PSD TECHNOLOGIES FOR PARTICLE PHYSICS

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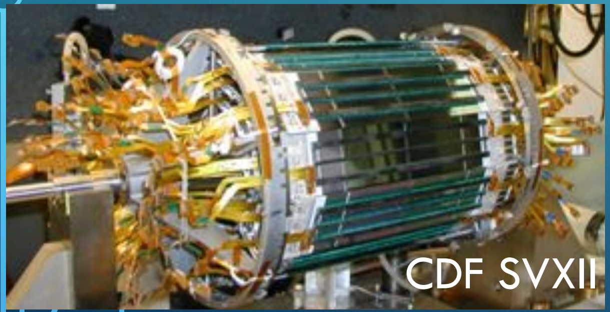
Apologies if I omitted your favorite detector!

OUTLINE

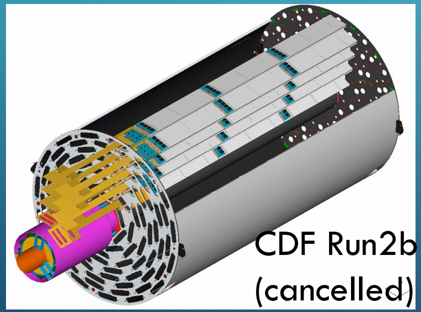
- Suite of recent detectors
- Nearterm additions
- Future challenges

Disclaimer:
Major tracking technologies for particle physics experiments include gaseous and fiber-based detectors. Here I focus on silicon-based systems only.

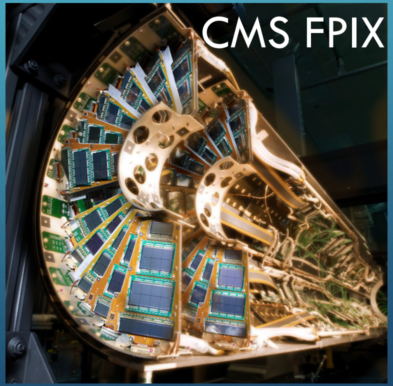
2001



2002

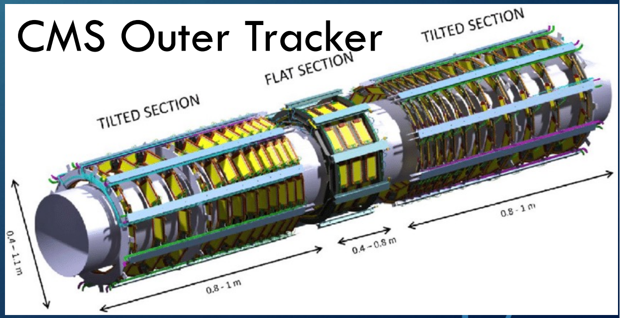


2008



2017

~2027

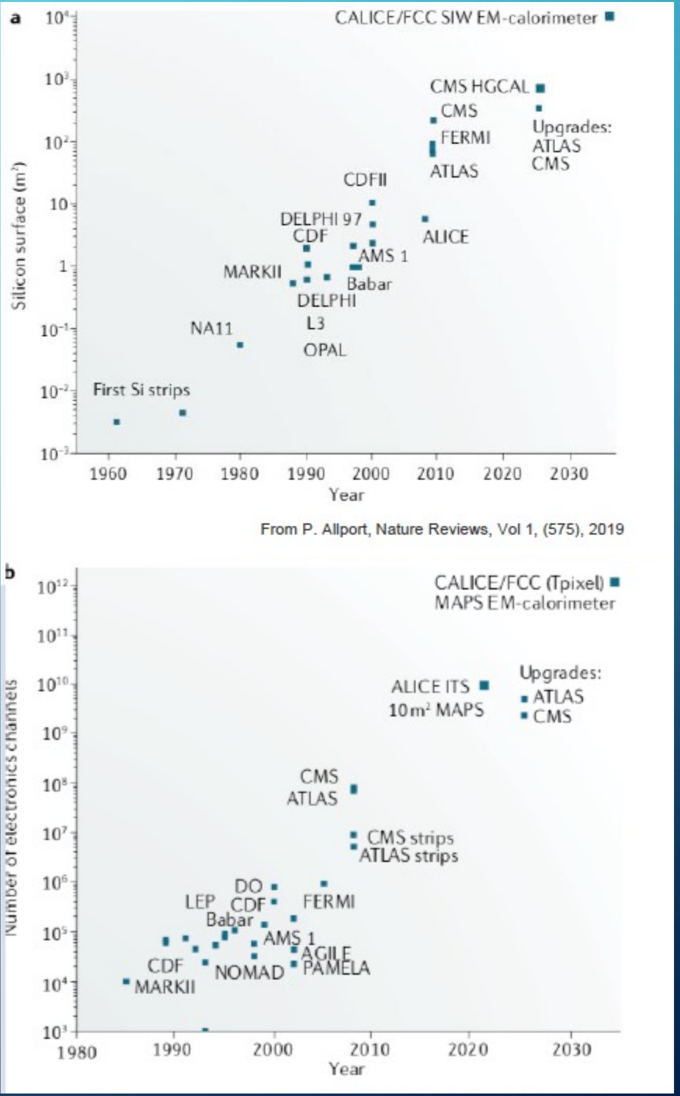


EVOLUTION OF SILICON TRACKERS FOR COLLIDERS

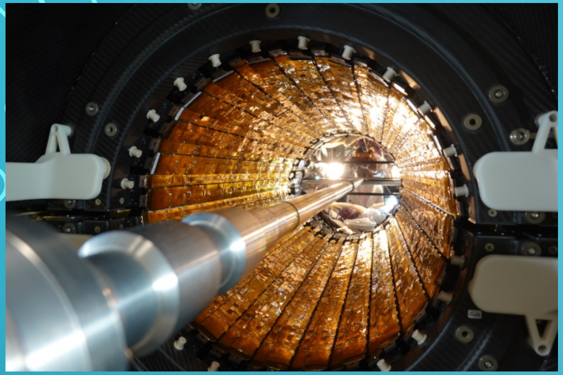
Dramatically increased challenges over the decades:

- Surface area
- Radiation exposure
- Readout channels

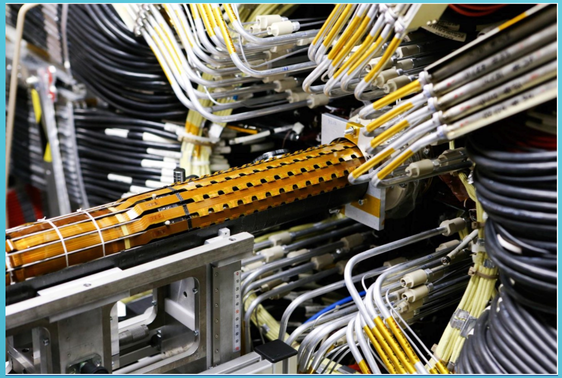
	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	10^{15}	10^{16}	10^{15}-10^{17}
TID	80 Mrad	2x500 Mrad	>1 Grad
Hit rate [MHz/cm^2]	100-200	2000	200-20000



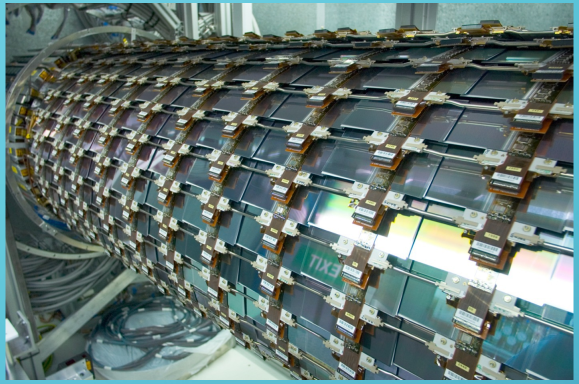
SILICON TRACKERS AT THE LHC



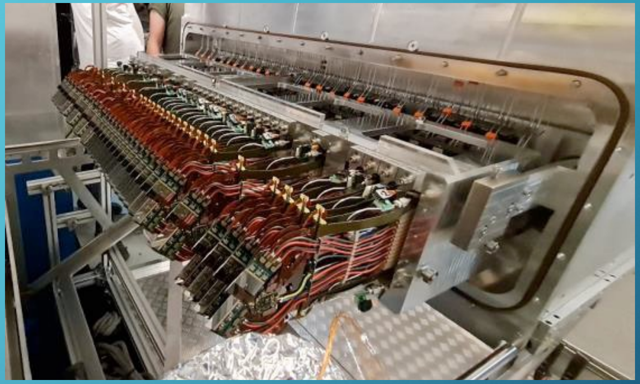
ALICE ITS Pixels



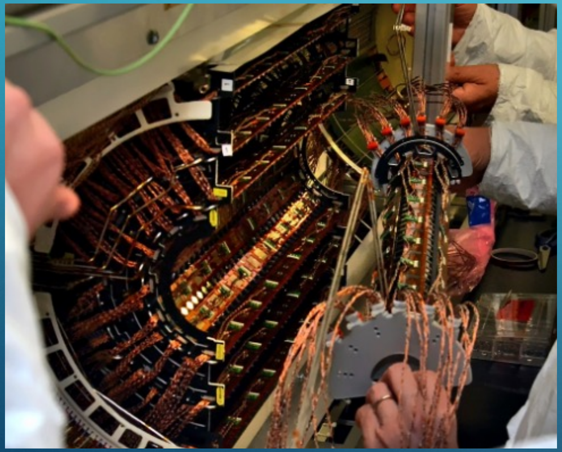
ATLAS Pixels with IBL



ATLAS SCT Strips



LHCb VELO Pixels



CMS Barrel Pixels

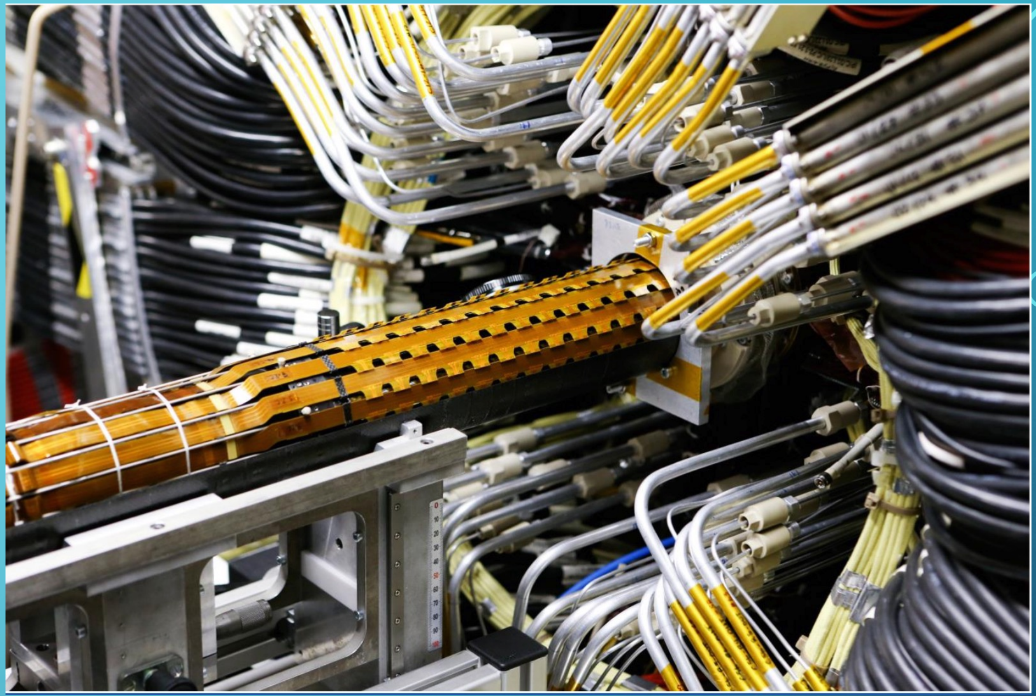
CMS Forward Pixels

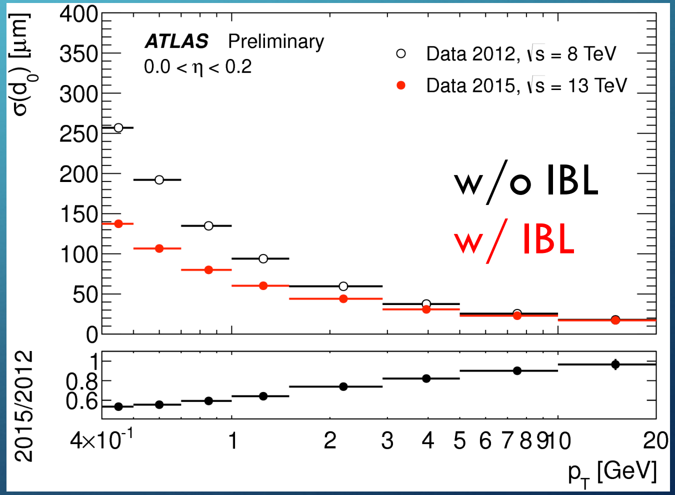
CMS Strip Tracker

ATLAS PIXELS

Insertable B-layer (IBL) upgrade in 2014

- closer to interaction point (3.35 cm)
- smaller pixels (50 x 250 μm^2)
- better sensors, better r/o chip (including 3D sensors at higher z)
- more rad hard
- significantly reduced X_0/Layer



