Silicon detectors for FCC

Current and future tracking and vertexing detectors
London, 7 November 2023

Attilio Andreazza
Università di Milano and INFN

Most material from:
ECFA Topical workshop on tracking and vertexing
https://indico.cern.ch/event/1264807/

and recent FCC, CEPC, ECFA Workshops
https://indico.cern.ch/event/1202105
https://indico.ph.ed.ac.uk/event/259/
https://agenda.infn.it/event/34841/

See also M. Dam and P. Azzi
Future Accelerator Seminar
https://indico.cern.ch/event/1285590/

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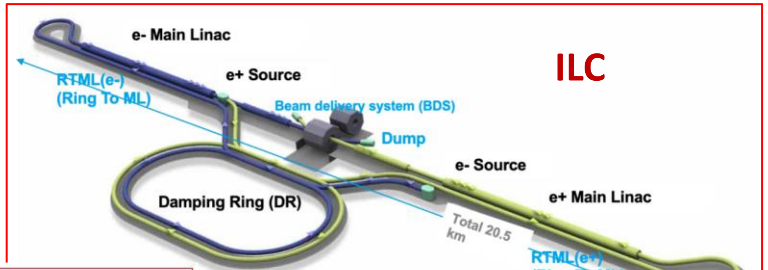
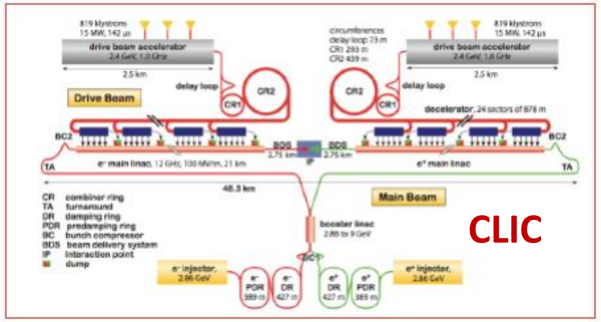
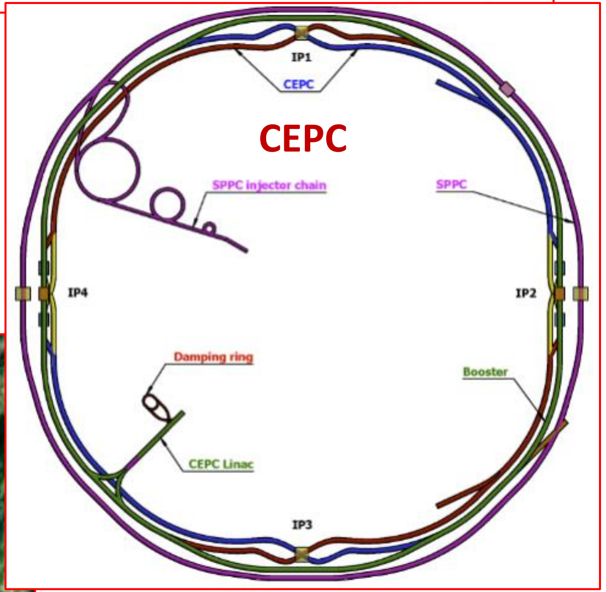
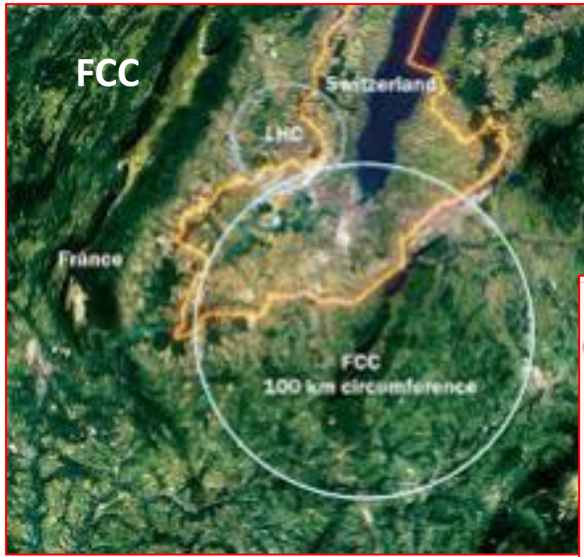
DIPARTIMENTO DI FISICA

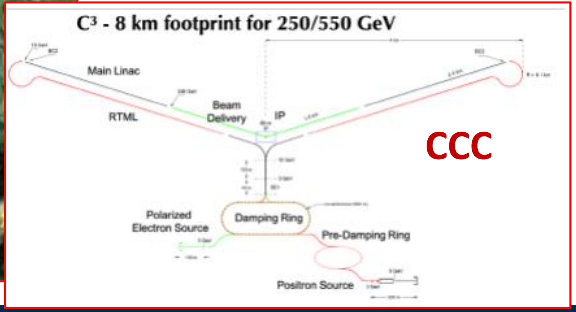
Future e^+e^- colliders

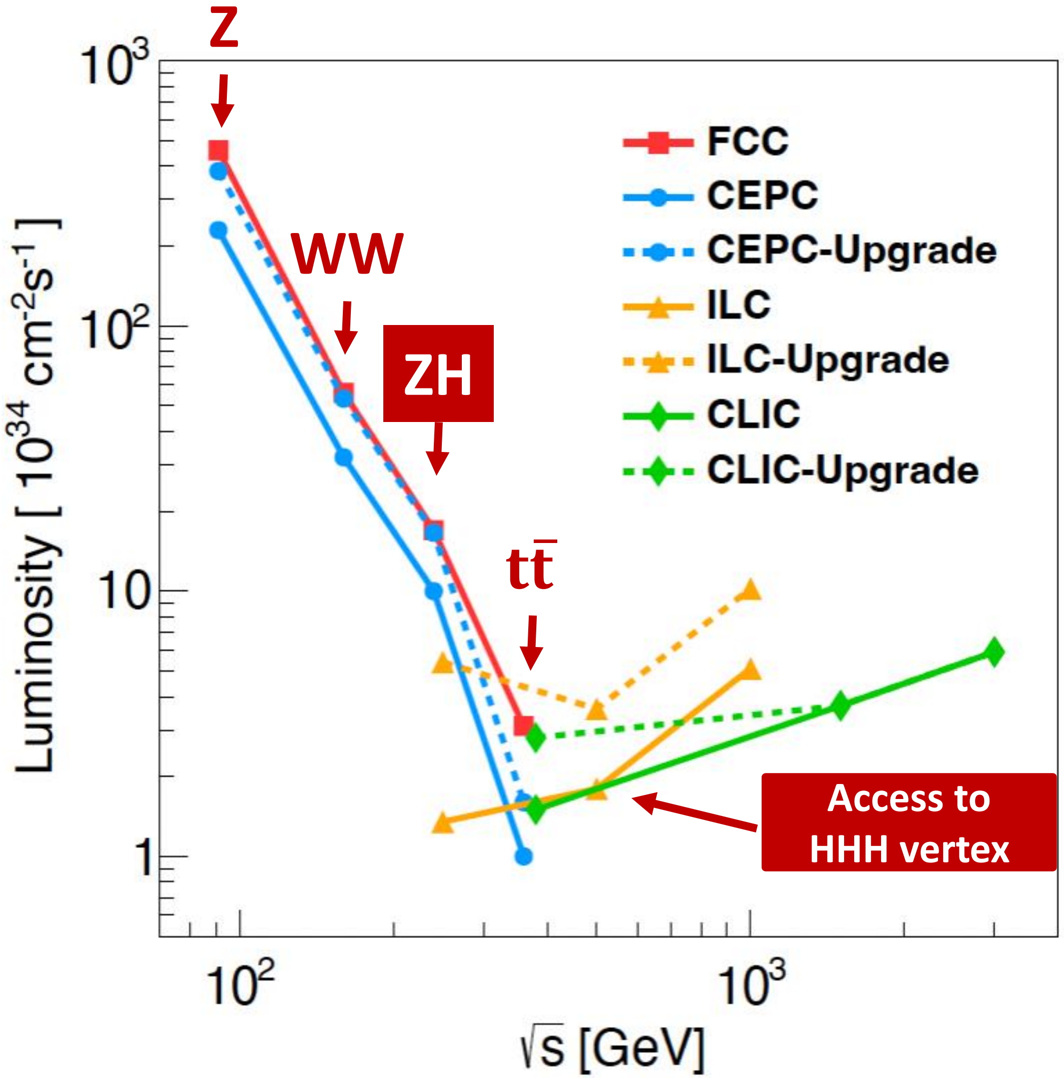












Collider parameters

Parameter	ILC		CLIC		
$\sqrt{s}$ [GeV]	250	500	380	1500	300
L [10^{34}cm^{-2}s^{-1}]	1.35	1.8	1.5	3.7	5.9
L>99%$\sqrt{s}$ [10^{34}cm^{-2}s^{-1}]	1.0	1.0	0.9	1.4	2.0
Repetition frequency [Hz]	5		50		
Bunch separation [ns]	554		0.5		
Bunches per train	1312		352	312	
Beam size at IP σ_x/σ_y [nm]	515/7.7	474/5.9	150/2.9	60/1.5	40/1
Crossing angle [mrad]	14		20		

Parameter	FCCee (CEPC similar)			
$\sqrt{s}$ [GeV]	91.2	160	240	365
L /IP [10^{34}cm^{-2}s^{-1}]	182	19.4	7.3	1.33
Bunch separation [ns]	20	300	1000	6000
Bunches per beam	15880	880	248	40
σ_x/σ_y [nm]	8/34	21/66	14/36	39/69
Crossing angle [mrad]	30			

Linear colliders

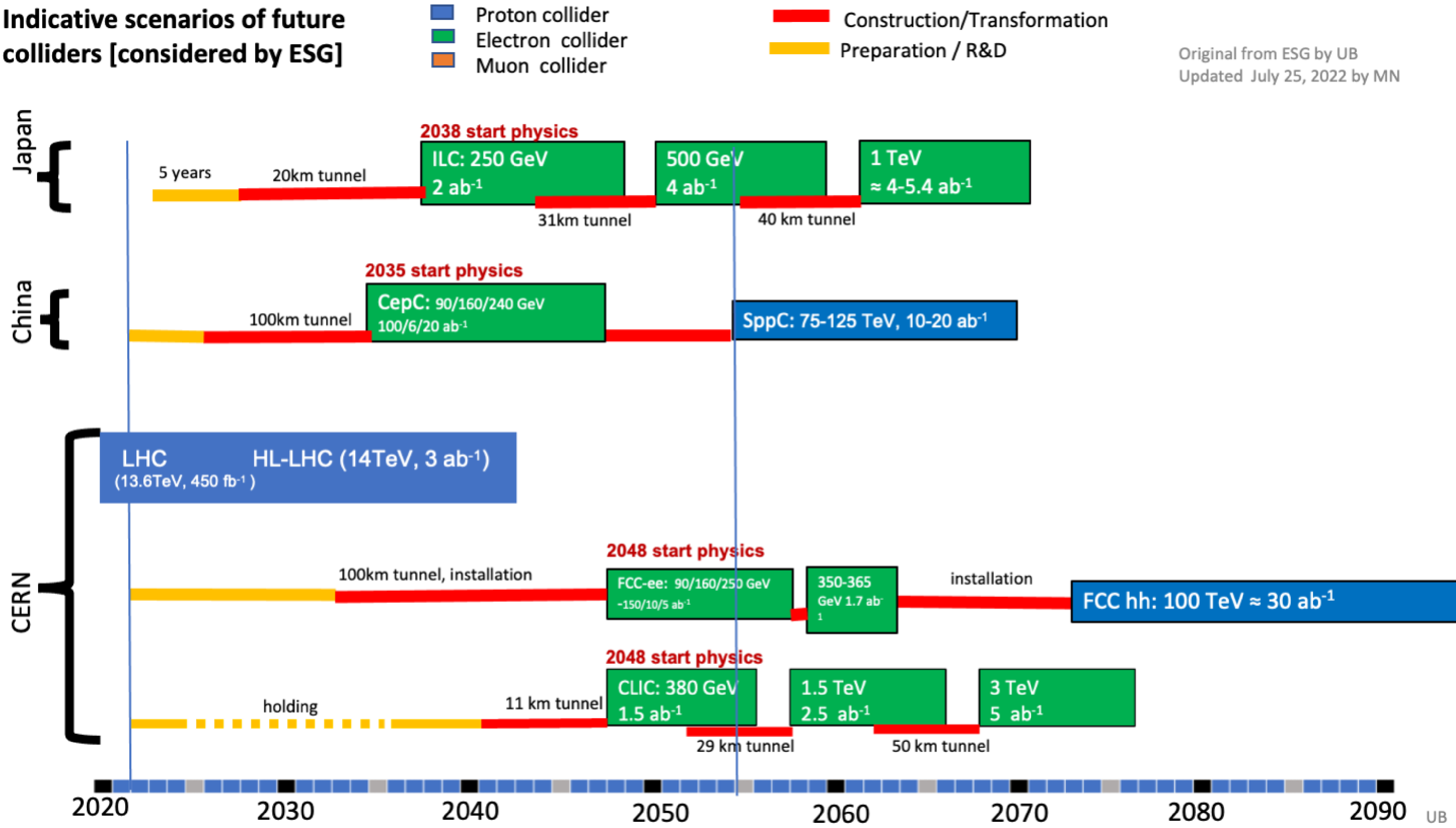
- Very narrow beams: beamstrahlung reduces available center-of-mass energy
- CLIC almost continuous beam drives detector timing requirements
- Low duty cycles: triggerless readout, power cycling

Circular colliders

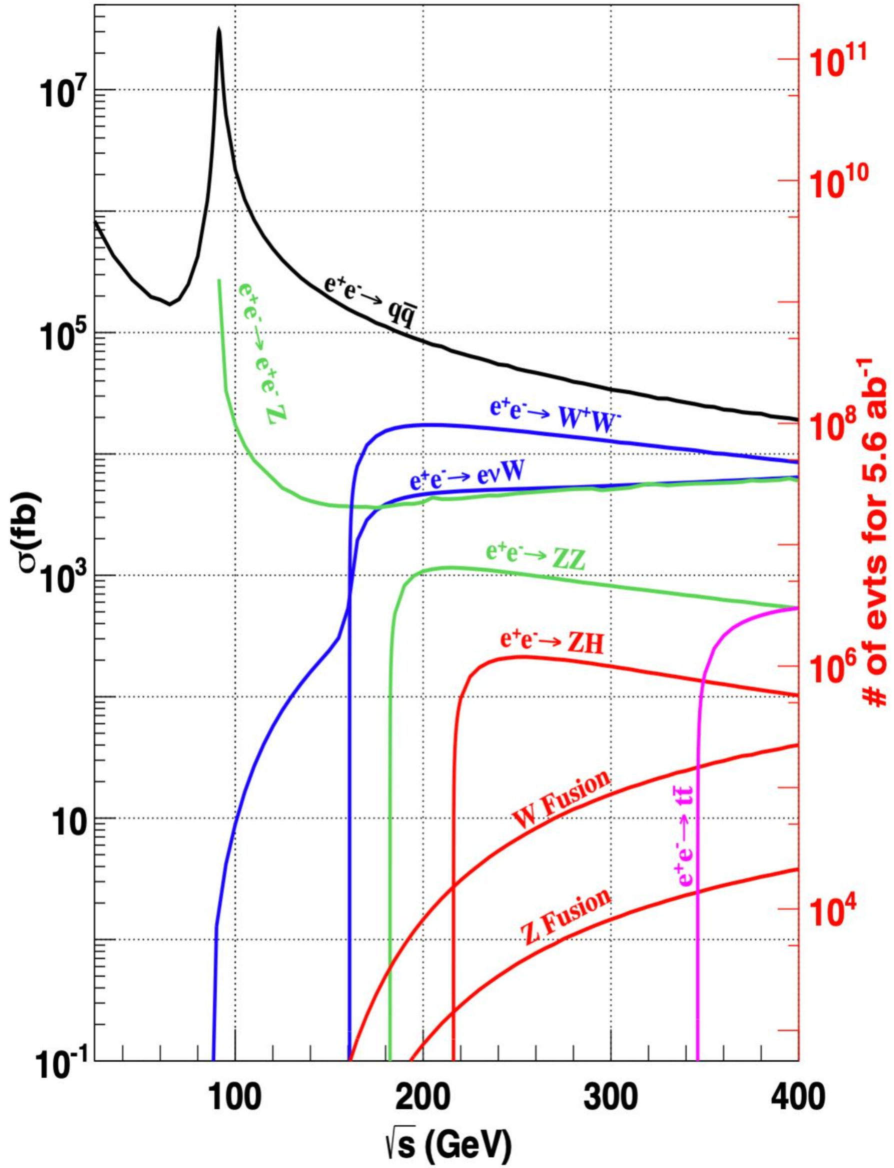
- Transverse beam polarization: center-of-mass energy measurable at 1 ppm
- High luminosity and high cross section at Z peak drives detector rate capabilities and accuracy requirements

- Beamstrahlung and synchrotron radiation dominate detector background
- Need to be minimized in Machine Detector Interface design

Future e^+e^- colliders



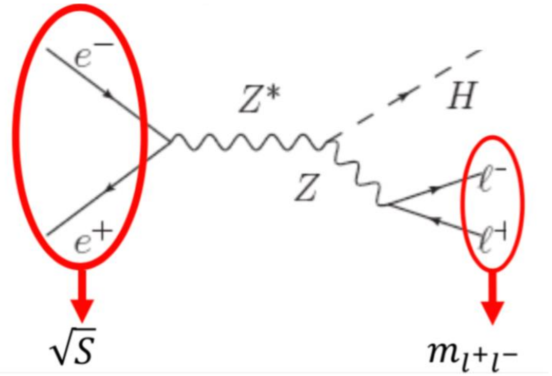
Physics rates



- Main constraint from Z peak running at circular machines
  - highest luminosities, large cross section
  - physics rate ~100 kHz
    - fast detector readout
    - triggerless readout may be challenging
    - zero suppression of data
    - occupancy at detector O(Hz/cm^2)
  - down to 100 Hz at $\sqrt{s} = 160\ \mathrm{GeV}$
- O(10 kHz) Bhabha scattering

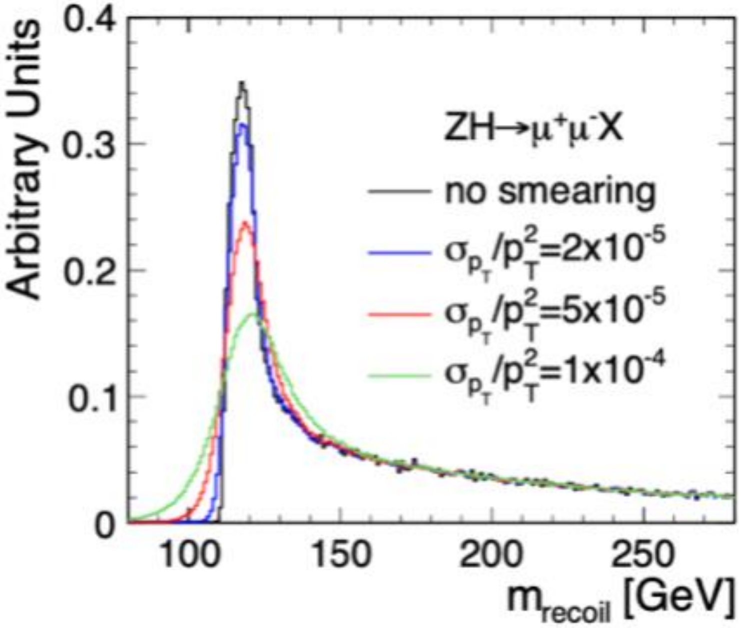
Physics requirements: momentum resolution

- Higgs identification from the Z recoil mass
- Higgs mass measurement from recoil mass peak
  - target is $\sigma_{m_h} \sim \Gamma_h \sim 4\ \mathrm{MeV}$
  - achievable if $\frac{\sigma_{p_t}}{p_t^2} = 2 \times 10^{-5}\mathrm{GeV}^{-1}$
    or $\frac{\sigma_{p_t}}{p_t} \sim 10^{-3}$ at 45 GeV



$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

- Monitoring of the Beam Energy Spread if
  $\frac{\sigma_{p_t}}{p_t} < BES$
  $\mathrm{BES} = 0.16\%(\sqrt{s} = 250\ GeV), 0.13\%(\sqrt{s} = 91.2\ GeV)$



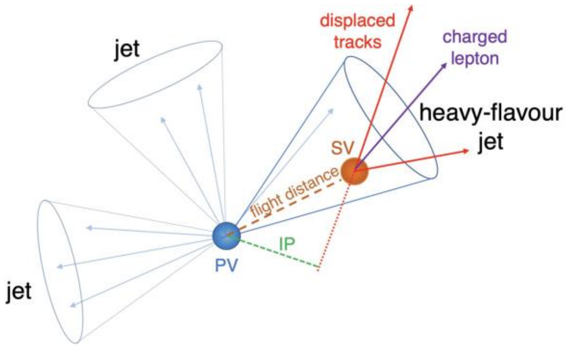
- $\sigma_{m_{ll}} \ll \Gamma_Z = 2.5\ \mathrm{GeV}$
  - no smearing of physical Z peak width

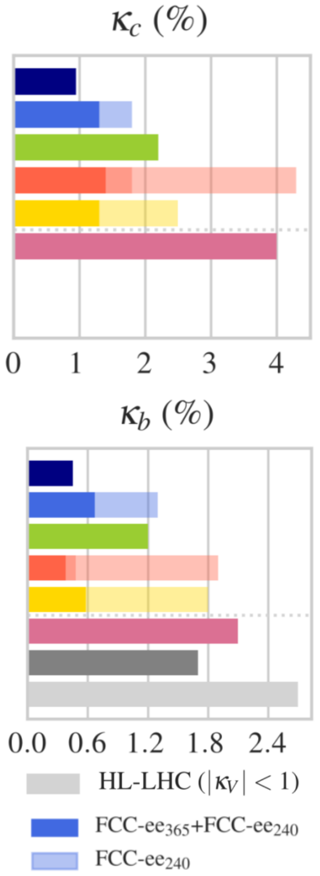
Physics requirements: position resolution

- Higgs identification from the Z recoil mass
- Model independent measurements of $BR(H \to b\bar{b}), BR(H \to c\bar{c}), BR(H \to g$
  - Difficult measurement at LHC
- Use of secondary vertices and displaced tracks
  - require good impact parameter resolution

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{\frac{3}{2}} \theta}, a = 5\ \mu\mathrm{m}, b = 15 \mu\mathrm{m} \cdot \mathrm{GeV}$$

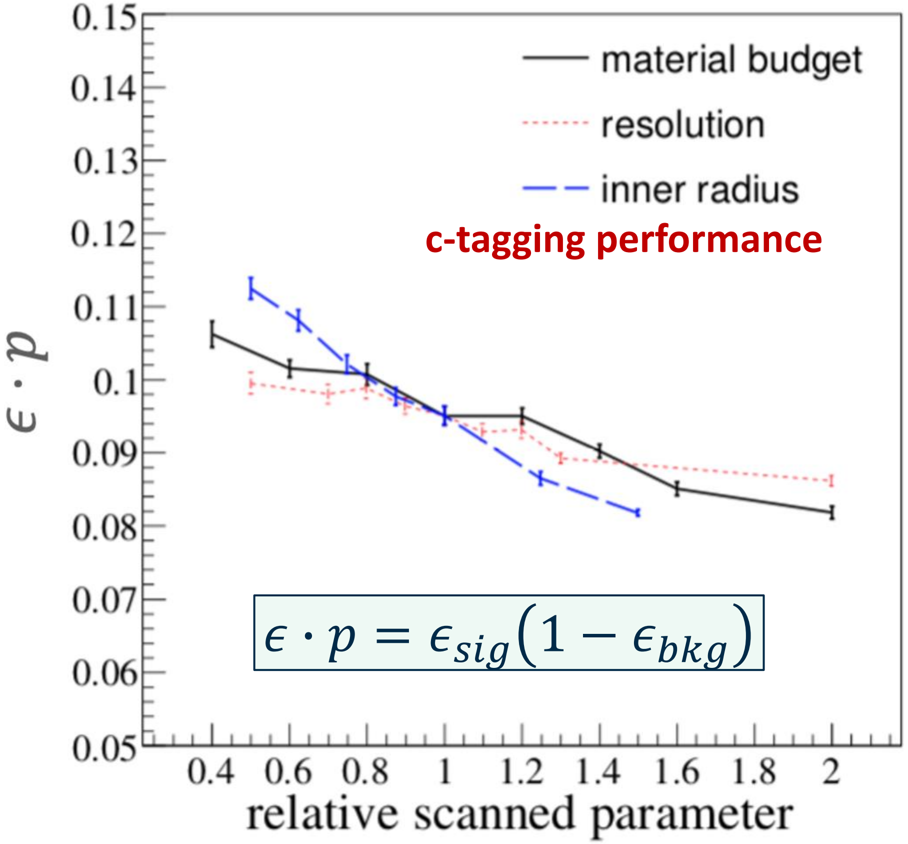
  - *b* more critical than *a*: optimize X_0, R_{in}





de Blas et al., 1905.03764

Manqi Ruan at *ECFA Topical workshop on tracking and vertexing 2023* and JHEP 11 (2022) 100
M. Selvaggi at FCC Week, London 2023



