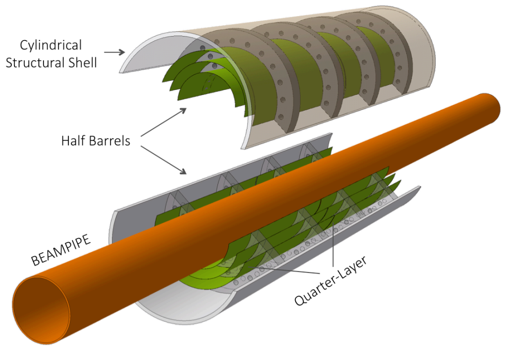
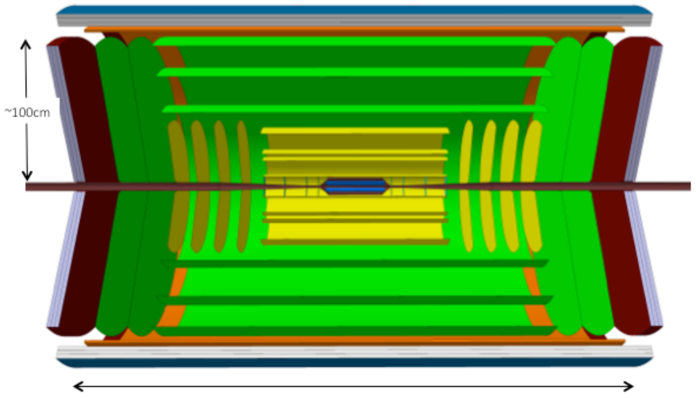
Concept for future detectors and experiments

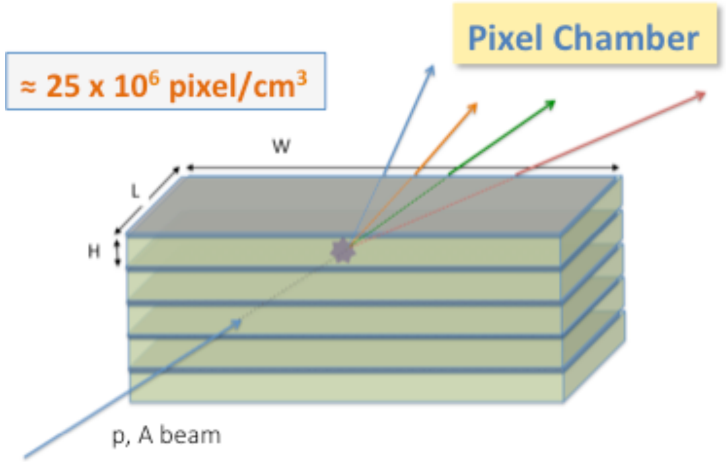
L. Musa - CERN

ALICE ITS 3



LS4+ HI Experiment





HF Imager

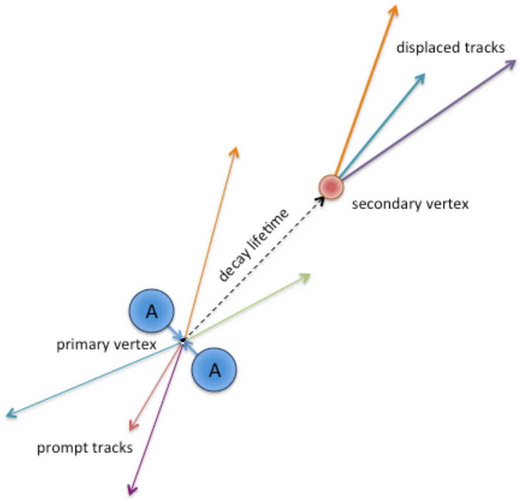
12th ITS Upgrade, MFT and O2 Asian Workshop
Inha University, Incheon, 19-21 November 2018

