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DMAPS for large area FCC Trackers

Liverpool, 9th February 2022

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For the INFN and UK CEPC CMOS Tracker communities

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CEPC CMOS Tracker Community

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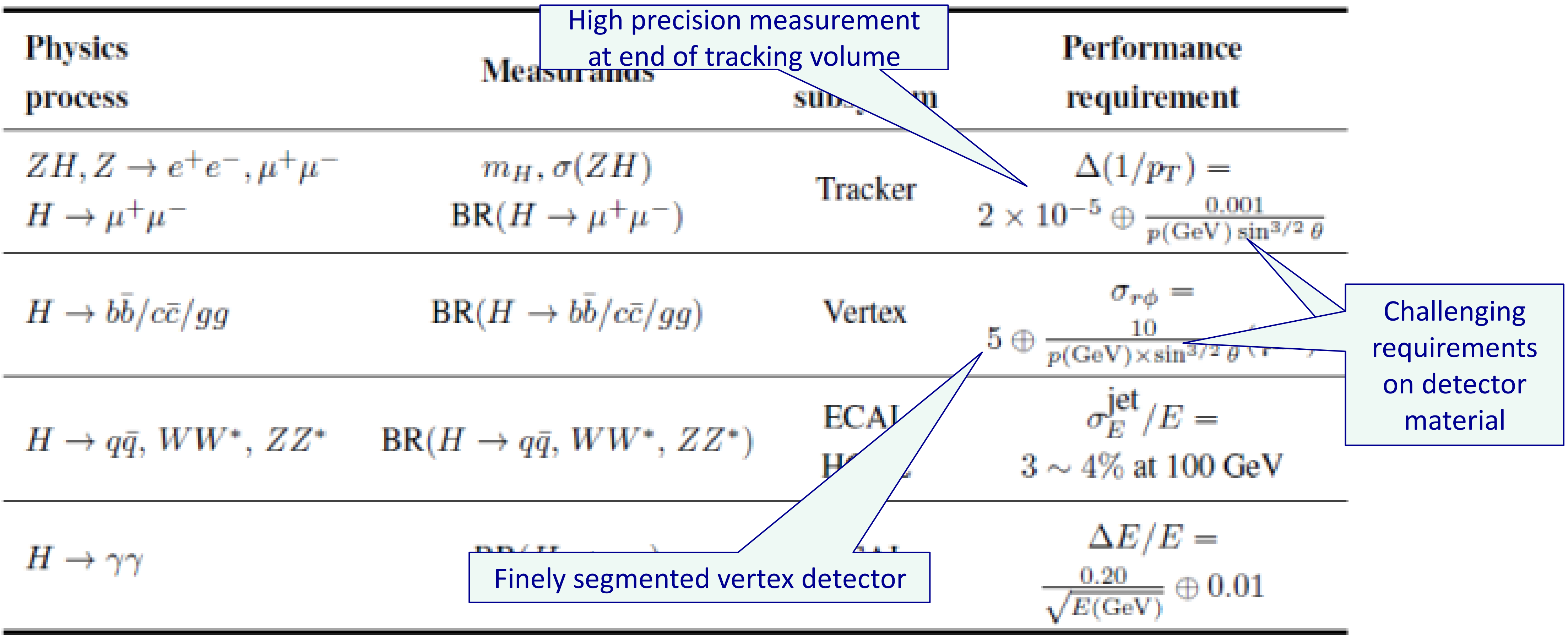
Outline

- Motivations
- ATLASPIX3 Prototyping for Feasibility Study
- Some trendlines in sensor development

e^+e^- Detector Requirements



Physics process	Measurands		Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta}$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$			$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

High precision measurement at end of tracking volume

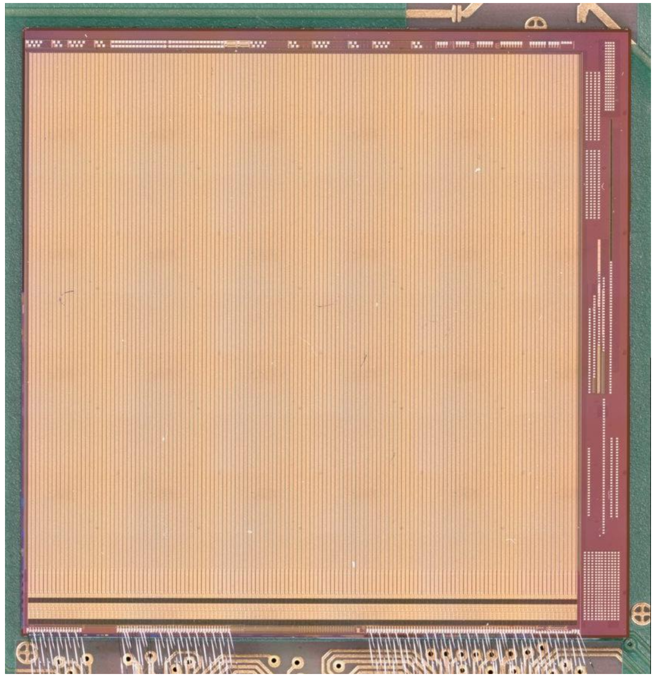
Challenging requirements on detector material

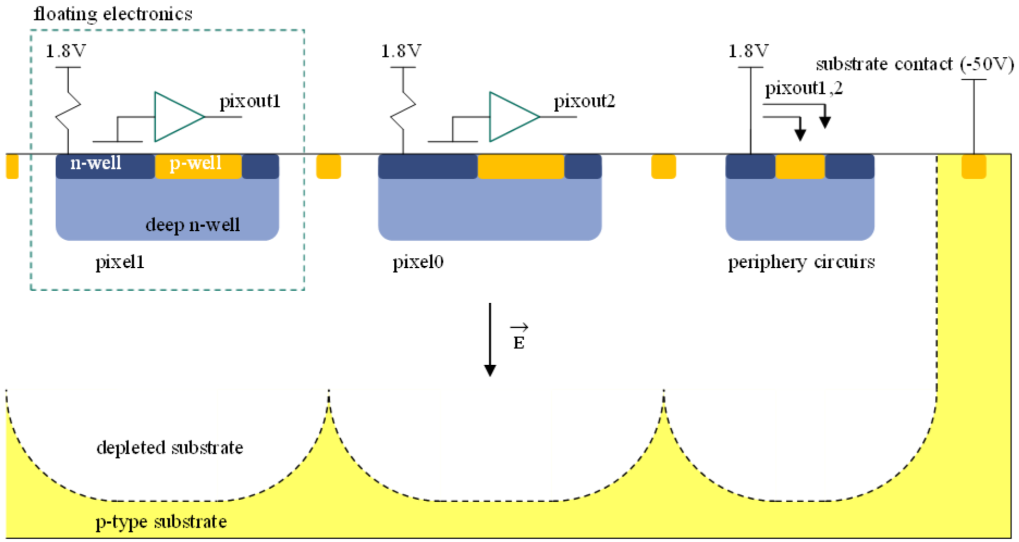
Finely segmented vertex detector

- Similar approaches for ILC, CLIC, FCCee, CepC:
  - High resolution **pixel vertex detector** O(few m^2)
  - Either **full silicon tracker** or **central gas chamber + Si wrapper** O(100 m^2)

DMAPS (example ATLASPIX3)

- **Depleted Monolithic Active Pixels Sensors**
  - CMOS process allows to produce **large areas**, **fast** and **cheap**
  - **no hybridization** (bump-bonding) needed
  - **single detection layer**, can be **thinned** keeping high signal efficiency and low noise rate
- **ATLASPIX3 features**
  - pixel size $50 \times 150\ \mu\mathrm{m}^2$ ($25 \times 165\ \mu\mathrm{m}^2$ feasible)
  - up to 1.28 Gbps downlink
  - reticle size $20 \times 21\ \mathrm{mm}^2$
  - TSI 180 nm process on 200 Ωcm substrate
  - 132 columns of 372 pixels
  - digital part of the matrix located on periphery
  - both **triggerless** and **triggered** readout possible:
    - two End of Column buffers
    - 372 hit buffers for triggerless readout
    - 80 trigger buffers for triggered readout



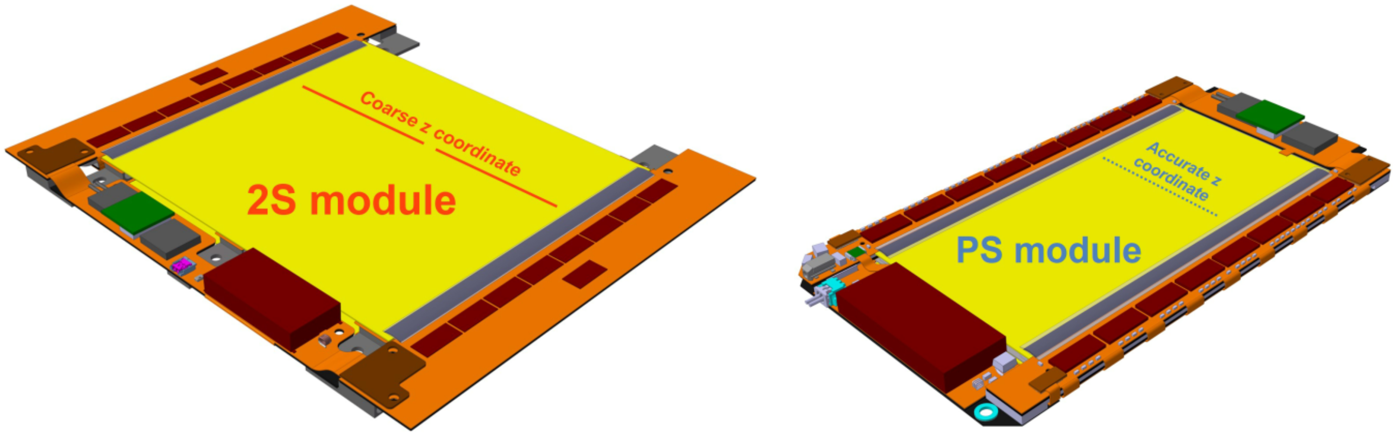


Si Wrapper: why DMAPS?

2S module	PS module
Sensor power (~ −20 °C) ~ 1.0 W	Sensor power (~ −20 °C) ~ 1.1 W

Precision θ measurements also improving systematics and accurate measurements on the Z pole
See A. Andreazza *From vertex to wrapper: the IDEA tracklng system for FCC-ee*
FCC Workshop June 2021

- Tracker area is similar to LHC trackers
- Area size within production capabilities of CMOS foundries
- One thin silicon layer instead of strip doublets
- The target power density of next generation DMAPS detector is comparable with HL-LHC strips
- Cost is not so different, if one considers half silicon area is needed



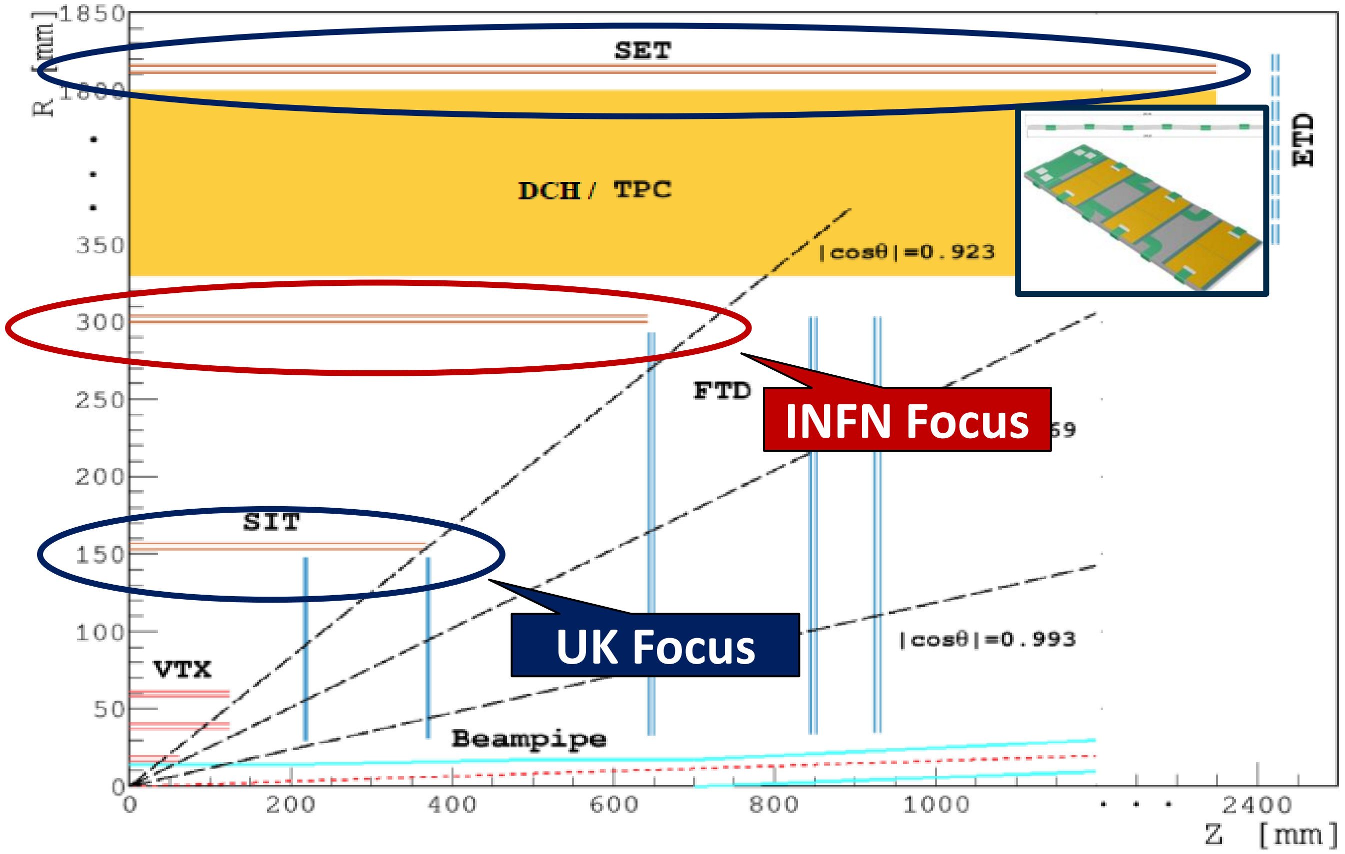
	2S	PS	Pixels	ATLASPIX3
Area	192 m^2	25 m^2	4.9 m^2	(estimation at ATLAS TDR)
Power density	27 mW/cm^2	89 mW/cm^2	700 mW/cm^2	150 mW/cm^2
Module cost (TDR)	26990 kCHF	20780 kCHF	11691 kCHF	
	140 kCHF/m^2	830 kCHF/m^2	2400 kCHF/m^2	400-500 kCHF/m^2