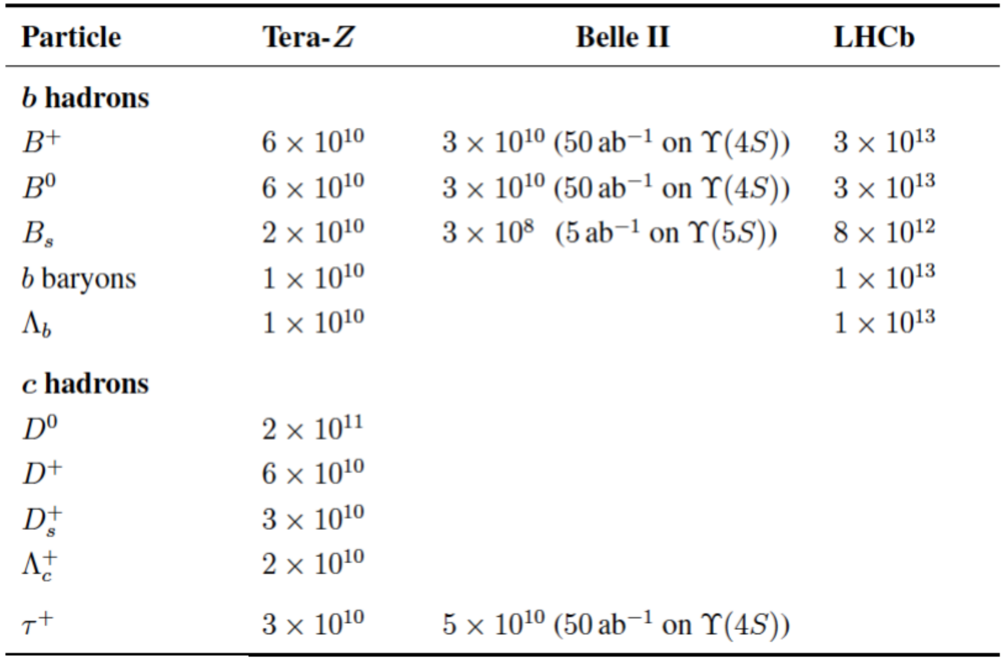
c-tagging performance

$$\boxed{\epsilon \cdot p = \epsilon_{sig}(1 - \epsilon_{bkg})}$$

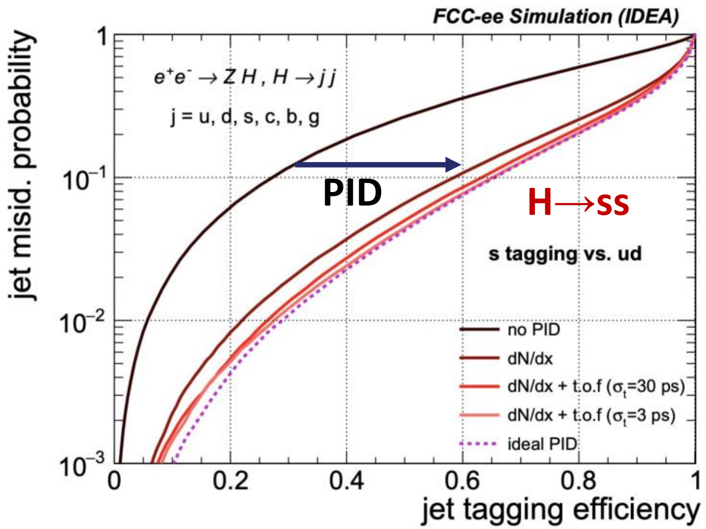
	Scenario A (Aggressive)	Scenario B (Baseline)	Scenario C (Conservative)
Material per layer/X_0	0.075 %	0.15%	0.3 %
Spatial resolution/μm	1.4 - 3	2.8 - 6	5 - 10.7
R_{in}/mm	8	16	23

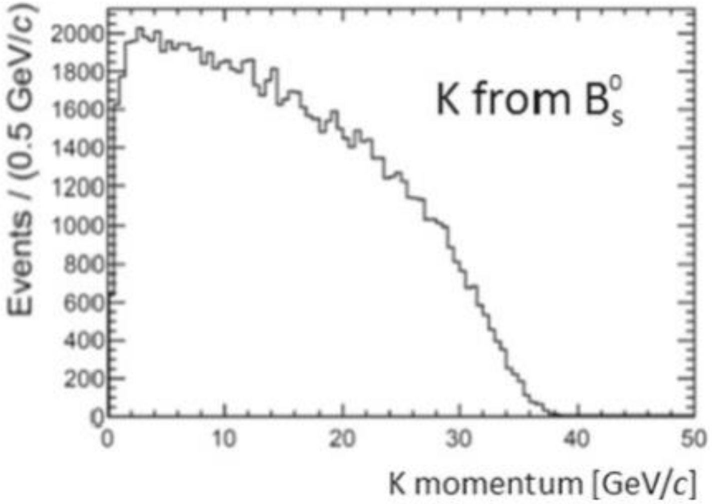
Physics requirements: PID

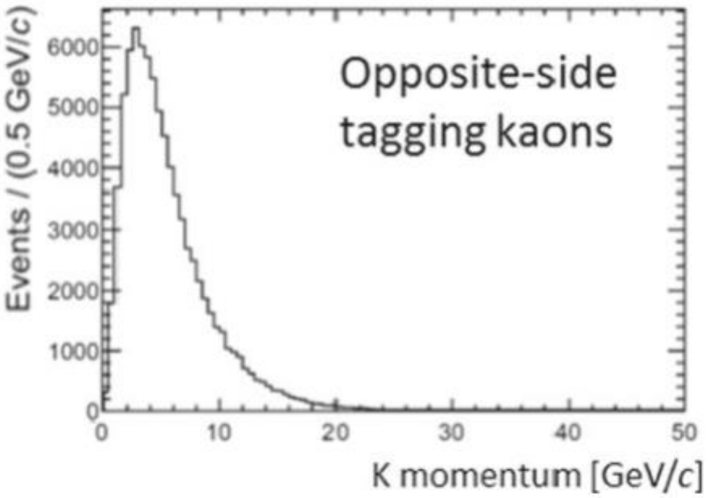
- A *Z*-factory is also a τ, *c*, *b* factory
- Particle Identification is essential for many physics measurements
- Needed on a wide momentum range
  - $B_s^0 \to D_s K$ has K up to 30 GeV/c
  - K for flavour tagging in $b \to c \to s$ decay chains are pretty soft
  - useful in tau physics for V_{us} measurements in $\tau \to K\nu$



Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	

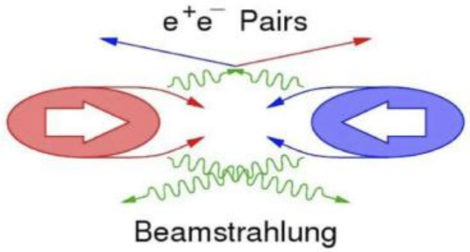


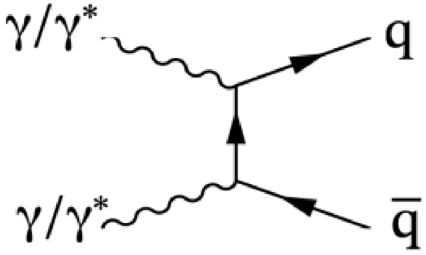


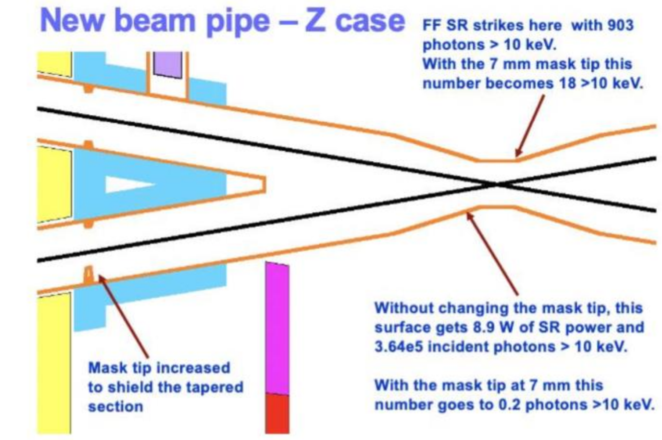


Machine Backgrounds

- Most relevant backgrounds at e^+e^- machines:
  - beamstrahlung (photons)
  - incoherent pair production (e^+e^-)
    - can lead to occupancy and energy in the detector
    - impact on space granularity, timing information
    - design of inner part of the detector
  - $\gamma\gamma \rightarrow q\bar{q}$ (hadrons)
  - synchrotron radiation (photons)
    - shielding in MDI
    - limits solenoid B-field
  - usually increasing with energy
- May sum up to count rates of 10-50 MHz/cm^2
- Radiation doses O(100 kRad/yr) – O(10^{11}n$_{eq}$/yr)



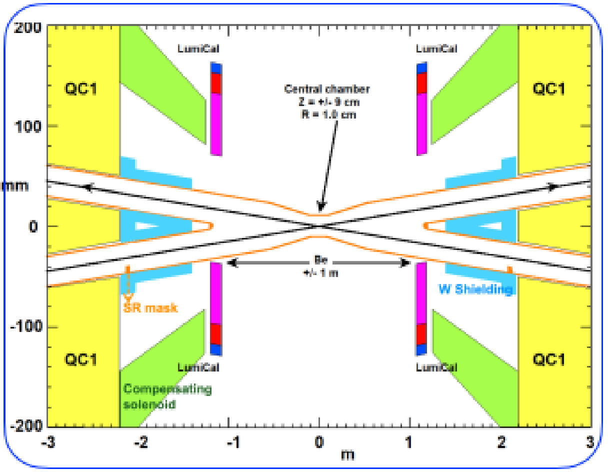




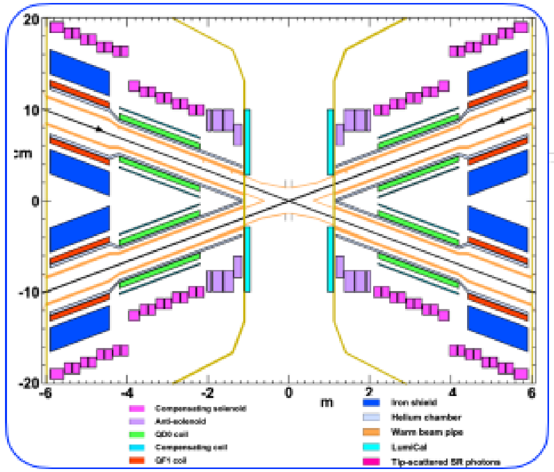
mask tips prevent FF quad radiation from striking nearby beam pipe elements

Interaction regions

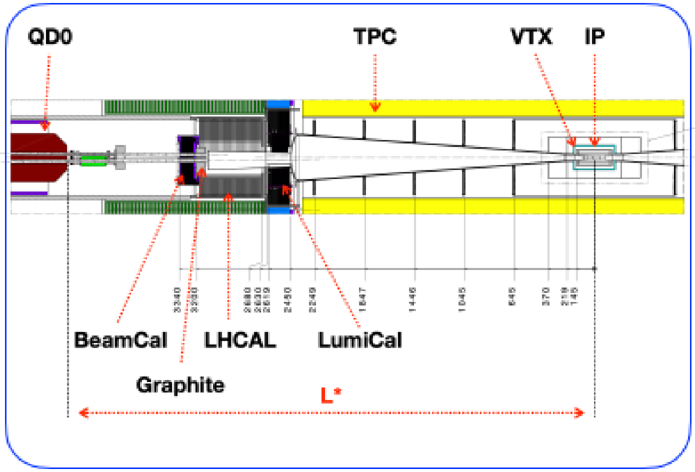
FCC-ee



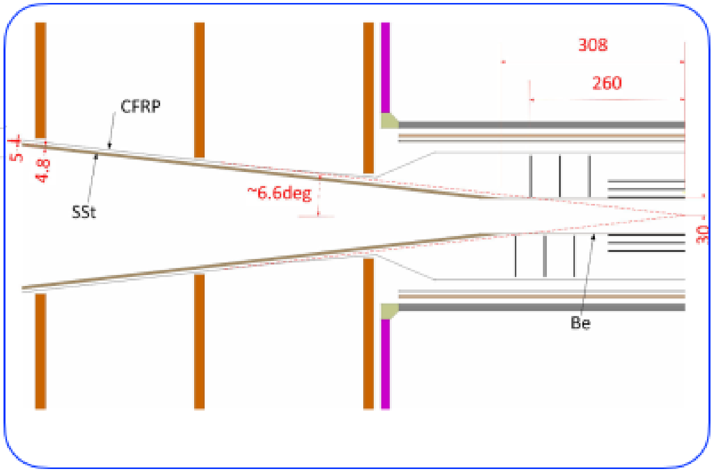
CEPC



ILC



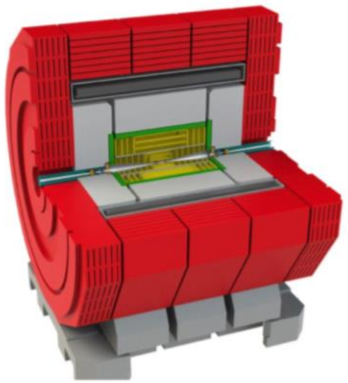
CLIC



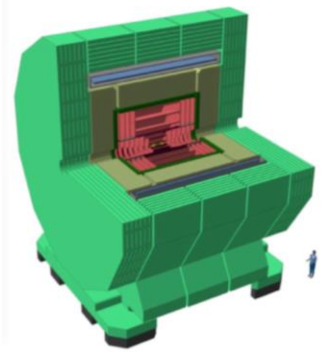
	FCC-ee	CEPC	ILC	CLIC
L* (Δz between IP and first	2.2 m	2.2 m	4.1 m	6 m
Position of final quadrupole	Inside detector	Inside detector	Outside detector	Outside detector
LumiCal position	z=1m, ~50-100 mrad (Constrained by compensating solenoid)	z~0.95~1.11m 26-105 mrad (fiducial volume 53-79 mrad)	z=2.5m, 33-80 mrad	z=2.5m, 39-134 mrad
Tracker acceptance	Down to ~9 degrees (defined by luminometer)	Down to ~8 degrees	Down to ~6° (defined by conical beam pipe)	Down to ~7° (defined by conical beam pipe)
Inner beam pipe radius	10 mm	10 mm	16 mm	29.4 mm
Crossing angle	30 mrad	33 mrad	14 mrad	20 mrad
Main solenoid B field	2T	3T (2T at Z pole)	3.5-5T	4T

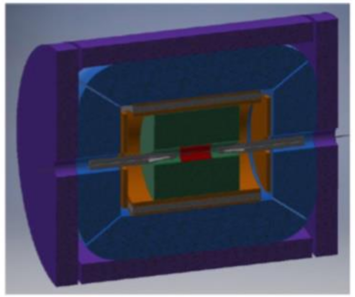
G. Marchiori at *ECFA Topical workshop on tracking and vertexing 2023*

Detector layouts



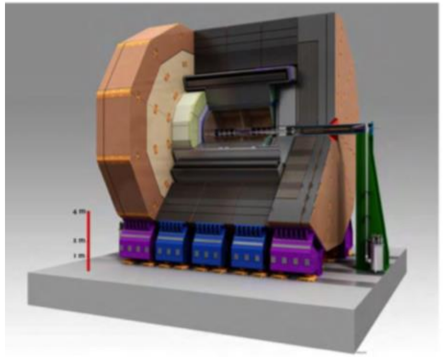
CLIC => **CLICdet**,
√s: 380 GeV, 1.5 TeV, 3 TeV

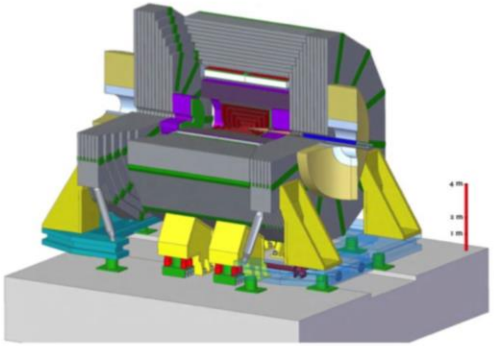




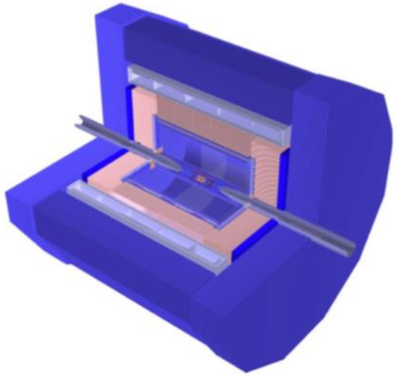
ALLEGRO

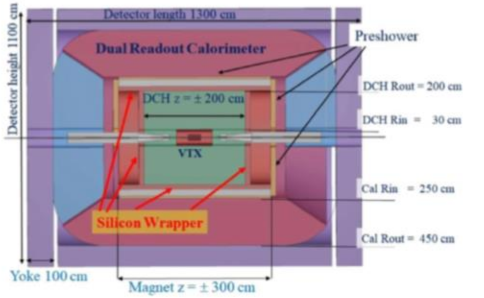
FCC-ee => **CLD** and **IDEA**
√s: 90 - 365 GeV



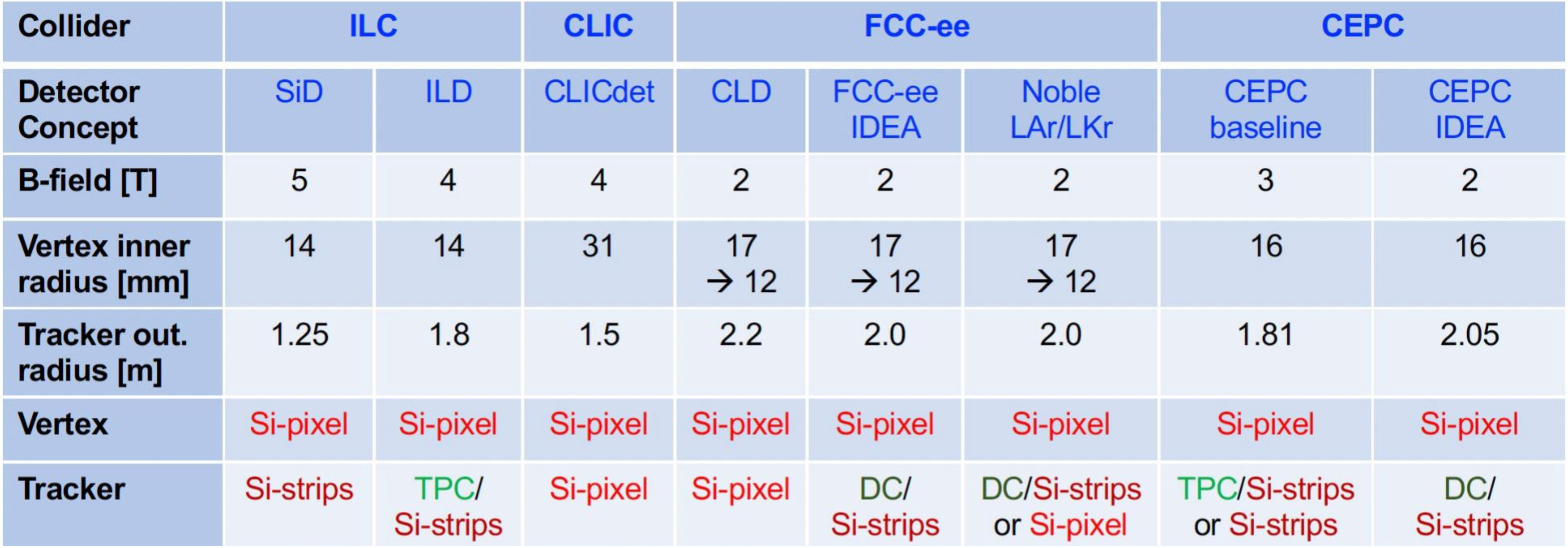


ILC => **ILD** and **SiD**:
√s: 250 – 500 GeV (1 TeV)





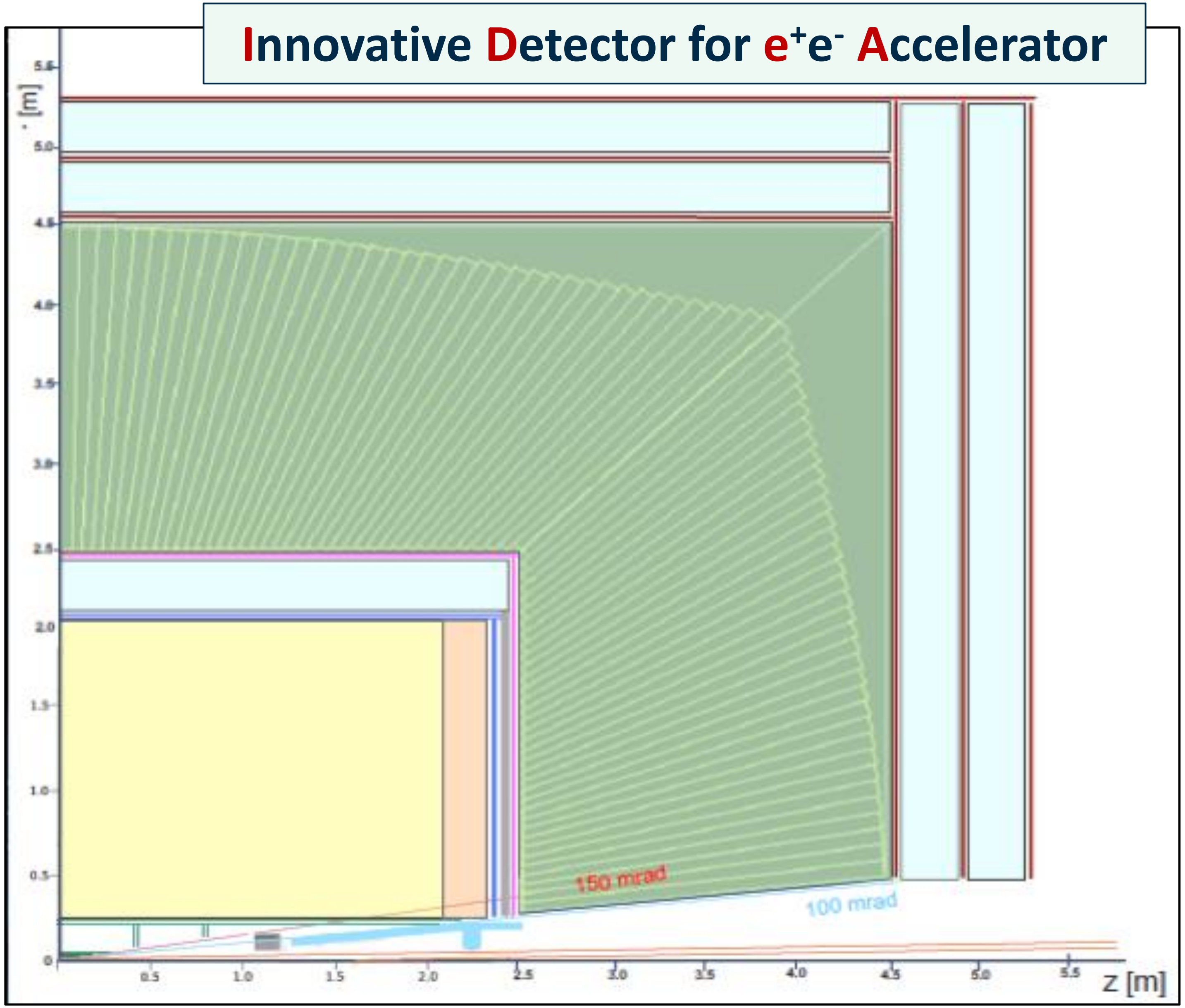
CEPC => **baseline** and **low-B**
√s: 90-240 GeV



Collider	ILC		CLIC	FCC-ee			CEPC	
Detector Concept	SiD	ILD	CLICdet	CLD	FCC-ee IDEA	Noble LAr/LKr	CEPC baseline	CEPC IDEA
B-field [T]	5	4	4	2	2	2	3	2
Vertex inner radius [mm]	14	14	31	17 → 12	17 → 12	17 → 12	16	16
Tracker out. radius [m]	1.25	1.8	1.5	2.2	2.0	2.0	1.81	2.05
Vertex	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel	Si-pixel
Tracker	Si-strips	TPC/ Si-strips	Si-pixel	Si-pixel	DC/ Si-strips	DC/Si-strips or Si-pixel	TPC/Si-strips or Si-strips	DC/ Si-strips

