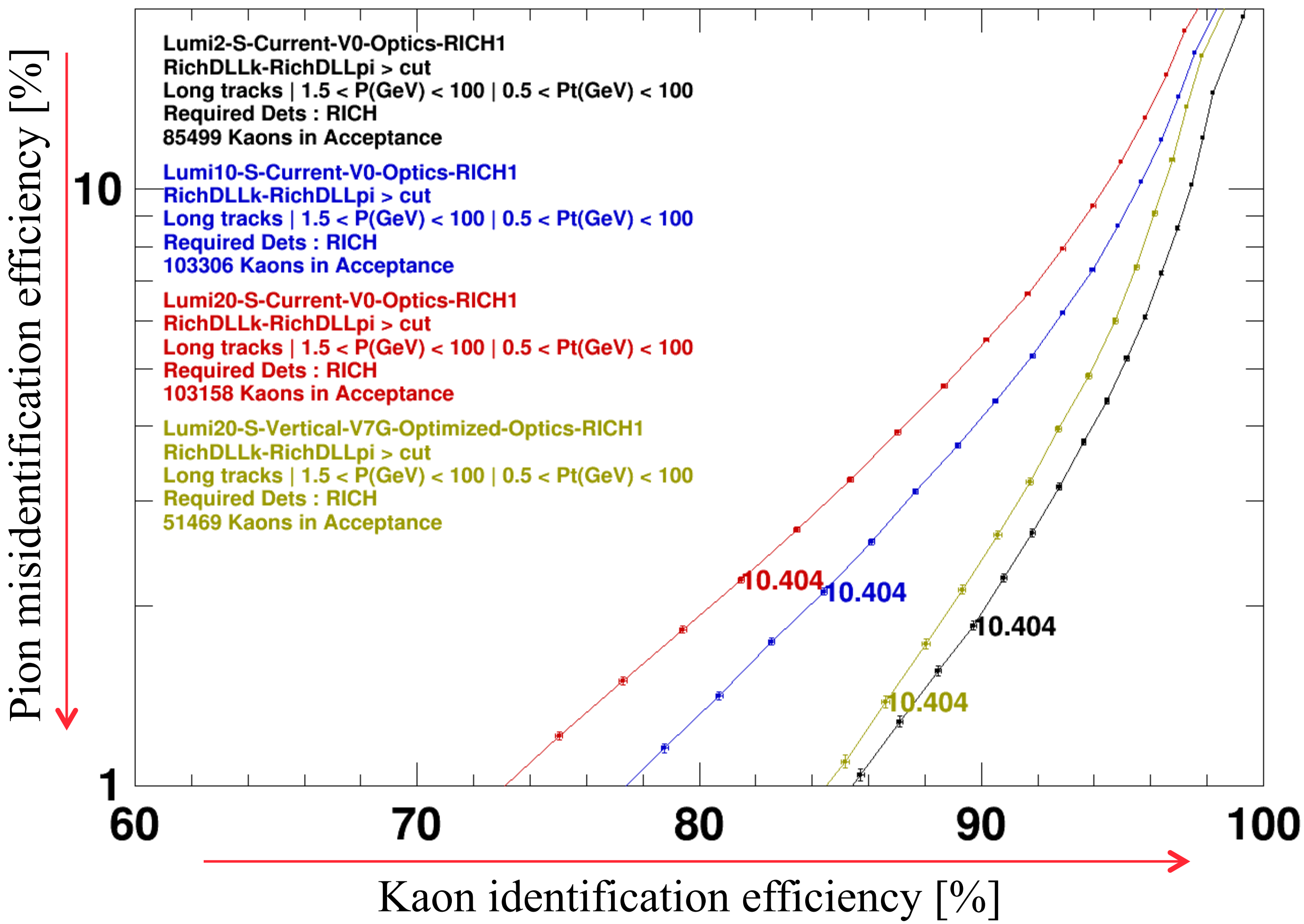
Prototype of photo-detector readout module

HPD prototype with external electronics



RICH upgrade

RICH Kaon ID RICH1-Optics-Comparison as function of luminosity



Current RICH1

- $2 \cdot 10^{32}\ cm^{-2}s^{-1}$
- $10 \cdot 10^{32}\ cm^{-2}s^{-1}$
- $20 \cdot 10^{32}\ cm^{-2}s^{-1}$

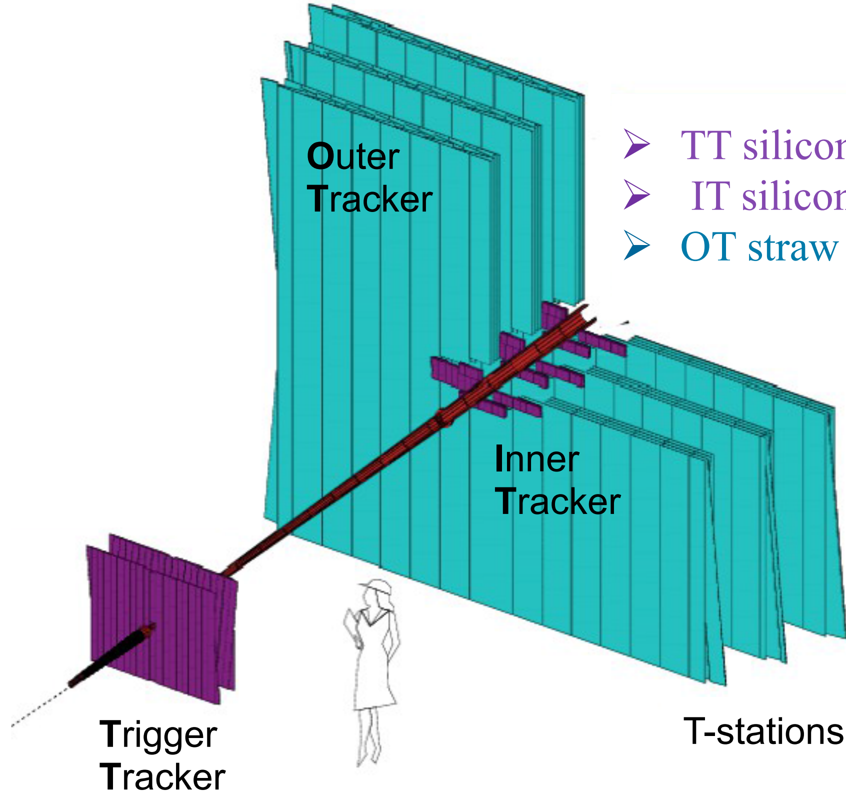
RICH1 upgrade

- $20 \cdot 10^{32}\ cm^{-2}s^{-1}$

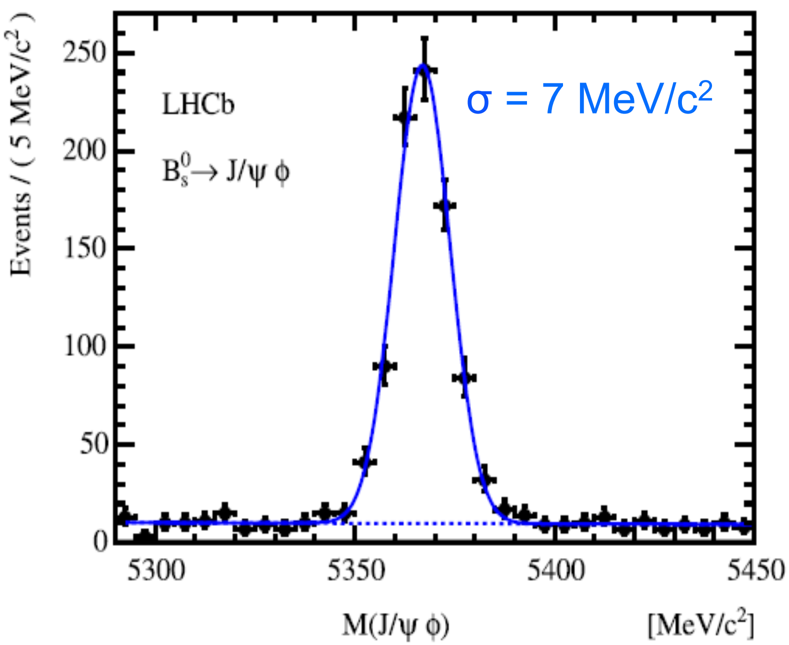
note:
full GEANT MC with standard LHCb simulation framework

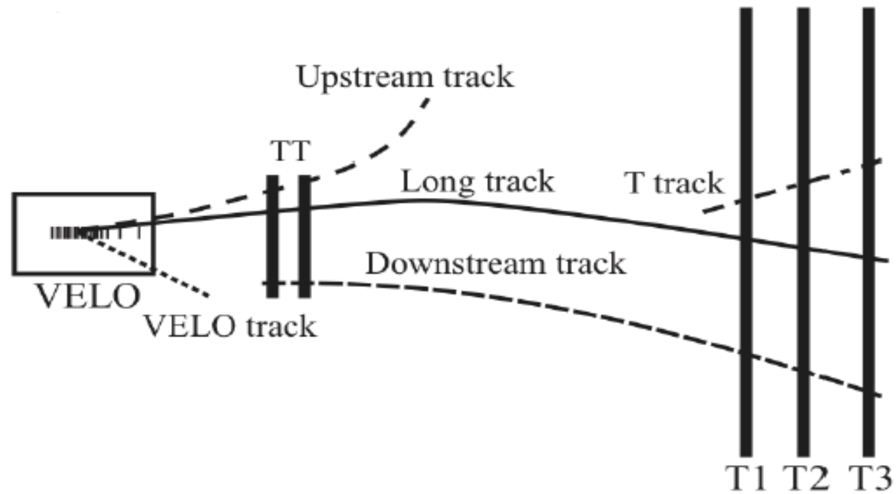
Tracking System

- excellent mass resolution
- very low background, comparable to e^+e^- machines
- worlds best mass measurements [PLB 708 (2012) 241]

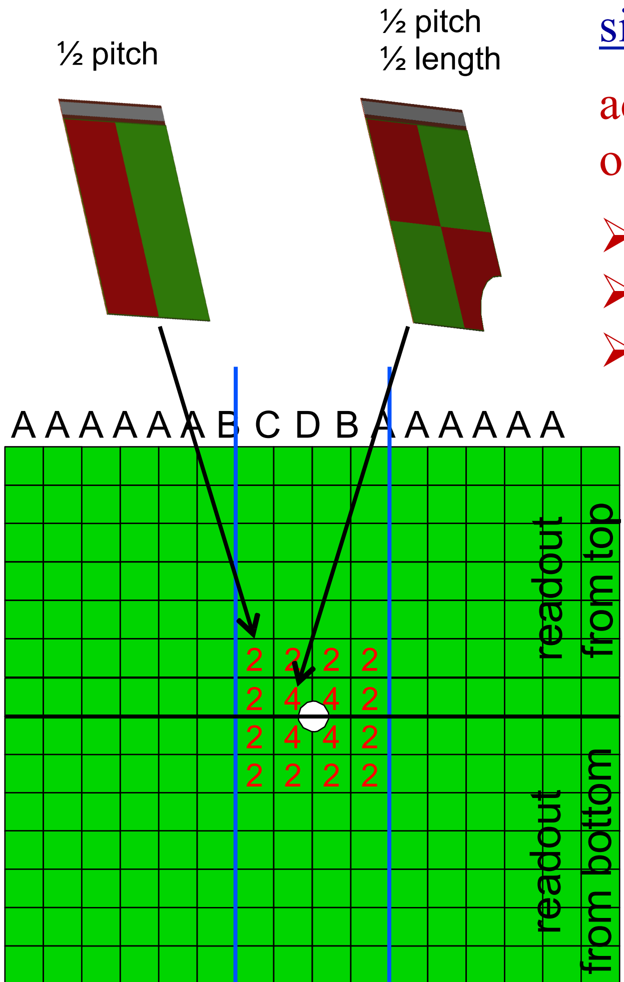


- TT silicon
- IT silicon
- OT straw tubes





TT upgrade: Upstream Tracker (UT)



Region 0
6/7 modules
84/98 sectors

Region 1
4 modules
80 sectors

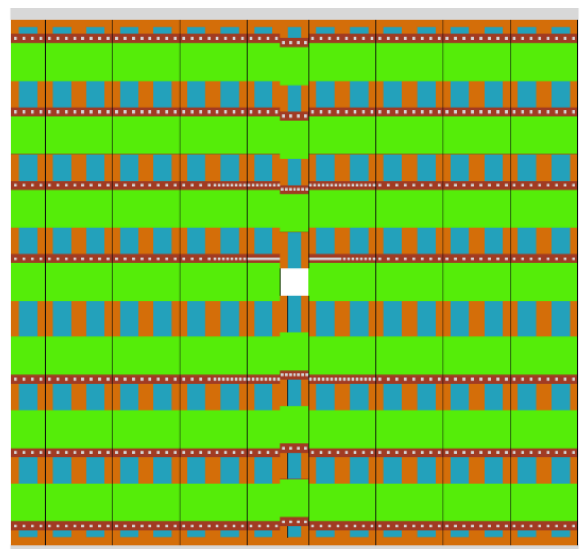
Region 2
6/7 modules
84/98 sectors

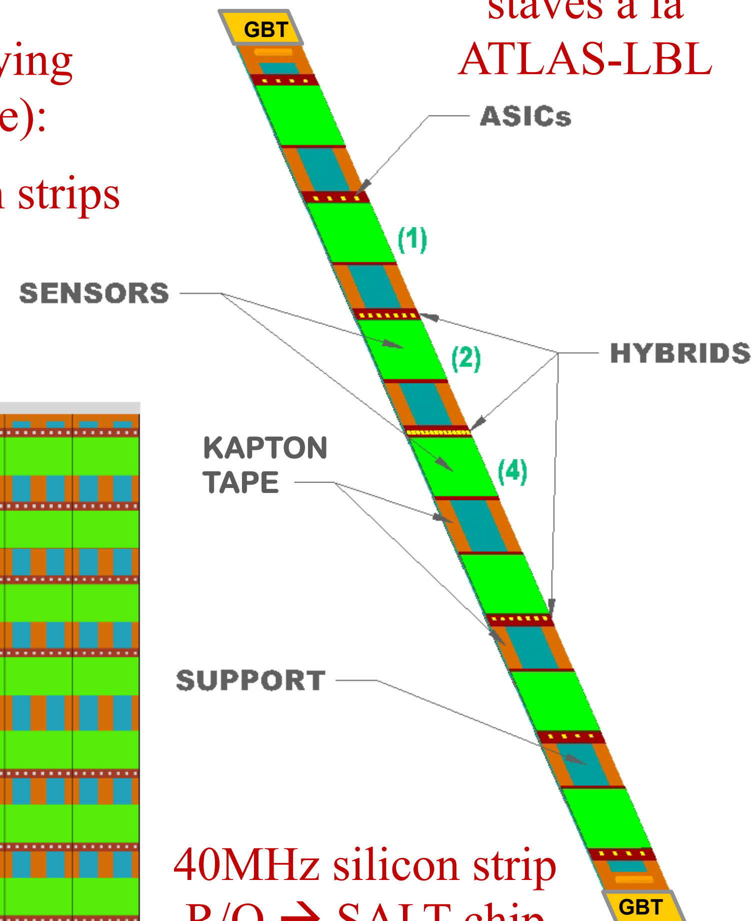
silicon strip detector

adapt segmentation to varying occupancies (out → in-side):

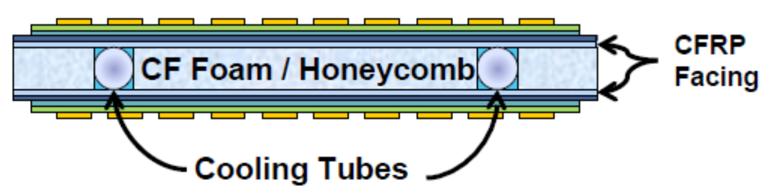
- 10 → 5 cm long silicon strips
- 180 → 90 μm pitch
- p-in-n → n-in-p

staves a la ATLAS-LBL





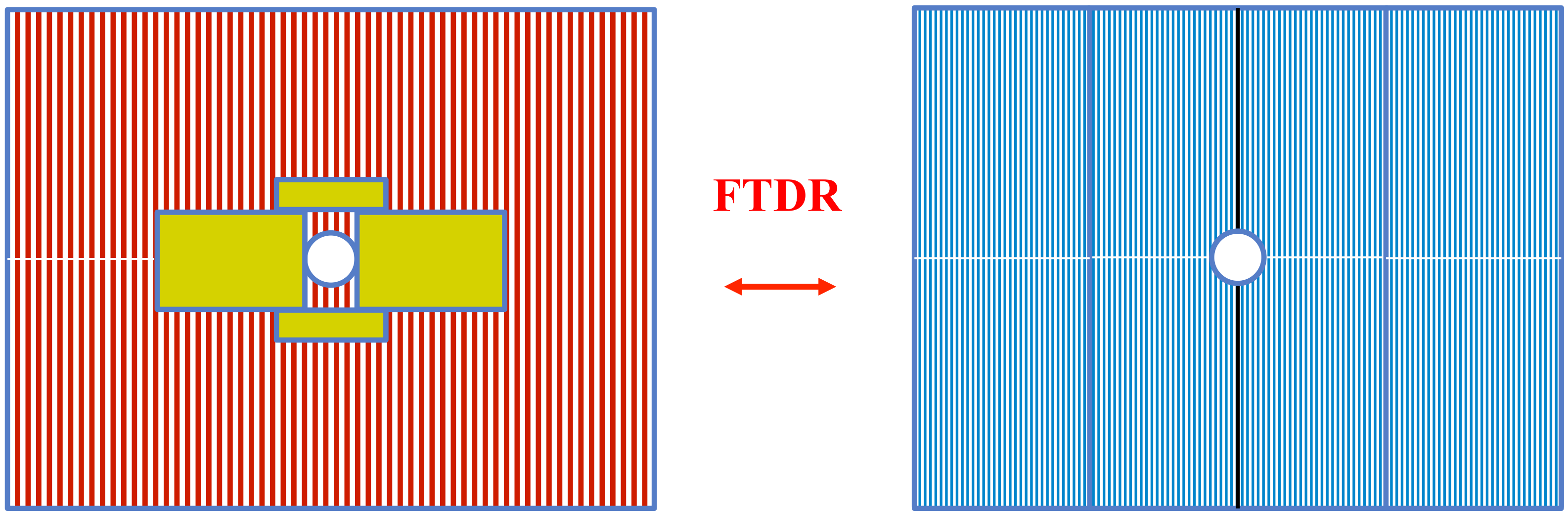
40MHz silicon strip R/O → SALT chip



T-stations upgrade

Inner Tracker & Outer Tracker

Full Fibre Tracker

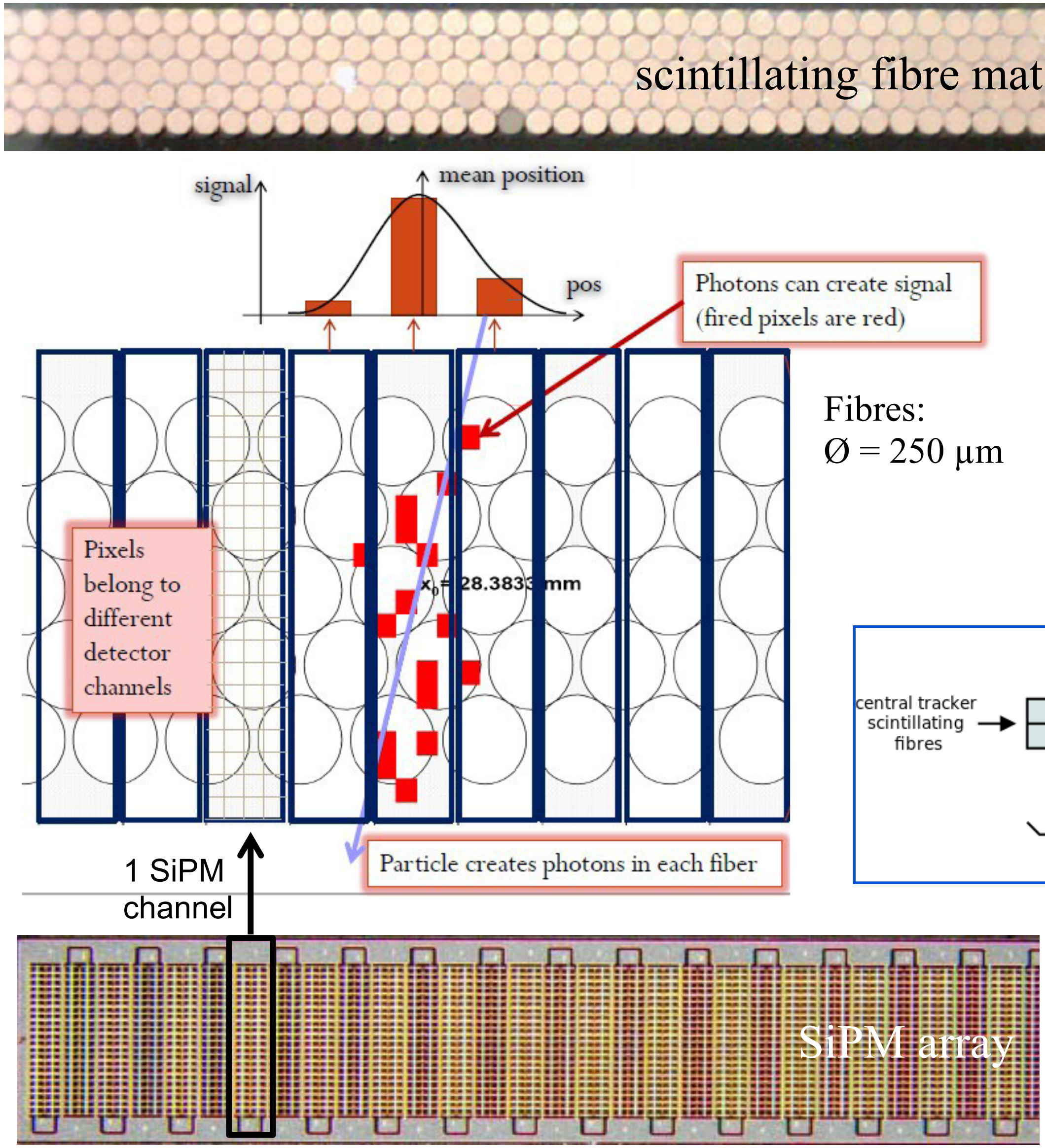


Outer Tracker with straw tube technology

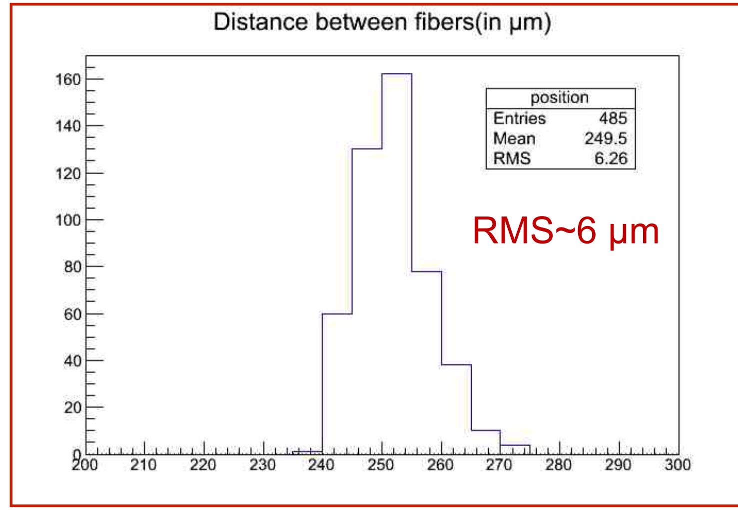
Inner Tracker with silicon strip technology