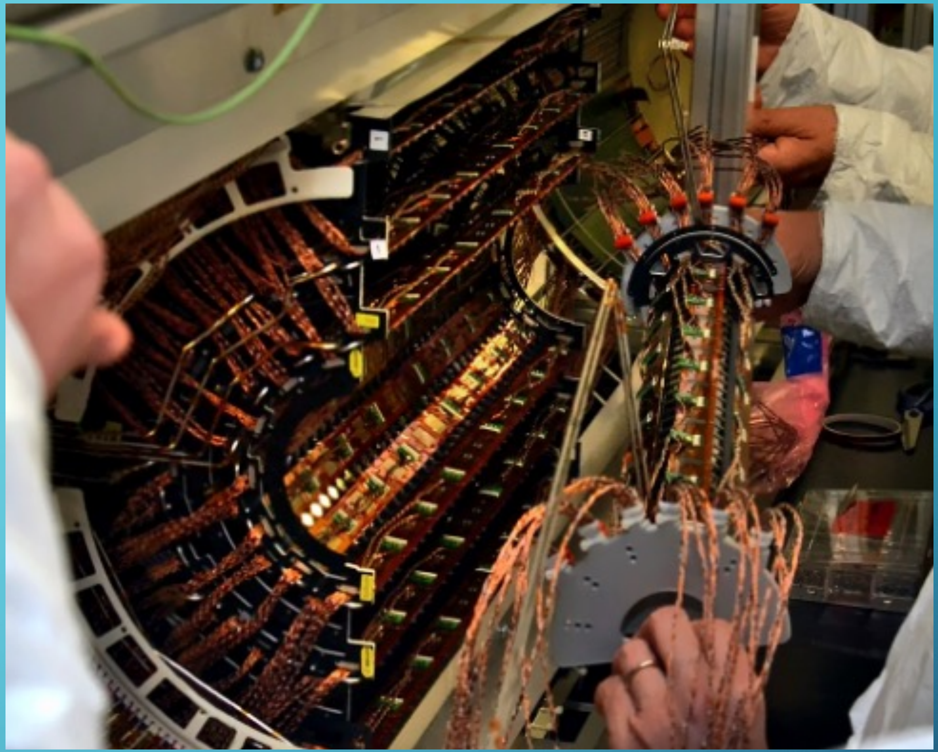


Improvement in impact parameter resolution

CMS PIXELS

Refurbishment during LS2

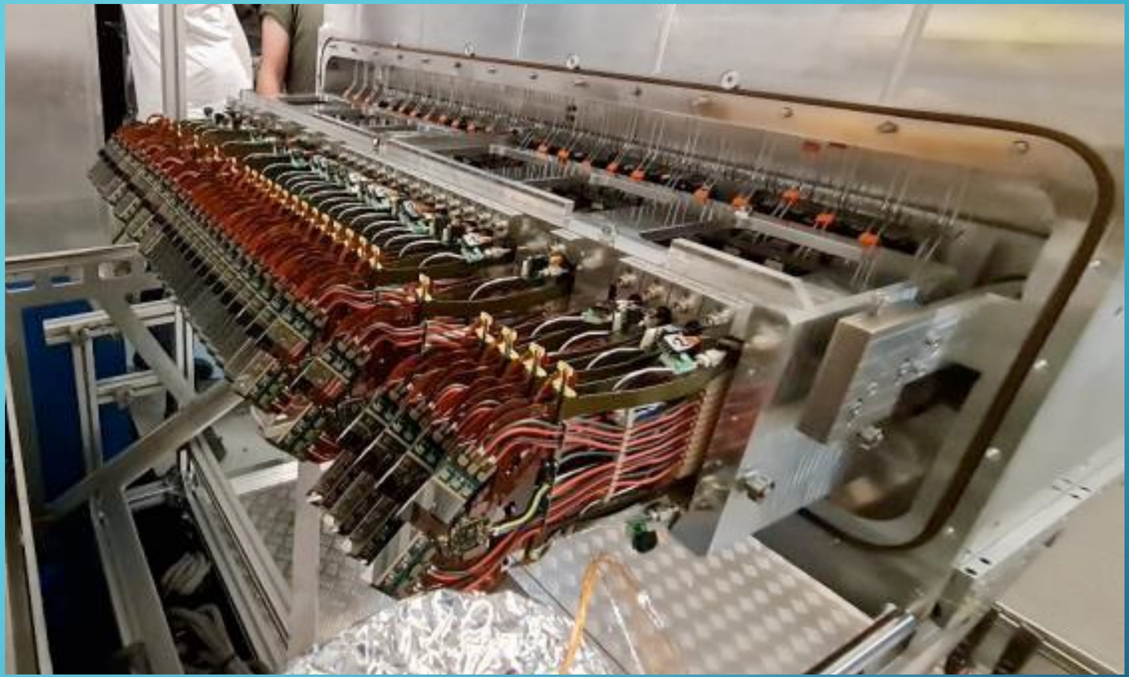
- new Barrel Layer1 with updated ASICs (lower thresholds)
- updated cooling and HV connections in the Endcap Disks
- new DC-DC converters with FEAST chip protected against failure in disabled output state
- upgraded HV power supplies up to 800 V (I_{max} = 15 mA)



LHCB VELO UPGRADE

The VErtex LOcator was updated from silicon strips to pixels in 2022

- closest pixel at 5.1 mm to the LHC beam
- read out every event at 40 MHz (ultra-highspeed VeloPix ASIC)
- 41M pixels across 52 modules in secondary vacuum



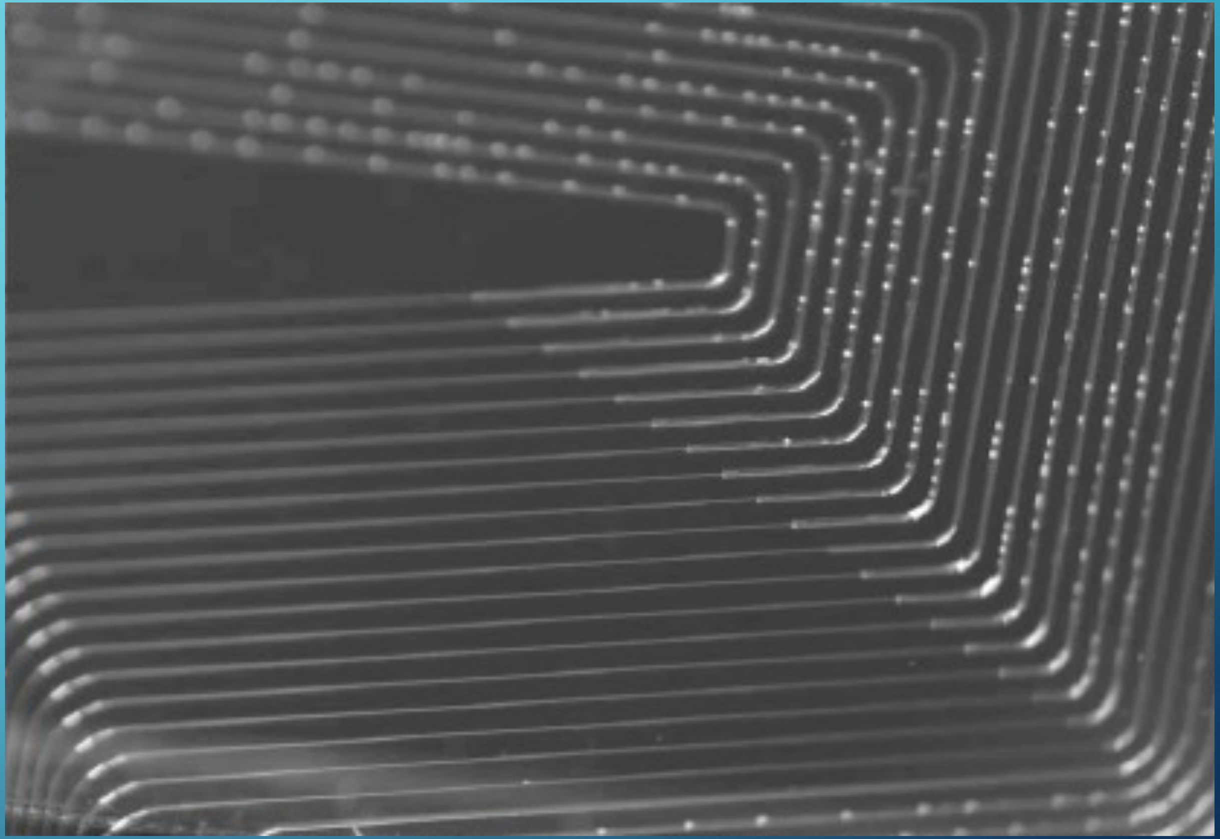
RF Foil separating VELO vacuum from LHC vacuum

- 150 μm thick shield (Torlon with NEG coating)
- 3.5 mm from beam and 0.9 mm from sensors
- thermally stable, shields against RF pick-up

