Progress on Instrumentation and its impact on EF

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

EF drivers for detector developments

- 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.
  - The muon collider's detector requirements are still being developed

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, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ 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 8×10^{17} $\text{n}_{\text{eq}}/\text{cm}^2$ 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 0.5×0.5 cm^2, hadronic cells of 1×1 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}) $\text{n}_{\text{eq}}/\text{cm}^2$ 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 8×10^{17} $\text{n}_{\text{eq}}/\text{cm}^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

DOE Basic Research Needs Study on Instrumentation

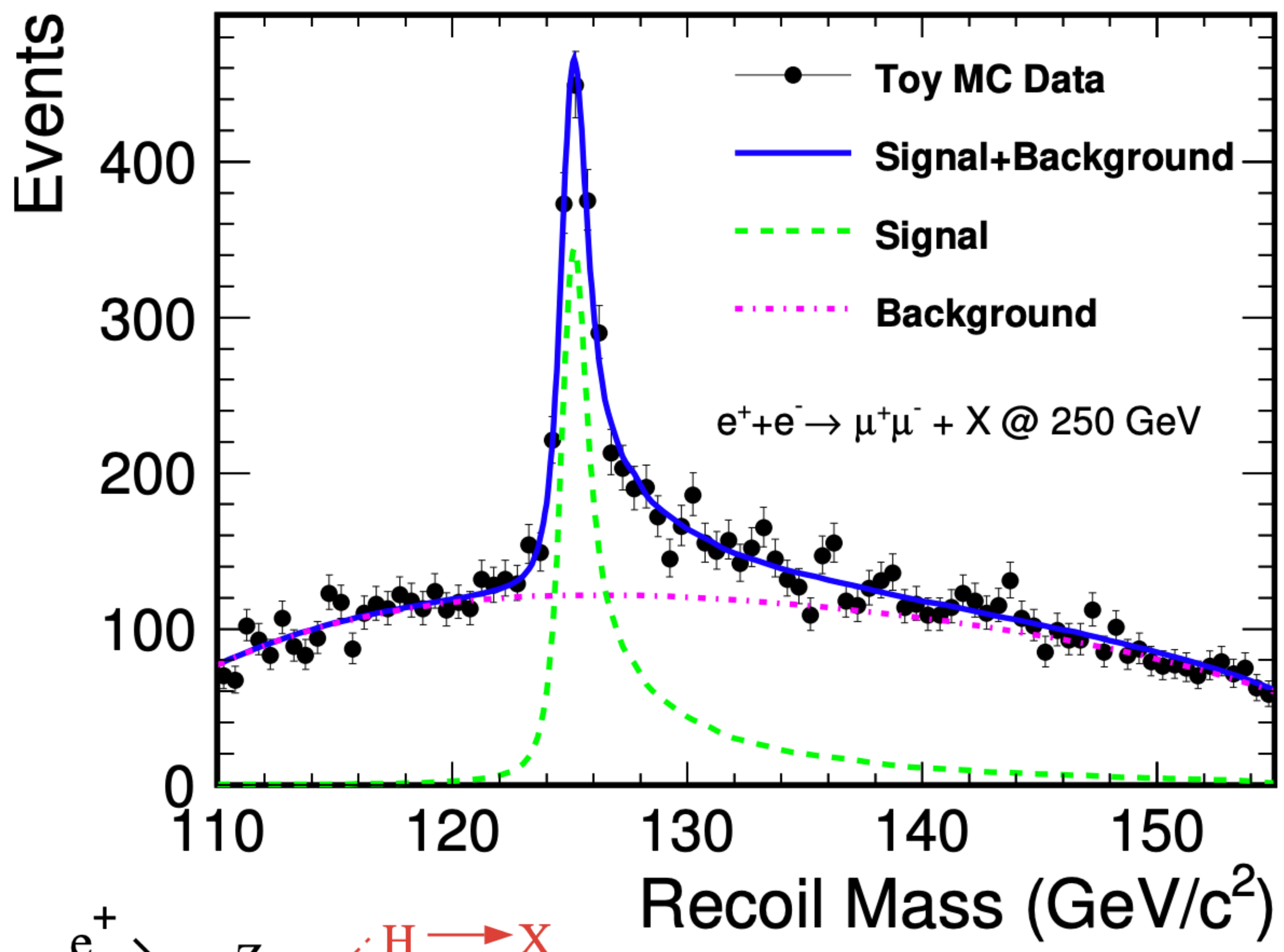
EF-IF - news

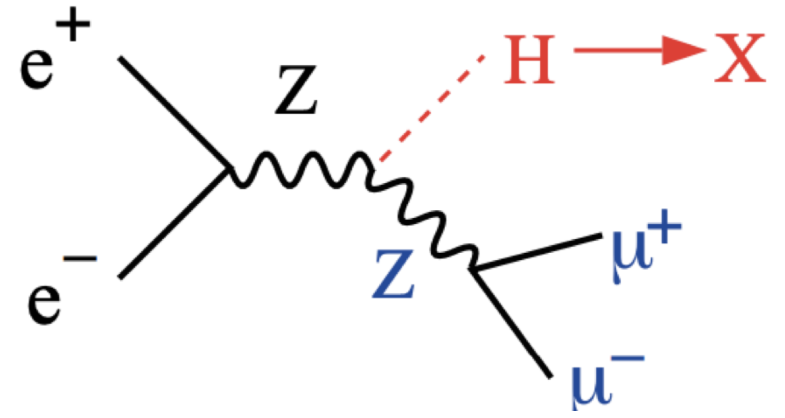
- First discussion at the CPM Oct, 2020
- Energy Frontier Restart workshop Aug 30 - Sept 3, 2021
- This talk summarizes (briefly):
  - Current discussions to identify physics requirements for future detectors
  - about ongoing R&Ds
- Please get in touch with us if you have any input / studies to suggest
    - maxim.titov@cea.fr and caterina@slac.stanford.edu

Physics requirements for tracking detectors at e+e-

arXiv:1306.6329
arXiv:2003.01116

- **ZH process**: Higgs recoil reconstructed from Z →μμ
  - Drives requirement on charged track momentum and jet resolutions
  - Sets need for high field magnets and high precision / low mass trackers
  - Bunch time structure allows high precision trackers with very low X_0 at **linear lepton colliders**
- **Higgs → bb/cc decays**: Flavor tagging & quark charge tagging at unprecedented level
  - Drives requirement on charged track impact parameter resolution → low mass trackers near IP
    - <0.3% X0 per layer (ideally 0.1% X_0) for vertex detector
    - Sensors will have to be less than 75 μm thick with at least 5 μm hit resolution (17-25μm pitch)

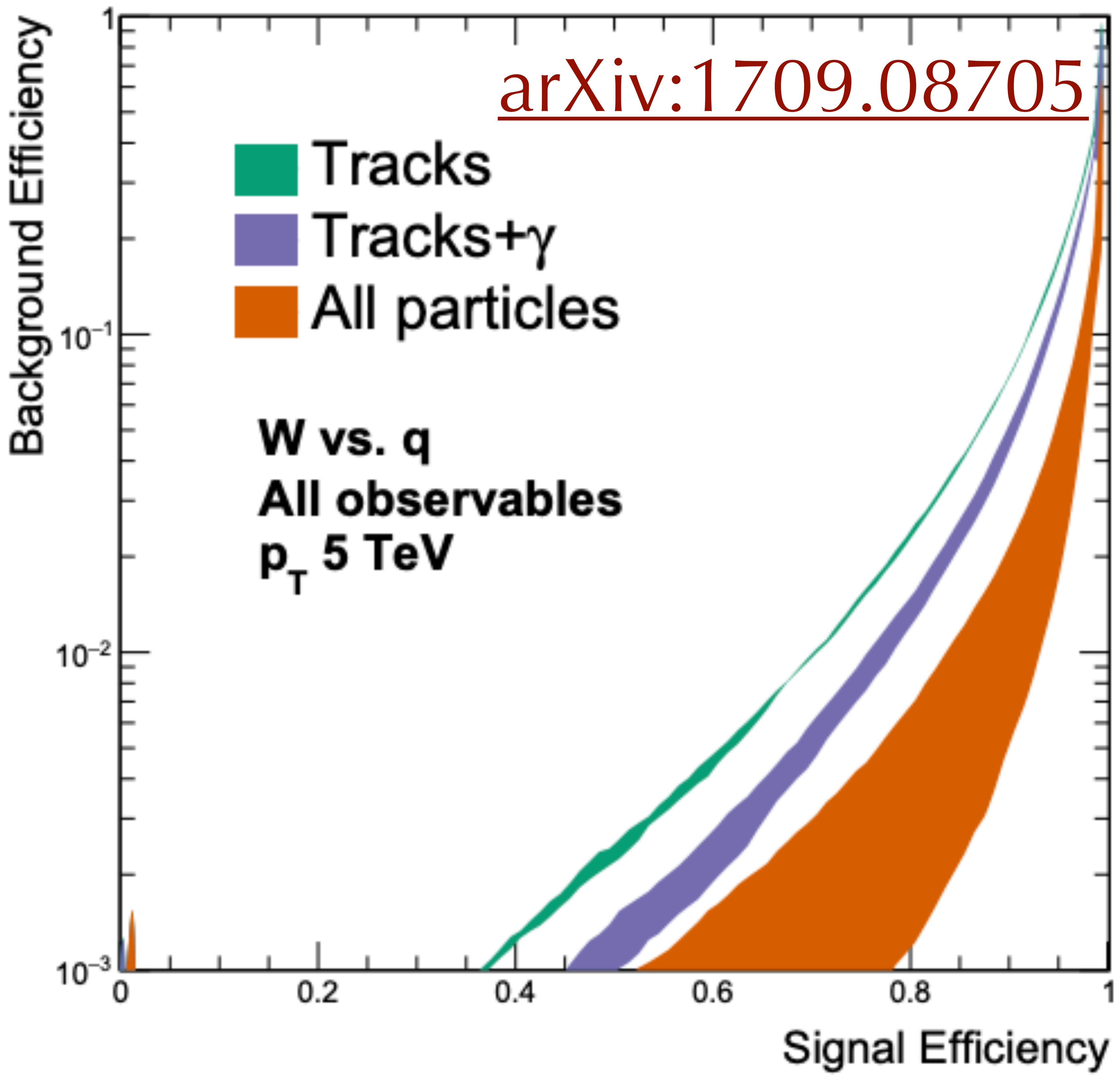




Need new generation of ultra low mass vertex detectors with dedicated sensor designs

