Future Collider Detectors and Technologies

2018 LHC days in Split

Split, Sep. 17-22, 2018

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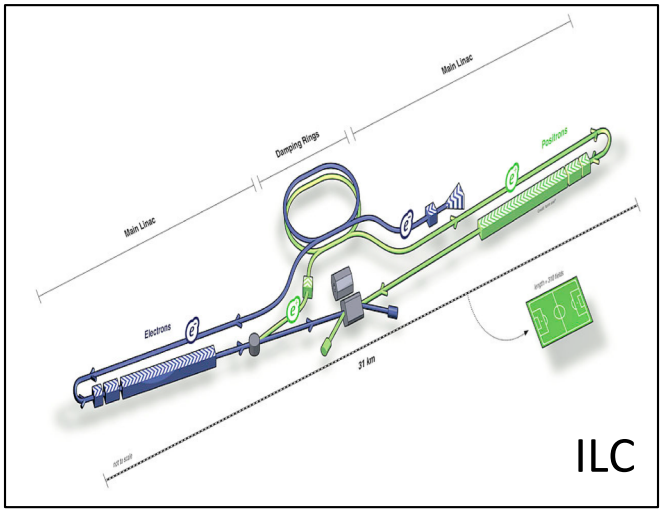
Outline

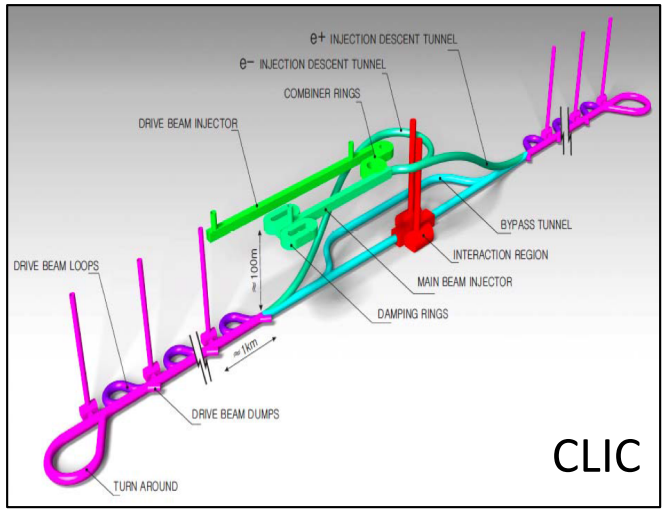
- Introduction to HEP collider projects and detector concepts
- Technology trends illustrated with HL-LHC upgrades

Future collider projects

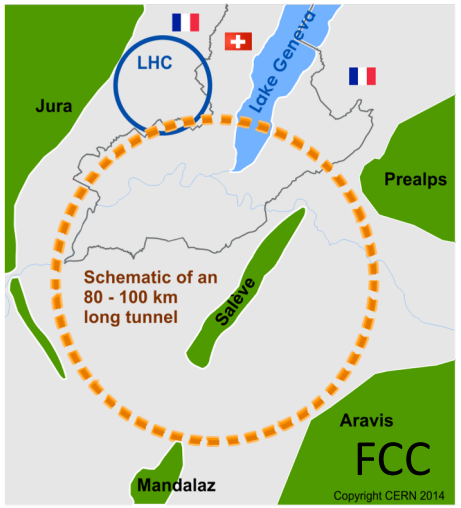
- International Linear Collider (ILC) e^+e^-
  - 2/3 steps $\sqrt{s} \simeq 250/380/500$ GeV, $\simeq 20$ years for 6 ab^{-1}, 2 push-pull experiments
- Compact LInear Collider (CLIC) e^+e^-
  - 2/3 steps $\sqrt{s} \simeq 0.38/1.5/3$ TeV, $\simeq 20$ years for 3 ab^{-1}, 2 push-pull experiments
- High Energy LHC (HE-LHC) pp
  - $\sqrt{s} \simeq 27$ TeV, $\simeq 10$ years for 15 ab^{-1}, 2 experiments operating in parallel
- Future Circular Collider (FCC):
  - FCC-pp $\sqrt{s} \simeq 100$ TeV, $\simeq 25$ years for 40 ab^{-1}, FCC-ee $\sqrt{s} \simeq 350$ GeV $\simeq 15$ years for 13 ab^{-1}, FCC-pe: $\sqrt{s} \simeq 3.5$ TeV, 2 experiments operating in parallel
- SPPC/CEPC China project comparable to FCC



2x11 km, 1.3 GHz SCRF cavities 30 MV/m (Japan)

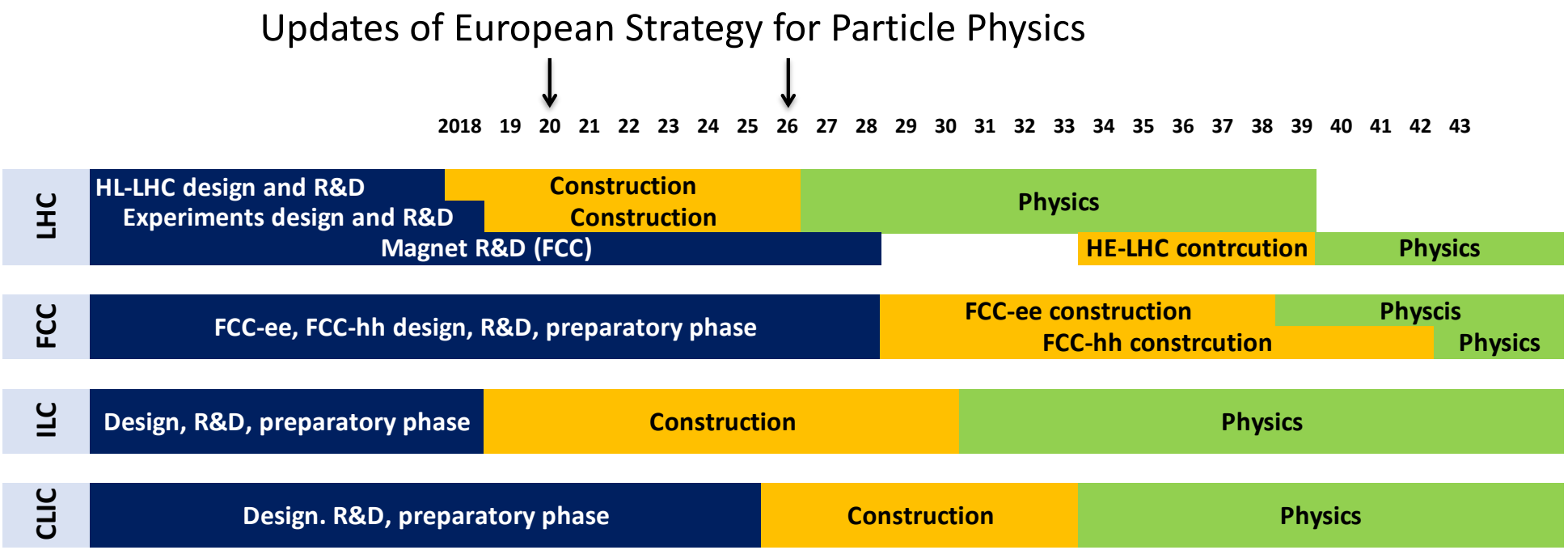


11/29/50 km for 0.38/1.5/3 TeV, drive beams provide RF power, 12 GHz, 100 MV/m (CERN)



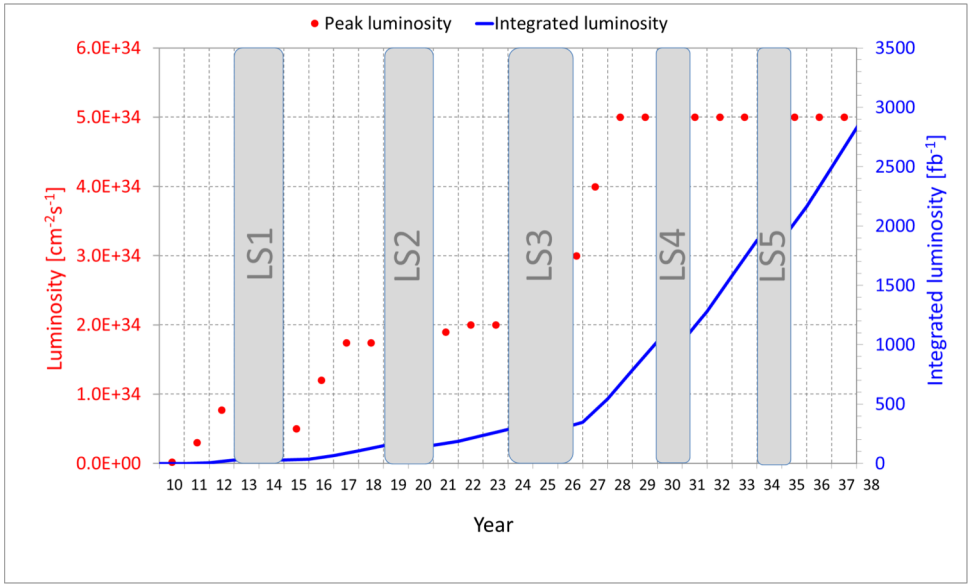
100 km, 16 T magnets (CERN)

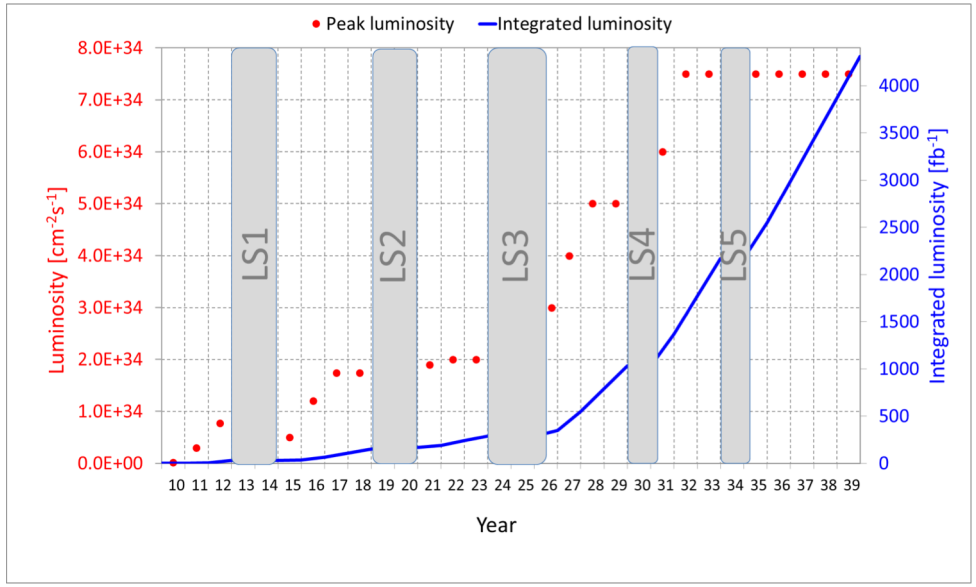
Future collider projects broad brush planning



- High Luminosity LHC program is entering production stage
- Japan decision on ILC end-2018?
- European Strategy decision in 2026?