LHCB VELO UPGRADE

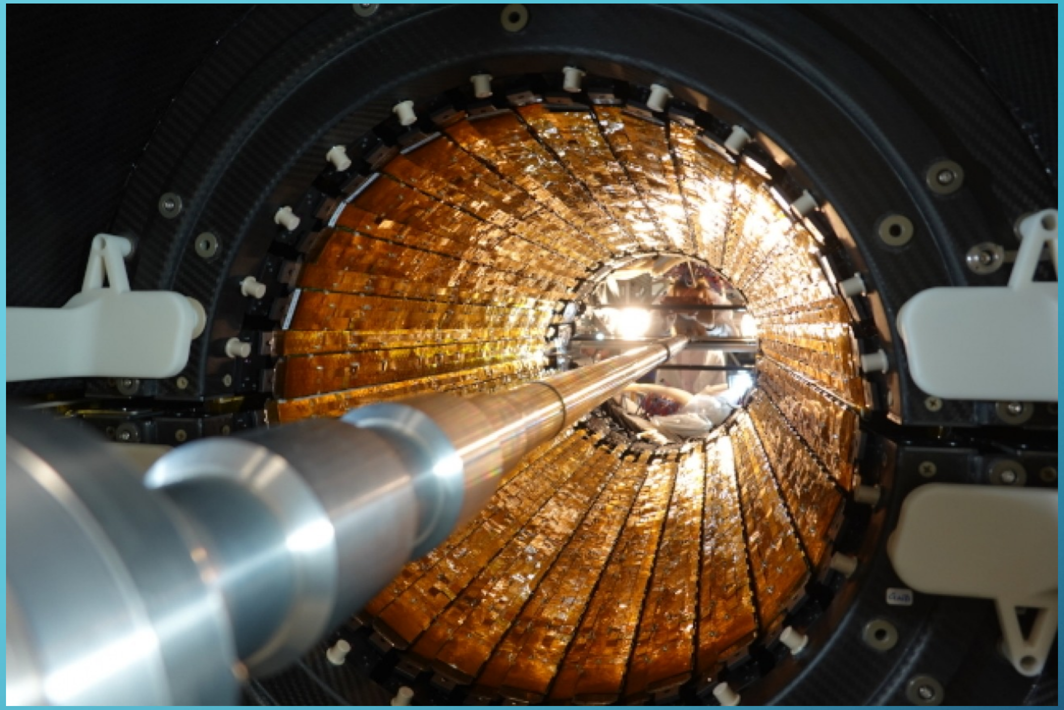
CO_2 cooling through microchannels

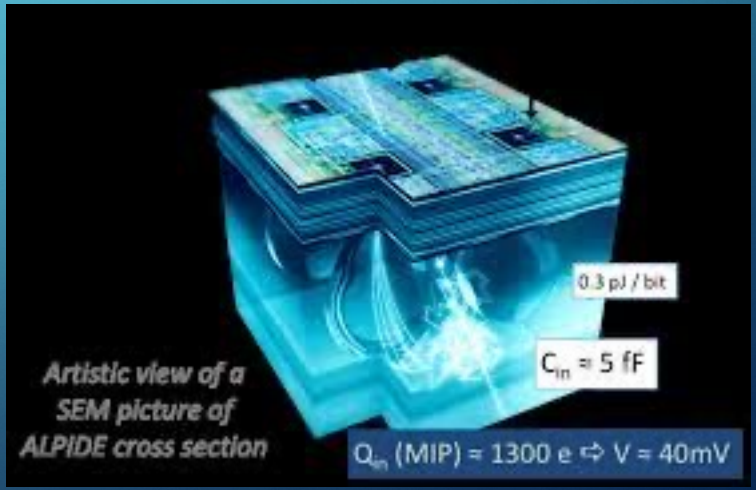
- efficient, light and powerful cooling needed for operating in vacuum, very close to the beam
- building on success from original LHCb evaporative CO_2 cooling
- 500 μm Si wafer with 120 x 200 μm^2 microchannels
- cooling power up to 40W at -30C



ALICE ITS UPGRADE

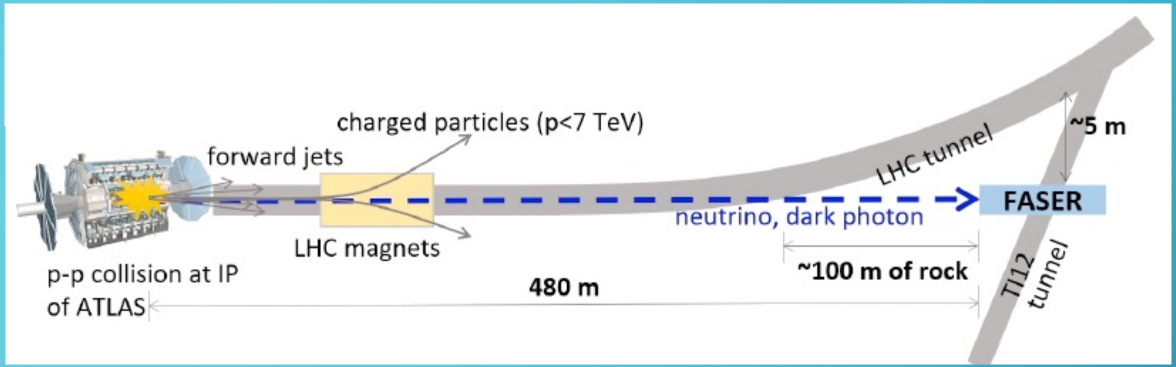
- New Inner Tracking System (ITS)
  - 10 m^2 of MAPS (Monolithic Active Pixel Sensor)
  - innermost layer: 2.2 cm from beam
- ALPIDE sensors
  - CMOS MAPS (180 nm TowerJazz technology)
    → first CMOS MAPS-based tracker at the LHC!
  - 50 / 100 μm thick (inner / outer ITS)
  - 130,000 pixels/cm^2
    - pixel size: 20 μm x 27 μm
    - sensor size: 15 mm x 30 mm
  - hit efficiency > 99%
  - spatial resolution: 5 μm



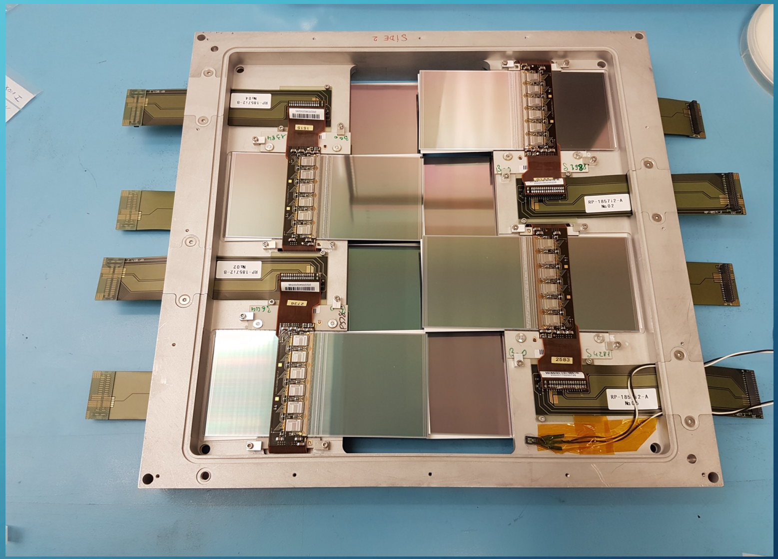


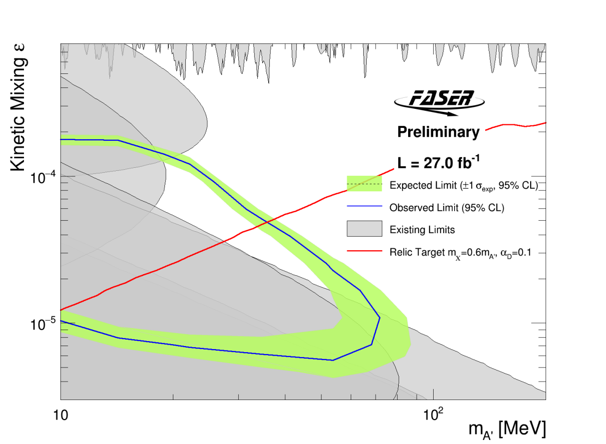
Artistic view of a SEM picture of ALPIDE cross section

FASER

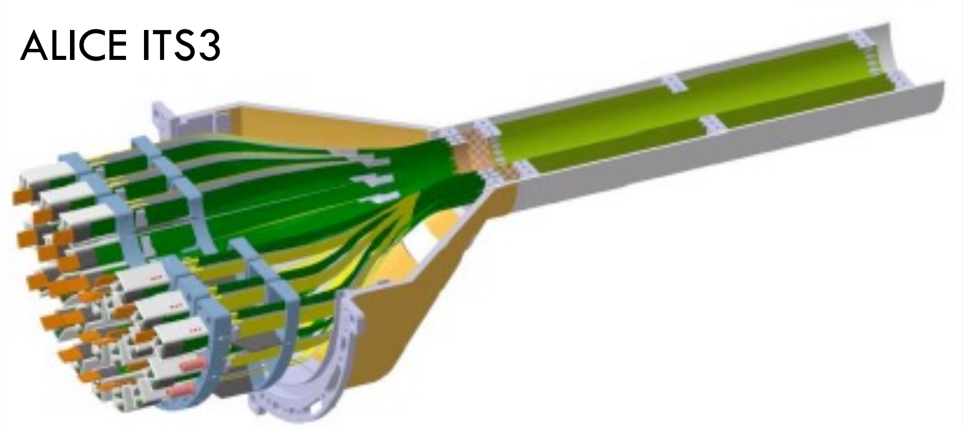


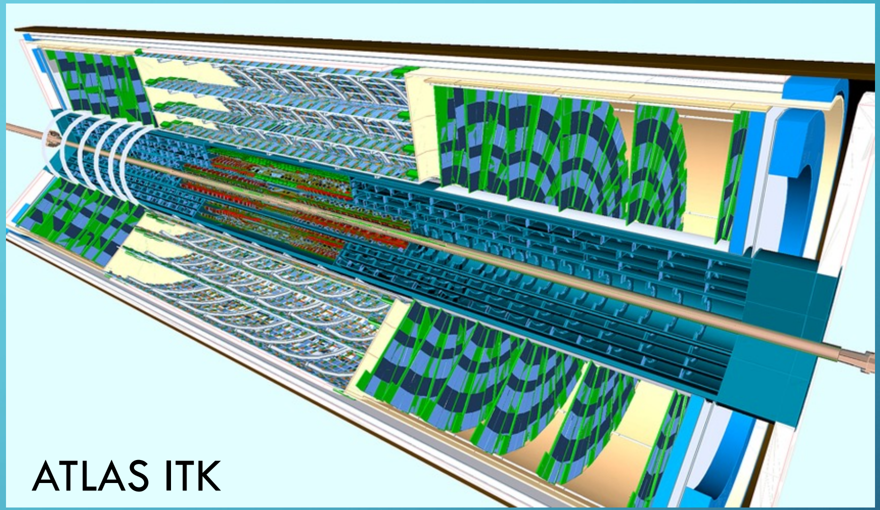
- New small experiment installed in an old LEP injector tunnel during LS2
- Designed to detect particles in forward region, such as dark photons, Axion-like particles, etc.
- Tracker: 72 ATLAS SCT modules
  - single-sided p-in-n strip detectors, 80 μm pitch
  - 10^5 channels in total in three stations