Beyond Higgs physics

- **Boosted/Substructure object reconstruction** is an important driver to guide detector design 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, particle-flow
- **Long Lived Particle 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

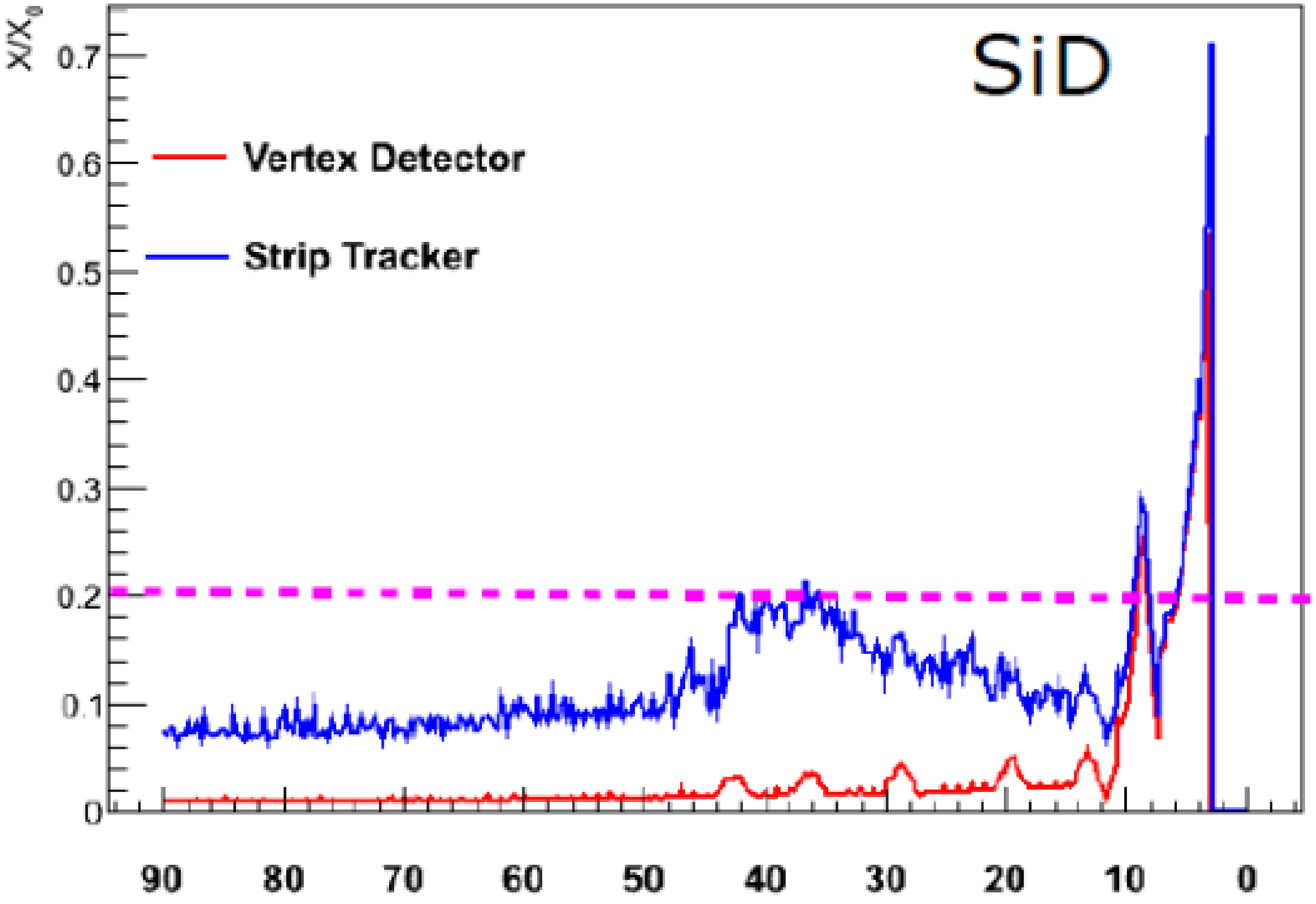


Dedicated discussion at the CPM Oct, 2020

Physics Drivers → Detector Design Requirements

Requirements on single point resolution, location of innermost layer, detector occupancy

- **Very small pixels** for excellent IP resolution and minimal pattern recognition ambiguity
- **Minimal material** as close to the interaction point as possible:
    - <0.3% X0 per layer (ideally 0.1% X0) for vertex detector
    - <1% X0 per layer for Si-tracker
- **Low power** → Linear colliders eliminate need for active cooling, circular collider do not

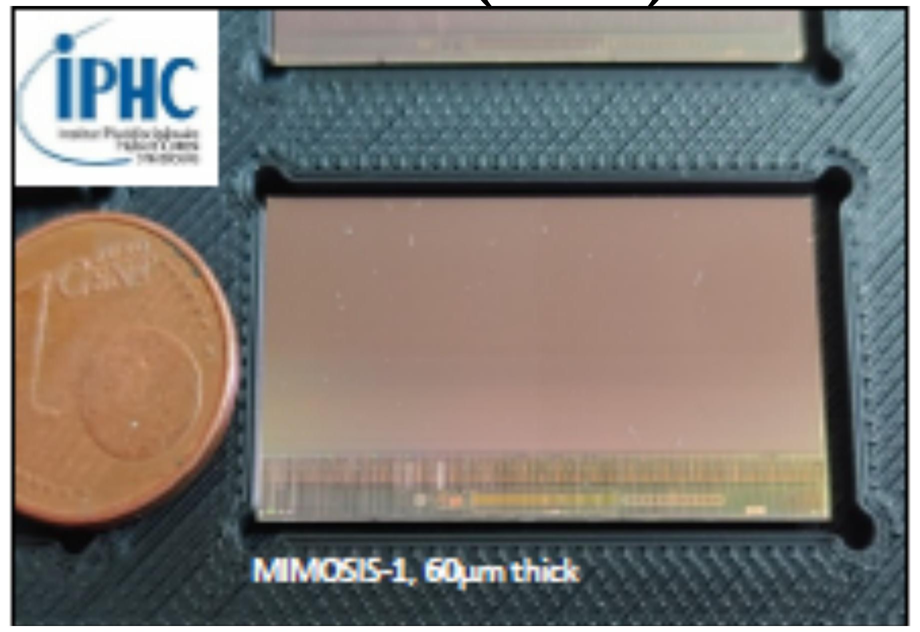


Sensors technology overview

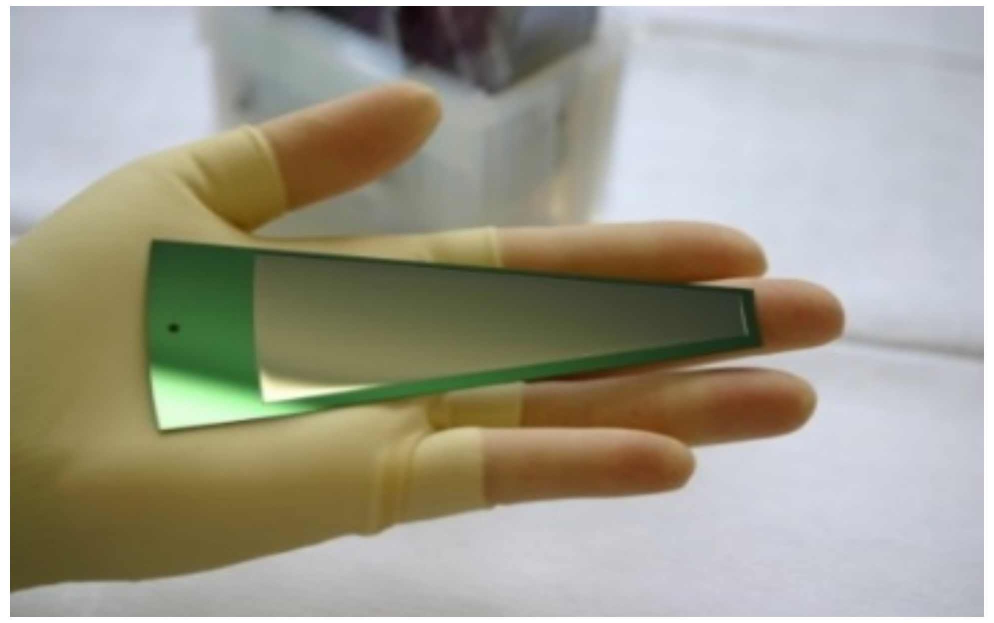
Several possible choices for the VTX detector:

- Monolithic Active Pixels (MAPS)
  - CMOS Pixel Sensors (CPS)
  - Fully Depleted on High Resistivity Substrate (DNwel sensing)
  - Fully Depleted SOI technologies
- Depleted Field Effect Transistors (DEPFET)
- Fine pixel Charged Coupled Devices (CCD)
- 3D integration
- The general landscape is also changing rapidly with advances in microelectronics

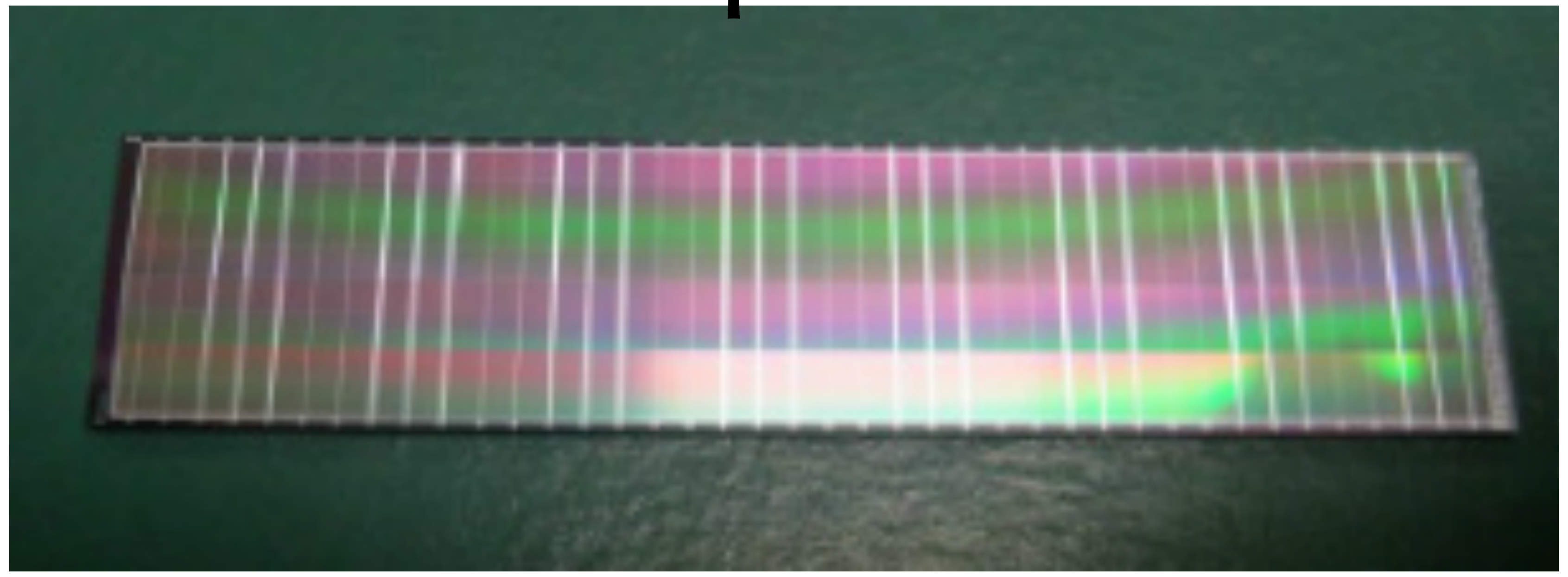
CMOS (CPS)