Proposal for an Upgrade of the ITS in LS3

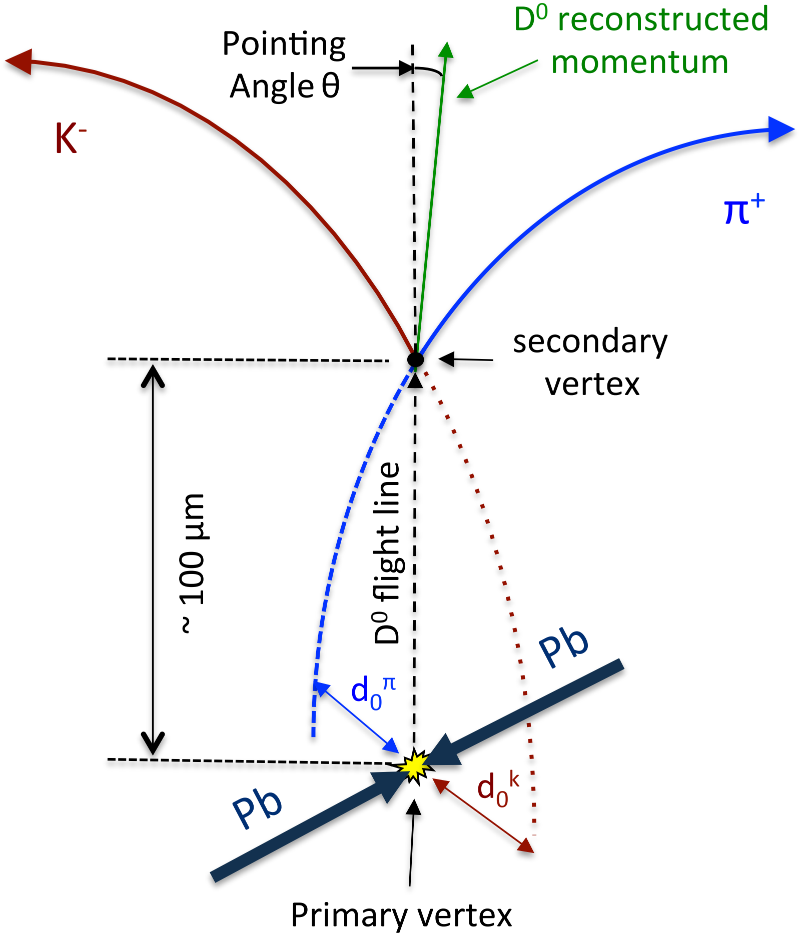
Secondary Vertex Determination

Open charm

Particle	Decay Channel	cτ (μm)
D^0	$K^- \pi^+$ (3.8%)	123
D^+	$K^- \pi^+ \pi^+$ (9.5%)	312
D_s^+	$K^+ K^- \pi^+$ (5.2%)	150
Λ_c^+	$p\, K^- \pi^+$ (5.0%)	60
Ξ_{cc}^{++}	$\Lambda_c^+ K^- \pi^+ \pi^+$ (?)	(?)
Ωccc		