LHC and HL-LHC p-p luminosity planning*



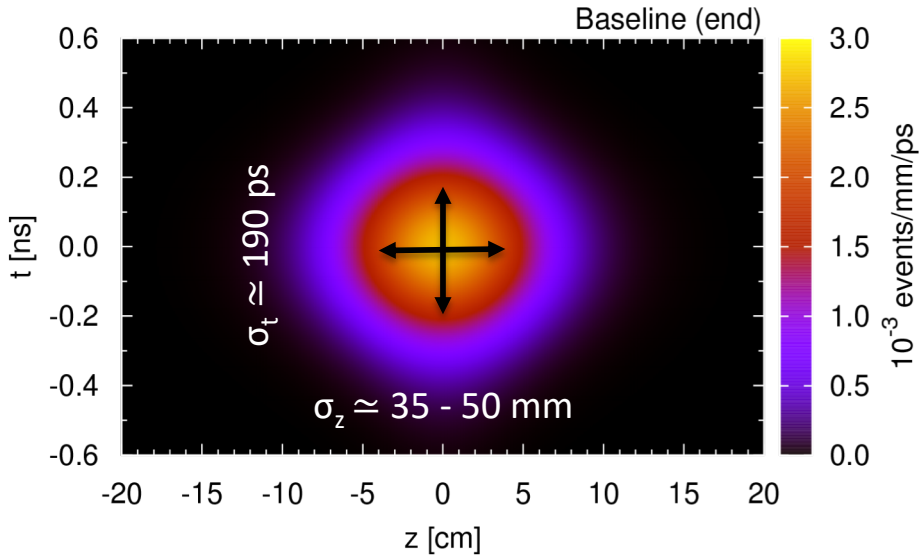


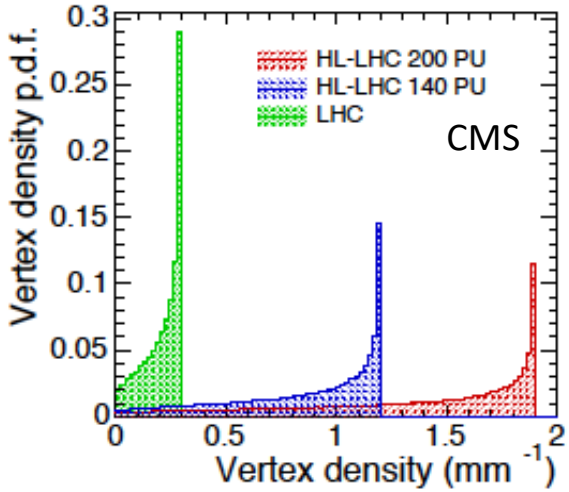
Nominal luminosity: 5 x 10^{34} Hz/cm^2 instantaneous - 140 collisions on average (pileup) per beam crossing (every 25ns)

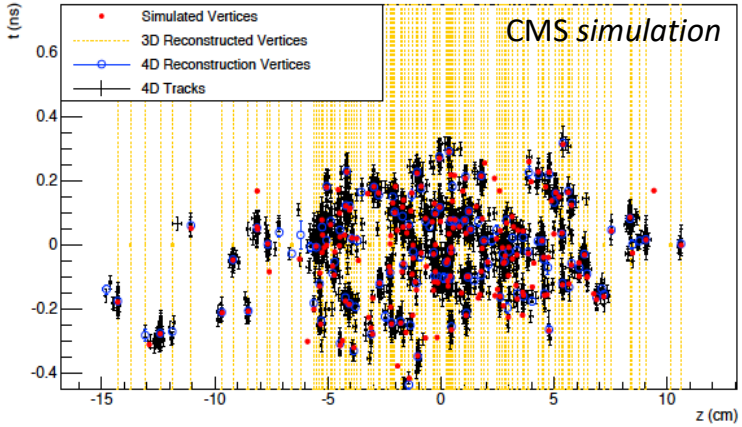
Ultimate luminosity: 7.5 x 10^{34} Hz/cm^2 instantaneous - 200 collisions on average (pileup) per beam crossing (every 25ns)

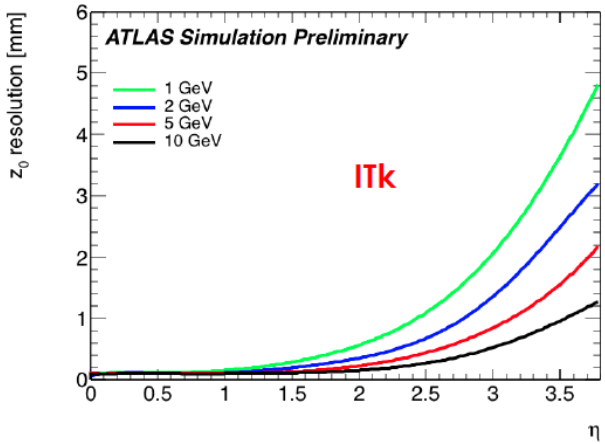
* It is also foreseen to continue the Heavy Ion physics program up to LS4

Luminous region and collision pileup at HL-LHC









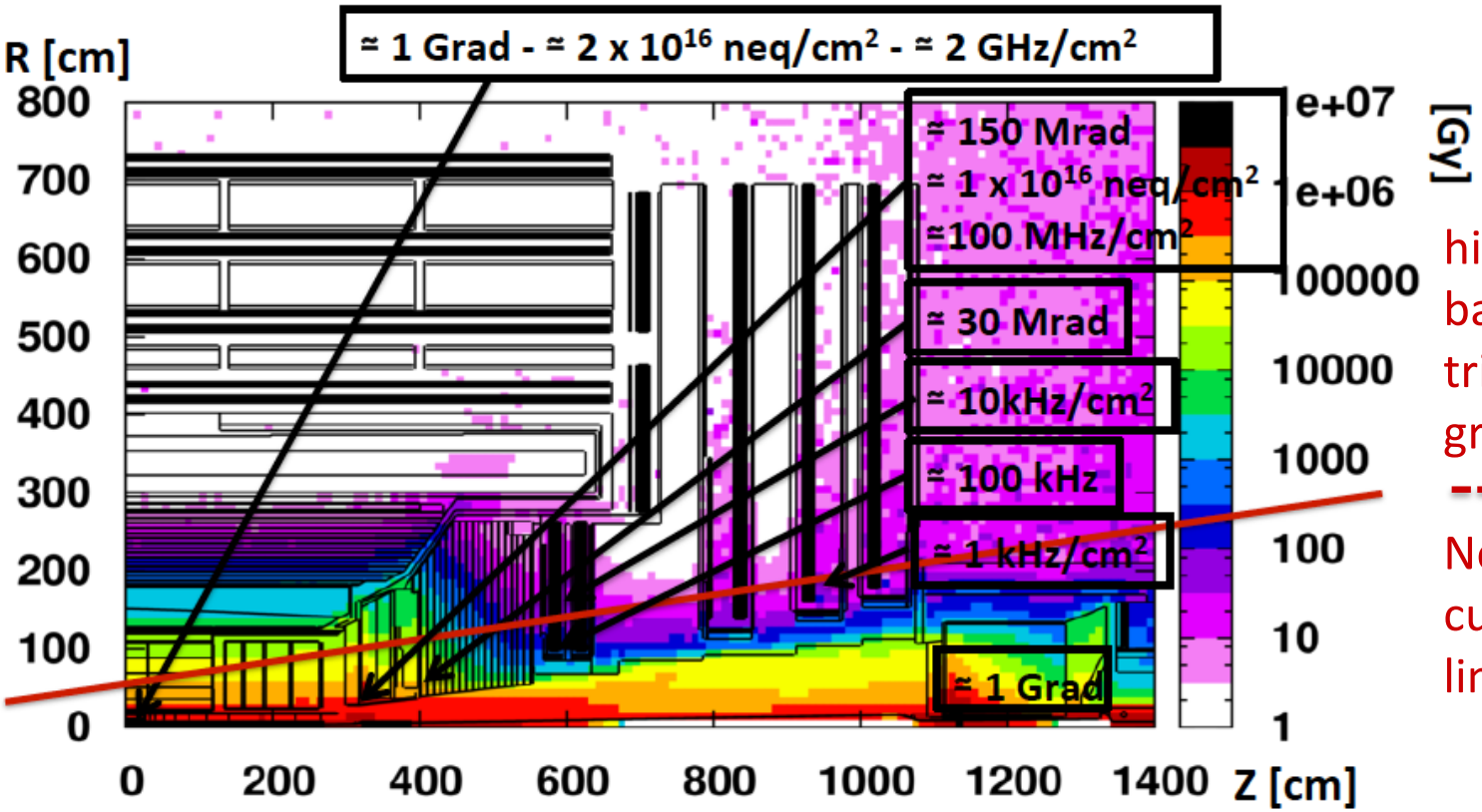
Performance is mostly sensitive to pileup density for reconstruction-ID of e/γ, μ, τ, jets - global variable as Hadron and Missing Energy Transverse are also sensitive to total pile-up

Precise time of flight measurement ≃ 30 ps allows to reduce effective pileup to about LHC

Increased event complexity requires more processing and storage power

Implication of irradiation and data flows at HL-LHC

Example of CMS irradiation and rate map for 5 x 10^{34} Hz/cm^2 and 3000 fb^{-1} luminosities



higher readout bandwidth & first level trigger with full granularity

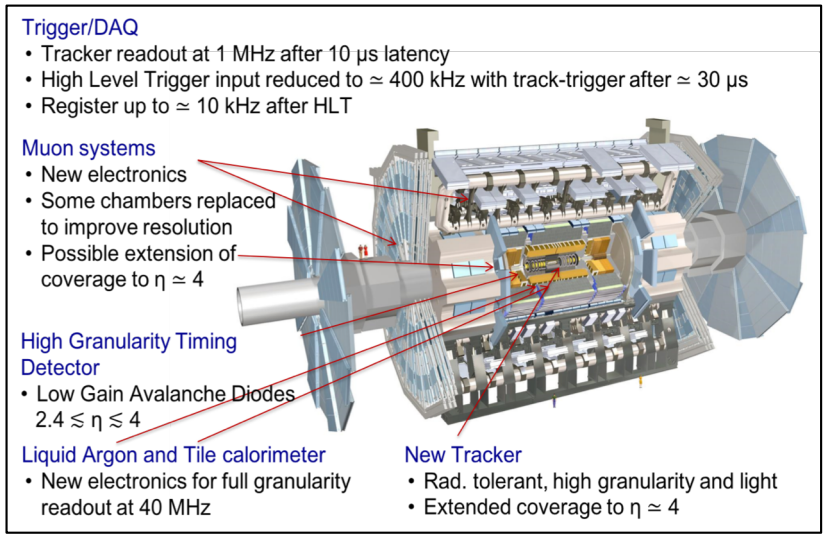
New detectors probing current technology limits (irradiation/rates)

Technology choices adapted to order of magnitudes across the detectors to optimize performance versus cost (even within a system)

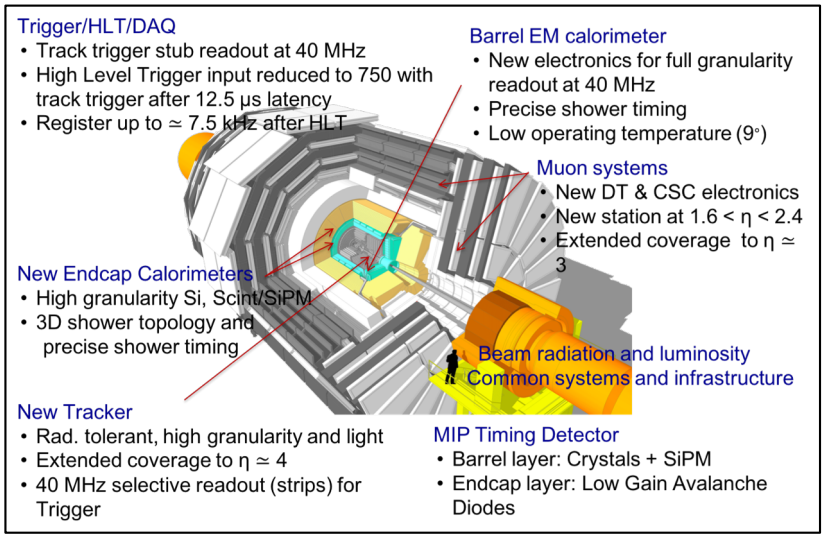
Activation of materials becomes an issue for detector maintenance

