Pixel vertex detector

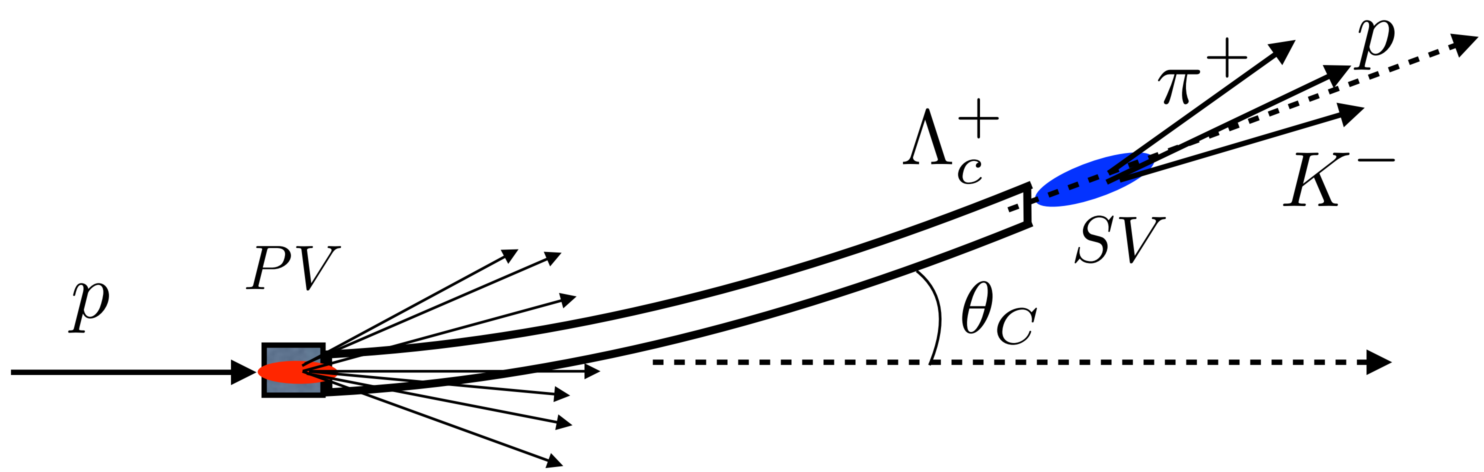
Nicola Neri
Università degli Studi e INFN Milano

Orsay, 11-12 December 2023

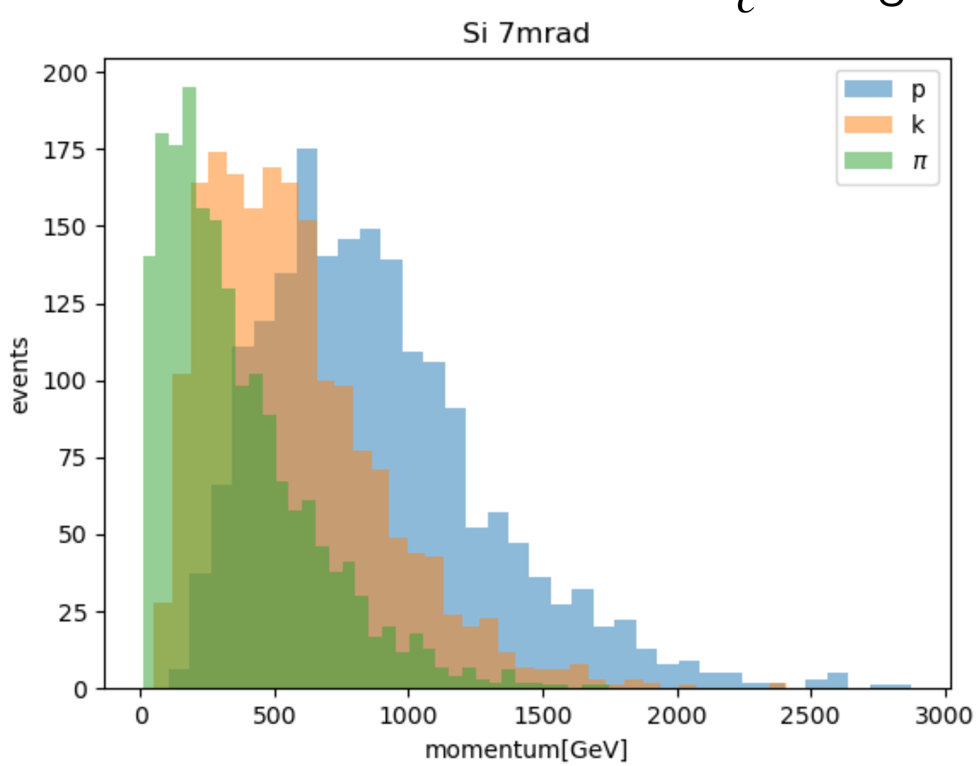
SELDOM webpage
@SeldomTeam

Λ_c^+ signal event topology

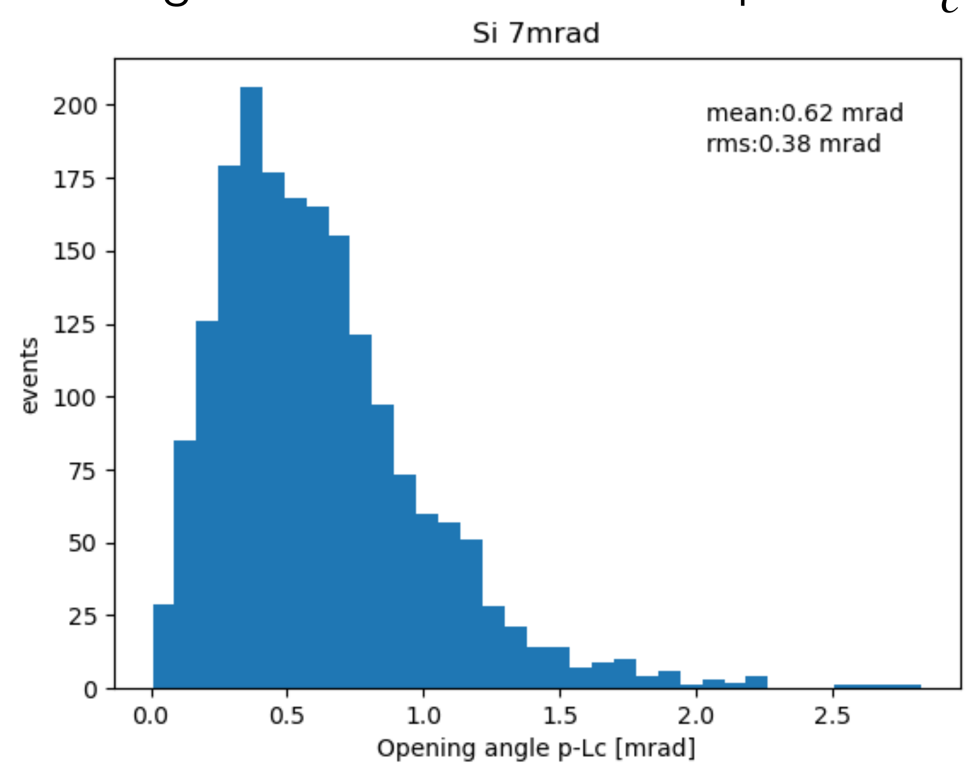
- Average momentum of 1 TeV for channeled Λ_c^+ baryons for bending angle $\theta_C = 7\ \mathrm{mrad}$



Momentum distribution of Λ_c^+ daughters



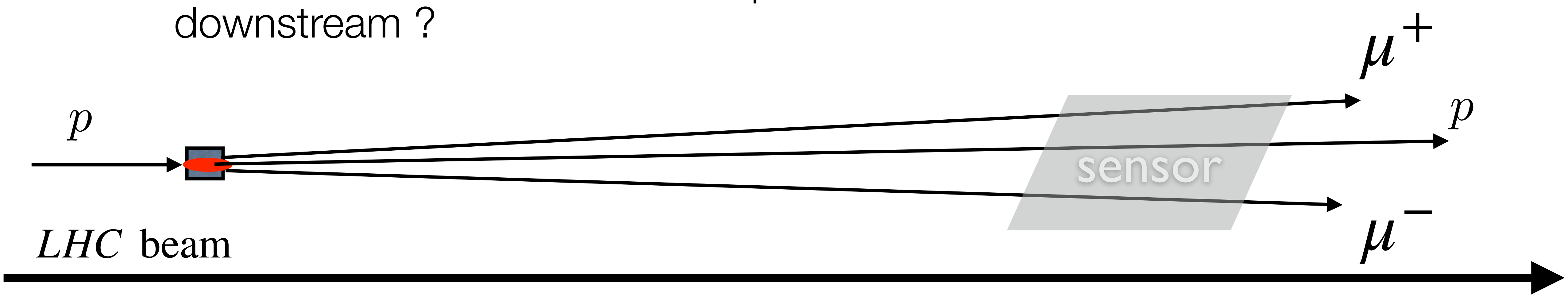
Angular distance between p and Λ_c^+



Plots from Sara

Photo-production

- Very forward production at $\eta \gtrsim 5$. For example $\gamma p \to J/\psi(\mu^+\mu^-)p$ with $p_{J/\psi} \approx 500\ \mathrm{GeV}$
- Need to reconstruct deflected proton, $\theta_p \approx 250\ \mu\mathrm{rad}$, and $\mu^+\mu^-$ pair to measure the $m(J/\psi p)$ invariant mass
- Veto additional particles in the event to identify photo-production events. Hermetic detector is required. Use veto detectors far downstream ?