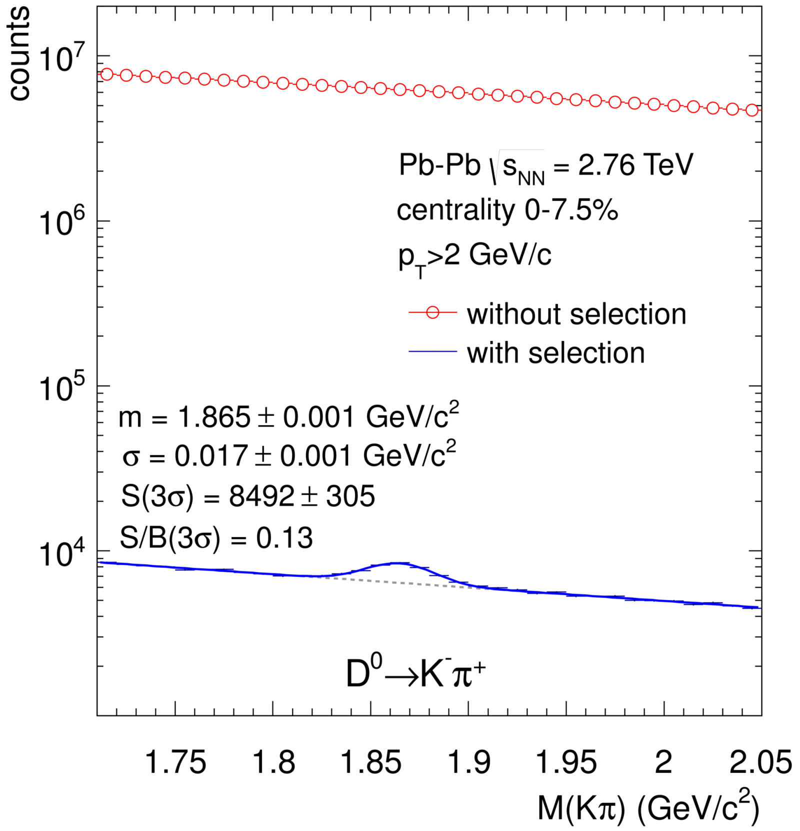
Example: D^0 meson



Analysis based on invariant mass, PID and <u>decay topology</u>

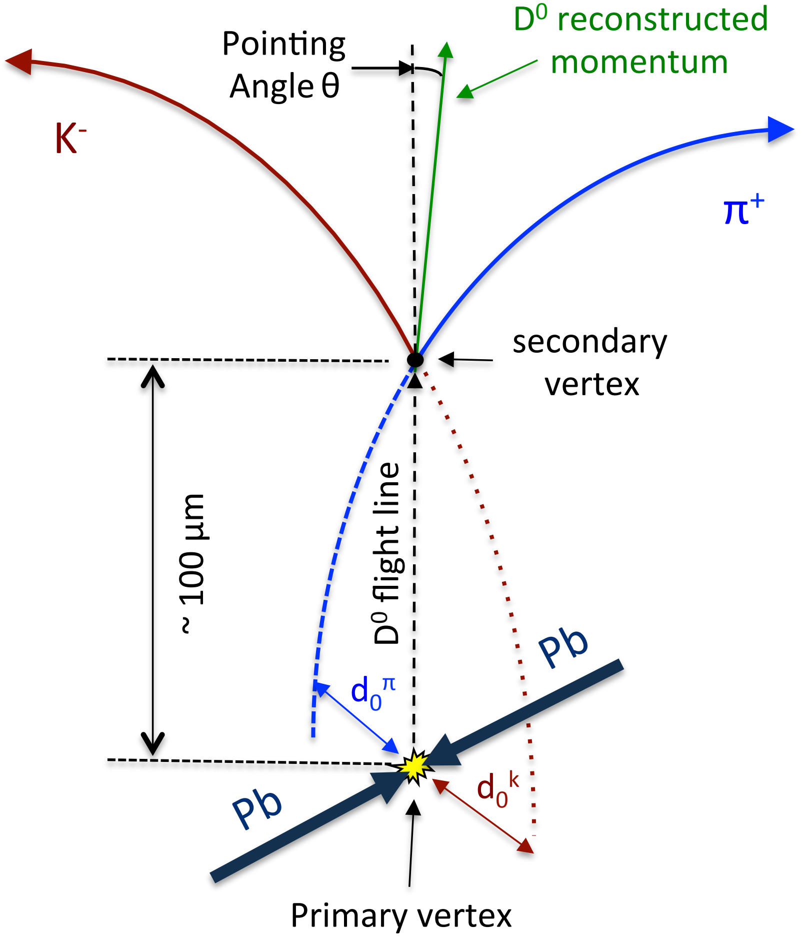
Secondary Vertex Determination

ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044



Invariant mass distribution of $K^-\pi^+$ pairs before and after applying selection criteria on the relation between the secondary (D^0 decay) and primary vertices

Example: D^0 meson



Analysis based on invariant mass, PID and decay topology

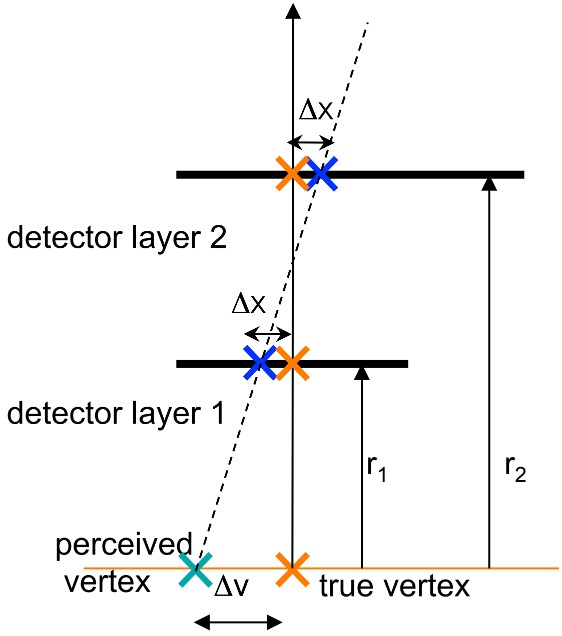
What determines the impact parameter resolution

