Physics and Detector Challenges @ Energy Frontier – Low-Mass Tracking and ps-Timing Detectors

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Session 130. Enabling technologies for low mass and ps timing detectors

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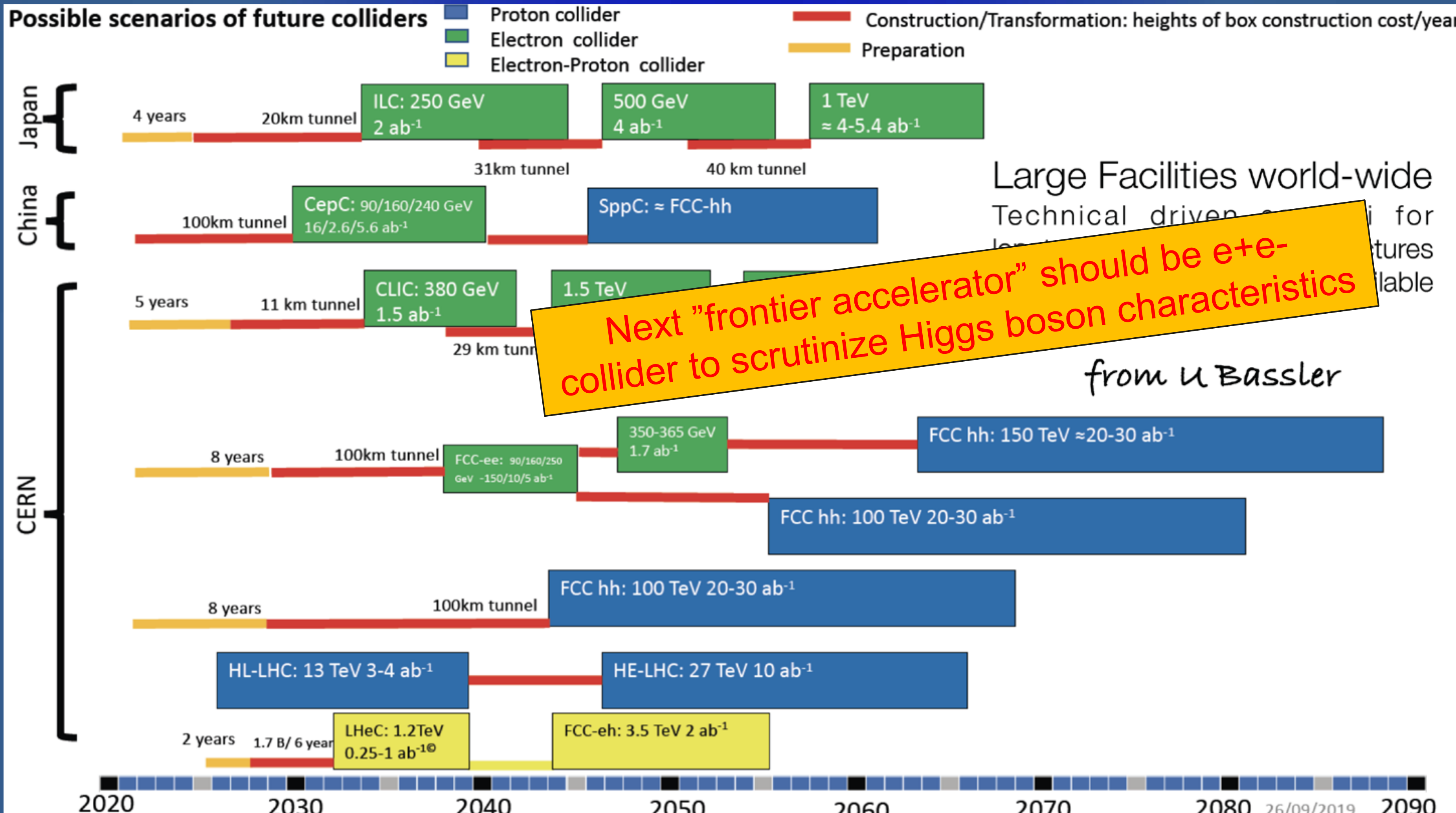
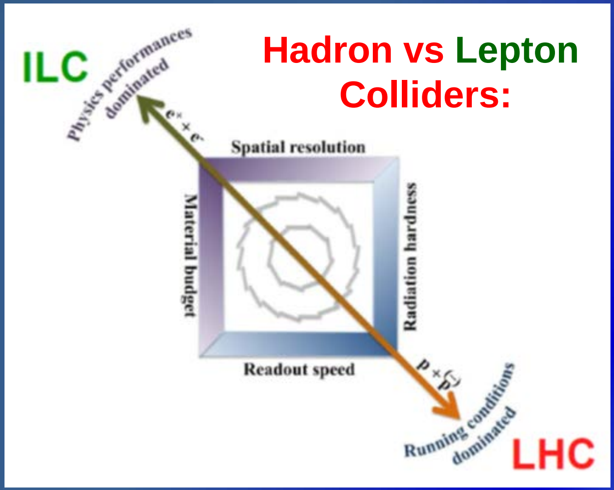
Shaping the Future of Particle Physics: Long-Term Options