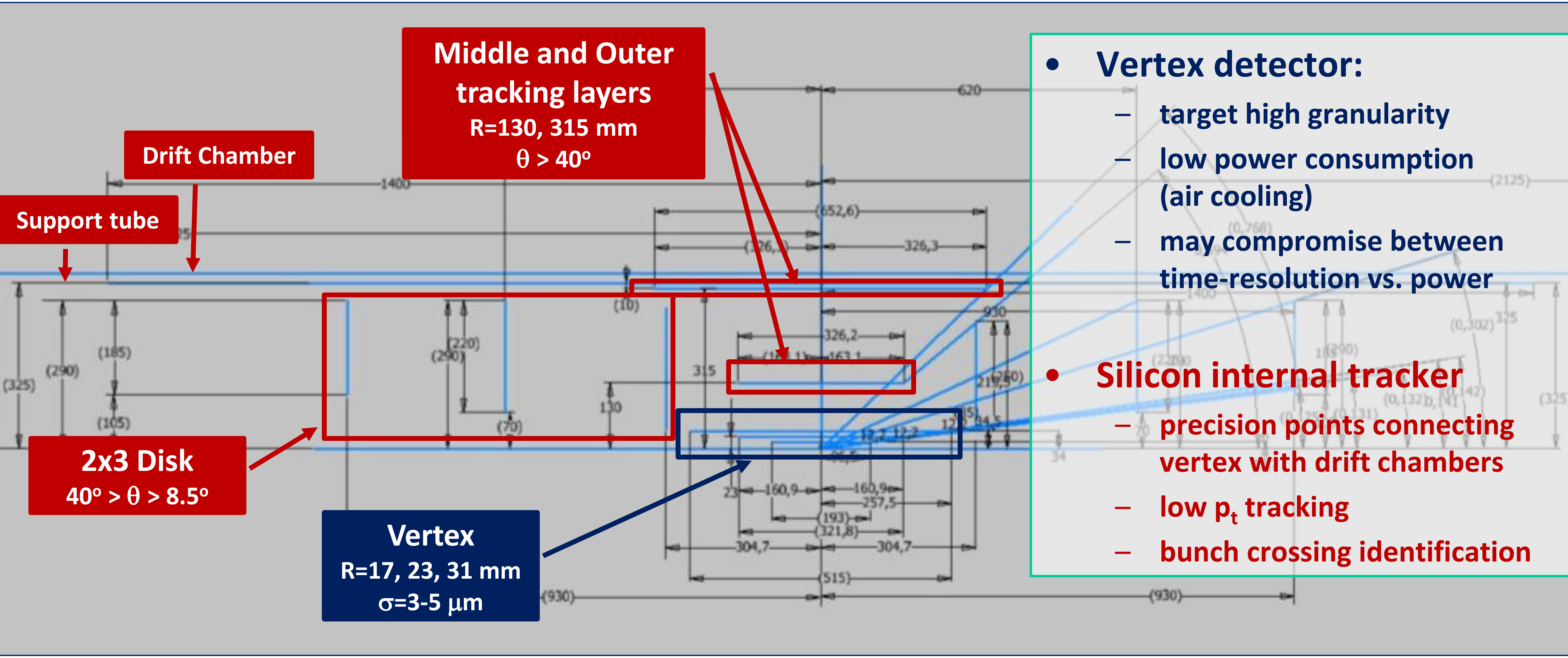
The IDEA Concept

Innovative Detector for e^+e^- Accelerator



- Central tracking device:
  - light Drift CHamber
- **Silicon detectors for precision measurements**
  - **vertex detector**
  - **silicon internal tracker**
  - **silicon wrapper/TOF**
- Thin solenoid with 2T field (according to MDI limits)
- Dual readout calorimeter
  - supplemented by a pre-shower detector
- Muon chambers in the solenoid return yoke

The IDEA Concept: inner tracking



Middle and Outer tracking layers
R=130, 315 mm
$\theta > 40^{o}$

Drift Chamber

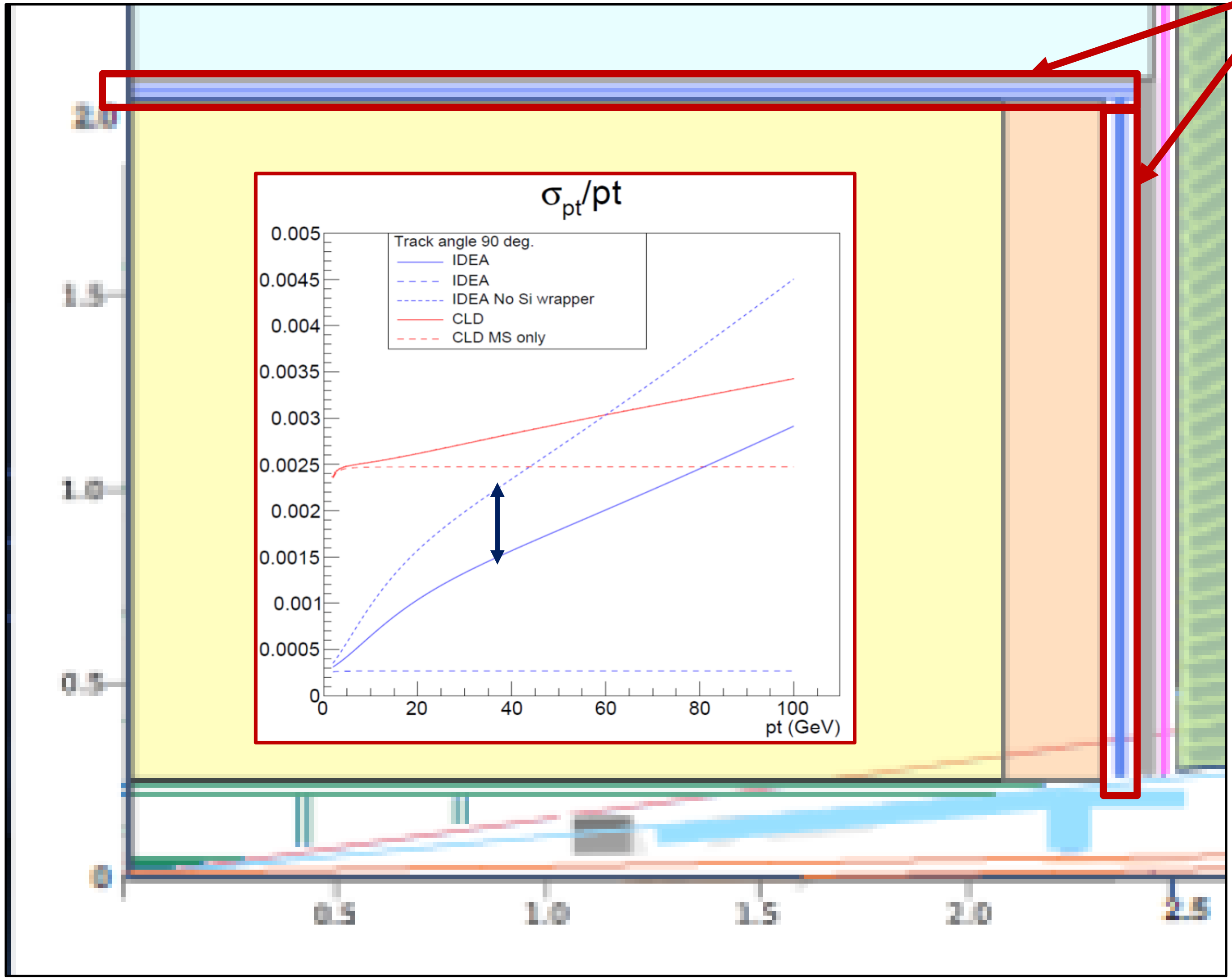
Support tube

2x3 Disk
$40^{o} > \theta > 8.5^{o}$

Vertex
R=17, 23, 31 mm
σ=3-5 μm

- **Vertex detector:**
  - target high granularity
  - low power consumption (air cooling)
  - may compromise between time-resolution vs. power
- **Silicon internal tracker**
  - precision points connecting vertex with drift chambers
  - low p_t tracking
  - bunch crossing identification

The IDEA Concept: Si Wrapper

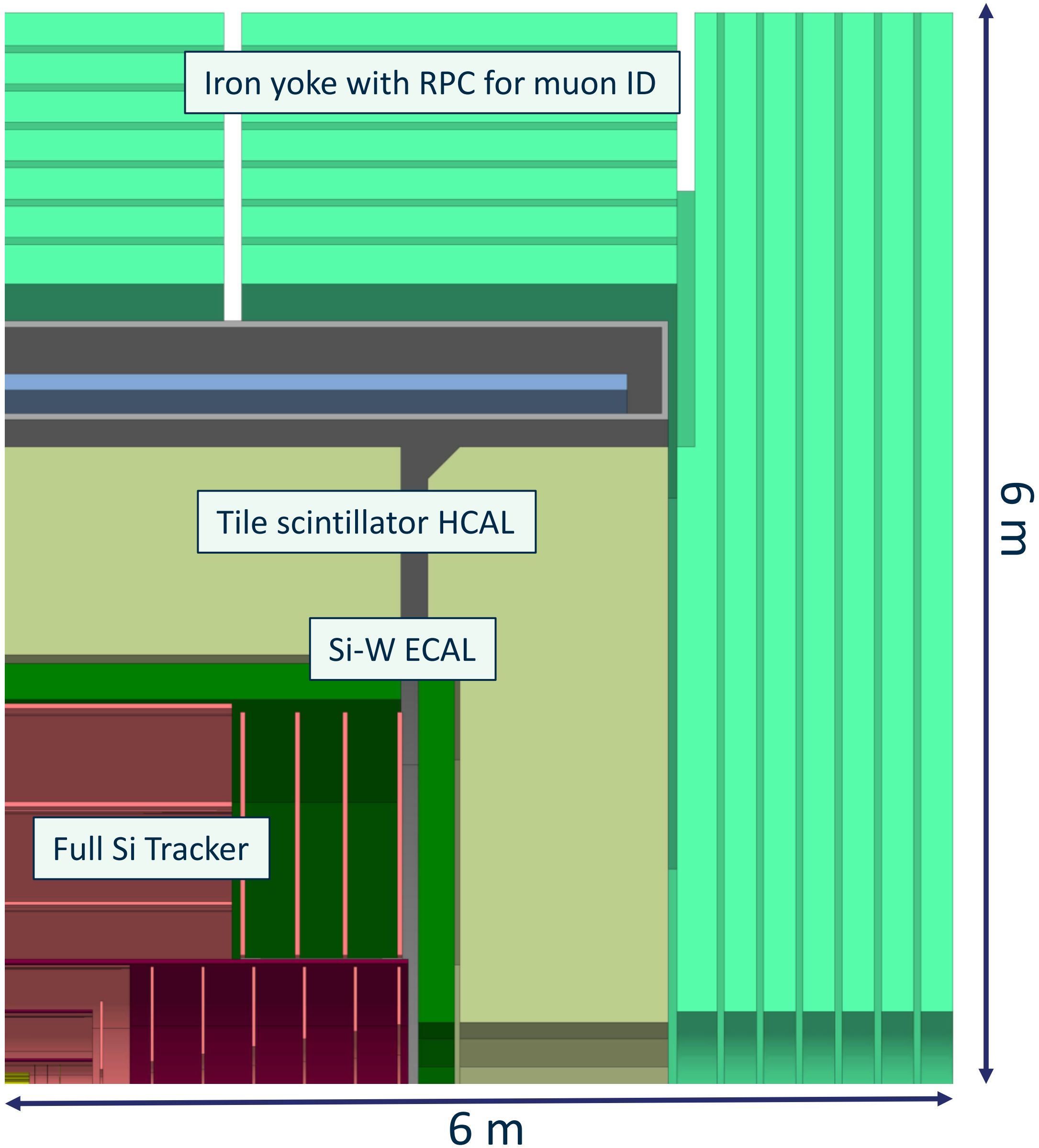


- **Precision silicon layer around the central tracker**
  - **improve momentum resolution**
  - **define θ resolution and acceptance**
  - **extend tracking coverage in the forward/backward region** by providing an additional point to particles with few measurements in the drift chamber
  - precise and stable ruler for acceptance definition
- Covered area ~90 m^2
  - important impact on services
  - technology suitable for large size production

The CLD Layout

Detector optimized for particle flow

- Outer Tracker:
  - 3 barrel+4 disks
  - 200 μm double Si-microstrip layers
  - 7 × 90 μm^2 resolution/layer
- Inner Tracker:
  - 3 barrel+7 disks
  - 200 μm double Si-microstrip layers
  - 7 × 90 μm^2 resolution/layer (5 × 5 μm^2 in the first disk)
- Vertex detector
  - R=13, 35, 57 mm
  - Pixel detector, 25 μm pitch
  - 3×3 μm^2 point resolution
- Design for ≥8 points/track for >8.5°
- Material budget 1.1-2.2% X_0/layer



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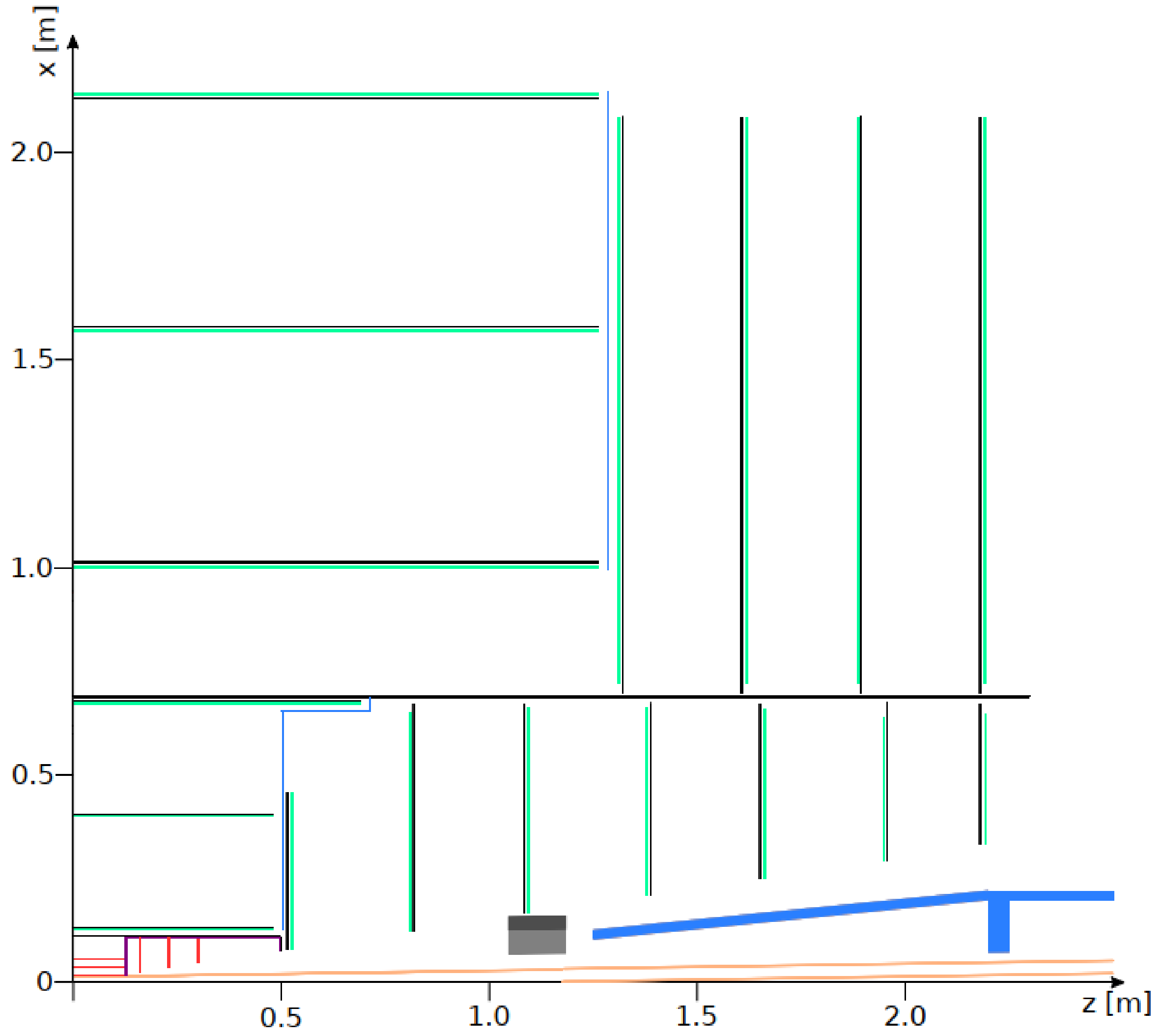
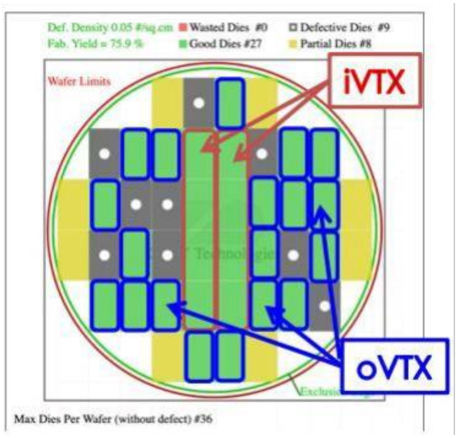
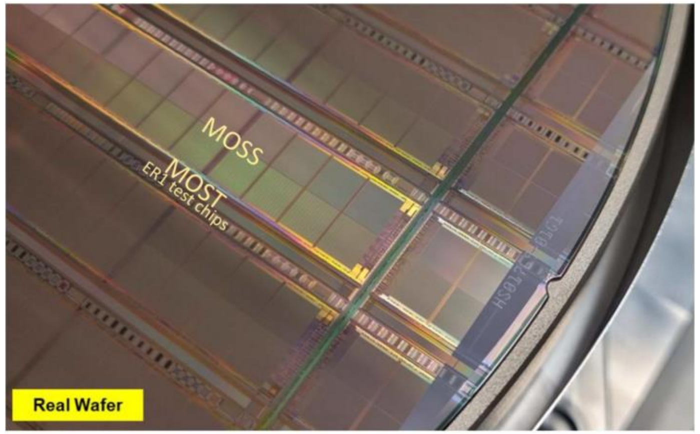


CLD_o2_v05 – A. Sailer at *2nd ECFA Workshop on H/EW/top factories*

Si Detector Technologies: Vertex

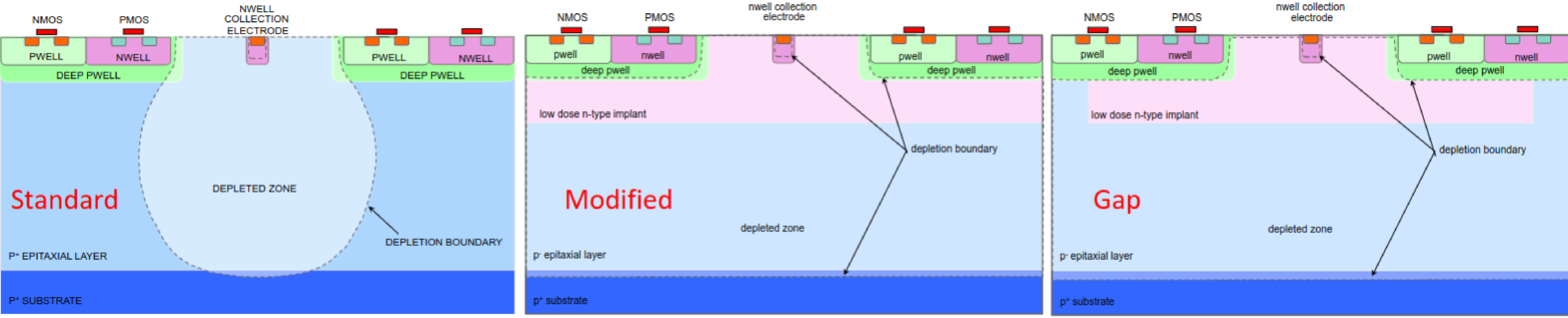
- In general focus on **depleted monolithic CMOS detectors**
  - High-Voltage/High-Resistivity CMOS processes commercially available
  - Depleted region provide fast rising and "high-amplitude" signals
  - No need of the complex and costly interconnection technique used in hybrid detectors
  - DRD7.6 support TPSCo 65 nm (ITS3) and LFoundry 110 nm (ARCADIA)
  - Low power to operate in the vertex region with air cooling
  - target 0.15% X_0/layer: develop self supporting structures integrating multiple chips
    - stitching and bending
  - open issue: do we need **time stamping at the Z pole**?





TPSCo 65 nm

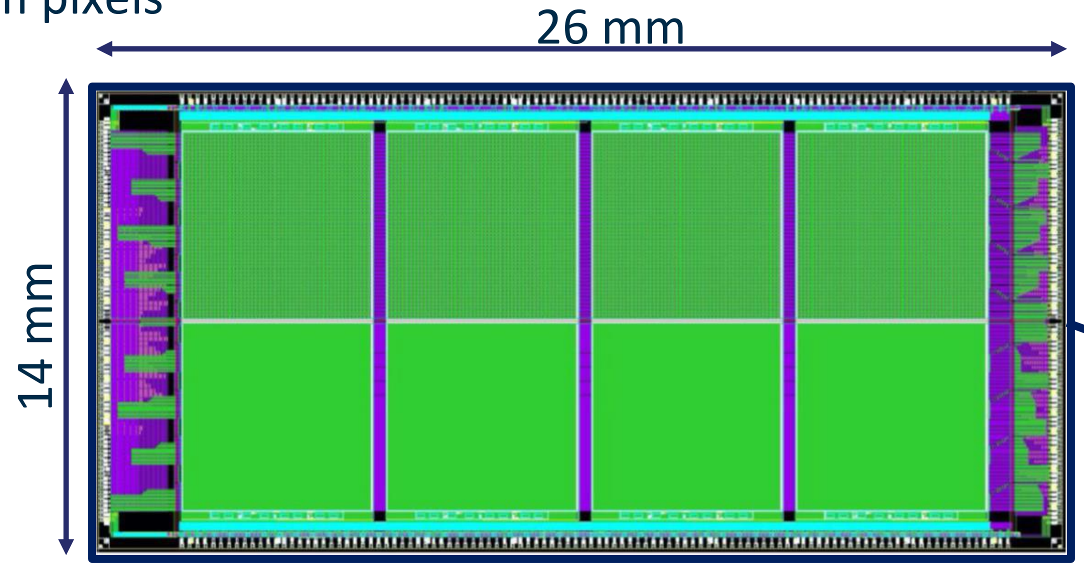
- TowerJazz 65 nm node
  - extensive experience on the TJ 180 nm node: Alpide, MALTA, TJ_Monopix, OBELIX
  - Better spatial resolution due to smaller feature size
  - Larger wafers: 300 mm vs 200 mm
  - Lower power consumption: power supply 1.2 V vs 1.8 V
- Provides 2D stitching
  - sensors up to 27x9 cm^2
- Thin sensitive layer ~10 μm
- Process modifications for full depletion:
  - Standard (no modifications)
  - Modified (low dose n-type implant)
  - Modified with gap (low dose n-type implant with gaps)

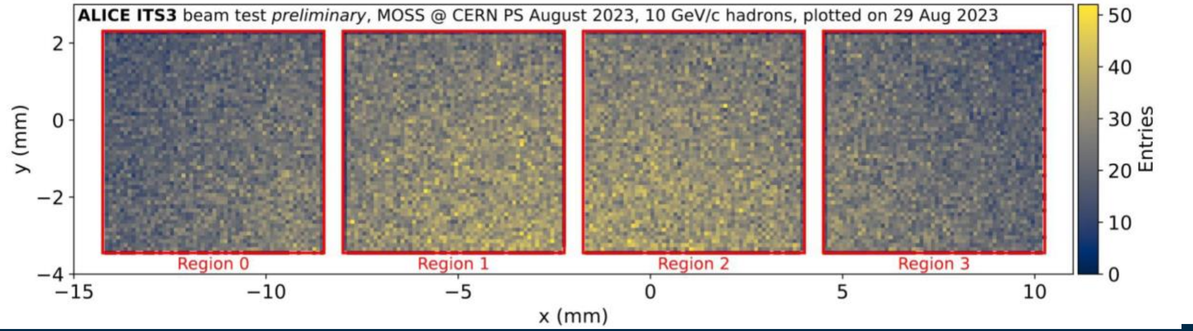


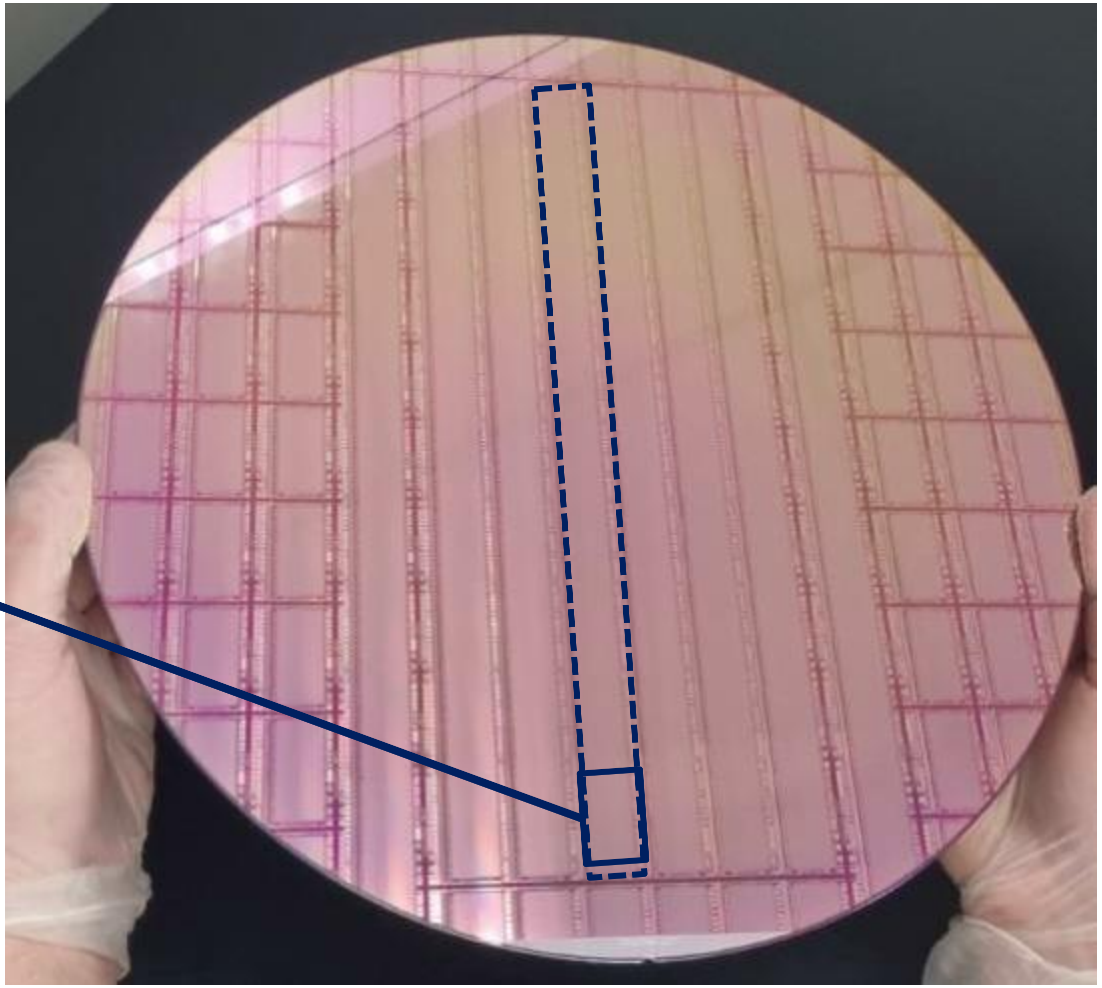
TPSco 65: Stitching

MOnolithic Stitched Sensor (MOSS)

