Progress on Instrumentation and its impact on EF

Caterina Vernieri (IF-EF liaison with Maksym Titov)

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

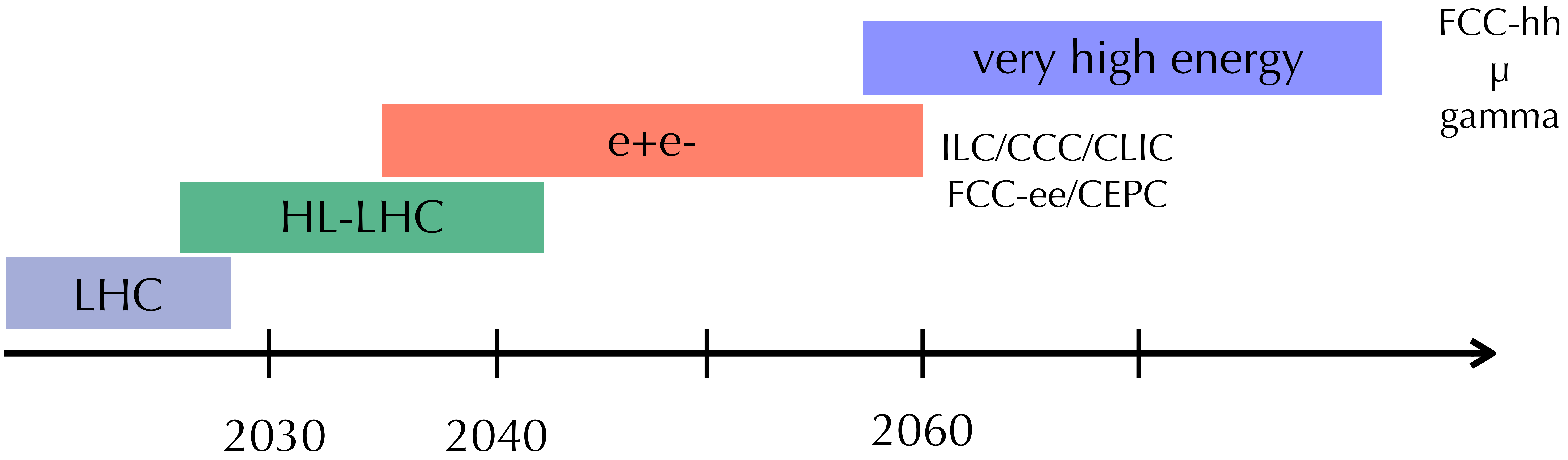
EF drivers for detector developments

- 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: $\sigma_{r\phi} = 5 \oplus 15\ (p\ [\text{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ 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 $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ 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 : $\sigma_E/E = 10\%/\sqrt{E} \oplus 1\%$ 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 $8 \times 10^{17}\ \text{n}_{\text{eq}}/\text{cm}^2$ 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

Looking to the future



H couplings to few %

H couplings to %

H couplings to ‰

H self-coupling to %

Which collider?

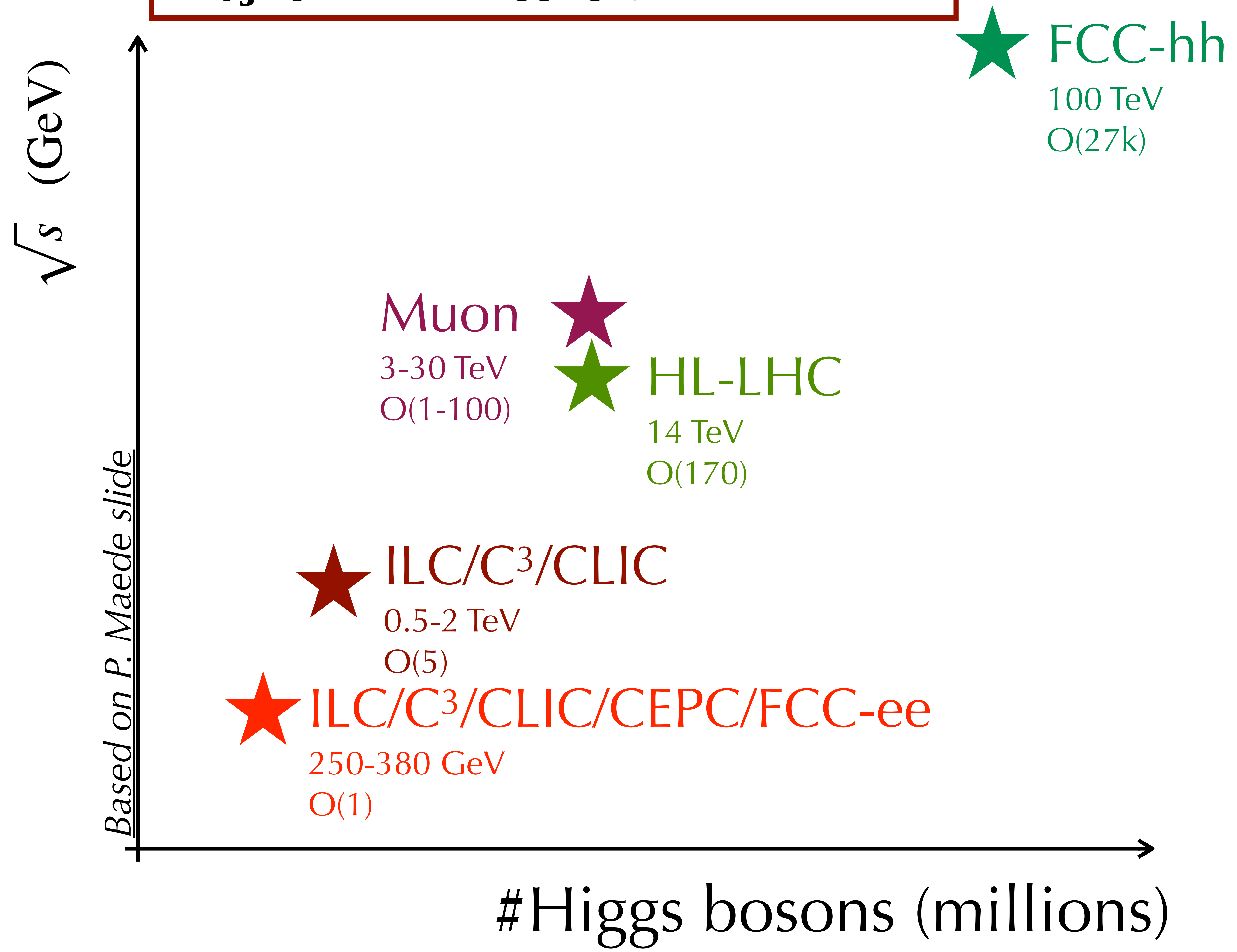
LEPTON COLLIDERS

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C[3])
  - **250 GeV — 3TeV**
  - *Reach higher energies, and can use polarized beams*
  - *Relatively low radiation / beam induced backgrounds*
  - ***C[3]** plans is to run at 250/550 GeV*
    C3 proposal - talk on Wed
- μ+μ-
  - **3-30 TeV**

HADRON COLLIDERS

- **75-200 TeV** (FCC-hh)

PROJECT READINESS IS VERY DIFFERENT



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Several collider options being studies to go beyond HL-LHC

Different colliders probe different dominant processes with their own experimental challenges

And also project readiness is VERY different

  - *C3 proposal - talk on Wed*
- μ+μ-
  - **3-30 TeV**

HADRON COLLIDERS

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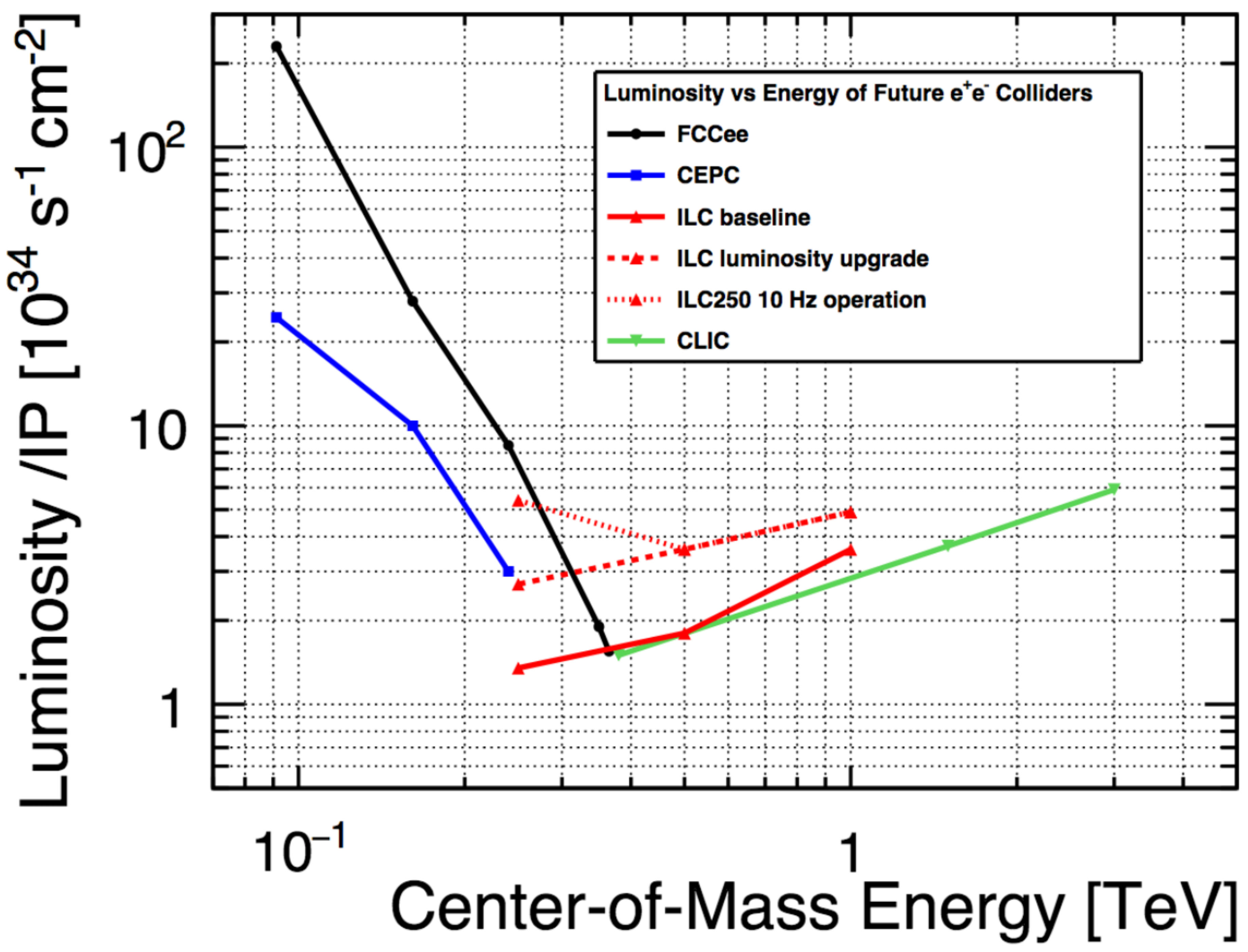
Linear & Circular Lepton Colliders

- **Linear e+e-** colliders: ILC, CCC, CLIC
  - Reach higher energies, and can use polarized beams
  - Relatively low radiation / beam induced backgrounds
  - Collisions in bunch trains
    - Power pulse - Turn off detector in between trains
    - Significant power saving → easier to cool detectors
- **Circular** e+e- colliders: FCC-ee, CEPC
  - Highest luminosity collider at Z / WW / Zh, energy limited by synchrotron radiation
  - No power pulsing → detectors need active cooling → more material in detector
  - Beam continues to circulate after collision → Limits magnetic field in detectors to 2T
- **Muon Collider**
  - Potential to reach high energy: 10 TeV range → Technology readiness?
  - Luminosity → muon decay in flight
  - Beam induced backgrounds → significant challenge, even at low energy



Higgs physics as a driver for future detectors R&D

- The goal of measuring Higgs properties with sub-% precision translates into ambitious requirements for tracker, calorimeters and timing detectors at e+e-
  - Advancing HEP detectors to new regimes of sensitivity
  - Building next-generation HEP detectors with novel materials & advanced techniques

	Measurement	Technical Requirement (TR)
Tracking	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_{T} resolution: $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}} = 0.2\%$ for central tracks with $p_{\mathrm{T}} < 100$ GeV, $\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}}^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_{\mathrm{T}} > 100$ 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 : $25 \times 50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps
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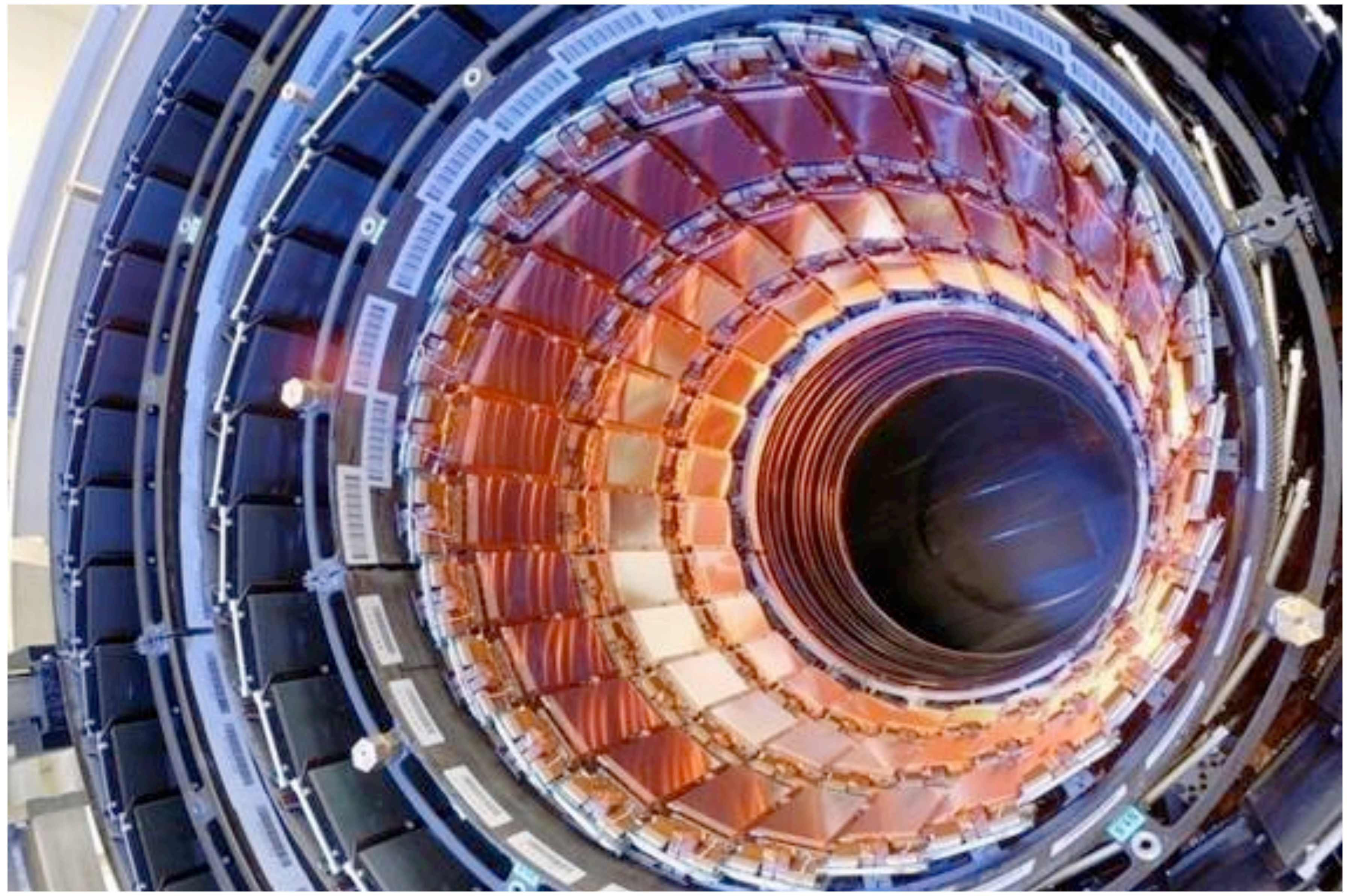
DOE Basic Research Needs Study on Instrumentation

