LES DETECTEURS DU FUTUR

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Thanks for material or discussion to F. Beaudette, D. Contardo,
C. de la Taille, A. Sartirana ,Y. Sirois, M Winter, …

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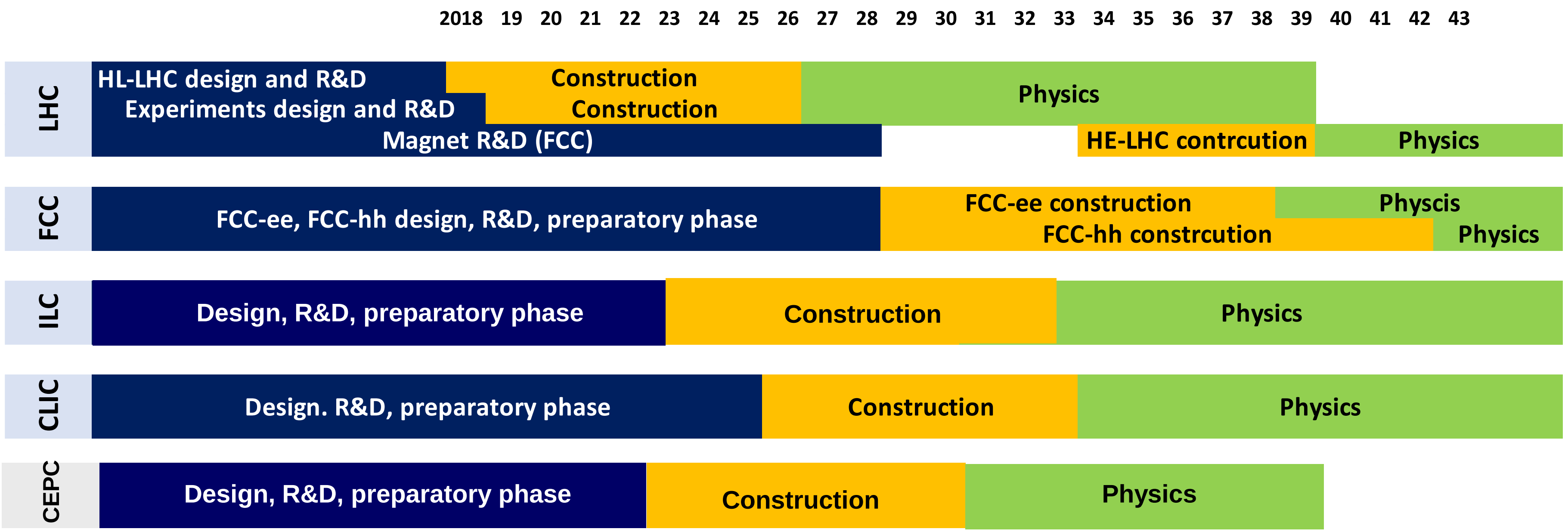
Disclaimer

- Many interesting and important R&D studies on-going towards future detectors.

- **Obviously, cannot cover everything in ~25-30 minutes…**

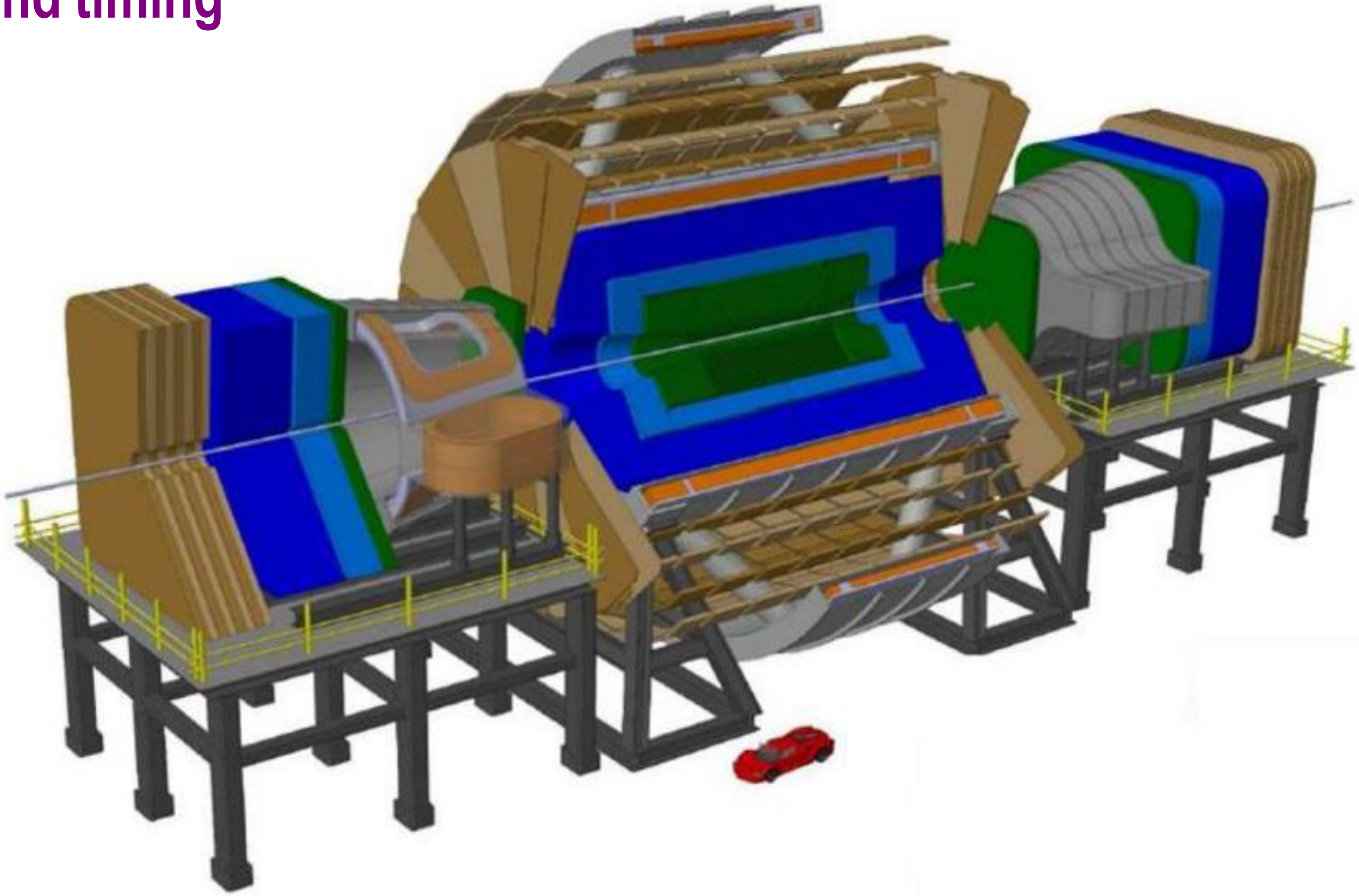
- Focus on a few selected topics (and technology) for the future ee and hh colliders.
    - **Try to emphasize on some of the "big" trends…**

- It is certainly a personal **biased** selection. Sorry by advance if your preferred detector/technology is not discussed in the following… it certainly does NOT mean it won't be used in the future !
(I won't cover in details Dual Readout or LAr calorimeter, all possible future pixel or tracker detectors, scintillators, TPC, …)



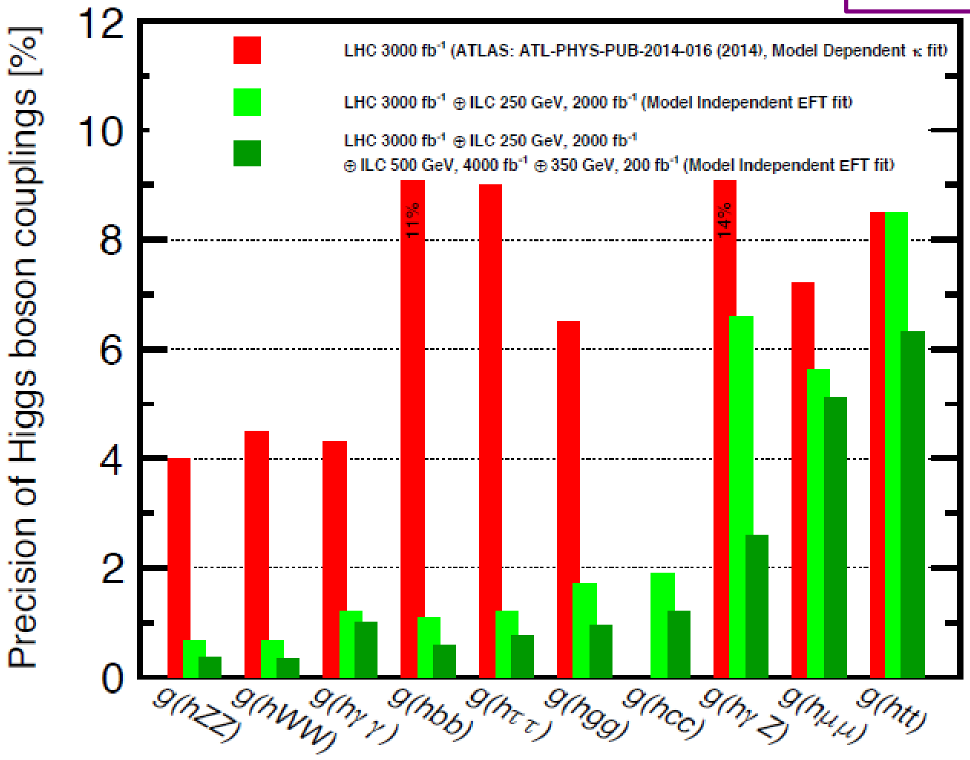
Outline

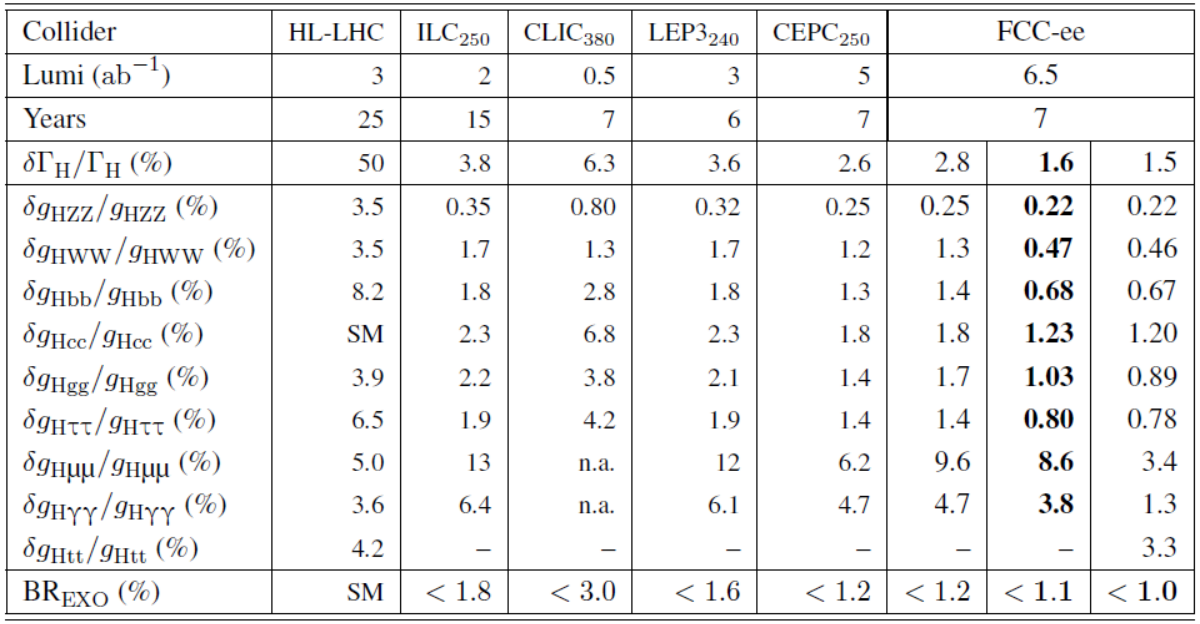
- **Main detector challenges & concepts**
- **Si Sensors**
- **Calorimeters**
- **A new paradigm: picosecond timing**
- **Muon system**
- **Other important aspects**
  (Mechanics, Electronics,
  Trigger, Computing)



Lepton Collider Challenges: Precision

Cf talk G. Hamel de Monchenault





Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	FCC-ee		
Lumi (ab^{-1})	3	2	0.5	3	5	6.5		
Years	25	15	7	6	7	7		
$\delta\Gamma_H/\Gamma_H$ (%)	50	3.8	6.3	3.6	2.6	2.8	**1.6**	1.5
$\delta g_{HZZ}/g_{HZZ}$ (%)	3.5	0.35	0.80	0.32	0.25	0.25	**0.22**	0.22
$\delta g_{HWW}/g_{HWW}$ (%)	3.5	1.7	1.3	1.7	1.2	1.3	**0.47**	0.46
$\delta g_{Hbb}/g_{Hbb}$ (%)	8.2	1.8	2.8	1.8	1.3	1.4	**0.68**	0.67
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	6.8	2.3	1.8	1.8	**1.23**	1.20
$\delta g_{Hgg}/g_{Hgg}$ (%)	3.9	2.2	3.8	2.1	1.4	1.7	**1.03**	0.89
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	6.5	1.9	4.2	1.9	1.4	1.4	**0.80**	0.78
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	5.0	13	n.a.	12	6.2	9.6	**8.6**	3.4
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	3.6	6.4	n.a.	6.1	4.7	4.7	**3.8**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	4.2	–	–	–	–	–	–	3.3
BR_{EXO} (%)	SM	< 1.8	< 3.0	< 1.6	< 1.2	< 1.2	< 1.1	< 1.0

From FCCee CDR

(sub-)Percent precision on some main Higgs couplings

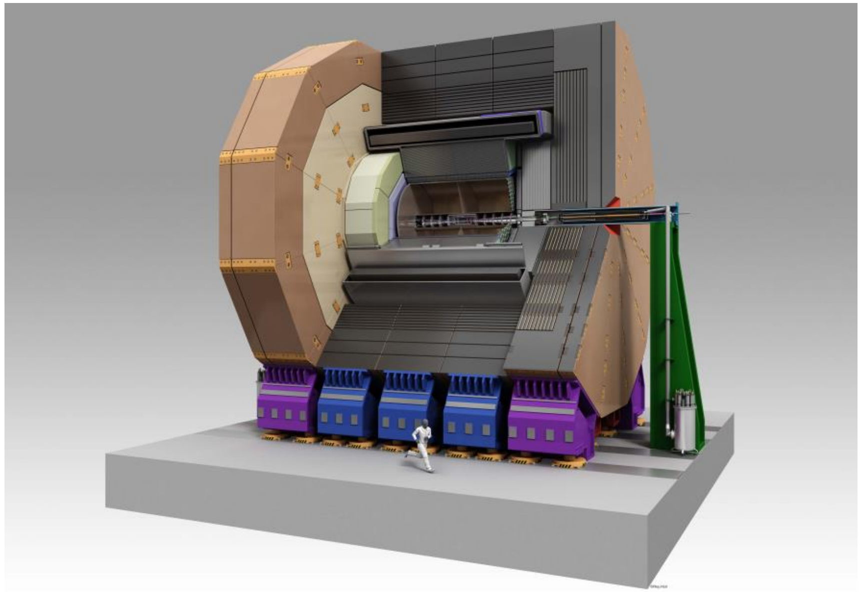
- **Requirements for high precision physics (ex: ILC):**
  - Vertex Resolution at IP < 5 µm (for H→bb/cc/ττ), CMS / 4
  - Tracking: σ(pT)/pT) 2.10^{-5} GeV^{-1}, CMS / 40
  - Jets: σ(E)/E ~ 3.5% (>=50 GeV) (for H→invisible) ATLAS / 2

Lepton colliders:
need (very) high granularity, low mass tracker, Particle Flow optimised calorimeters, …

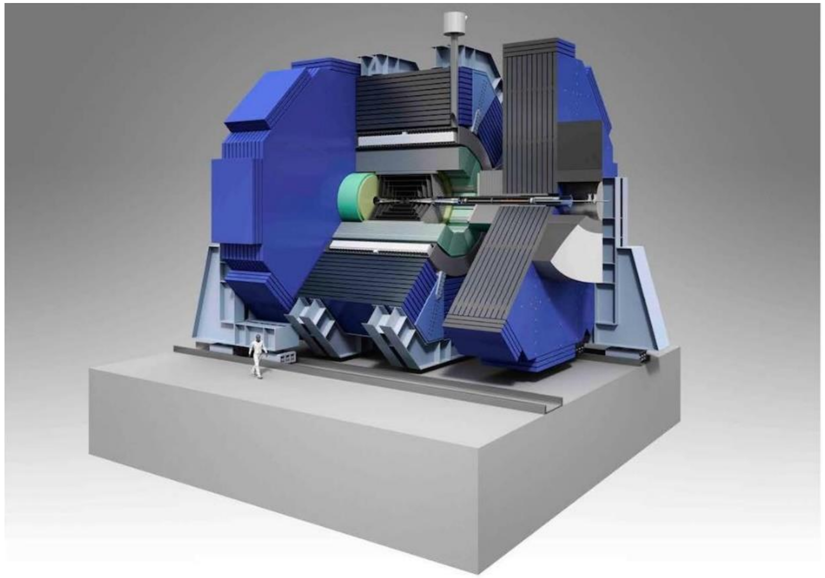
Lepton Colliders detectors concept

Examples from ILC:

ILD



SiD



	ILD	SiD
B-field:	3.5 T from Solenoid	5 T from Solenoid
Low mass tracker:	TPC (central tracking) +Si vertex	Full Si

Calorimeters: High-Granular PF-optimized Calorimeters:
Si or Scintillators/W for ECAL, (Semi-)Digital or Analogue HCAL

+ Muons & Forward

- **Power-pulsing electronics** (~switch off during beam-less time of 200ms).
  - Also for CLIC. Not for FCC-ee or CEPC.
- Similar detectors concept for FCC-ee or CLIC (with full Si tracking). But active cooling may be needed
- Radiations, data rate,… much less demanding than pp colliders

Hadron Colliders Challenges (1/)2: Pile-Up

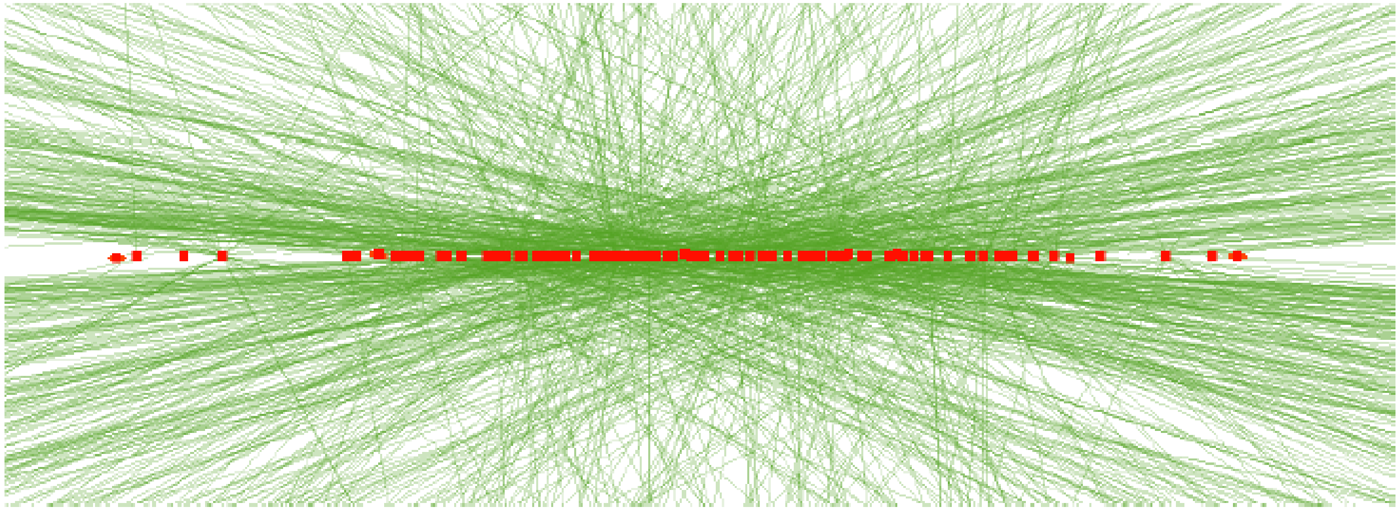


Figure 9.1: An event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector.

- In pp (future) colliders, **instantaneous luminosity** will go well beyond initial LHC plans:
  - 5x10^{34} for HL-LHC (**x2-3 LHC**)
  - … up to 30x10^{34} for FCC-hh ! (**x15 LHC**)

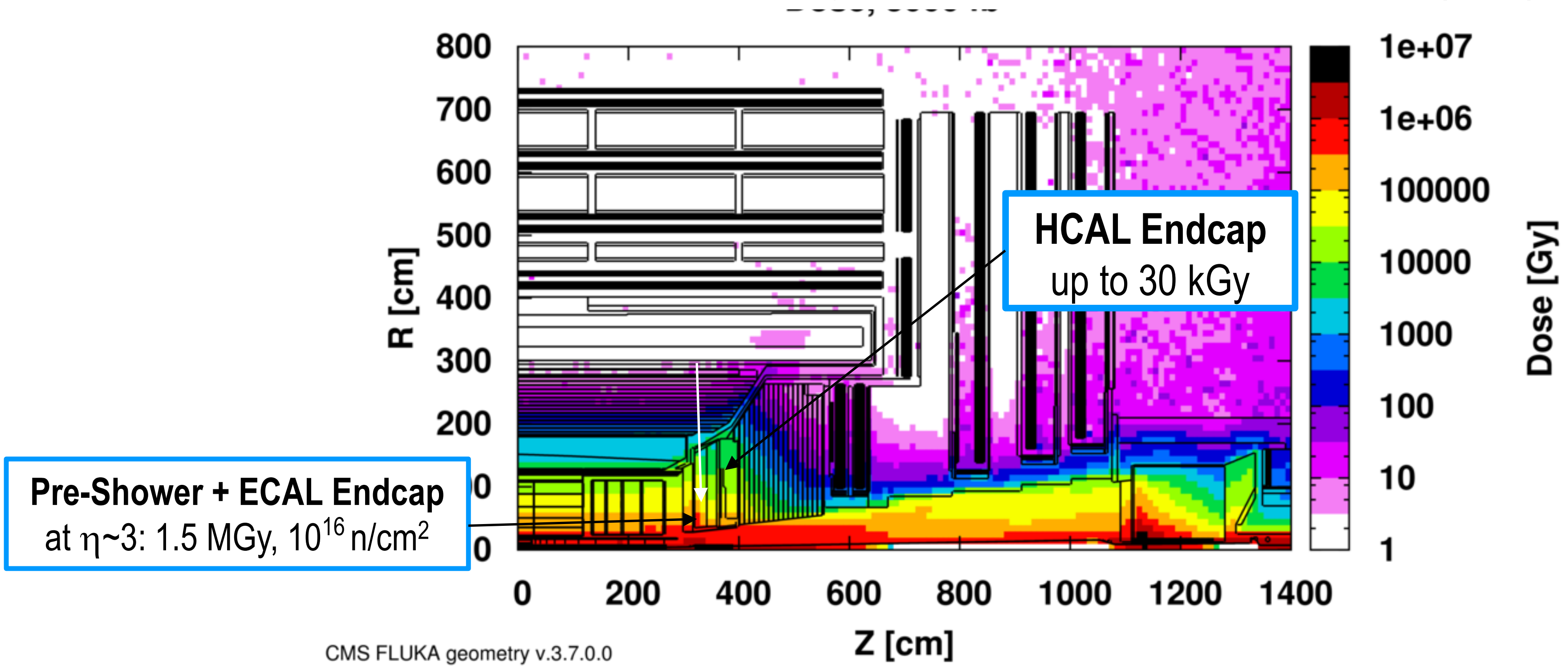
- **With (in-time) Pile-Up:**
  - From 140 to 200 for HL-LHC… (**x5 LHC**)
  - … to 800 for HE-LHC or ~1000 for FCC-hh ! (less if bunch spacing reduced to 5 ns) (**x25 LHC**)

Will put severe constraints on trigger, vertexing, computing/software and **may compromise object reconstruction & physics performance** (without proper mitigation)

HL-LHC, FCC-hh:
need (very) high granularity, sophisticated software algorithms and more (timing,…)

Hadron Colliders Challenges (2/2): Radiation damages

3000 fb-1 Absolute Dose map in [Gy] simulated with MARS and FLUKA (CMS)



HCAL Endcap
up to 30 kGy

Pre-Shower + ECAL Endcap
at η~3: 1.5 MGy, 10^{16} n/cm^2

- At future hh colliders, detectors will have to sustain unprecedented fluencies:
  - **Up to 1-2x10^{16} neq/cm-1 at HL-LHC**
    - ATLAS/CMS undergo major upgrades (tracker and/or calorimeters replacement, faster electronics, higher bandwidth and granularity for trigger, …)
  - **10 times more at FCC-hh.**