- 25.2 × 1.4 cm^2
- 10 repeated sensor units with in-silicon interconnection
- 22.5 μm pixels



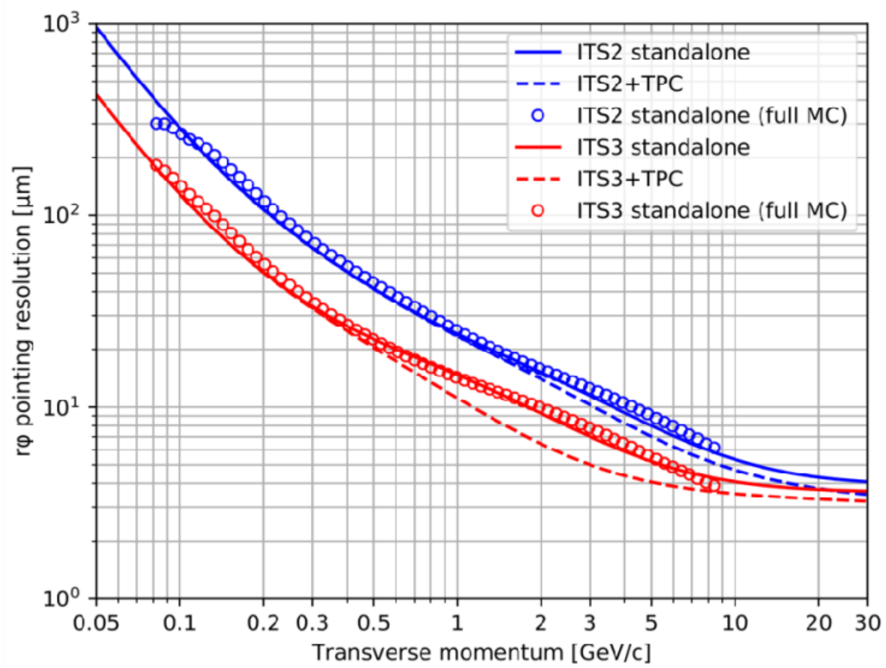




A. Villani – Maps Prototypes for ITS3 – *Vertex 2023*

TPSCo 65: Bent detectors

- Large area sensors can be thinned ane bent to build self supporting structure
- Approach explored for ALICE ITS3 upgrade
- Drastic improvement in the multiple scattering term



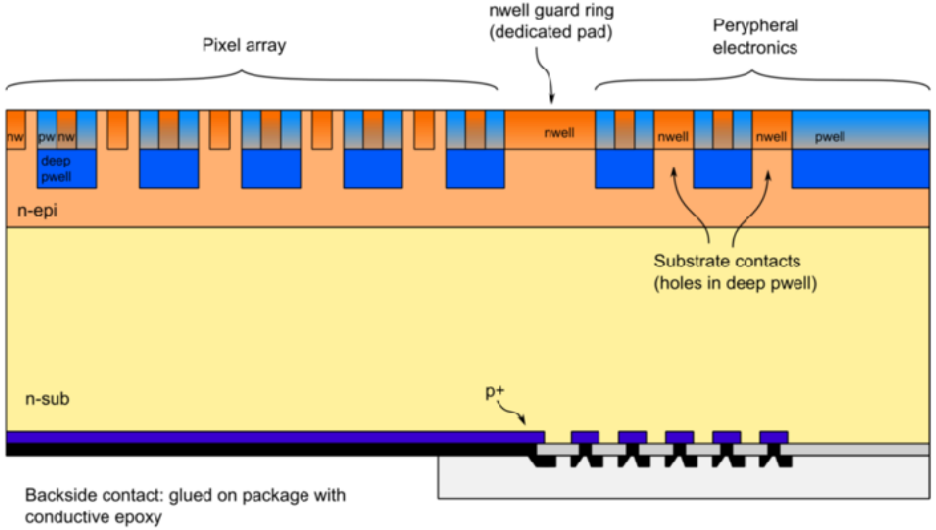
M. Magner, 2023 Workshop on CEPC – European Edition, Edinburgh

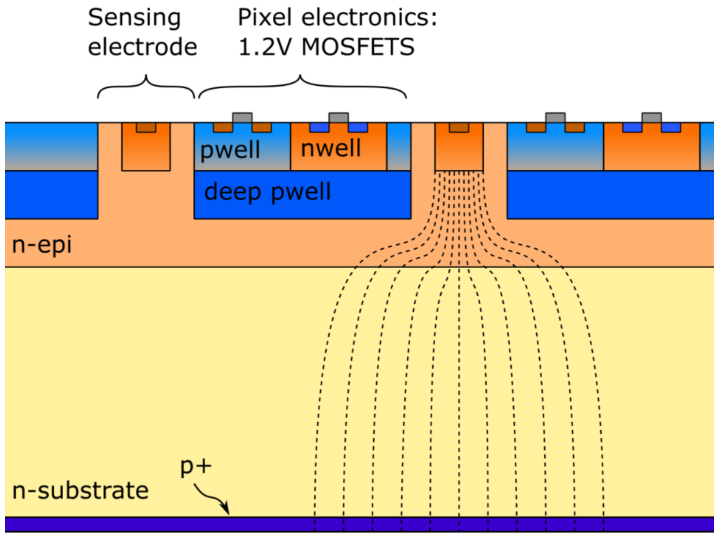
ARCADIA

Advanced Readout CMOS Architectures with Depleted Integrated sensor Arrays

Fully Depleted Monolithic Active Pixel CMOS sensor technology platform allowing for:

- Active sensor thickness in the range 50 µm to 500 µm;
- Operation in **full depletion** with fast charge collection by drift
- **Small collecting electrode** for optimal signal-to-noise ratio;
- Scalable readout architecture with ultra-low power capability O(**10 mW/cm^2**);
- Compatibility with standard CMOS fabrication processes: concept study with small-scale test structure (SEED), technology demonstration with large area sensors (ARCADIA)
- Technology: **LF11is** 110nm CMOS node (quad-well, both PMOS and NMOS), high-resistivity bulk
- Custom patterned backside, patented process developed in collaboration with LFoundry





ARCADIA: MD3 demonstrator

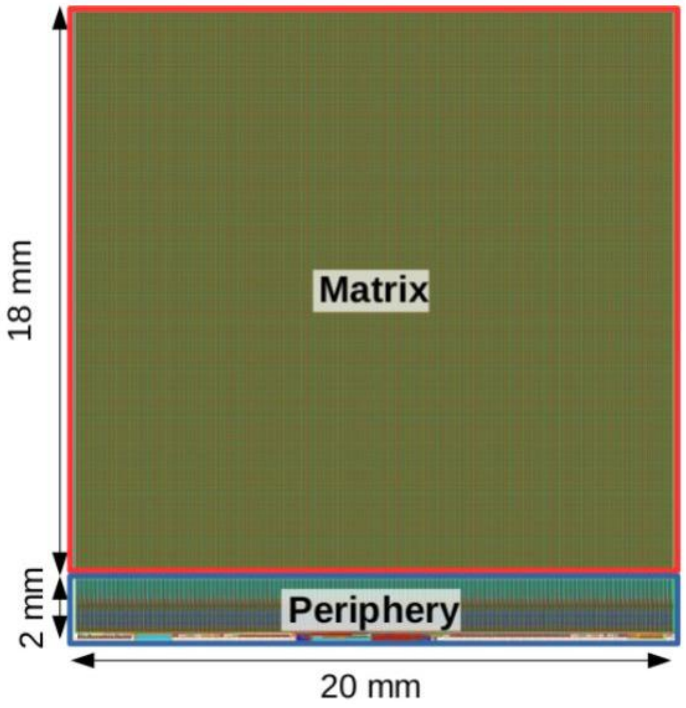
- Demonstrator layout:
  - **Top Padframe** Auxiliary supply, IR Drop Measure
  - **Matrix**
    - 512x512 pixels, Double Column arrangement
    - 25x25 μm^2 pixels
    - Clockless
  - **End of Sector (x16)** Reads and Configures 512x32 pixels
  - **Sector Biasing (x16)** Generates I/V biases for 512x32 pixels
  - **Periphery**
    - SPI, Configuration, 8b10b enc, Serializers
    - Triggerless data-driven readout
    - Event rate up to 100 MHz/cm^2
    - High-rate operation (16 Tx): 17-30 mW/cm^2
    - Low-power operation (1 Tx): 10 mW/cm^2
  - **Bottom Padframe** Stacked Power and Signal pads

Si Detector Technologies: Tracker

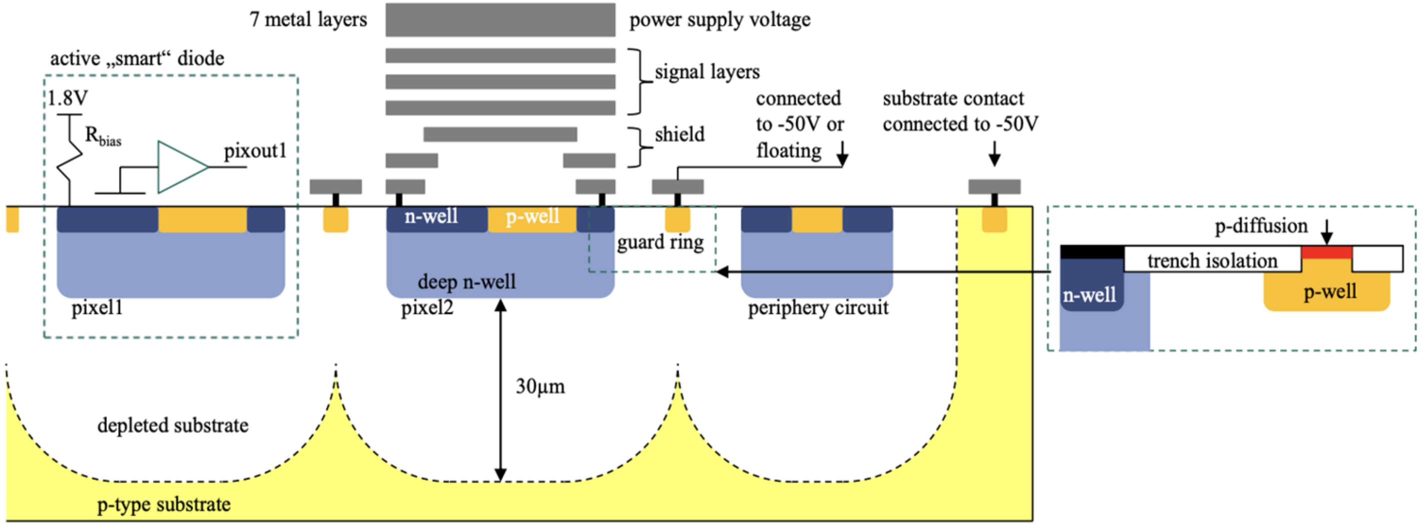
- Large silicon area to cover: ~100 m^2
  - Certainly Si-strips are able to sustain particle rates and radiation doses
  - But limited suppliers, even if passive CMOS strips are entering the game as an alternative procurement source
- **Depleted monolithic CMOS pixel detectors** are an option for large areas too
  - CMOS Foundries are able to produce large volume of detectors at a convenient price
  - Requirement on granularity and power consumption may be loose than for the vertex detector
  - Need at least time stamping of hits
  - To be practical need to aggregate multiple chips in larger units: **stitching**
  - Develop a power distribution scheme: **serial powering(?)** require HV capabilities, not available in all technologies

ATLASPIX3 Detector

- **ATLASPIX3 general features**
  - **TSI 180 nm HVCMOS** technology
  - full-reticle size **20×21 mm²** monolithic pixel sensor
  - 200 Ωcm substrate (other substrates up to 2 kΩcm also possible)
  - **132 columns of 372 pixels**
  - **pixel size 50×150 μm²** (25×150 μm² on recent prototypes)
  - **breakdown voltage ～-60 V**
  - up to **1.28 Gbps downlink**
  - **25 ns timestamping**
  - analog pixel matrix, digital processing in periphery

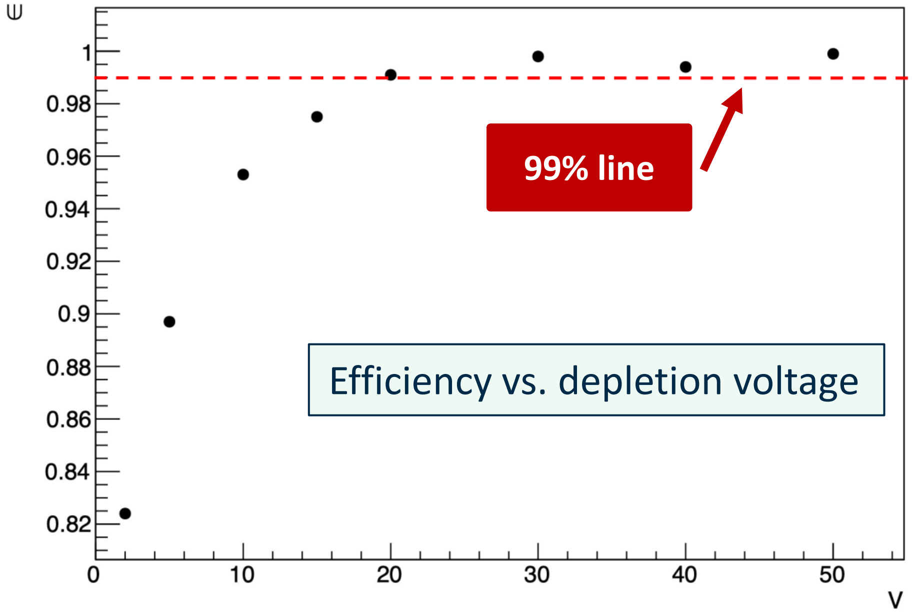


- Both **triggerless** and **triggered** readout modes:
  - two End of Column buffers
  - 372 hit buffers for triggerless readout
  - 80 trigger buffers for triggered readout



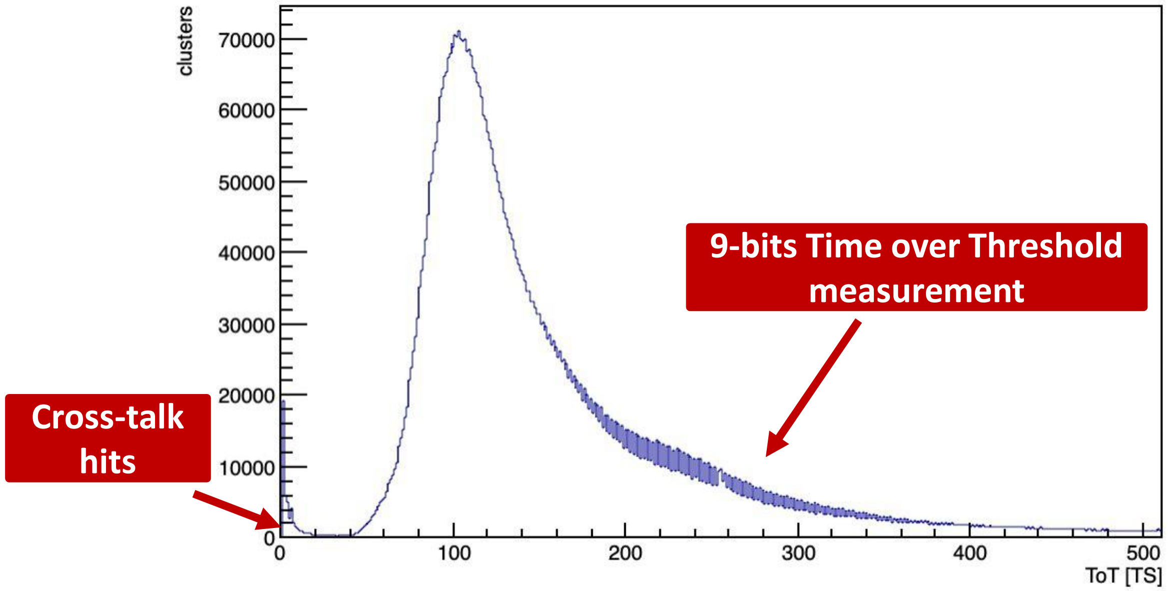
ATLASPIX3: Testbeam performance

- Telescope of 4 ATLASPIX3 single chips in DESY electron beam
- **Cross-talk** between pixels due to the capacitive coupling of the transmission lines between the matrix and the end-of-column logic is limited to **~1% of total hits**
- **Efficiency < 99%** and **uniform in the detector** for depletion voltages >20 V
- **Position resolution** in the **10-11 µm** range



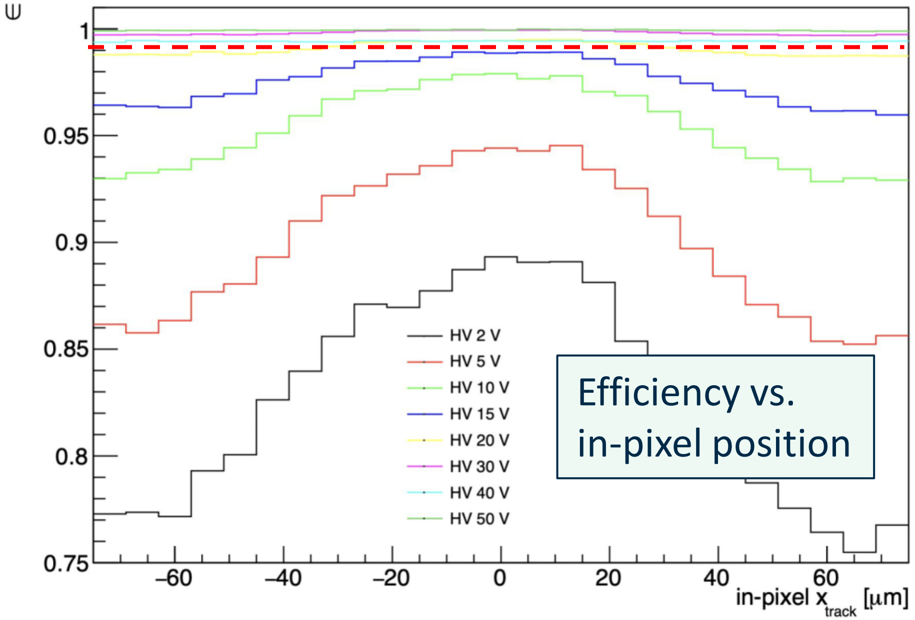
99% line

Efficiency vs. depletion voltage



9-bits Time over Threshold measurement

Cross-talk hits

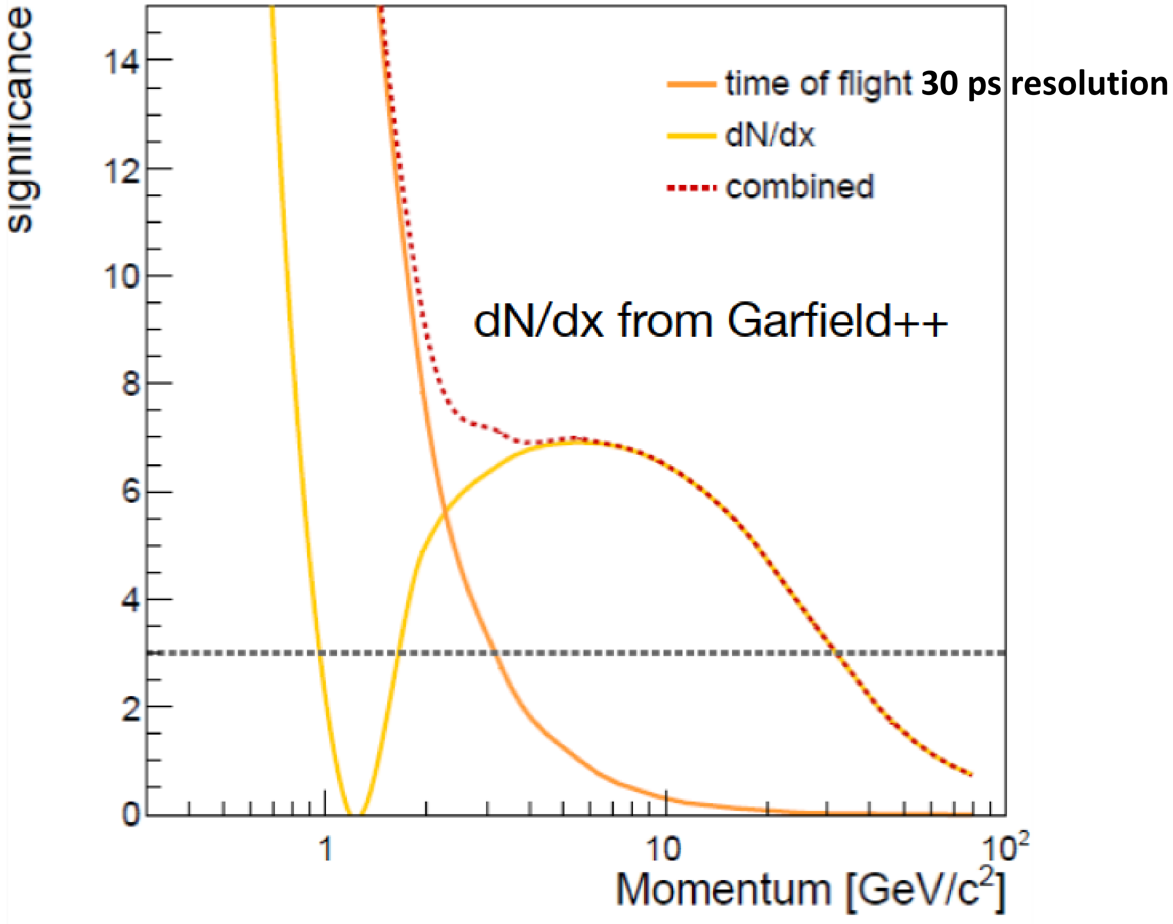


Efficiency vs. in-pixel position

TOF measurement in Si Wrapper

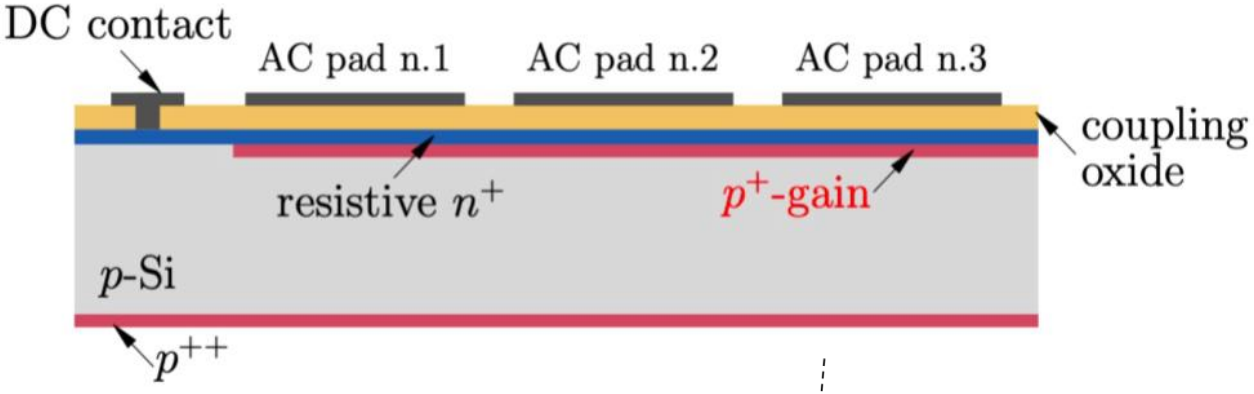
- **An interesting option** to investigate in the external tracker is to contribute to particle identification
- **dN/dx** measurements in Drift Chamber provides 3σ separation up to 30 GeV/c
- Confusion region about 1 GeV/c can be covered by **TOF** measurement with resolution **<100 ps**

- **Can it be implemented in the Si Wrapper without compromising the spatial resolution?**

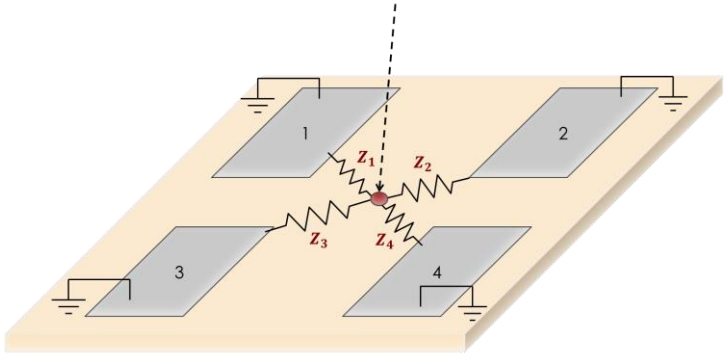


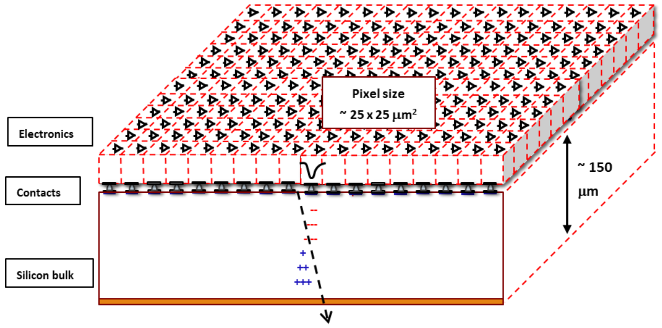
Resistive Silicon Detectors (RSD)