CEPC Baseline layout

Baseline tracker design: TPC

and 3 layers / 5 disks of silicon sensors,

50 m² (33 w/o ETD) if built in CMOS pixels (strips default)



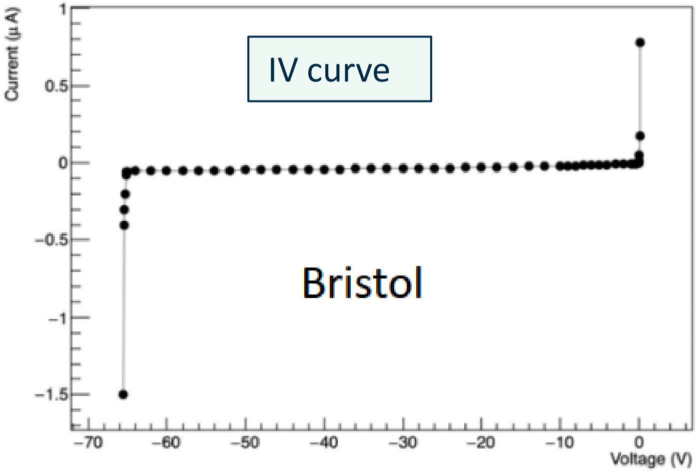
Detector		Radius R [mm]		$\pm z$ [mm]	Material budget [X_0]
SIT	Layer 1	153		371.3	0.65%
	Layer 2	300		664.9	0.65%
SET	Layer 3	1811		2350	0.65%
		R_{in}	R_{out}		
FTD	Disk 1	39	151.9	220	0.50%
	Disk 2	49.6	151.9	371.3	0.50%
	Disk 3	70.1	298.9	644.9	0.65%
	Disk 4	79.3	309	846	0.65%
	Disk 5	92.7	309	1057.5	0.65%
ETD	Disk	419.3	1822.7	2420	0.65%

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$

$\sigma_{r\phi} \approx 7\mu m$

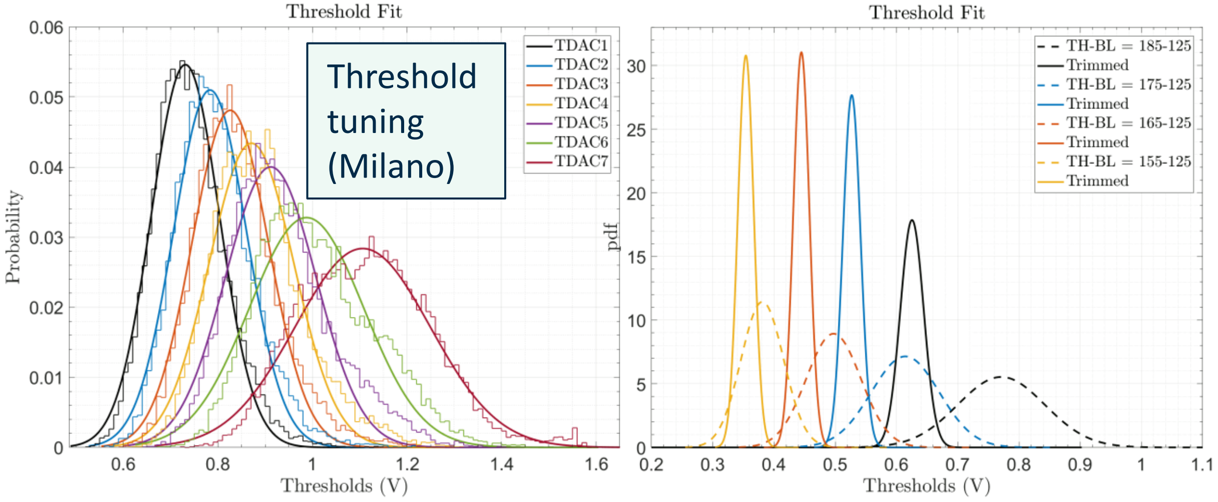
ATLASPIX3 Modules

- ATLASPIX3 performance tested in participating laboratories

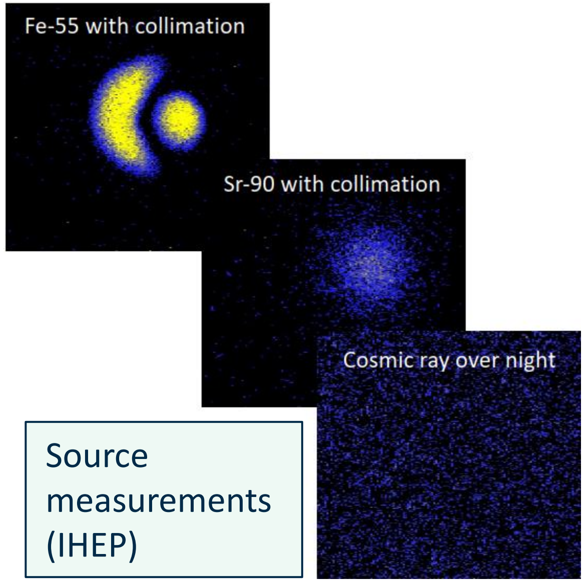


IV curve

Bristol

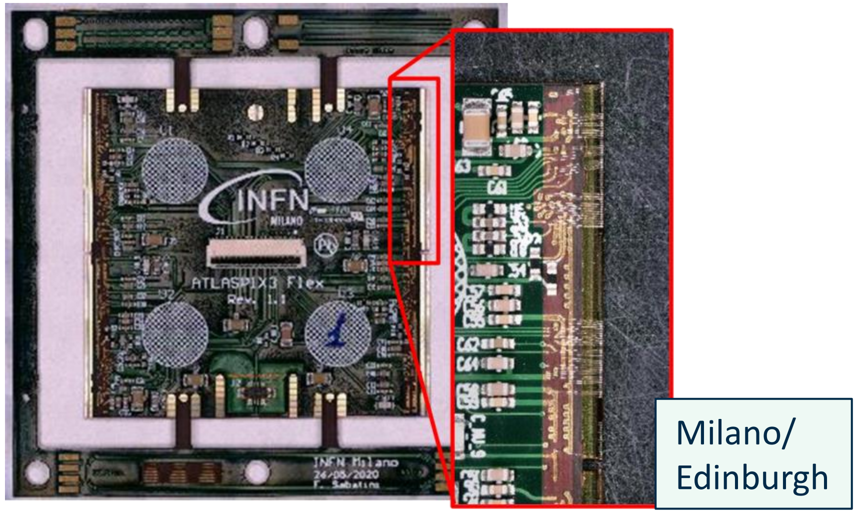


Threshold tuning (Milano)



Source measurements (IHEP)

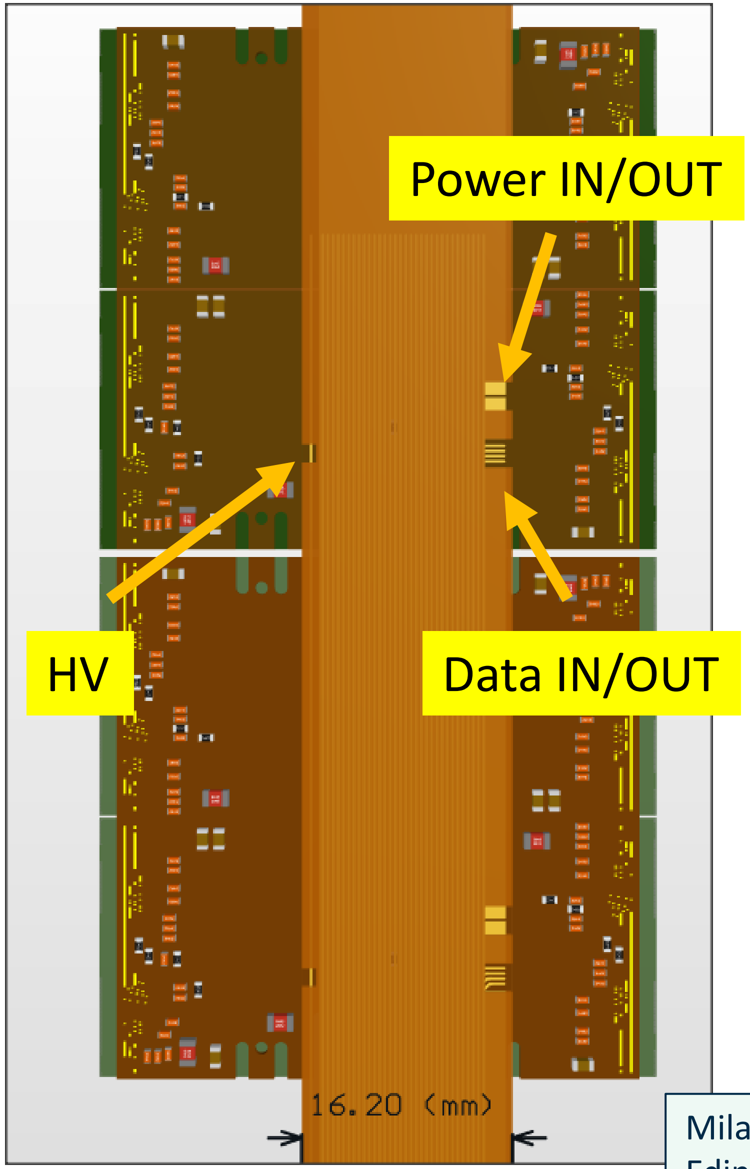
- Multi-chip module assembly
  - aggregates electrical services and connection for multiple sensors
  - quad module, inspired by ATLAS hybrid pixels
  - implemented interface to laboratory readout system
  - future version with **ATLASPIX3.1**:
    - full usage of on-chip internal regulators
    - compatible with serial powering



Milano/ Edinburgh

Stave Electrical Bus

- Distribute power and data signals along the stave structure
- Assume minimal I/O connection on chip:
  - All biases generated internally by shunt-LDO regulators
  - chip-to-chip data transmissions: local data aggregation on module
  - clock data recovery
- Requirements:
  - LVDS command input
  - LVDS data output at 640 Mbps on ~700 mm (half)stave length
  - Serial powering assuming 0.5 A/chip, 2 A/module
  - HV distributed in parallel to all modules
- Integrated signal and power bus:
  - Power distribution and return layers
  - Signal lines on top and bottom layers
  - Interconnection by soldering or wire bonding
- Alternative under study:
  - separate power cables + twinax for signal (the LHC way)



Milano/
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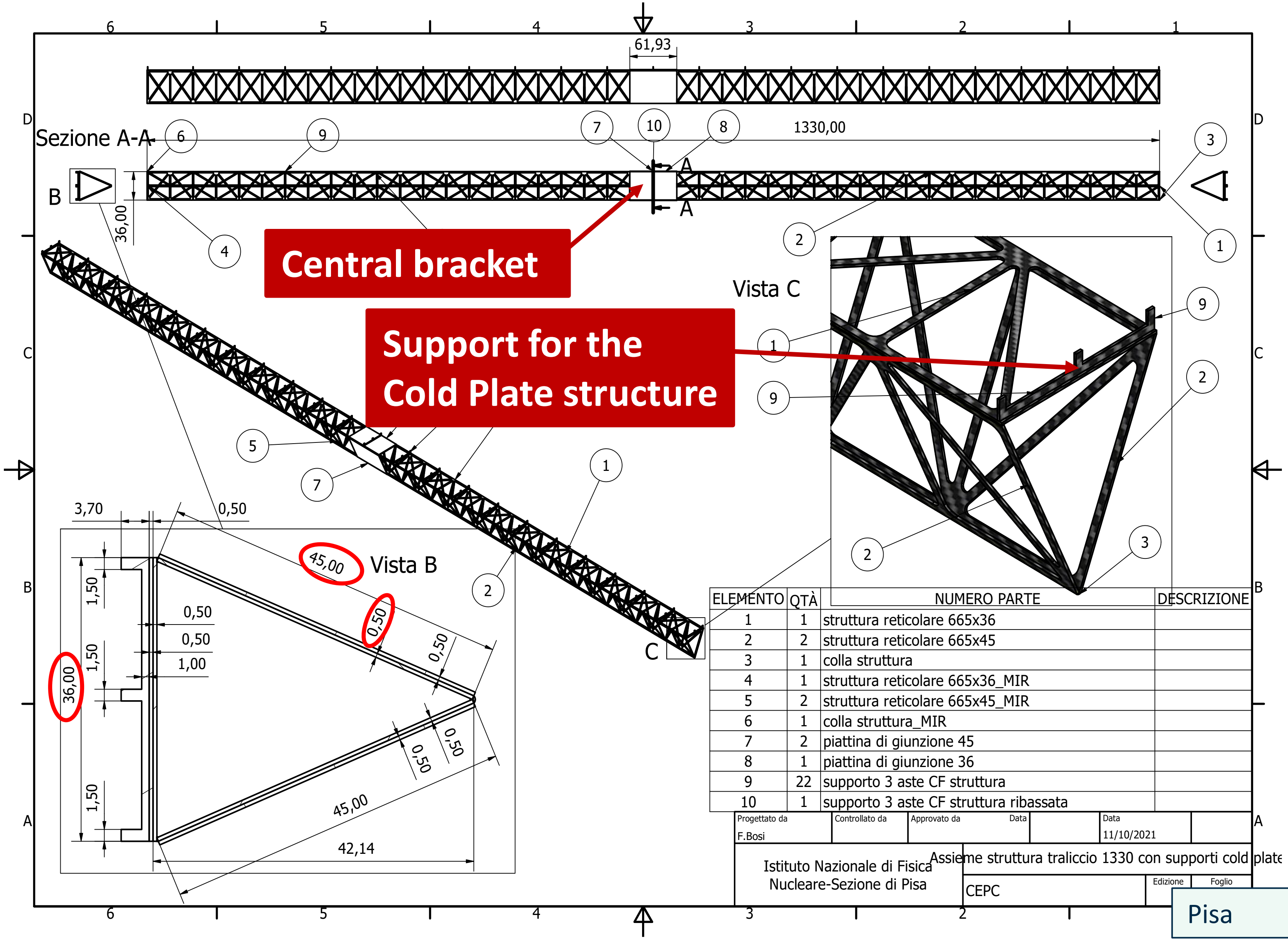
Long stave structure

