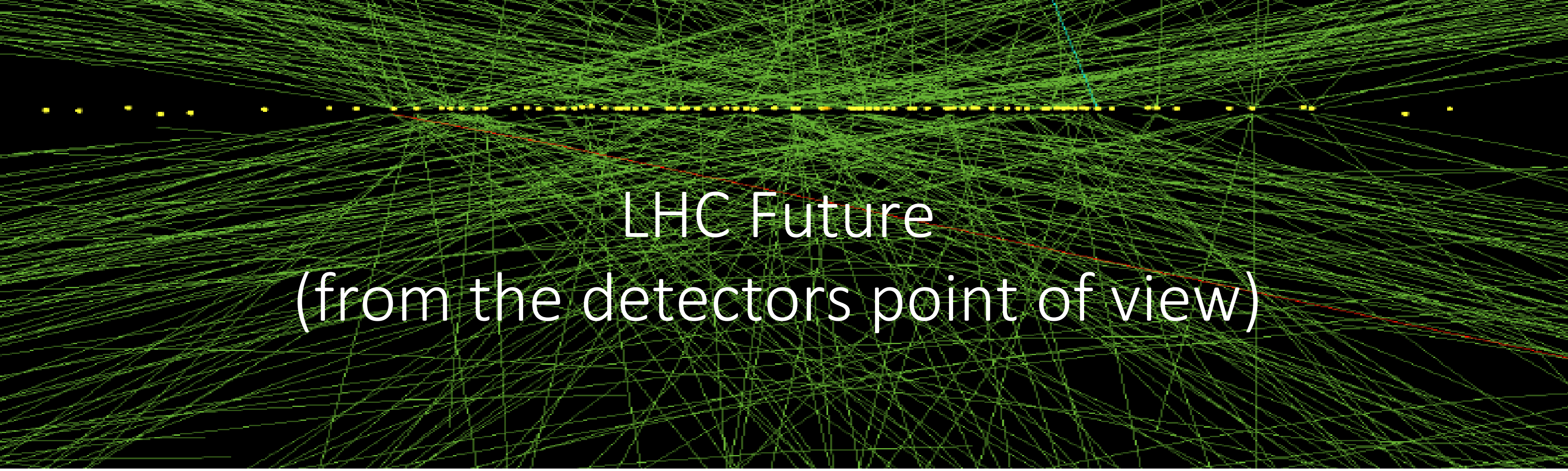


LHC Future
(from the detectors point of view)

Ignacio Redondo Fernández
CIEMAT

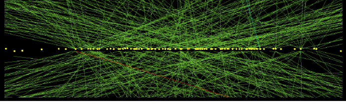
I. LHC Accelerator Complex Upgrade Path(s)

II. Some Introductory Detector Concepts

III. Experiment Upgrades for HL-LHC

http://redondo.web.cern.ch/redondo/TAE2014_redondo.pdf

Disclaimer



Personal taste and limited knowledge is involved in the selection of topics.

I confess I am biased :

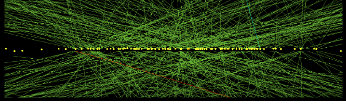
CMS member

Working for CIEMAT

Expert in Muon and Silicon tracker detectors

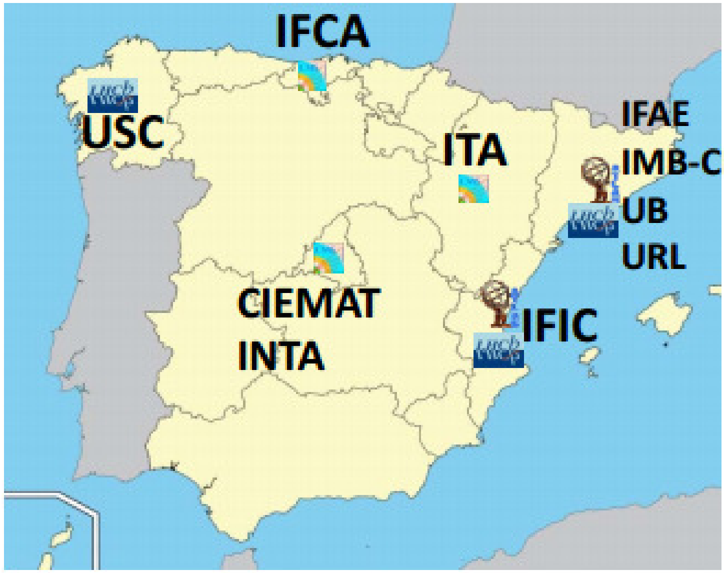
Apologies to projects/concepts not justly covered

References



- ECFA High Luminosity LHC Experiments Workshop – 2013 http://indico.cern.ch/event/252045/
    - ECFA High Luminosity LHC Experiments Workshop – 2014 23/24 October 2014
- Daniela Bortoletto’s CERN summer student lecture https://indico.cern.ch/event/243645/
- Werner Riegler CERN Lectures https://indico.cern.ch/event/266879/
- Grupen “Particle Detectors” (& Leo) textbooks
- Teresa Rodrigo’s TAE 2013 lecture http://benasque.org/2013tae/talks_contr/185_Rodrigo_benasque2013.pdf
- Helmut Spierer http://www-physics.lbl.gov/~spieler/
- Cristina F. Bedoya CPAN talk http://indico.ific.uv.es/indico/getFile.py/access?contribId=26&sessionId=0&resId=0&materialId=slides&confId=764

Spanish Contributions to LHC Detector Upgrades



Upgrade of the ATLAS IBL Pixel
IFAE
IMB-CNM-CSIC

Upgrade of the AFP (forward detector silicon roman pot) at ATLAS
IFAE

Upgrade of the ATLAS forward tracker
IMB-CNM-CSIC
IFIC

Upgrade of the ATLAS TileCal
IFIC
IFAE

Upgrade of the CMS Drift Tubes
CIEMAT

Upgrade of the CMS Tracker (Pixels phase 2)
IFCA
ITA
INTA
IMB-CNM-CSIC

Upgrade of the LHCb velo
USC

Upgrade of the LHCb SciFi
UB (Universitat de Barcelona)
IFIC

Upgrade of the LHCb Calorimeter FE
UB
IFIC
URL (La Salle - Universitat Ramón Llull)

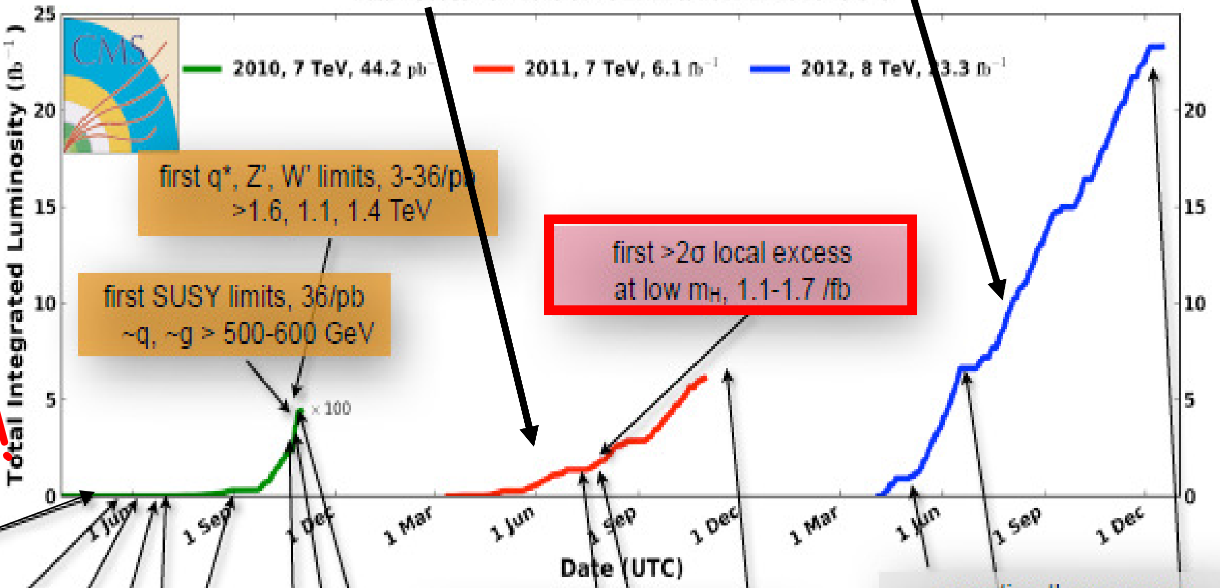
[See W. Riegler lectures for Alice upgrades]

Plenty of barrel muons in online display!

100 Khz barrel muons (all pt)

2009 running:
- Hard to see anything apart from min bias in the displays.
- Serious analysis to find muons in the barrel.

Back to buisness!



first q*, Z', W' limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb
~q, ~g > 500-600 GeV

first >2σ local excess
at low m_H, 1.1-1.7 /fb

first MinBias / UE
studies, particle multiplicities

first incl. b x-section, 8/nb
$\delta \sim 15\ \%$

first incl. jet x-section, PF jets
60/nb $\delta \sim 20\text{-}30\%$

first incl. W/Z x-sections, 200/nb
$\delta \sim 4\text{-}6\%$, +11% lumi

first incl. J/Ψ x-section, 100/nb
$\delta \sim 20\%$

first top xsec, 3/pb
$\delta \sim 40\%$

first single top xsec,
t-chan., 36/pb
$\delta \sim 36\%$

first m_{top}, 36/pb
$\Delta \sim 6.5$ GeV

first WW xsec, 36/pb
$\delta \sim 40\%$
first limit on HWW

first ZZ xsec, 1.1 /fb
$\delta \sim 40\%$

going more differential,
e.g. Z/W + j,b,c

first significant limit on
$B_s \rightarrow \mu\mu$, $BR < 1.9 \times 10^{-8}$

first particle discovered
by CMS: Ξ_b

BSM searches continue,
limits pushed

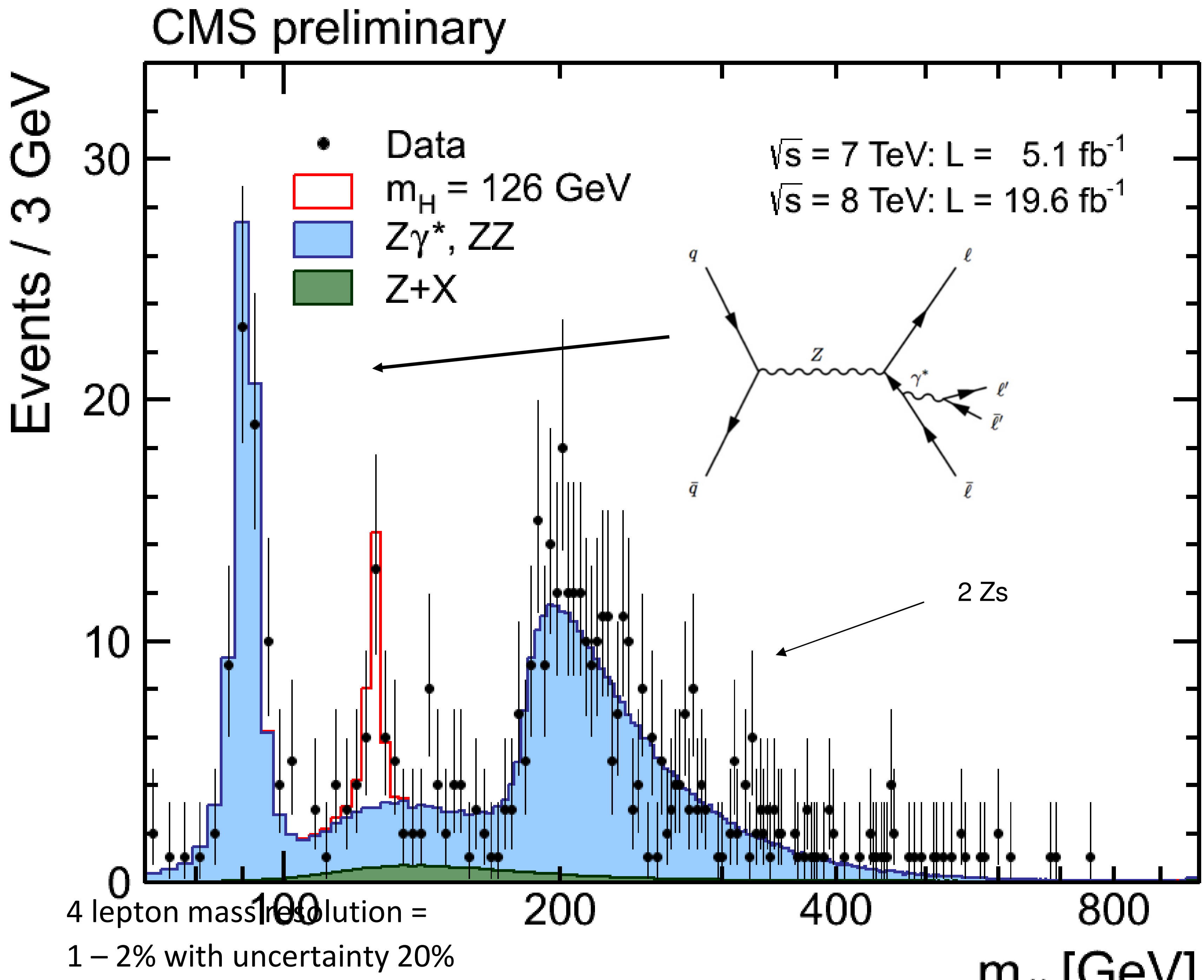
repeating the program
at 8 TeV

a new boson is
announced, 5 /fb

first spin parity
analysis of the boson,
17 /fb

elative uncert   Δ .. absolute uncert.

G. Dissertori



2 Zs

4 lepton mass resolution =
1 – 2% with uncertainty 20%

LHC Accelerator Complex Upgrade Path(s)

- Now, run II to start in 2015
    - Splices consolidated ➔ ~x2 in energy
- HL-LHC gives x10 in luminosity
    - New triplets
    - Crab cavities
- Dreams on the energy frontier from 2035 onwards
    - HE-LHC?
    - FCC-hh is another collider

LHC start was “explosive”

“On 19 September 2008, during powering tests of the main dipole circuit in Sector 3-4 of the LHC, a fault occurred in the electrical bus connection in the region between a dipole and a quadrupole, resulting in mechanical damage and release of helium from the magnet cold mass into the tunnel.”

http://press.web.cern.ch/press-releases/2008/10/cern-releases-analysis-lhc-incident

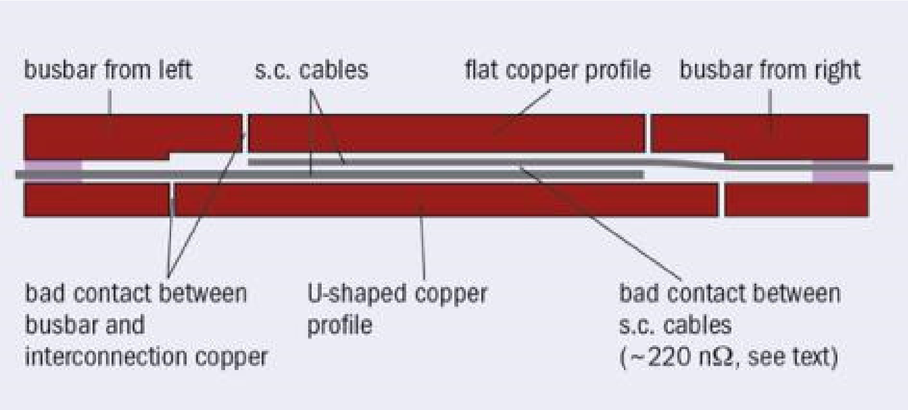
After important repairs and thorough evaluation, LHC started operation ~one year afterwards at half energy

➔In such complex project success is far from granted

LHC Long Shutdown 1

Development of Resistive contacts caused a major accident and subsequent delay early in the LHC program
That’s why LHC runs at ~half its design energy

LS1 main goal is to repair the magnet interconnects to allow nominal current in the dipole and lattice quadrupole circuits of the LHC.



It has become a major shutdown which, in addition, includes other repairs, maintenance, consolidation, upgrades and cabling across the whole accelerator complex and the associated experimental facilities.

.

The main 2013-14 LHC consolidations

Opening:100%
1695 Openings and final reclosures of the interconnections

Closure: 100%

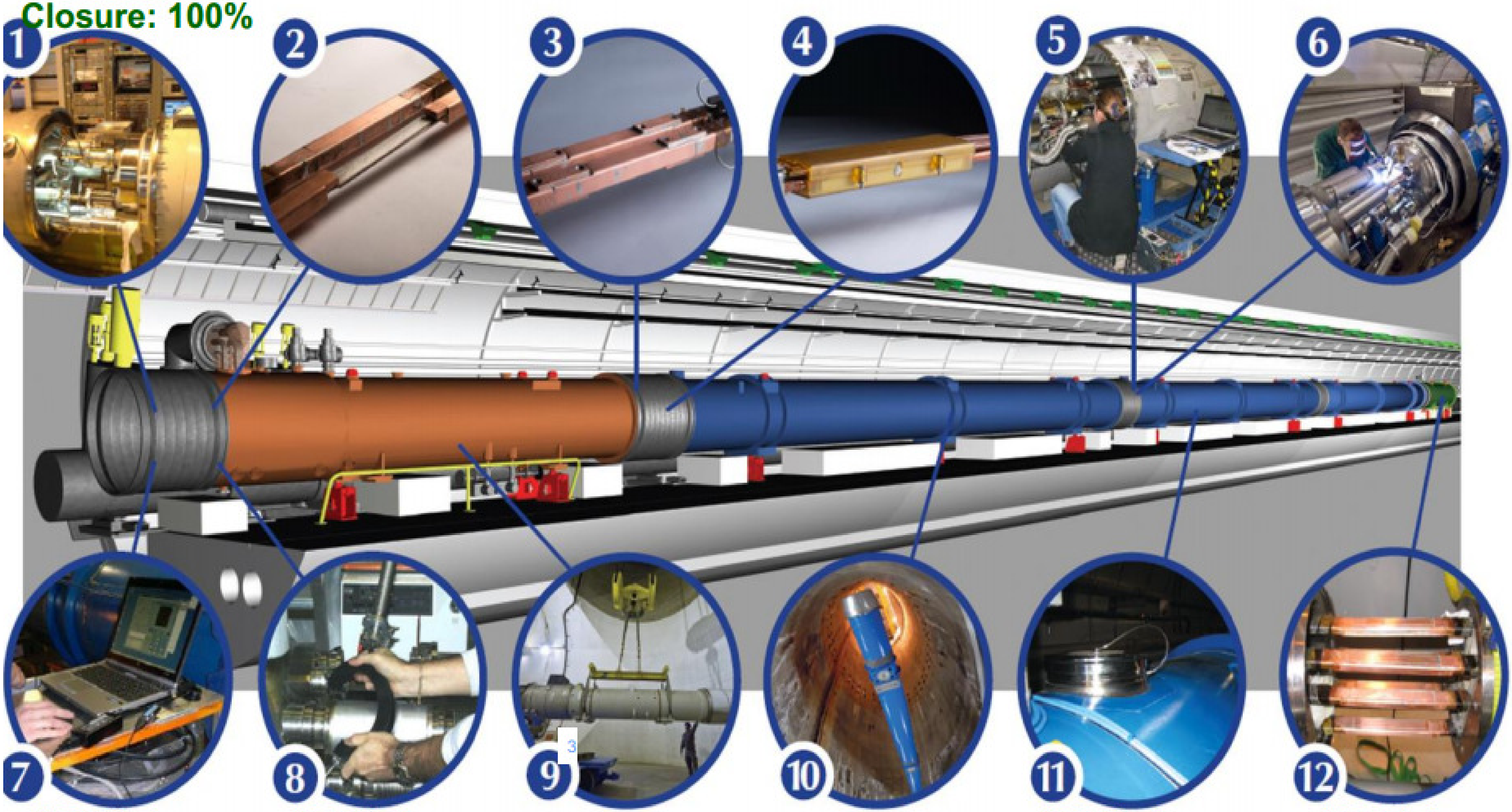
100 % done
Complete reconstruction of 3000 of these splices

100 % done
Consolidation of the 10170 13kA splices, installing 27 000 shunts

100 % done
Installation of 5000 consolidated electrical insulation systems

100 % done
300 000 electrical resistance measurements

100 % done
10170 orbital welding of stainless steel lines



100 % done
18 000 electrical Quality Assurance tests

100 % done
10170 leak tightness tests

3 quadrupole magnets to be replaced
Done

15 dipole magnets to be replaced
Done

100 % done
Installation of 612 pressure relief devices to bring the total to 1344

100 % done
Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

Expectations after Long Shutdown 1 (2015)

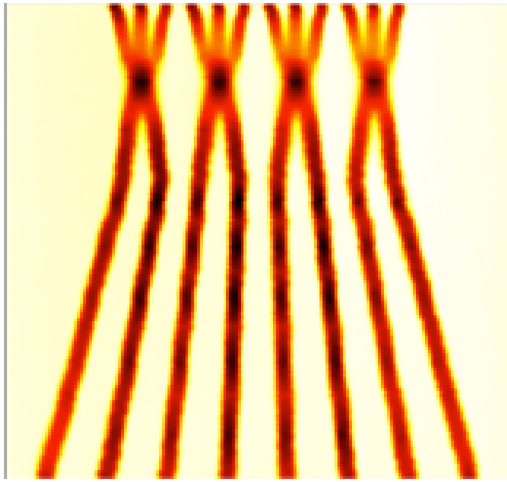
- Collisions at least at 13 **TeV** c.m.
- **25 ns** bunch spacing

  Using new injector beam production scheme (BCMS), resulting in brighter beams.

  (Note: emittance is conserved along the accelerator complex)

- **β^* ≤ 0.5m** (was 0.6 m in 2012)
- Other conditions:
  - Similar turn around time
  - Similar machine availability
- Expected maximum luminosity: **1.6 x 10^{34} cm^{-2} s^{-1}** ± 20%
  - Limited by inner triplet heat load limit, due to collisions debris

Batch Compression and Merging and splitting (BCMS)



Courtesy of the LIU-PS project team

	Number of bunches	Intensity per bunch	Transverse emittance	Peak luminosity	Pile up	Int. yearly luminosity
25 ns BCMS	2508	1.15 × 10^{11}	1.9 μm	1.6×10^{34} cm^{-2}s^{-1}	~43	~42 fb^{-1}

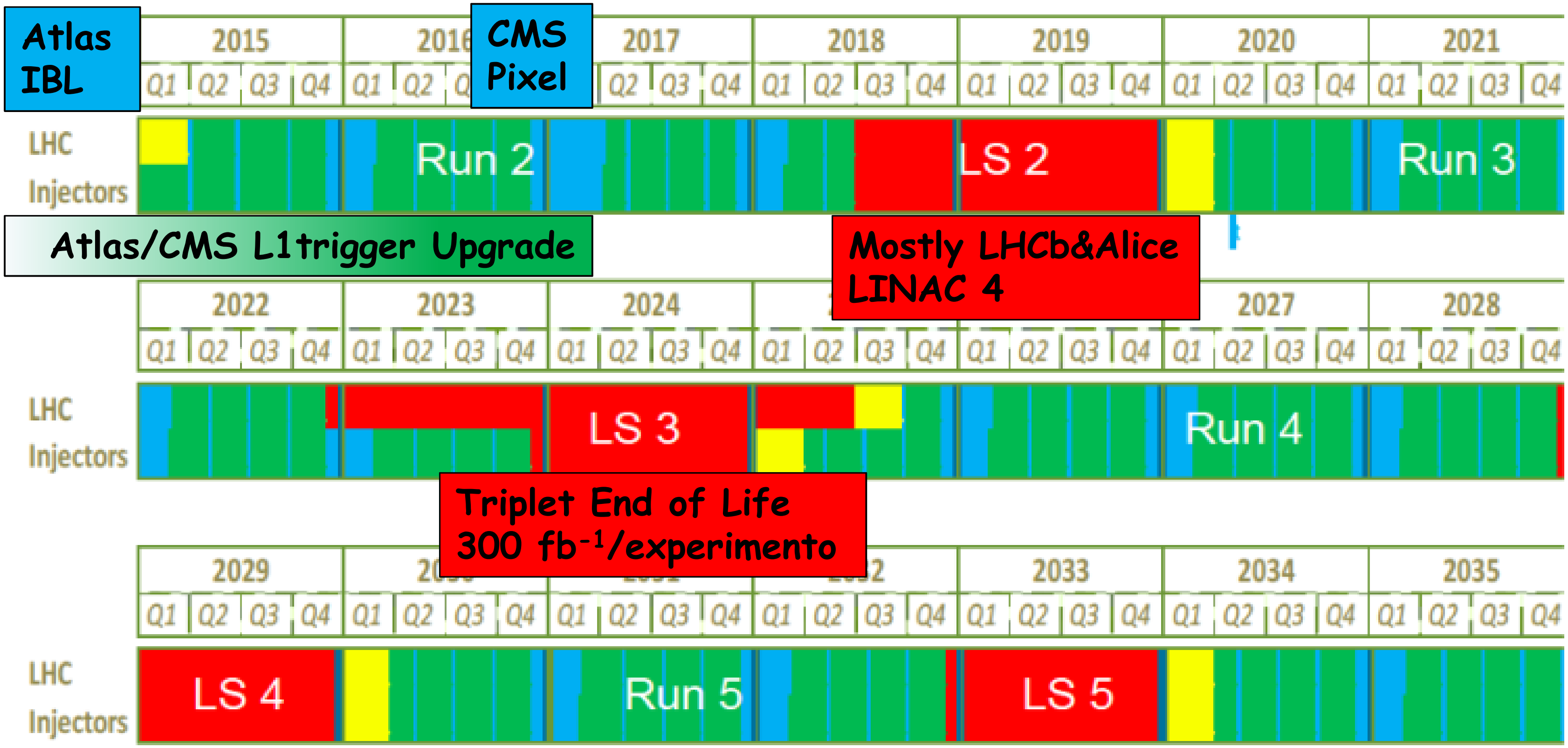
LHC nominal after Long S1? (x2 in Energy and ½ in pileup)

CMS Pixel installation (Radiation)

CMS target for LS3

LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)
LS3 LHC: starting in 2023 => 30 months + 3 BC
injectors: in 2024 => 13 months + 3 BC



Atlas IBL

CMS Pixel

Atlas/CMS L1trigger Upgrade

Mostly LHCb&Alice LINAC 4

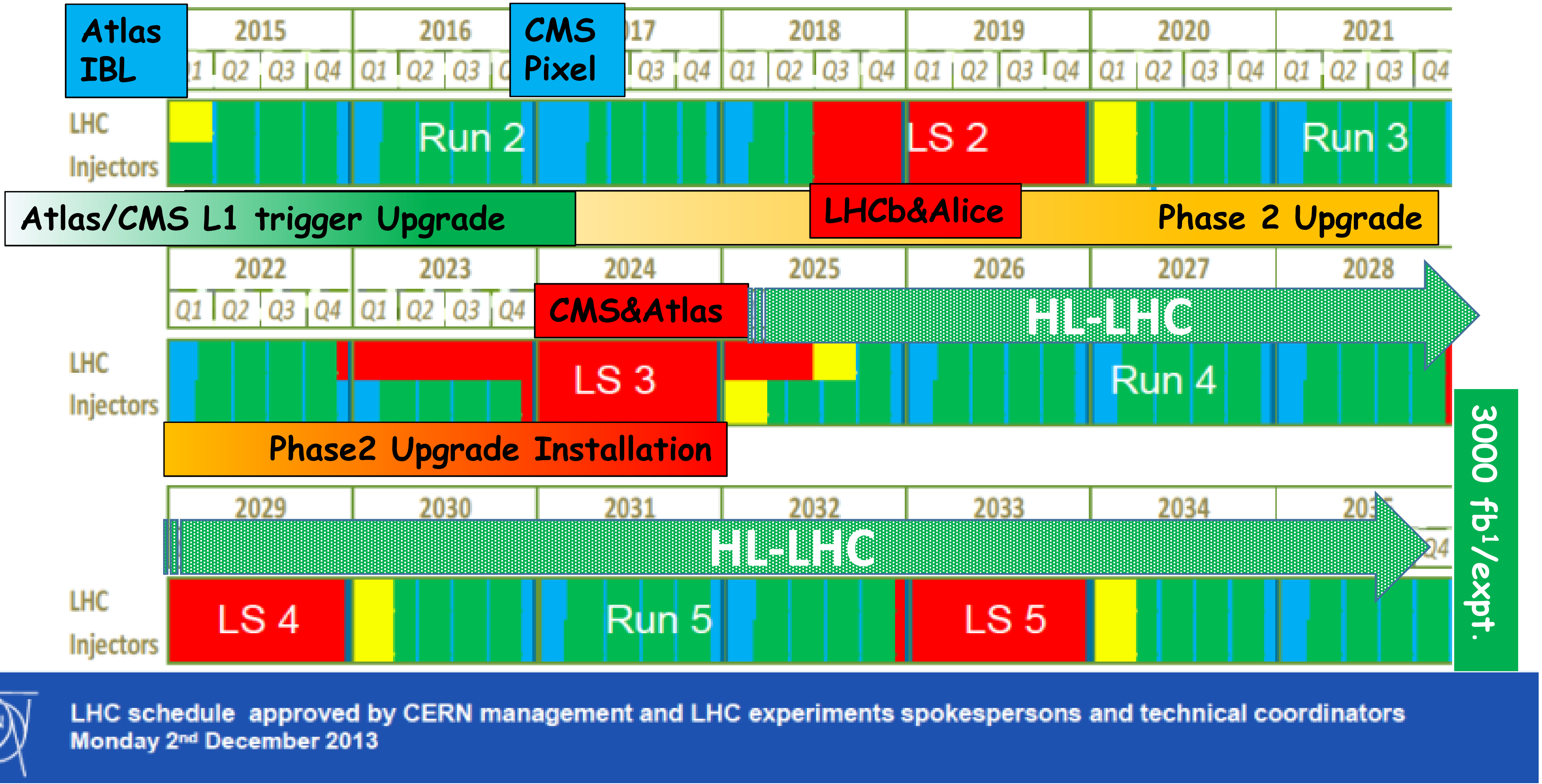
Triplet End of Life 300 fb^{-1}/experimento

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

LHC evolution → HL-LHC?

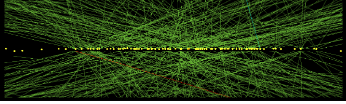
Until LS3 (Long Shutdown 3) adjusting to increasing pileup is the challenge :

- New pixel detector
- New L1 trigger (migrated to a new technology µTCA)
- Data processing.



LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

The european scene: ECFA and CERN



ECFA y CERN put the exploitation of LHC as the first priority in Europa. ECFA strategy update:

> *"Europe's top priority should be the exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030...will also provide exciting posibilities in the study of flavour physics and the quark-gluon plasma."*
>
> ECFA European Committee for Future Accelerators
>
> *"CERN should undertatake design studies for accelerator projects in a global context, with emphasis in proton-proton and electron-positron high-energy frontier machines."*

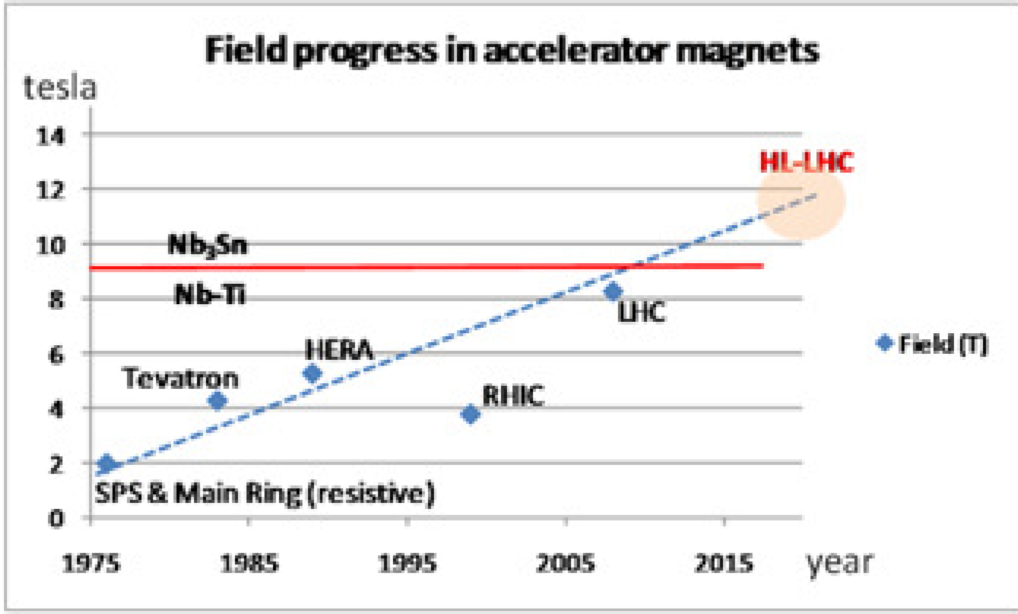
CERN gives priority to hadronic accelerators capable of exploring the energy frontier ➔ a decades R&D program that could give birth to several projects, not aproved yet.

2025

1. HL-LHC : New superconducting quadruplets (built in Nb_3Sn, instead of NbTi, used for LHC) needed to focus the beams next to the interaction points
2. HE-LHC : Nb_3Sn dipoles for High Energy LHC , increasing the energy by 2-2.5.
3. FCC-hh : To go beyond it will require a new tunnel of larger perimeter(~100 Km)
4. FCC-ee : could have a e+e− as a first step.

~2050

Squeezing the beams: High Field SC Magnets



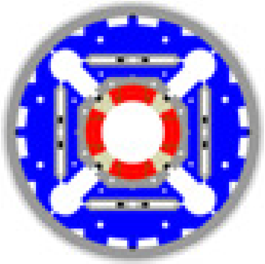
Quads for the inner triplet

Decision 2012 for low-β quads

Aperture ∅ 150 mm – 140 T/m

(B_{peak} ≈12.3 T)

(LHC: 8 T, 70 mm)



More focus strength,

β* as low as 15 cm (55 cm in LHC)

***thanks to ATS** (Achromatic Telescopic Squeeze)* **optics**

In some scheme even β down to 7.5 cm are considered*

- Dipoles for beam recombination/separation capable of 6-8 T with 150-180 mm aperture (LHC: 1.8 T, 70 mm)
- Dipoles 11 T for LS2 (see later)

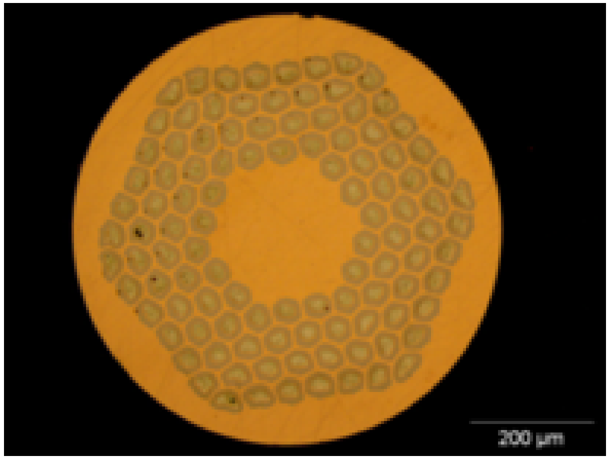
Courtesy Lucio Rossi

The « new » material : Nb_3Sn

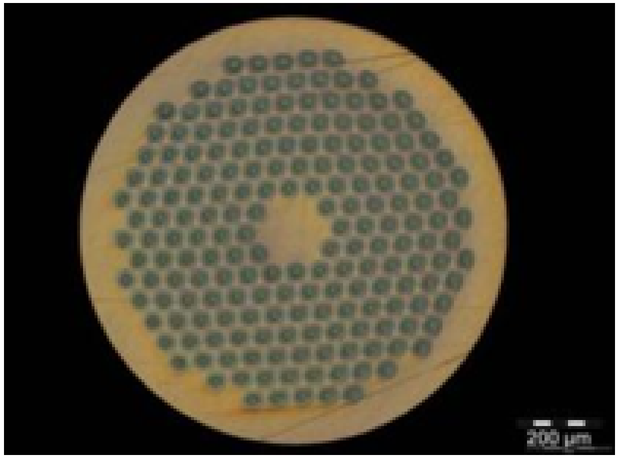
- Recent 23.4 T (1 GHz) NMR Magnet for spectroscopy in Nb_3Sn (and Nb-Ti).
- 15-20 tons/year for NMR and HF solenoids. Experimental MRI is taking off
- ITER: 500 tons in 2010-2015!

  It is comparable to LHC *(1200 tons of Nb-Ti but HL-LHC will require only 20 tons of Nb_3Sn)*

- HEP ITD (Internal Tin Diffusion):
  - High Jc., 3xJc ITER
  - Large filament (50 µm), large coupling current...
  - Cost is 5 times LHC Nb-Ti



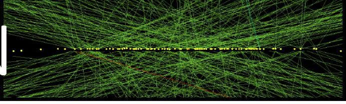
0.7 mm, 108/127 stack RRP from **Oxford OST**



1 mm, 192 tubes PIT from **Bruker EAS**

Courtesy Lucio Rossi

The global scene view from ECFA and CERN



European R&D contribution and/or participation to other projects

1. Looks likely the next e+e- accelarator will be built in Asia, either ILC (International Linear Collider, for which Japan is leading, either a ring project, for which there is a Chinese project(Circular Electron Positron Collider).

”Europe looks forward to a proposal from Japan *to discuss a* possible participation*.”*

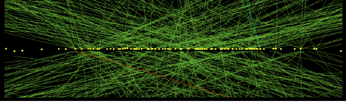
2. Japan (SuperKamikande,K2K) and later USA (LBNE) have invested heavily in neutrino instalations, in contrast to CERN, which has lately closed the neutrino beam to Gran Sasso.

”CERN should develop a neutrino programme to pave the way for a substantial European role in future long baseline experiments. Europe should explore the possibility of major participation *in leading long baseline neutrino projects* in the US and Japan*”*

HL-LHC is very likely

New accelerator: O($ 10^{10}) Acelerador upgrade: O($ 10^{9})

LHC goals I: Study H^0



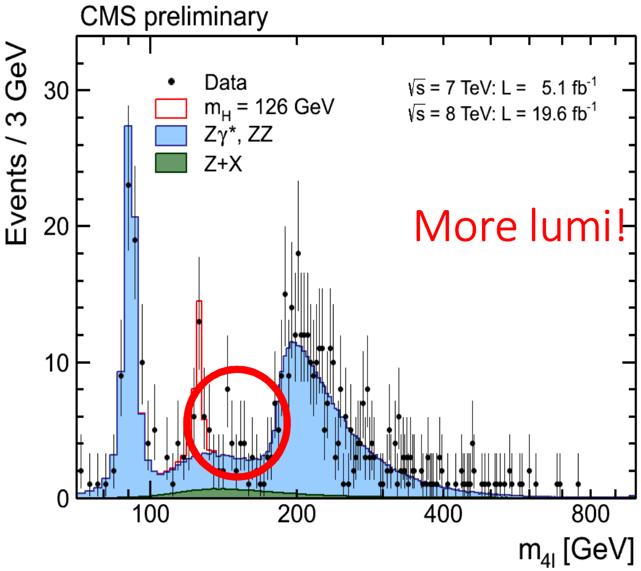
Exploring the mechanism responsable for the spontanous symetry breaking of the electrowek interaction, the BEH mechanism :

- from a schalar doublet and the electroweak gauge bosons (thus null mass) of SU(2)
- generate the three observed massive bosons (Z y $W^{\pm}$) and the scalar boson , lately observed, H^0

- Have to determine from observations the parameters of the Estándar Model lagrangian :
  - couplings to the different particles and to itself

$$\sigma \cdot B(i \to H \to f) = \frac{\boxed{\sigma_i \cdot \Gamma_f}}{\Gamma_H}$$

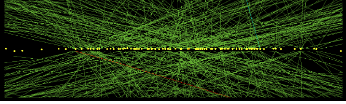
  - Measure the width of the H^0,Γ_{tot} ➔ constrain decays in an *"invisible"* sector



More lumi!