The Central Role of Tracking at e+e-

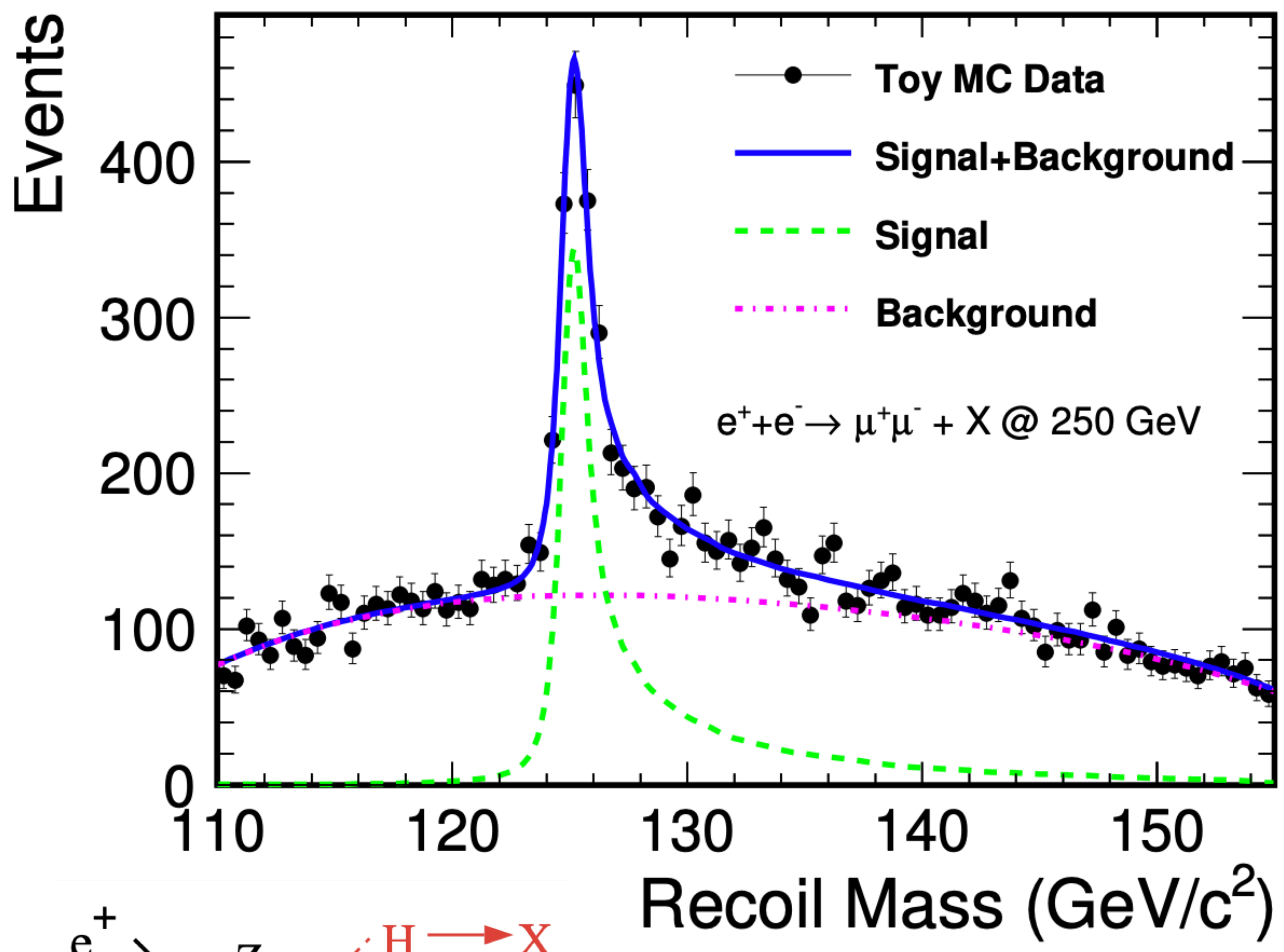
- Tracking detectors provide the primary measurements for charged particle momentum and impact parameter
  - Momentum and IP resolution are limiting factors in key precision measurements
- Detector systems at Lepton Colliders designed for **Particle Flow reconstruction**
- Primary, Secondary, and Tertiary vertex reconstruction
  - Key for identifying and separating heavy flavor jets
- Bunch crossing time stamping, leads to reduction of beam backgrounds

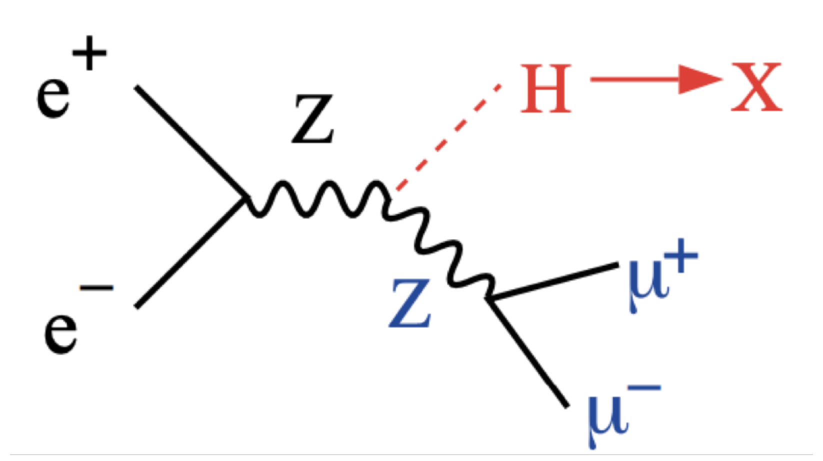


Physics requirements for tracking detectors at e+e-

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)

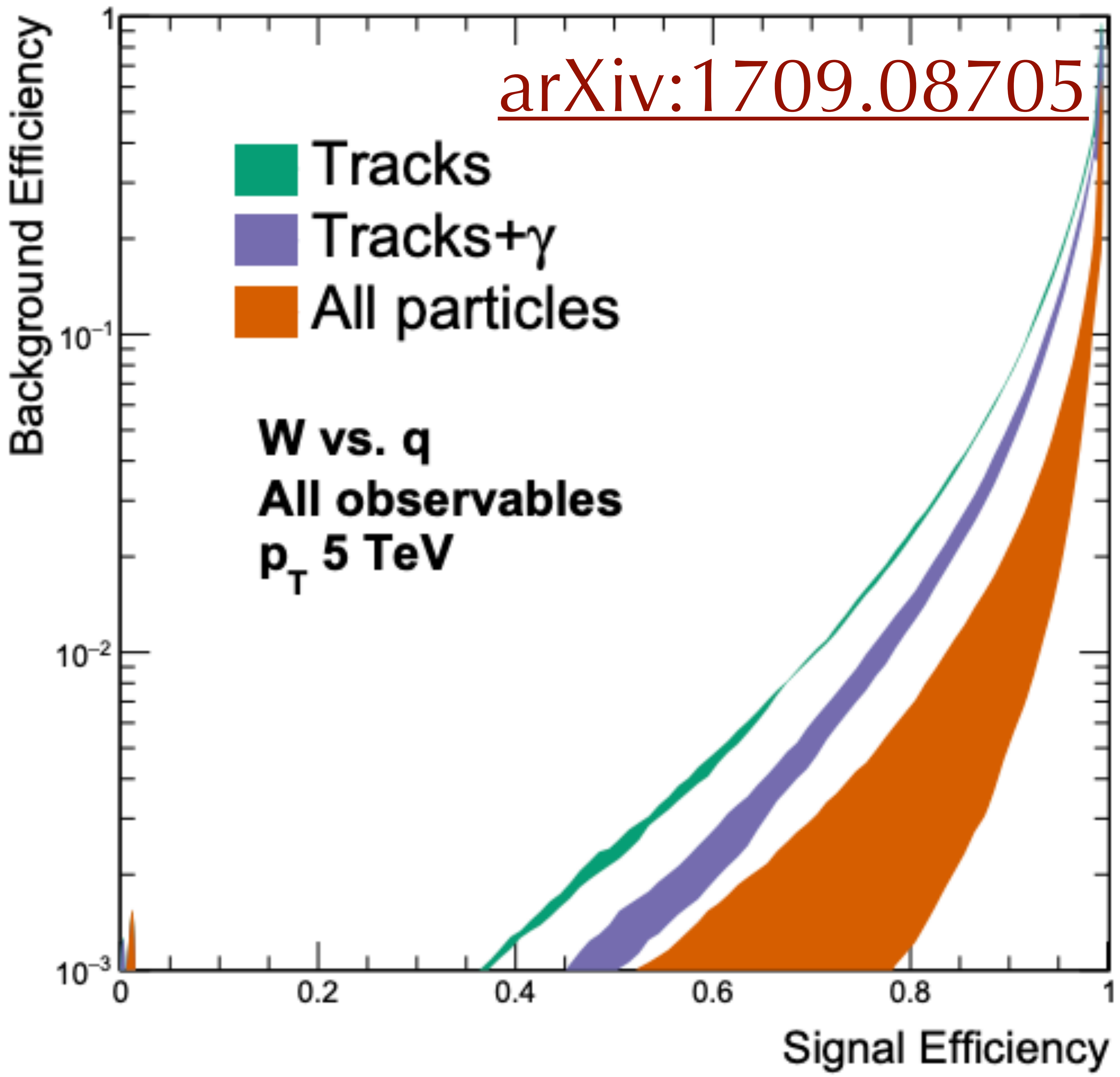




Need new generation of ultra low mass vertex detectors with dedicated sensor designs