Vertex projection from two points: a simplified approach (telescope equation)

expectations for the ITS upgraded ➡ pointing resolution = (5 ⊕ 22GeV/p·c) μm

From detector position error

From Coulomb scattering



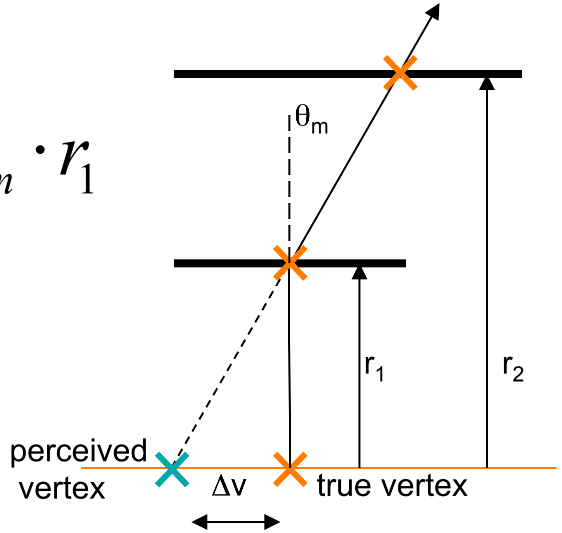
$$\Delta v = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

first pixel layer

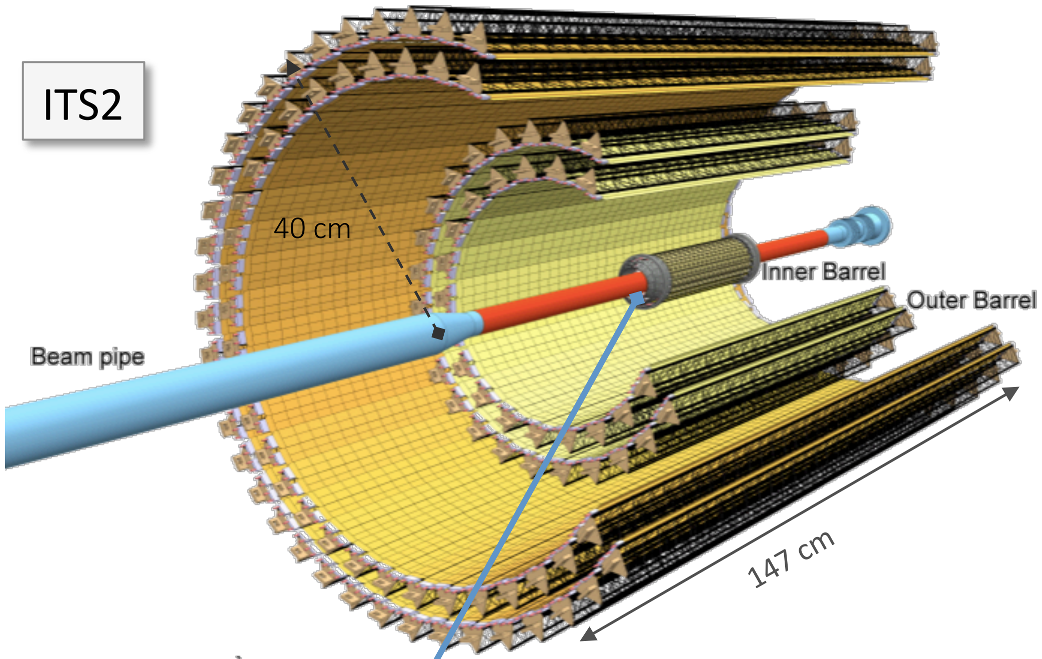
$$X_0 = 0.3\%$$

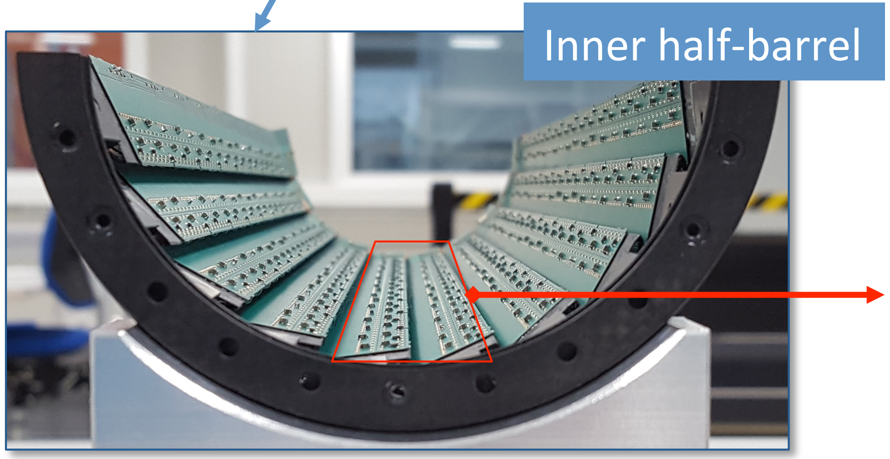
$$\theta_m = \frac{13.6Mev}{\beta \cdot c \cdot p} \cdot \sqrt{X_0}$$