- Pixel detector intercepts the proton deflected beam to improve the reconstruction of photo-production events
- What is the minimum acceptable distance from the main LHC beam? TOTEM, ALFA go at $10\sigma \approx 1\ \mathrm{mm}$

Pixel detector specifications

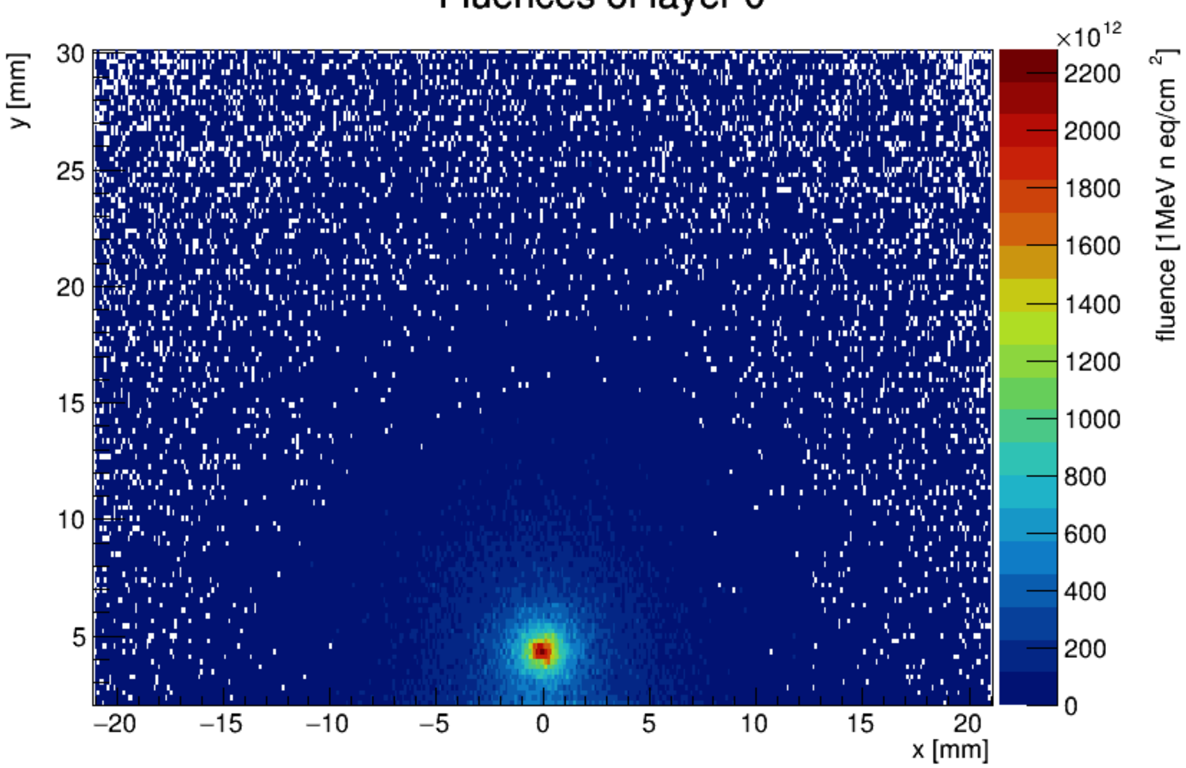
Simulation studies on minimum bias events (flux 10^6 p/s, 2 cm thick W target) and signal $\Lambda_c^+ \to pK^-\pi^+$ decays

- Very forward production. Track pseudo-rapidity $\eta \geq 5$
- Very fine granularity ≤ 100 µm pitch
- Hit rate: up to 200 MHz/cm^2
- Radiation hardness: fluence up to 10^{15} n_{eq}/cm^2
- High momentum tracks, material budget per layer $\sim 1\,\%\,X_0$
- Instrumented area per layer $\sim 10 \times 10$ cm^2
- Distance from the LHC beam ~ 5 mm ?
- Detector length ~ 1 m

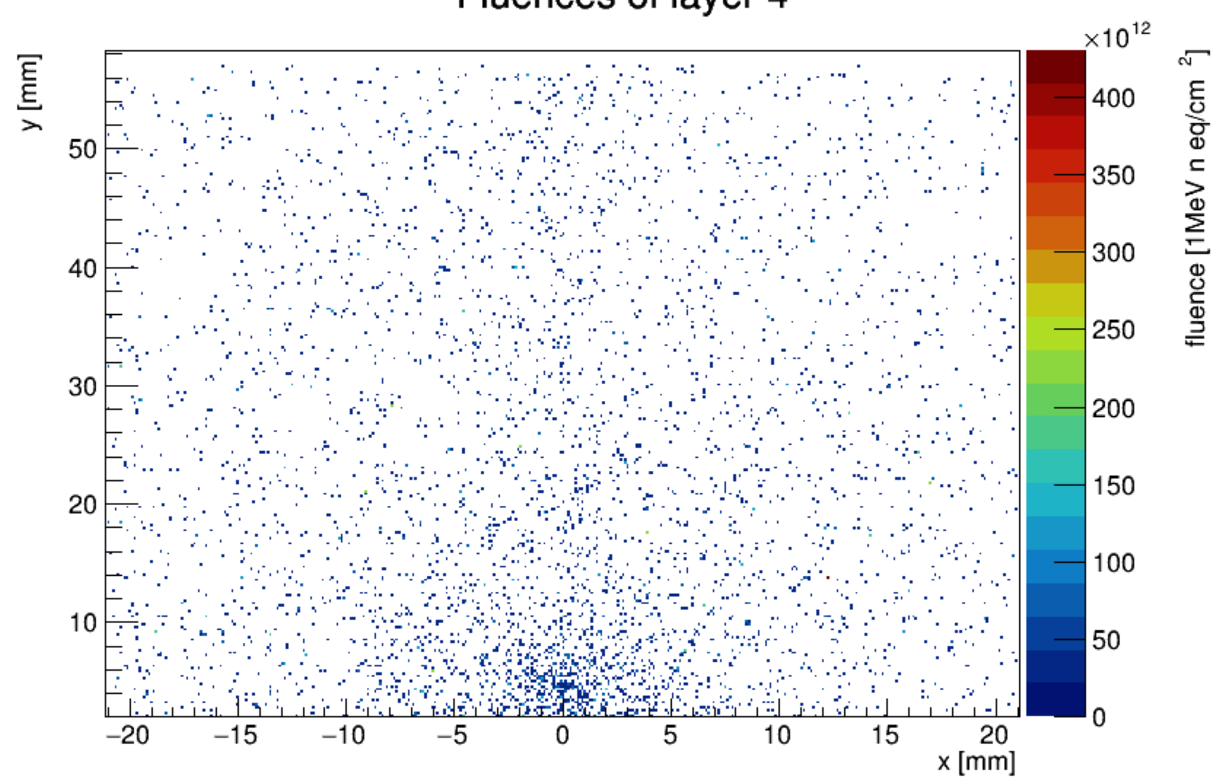
Fluence on detector layers

- Corresponding to 4×10^{13} PoT (≈ 8 years of data taking at 10^6 p/s)

Before the magnet $\approx 10^{15}\ (1\ \mathrm{MeV}\ \mathrm{n_{eq}})/\mathrm{cm}^2$



After the magnet $\approx 10^{14}\ (1\ \mathrm{MeV}\ \mathrm{n_{eq}})/\mathrm{cm}^2$



- Radiation concentrated in a very small region (few mm^2).
- **Silicon detectors** can cope with such fluence. Mitigation strategy:
  - move the detector in x, y to distribute the radiation on a wider region (requires a motion system inside the pot)
  - sensor cooling, operations at $T < 0\ \mathrm{C}^\circ$