- LGAD detector with **continuous gain layer**
- Charge collection through **resistive n-layer**
- Readout by induction on **AC coupled pads**
- Fully active detector
  - avoids inefficient regions due to the insulation between pixels needed in LGAD sensors
- Charge sharing defined by the relative impedance of the path between the charge deposition and readout electrodes
  - pad pitch >> lateral dimension of charge deposit
  - sharing is deterministic (in low pitch pixel detectors is dominated by Landau fluctutations)
  - resolution depends on the S/N ratio of the readout electronics

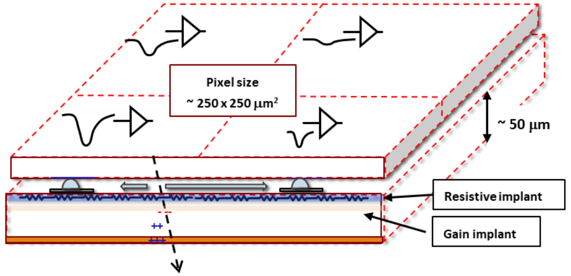


$$S_i = \frac{1/Z_i}{\sum 1/Z_i}$$





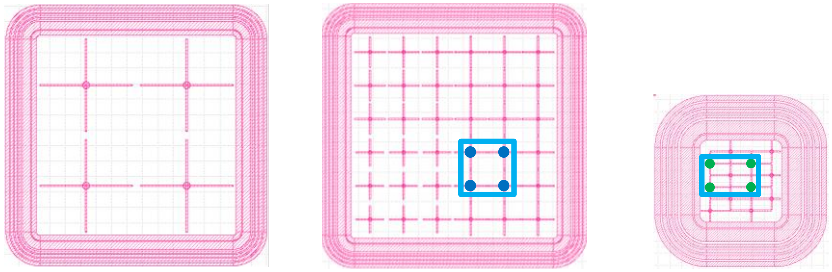
Standard Silicon Detector



Resistive Read-out Detector

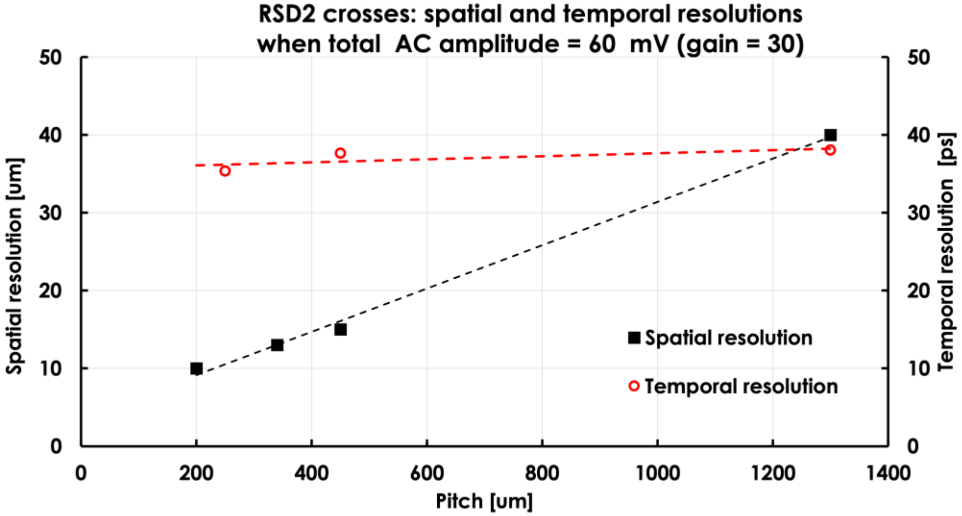
RSD: Prototype performance

- Spatial resolution << pixel pitch
  - 10 μm achieved in lab tests with 200 μm pixel pitch
  - more space in readout pixel cell to implement precision TDC
- Timing resolution about independent from pixel pitch
- Drawbacks:
  - hybrid detector (but bump-bond pitch is easily achievable commercially)
  - effective pitch is >2 readout pitch: particle flux limited by pixel size
- Suited for Si Wrapper:
  - particle density at 2 m from the interaction region should not be a concern for a e^+e^- colliders
  - no need to push for extremely low material: hybrid detector are acceptable



1.3 × 1.3 mm² 450 × 450 μm² 200 × 340 μm²

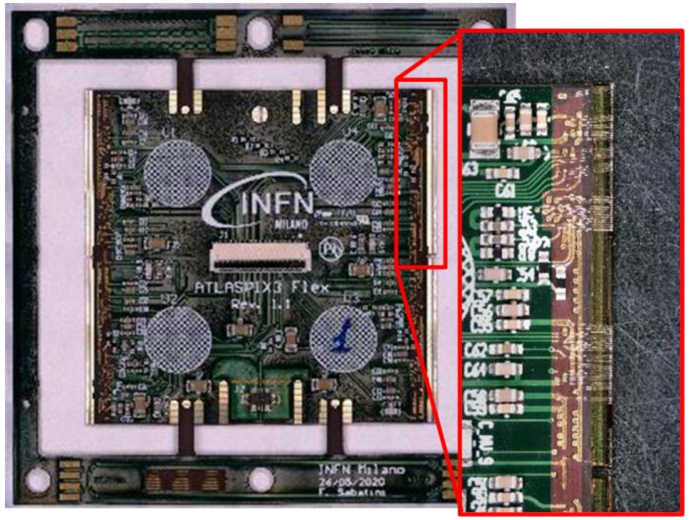
Cross-shaped electrodes



IDEA: integration with MDI

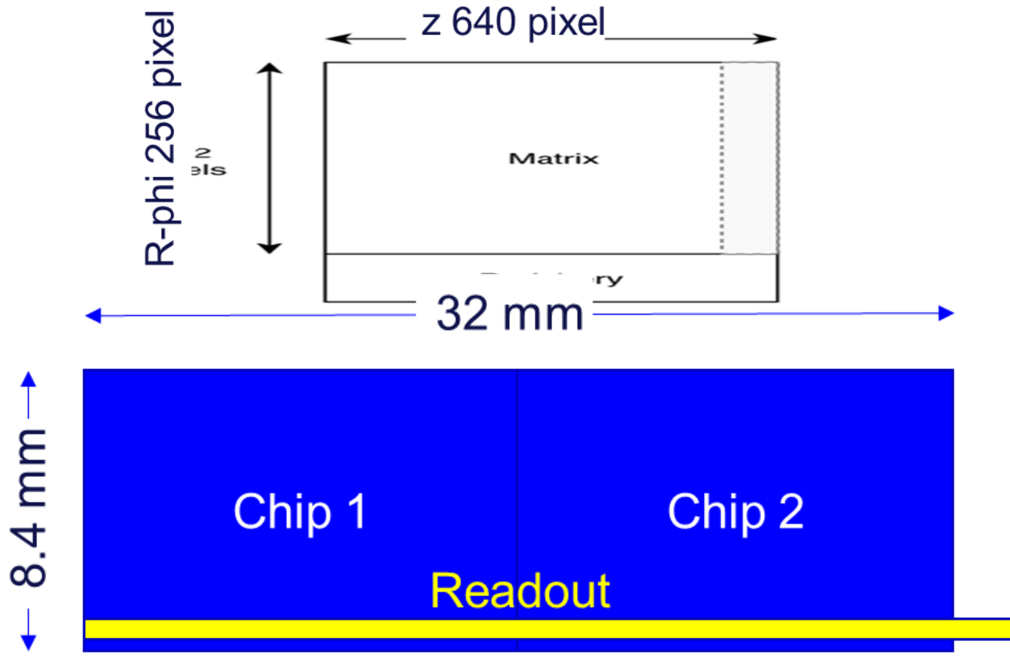
Internal tracker

- **Multi-chip** module **assembly**
  - **ATLASPIX3**: full size TSI 180 nm sensor
  - aggregates electrical services and connection for multiple sensors
  - **quad module**, inspired by ITk pixels
  - building block for staves and disks
  - implement serial powering capabilities (175 mW/cm^2)



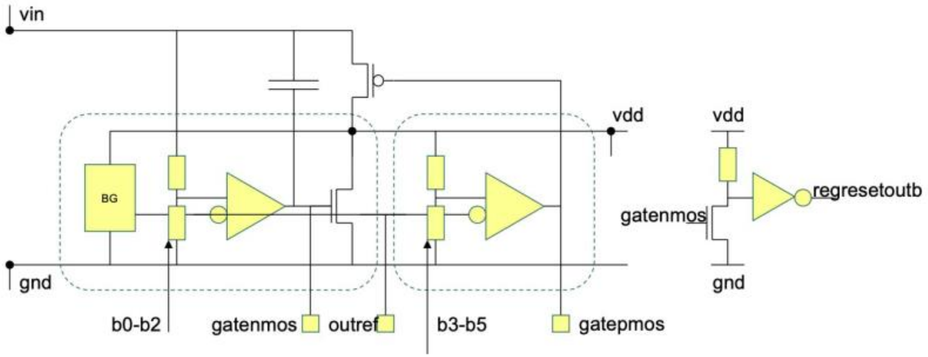
Vertex detector

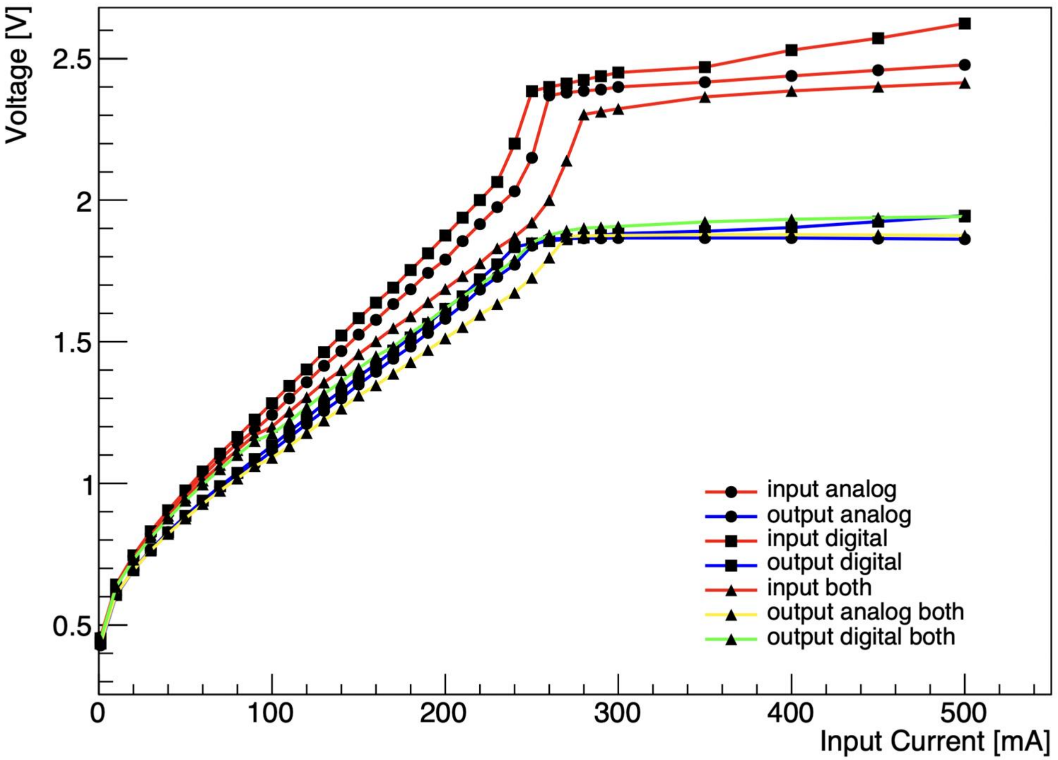
- **ARCADIA** inspired chip chain
  - Active area 640 pixel (16 mm) in z and 256 pixels (6.4 mm) in r−φ
  - Chip periphery plus an inactive zone: total of 2 mm in r−φ
  - Chips are side-abuttable in z
  - Power budget: assume 50 mW/cm^2 - including power and readout buses



ATLASPIX3: Serial powering

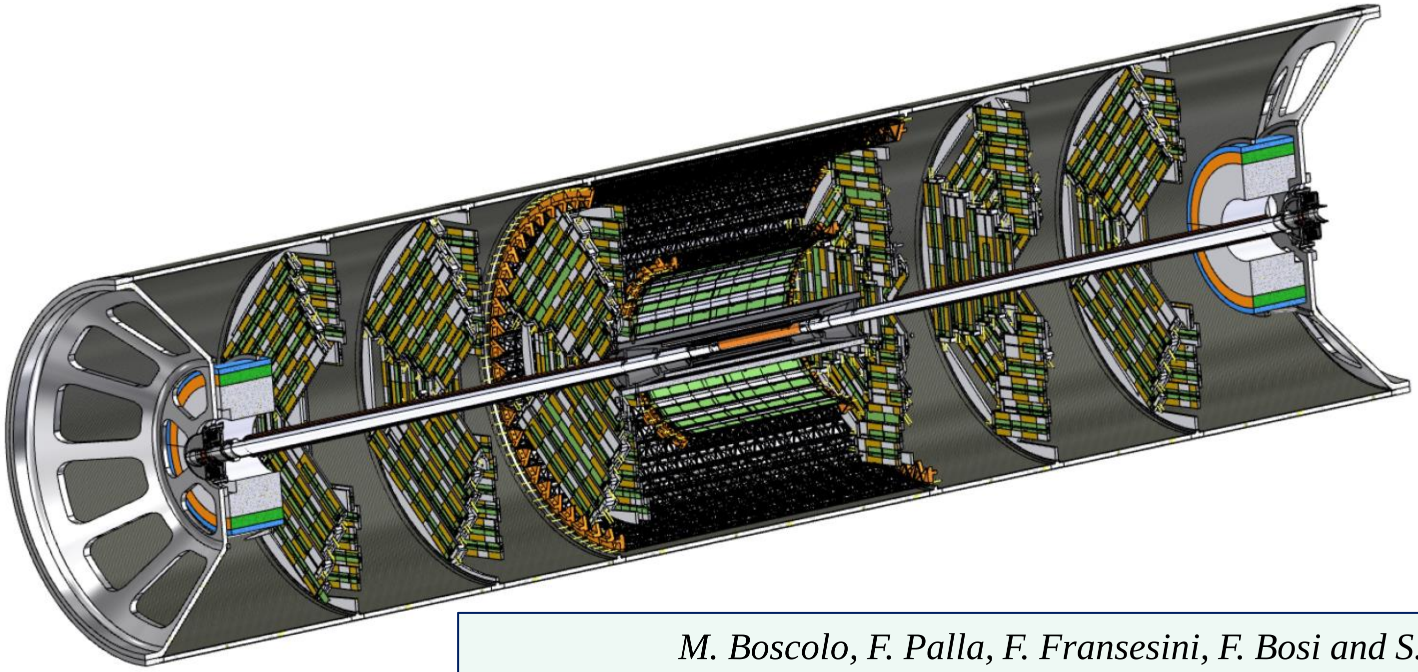
- Version ATLASPIX3.1 can be biased by serial powering through two shunt/low dropout regulators
  - digital and analog (VDDD/A)
  - 3 bits to tune threshold of shunt regulator
  - 3 bits to tune VDD
- Measured regulator performance
  - threshold and noise performance are the same usinfg SLDO or direct VDDD/A powering
  - DAC dinamic range of few tens of mV
  - Full chip turn-on at I=300 mA
  - Input voltage 2.3 V
  - Power consumption: ∼700 mW/chip or ∼175 mW/cm^2
- Integration model is to join modules by a bus implementing a serial powering chain
  - metal in the module hybrid and the power bus dominates the thickness of a detector layer (~0.44% X$_0$)
  - considering to move Al as conductor for PCBs

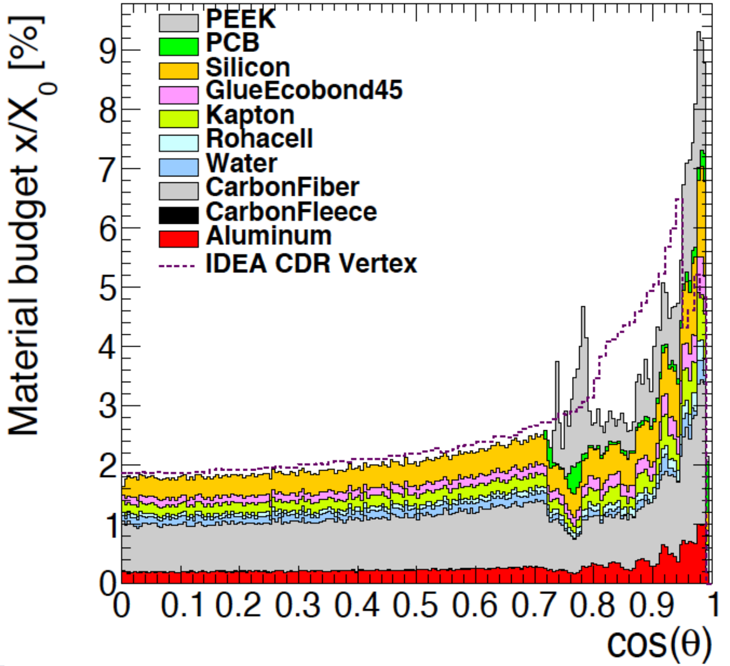




IDEA: integration with MDI

- Development with the FCCee MDI accelerator group
- Integration with **realistic** local support, cooling and electrical services
- Mockup to be build at LNF to demonstrate the interface with the machine and the mixel cooling
  - air cooling for vertex
  - watercooling for internal tracker





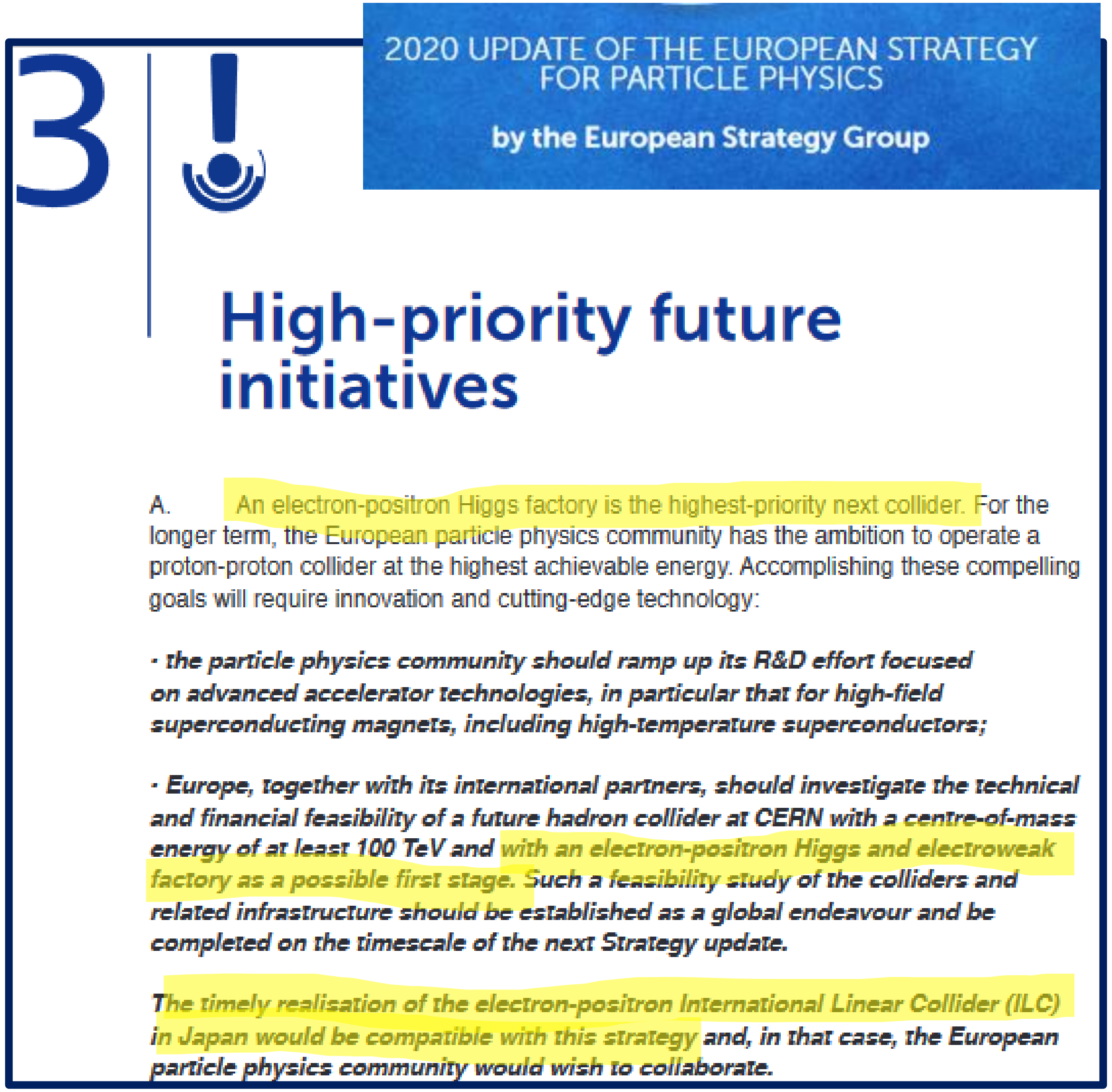
M. Boscolo, F. Palla, F. Fransesini, F. Bosi and S. Lauciani, Mechanical model for the FCC-ee MDI, *EPJ Techn Instrum* **10**, 16 (2023). https://doi.org/10.1140/epjti/s40485-023-00103-7

Summary and outlook

- Future Higgs factories are an important step in improving our understanding of QFT
  - Complementary to the HL-LHC physics program
  - Completing our understanding of the Higgs sector
  - Extending the program to lower energies (EW and flavour physics) and to higher energies (top mass and Higgs trilinear coupling
- There are stimulating technical challenges to face:
  - Can we have a vertex with <25 μm pitch, time stamping at 30 ns and 10 mW/cm^2 power?
  - Can we build a fully pixelated tracker (stitching, serial powering, technology node...)?
  - How do we perform PID in an effective way (cluster counting, TOF, cherenkov...)?
- Timeline is not closed yet: expect to start detector construction between early '30s and mid '40s
  - The technologies we are developing now are likely not the ones we will use then!
  - Nevertheless, building realistic prototypes with what is available now will allow to focus on some critical system issues:
    - **understand and improve**, instead of dreaming on paper and face reality reality later

BACKUP

e^+e^- Colliders: the next global machines



2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

3

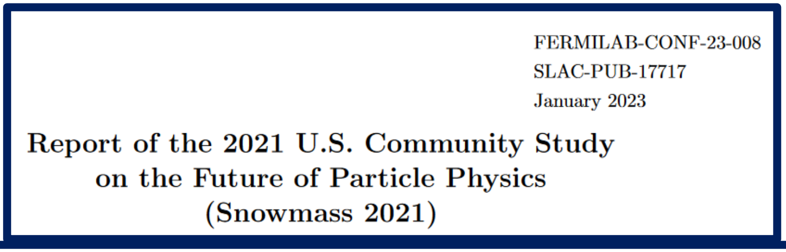
High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

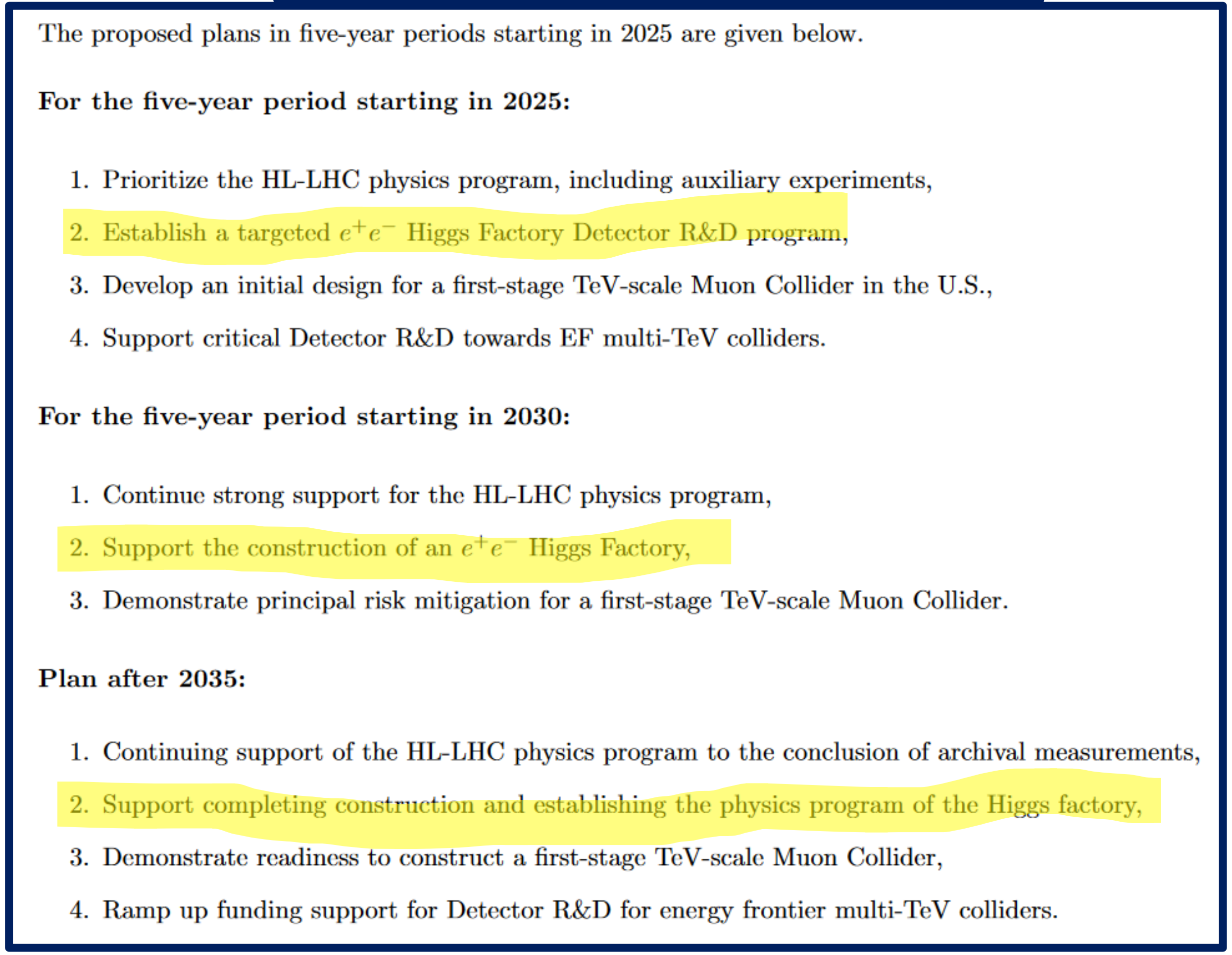
- ***Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.