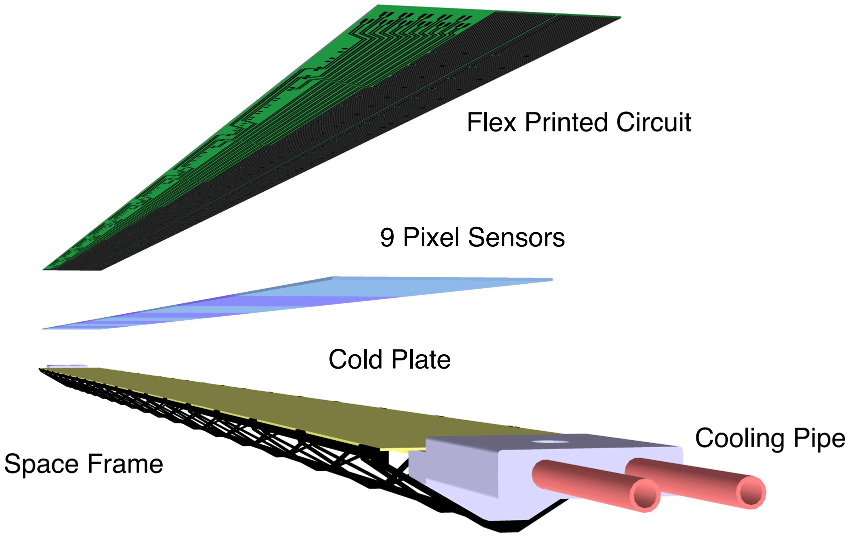
$$\Delta v = \theta_m \cdot r_1$$



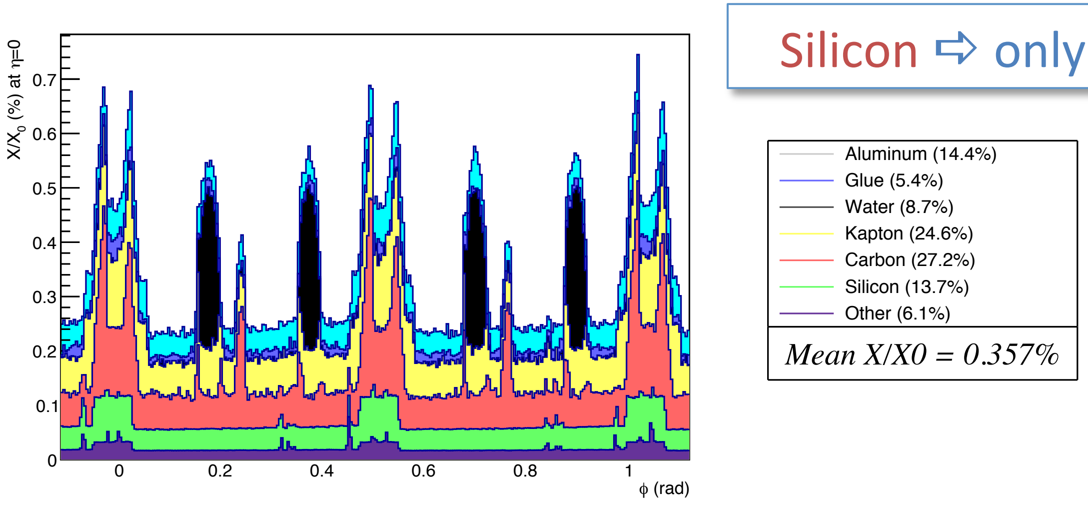
ITS2 – Layout and Material Budget



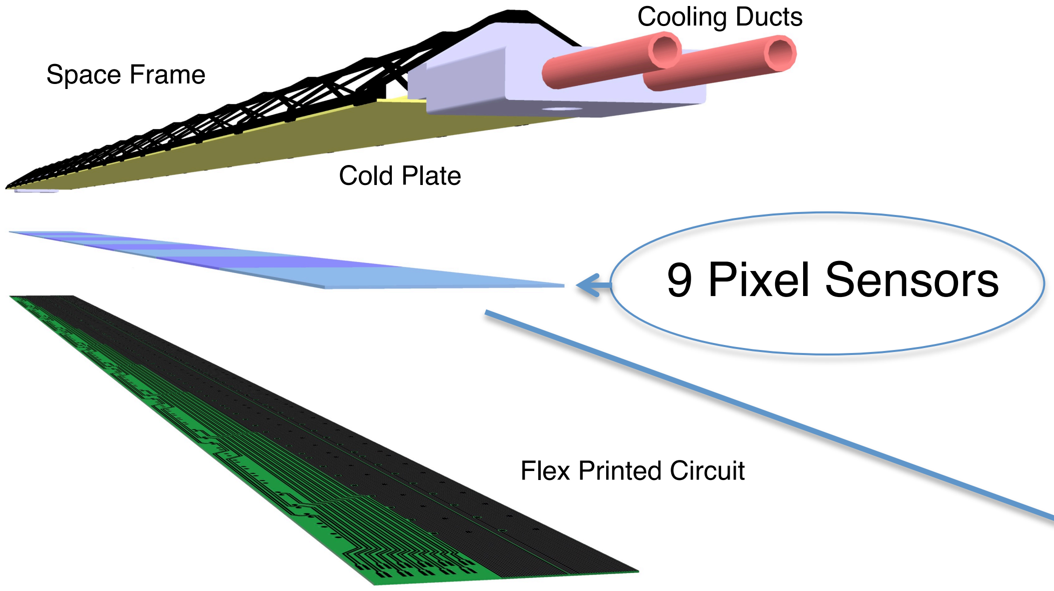




Silicon ⇨ only 15%



Can we further reduce the material budget?



How to further reduce material budget?

Eliminate active cooling (replace with forced air flow)