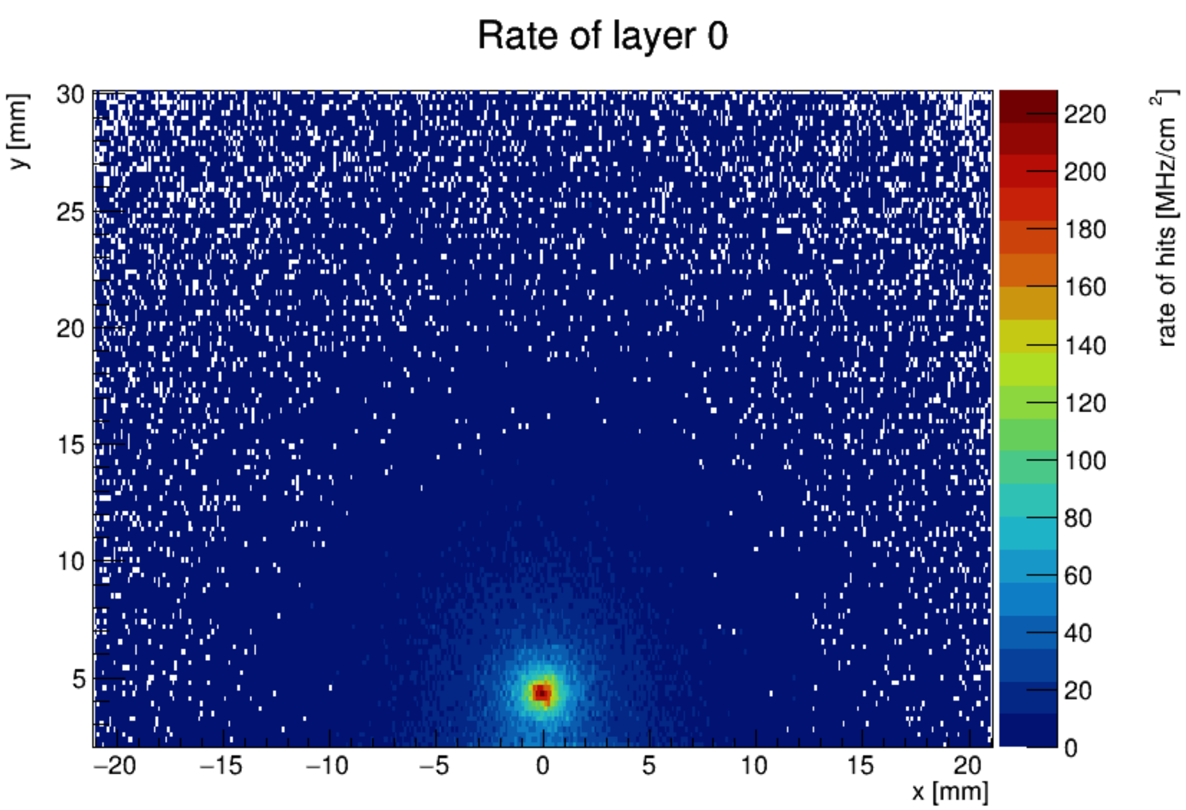
Plots from Sara, Elisabetta

Rates on detector layers

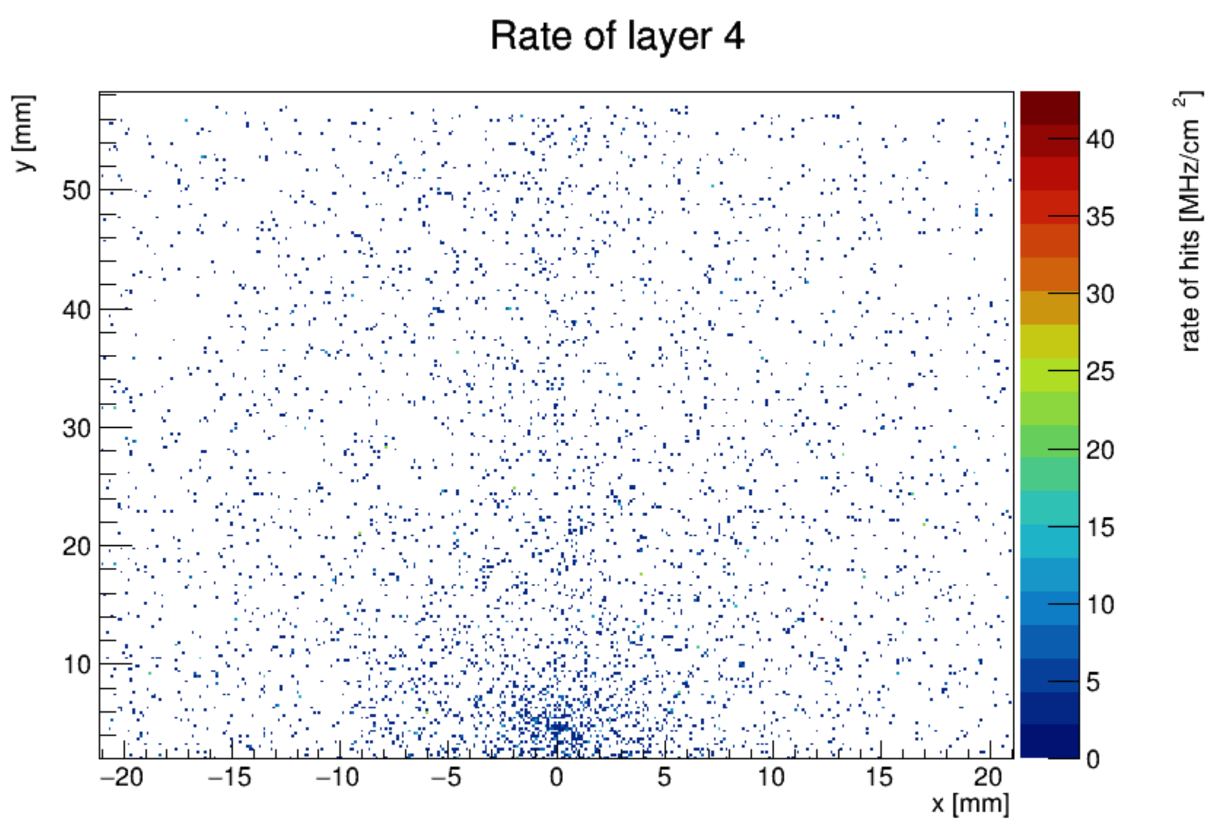
- Corresponding 1.0×10^6 p/s on 2.0 cm thick W target

Plots from Sara, Elisabetta

Before the magnet $\approx 200\ \mathrm{MHz/cm^2}$



After the magnet $\approx 20\ \mathrm{MHz/cm^2}$

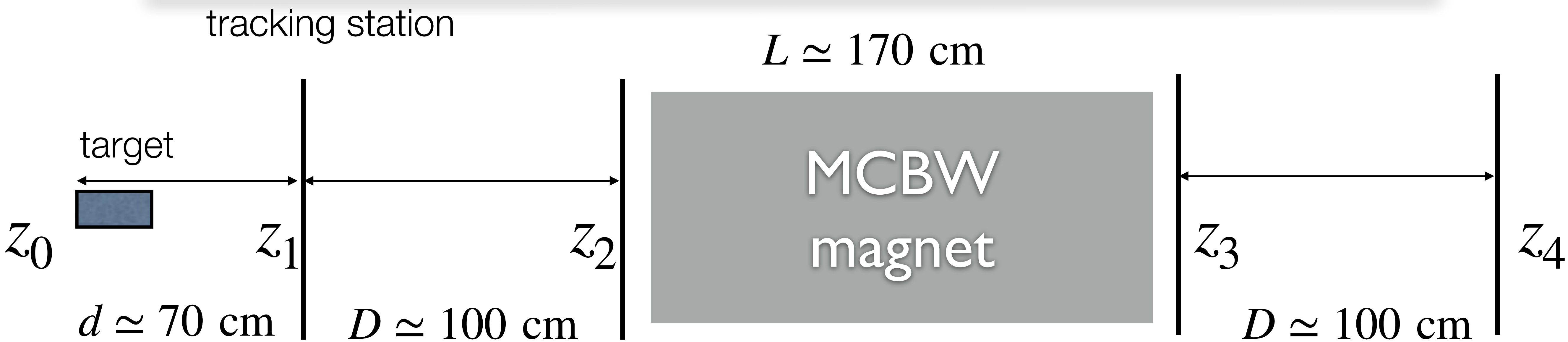


- High-granularity **pixel detector** before the magnet. At 200 MHz/cm^2
  - 55 μm pixel size, pixel rate = 6.6 kHz ✓ YES
  - 90 μm pitch, 5 cm strip length, strip rate = 9 MHz NO

Vertex detector geometry

- Resolve the 3 tracks on the detector $d\theta \gtrsim 5 \times \text{pitch} \;\Rightarrow d \gtrsim 50 \text{ cm}$ with $\theta \approx 0.5 \text{ mrad}$, $\text{pitch} = 55 \; \mu\text{m}$
- Track angle resolution $\sigma_\theta \approx \sqrt{2}\sigma_x/D = 14 \; \mu\text{rad}$ with $\sigma_x \approx 10 \; \mu\text{m}$
- Λ_c^+ decay vertex $\sigma_{x,y} \approx \left(\frac{z_1^2\sigma_2^2 + z_2^2\sigma_1^2}{(z_2 - z_1)^2} + z_1^2\theta_{\text{ms}}^2 \right)^{1/2} \approx 20 \; \mu\text{m}$
  $\sigma_z \approx \sigma_y/\tan\theta_C = 2.8 \text{ mm}$
- $\theta_{\text{ms}} \approx 5 \; \mu\text{rad}$ at 500 GeV and $x/X_0 = 4\,\%$