Activation of material becomes an issue for maintenance

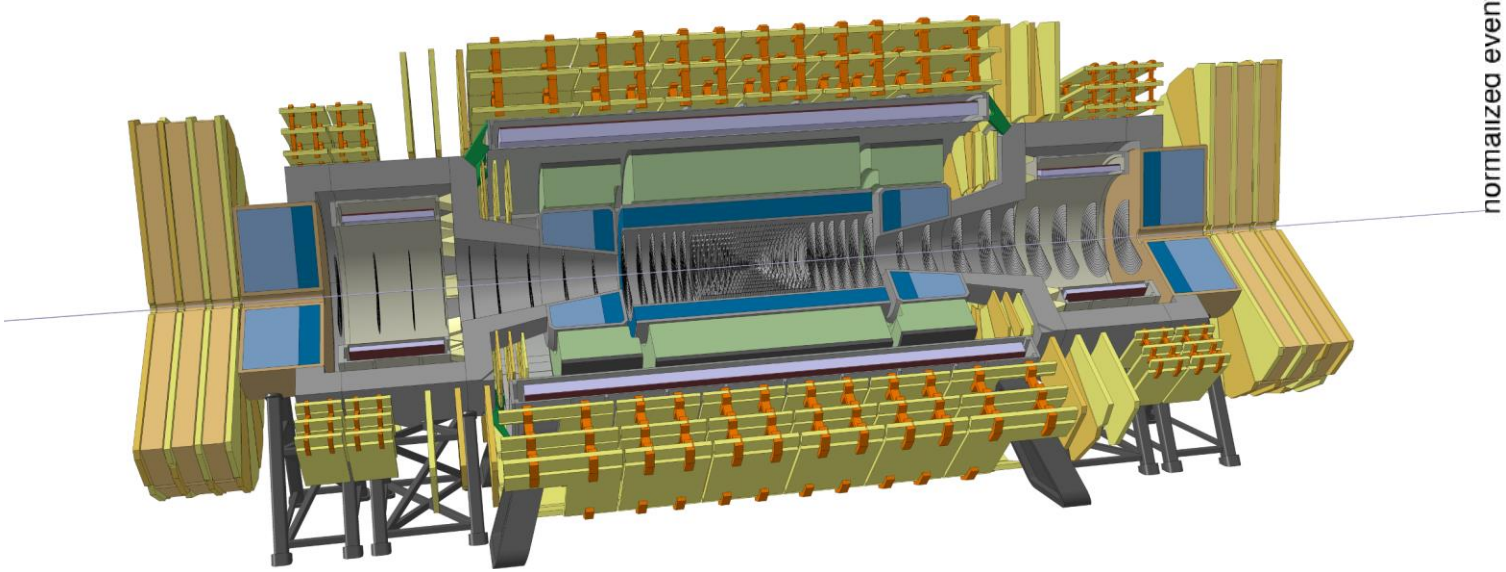
HL-LHC, FCC-hh:
Need rad-hard detectors (sensitive elements, supporting material, on-board electronics, …)

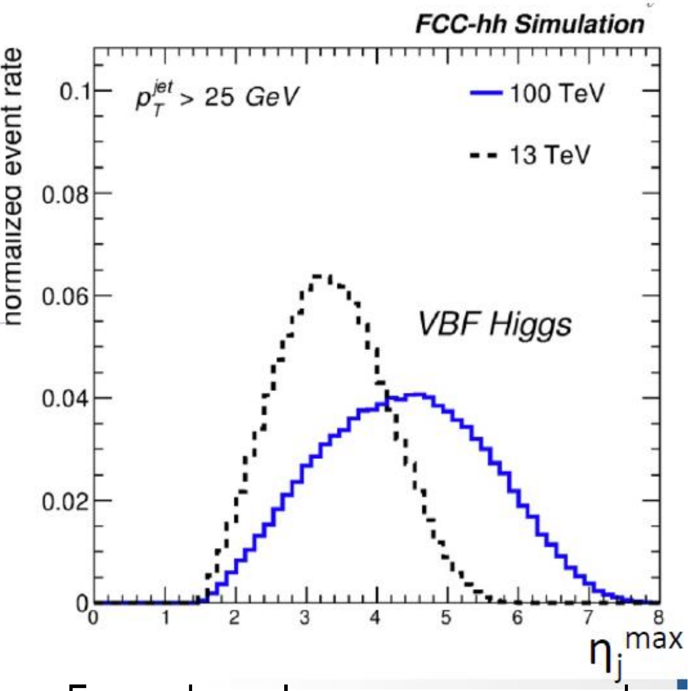
Hadron colliders detector concept

- **HL-LHC: Major upgrades of ATLAS and CMS detectors**
  - Tracker replacement (granularity increased by factor ~5), extension to η~4, reduced material budget (/2)
  - New high granular calorimeter (CMS)
  - Timing detectors
  - Higher bandwidth and granularity at trigger level
  - L1 Track Trigger

- **Also major Phase I upgrades of LHCb** (online trigger at 40 MHz, SciFi tracker, VELO upgrade, …) **and ALICE** (online reco with GPU & FPGA, ITS: largest and most accurate pixel system, Muon Forward Tracker, …)

- **FCC-hh concept:**





Forward angular coverage more and more essential as E_{CM} increases

- Main solenoid (10m, 4T) + forward solenoids (5m, 4T)
- Precision Calorimeters & Tracking up to η=4, Efficient Jet Tagging up to η=6
- Baseline (for study): ATLAS-like LAr and Tile-Cal (with 10x granularity)
  - Depth: >= 30 X0 for ECAL, 12 λ for HCAL

“Particle Flow” as driving concept

- Pile-up mitigation, jet substructure, precision physics… results **in similar needs for high granular detectors in the future.**

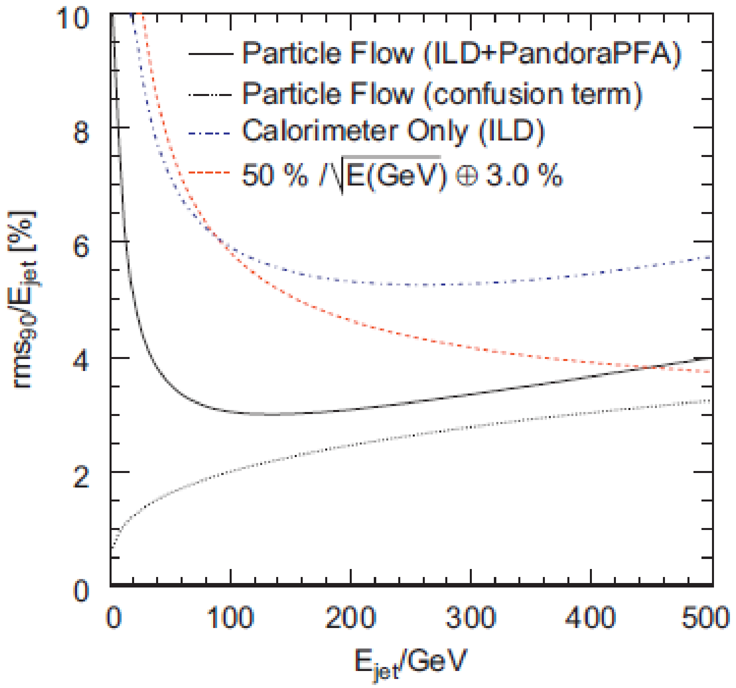
“Particle Flow” paradigm emerging as baseline for future detector design

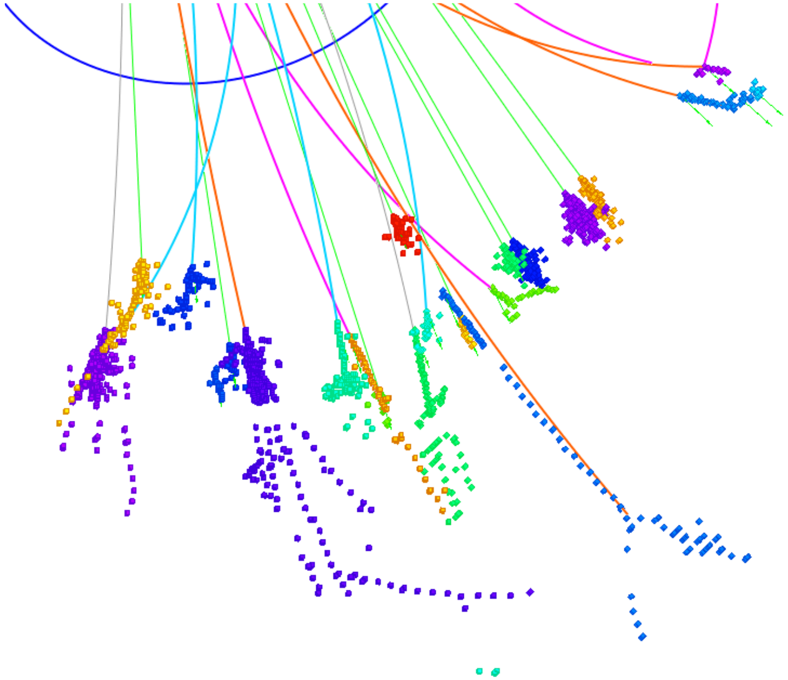
- **“low mass”** (inside the coil) high granular **tracker**
- **High field integral** BxR (“effective granularity”)
  - Separation neutral from charged particles
- **High Granular “imaging” calorimeters**
  - Small Moliere radius (minimize shower overlap)

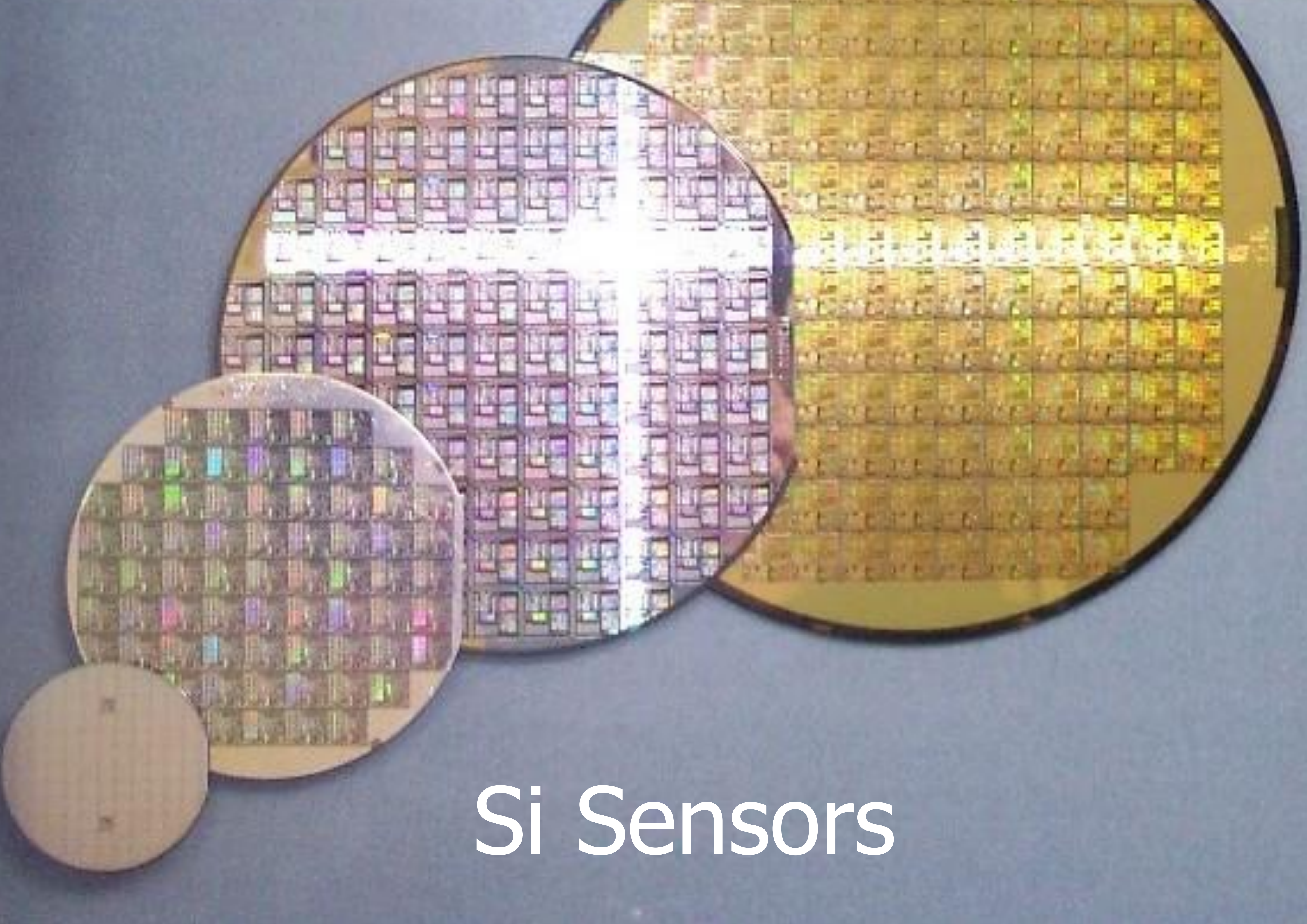
Individual reconstruction of all particles by optimal use of all sub-detectors

- … coupled to powerful software algorithms for reconstruction, calibration, …

PFLow always “wins” against standard calorimetry



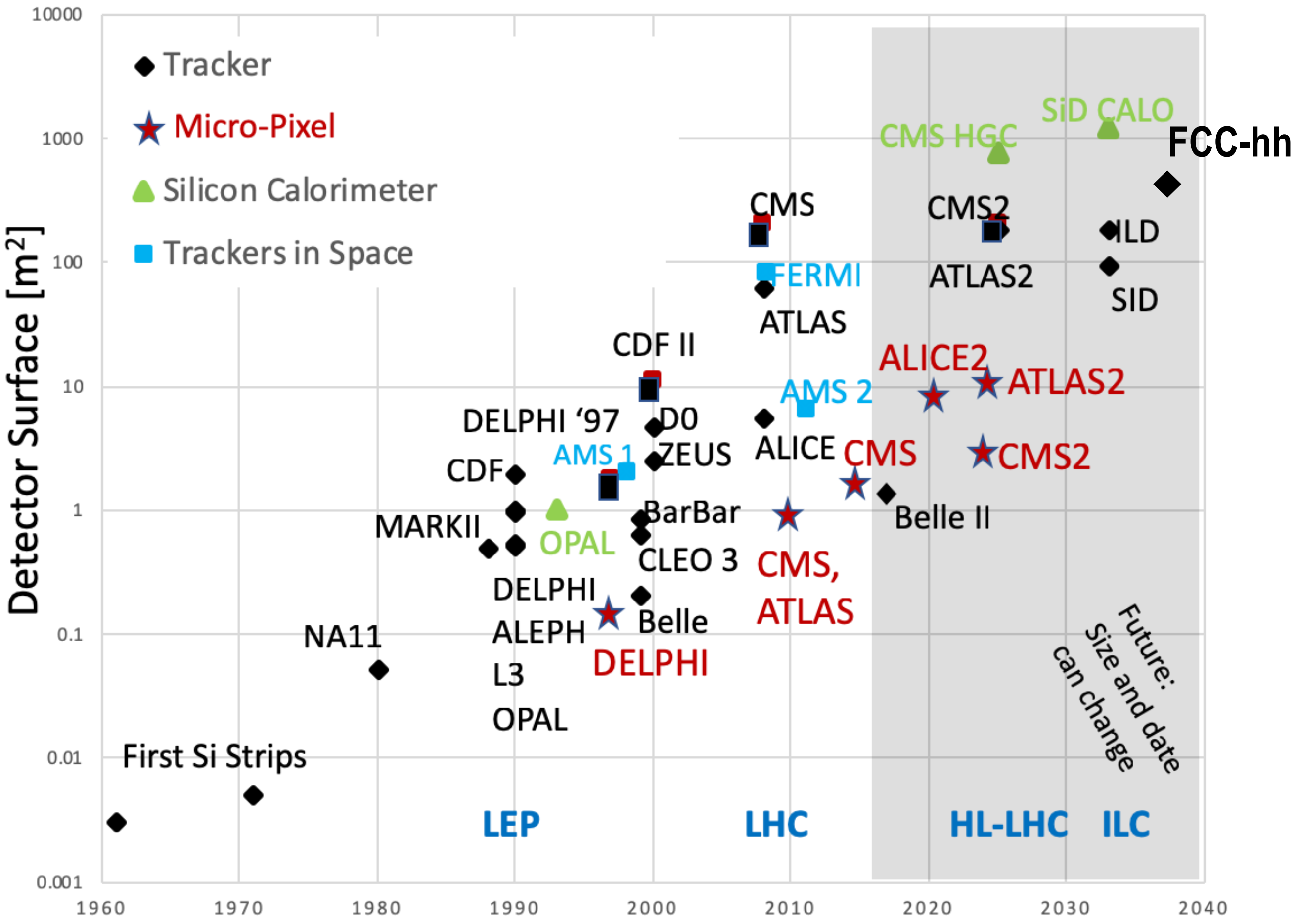




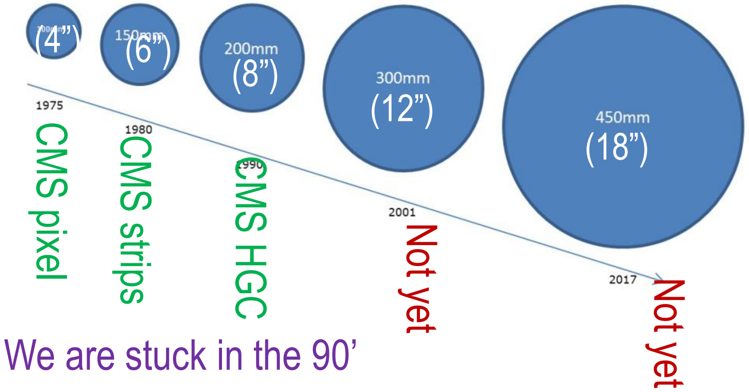
Si Sensors

Si Sensors

- **Si: widely used in HEP detectors as sensitive medium**
  - rad-hard, small cell size, good timing resolution, cost decrease thanks to synergy with µ-electronics industry, …



Wafer Areas in Chip industries:



We are stuck in the 90'

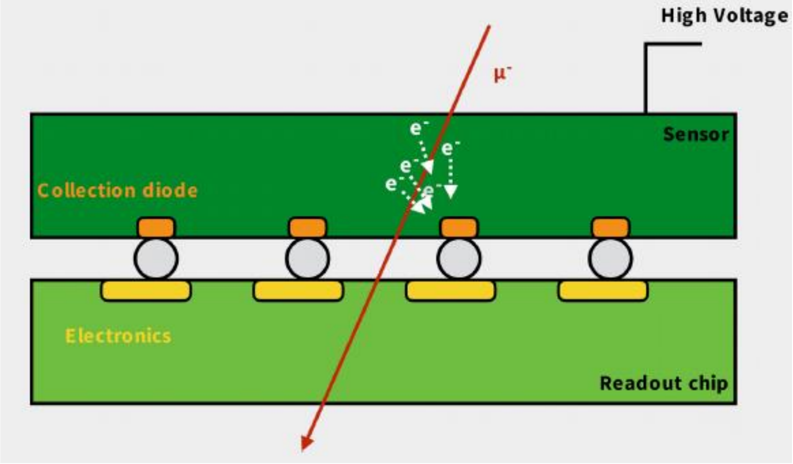
Growing demands for tracker (more and more granular)… but also for calorimeters now !

Widely and massively used in industry (CCD camera, solar cells, …)
Only one producer validated (HPK) for "large" HEP quantities

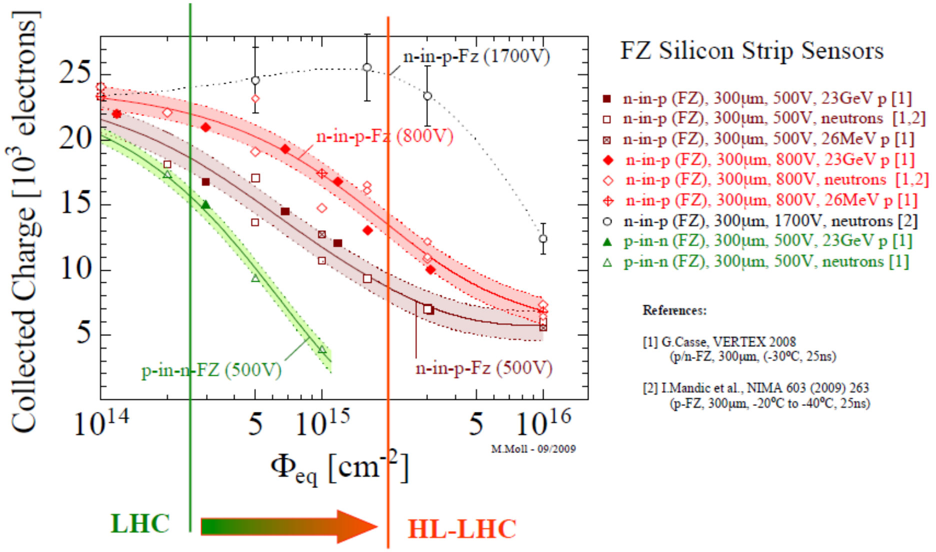
Si Sensors: Hybrid solution

“Traditional” design of HEP Si pixel/strips detectors (ATLAS, CMS, LHCb, Pads for future calorimeters)

Sensors (high-resistivity Si with pn junction) connected
to CMOS readout chip via bump or wire bonding techniques



- **Small pixel size achievable** (25 µm – 250 µm)
- **Radiation hardness:** Current stage of the art (n-in-p or 3D-columns): ~10^{16} neq/cm².
  - To be pushed further for FCC needs (thinner sensors, …)



- **Bump-bonding:**
  - limiting factors for Pixel size,
    - Usage of capacitive coupling (CCPD) may improve this
  - Cost-driver factor on detector production

Hybrid sensors provide route to meeting the most extreme performance requirements.
Due to cost they are less attractive for pixel tracking requiring large area coverage.

Si Sensors: CMOS (1)

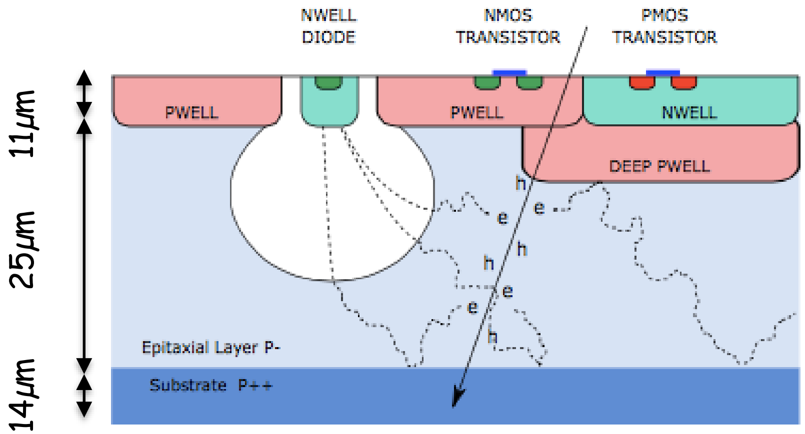
CMOS: Based on regular process at microelectronics foundries (**cheap**, large wafer sizes)

- Sensors diode and electronics on the same wafer
- **Thin** epitaxial sensors ≤ 50 μm with built-in readout electronics, **small pixels** ≤ 30 x 30 μm^2

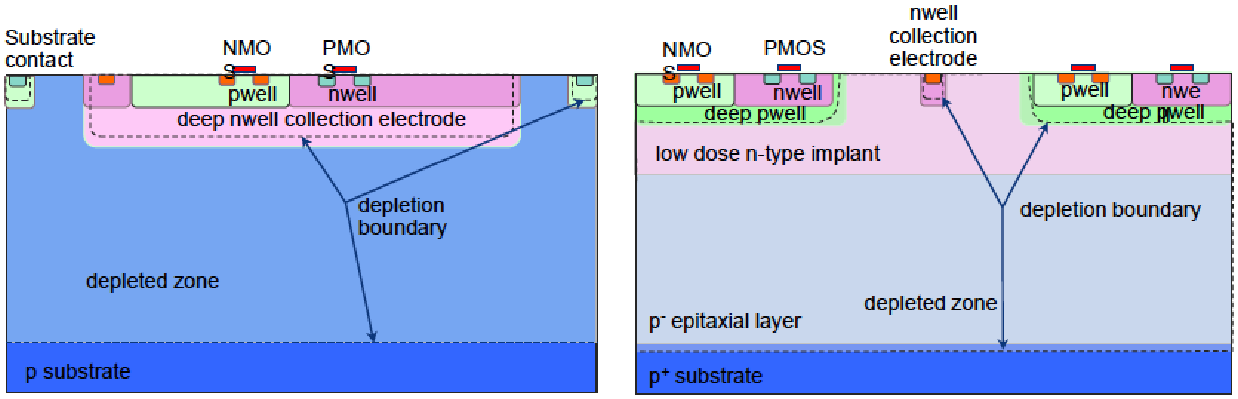
- **Monolithic Active Pixels (MAPS):** collect electrons through diffusion
  - Limitation in radiation tolerance ≃ 2 x 10^{13} neq/cm^2
  - Large integration time ≃ μs

- **Depleted-MAPS** (HV/HR CMOS)- allow depletion voltage ≃ 100 V
  - charge collection by drift
  - Improved radiation tolerance ≃ 10^{15} neq/cm^2
  - Recover integration time of O(ns)

Combine benefits from hybrid (rad-hard, speed) with those of MAPS (integration of analogue and digital logic,lower cost, lower material)



MAPs CMOS Tower Jazz Techno. (0.18 mm)



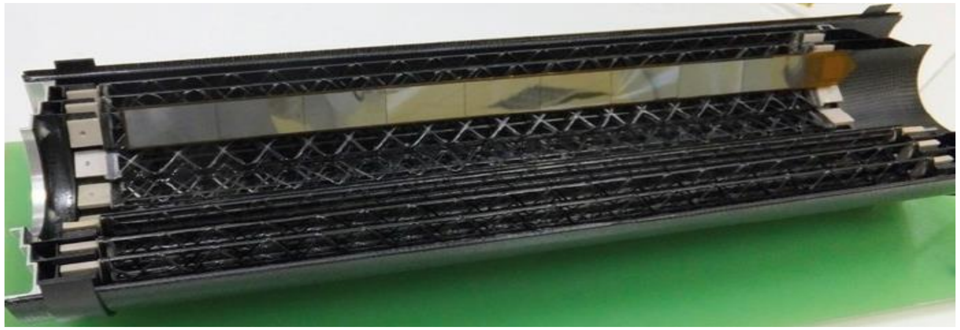
HV CMOS modified large (left) small (right) collection electrodes

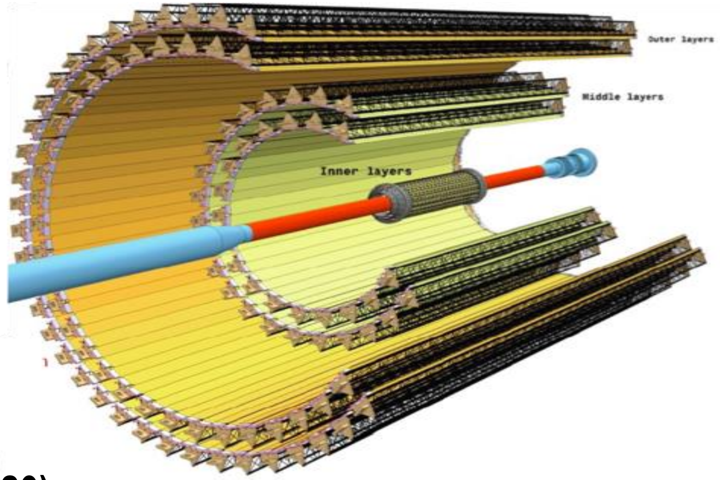
Si Sensors: CMOS (2)