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

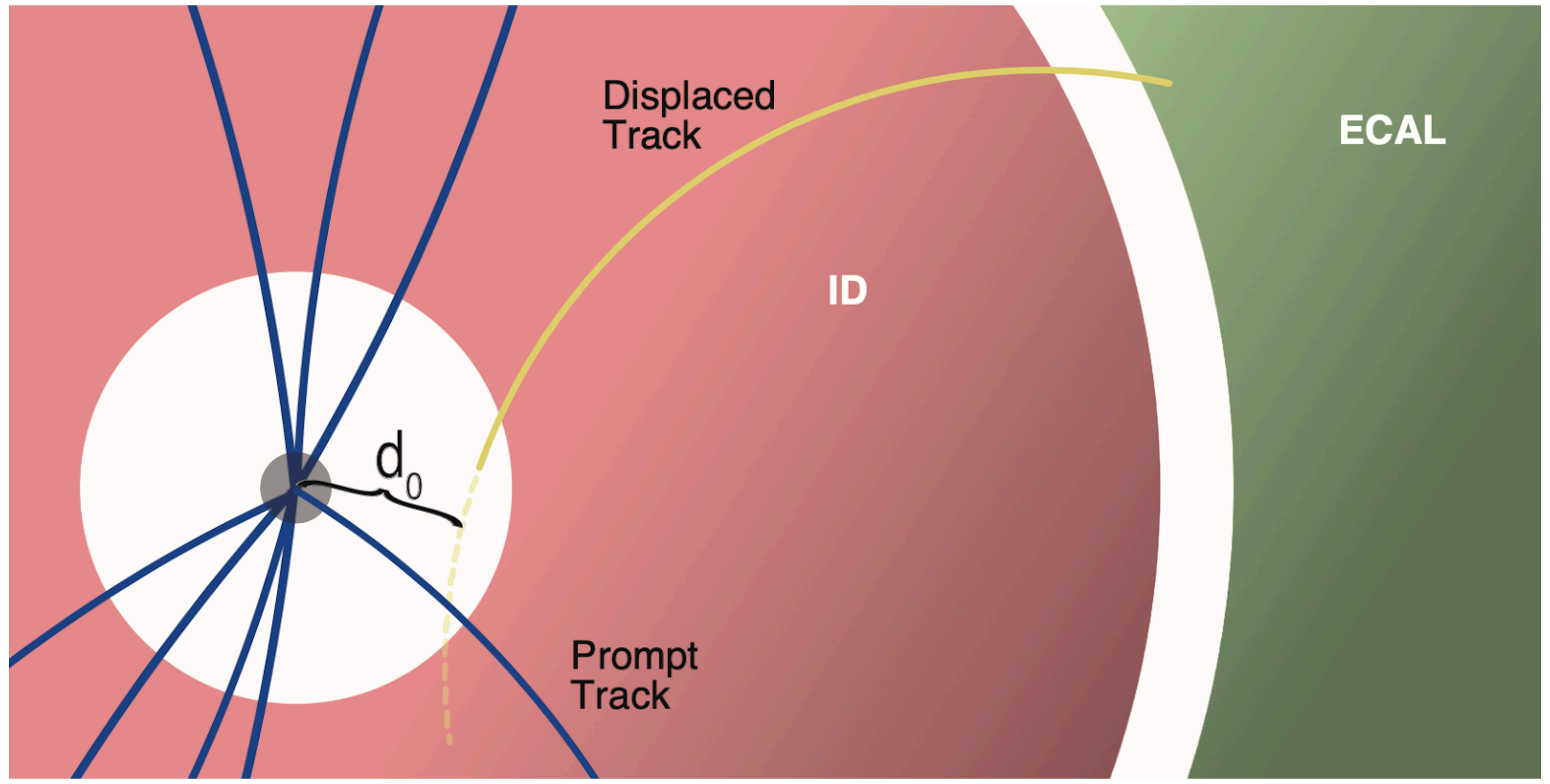


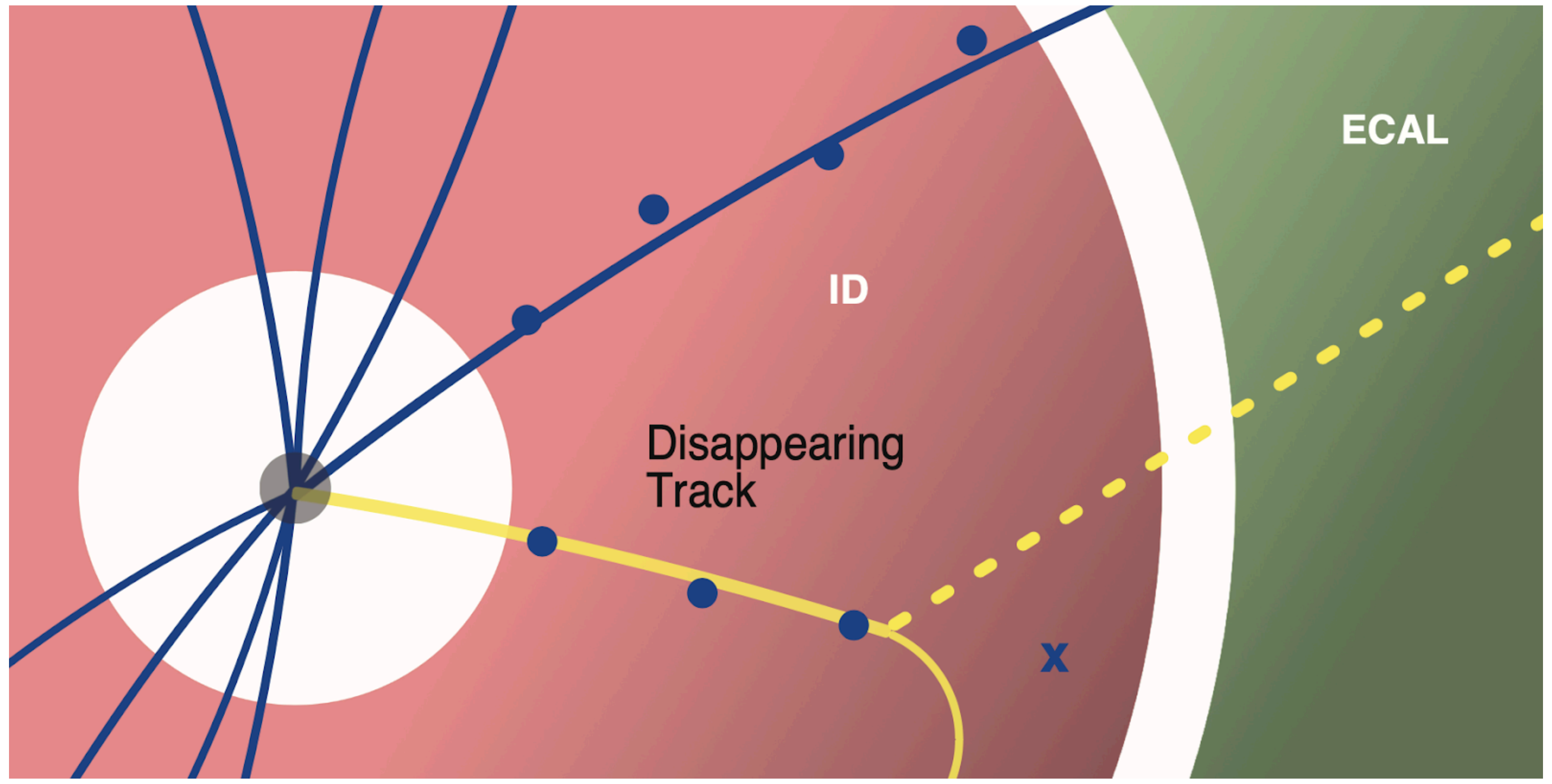
Dedicated discussion at the CPM Oct, 2020

LLP requirements

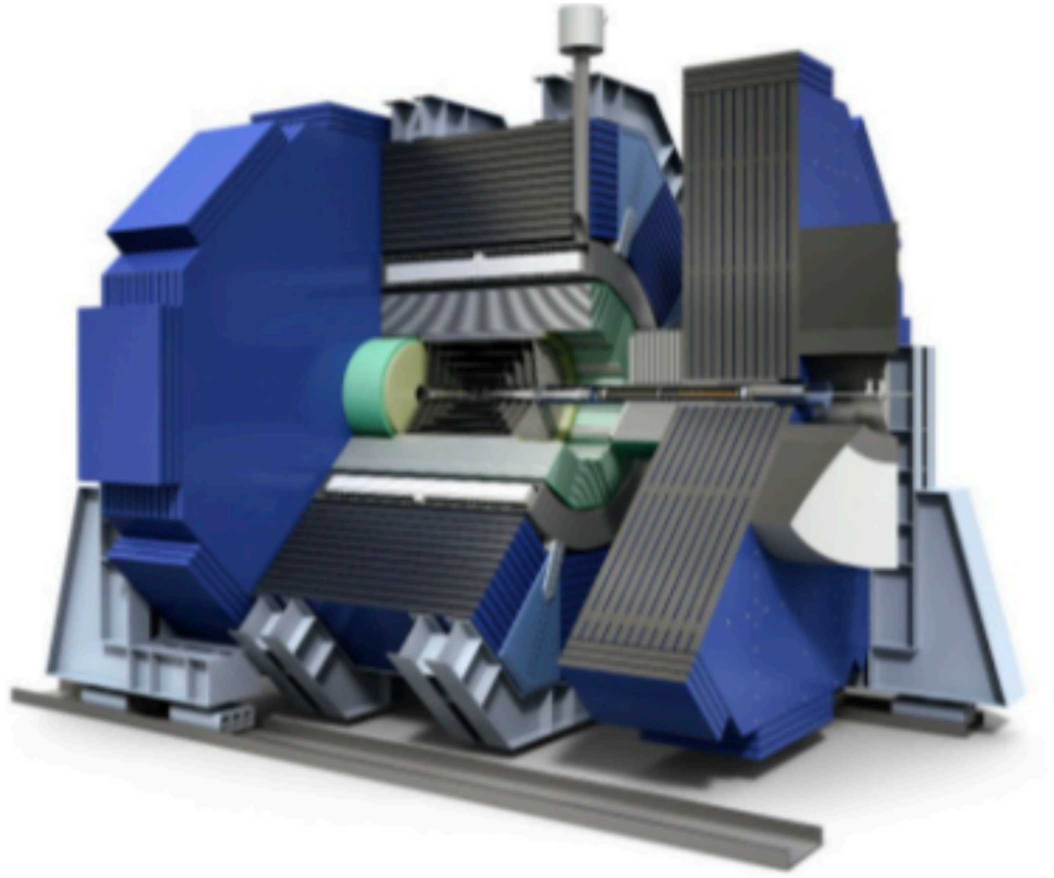
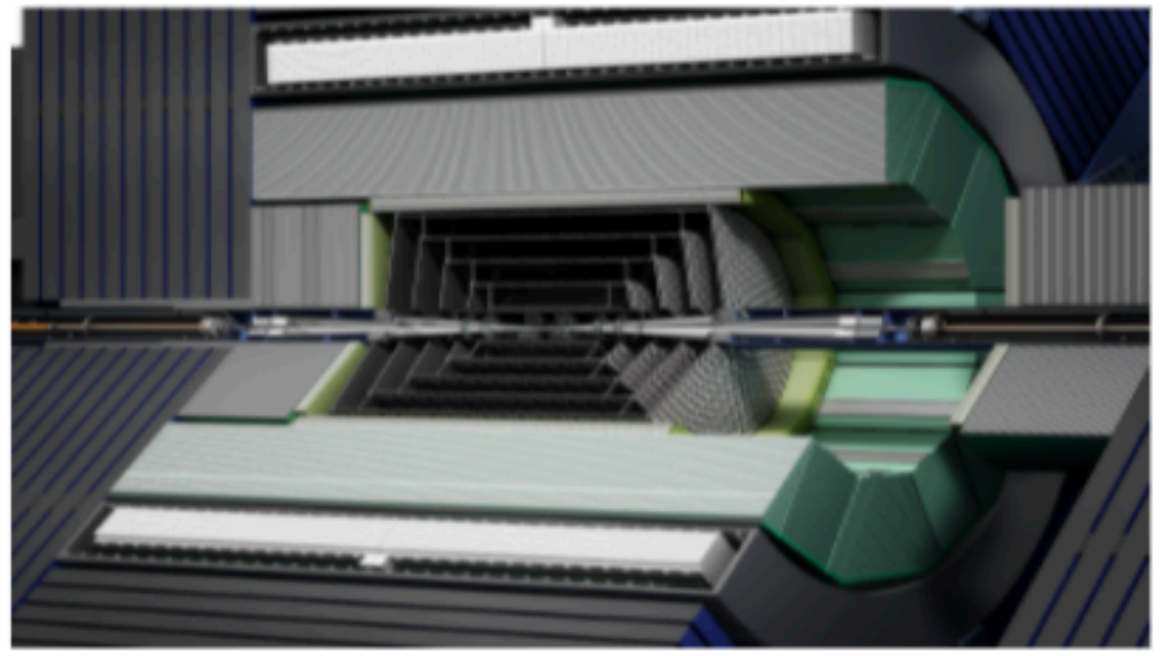
- Different **geometry** choices that provide similar hermeticity for prompt particles can differ drastically in their coverage of particles not originating at the interaction point
  - Interplay of **geometry** choice with hermeticity, trigger-capabilities, and even data-rate reduction need to keep in mind LLP needs
- High **granularity** at large radius: ability for precision-tracking at outer radii
- Identifying decays of LLP in various sub-systems away from the interaction point and distinguish them from detector-specific backgrounds (including beam-induced backgrounds)
- Measurement of ionization energy loss and timing can boost **particle ID** capabilities and offer unique handles for LLP direct identification
  - Depending on environment, one can also explore the advantages of TPCs or a mixed TPC+Si system to allow identification of LLP-specific signatures
  - E.g. kinked track, or good measurement of ionization energy loss

CPM Oct, 2020

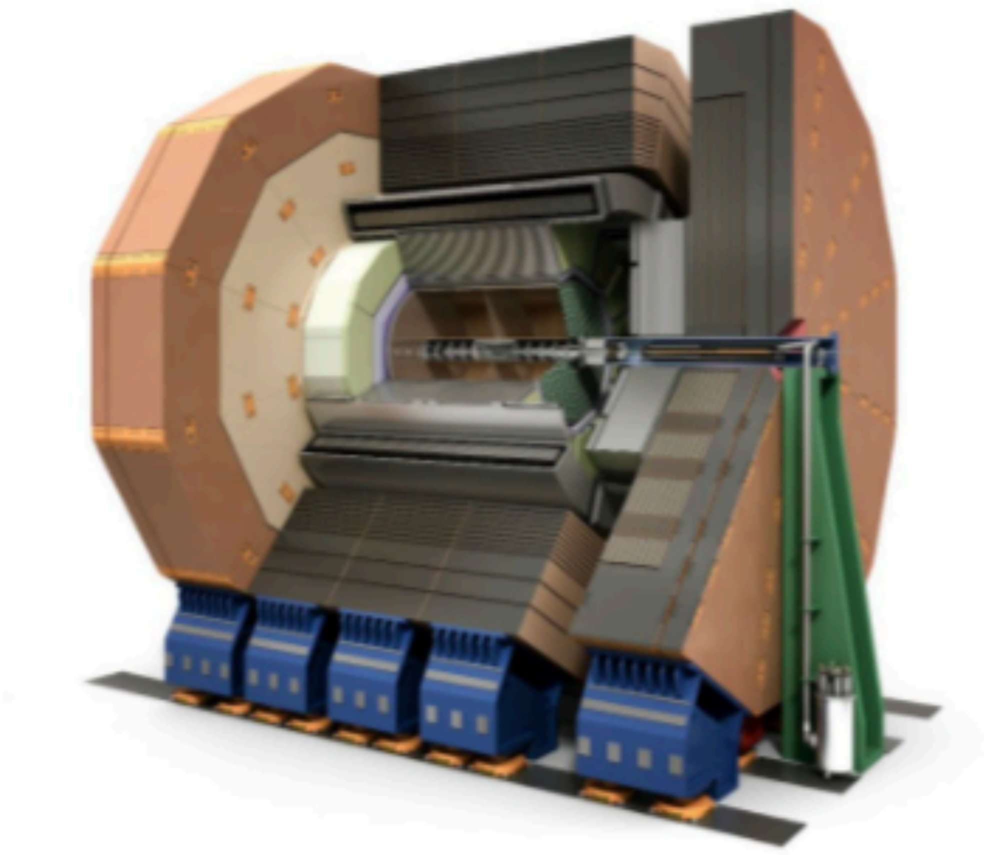
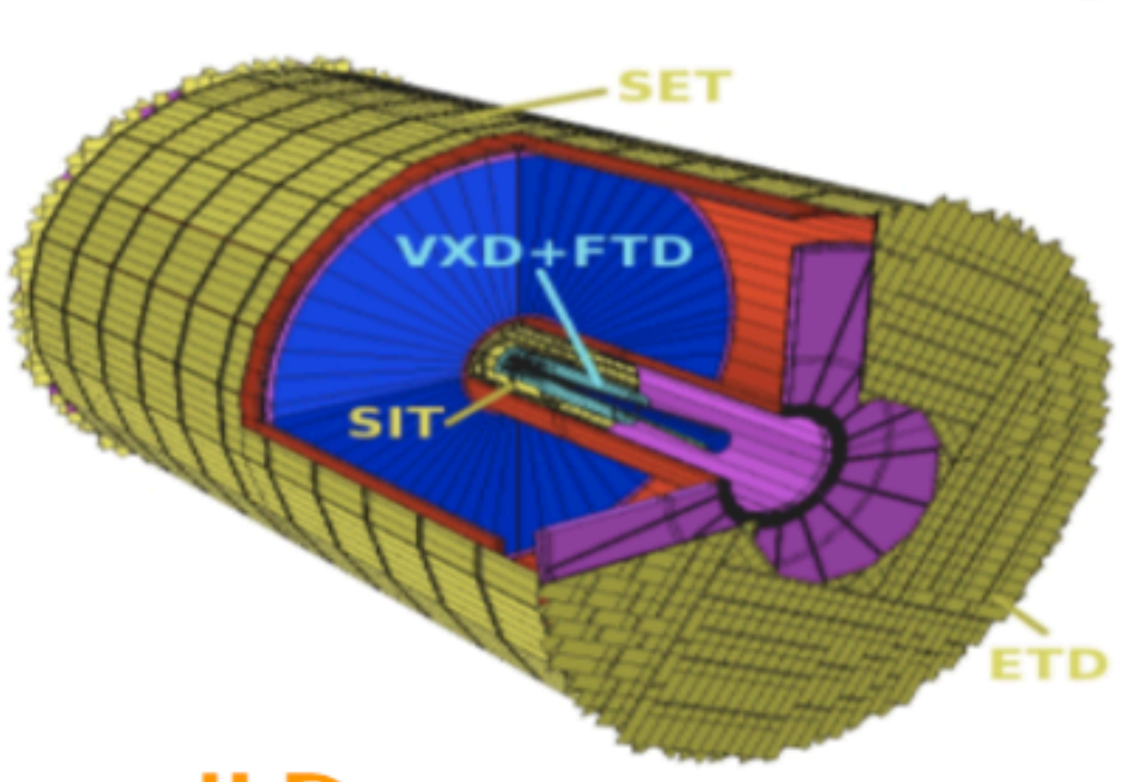