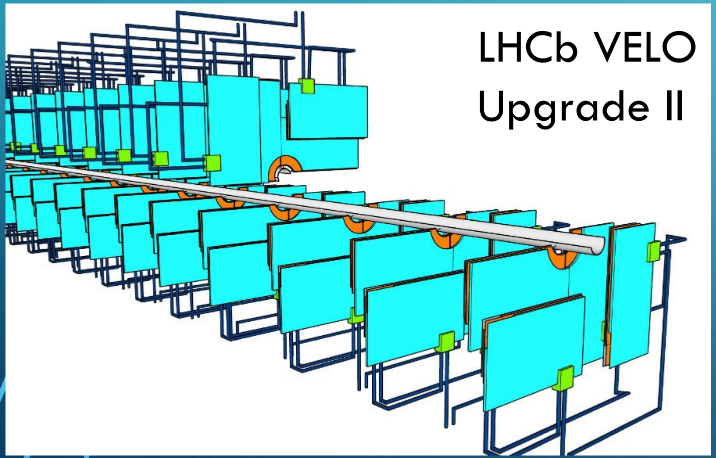


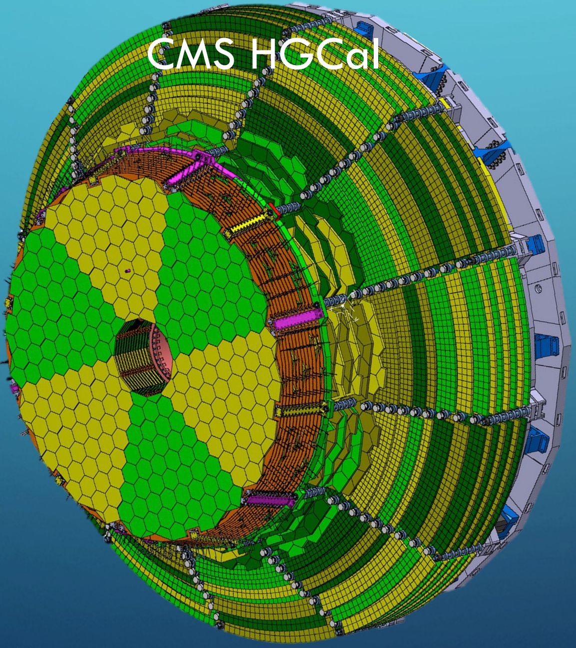


SILICON UPGRADES FOR HL-LHC

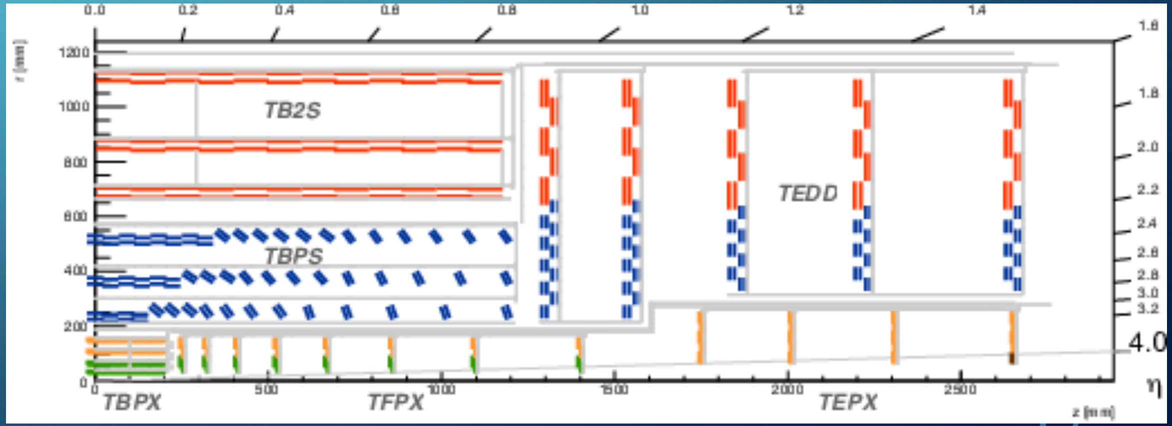






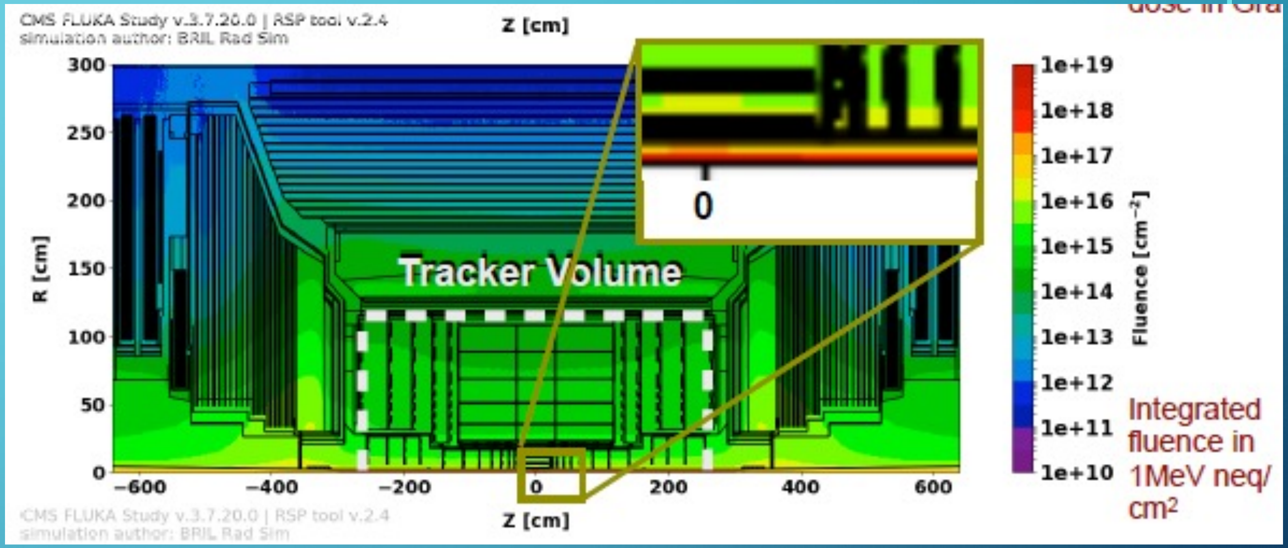


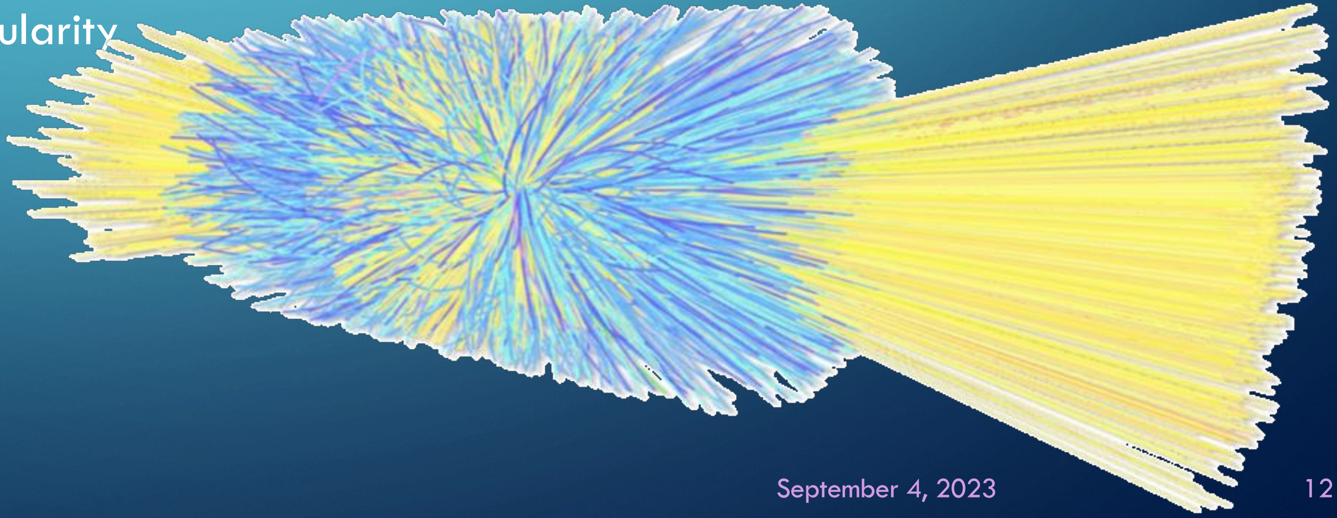
CMS Tracker Upgrade



HL-LHC UPGRADES: REQUIREMENTS

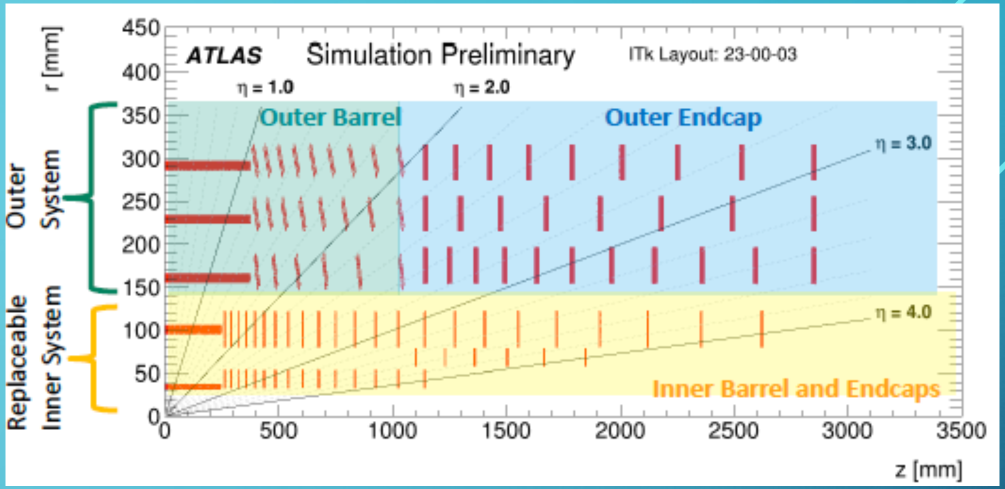
- New environment:
  - Luminosity @ 5-7 x 10^{34} $cm^{-2}s^{-1}$
  - Integrated luminosity ≥ 3000 fb^{-1} (x10 increase)
  - Pile-up up to $<\mu>$ = 200 (4x increase)
- Detector requirements:
  - High radiation tolerance
  - Improved track separation → high granularity
  - Low occupancy, high bandwidth
  - Low mass

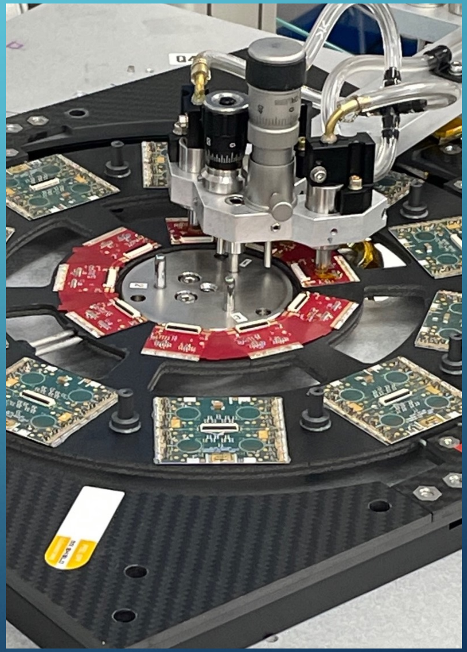


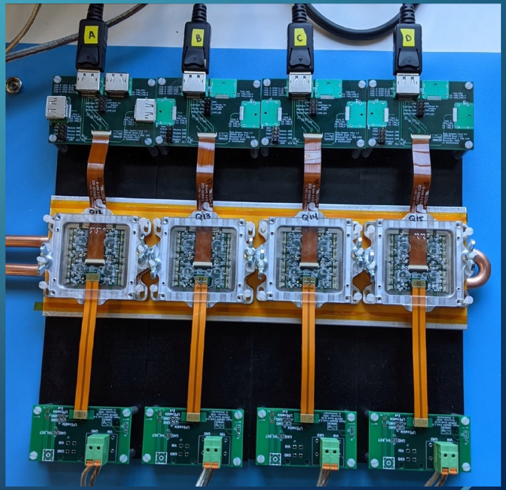


ATLAS ITK PIXELS

- Solutions for increased challenges:
  - All-silicon tracker with higher granularity (5×10^9 pixels)
  - Increased transparency: x2 lower (2.4 X_0/Layer)
  - Increased acceptance ($|\eta|<4$): 5 barrel layers, up to 28 disks per endcap
  - 13m² active area
- Planar and 3D sensors
  - 3D (L0): 25x100μm² (Barrel), 50x50μm² (Endcap); more rad tolerant
  - Planar (L1-L4): 50x50μm²
- ITkPix chip developed out of RD53 (ATLAS-CMS common ASIC, 65nm TSMC)
- **Challenges**: large ASIC (20x20mm²); high density, low-pitch bump bonding; large V_{bias} across thin air gap (10μm) → Parylene coating; large T_{ops} range; serial powering; low-mass services