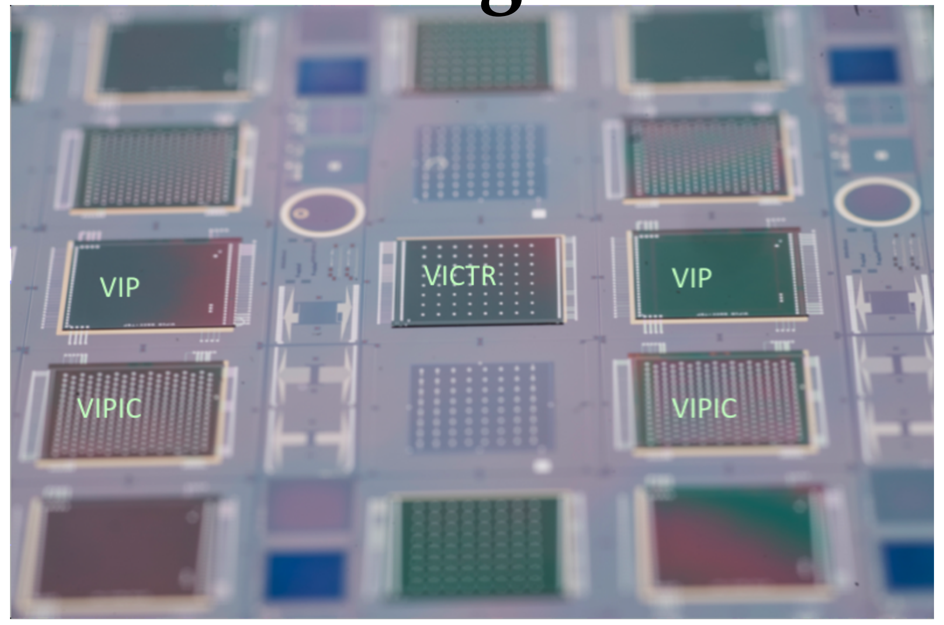
DEPFET



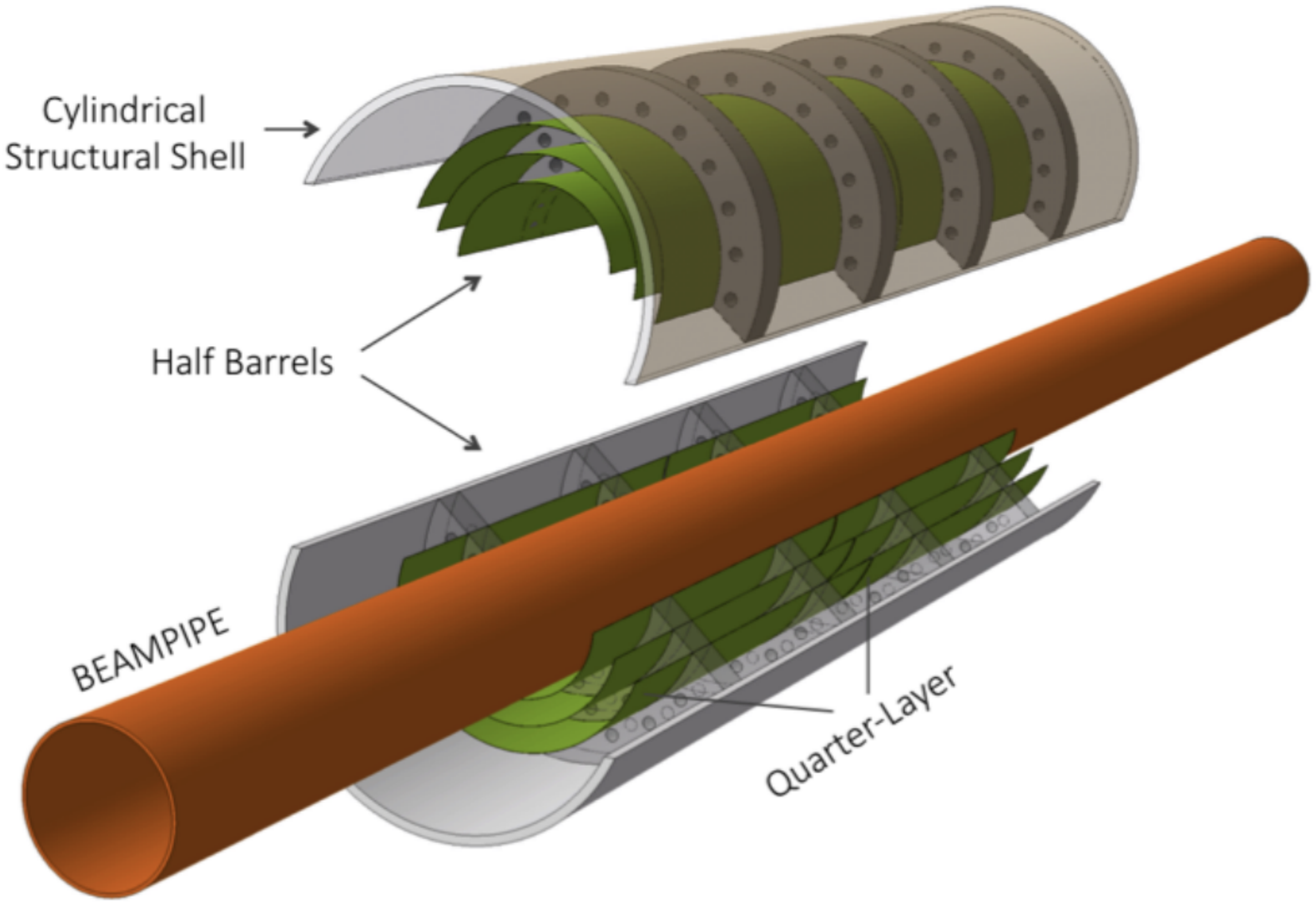
Fine pixel CCD



3D Integration



ALICE: Bent MAPS for Run 4



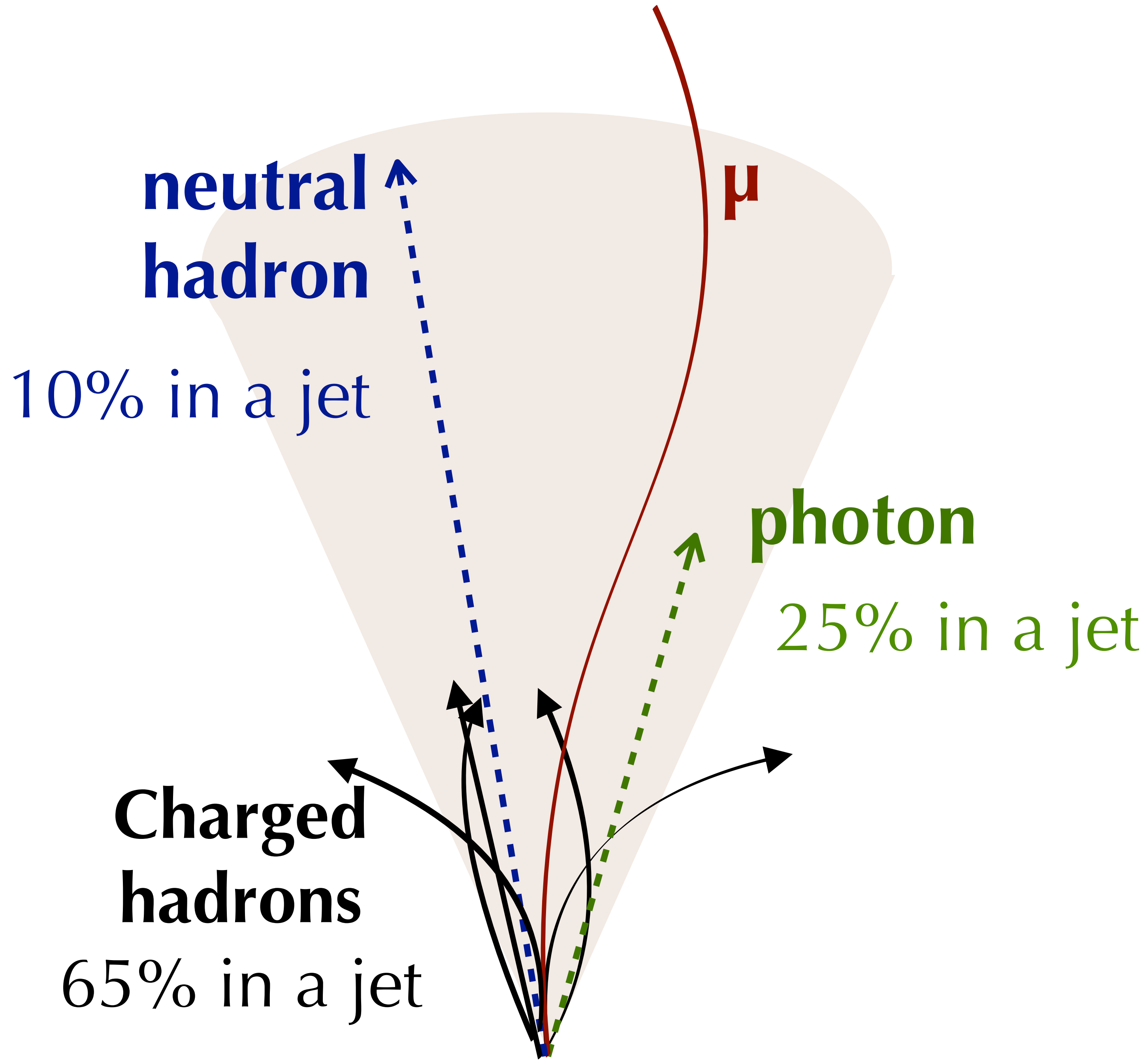
Bending Si wafers + circuits is possible

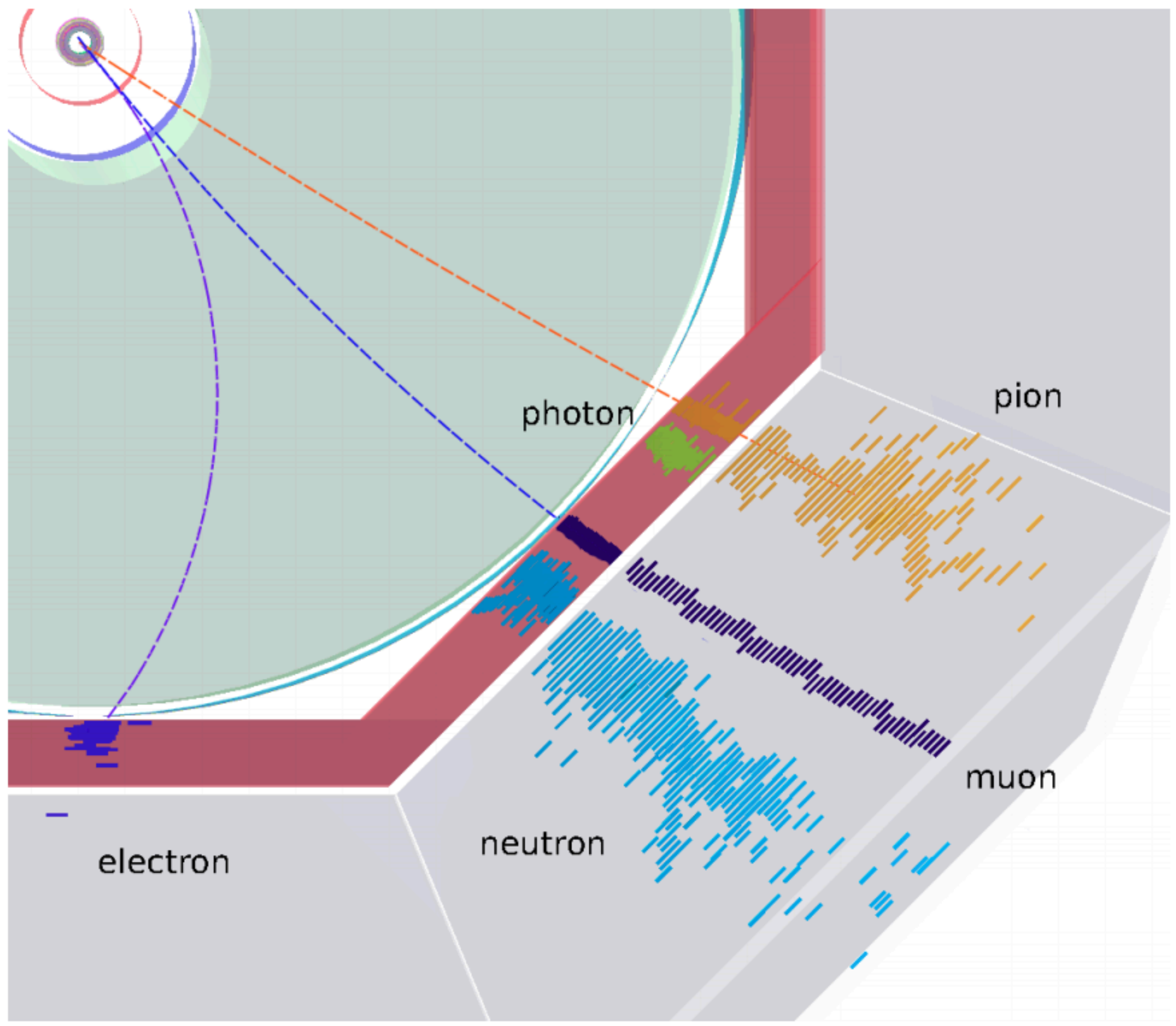
Recent ultra-thin wafer-scale silicon technologies allow:

- Sensor thickness = 20-40 µm - 0.02-0.04% X0
- Sensors arranged with a perfectly cylindrical shape
  - a sensors thinned to ~30µm can be curved to a radius of 10-20mm (ALICE-PUBLIC-2018-013)
- Industrial stitching & curved CPS along goals of ALICE-ITS3, possibly with 65 nm process

Particle Flow Calorimeters

- CALICE collaboration: development and study of finely segmented and imaging calorimeters
  - Precise reconstruction of each particle within the jet
  - Issues: overlap between showers, complicated topology, separate physics event particles from beam-induced background
- CALICE R&D inspired CMS high granularity solution HGCAL - Common test beams with the AHCAL prototype
  - New ideas/technologies being explored: high precision (ps) timing calorimeters and new sensors ideas (ex: MAPS, LGADs)