Detectors design at lepton colliders

SiD

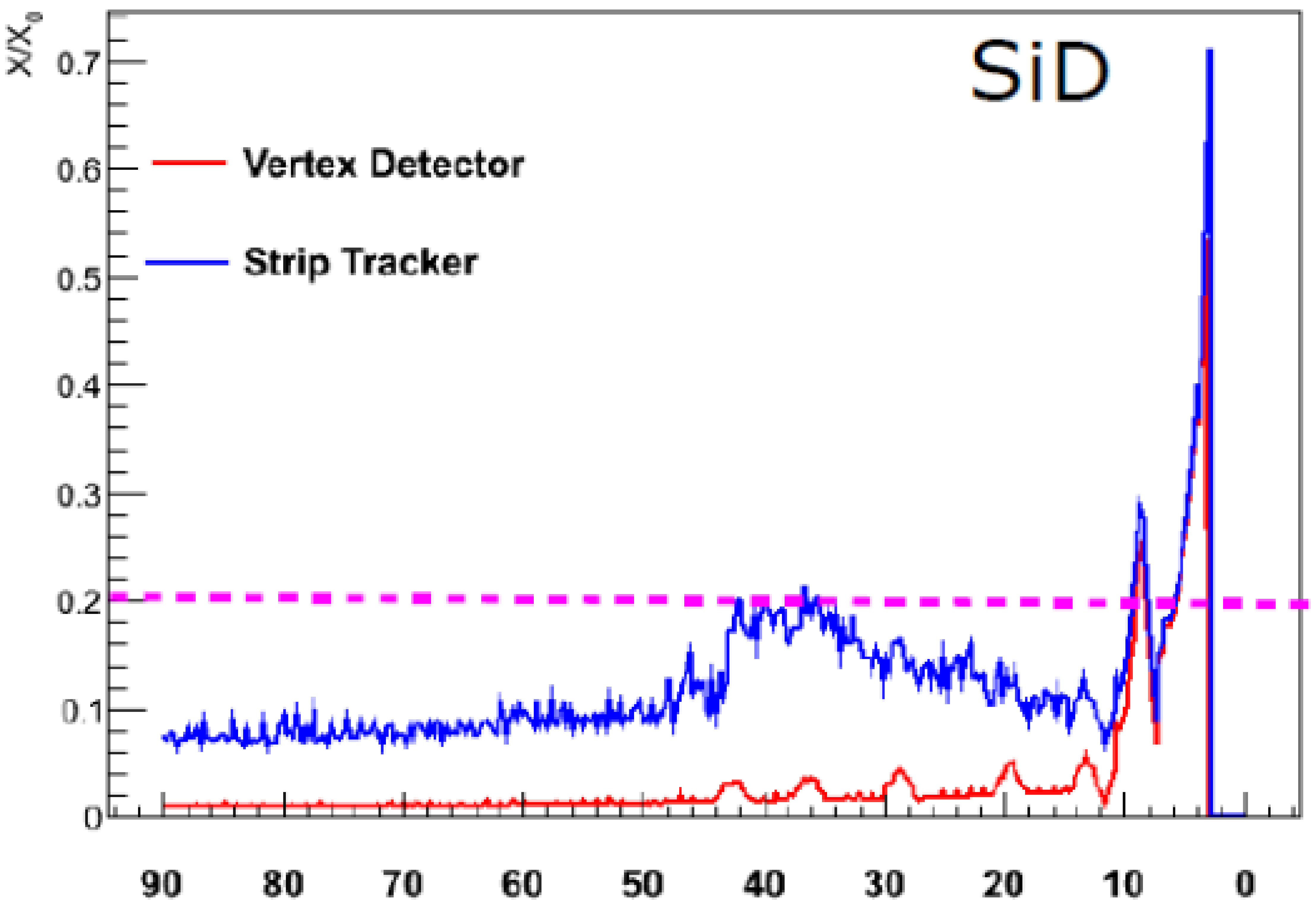
ILD

- Detector designs at e+e- colliders are converging to very similar strategies
  - Particle Flow reconstruction → plays a big part in many designs
- SiD like detector - Compact all silicon detector
- ILD like detector - Larger detector with Silicon+TPC tracker
  - Larger detector. Simulation and design work active in Europe / Japan
- IDEA detector - Using dual readout calorimeter, under study at CEPC/FCC-ee

Physics Drivers → Detector Design Requirements

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

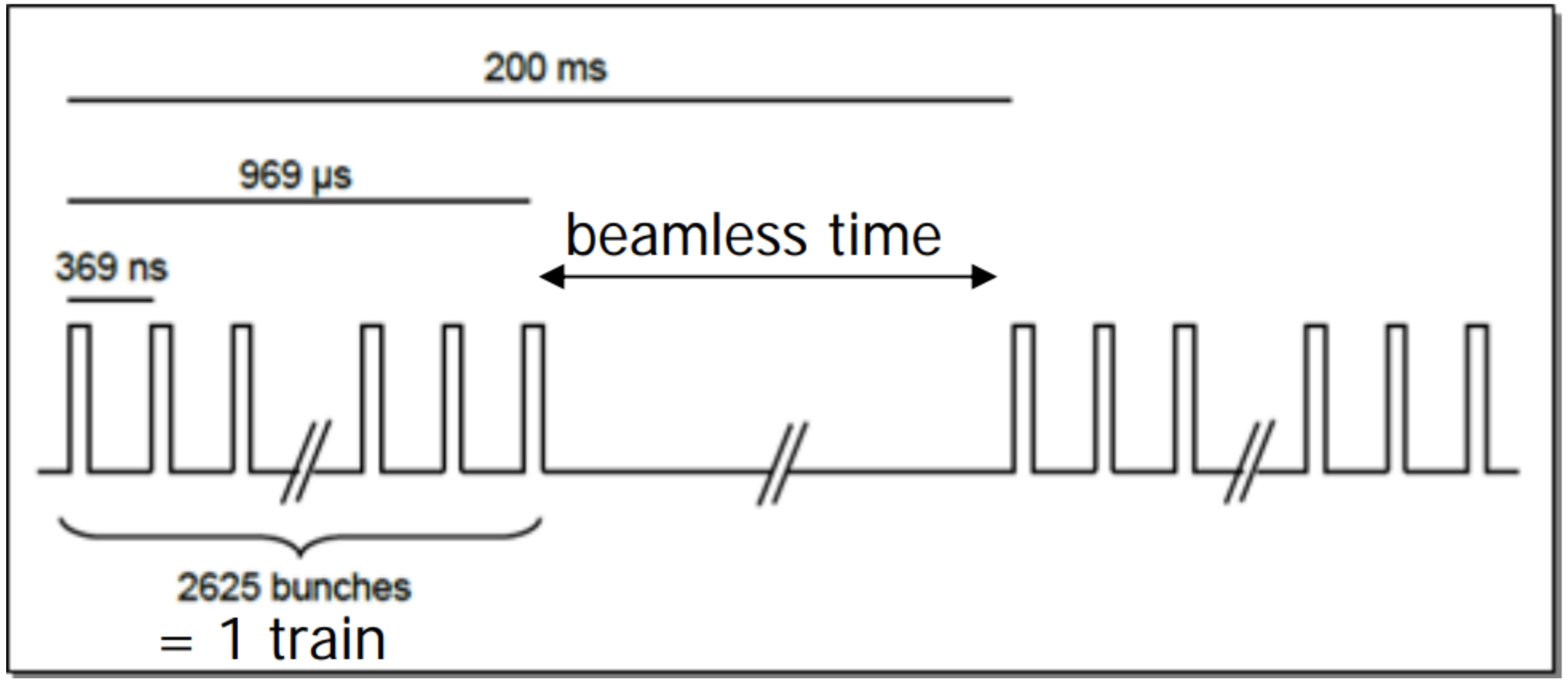
- **Very small pixels** for excellent IP resolution and minimal pattern recognition ambiguity
- **Minimal material** as close to the interaction point as possible:
  - <0.3% X0 per layer (ideally 0.1% X0) for vertex detector
  - <1% X0 per layer for Si-tracker
- **Low power** → Linear colliders eliminate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



Physics Drivers → Detector Design Requirements

Linear Collider timing structure: Fraction of a percent duty cycle

- **Power pulsing possible**, significantly reduce heat load
  - Factor of 50-100 power saving for FE analog power
- Si vertexing & tracking detectors **don't need active cooling**
  - Significantly lowers mass budget
- **Triggerless readout** is the baseline



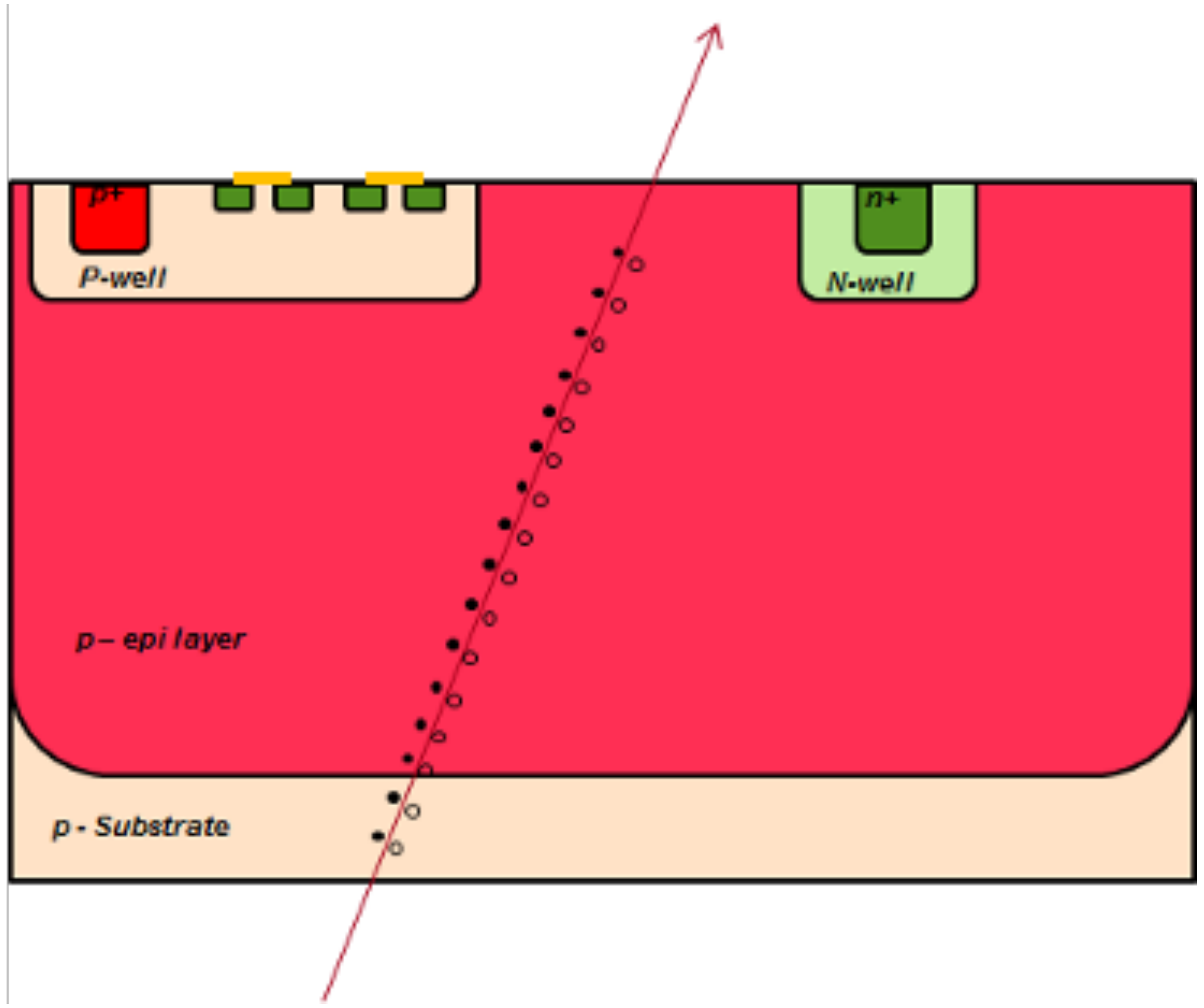
1 ms long bunch trains at 5 Hz

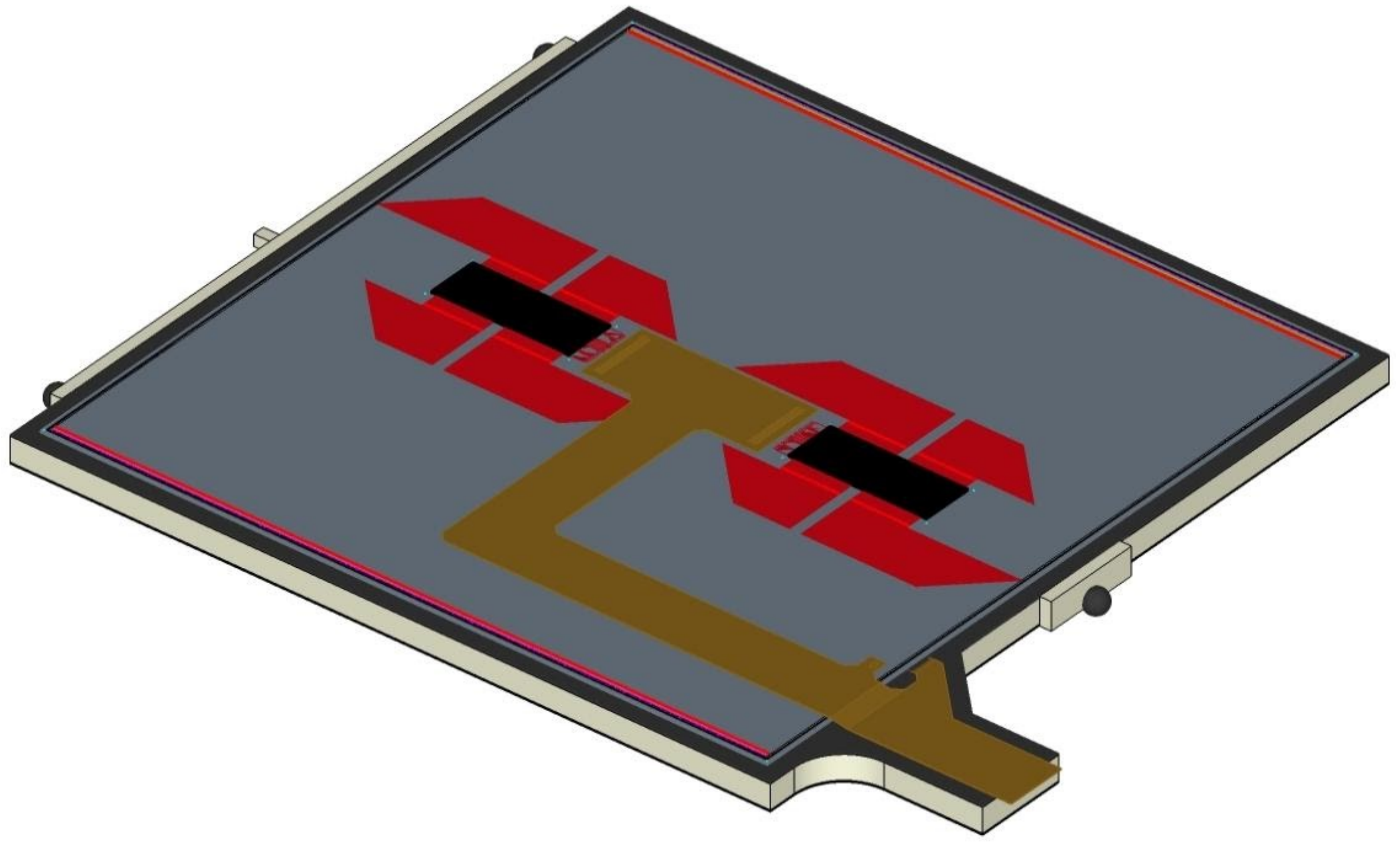
2820 bunches per train

308ns spacing (ILC TDR)