➔ viable for power densities below 20mW/cm^2

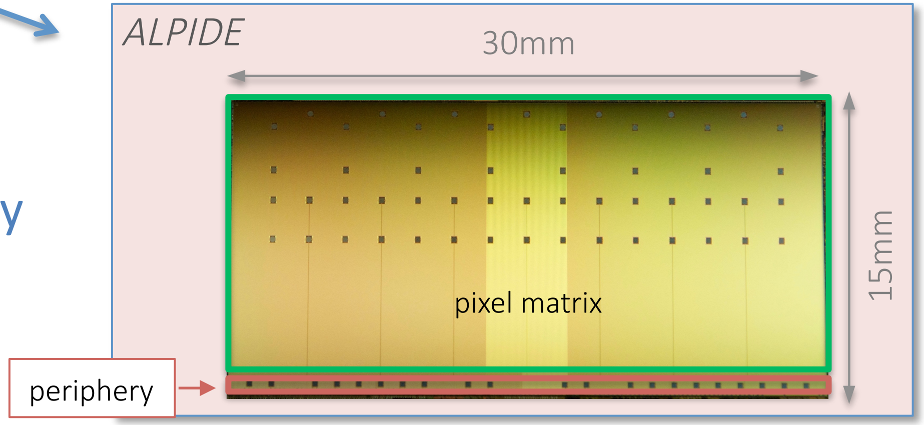
Eliminate electrical substrate

➔ Possible if sensor covers the full stave length

ALPIDE Chip: pixel matrix power 7mW/cm^2 …

… the rest (~33mW/cm^2) is dissipated by the peripheral circuitry

⇨ Can we put the circuit periphery at the periphery of the detector?