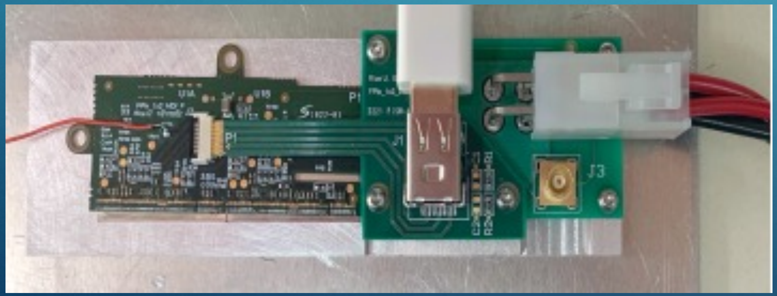




CMS PIXEL UPGRADE

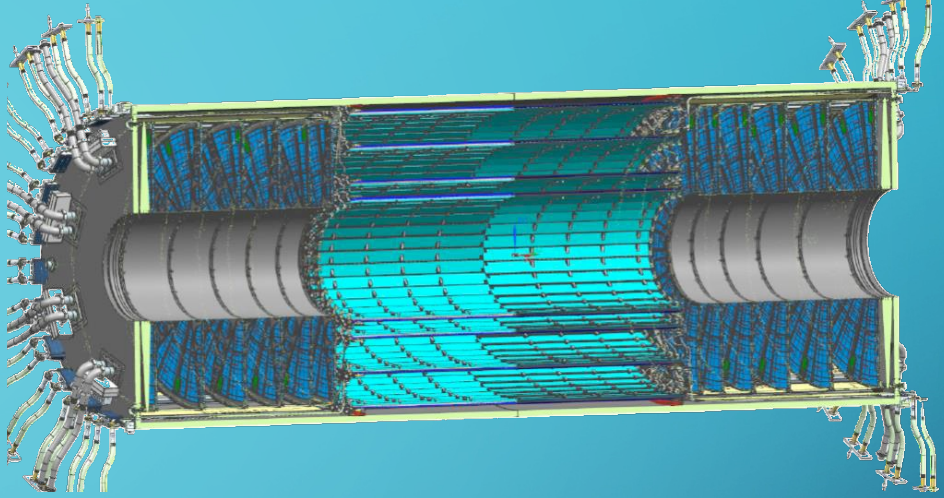
light-weight mechanics: inner tracker can be removed for maintenance in an extended technical stop

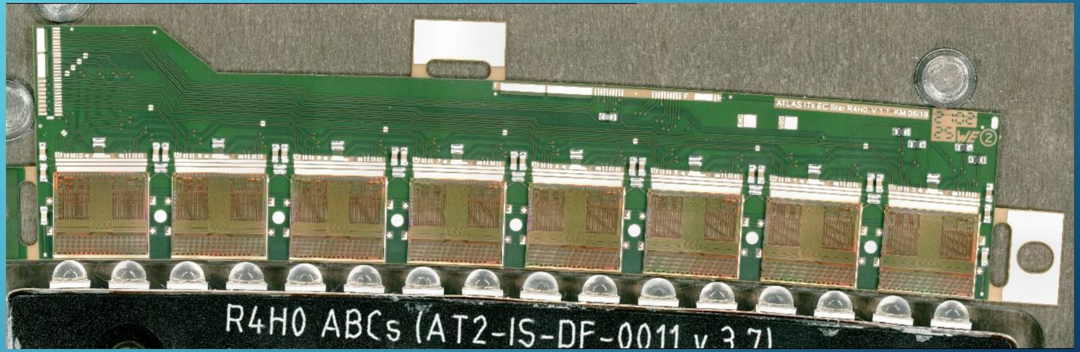
- $4.9m^2$, $2x10^9$ pixels , $100x25\mu m^2$ cell size
- Tracking coverage extended to $|\eta| \leq 4$
- 3D sensors in L1, planar n-in-p sensors everywhere else
- CROC chip based on common RD53 ASIC
- Parylene coating for spark protection
- Serial powering (insensitive to voltage drops, low mass cables)

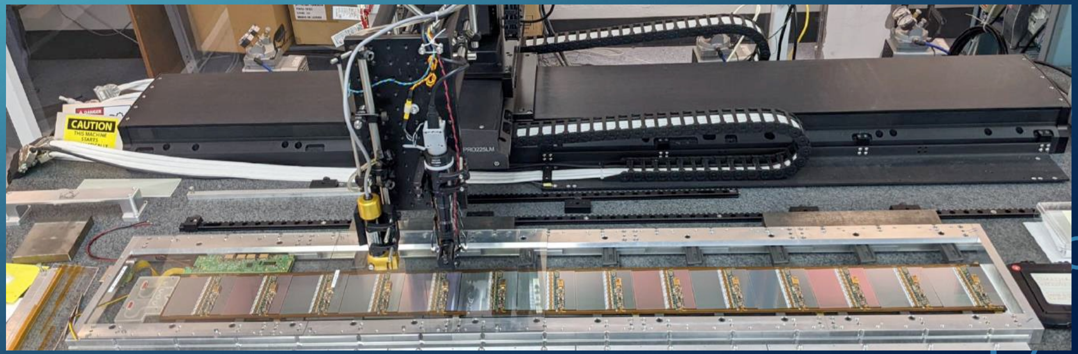


ATLAS ITK STRIPS

- $180m^2$ silicon, 60M channels
- 4 barrel cylinders, 6 disks per endcap
  - Barrel is made up of 1.4m long staves
  - Disks are made up of petals (60cm in r x 30cm in ϕ)
  - CF-based sandwich with embedded cooling
- n-in-p type FZ sensors from HPK
- ABCStar/HCCStar/AMC chip family (130nm CMOS, GF), binary readout



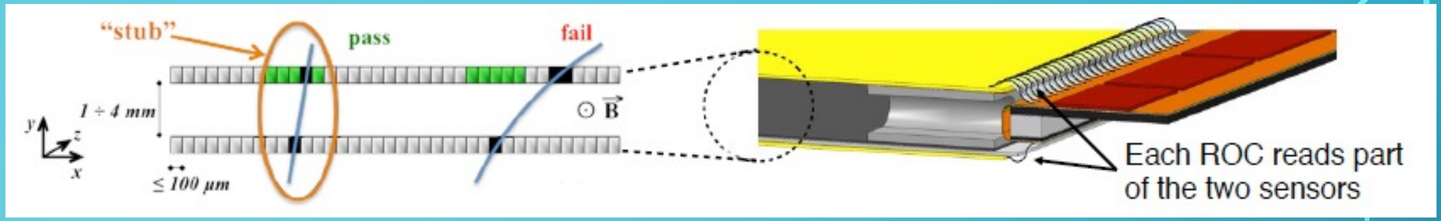


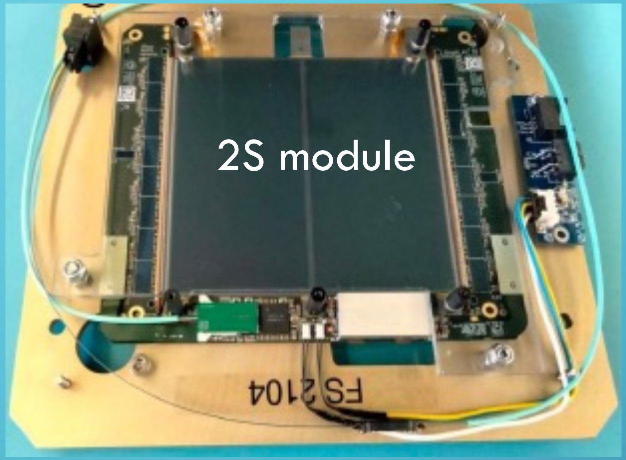


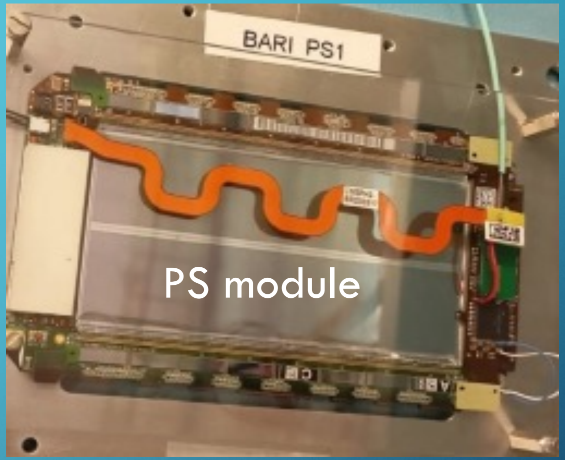
CMS OUTER TRACKER

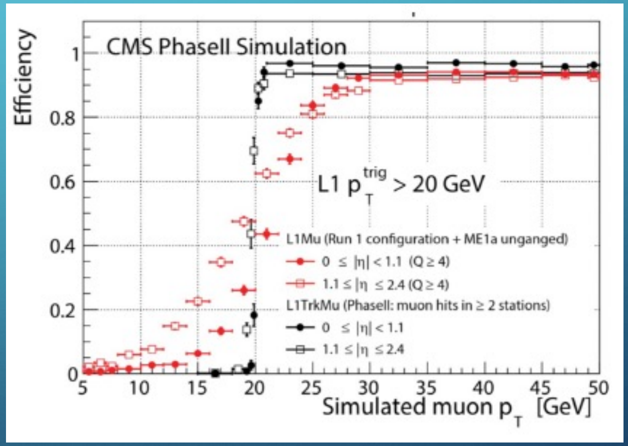
provides track information @ L1 trigger
for 1st time at a hadron collider

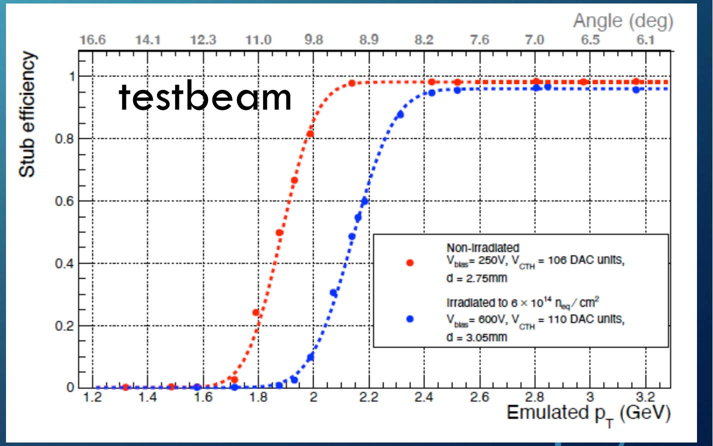
- OT designed to provide L1 trigger stubs: p_T module concept
  - two closely spaced sensors read out by common set of ASICs
  - correlated stubs sent to backend at 40MHz
- Two types of module:
  - 2S (strip-strip) at outer radii
  - PS (pixel-strip) in inner layers
- 190m^2 silicon, 213M channels