Inspired to ALICE project, but with different specifications

- **Easier process** implemented by WaterJet cut process (instead of winding process) on carbon fiber laminated (50 µm precision)
- **Gluing mask** for realization of the 3D truss structure
- Goal of the mechanical structure: **max radiation length 0.3% X_0**



Central bracket

Support for the Cold Plate structure

ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	1	struttura reticolare 665x36	
2	2	struttura reticolare 665x45	
3	1	colla struttura	
4	1	struttura reticolare 665x36_MIR	
5	2	struttura reticolare 665x45_MIR	
6	1	colla struttura_MIR	
7	2	piattina di giunzione 45	
8	1	piattina di giunzione 36	
9	22	supporto 3 aste CF struttura	
10	1	supporto 3 aste CF struttura ribassata	

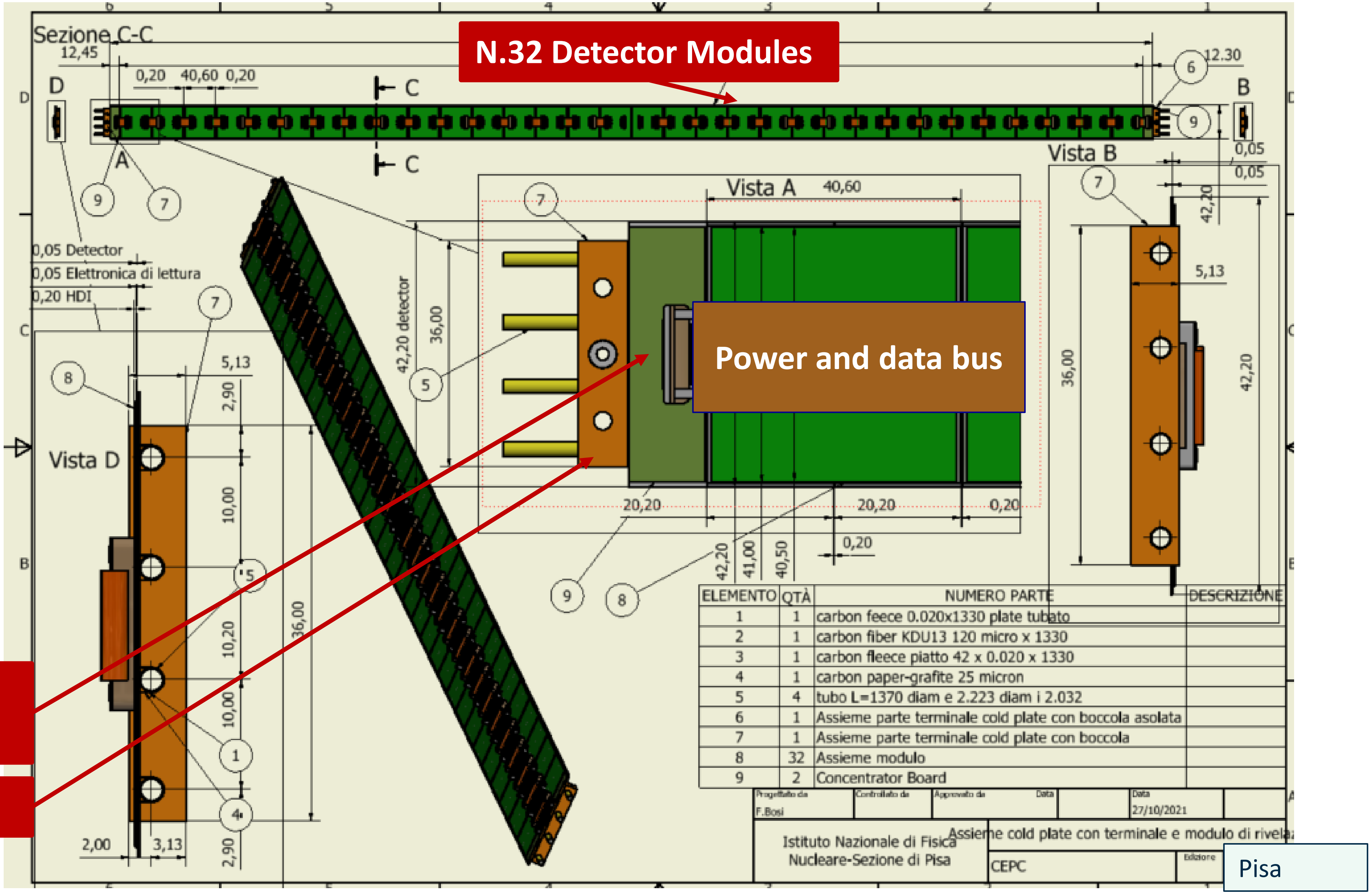
Progettato da F.Bosi
Controllato da
Approvato da
Data
Data 11/10/2021
Istituto Nazionale di Fisica Nucleare-Sezione di Pisa
Assieme struttura traliccio 1330 con supporti cold plate
CEPC
Edizione
Foglio

Pisa

Populated cold plate

Cold plate to hold and cool a row of 32 modules.

- Carbon fiber plate
- Refrigerant: demineralized water below atmospheric pressure, at T=15 °C
- Heat dissipation 200 mW/cm^2
- Thin Kapton pipes, 2mm diameter, held by carbon paper



ELEMENTO	QTÀ	NUMERO PARTE	DESCRIZIONE
1	1	carbon feece 0.020x1330 plate tubato	
2	1	carbon fiber KDU13 120 micro x 1330	
3	1	carbon fleece piatto 42 x 0.020 x 1330	
4	1	carbon paper-grafite 25 micron	
5	4	tubo L=1370 diam e 2.223 diam i 2.032	
6	1	Assieme parte terminale cold plate con boccola asolata	
7	1	Assieme parte terminale cold plate con boccola	
8	32	Assieme modulo	
9	2	Concentrator Board	

Progettato da F.Bosi

Controllato da

Approvato da

Data

Data 27/10/2021

Istituto Nazionale di Fisica Nucleare-Sezione di Pisa

Assieme cold plate con terminale e modulo di rivela

CEPC

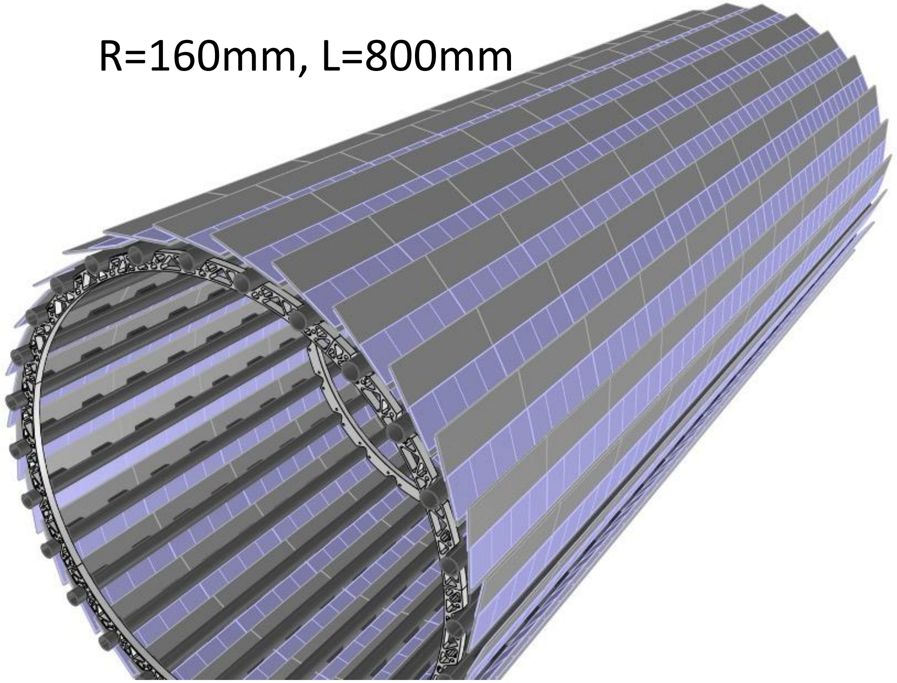
Edizione

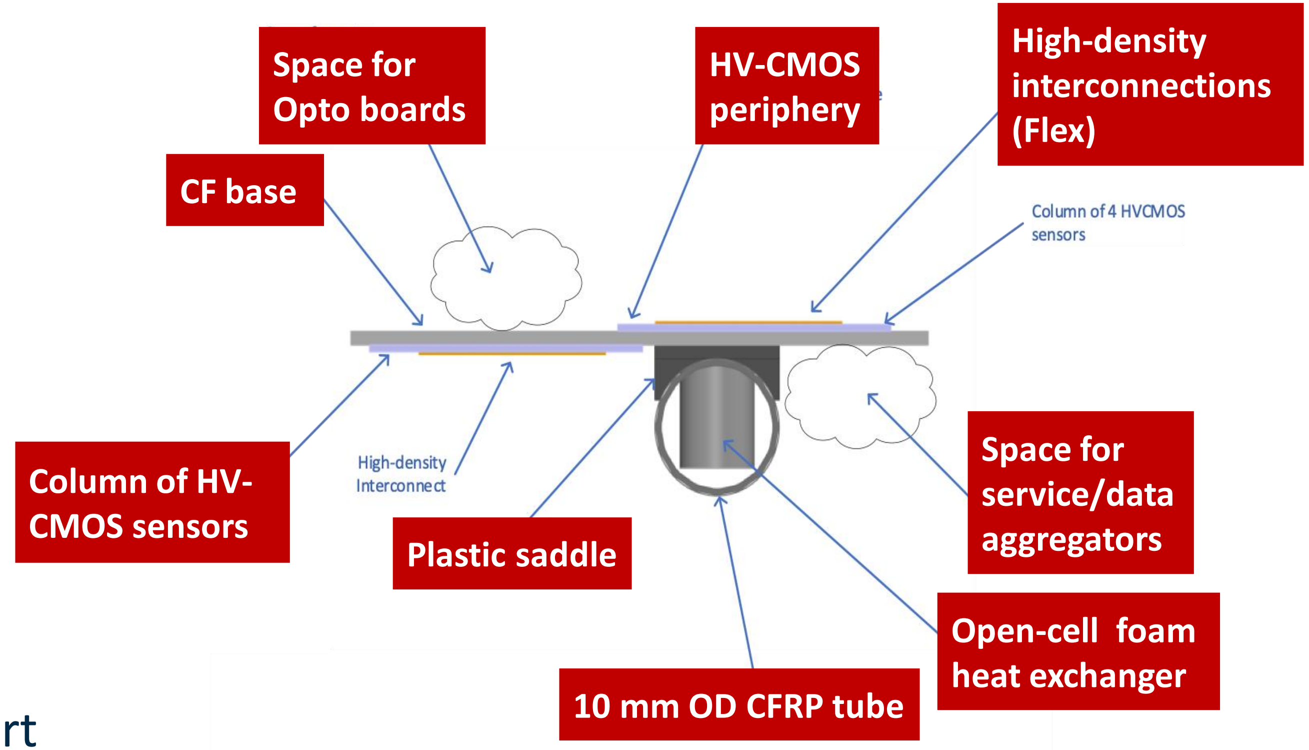
Pisa

Electronic Chip Concentrator

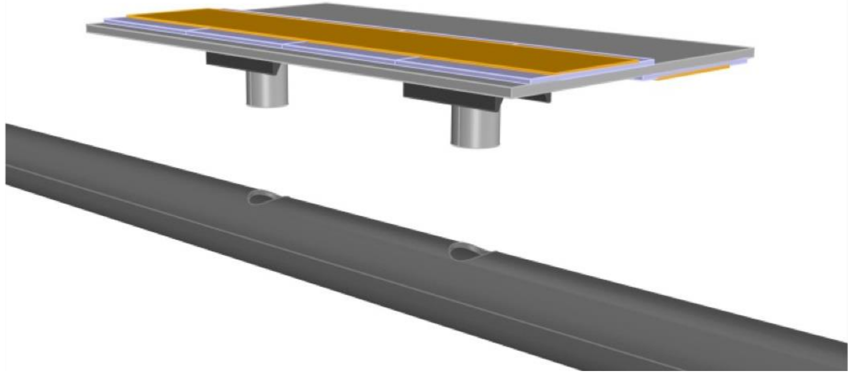
Cold Plate Terminal Part

Low radius structures


R=160mm, L=800mm



- Functional 8-chip unit glued on carbon support
- Asymmetric arrangement:
  - hermeticity along φ
  - space for data and power connection
- Carbon tube support
- Saddles provide mechanical and thermal connection to support by foam heat exchanger