Spectrometer geometry



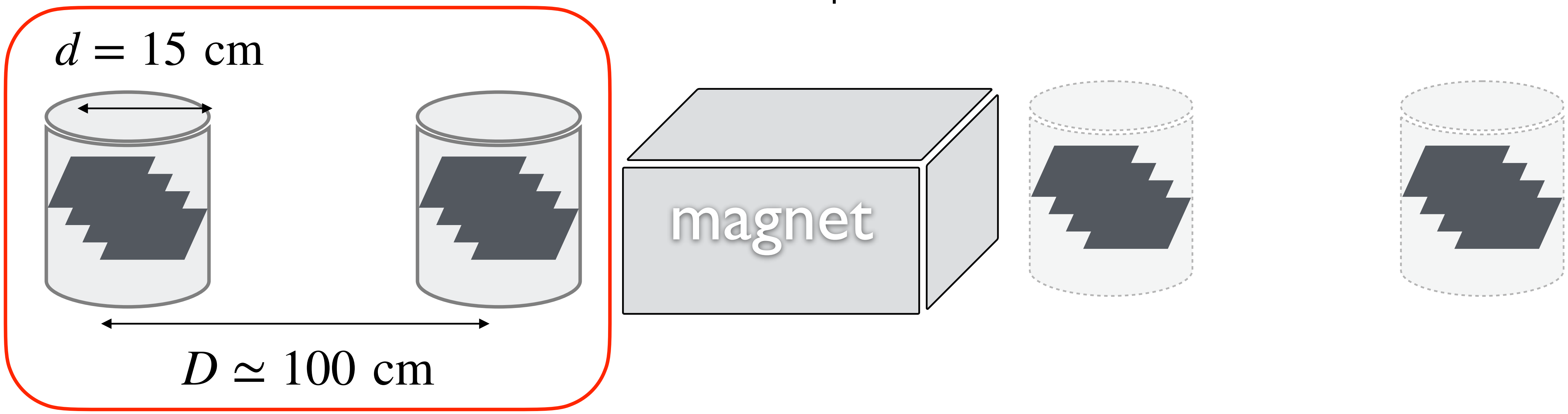
- Momentum resolution $\frac{\sigma_p}{p} \approx \frac{2p}{0.3BLD}\sigma_x = 2\,\%$ (neglecting multiple scattering) with $p = 500$ GeV, $BL = 1.9$ Tm, $D = 100$ cm, $\sigma_x = 10\ \mu m$

- Momentum resolution could be improved by reducing $\frac{\sigma_x}{BLD}$

- A compact magnet $L \approx 50$ cm with $BL \gtrsim 4$ Tm would be beneficial for momentum resolution (x2 improvement) and acceptance/hermeticity (70%→90%) (see Elisabetta's talk)

Conceptual design for pixel vertex detector

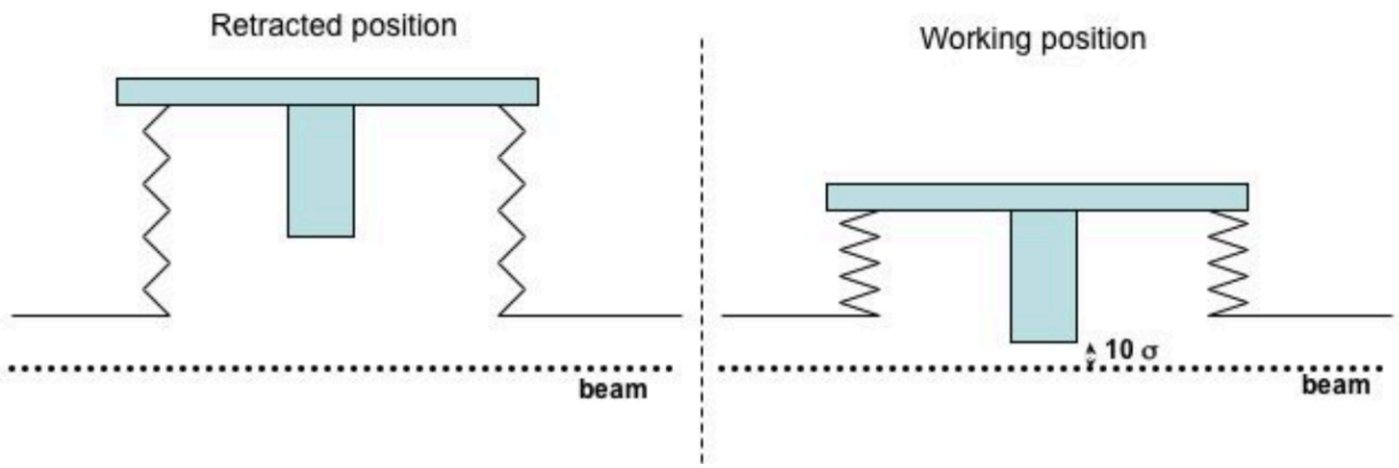
- Silicon pixel detectors housed in 2 Roman Pots
  - Hybrid pixel sensors: VELO sensors, 4 layers/station
  - Roman Pots: ALFA/TOTEM pots

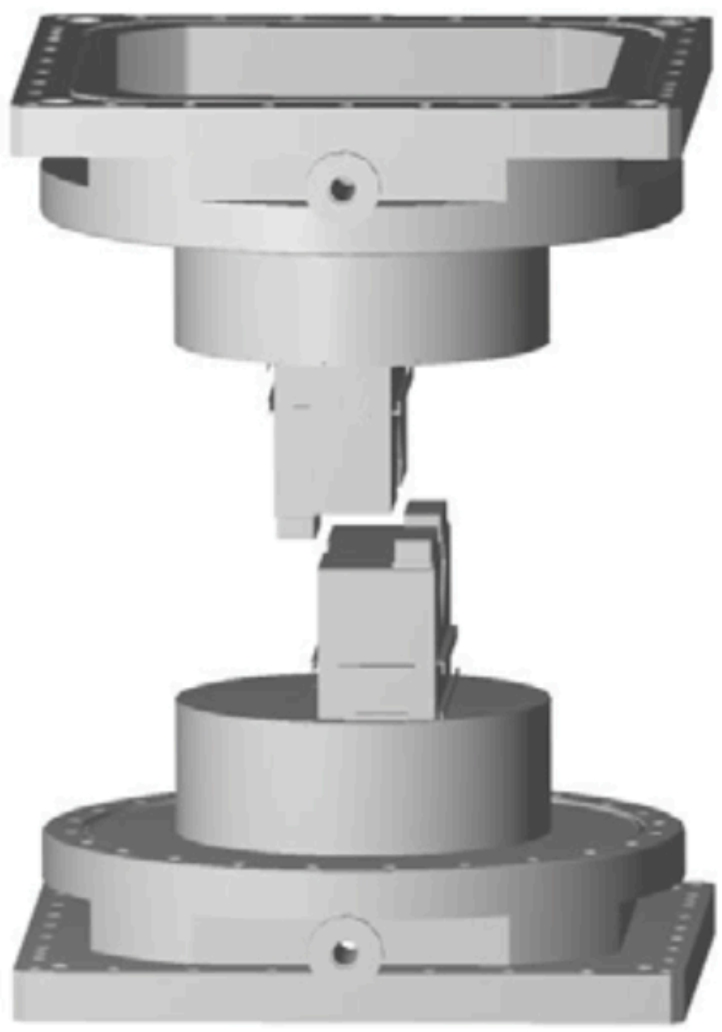


- hit resolution $\sigma_{\rm hit} \sim 15~\mu{\rm m} \Rightarrow \sigma_x \approx \sigma_{\rm hit}/\sqrt{4} = 7.5~\mu{\rm m}$
- $\sigma_{\rm ms} \approx D\theta_{\rm ms} = 4.8~\mu{\rm m}$ at 500 GeV and $x/X_0 = 4\,\%$
- Λ_c^+ vertex position $\sigma_{\rm vtx} \sim (0.015, 0.015, 2.1)$ mm
- track angle $\sigma_\theta \approx (\sigma_1^2 + \sigma_2^2)^{1/2}/(z_2 - z_1) = 12~\mu{\rm rad}$, with $\sigma_1 = \sigma_x$, $\sigma_2 = \sigma_1 \oplus \sigma_{\rm ms}$

Detector operations in a Roman Pot

- Roman Pots (RP) are movable devices allowing to perform measurements inside the beam pipe. In ALFA, TOTEM down to 10σ ($\sim 1\ \mathrm{mm}$) from the main LHC proton beam