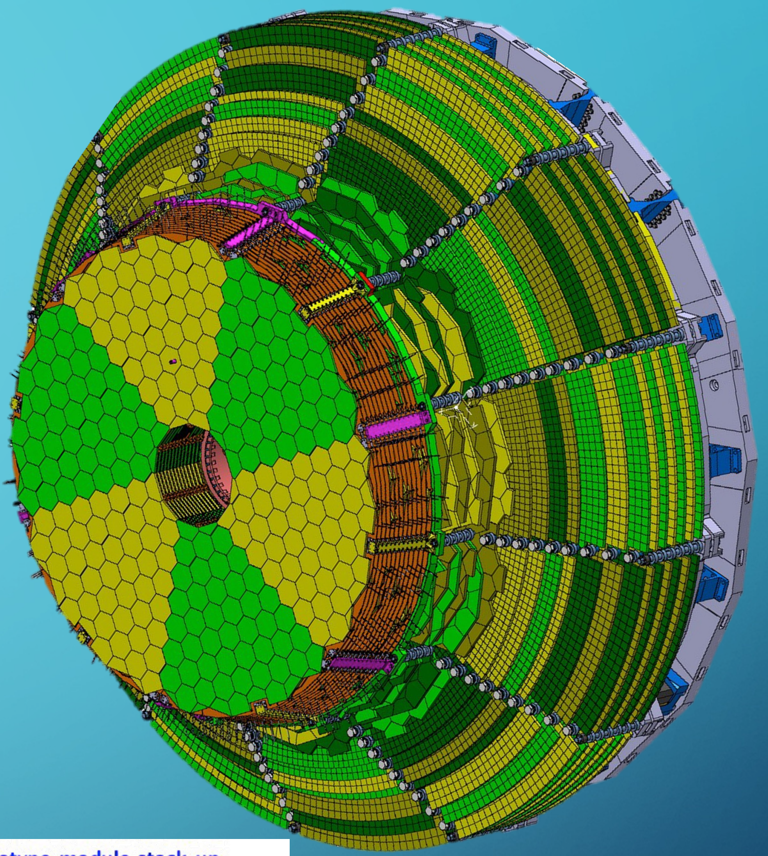


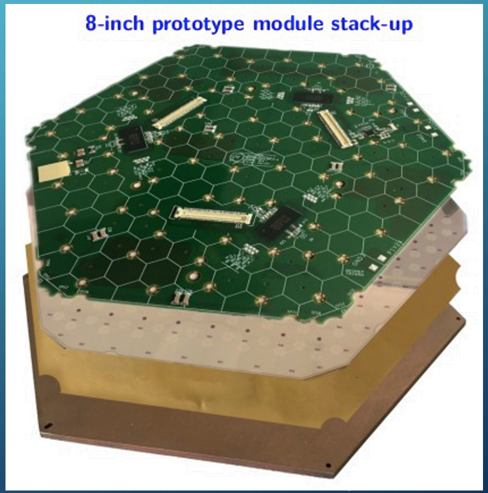


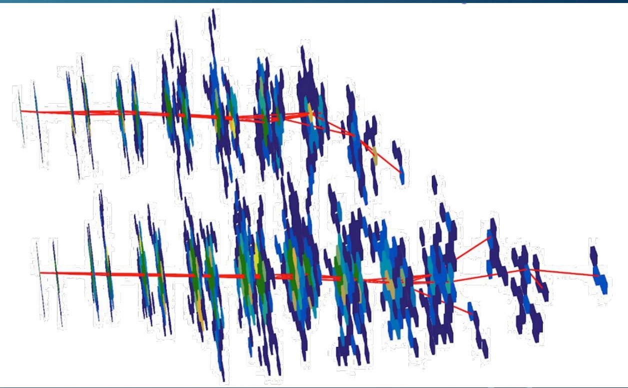


CMS HGCAL

- Composed of cassettes, multiple modules mounted on cooling plates with electronics and absorbers
  - Hexagonal modules based on silicon sensors in high-radiation regions (EM+HAD)
  - Scintillating tiles with SiPM readout in low-radiation areas (HAD)
- $1.5 < |\eta| < 3.0$, ~215 tonnes per endcap
- ~600m^2 of silicon, 8” wafers, 6M channels (0.5 or 1cm^2 cell size)
- ~500m^2 of scintillators
- ~110kW(!) per endcap at end-of-life

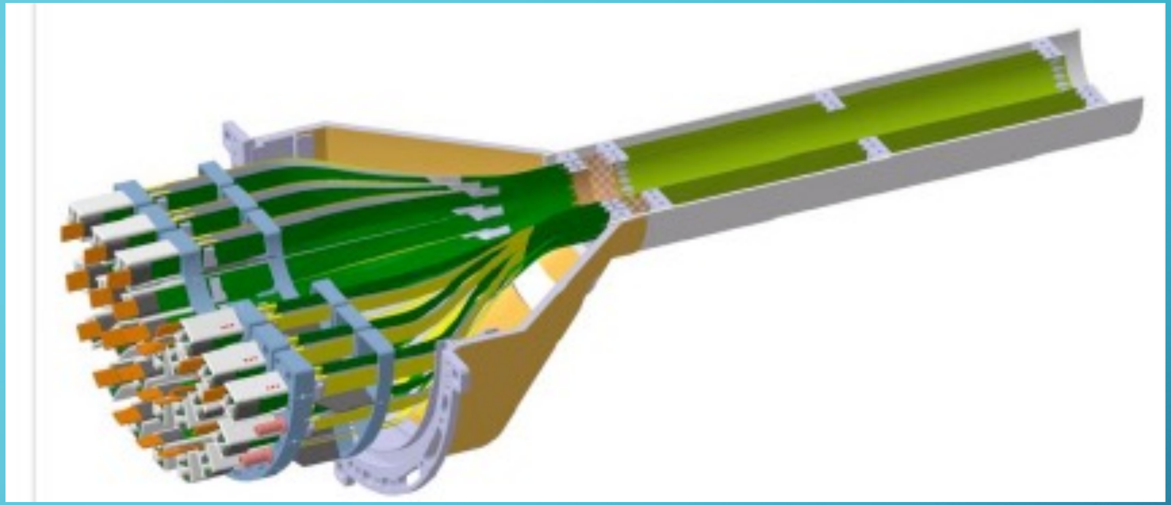


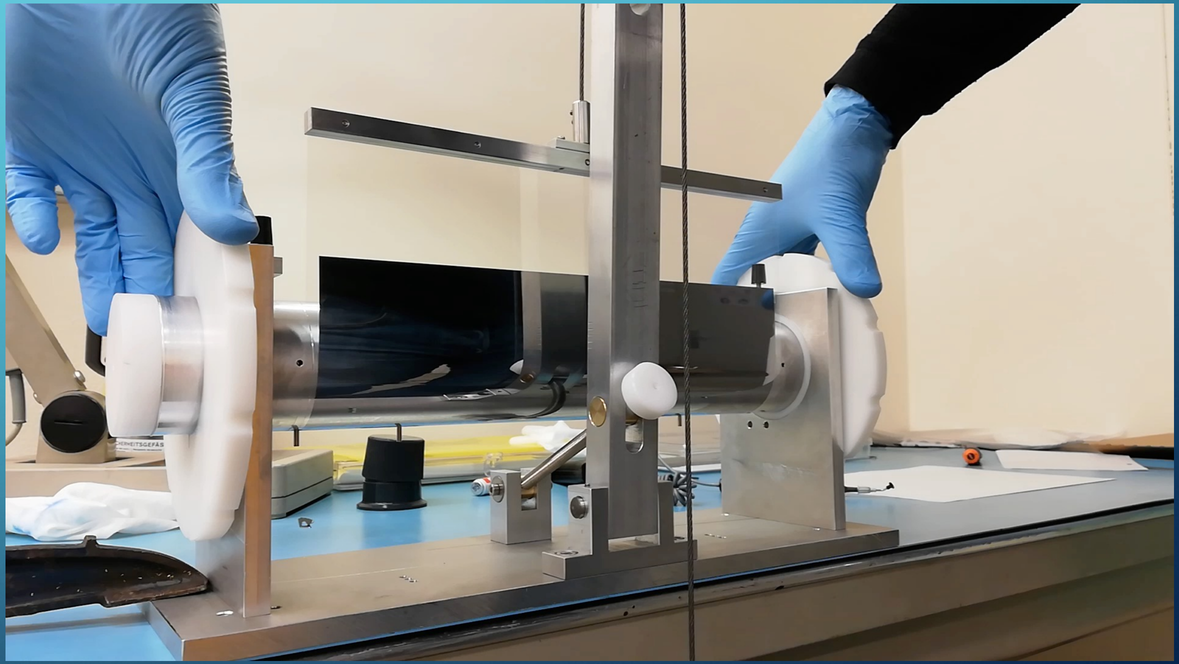




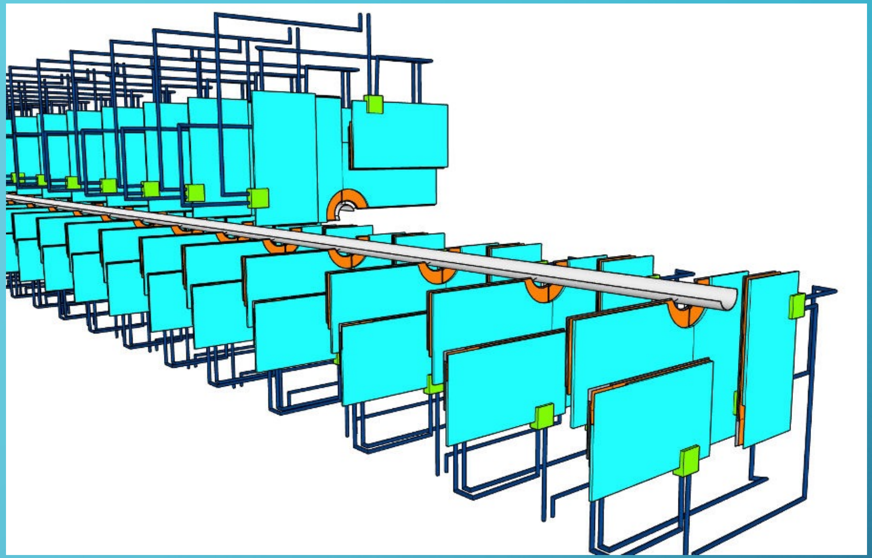
ALICE ITS3

- 300mm wafer-scale MAPS (65nm TPSCo), fabricated using stitching
  - thinned down to ≤50μm making them flexible; bent to target radii
  - mechanically held in place by carbon foam ribs
- Extremely low material budget: <0.05% X_0, homogeneous material distribution
- Planning to use air cooling





LHCB VELO UPGRADE II

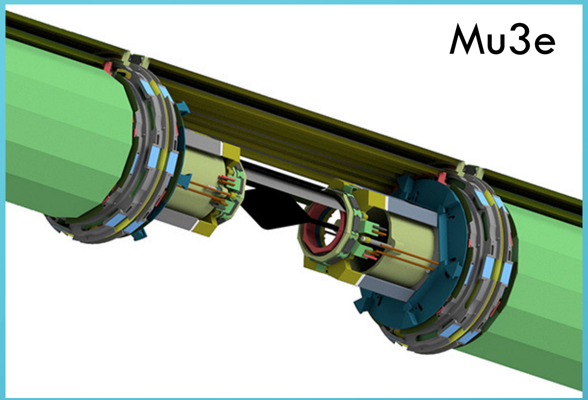


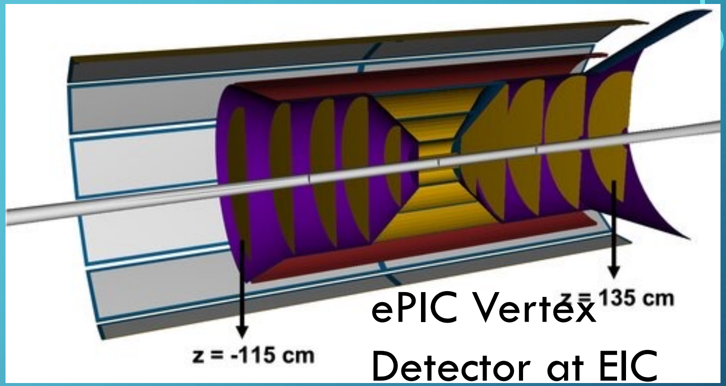
- Planned for Run5 (2035+)
- Increased pileup x10 → add timing (50ps/hit)
- R&D on candidate sensors:
  - 3D pixels, LGADs, SiEM (Silicon electron multiplier sensor)
- Radiation tolerance up to 6×10^{16} 1MeV n_{eq}/cm^2 (or regular module replacement)
  - extreme rates: 350kHz/pixel, 250Gb/s per ASIC
- Need to reduce mass by 80% X0 before 2nd hit → operation in LHC vacuum