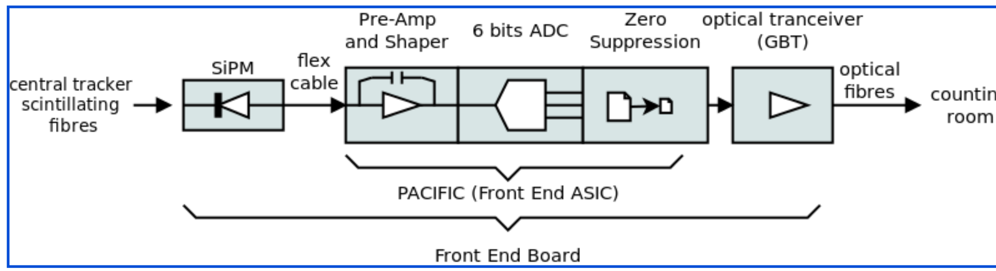
Tracker with scintillating fibre technology

T-stations upgrade: Fibre Tracker (FT)



Fibres:
Ø = 250 µm





analog readout by dedicated
40 MHz PACIFIC chip

T-stations upgrade: Fibre Tracker (FT)

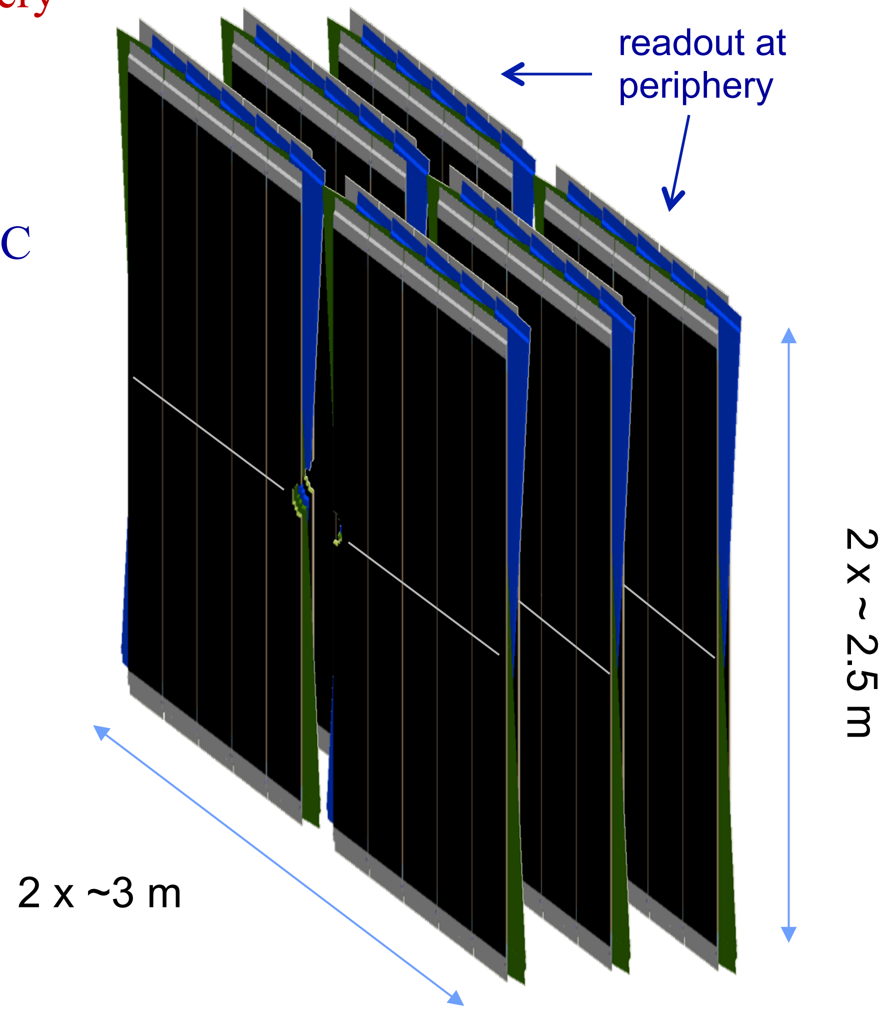
- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 μm fibres, 2.5 m long
- 40 MHz readout and Silicon PMs at periphery

Challenges → radiation environment

- ionization damage to fibres → tested ok
- neutron damage to SiPM → operate at -40°C

Benefits of the SciFi concept:

- ✓ a single technology to operate
- ✓ uniform material budget
- ✓ SiPM + infrastructure outside acceptance
- ✓ fine channel granularity of 250 μm
- ✓ x-position resolution of 50 – 75 μm
- ✓ high hit detection efficiency (≥ 99%)
- ✓ fast pattern recognition



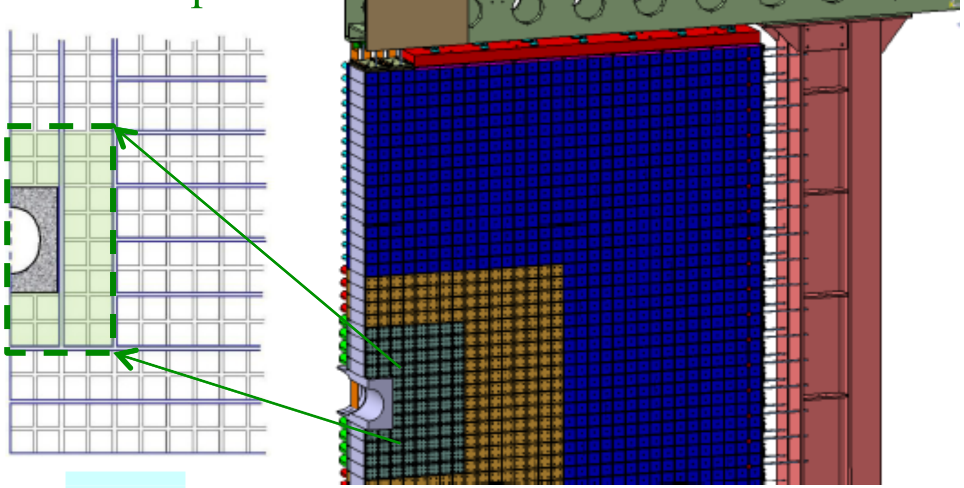
Calorimeters upgrade

Radiation damage and occupancies:

- ✓ Preshower and SPD removed
- ✓ HCAL modules ok up to ~50 fb^{-1}
- ✓ irradiation tests show that most exposed ECAL modules resist up to ~20 fb^{-1} → LS3

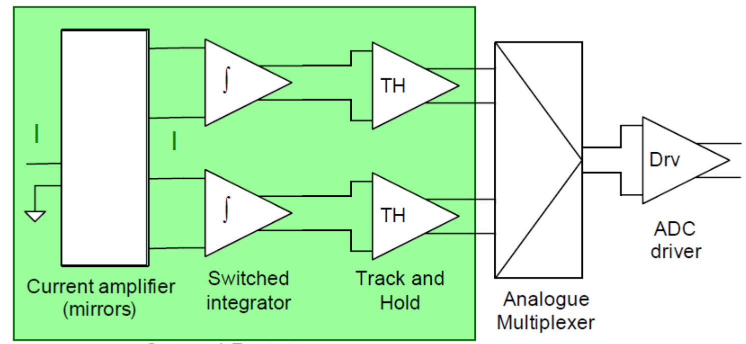
E beam, GeV	module #1 (irradiated 2Mrad) light yield ph.el./GeV	module #1 (irradiated 2Mrad) resolution, %	module #2 (not irradiated) light yield, ph.el./GeV	module #2 (not irradiated) resolution, %
50	583±12	2.16±0.04	2598±52	1.37±0.04
100	576±12	1.57±0.03	2611±52	1.01±0.03
120	571±12	1.36±0.03	2604±52	0.98±0.03

most inner ECAL modules around beam-pipe can be replaced

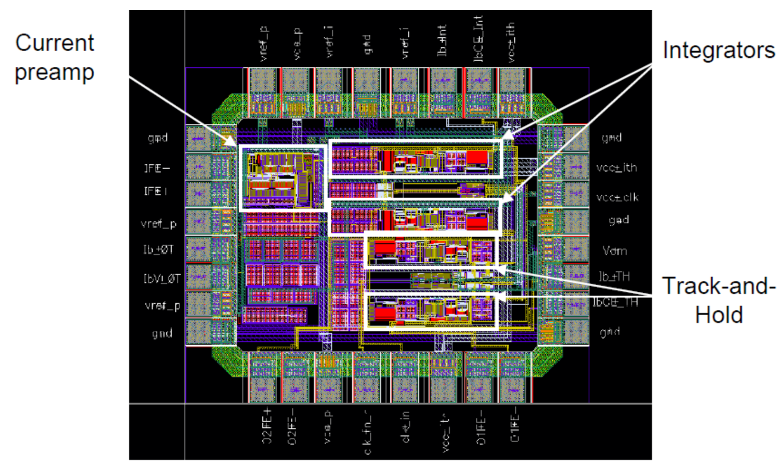


40 MHz readout electronics:

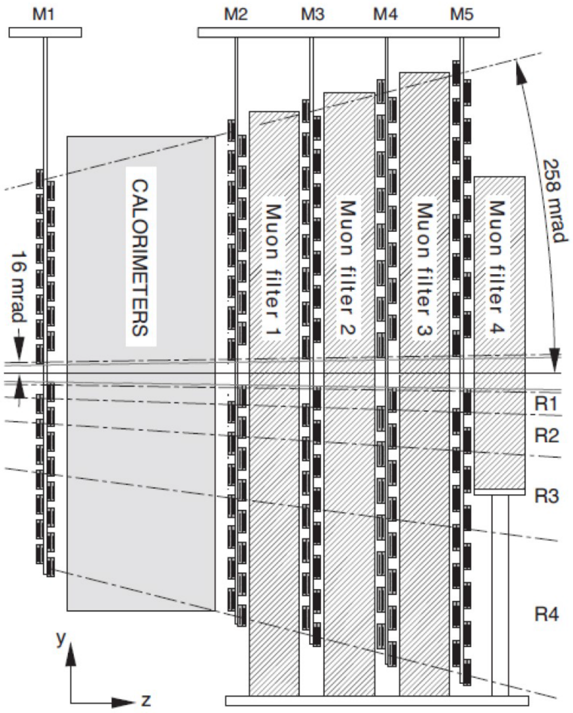
- ➢ reduce photomultiplier gain
- ➢ two interleaved integrators at 20 MHz
- ➢ fully differential implementation
- ➢ Track and Hold



Second Prototype: ICECAL2



Particle identification with Muon System



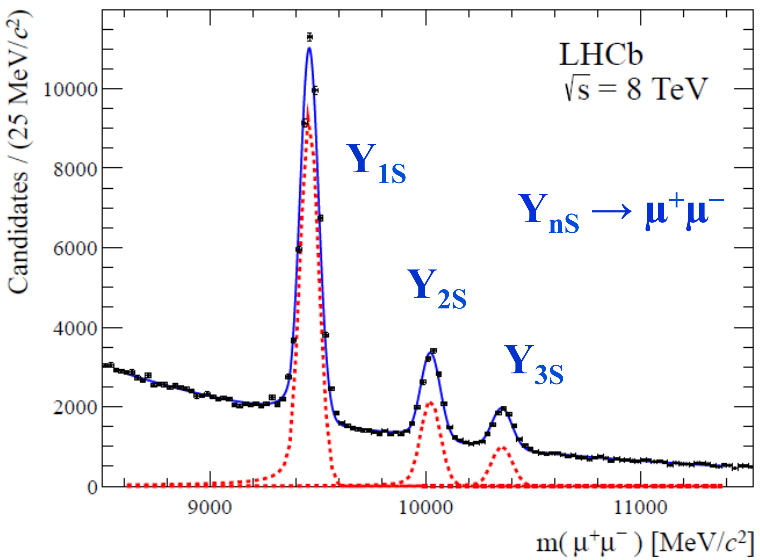
5 stations M1 to M5

high detection efficiency: ε(μ) = (97.3±1.2)%

low misidentification rates:
ε(p ⟶ μ) = (0.21 ± 0.05)%
ε(π⟶ μ) = (2.38 ± 0.02)%
ε(K⟶ μ) = (1.67 ± 0.06)%

Modifications due to higher luminosity and 40 MHz readout:

- remove M1 due to too high occupancies
- keep on-detector electronics (CARIOCA), already at 40 MHz readout
- new off-detector electronics for an efficient readout via TELL40
- production of spare MWPC for installation in LS3 in hottest regions



Summary

- due to its excellent detector performance LHCb is producing world best measurements in the b and c-quark sector
- by 2018 with ~8 fb^{-1} LHCb will find or rule-out large sources of flavour symmetry breaking at the TeV scale

- the LHCb upgrade is mandatory to reach experimental precisions of the order of the theoretical uncertainties

- an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing will allow to collect the necessary $\geq 50\ fb^{-1}$ within ~10 years

- the installation during LS2 requires an 18 months shutdown

Excursion to Photon Detectors

The classical domains of application

❑ Calorimetry

- Readout of organic and inorganic scintillators, lead glass, scint. or quartz fibres → Blue/VIS, usually 10s – 10000s of photons

❑ Particle Identification

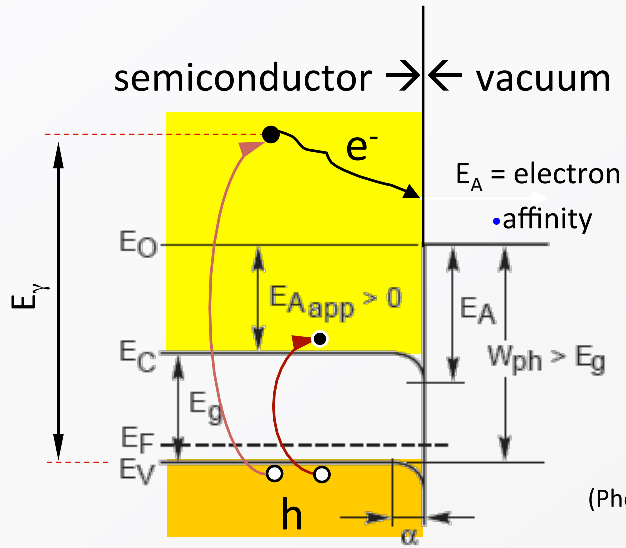
- Detection of Cherenkov light →UV/blue, single photons
- Time Of Flight → Usually readout of organic scintillators (not competitive at high momenta) or Cherenkov radiators

❑ Tracking

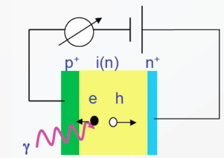
- Readout of scintillating fibres → blue/VIS, few photons

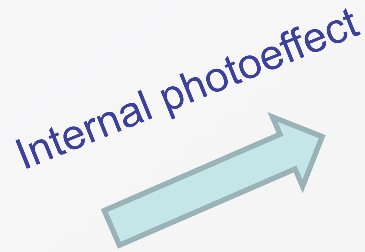
Basics of photodetection

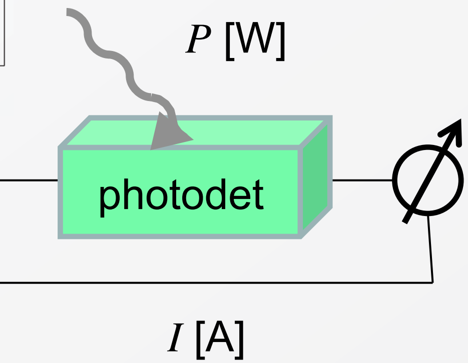
Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

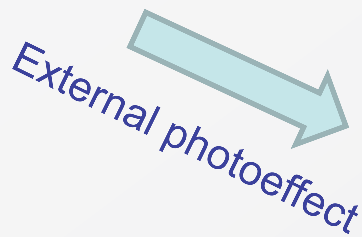


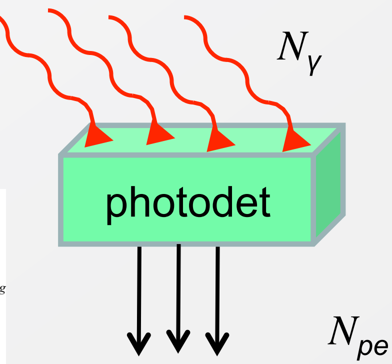
(Photonis)

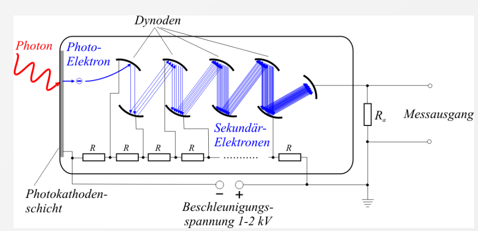












Internal photoeffect: $E_\gamma > E_g$

External photoeffect: $E_\gamma > E_g + E_A$

XII ICFA School on Instrumentation in Elementary Particle Physics, Bogota, 2013

Photo-multiplier tubes (PMT's)

Basic principle:

Photo-emission from photo-cathode

Secondary emission from N dynodes:

- dynode gain $g \approx$ 3-50 (function of incoming electron energy E);
- total gain M:

$$M = \prod_{i=1}^{N} g_i$$

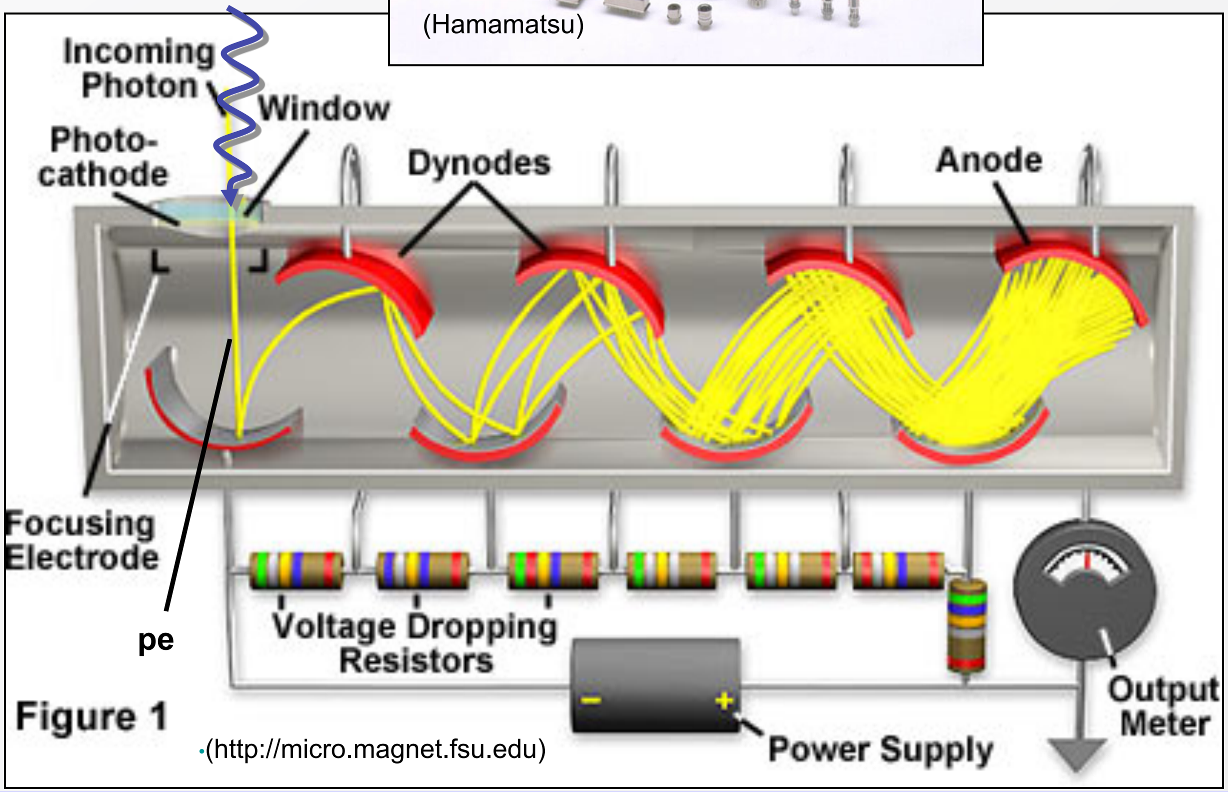
Example:

- 10 dynodes with $g = 4$
- $M = 4^{10} \approx 10^6$

Very sensitive to magnetic fields, even to earth magnetic field (30-60 μT = 0.3-0.6 Gauss).