MAPS for SiD tracker detector

- Monolithic technologies have the potential for providing higher granularity, thinner, intelligent detectors at lower overall cost.
  - Significantly **lower material budget**: sensors and readout electronics are integrated on the same chip
    - Eliminate the need for bump bonding and can be thinned to less than 100μm
  - Smaller pixel size, not limited by bump bonding
  - Lower costs - can be implemented in standard commercial CMOS technologies
- Over the past decade, SiD has developed a first generation of sensors, readout with KPiX
  - 25 x 100 μm^2 pixels



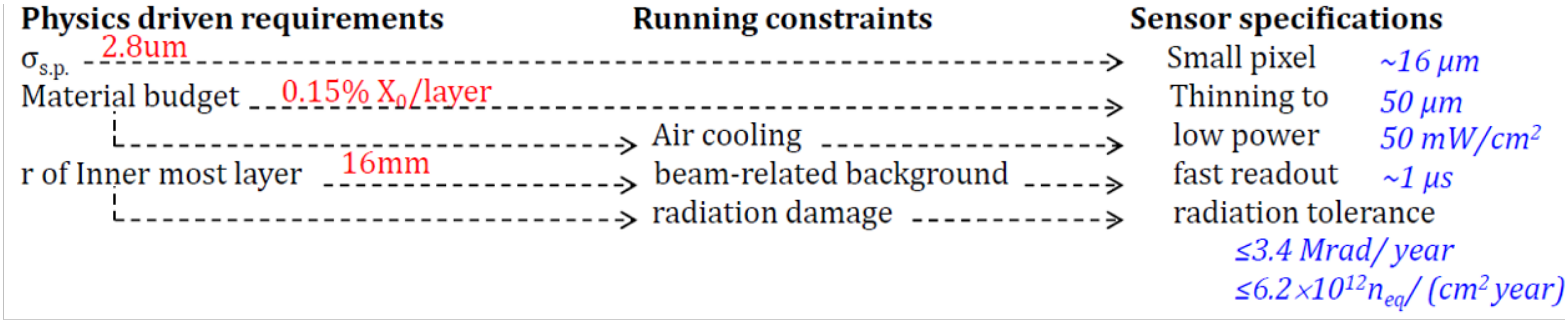


Sensors technology requirements for Vertex Detector

Several technologies are being studied to meet the physics performance :

sensors will have to be less than 75 μm thick with at least 3-5 μm hit resolution (17-25 μm pitch) and low power consumption:

- continuous r/o during the train with power cycling
- delayed after the train → either ~5μm pitch for occupancy or in-pixel time-stamping

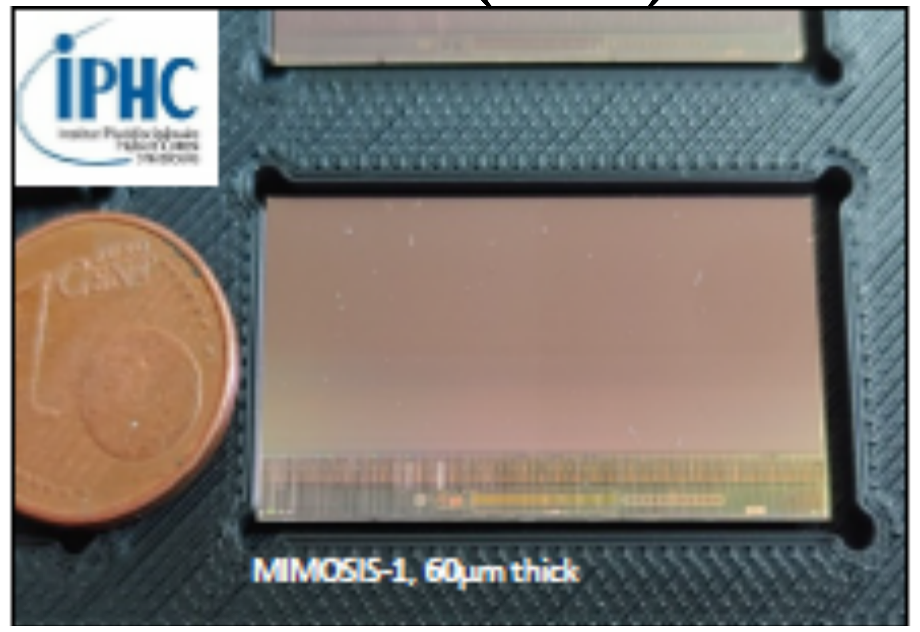


Sensors technology overview

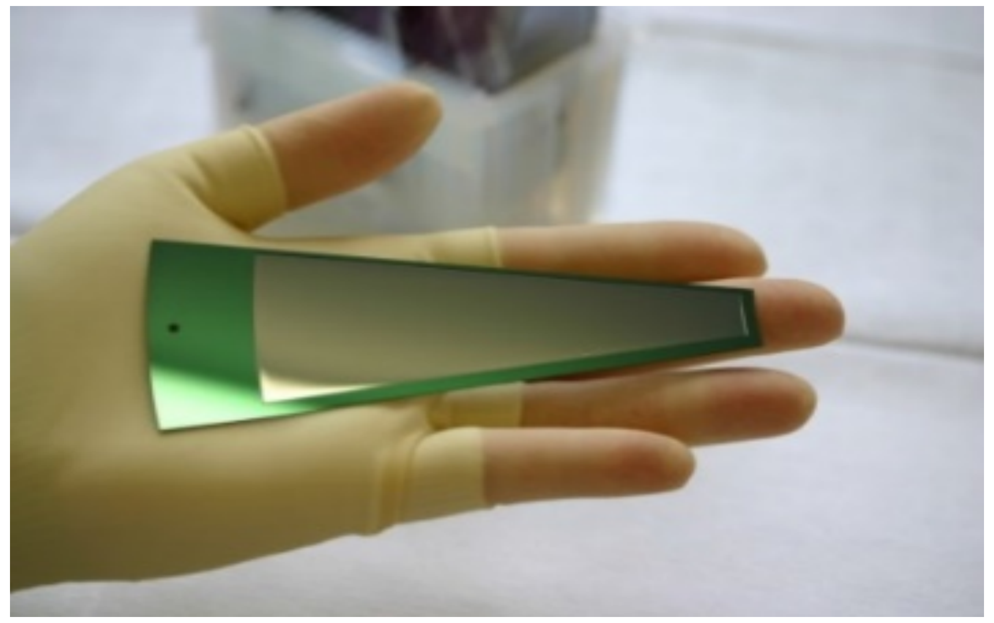
Several possible choices for the VTX detector:

- 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

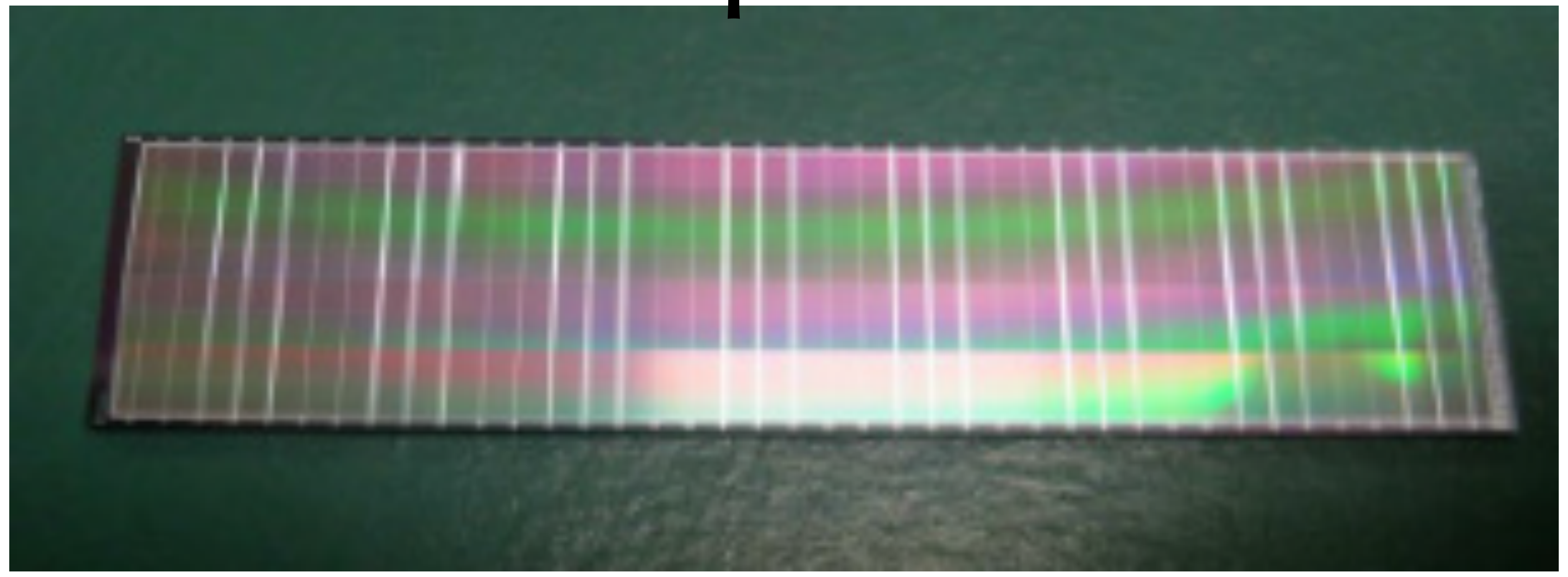
CMOS (CPS)