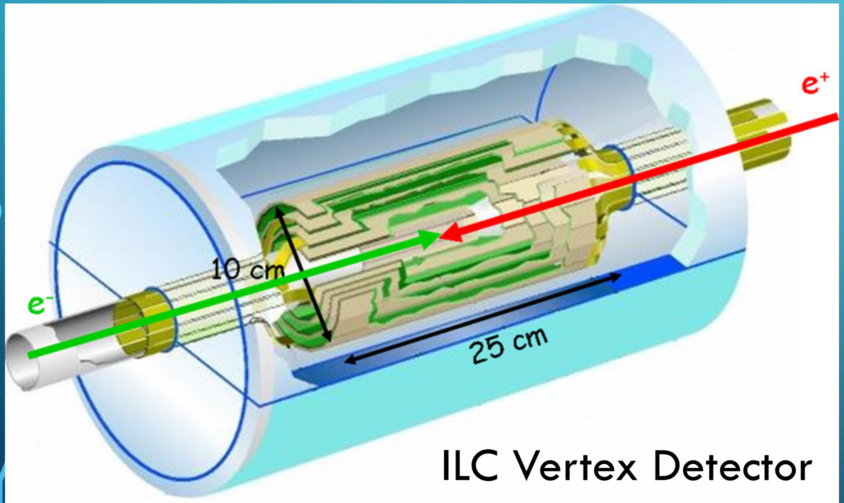
R&D needed for RF shielding:
e.g. NEG coating → amorphous carbon coating

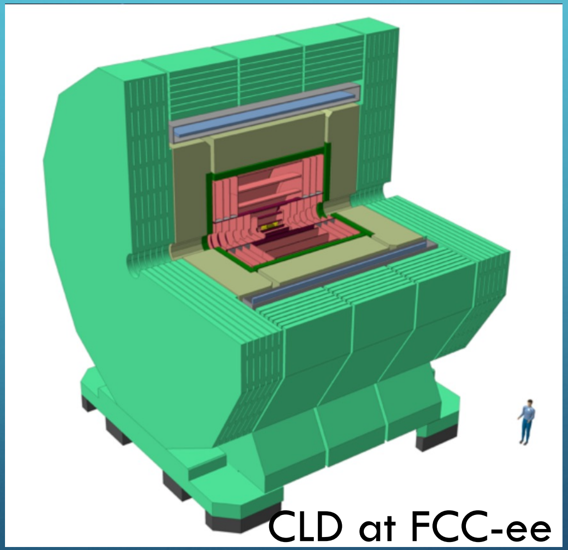
R&D needed for active cooling:
e.g. considering bi-phase Krypton cooling for operation <-40C

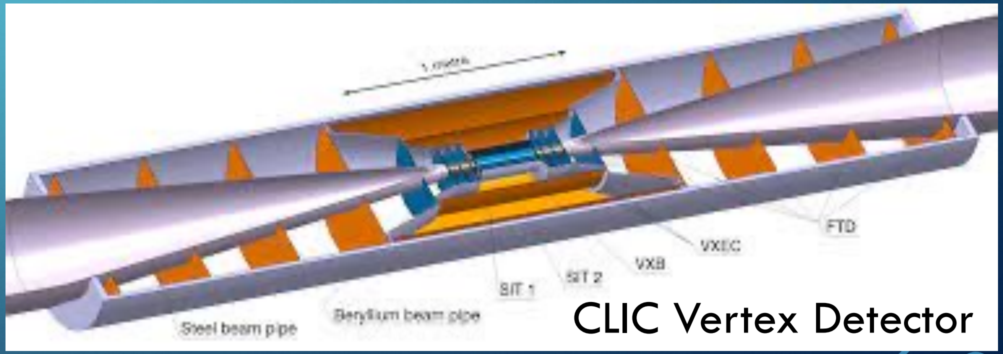
SILICON BEYOND THE LHC





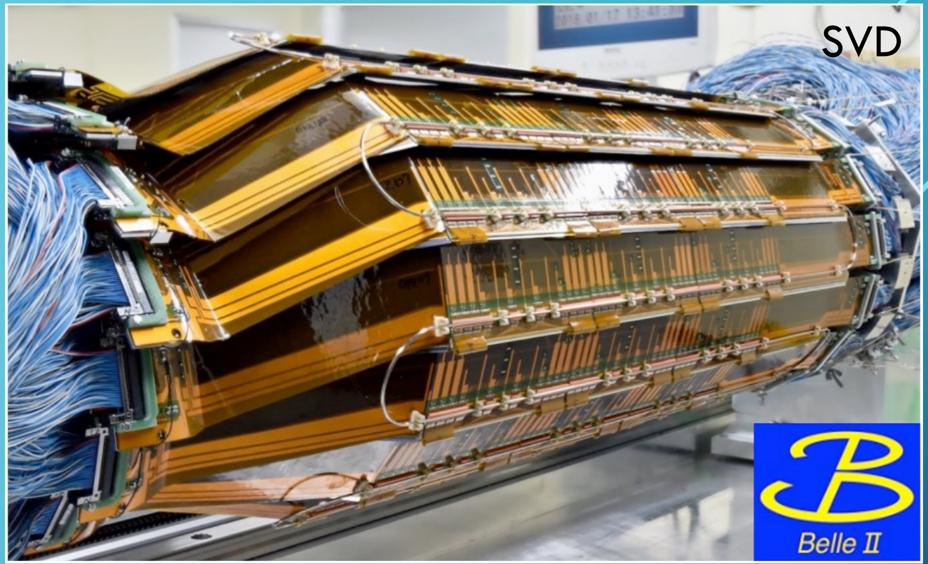


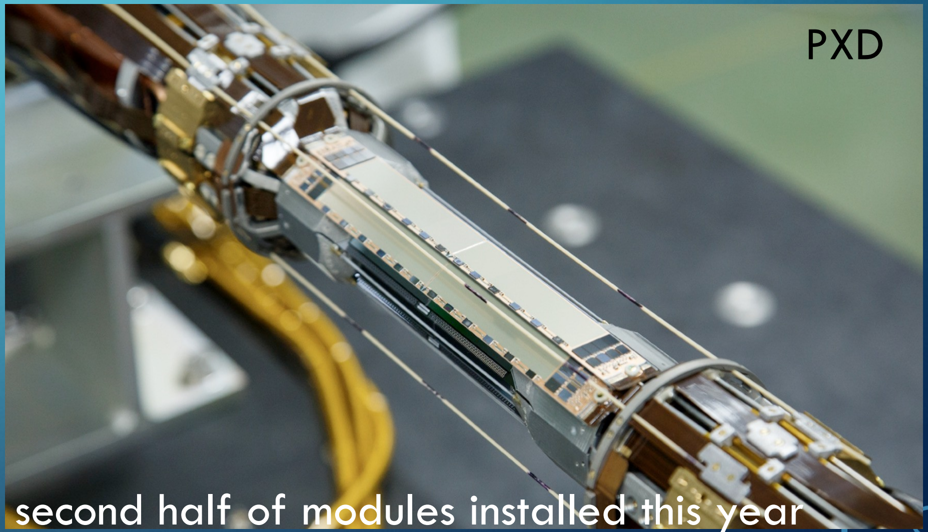




BELLE II PIXELS AND STRIPS

- SVD: double-sided strip sensors
  - AC-coupled strips on N-type substrate
  - $1.2m^2$ sensor area, 224k strips
  - Wrapped flex circuit to read both side
- PXD: DEPFET pixel sensors
  - Ultra-thin sensor (75μm), pixel size (50x55-85μm^2)
  - Low power consumption
  - High signal-to-noise
  - Switcher: rolling-shutter readout, 20μs integration time
  - Experienced some damage from beam loss events



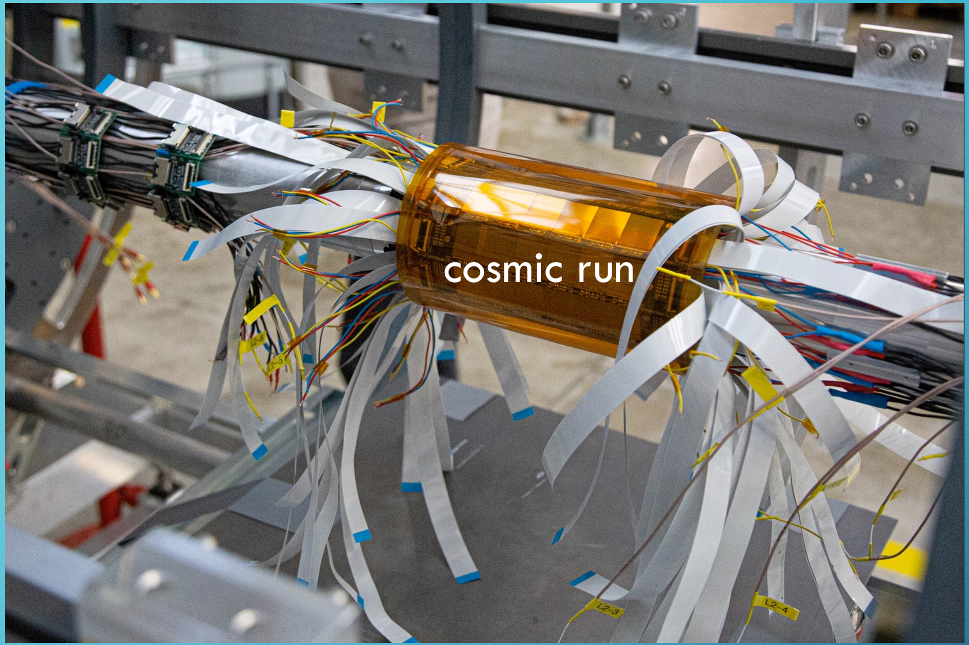


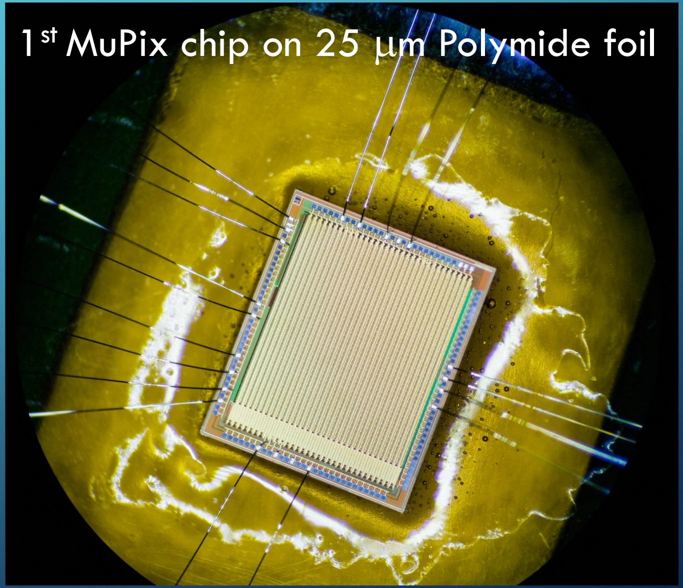
MU3E

- Search for lepton flavor violating decay at PSI, under construction
- High-rate capability (>10^9 muons/s)
- Excellent momentum resolution (<0.5 MeV/c)

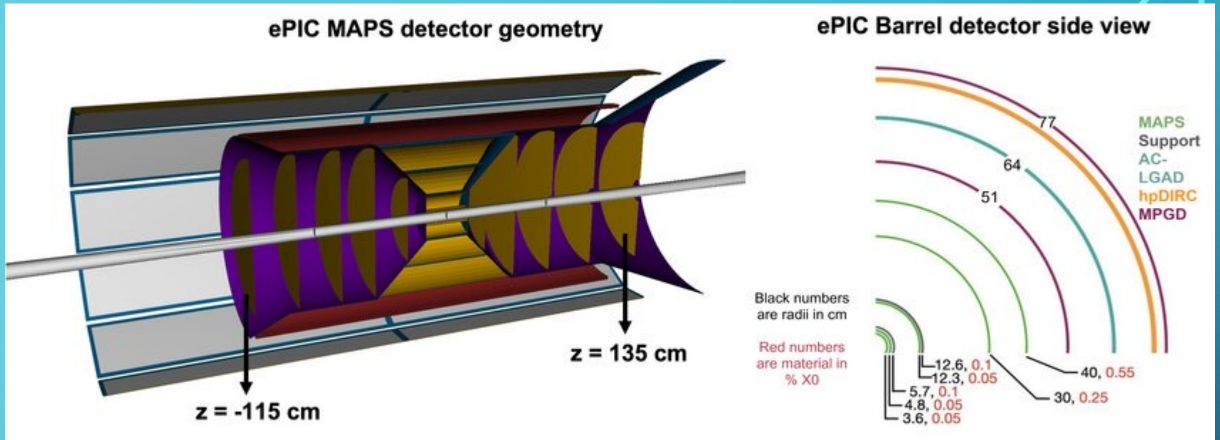
→ Extremely low material budget

- Ultra-thin (50 μm) HV-CMOS MAPS sensor modules (X/X_0 = 1.1 ‰)
- Gaseous Helium cooling