Vast experimental program of key relevance, not LHC exclusive

LHC goals I : Study H^0



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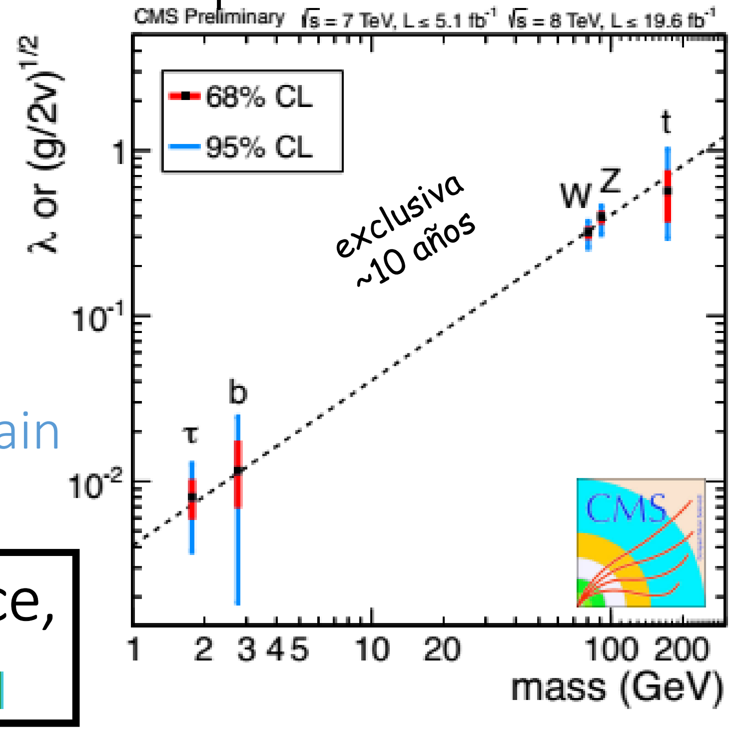
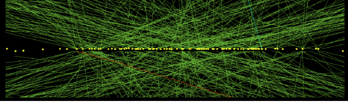


Vast experimental program of key relevance, not LHC exclusive

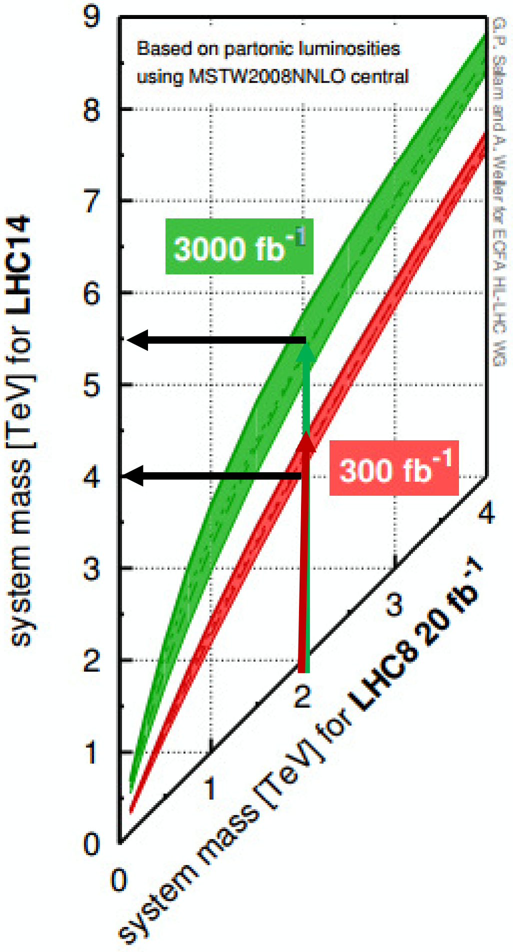
LHC goals II: Explore the frontier



LHC7-8 has excluded new physics beyond the standar model for the available energies. In 2015 with x2 in energy,

exclusive
~20 años

- a new window of discovery



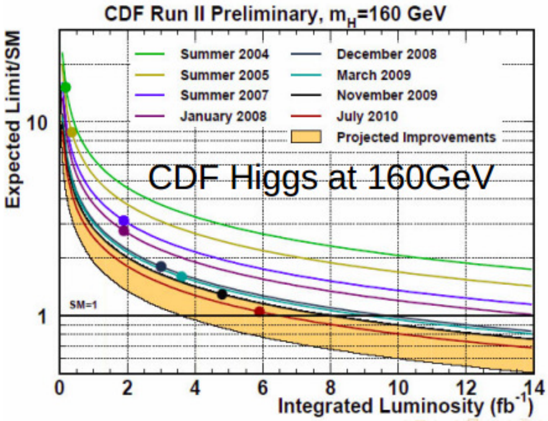
G.P. Salam and A. Weiler for ECFA HL-LHC WG

- Looking at the parton kinematics
  - LHC pushes the explored región from 2 TeV to 4 TeV
  - HL-LHC advances *only* until 5.5 TeV

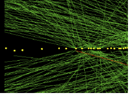
    a e+e- colllider with this reach is not on the map
- In practice, in hadronic colliders :
  - High pileup is a difficult energy regime in which the trigger decisión is crucial…. ➔Repeating the experiment is not a luxury
  - Anomalies appear…
  - Systemátics improve with available statistics…

    …with peoplepower/analysis

    …adn with cumulative knowledge

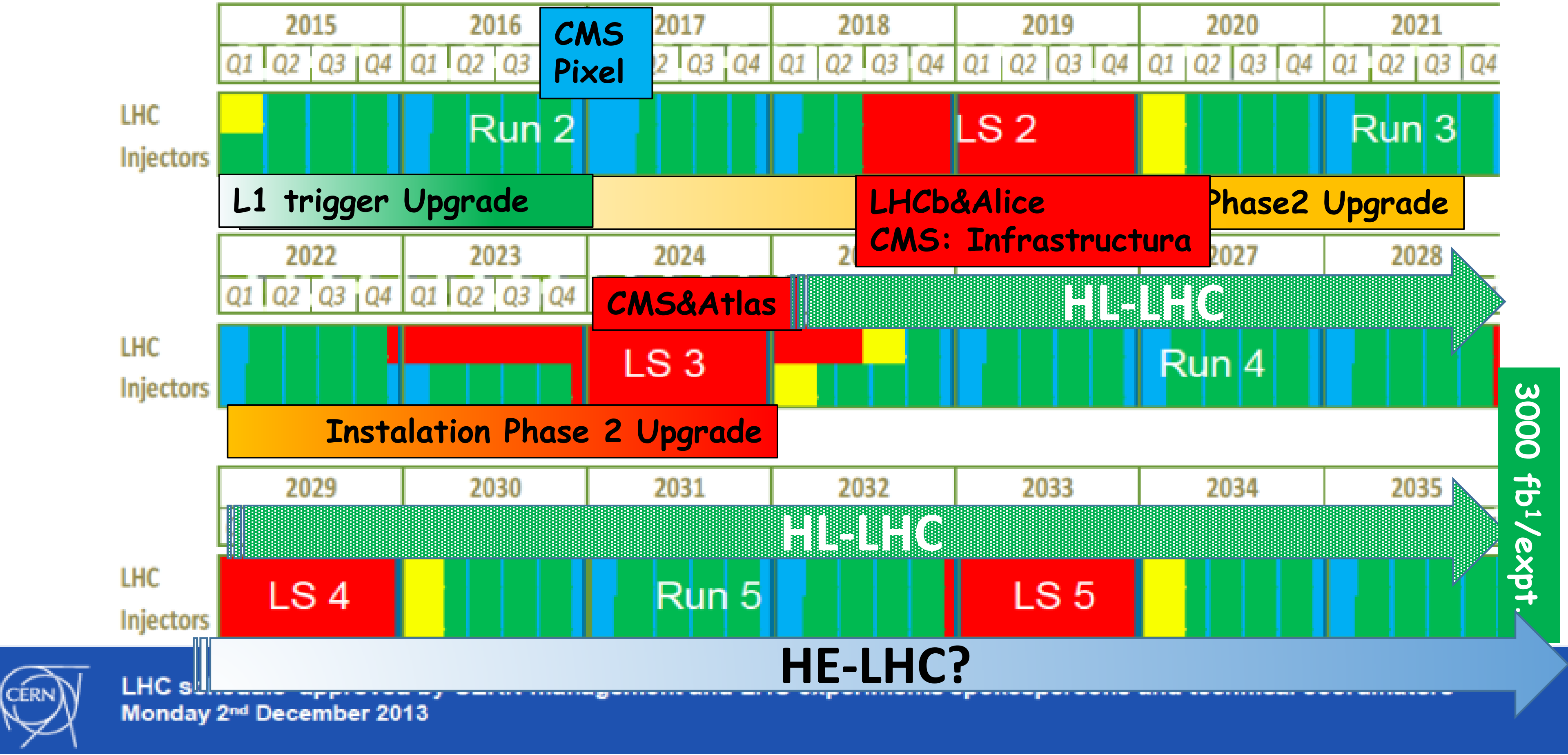


LHC Evolution. HE-LHC??



LS3 upgrades(Long Shutdown 3) to adapt for x5 en pileup are not lost
If we a get higher energy earlier :

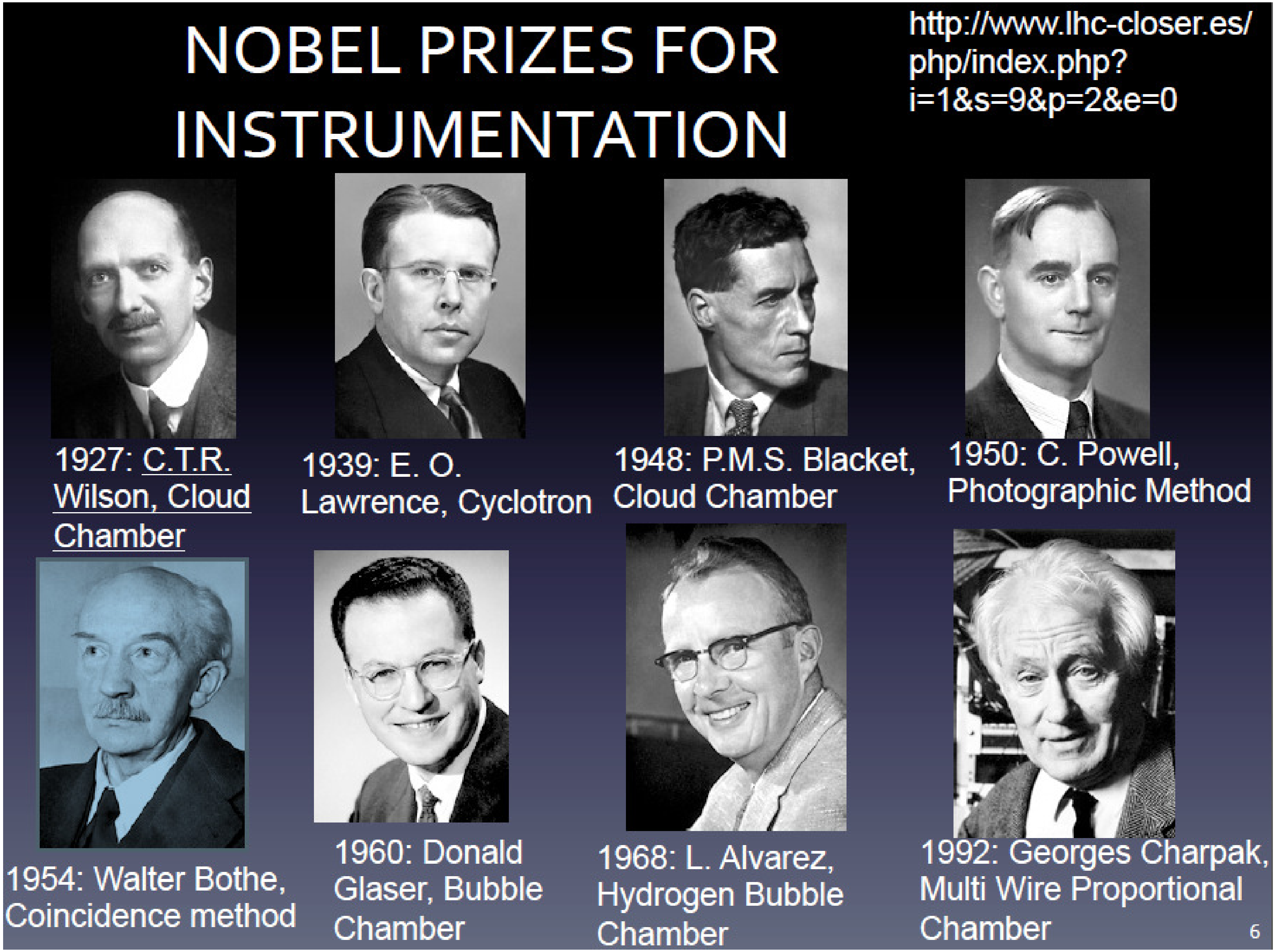
HE-LHC depends on disponility of high field dipoles (*High Energy &Luminosity LHC* , *HELL*)



Some Introductory Detector Concepts

- Detector systems development matters
    - Complexity
- Signal formation
    - **…or why electronics also matters**
- Noise
    - Anlogue vs Digital solutions
- Filtering technologies
    - Bandwidth vs. Smart L1 decision

Detector developement matters



NOBEL PRIZES FOR INSTRUMENTATION

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron

1948: P.M.S. Blackett, Cloud Chamber

1950: C. Powell, Photographic Method

1954: Walter Bothe, Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez, Hydrogen Bubble Chamber

1992: Georges Charpak, Multi Wire Proportional Chamber

Discovery is fueled by new instruments

- “New directions in science are launched by new tools much more often than by new concepts.
  - The effect of a concept-driven revolution is to explain old things in new ways.
  - The effect of a tool-driven revolution is to discover new things that have to be explained”

Freeman Dyson

- Nowadays evolution of HEP Detector Systems is driven by

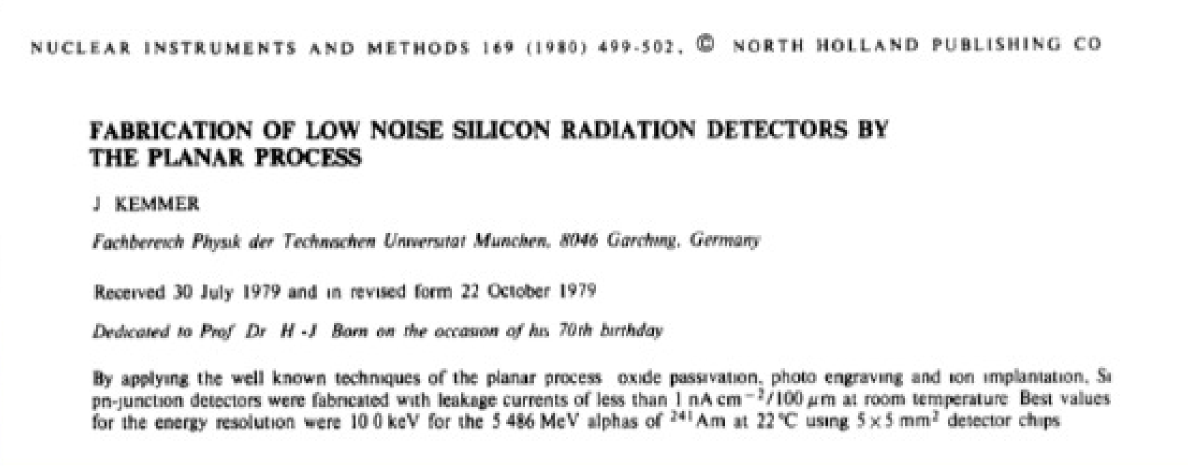
Smart Customization of Technology

  - rather than high-end technology developement, which requires huge resources

Smart technologists + Challenging Scientific Goals

Advent of micropattern Silicon detectors

- J. Kemmer 1979



NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

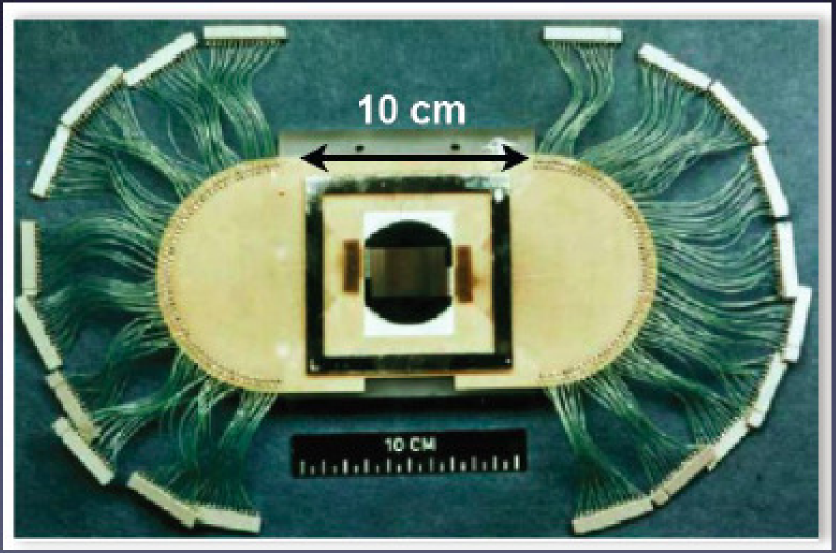
Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

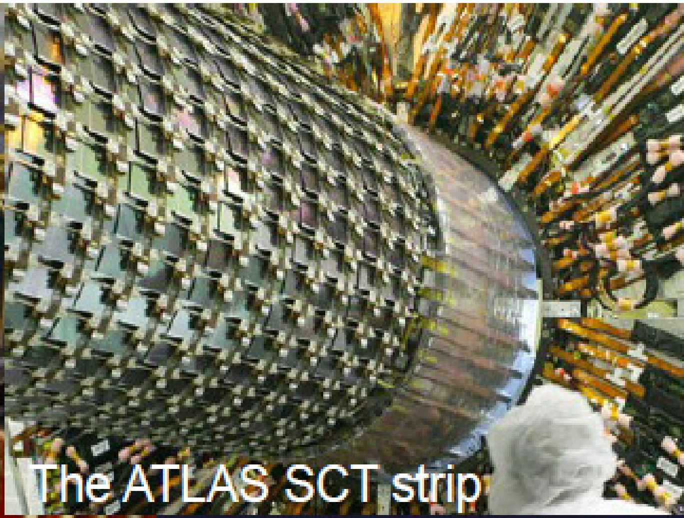
Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

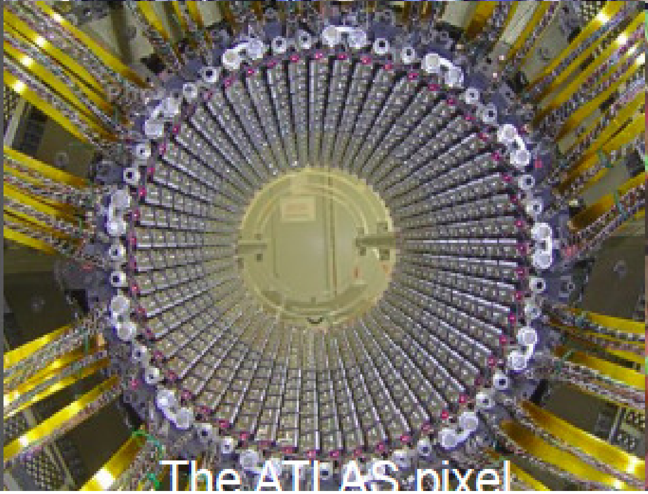
By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 µm at room temperature Best values for the energy resolution were 10.0 keV for the 5.486 MeV alphas of ^{241}Am at 22 °C using 5 × 5 mm^2 detector chips

- NA11 at CERN
  - First use of a position-sensitive silicon detector in HEP experiment
  - Measurement of charm quark lifetimes
  - 1200 diode strips on 24x 36 mm^2
  - 250-500 µm thick bulk material
  - 4.5 µm resolution



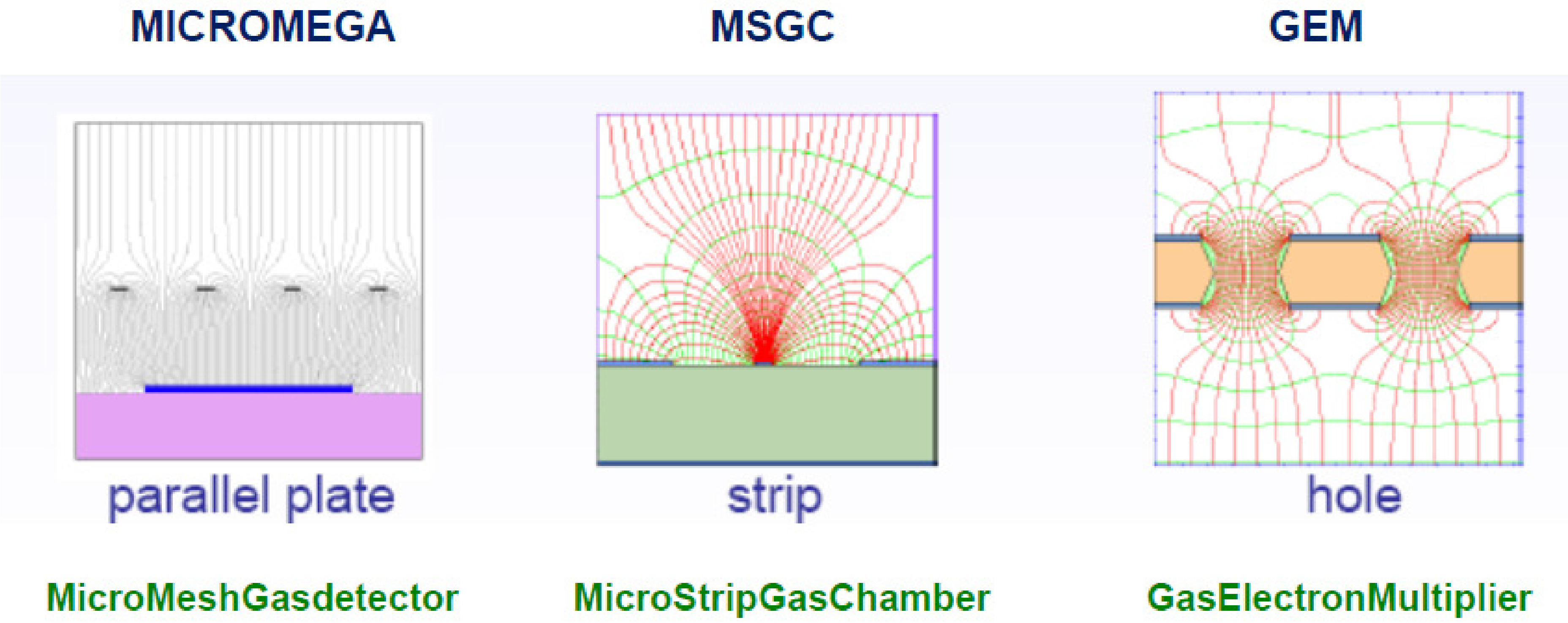
…no-brainer choice in a collider





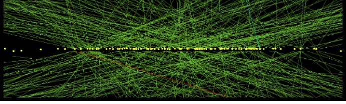
Without these devices the precision tracking possible at collider experiments would not be available, B-physics would be at its infancy

Micro-pattern *gas* detectors



- Hard to compete with silicon in inner regions
- Large electric fields➔ sparks
  - Lots of lessons learnt
- 3-4 decades later being seriously projected for large area upgrades ➔ external layer ➔ muons

Complex Detector Systems- Integration



Muon tracking detector

Maximize field between layers to increase pt resolution →

increase magnetic material between layers →

increase multiple scattering and (even worse), increase radiation probability at high energy

Vertex detectors

Conflicts

Custom integrated circuits essential for vertex detectors in HEP.

Requirements

1. low mass to reduce scattering
2. low noise
3. fast response
4. low power
5. radiation tolerance

reduction in mass ⇒ thin detector

radiation tolerance ⇒ thin detector

thin detector ⇒ less signal ⇒ lower noise required

lower noise ⇒ increased power

fast response ⇒ increased power

increased power ⇒ more mass in cabling + cooling

immunity to external pickup ⇒ shielding ⇒ mass

\+ contain costs

How to deal with these conflicting requirements?

Conflicts and compromises in each subdetector and then at the global integration…

Huge choice phase space

Design criteria depend on application

1. Energy resolution
2. Rate capability
3. Timing information
4. Position sensing

Large-scale systems impose compromises

1. Power consumption
2. Scalability
3. Straightforward setup + monitoring
4. Cost

Technology choices

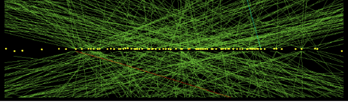
1. Discrete components – low design cost
   fix "on the fly"
2. Full-custom ICs – high density, low power, but
   better get it right!

Successful systems rely on many details that go well beyond "headline specs"!

How to built the best detector?

The best detector is not always the one with the best components

“The team that make the most of its stronger individualities will win”



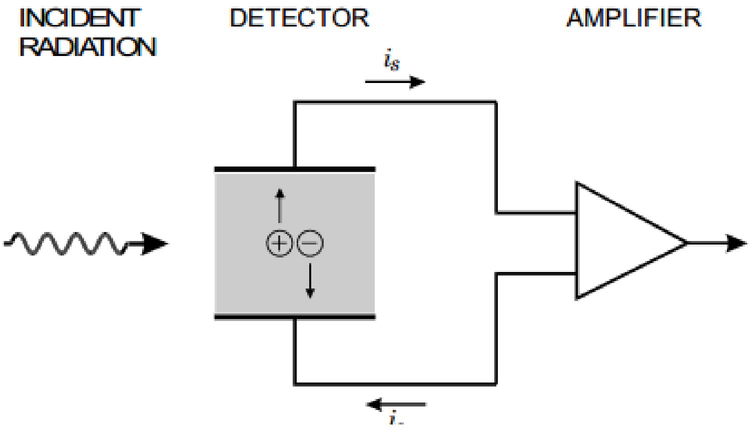
Let’s go back ~1/10E8 in complexity

Two common schemes

Examples:

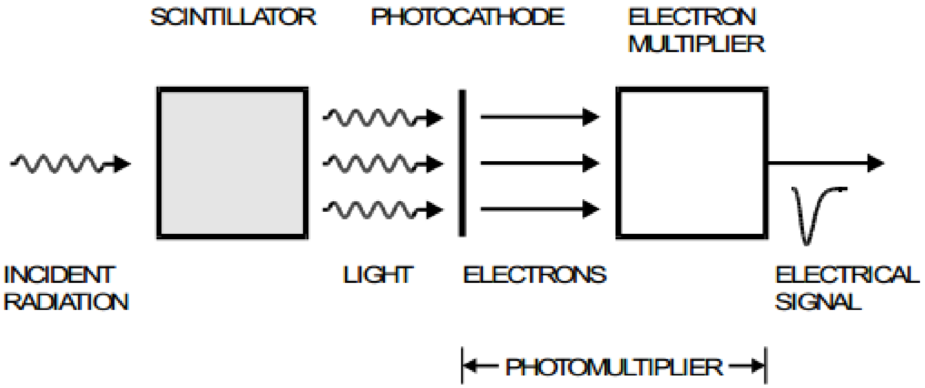
1. Direct Detection

a) ionization chamber
(>eV photons, charged particles)



Detector Functions

Processes in Scintillator – Photomultiplier



number of photons
$\propto$ absorbed energy

number of photoelectrons
$\propto$ absorbed energy

charge in pulse
$\propto$ abs. energy

Signal Fluctuations in a Scintillation Detector

Example: Scintillation Detector - a typical NaI(Tl) system (from Derenzo)

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = 2\% \text{ rms} = 5\% \text{ FWHM}$$

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.

511 keV gamma ray

⇓

25000 photons in scintillator

⇓

15000 photons at photocathode

⇓

3000 photoelectrons at first dynode

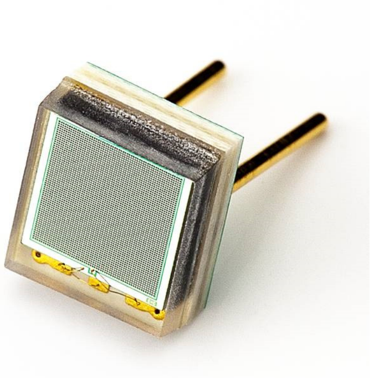
⇓

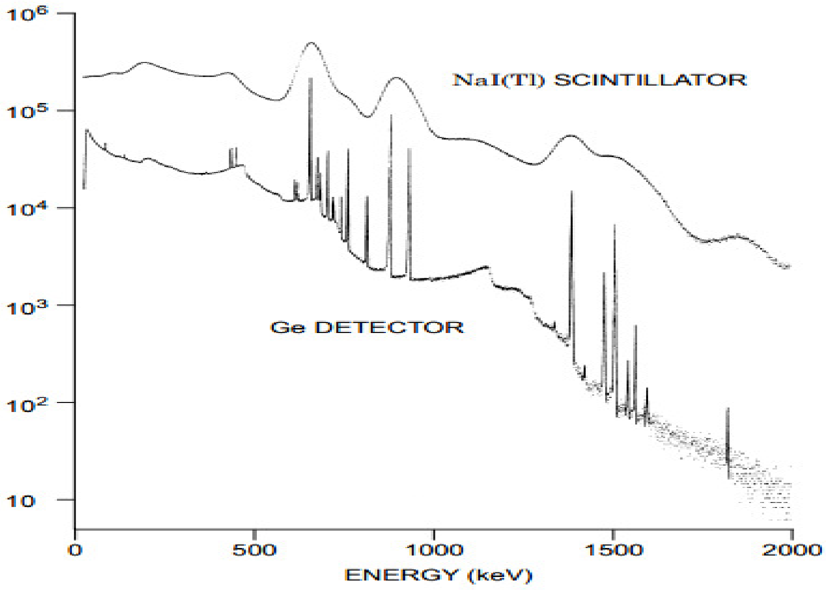
$3 \cdot 10^9$ electrons at anode

2 mA peak current

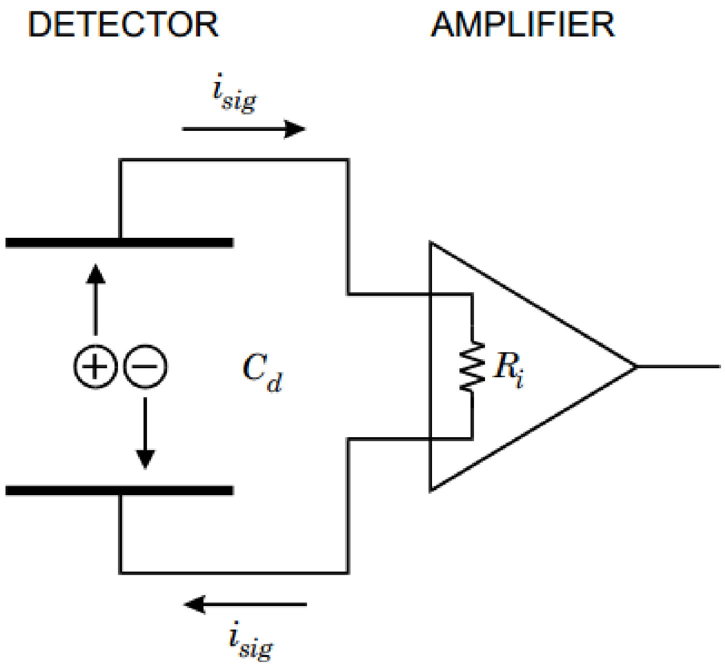
The holy grail of photodetectors is increasing QE

➔Si PMs





Time Dependence of the Signal Current



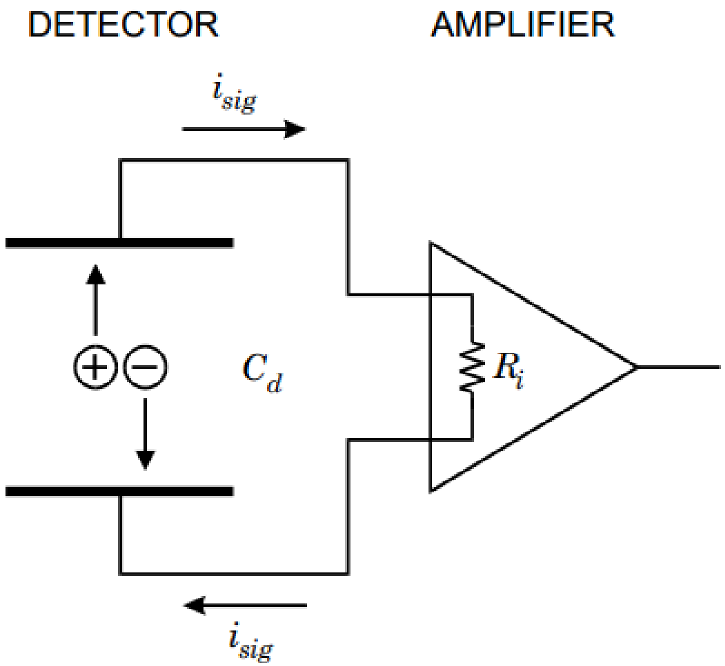
When does the signal current begin?

a) when the charge reaches the electrode?

or

b) when the charge begins to move?

Time Dependence of the Signal Current



When does the signal current begin?

a) when the charge reaches the electrode?

or

b) when the charge begins to move?

Although the first answer is quite popular (encouraged by the phrase “charge collection”), the second is correct.

When a charge pair is created, both the positive and negative charges couple to the electrodes and induce mirror charges of equal magnitude.

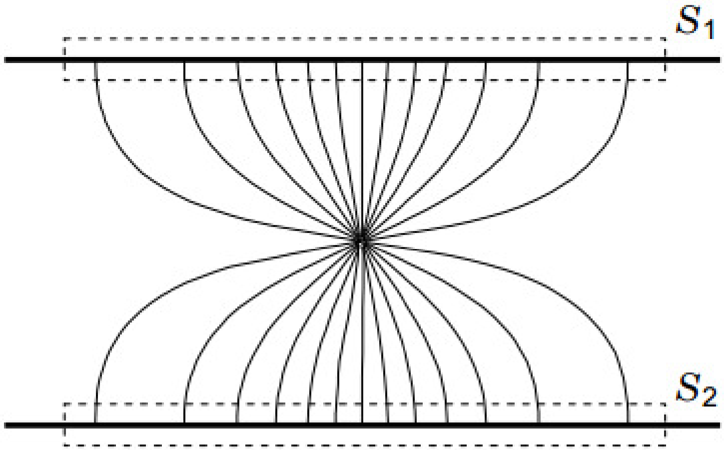
The following discussion applies to ALL types of structures that register the effect of charges moving in an ensemble of electrodes, i.e. not just semiconductor or gas-filled ionization chambers, but also resistors, capacitors, photoconductors, vacuum tubes, etc.

A pad detector

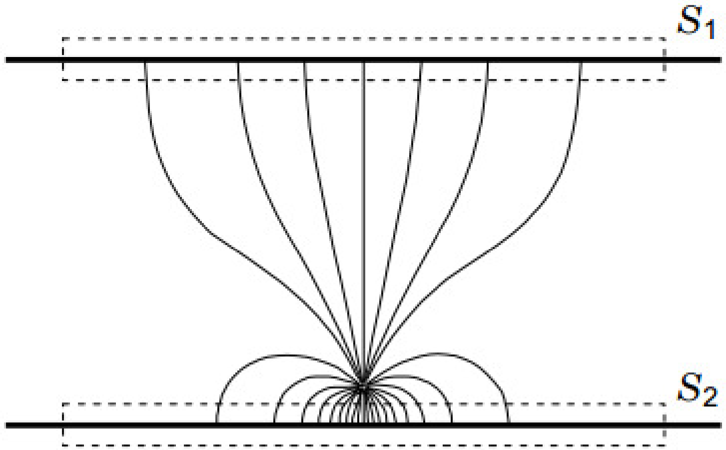
Induced Charge

Consider a charge q in a parallel plate capacitor:

When the charge is midway between the two plates, the charge induced on one plate is determined by applying Gauss' law. The same number of field lines intersect both S_1 and S_2, so equal charge is induced on each plate (= q / 2).



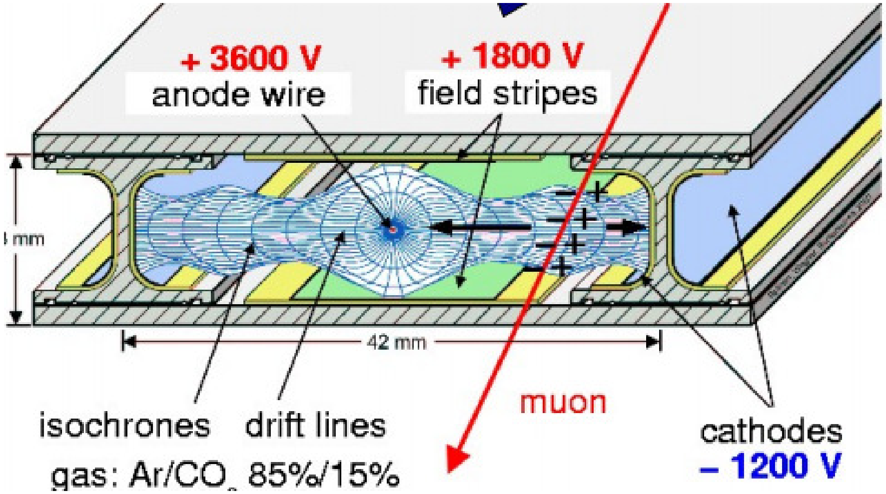
When the charge is close to one plate, most of the field lines terminate on that plate and the induced charge is much greater.



As a charge traverses the space between the two plates the induced charge changes continuously, so current flows in the external circuit as soon as the charges begin to move.
Mathematically this can be analyzed conveniently by applying Ramo's theorem.