New paradigms of LHC experiment upgrades

- ATLAS and CMS Tracker granularity increased by ≃ 5 (pixels and strips), reduced material by ≃ /2, extension to η ≃ 4
- CMS High Granularity Calorimeter - based on CALICE concept (ILC)
- ATLAS and CMS precision timing detectors
- ATLAS and CMS track reconstruction in hardware trigger level
  - ATLAS L0 at 1 MHz possible upgrade to 4 MHz with regional tracker readout and L1-Level
  - CMS 40 MHz Outer Tracker Pt ≥ 2 GeV
- LHCb online trigger only at 40 MHz for 20 kHz events registered (throughput 4 TB/s ≃ ATLAS/CMS at HL-LHC) - pixel detector very similar to ATLAS and CMS HL-LHC (in LS2)
- ALICE 50 kHz full online reconstruction with FPGAs and GPUs (reduce 1 TBps to 90 GBps for storage) - largest and most accurate pixel system at LHC



ATLAS at HL-LHC



CMS at HL-LHC

HE-LHC, FCC and SPPC p-p beam parameter scenarios

parameter	FCC-hh		SPPC	HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	5 (7.5)
Mean collisions/crossing (PU)	170	<1020 (204)	400	850	140 (200)

Detectors will have to cope with ≃ x5 more rates, pileup, data volumes and irradiation* (for equivalent exploitation time) than at HL-LHC:

- New technologies or (several) detector replacements for irradiation
- Another step in systems granularity and tracking precision for pileup
- Precision timing for both charged and neutral particles for pileup

A 5 ns bunch spacing at FCC would still require a granularity step (to avoid out of time pileup in same channel), and precision timing (due to signal time constants)

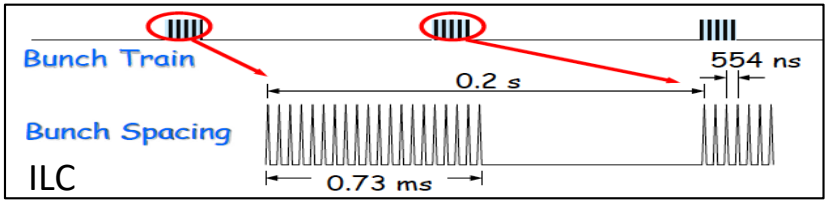
* FCC min bias event are not too different from HL-LHC: 5.4 → 8 charged/η - <Pt> 0.6 → 0.8 GeV/c

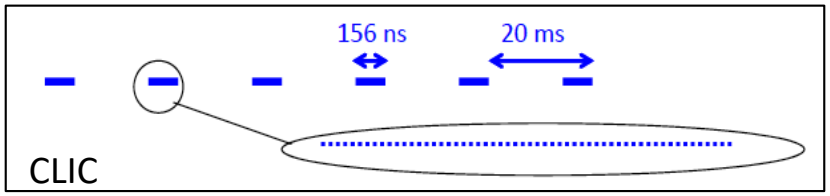
ILC, CLIC, FCC-ee beam parameter scenarios

	ILC at 500 GeV	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	$2x10^{34}$	$6x10^{34}$
BX separation	554 ns	0.5 ns
#BX / train	1312	312
Train duration	727 µs	156 ns
Train repetition rate	5 Hz	50 Hz
Duty cycle	0.36%	0.00078%
σ_x / σ_y (nm)	474 / 6	≈ 45 / 1
σ_z (µm)	300	44

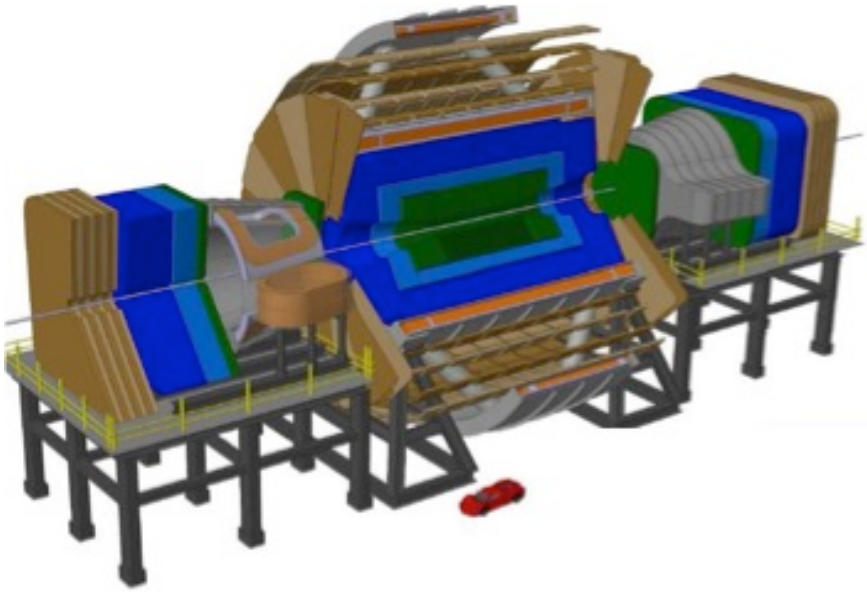
parameter	FCC-ee (400 MHz)				
Physics working point	Z		WW	ZH	tt_{bar}
energy/beam [GeV]	45.6		80	120	175
bunch spacing [ns]	7.5	2.5	50	400	4000
Lumi./IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3

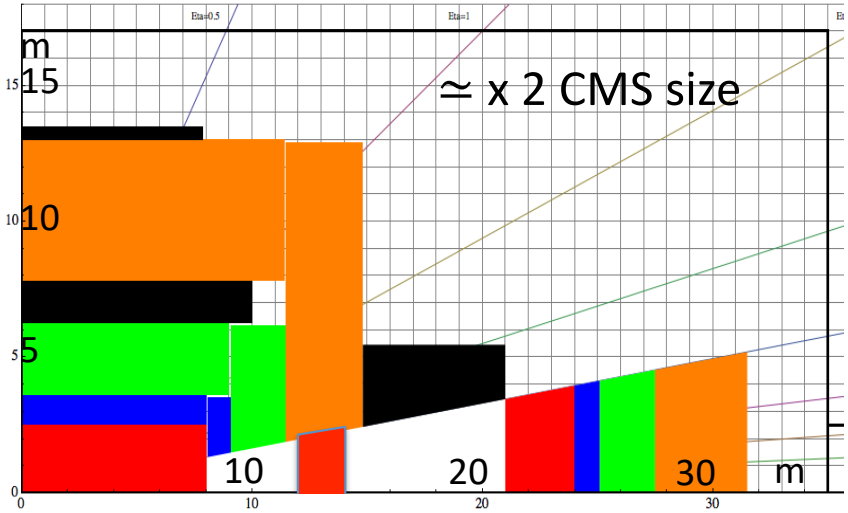
- No pile-up effect, but ILC and CLIC large beam backgrounds require high granularity
- Low integrated rates (duty cycle) at ILC & CLIC allow full offline reconstruction for event selection (no hardware trigger), FCC-ee requires 100 kHz DAQ to register all Z events
- Power pulsing (low mass in tracker & high channel density in calorimeters) possible for ILC and CLIC (not for FCC-ee)
- CLIC requires precise time stamp ≃ 1 ns and short reconstruction windows ≃ 10 ns
- Radiation tolerance is not an issue





FCC-pp detector concept



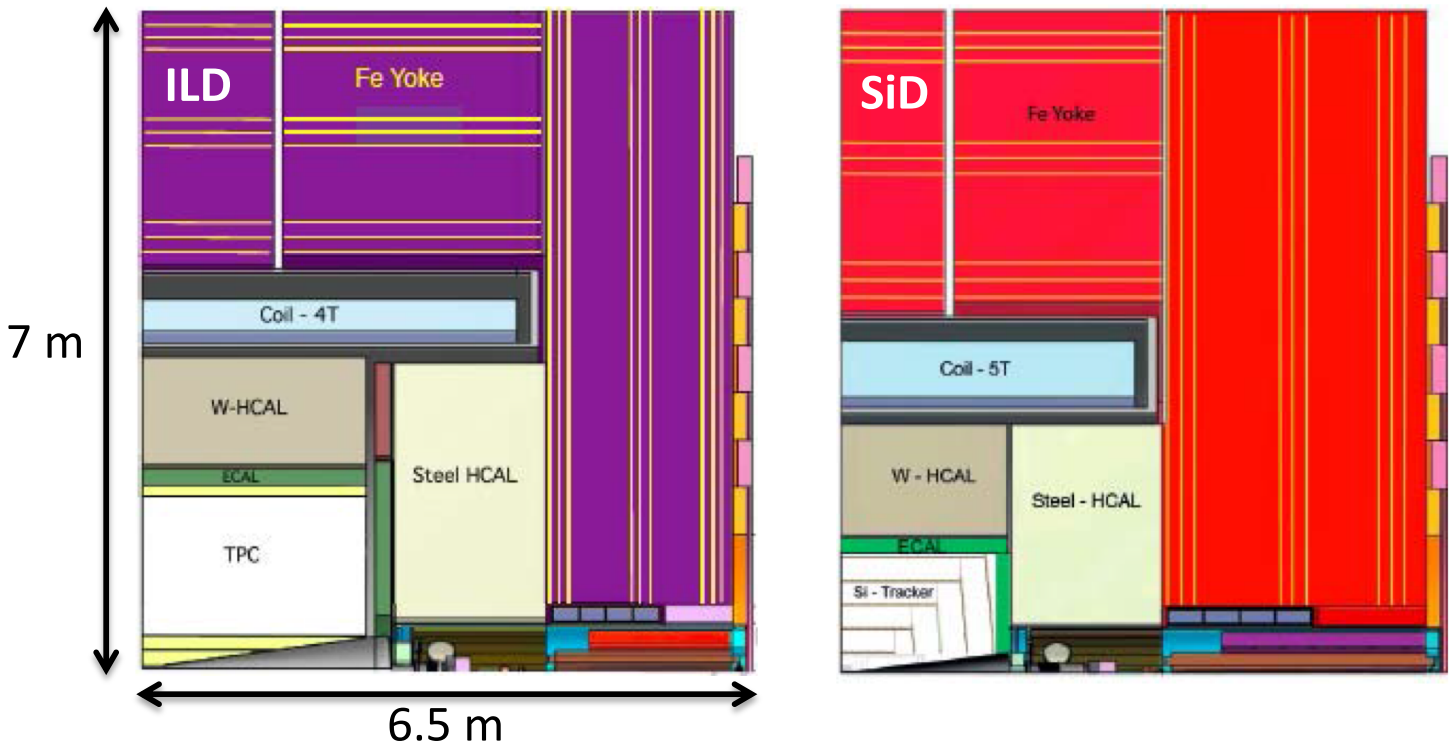


Similar performance as HL-LHC detectors, substantial scale effect with energy

- Twin solenoid ≃ 6T (12 m, no yoke)
  - Tracker resolution ≲ 10% at p_T = 10 TeV
- ECAL 30 X_0 and HCAL 12 λ_i
  - EM(Had) Calo. resolution 10(50)% (sampling) + % (constant), up to eta = 4
- Tracking and calorimetry extended coverage up to η = 6, with 6T dipoles in forward region

ILC detector concepts

- Precision for Higgs width, couplings, Z/W di-jet separation requires:
  - Vertex resolution at IP of ≤ 5 µm → ≃ /4 HL-LHC
  - Tracking $\sigma(pt)/pt^2 \simeq 2 \times 10^{-5}$ GeV^{-1} → ≃ /10 HL-LHC
  - Jets $\sigma(E)/E \simeq 3.5\%$ (≥ 50 GeV) → ≃ /3 HL-LHC
- 2 detector concepts for ILC
  - SiD: 5 T solenoid - full Si-tracker 1.2 m - High Granularity Calorimeter
    - Similar concept for CLIC (4T) and FCC-ee (2T)
  - ILD: 3.4 T solenoid, Pixel vtx - Si + TPC/MPGD tracker 1.8 m - Calorimeter as for ILD



Silicon sensors - Hybrid solution

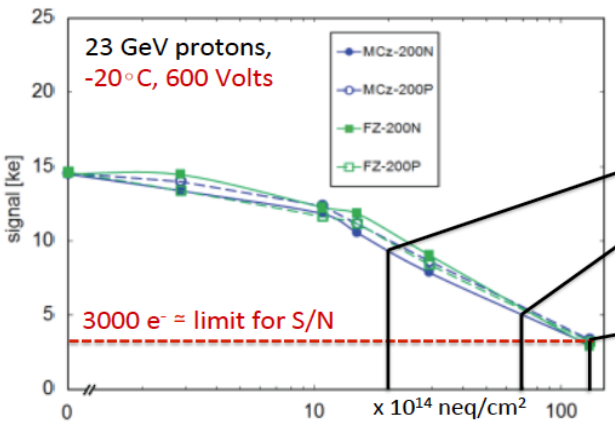
Si-sensors are connected to FE ASIC through bump or wire bonding techniques

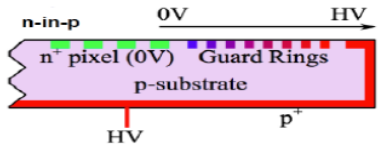
- Pixels, and Strip Trackers in ATLAS, CMS and LHCb
- Pads for High Granularity Calorimeter for CALICE and CMS

n-in-p type sensors thinned to 200 µm provide radiation tolerance up to $2x10^{16}$ neq/cm - bias up to 600 - 800 V - FZ material (Czochralski preferred but no more avail.)