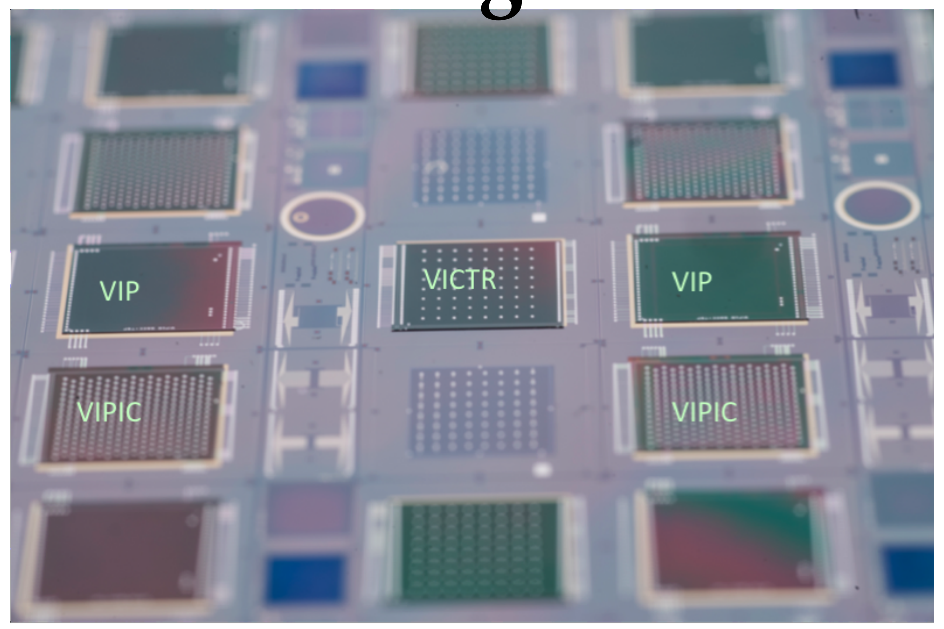
DEPFET



Fine pixel CCD

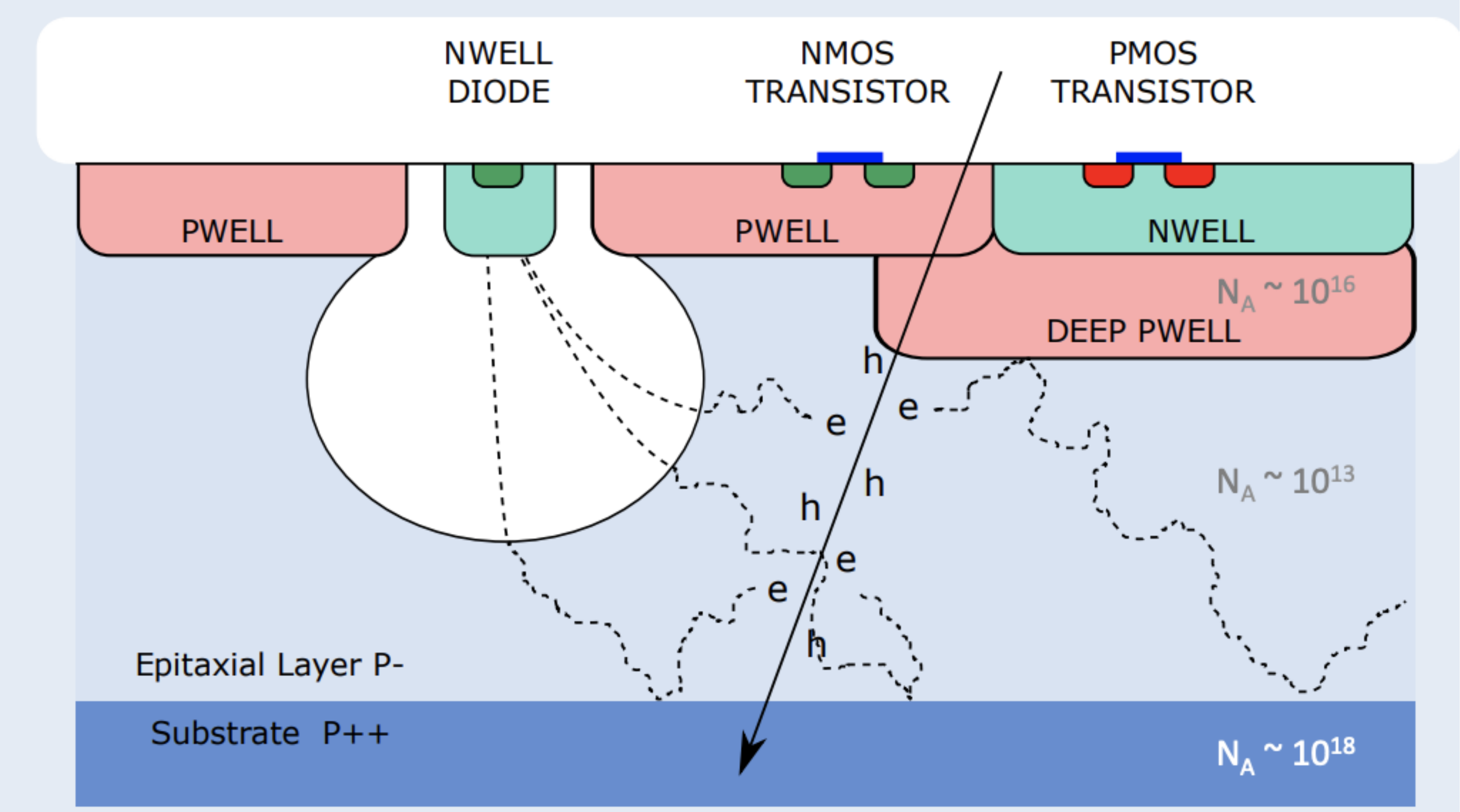


3D Integration



ALPIDE

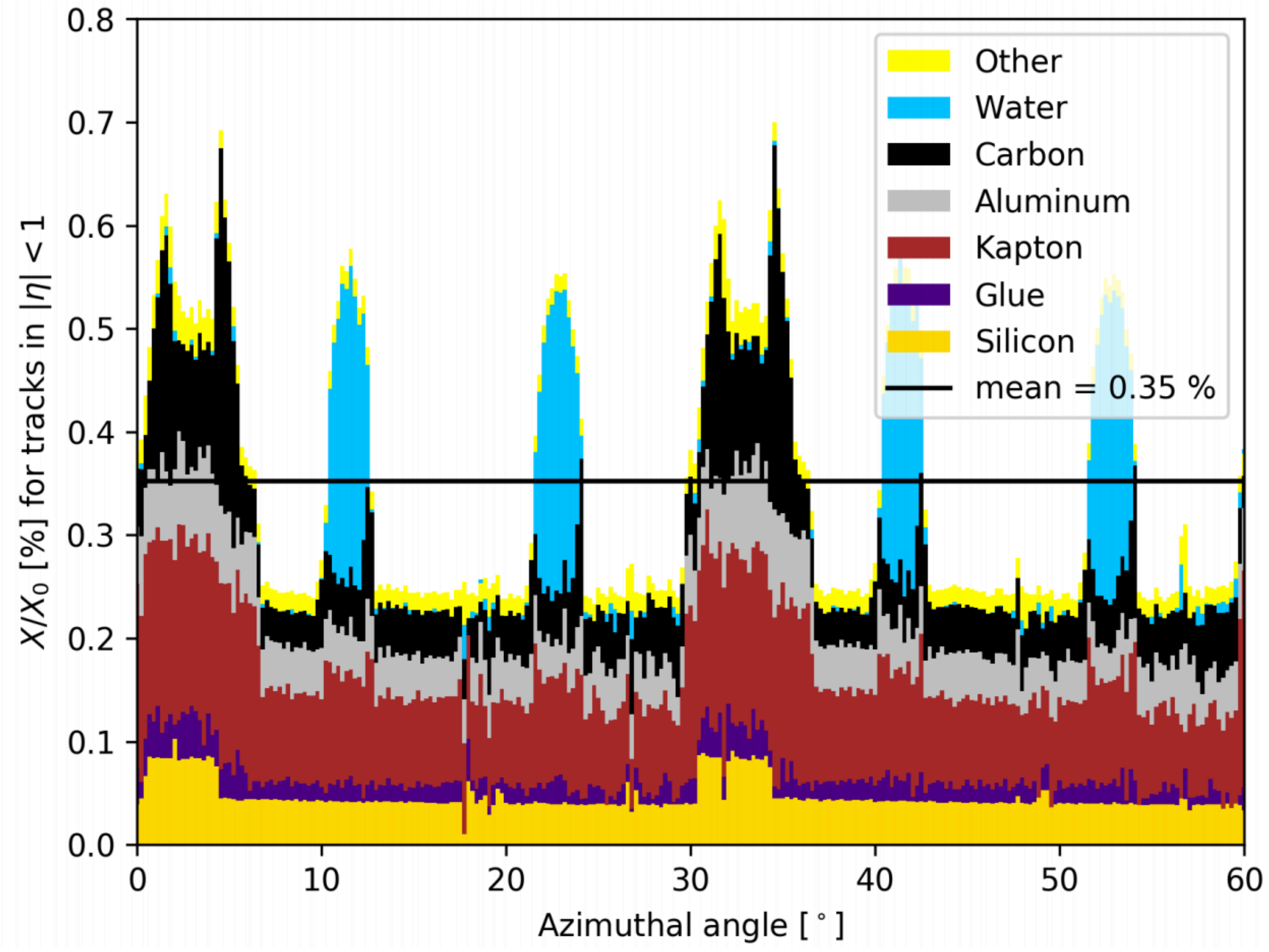
- With the current tracker upgrade ALICE redefined the new state-of-the art in CMOS MAPS technology and its applications in HEP
- ALice PIxel DEtector (ALPIDE) uses CMOS Pixel sensor used in imaging process
  - full CMOS circuitry within active area
  - Sensor thickness = 20-40 µm (0.02-0.04% X0)
  - 5µm spatial resolution
  - radiation hard to 10^{13} 1 MeV n_{eq}



V. Manzari, 2019

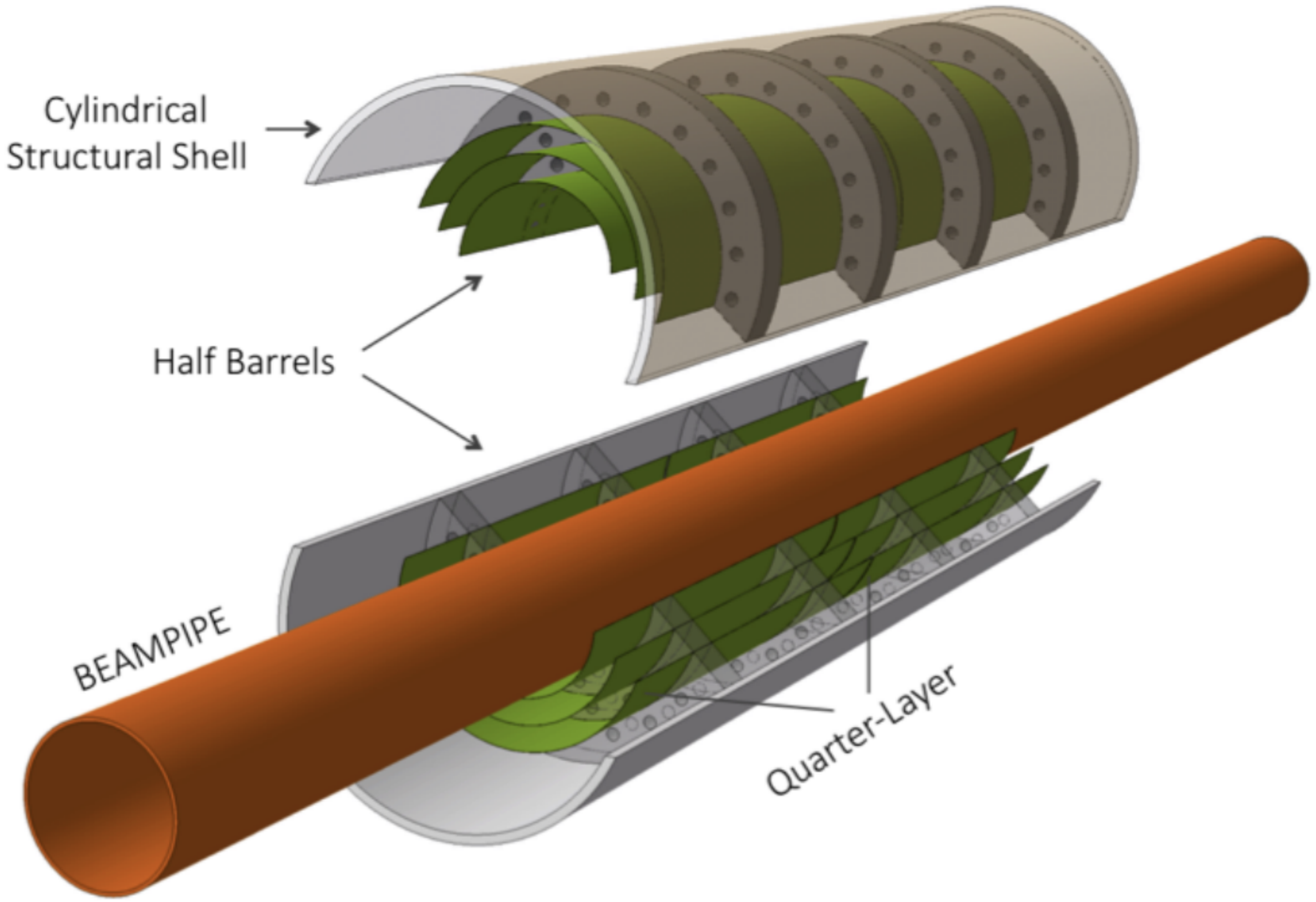
The used technology offers further opportunities: smaller feature size, **bending** that directly impact the key measurements that highly rely on precise vertexing and low material budget

Towards ultra low mass trackers



- Sensor's contribution to the total material budget is 15-30%
  - cables + cooling + support make up most of the detector mass
- Challenges (beam backgrounds, cooling, material budget) needs to be addressed by emerging R&D's:
  - Reduce impact of mechanical supports, services, overlap of modules/ladders
  - Beam related background suppression $\Longrightarrow$ evolve time stamping toward a few 100 ns (bunch-tagging)
- At linear colliders the baseline consists in air-cooling which is expected to be able to extract the total power dissipation of the vertex detector (< 40 mW/cm^2)
  - more specific developments are also being pursued as micro-channel cooling for DEPFET

ALICE: Bent MAPS for Run 4



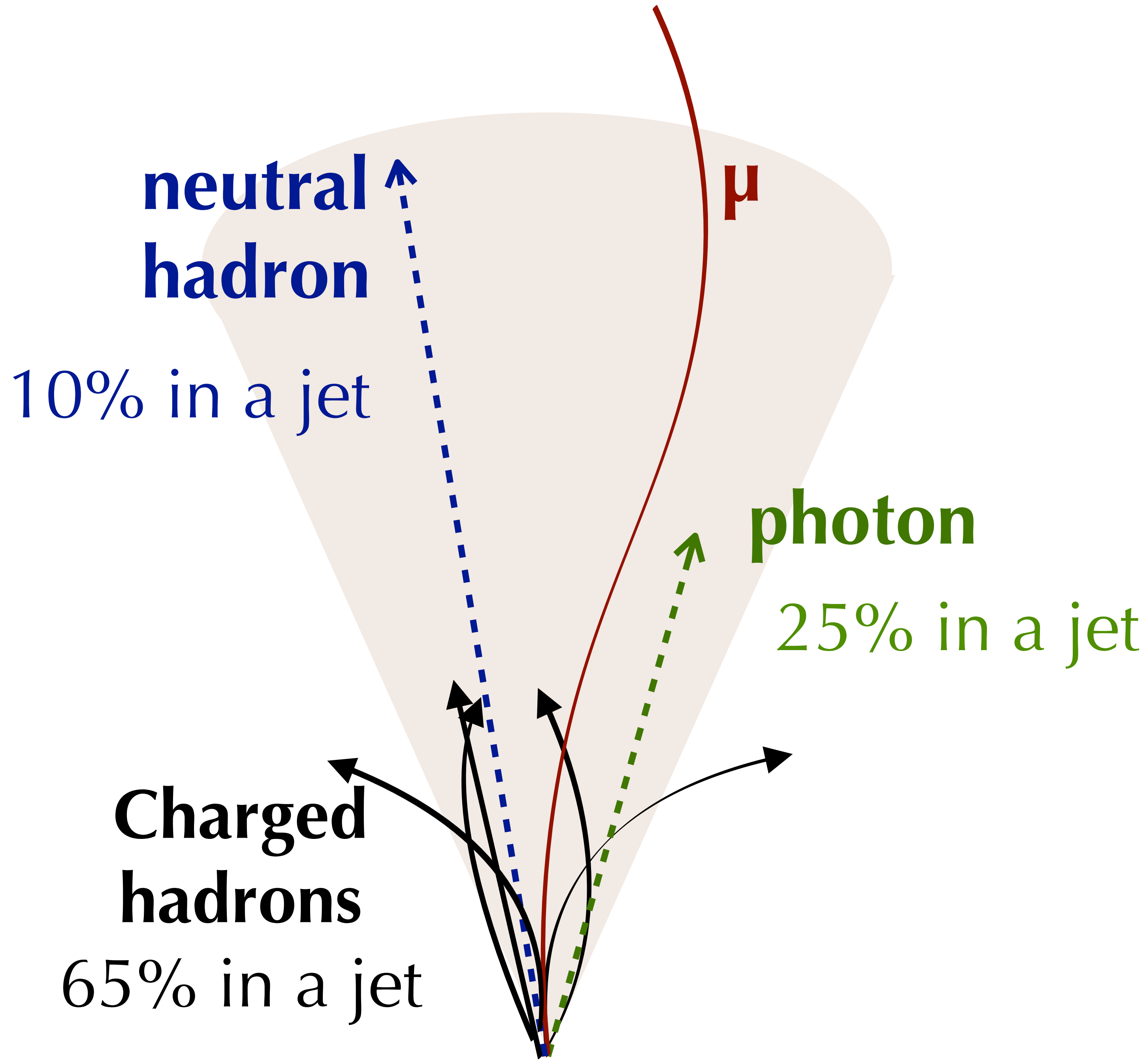
Bending Si wafers + circuits is possible

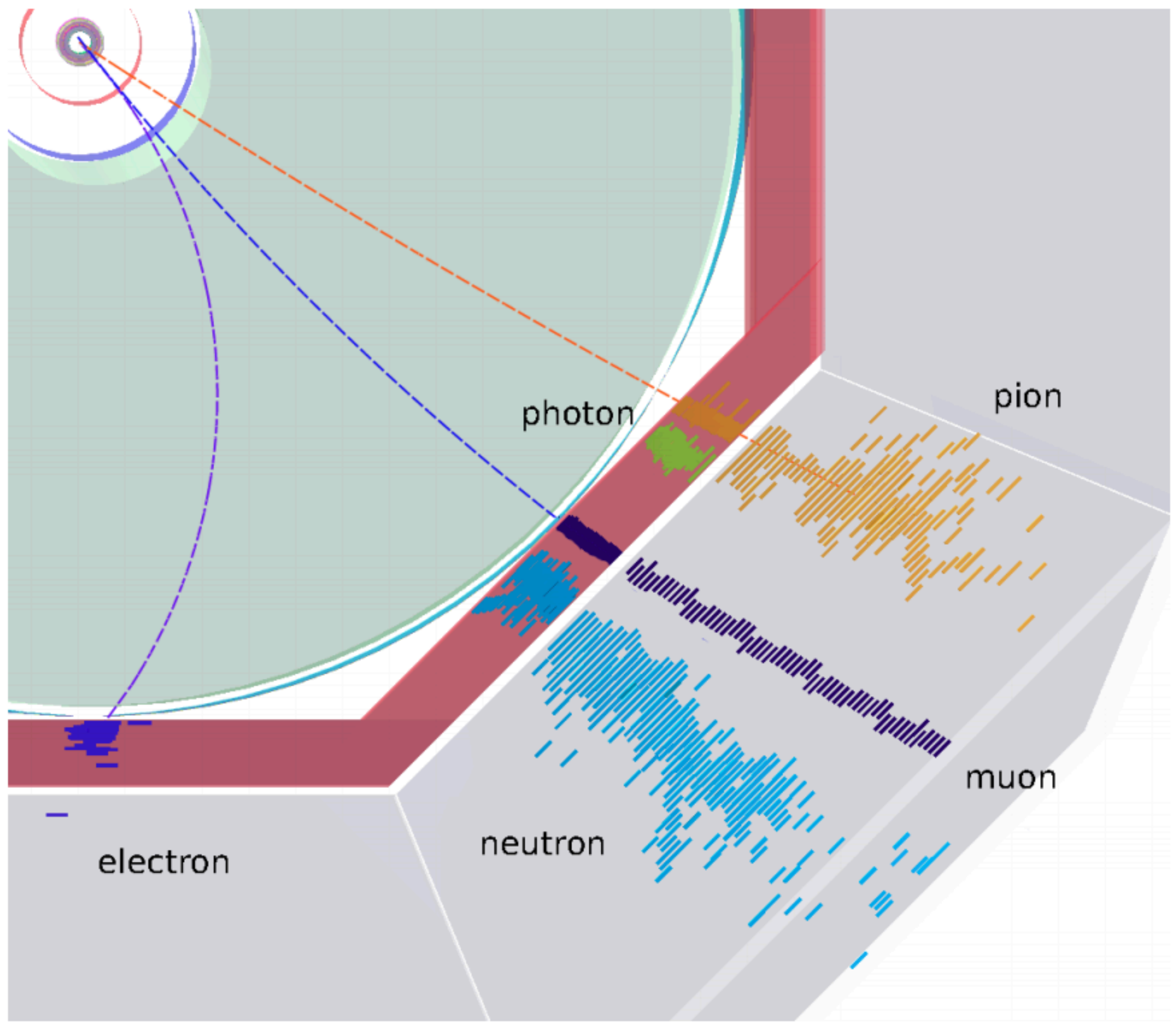
Recent ultra-thin wafer-scale silicon technologies allow:

- 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)



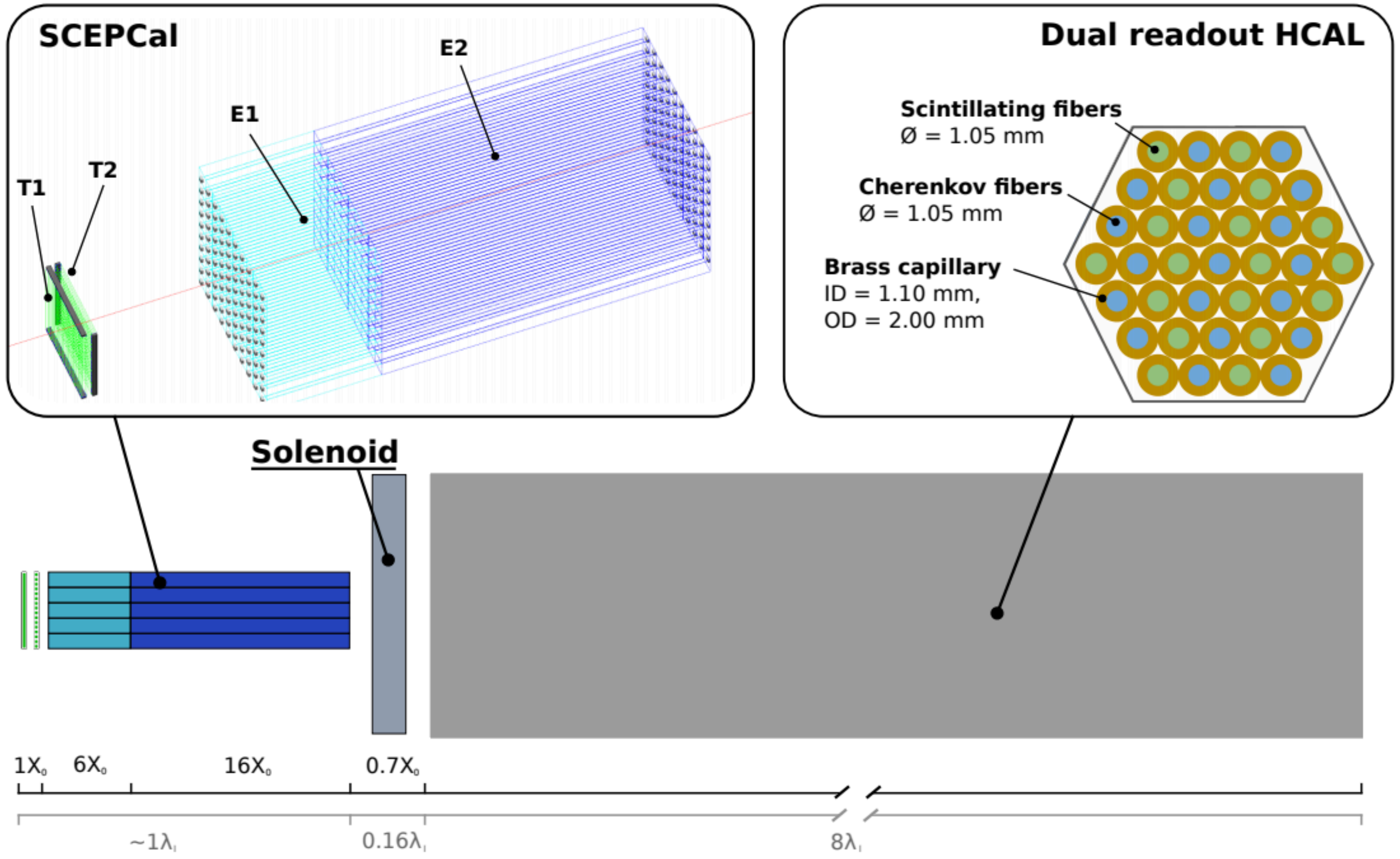


Dual Readout calorimetry

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



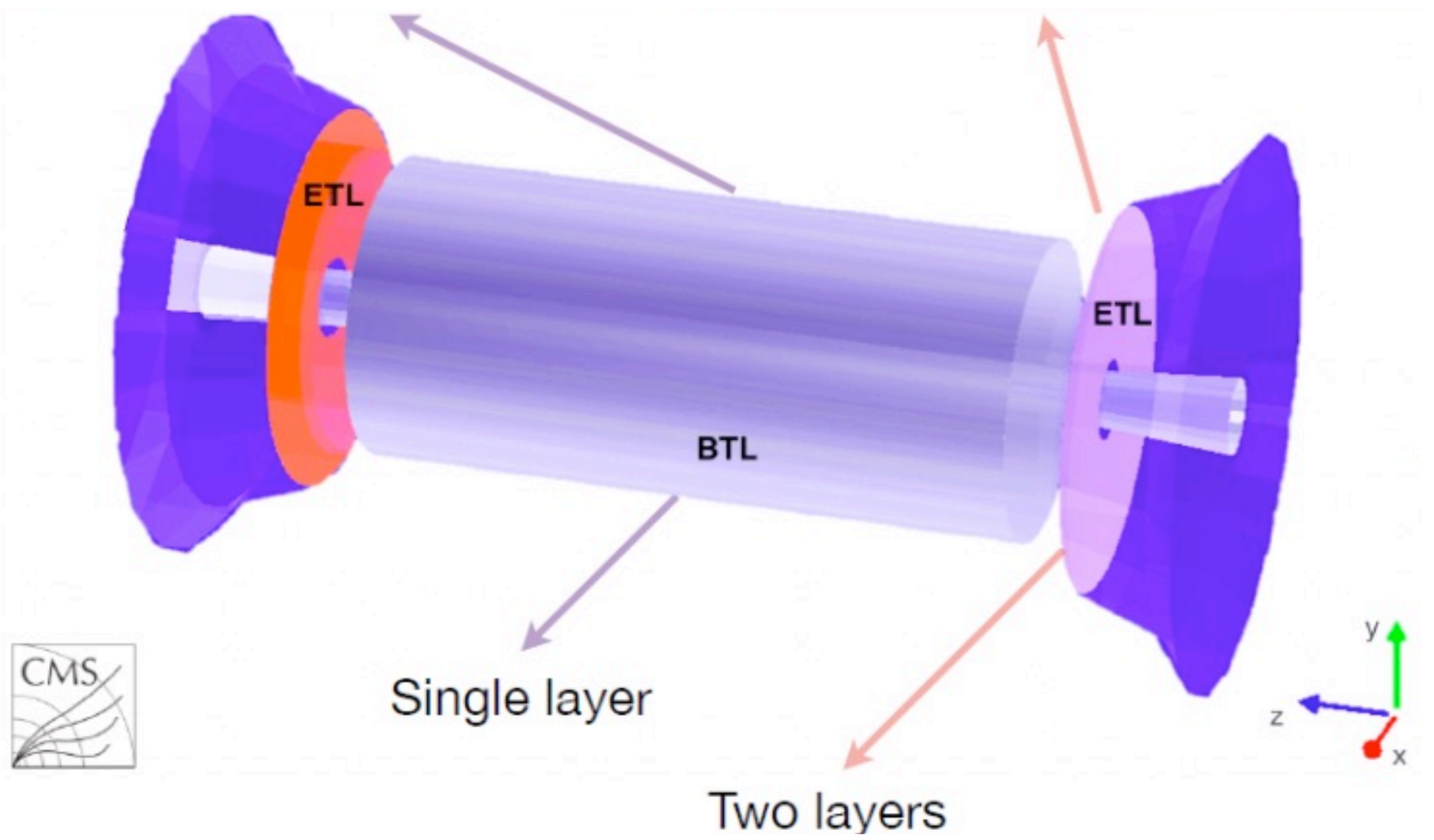
Timing detectors with a O(10) picosecond resolution

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:

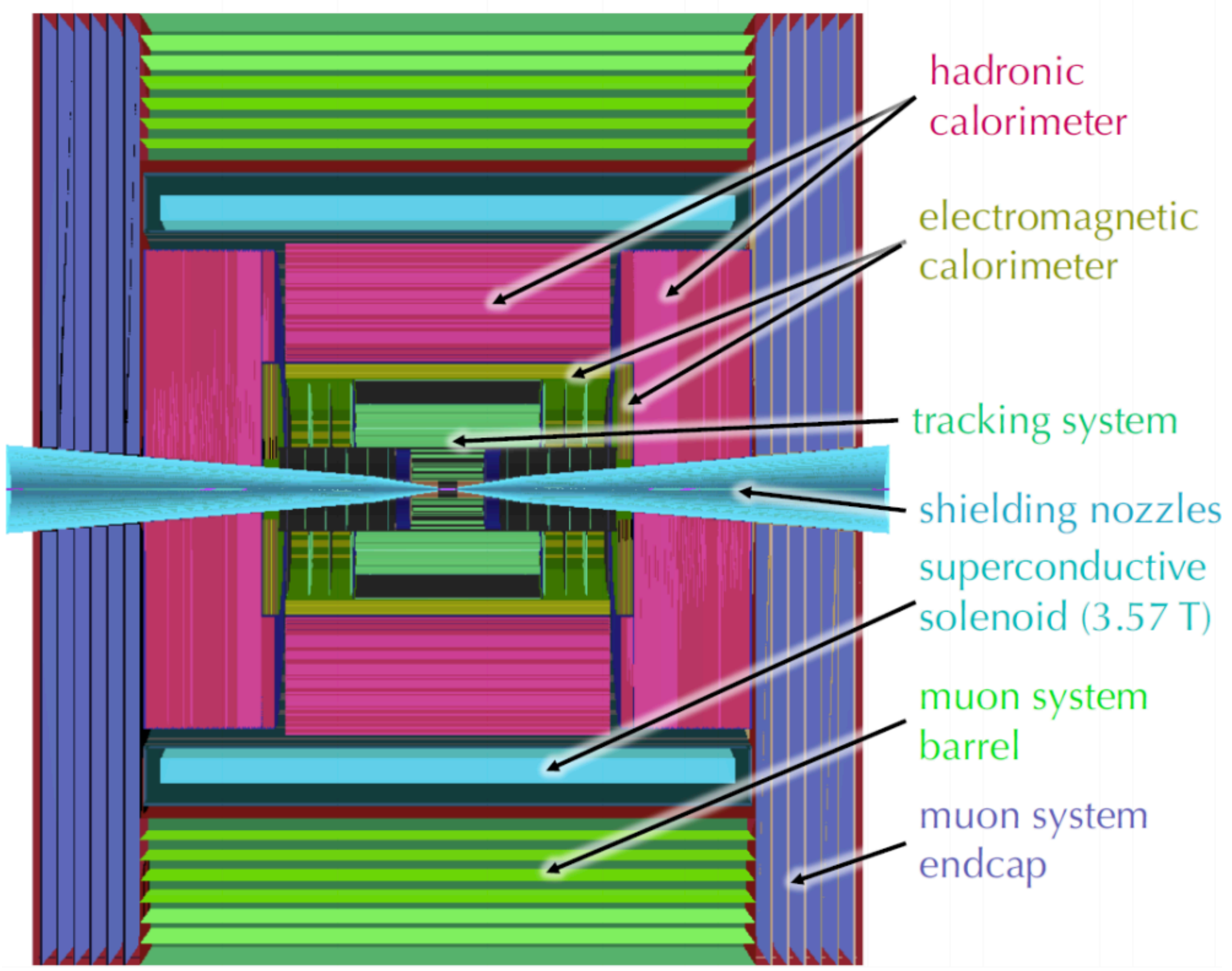
- Radiation hardness
  - LGAD-sensors ~ 25 ps for 50 μm sensors and $2x10^{15}$ n_{eq}/cm^2
  - 3D-trench Si sensors: O(100 ps) and a goal of 10^{16} - 10^{17} n_{eq}/ cm2
- "5D reconstruction": space-points / ps-timing are available at each point along the track
  - LHCb EoI for LS4 is of general interest



More in Artur's talk tomorrow

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**

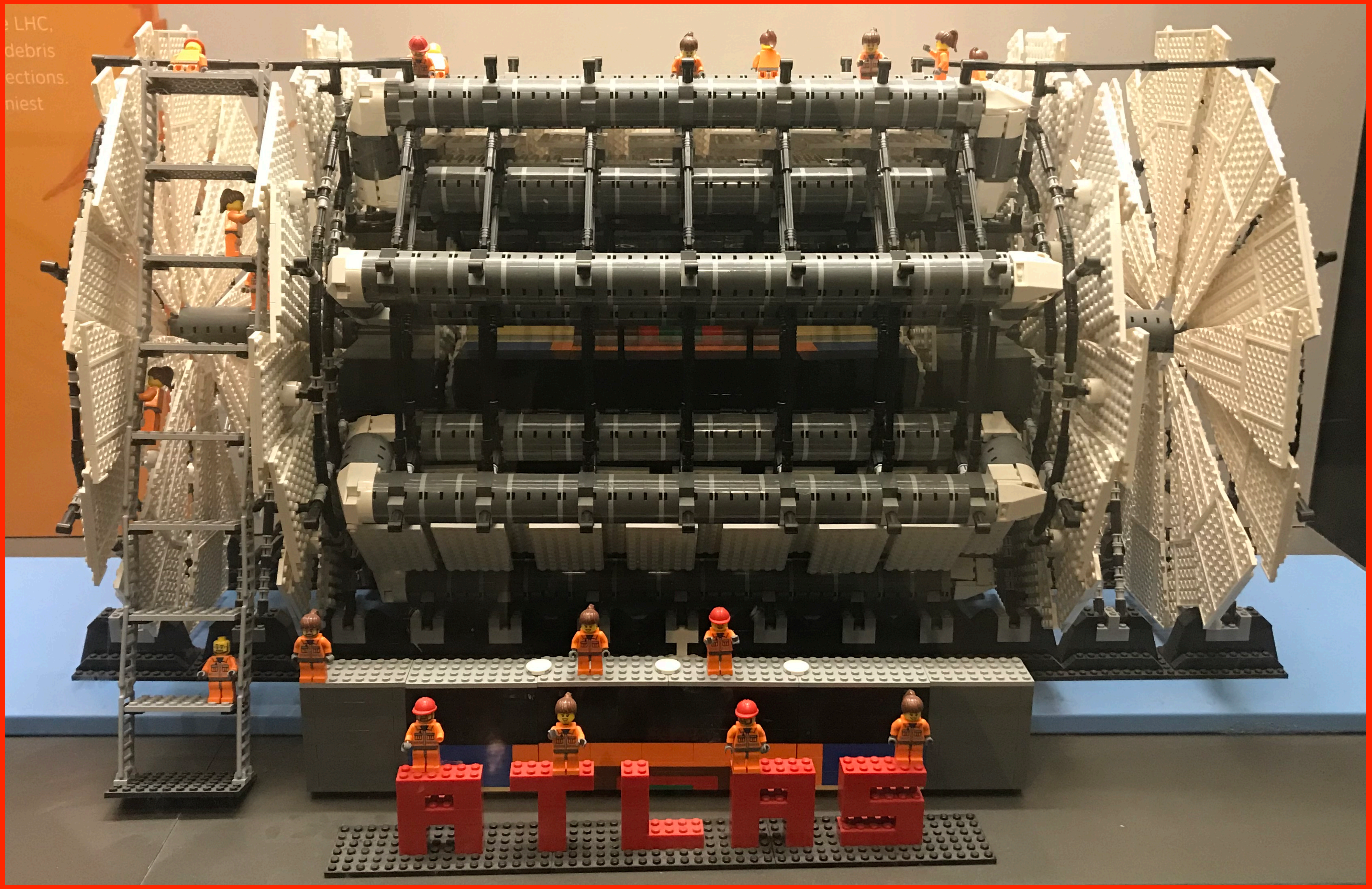
- Advancements in timing sensors to get to radiation hard and O(10)ps resolution
  - 4D tracking (with precision timing information) potentially could be considered for e+e- - if the physics gain is significant with respect to increased material budget

- 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!