Two major drivers for the Energy - Instrumentation Frontier:

- Detector R&Ds towards future hadron colliders: (HL-LHC) / HE-LHC, SppC, FCC-hh
- Detector R&Ds towards future lepton colliders: e+e- Higgs Factory

Si-Vertex and Tracking Detectors



Major challenges:
pp: radiation hardness, speed; e+e-: granularity, material budget

Sensor-type options (can be thinned to become flexible):

- ✓ Hadron colliders: hybrid pixel detectors (planar and 3D-sensors); HV/HR-CMOS for outer pixel layers for HL/LHC; LGADs for ps-timing
- ✓ Lepton Colliders: CMOS (since 1998 for ILC) , DEFPET, Chronopix, SoI, FPCCD, 3D-IC (Global Foundries, LAPIX, TJas,…)

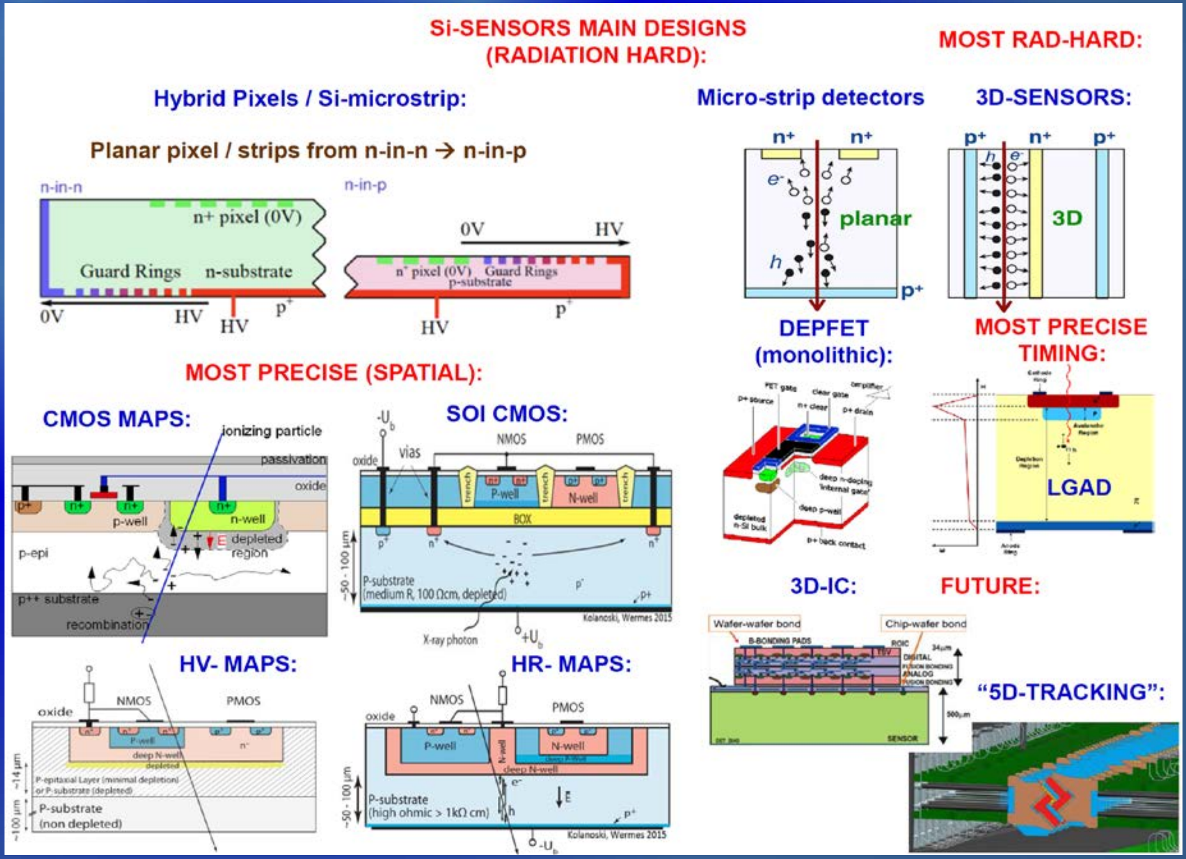
Hadron Colliders: Fast Readout / Radiation Hardness:

- ✓ Readout in 65 nm technology (RD53 – ATLAS/CMS ASICs)
- ✓ Small pixels down to 50 x 50 μm^2
- ✓ Output bandwidth 10 Gbit/s

Lepton Colliders: Low-Mass Trackers

- ✓ CMOS: STAR HFT, ALICE ITS, CBM
- ✓ DEPFET: Belle II

Development of large-area CMOS MAPS (up-to the full wafer size) using stitching technology



Vertex Technologies for Linear Colliders: Challenges

Sensor's contribution to the total material budget of vertex detectors is 15-30%

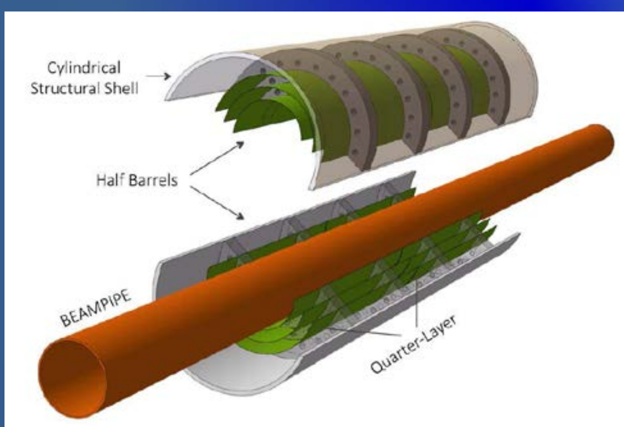
Technology	Examples	Small pixels	Low mass	Low power	Fast timing
Monolithic CMOS MAPS	Mimosa CPS	++	++	**++**	-
Integrated sensor/amplif. + separate r/o	DEPFET, FPCCD	+/++	0	+	-
Monolithic CMOS with depletion	HV-CMOS, HR-CMOS	+	++	**o**	**+**
3D integrated	Tezzaron, SOI	++	+	0	++
Hybrid	CLICpix+planar sensor, HV-CMOS hybrid	+	0	+	++

LC vertex-detector challenges

- $\sim 1\,\mathrm{m}^2$ surface
- Single point resolution of $\sigma < 3-5\,\mu\mathrm{m}$
  - $\rightarrow$ Pixel pitch $\approx 17-25\,\mu\mathrm{m}$
- Low power dissipation of $\lesssim 50\,\mathrm{mW/cm}^2$
- Material budget $< 0.1-0.3\,\%X_0$ per layer
  - $\rightarrow$ Thin sensors and ASICs, low-mass support, power pulsing, air cooling
- Time stamping
  - $\rightarrow\sim 10\,\mathrm{ns}$ (CLIC)
  - $\rightarrow\sim 300\,\mathrm{ns}-\mu\mathrm{s}$ dep. on technology (ILC)