- Thinner sensor 100 -150 µm being investigated to further improve
- Epitaxial sensors preferred for CMS HGC 120 µm active thickness

3D sensors variant foreseen for inner (most exposed) pixel layer, higher radiation tolerance and lower bias voltage (leakage current) but more expensive

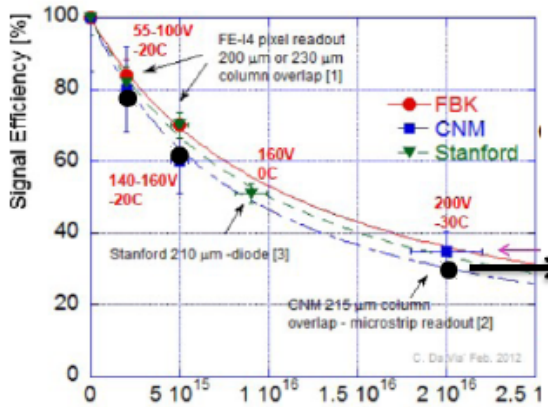


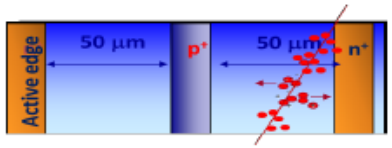


≈ 4000 fb^{-1} at 20 cm 1st strip layer

≈ 4000 fb^{-1} at 7 cm 2nd pixel layer and also ≈ LHCb pixels

≈ 3000 fb^{-1} at 3 cm 1st pixel layer
≈ 5000 fb^{-1} Si/W calorimeter η ≈ 3
confirmed with neutron irradiation





6000 e⁻ after 2 x 10^{16} neq/cm² at -30◦C

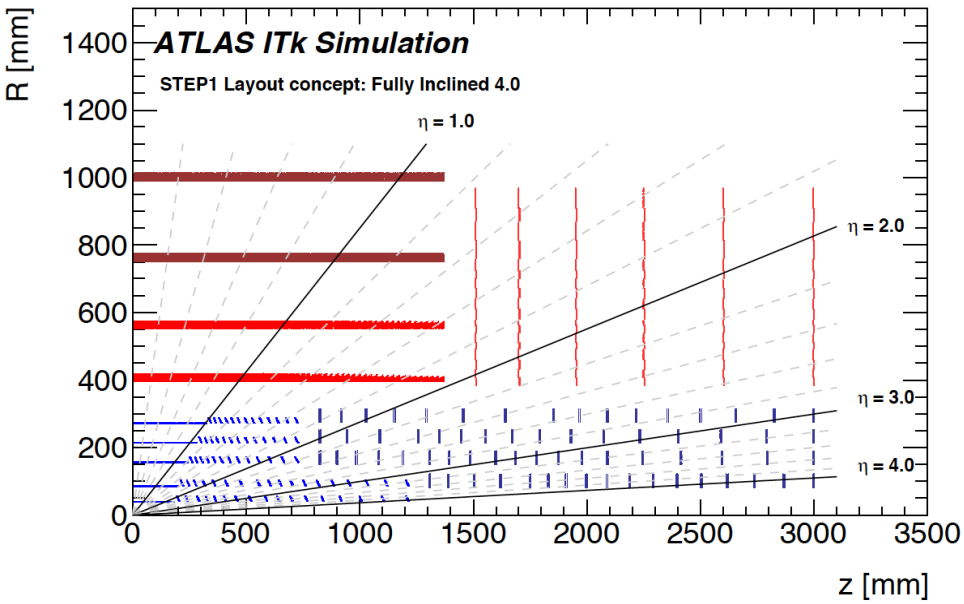
Replacement of the inner pixel layer foreseen at HL-LHC, also due to the radiation tolerance of the electronics, demonstrated so far up to 500 Mrad

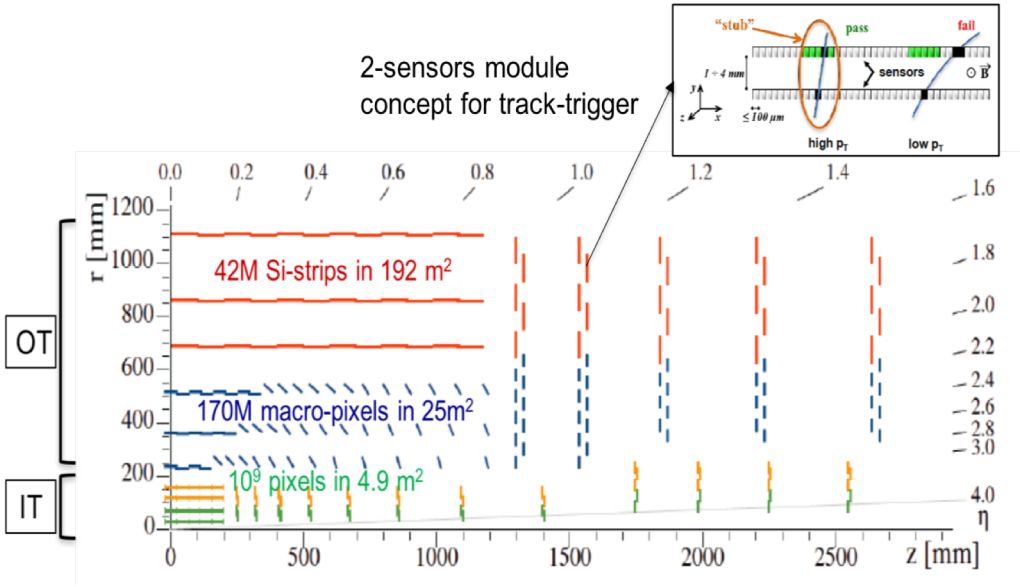
Silicon sensors - Hybrid solution

HL-LHC: pixel size ≃ 50 x 50 / 25 x 100 µm^2 - vertex resolution at IP ≃ 20 µm

- Low momentum track resolution is limited by multiple scattering

Only one producer demonstrated for large quantities (however small at scale of microelectronics foundries) - thin 8” sensors for CMS HGC production now available





Hybrid solution is still highest rad. tol. device, but coverage for CMS HGC limited to η = 3, 4 would require 10^{17} neq/cm^2 - it could be up a factor 10 more at a FCC-pp (20 years)

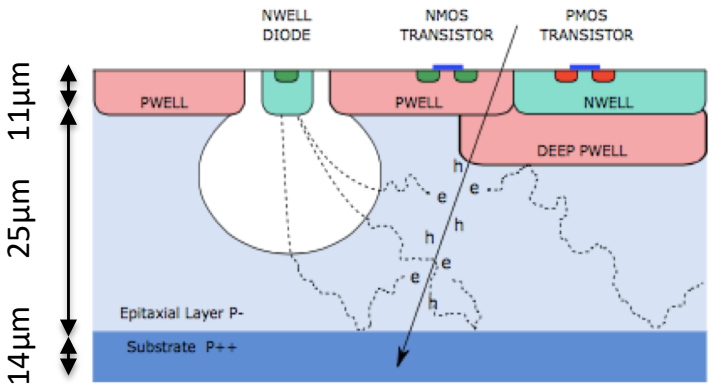
- Thinner sensors and smaller pitch are of interest
- Bump bonding for pixels is expensive - R&D in alternative with Solid Liquid Inter-Diffusion connection (can also allow smaller pitch) - and also decoupling amplifying stage and digital chip with Through Silicon Via technics for ASIC rad. tol. power consumption…

Silicon sensors - CMOS solution

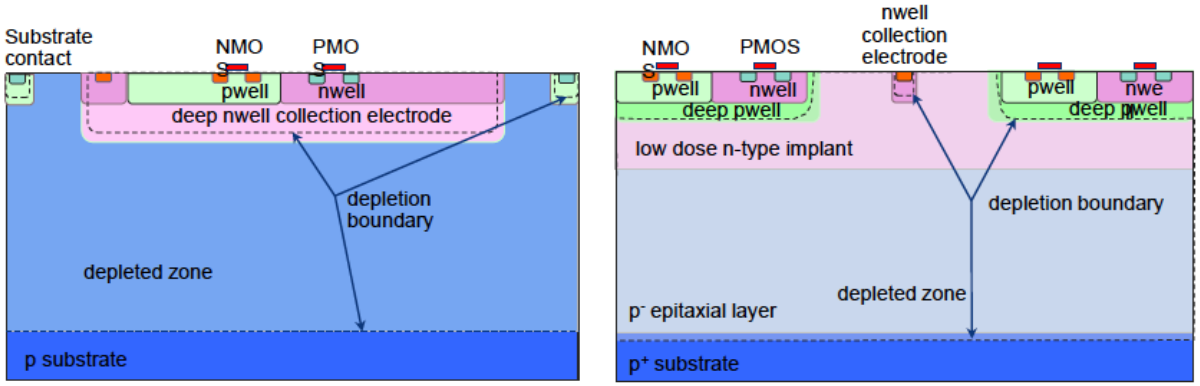
Based on regular process at microelectronics foundries (cheap, large wafer sizes)

Thin epitaxial sensors ≤ 50 µm with built-in readout electronics, pixels ≤ 30 x 30 μm^2

- Monolithic Active Pixels - collect electrons through diffusion
  - Limitation in radiation tolerance ≃ 2 x 10^{13} neq/cm^2
  - Large integration time ≃ µs
- HV/HR CMOS - allow depletion voltage ≃ 100 V
  - Improved radiation tolerance ≃ 10^{15} neq/cm^2
  - Recover integration time of O(ns)



MAPs CMOS Tower Jazz Techno. (0.18 µm)



HV CMOS modified large (left) small (right) collection electrodes

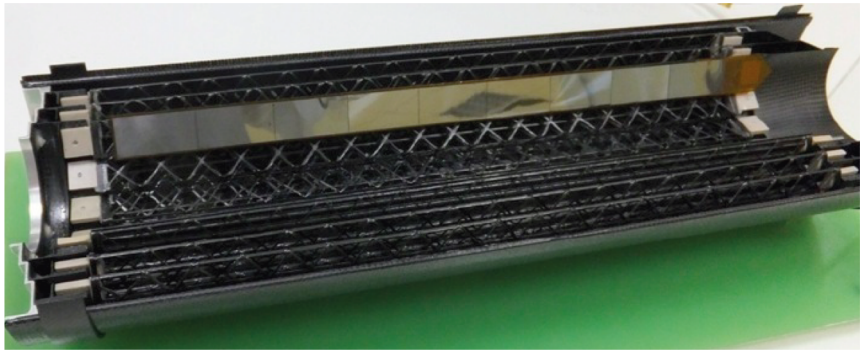
Silicon sensors - CMOS solution

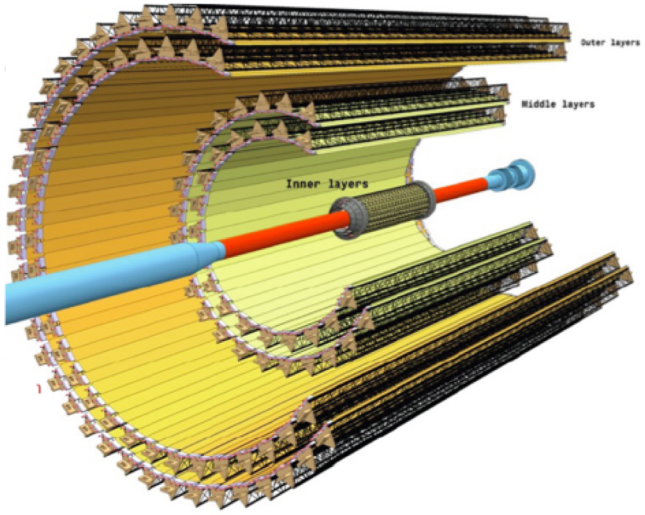
Used for high precision with low material budget and small pixels