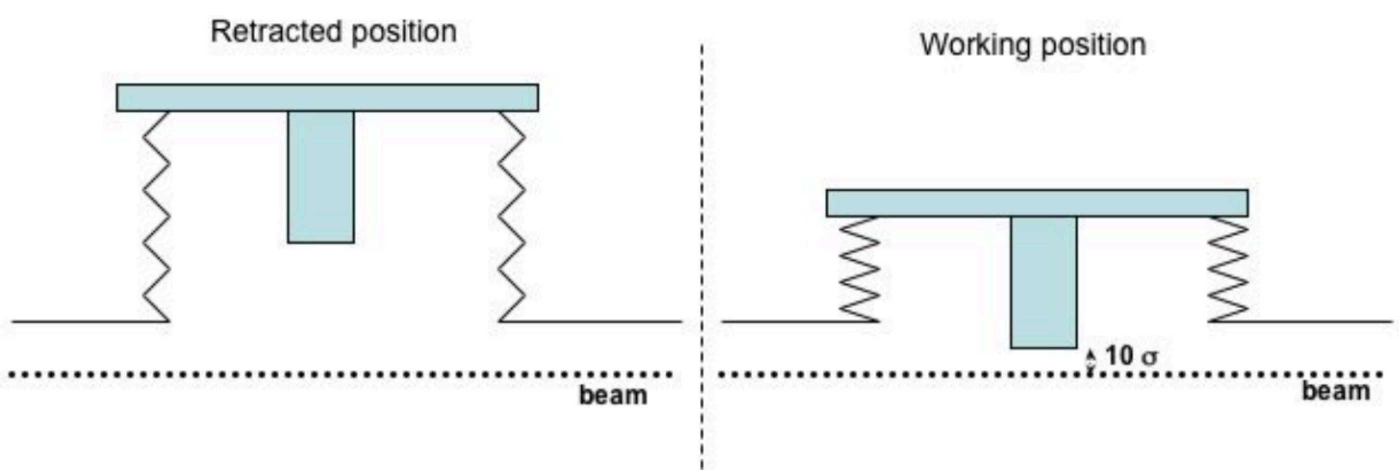




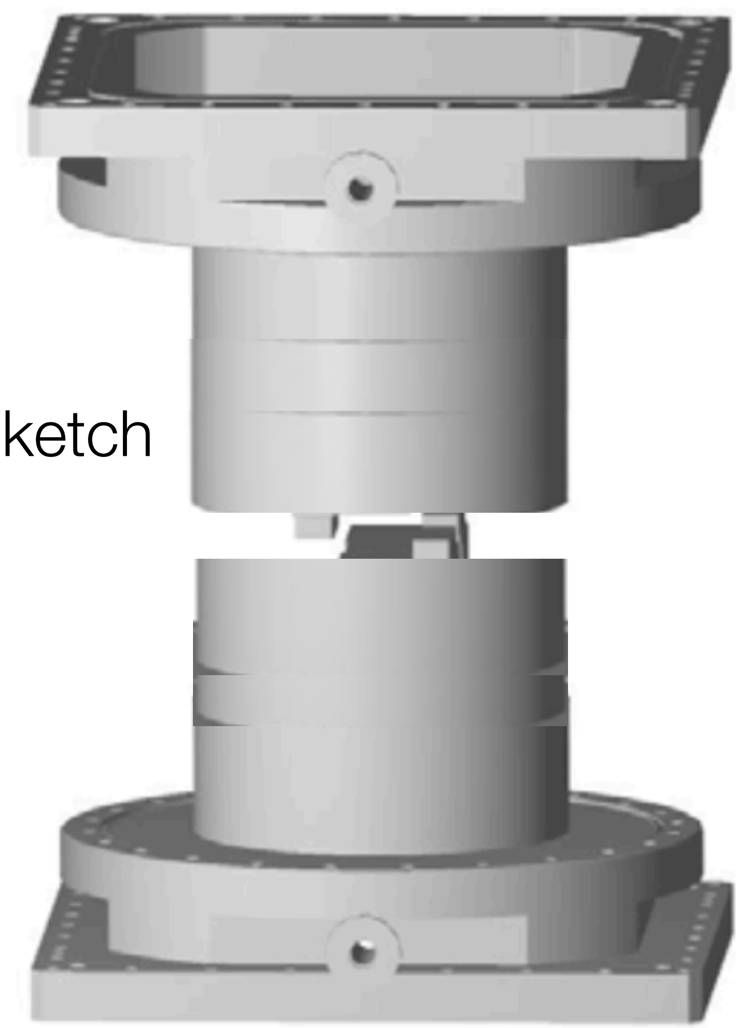
- Possibility to use 2 vertical pots to increase acceptance and detector hermeticity. Rectangular extrusion dimension 128 x 60 x 46 mm^3

Detector operations in a Roman Pot

- Roman Pots (RP) are movable devices allowing to perform measurements inside the beam pipe. In ALFA, TOTEM down to 10σ ($\sim 1\ \mathrm{mm}$) from the main LHC proton beam

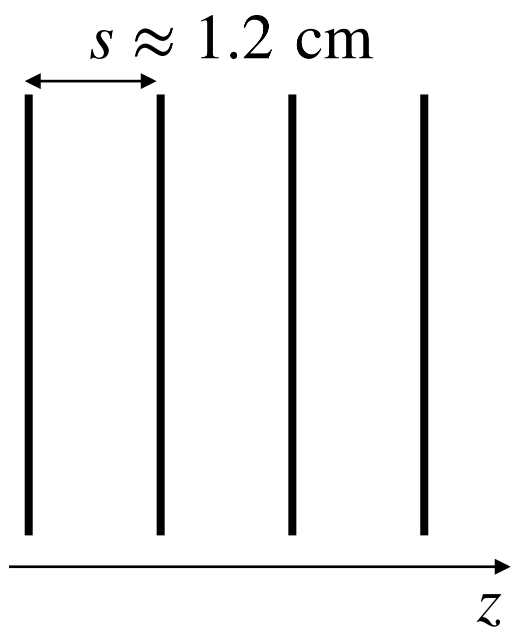


Artistic sketch

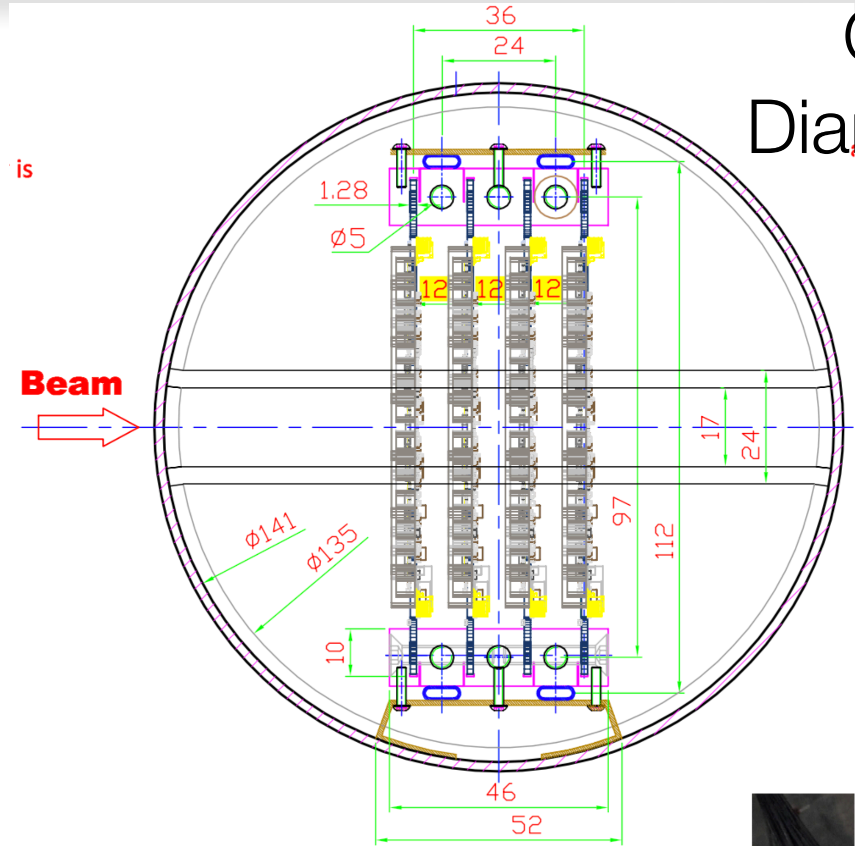


- Possibility to use cylindrical RPs, developed by TOTEM experiment, to increase the space available for the detector package (diameter 15 cm)