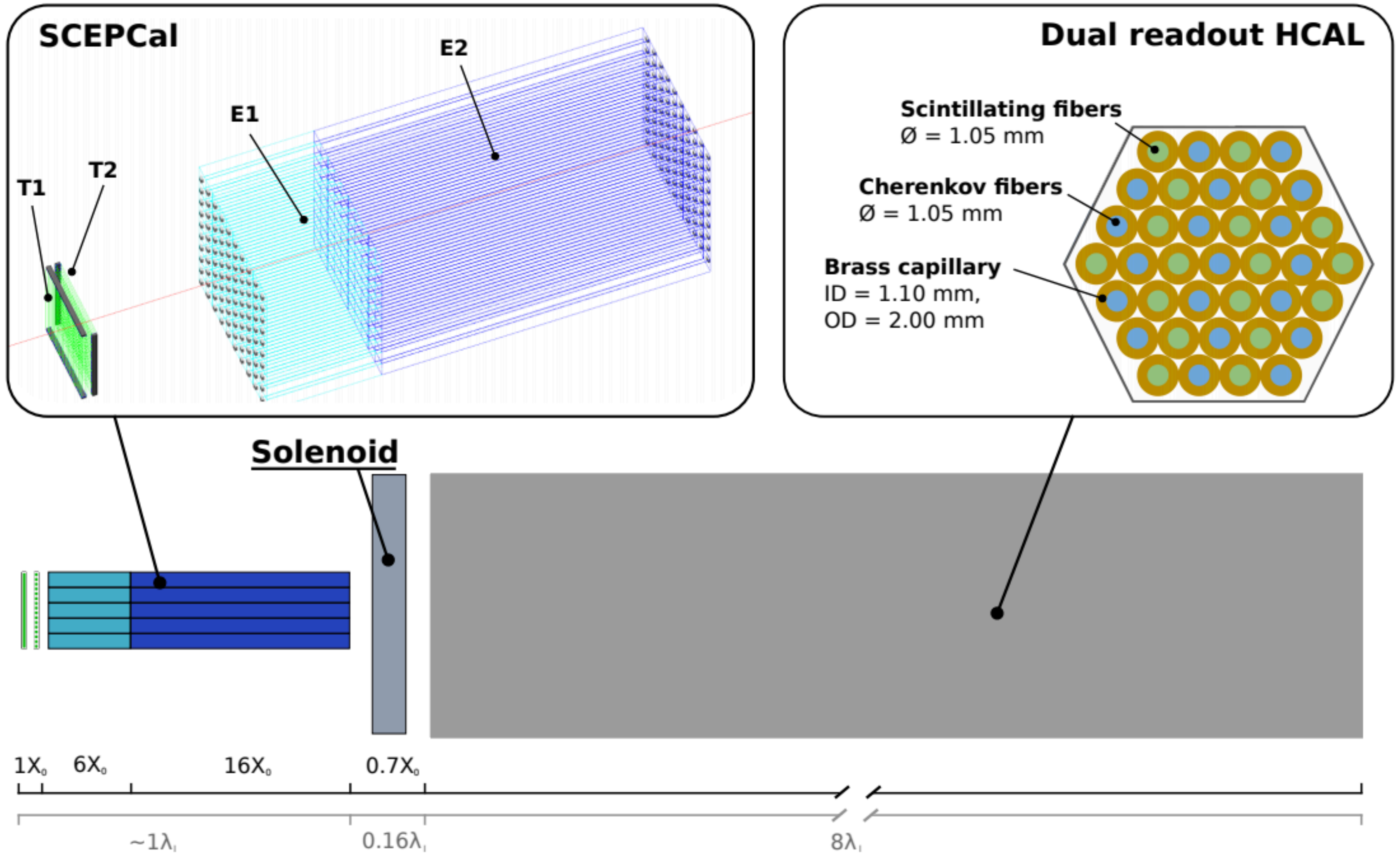


Dual Readout calorimetry

ArXiv:2008.00338

- **Dual readout Calorimetry**, e.g. DREAM (FCC-ee, CePC) improvement of the energy resolution of hadronic calorimeters for single hadrons:
  - Cherenkov light for relativistic (EM) component
  - Scintillation light for non-relativistic (hadronic)
- Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

Marco Lucchini, EPS 2021



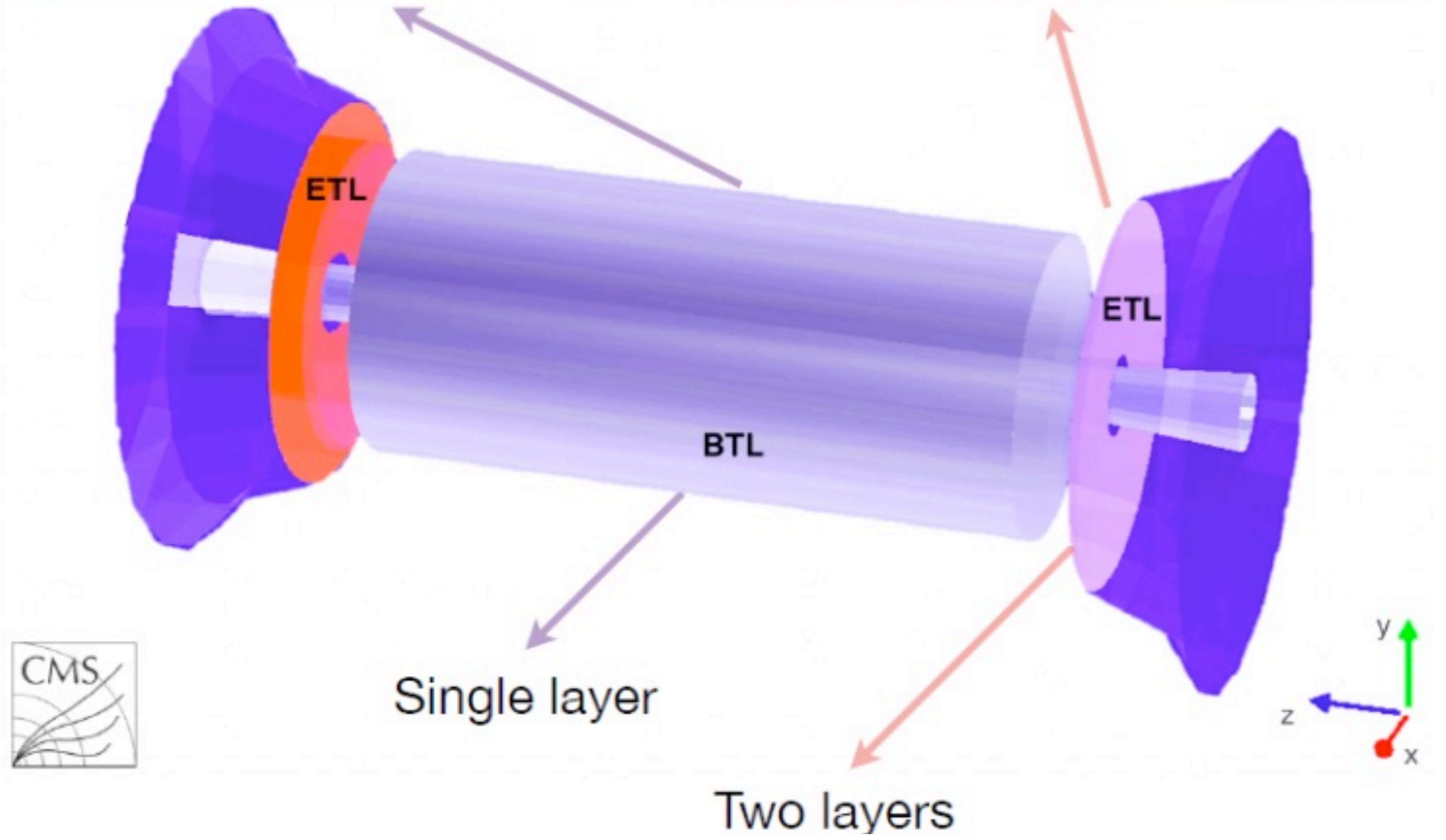
Timing detectors with a O(10) picosecond resolution

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 development of hadron showers, triangulate H to photons primary vertices
  - CMS HGCAL (Si & Sci.+SiPMs)