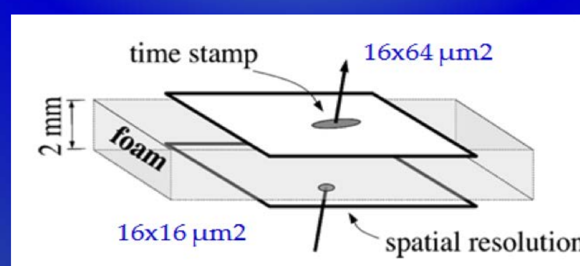
Challenges (beam backgrounds, cooling, material budget) addressed by emerging R&D steps:

- ✓ Material budget reduction → reduce impact of mechanical supports, services, overlap of modules/ladders
- ✓ Beam related (beamstrahlung) bkg. suppression → evolve time stamping toward a few 100 ns (bunch-tagging)

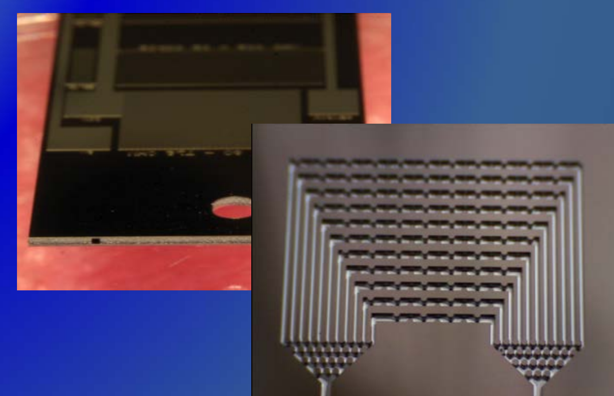


CMOS (CPS): Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with 65 nm process

CMOS (CPS): 2-sided ladders: mini-vectors with high spatial resolution & time stamping



Introduce NN in CPS to mitigate data flow from beam-related background



Microchannel cooling: DEPFET in collaboration with AIDA2020

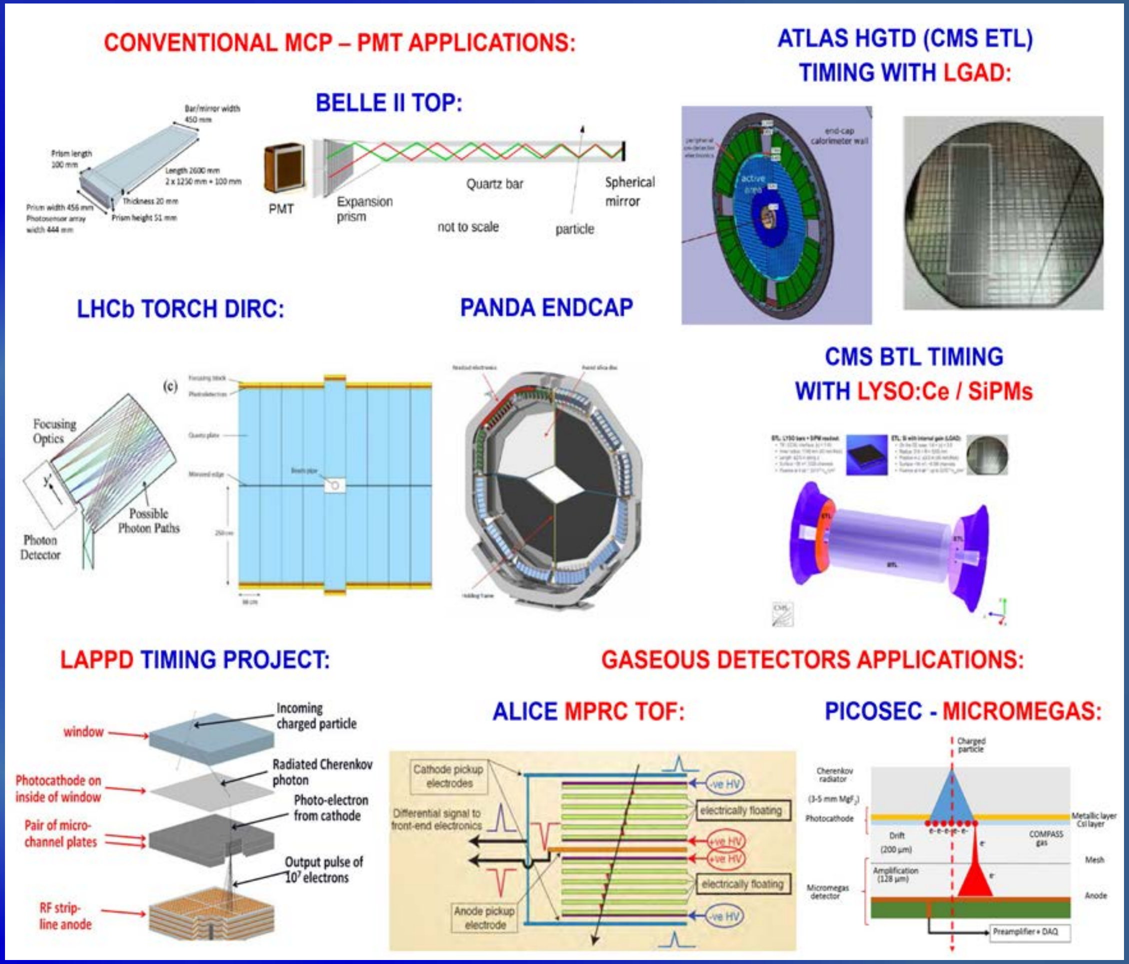
TIMING Detectors with a few 10's of picosecond resolution