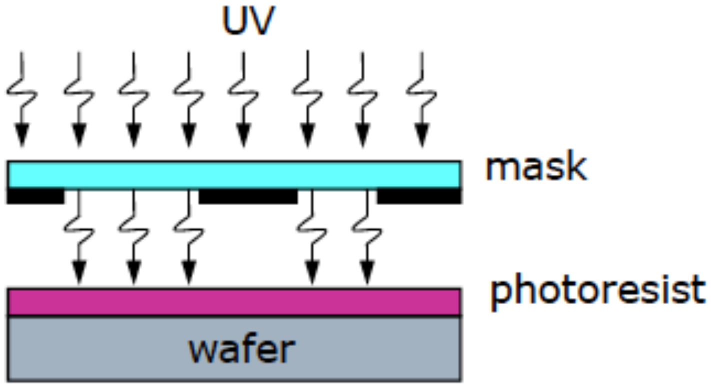


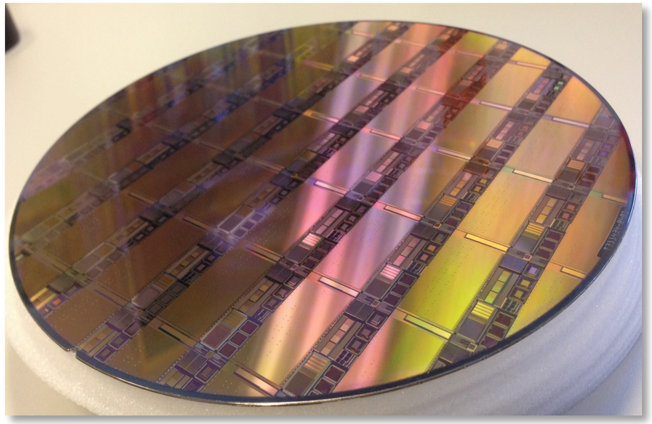
Stitching allows the fabrication of wafer scale sensors

CMOS photolithographic process defines wafer reticles size

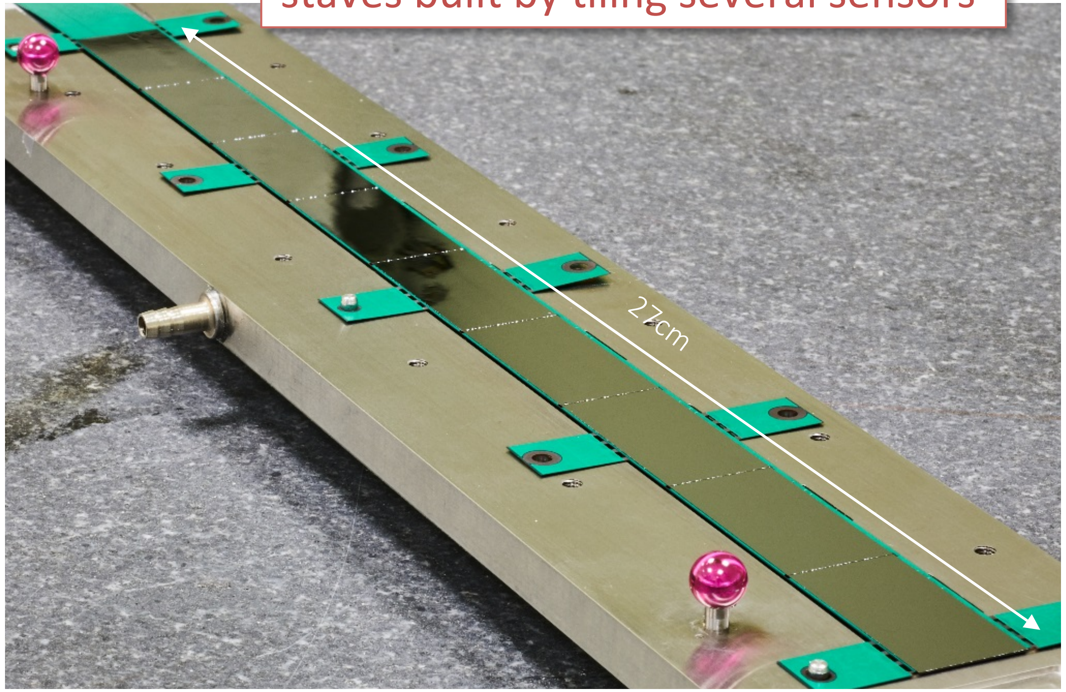
⇨ Typical field of view O(2 x 2 cm^2)

Reticle is stepped across the wafers to create multiple identical images of the circuit(s)