→ Shielding required (mu-metal).

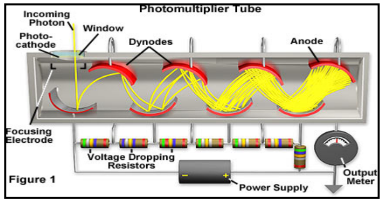

(Hamamatsu)



(http://micro.magnet.fsu.edu)

XII ICFA School on Instrumentation in Elementary Particle Physics, Bogota, 2013

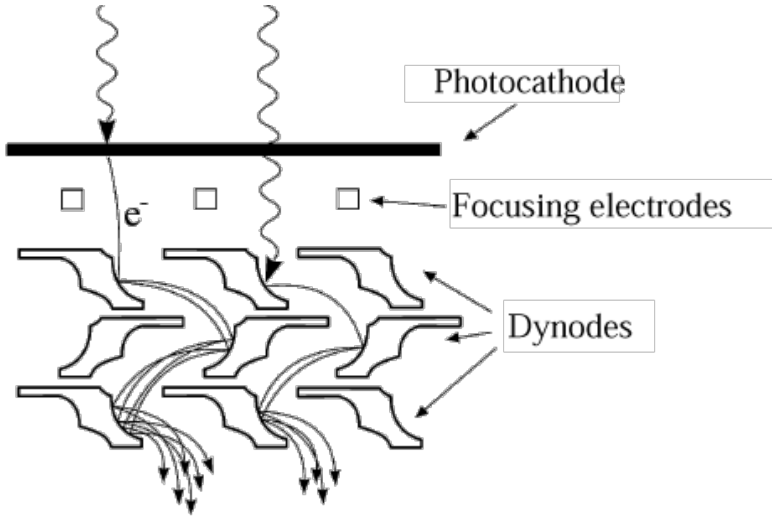
Photon Detectors at LHC

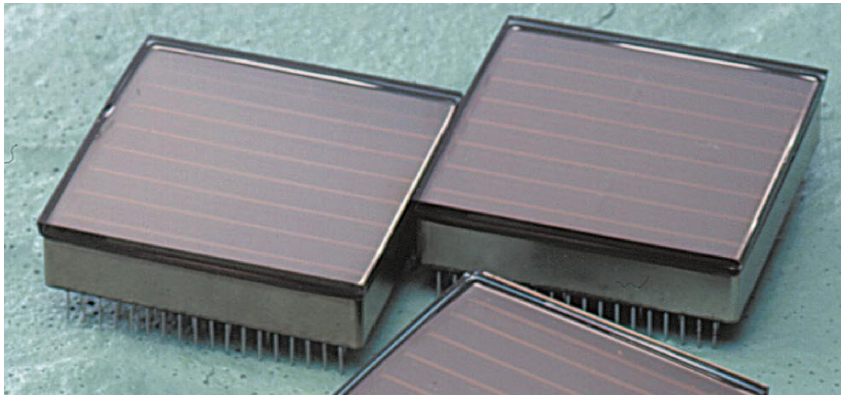


Photomultipliers (PMT):

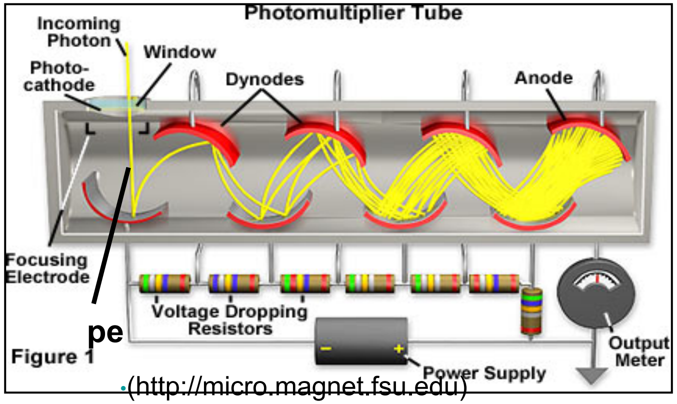
- Used for ATLAS Barrel Hadron Calorimer scintillator readout
- Used for ALICE T0 cherenkov detector and V0 scintillator trigger detector
- Used for LHCb ECAL and HCAL scintillator readout
- Used for CMS Hadron Forward Calorimeter quartz fiber readout

Multi-anode and flat-panel PMT's





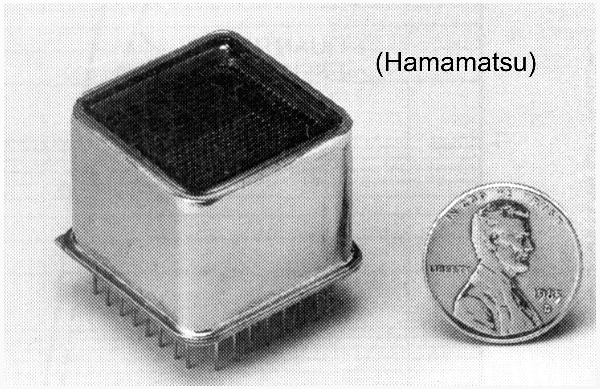
= many times →



PMT, MA PMT

Multi-anode and flat-panel PMT's

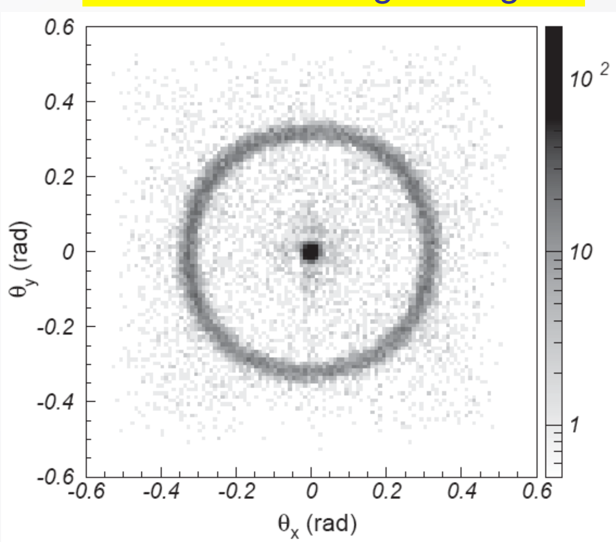
PMT
MAPMT



Multi-anode PMT (Hamamatsu)

- Up to 8 × 8 channels (2 × 2 mm^2 each);
- Size: 28 × 28 mm^2;
- Bialkali PC: QE ≈ 25 - 45% @ λ_{max} = 400 nm;
- Gain ≈ 3 10^5;
- Gain uniformity typ. 1 : 2.5;
- Cross-talk typ. 2%

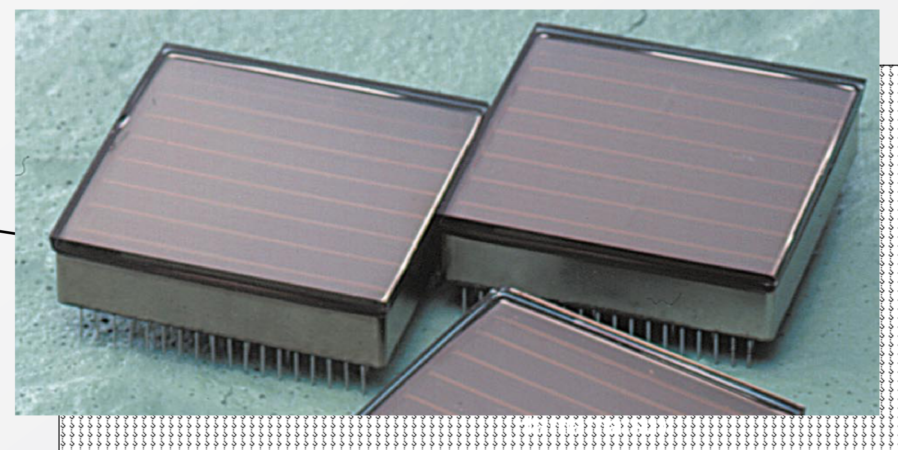
Cherenkov rings from 3 GeV/c π^- through aerogel



(T. Matsumoto et al., NIMA **521** (2004) 367)

Flat-panel (Hamamatsu H8500):

- 8 x 8 channels (5.8 x 5.8 mm2 each)
- Excellent surface coverage (89%)



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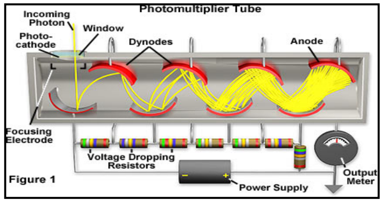
Photon Detectors at LHC



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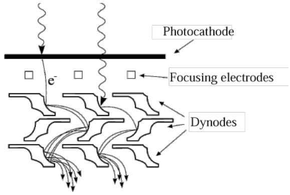
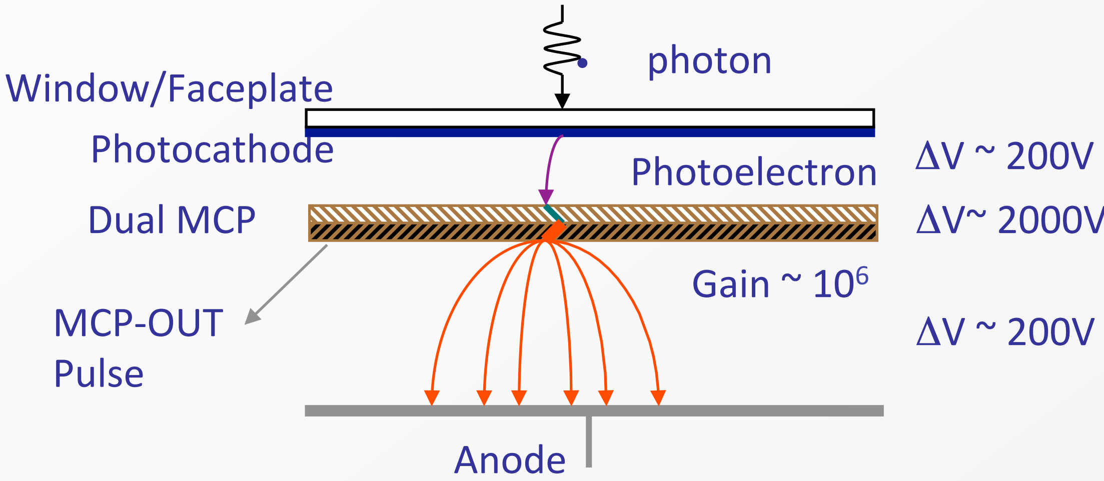


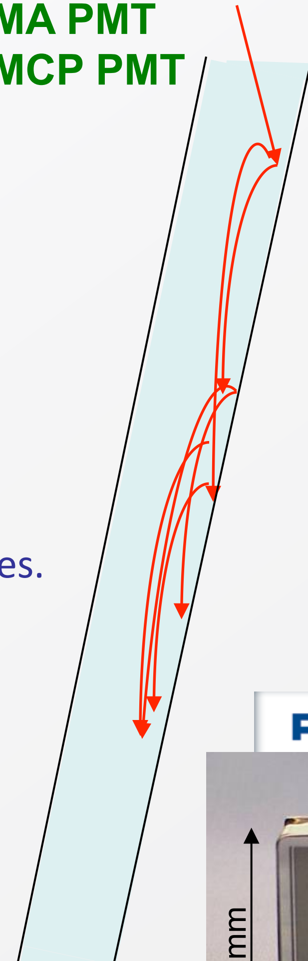
Multi Anode Photomultipliers (MA PMT):

- Planned for LHCb RICH upgrade to replace HPDs
- Planned for CMS Hadron Forward Calorimeter upgrade to replace PMTs

Micro Channel Plate (MCP) based PMTs



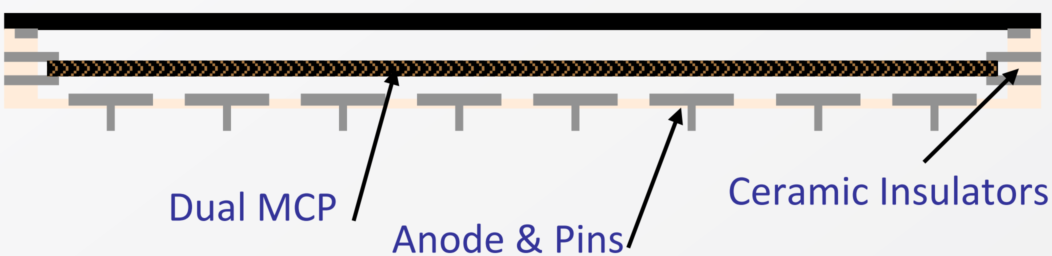
PMT
MA PMT
MCP PMT

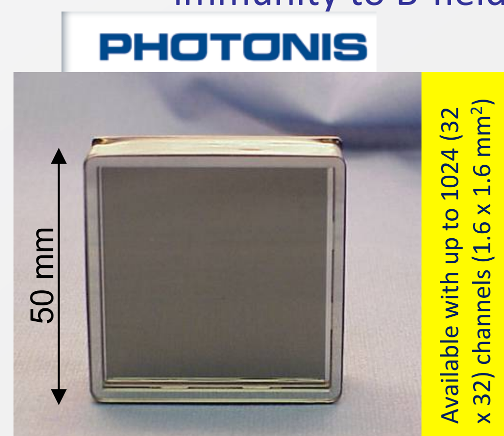


- Typical secondary yield is 2
- For 40:1 L:D there are typically 10 strikes (2^{10} ~ 10^3 gain per single plate)
- Pore sizes range from <10 to 25 μm.
- Small distances → small TTS and good immunity to B-field

MCPs are usually based on glass disks, with lots of aligned pores.
The surface of the pores are metal coated.

Gain stage and detection are decoupled → lots of potential and freedom for MA-PMTs: Anode can be easily segmented in application specific way.





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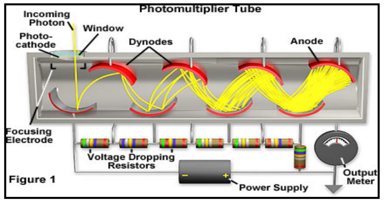

Multi Anode Photomultipliers (MA PMT):

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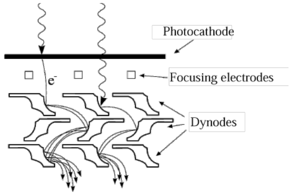
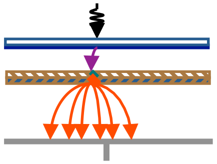
- Planned for CMS Hadron Forward Calorimeter upgrade to replace PMTs



Micro Channel Plate Photomultipliers (MCP PMT):

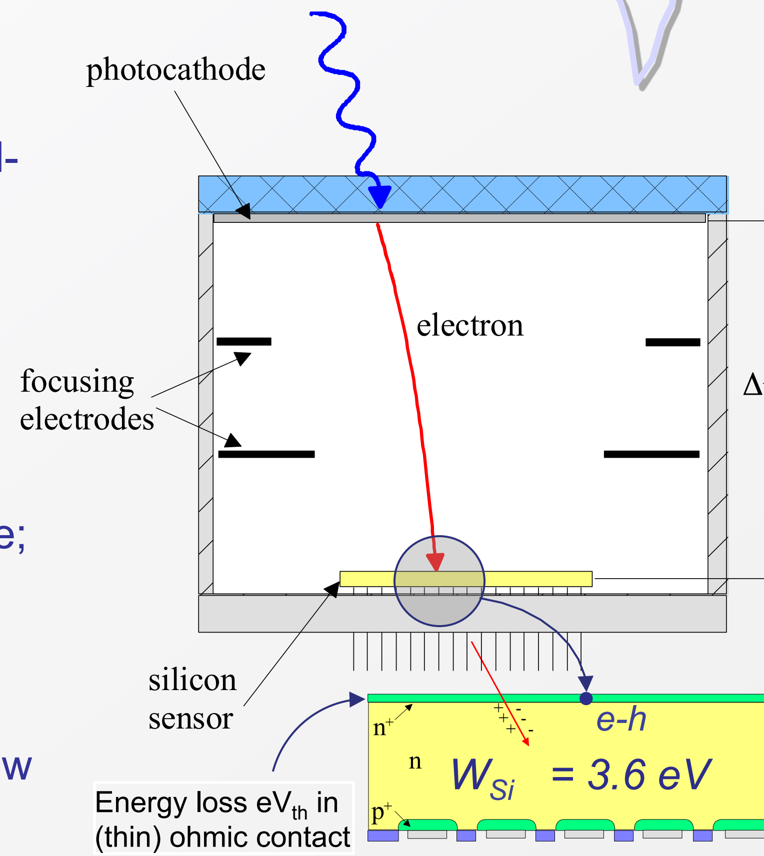
- Planned for ALICE T0 cherenkov detector upgrade to replace PMTs



Hybrid Photon Detectors (HPD's)

Basic principle:

- Combination of vacuum photon detectors and solid-state technology;
- Optical window, (semitransparent) photo-cathode;
- Electron optics (optional: demagnification)
- Charge Gain: achieved *in one step* by energy dissipation of keV pe's in solid-state detector anode; this results in low gain fluctuations;
- Encapsulation of Si-sensor in the tube implies:
  - compatibility with high vacuum technology (low outgassing, high T° bake-out cycles);
  - internal (for speed and fine segmentation) or external connectivity to read-out electronics;
  - heat dissipation issues;



$$M = \frac{e(\Delta V - Vth)}{W_{Si}}$$

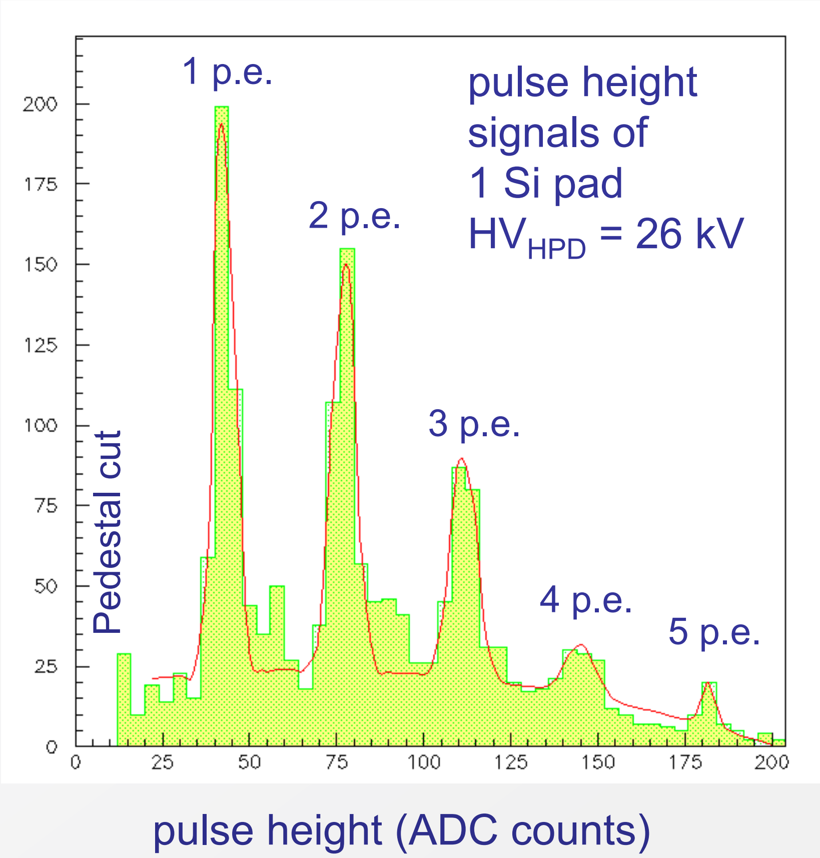
ΔV = 20 kV
→ M ~ 5000

$$\sigma_M = \sqrt{F \times M}$$

F = Fano factor
F_{Si} ~ 0.1

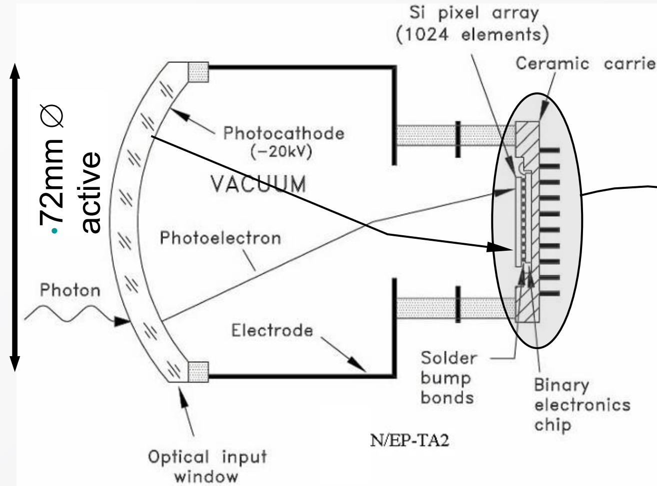
Hybrid Photon Detectors (HPD's)

10-inch prototype HPD (CERN)
for Air Shower Telescope CLUE.

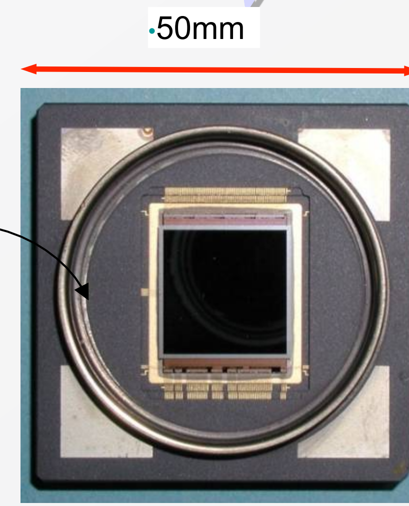


Photon counting. Continuum due to electron back scattering.