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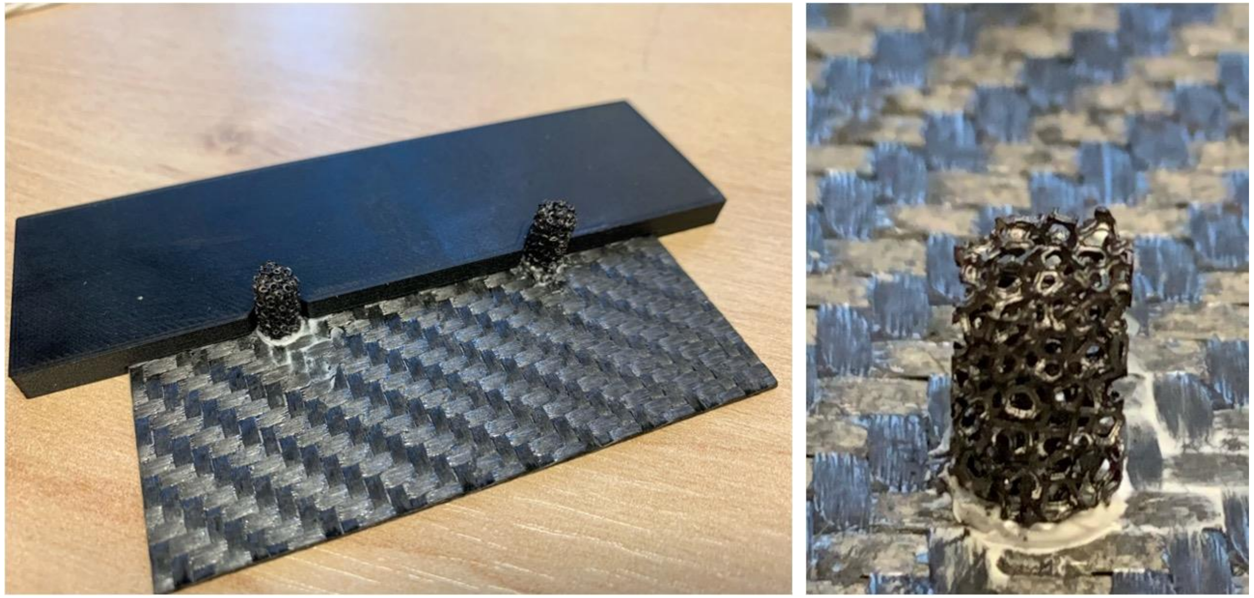
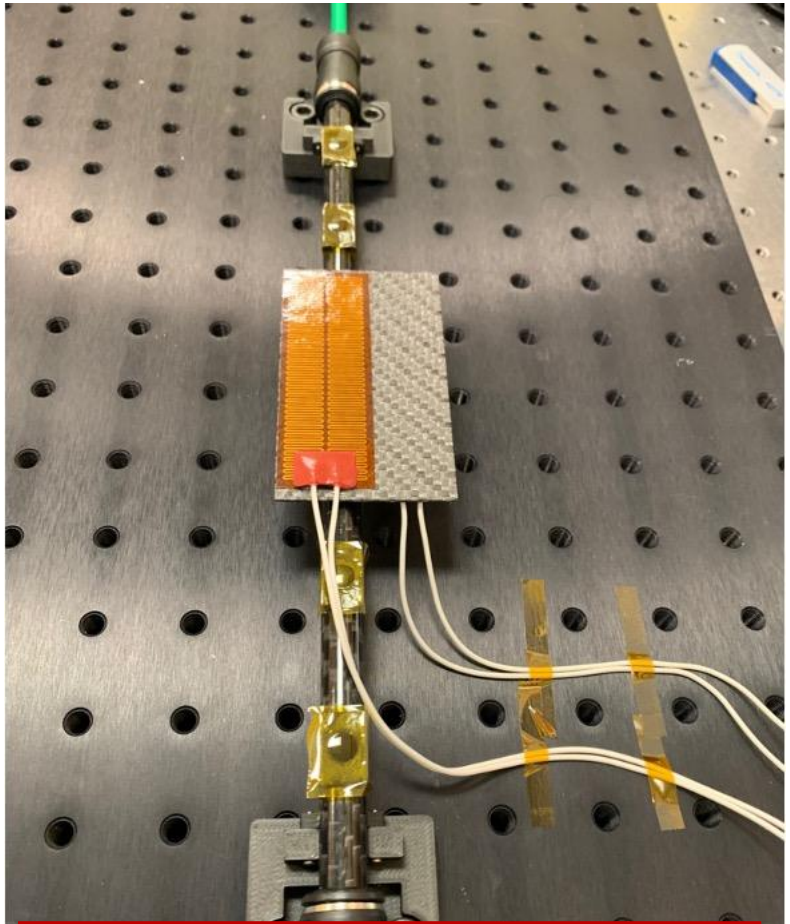
Pre-prototypes thermal evaluation

Pre-prototype: Base attached to tube & heaters on



- Investigate performance of high-thermal conductivity (eg Allcomp) foams as a heat exchanger
- Combination of large area and increased stream velocity through foam can lead to high efficiency
- Characterise performance (i.e. temperature rise vs power) for different flow velocities
- Develop FEA models simulating the fluid flow through foams



First look: at 3.1W power (expected from 8cm × 4cm area), temperature rise ~10°C w.r.t. CDA

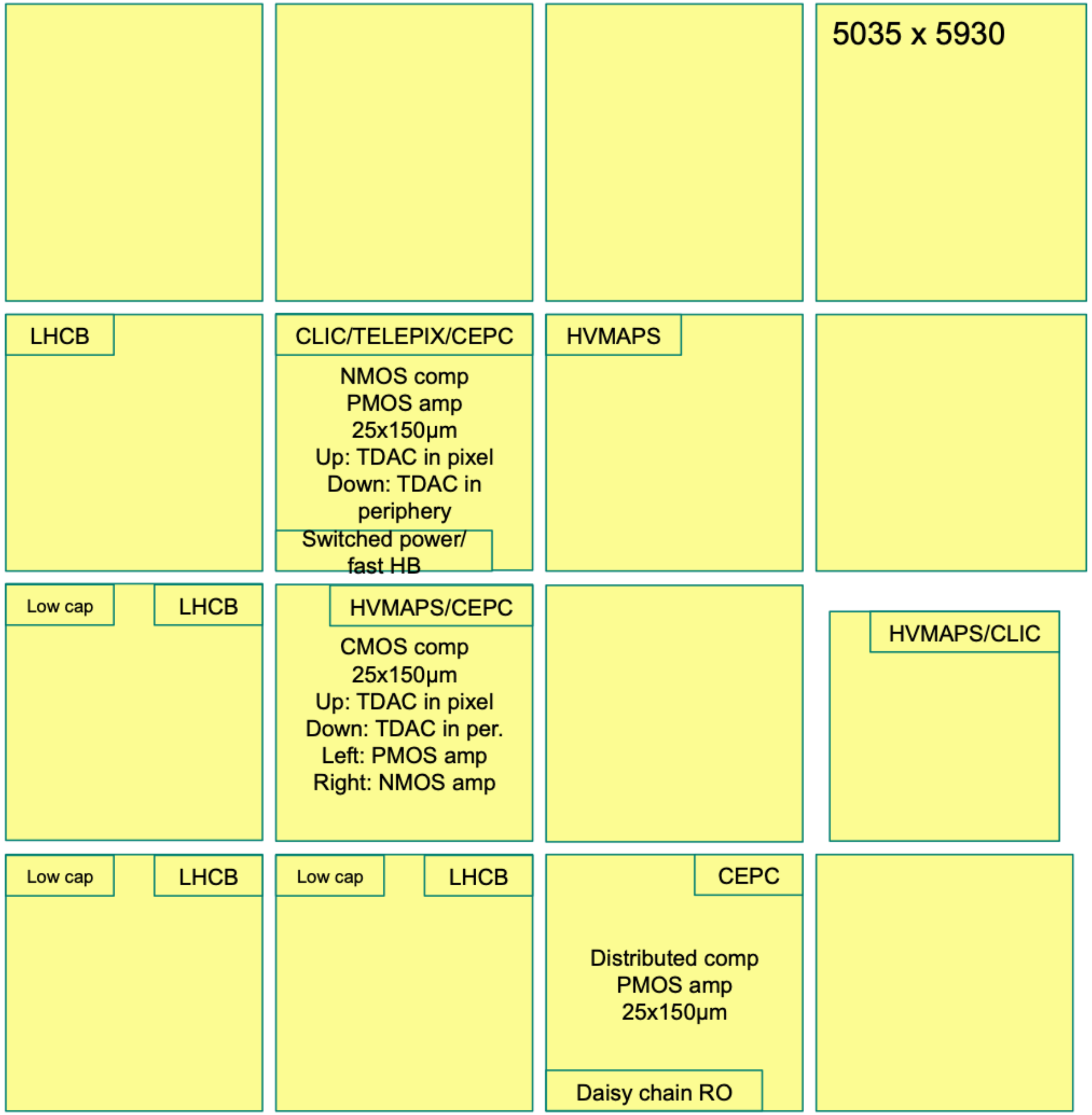
Liverpool

Si tracker: system considerations

- **Complete system consists of 900'000 cm² area / 4 cm² 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/quad-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/cm²**
  - 600 mW/chip → 2.4 W/module → **total FE power 130 kW**
  - additional power for on detector aggregation and de-randomizations **~2W/link**

Further ATLASPIX developments

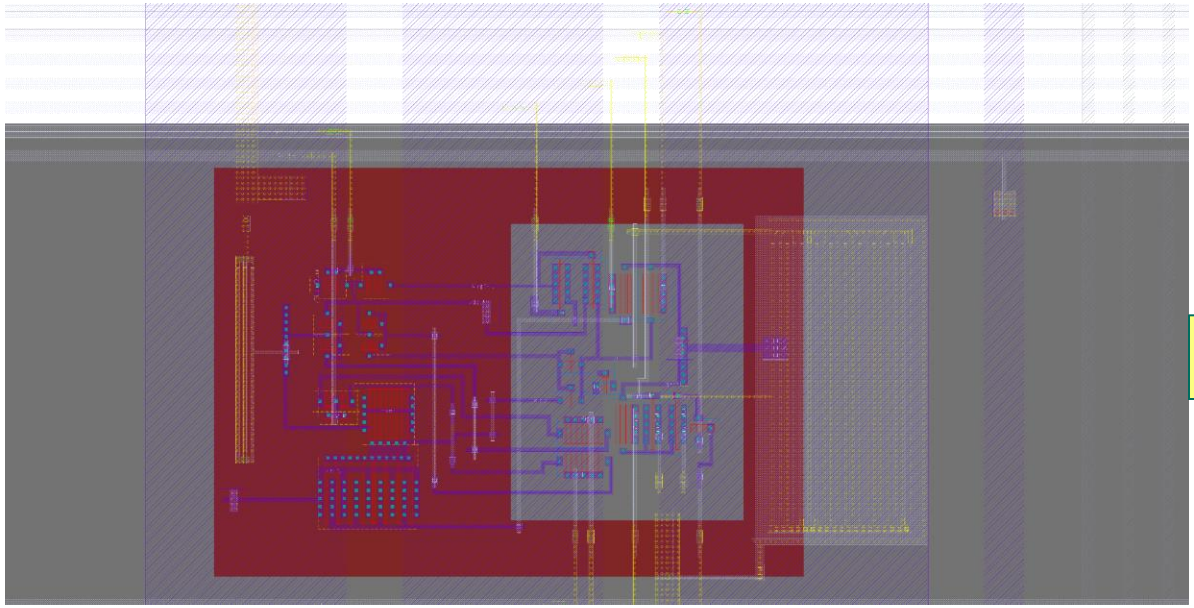
- Engineering run developing the ATLAPIX3 family
- Design driven by KIT
- Contribution from LHCb Mighty Tracker, CEPC and other projects
- To test evolutions of ATLASPix3:
    - 25 μm pitch in the bending plane
    - Lower capacitance
    - Amplifier (PMOS→N/C-MOS) and comparator (NMOS → P/C-MOS) designs
    - Electronics in pixel or in periphery
    - **Daisy chain readout**

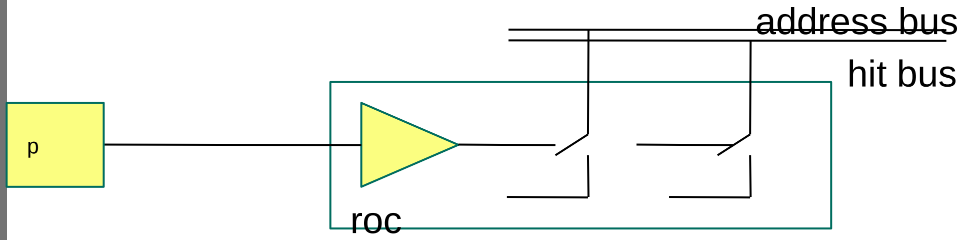


Higher integration technologies

Started development with Shangai Huali Microelectronics Corporation

- HLMC 55 nm HVCMOS technology
  - also 40 nm and 28 nm nodes available
- HLMC technology offers similar layers as TSI:
  - deep n-well
  - maximum voltage for HV transistors is 32V
  - Metal layers 1–6 can be used for fine pitch routing
  - three more thick metal layers, suitable for power
  - LV 1.2V
- The realistic pitch is down to 0.2 μm
  - relaxed and according to recommendation it is 0.3 μm (in 180 nm it was 0.6 μm)
- Test sensor of 3 × 2 mm^2 will be submitted as MPW run in March 2022

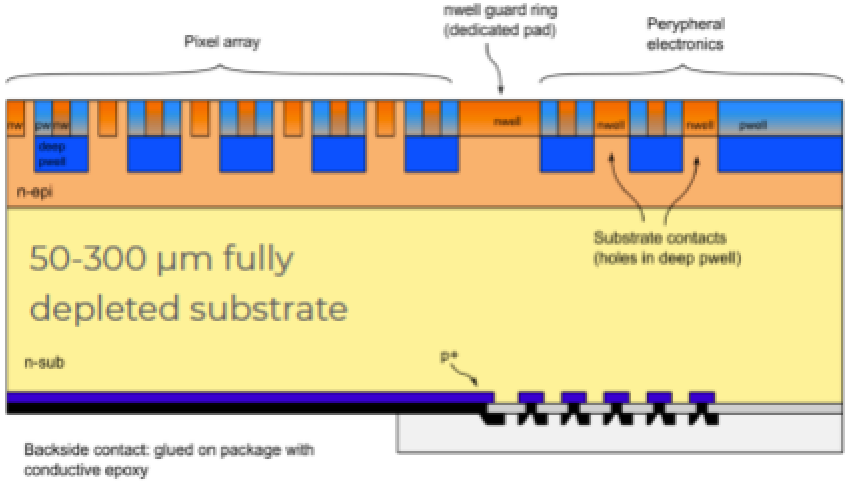


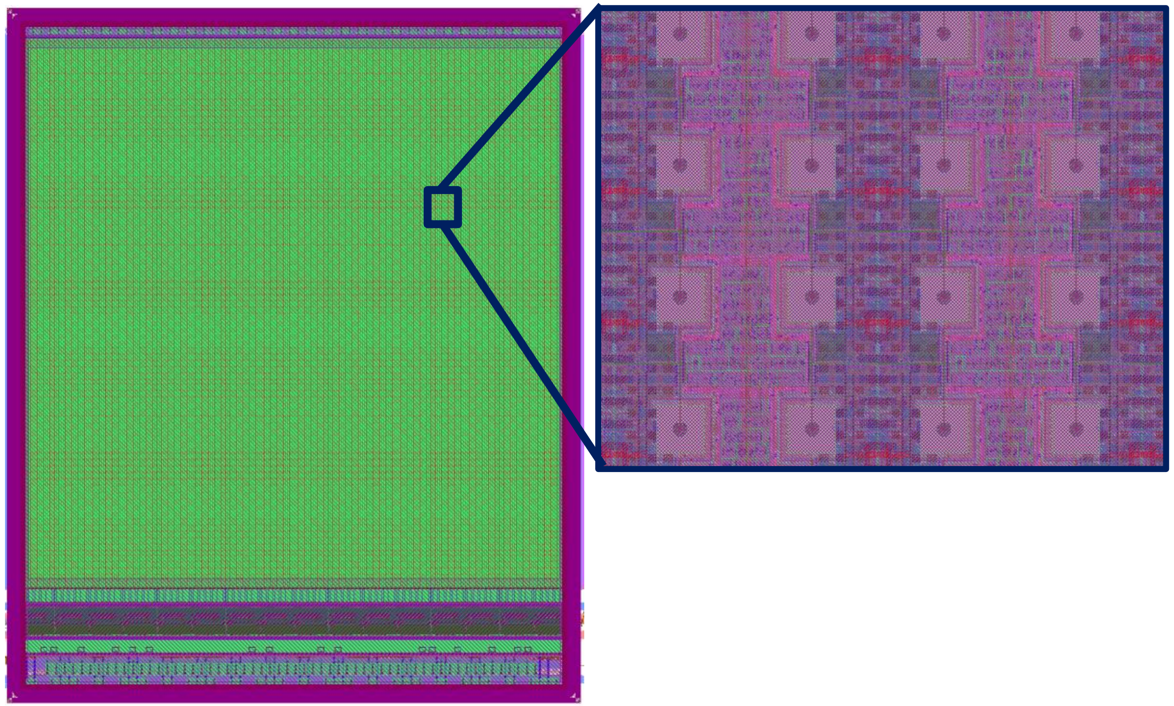


pixel p and readout cell

ARCADIA Project

- CMOS DMAPs Platform
  - Started as INFN project, collaborations with Switzerland and China
  - Project within AIDAInnova WP5
- Fully depleted monolithic sensor
- LFoundry 110 nm CMOS process
- Pixels:
  - sensor and back-side processing already tested on silicon
  - 25 × 25 μm^2 size
  - pixel area 50% analog – 50% digital
  - small collection electrode (20% of pixel area)
  - versions with ALPIDE and BULKDRIVEN front-ends
  - characterization of the readout architecture ongoing