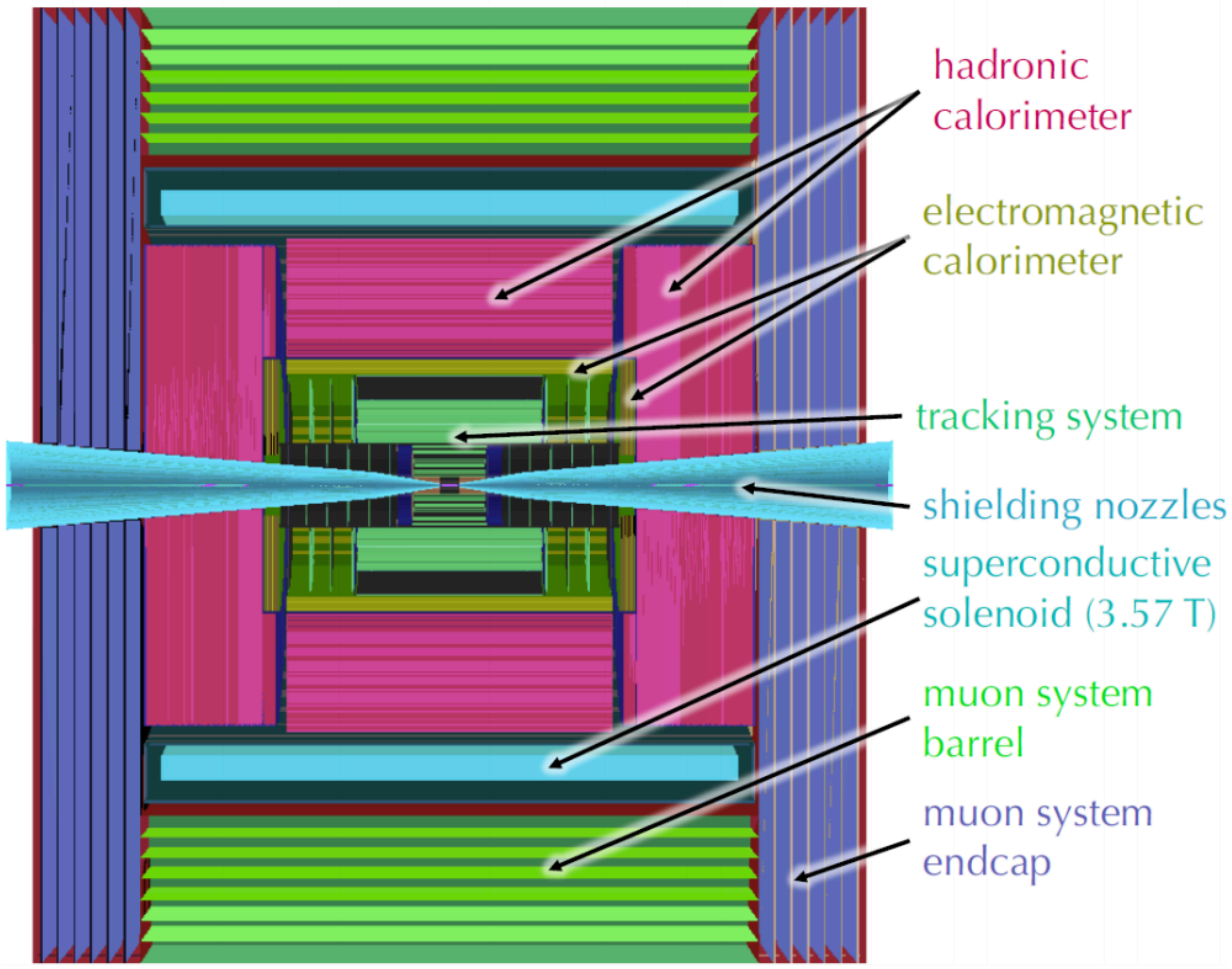
Future challenges:

- Radiation hardness
  - LGAD-sensors ~ 25 ps for 50 µm sensors and $2x10^{15}$ n_{eq}/cm^2
  - 3D-trench Si sensors: O(100 ps) and a goal of 10^{16} - 10^{17} n_{eq}/cm^2
- "5D reconstruction": space-points / ps-timing are available at each point along the track
    - LHCb EoI for LS4 is of general interest



Muon collider - detector requirements

- Beam Induced Background (BIB) in detector
  - O(100) million (mostly soft) particles per beam crossing —> 1% are charged
- Vertex tracker detector expected occupancy is x10 larger than CMS pixels in HL-LHC
  - large bandwidth for sending data off the detector
- Emerging detector developments for the muon collider inspired to e+e- linear colliders
  - CLIC Detector technologies adopted with important tracker modifications to cope with BIB
- Challenges for tracking system:
  - high number of BIB particles —> Need high granularity (25-50μm), fast timing (20-30ps), intelligent readout, directional information



Nadia Pastrone, Feb 2021

Conclusions

- Future lepton colliders have the potential to develop high precision silicon detectors to help reach unprecedented physics goals
  - Requires excellent momentum and impact parameter resolution
  - Bunch time structure allows high precision trackers with very low X_0 at **linear lepton colliders**

- Pixel detectors with very fine pixel pitch, excellent single point resolution, and low X_0 required
  - Favors technologies which allow to focus on resolution and material budget
  - **Reaching the specifications all together is the real challenge**

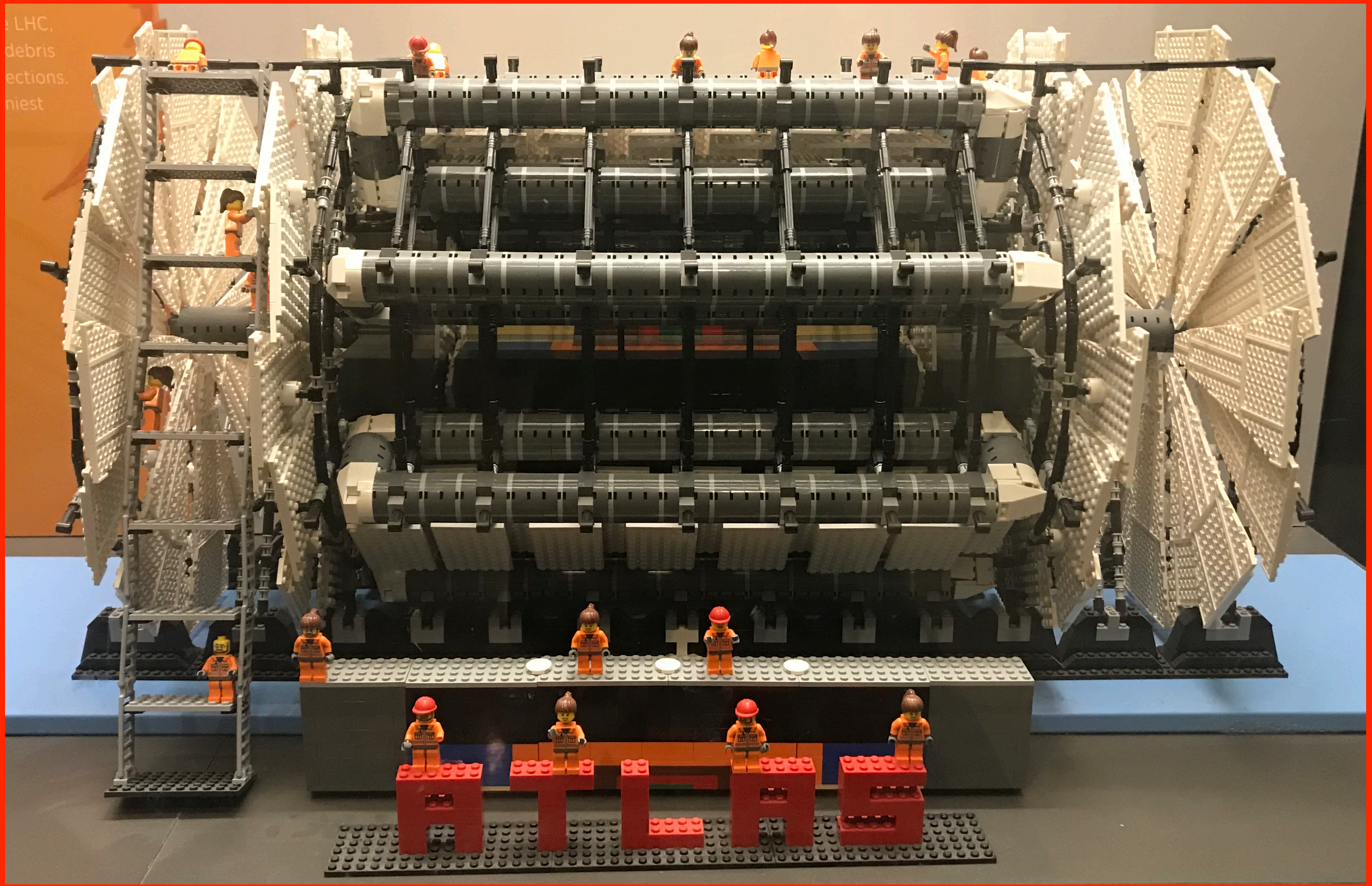
- Advancements in timing sensors to get to radiation hard and O(10)ps resolution
  - 4D tracking (with precision timing information) potentially could be considered for e+e- - if the physics gain is significant with respect to increased material budget

- New ideas/technologies being explored for particle flow calorimetry : high precision (ps) timing calorimeters, new sensors ideas (ex: MAPS, LGADs) and dual readout technology

Steps ahead

All these technologies being discussed within Snowmass21 as a follow up of the priority research directions (PRD) of the new DOE BRN report

- ECFA Detector R&D Process is expected to release the final report in the Fall 2021
  - describe diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics program in the near and long term
  - Starting point is the the future science programs to identify :
    - main detector technology challenges
    - estimate the timelines of the required detector R&D programs