- MAPs: Eudet telescope, Star vertex detector, ALICE upgrade in LS2
  - Good candidate for LC experiments targeting $\simeq$ 3 µm hit resolution with $\lesssim$ 25 µm^2 pixels, $\lesssim$ 0.2% X_0 per pixel(outer)layer, with power pulsing and airflow cooling
- HR/HV CMOS:
  - R&D in full chip integration and capacitive coupling through glue between on sensor preamplification stage and complex digital chip
  - Good candidate for CLIC and FCC experiments (improved rad. tol. although not most exposed areas) - CLIC needs charge sharing for resolution

State of the art: ALICE ITS 7 layers of MAPs $\simeq$ 10 m^2 with 12.5 Gpix

- 3 inner layer each 0.3% X/X0 from 20 to 40 mm
- 4 outer layers of 1% X/X0 up to 400 mm
- 2 µs peaking time, 100 kHz sparsified binary output

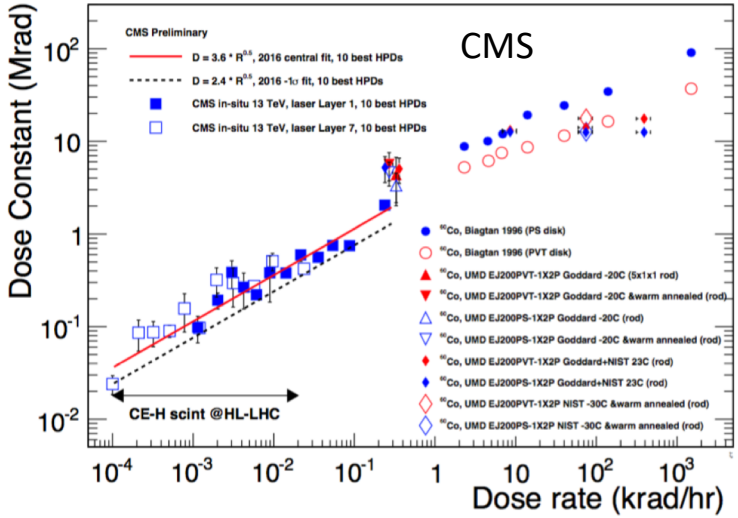




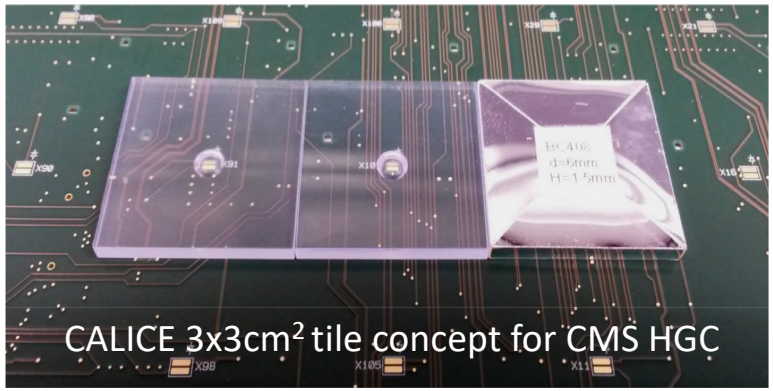
Scintillators

Large and fast signals, can provide good timing precision

- PVT and Plastic scintillators
  - Cheap, but rad. tol. limited to ≤ 500's kRads (for ≃ 50% signal), aging depends on several parameters including dose rates, operation environment… difficult to predict - needs long irradiation test
- Crystals
  - LYSO:CE (commercial) rad. tol. ≃100MRad
  - Developments for less expensive crystals (ex GAGG:Ce,Mg) also in form of fibers…
- Read-out
  - WLS (fibers, liquid scintillator, Cerenkov…) - clear fiber - also radiation tolerance issues - large light loss in interfaces (complex monitoring/calibration)
  - SiPM provide best performance for photon conversion and can be directly mounted on scintillators, rad. tol. limited to ≃ 10^{14} neq/cm^2 (at low operating temperature - 35°) - R&D in large area, new materials, higher PDE, packaging (for cost)



Plastic scintillator response ∝ exp-d/D
(d total dose - D dose constant)



Scintillators

Tiles extensively used in Hadron Calorimeters, relatively small granularity possible

- Tiles + SiPM solution is a good candidate for calorimetry at future experiments

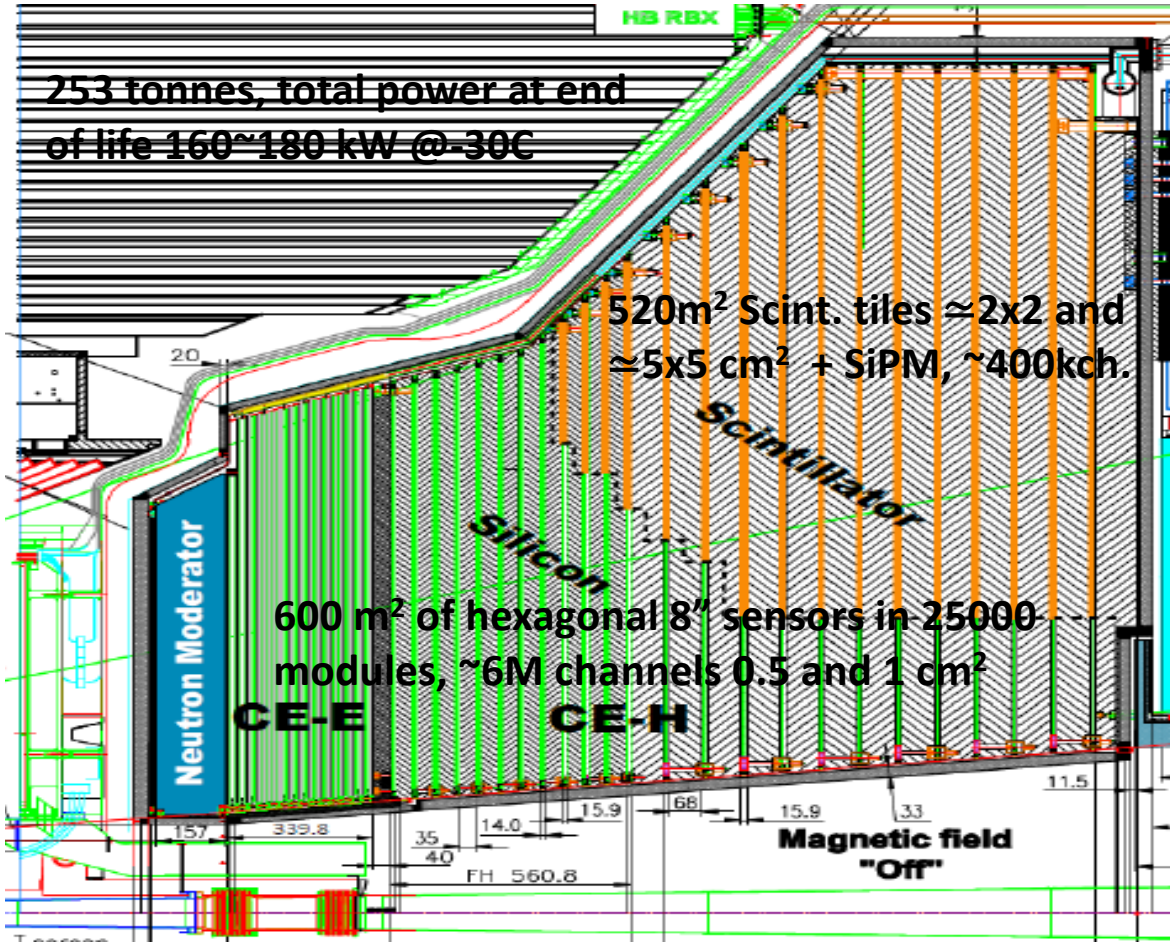
Fibers/strips provide precise tracking, ex. LHCb Fiber Tracker

CMS HGC (CALICE concept)

- Electromagnetic
  - 28 layers of Silicon sensors in W/Pb absorber (25 X_0 - 1.7 λ)
- Hadronic (CE-H)
  - 24 layers: 8 silicon + 16 silicon/scint. tiles at high/low η in stainless steel absorber (9 λ)

LC High Granularity Calorimeter

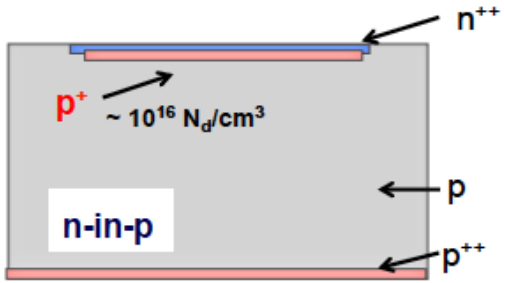
- Very similar with alternative DHCAL with 1 x 1 cm^2 RPCs pads with multi-thresholds
  - ≃ 80 M channels (x 12 CMS HGC)
  - Time window at CLIC ≃ 10 ns (EM) 100ns (Had.)



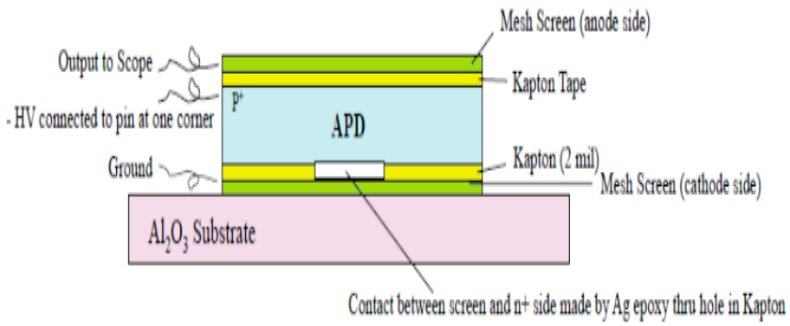
Si/Scint transition at 350 krad, maintains S/N ≥ 5 for MIP calibration (consistently with SiPM rad. tol.)