- **Used for high precision with low material budget and small pixels**
  - MAPs: Eudet telescope, STAR vertex detector **(“ULTIMATE”, first MAPs in HEP!**), ALICE upgrade in LS2 (“ALPIDE”), …
  - 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

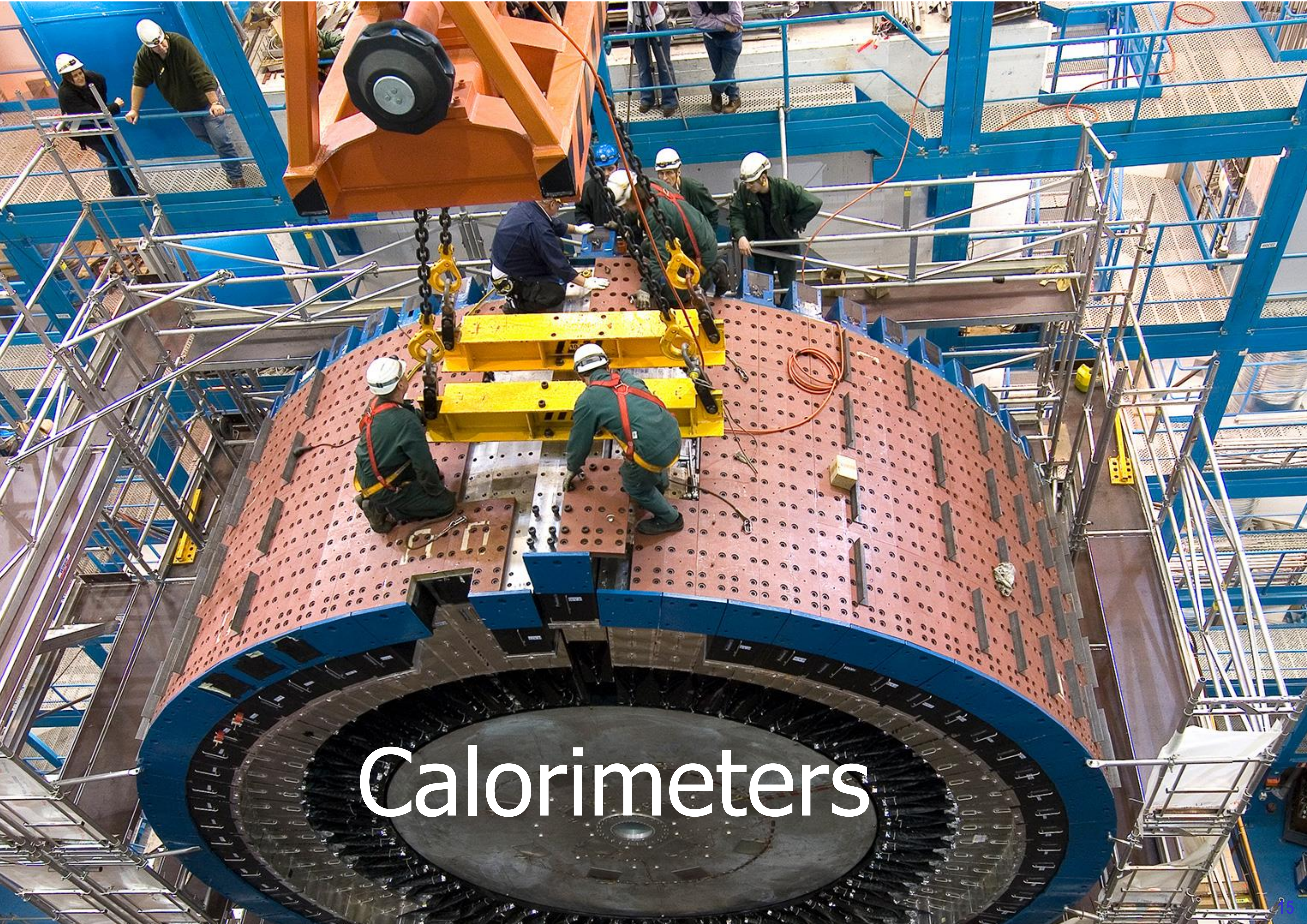
- Depleted-MAPS: HR/HV CMOS:
  - R&D in full chip integration and capacitive coupling through glue between on sensor preamplification stage and complex digital chip
  - Good candidate for CLIC and FCC experiments (improved rad. tol. although not most exposed areas) - CLIC needs charge sharing for resolution

- **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 (similar to hybrid)





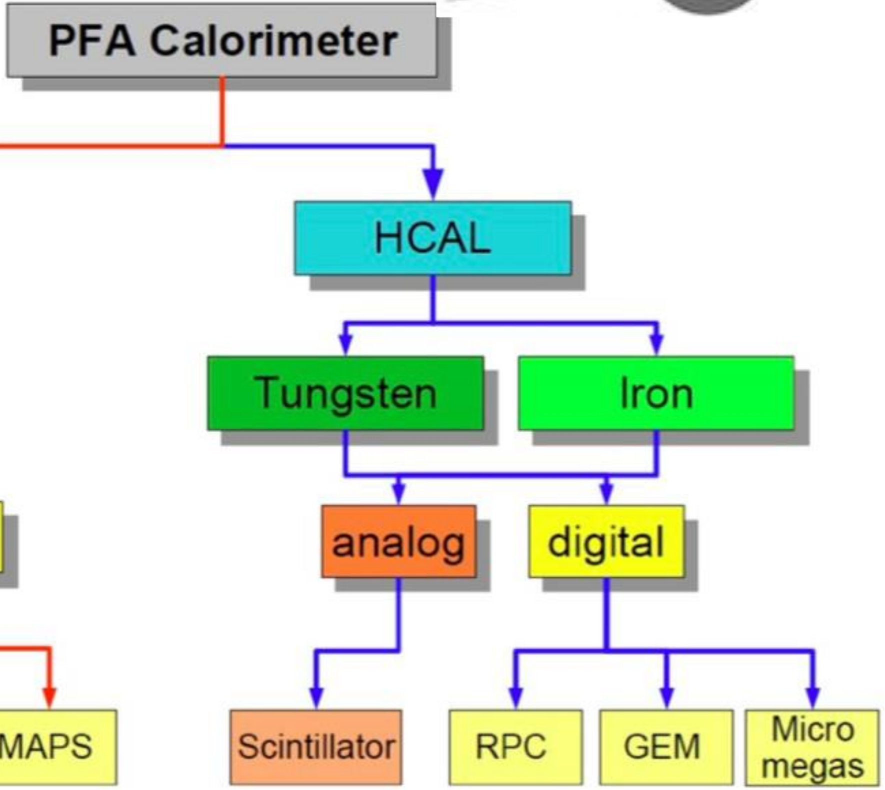
To be installed during LS2 (2019-2020)



Calorimeters

“Imaging” Calorimeters at lepton colliders

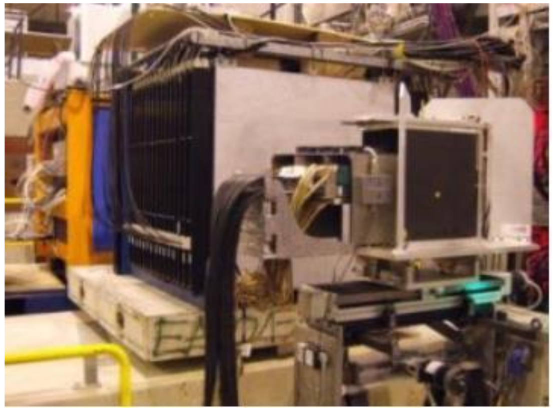
- Development of high granular calorimeters mainly organized within CALICE collaboration for ILC.
- Wide variety of prototypes demonstrating deep understanding of detector technologies
- Ideal devices to tune shower models (**see back-up**)



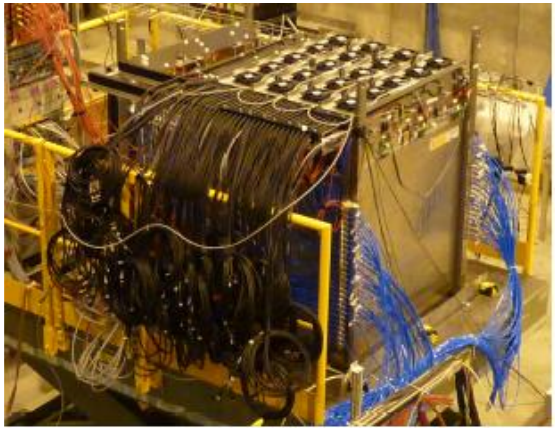
- PFA Calorimeter
  - ECAL
    - Tungsten
      - analog
        - Silicon
        - Scintillator
      - digital
        - MAPS
  - HCAL
    - Tungsten / Iron
      - analog
        - Scintillator
      - digital
        - RPC
        - GEM
        - Micro megas

Si/W ECAL

Analog Sci.+Fe

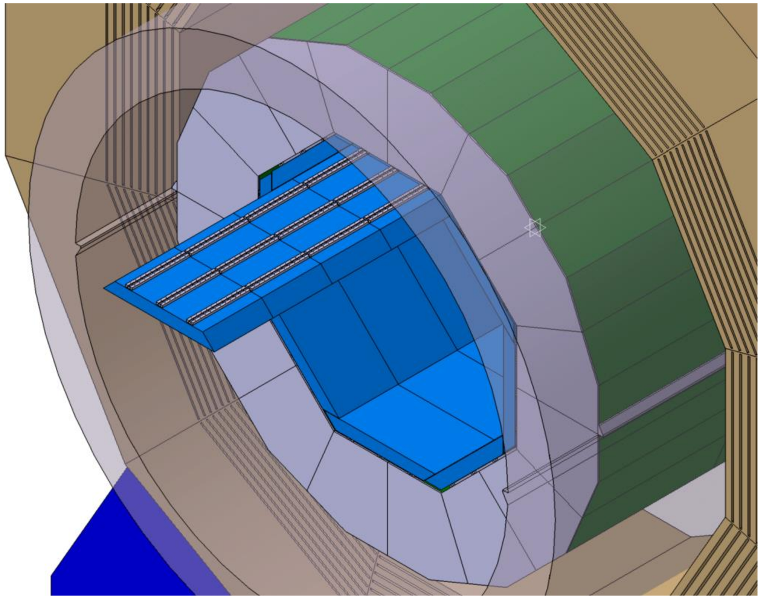


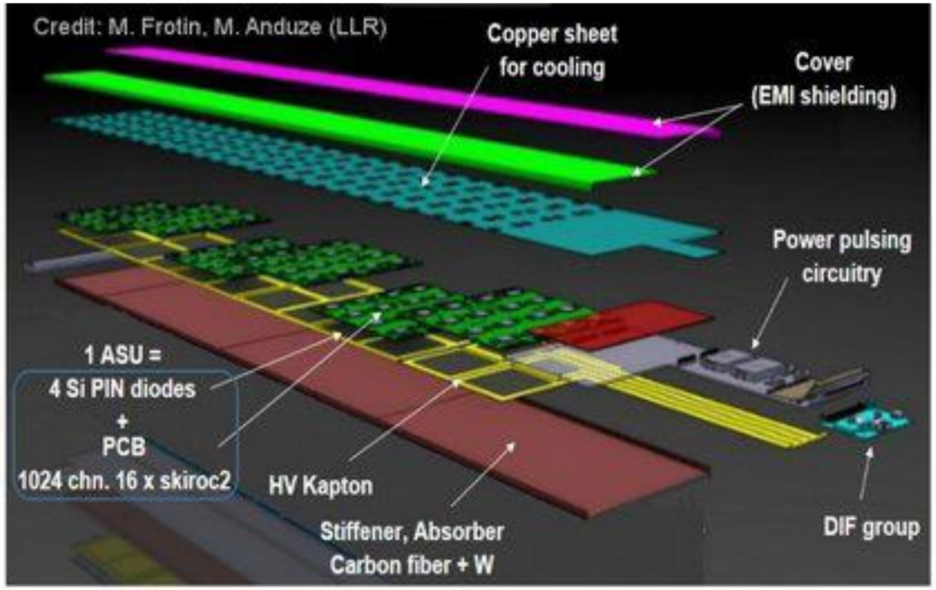
SDHCAL, RPC+Fe



Similar concepts for CLIC (also adapted to FCC-ee, without power pulsing)

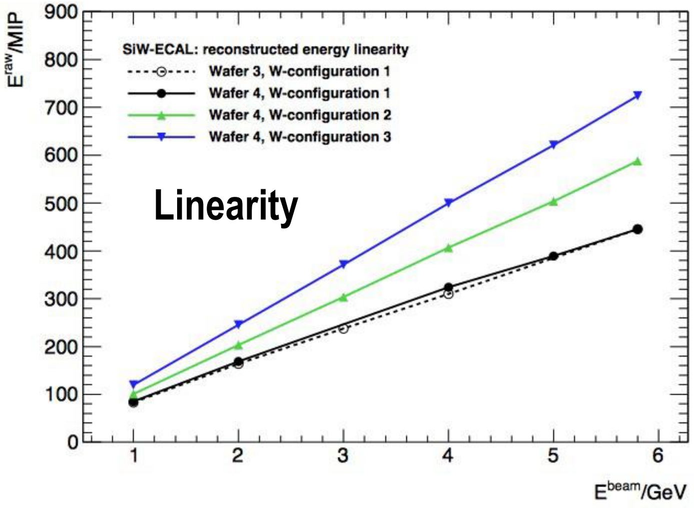
Si/W ECAL



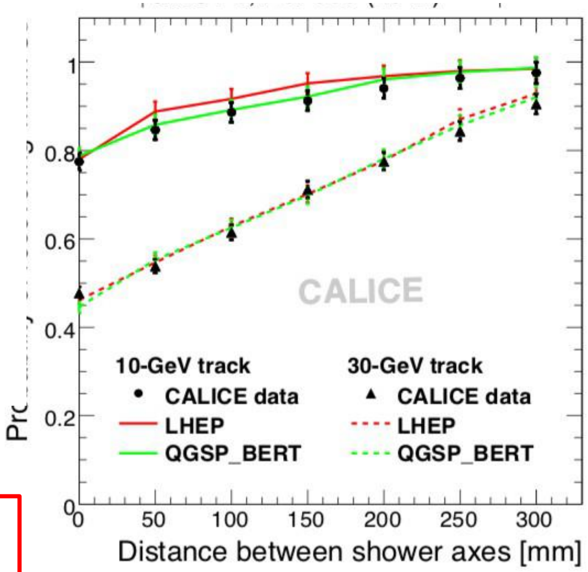


Long "slab" recently tested

- R~1.4m
- **W absorber**
  - Ensure compactness (~20 cm thickness),
  - small R_M
- **Si as active medium**
  - for 26 layers: ~2000 m² of Si,
  - Large S/N
- **Extreme high granularity**
  - (O) 10^8 channels (vs 10^5 at LHC !!!)



Particle Separation

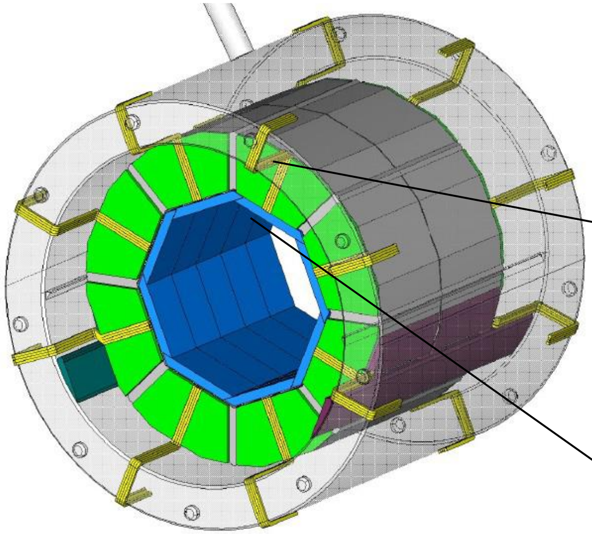


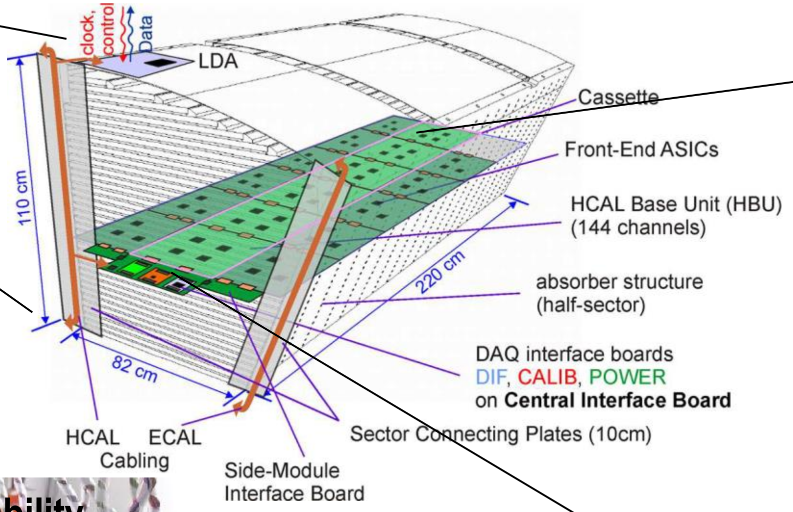
Mature concept, validated with several prototypes

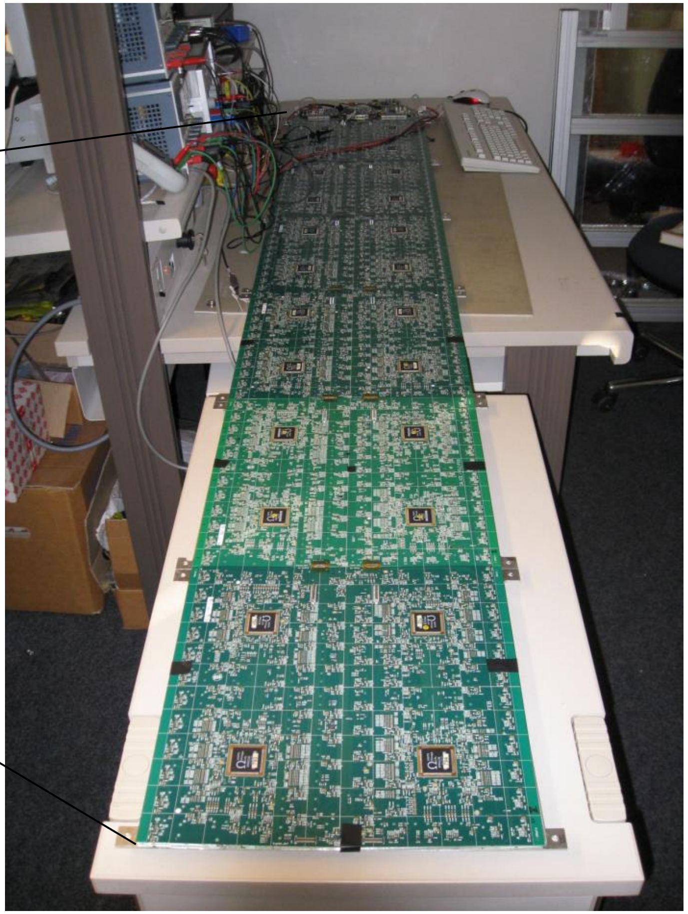
Inspire initial design of CMS HGCAL (**see later**)

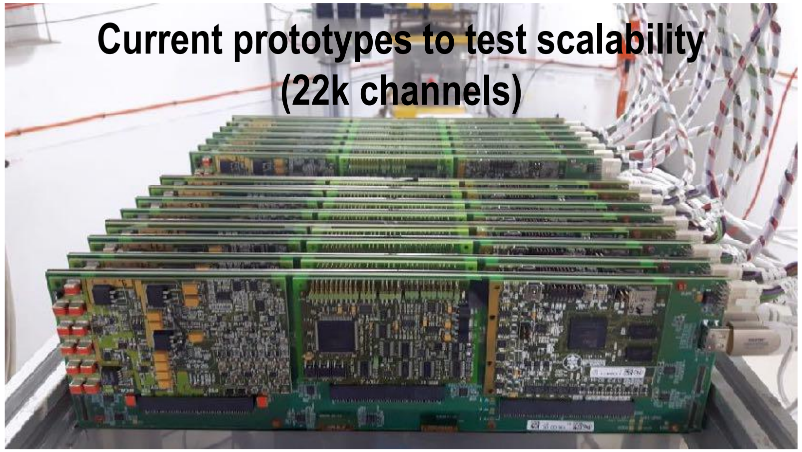
Analog HCAL

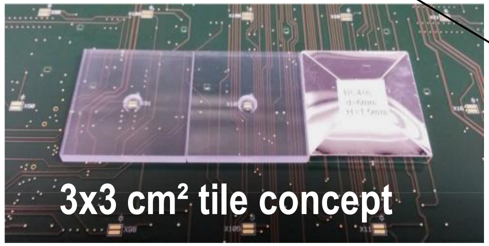
- Sandwich calorimeter based on Scintillator tiles (3x3 cm²) readout using Silicon Photomultipliers (SiPM)
  - ~8M channels (ILC)







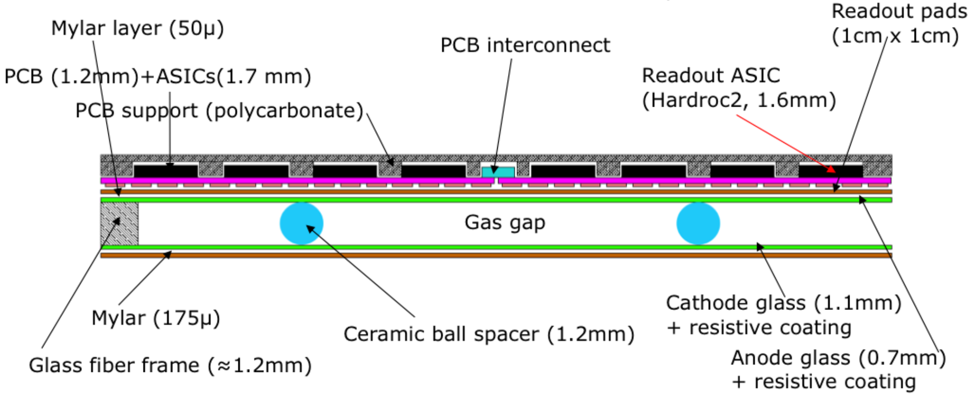

Current prototypes to test scalability (22k channels)

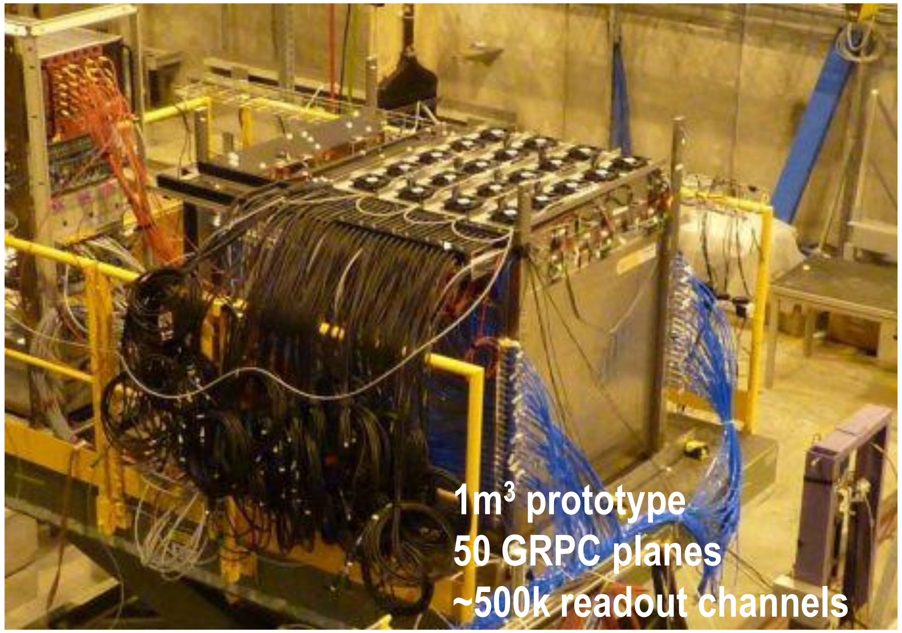

3x3 cm² tile concept

- ~50%/σ(E) achieved in test beam (with software compensation)
- SiPM-on-tile concept adapted to CMS HGCAL HCAL part (**see later**)

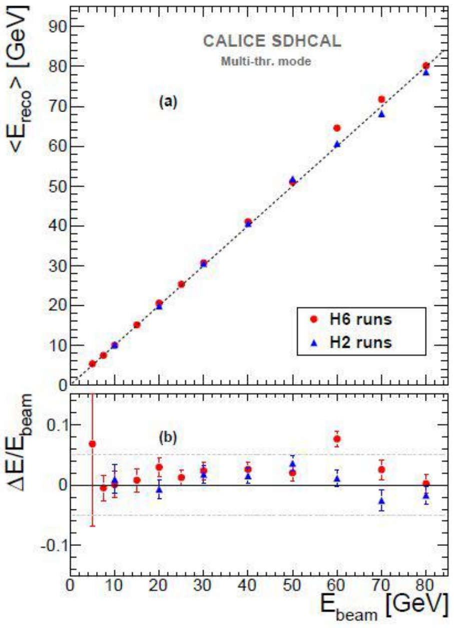
Semi-Digital HCAL

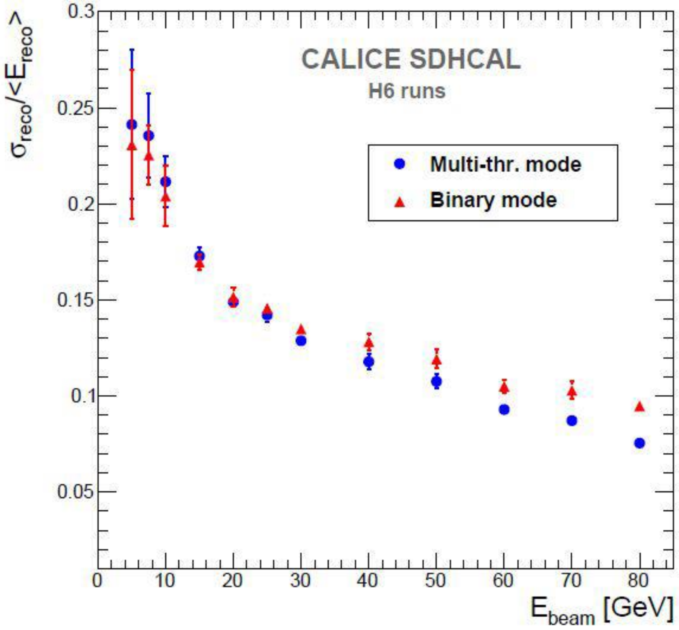
- Sampling calorimeter (48 layers) based on Gas Resistive Plate Chambers (1x1 cm² pads)
  - Semi-digital readout (2 bits, 3 thresholds): counts how many and which pads have signal larger than one of the 3 thresholds