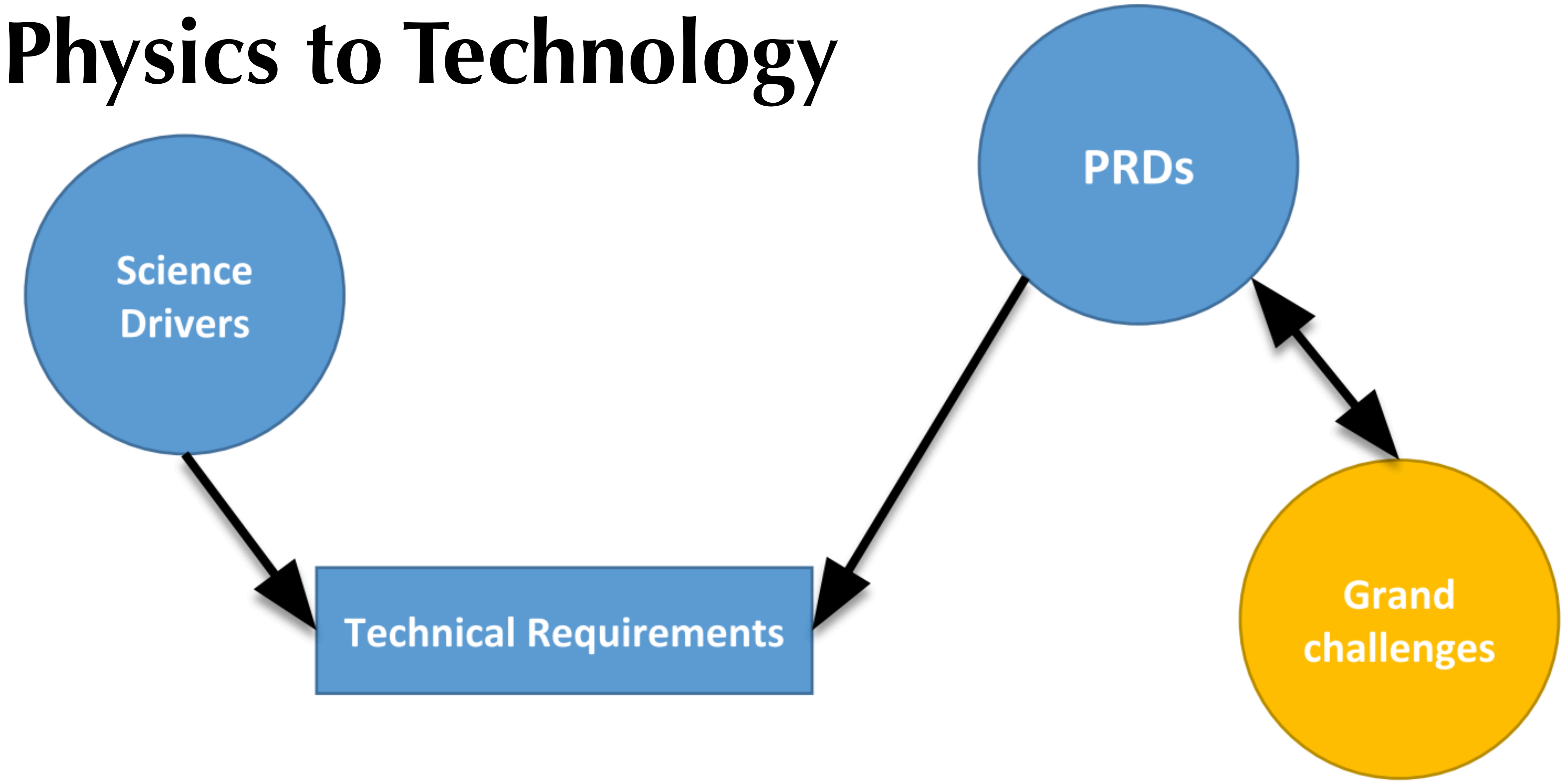
thank you!

b/c/strange tagging

- A class of BSM models predicts that the origin of the 1st and 2nd generation fermion masses is an additional source of EWSB, predicts large deviations from the SM values
  - Higgs to ss as well as cs at future colliders is the next milestone to probe the nature of Yukawa couplings
- Strange quarks mostly hadronize to prompt kaons which carry a large fraction of the jet momentum
  - The most powerful high momenta $K^{\pm}$ tags with dedicated particle identification detectors may be an exclusive territory of **e+ e- colliders**
  - The leading V0 s (K0 s and Lambda) have a distinctive 2-prong vertices topology
- The use of **precise timing information** would become very relevant for flavor tagging and providing an additional handle for separation between light quarks.
  - intermediate momentum $K^{\pm}$ ID from fast timing can become a significant contributor for b and c decays (s tag $K^{\pm}$ could be too high momentum for timing)
  - Detector design have a role too in capturing the high momenta V0 s that can decay deep into the tracker
    - Investigate optimal configurations for 4D tracking at future e+e- machines

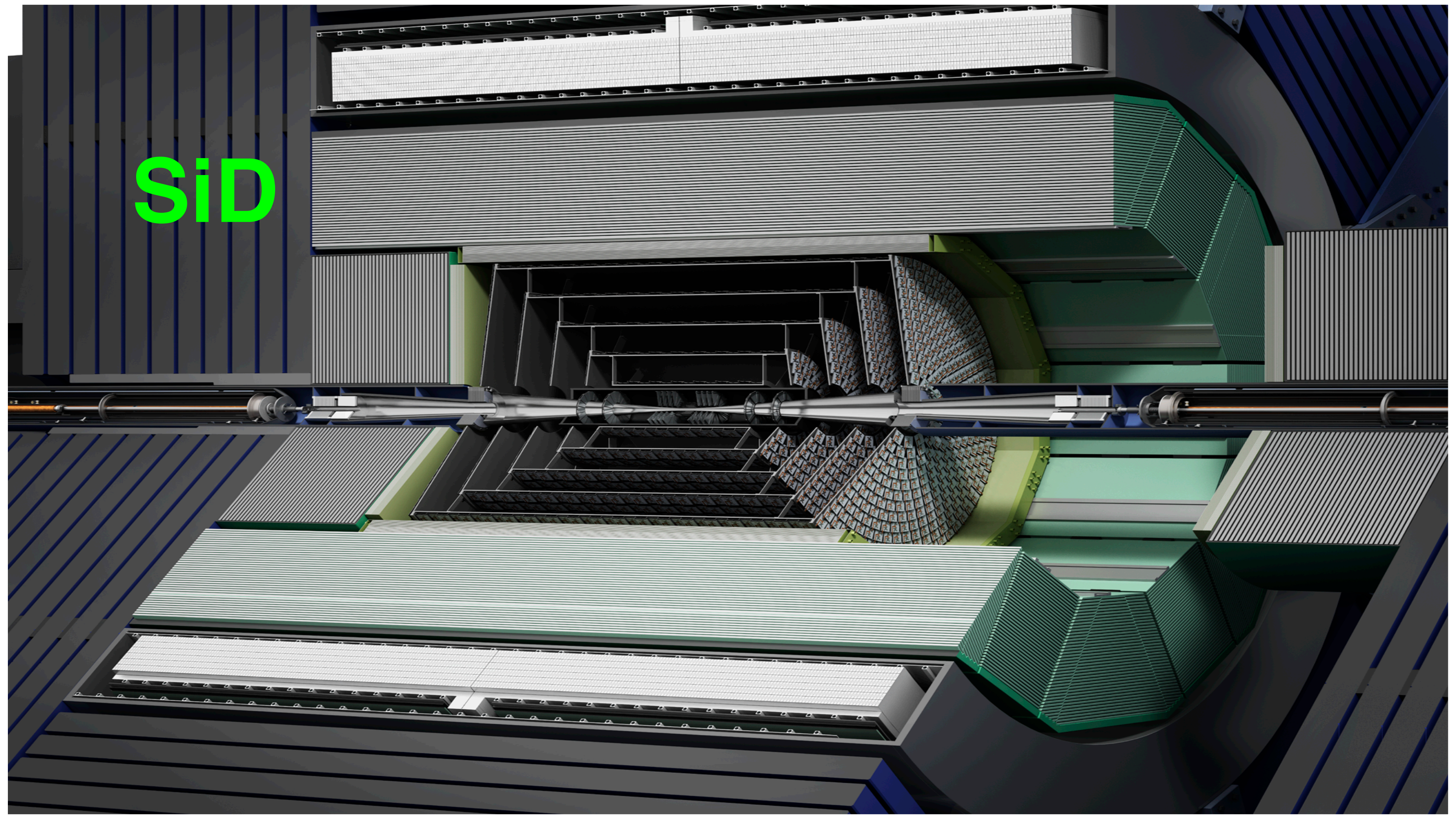
Four Grand Challenges for the Instrumentation revolution