FERMILAB-CONF-23-008
SLAC-PUB-17717
January 2023

Report of the 2021 U.S. Community Study
on the Future of Particle Physics
(Snowmass 2021)



The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

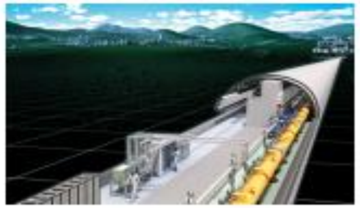
1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

Future e^+e^- colliders

- **ILC:**
  - Under consideration by the Japanese Ministry / Government as a **global project**
  - 2023: increased resources, ILC Technology Network established, incl. CERN (coordination for Europe)



- **FCC-ee**:
  - Feasibility study ongoing, very good progress in many areas, mid-term report expected in November 2023;
  - **Priority 1 for CERN / Europe (CERN Council)**
  - Outcome (technical feasibility, costs,…) decisive for Europe

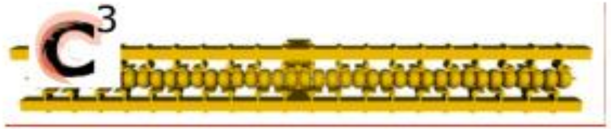
- **CEPC:**
  - TDR in preparation, incl. cost review
  - A lot of progress on the technical side
  - **Aiming for approval in next 5-year plan (2025)**
  - Ranked 1st in Chinese HEP preselection

- **CLIC**:
  - Possible alternative for CERN

    CLIC community is preparing a Project Readiness Report (PRR) for the next ESPP (2026/27)

- **CCC:**
  - R&D towards a demonstrator moving forward at SLAC;

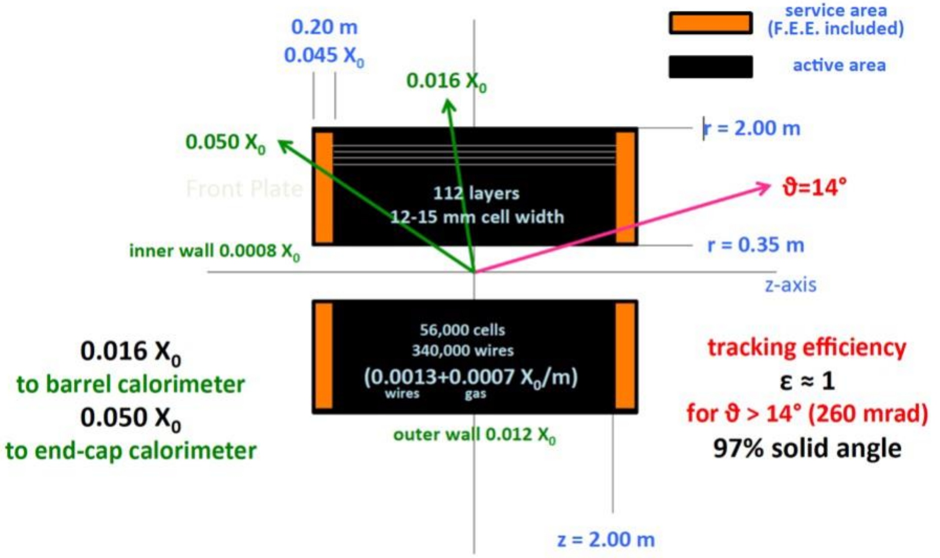
    Waiting for P5, and for a commitment of a laboratory to host it



Karl Jacobs at *2nd ECFA Workshop on H/EW/top factories*

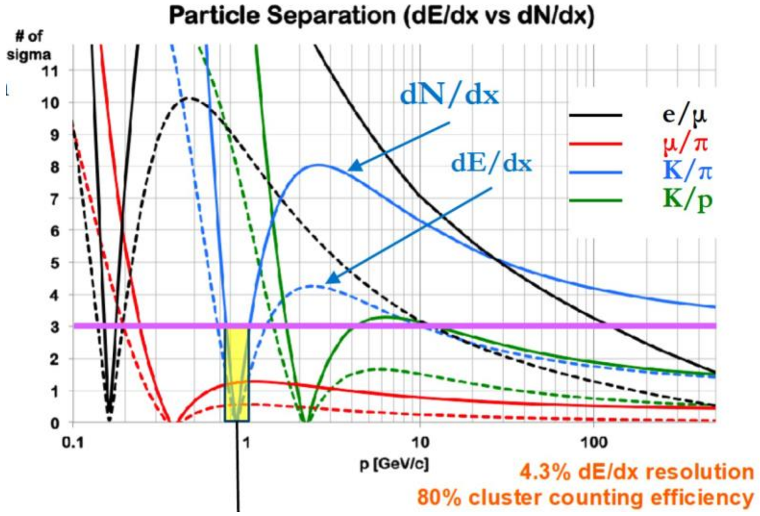
Gas tracker challenges: Drift chamber

- Long and small size drift chamber
  - 4 m wire length
  - >100 sampling on track
  - $\sigma_{R\phi}$~80 μm, σ_z ~ 0.6 mm (stereo)
- Increase wire tensile strength (C wires)
- Stress on mechanical structures
- Implement on-line pulse processing for cluser cour
  - improves position and dE/dx for particle ID

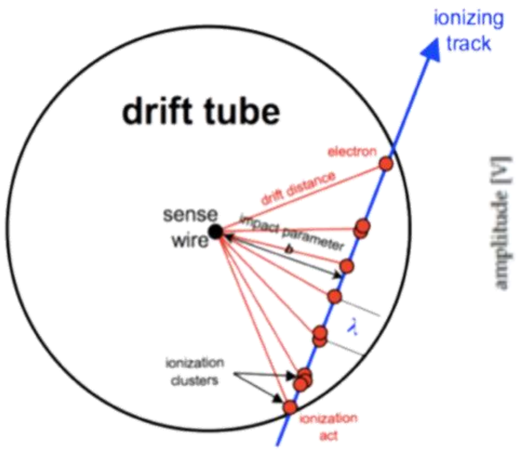


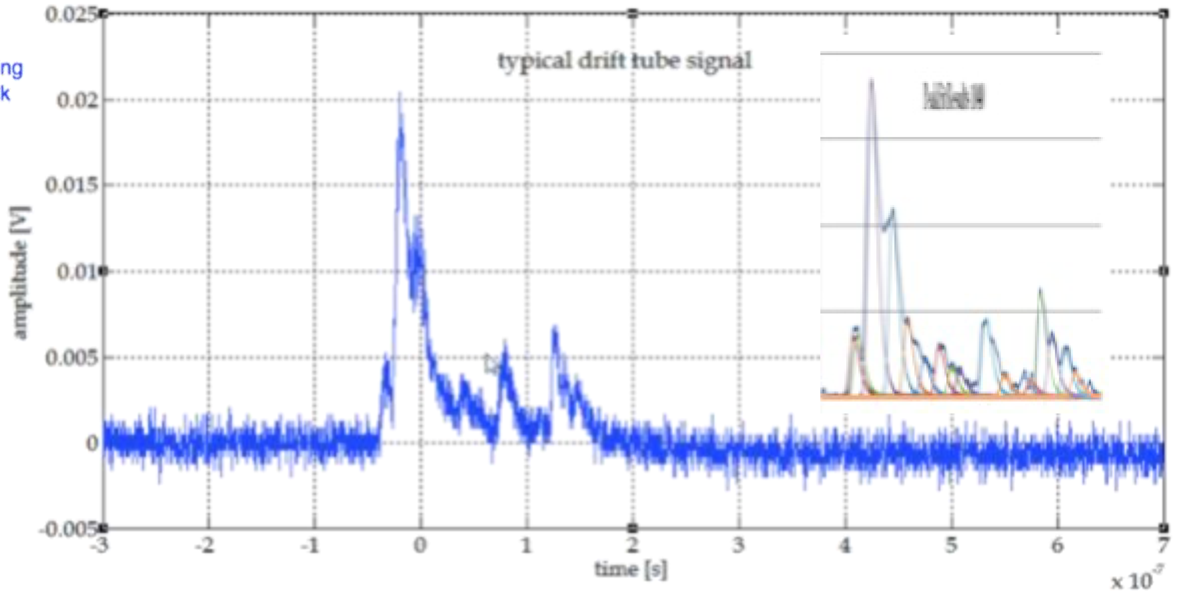
0.016 X_0 to barrel calorimeter
0.050 X_0 to end-cap calorimeter

tracking efficiency
ε ≈ 1
for ϑ > 14° (260 mrad)
97% solid angle



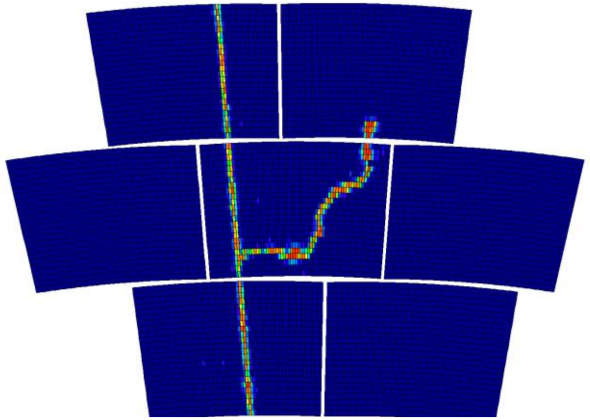
4.3% dE/dx resolution
80% cluster counting efficiency



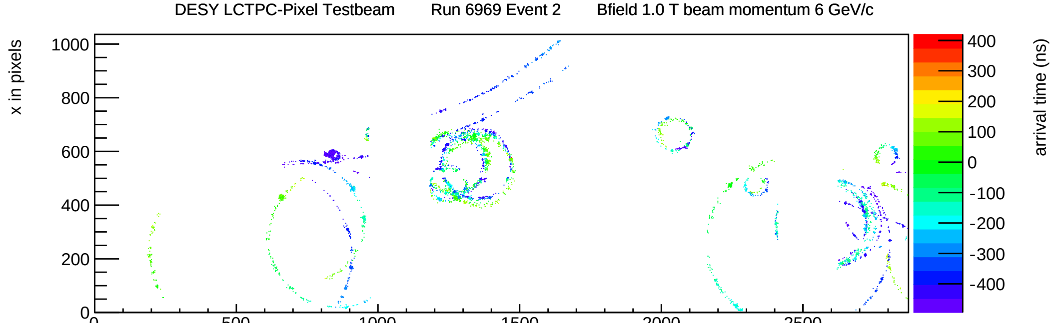


Gas tracker challenges: TPC

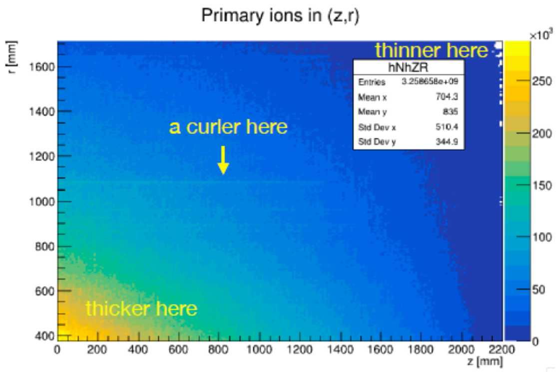
- Charge multiplication with GEM or Micromegas
  - ~100 measurments
  - $\sigma_{R\phi}$~100 μm, σ_z ~ 0.3 mm
- Readout
  - **Pads:** O(mm²) area: ~50-100 electrons each. PID by dE/dx (truncated mean charge)
  - **Digital TPC** (Si-pixels) : detect individual electrons with on O(50μ) digital pixels. PID by dN/dx (cluster counting)
- Ion backflow
  - The possibility of gating exists only at ILC. For other colliders (continuous beam or high rate bunch crossings) gating is not possible.
  - There is a natural ion backflow suppression in Micromegas, but not sufficient at the Z pole.
  - R&D needed



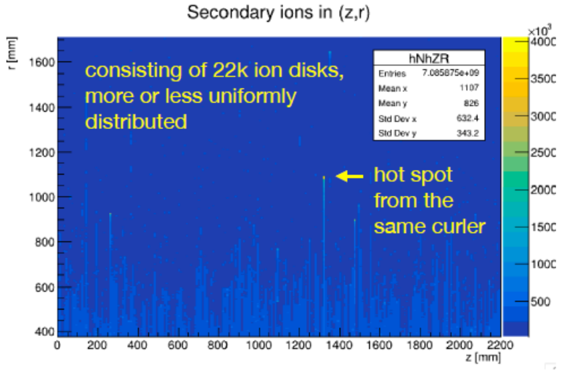
P. Colas at *ECFA Topical workshop on tracking and vertexing 2023*



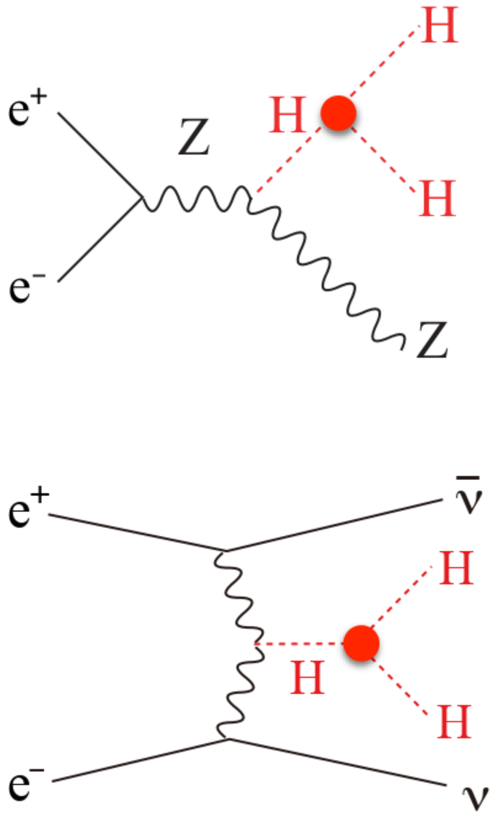
Primary Ions

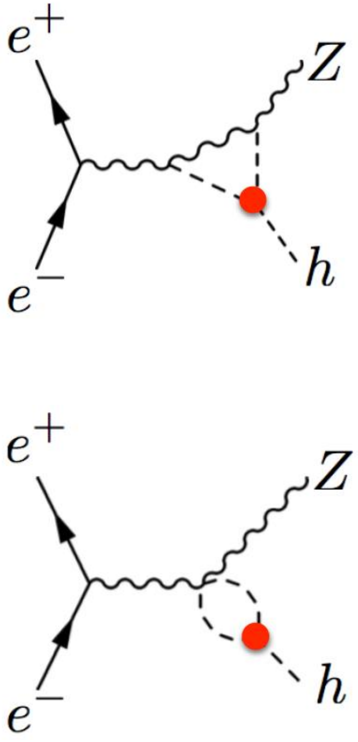


Ion Back Flow



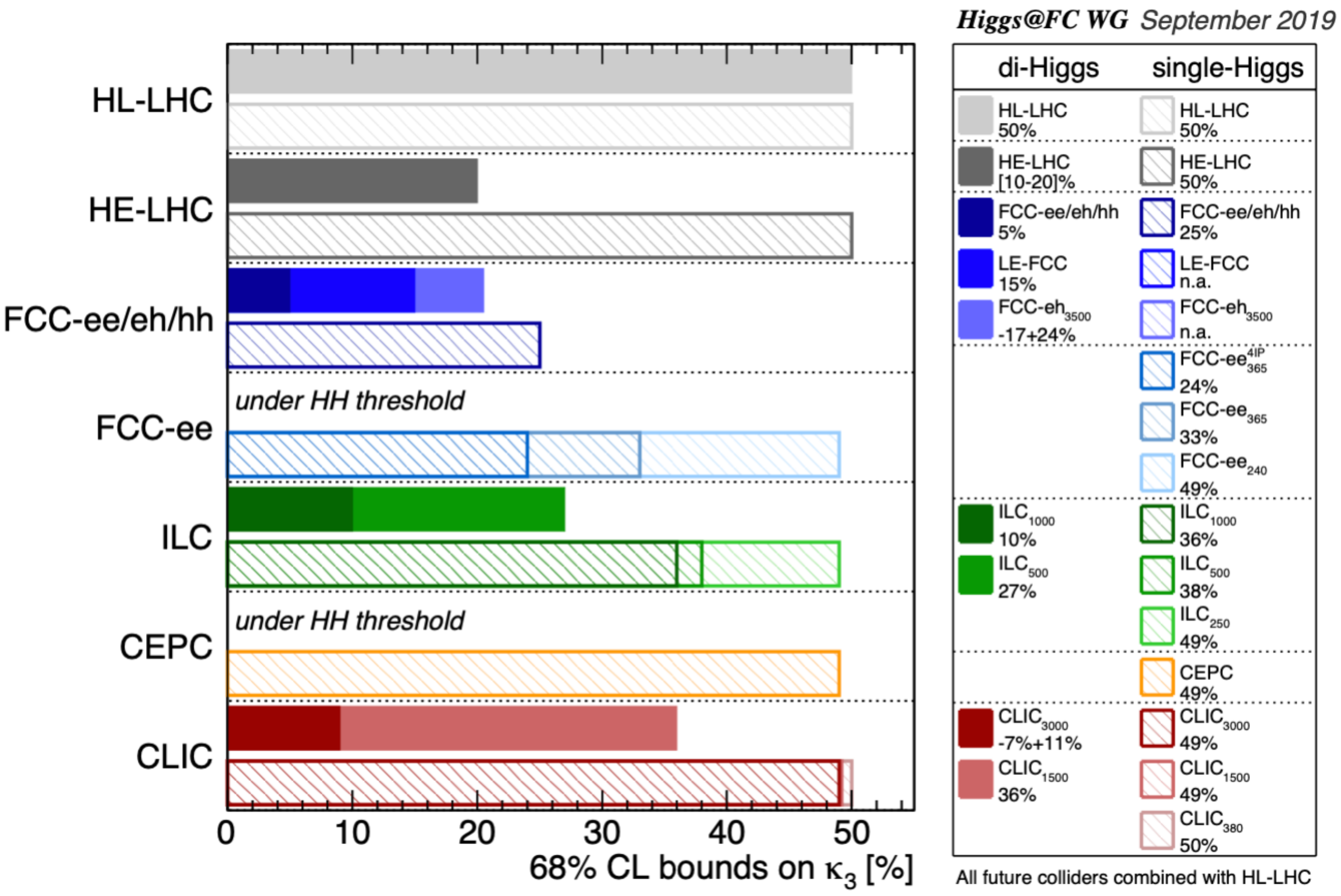
Higgs self-coupling





at $\sqrt{s} > 500$ GeV $\sigma(HH) = O(0.1\text{ fb})$

at $\sqrt{s} = 250$ GeV sensitive to variations of $\sigma(ZH) = O(1\%)$

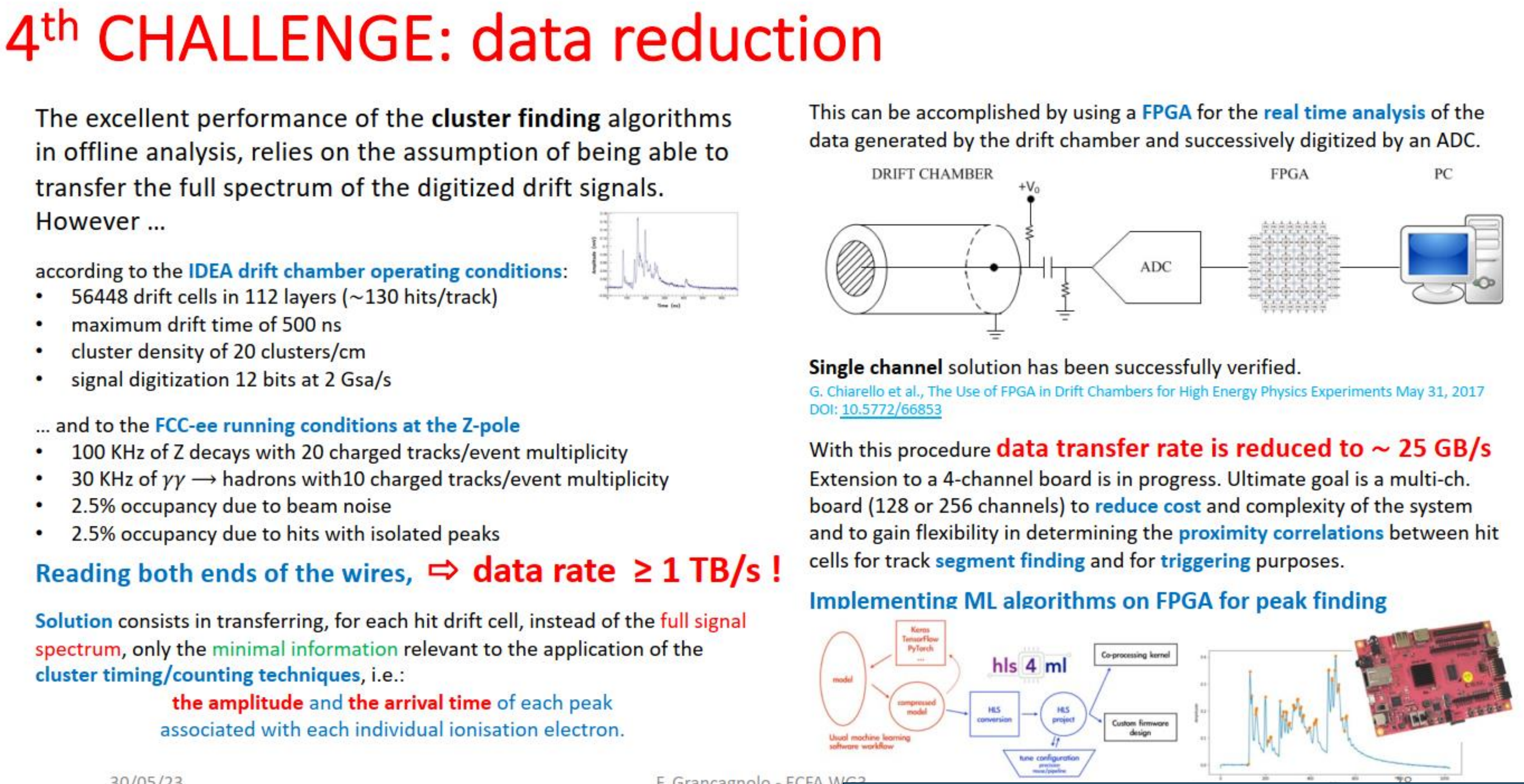


All future colliders combined with HL-LHC

Si tracker: system considerations

- **Complete system consists of 900'000 cm^2 area / 4 cm^2 chip = 225k chips (56k quad-modules)**
  - aggregation of several modules for data and services distribution is essential
  - inner tracker will be 5--10% of this
- **Data rate** constrained by the inner tracker
  - average rate 10^{-4} - 10^{-3} particles cm^{-2} event^{-1} at Z peak
  - assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
  - **640 Mbps link/module** (assuming local module aggregation) provides ample operational margin
  - 16 modules can be arranged into **10 Gbps fast links**: **3.5k links**
    - can also assume 100 Gbps links will be available: 350 links
- **DAQ architecture**
  - **triggerless readout** will fit the data transmission budget but requires off-chip re-ordering of data
  - **triggered readout** will be **simpler** and would also reduce the bandwidth occupancy
- **Power consumption**
  - ATLASPIX3 power consumption **150 mW/cm^2**
  - 600 mW/chip → 2.4 W/module → **total FE power 130 kW**
  - additional power for on detector aggregation and de-randomizations **~2W/link**

Drift chamber signal processing



4th CHALLENGE: data reduction

The excellent performance of the **cluster finding** algorithms in offline analysis, relies on the assumption of being able to transfer the full spectrum of the digitized drift signals.
However …

according to the **IDEA drift chamber operating conditions**:
- 56448 drift cells in 112 layers (~130 hits/track)
- maximum drift time of 500 ns
- cluster density of 20 clusters/cm
- signal digitization 12 bits at 2 Gsa/s

… and to the **FCC-ee running conditions at the Z-pole**
- 100 KHz of Z decays with 20 charged tracks/event multiplicity
- 30 KHz of $\gamma\gamma \longrightarrow$ hadrons with10 charged tracks/event multiplicity
- 2.5% occupancy due to beam noise
- 2.5% occupancy due to hits with isolated peaks

Reading both ends of the wires, ⇨ data rate ≥ 1 TB/s !

Solution consists in transferring, for each hit drift cell, instead of the full signal spectrum, only the minimal information relevant to the application of the **cluster timing/counting techniques**, i.e.:

the amplitude and **the arrival time** of each peak associated with each individual ionisation electron.

This can be accomplished by using a **FPGA** for the **real time analysis** of the data generated by the drift chamber and successively digitized by an ADC.