$1\,m^3$ prototype
50 GRPC planes
~500k readout channels





- SDHCAL demonstrated to fulfil criteria of HCAL at linear collider

(imaging) Calorimetry at pp colliders: CMS High Granular CALorimeter (1)

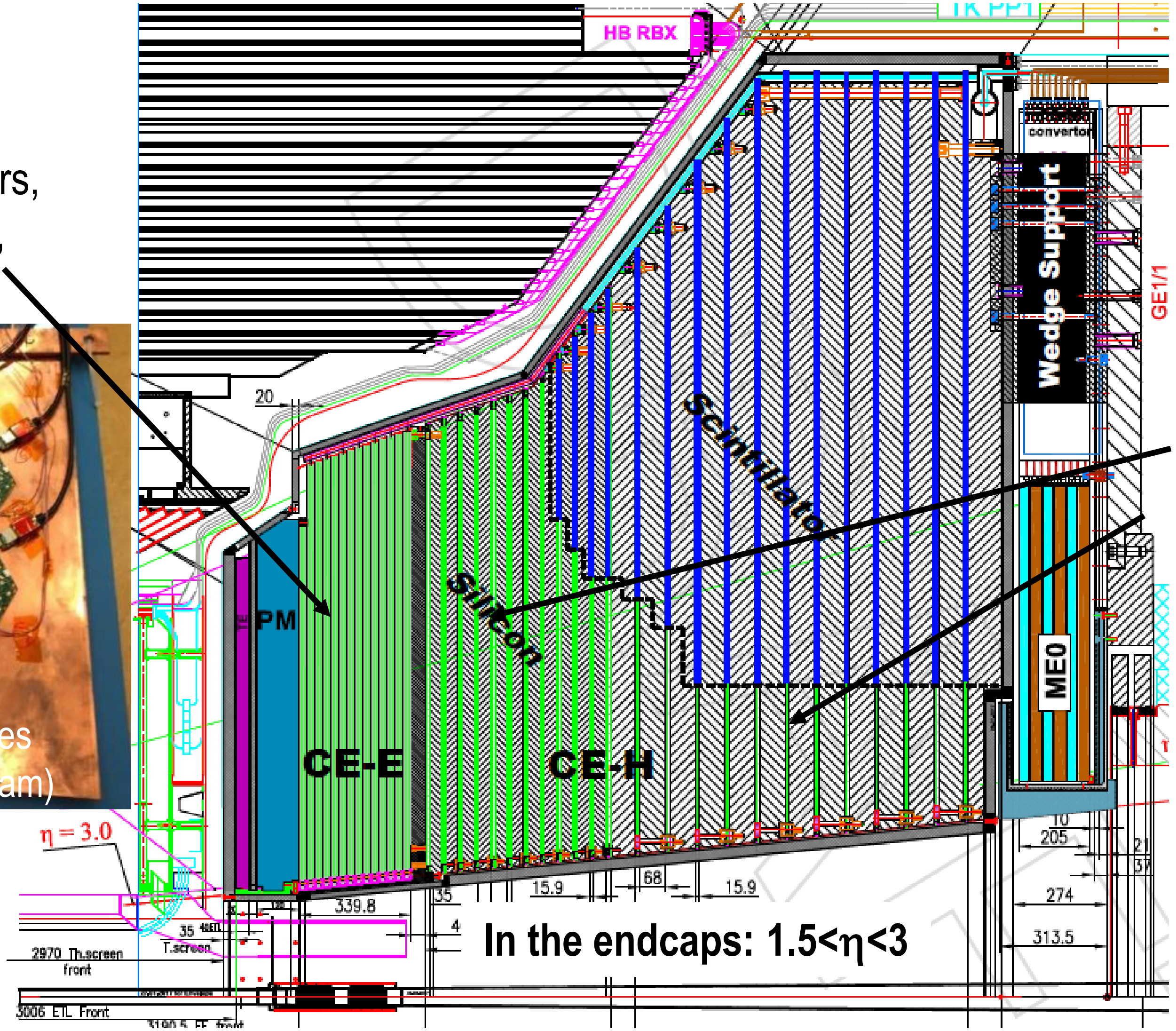
Radiation, PU, data taking conditions
=> Radically different solutions wrt e+e-:
(FE electronics, mechanics, trigger, timing, …)

CMS HGCAL: « 5D » hybrid detector:

- Energy (calorimétrie)
- 3D Position (« tracking »)
- Timing (résolution 50 ps/cell) [see later]

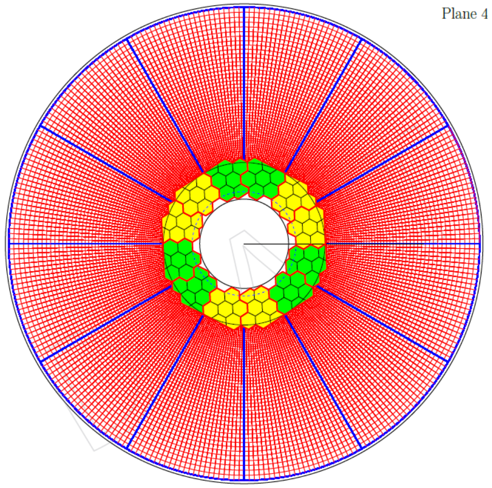
ECAL: 28 layers,
Si+Pb/Cu/W,

7 hexagonal Si modules
(for October 18 Test Beam)



In the endcaps: 1.5<η<3

Steel HCAL (24 layers):
Full Si (8 layers)
or Mixed Si / SiPM on tiles
(16 layers)



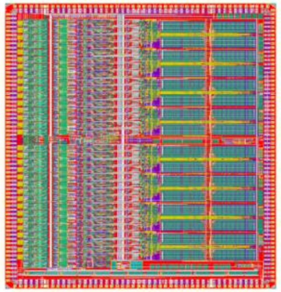
6M Si Channels (x100 CMS calo), ~600 m² Si, 500m² scintillators

(imaging) Calorimetry at pp colliders: CMS High Granular CALorimeter (2)

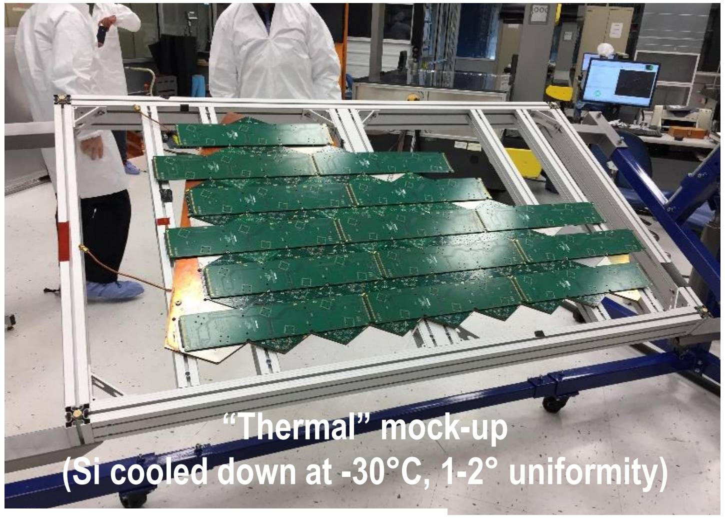
"There are no show-stoppers; it is all just engineering"

"HGCAL is perhaps the most challenging engineering project ever undertaken in particle physics"

"low-power, low-noise, rad-hard, large dynamic range, good resolution on time" FE chip

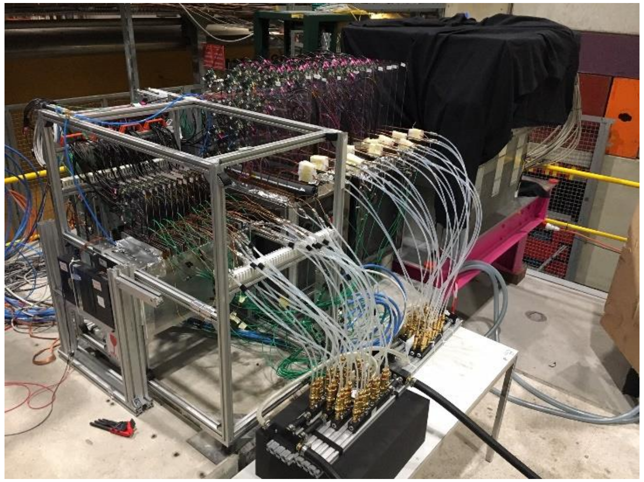


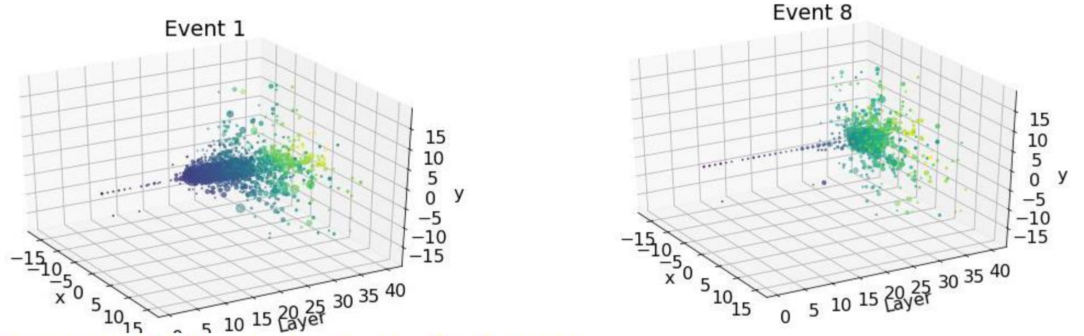
Services (LV, HV, signal, pipes) mock-up



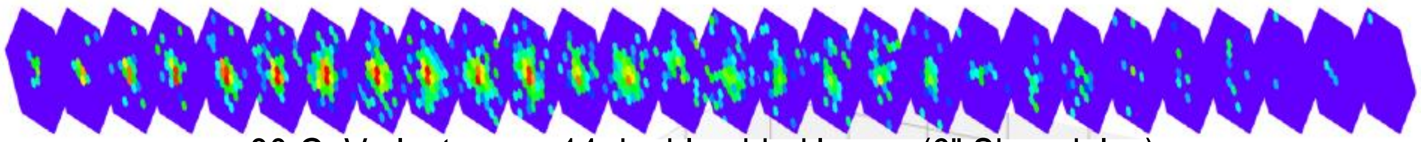
"Thermal" mock-up
(Si cooled down at -30°C, 1-2° uniformity)

Oct 18 Test Beam with (O) 100 modules





ECAL (**blue**)
HCAL (**green**)

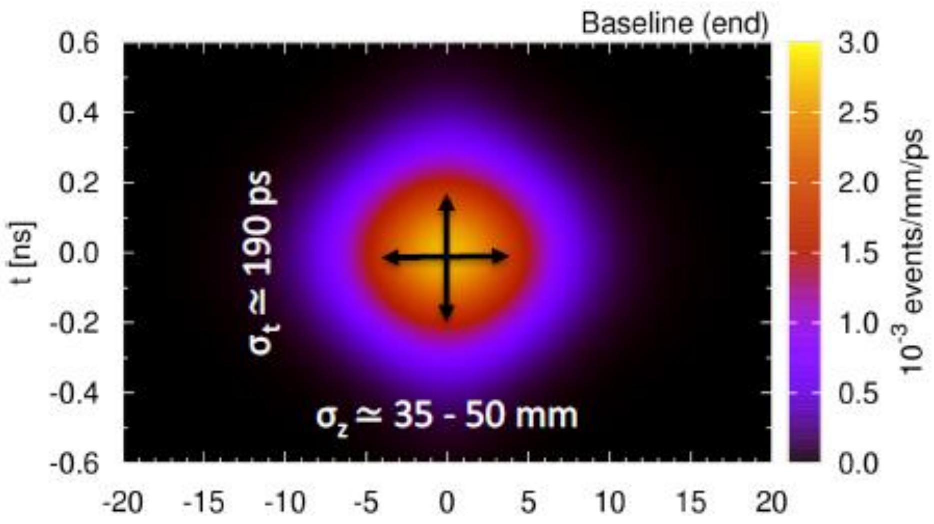


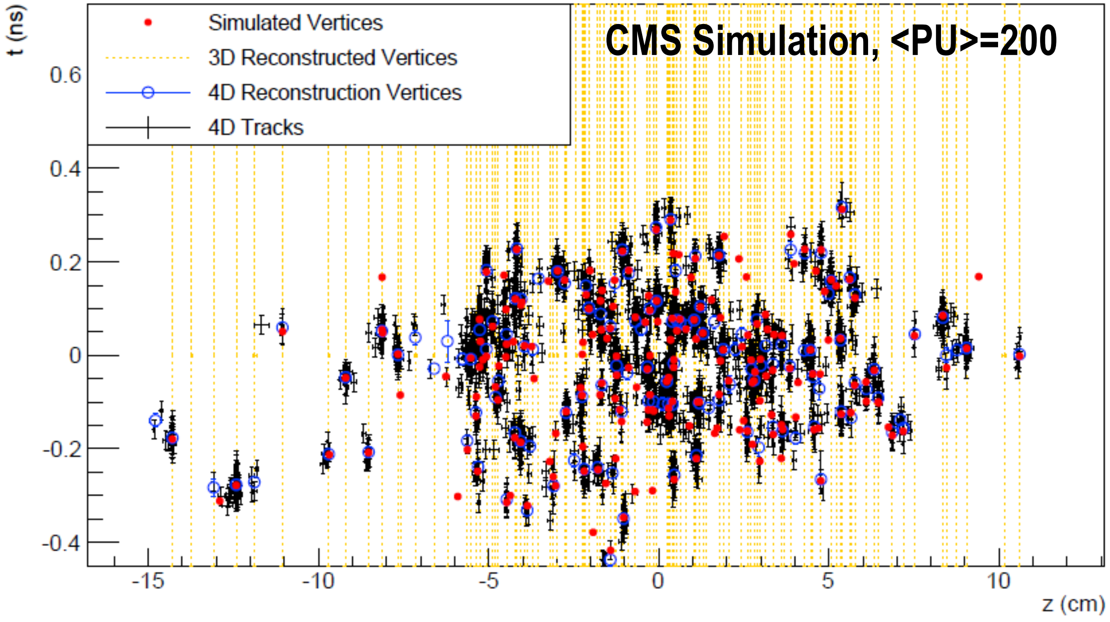
80 GeV electron on 14 double-sided layers (6" Si modules)

High Granularity with E, p and timing becoming real the LHC !
To be installed during LS3 (2024-2026)
Likely the first "imaging" calorimeter in operation

(fast) Timing

(picosecond) Timing

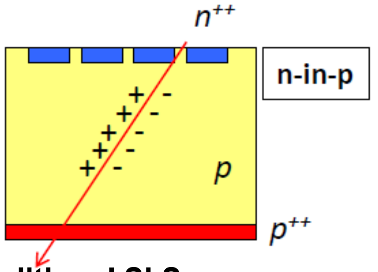




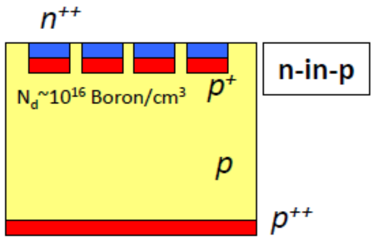
- 10-15% vertices merged in space…
- … could be reduced to ~1% using the timing information (30 ps precision on time-of-flight needed)

Could now be achieved thanks (in particular) to the **development of Ultra Fast Silicon Detectors** (especially in high radiation field)

Ex: Low Gain Avalanche Diode (LGAD)



Traditional Si Sensors



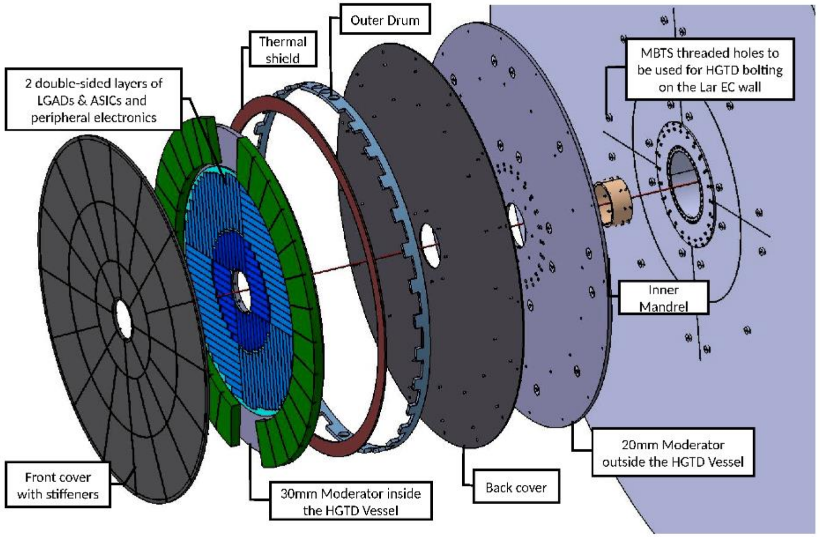
LGAD

n-in-p Si Sensors with amplification through p-implant below the collection electrode (thin layer of doping to produce low controlled multiplication) $\sigma_{jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$

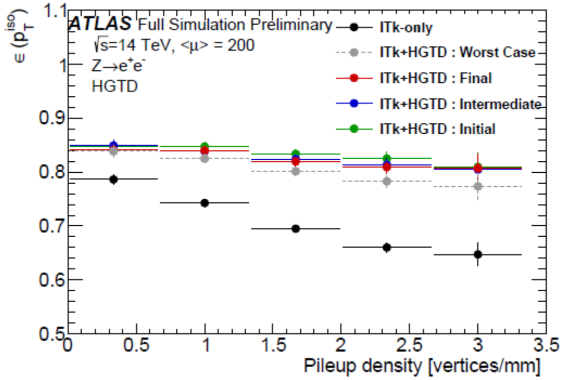
- **Usage of fast timing** (both for charged and neutral particles):
  - **game changer** (especially at hadron colliders)
  - Will take more and more importance in the years to come (**4D tracking, …**)

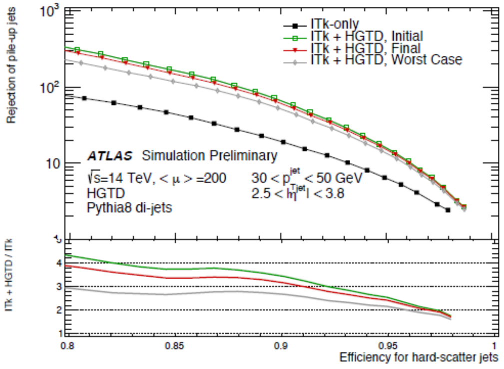
(MIPs) Timing at HL-LHC

High Granular Timing Detector (HGTD)



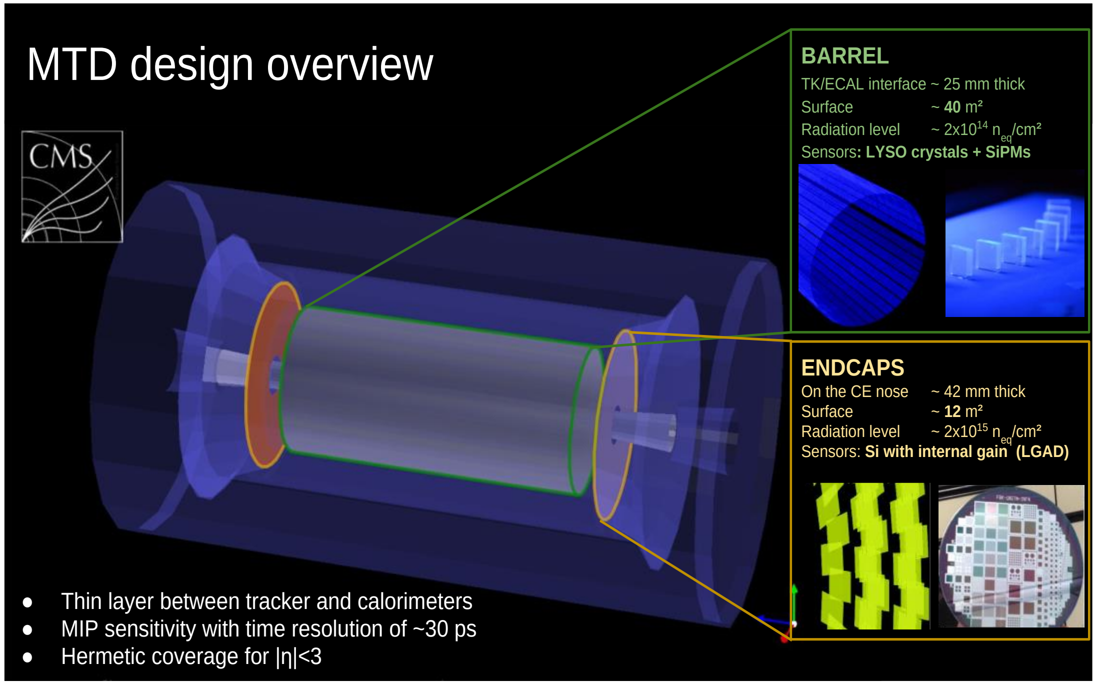
- ➢ 2 layers of LGAD (2.4<η<4), in front Calo endcaps
  - ▪ 1.3 x 1.3 mm² pixels (3.5M channels)
  - ▪ 2 (3) hits per track for R>(<) 320mm (average)





(a) Jets with $30 < p_T < 50$ GeV.

MIPs Timing Detector



MTD design overview

BARREL

TK/ECAL interface ~ 25 mm thick

Surface ~ **40** m²

Radiation level ~ 2x10¹⁴ n_{eq}/cm²

Sensors: **LYSO crystals + SiPMs**

ENDCAPS

On the CE nose ~ 42 mm thick

Surface ~ **12** m²

Radiation level ~ 2x10¹⁵ n_{eq}/cm²

Sensors: **Si with internal gain (LGAD)**

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for |η|<3

- ➢ Barrel (η <1.5) LYSO:Ce crystal+SiPM
  - ▪ Inside tracker volume
- ➢ Endcaps (1.5<η<3) : 1 layer of LGAD
  - ▪ 1x1.3 mm²pixels (1.8 M channels)
  - ▪ In front of HGCAL

Resolution of 30-40 ps (after irradiation). LGAD Rad. Hard up to 2.10¹⁵ neq/cm² (10 times less for LYSO+SiPM)

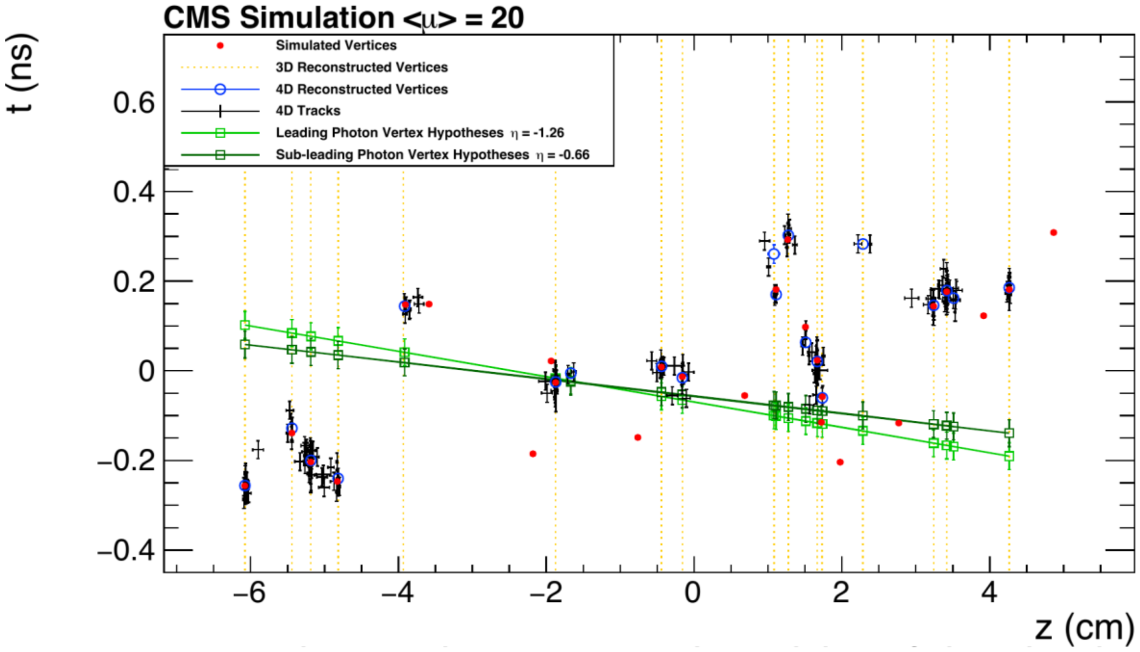
Clock distribution: Need 10-15 ps in order not to spoil the performance of the detectors…

(picosecond) Timing… for showers !