Pixel-HPD's for LHCb RICH detectors

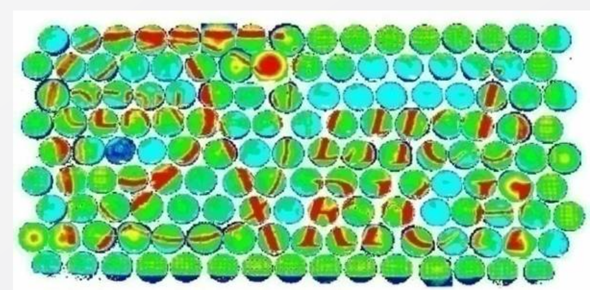


T. Gys, NIM A 567 (2006) 176-179



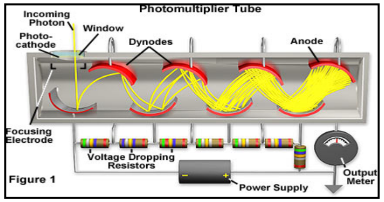
Pixel-HPD anode

- Cross-focused electron optics
- pixel array sensor bump-bonded to binary electronic chip, developed at CERN
- 8192 pixels of 50 × 400 μm.
- specially developed high T° bump-bonding;
- Flip-chip assembly, tube encapsulation (multi-alkali PC) performed in industry (VTT, Photonis/DEP)



During commissioning: illumination of 144 tubes by beamer. In total : 484 tubes.

Photon Detectors at LHC



Photomultipliers (PMT):

- Used for ATLAS Barrel Hadron Calorimer scintillator readout
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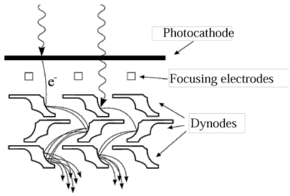

Multi Anode Photomultipliers (MA PMT):

- Planned for LHCb RICH upgrade to replace HPDs
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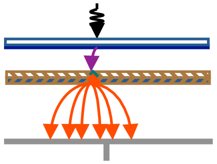

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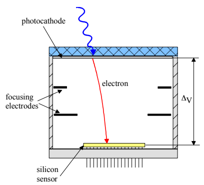
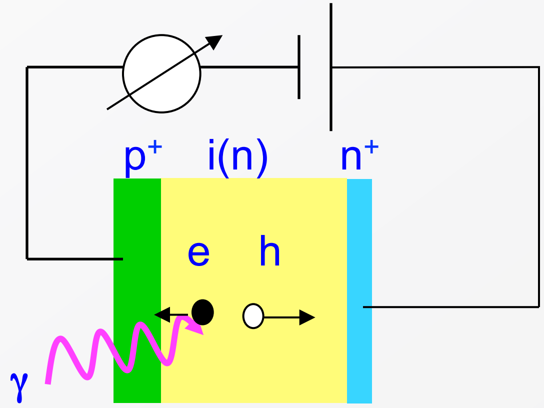


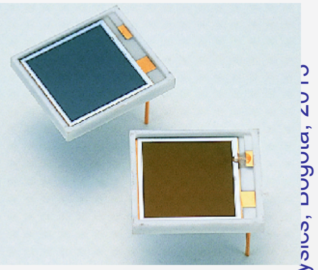
Hybrid Photon Detectors (HPD):

- Used for CMS Hadron Barrel and Hadron Endcap Calorimeter Scinitillator readout
- Used for LHCb RICH detector

(Si) – Photodiodes (PIN diode)

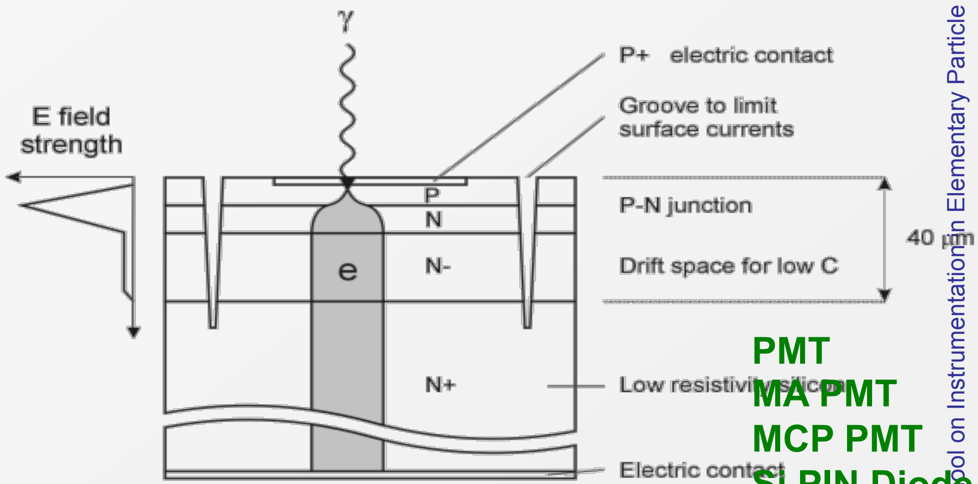
- P(I)N type
- p layer very thin (<1 μm), as visible light is rapidly absorbed by silicon
- High QE (80% @ $\lambda \approx$ 700nm)
- Gain = 1





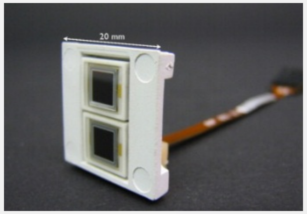
Avalanche photodiode (APD)

- High reverse bias voltage: typ. few 100 V
- Special doping profile → high internal field ($>10^5$ V/cm) → avalanche multiplication
- Avalanche stops due to statistical fluctuations.
- Gain: typ. O(100)
- Rel. high gain fluctuations (excess noise from the avalanche). CMS ECAL APD: ENF = 2 @G=50.
- Very high sensitivity on temp. and bias voltage ΔG = 3.1%/V and -2.4 %/K



PMT
MA PMT
MCP PMT
Si PIN Diode
APD

Hamamatsu S8148.
(140.000 pieces used in CMS barrel ECAL).



XII ICFA School on Instrumentation in Elementary Particle Physics, Bogotá, 2013

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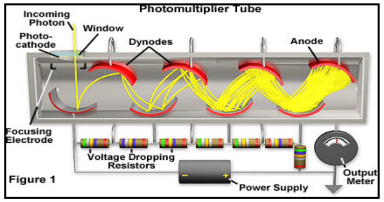

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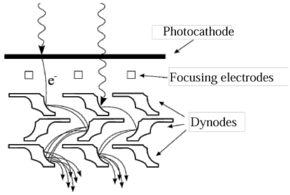

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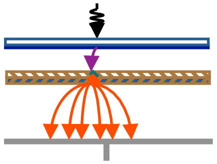

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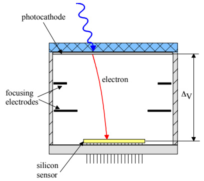

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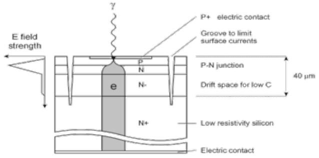
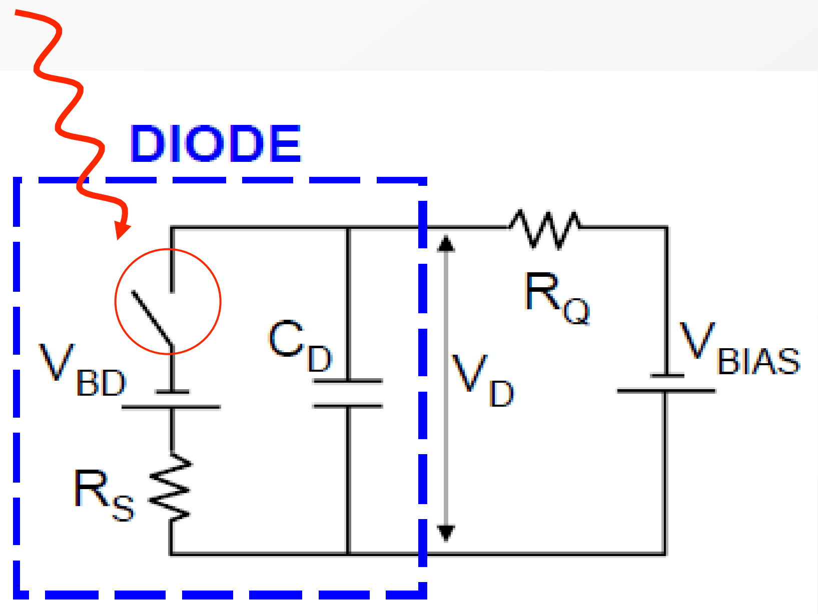


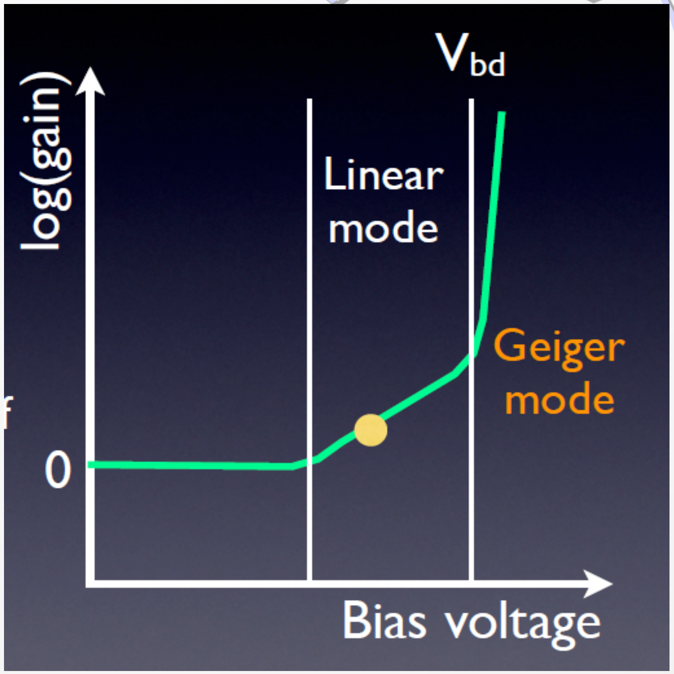
How to obtain higher gain (= single photon detection) without suffering from excessive noise ?

Operate APD cell in Geiger mode (= full discharge), however with (passive) quenching.

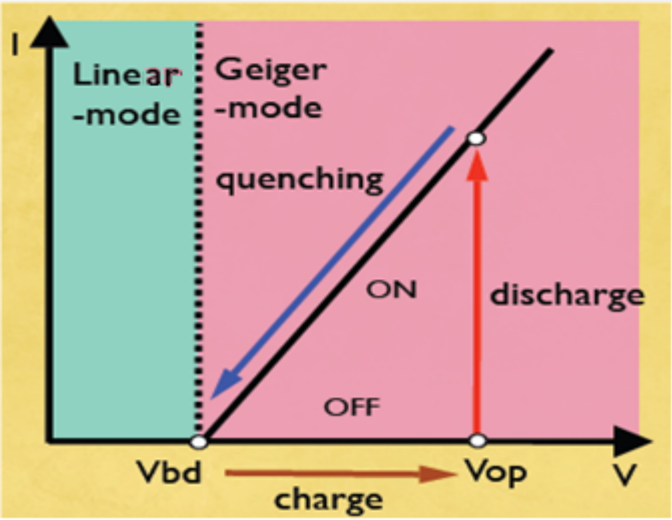
Photon conversion + avalanche short-circuits the diode.



J. Haba, RICH2007

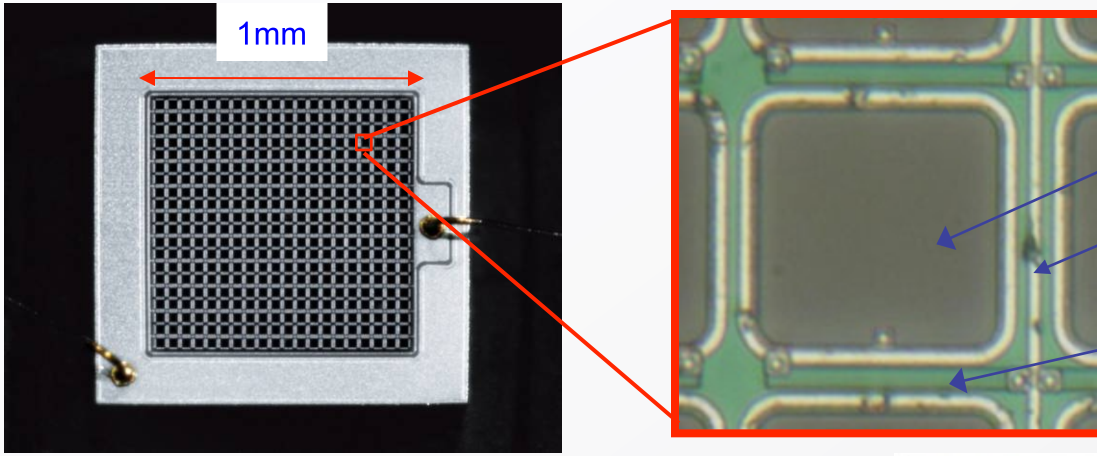


J. Haba, RICH2007



J. Haba, RICH2007

Multi pixel G-APD, called G-APD, MPPC, SiPM, …



100 – several 1000 pix / mm^2

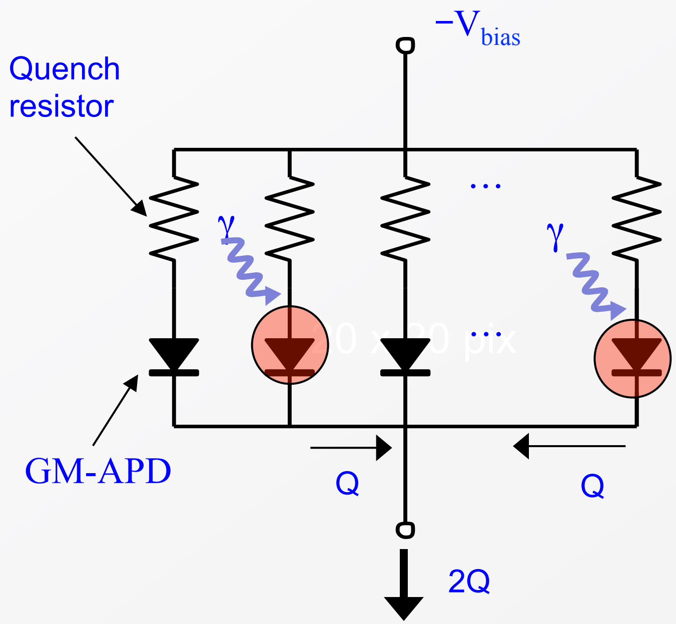
GM-APD

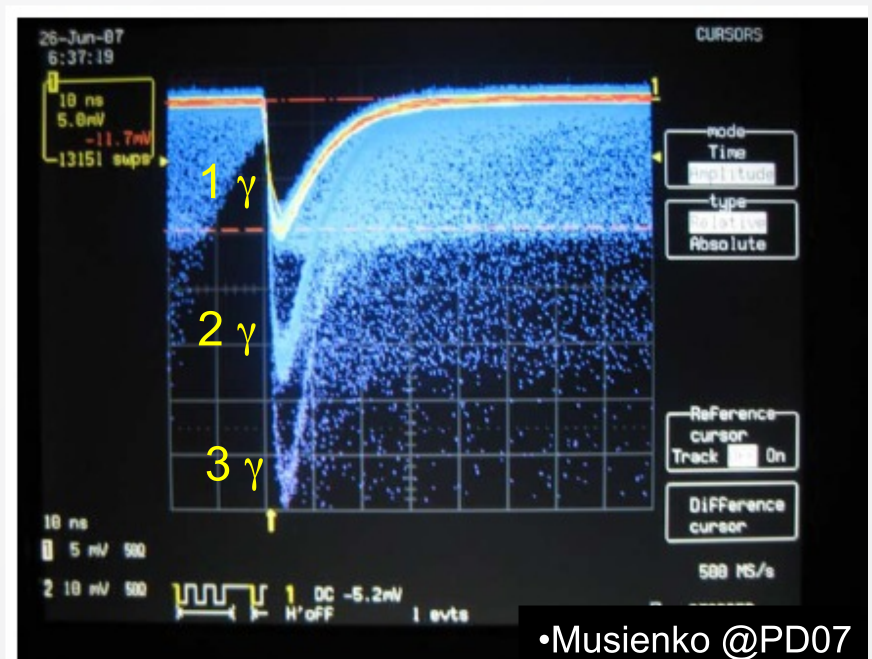
Bias bus

Quench resistor

Only part of surface is photosensitive!

Sizes up to 6×6 mm^2 now standard.





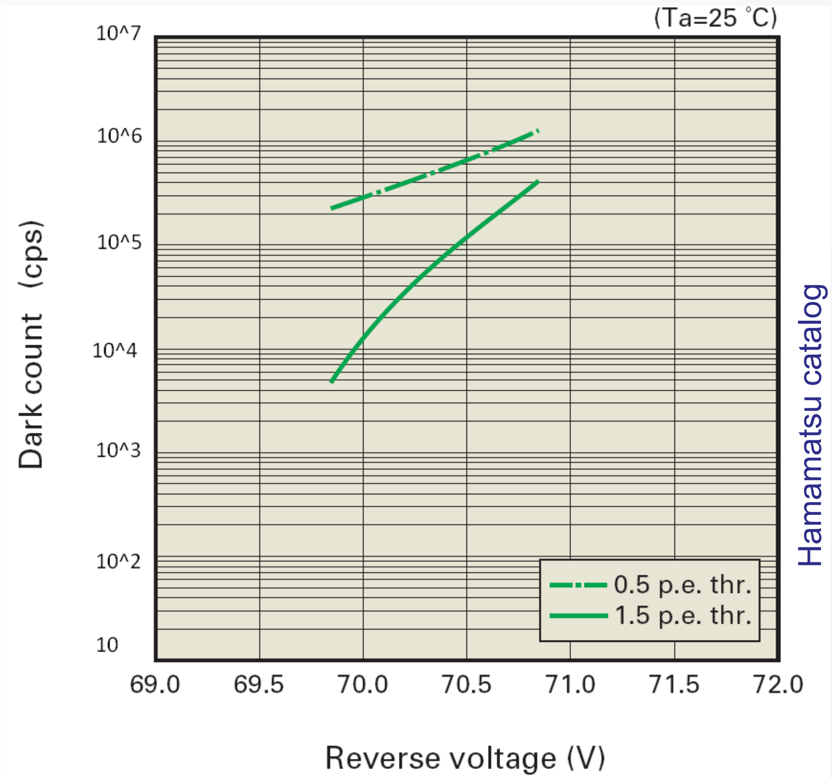
Quasi-analog detector allows photon counting with a clearly quantized signal

Multi pixel G-APD = G-APD, MPPC, SiPM, …

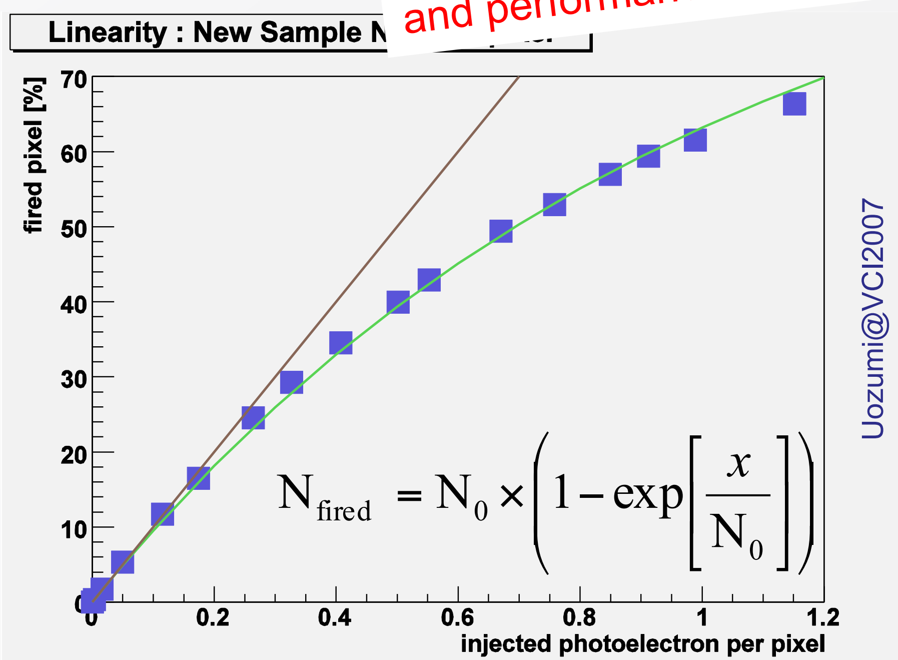
You cannot get "something for nothing"

- G-APD show dark noise rate in the O(100 kHz – MHz / mm^2) range.
- The gain is temperature dependent O(<5% /°K)
- The signal linearity is limited
- The price is (still too) high

~10 producers are now in the market. Continuous improvement in technology and performance.