Single channel solution has been successfully verified.
G. Chiarello et al., The Use of FPGA in Drift Chambers for High Energy Physics Experiments May 31, 2017
DOI: 10.5772/66853

With this procedure **data transfer rate is reduced to ~ 25 GB/s**
Extension to a 4-channel board is in progress. Ultimate goal is a multi-ch. board (128 or 256 channels) to **reduce cost** and complexity of the system and to gain flexibility in determining the **proximity correlations** between hit cells for track **segment finding** and for **triggering** purposes.

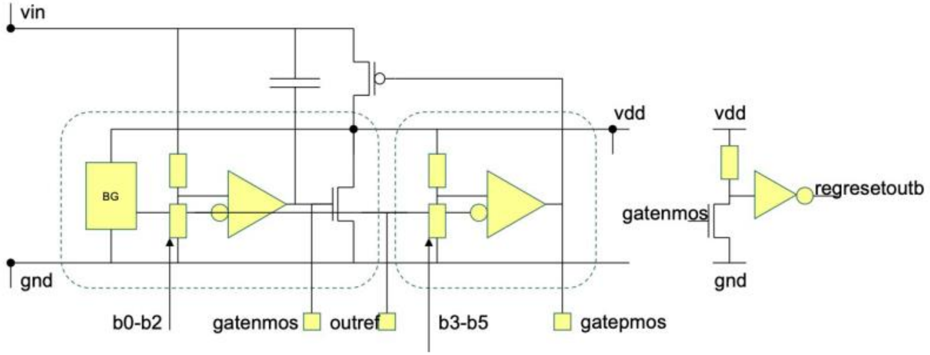
Implementing ML algorithms on FPGA for peak finding

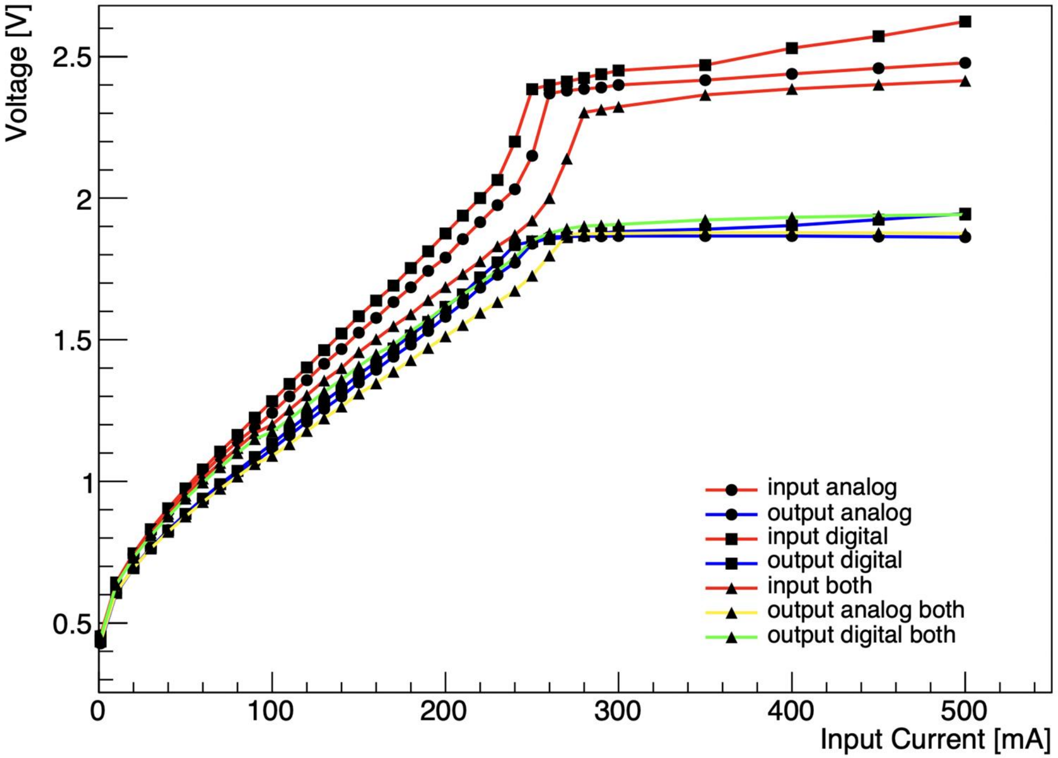
30/05/23 F. Grancagnolo - ECFA W

F. Grancagnolo at *ECFA Topical workshop on tracking and vertexing 2023*

ATLASPIX3: Serial powering

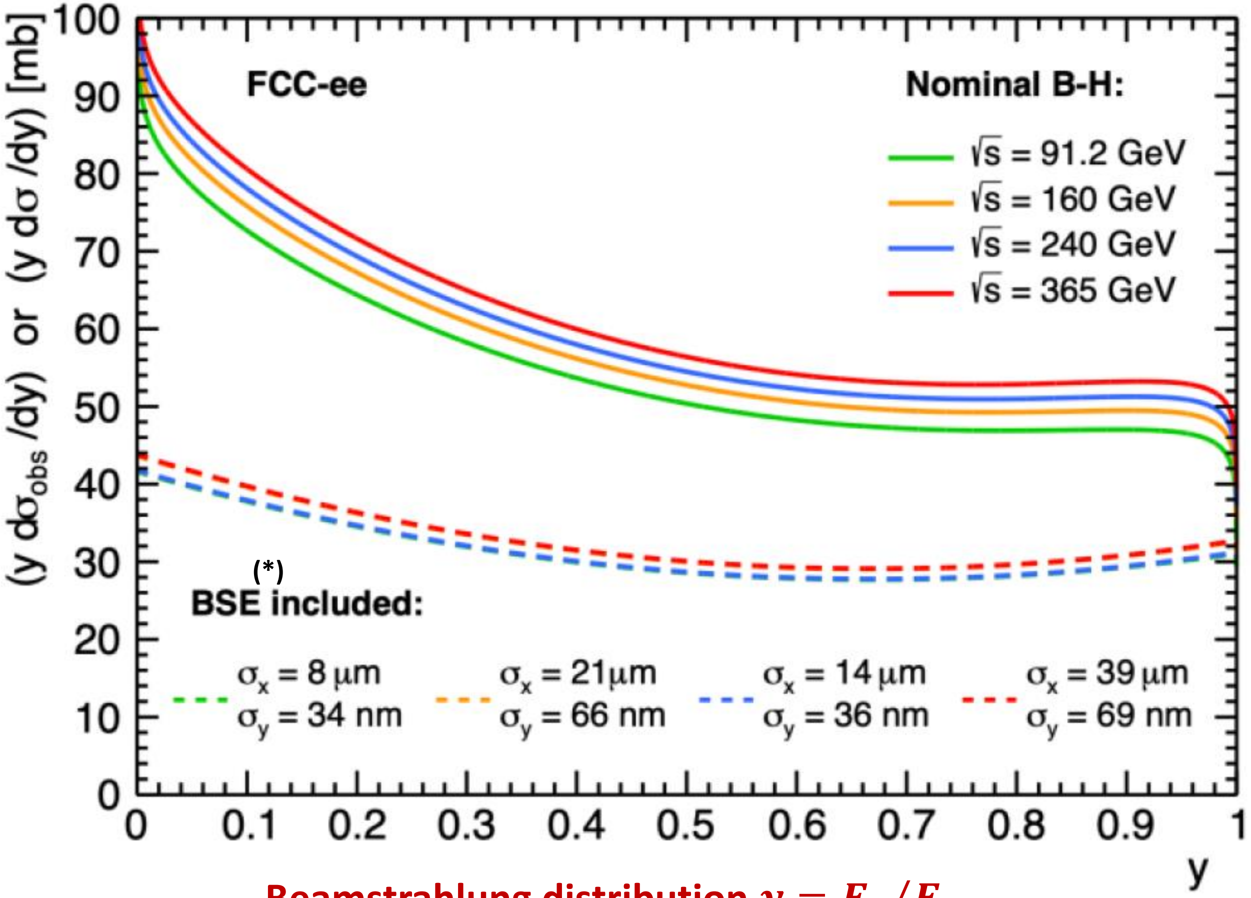
- Version ATLASPIX3.1 can be biased by serial powering through two shunt/low dropout regulators
  - digital and analog (VDDD/A)
  - 3 bits to tune threshold of shunt regulator
  - 3 bits to tune VDD
- Measured regulator performance
  - threshold and noise performance are the same usinfg SLDO or direct VDDD/A powering
  - DAC dinamic range of few tens of mV
  - Full chip turn-on at I=300 mA
  - Input voltage 2.3 V
  - Power consumption: ∼700 mW/chip or ∼175 mW/cm^2
- Integration model is to join modules by a bus implementing a serial powering chain
  - examples in F. Palla's talk
  - metal in the module hybrid and the power bus dominates the thickness of a detector layer (~0.44% X_0)
  - considering to move Al as conductor for PCBs





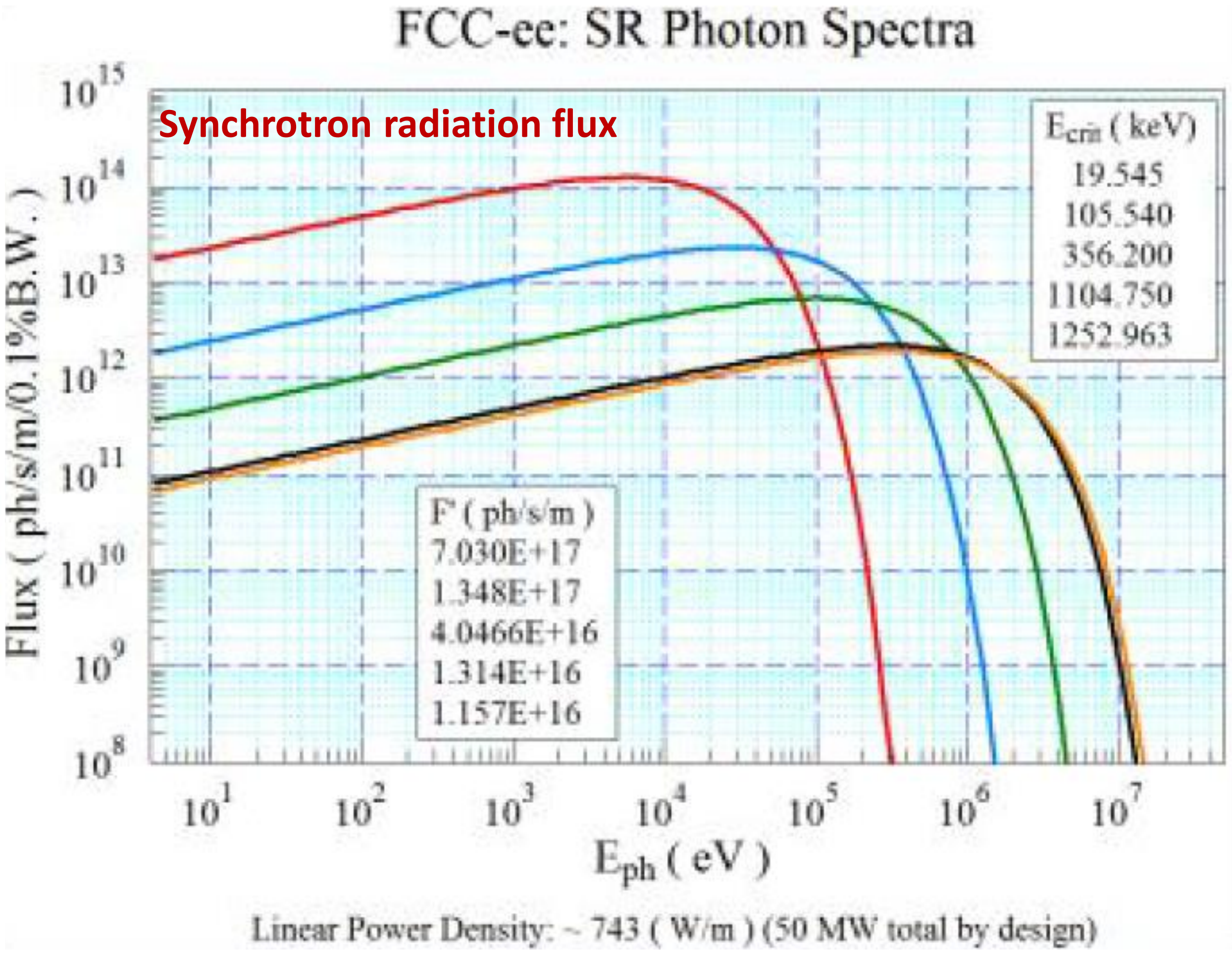
Radiation spectra

arXiv:2305.12033



Beamstrahlung distribution $y = E_\gamma / E_e$

T. Lefevre at FCC week, London 2023

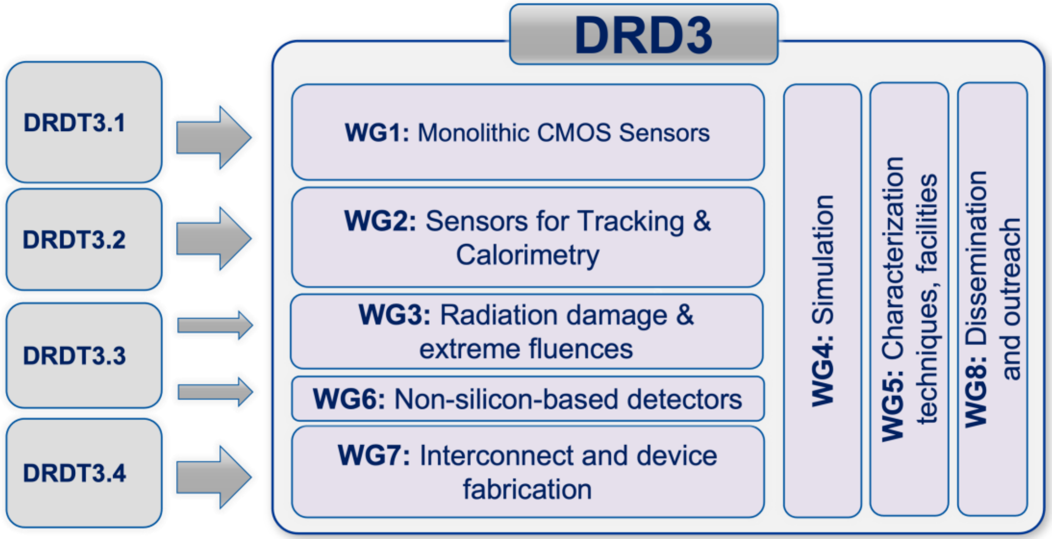


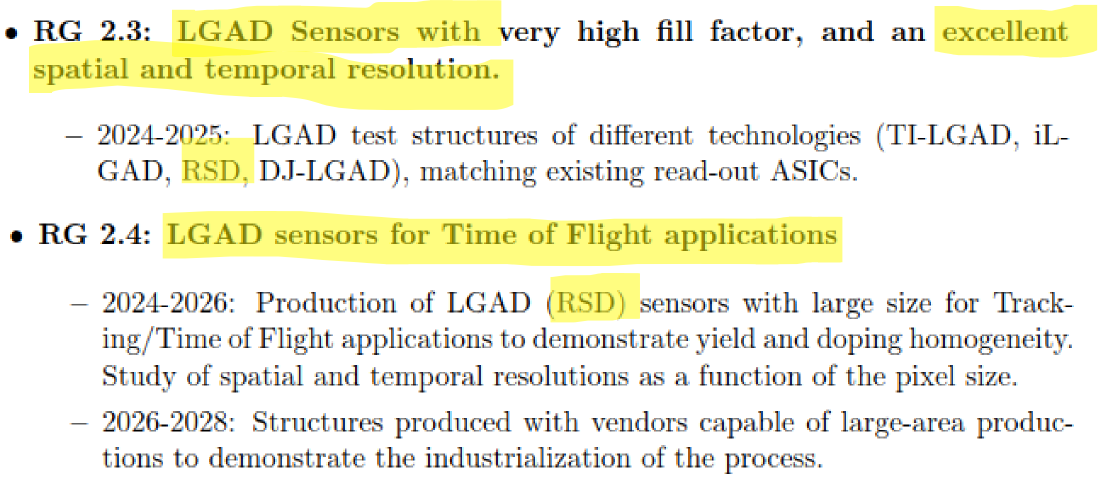
Synchrotron radiation flux

(*) Beam size effects

Participation to DRD3 and DRD7

- Circulated drafts of the DRD3 and DRD7 proposals
- Monolithic CMOS developments are shared between DRD3.1 (sensor development) and DRD7.6 (large systems)
  - TSI180 is within the technologies considered in DRD3.1
  - the LF110nm ARCADIA platform is one of the two technologies included in DRD7.6 together with TowerJazz 65nm
- Developments on power distribution are the subject of a DRD7.1 process
  - SLDO has not been much investigated for Monolithic CMOS detector (depends on HV capabilities)
- LGAD in RSD technology are considered for two research goals in DRD3.2





- **RG 2.3: LGAD Sensors with very high fill factor, and an excellent spatial and temporal resolution.**
  - 2024-2025: LGAD test structures of different technologies (TI-LGAD, iLGAD, RSD, DJ-LGAD), matching existing read-out ASICs.
- **RG 2.4: LGAD sensors for Time of Flight applications**
  - 2024-2026: Production of LGAD (RSD) sensors with large size for Tracking/Time of Flight applications to demonstrate yield and doping homogeneity. Study of spatial and temporal resolutions as a function of the pixel size.
  - 2026-2028: Structures produced with vendors capable of large-area productions to demonstrate the industrialization of the process.

Participation to DRD3 and DRD7

- Circulated drafts of the DRD3 and DRD7 proposals
- Monolithic CMOS developments are shared between DRD3.1 (sensor development) and DRD7.6 (large systems)
  - TSI180 is within the technologies considered in DRD3.1
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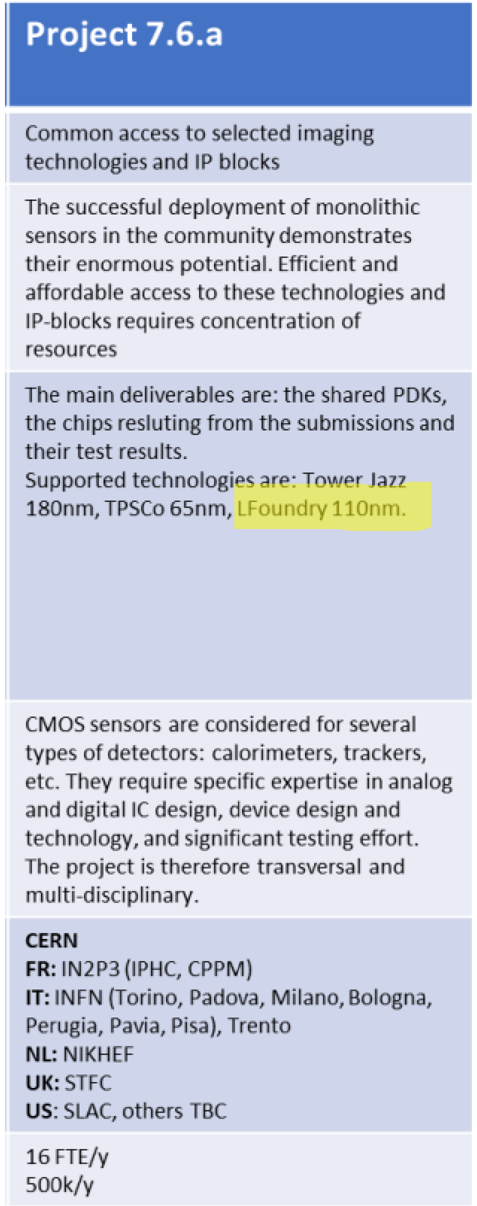
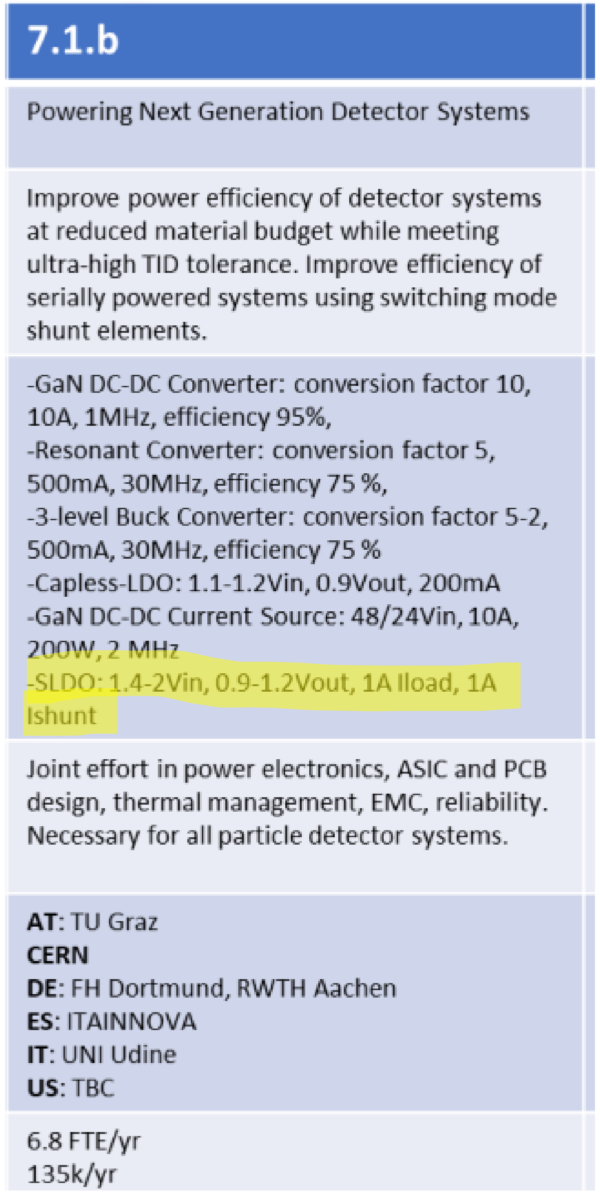


Project 7.6.a
Common access to selected imaging technologies and IP blocks
The successful deployment of monolithic sensors in the community demonstrates their enormous potential. Efficient and affordable access to these technologies and IP-blocks requires concentration of resources
The main deliverables are: the shared PDKs, the chips resluting from the submissions and their test results. Supported technologies are: Tower Jazz 180nm, TPSCo 65nm, LFoundry 110nm.
CMOS sensors are considered for several types of detectors: calorimeters, trackers, etc. They require specific expertise in analog and digital IC design, device design and technology, and significant testing effort. The project is therefore transversal and multi-disciplinary.
CERN **FR:** IN2P3 (IPHC, CPPM) **IT:** INFN (Torino, Padova, Milano, Bologna, Perugia, Pavia, Pisa), Trento **NL:** NIKHEF **UK:** STFC **US:** SLAC, others TBC
16 FTE/y 500k/y

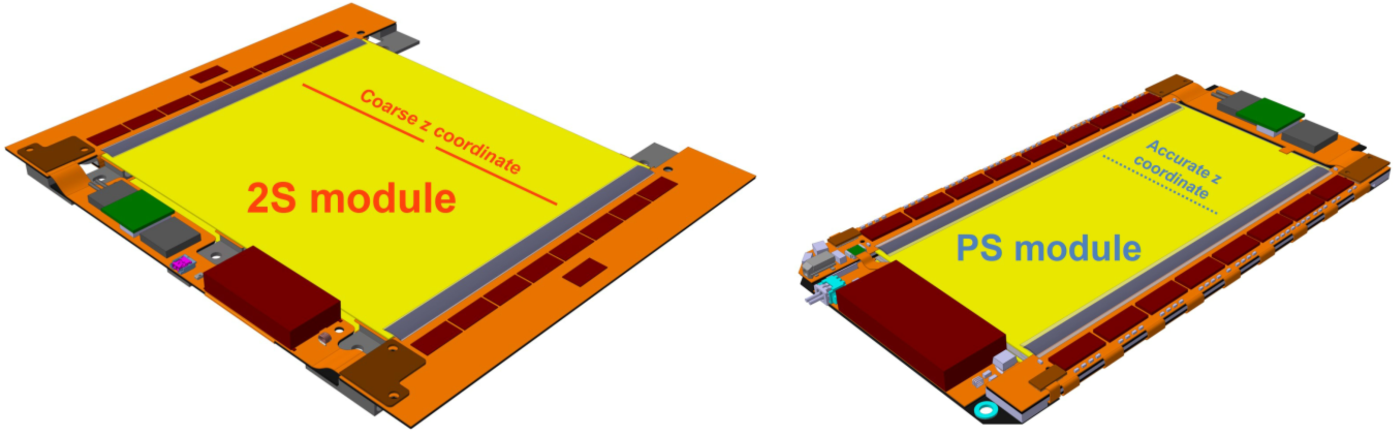


7.1.b
Powering Next Generation Detector Systems
Improve power efficiency of detector systems at reduced material budget while meeting ultra-high TID tolerance. Improve efficiency of serially powered systems using switching mode shunt elements.
-GaN DC-DC Converter: conversion factor 10, 10A, 1MHz, efficiency 95%, -Resonant Converter: conversion factor 5, 500mA, 30MHz, efficiency 75 %, -3-level Buck Converter: conversion factor 5-2, 500mA, 30MHz, efficiency 75 % -Capless-LDO: 1.1-1.2Vin, 0.9Vout, 200mA -GaN DC-DC Current Source: 48/24Vin, 10A, 200W, 2 MHz -SLDO: 1.4-2Vin, 0.9-1.2Vout, 1A Iload, 1A Ishunt
Joint effort in power electronics, ASIC and PCB design, thermal management, EMC, reliability. Necessary for all particle detector systems.
AT: TU Graz **CERN** **DE**: FH Dortmund, RWTH Aachen **ES**: ITAINNOVA **IT**: UNI Udine **US**: TBC
6.8 FTE/yr 135k/yr