Precise Time of Flight - MIPs

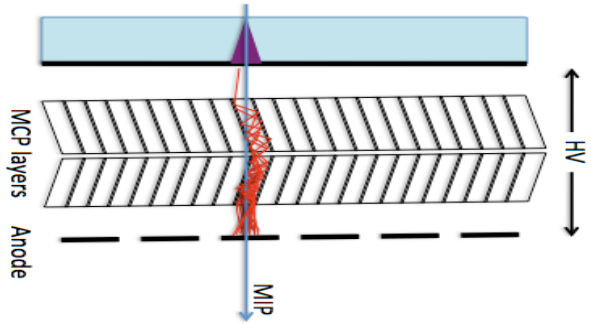
- Crystals + SiPMs solution for lower irradiation
  - LYSO + SiPM tiles can provide 20 ps before irradiation with known impact point and 30-40 ps after $\simeq 10^{14}$ neq/cm^2 limited by SiPM DCR
- Low Gain Avalanche Diodes for higher irradiation
  - n-in-p silicon sensors with amplification through p-implant below the collection electrode
  - Intrinsic resolution limited by Landau fluctuation $\simeq$ 20 ps for 50 µm sensors - ≤ 40 ps up to $\simeq 2 \times 10^{15}$ neq/cm^2
  - R&D in dopant composition (add C to Boron) to improve rad. tol., thinner and smaller pad sensors may also help - fill factor & full size sensors



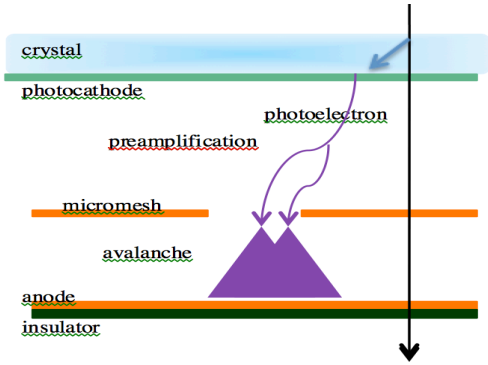
- Alternative technologies could provide high granularity with good/better resolutions ? - rad. tol. implementation and cost to be demonstrated



High Gain APDs



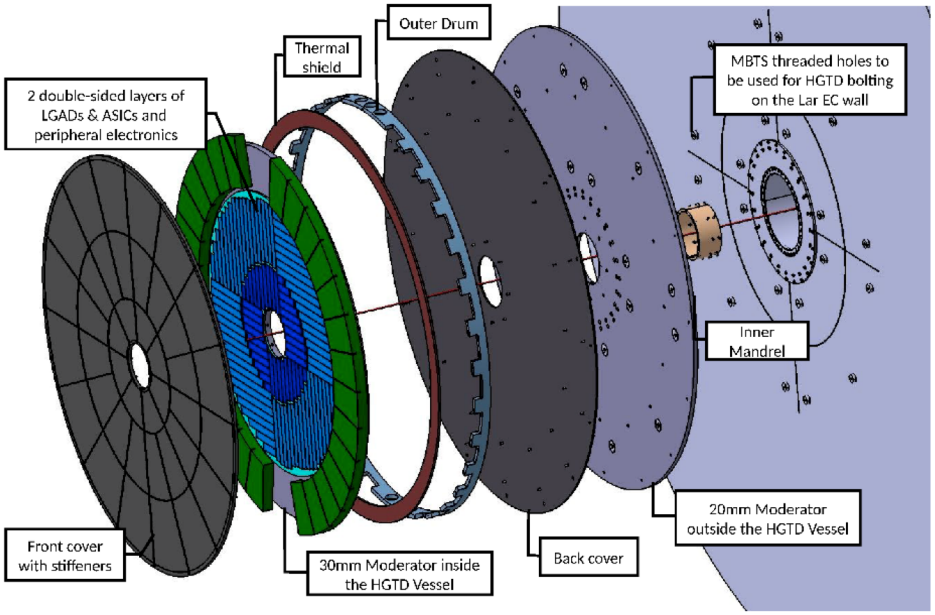
Cerenkov radiator + MCP-PMT - ALICE
20 ps resolution for collision time tagging
- Thicker quartz radiators are a rad. tol. alternative to crystals



Photocathode + MicroMegas

Precise Time of Flight - MIPs

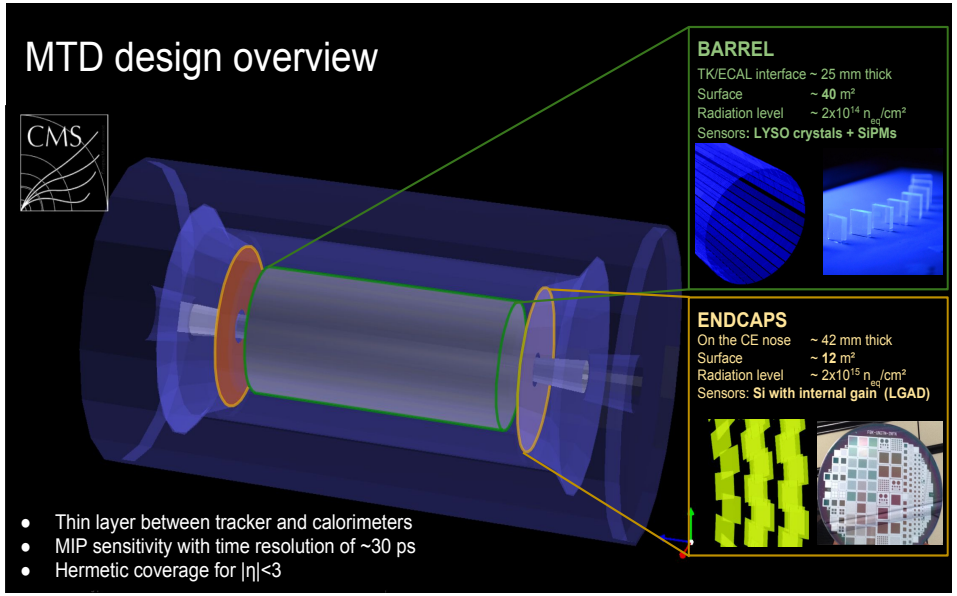
ATLAS High Granularity Timing Detector



Two double sided layers covering 2.4 < η < 4.0 in Front of Calo. endcap

- 2(3) hits per track for R >(<) 30 cm
- LGADs 15x15 array of 1.3 x 1.3 mm pixels

CMS MIP Timing Detector



Barrel layer in Tracker volume (25mm)

- Lyso tiles 11x11mm^2, 4-2.4mm thick (depending on η) + SiPM 4x4mm^2, ≃ 250k channels, 40m^2

Endcap layer in front of Calo. Endcap (42mm)

- LGAD 1x3 mm^2 pads, ≃ 250k ch, 12 m^2

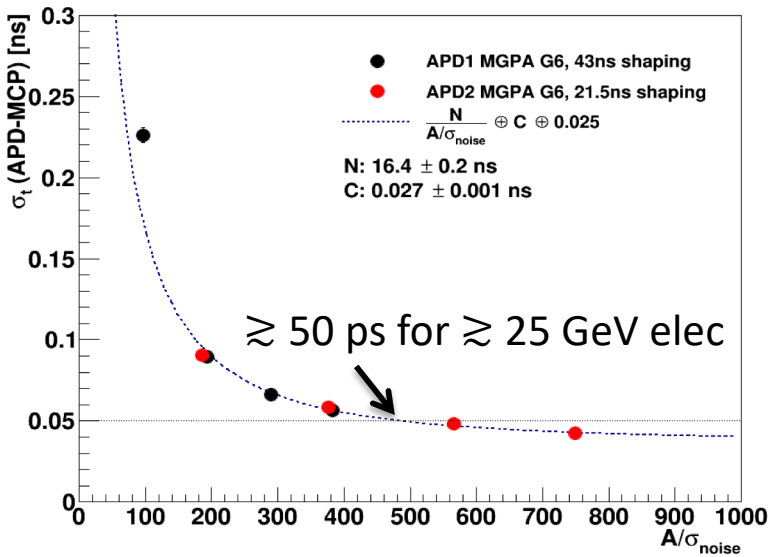
- Clock distribution precision target ≃ 10 ps
  - First demonstrator through BE boards and LpGBT (OL) with specific clock monitoring calibration in boards (back-up option with direct clock distribution to FE)

Precise Time of Flight - e/γ/h showers

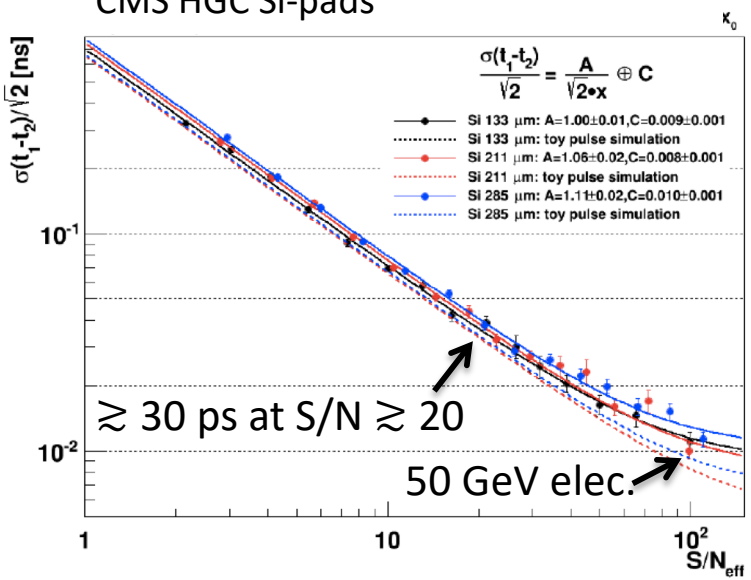
Calorimeters can also provide precise timing for neutrals to determine γ's origin in conjunction with vertex timing and to mitigate pileup in Jet-ID and MET resolution

- CMS ECAL with $PbWO_2$ crystals + APDs + new FE can provide ≃ 30 ps for 30 GeV γ
- CMS HGC Sampling calorimeters benefit from large number of layers to provide 30 ps for few GeV γ and good efficiency for hadrons above 2 GeV Pt
  - Limitation in S/N is in electronics noise (pad size capacitance)

CMS $PbWO_2$ Crystals+ APDs + new FE



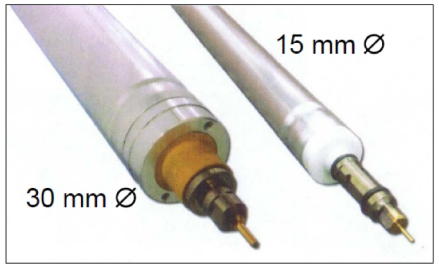
CMS HGC Si-pads



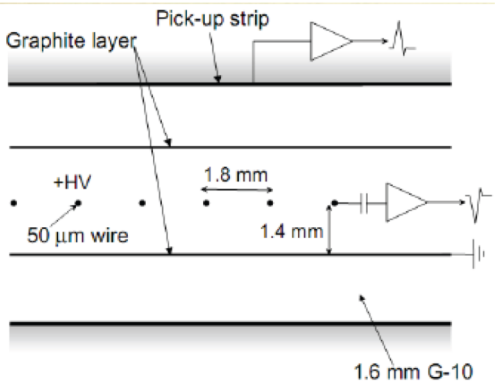
Micro Pattern Gas Detector

- Muon systems in ATLAS and CMS are expected to sustain HL-LHC
  - Tests at GIF++ are on-going to validate margins, limits are not fully known, however
    - R&D in lower gain (operation, geometry, more performant readout) to reduce aging
    - R&D on eco-gas mixtures but not solution identified yet for CSC's and RPCs
- Increase granularity, rate capability and precision, exploiting MPGDs
  - Multilayer designs - ex multigap RPCs to reduce aging and improve rate capabilities and timing performances (≤ 100ps)
  - New μ-Resistive-Well design close to Micro Gap Chambers with PCB technology

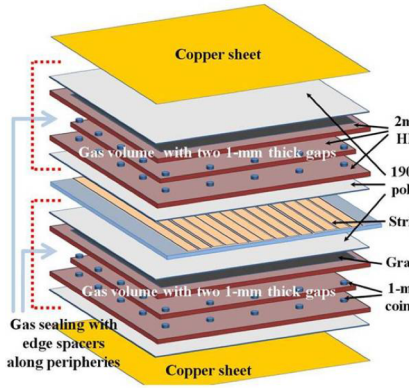
DT, CSC, RPCs for lower granularity/rates