Hamamatsu catalog

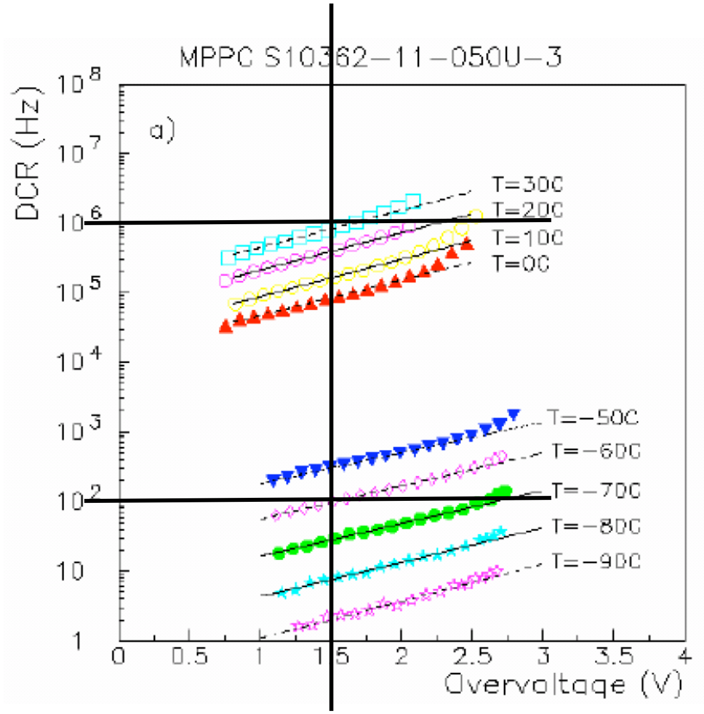


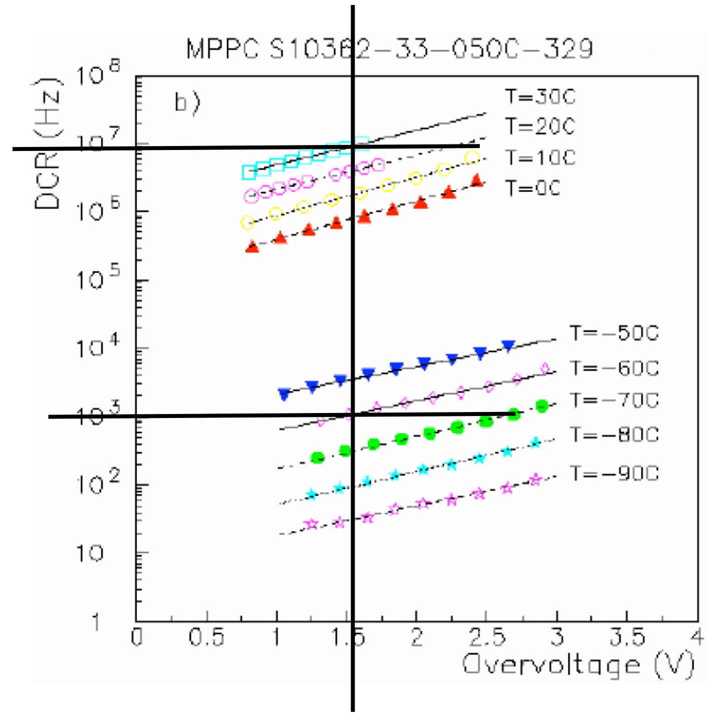
$$N_{fired} = N_0 \times \left(1 - \exp\left[\frac{x}{N_0}\right]\right)$$

Uozumi@VCI2007

XII ICFA School on Instrumentation in Elementary Particle Physics, B

Si PMs = G APD = MPPC: Dark Count Rate vs. Temperature



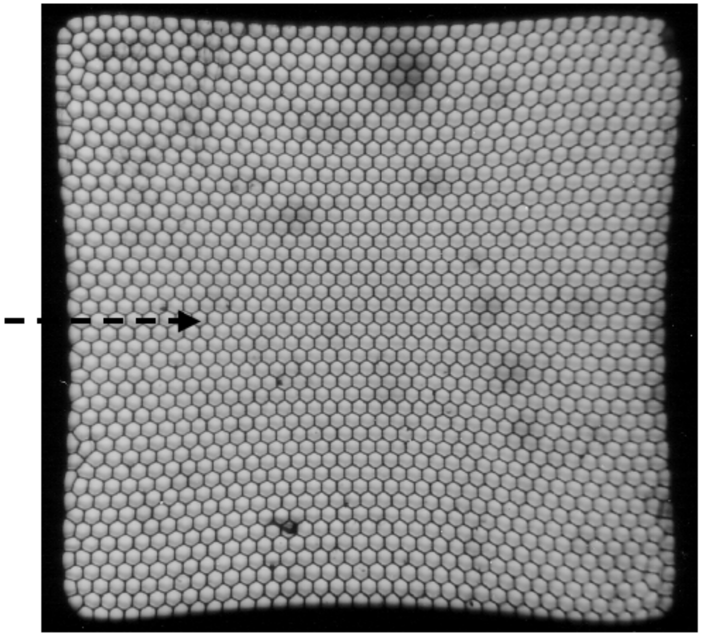


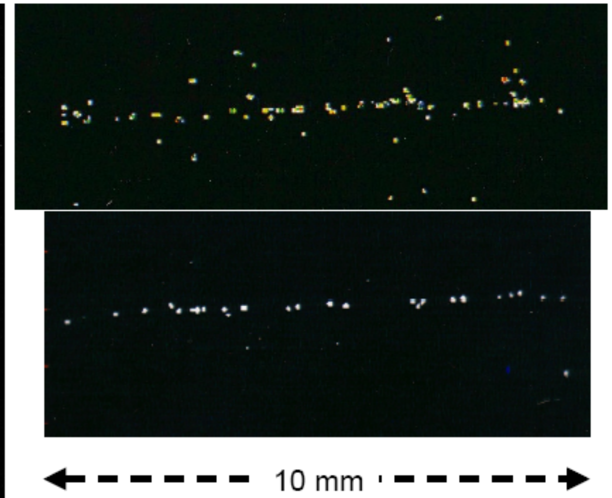
Nicoleta Dinu, LAL Orsay

Darc Count Rate (DCR) E.g. 1.5 V:

1-10 MHz at T=30 C and 0.1-1kHz at -60 C !!!

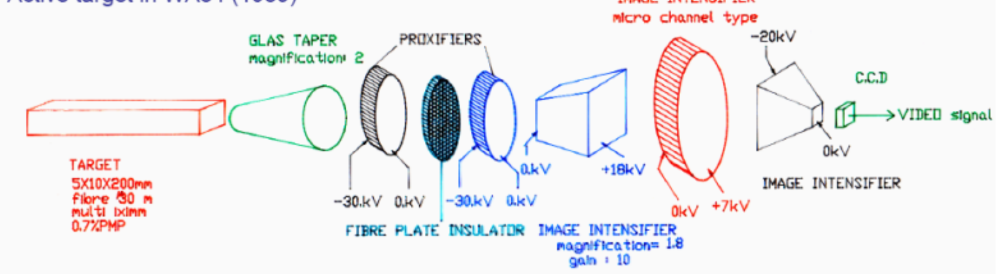
Fiber Tracking





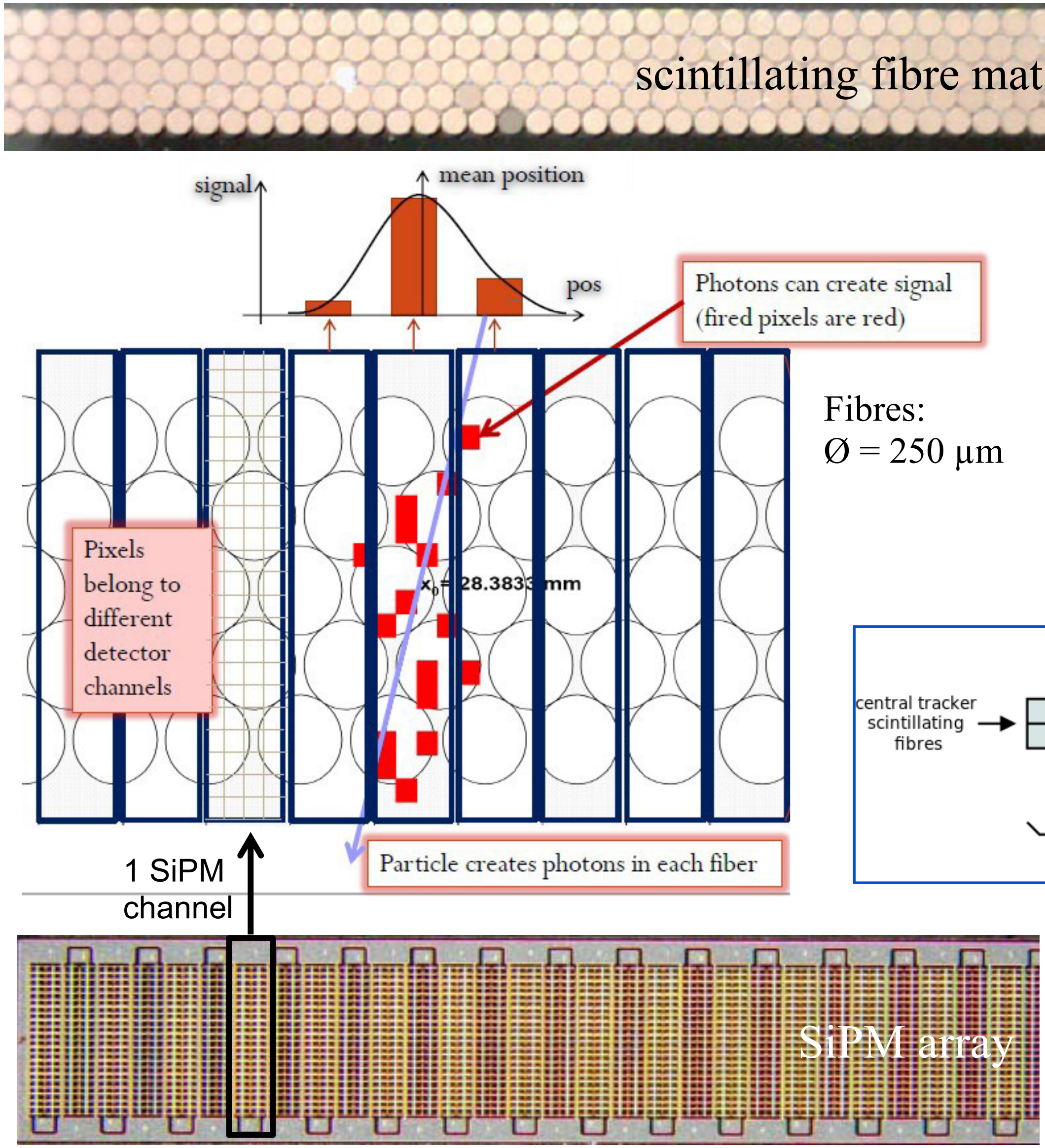
Images of tracks from 5 GeV/c pions (1989)

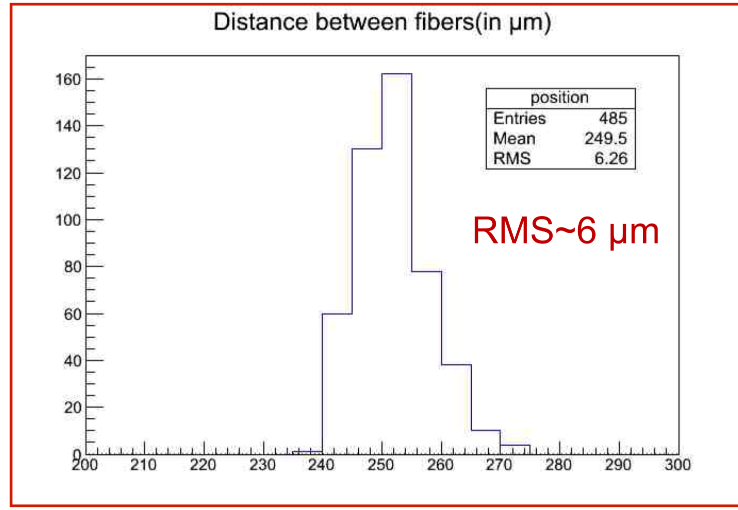
Active target in WA84 (1989)

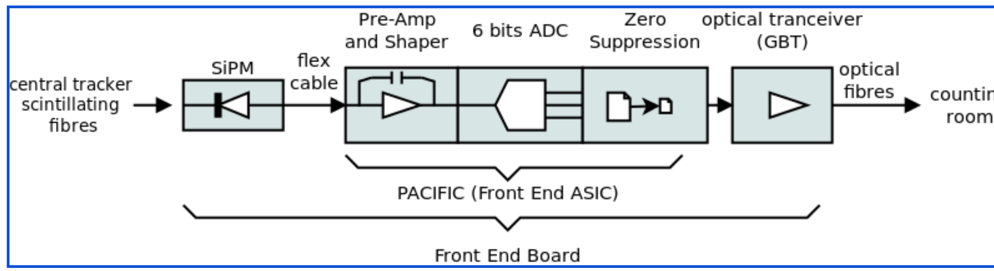


Readout of photons in a cost effective way is rather challenging.
Only a few photons per fiber, i.e. single photon sensitivity is necessary

T-stations upgrade: Fibre Tracker (FT)







analog readout by dedicated 40 MHz PACIFIC chip

→ **Operate at -40 C**

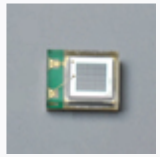
SiPM designs (just examples)

Hamamatsu HPK (http://jp.hamamatsu.com/)

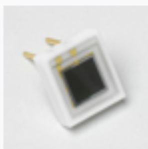
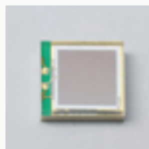
25x25µm², 50x50µm², 100x100µm² pixel size

1x1mm²

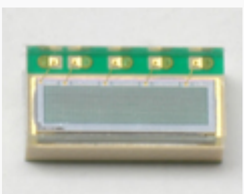




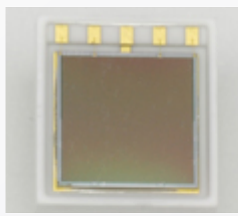
3x3mm²

Arrays



1x4mm²
1x4 channels

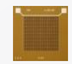


6x6 mm²
2x2 channels

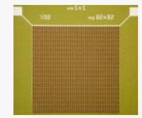
FBK-IRST

50x50µm² pixel size

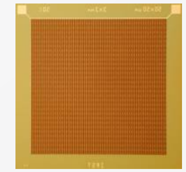
1x1mm²



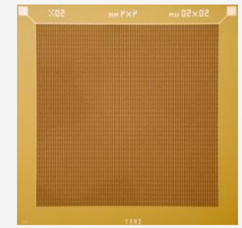
2x2mm²



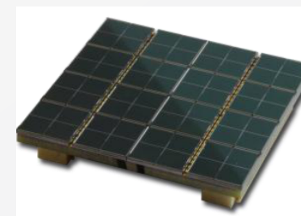
3x3mm²



4x4mm²



4x4mm²
2x2 channels



3x3 cm²
8x8 channels

SensL (http://sensl.com/)

20x20µm², 35x35µm², 50x50µm², 100x100µm² pixel size

3.16x3.16mm²
4x4 channels

3.16x3.16mm²
4x4 channels

6 x 6 cm²
16x16 channels

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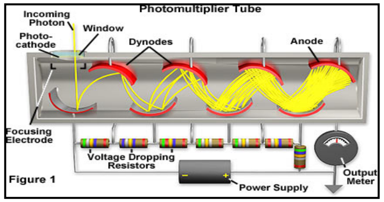

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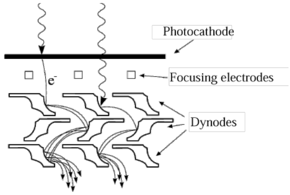

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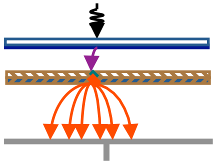

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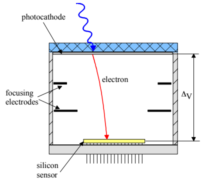

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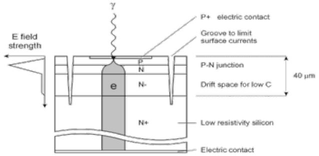
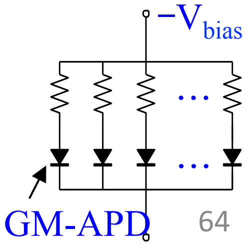


Geigermode APDs (GAPD) = Multi Pixel Photon Counters (MPPC) = Silicon Photo Multiplier (SiPM):

- Planned for CMS Hadron Barrel and Hadron Endcap Calorimeter to replace HPDs
- Planned for LHCb Fiber Tracker (operation around -40 degrees)



The CMS Experiment Upgrade

The CMS Upgrade Program

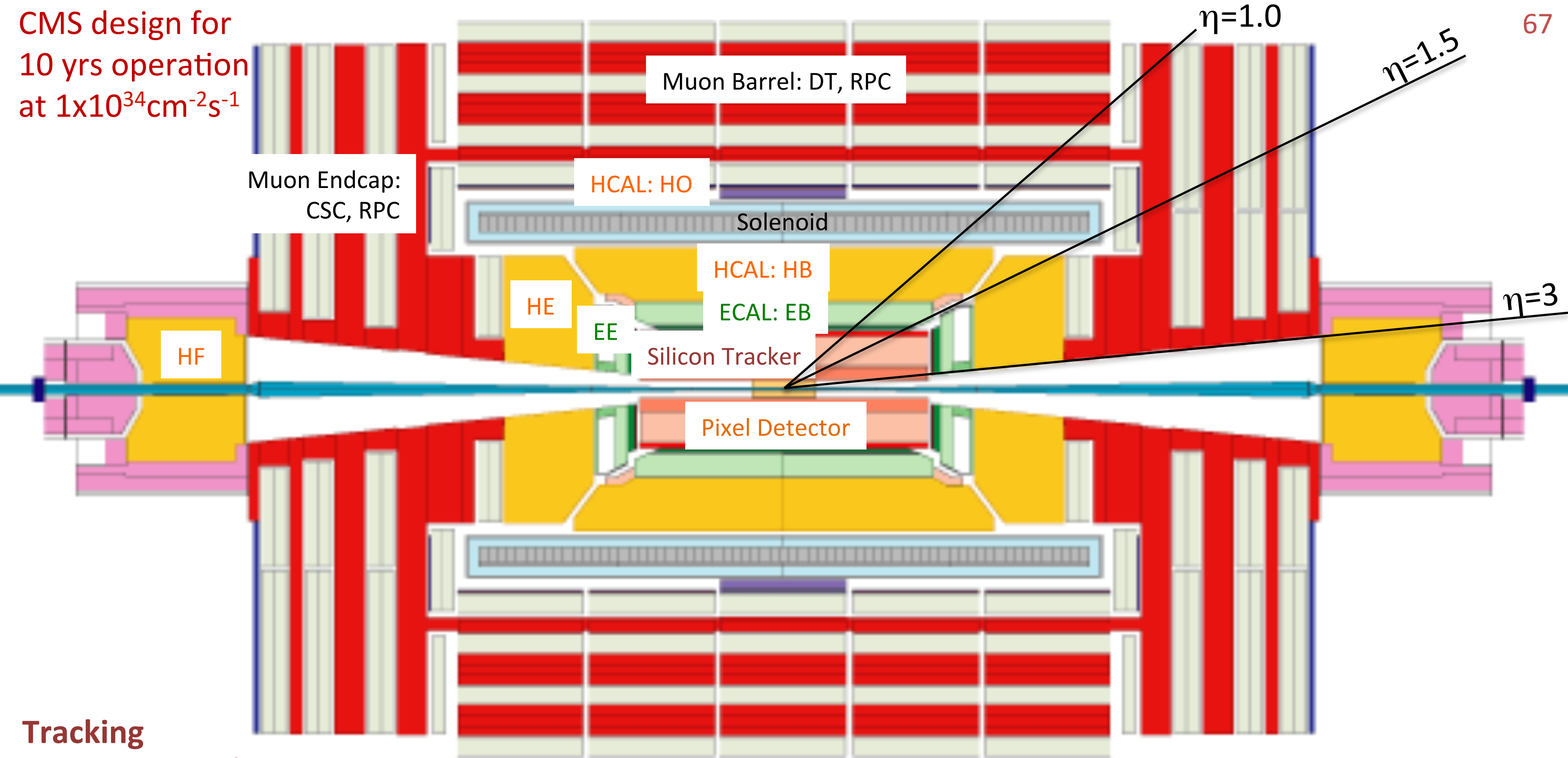
ECFA High Luminosity LHC Experiments Workshop

Aix-les-Bains, October 1, 2013

J. Spalding, on behalf of the CMS Collaboration

An outline of the upgrade program

CMS design for 10 yrs operation at $1\times10^{34} cm^{-2}s^{-1}$



Tracking

More than 220m² surface and 76M channels (pixels & strips)

6m long, ~2.2m diameter

Tracking to |η|<2.4

ECAL

Lead Tungstate ($PbWO_4$)

EB: 61K crystals, EE: 15K crystals

HCAL

HB and HE: Brass/Plastic scintillator

Sampling calorimeter. Tiles and WLS fiber

HF: Steel/Quartz fiber Cerenkov calo.