Layers per RP station



Courtesy of N. Turini
Diamond detector TOTEM



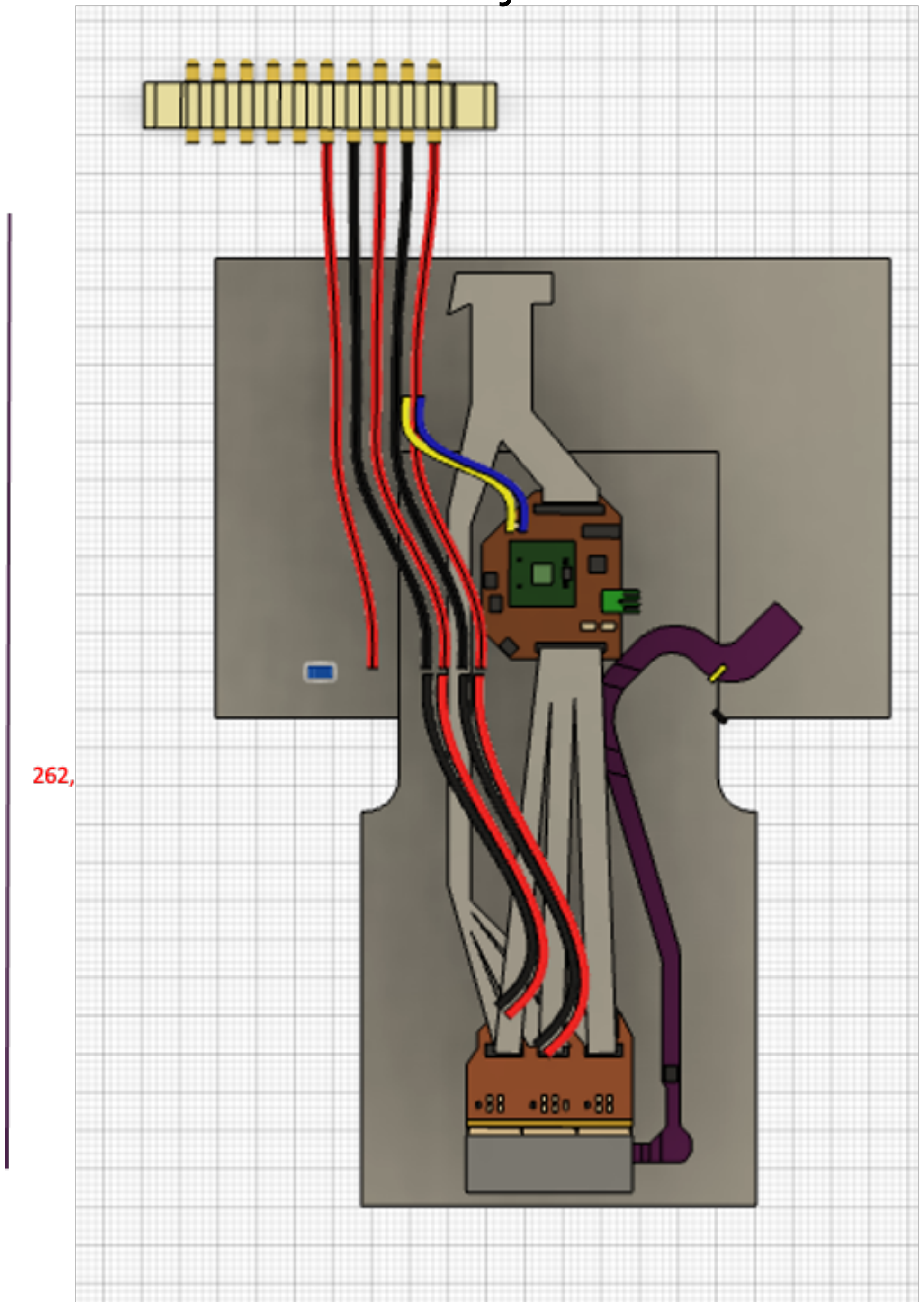
- Number of layers $N \geq 3$ to confirm that the hits belong to a track. Pattern recognition and resolution studies ongoing to determine the optimal number

- Distance s between layers determined by the space available in the RP (46 mm along z) and the thickness of a sensor module. More space available with cylindrical RPs (150 mm diameter)

Sensors per layer

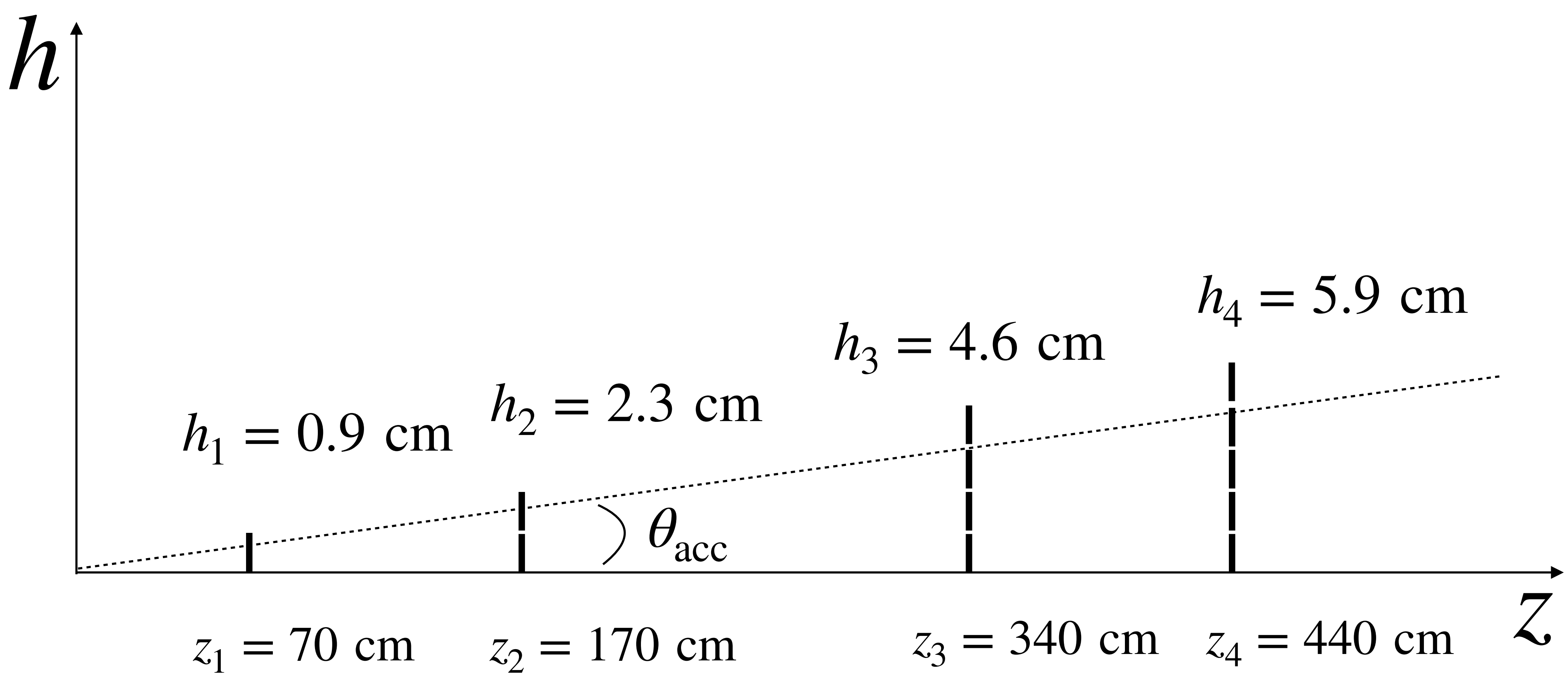
- VELO tile: 3 ASICS, active area 14x42 mm^2
- VELO tile design adapted to fit inside the RP by modifying the geometry of the flex cables (straight instead of curved cables)
- Multiple tiles can fit in on layer. Design to be developed

Courtesy of S. Cesare



Spectrometer coverage

- For a coverage $\eta \geq 5$, i.e. $\theta_{\mathrm{acc}} \sim 13\ \mathrm{mrad}$, sensor size varies $h_i = z_i \theta_{\mathrm{acc}}$ but still compact detector in the transverse plane
- Complementary to LHCb coverage $2 \leq \eta \leq 5$



VELO pixel solution

- VELO tiles are the baseline solution for the pixel vertex detector
- Purchased 48 tiles at Hamamatsu. Currently at Advafab for bump-bonding with VELO chips. Ready in February 2024

Pixel sensor parameter	Rating
silicon type	p-type
thickness	200 μm
active area	14x42 mm^2
pixel pitch	55 μm
full depletion V *	40-150 V
breakdown V *	800 V
leakage current *	20-100 nA