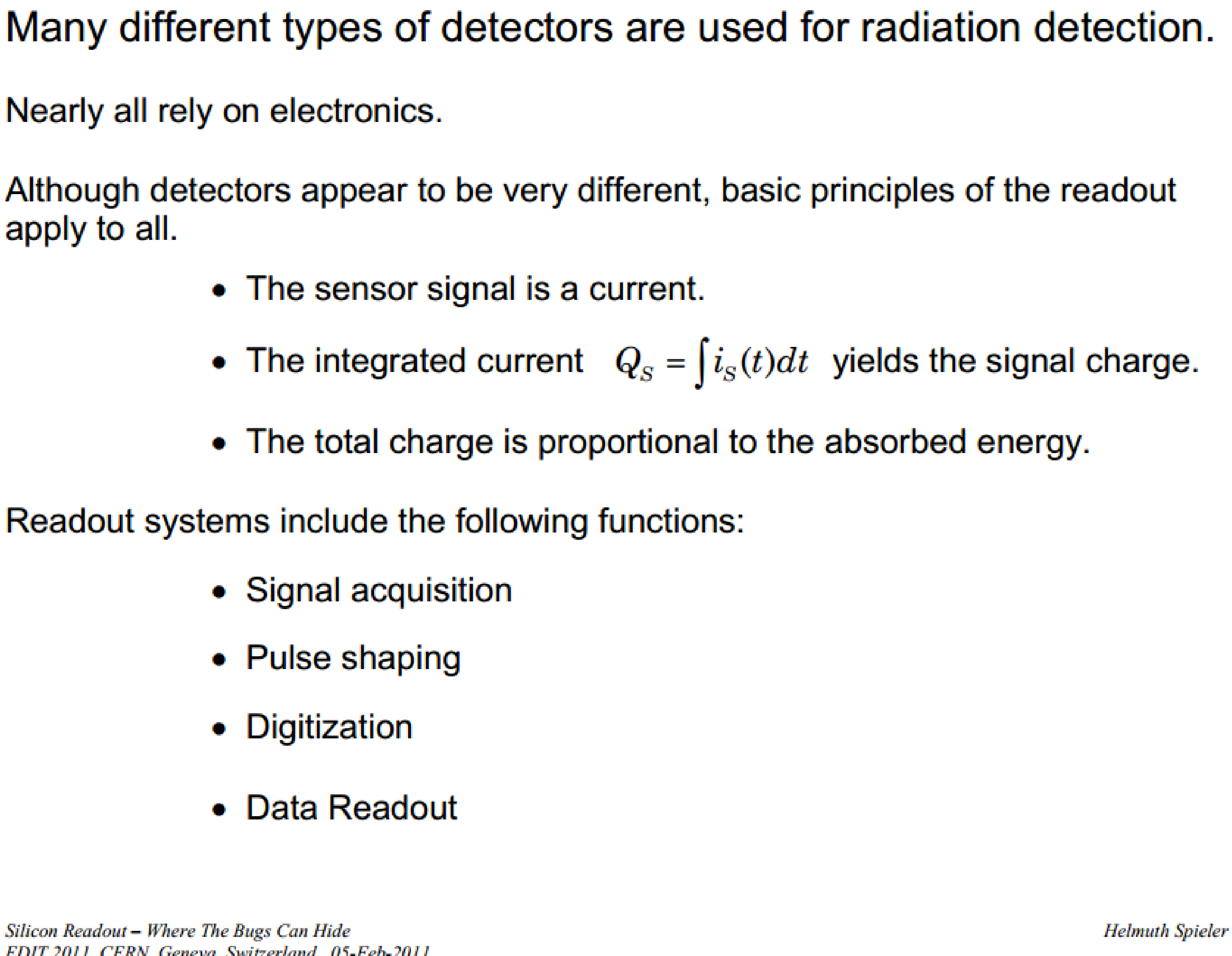
A drift tube

- Ionization charge drifts at constant speed
  - Induced signal while drifting bellow threshold
- Smart field distribution such that avalanche starts only close to the collecting wire
  - Signal goes above threshold
  - This allows to convert avalanche start-time to a precise coordinate
  - Drifting time (~20 bx) acts in practice as an electronics pipeline



Signal formation

[Interaction of radiation with matter → textbooks]



Many different types of detectors are used for radiation detection.

Nearly all rely on electronics.

Although detectors appear to be very different, basic principles of the readout apply to all.

- The sensor signal is a current.
- The integrated current $Q_S = \int i_S(t)dt$ yields the signal charge.
- The total charge is proportional to the absorbed energy.

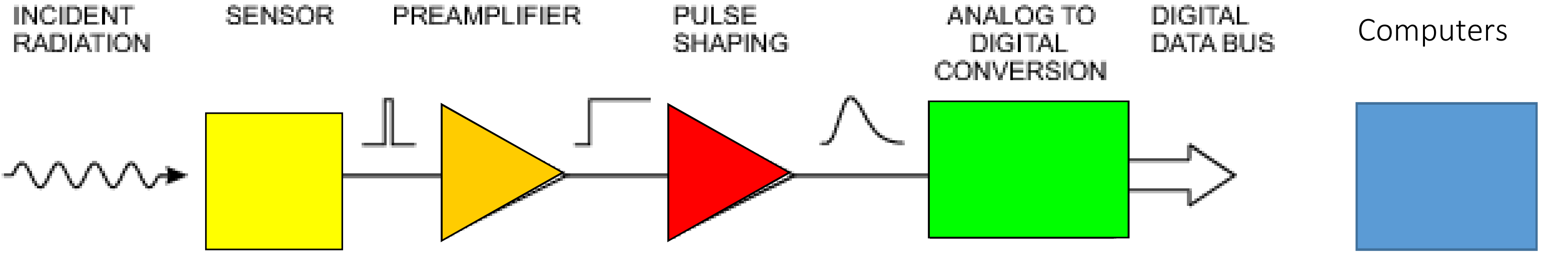
Readout systems include the following functions:

- Signal acquisition
- Pulse shaping
- Digitization
- Data Readout

Silicon Readout – Where The Bugs Can Hide
EDIT 2011, CERN, Geneva, Switzerland, 05-Feb-2011
Helmuth Spieler

Front End Electronics Art

Amplification, shaping, digitization



<u>Analogic part:</u>

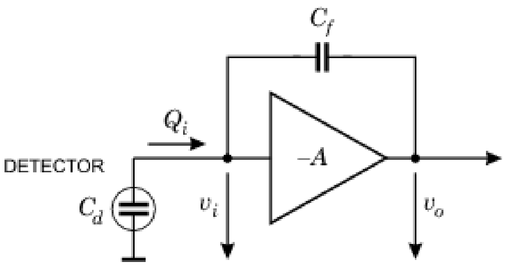
- Noise,
- Lineality,
- Speed,
- Cross talk,
- Keep the relevant part of the signal

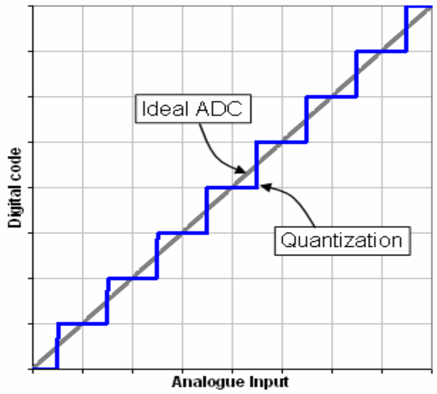
<u>Digital Convertion:</u>

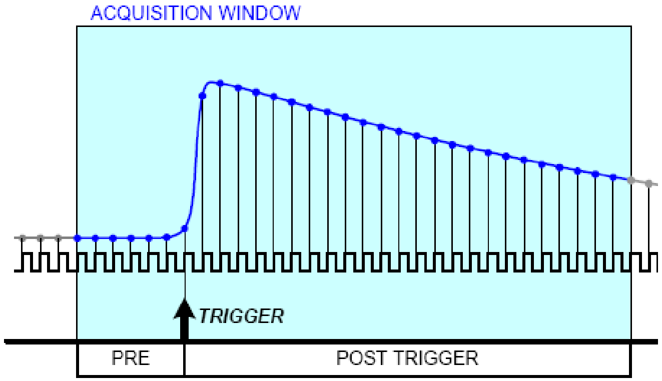
- Resolution,
- Dynamic range
- Lineality
- Dead time, etc

ADC, TDC, QDC, CFD, Scaler, peak sensing ADC....

Waveform digitizer







Noise limits the achievable precision

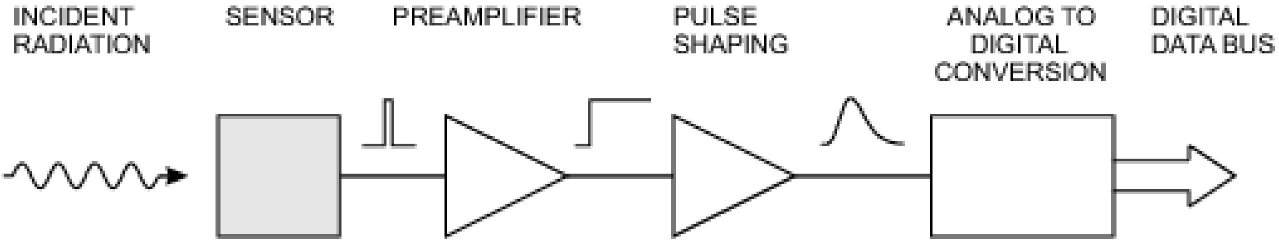
Considering noise from an holistic point of view you can reverse the sentence:

  - What limits your precision *is* noise
  - (well, not really)

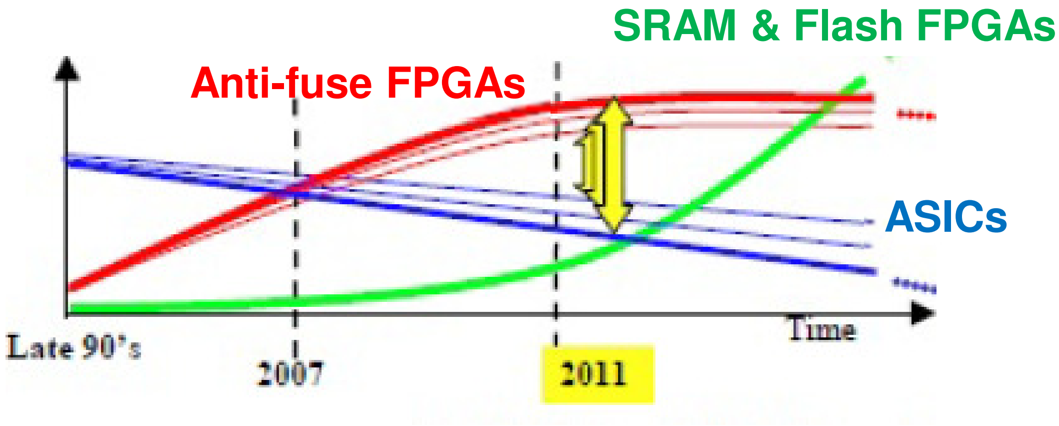
- Analogic *noise*
  - Thermal noise
  - Shot noise
  - Pick-up, common mode noise, cross-talk,..
- Digital *noise*
  - Bit errors, link locking, lack of linearity,…
- Background *noise* leaves signal in your detector
  - From out of time particles, activated materials, natural radioactivity, cosmics,…

“Time quantization”

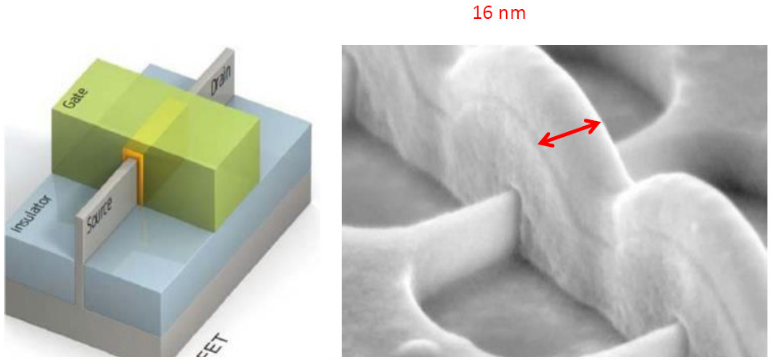
- Colliders experiments have it “easy”
  - The accelerator gives a “clock” signal which defines when events are expected to happened, ie. when opposed beams collide in the interaction regions
    - LHC uses 40 MHz clock, 25 ns bunch crossing spacing
  - Astroparticle “observing” experiments typically need fast sampling (GHz) to compensate for this disadvantage
- The signal left in the detectors from collisions particles can be efficiently integrated, amplified, registered, be digitized, read-out and eventually saved to disk



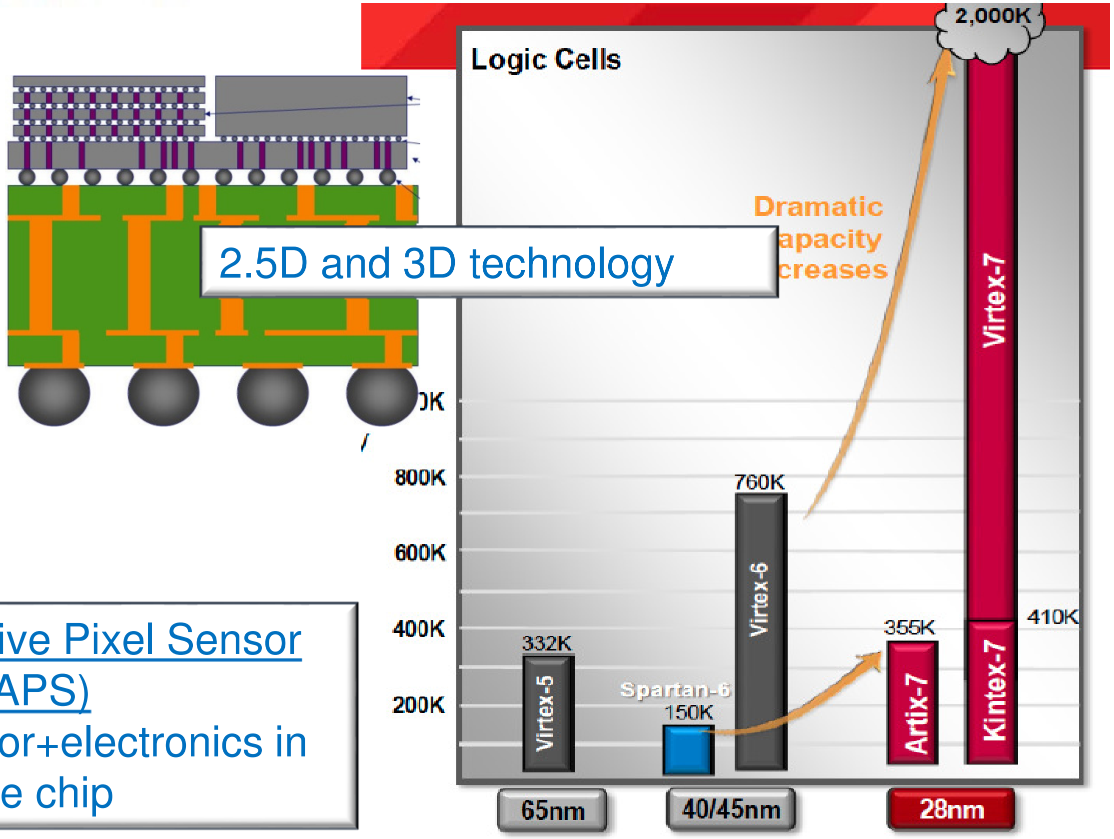
Integrated circuits technology trends



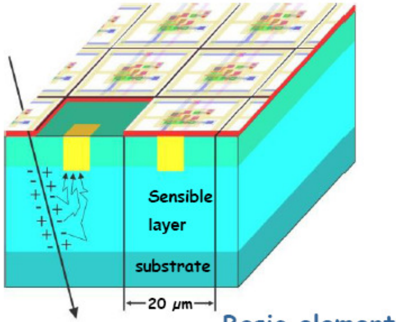
State of the art 2013: 16 nm FINFET



- ↑ Integration
- ↑ Complexity
- ↑ Speed
- ↓ Power consumption
- ↑ Less storage capacity
- ↑ Reliabiltiy



2.5D and 3D technology



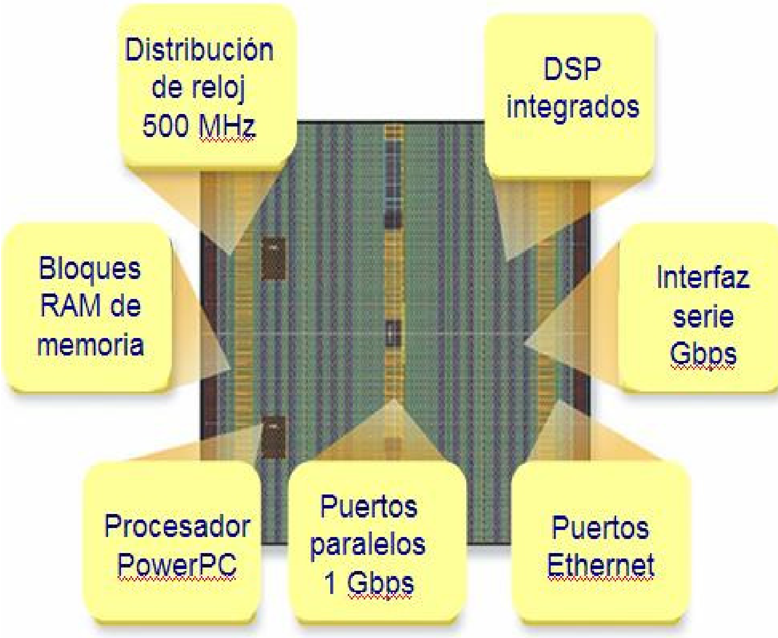
Monolithic Active Pixel Sensor (MAPS)

Combine sensor+electronics in same chip

Advance Digital Devices

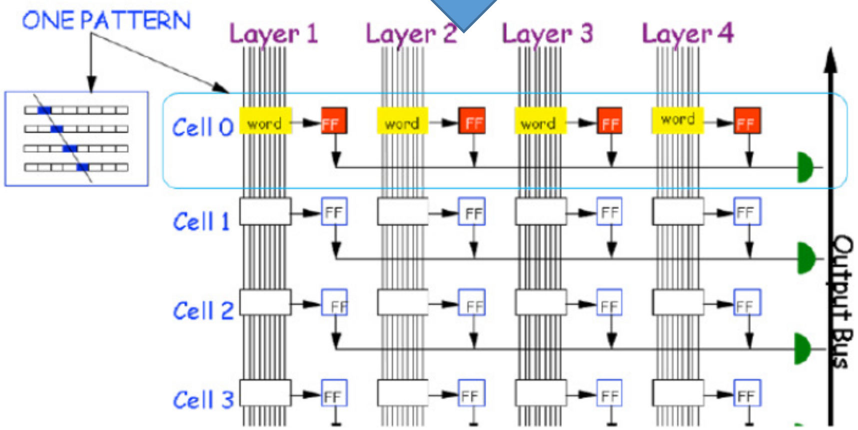
Field Programable Gate Arrays (FPGAs.)

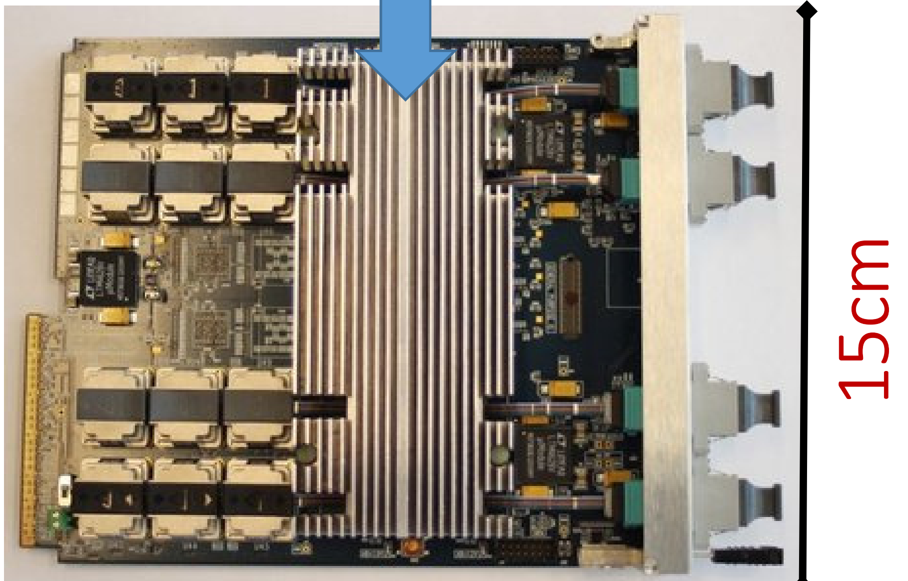
- Flexibiity
- High performance
- Evolve on an industry Moore-law
- Off-the-shelf



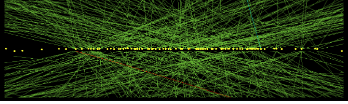
- ASICs (Application-specific IC) keep a niche in the FrontEnd
  - Better get it right
- Associative memories to identify patterns

(CDF/Atlas)





Break?

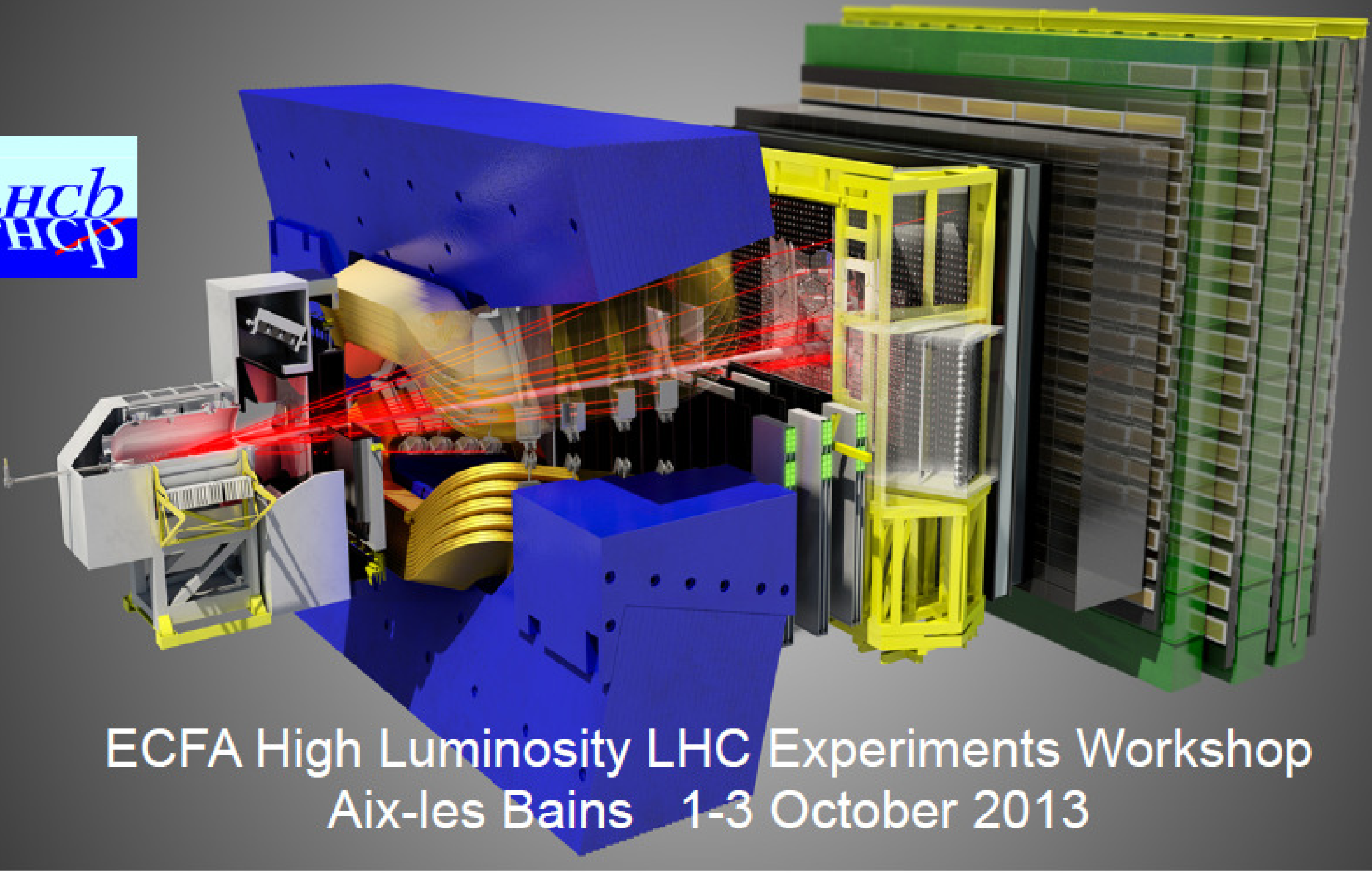


Filtering

- … but most of the events are uninteresting
  - (and so far we did not have money/technology to have it all written to disk)
- So typically, the **trigger** electronics system provides an online decision of which events to keep based on a subsample of the information available
  - Used to be simple analogic values (to avoid digitization)
  - Today we trigger with complex digital operations thanks to FPGAs
    - Used on relatively fast detectors: calorimeters and muons
  - Triggering on tracking detectors is on the works
- Alternatively, todays commercial network technology starts to allow to read it ALL and analyzed it in pc farms

➔Trigger-less system

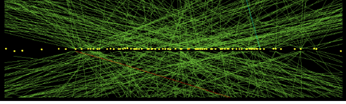
The LHCb Upgrade Program



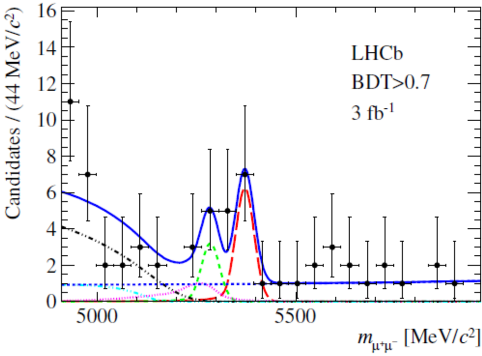
ECFA High Luminosity LHC Experiments Workshop
Aix-les Bains   1-3 October 2013

Andreas Schopper on behalf of

LHCb upgrade motivation



- LHCb had done beautiful measurements in the B sector
  - No hint of new physics, so far
  - Need to increase precision of the measurement



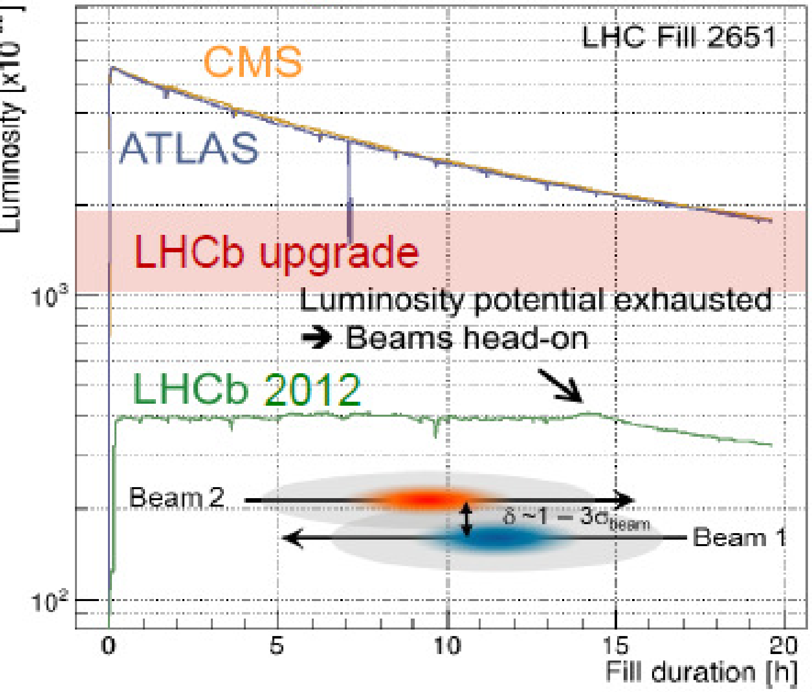
PRL 111 (2013) 101805

$$BR(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$$

- LHCb is “different”
  - LHCb is an spectrometer (low acceptance) using the high b cross section (and boost) in the forward region.
  - Energy increase does not help for precision
  - Luminosity increase to be treated with care,
    - LHCb already operating at lower luminosity (lumi leveling) because of bandwidth limitations
    - LHCb plans to increase bandwidth go trigger-less
      - (actually, L1 trigger-less only)

How to increase LHCb statistics significantly

2012 running conditions

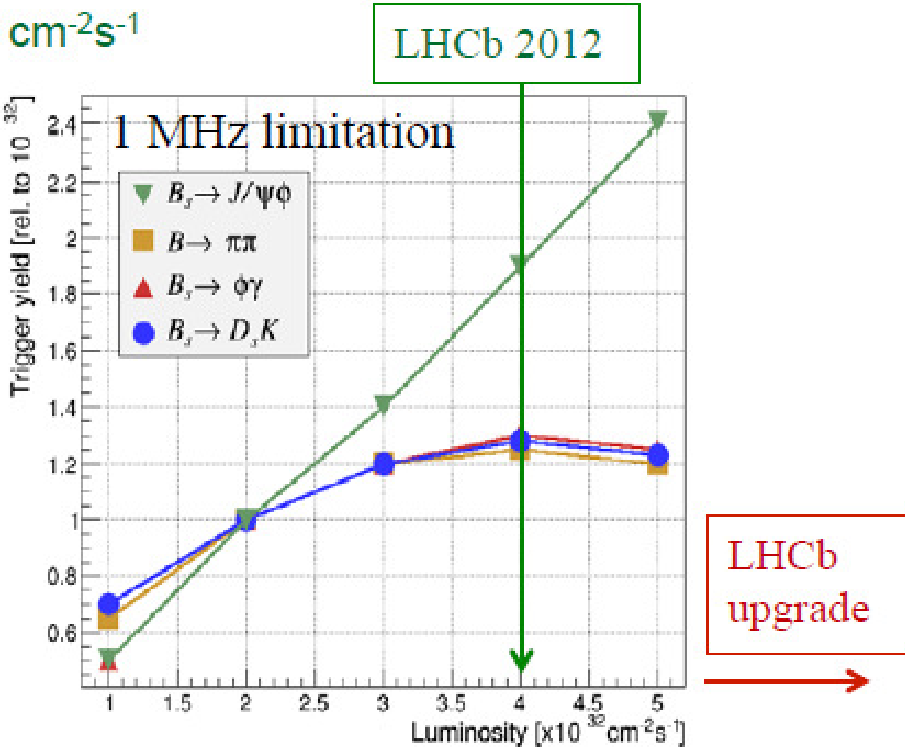


← $1\text{-}2 \cdot 10^{33}$ cm^{-2}s^{-1}

← ~ $4 \cdot 10^{32}$ cm^{-2}s^{-1}

LHCb up to LS2

- ➢ running at levelled luminosity of ~ $4 \cdot 10^{32}$ cm^{-2}s^{-1}, pile-up~1
- ➢ first level hardware trigger running at ~1 MHz
- ➢ record ~3-5 kHz



LHCb upgrade

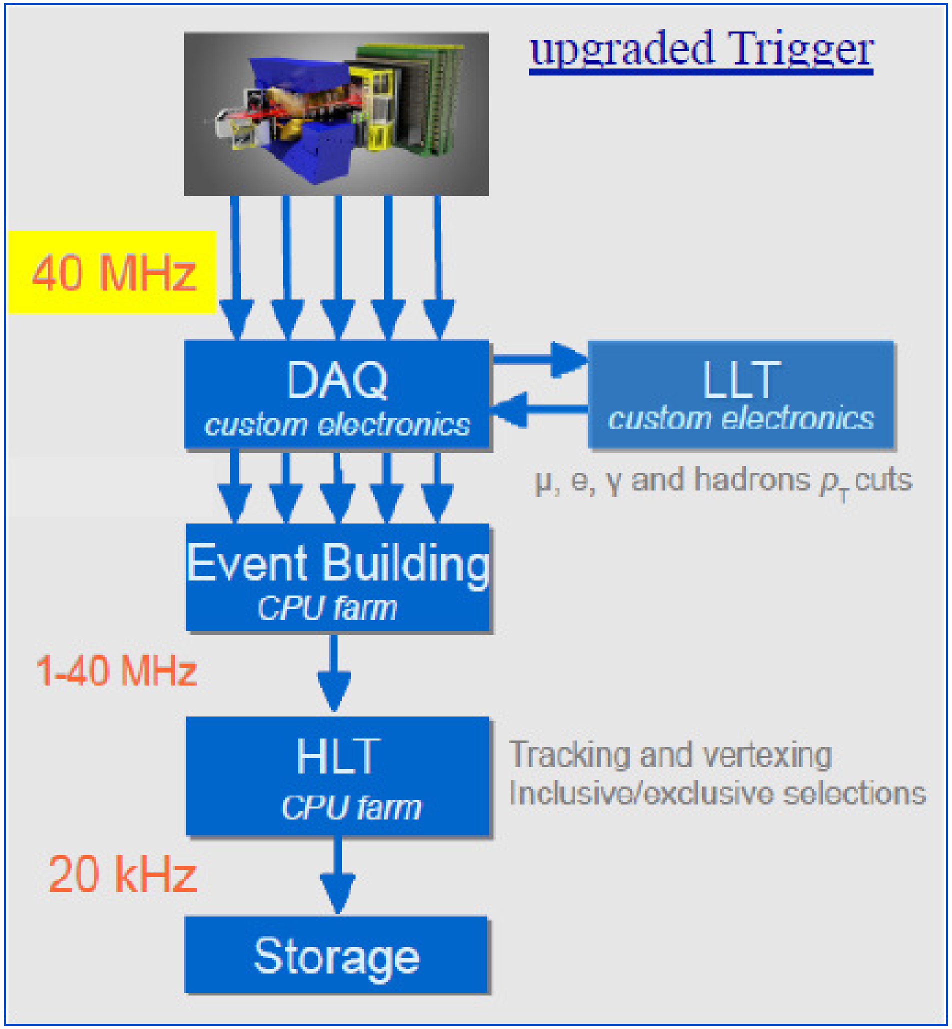
- ➢ increase luminosity to a levelled $1\text{-}2 \cdot 10^{33}$ cm^{-2}s^{-1}, pile-up~5
- ➢ run fully flexible & efficient software trigger up to 40 MHz
- ➢ record ~20 kHz