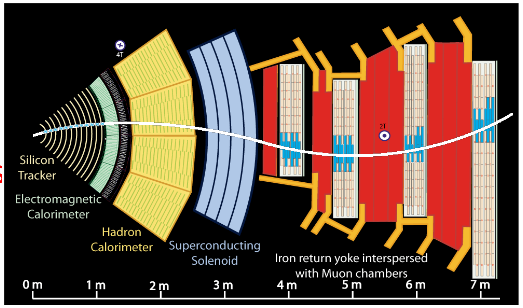
HO: Plastic scintillator “tail catcher”

Muon System

Muon tracking in the return field

Barrel: Drift Tube & Resistive Plate Chambers

Endcap: Cathode Strip Chambers & RPCs



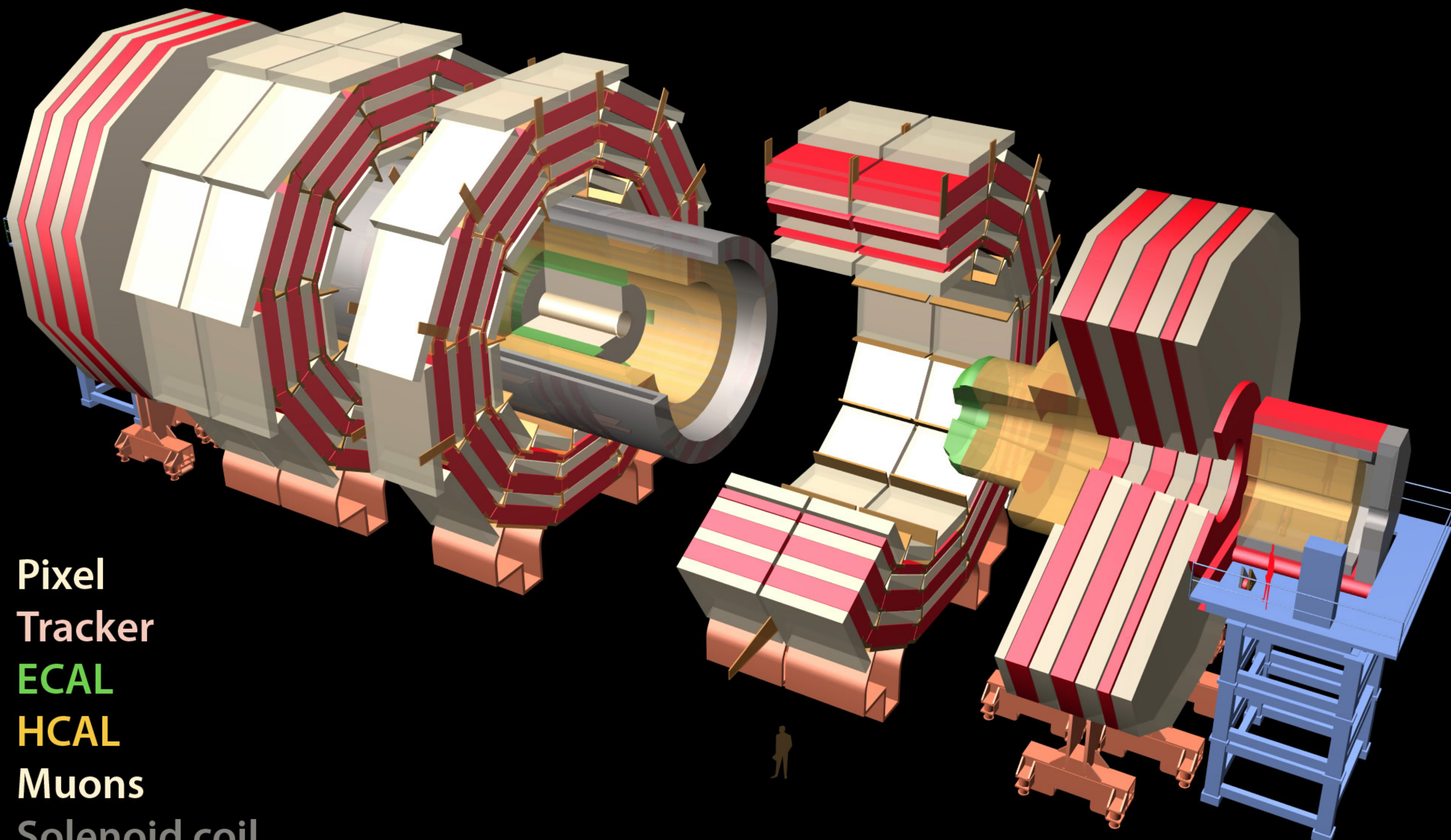
Trigger

Level 1 in hardware, 3.2μs latency ,100 kHz

ECAL+HCAL+Muon

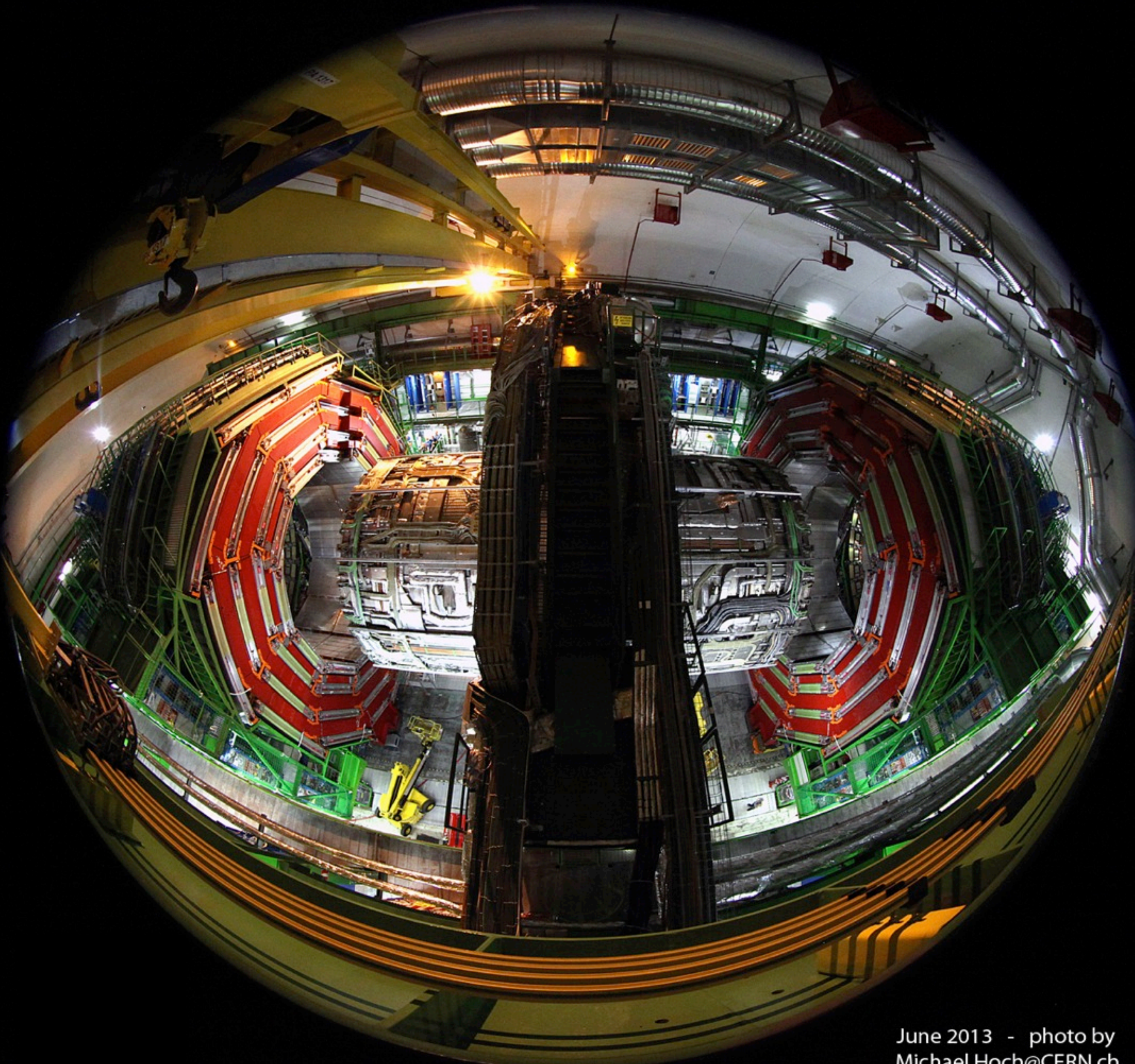
HLT Processor Farm,1 kHz: Tracking , Full reco

CMS



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

CMS



LHC to HL-LHC - The Challenge

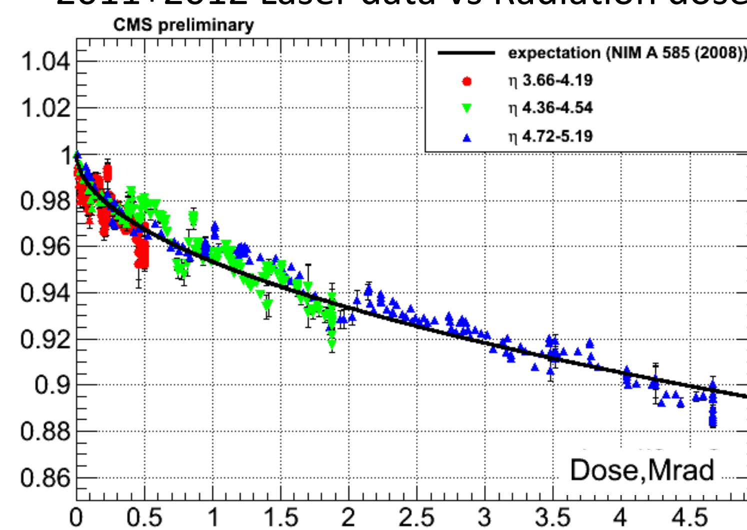
The accelerator upgrades will enable an extensive and rich physics program

- Experiment must maintain full sensitivity for discovery and precision measurements at low p_T, under severe conditions

This will be a very typical event

- Pileup
  - <PU> will approach 50 events per crossing by LS2
  - <PU> ≈ 60 by LS3
  - and <PU> up to 140 (accounting for uncertainty and bunch-to-bunch variations) for lumi-leveling at $5x10^{34}cm^{-2}s^{-1}$ at HL-LHC

Observed signal loss in HF quartz fibers, 2011+2012 Laser data vs Radiation dose



- Radiation damage
  - Light loss (calorimeters), increased leakage current (silicon detectors)
  - Requires work to maintain calibration
  - And eventually limits the performance-lifetime of the detectors

CMS Upgrade program

LS1
2013-14

LS2
2018

LS3
2022-23

LS1 consolidation: Complete detector & consolidate operation for nominal LHC beam conditions ~13 TeV, 1 x Hz/cm^2, <PU> ~25

- Complete Muon system (4th endcap station), improve RO of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors and HF backend electronics
- Tracker operation at -20°C
- Prepare and install slices of Phase 1 upgrades

Phase 1 upgrades: Prepare detector for 1.6 x 10^{34} Hz/cm^2, <PU> ~40, and up to 200 fb^{-1} by LS2, and 2.5 x 10^{34} Hz/cm^2, <PU> ~ 60, up to 500 fb^{-1} by LS3

- New L1-trigger systems (Calorimeter - Muons - Global) (ready for 2016 data taking)
- New Pixel detector (ready for installation in 2016/17 Year End Technical Stop)
- HCAL upgrade: photodetectors and electronics (HF 2015/16 YETS, HB/HE LS2)

Phase 2 upgrades: $\gtrsim$ 5 x 10^{34} Hz/cm^2 luminosity leveled, <PU> ~128 (simulate 140), reach total of 3000 fb^{-1} in ~10 yrs operation

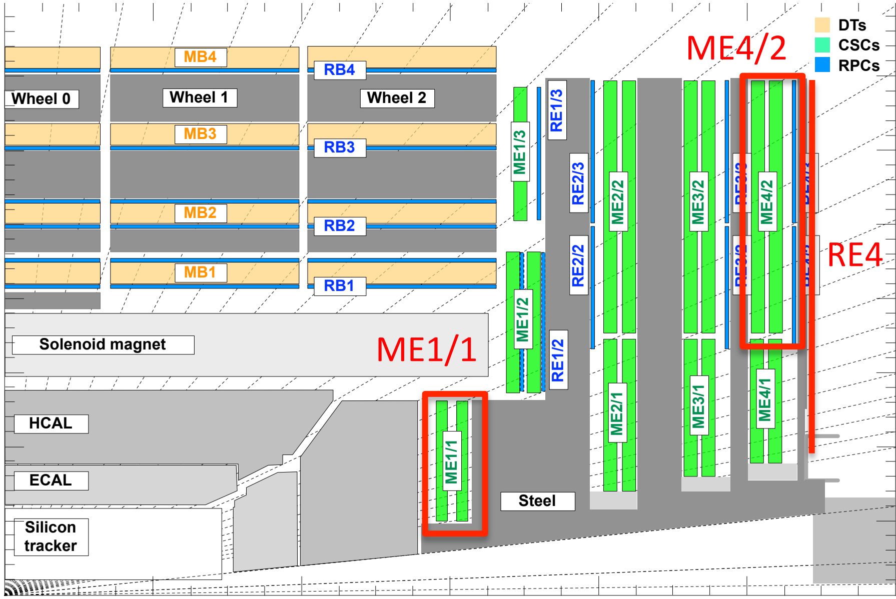
- Replace detector systems whose performance is significantly degrading due to radiation damage
- Maintain physics performance at this very high PU

LS1 and Phase 1

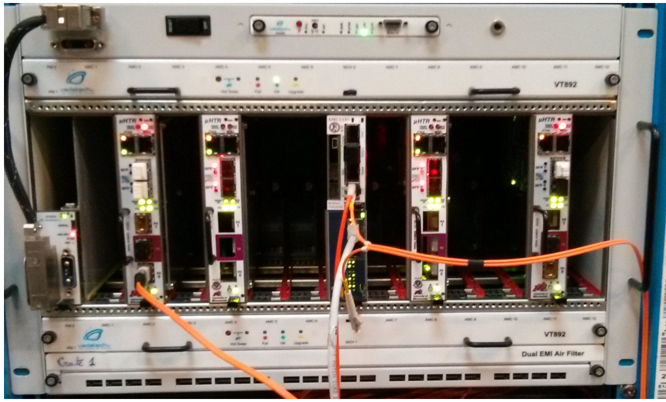
LS1

- Completion of the design for $1x10^{34}cm^{-2}s^{-1}$
  - Muon endcap system
    - ME1/1 electronics (unganging)
    - ME4/2 completion of stations & shielding
  - Tracker
    - Prepare for cold operation (-20°C coolant)
- Address operational issues in Run 1
  - HF photo-detectors
    - Reduce beam-related background
  - HO photo-detectors
    - operation in return field: replace with Silicon PhotoMultipliers (SiPM)
- Preparatory work for Phase 1 Upgrades
  - New beam pipe and "pilot blade" installation for the Pixel Upgrade
  - New HF backend electronics - ahead of HCAL frontend upgrade
  - Splitting for L1-Trigger inputs to allow commissioning new trigger in parallel with operating present trigger

ME1/1 ad ME4/2 consolidation during LS1



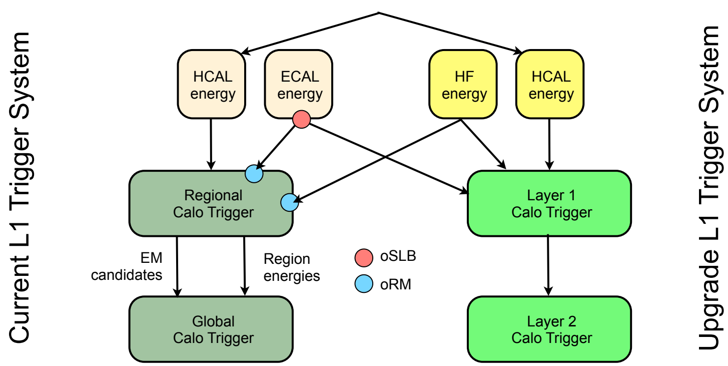
Slice test: μTCA BE electronics for HF



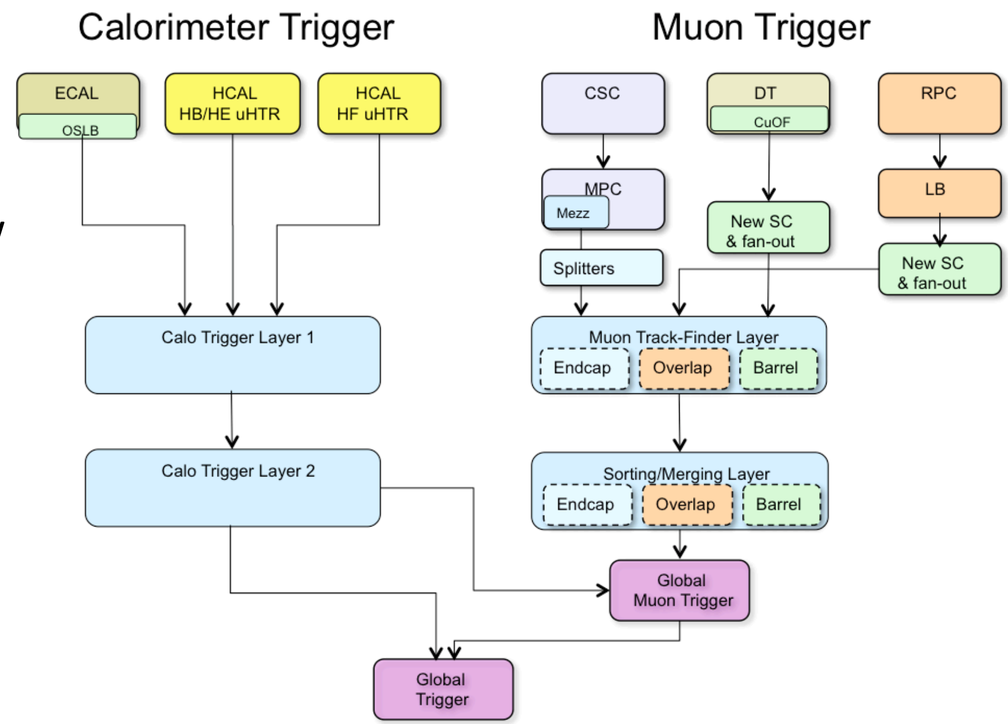
Phase 1 Upgrades – L1 Trigger

Architecture based on powerful FPGAs and high bandwidth optics

- Entire upgrade (Calorimeter, Muon and Global triggers) built with three types of board, all using virtex 7 FPGA
- Allows much improved algorithms for PU mitigation and isolation
- Trigger inputs split during LS1 to allow full commissioning of new trigger in parallel to operating legacy system



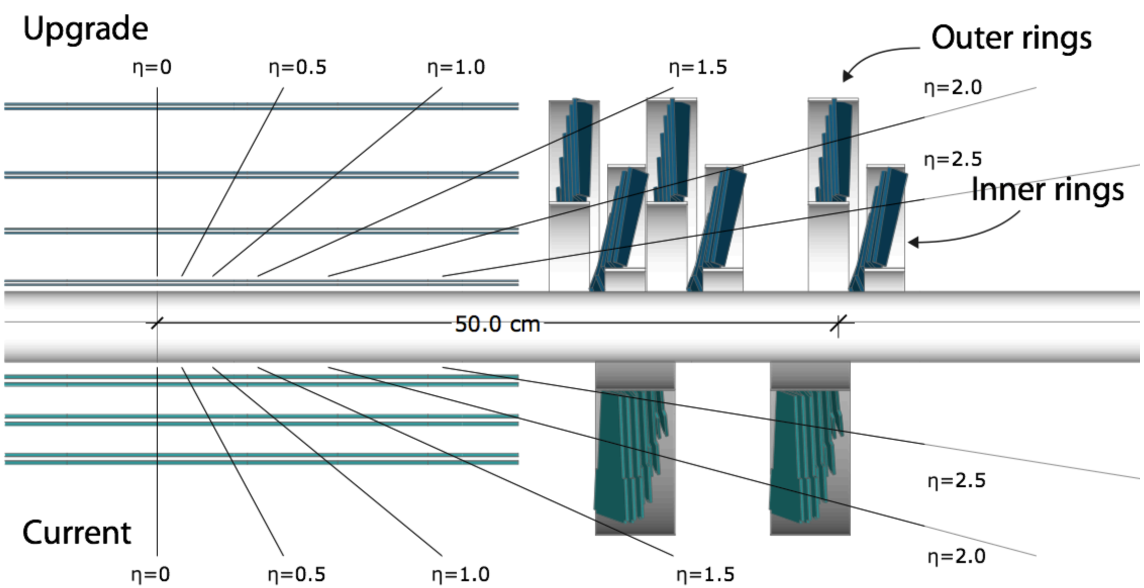
Optical splitting for parallel commissioning, calorimeter trigger

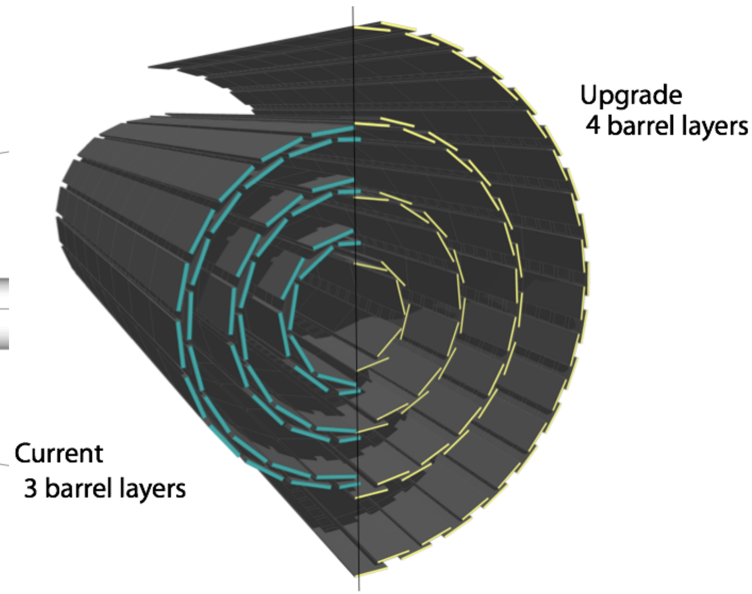


Level 1 Trigger Upgrade

Staged approach: grow from slice tests to full system commissioning through 2015 - ready for physics in 2016

Phase 1 Upgrades – Pixel Detector





- 4 layers / 3 disks
  - 1 more space point, 3 cm inner radius
  - Improved track resolution and efficiency
- New readout chip
  - Recovers inefficiency at high rate and PU
- Less material
  - CO2 cooling, new cabling and powering scheme (DC-DC)
- Longevity
  - Tolerate up to 100 PU and survive to 500 fb^{-1}, with exchange of innermost layer