ELECTRON ION COLLIDER



Advanced silicon technologies under study:

- LGAD and AC-LGAD (Low Gain Avalanche Detectors)
  - Pixel size: 0.5 – 1.3 mm
  - Resolution: spatial ~30μm, temporal <30ps
- DMAPS (Depleted MAPS), e.g. MALTA
  - Pixel size: 36.4 μm
  - Resolution: spatial ~7μm, temporal ~2ns
- Lots of synergies with HEP developments → early deployment of new ideas

LGAD irradiation tests at LANSCE

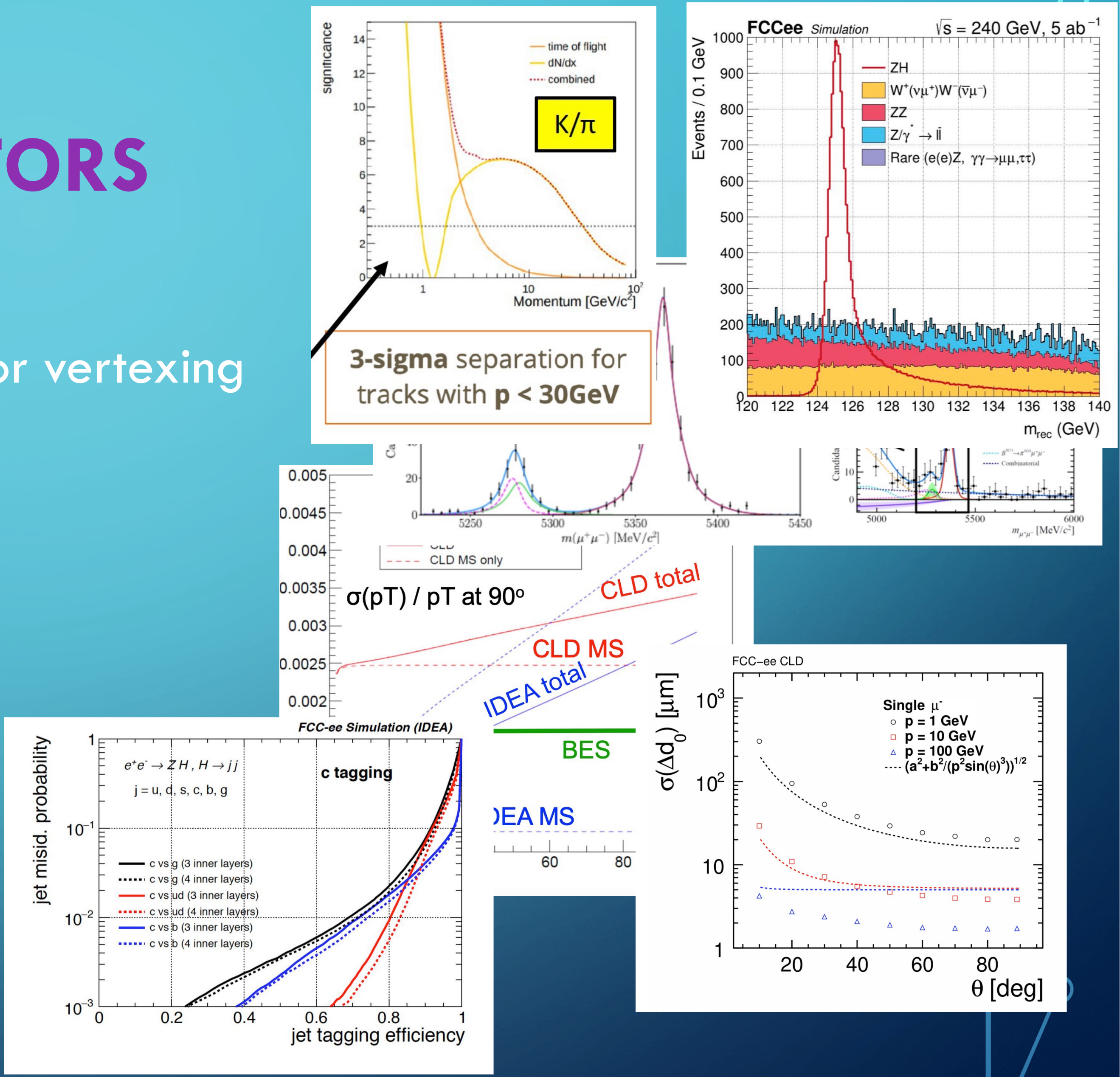
FUTURE COLLIDER DETECTORS

Focusing on e^+e^- Higgs factories

Physics goals set stringent requirements for vertexing and tracking at Lepton Colliders:

- fast readout, low power (<20mW/cm^2)
- low material (~0.15 X_0)
- spatial resolution (~3μm)
- "perfect" hit finding efficiency (~100%)
- extremely low fake rate

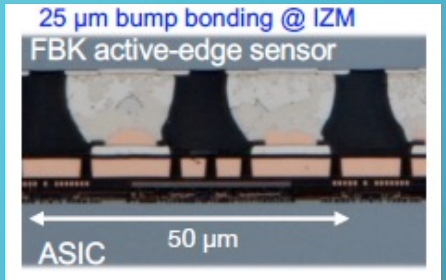
For future hadron or muon colliders, need R&D into radiation hardness and ultrafast timing



FUTURE COLLIDER DETECTORS

e.g. R&D on fine-pitch hybridization

- 25µm pitch bump bonding, sensor thickness down to 50µm
  - excellent interconnect yield >99.7% at IZM
- Hybridization with Anisotropic Conductive Films



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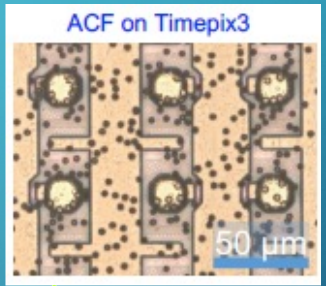
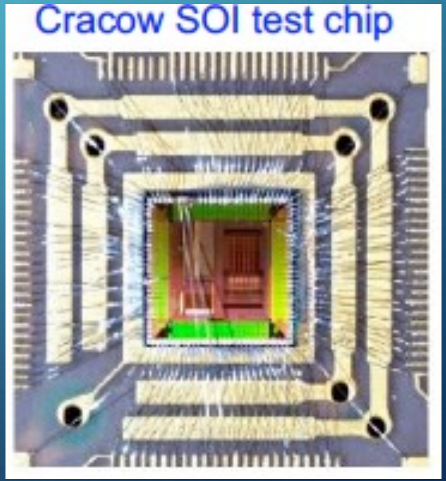


reference

e.g. R&D on Silicon-on-Insulator / 3D Integration

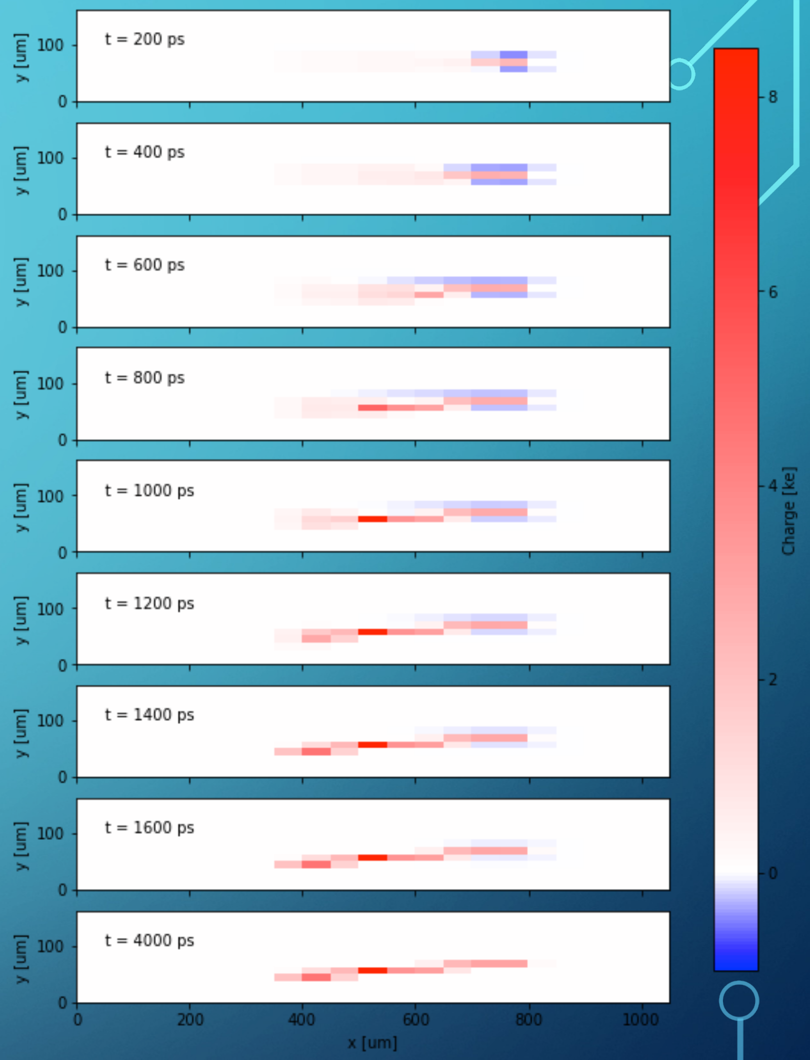
- SOI r/o electronics on thin low-resistivity wafer separated from high-resistivity sensor wafer by buried insulation oxide layer
- thin and fast "monolithic" sensors
- challenge: specialized and complex fabrication

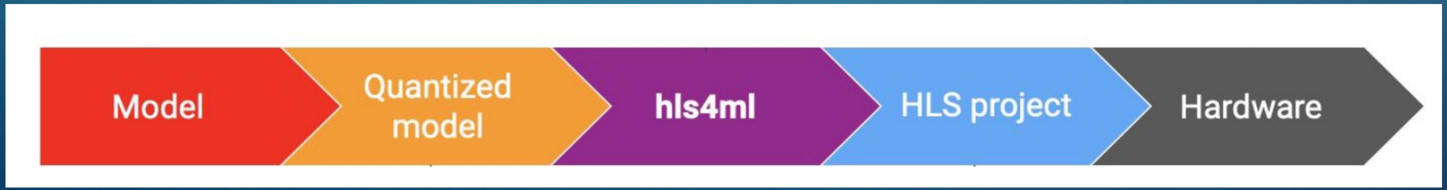


reference

SMART PIXELS

- Idea: read out incident particle's properties (e.g. angle, or p_T) instead of raw data
  - reduces data rates to manageable levels
  - use AI to perform physics-motivated data reduction on-ASIC
- Use CMS Run2 data and simulation of charge evolution with time
  - train classifier to select clusters with p_T>200 MeV
  - Implement classifier on-ASIC: 1,163 parameters, <300μW, area<0.2mm^2





presentation

SUMMARY

- Silicon-based detectors are vital to the physics program of many different kinds of experiments
- In future collider experiments they will be even more ubiquitous
- However, in some cases we might be nearing the end of the possible (radiation hardness, feature size, low mass, timing, etc.)

→ Need for a strong and diverse R&D program to explore novel concepts, including new materials

THANK YOU!

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