CMS Outer Tracker modules

Ref. 4-5

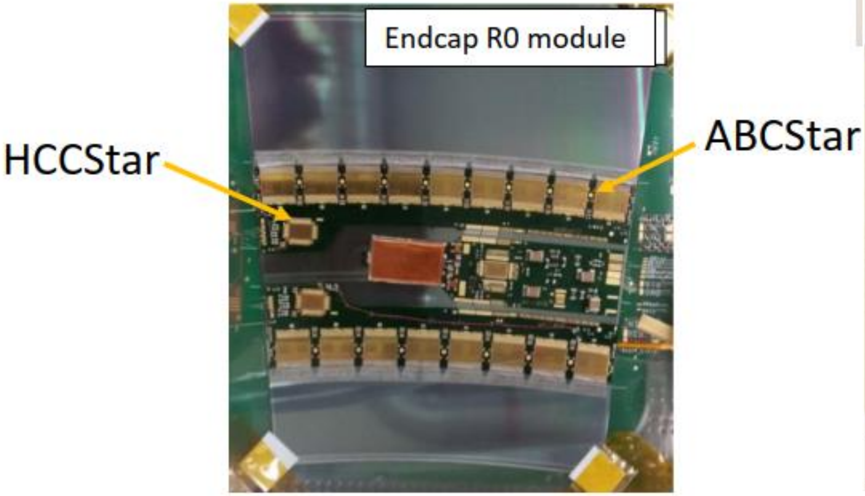
2S module	PS module
∼ 2 × 90 cm^2 active area	∼ 2 × 45 cm^2 active area
2 × 1016 strips: ∼ 5 cm × 90 μm 2 × 1016 strips: ∼ 5 cm × 90 μm	2 × 960 strips: ∼ 2.4 cm × 100 μm 32 × 960 macro-pixels: ∼ 1.5 mm × 100 μm
Front-end power ∼ 5 W Sensor power (−20 °C) ∼ 1.0 W	Front-end power ∼ 8 W Sensor power (−20 °C) ∼ 1.4 W

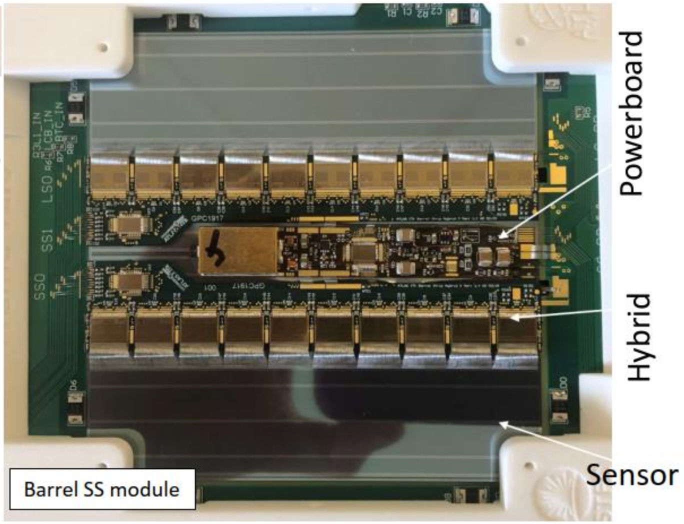


	2S	PS	Pixels
Area	192 m^2	25 m^2	4.9 m^2
Power density	27 mW/cm^2	89 mW/cm^2	700 mW/cm^2
Module cost (TDR)	26990 kCHF	20780 kCHF	11691 kCHF
	140 $kCHF/m^2$	830 $kCHF/m^2$	2400 $kCHF/m^2$

ATLAS Strip modules

Ref. 7-8



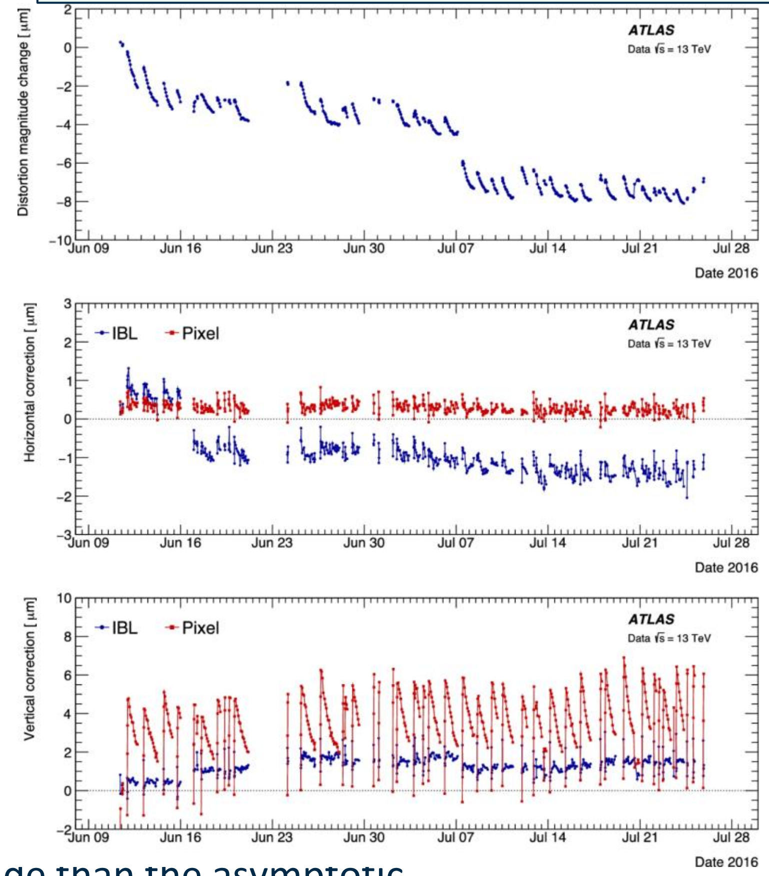


	Strip	Pixels
Area	165 m^2	13 m^2
Power density	43 mW/cm^2	700 mW/cm^2
Module cost (TDR)	36900 kCHF	25067 kCHF
	224 $kCHF/m^2$	1900 $kCHF/m^2$

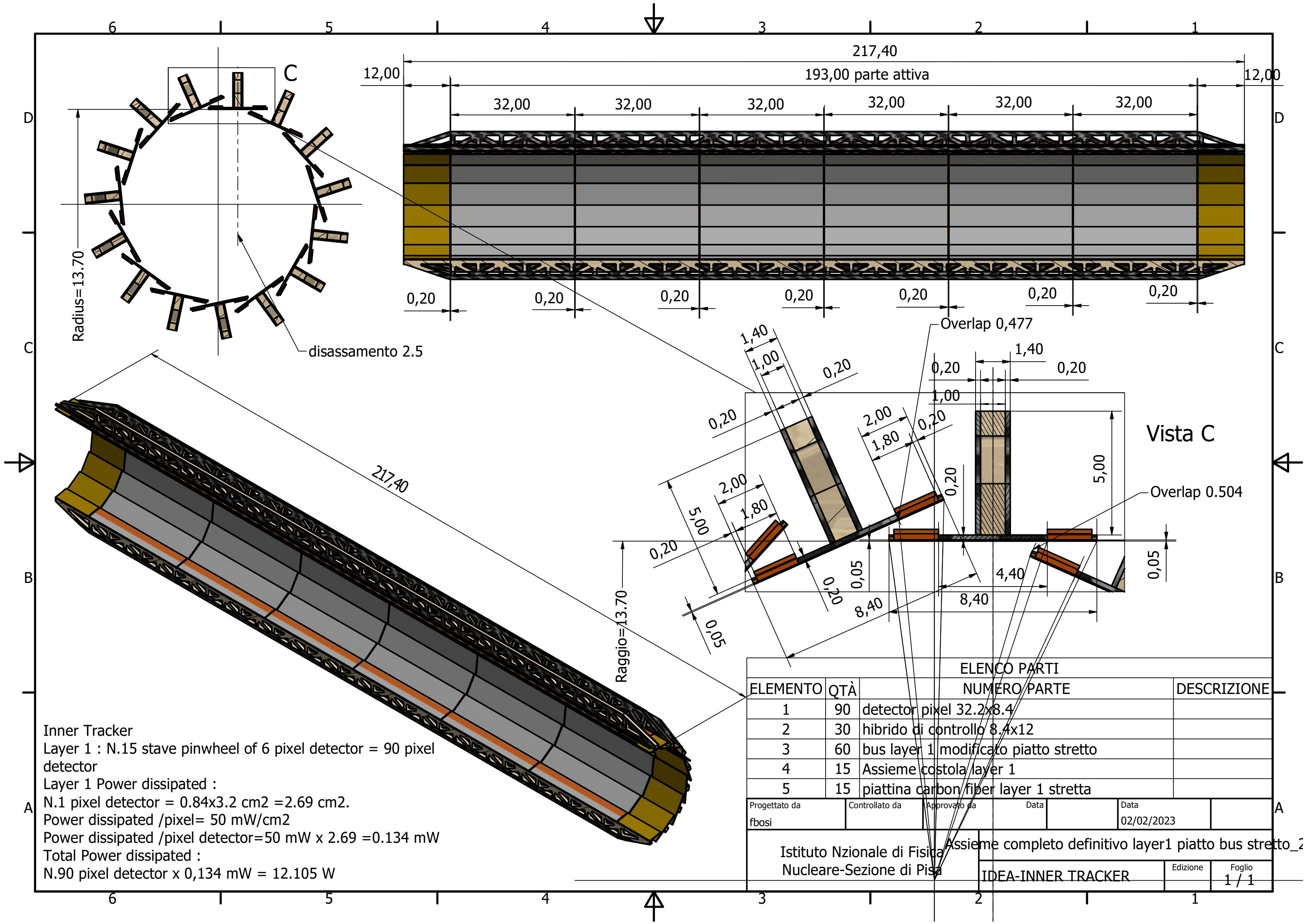
Si Wrapper: why pixels?

- **For cross section measurements need to keep systematics on the angular acceptance at the level of 50 μrad at $\theta = 10°$.**
- in principle, silicon is a very good ruler:
  - Inner Silicon Tracker disks: at 40 cm, $\delta R_{sys}<20\ \mu m$
    - alignment in principle is better than that, but stability need to be followed accordingly
    - for example: in ATLAS seen few μm systematics movements, but the tracker support will be much lighter in IDEA
  - SiWrapper: at 2 m, $\delta R_{sys}<100\ \mu m$
    - benefits from pixel structure (order of pixel size)
    - if anchored to the calorimeter provides an independent frame, giving some redundancy
- With 50 μm pitch pixels and digital readout, $\sigma_z = 14\ \mu m$, expect a θ resolution below 10 μrad
  - with the caveat that multiple scattering effects can be of a similar order of magnitude than the asymptotic resolution even for $Z \rightarrow \mu\mu$ events: 1% X_0 is 30 μrad for p=45 GeV at 90°
  - instabilities at the μm level may have an impact in the accuracy of the acollinearity measurement for beam angle crossing determination
  - having an independent detector with 2 m lever arm and same resolution as the inner tracker will allow the monitoring and correction of instabilities in both coordinates

https://doi.org/10.1140/epjc/s10052-020-08700-6



IDEA Vertex Detector



Inner Tracker
Layer 1 : N.15 stave pinwheel of 6 pixel detector = 90 pixel detector
Layer 1 Power dissipated :
N.1 pixel detector = 0.84x3.2 cm2 =2.69 cm2.
Power dissipated /pixel= 50 mW/cm2
Power dissipated /pixel detector=50 mW x 2.69 =0.134 mW
Total Power dissipated :
N.90 pixel detector x 0,134 mW = 12.105 W

ELENCO PARTI

ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	90	detector pixel 32.2x8.4	
2	30	hibrido di controllo 8.4x12	
3	60	bus layer 1 modificato piatto stretto	
4	15	Assieme costola layer 1	
5	15	piattina carbon fiber layer 1 stretta	

Progettato da: fbosi
Controllato da:
Approvato da:
Data:
Data: 02/02/2023
Istituto Nzionale di Fisica Nucleare-Sezione di Pisa
Assieme completo definitivo layer1 piatto bus stretto_2
IDEA-INNER TRACKER
Edizione:
Foglio: 1 / 1

Layer 1

15 overlapping staves of 6 modules each

Overlap to allow alignment ~500 µm

Pinwheel geometry: all modules at the same (smallest) radius

Power budget ~12 W

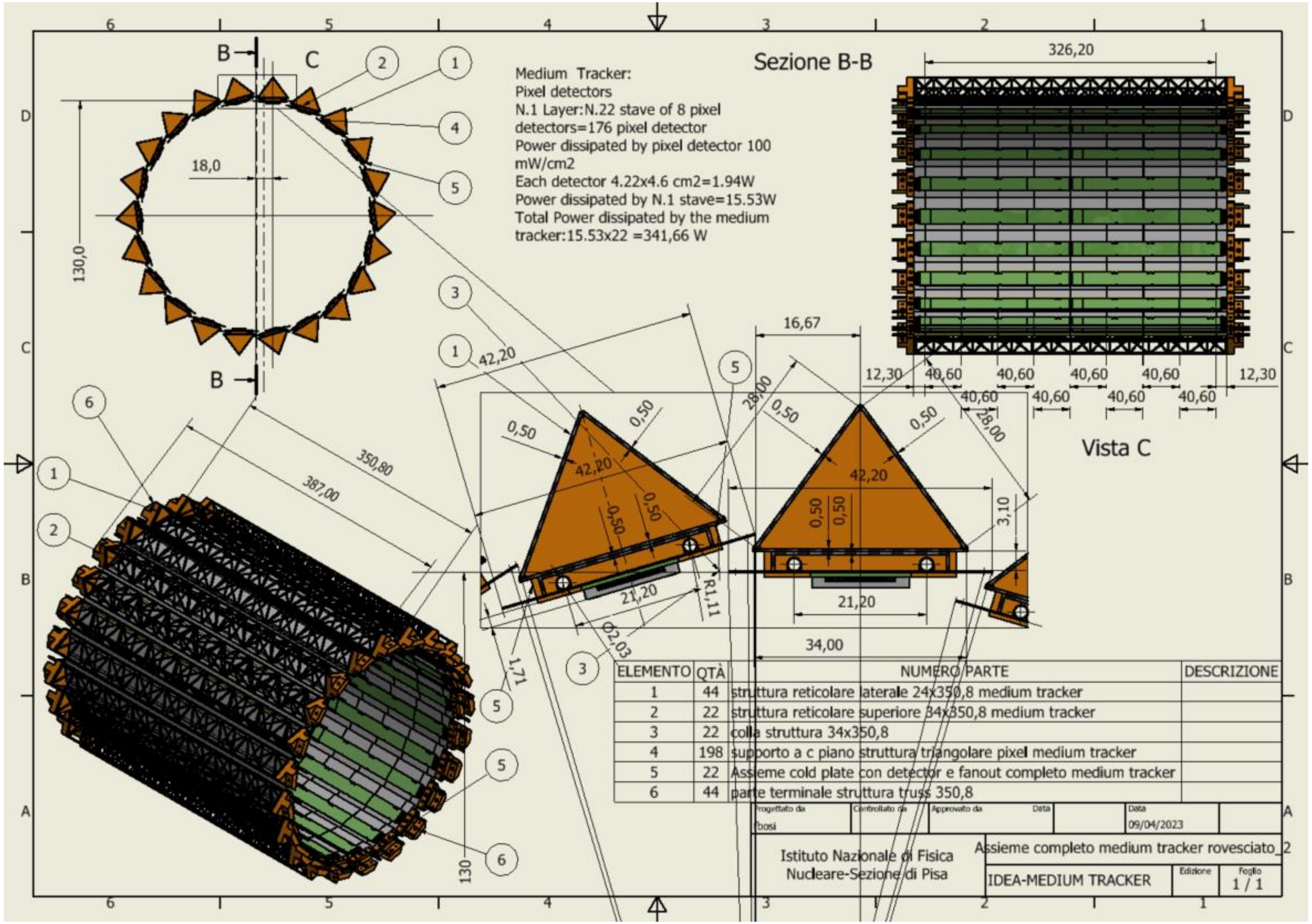
Total weight ~22 grams

Total thickness 0.25% X_0

Silicon: 0.053% X_0

Power and readout bus: 0.056% X_0

IDEA Tracker



Medium Tracker:
Pixel detectors
N.1 Layer:N.22 stave of 8 pixel detectors=176 pixel detector
Power dissipated by pixel detector 100 mW/cm2
Each detector 4.22x4.6 cm2=1.94W
Power dissipated by N.1 stave=15.53W
Total Power dissipated by the medium tracker:15.53x22 =341,66 W

ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	44	struttura reticolare laterale 24x350,8 medium tracker	
2	22	struttura reticolare superiore 34x350,8 medium tracker	
3	22	colla struttura 34x350,8	
4	198	supporto a c piano struttura triangolare pixel medium tracker	
5	22	Assieme cold plate con detector e fanout completo medium tracker	
6	44	parte terminale struttura truss 350,8	

Progettato da fbosi
Controllato da
Approvato da
Data
Data 09/04/2023
Istituto Nazionale di Fisica Nucleare-Sezione di Pisa
Assieme completo medium tracker rovesciato_2
IDEA-MEDIUM TRACKER
Edizione
Foglio 1 / 1

Middle Vertex Barrel
At 13 cm radius

22 staves of 8 modules each.

Lightweight reticular support structure (ALICE/Belle-II like)

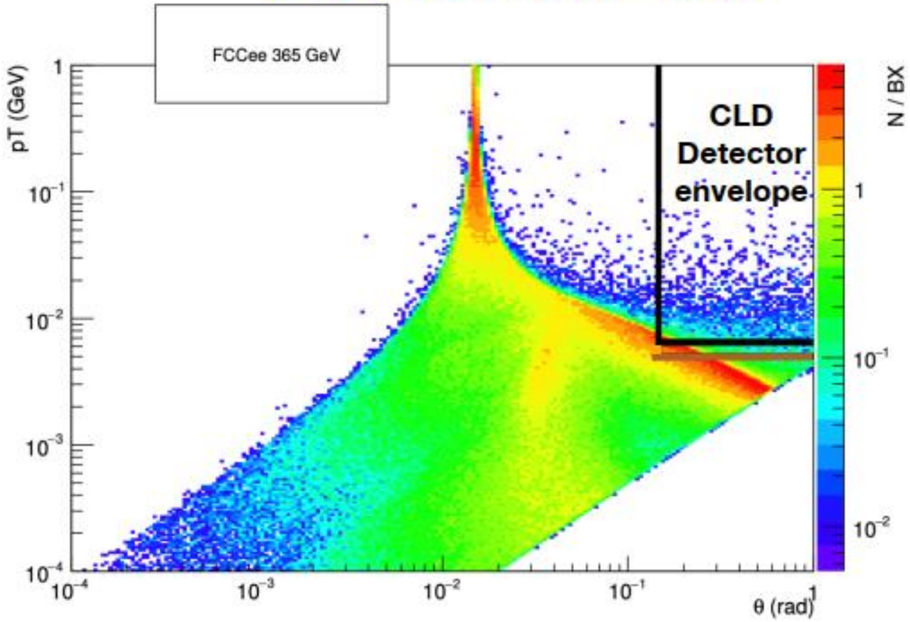
Readout chips either side
Power budget
~342 W

Total weight ~1 kg
Water cooled (2 pipes of 2 mm diameter)

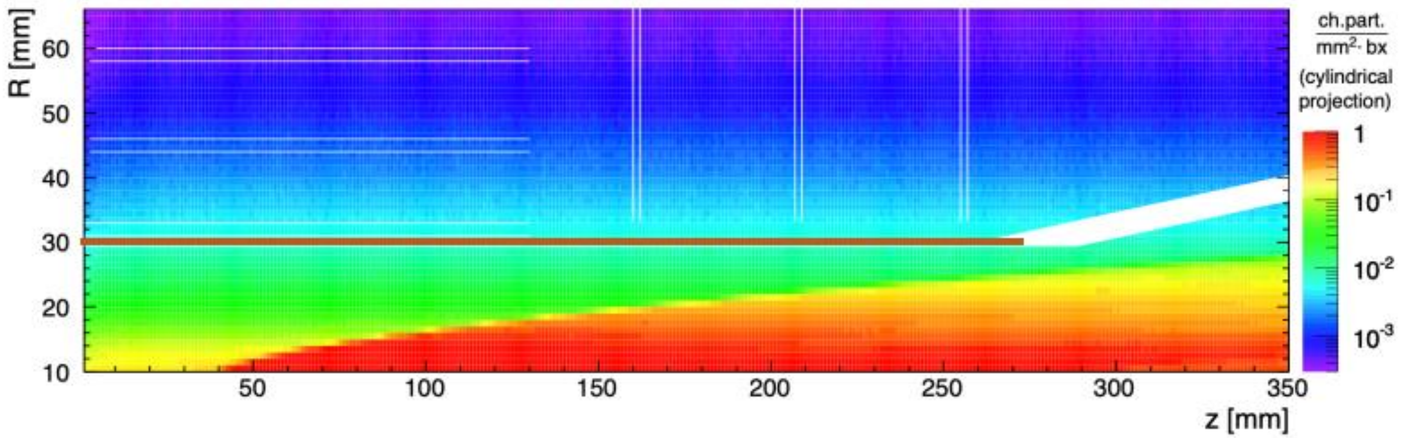
Machine Backgrounds

- Large flux of scattered ee pairs spiralling in main solenoid's field **determines radius of beam pipe** (envelope of high-p_T component)
  - **CLIC** (B=4T, $\sqrt{s}$ = 3 TeV) : 30 mm
  - **ILC** (B=3.5-5T, $\sqrt{s}$ = 500 GeV) : 16 mm
  - **FCC-ee** (B=2T, $\sqrt{s}$ = 365 GeV) : 10 mm

FCC-ee 365 GeV



CLIC 3 TeV



G. Marchiori at *ECFA Topical workshop on tracking and vertexing 2023*

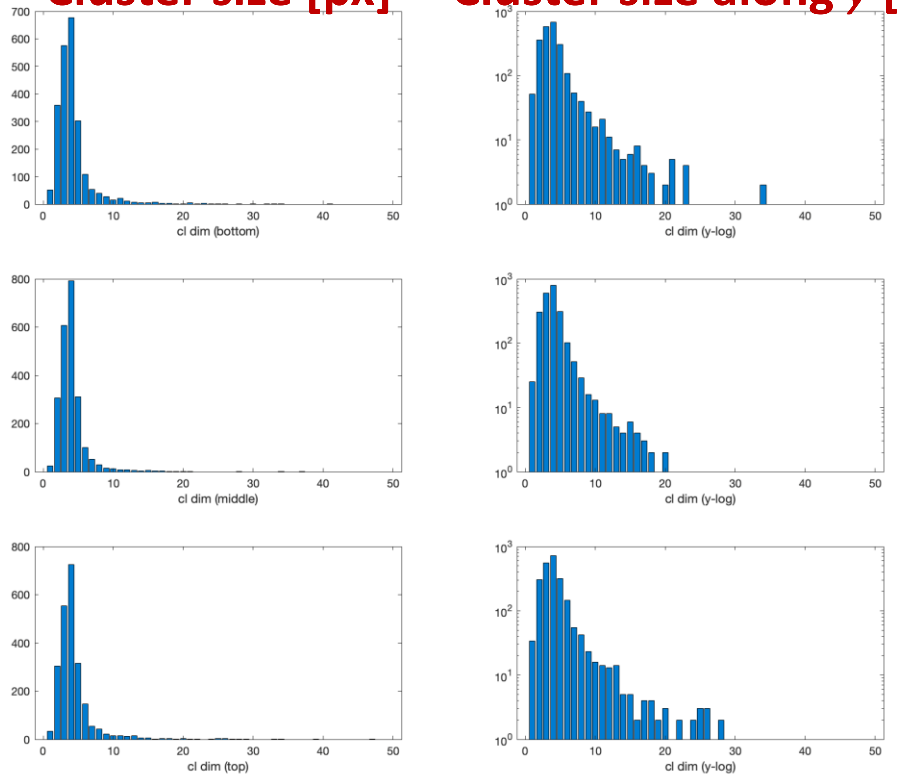
ARCADIA: MD3 Results with cosmics

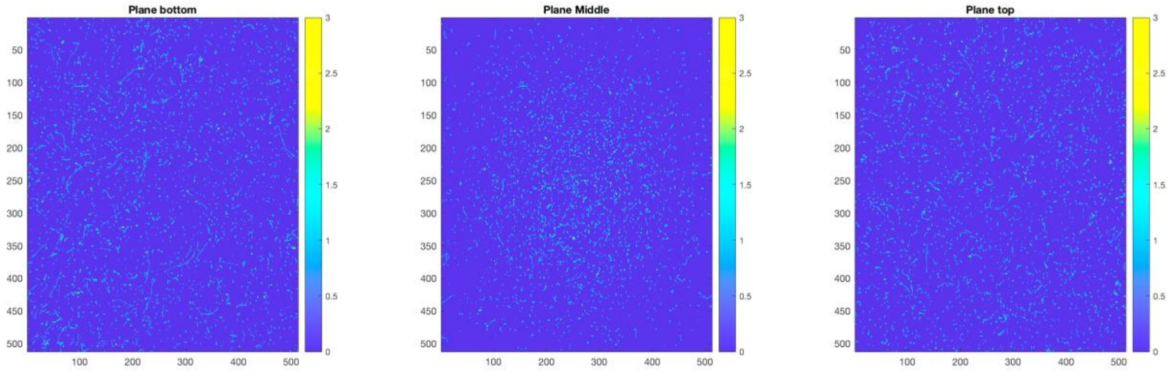
Cluster size [px] **Cluster size along *y* [px]**

Bottom layer

Middle layer

Top layer





- Cosmic ray data taking: 1 week
- 3-plane MD3 installed on a black box
- Threshold 290 e-, MPV = 4 pixels
- More than 90% of clusters with less than 6 fired pixels
- Preliminary results on residuals show a standard deviation of 12-14 μm (multiple scattering...)