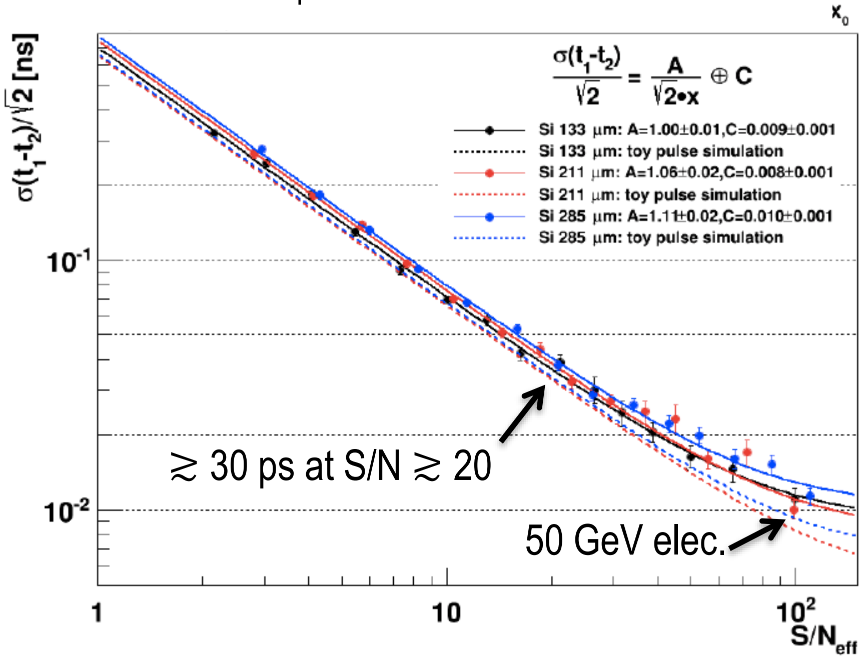
Calorimeters can also provide precise timing for neutrals to determine γ's origin in conjunction with vertex timing to mitigate PU in Jets-ID, MET resolution or Lepton Isolation

- Examples at HL-LHC:
  - CMS ECAL with $PbWO_4$ crystals + APDs + new FE can provide $\simeq$ 30 ps for 30 GeV γ
  - CMS HGCAL Sampling calorimeters benefit from large number of layers to provide 30 ps for few GeV Photons and good efficiency for hadrons above 2 GeV Pt.
    - Limitation in S/N is in electronics noise (pad size capacitance)

H→γγ vertex finding (4D Tracking+calo timing)



CMS HGC Si-pads



$\gtrsim$ 30 ps at S/N $\gtrsim$ 20

50 GeV elec.

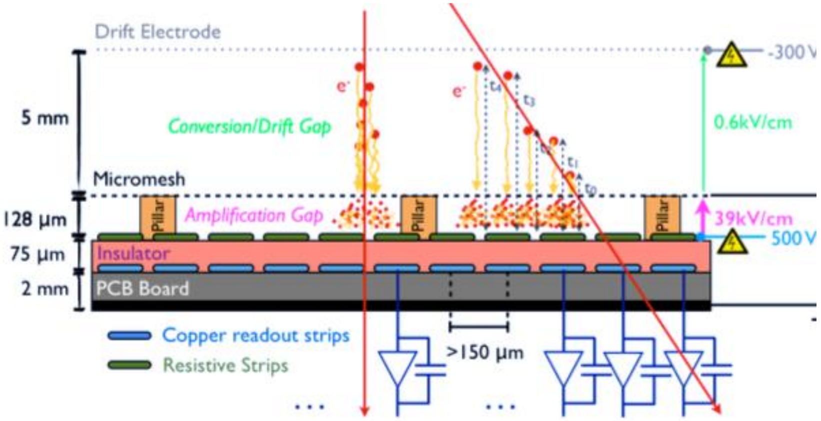
From D. Contardo

Gaseous Tracking detectors & Muons

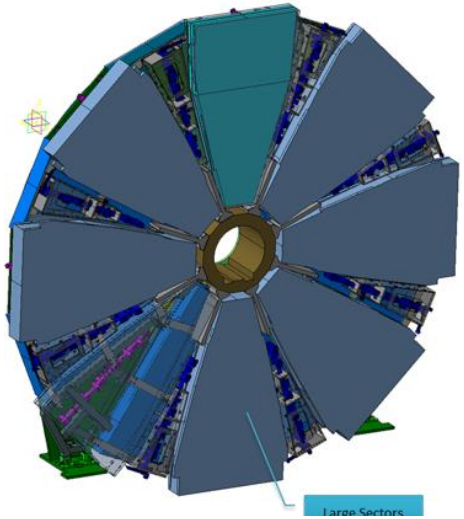
Besides “traditional” gaseous techniques, wire detectors (DTs, CSCs, MDT,…) and RPCs for low rates/granularity a newer technology is mature: Micro Pattern Gas Detectors (GEM, MicroMegas, μRWell, …) for higher rates:

➢ MPGDs provide:

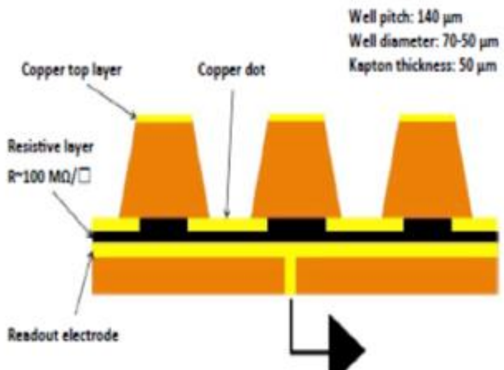
- Fine position resolution (<100 μm),
- Good timing resolution (< 10 ns),
- High Rate capability (>10^7 counts/mm)
- Excellent radiation hardness
- Can be mass produced by industry



MicroMegas



New Small Wheel (1.3<η<2.7)
(MM+TGCs)

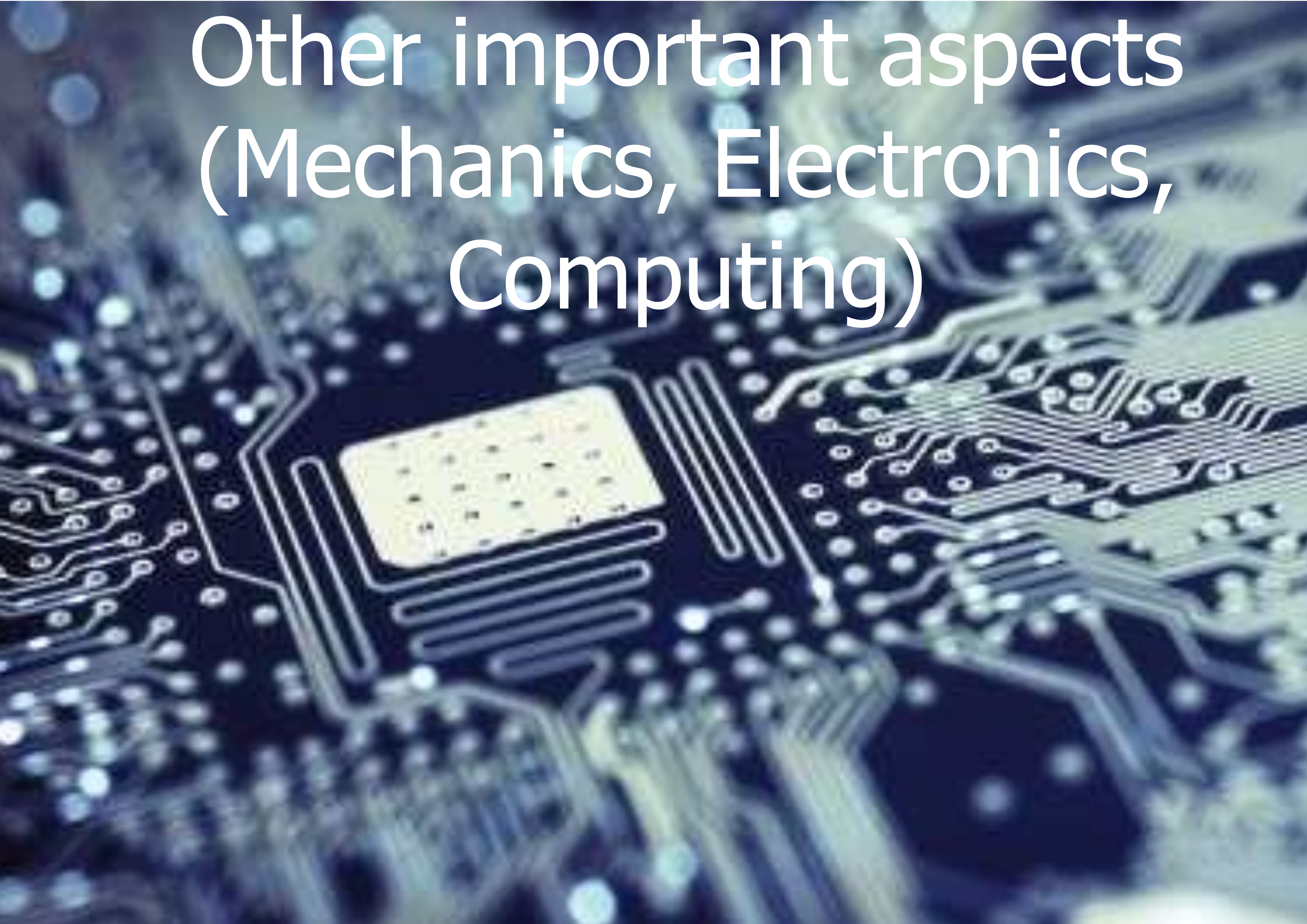


μ-Resistive-Well design

➢ MPGDs:

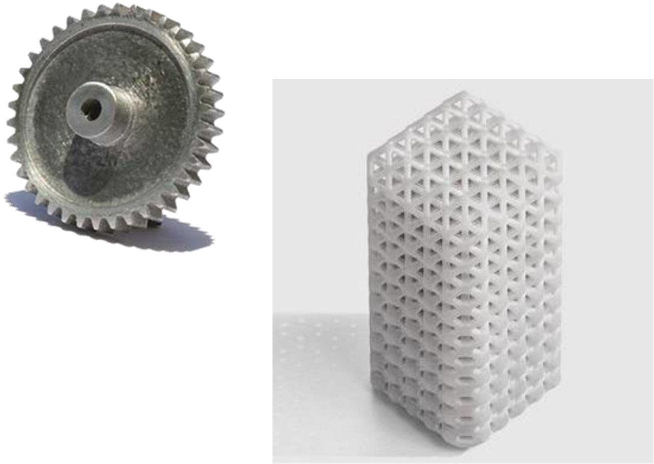
- widely used for LHC Upgrades: GEM (CMS forward chambers, ALICE TPC, current LHCb), MicroMegas and Thin Gap Chambers (ATLAS forward chambers), …
- Also good candidates for future colliders

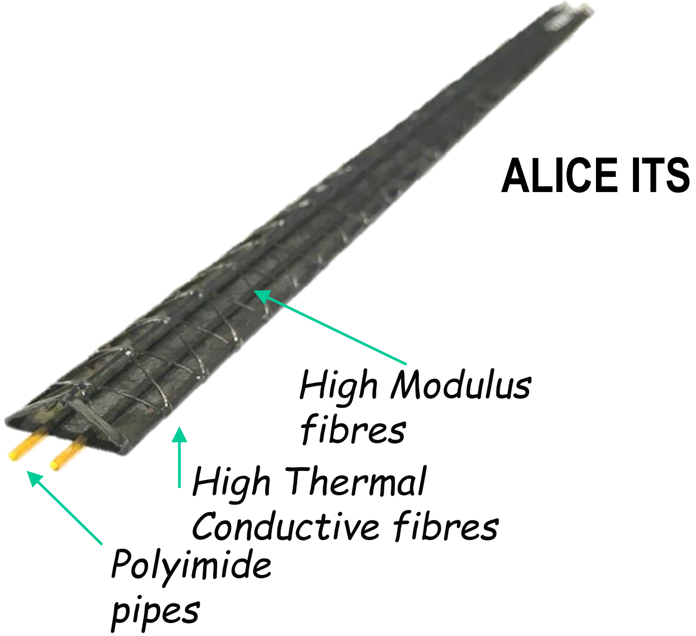
Other important aspects (Mechanics, Electronics, Computing)



Mechanics & Cooling

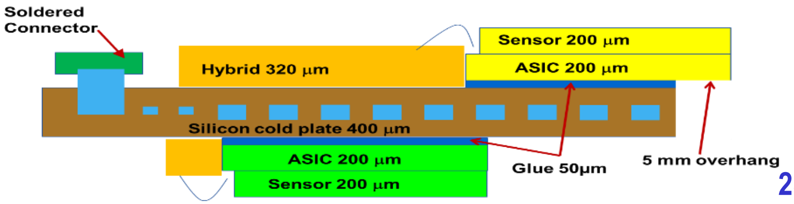
- **Future detector mechanics has to cope with large range of demands:**
  - Provide high dimensional and dynamic stability
  - Radiation hardness
  - **Minimal material budget**: $X/X_0 < 0.1\%$ per tracker layer for Lepton colliders!
    - R&D on new material:
      - Carbone nano-tube or Graphene used to enhance composite thermal and mechanical properties,
      - Resins with better radiation resistance,
      - 3D printing (metal, ceramics, polymer)





  - **Provide cooling and thermal stability**
    - Needed to dissipate power and mitigate leakage currents in radiative environment.
    - **Two-phase CO2** current state-of-the art (LHCb VELO, ATLAS IBL, ATLAS&CMS Phase II Trackers, …).
    - R&D on CO2/N2O mixture to go below ~-40°
    - Also: **µ-channels** embedded within thin Si plates to further minimize material budget

LHCb micro-channel cooling

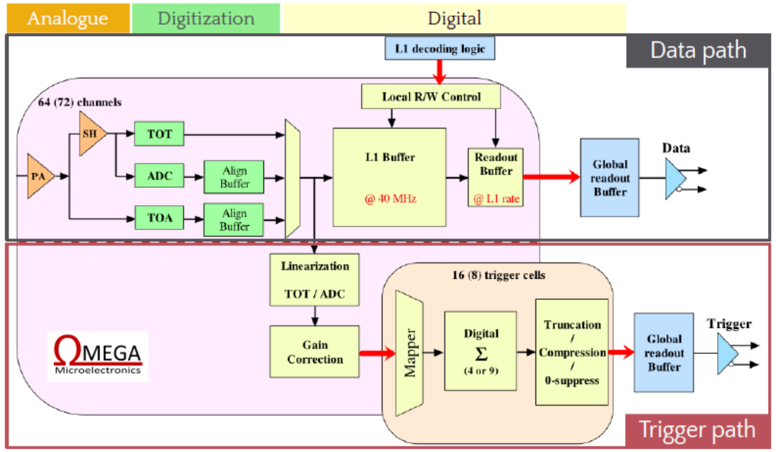


(Front-End) Electronics

More complex and granular detectors inevitably lead to more and more stringent requirements on Front-end ASICs.

Ex: HGROC (for CMS HGCAL)

- Large dynamic range (0.4 fC ->10 pC)
- Low noise (MIPs sensitivity)
- Low power (~10 mW / channel)
- Radiation-hard
- Time resolution (50 ps/cell)
- High-level integration

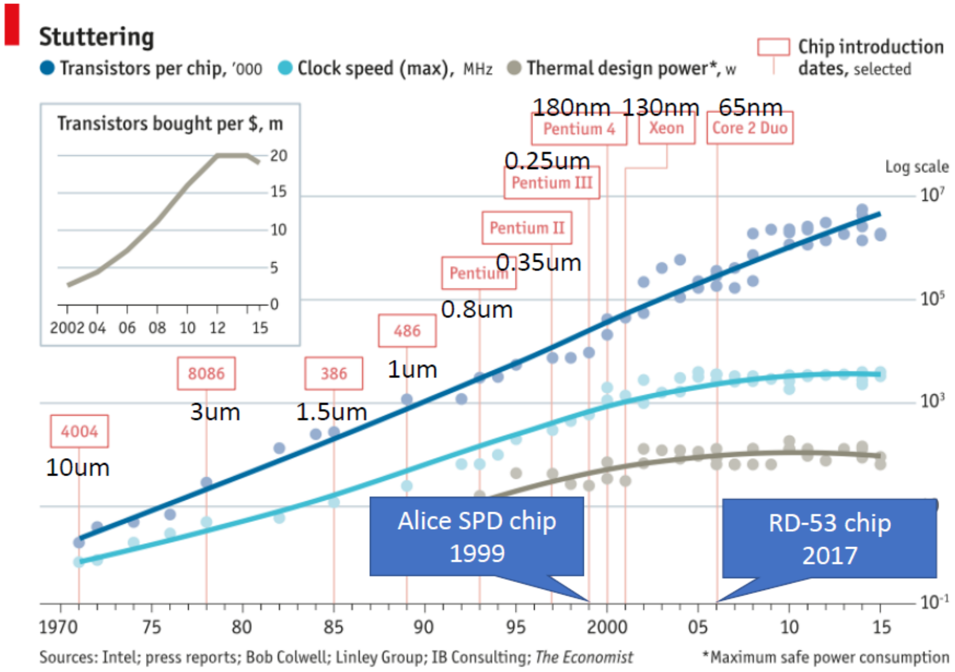


➢ **Deeper submicron technologies:** 0.35 µm Si/Ge widely used at LHC → TSMC 130 nm (HL-LHC calorimeters), 65 nm (HL-LHC pixels)

- **Increase digital functionalities**,
- **lower pixel sizes** (50x50 µm² for RD53 pixel ASIC),
- **reduce power consumption** (digital part),
- improve radiation tolerance (up to 500 MRads for 65nm)

- 28nm ? Radiation hardness tests started.
  Candidate for FCC-hh ?

- Any interest in going below 28 nm (FinFETS) ??



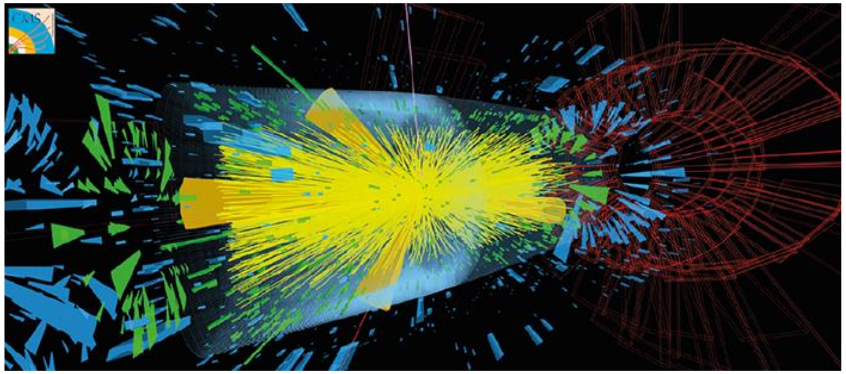
Sources: Intel; press reports; Bob Colwell; Linley Group; IB Consulting; *The Economist*

*Maximum safe power consumption

(some) Challenges for Trigger / DAQ

- More complex events (PU<=>high multiplicity),
- More granular detectors (calo, tracker)
- Physics range (“from EW to TeV scale“)

Challenges for future trigger system
(both hardware & software parts)



- **Example of requirements for HL-LHC (ATLAS & CMS)**
  - L1 latency: 2.5-3.2 µs → 10-12.5 µs (**x4 LHC**)
  - Readout rate: 100 kHz → 750-1000 kHz (**~x10 LHC**)
  - Overall throughput: 2 Tb/s → 50 Tb/s (**~x25 LHC**)
  - Rate to permanent storage: 1kHz → 7.5-10 kHz (**~x10 LHC**)

- **Benefits from commercial progress** in FPGA, bandwidth/high speed links (up to 25 Gb/s?), ATCA crates, …

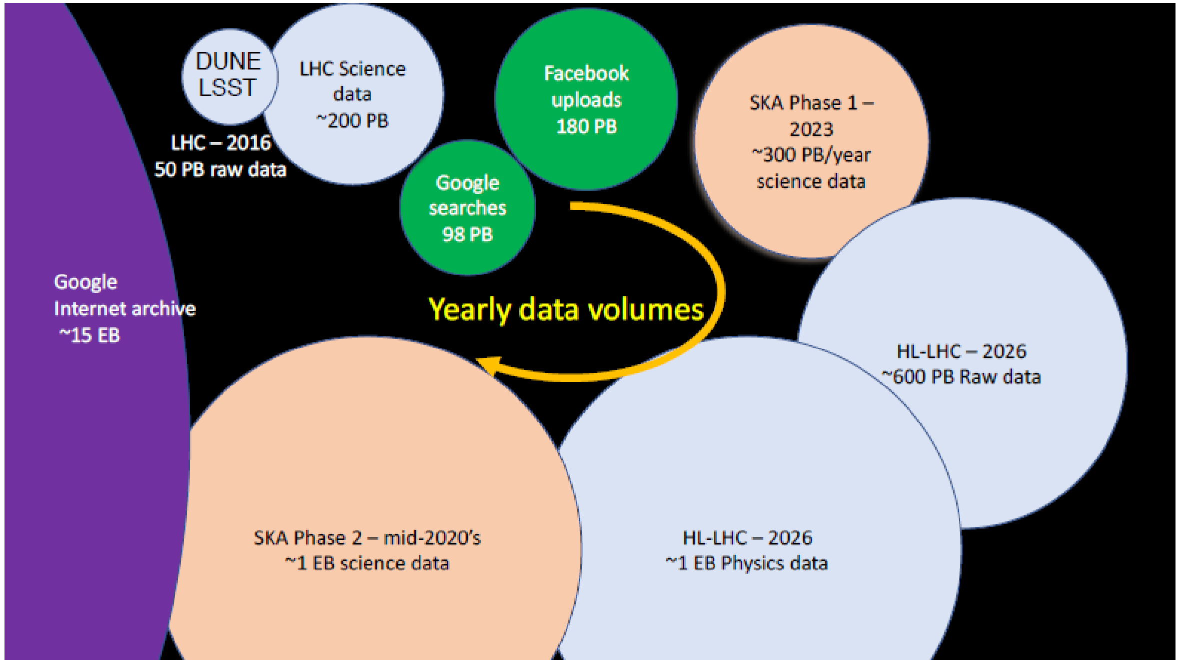
- **Flexibility and Scalability are the keys !**
  - Ideally (?): read ~full detector -> send everything out -> use complex & powerful algorithms for trigger decisions
    - **Limited by data output** (FCC-hh: 1-2 PB/s !!!) **and number/speed of (optical) links** (ie, cost !).
  - In practice, **compromise between data reduction** (compression, cells merging, …) and **loss of information**
    - Process on FPGA: re-programmable <=> adaptation to new data taking conditions

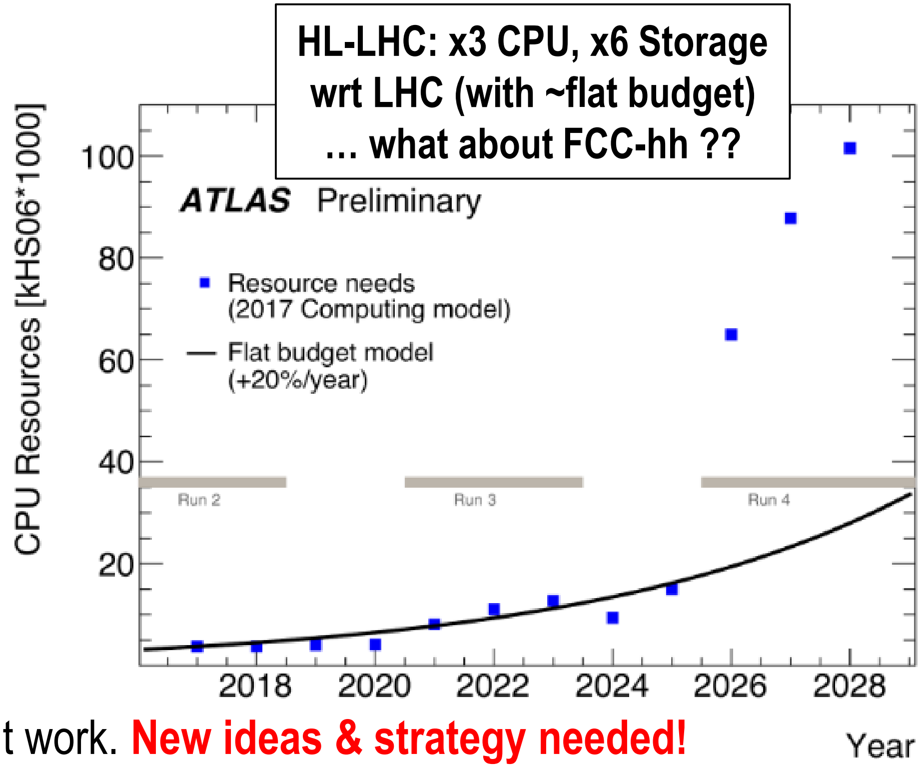
- **“Triggerless” LHCb architecture?**
  - What are the consequences on on-line computing ?

- **Software trigger with GPU ?**
  - Demonstrated by ALICE for track reconstruction

(some) Challenges for Computing & Software

Large Si detectors and cameras with growing granularity are driving us to large computing, data handling & software challenges.




HL-LHC: x3 CPU, x6 Storage wrt LHC (with ~flat budget) … what about FCC-hh ??

Simple scaling of current architecture/ways to work won't work. **New ideas & strategy needed!**

- **Lots of R&D:**
  - **Computing:**
    - Rise of heterogeneous hardware: many-core CPU's, acceleration (GPU, FPGA, ARM?), usage of opportunistic resources (commercial clouds), …
    - Reconcile the split between HPC$^{(*)}$ and HTC$^{(**)}$ ecosystems ?
    - … quantum computing?
  - **Storage:** **main issue.** Data compression, slimming, …, "data lakes", grow usage of tapes ?
  - **Simulation:** adapt to new (vectorised?) computing architecture, develop fast sim., GANs…
  - **Machine Learning**: Deep Learning revolution… comes with heavy computational demands !