Hadron Colliders:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10's) μm & timing detectors ~O(10's) ps
  - → ATLAS HGTD, CMS ETL (LGAD)
  - → CMS BTL (LYSO +SiPM)
- ✓ ps-timing reconstruction in calorimetry (resolve develop. of hadron showers, triangulate H → $\gamma\gamma$ prim. vertices)
  - → CMS HGCAL (Si & Sci.+SiPMs)
- ✓ TOF and TOP (RICH DIRC) PID
  - → both at hadron/lepton colliders

Future challenges:

- ✓ Radiation hardness: LGAD-sensors 3D-trench Si sensors, …
- ✓ Large-scale applications → system aspects of timing det. (e.g. clock distr.)
- ✓ "5D reconstruction": space-points / ps-timing are available at each point along the track → LHCb EoI for LS4 is of general interest (see M. Artuso talk);



LAPPD → large-area ps- PID/TOF for hadron/lepton colliders (intended as a direct replacement for PMTs)

- Incom Inc. company started to produce LAPPDs with RF-strip readout (US provisional patent) → cost still has to be controlled

Starting Point: Energy Frontier Drivers in BRN

- **2019: US – CPAD Report "New Technologies for Discovery":**
  DPF Coordinating Panel for Advanced Detectors, arXiv: 1908.00194 (2019)
- **2020 US - BRN Report**
  https://science.osti.gov/hep/Community-Resources/Reports

The transformative physics goals include 4 inspiring & distinct directions:

- Higgs properties @ sub-%
- Higgs self-coupling @ 5%
- Higgs connection to DM
- New multi-TeV particles

Technical requirements mostly from existing detector proposals.

- muon collider is not on the map

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2\times10^{-5}/\mathrm{GeV}$ for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\mathrm{m}$ TR 1.1.3: Granularity : $25\times50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5\times0.5\ \mathrm{cm}^2$, hadronic cells of $1\times1\ \mathrm{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

EF and IF Drivers / Interplay Beyond BRN

In the BRN physics drivers are very Higgs-centered, beyond Higgs:

- LLP searches could be an important benchmark for timing/trigger
  - Study of min radius for (few layers of) tracking detectors at future colliders
  - "Acceptance" for non-prompt charged particles at future detectors
- Boosted/Substructure object reconstruction is an important driver at future multi-TeV machines
  - pixel hit merging as one of the limiting factors
  - Also any improvement in tracking will directly impact jet reconstruction and calibration, pflow
- Higgs Couplings to light quarks (charm, strange) and tau-tagging could push requirements for both lepton and hadron colliders

→ See discussuion session # 131 « Physics Requirements for HEP Detectors at Colliders »

✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements for power, data readout bandwidth & selective readout/sparsification;

✓ Design problems include: granularity vs the power (particularly for precision timing) and the inactive material to service power and data readout etc. for both accelerator types. Radiation hardness is an issue for hadron colliders.