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

40 MHz

DAQ
custom electronics

LLT
custom electronics

μ, e, γ and hadrons p_T cuts

Event Building
CPU farm

1-40 MHz

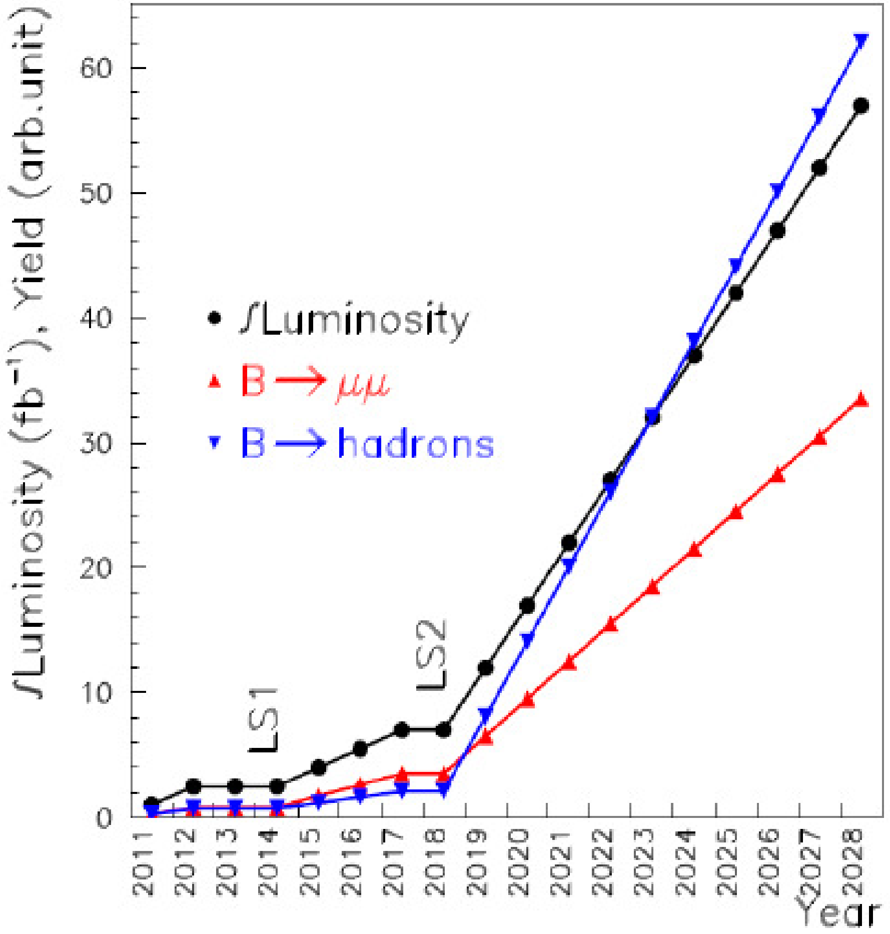
HLT
CPU farm

Tracking and vertexing
Inclusive/exclusive selections

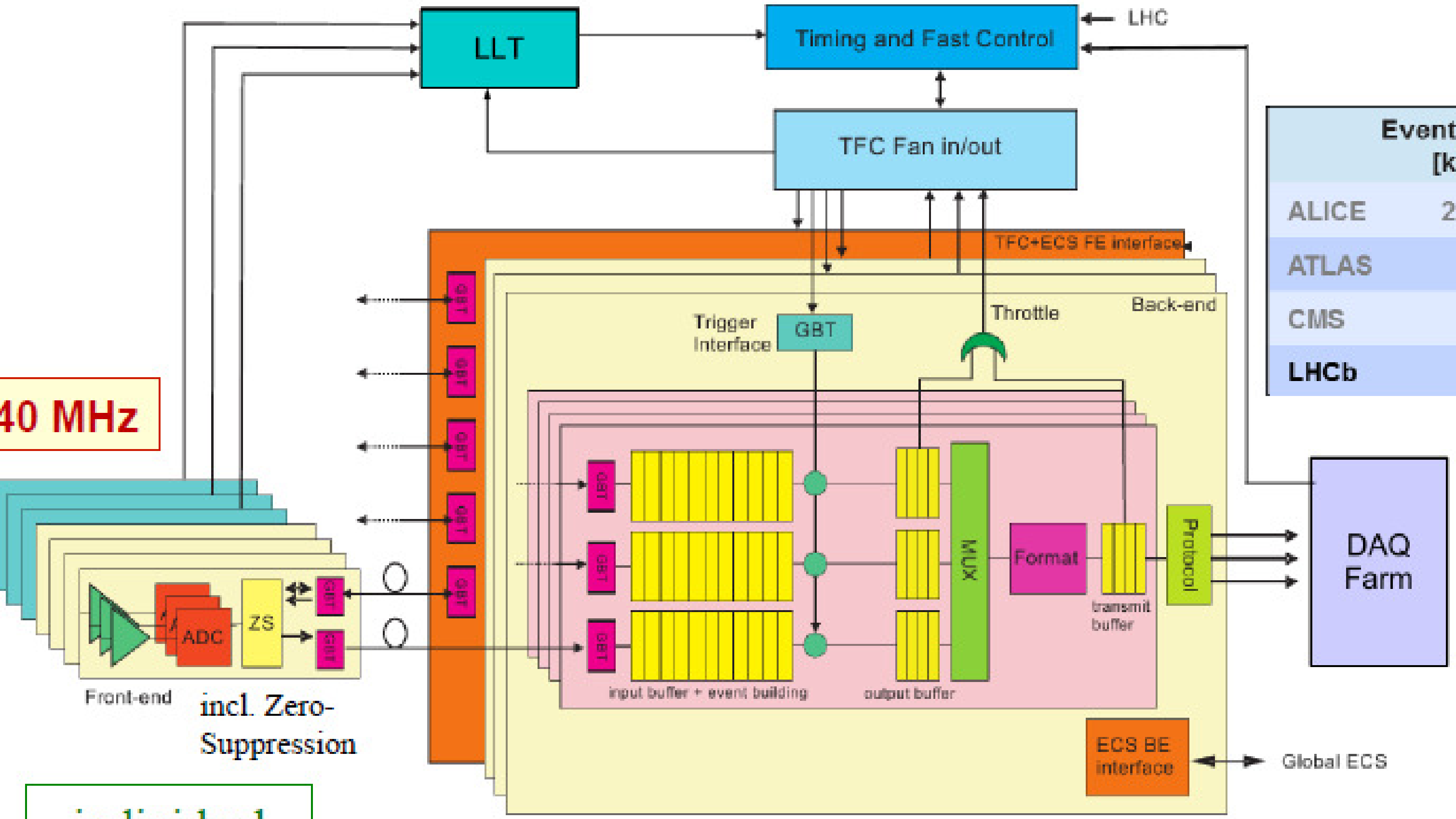
20 kHz

Storage

effect on luminosity and signal yields



40 MHz architecture overview



40 MHz

incl. Zero-Suppression

20 KHz

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**

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

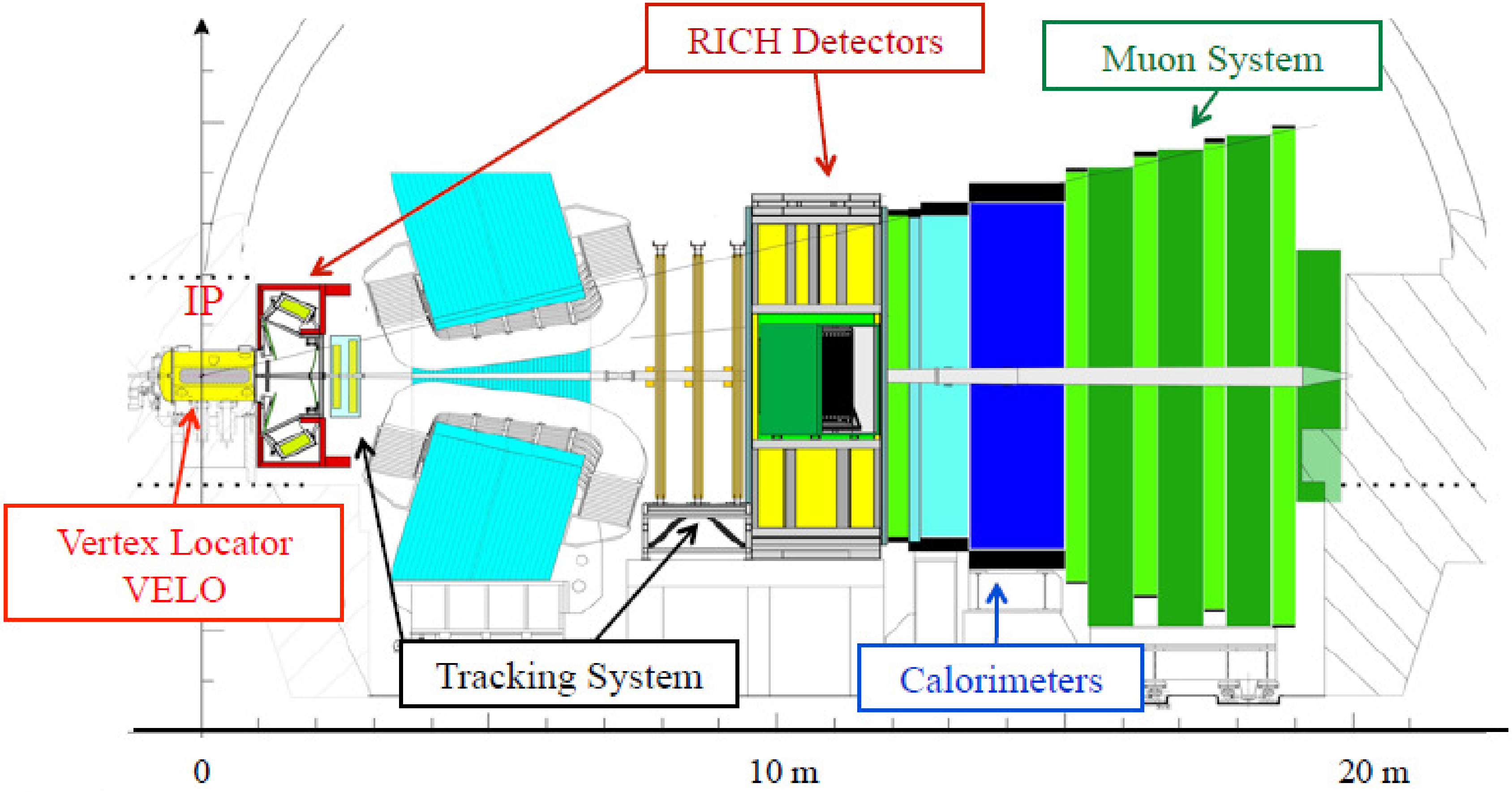
underground

~300m

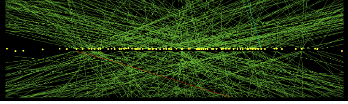
on surface

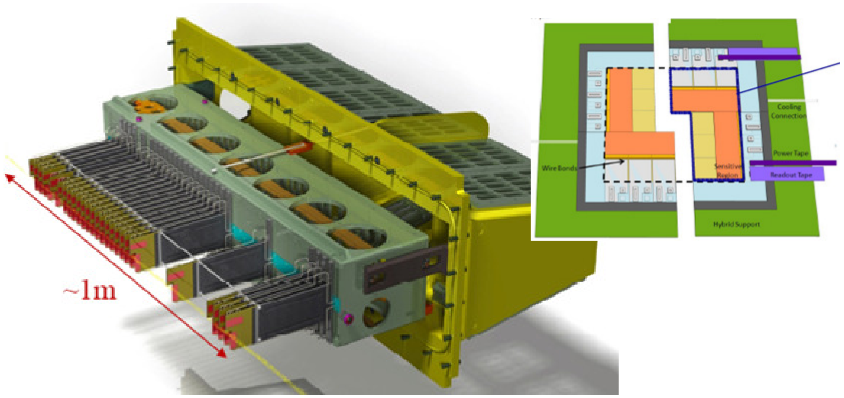
Detector upgrade to 40 MHz readout

- ✓ 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



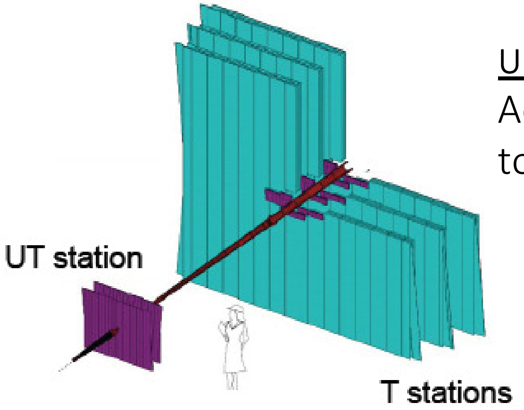
LHCb detectors Upgrade



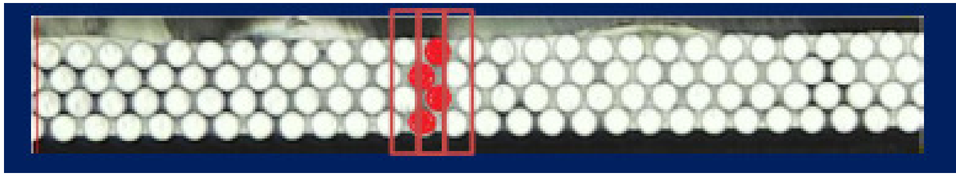


New VELO

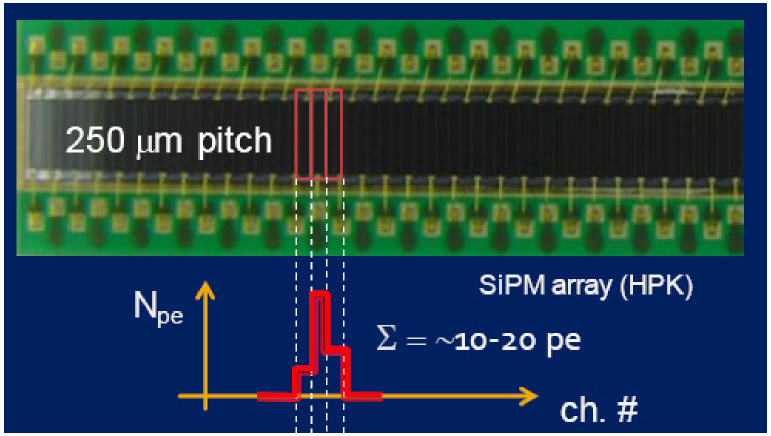
- Increased radiation tolerance
- Higher granularity: 55x55 μm^2 pixel sensors (based on Timepix)
- Novel microchannel CO$_2$ cooling
- Data driven readout at 40 MHz -> >2Tbits/s from the whole VELO



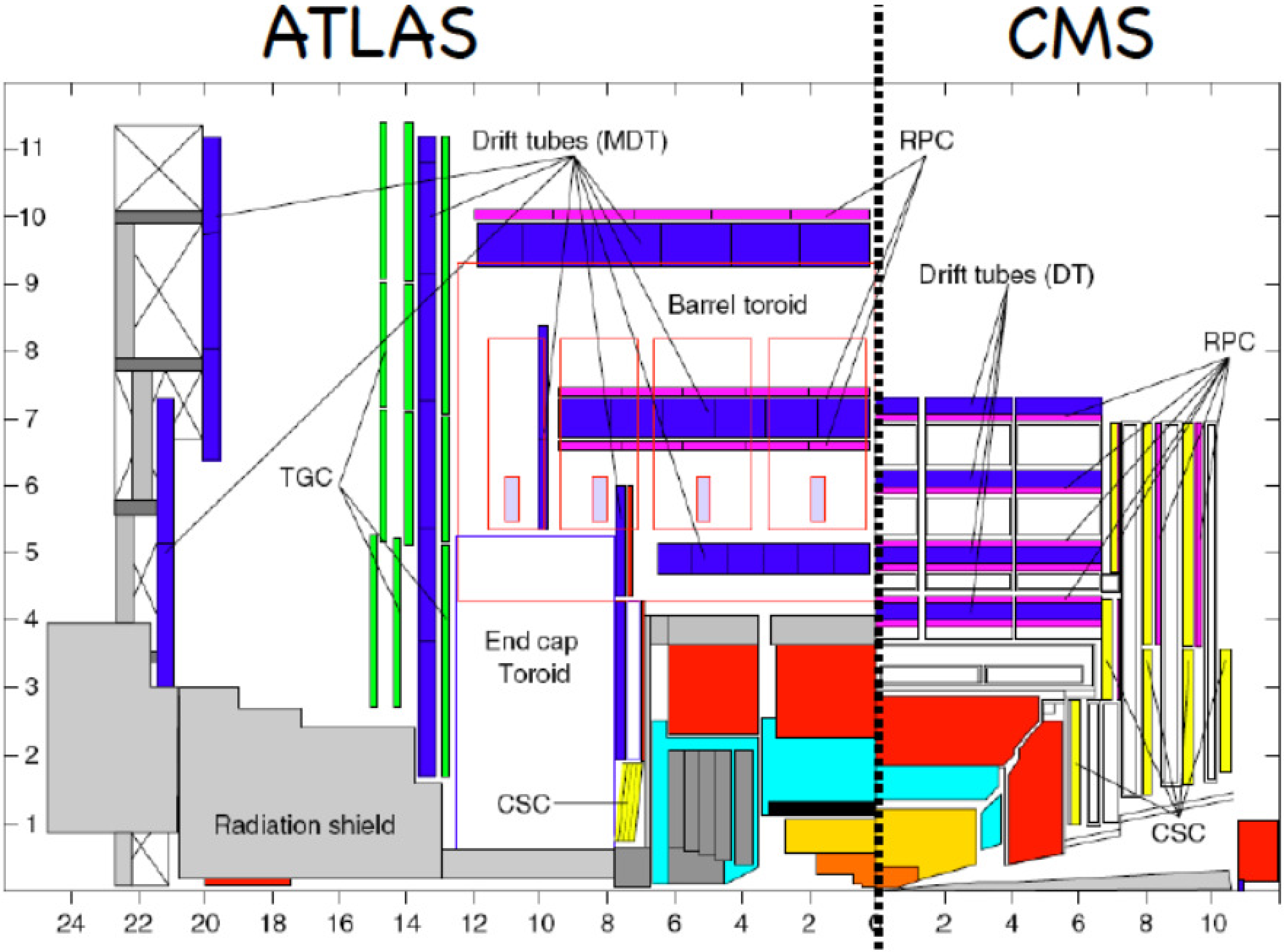
Upstream Tracker
Adapt segmentation to occupancies



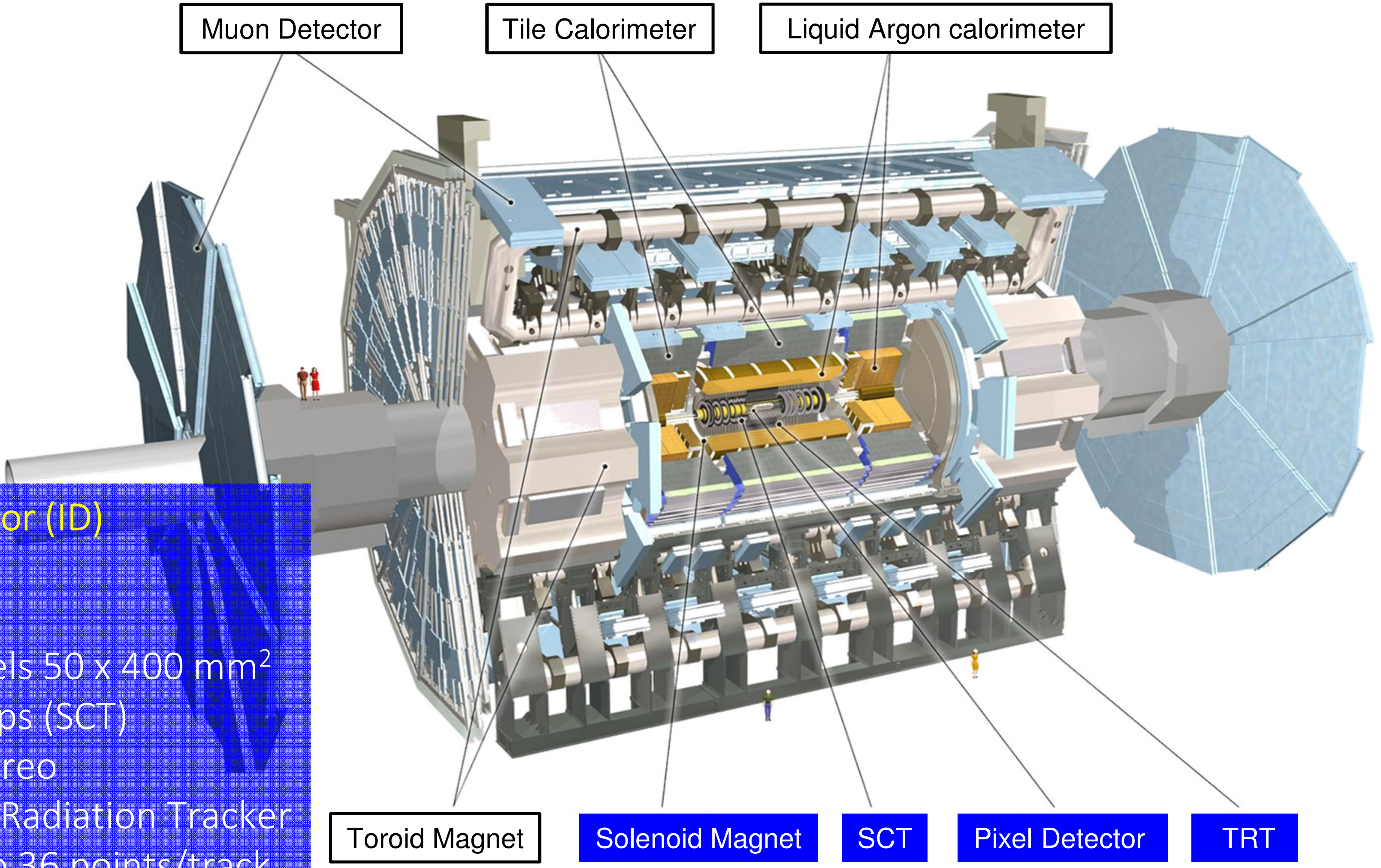
- 250μm diameter scintillating fibers 2.5m long
- SiPM readout (must be cooled to -40ºC for noise reduction)
- Fiber inner ends will experience up to 22 kGy
- High hit detection efficiency and fast pattern recognition



Atlas & CMS : Many (two) ways to skin a cat



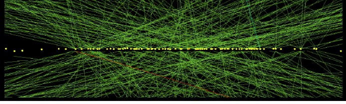
The ATLAS Detector

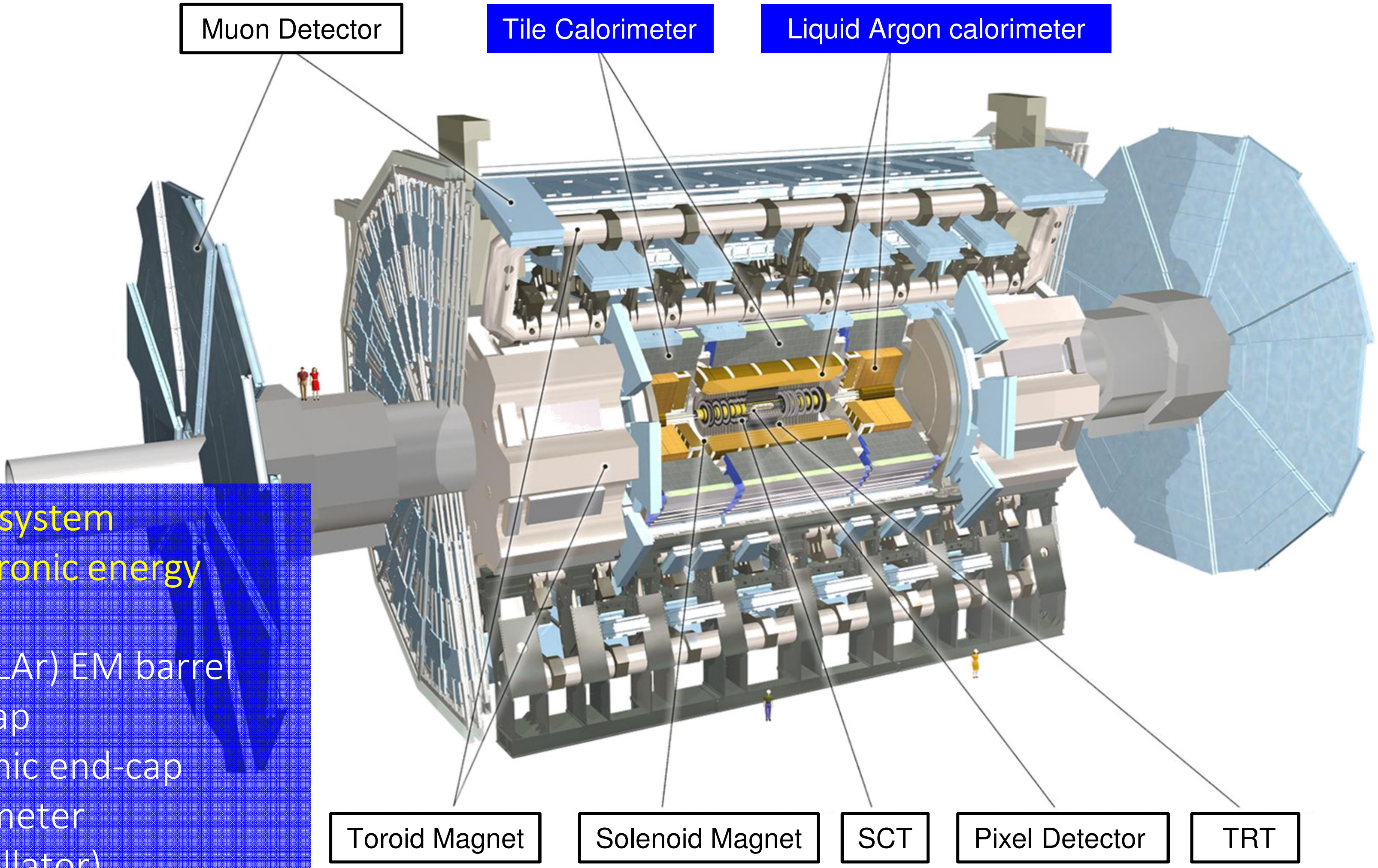


Inner Detector (ID)
Tracking

- Silicon Pixels 50 x 400 mm^2
- Silicon Strips (SCT)
  80 mm stereo
- Transition Radiation Tracker (TRT) up to 36 points/track
- 2T Solenoid Magnet

The ATLAS Detector

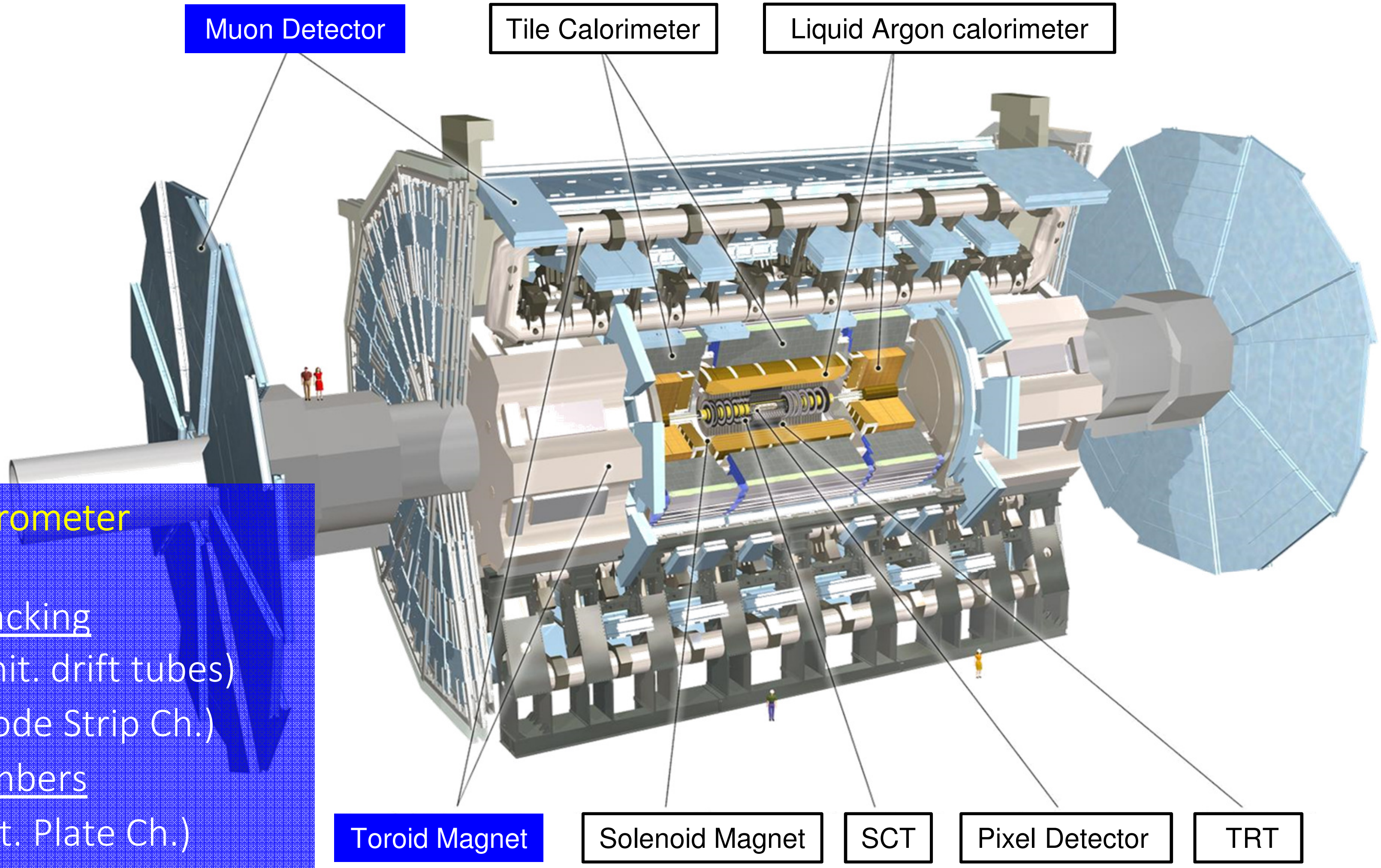




Calorimeter system
EM and Hadronic energy

- Liquid Ar (LAr) EM barrel and end-cap
- LAr Hadronic end-cap
- Tile calorimeter (Fe – scintillator) hadronic barrel

The ATLAS Detector



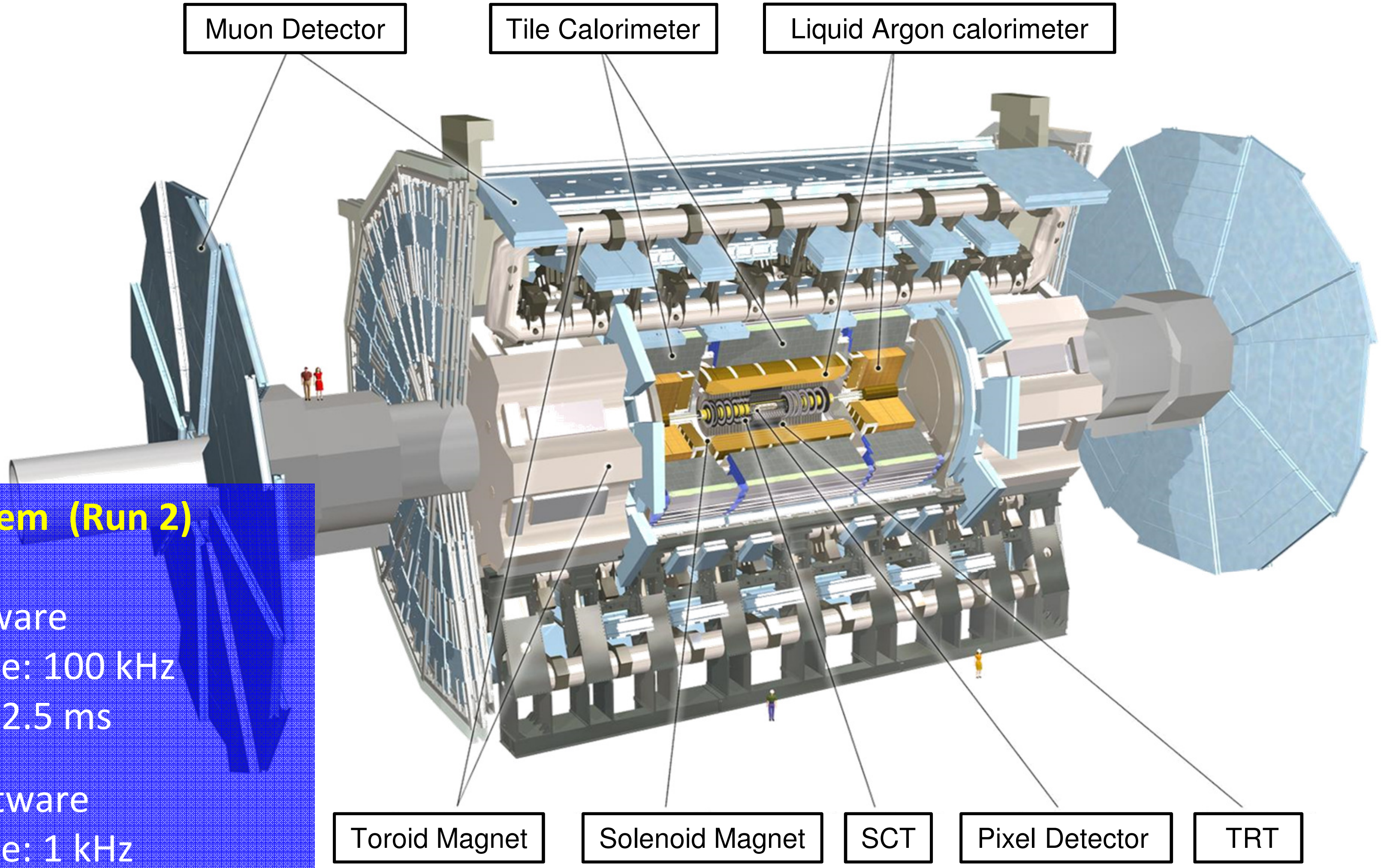
Muon spectrometer
m tracking

Precision tracking
- MDT (Monit. drift tubes)
- CSC (Cathode Strip Ch.)

Trigger chambers
- RPC (Resist. Plate Ch.)
- TGC (Thin Gap Ch.)

- Toroid Magnet

The ATLAS Detector



Trigger system (Run 2)

- L1 – hardware
  output rate: 100 kHz
  latency: < 2.5 ms
- HLT – software
  output rate: 1 kHz
  proc. time: ~ 550 ms

CMS state summer 2013

Total weight 14000 t

Overall diameter 15 m

Overall length 28.7 m

ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

MUON ENDCAPS

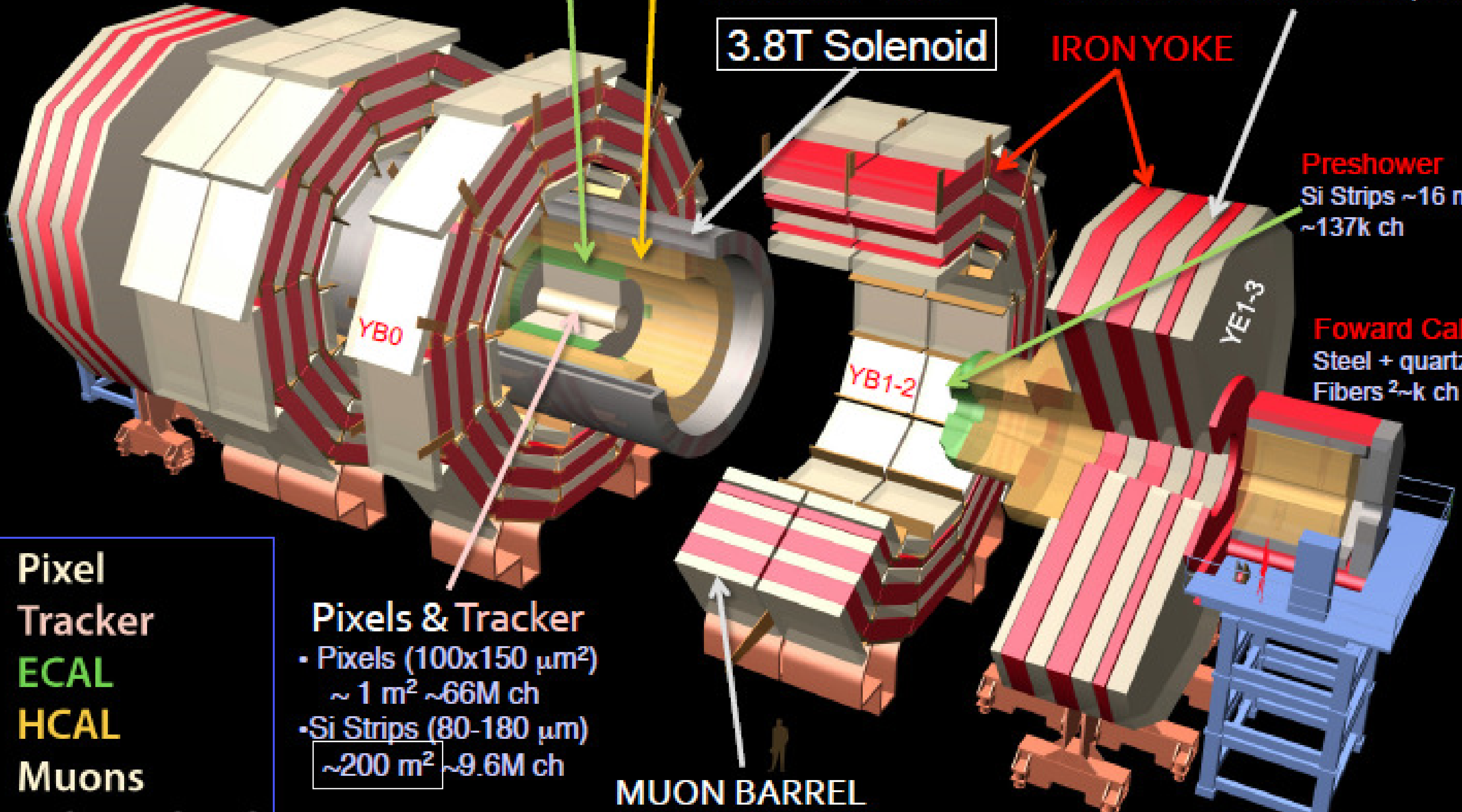
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE

Preshower
Si Strips ~16 m²
~137k ch

Foward Cal
Steel + quartz
Fibers ²~k ch



Pixels & Tracker

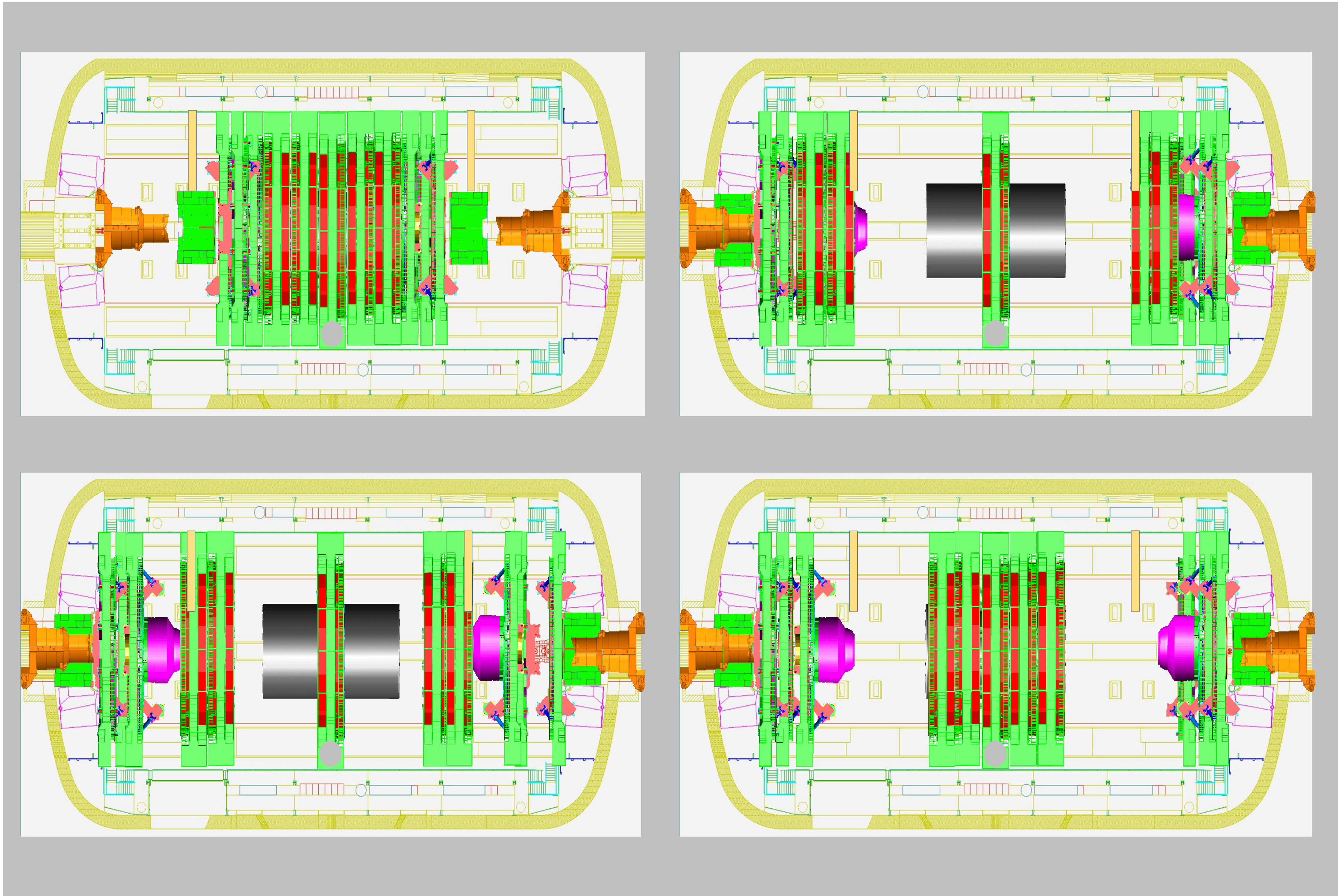
- Pixels (100x150 μm²)
  ~ 1 m² ~66M ch
- Si Strips (80-180 μm)
  ~200 m² ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Being compact helps to be (relatively) nimble.