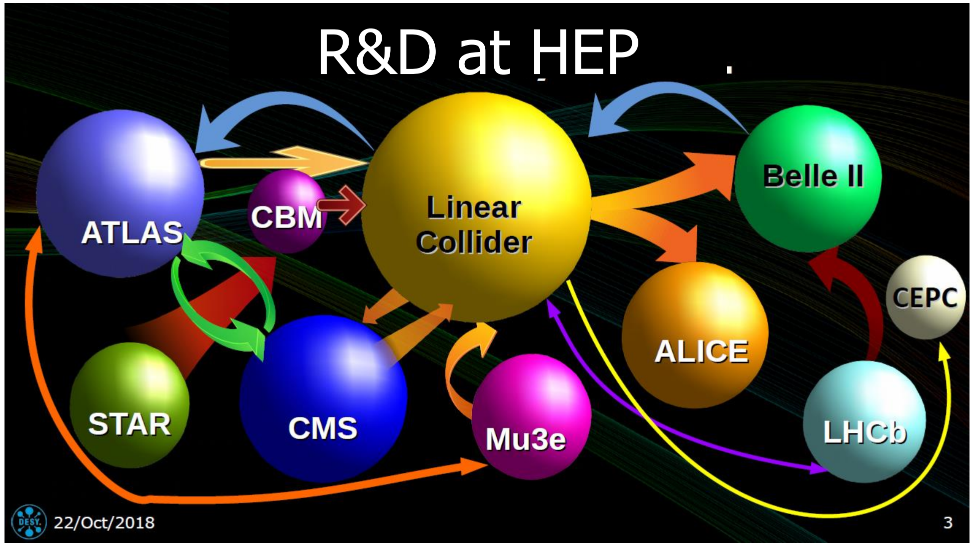
(*) High Performance Computing
(**) High Throughput Computing

Summary / Outlook

- Only scratched the surface of all future detectors/technologies (challenges, R&D, achievements, …)

- **Try to highlight some of the new paradigms emerging for future detectors:**
  - High granularity (for precision in e+e-, for pile-up & radiation at in pp)
  - Particle Flow as driving concept for detector design
  - (Ultra-)Fast timing

- **Frontier becoming less clear:**
  - Between detector functionalities when going to 4D tracking / 5D devices (E, x, y, z, t)
  - Between on-line / off-line



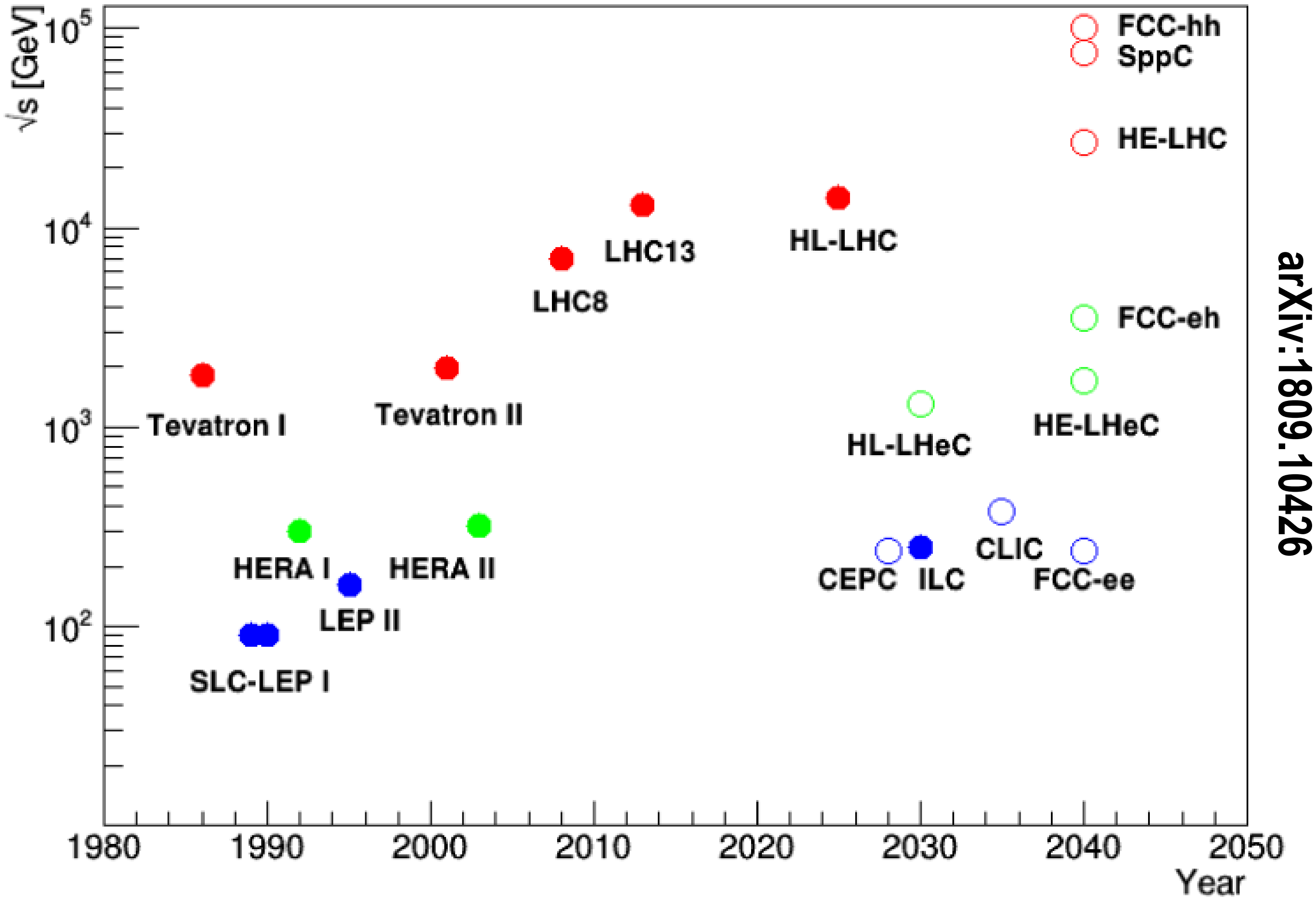
From M. Stanitizki

(inter-)Irrigation of the various R&D programs very important (and effective!)

French groups strongly involved in these (r-)evolutions, with leadership in key areas
(imaging calorimeters, micro-electronics, CMOS pixels, …)
But threatened by loss of expertise / lack of recruitments

BACK UP SLIDES

Past, present and future Colliders



arXiv:1809.10426

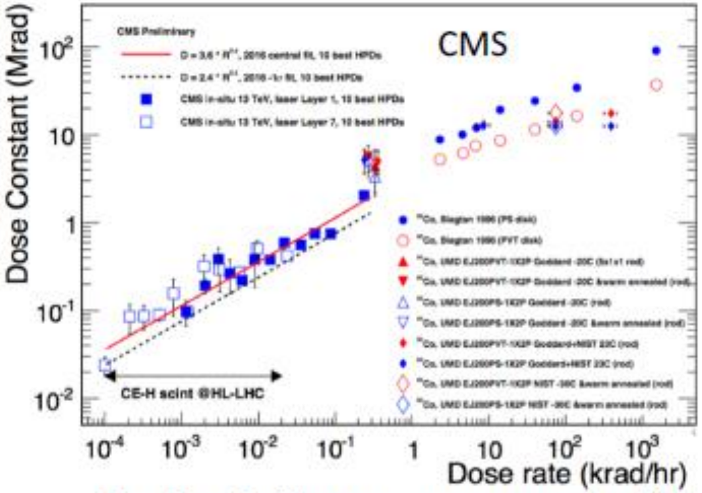
Figure 3: *Past and present projects of pp or $p\bar{p}$ (red symbols), ep (green symbols) and e^+e^- (blue symbols) colliders at the energy frontier since around 1990 indicating the (tentative) start of operation and the centre-of-mass energy. Full bullets represent projects that either have been completed, that are currently running or for which a TDR is a available. Projects represented by open circles are in the CDR or pre-CDR phase*

Scintillators

Scintillators

Large and fast signals, can provide good timing precision

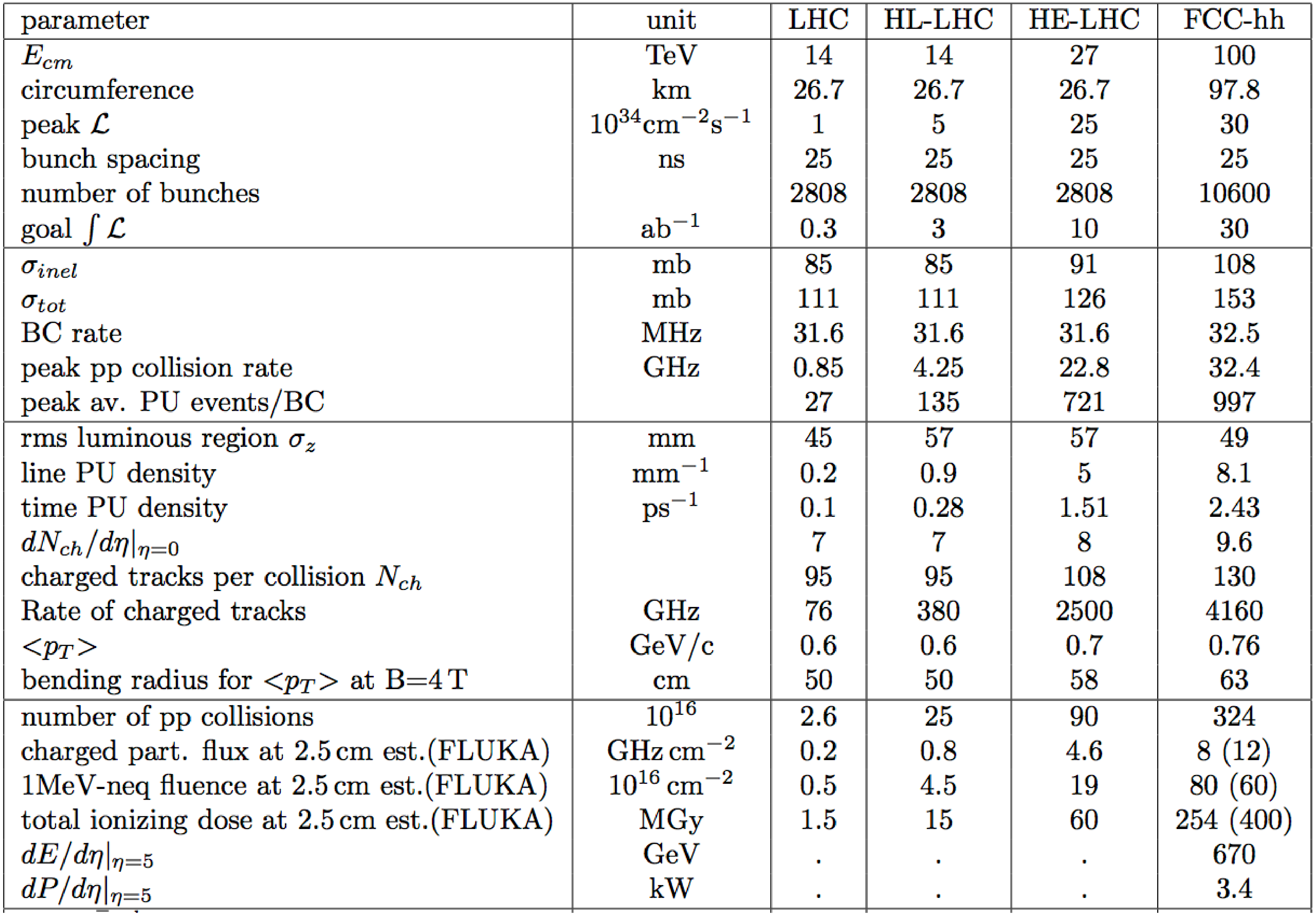
- PVT and Plastic scintillators
    - Cheap, but rad. tol. limited to ≤ 500's kRads (for ≃ 50% signal), aging depends on several parameters including dose rates, operation environment... difficult to predict - needs long irradiation test
- Crystals
    - LYSO:CE (commercial) rad. tol. ≃100MRad
    - 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)

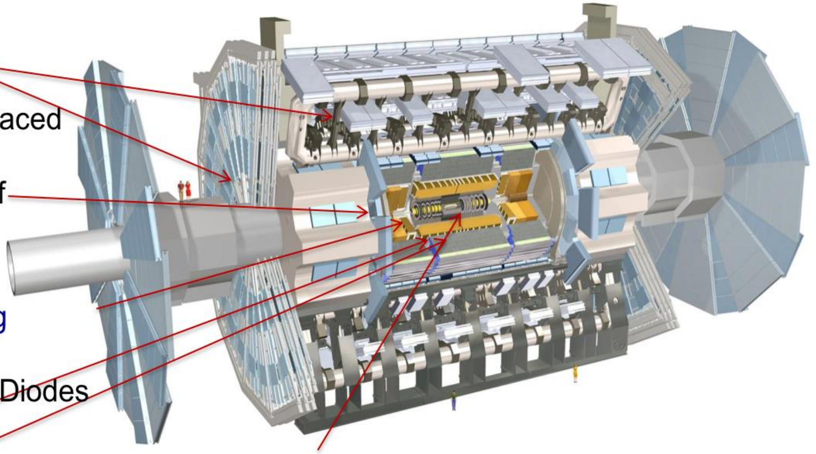
CALICE 3x3cm^2 tile concept for CMS HGC

Hadron Colliders main Parameters



parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mb	85	85	91	108
σ_{tot}	mb	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
bending radius for $<p_T>$ at B=4 T	cm	50	50	58	63
number of pp collisions	10^{16}	2.6	25	90	324
charged part. flux at 2.5 cm est.(FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.2	0.8	4.6	8 (12)
1MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,\mathrm{cm}^{-2}$	0.5	4.5	19	80 (60)
total ionizing dose at 2.5 cm est.(FLUKA)	MGy	1.5	15	60	254 (400)
$dE/d\eta\|_{\eta=5}$	GeV	.	.	.	670
$dP/d\eta\|_{\eta=5}$	kW	.	.	.	3.4

ATLAS & CMS at HL-LHC



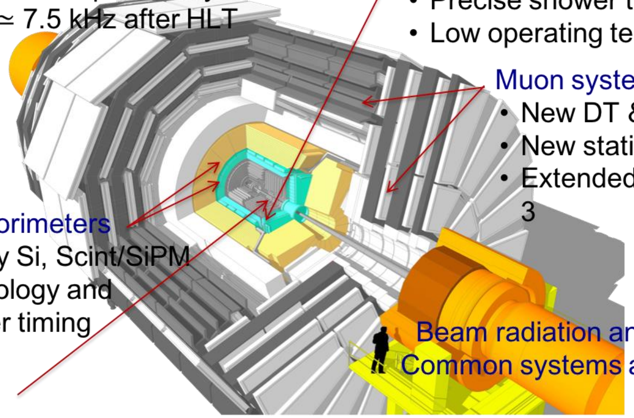
Trigger/DAQ
- Tracker readout at 1 MHz after 10 μs latency
- High Level Trigger input reduced to ≃ 400 kHz with track-trigger after ≃ 30 μs
- Register up to ≃ 10 kHz after HLT

Muon systems
- New electronics
- Some chambers replaced to improve resolution
- Possible extension of coverage to η ≃ 4

High Granularity Timing Detector
- Low Gain Avalanche Diodes 2.4 ≲ η ≲ 4

Liquid Argon and Tile calorimeter
- New electronics for full granularity readout at 40 MHz

New Tracker
- Rad. tolerant, high granularity and light
- Extended coverage to η ≃ 4



Trigger/HLT/DAQ
- Track trigger stub readout at 40 MHz
- High Level Trigger input reduced to 750 with track trigger after 12.5 μs latency
- Register up to ≃ 7.5 kHz after HLT

Barrel EM calorimeter
- New electronics for full granularity readout at 40 MHz
- Precise shower timing
- Low operating temperature (9°)

Muon systems
- New DT & CSC electronics
- New station at 1.6 < η < 2.4
- Extended coverage to η ≃ 3

New Endcap Calorimeters
- High granularity Si, Scint/SiPM
- 3D shower topology and precise shower timing

Beam radiation and luminosity
Common systems and infrastructure

New Tracker
- Rad. tolerant, high granularity and light
- Extended coverage to η ≃ 4
- 40 MHz selective readout (strips) for Trigger

MIP Timing Detector
- Barrel layer: Crystals + SiPM
- Endcap layer: Low Gain Avalanche Diodes

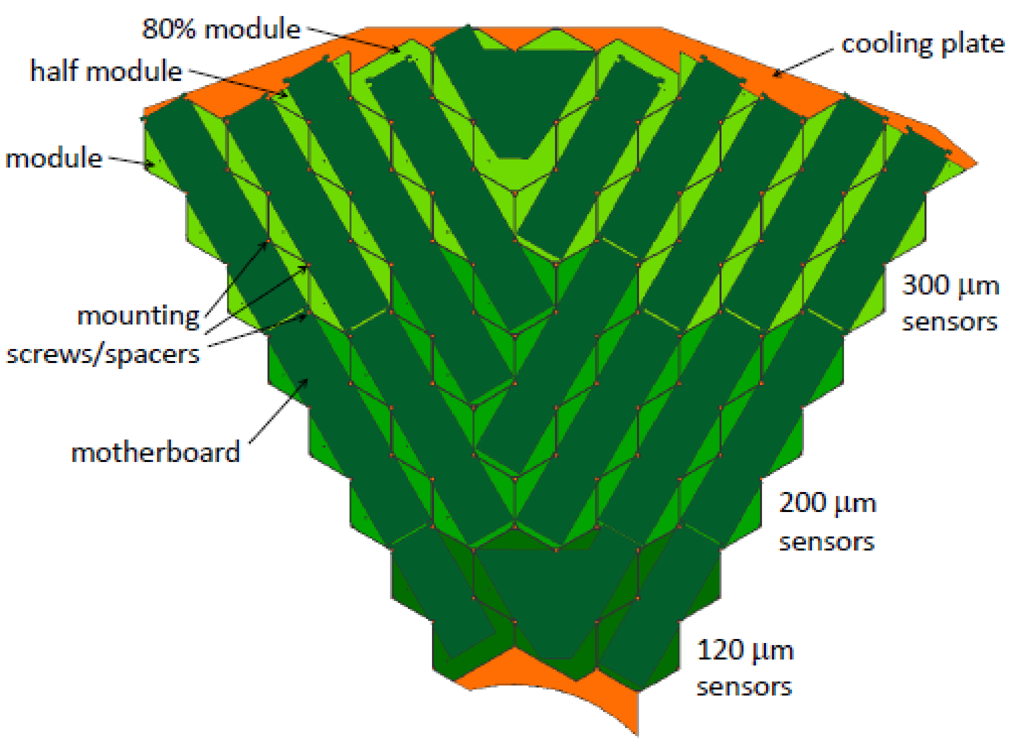
FCC-hh Tracker : 430m²
ATLAS Inner Tracker: Pixel (580M, 13m²), Strip (60M, 165m²)
CMS: 4.9m² (pixel) + 192m²

Requirements: Endcap (EC) Calorimetry

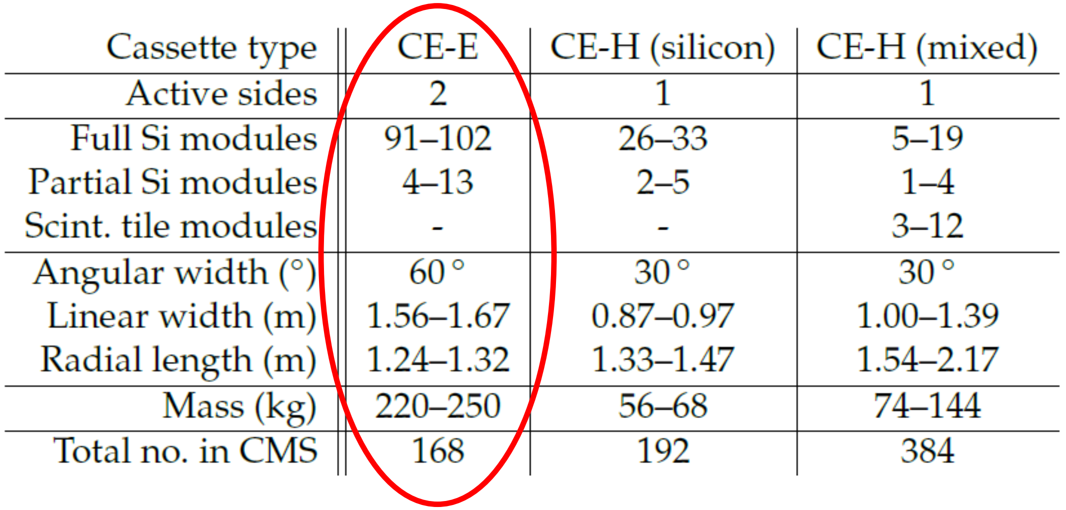
- ***Radiation tolerance***: fully preserving the energy resolution after 3000fb^{-1}, requires good inter-cell calibration (≈3%) - use minimum-ionizing particles
- ***dense calorimeter***: to preserve lateral compactness of showers
- ***fine lateral granularity:*** for low energy equivalent of electronics noise so as to give a high enough *S/N* to allow MIP calibration, to help with two shower separation and the observation of narrow jets, as well as limiting the region used for energy (and timing) measurement minimizing the inclusion of energy from particles originating in pileup interactions,
- ***fine longitudinal granularity***: enabling fine sampling of the longitudinal development of showers, providing good electromagnetic energy resolution (e.g. for H → ©©), pattern recognition, discrimination against pileup, angle measurement,..
- ***precision measurement of the time of high energy showers****: obtain precise timing from each cell with a significant amount of deposited energy, aiding rejection of energy from pileup, and the identification of the vertex of the triggering interaction
- ***ability to contribute to the level-1 trigger decision.***

TDR Section 1.2

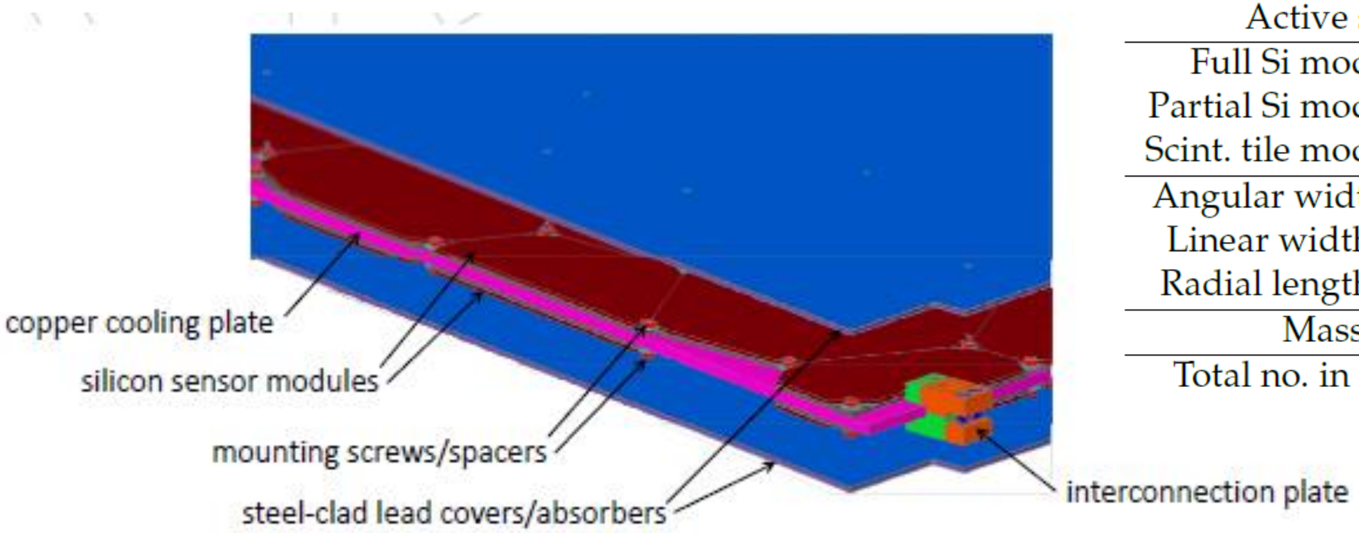
CE-E: cassettes & mechanical structure (1)



- Modules mounted on both side of 6mm Cu cooling plate.
- Pb (2.1mm)/SS (0.3mm) absorber on both side
  ⇒ **Cassette (60° wide in CE-E)**
- 14 types of cassettes
- **One cassette:**
  - ~1500mm x 1500mm
  - ~80 kg (Cu plate), >200 (with modules & absorber)
  - ~100 modules & ~ 40 motherboards per cassette
  - ~100 spacers
  - 6-7m of cooling pipes (∅4mm, 100-150 bar)



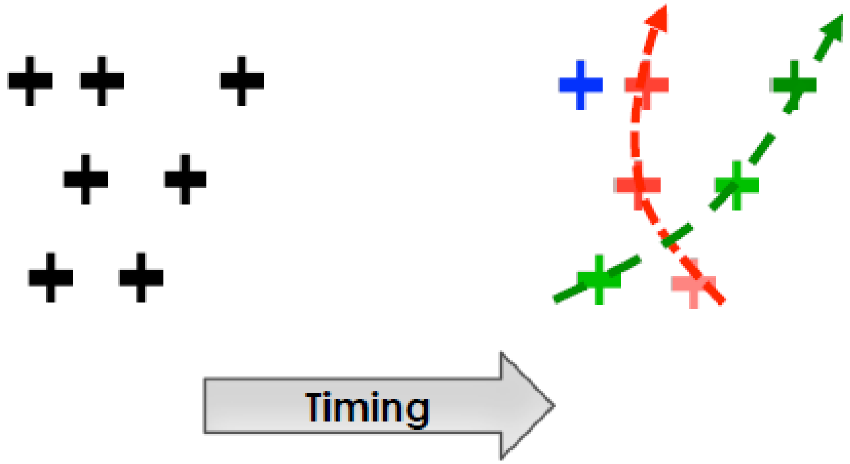
Cassette type	CE-E	CE-H (silicon)	CE-H (mixed)
Active sides	2	1	1
Full Si modules	91–102	26–33	5–19
Partial Si modules	4–13	2–5	1–4
Scint. tile modules	-	-	3–12
Angular width (°)	60 °	30 °	30 °
Linear width (m)	1.56–1.67	0.87–0.97	1.00–1.39
Radial length (m)	1.24–1.32	1.33–1.47	1.54–2.17
Mass (kg)	220–250	56–68	74–144
Total no. in CMS	168	192	384