Ready to install at end of 2016

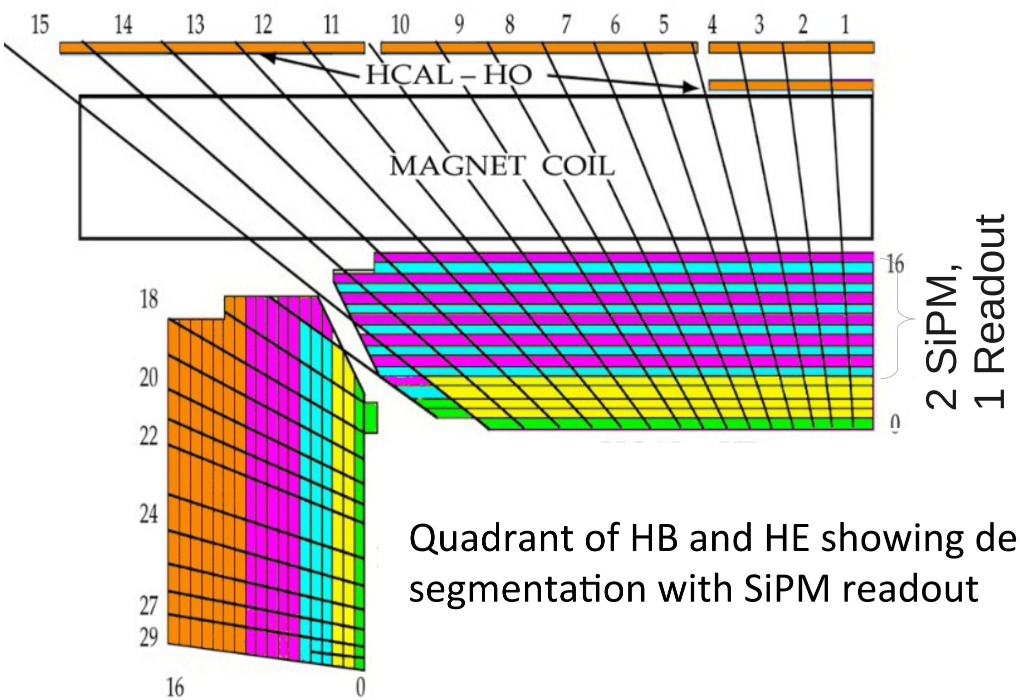
Pilot blade (partial disk) in LS1

Phase 1 Upgrades – HCAL

- Backend electronics upgrade to μTCA
- New readout chip (QIE10) with TDC

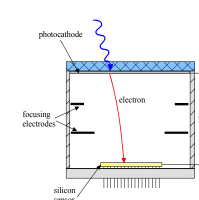
} HF BE upgrade in LS1, FE at end of 2015

  - Timing: improved rejection of beam-related backgrounds, particularly HF
- Replace HPDs in HB and HE with SiPMs — HB/HE FE upgrade in LS2
  - Small radiation tolerant package, stable in magnetic field
  - PDE improved x3, lower noise
  - Allows depth segmentation for improved measurement of hadronic clusters, rejection of backgrounds, and re-weighting for radiation damage



Quadrant of HB and HE showing depth segmentation with SiPM readout

SiPMs: successful R&D program
- Tested to 3000 fb-1
- Neutron sensitivity low



Phase 2

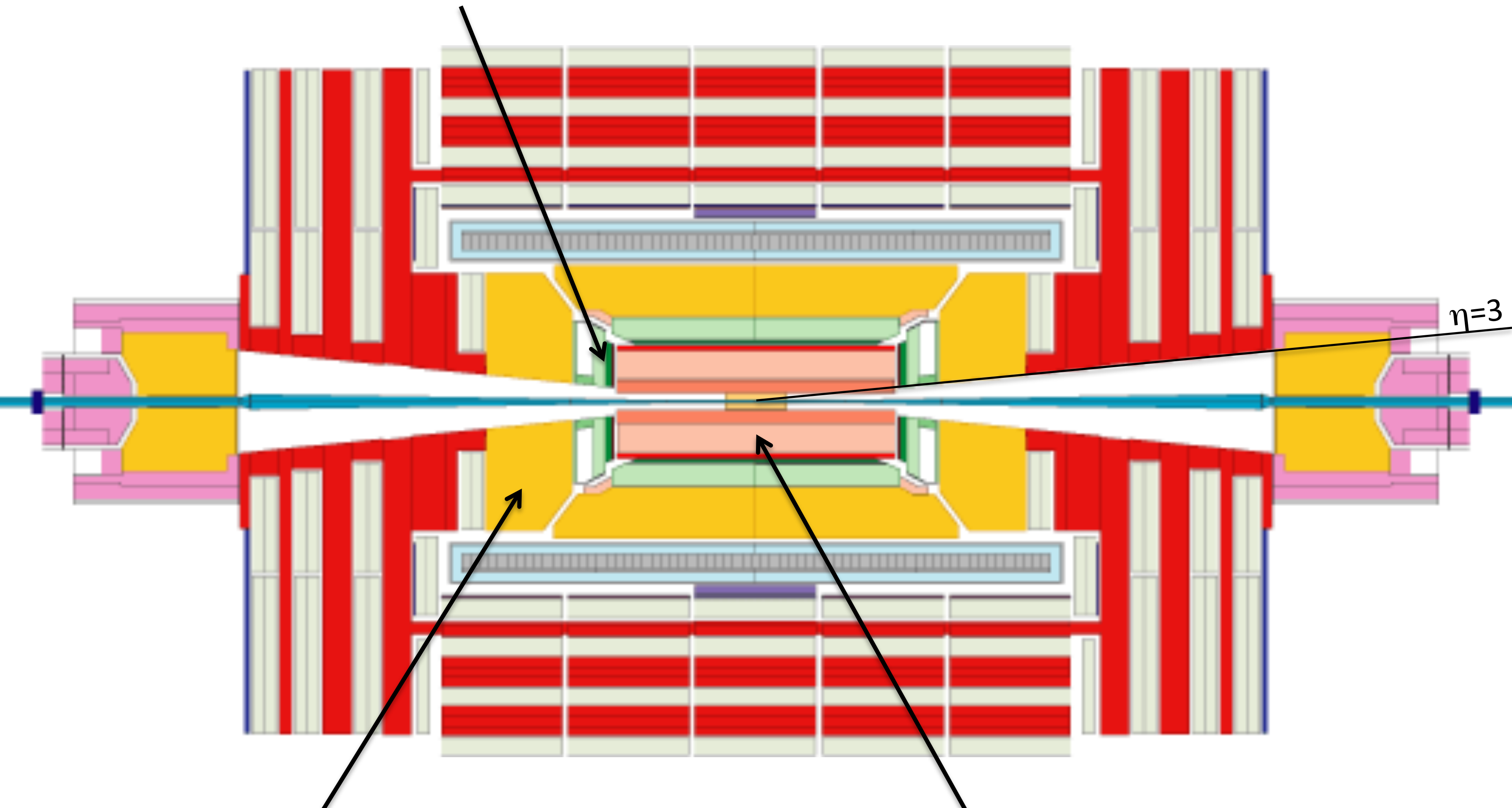
Driving Considerations for the Phase 2 Upgrade

- By LS3 the integrated luminosity will exceed 300 fb^{-1} and may approach 500 fb^{-1} (use 500 for detector studies)
- We will look forward to over 5x more data beyond that, at significantly higher PU (and steady throughout the fill) and radiation
- HL-LHC with lumi-leveling at $5x10^{34}cm^{-2}s^{-1}$ will deliver 250 fb^{-1} per year

- Driving considerations in defining the scope for Phase 2
  - Performance longevity of the Phase 1 detector
  - Physics requirements for the HL-LHC program and beam conditions
  - Development of cost effective technical solutions and designs
  - Logistics and scope of work during LS3

- The performance longevity is extensively studied and modeled, and the radiation damage models are included in full simulation
- While the barrel calorimeters, forward calorimeter (HF) and muon chambers – will perform to 3000 fb^{-1}, it is clear that the tracking system and endcap calorimeters must be upgraded in LS3

Electromagnetic Endcap Calorimeter ($PbWO_4$ Crystals), light output will become too small due to radiation damage



Hadron Endcap Calorimeter (Brass Scintillator) has to be replaced. Crytals, Plastic Scintillators and WLS fibers will broken by radiation.

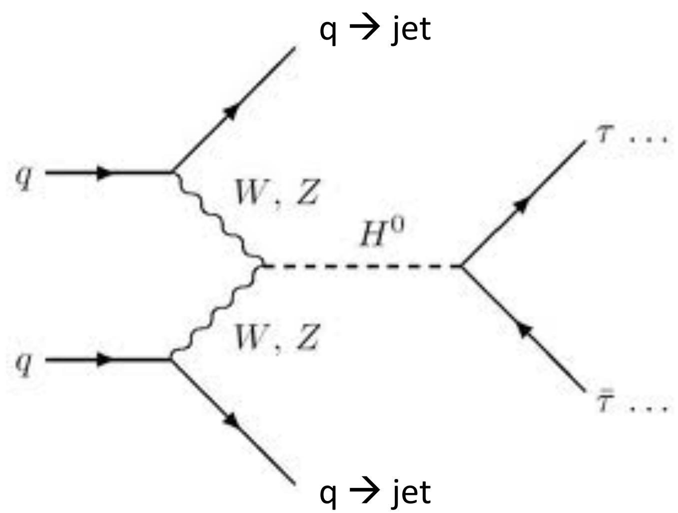
Entire silicon Tracker has to be replaced → radiation hardness and readout (track triggering)

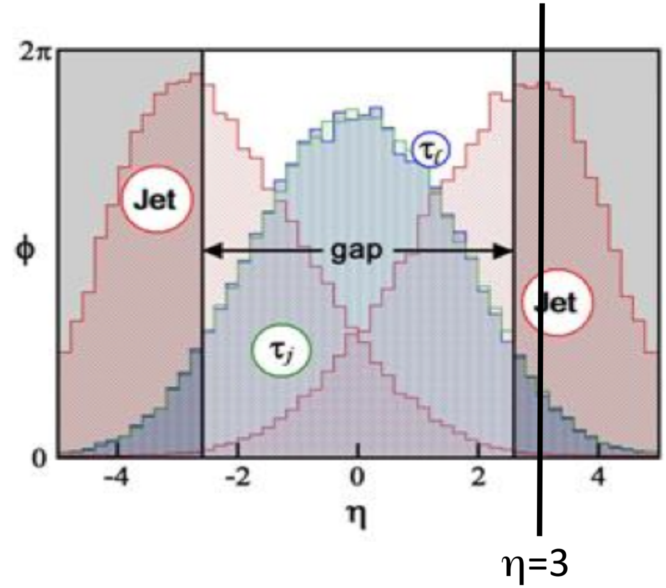
Performance Considerations

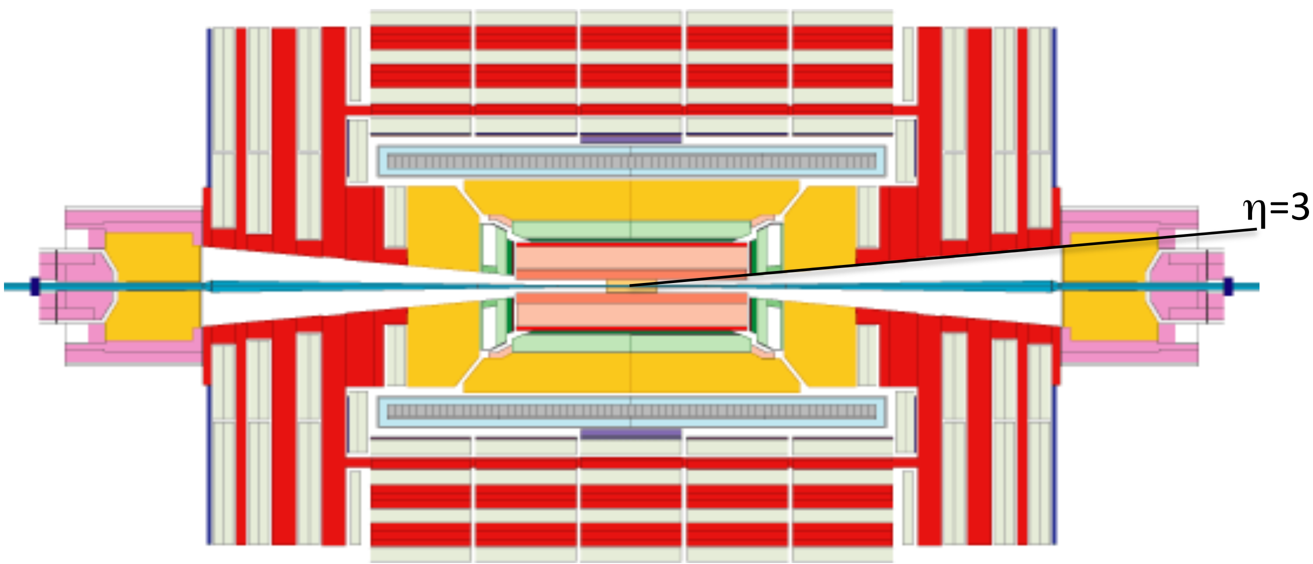
- Mitigation of the effects of high PU relies on particle flow reconstruction and excellent tracking performance.
  - The Phase 2 tracker design must maintain good performance at very high PU
  - We propose to extend the tracker coverage to higher η - the region of VBF jets
  - We are investigating precision timing in association with the calorimeters as a means to mitigate PU for neutral particles

- Endcap coverage
  - The present transition between the endcap and HF, at $|\eta| = 3$, is at the peak of the distribution of jets from VBF. We are studying the feasibility of extending the endcap coverage, and integrating a muon tagging station.
  - This has the potential for a significant improvement for VBF channels, but will have implications for radiation and background levels. Studies are ongoing.
  - Physics studies ongoing to optimize the requirements in resolution & granularity.

Vector Boson Fusion (VBF) -Jets







Very important channel to measure.

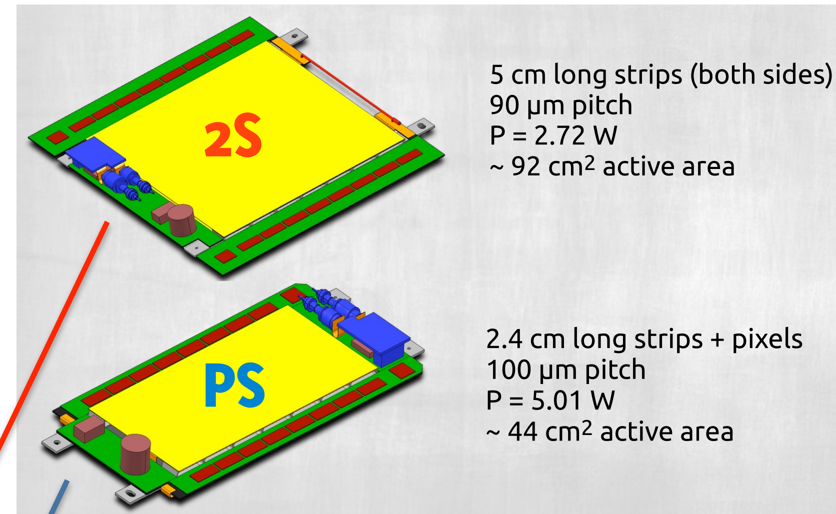
Quarks do not interact through color exchange i.e. the jets are peaked in forward direction at η=3.

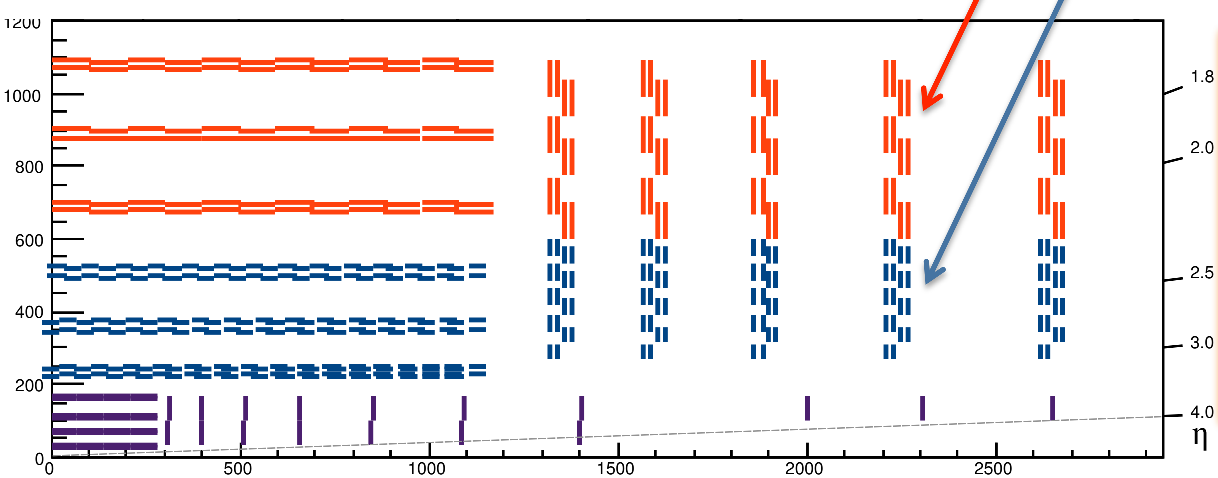
Signature: high jet activity in forward region, little hadronic activity in the barrel.

η = 3 is exactly in the transition region of the endcap calorimeters !

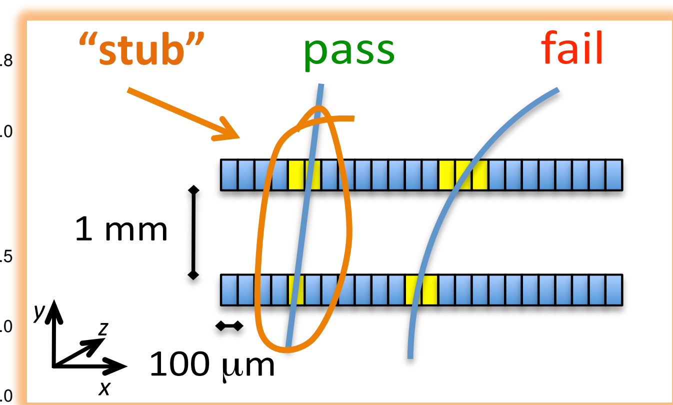
Phase 2 Tracker: conceptual design

- Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget
- Pixel detector
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to $|\eta| = 4$
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
- R&D activities
  - In progress for all components - prototyping of 2S modules ongoing
  - BE track-trigger with Associative Memories





Trigger track selection in FE

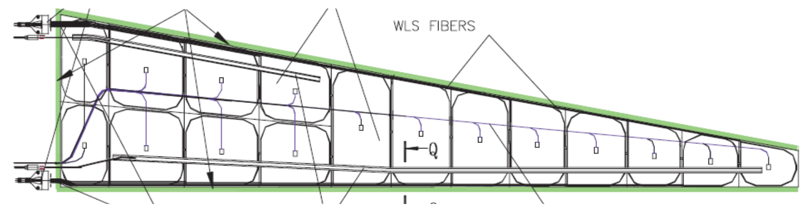


Endcap Calorimeters

Two approaches

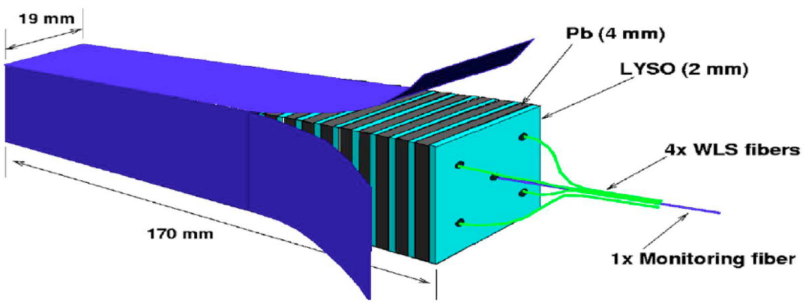
a) Maintain standard tower geometry - develop radiation tolerant solutions for EE and HE to deliver the necessary performance to 3000 fb^{-1}

- Build EE towers in eg. Shashlik design (crystal scintillator: LYSO, CeF)
- Rebuild HE with more fibers, rad-hard scintillators



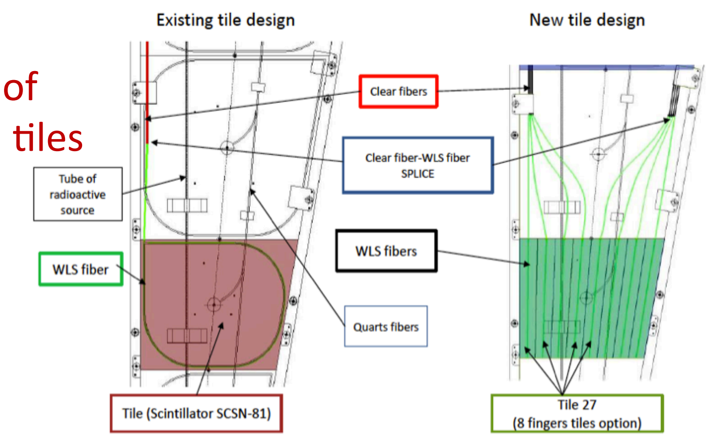
EE

- Rad tolerant WLS fibers (capillaries under development)
- Rad tolerant GaInP "SiPMs" (or fibers to high radius)



HE

- Development of radiation hard tiles



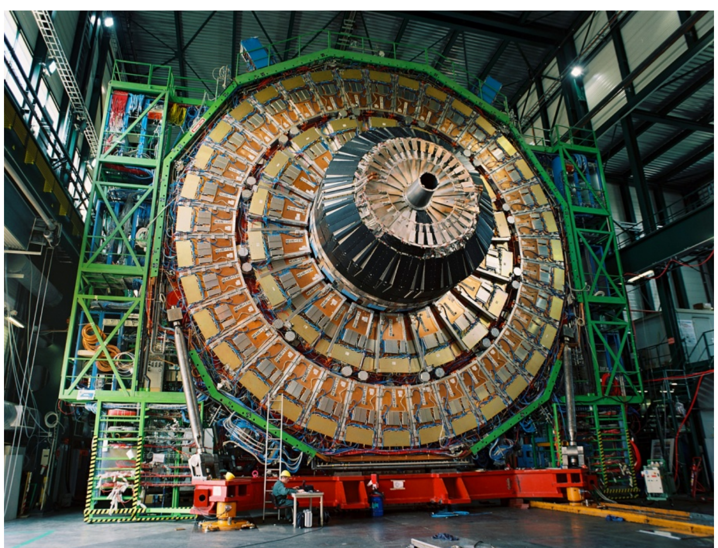
b) Study alternative geometry/concepts with potential for improved performance and/or lower cost. Two concepts under consideration