LS1: A ballet with 1000 ton elephants



When compared to a previous generation :

1. All Si tracker
2. Calorimeters inside large 3.8 T, 3m radius solenoid
3. Muon detectors actually a rather precise gas tracker system covering a huge volume
4. 100 KHz readout rate (~1 MB event size)
5. ...last but not least, photogenic

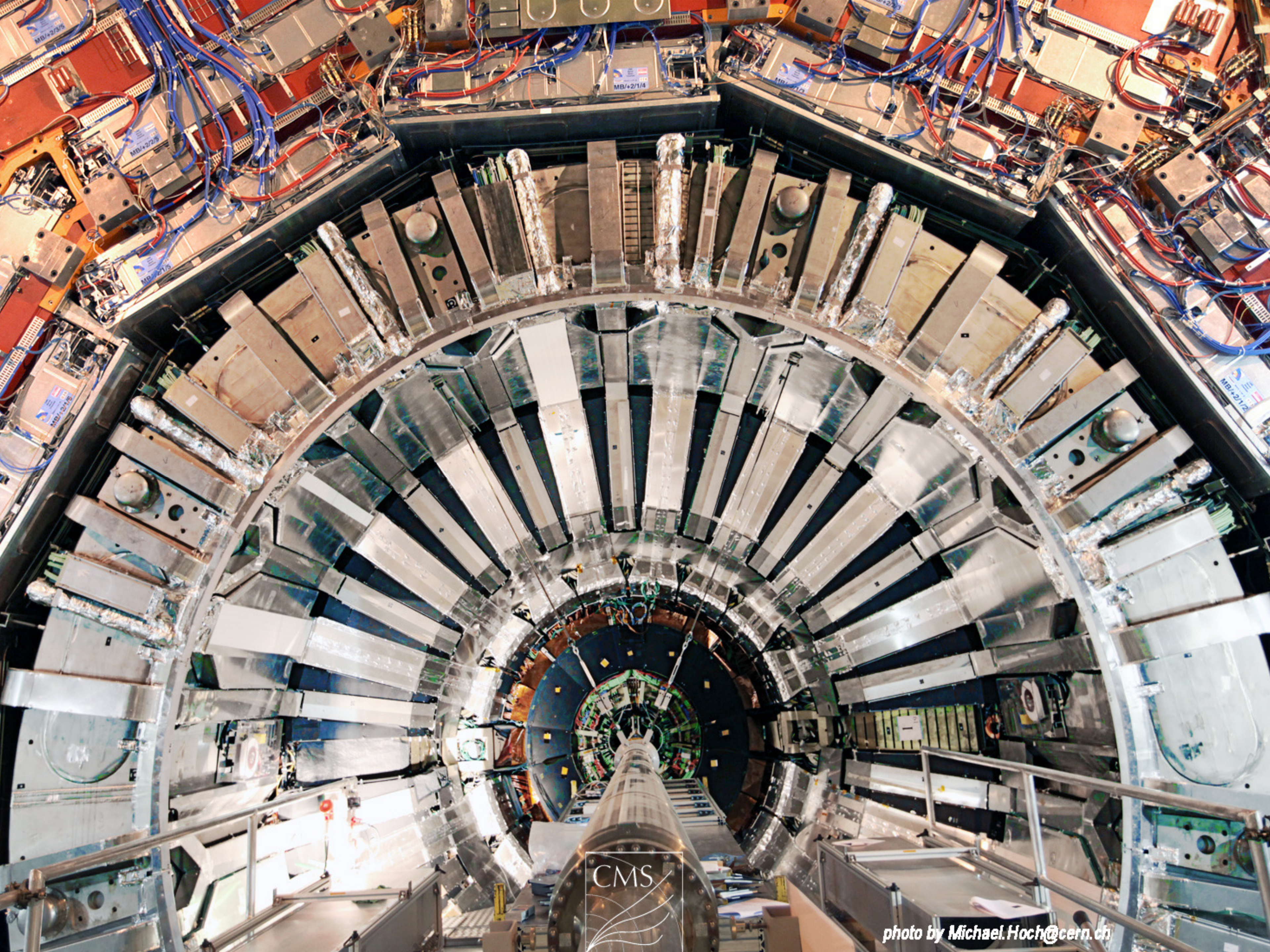


photo by Michael.Hoch@cern.ch

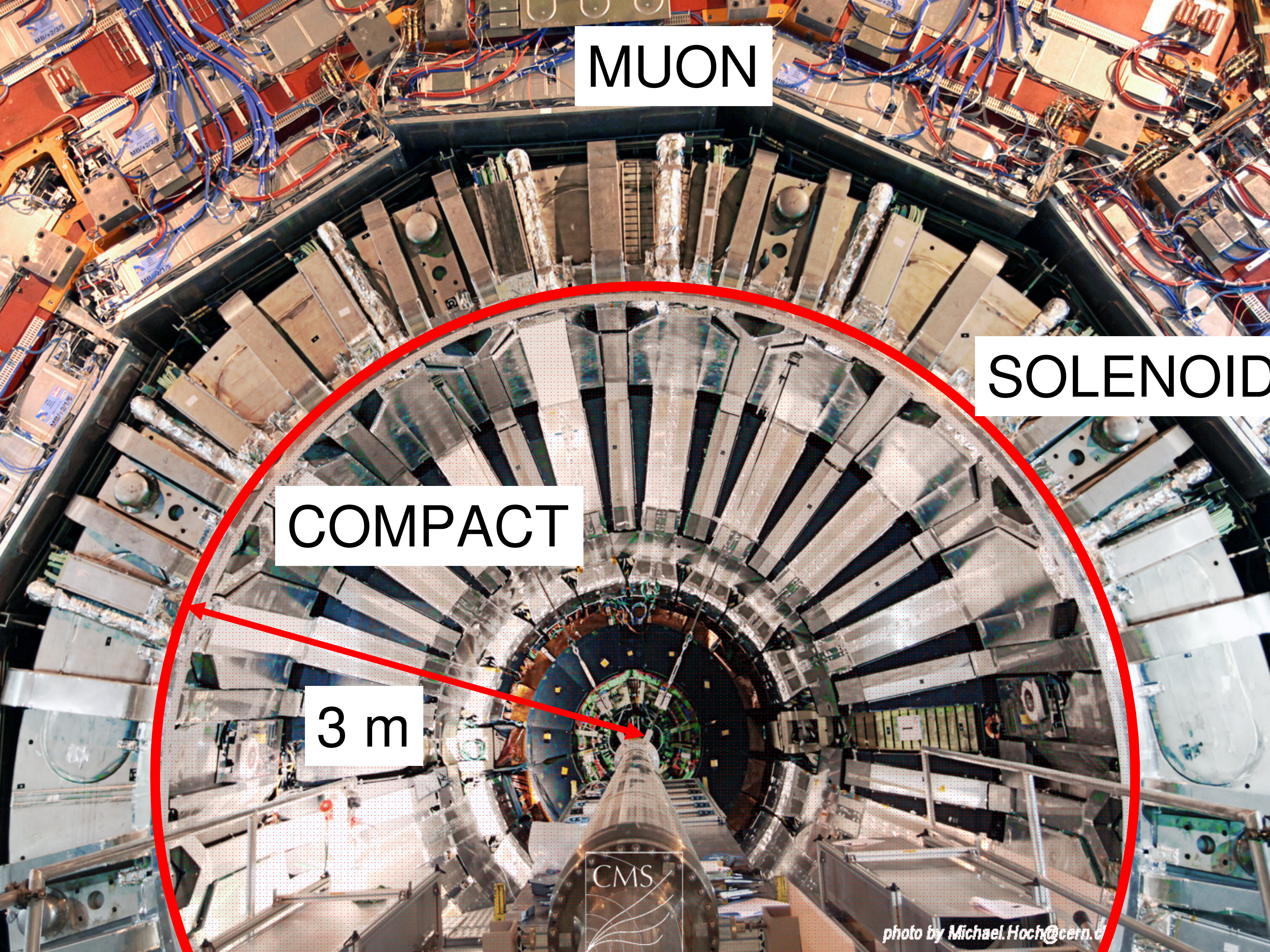
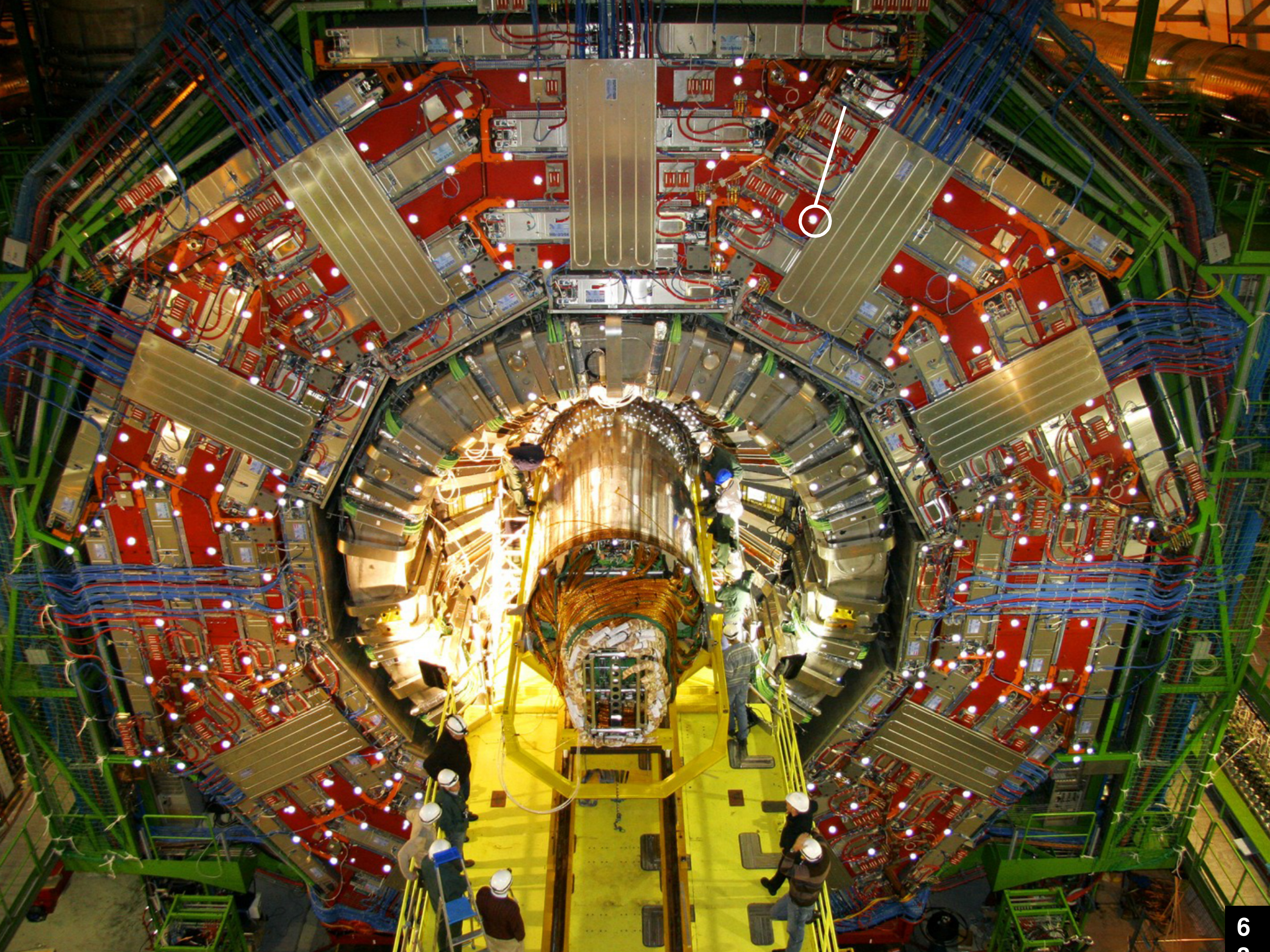
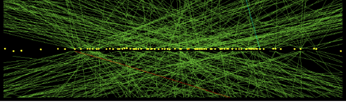


photo by Michael.Hoch@cern.ch



Atlas & CMS : Many (two) ways to skin a cat



The choice of the magnet system shaped the experiments in a major way. The magnet is required to measure momenta and directions of charged particles near vertex and also to at the outer muon detectors

ATLAS choice: separate magnet systems (“small” 2 T solenoid for tracker and huge toroids with large BL^2 for muon spectrometer)

Pros: large acceptance in polar angle for muons and excellent muon momentum resolution outside, without using inner tracker

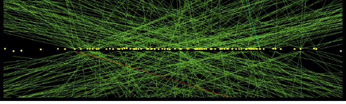
Cons: very expensive and large-scale toroid magnet system with complicated field configuration

CMS choice: one large 4 T solenoid with instrumented return yoke

Pros: excellent momentum resolution using inner tracker and more compact experiment with well defined field configuration

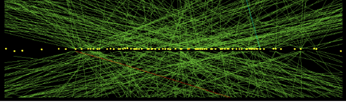
Cons: limited bending power for endcap and limited space for calorimeter inside coil

Specifications : advantage CMS



	ATLAS	**CMS**
MAGNET	4 magnets: 4T, 2T Air toroids + Solenoid Calorimeters outside field	1 magnet: 4T Solenoid Calorimeters inside field
TRACKER $\lvert\eta\rvert<2.5$	Si pixels + strips + TRT $\sigma/p_t \sim 4\times10^{-4} \oplus 0.015$	Si pixels + strips $\sigma/p_t \sim 1.5\times10^{-4} \oplus 0.005$
EM CALO $\lvert\eta\rvert<5$	Pb-Liquid Argon w/ long. segmentation $\sigma/E \sim 10\%/\sqrt{E}$	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$
HAD CALO $\lvert\eta\rvert<5$	Fe-scint + Cu-LA (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu+scint (5.8 λ + catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON $\lvert\eta\rvert<2.6$	Precision+Trigger Air→ $\sigma/p_t \sim 7\%$ @ 1 TeV w/ tracker (~10% standalone)	Precision+Trigger Fe→ $\sigma/p_t \sim 5\%$ @ 1 TeV w/ Tracker (~10-30% standalone)

Specifications : advantage Atlas



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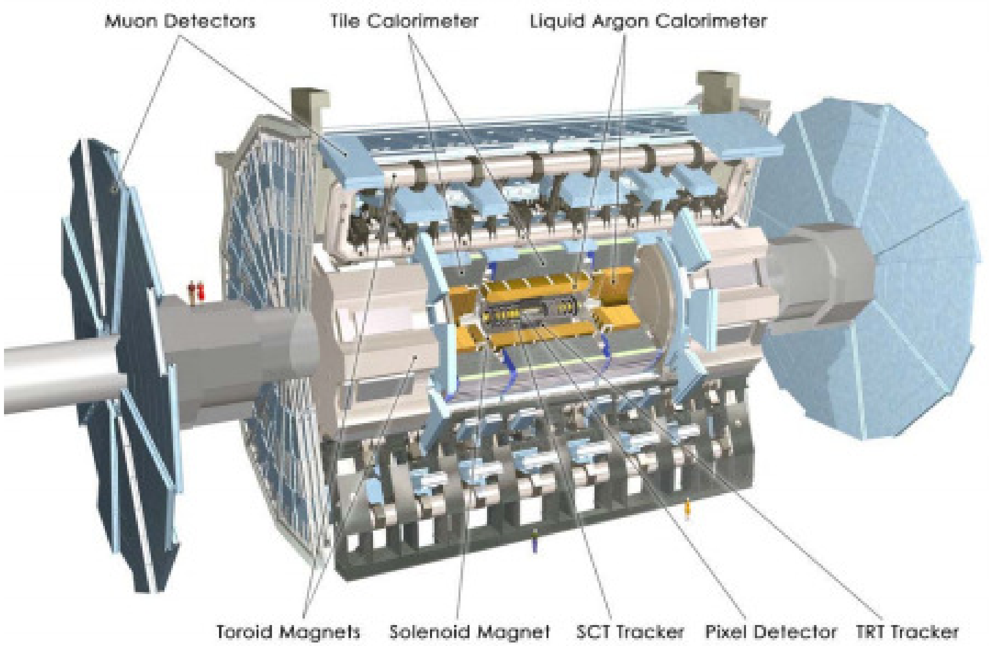
The ring

Volume of ATLAS 20000 m3



From LS1 to LS3:

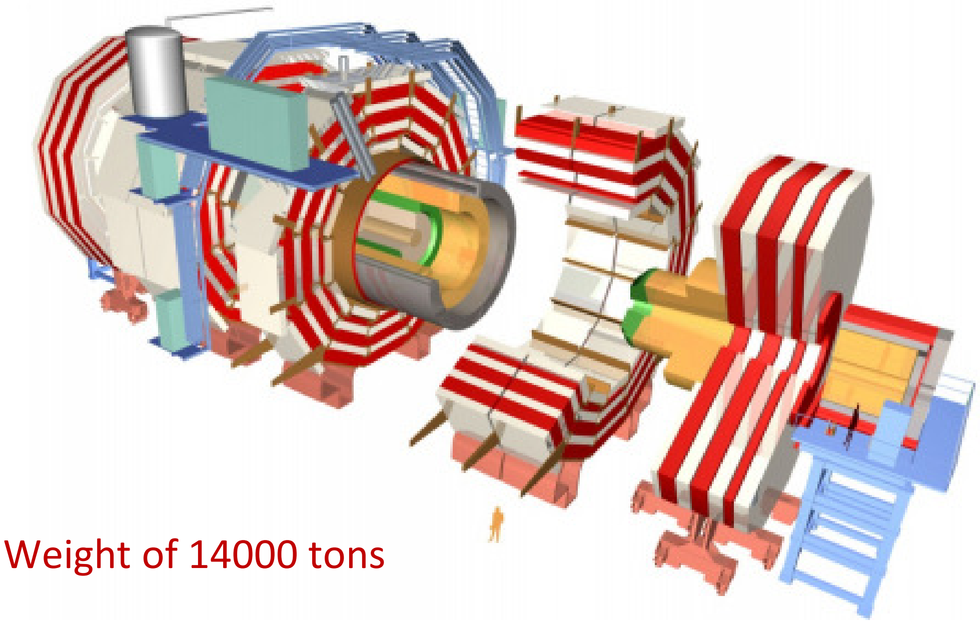
- $2 * 10^{34}$ cm^{-2}s^{-1}
- PU ~50
- 300 fb^{-1}

Beyond LS3:

- $5 * 10^{34}$ cm^{-2}s^{-1}
- (with lumi-leveling)
- PU ~140
- 3000 fb^{-1} (250 fb^{-1}/year)

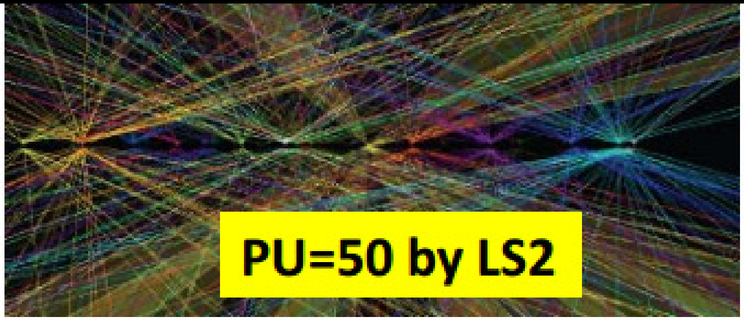
Full upgrade program to cope with increasing luminosity:

Radiation damage, pile-up mitigation, bandwidth limitations, aging...



Weight of 14000 tons

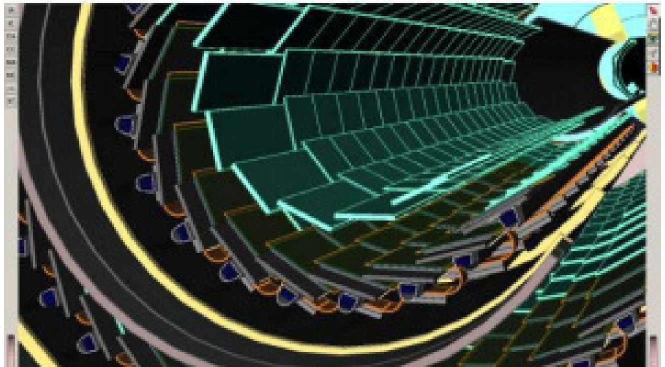
Atlas & CMS Pixels upgraded early



PU=50 by LS2

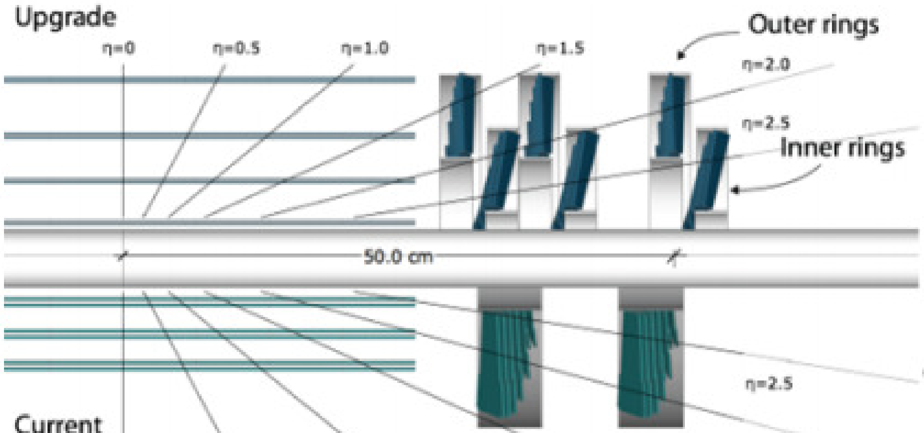
New Insertable B-layer (IBL) in LS1

- Average radius of 3.3 cm
- Pixel size (50mmx250mm) compared to the present 50mmx400mm
- Thin planar sensors and 3D double side sensors
- Reduce the fake tracks arising from random combinations of hits and enhance efficiency of tagging heavy flavour quarks



New Pixel in 2017

- New beam pipe in LS1
- 4 layers/3 disks
- 3 cm inner radius
- New readout chip: recovers inefficiency at high rate and PU
- Significantly reduced material budget
- CO_2 cooling, DC-DC powering scheme
- Improved track resolution and efficiency
- Improved vertex resolution and b-tagging



Atlas &CMS upgrade L1 trigger before LS3

Increase of luminosity forces upgrading present system in order to control the rates maintaining similar thresholds already before LS3

High Precision L1 Calorimeter Trigger

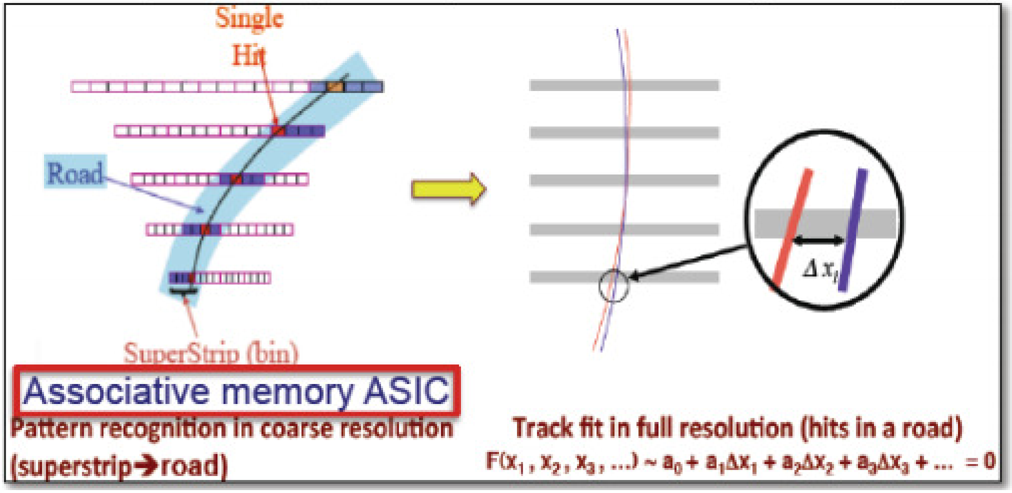
- Readout of super-cells in LAr with higher granularity and higher precision

Fast TracKing (FTK) for the Level-2 trigger

- Finds and fits tracks (~ 25 µs) in the ID silicon layers at an "offline precision"

hit pattern matching to pre-stored patterns (coarse)

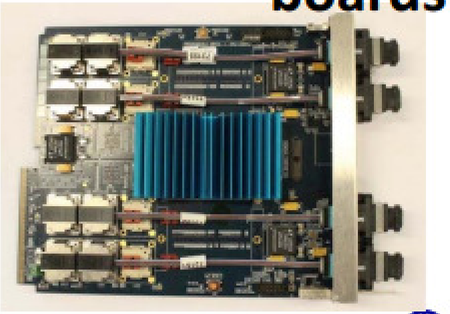
subsequent linear fitting in FPGAs (precise)



New Level1 back-end electronics

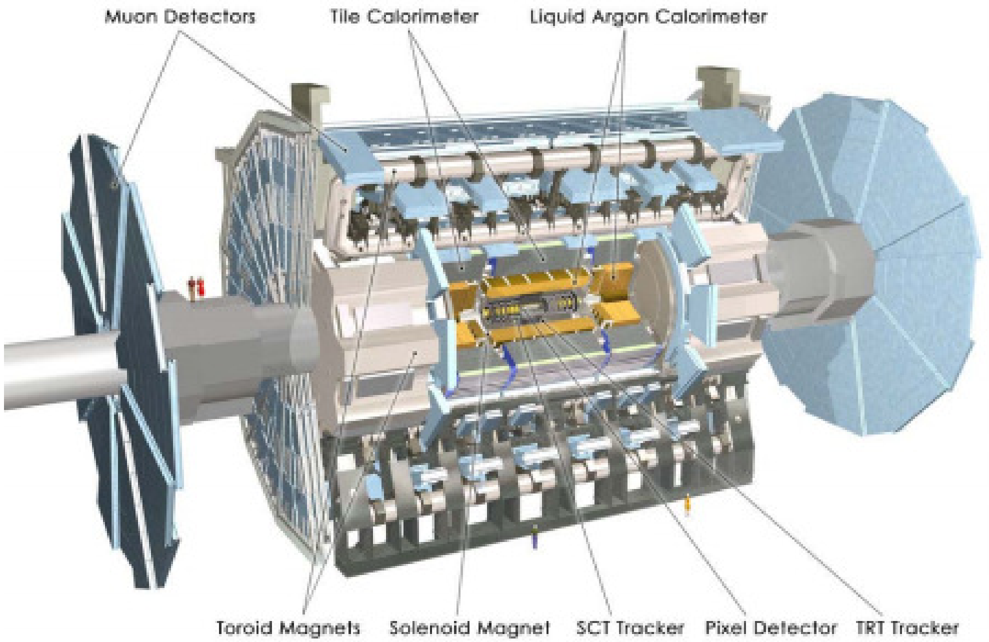
- Upgrade of the off-detector electronics using uTCA technologies:
- Powerful FPGAs and high bandwidth optics
- Allows much improved algorithms for PU mitigation and isolation
- Improve L1 Trigger capabilities to cope with higher rates

uTCA boards



The ring

Volume of ATLAS 20000 m3



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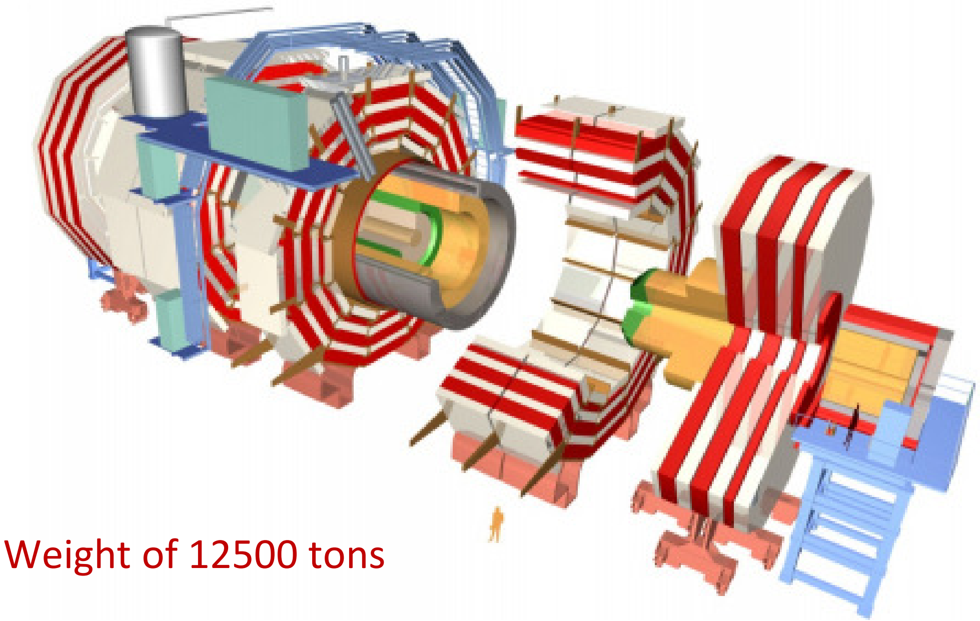
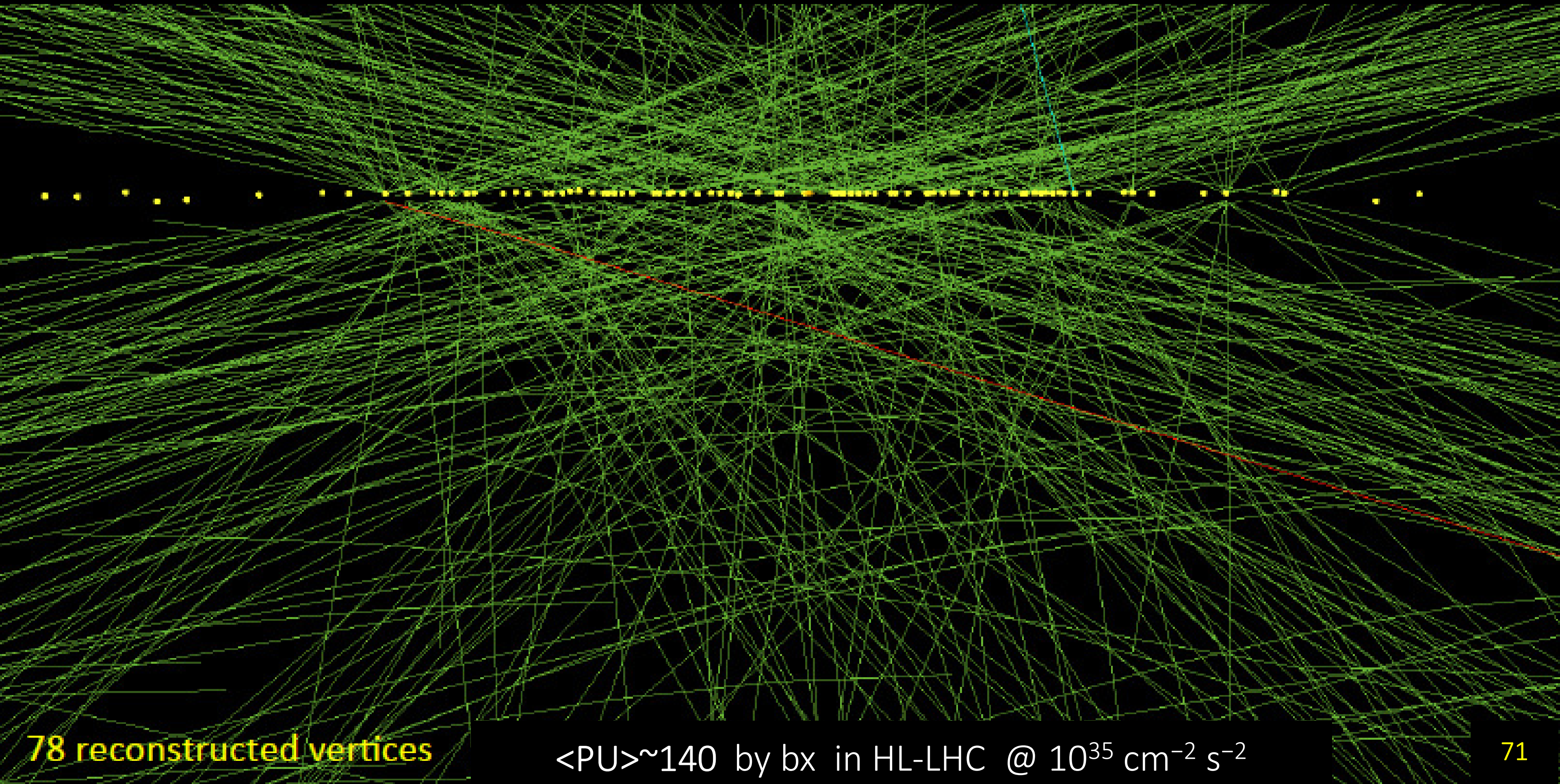
Radiation damage, pile-up mitigation, bandwidth limitations, aging...



Weight of 12500 tons

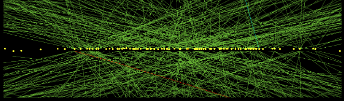
The HL-LHC challenge

1. How to select events O (<pb) in a O(0.1b)?
2. How to reconstruct the objects and interprete the resultalts?
3. What acceptance and with which goals?
4. How to operate efficiently over 2 decades ?



<PU>~140 by bx in HL-LHC @ 10^{35} cm^{-2} s^{-2}

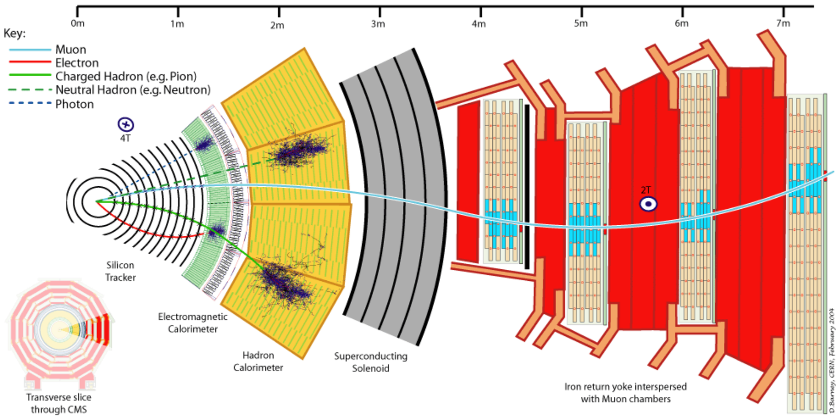
Strategy in HL-LHC : 1. Selection



Pileup. The elastic cross section is huge (10^{-1}barn @ $\sqrt{s}$ = 14 TeV) vs. the cross section of the interesting proccesses (10^{-12} barn).

- Up to 200 interaction pre crossing @ HL-LHC 10^{35} cm^{-2} s^{-1}
- if LHC manages to operate at 25 ns bx difference

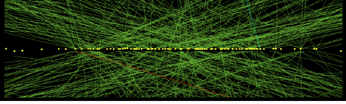
- One of the most robust sellection tools are high p_T leptons. In CMS, the muon momentum measurement depends on the tracker. The combination of tracker and muon is already crucial at the reconstruction level.



- Phase 2 Silicon tracker will provide online information (tracking trigger).
  - Precise correlation of tracker and muon detector information is key

Temporal and geometric aligment of tracker and muon detectors is key

Strategy in HL-LHC : 2. Reconstruction



Independently of the new physics scenario we will need to keep under control the reconstruction of the heaviest Standard Model particles (W, Z, H^0,t):

leptons (μ & e), γ MET, jets with b/c y τ .

- Higgs is light.

  ➔ Imperative to keep low pT thresholds,

  +increase granularity to minimize occupancy detector occupancy

  + Increse event complexity, more superposed evntes (pileup 140)

  + L1 “Trigger-less” trend ➔ 1 MHz en tasa de disparo L1

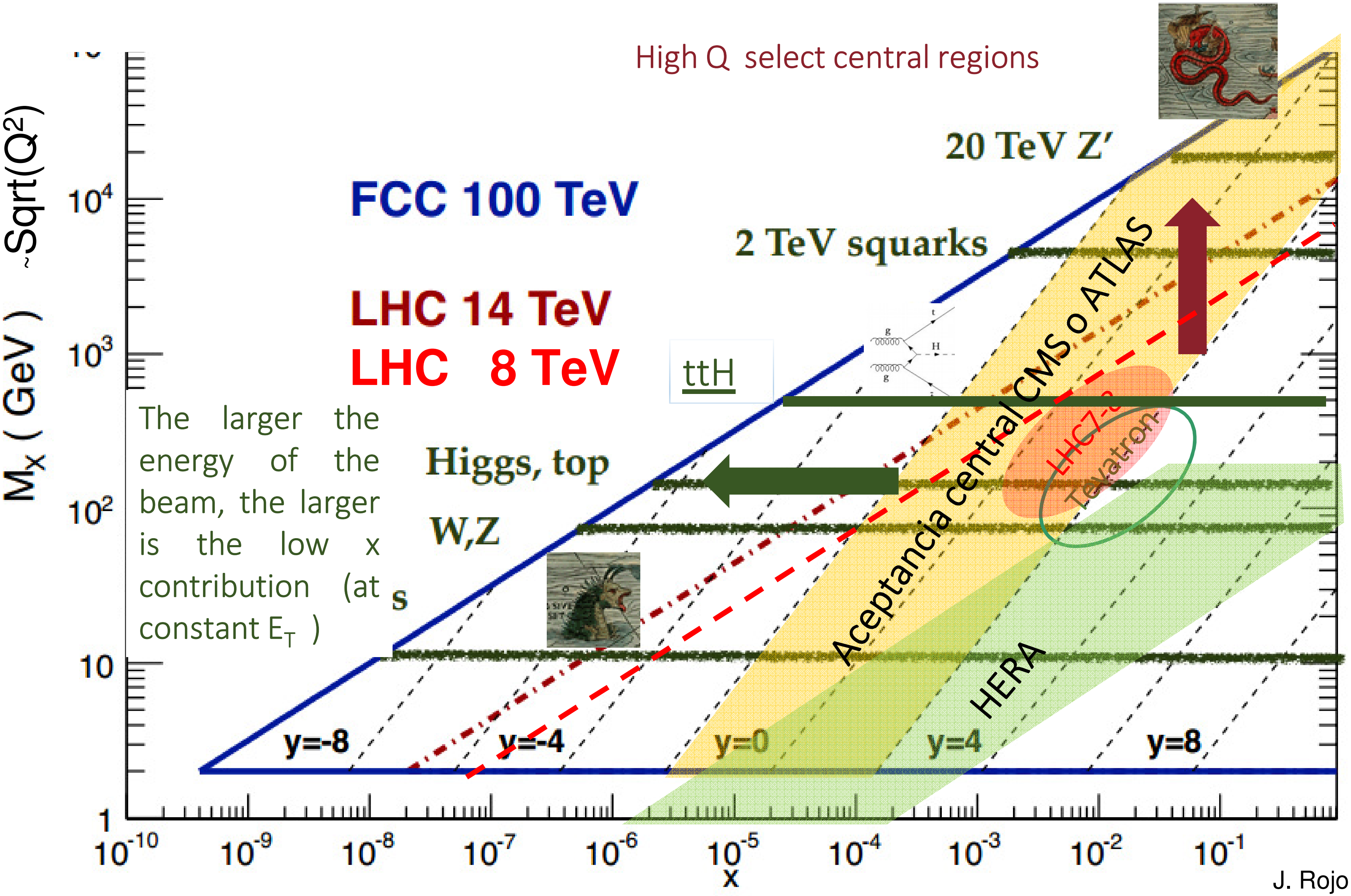
  HLT projects an increment x10 of “on tape” events (10 KHz)

  ➔Huge computing resources (x50 con wrt. 2015 x10 wrt. run I)

- Longitudinal momentum of initial partons is not known.
  - To compare with theory one needs to know the partonic luminosities
  - LHC xsec dominated by g(x)g(x′) where x << x′, becasue g(x) grows at low x

FCC-hh phase space@100 TeV

Having pdfs under control is (nearly) as important as luminosity

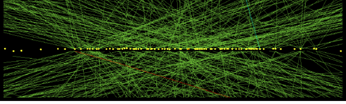


High Q select central regions

The larger the energy of the beam, the larger is the low x contribution (at constant E_T)

J. Rojo

Strategy in HL-LHC : 3. Acceptance



The larger the energy, the larger the low x contribution

- ➔ Less central are the η distributuibs at a given threshold in E_T dado (for instanceH^0) .