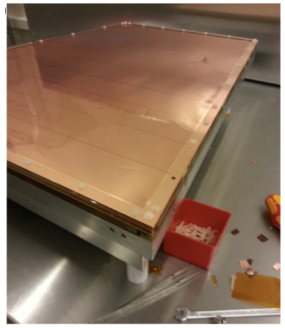
sMDT



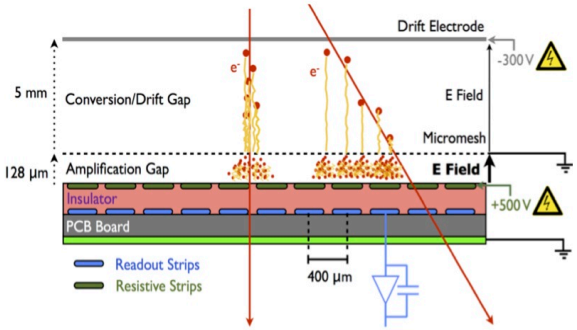
sTGC



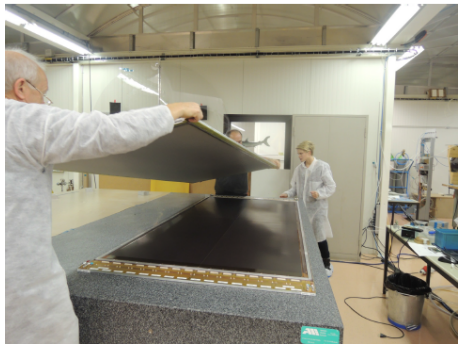
RPC

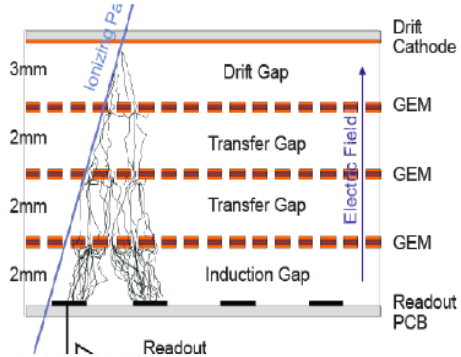


Micro Pattern Gas Detector for high rates

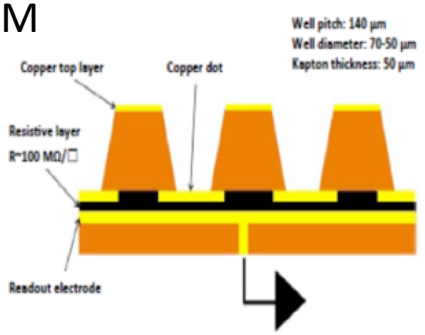


Micromegas





GEM



μ-Resistive-Well design

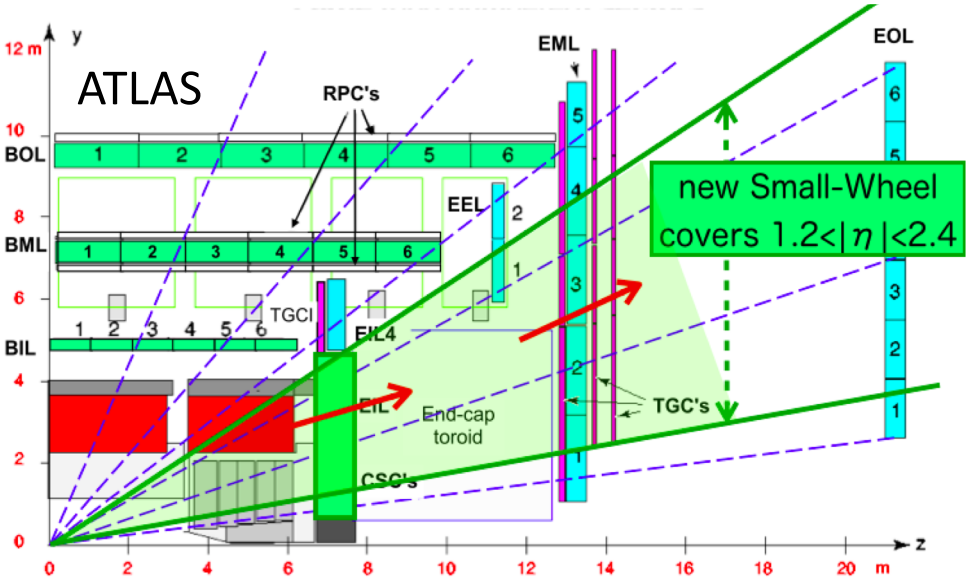
Micro Pattern Gas Detector

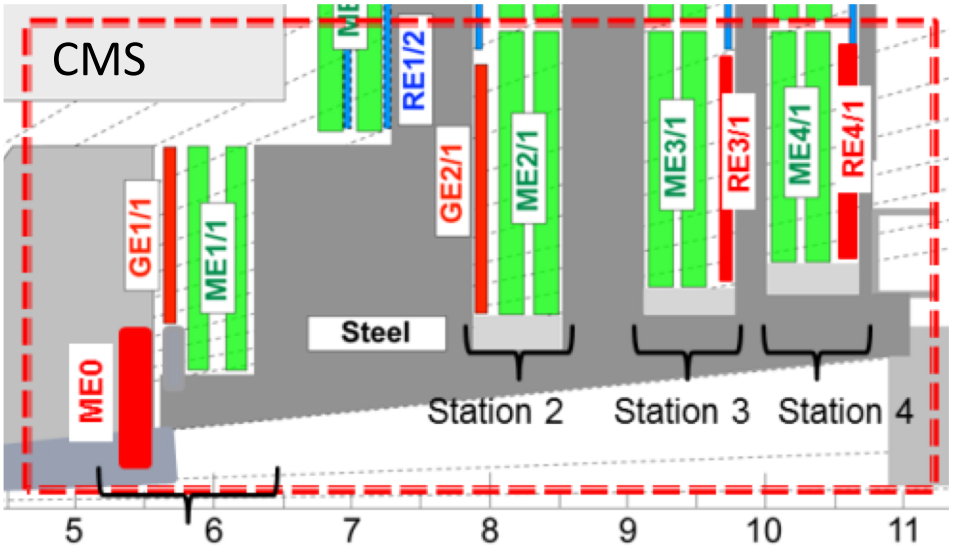
ATLAS

- New Small Wheels - small Thin Gap Chambers strips 2 cm → 3.2 mm (3mm pitch), thinner gap and Micro-Megas (0.5 mm pitch)
- Monitoring Drift Tubes - reduced diameter 30 mm & 200 Hz/cm^2 → 15 mm & 2 kHz/cm^2

CMS

- Triple GEM - 140 µm pitch, single mask and new assembly technique
- iRPC's - few kHz/cm^2 low-ρ Bakelite* - multi-gap - thinner electrodes - higher gain FE
  (* also R&D in glass for higher rates)





GEM and Micro-Megas used to solve TPC ion feedback rate issues

- GEM for ALICE TPC upgrade with continuous readout
- GEM or Micro-Megas for ILD TPC readout 1x6 mm^2 pads

Front-End ASICs

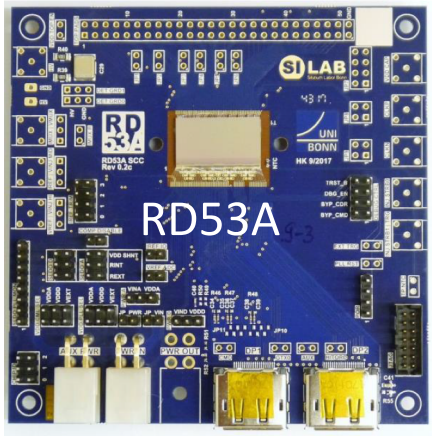
Deeper submicron technologies to increase digital functionalities, allow lower pixel sizes, reduce power consumption in digital part, improve radiation tolerance

- TSMC 65 nm technology for HL-LHC considered demonstrated to 500 MRads (possibly more, to be validated)
- Needs very specific design rules to ensure radiation tolerance (limiting reduction of size for transistors)
- Radiation hardness studies in 28nm started - 3D integration separating analog and digital functionalities may help

ATLAS/CMS Pixel ASIC TSMC 65 nm

- Smaller Pixel size
- Larger chips ($\gtrsim$ 2 x 2 cm^2)
- Hit rates up $\simeq$ 2-3 GHz/cm^2
- Rad. Tol. up to 1 Grad, 2x10^{16} n/cm^2
- High trigger rate and latency up to 1 MHz and $\gtrsim$ 10 μs
- Low power budget $\lesssim$ 1 W/cm^2
- Low noise $\simeq$ 1000 e$^-$

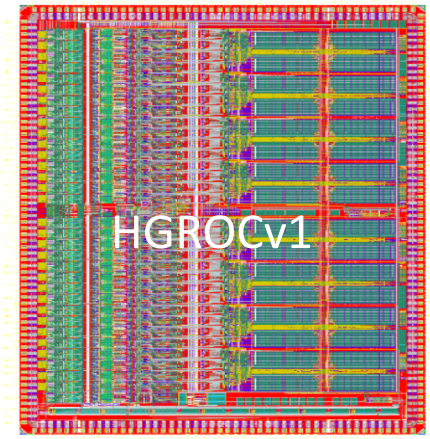
First chip received end-2017 works well



CMS HGC FE ASIC TSMC 130 nm

- Shaping $\simeq$ 15 ns - noise $\simeq$ 2000 e$^-$ (after 3000 fb^{-1})
- Low power $\lesssim$ 10 mW/ch
- Dynamic range 10 pC - 10 bit ADC $\leq$ 100 fC and Time over Threshold (ToT) $\geq$ 80 fC
- Channel calibration better than 1%
- ToA for time resolution $\lesssim$ 50 ps

IP blocks selected and mostly validated



ATLAS HGTD ALTIROC TSMC 130 nm

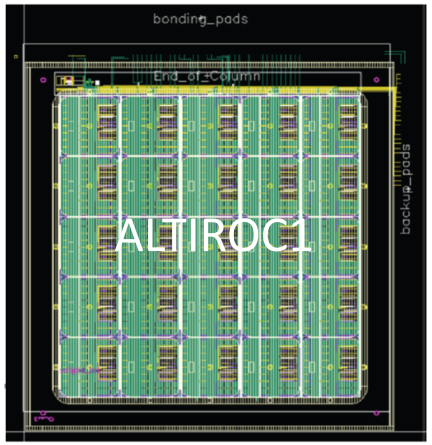
- Low power $\lesssim$ 300 mW/cm^2
- Dynamic range 1-20 MIPs
- Jitter $\lesssim$ 20 ps, timewalk $\lesssim$ 10ps
- 20 ps bin and 7 bit ToA
- 20 ps bin and 9 bit ToT

First proto. provide expected resolution

CMS MTD TOFHIR TSMC 130 nm

- Low power 13 mW/ch
- Dynamic range 600 pC
- Time resolution 20 ps
- 10 bit ADC
- 20 ps bin TDC