Conclusions

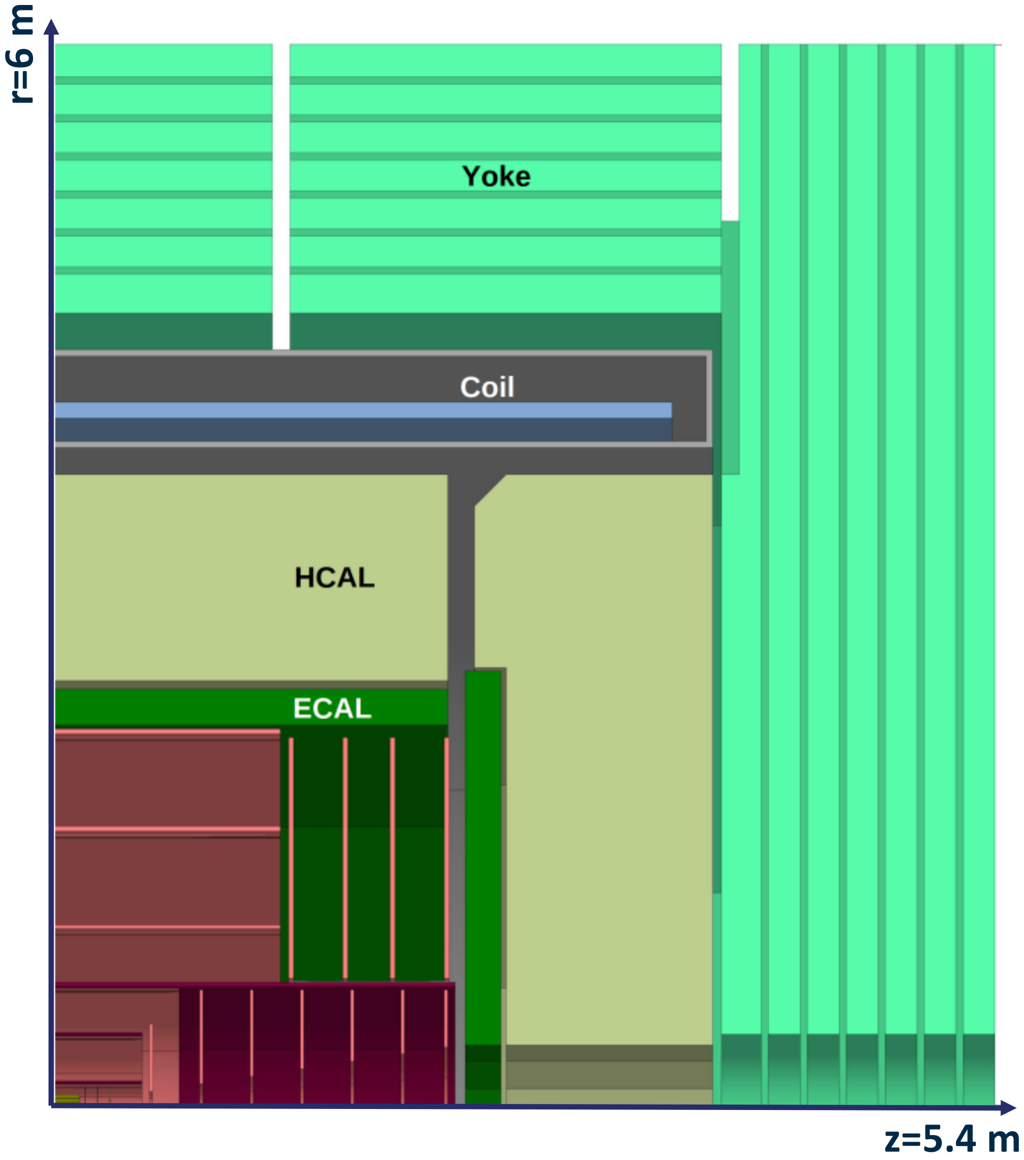
- Large area O(100 m^2) silicon trackers are a key feature of FCCee layouts
- DMAPS are an attractive solution
  - pixelated readout gives equal resolution in both coordinates, and it may help in reducing systematics of high precision measurements
  - monolithic solution provides low material and it is affordable in term of services and power
- The ATLASPIX3 chip already allows to build demonstrators
  - feasibility studies of the detector concepts and services
  - low material large size mechanical structures
- R&D is on-going on sensors improving performance and adding features
  - low power consumption readout architectures
  - small feature size for finer segmentation and more digital functionalities

BACKUP

FCC-ee Detectors: CLD

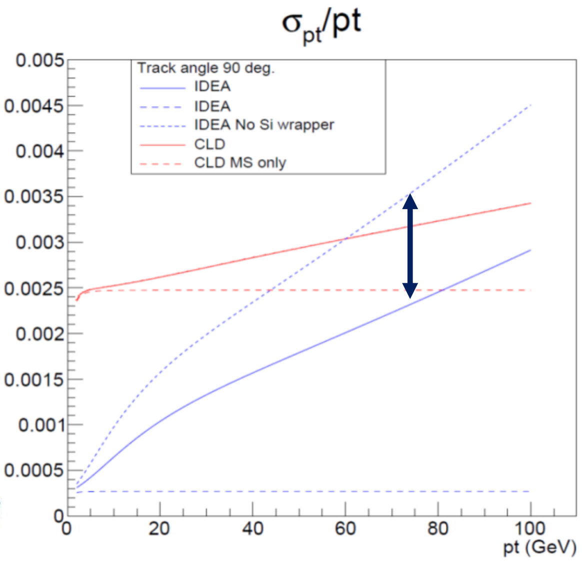
Full Silicon Tracker

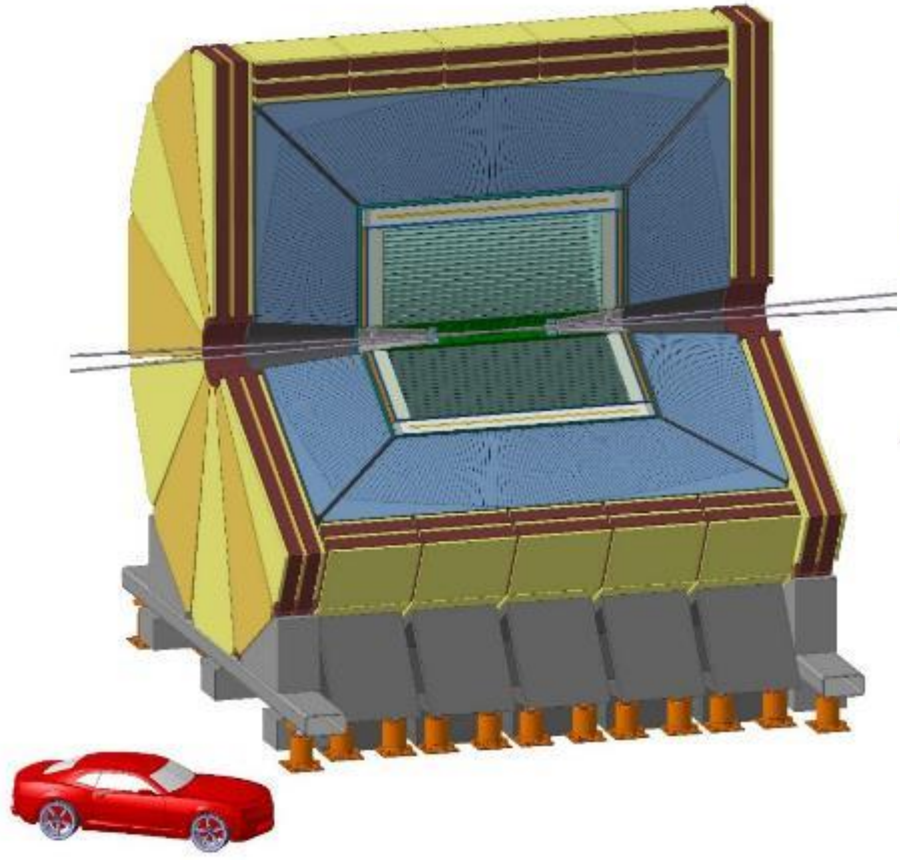
- Pixel vertex detector:
  - Barrel, 3 double layers, r=1.7, 2.7, 5.7 cm
  - Disks, 3 double layers, |z|=16, 23, 30 cm
  - 0.6-0.7% X_0 per double layer
- **Inner tracker:**
  - **Strips and pixels**
  - **12.7<R<57.5 cm, |z|<2.2 m**
  - **1.1-1.5% X_0 per layer**
- **Outer tracker:**
  - **Strips**
  - **67.5<R<210 cm, |z|<2.2 m**
  - **1.1-1.5% X_0 per layer**

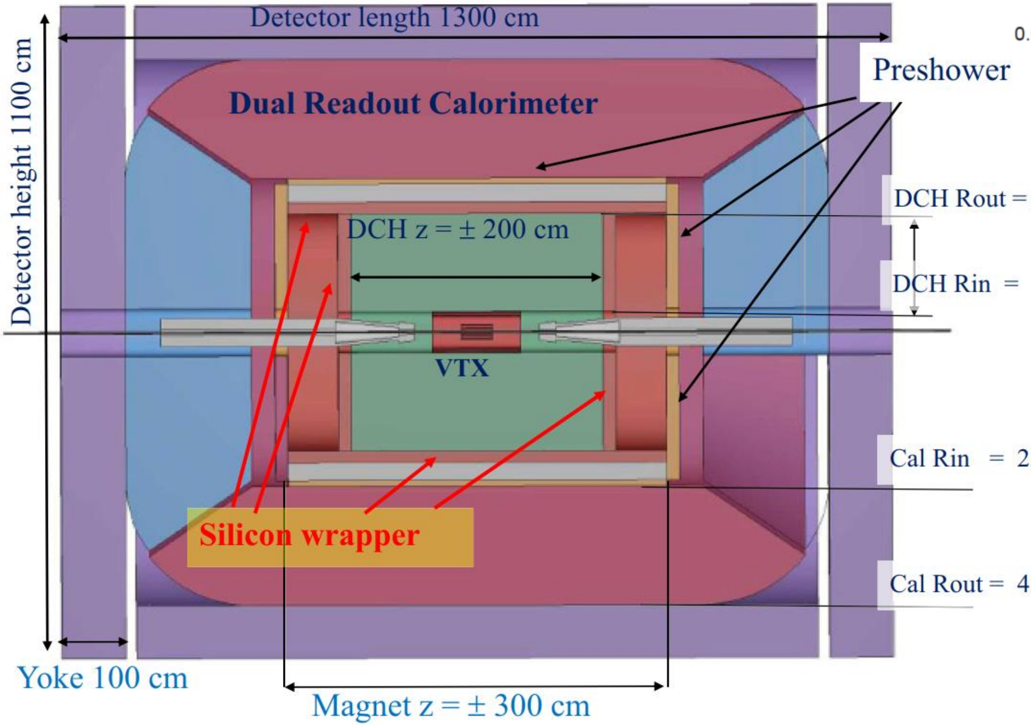


FCC-ee Detectors: IDEA

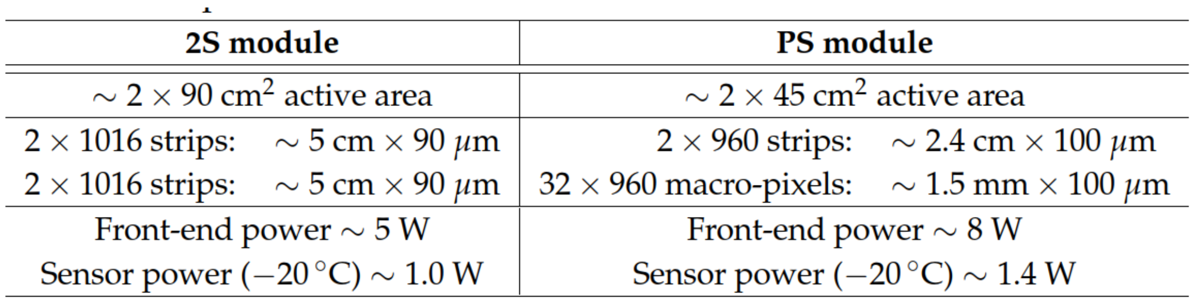
- **Vertex detector:** **5 (Depleted)MAPS layers r = 1.7 – 34 cm**
- Drift chamber (112 layers): 4 m long, r = 35 – 200 cm
- **Si wrapper:** **Strips, barrel at r=2 m and drift chamber endplates z=2 m**