* at T=25 °C

VeloPix chip specifications

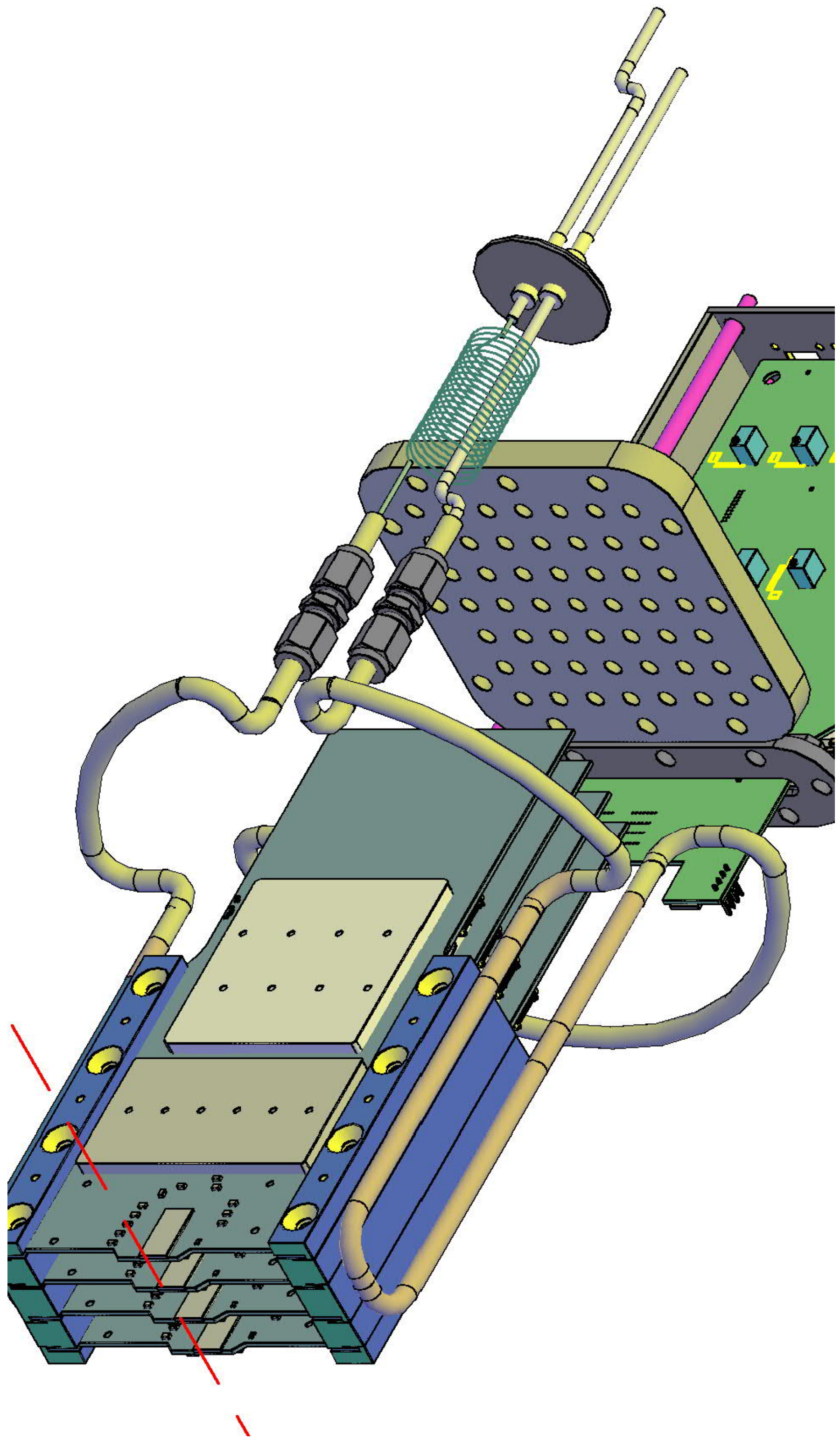
Specification	Timepix3	VeloPix
pixel dimension	$55 \times 55\ \mu m^2$	$55 \times 55\ \mu m^2$
matrix size	256×256	256×256
timewalk	< 25 ns	< 25 ns
Time over Threshold range	10 bit	6 bit (calibration mode only)
leakage current compensation (per pixel)	20 nA	20 nA
Time stamp resolution	1.6 ns	25 ns
Time stamp range	18 bit	9 bit
average pixel hit rate	n.a.	600 MHits/s
peak pixel hit rate	80 MHit/s	900 MHits/s
peak super-pixel packet rate	n.a.	520 MHits/s
min. output bandwidth	2.56 Gbit/s	18 Gbit/s
max. pixel hit loss at max. rate	-	1%
power consumption per ASIC	< 2 W	< 3 W
radiation hardness	no spec.	> 400 Mrad
single event upset robust	no	yes

- VeloPix can cope with *p* collisions up to 10^7 p/s on 2 cm W target (safe) but not 10^8 p/s
  - Analog signal pileup at pixel rate > 3 MHz. Maximum data transfer rate 13.3 M packets/s

Sensor cooling

Courtesy of N. Turini

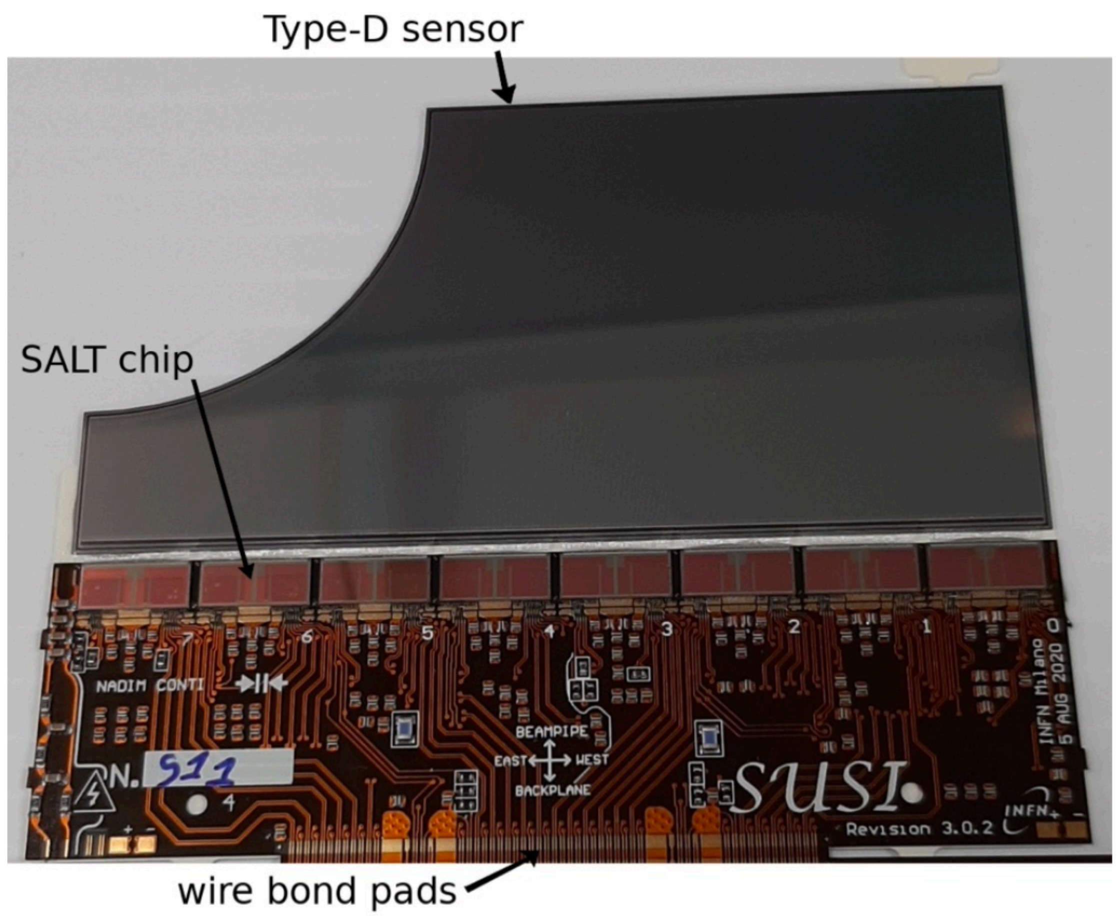
- Need to determine the sensor operation temperature. E.g. to avoid thermal run-away, the VELO silicon sensors are operated at $T \lesssim -20$ °C (400 Mrad), while the UT silicon sensors at $T \lesssim -5$ °C (40 Mrad)
- Simplify the cooling system. No evaporative CO_2 microchannel cooling. A water-based (+glycol) solution has been proposed by N. Turini. It can reach negative temperatures
- Alternative solution proposed by Sune without water inside the RP



Tracker detectors

- For the tracker detectors after the magnet, 2 possible solutions are proposed: 1) sensors in RPs, 2) sensors in air using a "Hamburg" beam pipe (see Elisabetta's slides)
- Silicon pixel and strip detectors could be considered for the tracker stations with larger area and lower rates (20 MHz/cm²)