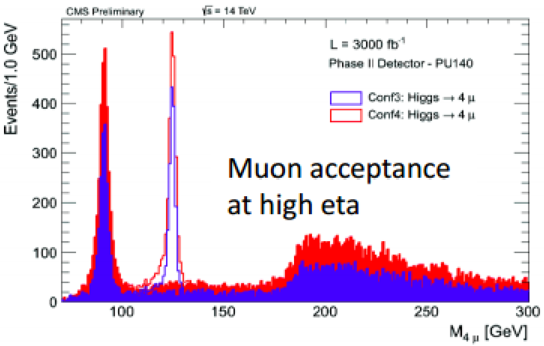
Justifies muon aceptance extension up to η~4

Posible because CMS projects CMS replacement and extention of the forward calorimeter due to radiation damage

- ➔ study VBF using forward jet tagging,

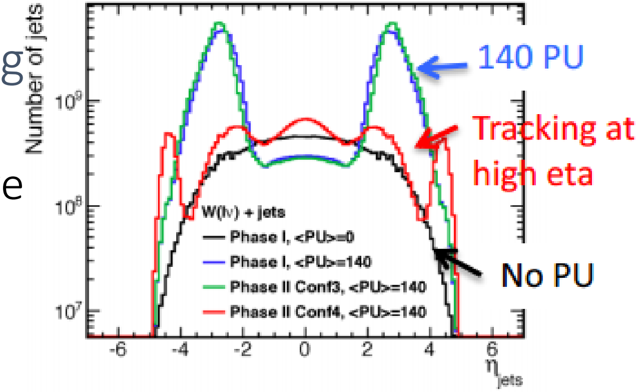
Justifies extensión of the tracking detector, allowing particle flow methods

Increasing the E_T threshold (for instance generating massive particles) favors the central regions of the detector



Muon acceptance at high eta

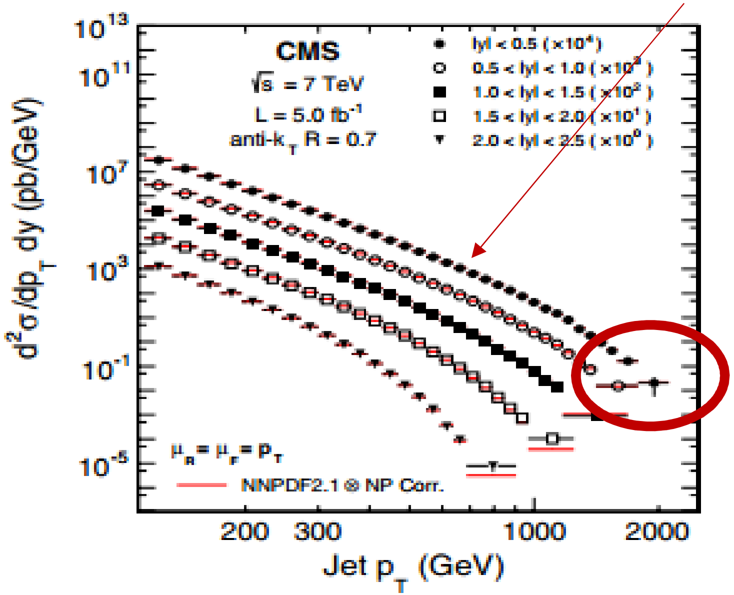
VBF/VBS Jet-tagging



140 PU

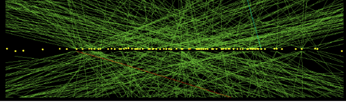
Tracking at high eta

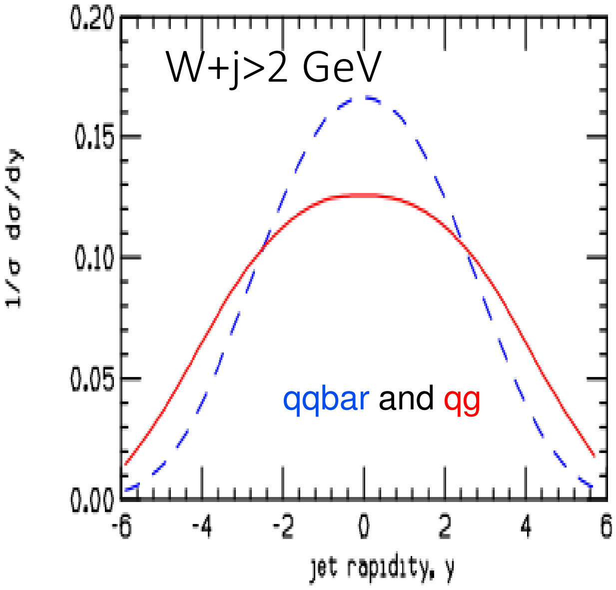
No PU

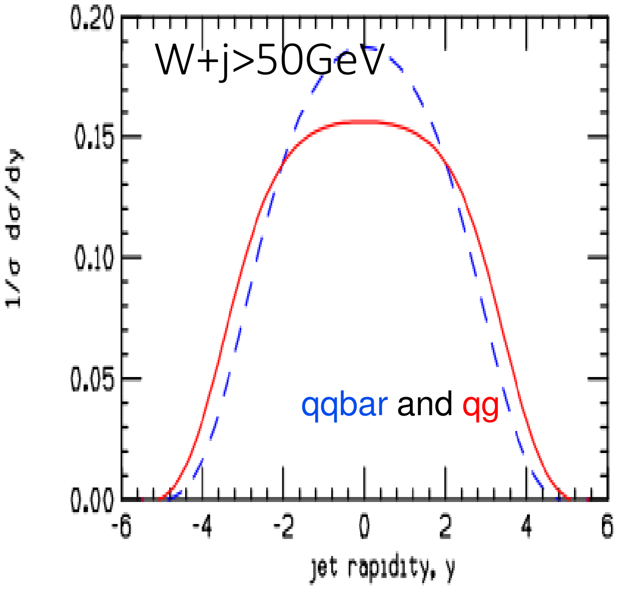


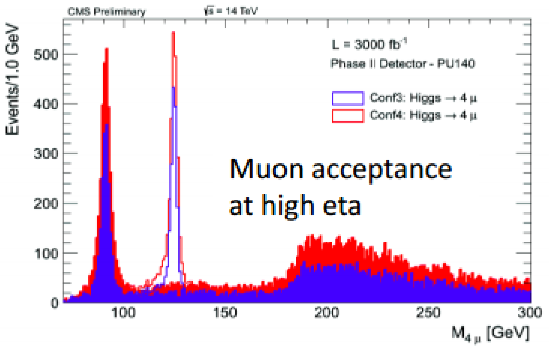
Keeping high efficiency in the central region of the detector during the full HL-LHC operation will determine the máximum reach for new physics

Strategy in HL-LHC : 3. Acceptance

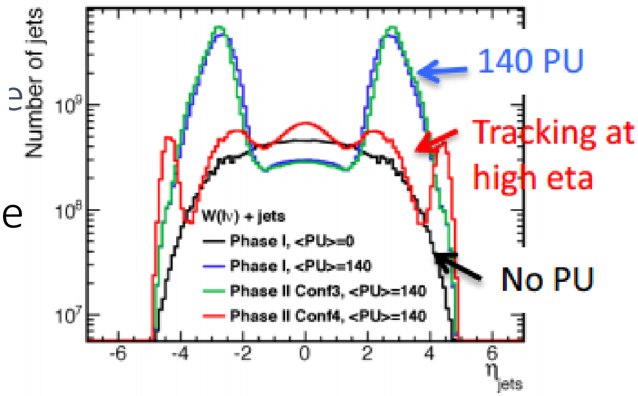








VBF/VBS Jet-tagging



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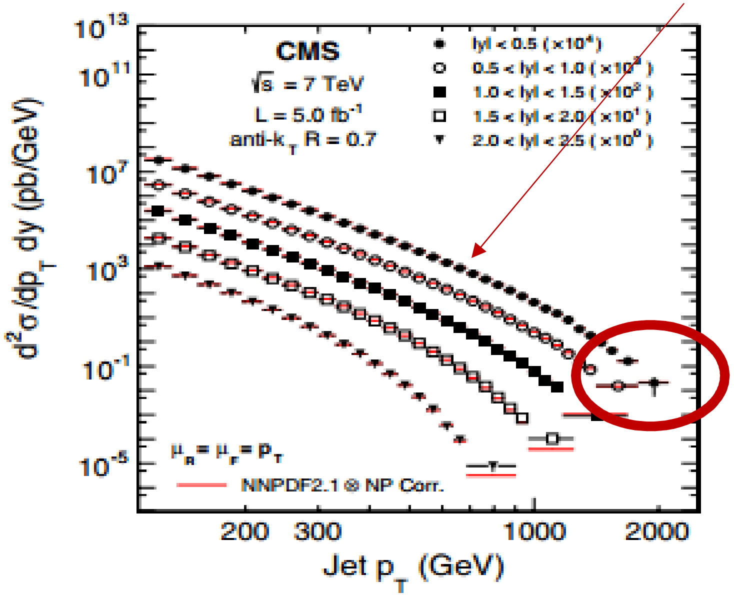
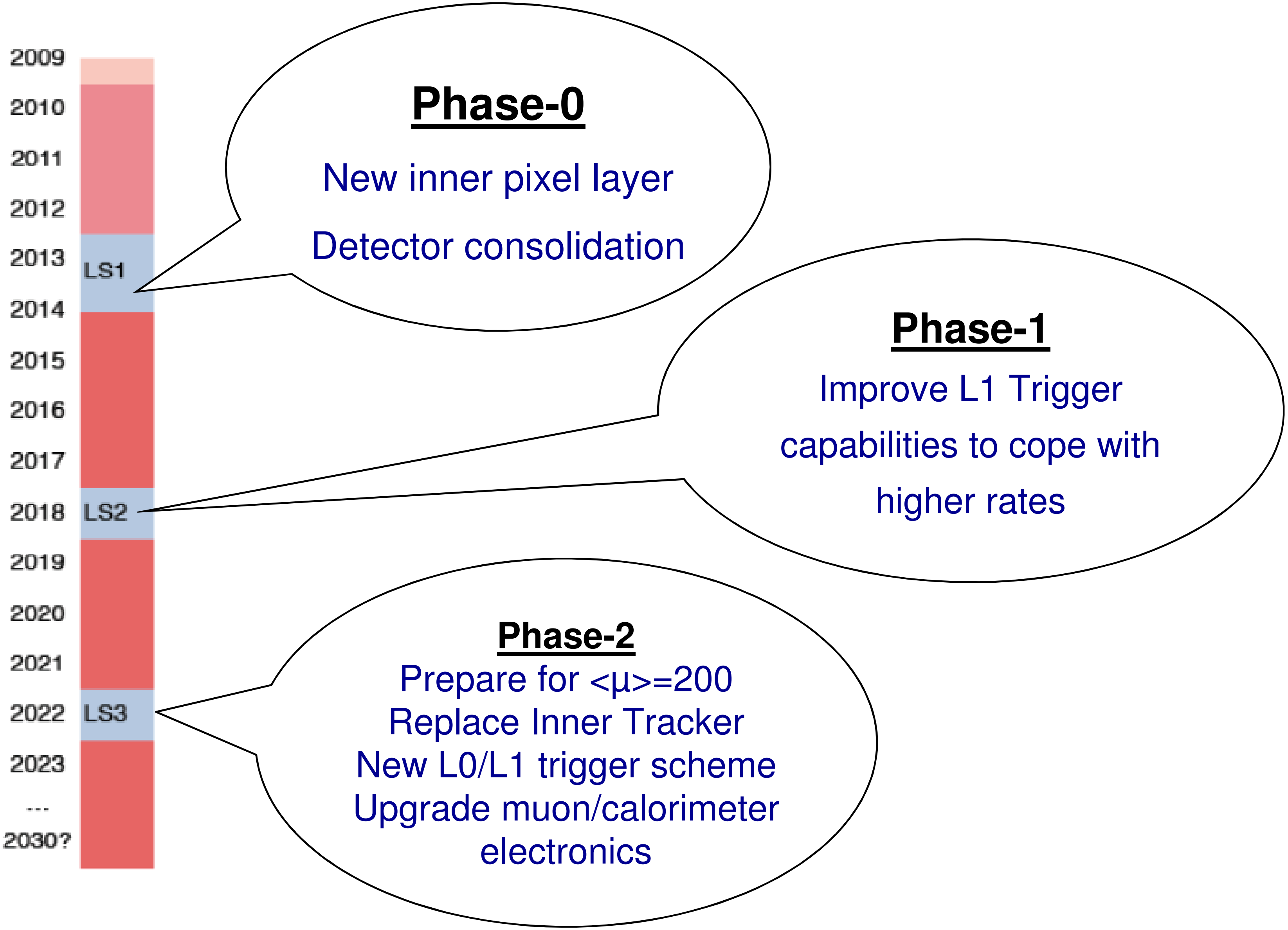


Keeping high efficiency in the central region of the detector during the full HL-LHC operation will determine the máximum reach for new physics

4- How to operate efficiently over 2 decades ?

"Hay que ir partido a partido"

Atlas Upgrade Roadmap



Phase-0

New inner pixel layer

Detector consolidation

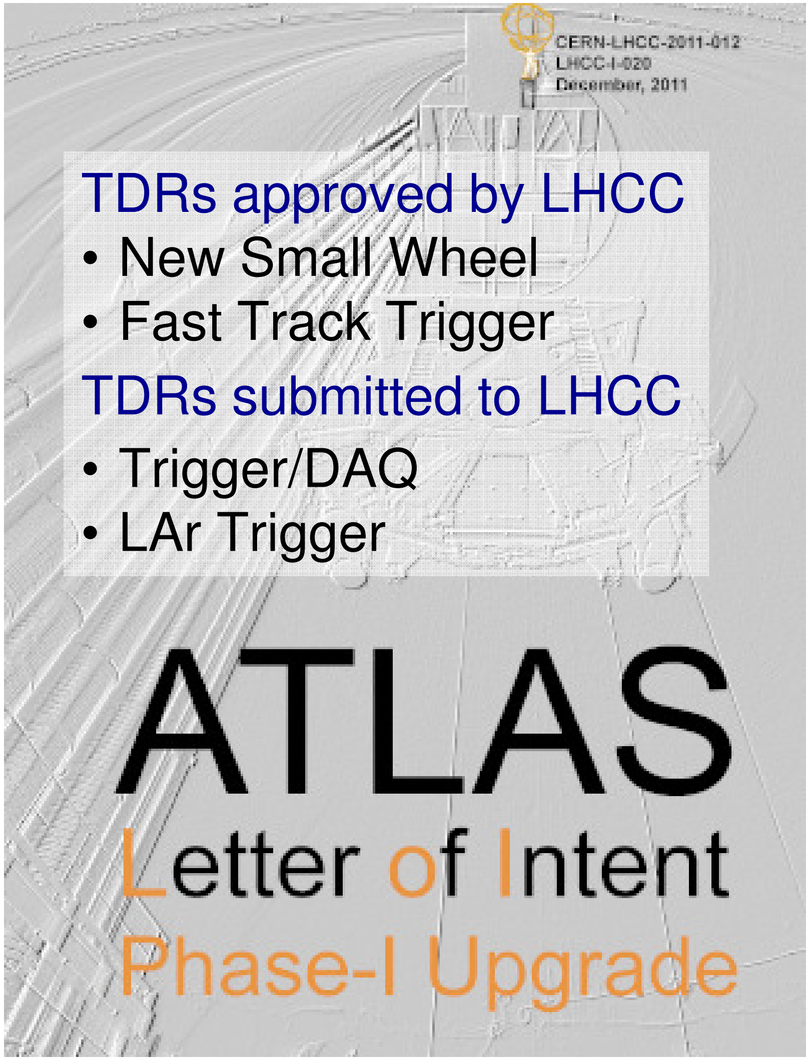
Phase-1

Improve L1 Trigger capabilities to cope with higher rates

Phase-2

Prepare for <μ>=200
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics

The ATLAS upgrade programme

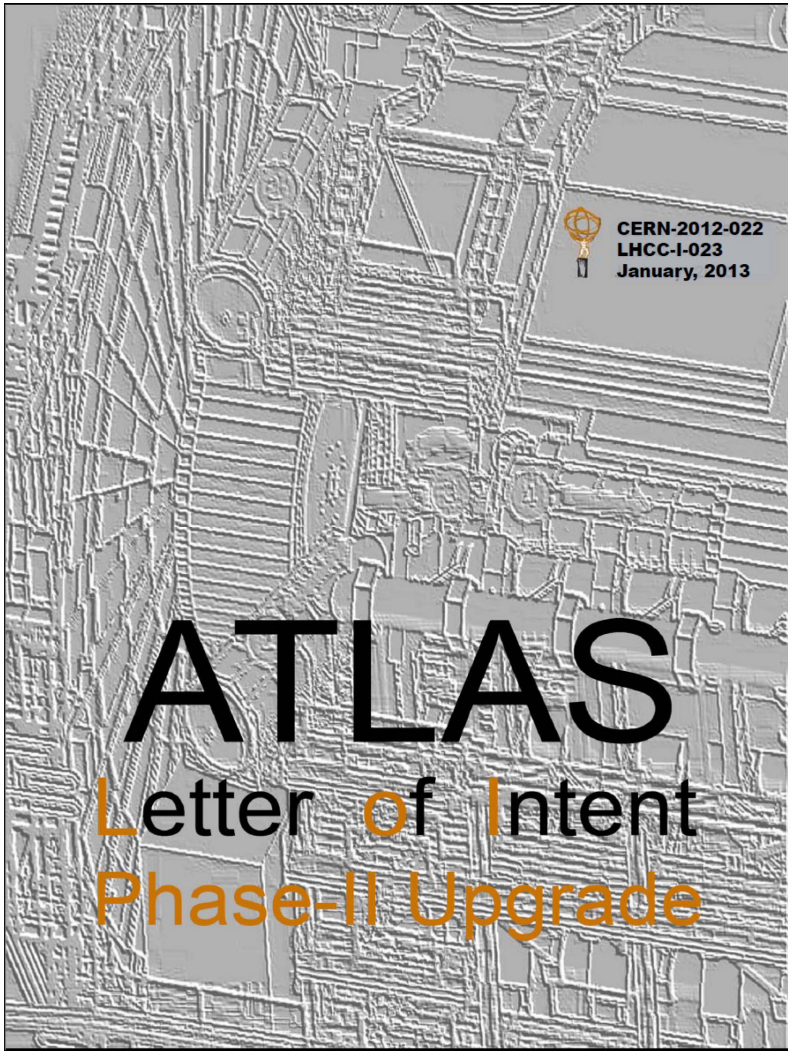


CERN-LHCC-2011-012
LHCC-I-020
December, 2011

TDRs approved by LHCC
- New Small Wheel
- Fast Track Trigger

TDRs submitted to LHCC
- Trigger/DAQ
- LAr Trigger

ATLAS
Letter of Intent
Phase-I Upgrade

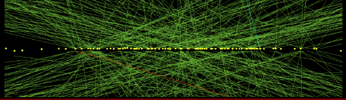


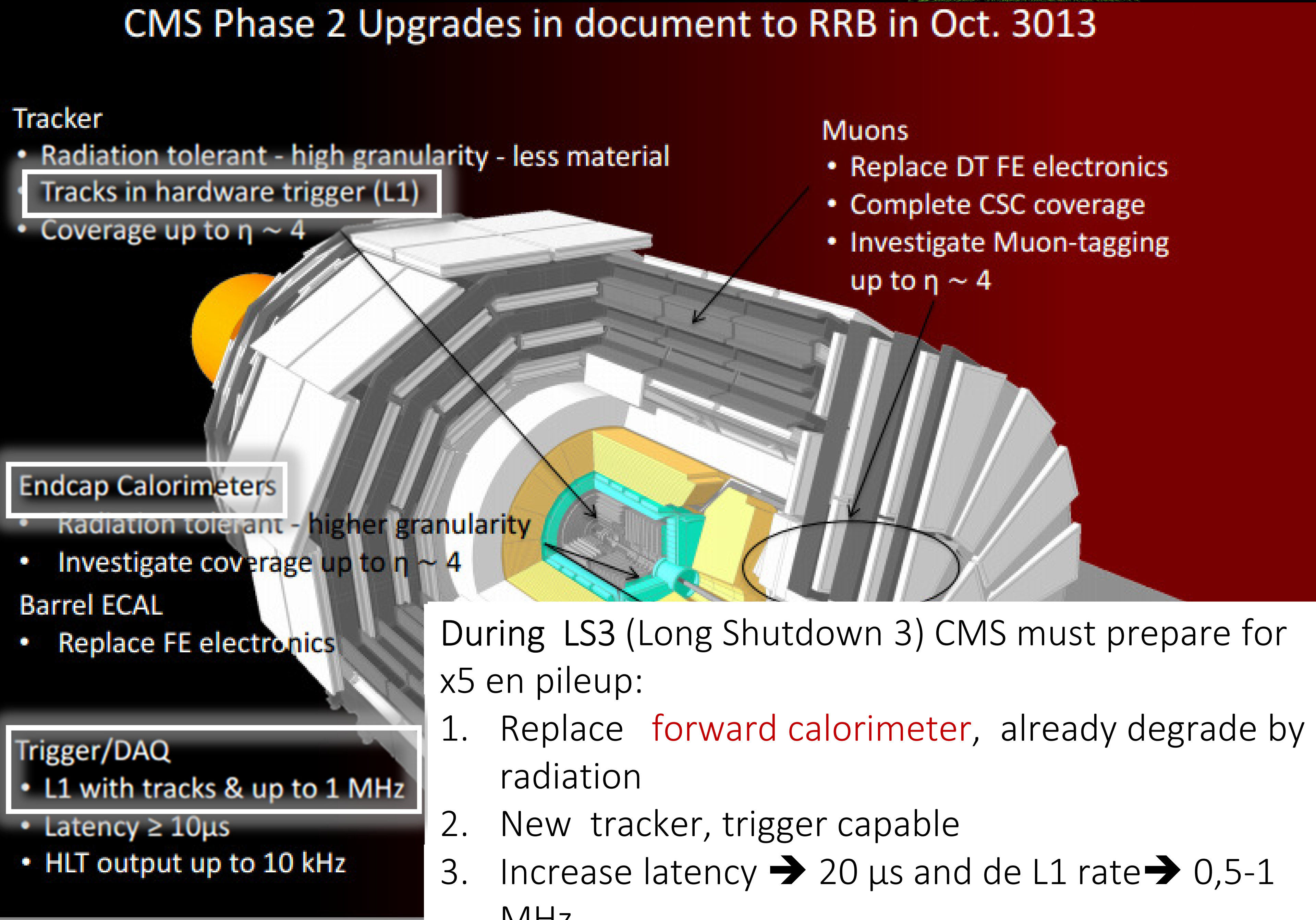
CERN-2012-022
LHCC-I-023
January, 2013

ATLAS
Letter of Intent
Phase-II Upgrade

+ TDR of Insertable B-Layer (Phase-0)

Roadmap of CMS Phase 2 upgrade





CMS Phase 2 Upgrades in document to RRB in Oct. 3013

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete CSC coverage
- Investigate Muon-tagging up to η ~ 4

Endcap Calorimeters
- Radiation tolerant - higher granularity
- Investigate coverage up to η ~ 4

Barrel ECAL
- Replace FE electronics

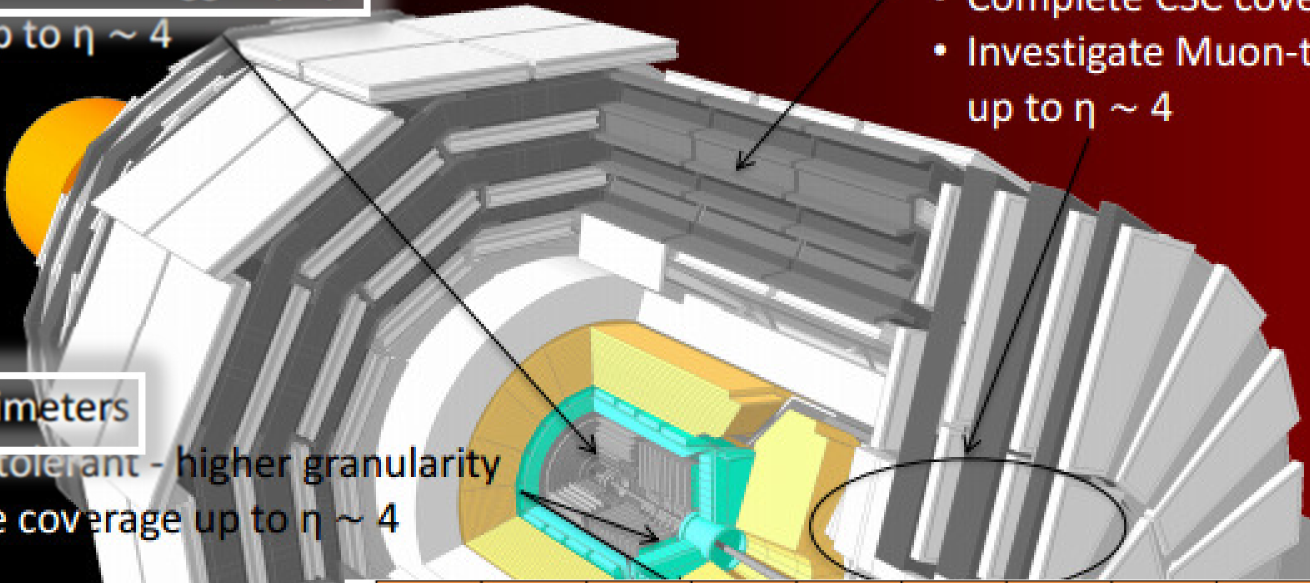
Trigger/DAQ
- L1 with tracks & up to 1 MHz
- Latency ≥ 10µs
- HLT output up to 10 kHz

During LS3 (Long Shutdown 3) CMS must prepare for x5 en pileup:

1. Replace forward calorimeter, already degrade by radiation
2. New tracker, trigger capable
3. Increase latency ➔ 20 µs and de L1 rate➔ 0,5-1 MHz

Roadmap of CMS Phase 2 upgrade

CMS Phase 2 Upgrades in document to RRB in Oct. 3013



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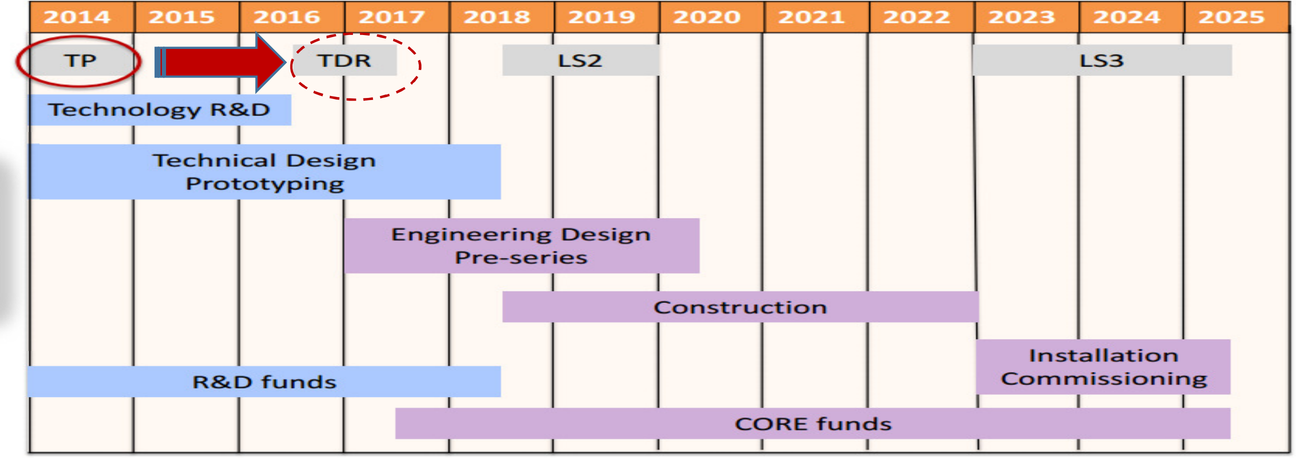


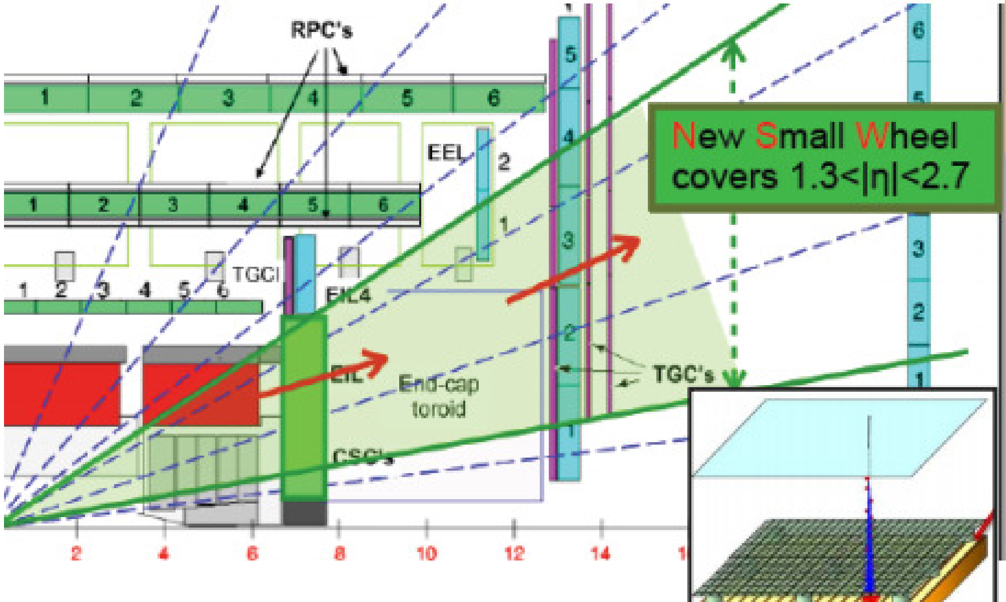
Atlas & CMS Muon Detectors

Existing detectors are expected to cope with HL-LHC radiation and luminosity, but much of the electronics may be replaced due to trigger needs.

LS1 upgrades:
End-cap Extension (EE) MDT
- coverage at 1.0 < |η| < 1.3

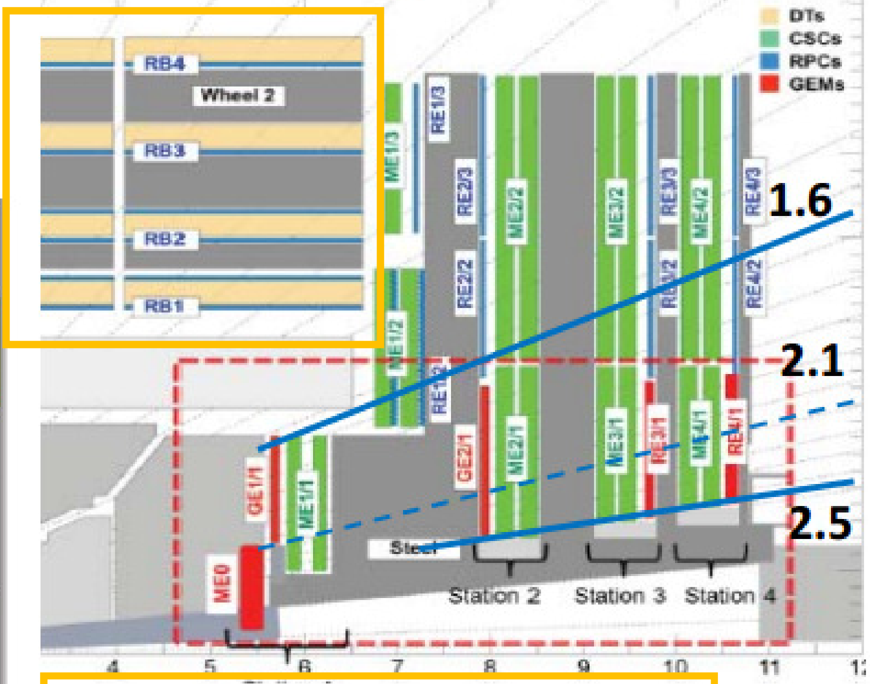
New Small Wheel (NSW) in LS2

- **Micromegas & sTGC** :
  precision measurement and trigger
- First large system based on Micromegas
- Finer granularity
- Resistive strips for spark immunities
- 'Floating mesh' configuration
- Good spatial resolution also for inclined tracks thanks to μTPC operation mode



New Small Wheel covers 1.3<|η|<2.7

- **New stations** to improve redundancy in the most complicated region: **GEMs and GRPC or iRPC**
- Extension to **η~4 (ME0)?**
- R&D in new gas mixtures



- New **DT barrel electronics** to allow higher trigger rate

DT Phase II Electronics Upgrade

i. Simplify the on-detector electronics to timing digitization and the transmission of such data to the service cavern via fiber optics.

\+ based on FPGAs (not ASICs, not wire bonds) radiation-resistant, flexibility

We have already implemented TDC time resolution of 1 ns in FPGAs, a radiation-tolerant

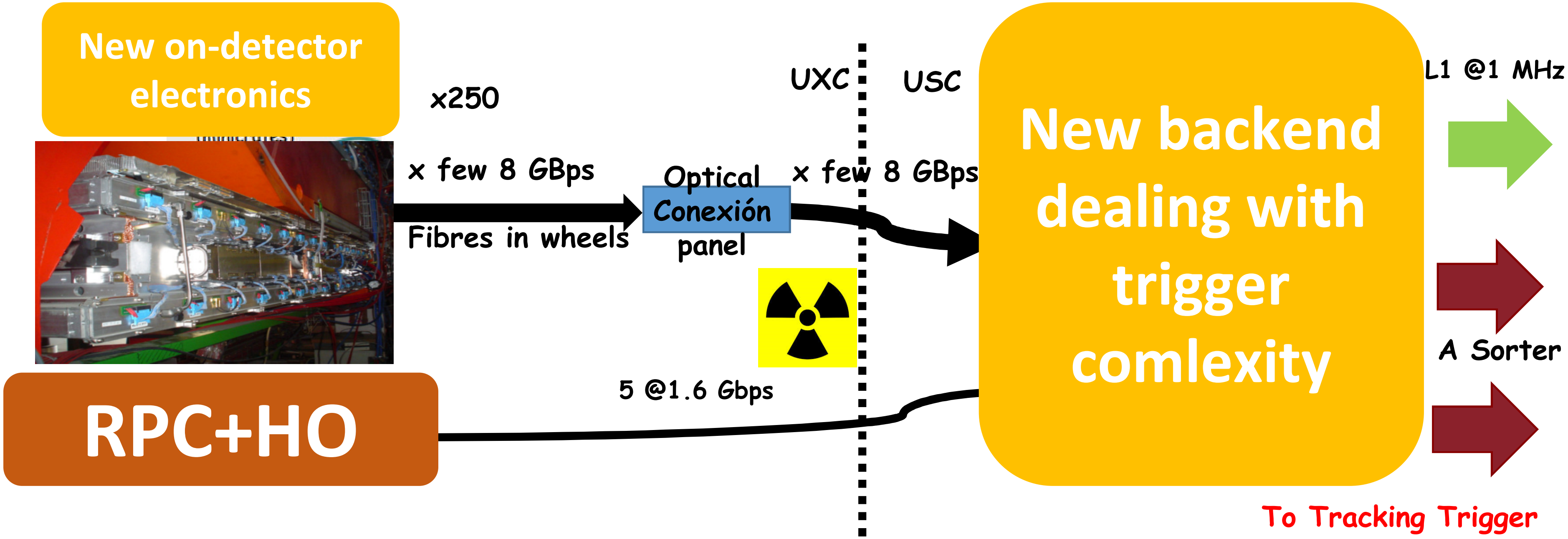
ii. Intelligence and complexity of the generation of the trigger would take place in an environment without radiation,

++ It allows the use of powerful commercial electronic components that are not particularly expensive.

Today a camera/FPGA ➔ 2023: sector/FPGA?

iii. A simpler system (fewer parts) and robust (much less dissipation)

+++ Impact on the longevity of cameras (FED boards) and the infrastructure



New on-detector electronics

x250

x few 8 GBps

Fibres in wheels

Optical Conexión panel

UXC

USC

x few 8 GBps

New backend dealing with trigger comlexity

L1 @1 MHz

A Sorter

RPC+HO

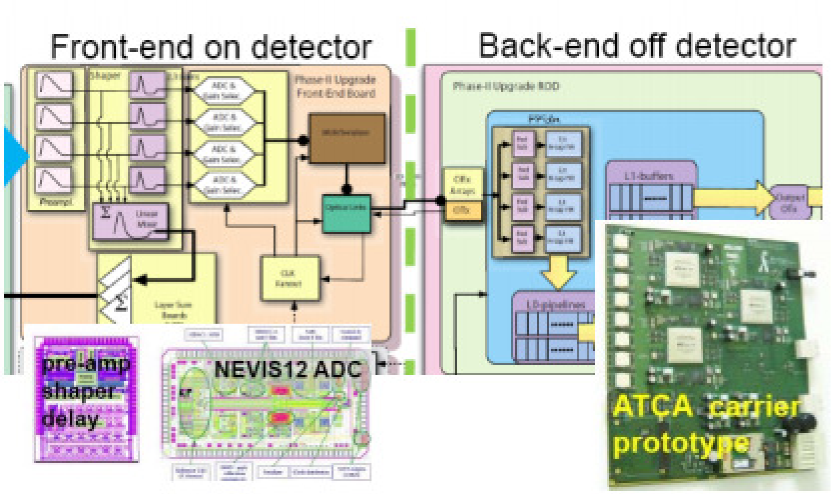
5 @1.6 Gbps

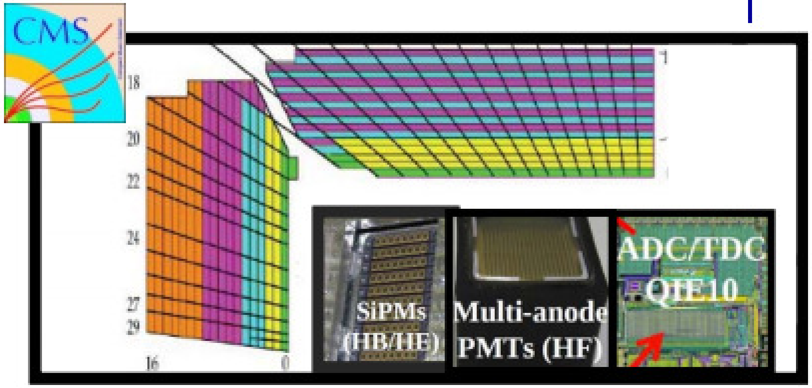
To Tracking Trigger

Atlas&CMS Calorimetry Electronics

Tile and LAr electronics in LS3

- Replacement due to ageing and radiation tolerance
- Limited on-detector pipelines prevent application of more advanced trigger algorithms
- On-detector digitization of all signals at 40 MHz
- Radiation tolerant chips on detector
- ATCA technology in the back-ends



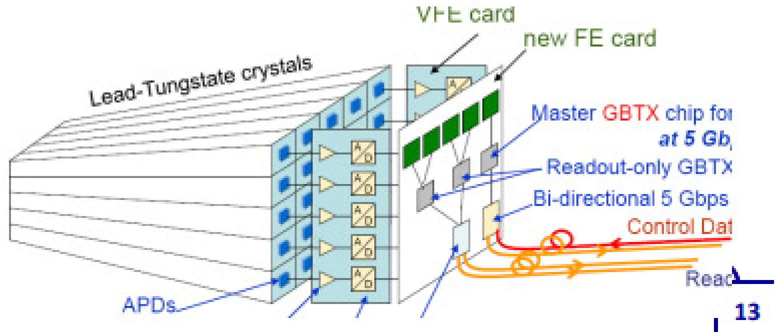


HCAL electronics in LS2

- replaced to improve system performance: reduce noise, increase depth segmentation and allow timing measurement

ECAL barrel electronics in LS3

- to accommodate to higher trigger rates and latency
- Implement a 40 MHz continuous read-out



Atlas&CMS Calorimetry

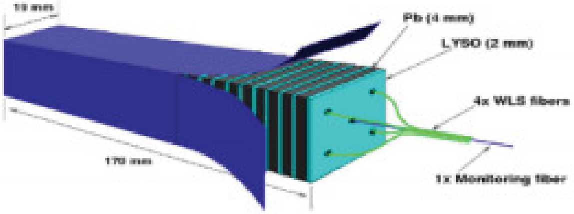
The ATLAS & CMS Barrel calorimeters are sufficiently rad-hard to operate through Phase II

- End-Cap LAr is intrinsically radiation hard
- Lar Hadron End-Cap Calorimeter (HEC) cold electronics is under evaluation: replacing this would necessitate opening of the cryostat
- LAr FCAL may suffer and may need replacement (under study)

<u>EndCap ECAL and Endcap HCAL</u>
need to be replaced in LS3 due to radiation degradation.

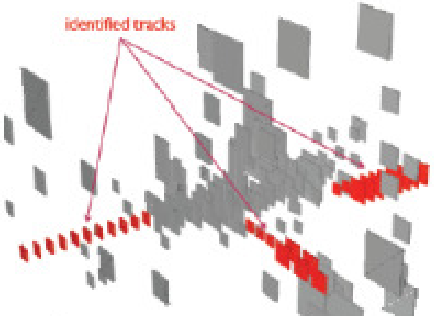
Two options:

1- Maintain present subdivision in more radiation tolerant designs



Shashlik EE towers (crystal scintillator: LYSO, CeF)

HE with rad-hard fibers

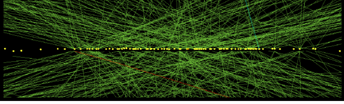


2- Integrated calorimeters with adequate electromagnetic resolution and significantly improving hadronic resolution and jet response

-Dual fiber read-out: scintillation & Cerenkov (DROC) (DREAM/RD52)

-Particle Flow Calorimeter (PFCAL) CALICE, with GEM/Micromegas

CMS Endcap calorimeter for HL-LHC



High Granularity Silicon Calorimeter

Athens, Beijing, CERN, Demokritos, Imperial College, Iowa, LLR Polytechnique, Minnesota, SINP (Kolkata) & UC Santa Barbara

1 of 2 options in the TP

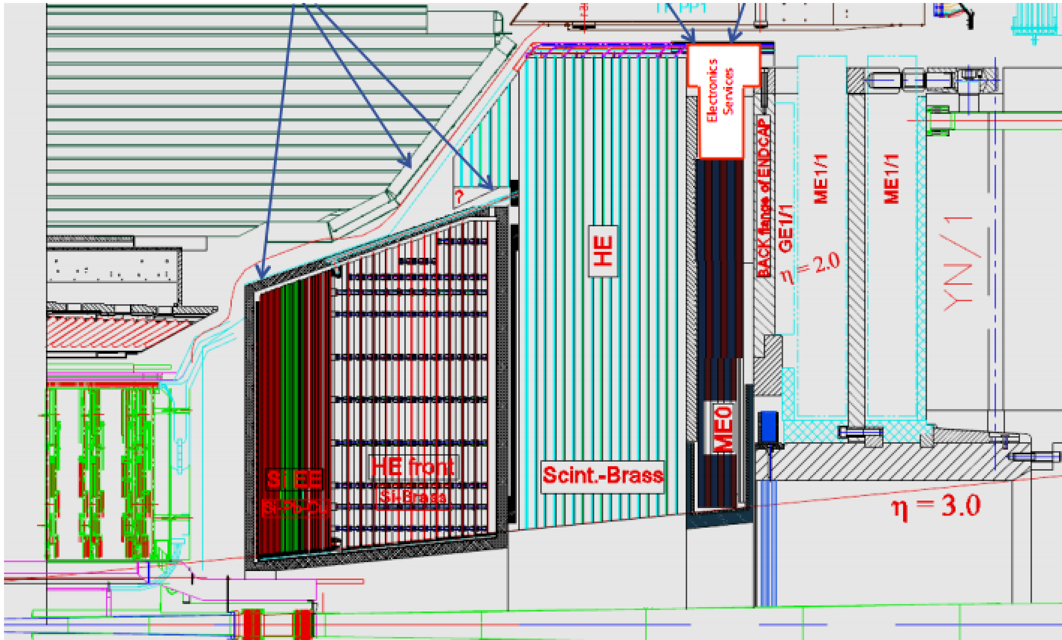
- High granularity, Si active layer
  - With tracker forward extention allow particle flow *`a la* CALICE
- “Analogic” readout, 10 bits
  - FE ASICs, 0.9-1.8 cm^2 pad
- External layer could use gaseosos detectors or scintillators

Muon acceptance extensión would use GEMs,RPCs and/or glass RPCs

The Basic Design

- ***Electromagnetic Calorimeter:***
  - 30 samplings of lead/copper total of 25 X_0
    - 11 layers of 0.5 X_0/10 layers of 0.8 X_0/10 planes of 1.2 X_0.
    - Pad size 0.9 cm^2 for first 20 layers, 1.8 cm^2 for the last 10 layers.
  - 420 m^2 of silicon pad detectors.
  - 3.7M channels.
- ***Front Hadronic Calorimeter***
  - 4 interaction lengths.
  - 12 layers of brass/silicon each 0.33l.
  - Pad size is 1.8 cm^2
  - 1.4M channels.
- ***Backing calorimeter***
  - Five interaction lengths (e.g. sampling of 0.5l).
  - Radiation levels are lower so can use plastic scintillator or MPGD’s.