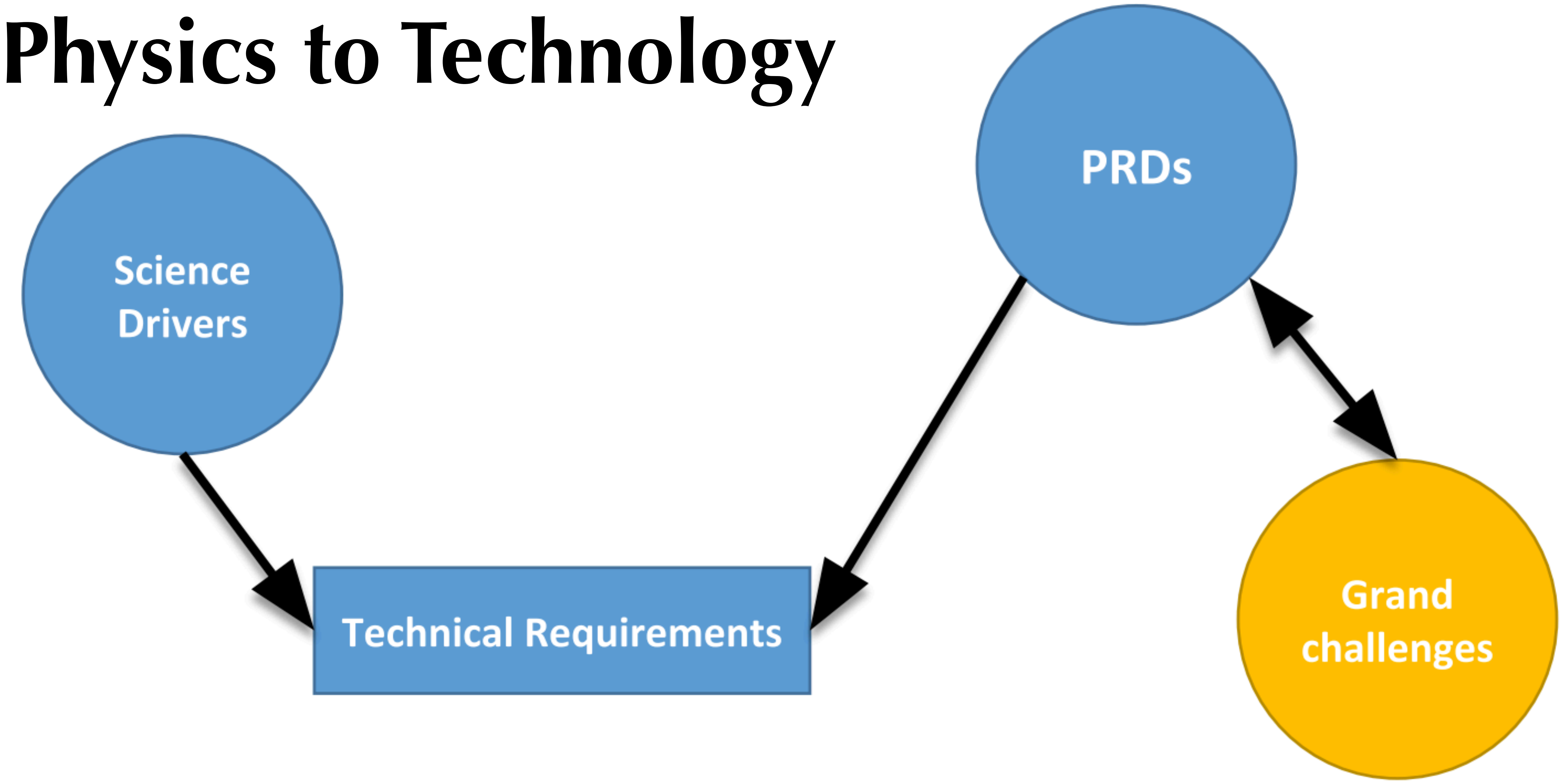
b/c/strange tagging

- 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

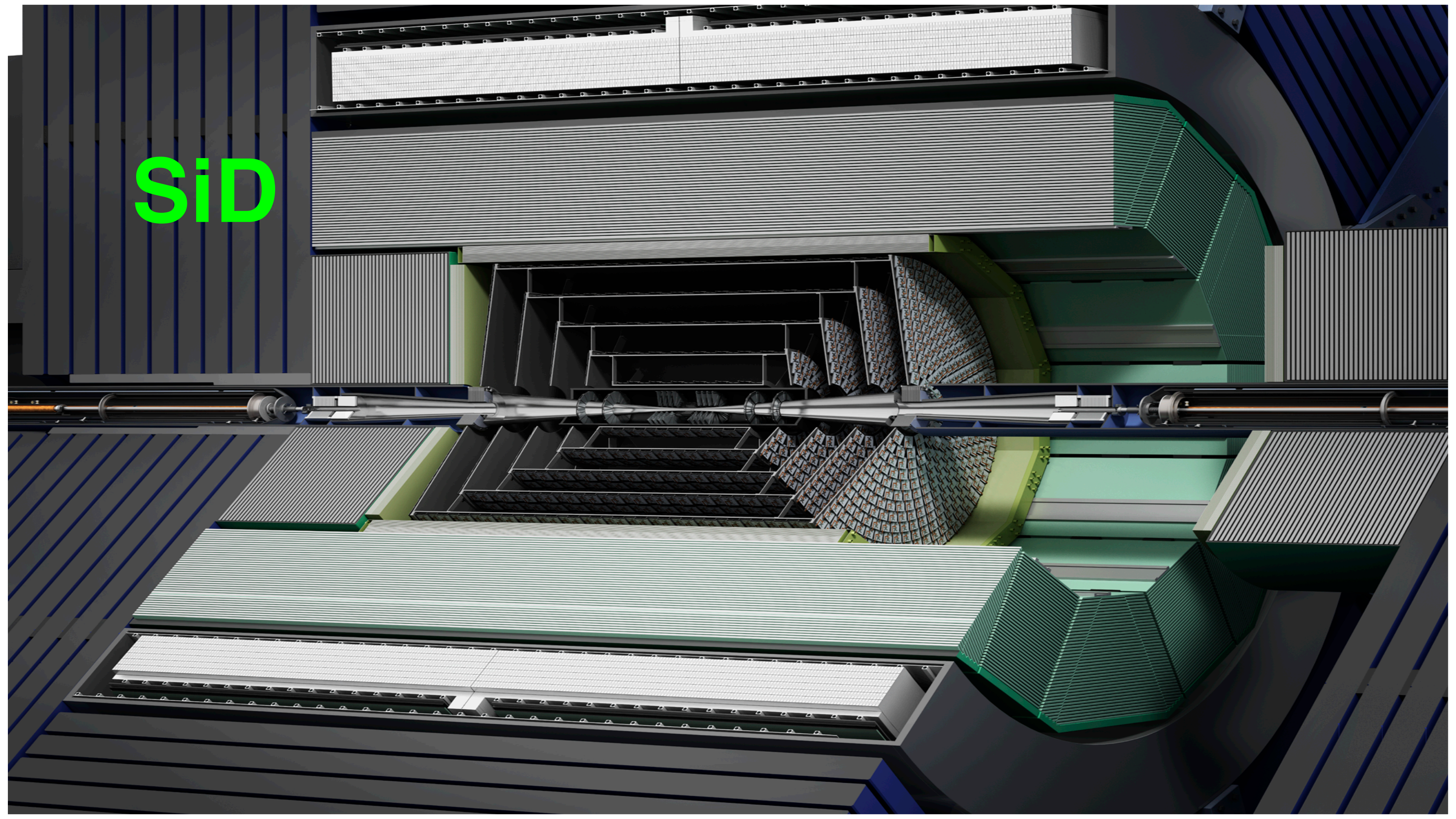
- Advancing HEP detectors to new regimes of sensitivity
- Using Integration to enable scalability for HEP sensors
- Building next-generation HEP detectors with novel materials & advanced techniques
- Mastering extreme environments and data rates in HEP experiments

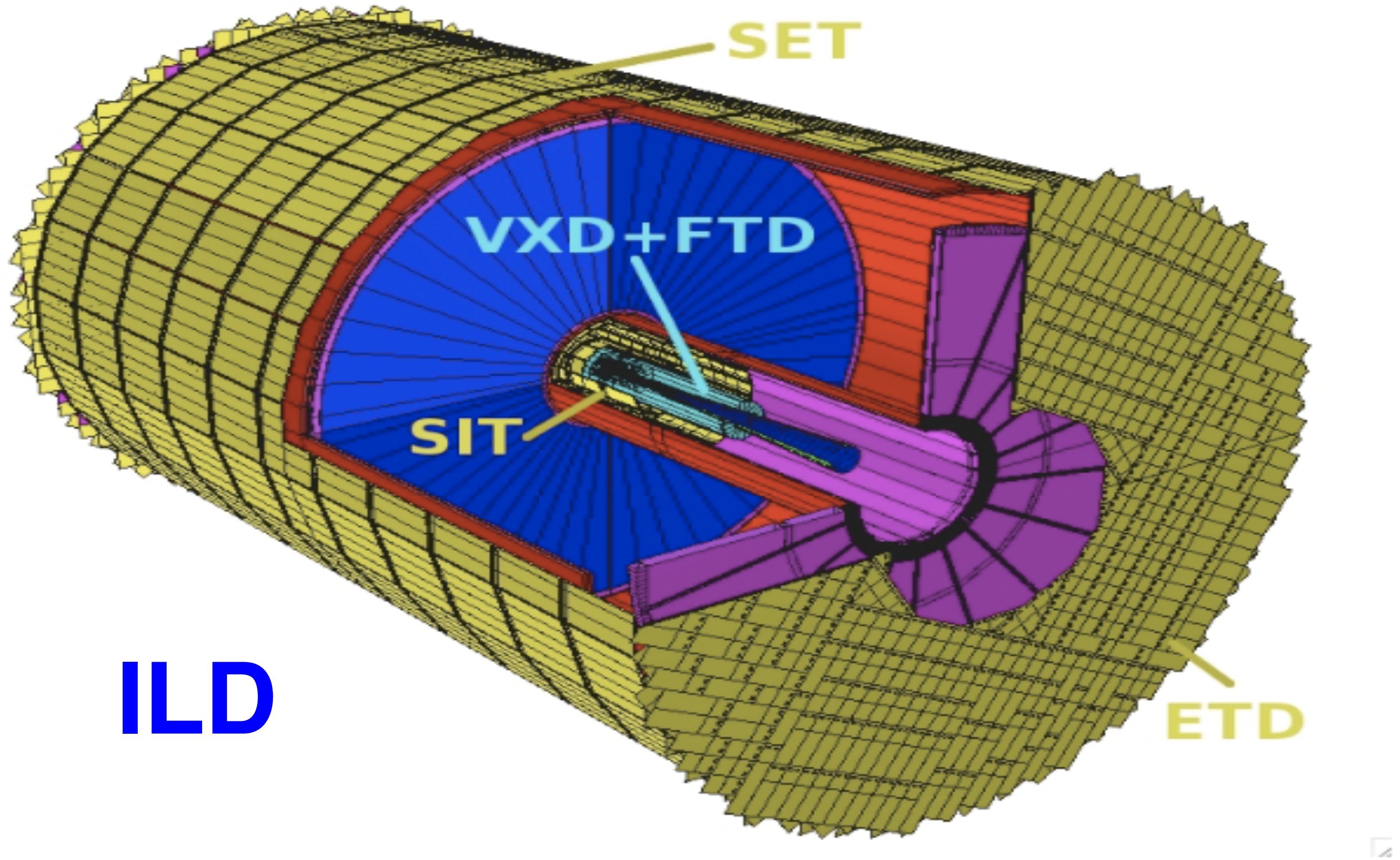
Physics to Technology



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

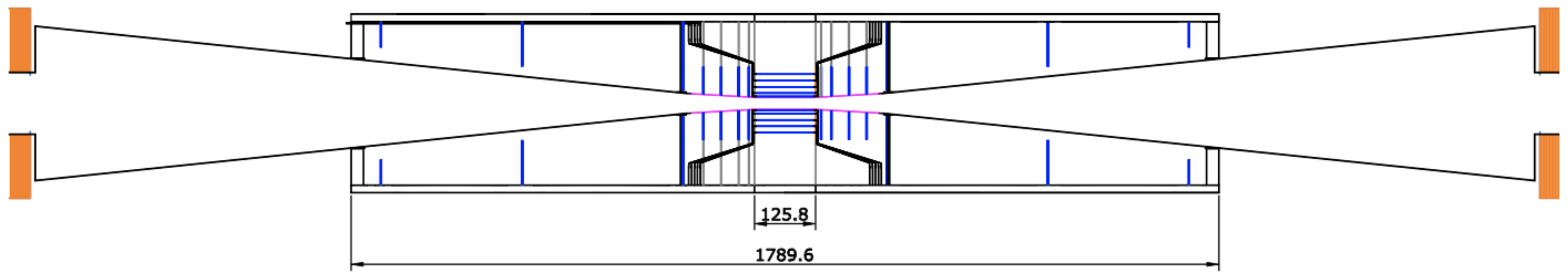
SiD

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

- Pixel Vertex detector
  - 1 kGy and 10^{11} n_{eq}/cm^2 per year
  - **Pixel hit resolution** better then 5 μm 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)

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



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

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