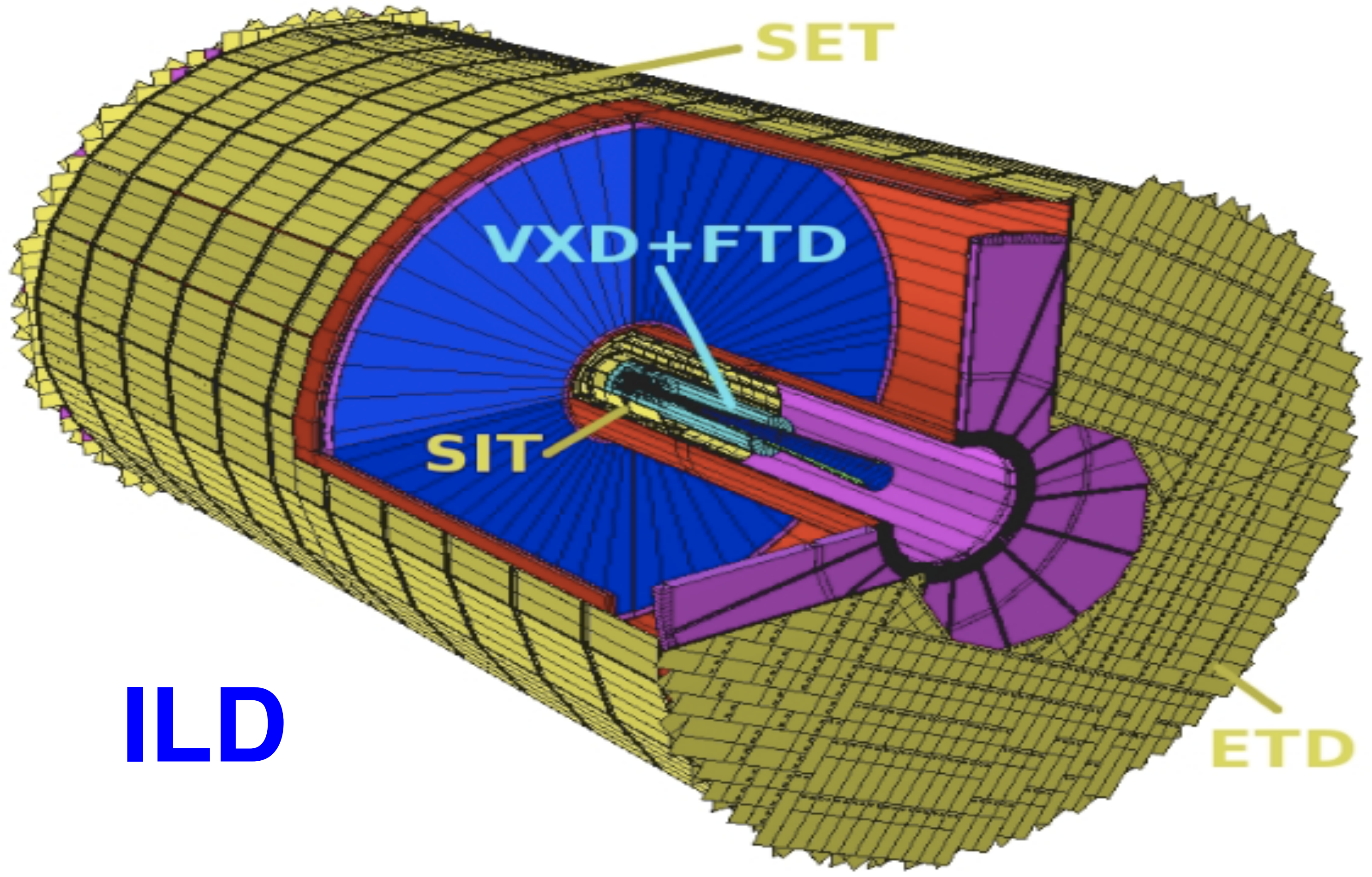
- Advancing HEP detectors to new regimes of sensitivity
- Using Integration to enable scalability for HEP sensors
- Building next-generation HEP detectors with novel materials & advanced techniques
- Mastering extreme environments and data rates in HEP experiments



B. Fleming and I. Shipsey

ILC silicon detectors

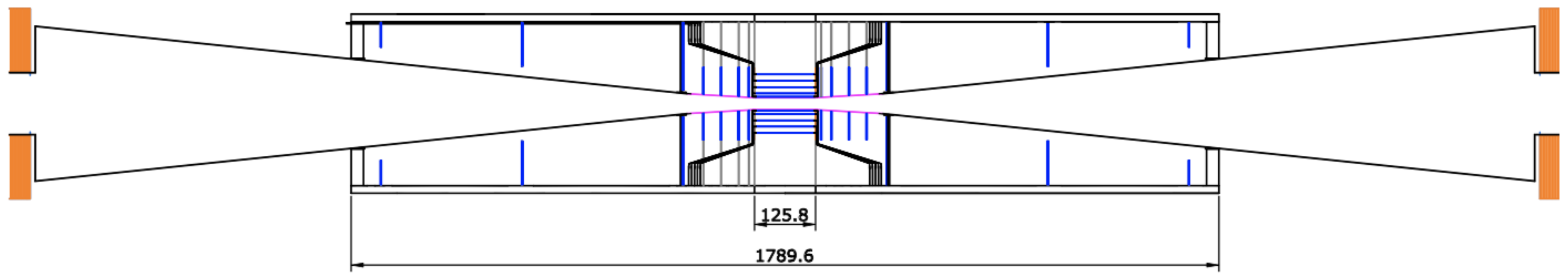




- Future lepton colliders target unprecedented precision on physics ↔ extremely high precision detectors
- Silicon strip and pixel detectors are **key** for precision charged particle tracking, secondary vertexing, and as input to Particle Flow reconstruction - which is assumed as baseline
- Minimizing material budget is vital → Exciting Si pixel & strip technologies in development

Arxiv: 1306.6329

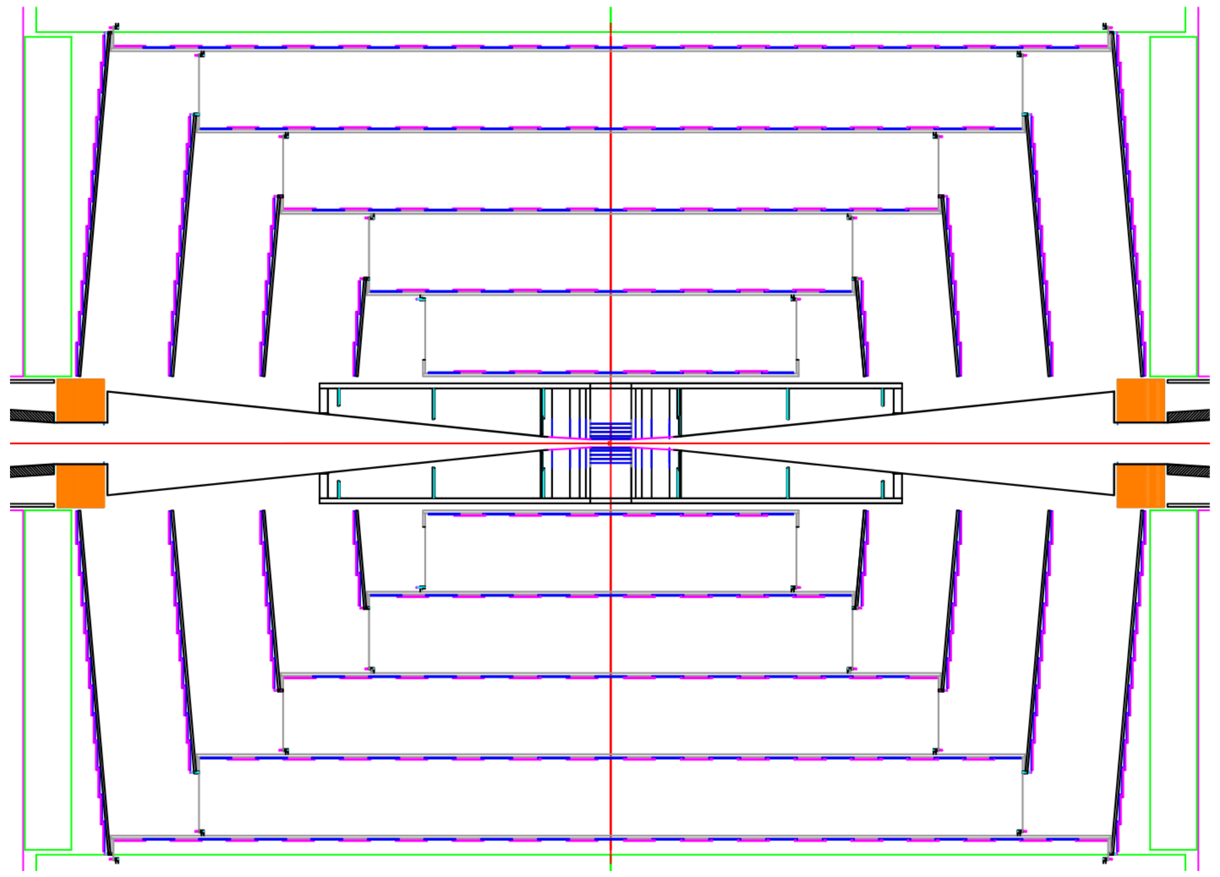
- Compact, cost constrained detector
  - 5 T solenoid B-field with with R_{ECAL}=1.27 m
  - All silicon pixel vertex + tracking system
  - Highly granular Si calorimeter optimized for PFLOW



Barrel	R	z_{max}	
Layer 1	14	63	
Layer 2	22	63	
Layer 3	35	63	
Layer 4	48	63	
Layer 5	60	63	
Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172
Forward Disk	R_{inner}	R_{outer}	z_{center}
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832

- Pixel Vertex detector
  - 1 kGy and 10^{11} n_{eq}/cm^2 per year
  - **Pixel hit resolution** better then 5 *μ*m in barrel
    - Better if charge sharing is used
  - Less than **0.3% X_0** per pixel layer
    - air cooling → low-mass sensor
  - Single bunch time resolution
    - Low capacitance and high S/N allows for acceptable power dissipation for single-crossing time resolution (~ 300-700 ns)

20x20 μm pixels in the central region
50x50 μm for the forward tracker disks



- Outer pixel Tracker:
  - 0.1-0.15% X_0 in the central region