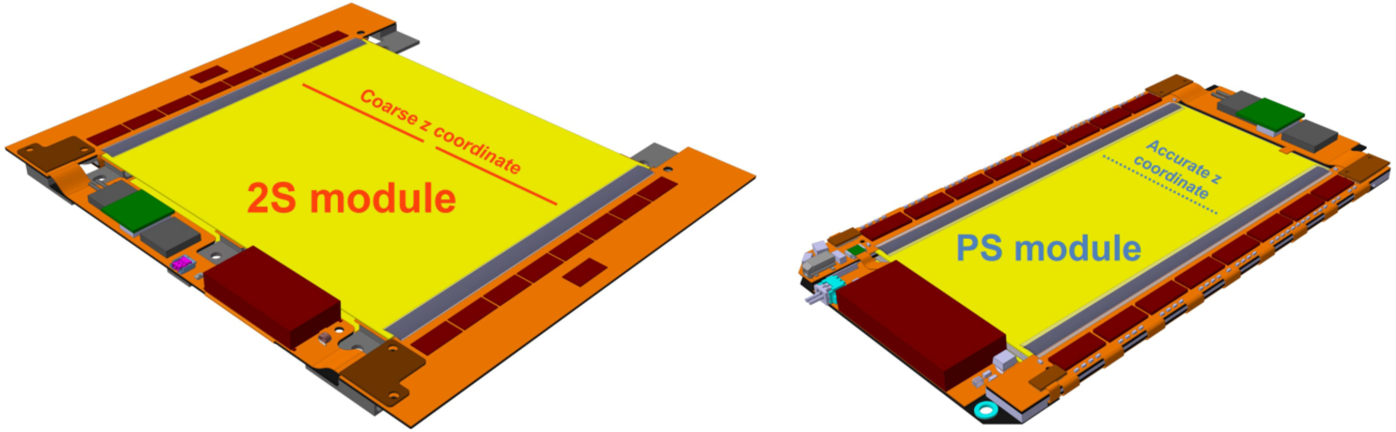




CMS Tracker Modules



2S module	PS module
$\sim 2 \times 90$ cm^2 active area	$\sim 2 \times 45$ cm^2 active area
2×1016 strips: ~ 5 cm $\times$ $90\ \mu$m 2×1016 strips: ~ 5 cm $\times$ $90\ \mu$m	2×960 strips: ~ 2.4 cm $\times$ $100\ \mu$m 32×960 macro-pixels: ~ 1.5 mm $\times$ $100\ \mu$m
Front-end power ~ 5 W Sensor power ($-20\,^\circ$C) ~ 1.0 W	Front-end power ~ 8 W Sensor power ($-20\,^\circ$C) ~ 1.4 W

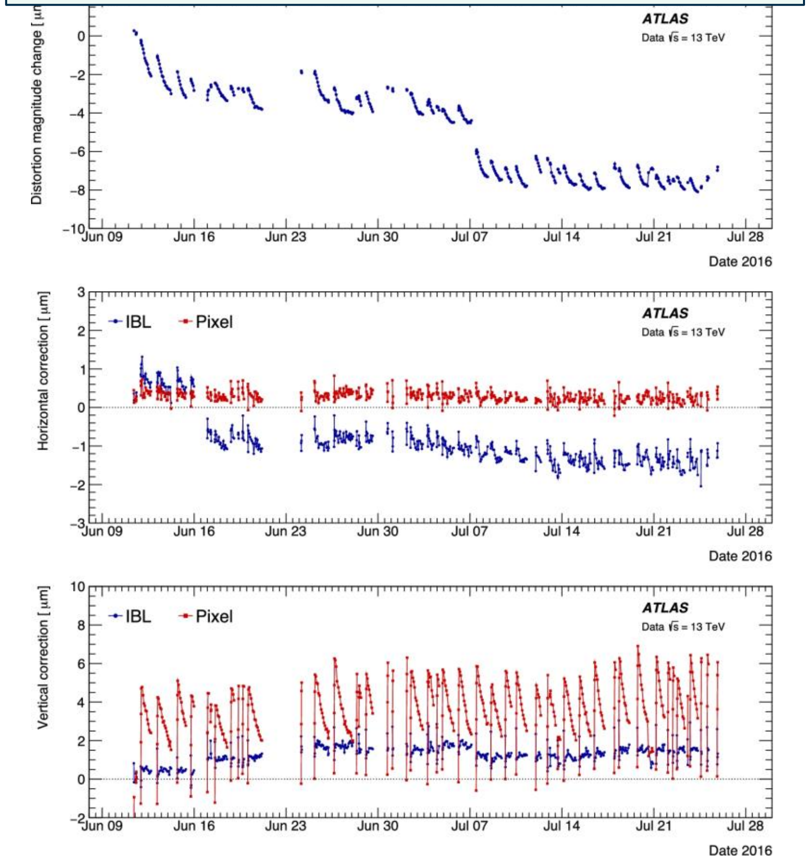


	2S	PS	Pixels
Area	192 m^2	25 m^2	4.9 m^2
Power density	27 mW/cm^2	89 mW/cm^2	700 mW/cm^2
Module cost (TDR)	26990 kCHF	20780 kCHF	11691 kCHF
	140 kCHF/m^2	830 kCHF/m^2	2400 kCHF/m^2

Si Wrapper: why pixels?

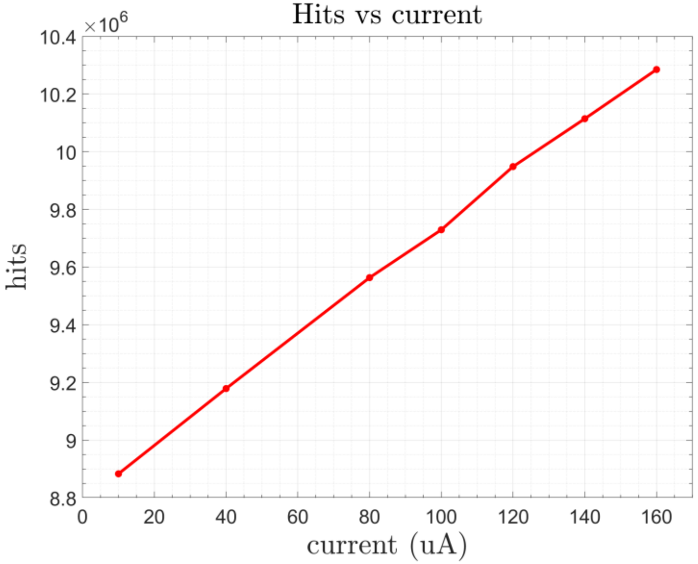
- **For cross section measurements need to keep systematics on the angular acceptance at the level of 50 μrad at $\theta = 10°$.**
- in principle, silicon is a very good ruler:
  - Inner Silicon Tracker disks: at 40 cm, δR_{sys}<20 μm
    - alignment in principle is better than that, but stability need 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, δR_{sys}<100 μm
    - 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, $\sigma_z = 14$ μm, 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

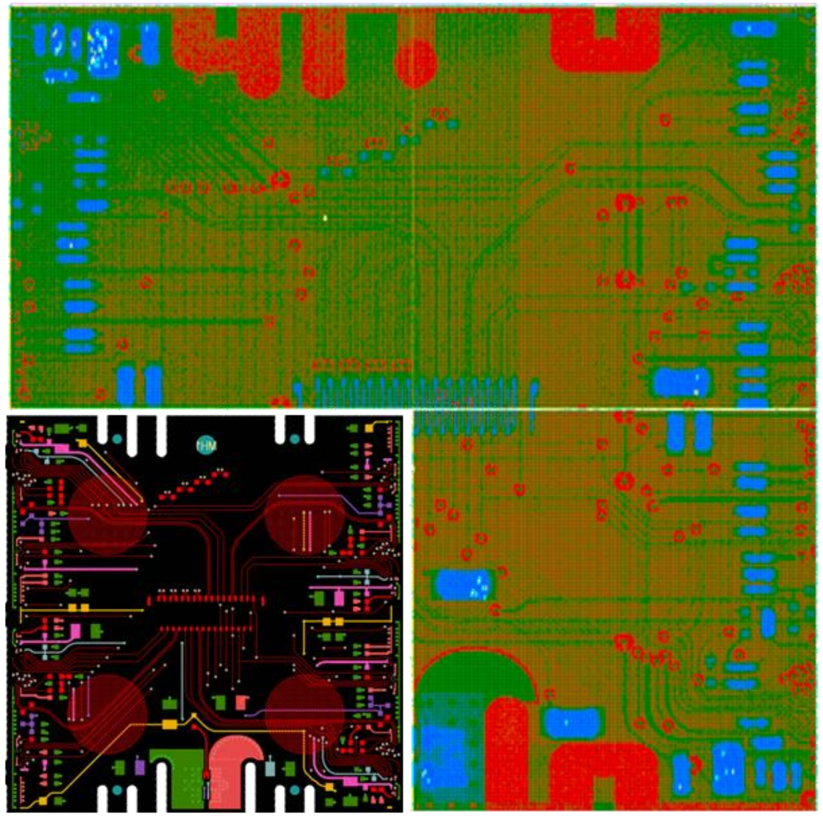
https://doi.org/10.1140/epjc/s10052-020-08700-6



Lab tests with X-ray tube

- Amptek Mini-X2 with silver anode, max energy 50 kV
- **Linear readout rate** from **10 uA – 160 uA** at 25 kV without low-energy filters
  - 5 minutes source runs without biasing voltage
  - Missing threshold tuning, set average DAC value
  - Rate range: ~1.5 x 10^4 hits/s to ~ 3.4 x 10^4 hits/s
- Components on the PCB can be easily identified



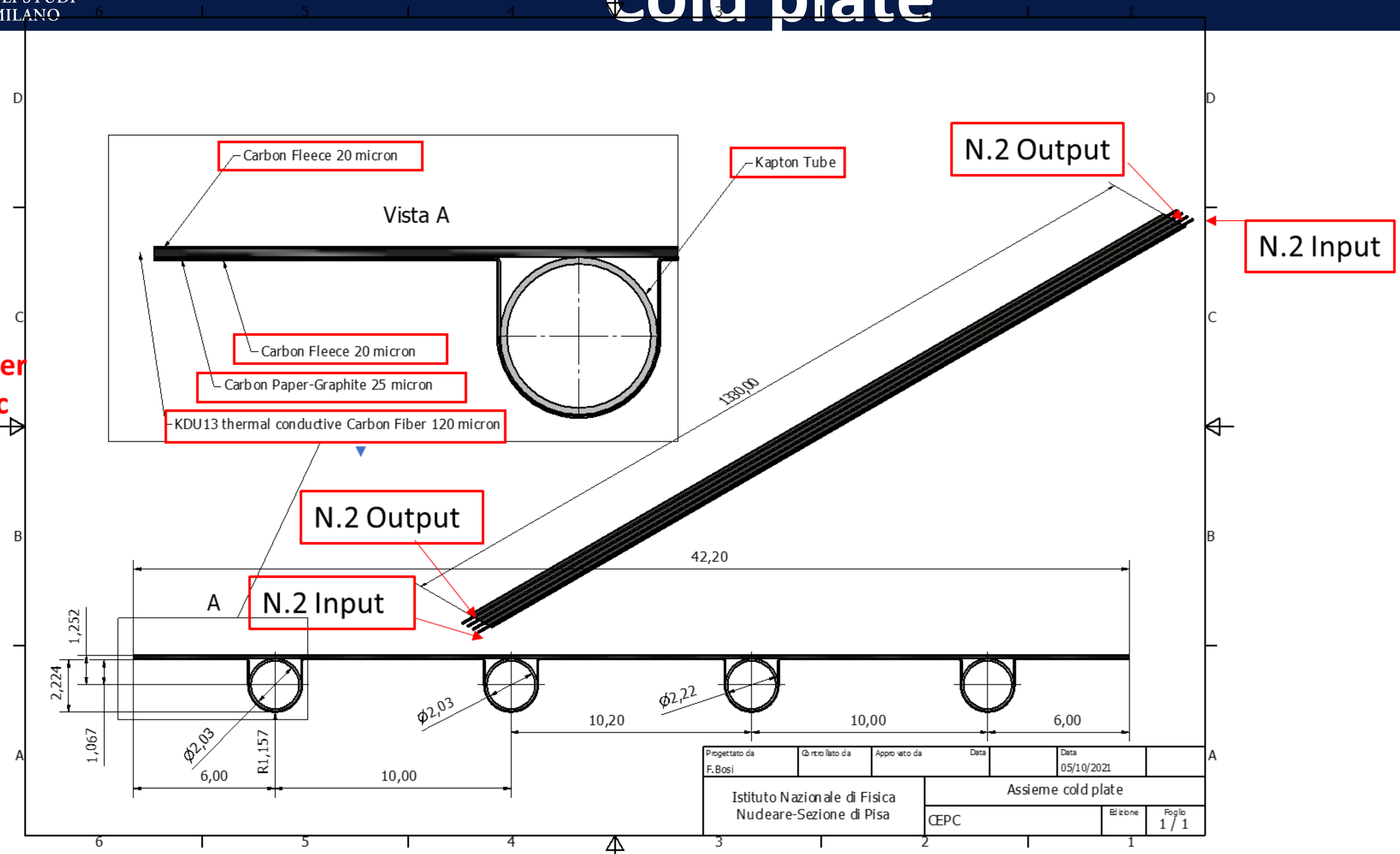


Cold plate

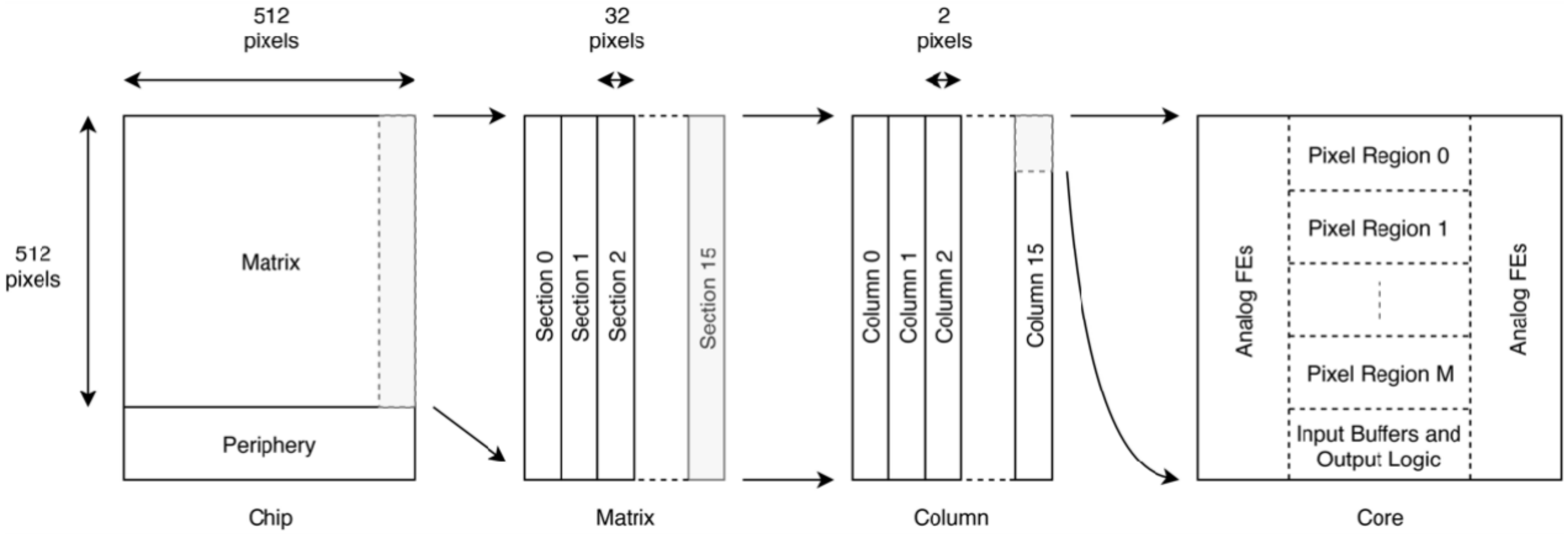
Refrigerant: demineralized water below atmospheric pressure.