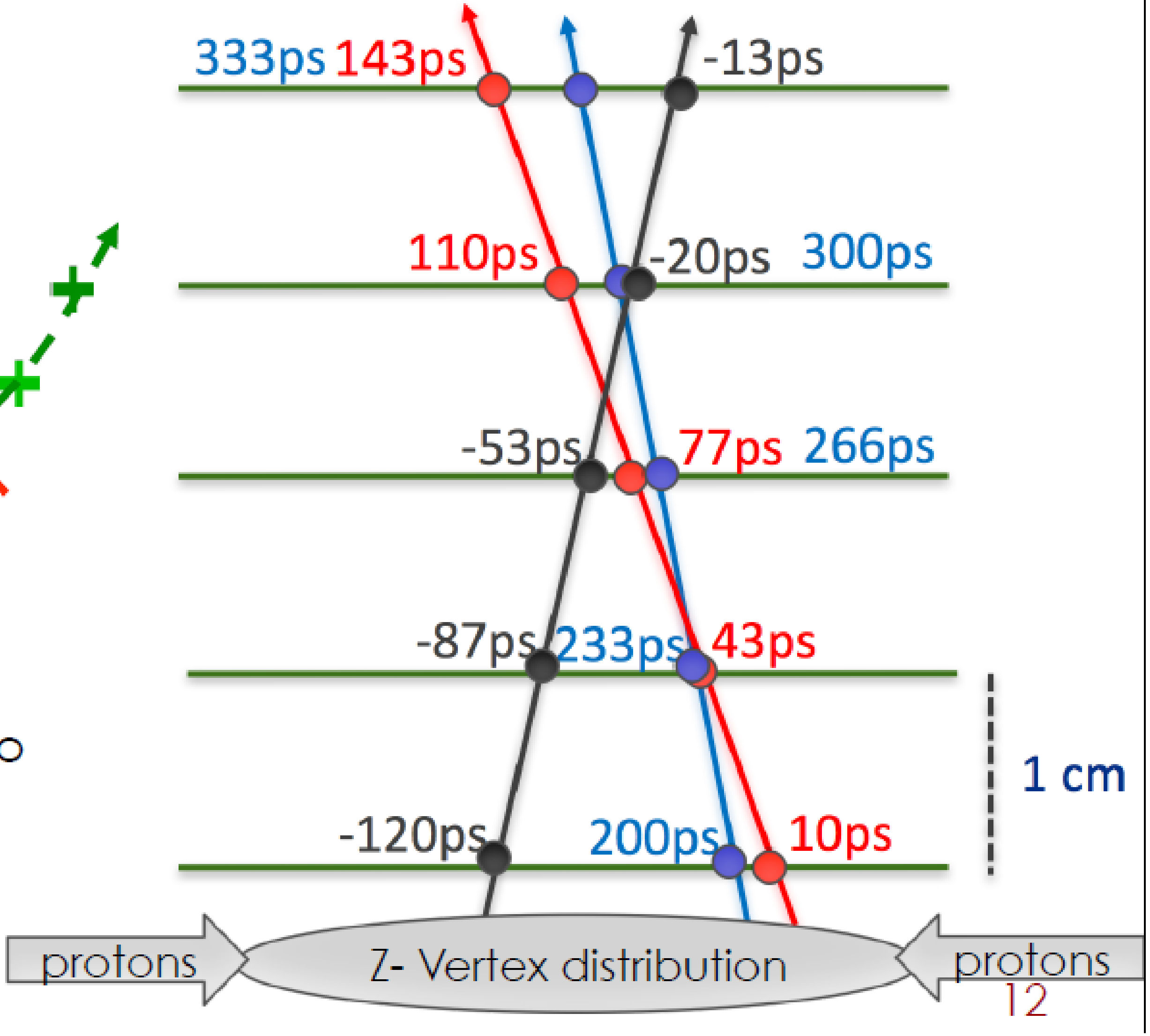
4D tracking: timing at each point along the track

→Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

→ Use only "time compatible points"



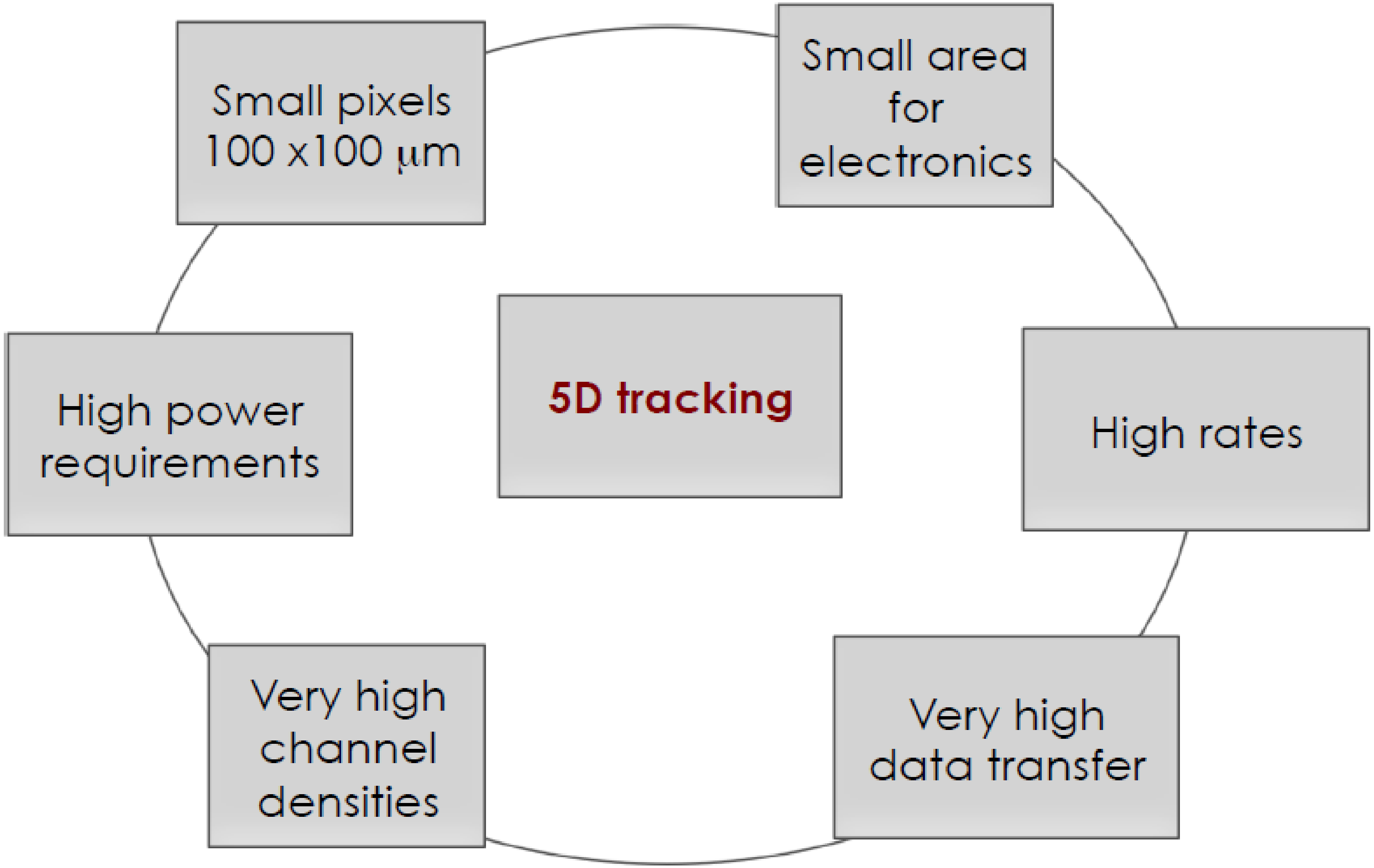
Present hypothetical LHCb Velo upgrade precision: ~ 100ps



5D-tracking: space-time at high rate

Imagine tracking with ~ 1000-2000 tracks @ 40 MHz crossing

This situation is the pinnacle of complications..



Small pixels 100 x100 μm

Small area for electronics

High power requirements

5D tracking

High rates

Very high channel densities

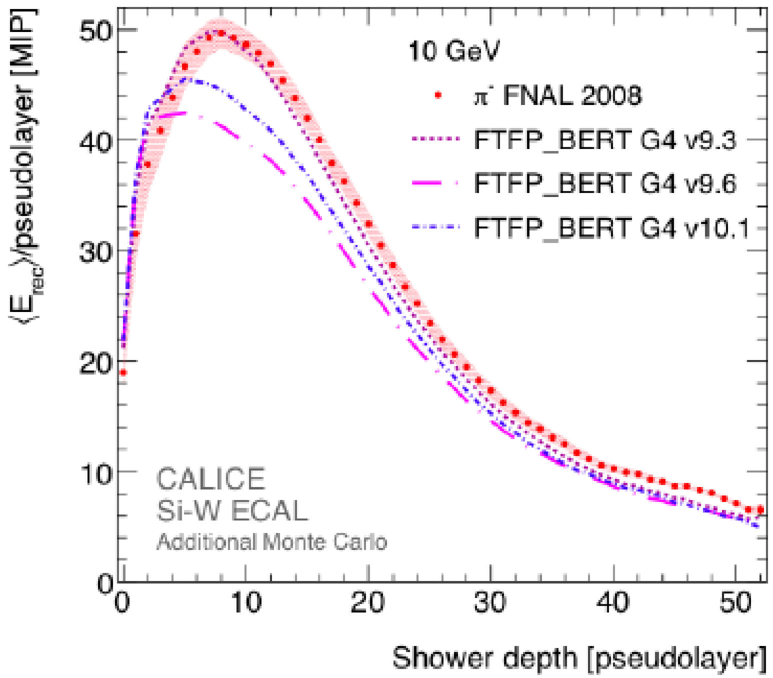
Very high data transfer

Hadronic shower profiles in Si-W ECAL

Test of hadronic shower models at low energies *[NIM A794 (2015) 240-254]*

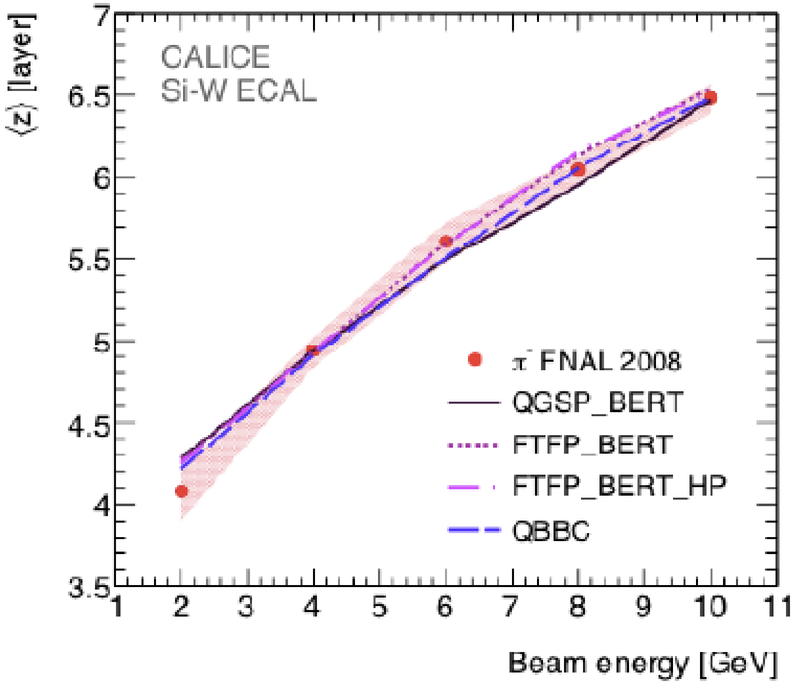
- depth of Si-W ECAL prototype is $\sim 1\lambda_I$, ~60% of hadrons interact in ECAL
- 3 segments with different absorber thickness - converted into pseudolayers for analysis
- interacting events are distinguished from MIP-like events
- test beam pions 2–10 GeV; Geant4 versions 9.6 and 10.1

Visible energy / pseudolayer



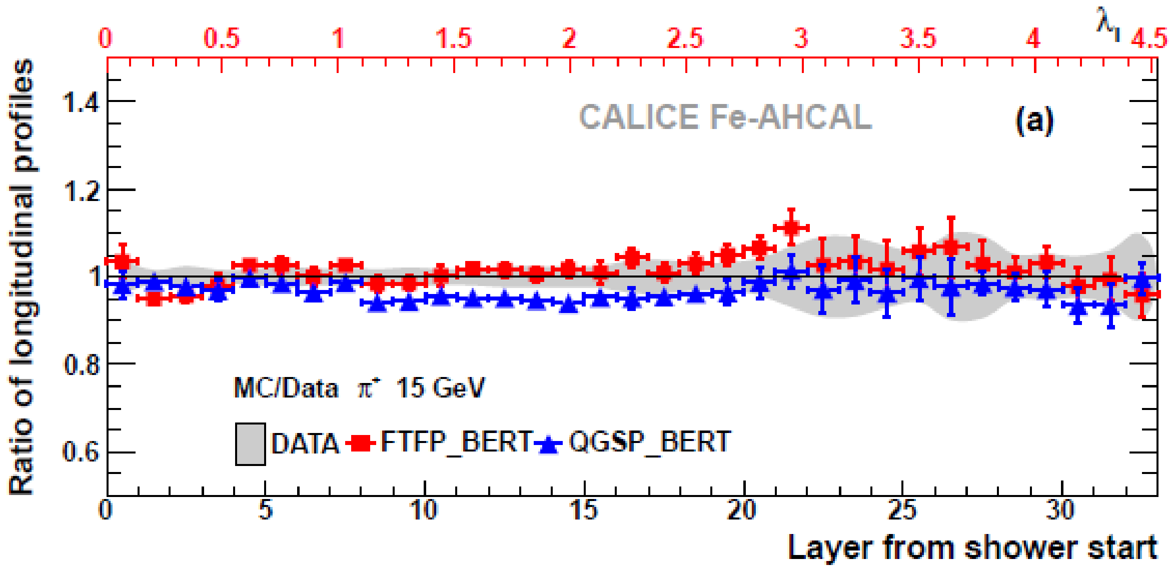
Significant differences between G4 versions

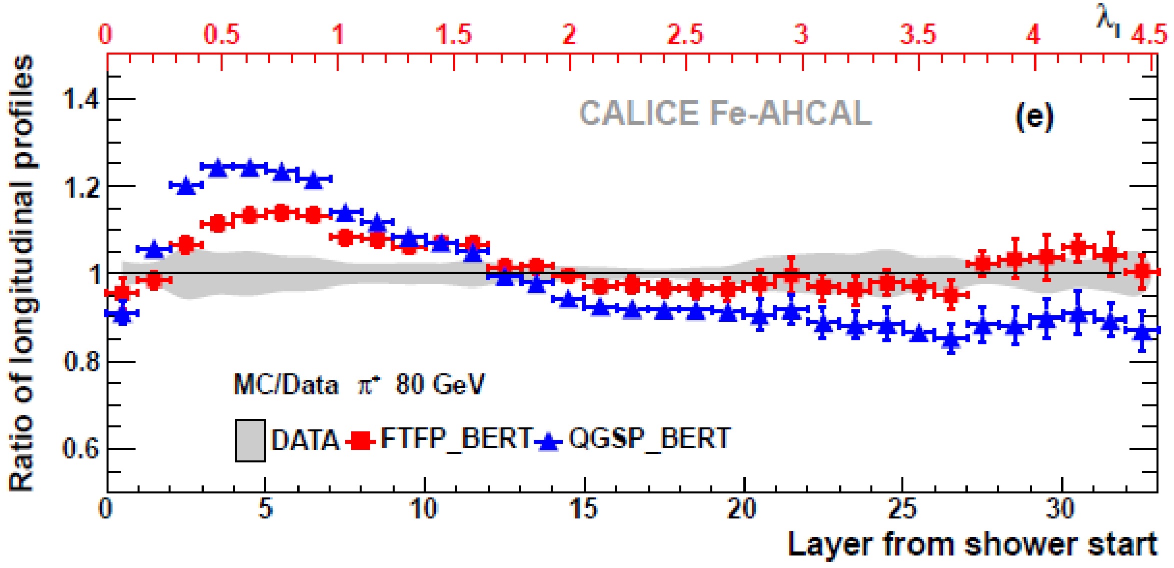
Mean of longitudinal hit position distribution



Good agreement for all G4 models

MC/data ratio of longitudinal profiles in Sc-Fe AHCAL





Longitudinal profile:

visible energy ΔE per layer vs. long. distance from the identified shower start

Comparison with Geant4 v9.6

π^+ 15 GeV

FTFP_BERT: agreement within uncertainties

QGSP_BERT: little underestimation

π^+ 80 GeV

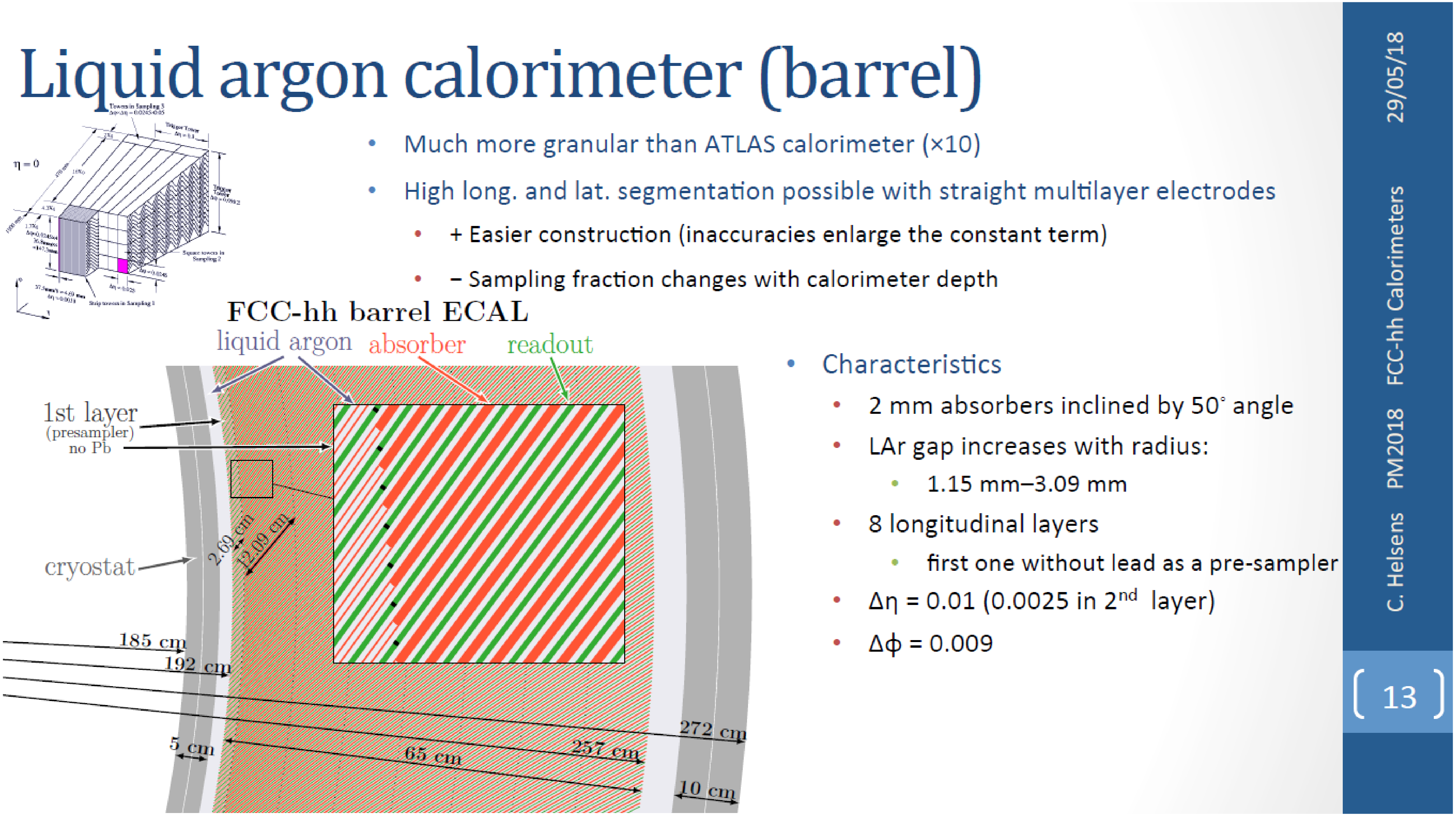
Overestimation around shower maximum:

FTFP_BERT: by ~10%

QGSP_BERT: by ~20%

[JINST 11 (2016) P06013]

FCC-hh: ECAL barrel (LAr)

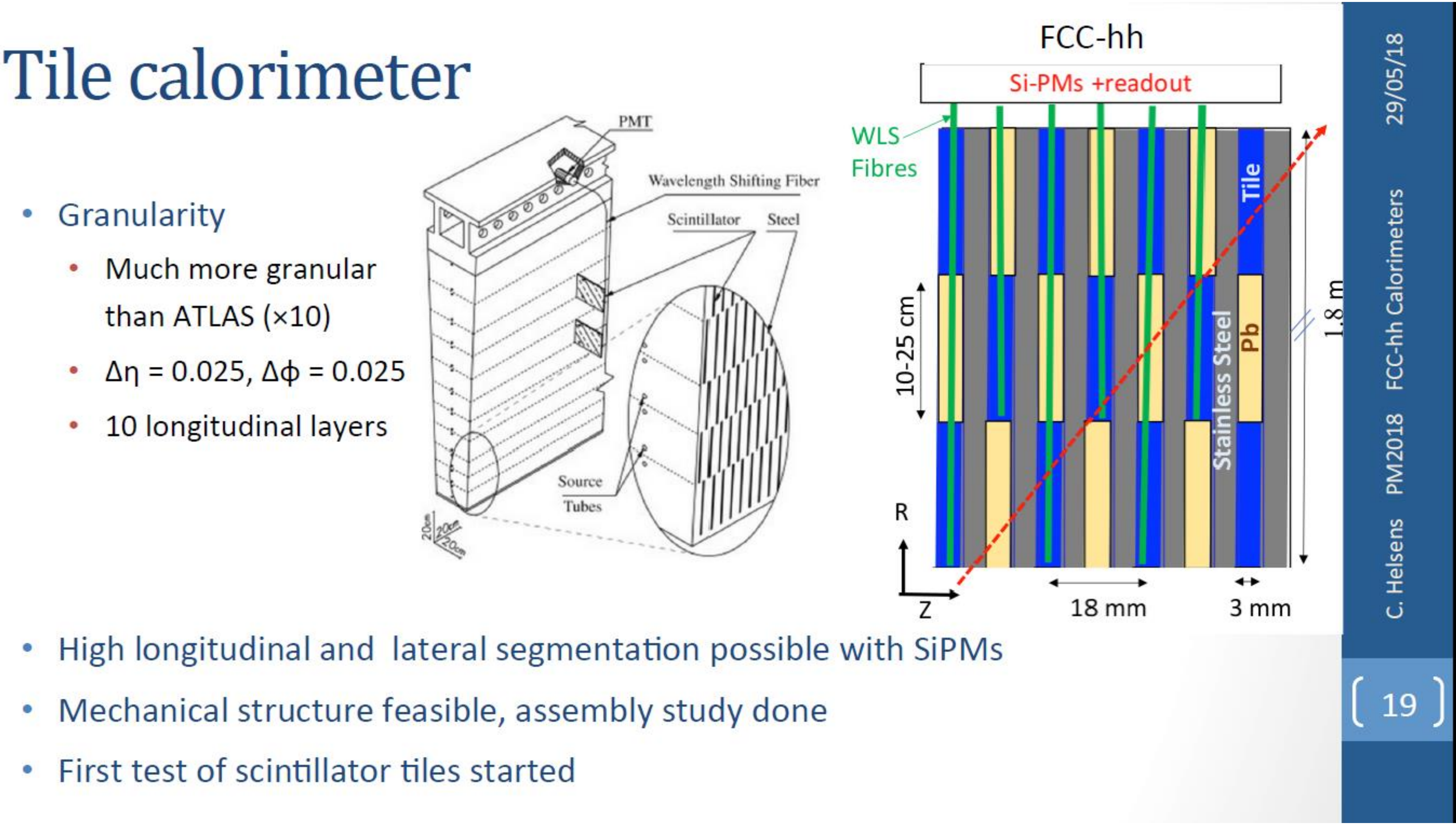


Liquid argon calorimeter (barrel)

- Much more granular than ATLAS calorimeter (×10)
- High long. and lat. segmentation possible with straight multilayer electrodes
  - + Easier construction (inaccuracies enlarge the constant term)
  - – Sampling fraction changes with calorimeter depth

- Characteristics
  - 2 mm absorbers inclined by 50° angle
  - LAr gap increases with radius:
    - 1.15 mm–3.09 mm
  - 8 longitudinal layers
    - first one without lead as a pre-sampler
  - Δη = 0.01 (0.0025 in 2nd layer)
  - Δϕ = 0.009

FCC-hh: HCAL Barrel (Tile-Cal + SiPM)

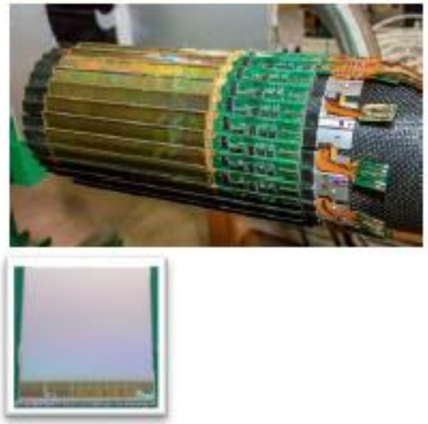


Tile calorimeter

- Granularity
  - Much more granular than ATLAS (×10)
  - Δη = 0.025, Δϕ = 0.025
  - 10 longitudinal layers

- High longitudinal and lateral segmentation possible with SiPMs
- Mechanical structure feasible, assembly study done
- First test of scintillator tiles started