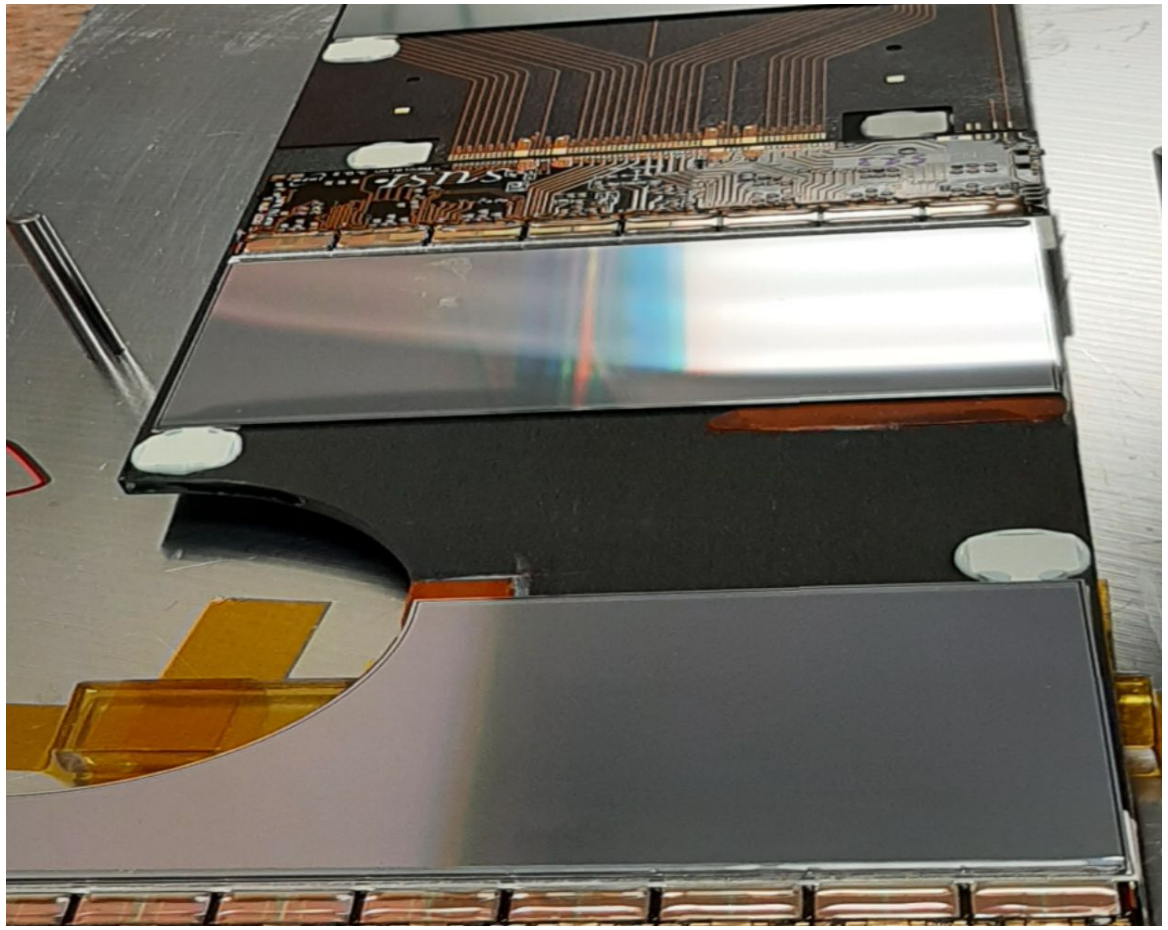
Strip sensor parameter	Rating
silicon type	p-type
thickness	250 μm
active area	51.45x97.35 mm²
strip pitch	93.5 μm
strips	1024
full depletion V	200-300 V



Tracker detectors

- For the tracker detectors after the magnet, 2 possible solutions are proposed: 1) sensors in RPs, 2) sensors in air using a "Hamburg" beam pipe (see Elisabetta's slides)
- Silicon pixel and strip detectors could be considered for the tracker stations with larger area and lower rates (20 MHz/cm^2)

Strip sensor parameter	Rating
silicon type	p-type
thickness	250 μm
active area	51.45x97.35 mm^2
strip pitch	93.5 μm
strips	1024
full depletion V	200-300 V



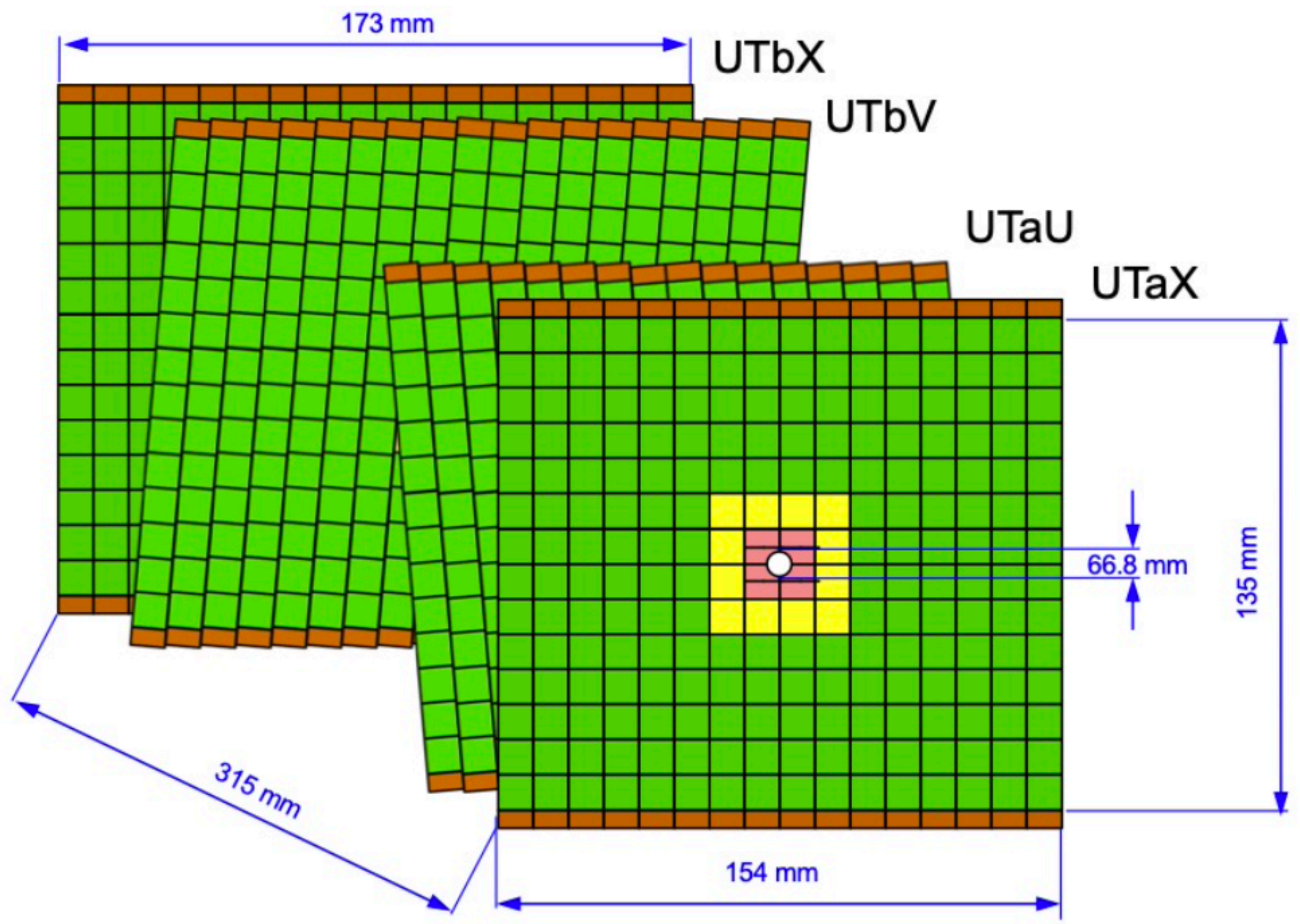
Courtesy of P. Gandini

SALT chip specifications

Variable	Specification
Technology	TSMC CMOS 130 nm
Channels per ASIC	128
Input / Output pitch	80 µm / 140 µm
Total power dissipation	< 768 mW
Radiation hardness	0.3 MGy
Sensor input capacitance	1.6–12 pF
Noise	$\sim 1000\, e^{-}$@10 pF + 50 e^{-}/pF
Maximum cross-talk	Less than 5% between channels
Signal polarity	Both electron and hole collection
Dynamic range	Input charge up to $\sim 30\,000\, e^{-}$
Linearity	Within 5% over dynamic range
Pulse shape and tail	$T_{peak} \sim 25$ ns, amplitude after $2{\times}T_{peak}$ <5% of peak
Gain uniformity	Uniformity across channels within ~5%
ADC bits	6 bits (5 bits for each polarity)
ADC sampling rate	40 MHz
DSP functions	Pedestal and MCM subtraction, zero suppression
Output formats	Non-zero suppressed, zero suppressed
Calibration modes	Analogue test pulses, digital data loading
Output serialiser	Three to five serial e-links, at 320 Mbit/s
Slow controls interface	I2C
Fast digital signals interface	Differential, SLVS

Strip sensor configuration

- For momentum measurement it is relevant the measurement of the position in the bending plane
- LHCb UT silicon strip layers are organised in X-U-V-X configuration. U-V with $+5^{\circ}$ and -5°stereo angle
- Very good resolution in x, $\sigma_x \approx 25\ \mu\mathrm{m}$, and appreciable in y: $\sigma_y \approx \sigma_x / \sin\alpha = 290\ \mu\mathrm{m}$



Pixel vs Strip sensors

	Pixel	Strip
Cost per unit area	higher (x 50)	lower
Granularity	55x55 μm^2	51.45 cm x 93.5 μm
Material budget per layer	1% x/X_0	1% x/X_0
Radiation hardness (ASIC)	400 Mrad	30 Mrad
Position measurement	2D	1D
Hit resolution	15 μm	25 μm
Patter recognition	Excellent	Very good

Summary

- A pixel vertex detector based on silicon pixel sensors has been discussed
  - VELO sensors housed inside Roman Pots represent a suitable solution
- The detectors for the spectrometer have been also discussed
  - Detectors could be positioned outside the beam pipe
  - VELO sensors represent a suitable solution also in this case. Silicon strip detectors can also be used to reduce costs and enlarge the active area