Refrigerant Temperature: 15°C

Heat dissipated: 200 mW/cm^2



ARCADIA Main Demonstrator



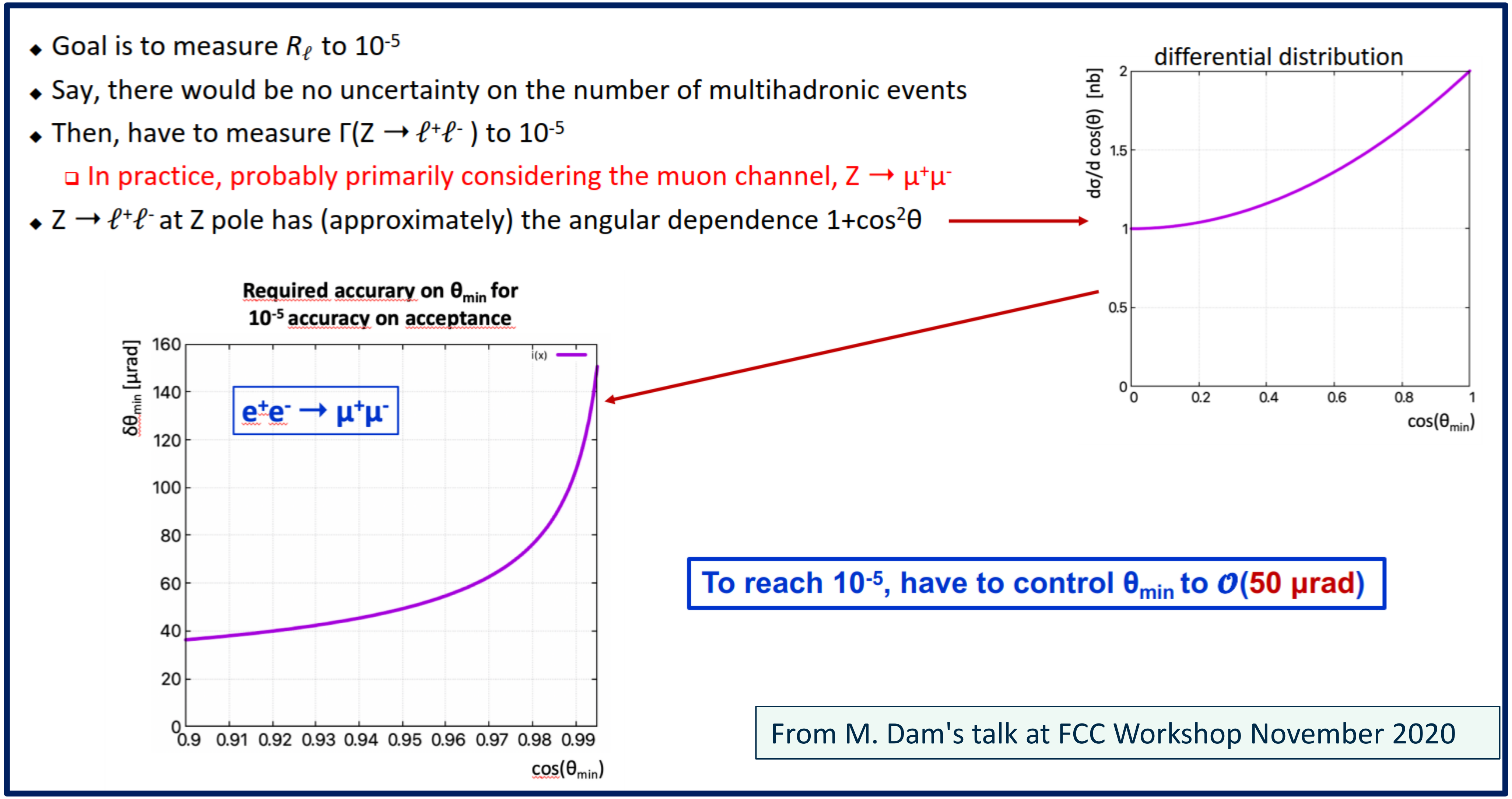
- Matrix core 512 x 512, “side-abuttable” to accomodate a 1024 x 512 silicon active area (2.56 x 1.28 cm^2)
- Each 2x512 Column is composed of 2x32-pixel Cores
- Matrix and EoC architecture, data links and payload ID: scalable to 2048 x 2048
- Clock-less matrix integrated on a power-oriented flow
- Triggerless binary data readout, event rate up to 100 MHz/cm^2
- Submitted 11/2020, back from foundry on 04/2021, now under characterization. 2nd and 3rd run expected in 2021 and 2022.

High precision measurements (1)

Strong requirements on detector design come from the systematics in high precision measurements

Example:

$$R_\ell = \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \ell^+\ell^-)}$$



- Goal is to measure R_ℓ to 10^{-5}
- Say, there would be no uncertainty on the number of multihadronic events
- Then, have to measure $\Gamma(Z \to \ell^+\ell^-)$ to 10^{-5}
  - In practice, probably primarily considering the muon channel, $Z \to \mu^+\mu^-$
- $Z \to \ell^+\ell^-$ at Z pole has (approximately) the angular dependence $1+\cos^2\theta$

Required accurary on θ_{min} for 10^{-5} accuracy on acceptance

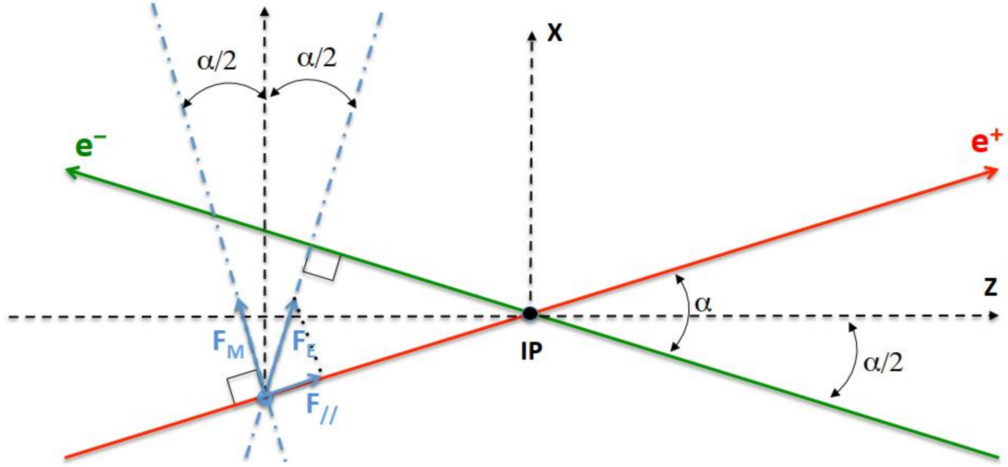
To reach 10^{-5}, have to control θ_{min} to $\mathcal{O}$(50 μrad)

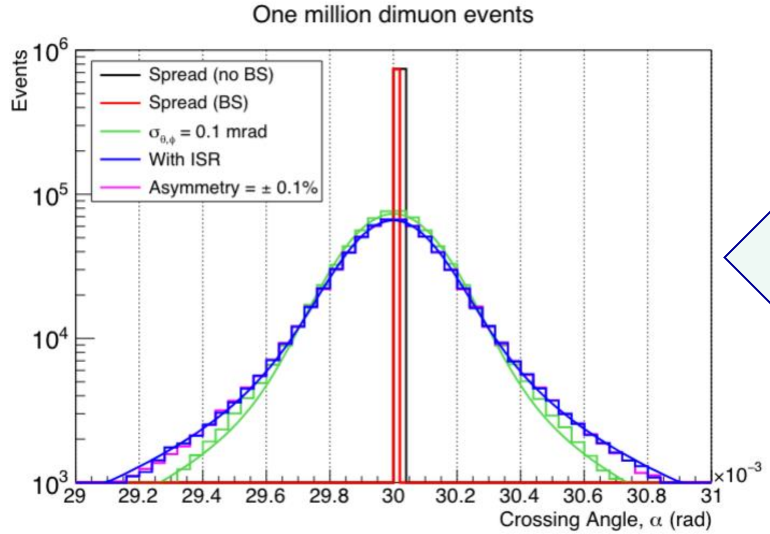
From M. Dam's talk at FCC Workshop November 2020

High precision measurements (2)

Strong requirements on detector design come from the systematics in high precision measurements

Example:
center of mass energy correction from beam-beam interactions





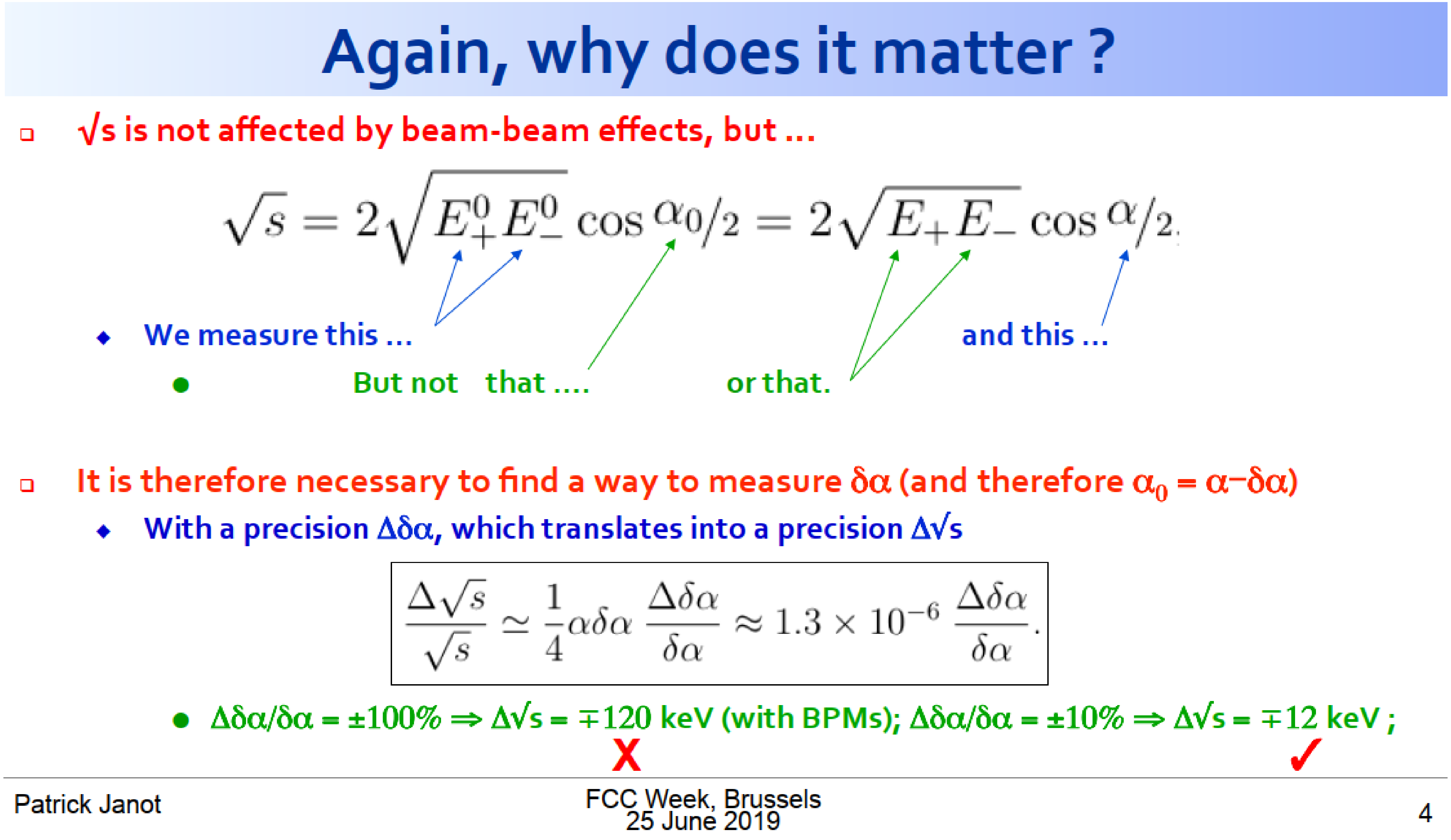
Beam-beam interactions change the energy and direction of the beams:

- changes are correlated such that center of mass energy is constant:
$$\sqrt{s} = \sqrt{E_0^+ E_0^-}\cos\frac{\alpha_0}{2} = \sqrt{E^+ E^-}\cos\frac{\alpha}{2}$$
- but α_0 is only measured with 0.1 mrad accuracy by the BPM
- It can be derived by monitoring the measured value of α as a function of the beam intensity
- With statistical uncertainties $\sigma_{\theta,\varphi}$ of 0.1 mrad, can get a 0.3 μrad uncertainty on α in ~5 minutes

See P. Janot's talk at FCC Week 2019

But what about systematics?

Beam-beam effects



Again, why does it matter ?

- √s is not affected by beam-beam effects, but …

$$\sqrt{s} = 2\sqrt{E_+^0 E_-^0}\cos{\alpha_0/2} = 2\sqrt{E_+ E_-}\cos{\alpha/2}$$

- We measure this … and this …
  - But not that …. or that.