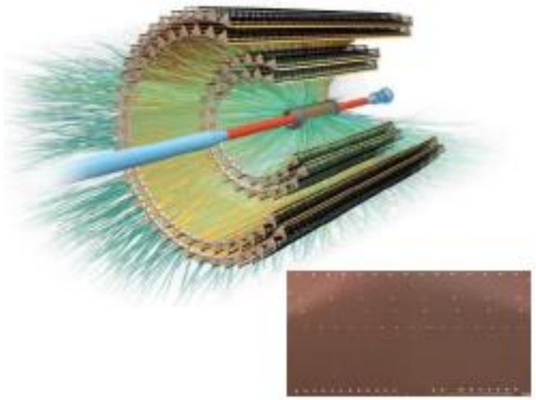
Monolithic CMOS sensors in HEP



ULTIMATE in STAR

IPHC Strasbourg

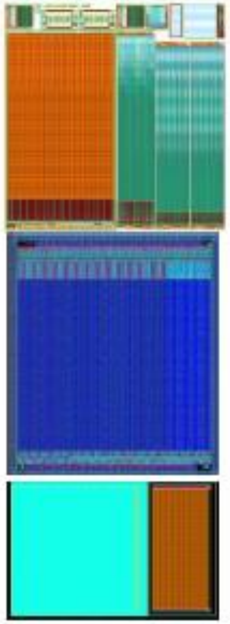
First HEP MAPS system



ALPIDE in ALICE

First MAPS with sparse readout similar to hybrid sensors

Chip-to-chip communication for data aggregation



ATLAS CMOS

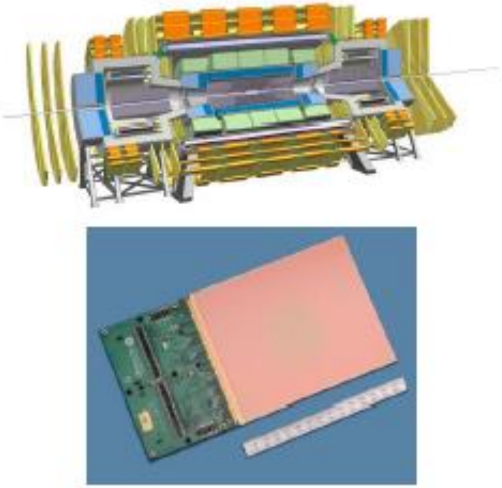
Depleted radiation hard MAPS with:

Sparse readout

Chip-to-chip communication

Serial power

…



FCC, CLIC, …

Large stitched fast radiation hard MAPS with:

Sparse readout

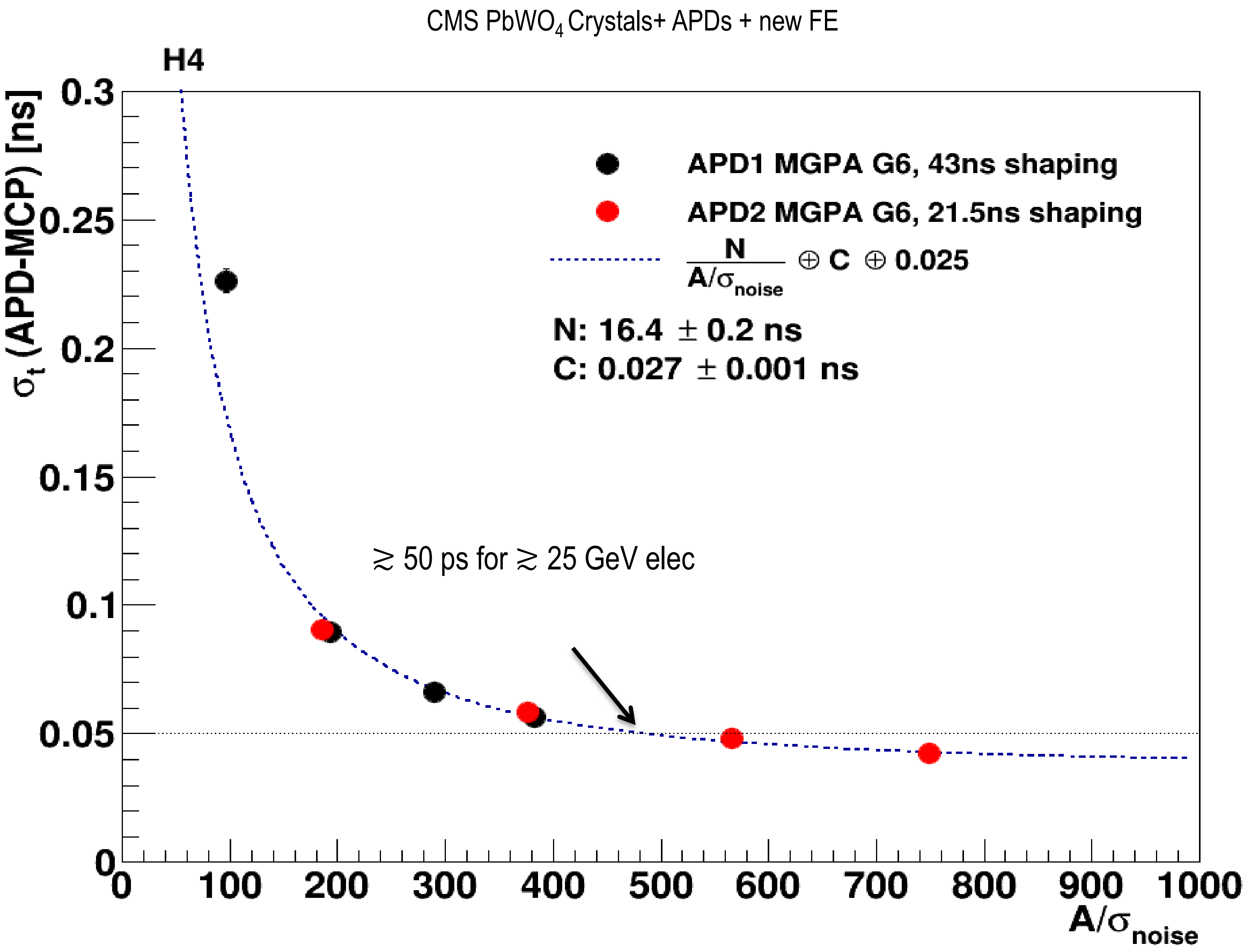
Chip-to-chip communication

Serial power

…

Important steps in every iteration

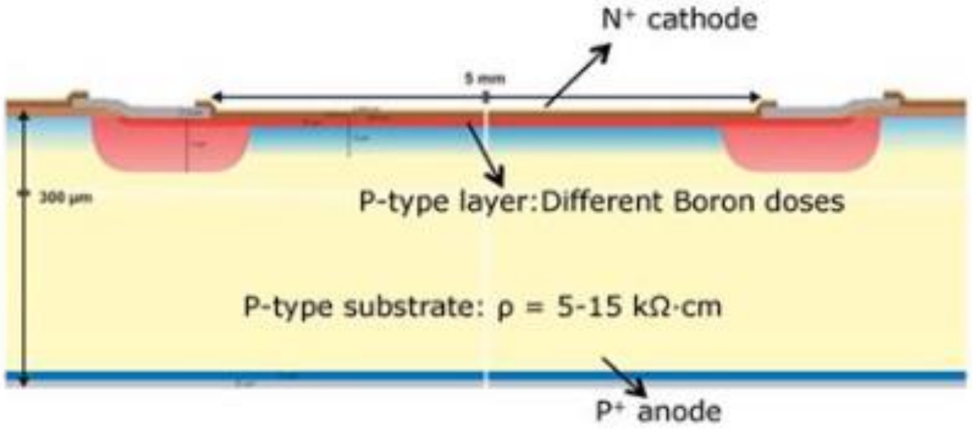
Timing (CMS ECAL crystals)



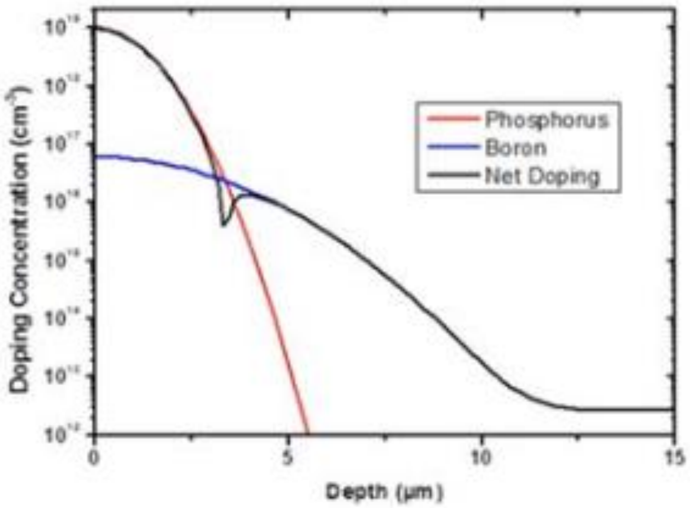
$\gtrsim$ 50 ps for $\gtrsim$ 25 GeV elec

Low-Gain Avalanche Detectors (LGAD)

Low-Gain Avalanche Detectors (LGAD) are based on the principle of SiPM or APD, but with moderate internal gain (10 – 20) and analog response.
Adding a thin p-layer to a n-on-p silicon sensor to increase the E-field and deep n-implants at the edges generate **moderate** charge multiplication without breakdown.



High-Field: Gain



The technology is being developed as a RD50 Common Project.
After 7+ manufacturing cycles at CNM (Barcelona) addressing general issues like gain variations, bias voltage reach, leakage current reduction, segmented sensors etc. we now have submissions targeting specific applications mentioned previously.
A second supplier, FBK (Trento), is starting fabrication with mainly INFN funding.

Ultra Fast Silicon Detectors

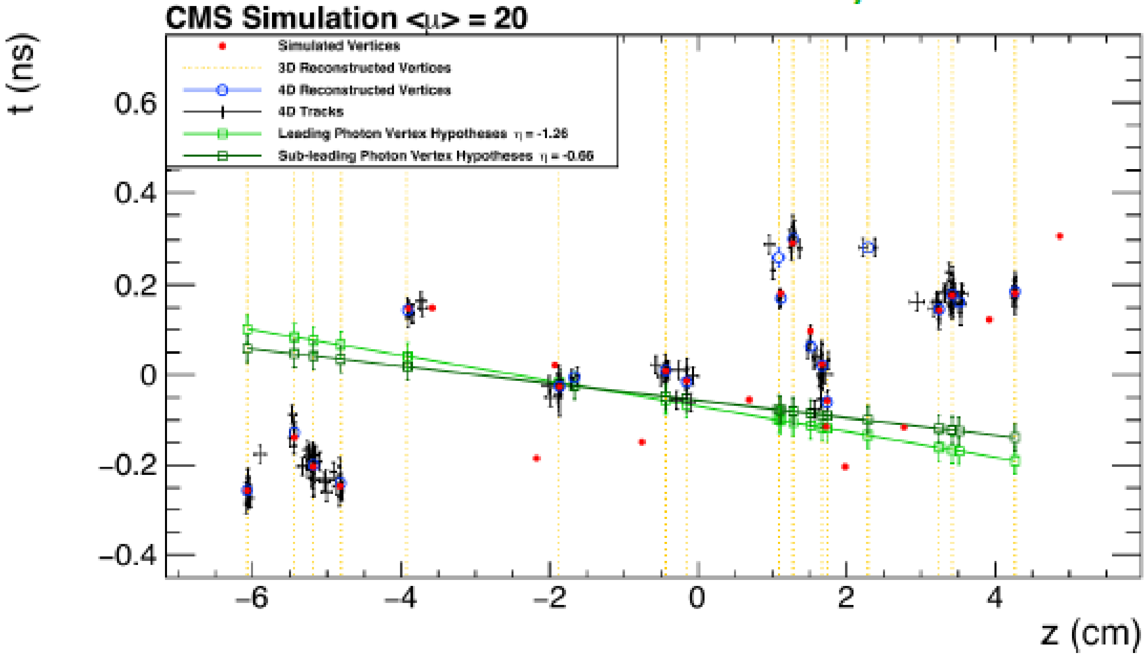
UFSD are LGAD detectors optimized to achieve the best possible time resolution

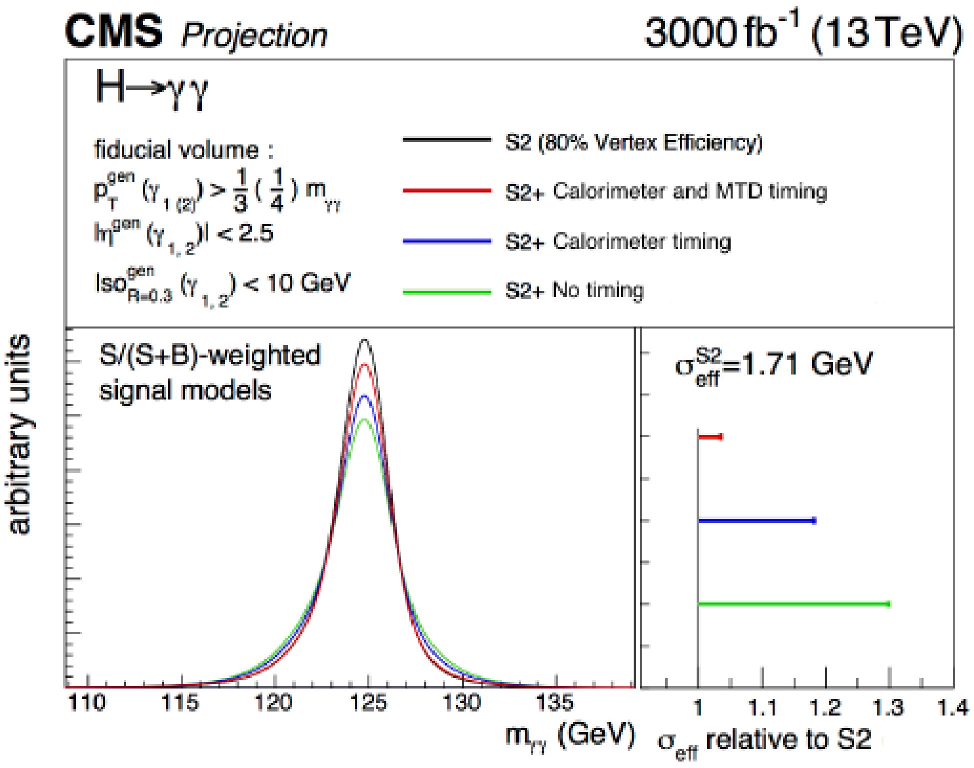
Specifically:

1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the leakage current low (shot noise)

Higgs to Di-photon Vertex Tagging

Calculate photon time at each vertex location: consistency test





- Unique capability to match photon time to vertex time + position
  - CMS ECAL is non-pointing, but has photon timing capability
  - 50% of events additionally require MIP timing to find correct vertex

- Identifies photon vertex: improves di-photon mass resolution by 25% and also H(γγ) signal significance

Timing resolution (Si Sensors)

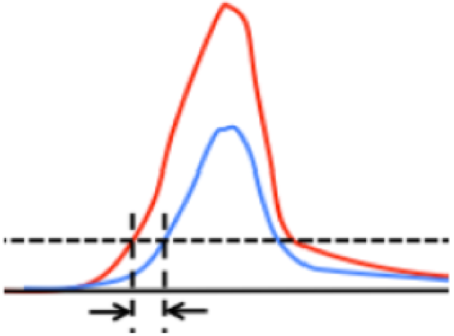
Timing Resolution: $$\sigma_T^2 = \sigma_L^2 + \sigma_{jitter}^2 + \sigma_{TW}^2 + \sigma_{clock}^2$$

σ_L : Landau fluctuation, depends on deposited charge in sensor, dominates at high gain

σ_{jitter} : Variation from the noise in the signal; $\sigma_{jitter}^2 = \frac{N}{dV/dt} \sim \frac{t_{rise}}{S/N}$

σ_{TW} : Arise from signal of different amplitudes, crossing the threshold at different times
Mitigated by applying corrections from TOT measurement

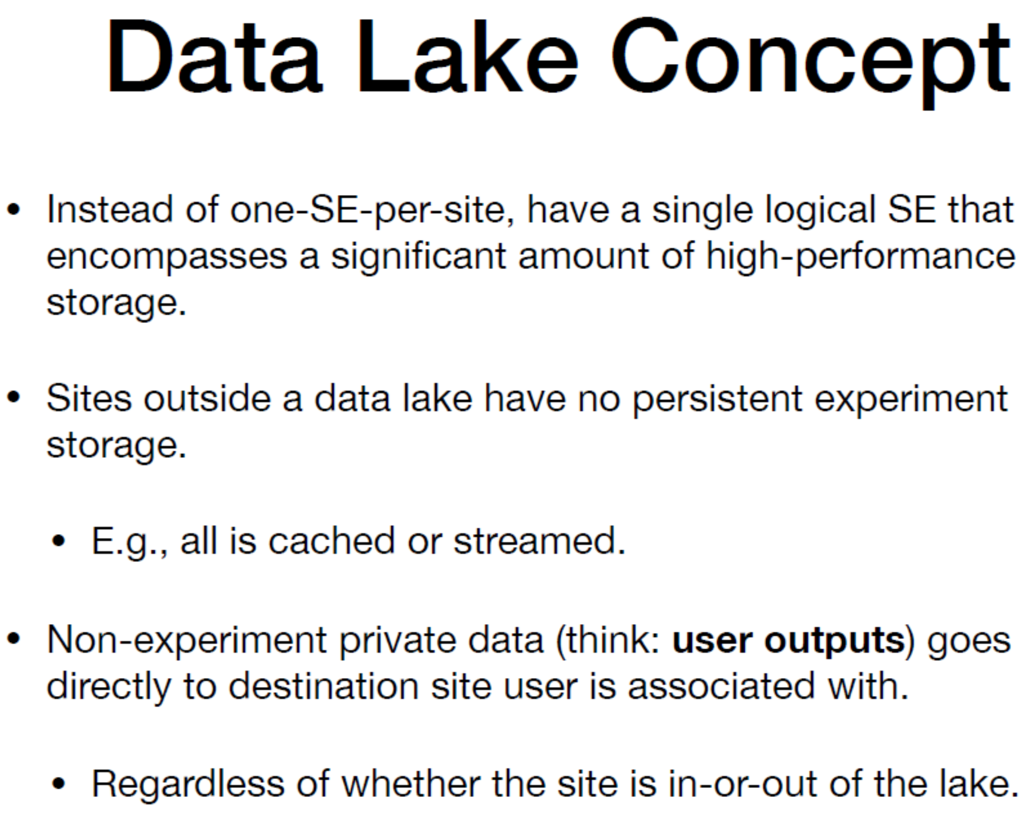
$$\sigma_{TW}^2 = [\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto [\frac{N}{dV/dt}]_{RMS}$$



σ_{clock} : Clock distribution, expected to be ≤ 10 psec

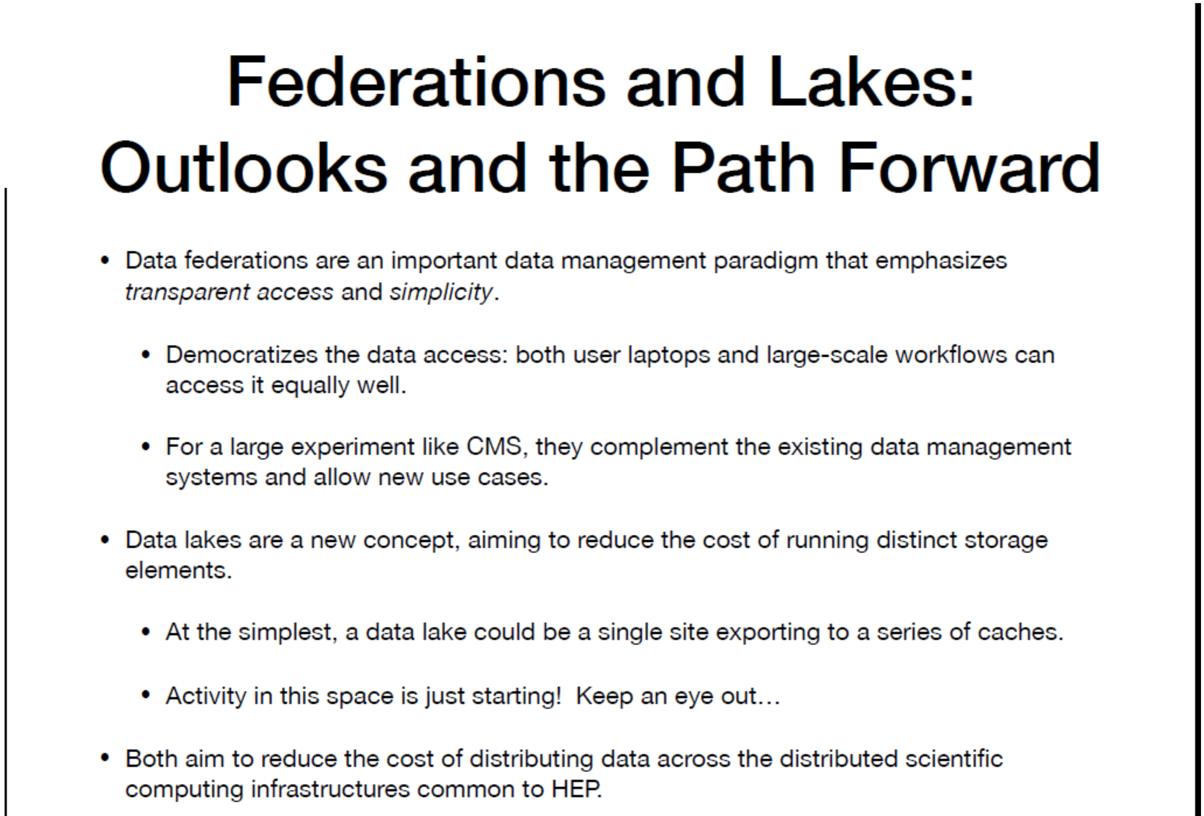
Some other contributions from TDC and t0 are considered to be negligible.

Computing: future of storage



Data Lake Concept

- Instead of one-SE-per-site, have a single logical SE that encompasses a significant amount of high-performance storage.
- Sites outside a data lake have no persistent experiment storage.
  - E.g., all is cached or streamed.
- Non-experiment private data (think: **user outputs**) goes directly to destination site user is associated with.
  - Regardless of whether the site is in-or-out of the lake.

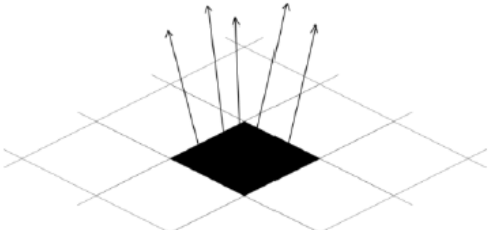


Federations and Lakes: Outlooks and the Path Forward

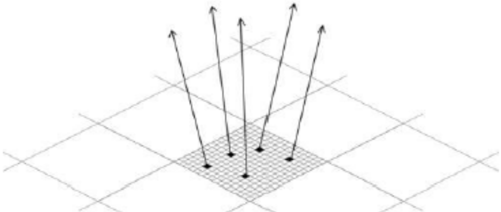
- Data federations are an important data management paradigm that emphasizes *transparent access* and *simplicity*.
  - Democratizes the data access: both user laptops and large-scale workflows can access it equally well.
  - For a large experiment like CMS, they complement the existing data management systems and allow new use cases.
- Data lakes are a new concept, aiming to reduce the cost of running distinct storage elements.
  - At the simplest, a data lake could be a single site exporting to a series of caches.
  - Activity in this space is just starting! Keep an eye out…
- Both aim to reduce the cost of distributing data across the distributed scientific computing infrastructures common to HEP.

Digital Calorimetry: The Concept

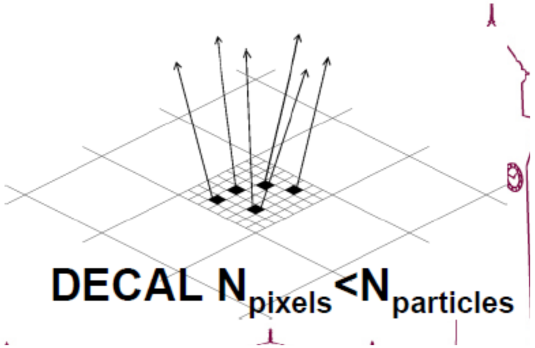
- ☐ Make a pixelated calorimeter to count the number of particles in each sampling layer
- ☐ Ensure that the pixels are small enough to avoid multiple particles passing through a single pixel to avoid undercounting and non-linear response in high particle density environments
- ☐ Digital variant of ILD ECAL would require 10^{12} channels



Analogue ECAL

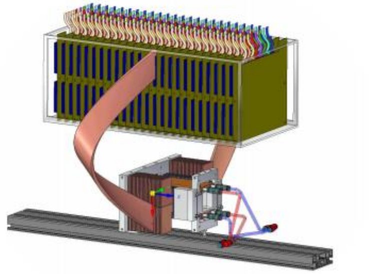


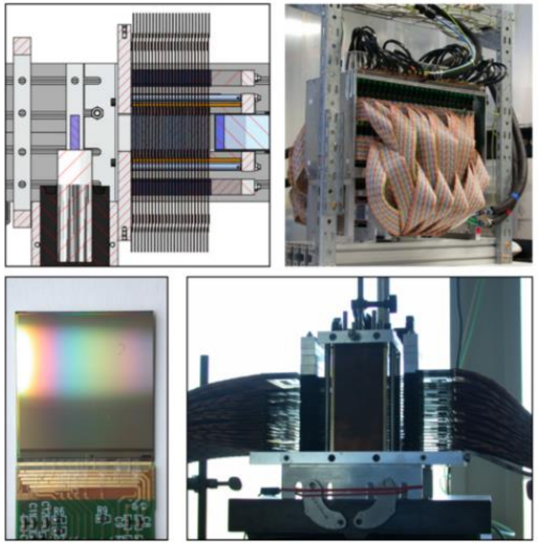
DECAL $N_{pixels}=N_{particles}$



DECAL $N_{pixels}<N_{particles}$

Digital Si-W Pixel Calorimeter Prototype





full prototype with pixel sensors
- CMOS (MIMOSA23), $30\mu m$ pitch

24 layers
- 3mm W
- 1mm sensor layer
  - $120\mu m$ sensor + PCB, glue, air, …

"world records":
- smallest Moliere radius
  - $R_M \approx 11$ mm
- highest granularity:
  - 39 M pixels in $4x4x10$ cm^3 !

other R&D for FoCal ongoing in Tsukuba (Japan), Bergen (Norway), Kolkata & Mumbai (India)