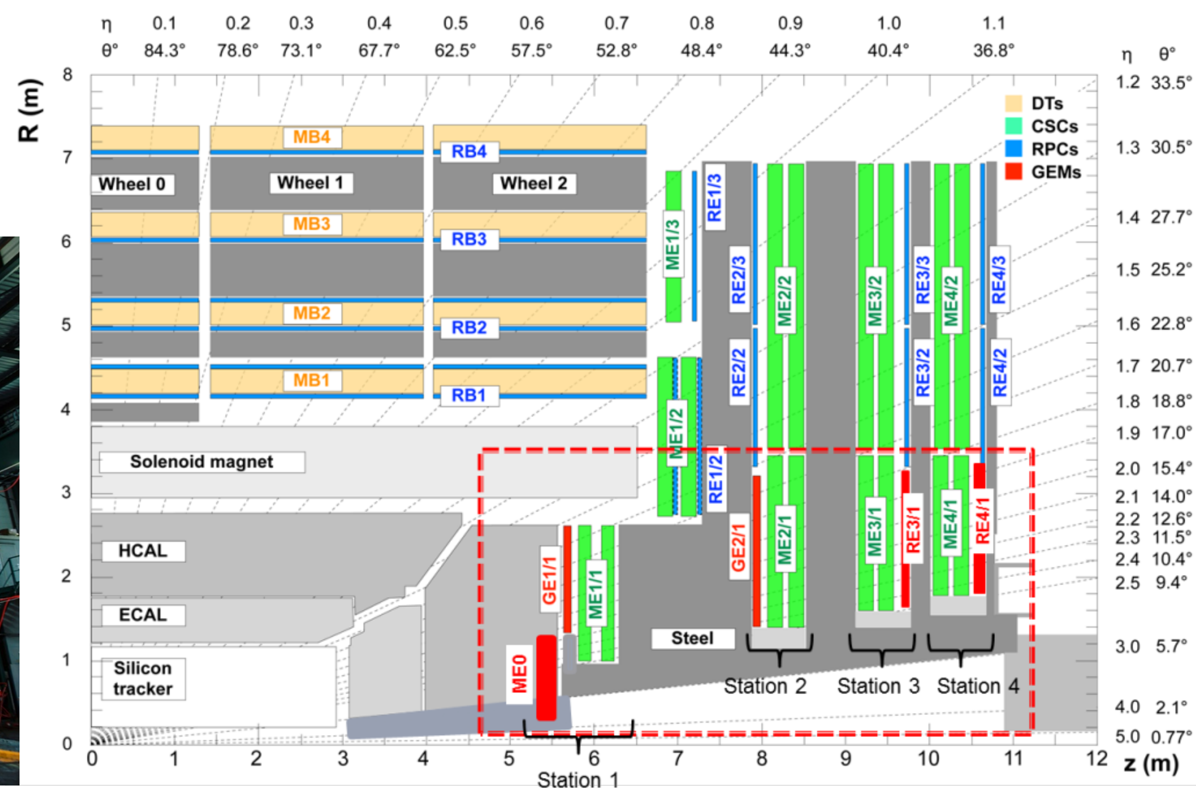
- Dual fiber read-out: scintillation & Cerenkov (DROC) – following work of DREAM/RD52
  - using doped/crystal fibers - allows e/h correction for improved resolution
- Particle Flow Calorimeter (PFCAL) – following work of CALICE
  - using GEM/Micromegas – fine transverse & longitudinal segmentation to measure shower topology

Muon systems

- Improve offline and trigger performance, and provide redundancy in the high rate, high PU forward region
  - Concept under study to complete muon stations at $1.6 < |\eta| < 2.4$
    - GEM in 2 first stations (Pt resolution)
    - Glass-RPC in 2 last stations (timing resolution to reduce background)
  - Investigating increase of the muon coverage beyond $|\eta| < 2.4$ with GEM tagging station (ME0) coupled with extended pixel (depending on HE upgrade)

- R&D activities well underway for GEM and Glass-RPCs





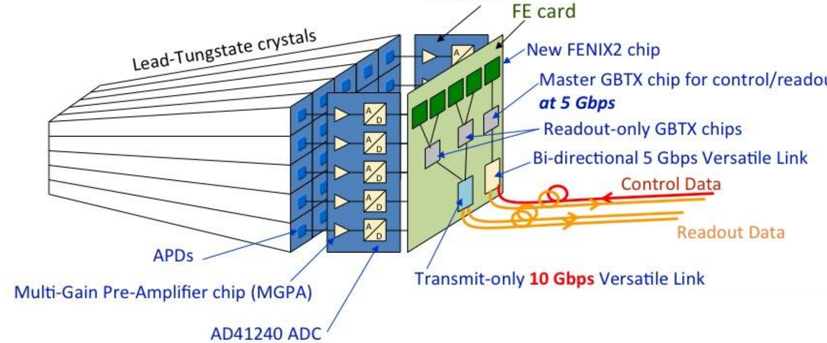
Trigger and DAQ

- The L1-trigger will build on the Phase 1 architecture, with
  - track information (from outer tracker) available to all trigger objects
  - with increased granularity (EB at crystal level)
  - ability to operate up to 1 MHz

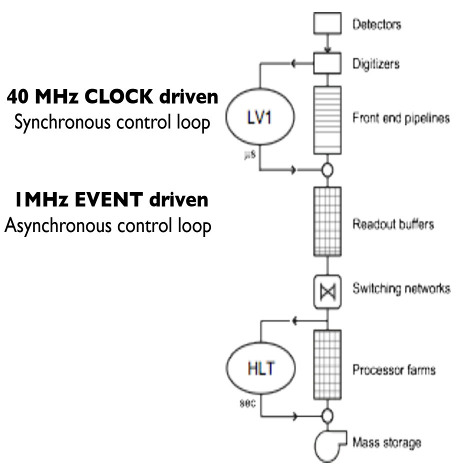
- Match leptons with high resolution tracks
- Improved isolation of e, γ, μ, τ candidates
- Vertex association to reduce effect of pileup in multiple object triggers

- This requires replacement of ECAL Barrel FEE
  - Allow 10 μs latency at L1 (limited by CSC electronics)
  - Provides improved APD spike rejection at L1

New EB FE board



- HLT and DAQ will be upgraded to handle up to 1 MHz into HLT and 10 kHz out, maintaining present HLT rejection factor



"Moore's Law" (for CPUs, networks, and storage) suggests that "normal technology improvements" will handle this on the timescale of LS3

R&D

- R&D is essential to develop cost effective solutions that meet the challenge of high radiation and bandwidth
- Ongoing developments for Tracker, Track Processor, Calorimeters and Muon chambers. In many cases final design choices are needed in 3-4 years.
- Some of the key areas of development include
  - Radiation tolerant silicon sensors for the pixel and strip detectors
  - Radiation tolerant ASIC development (including 65 μm process), especially for trackers
  - High bandwidth and radiation tolerant optical data transmission
  - Radiation tolerant powering scheme
  - Light mechanical structures, detector assemblies and high density interconnections
  - Fast processors for track-triggers
  - Radiation tolerant crystals, tiles and fibres for calorimeters, and radiation hard photo-detectors
  - High rate gas chambers with improved spatial and timing resolution
  - Demonstration of high precision timing in calorimeter pre-sampling
  - Software development for new processing technologies (multicore processing, GPU, etc…)
- Many of these areas are are common with other experiments
- Progress will be discussed at this workshop – encouraging sharing ideas and common development where possible

Concluding remarks

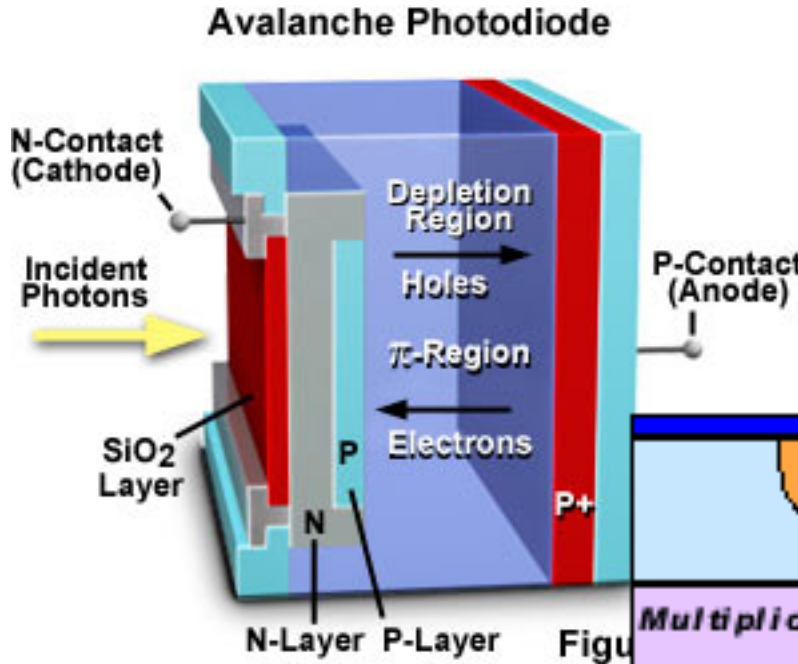
CMS has a phased upgrade program to allow the experiment to fully capitalize on the physics potential of the accelerator upgrades.

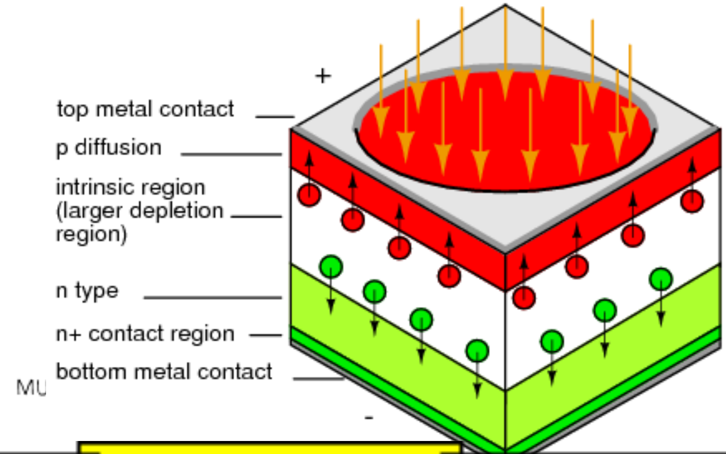
Phase 1 upgrades are progressing well and will ensure that CMS performs well up to peak luminosities >2 x $10^{34}cm^{-2}s^{-1}$, which will be reached by LS3.

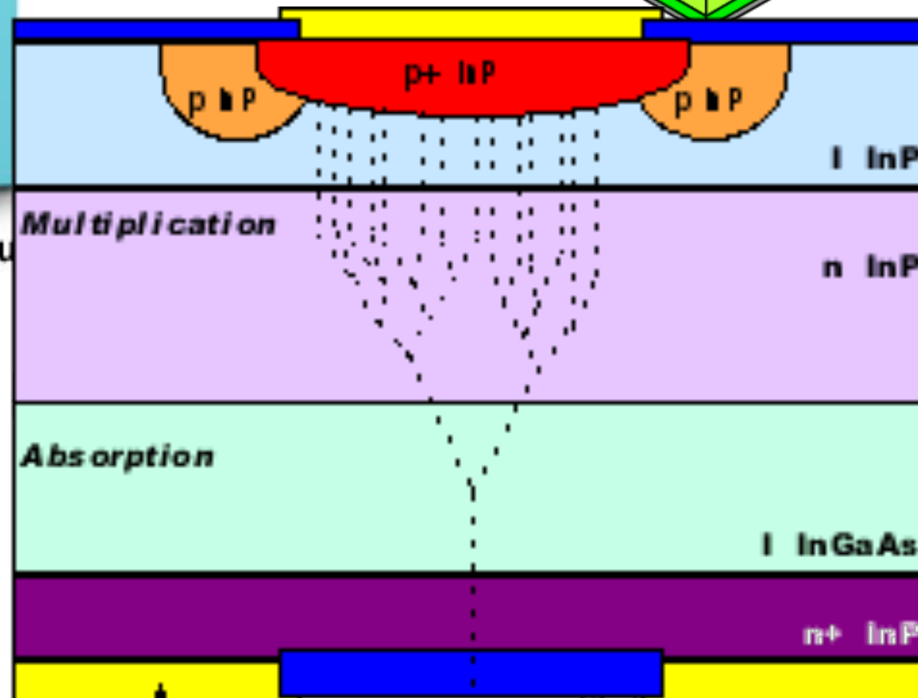
The longevity of detectors has been thoroughly studied. We conclude that the tracker and end-cap calorimeters must be replaced in LS3.

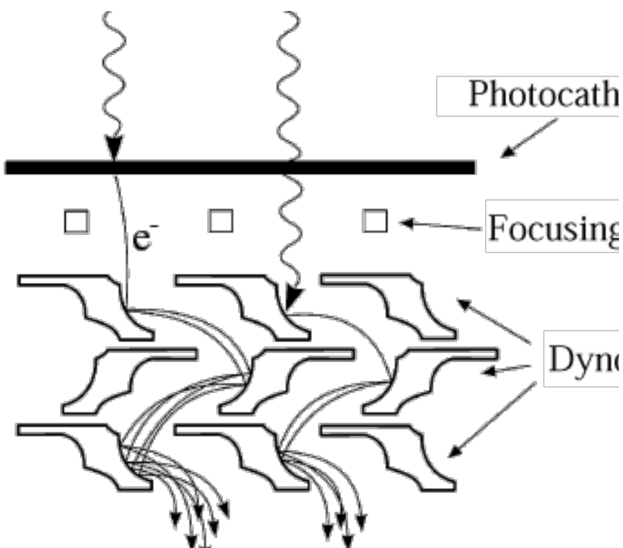
We are developing the full scope of Phase 2 to meet high PU and radiation challenges, supporting a broad and rich physics program at the HL-LHC.

R&D support in the 3-4 coming years is critical to demonstrate cost-effective technical solutions for the upgrades.









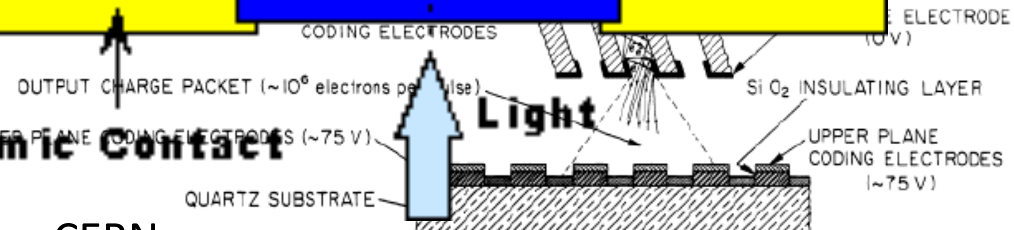
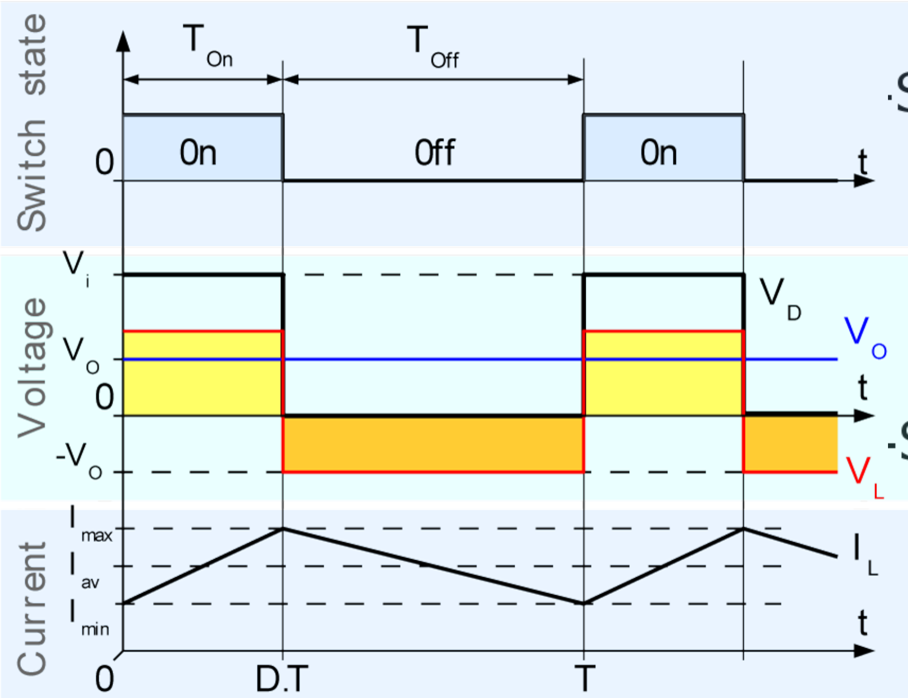


FIG. 16—Schematic of a multilayer coincidence-anode array.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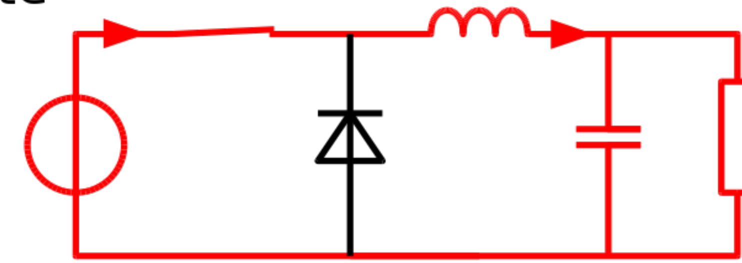

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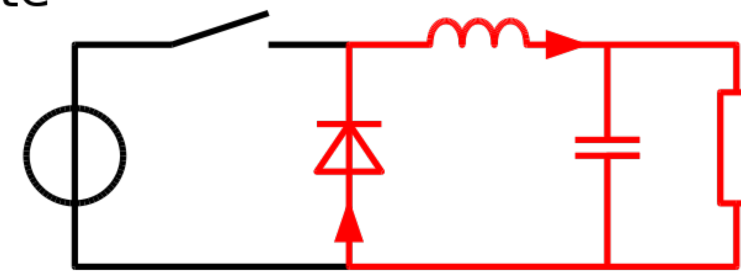

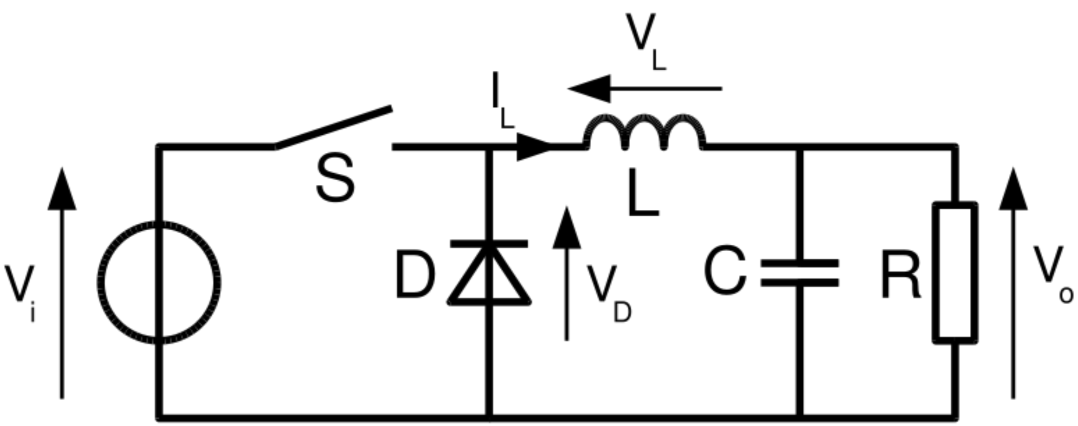
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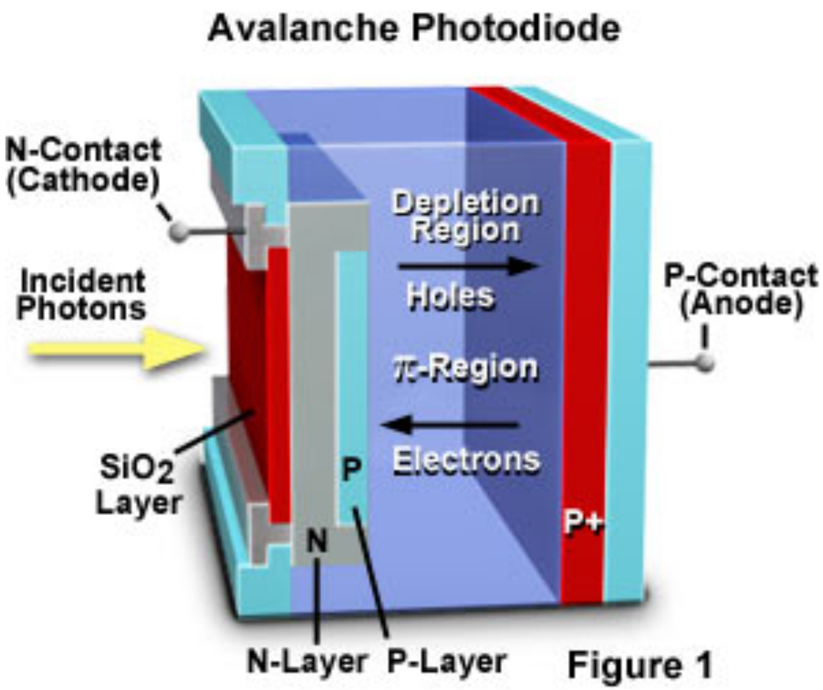
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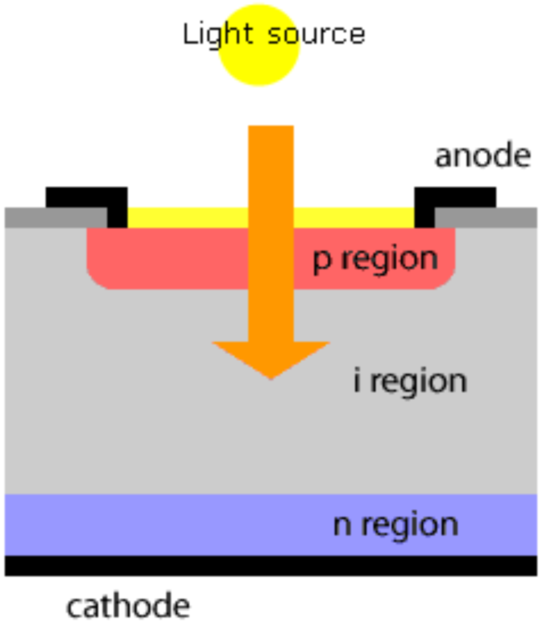
Figure 1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