Operate silicon at -30°C



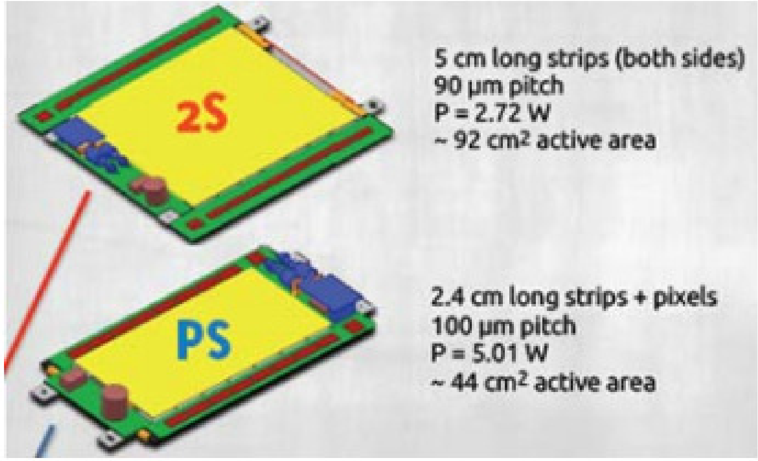
Atlas&CMS Phase 2 Tracker

Tracker (and pixel) of both ATLAS and CMS need to be rebuilt in LS3 due to radiation damage

Novel technologies will improve:

- Tracking reconstruction efficiency, transverse momentum and impact parameter resolution
- Minimize amount of material in the tracker volume

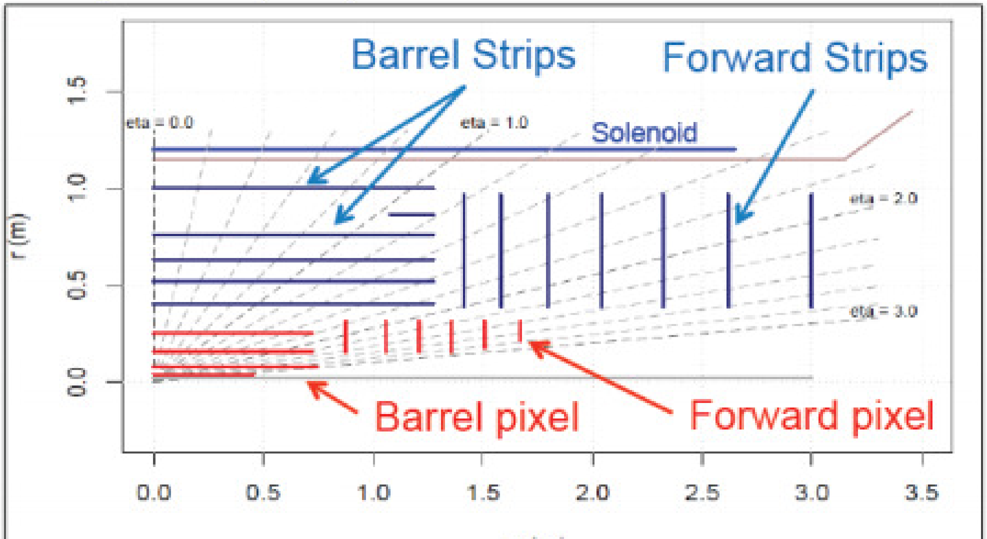
- Inner volumes up to $10^{16}\text{cm}^{-2}\ n_{eq}$
- Both consider extension to η~4
- Both will contribute to the Level-1 trigger (↑**purity** of trigger, what is done in **SW → HW**):
  - ATLAS: Region of interest with a Level-0
  - CMS: p_t modules to discard signals p_t<2 GeV



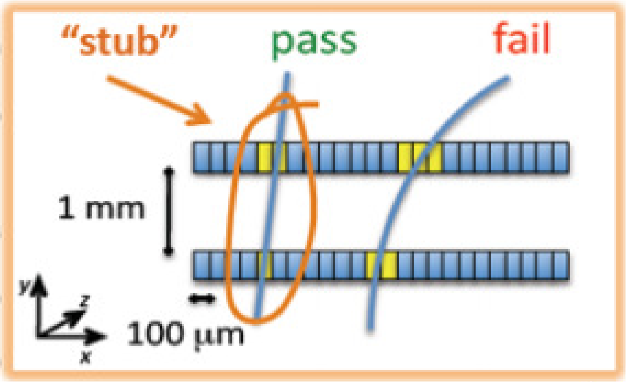
5 cm long strips (both sides)
90 µm pitch
P = 2.72 W
~ 92 cm² active area

2.4 cm long strips + pixels
100 µm pitch
P = 5.01 W
~ 44 cm² active area

LoI layout new (all Si) ATLAS Inner Tracker for HL-LHC



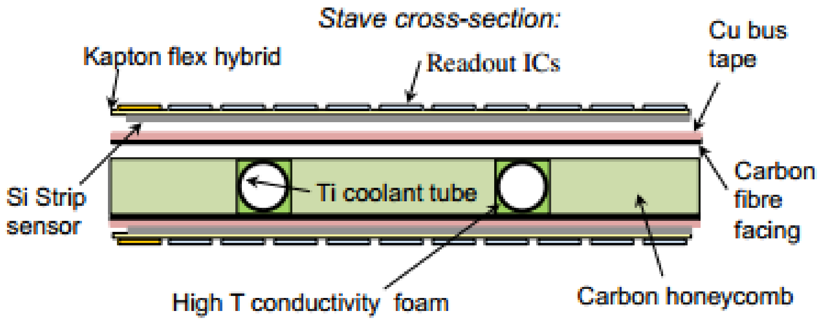
Trigger track selection in FE

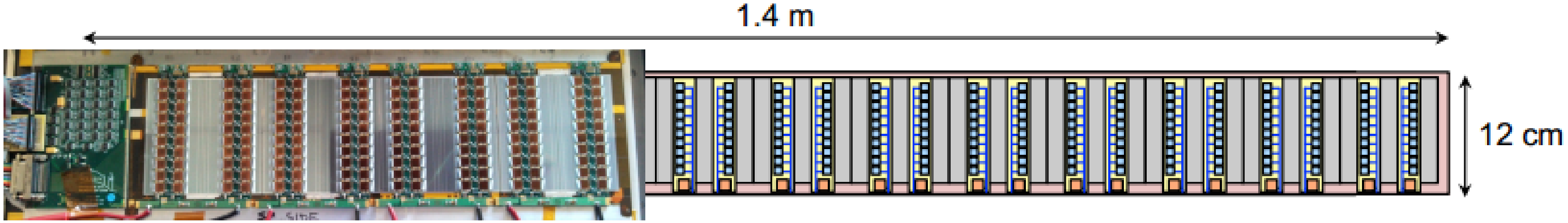


ATLAS SILICON STRIP TRACKER

- Outer tracker is a silicon strip detector with n-in-p sensors
  - 5 barrel layers, 7 discs EC, “stubs”
- Double-sided layers with axial strip orientation and rotated by 40mrad on other side (z-coordinate)
  - Short (23.8 mm) and long strips (47.8 mm) with 74.5 µm pitch in barrel
  - End-Cap with radial strips of different pitch (6 different module designs)
- Efforts are directed at low cost

- Silicon Modules directly bonded to a cooled carbon fibre plate.
- A sandwich construction for high structural rigidity with low mass.
- Services integrated into plate including power control and data transmission.
- R&D already in full swing


Stave cross-section:



Atlas &CMS Trigger and DAQ in Phase 2

Increase of luminosity forces upgrading present system in order to control the rates maintaining similar thresholds

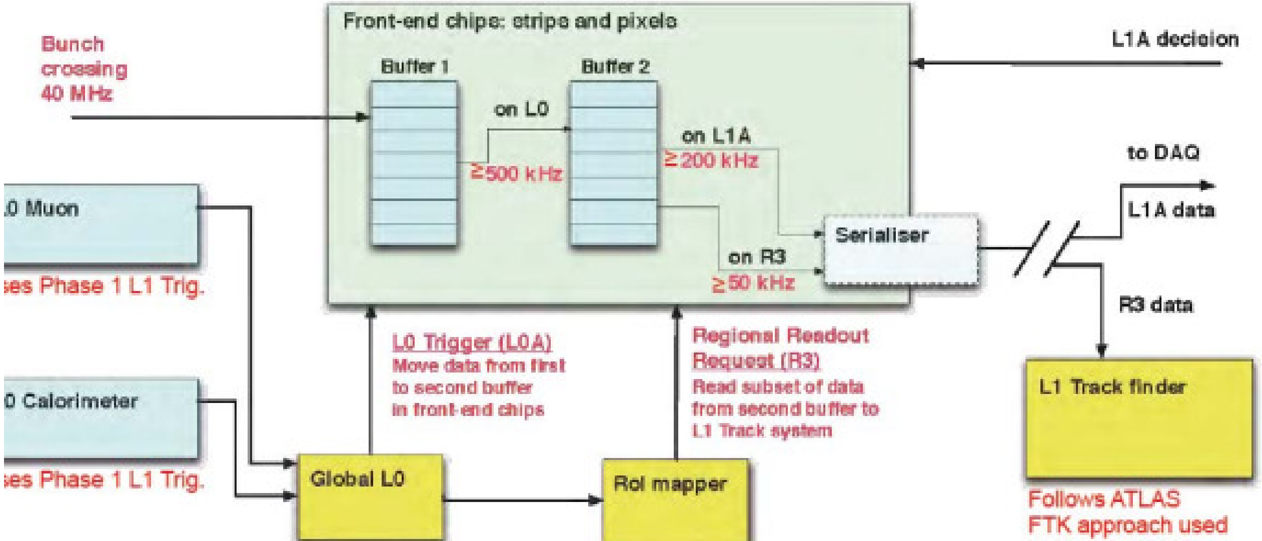
Level-0
Rate ~ 500 kHz, Lat. ~6 μs
Muon + Calo
Level-1
Rate ~200 kHz, Lat. ~20 μs
Muon + Calo + Tracks

New L0/L1 trigger
- "Pull" option
- L0 uses:
  - Calo. & μ Triggers
- L1 uses:
  - Track Trigger & more μ detectors & more fine grained calo.
- HLT output rate of 5 - 10 kHz

- Only one level of HW trigger
- "Push" option
- L1 uses:
  - Track Trigger, finer granularity μ & calo.
- HLT output rate of 10 kHz
- Impact on EB and DT electronics

L1 latency from 3 μs → 10 μs (20 μs?)

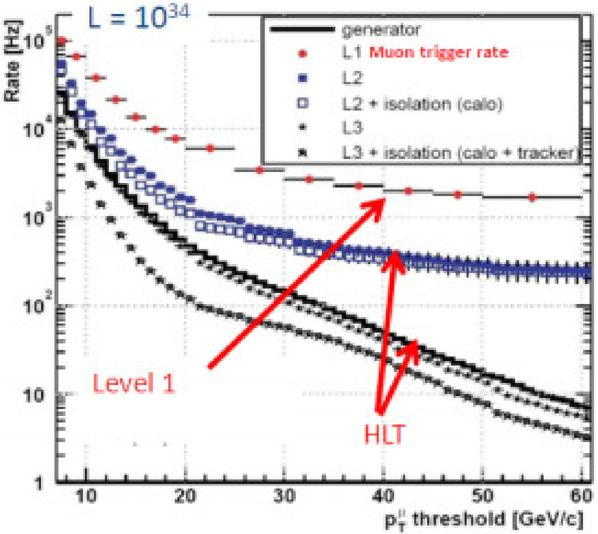
L1 rate from 100 kHz → 500kHz-1 MHz

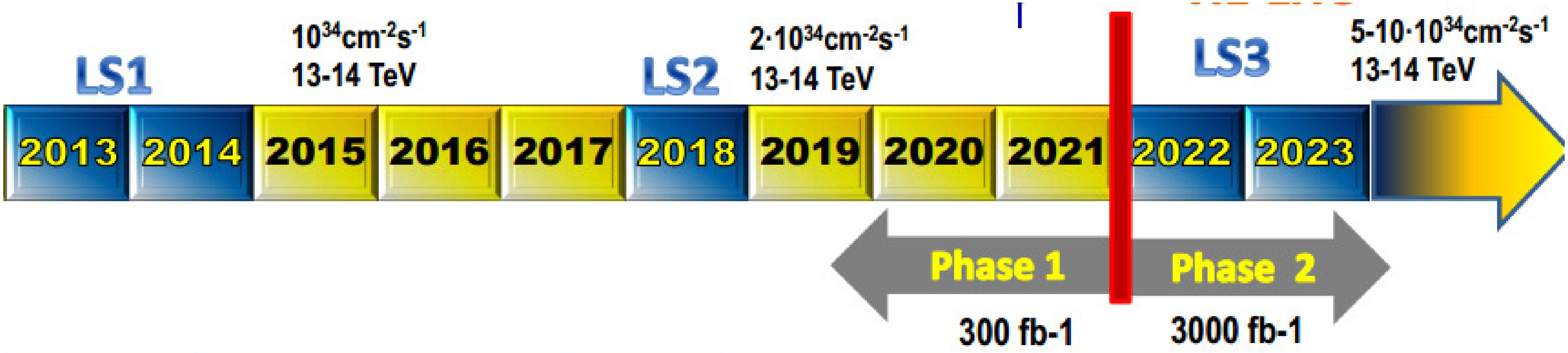


L0 Trigger (L0A)
Move data from first to second buffer in front-end chips

Regional Readout Request (R3)
Read subset of data from second buffer to L1 Track system

Follows ATLAS FTK approach used





LS1

$10^{34}cm^{-2}s^{-1}$
13-14 TeV

LS2

$2\cdot10^{34}cm^{-2}s^{-1}$
13-14 TeV

LS3

$5\text{-}10\cdot10^{34}cm^{-2}s^{-1}$
13-14 TeV

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

Phase 1
300 fb-1

Phase 2
3000 fb-1

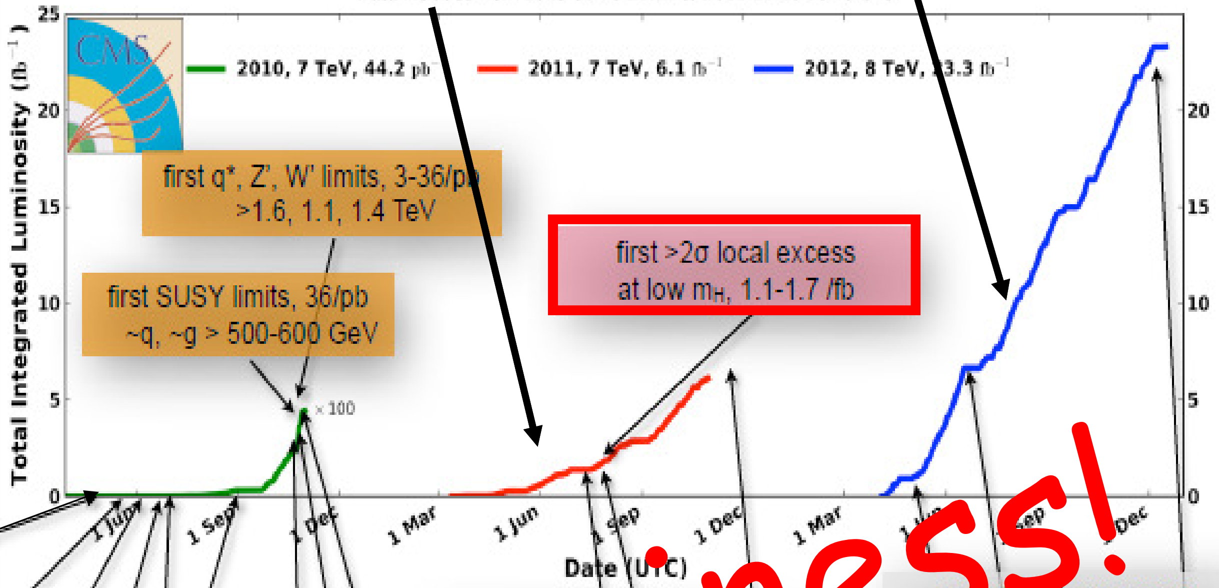
	LS1	2016-17	LS2	LS3
ATLAS	New inner pixel layer Muon extension		Trigger upgrade (L2 FTT), MSW	New Tracker New trigger L0/L1 Muon and calorimeter electronics
CMS	Muon forward HF and HO photodetectors	Pixel	HCAL electronics	New Tracker EE and HE replacement New Muon stations and electronics
ALICE	-	-	Readout 50 kHz. ITS, TPC, MFT	-
LHCb	-	-	Readout 40 MHz. VELO, RICH, Tracking	-

Plenty of barrel muons in online display!

100 Khz barrel muons (all pt)

2009 running:

- Hard to see anything apart from min bias in the displays.
- Serious analysis to find muons in the barrel.



first q*, Z', W' limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb
~q, ~g > 500-600 GeV

first >2σ local excess
at low m_H, 1.1-1.7 /fb

repeating the program
at 8 TeV

first MinBias / UE
studies, particle multiplicities

first top xsec, 3/pb
δ ~ [illegible]

first ZZ xsec, 1.[illegible] /fb
δ ~ [illegible]0%

first incl. [illegible] x-section, 8/nb
δ ~ 1[illegible] %

first single top xsec,
t-chan., 36/pb
δ ~ 36%

going more differential,
e.g. Z/W + j,b,c

a new boson is
announced, 5 /fb

first incl. jet x-section, PF jets
60/nb δ ~ 20-30%

first significant limit on
$B_s \rightarrow \mu\mu$, BR<1.9×10^{-8}

first m_{top}, 36/pb
Δ ~ 6.5 GeV

first incl. W/Z x-sections, 200/nb
δ ~ 4-6%, +11% lumi

first particle discovered
by CMS: Ξ_b

first WW xsec, 36/pb
δ ~ 40%
first limit on HWW

BSM searches continue,
limits pushed

first spin parity
analysis of the boson,
17 /fb

first incl. J/Ψ x-section, 100/nb
δ ~ 20%

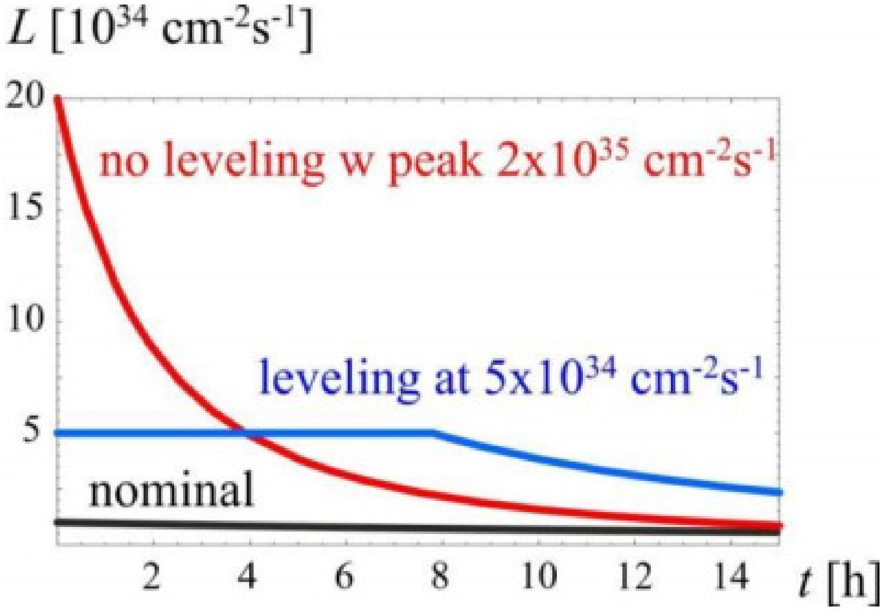
Back to business!

elative uncert Δ .. absolute uncert.

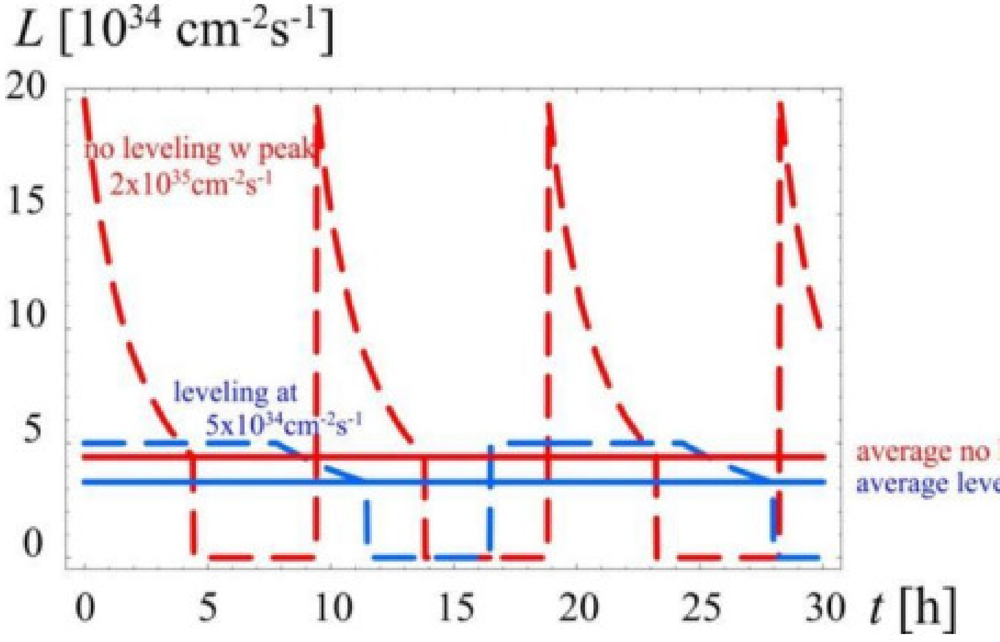
G. Dissertori

End

Luminosity Levelling, a key to success



- High peak luminosity
- Minimize pile-up in experiments and provide “constant” luminosity

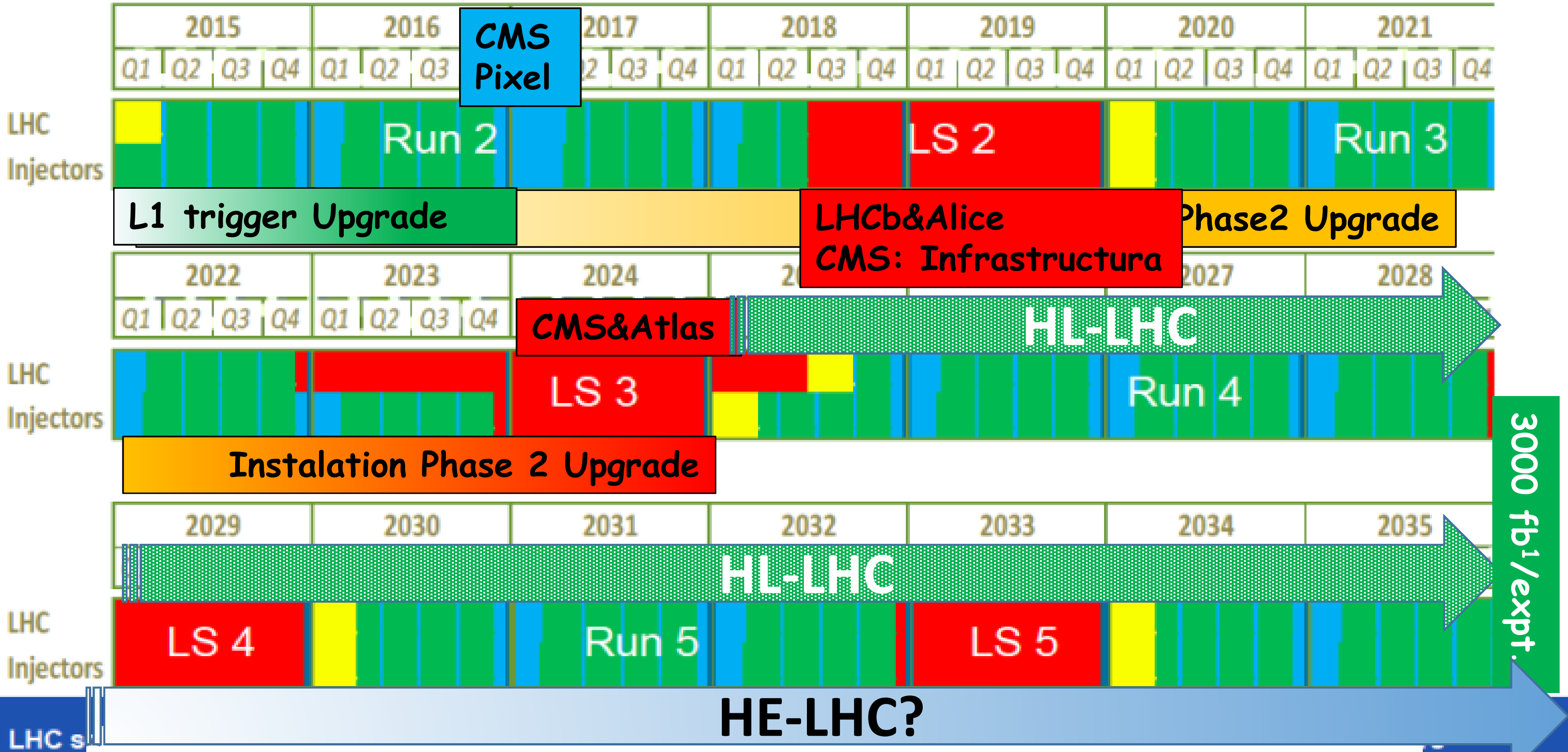


Obtain about 3 - 4 fb^{-1}/day (40% stable beams)

About 250 to 300 fb^{-1}/year

LHC Evolution. HE-LHC??

CMS& Atlas investments for HL-LHC detectors would be also necessary for HE-LHC

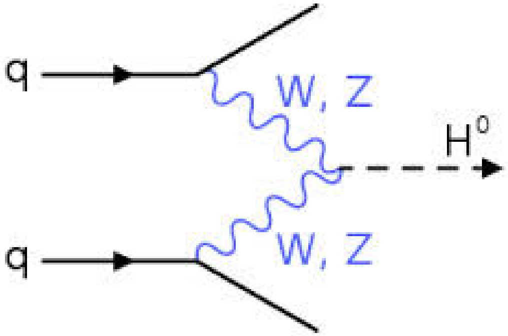


HE-LHC depends on disponility of high field dipoles (*High Energy &Luminosity LHC* , *HELL*)

El HL-LHC es una Factoría de Higgs

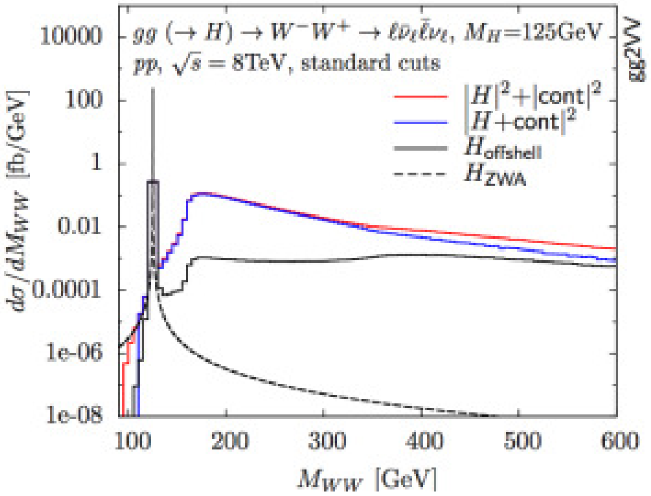
¿Qué se puede hacer con x10 en estadística?

- Verificar BEH estudiando producción de H0 a través del proceso Vector-Boson-Fusion
  - ~estudiar colisiones de bosones vectoriales, proceso donde en ausencia de H^0 la sección eficaz W_LW_L debería divergir.
  - Dos jets en la zona hacia delante

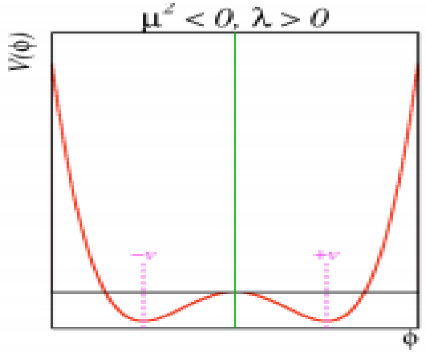


- Medir canales de desintegración raros como el $H^0 \rightarrow \mu^+\mu^-$, el $H^0 \rightarrow c\bar{c}$ (~4 %), pero de difícil detección

- Medida indirecta de la anchura

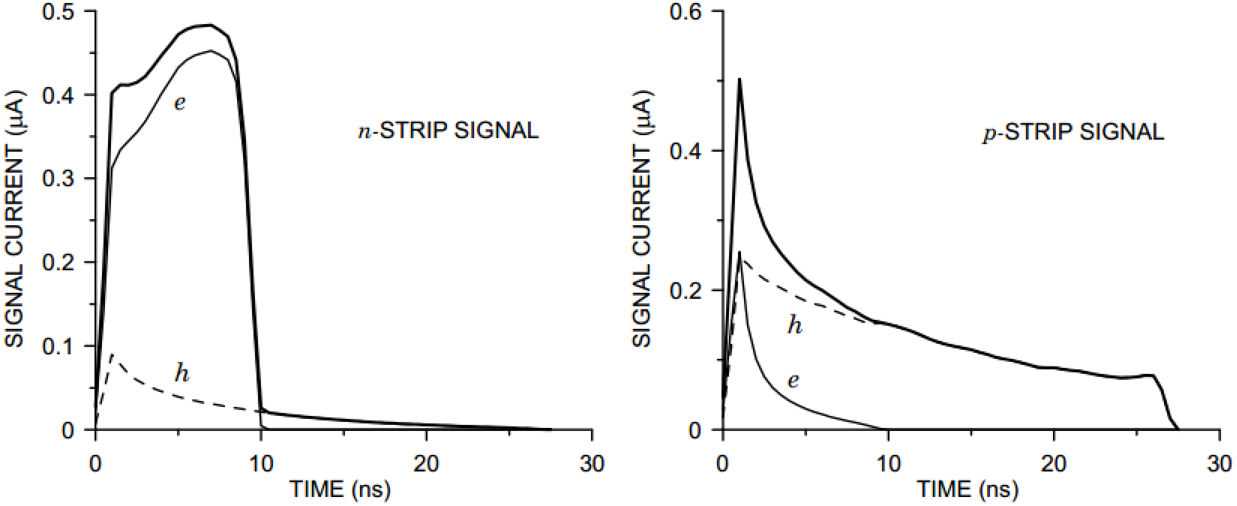


- Medir los acoplos del H^0 consigo mismo usando eventos con 2 H^0



Desafíos experimentales ➔ requiere mejorar los detectores

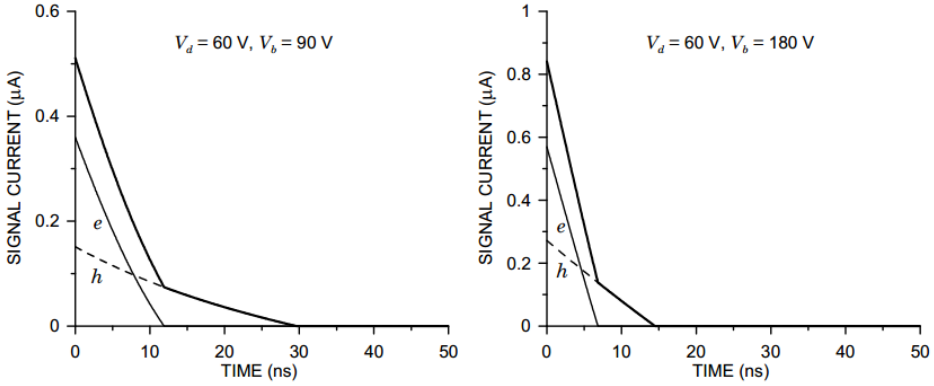
Current pulses in strip detectors (track traversing the detector)



The duration of the electron and hole pulses is determined by the time required to traverse the detector as in a parallel-plate detector, but the shapes are very different.

For comparison:

Current pulses in pad detectors (track traversing the detector)

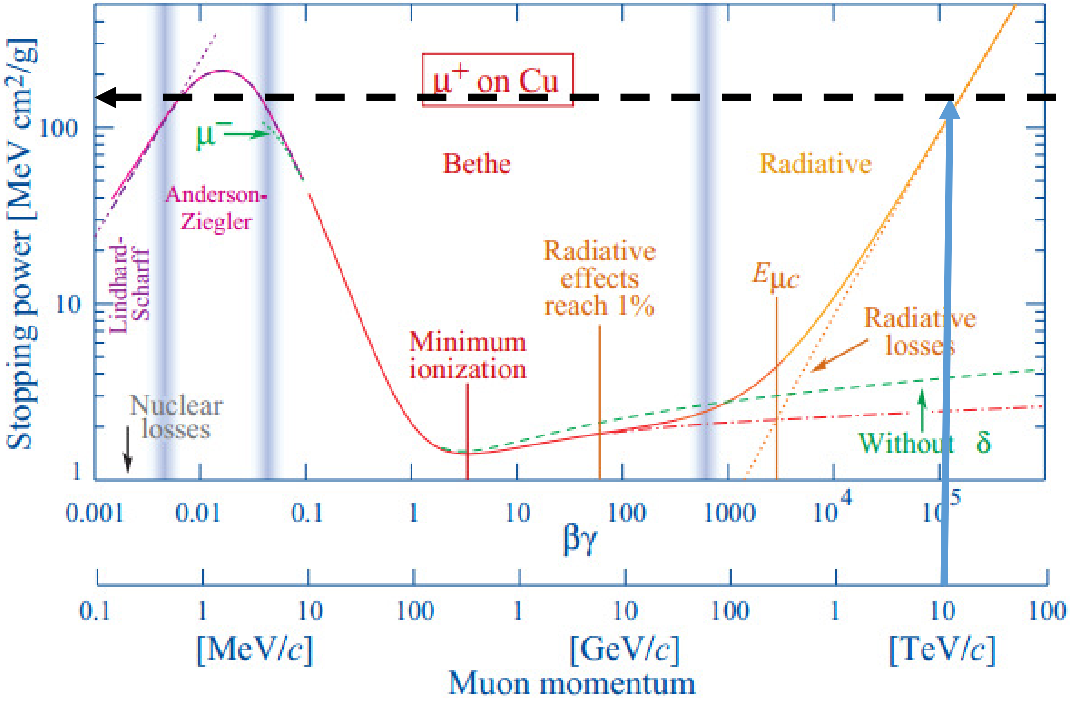


For the same depletion and bias voltages the pulse durations are the same as in strip detectors, although the shapes are very different.

Overbias decreases the collection time.

FCC-hh 100 TeV: Cuando un muon no es un mip…

Medir muones por encima de >10 TeV ~ Medir electrones>100 MeV



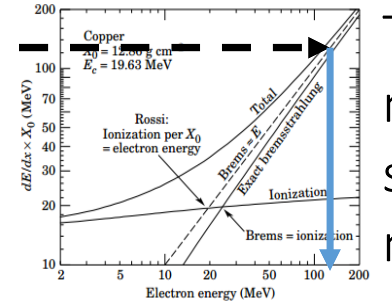


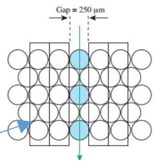
Figure 31.13: Two definitions of the critical energy E_c.