- It is therefore necessary to find a way to measure δα (and therefore $\alpha_0 = \alpha - \delta\alpha$)
  - With a precision Δδα, which translates into a precision Δ√s

$$\boxed{\frac{\Delta\sqrt{s}}{\sqrt{s}} \simeq \frac{1}{4}\alpha\delta\alpha\,\frac{\Delta\delta\alpha}{\delta\alpha} \approx 1.3\times10^{-6}\,\frac{\Delta\delta\alpha}{\delta\alpha}.}$$

- Δδα/δα = ±100% ⇒ Δ√s = ∓120 keV (with BPMs); Δδα/δα = ±10% ⇒ Δ√s = ∓12 keV ;
  ✗ ✓

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25 June 2019

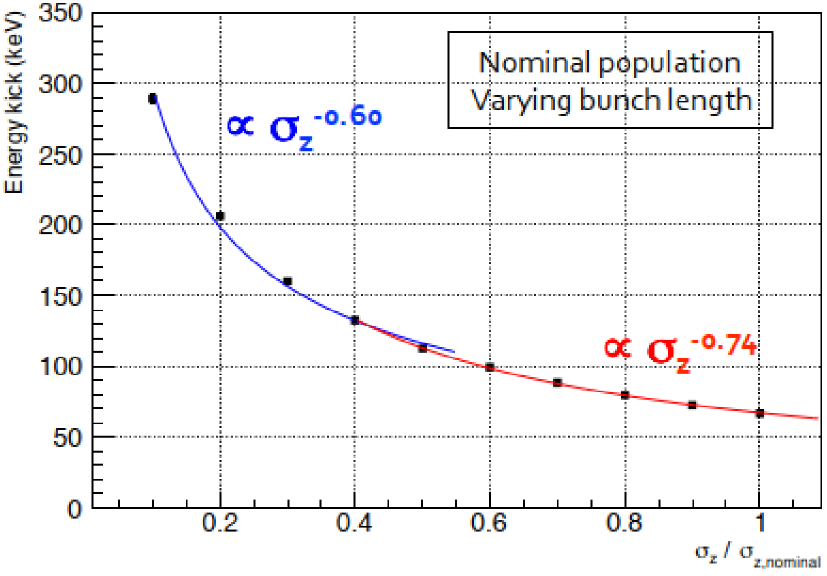
4

Extrapolation to $N^{\pm} = 0$

- Energy kicks $\delta E^{\pm}$ directly proportional to opposite bunch population $N^{\mp}$
  - Also increases when opposite bunch length decreases (charge density increases)
    - From independent numerical integration
      - (Code from E. Perez)
    - Fit to a power law in σ_z (or in σ_δ, equivalently)

$$\delta E^{\pm} \propto \frac{N^{\mp}_{\text{part}}}{\sigma_\delta^{\mp\,2/3}}.$$

Bunch length/energy spread



- Uncertainty of ±0.05 on the exponent

Treated as systematic uncertainty in the following

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Measurement of $\delta\alpha$

- **For equal e^+ and e^- bunch populations, $\delta\alpha$ is proportional to the common δE:**

$$\boxed{\delta\alpha = \frac{1}{\tan {}^{\alpha}/_{2}} \left(\frac{\delta E_+}{E_+} + \frac{\delta E_-}{E_-} \right)}$$

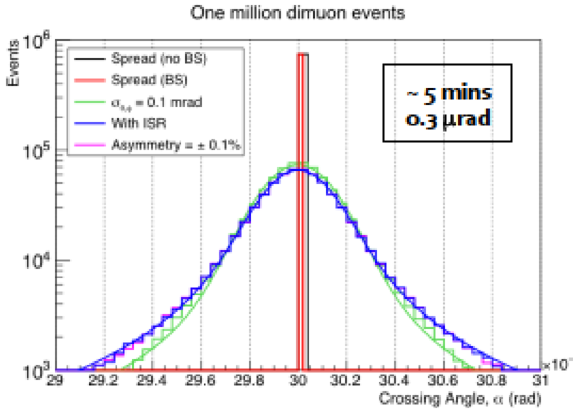
  - Therefore, $\delta\alpha$ follows the same power law as δE: $\delta\alpha \propto \frac{N_{\rm part}}{\sigma_{\sqrt{s}}^{2/3}}$. with $\sigma_{\sqrt{s}} = \sigma_\delta^+ \oplus \sigma_\delta^-$
  - The bunch population $N_{\rm part}$ is in turn related to the luminosity: $\mathcal{L} \propto \frac{N_{\rm part}^2}{\sigma_z} \Leftrightarrow \mathcal{L} \propto \frac{N_{\rm part}^2}{\sigma_{\sqrt{s}}}$.
  - Leading to the remarkable power law: $\boxed{\delta\alpha \propto \frac{\mathcal{L}^{1/2}}{\sigma_{\sqrt{s}}^{1/6}}.}$
    - It turns out that the beam crossing angle, the luminosity, and the centre-of mass energy spread can be measured altogether with $\mu^+\mu^-(\gamma)$ events **[see slide 10]**
      - ➨ Linear fit of a vs $L^{1/2}/\sigma_{\sqrt{s}}^{1/6}$ will give in turn the values of $\delta\alpha$ and α_0

Measurement with $\mu^+\mu^-(\gamma)$ events

- **From total energy-momentum conservation**
  - In the transverse plane [p_x, p_y, E] : see slide 3

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

$$\Delta\alpha = \frac{0.3\,\mathrm{mrad}}{\sqrt{N_{\mu\mu}}}.$$



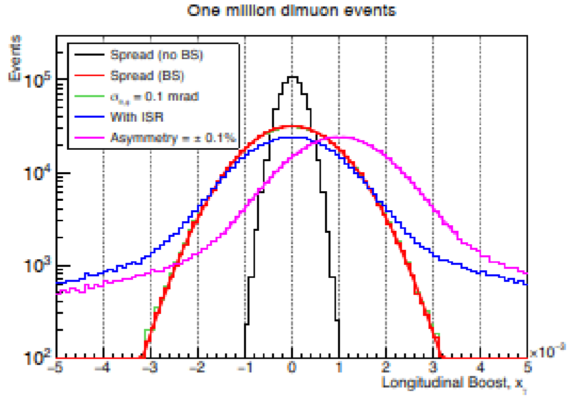
~ 5 mins
0.3 μrad

  - In the longitudinal direction [p_z, E] : see my presentation in Amsterdam and the Energy Calibration paper
    - Longitudinal boost distribution ~ √s spread due to σ_δ

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|},$$

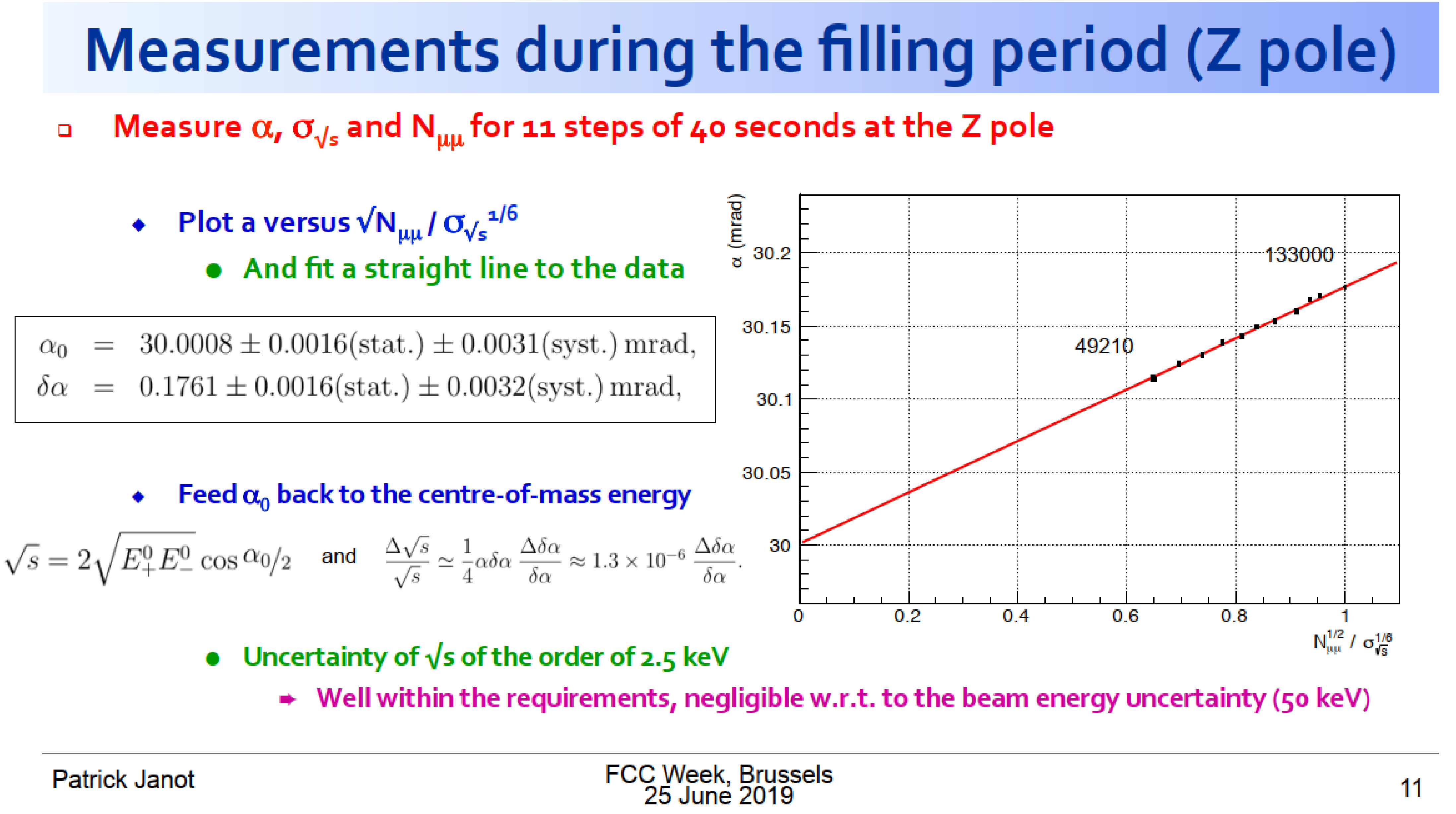
$$\text{with} \quad x_\pm = \frac{\mp\sin\theta^\mp\sin\varphi^\mp}{\sin\theta^+\sin\varphi^+ - \sin\theta^-\sin\varphi^-}.$$

$$\frac{\Delta\sigma_{\sqrt{s}}}{\sigma_{\sqrt{s}}} = \frac{1}{\sqrt{N_{\mu\mu}}}$$



  - Luminosity directly proportional to $N_{\mu\mu}$

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{1}{\sqrt{N_{\mu\mu}}}$$



Measurements during the filling period (Z pole)

- Measure α, $\sigma_{\sqrt{s}}$ and $N_{\mu\mu}$ for 11 steps of 40 seconds at the Z pole
  - Plot a versus $\sqrt{N_{\mu\mu}} / \sigma_{\sqrt{s}}^{1/6}$
    - And fit a straight line to the data

$$
\begin{aligned}
\alpha_0 &= 30.0008 \pm 0.0016(\text{stat.}) \pm 0.0031(\text{syst.})\ \text{mrad},\\
\delta\alpha &= 0.1761 \pm 0.0016(\text{stat.}) \pm 0.0032(\text{syst.})\ \text{mrad},
\end{aligned}
$$

  - Feed α_0 back to the centre-of-mass energy

$$\sqrt{s} = 2\sqrt{E^0_+ E^0_-}\cos\alpha_0/2 \quad \text{and} \quad \frac{\Delta\sqrt{s}}{\sqrt{s}} \simeq \frac{1}{4}\alpha\delta\alpha\,\frac{\Delta\delta\alpha}{\delta\alpha} \approx 1.3\times10^{-6}\,\frac{\Delta\delta\alpha}{\delta\alpha}.$$

    - Uncertainty of √s of the order of 2.5 keV
      - ➨ Well within the requirements, negligible w.r.t. to the beam energy uncertainty (50 keV)

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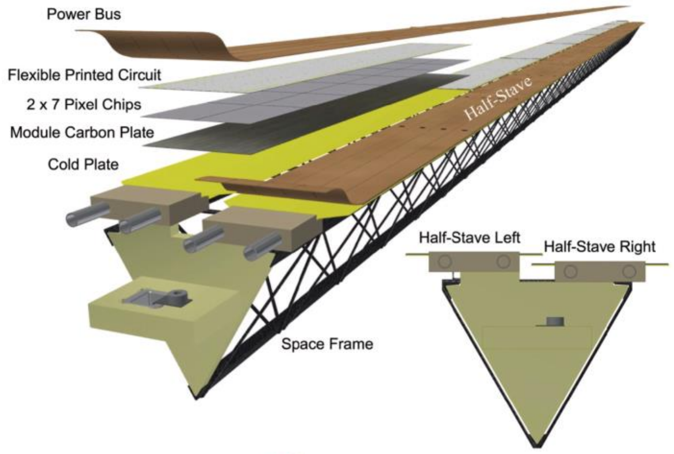
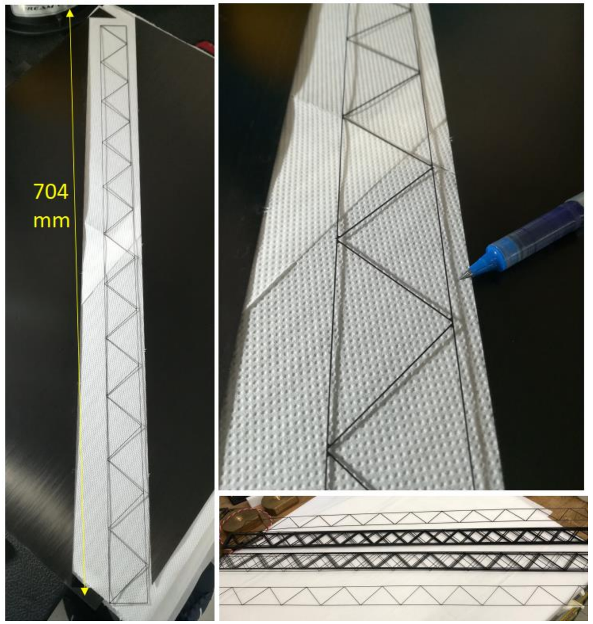
11

Si tracker - Mechanics

- Local supports needs original solutions for the internal tracker (lightweight) and the wrapper (long-term stability)

- Just a couple of examples:
  - ALICE like staves, but built with subtractive technology
  - Stavelets with ATLASPIX3 modules as option for the Si Wrapper





- Different cooling options available
  - pipes materiale: Titanium, steel, carbon, microchannel
  - CO_2 or water cooling
  - alternative cooling of edge supports for the vertex (à la Belle II)