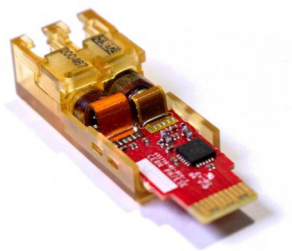
First proto in CMOS 110 nm submitted

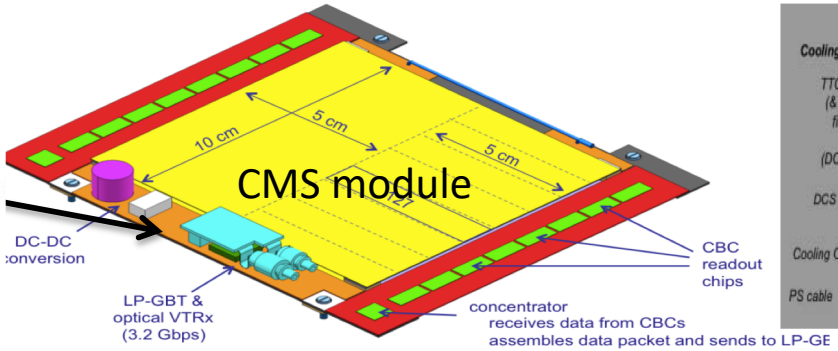


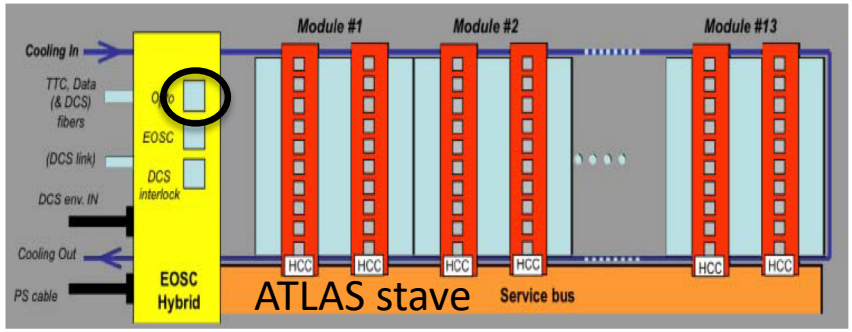
On-detector data transmission

Common development at CERN of high bandwidth OL for HL-LHC

- GigBitTranciever (GBT) & Versatile Link
  - R&D on Low power GBT (≃ 0.5 W) in 65 nm TSMC with 10 Gb/s data transmission
  - Miniaturization is also important
- Radiation tolerance of optical devices is limited to $3x10^{15}$ neq/cm^2
  - Insufficient for inner radii (1st pixel layer, CMS HGC), need light high BW electrical link before OL transfer (twinax cables…) ≃ 1 to 10 Gbps from ≃ cm to m length (6m in ATLAS at 5 Gbps)
- Higher bandwidth is highly desirable to extract trigger data from high occupancy detectors while minimizing cost and material
  - Higher bandwidth possible with FPGA chips, multiple amplitude modulation, multi-lanes…
  - Silicon photonics is likely the future (laser, wave guide, modulator, electronics grown on same silicon), MZM may provide better NIEL tolerance but are sensitive to dose
  - Wireless transmission HF modulation with highly directive antenna can allow inter-layer communication (w/o optics and fibers up to system edges optical transfer)







Cooling and Mechanics

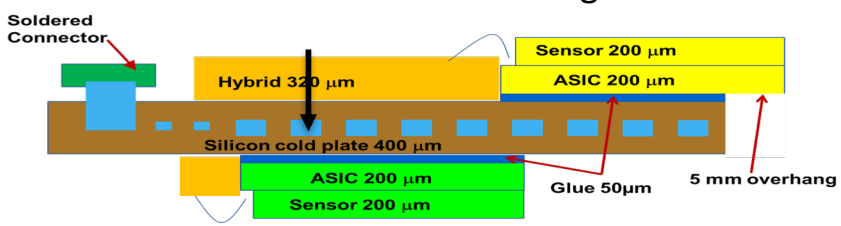
Two-Phase CO_2 cooling ≃ 50 kW and ≃ -35° plants

- Low-T operation crucial to mitigate radiation damage - low mass material needed
- Micro-channel embedded in sensors (LHCb VELO) to minimize material
- Air-flow cooling for low power application (ILD)

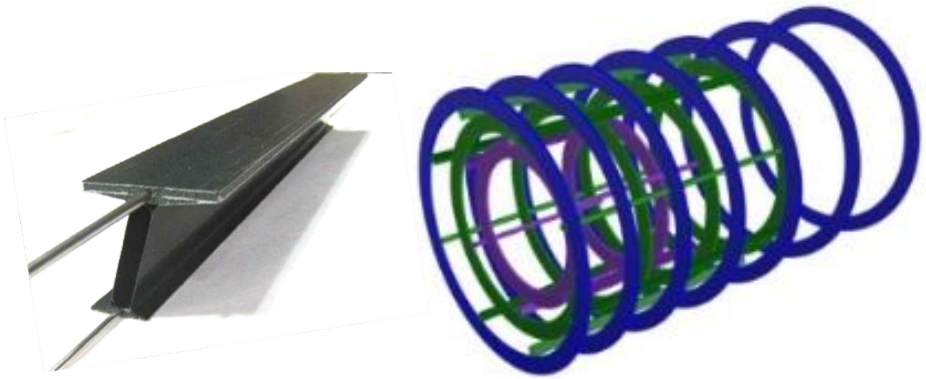
Light mechanics with high conductive CF polymer skins and thermal foam core…

- Low-weight crucial for multiple scattering, interactions & photon conversions
- R&D in new materials and glues: CFRPs adhesive bonding, new thermal foams, phase change adhesives - 3D printing

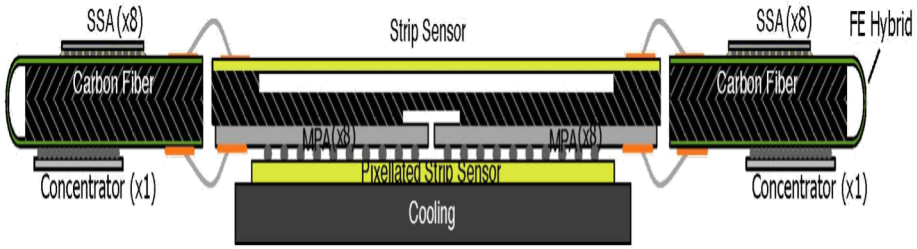
LHCb micro-channel cooling



ALICE ITS carbon fiber plate and support, carbon foam and polyimide pipes



ATLAS pixel CF plate, foam, Ti pipes and barrel CF mechanics



CMS PS-module AlCF frame

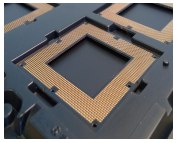
Back-End Boards

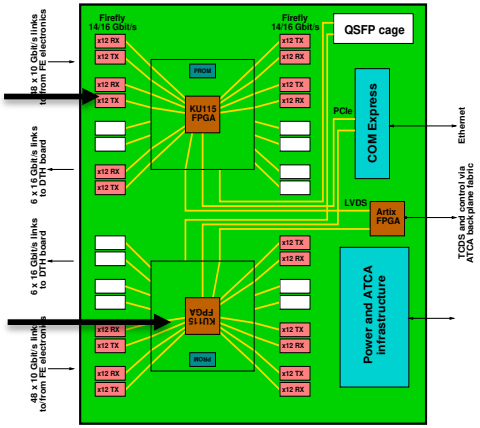
Benefit from commercial progress in FPGA power and bandwidth, and ATCA form factor and crate backplanes

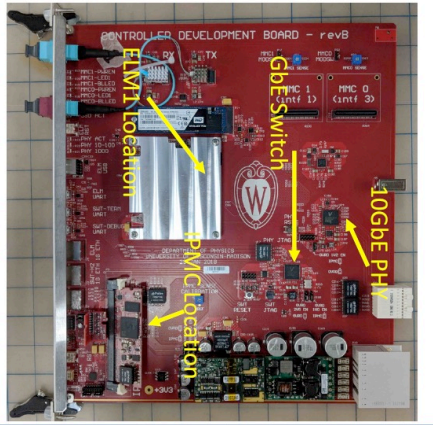
- Several boards variants needed to optimize perf. vs cost according to system needs
  - Number of FPGA/links per board, number of boards versus FPGA/links power…
- Generic platform designs can allow flexible implementation of links and FPGA
- Common framework for control, firmware and software developments are also important for easier maintenance
- First prototypes for HL-LHC successfully demonstrate powerful boards, with up to 28 Gbps links and Ultrascale+ grade FPGAs

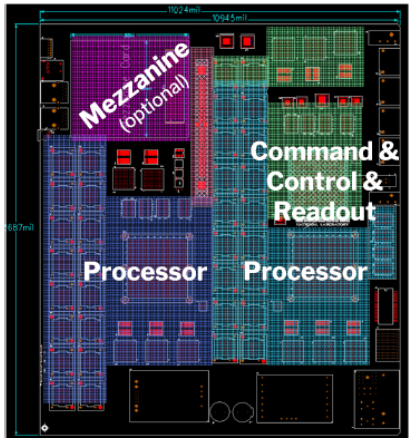
Pluggable FO transceivers

Interposers









Exemple CMS Serenity (left)and APx (right) platforms

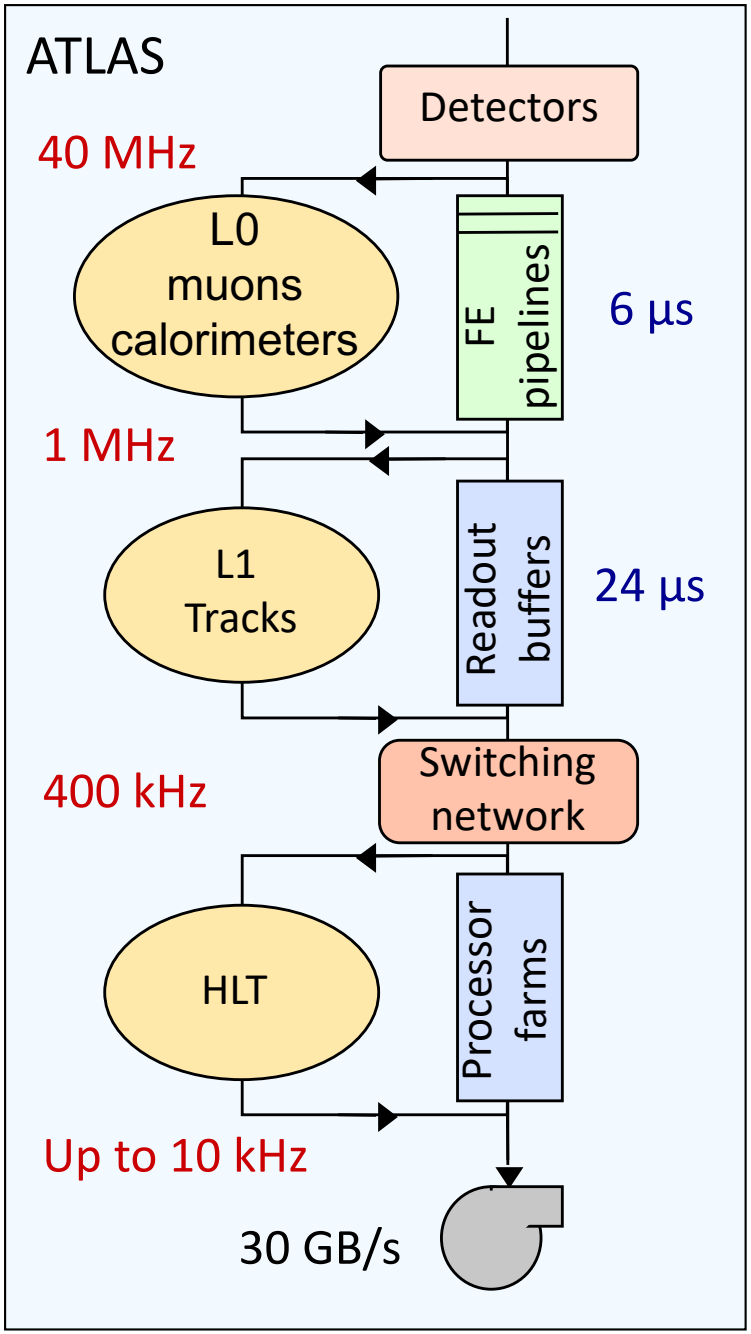
ATLAS global tirgger board

Summary

- Pileup mitigation or precision at pp and e^+e^- experiments result in similar needs for highly granular detectors
  - Granularity is not a cost driver - more an issue for power consumption
  - R&D for ILC detectors has benefited LHC and HL-LHC upgrades - ALICE ITK with MAPs and HGC for CMS are major examples
- Technologies for HL-LHC and e^+e^- experiments are available (even with some limits) - large efforts in final engineering are still needed
- Radiation tolerance will be the major challenge for future pp experiments both for sensitive and readout components - the size of the experiments is also a cost driver
  - Several technologies may be needed to contain costs
  - Wide R&D programs and efforts are needed - timescales to develop new technologies are long, HEP has also some time lapse to exploit progress in commercial technologies

Additional information

ATLAS and CMS Trigger/DAQ upgrades



CMS Outer Tracker
tracks Pt ≥ 2GeV

ATLAS option for 4 MHz
L0 regional Tracker RO

CMS full Tracker RO

High Level trigger output