Tras radiar el muon sigue siendo un muon

1. Instrumentar el yoke , para identificar cascadas EM
   - Los muones radian ya en el calorímetro

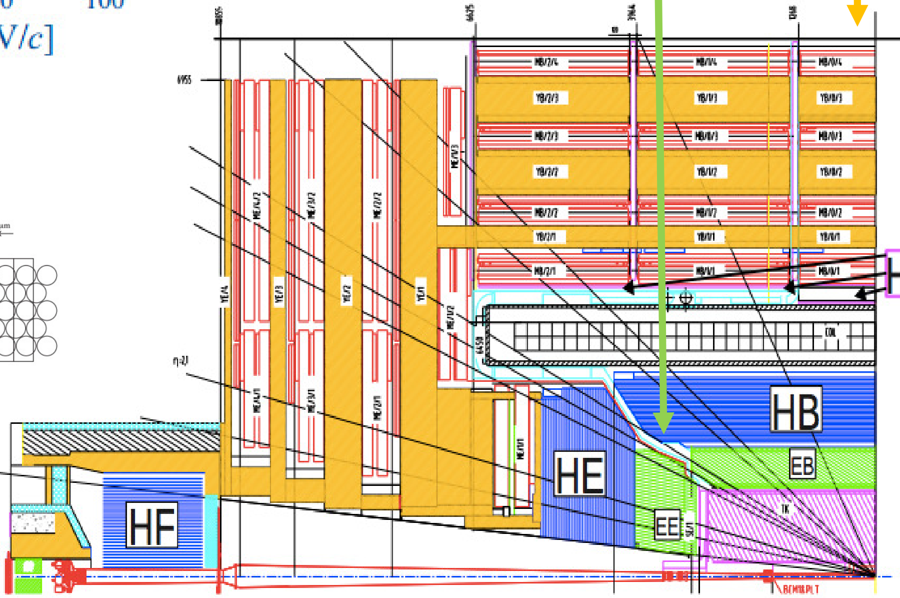
2. Ser capaz de **identificar** a cualquier profundidad del calorímetro al mismo tiempo

- Traza aislada del muon
- Cascada electromagnética

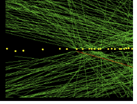


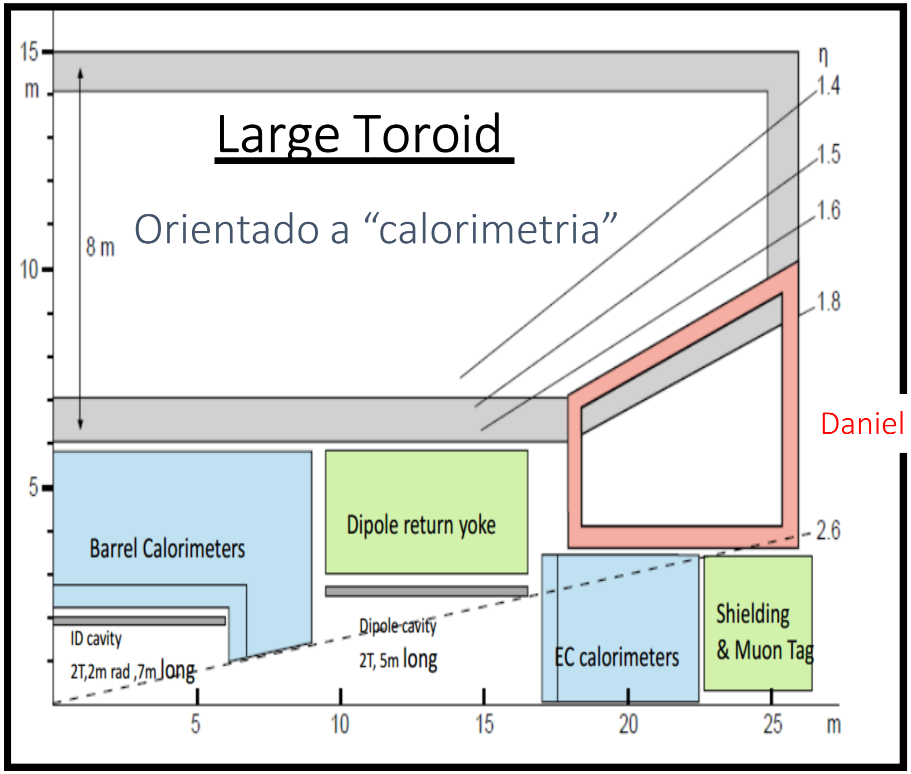
LHCb tracker upgrade

➔ **varios planos** (MPGD stack o fibras) en la zona de sampling activo de un calorímetro de **alta granularidad** para poder **medir segmentos** y así reconstruir trazas de muones



Conceptos de detectores en FCC-hh 100 TeV





Large Toroid

Orientado a "calorimetria"

Daniel Fournier

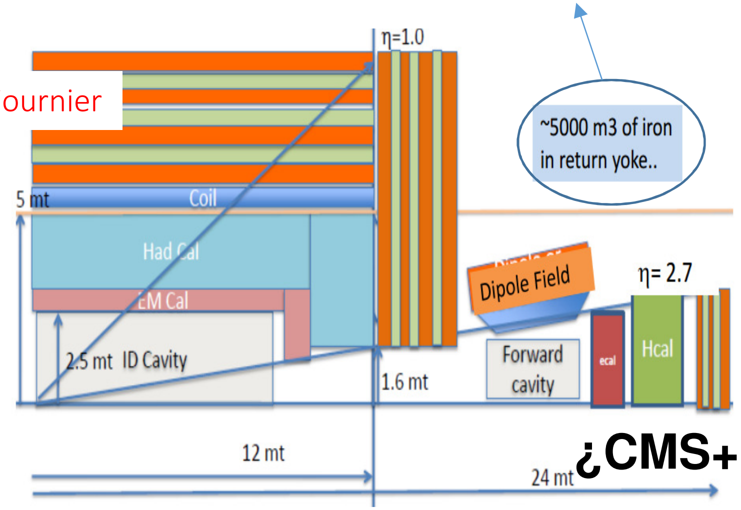
Large Solenoid

Orientado a *"Tracking"*

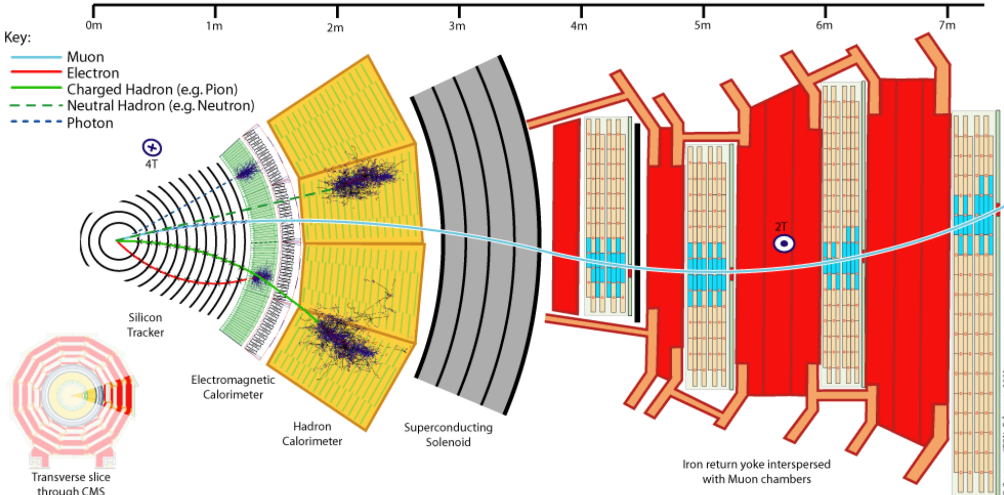
5 T, con Nb_3Sn disponible ➔¿demasiado conservador?

Respecto a CMS: $R_{interno}$ ~x 5/3 : $R_{externo}$ ~x10/7

- ~x 2 superficie de cámaras de muones



¿CMS+LHCb?



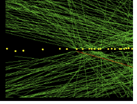
¿Insistir en calorimetría hadrónica fina dentro del solenoide a 100 TeV?

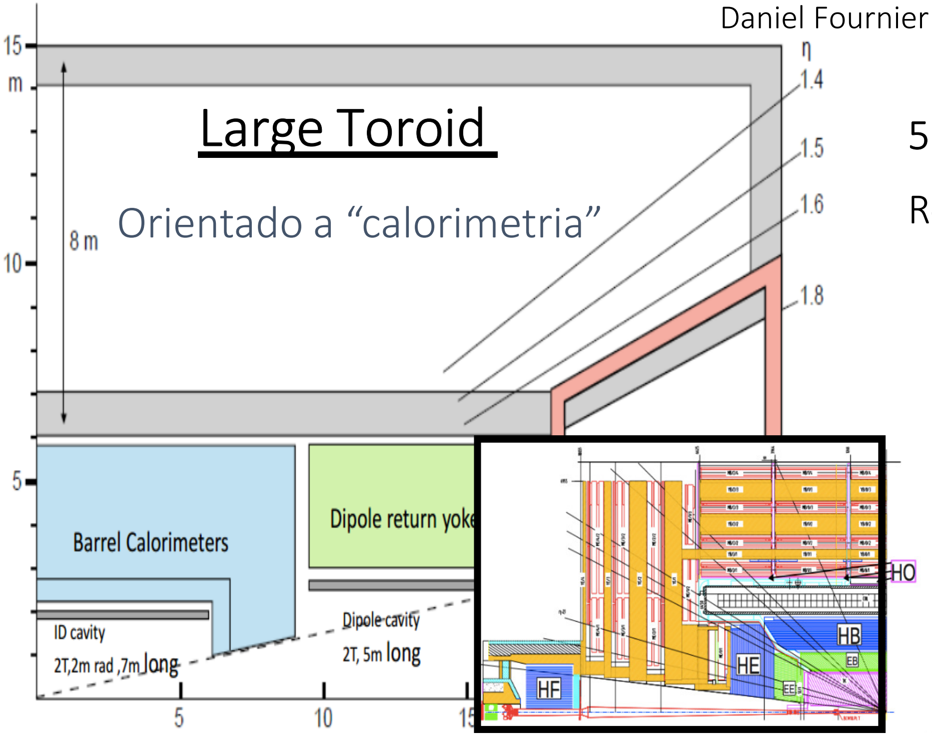
¿Material dentro del calorímetro EM x2?

¿Combinación muones- tracker?

¿10 TeV Muon+γ?

Conceptos de detectores en FCC-hh 100 TeV





Daniel Fournier

Large Toroid

Orientado a "calorimetria"

¿Insistir en calorimetría hadrónica fina dentro del solenoide a 100 TeV?

¿Material dentro del calorímetro EM x2?

¿Combinación muones- tracker?

¿10 TeV Muon+γ?

El mejor detector no es la suma de las mejores componentes

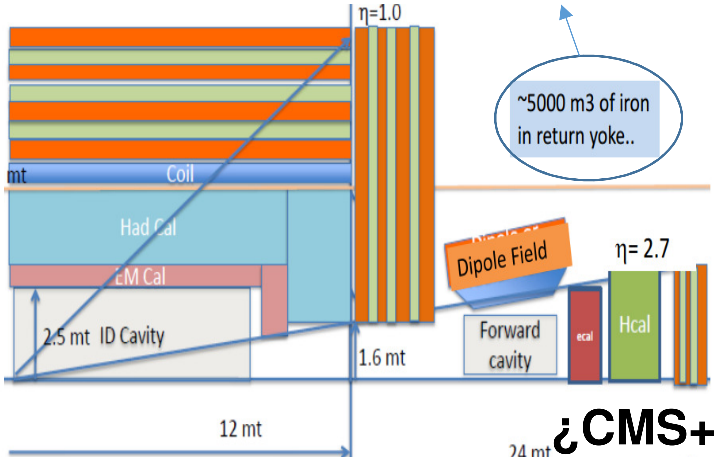
Large Solenoid

Orientado a "*Tracking*"

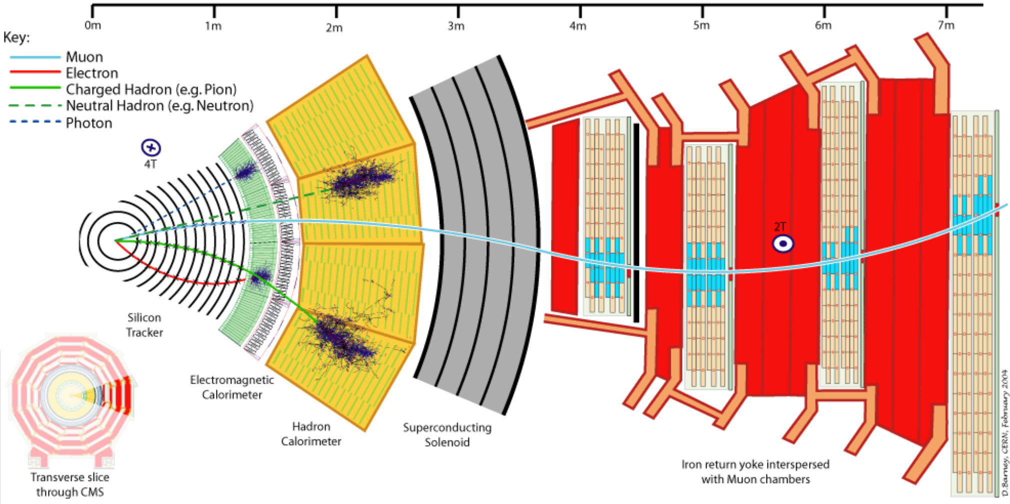
5 T, con Nb_3Sn disponible ➔¿demasiado conservador?

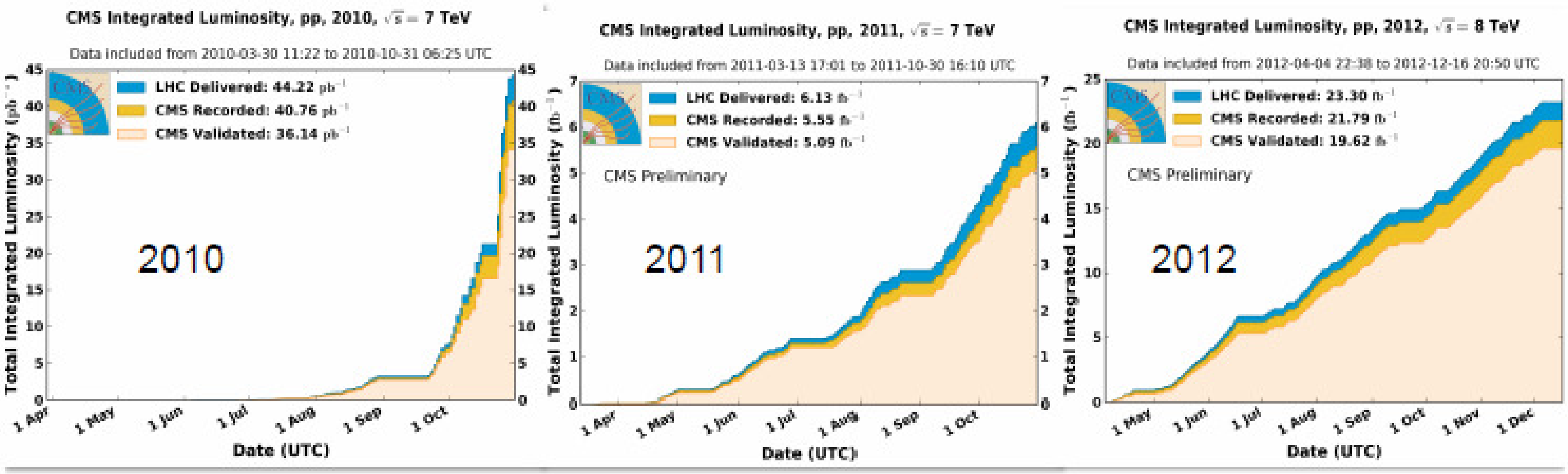
Respecto a CMS: $R_{interno}$ ~x 5/3 : $R_{externo}$ ~x10/7

- ~x 2 superficie de cámaras de muones



¿CMS+LHCb?

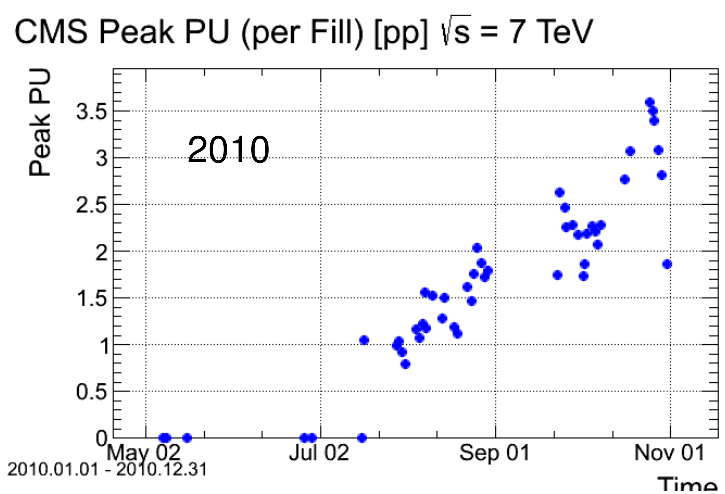


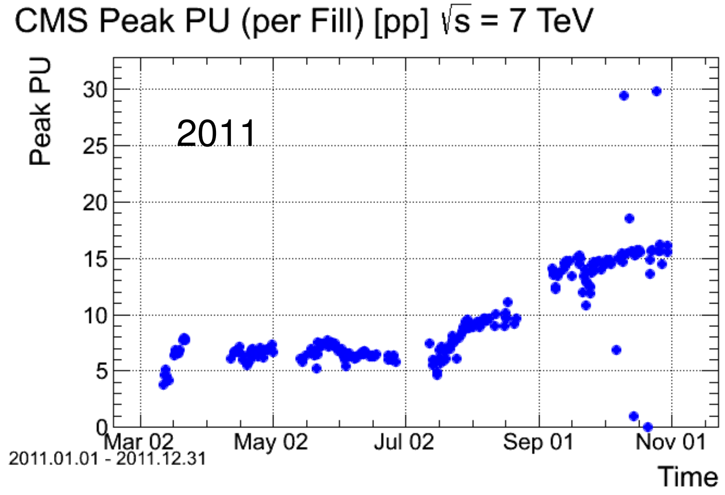


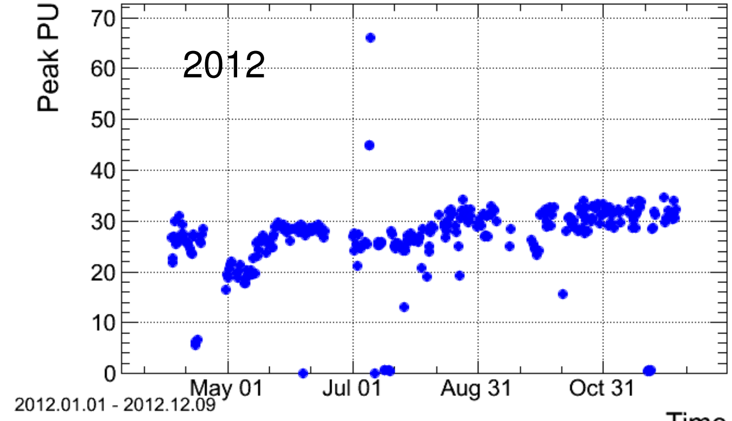
- •Final refinements in automation during 2012
- •Excellent data taking efficiency
- •Expertise did not fly away to the next collider (Where?)
- •Data validated stable at 90 %

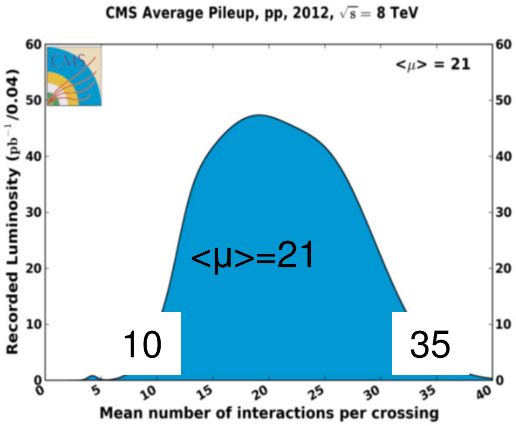
Period	$\sqrt{s}$ [GeV]	Delivered luminosity [fb^{-1}]	Data taking efficiency [%]	Data validated [%]
2010	7	0.044	92.2	88.6
2011	7	6.13	90.5	90.1
2012	8	23.20	93.5	90.0

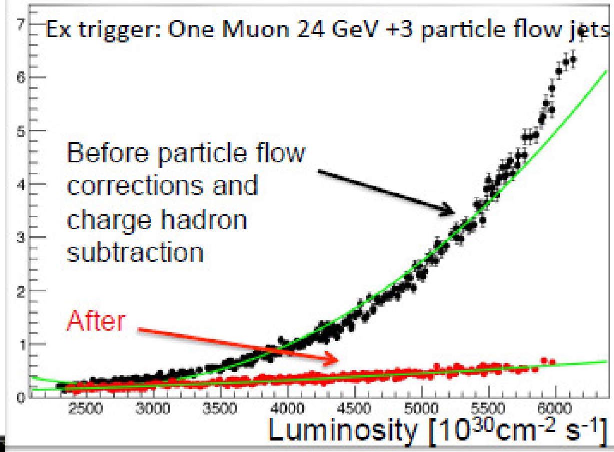
- Pileup increase forced CMS to adapt to varying data taking conditions
- From FW changes to trigger menus
- Offline algorithms (Particle flow) moved to HLT helped

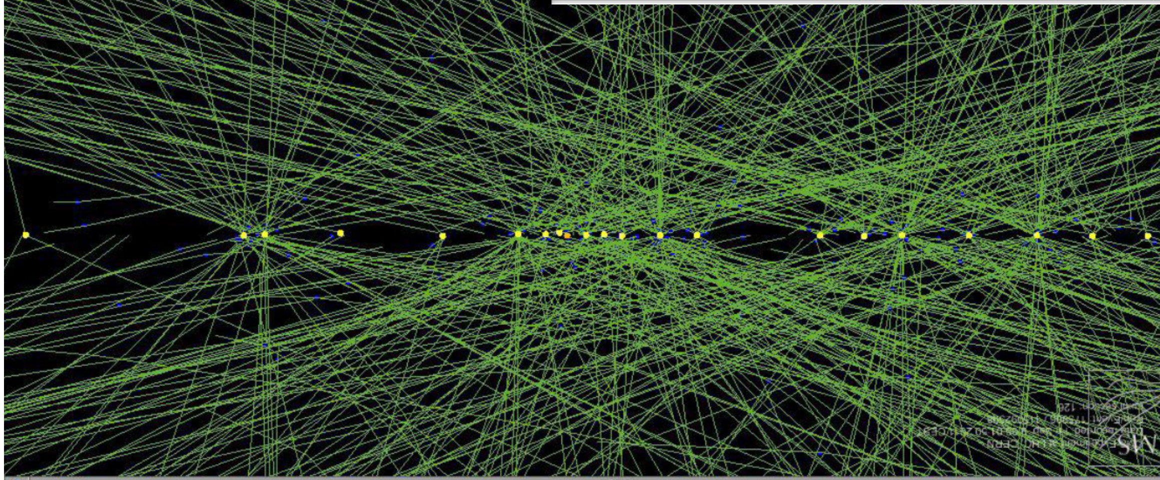




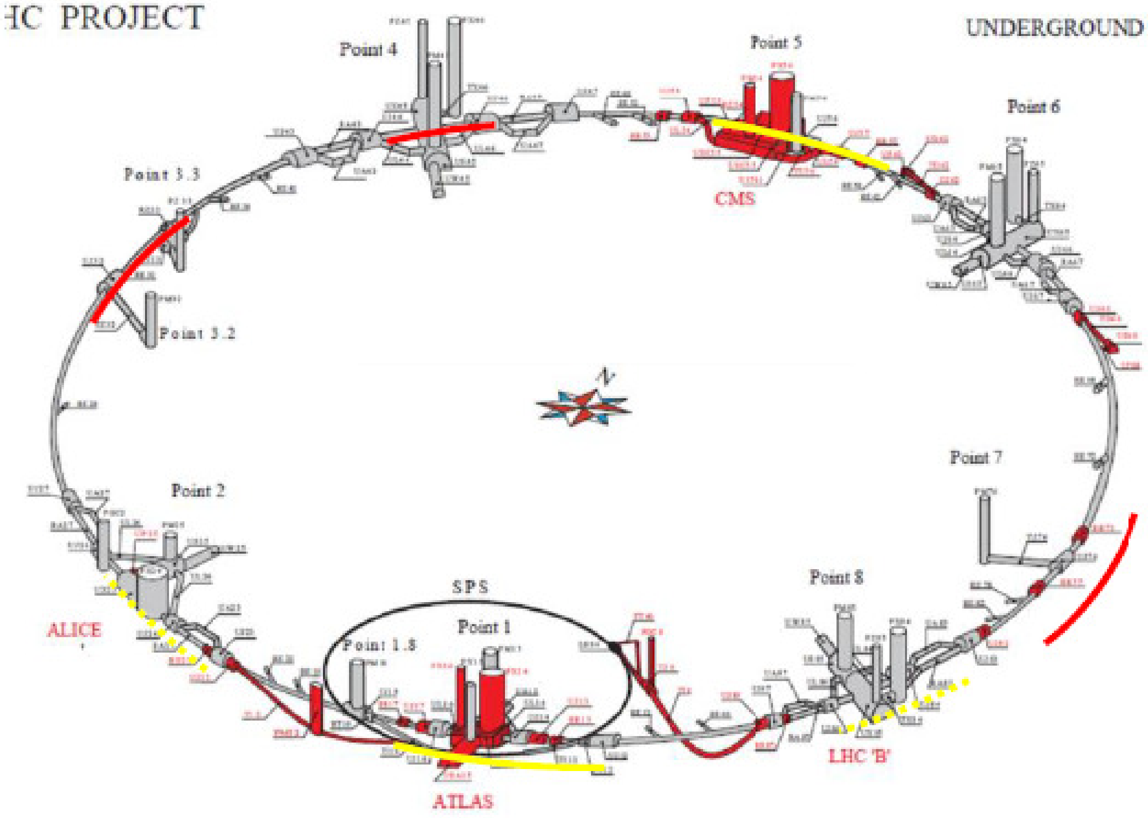








The HL-LHC Project



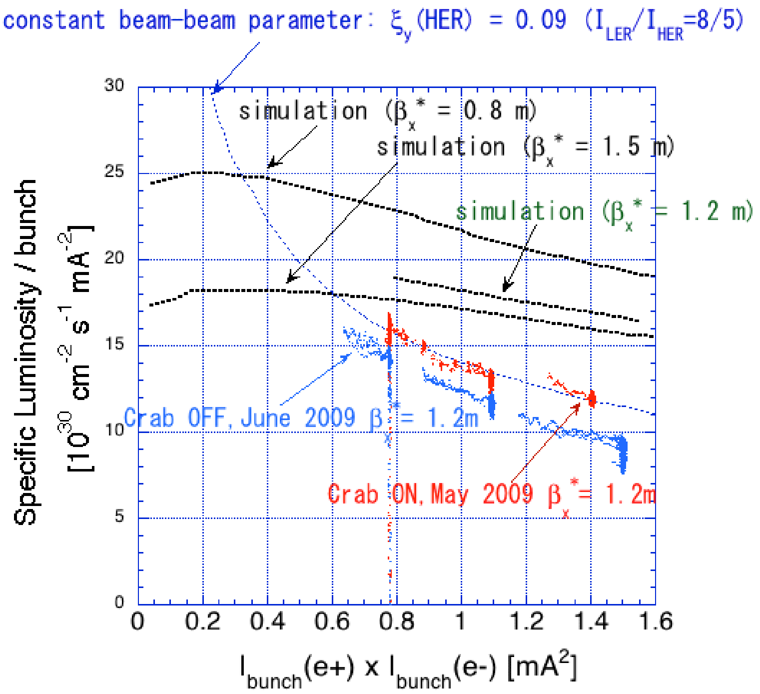
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Brüning

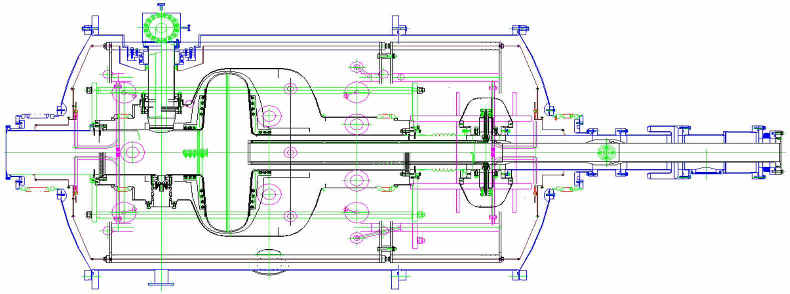
Crab Cavities History: 1988 to 2009

K. Hosoyama, 2010



R. Palmer, 1988, LC

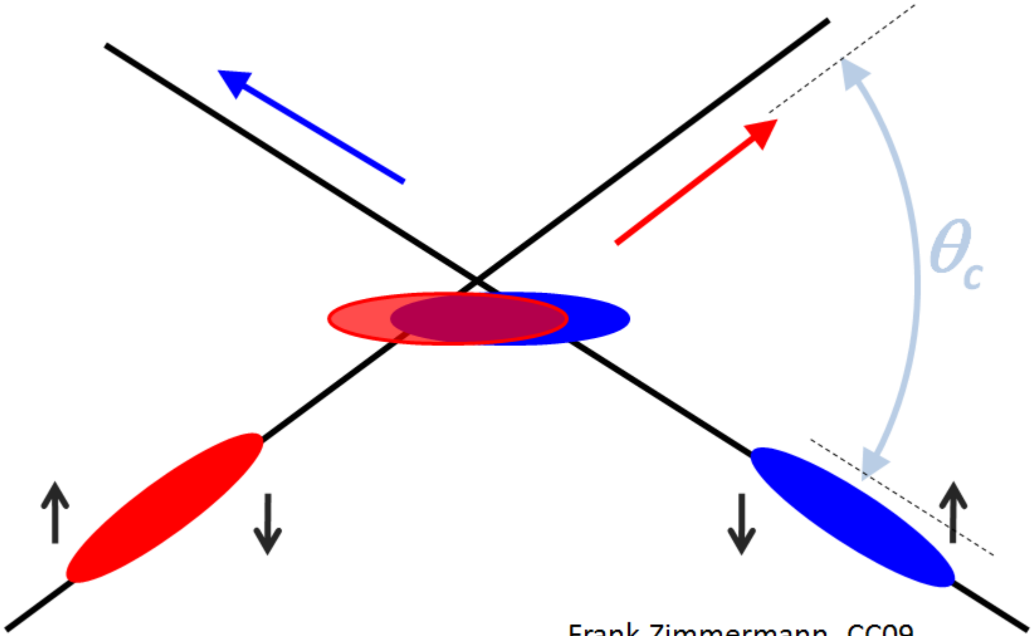
Elliptical Technology



In operation at KEKB 2007 - 2011 →

world record luminosity!

Principle of Crab Cavity operation

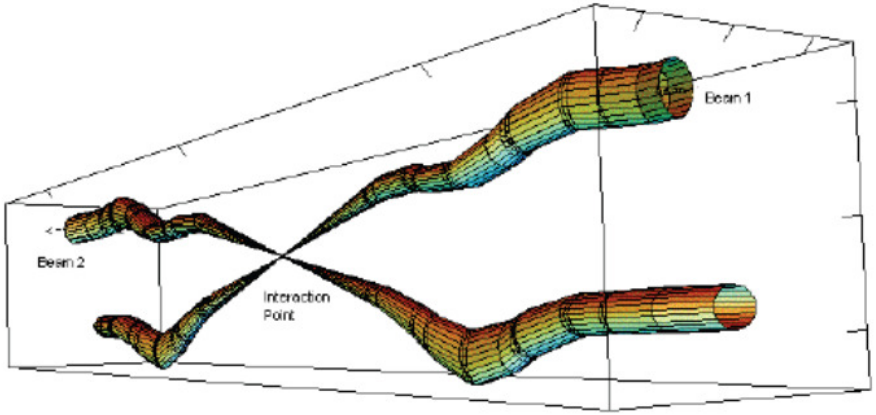


Frank Zimmermann, CC09

RF crab cavity deflects head and tail in opposite direction so that collision is effectively "head on" for luminosity and tune shift

Bunch centroids still cross at an angle (easy separation)

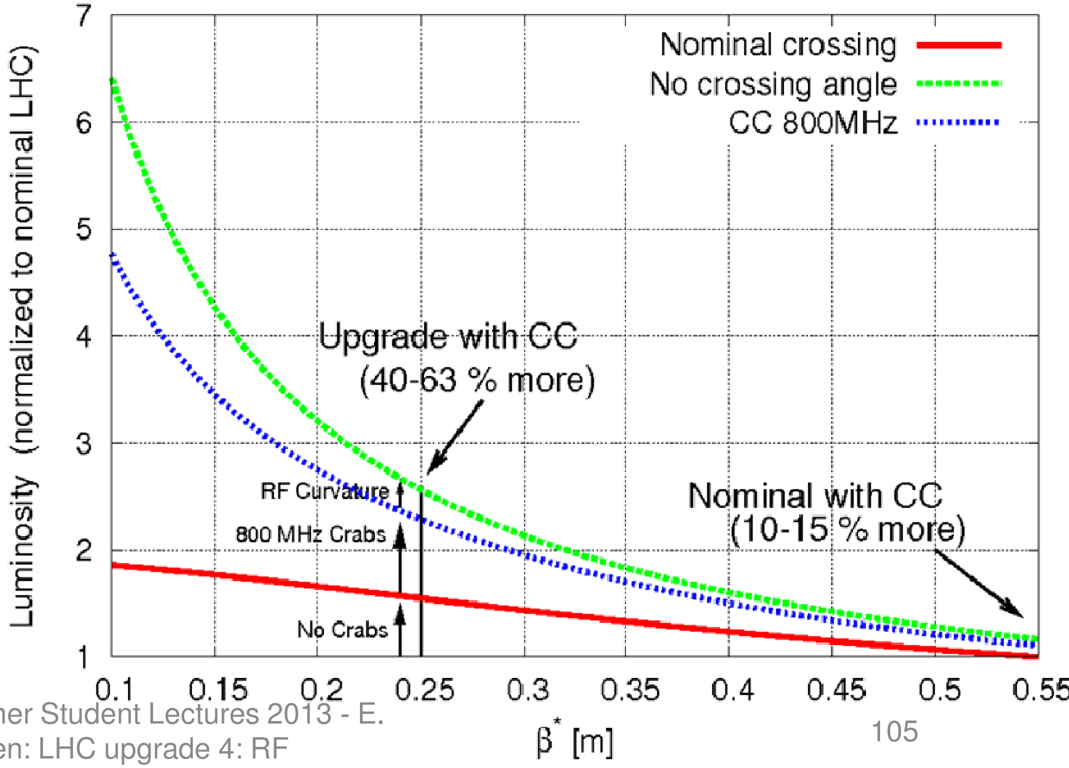
Crab Cavities – context



Relative beam sizes around IP1 (Atlas) in collision

- Many bunches require **non-zero crossing angle** to avoid parasitic collisions and to reduce beam-beam effects;
- With non-zero crossing angle, luminosity gain by squeezing beams further is small (red curve below).

- Crab cavities can compensate for this geometric effect and thus allow for a luminosity increase of about 50 % at *β** of 25 cm.
- In addition, crab cavities provide a knob for **luminosity levelling**;
- This allows optimizing for **integrated** rather than peak **luminosity**!

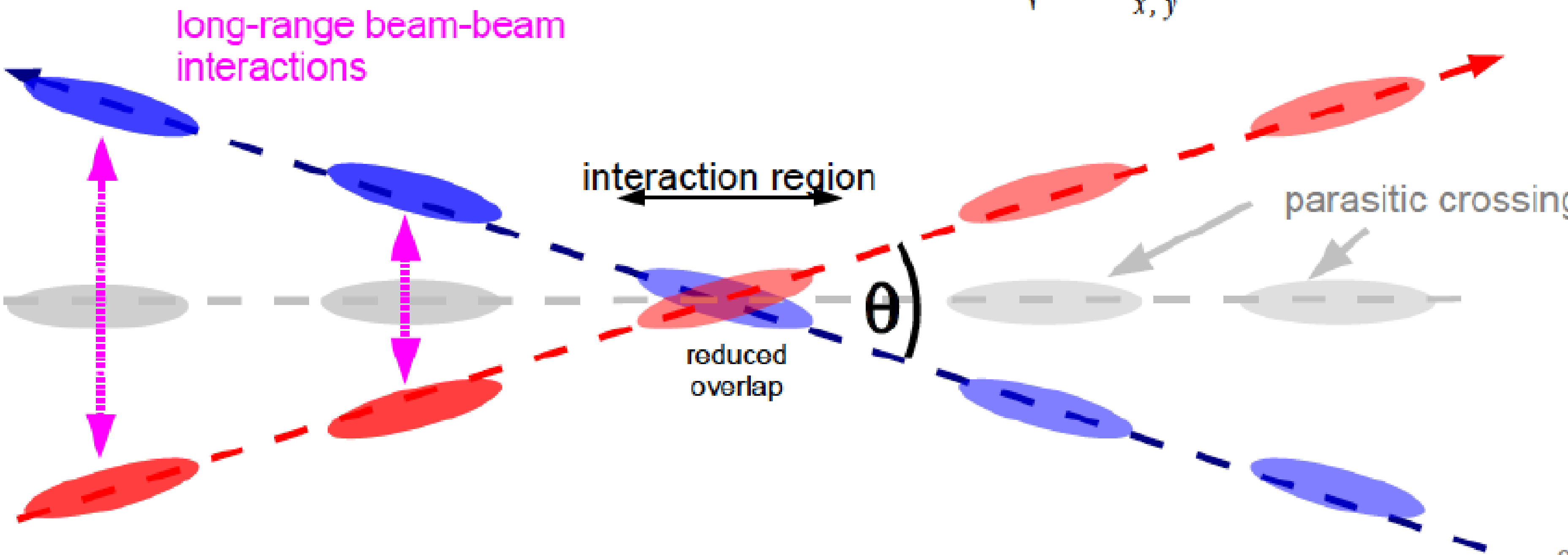


Beam-Beam Interactions in a Nutshell

- Need crossing angle θ to avoid parasitic crossings
  → reduces bunch overlap & luminosity
- Two mitigations:
  - "crab cavities" rotating the bunches before and after the IR
  - beam-beam compensator (BBC) mitigating effect of long-range interactions
  - present LHC: $F_{crossing} \approx 0.7 \rightarrow$ HL-LHC ~ 0.2

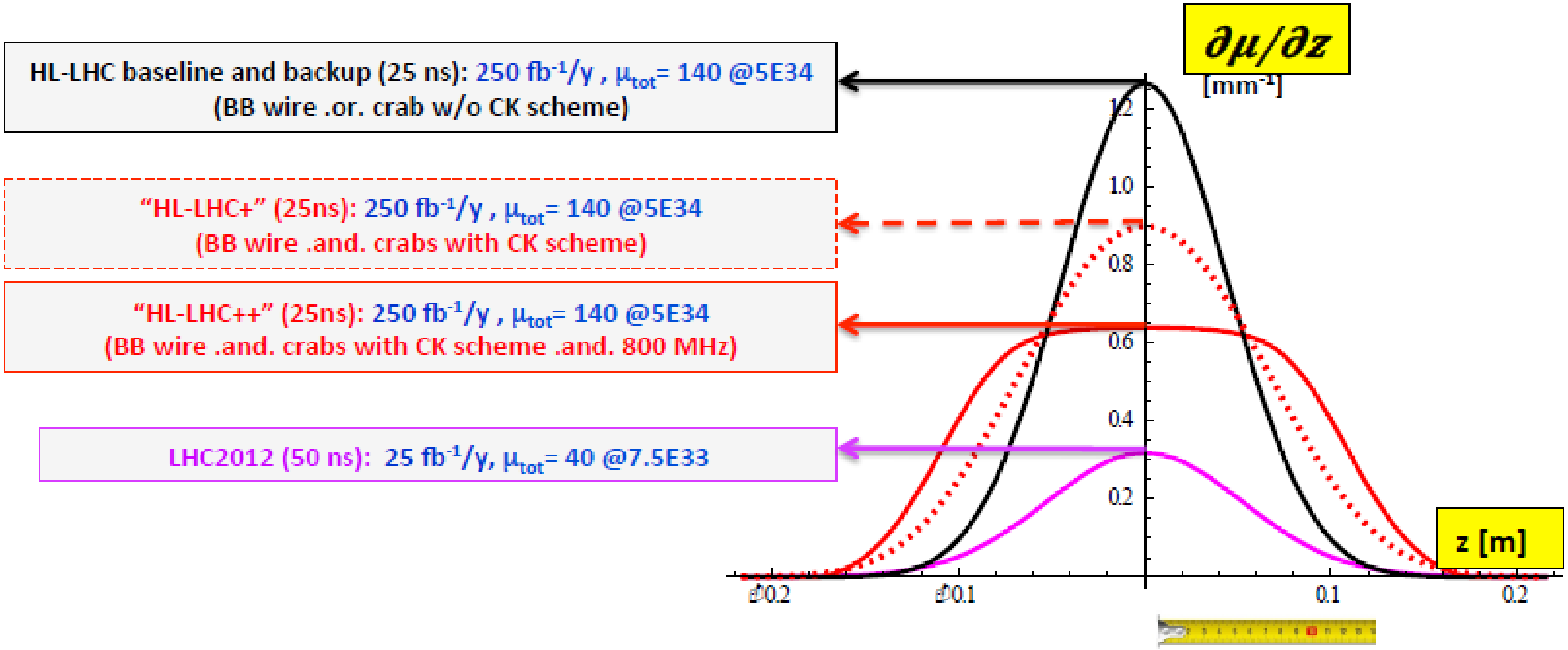
$$L = L_0 \cdot F_{crossing} \cdot \ldots$$

$$F_{crossing} = \frac{1}{\sqrt{1 + \frac{\sigma_s}{\sigma_{x,y}} \tan(\theta/2)}}$$



Interaction region customization

Pileup Density



HL-LHC baseline and backup (25 ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .or. crab w/o CK scheme)

"HL-LHC+" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme)

"HL-LHC++" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme .and. 800 MHz)

LHC2012 (50 ns): 25 fb^{-1}/y, μ_{tot}= 40 @7.5E33

Some of these schemes produce interaction regions that vary over time

➔ Experiments should monitor over an accelerator fill and translate to luminosity estimations…