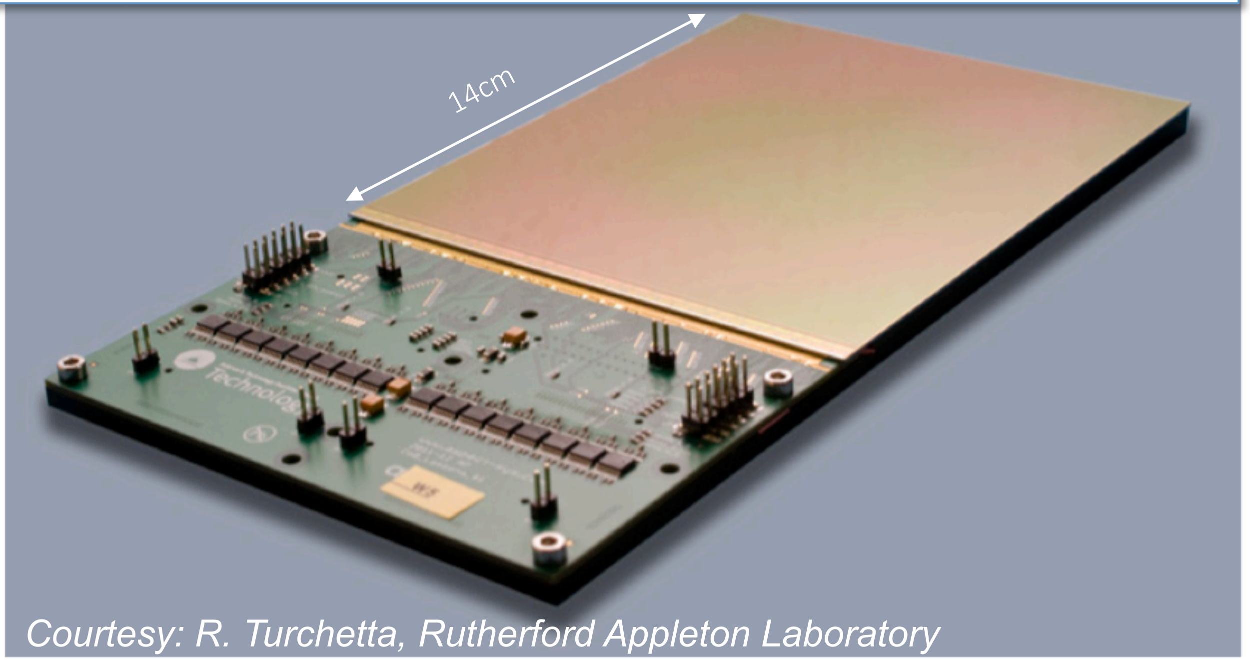




staves built by tiling several sensors

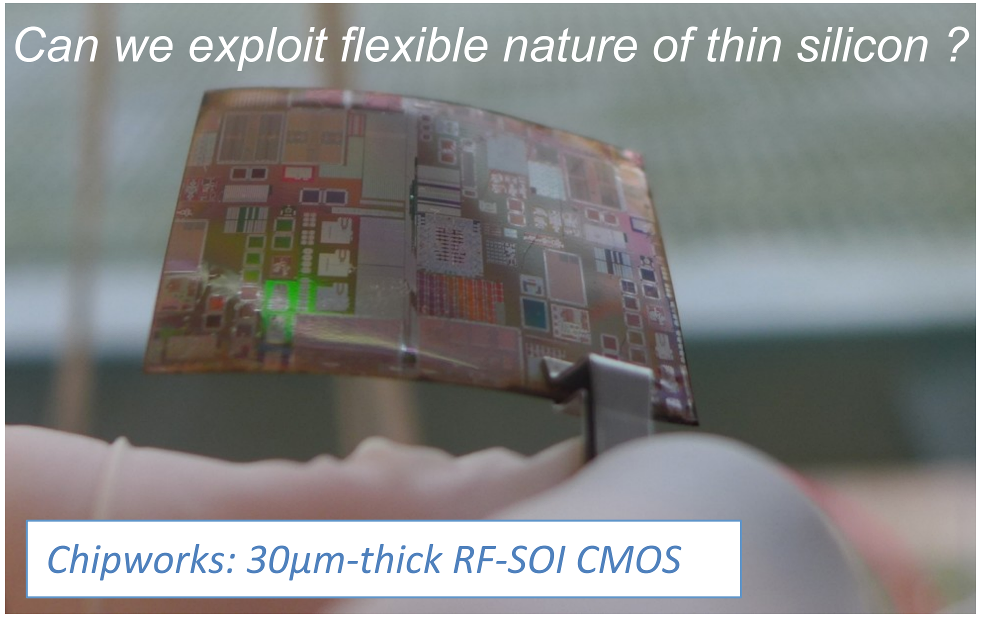


Stitching allows fabrication of sensors larger than the reticle size



Courtesy: R. Turchetta, Rutherford Appleton Laboratory

Ultra-thin curved silicon chips



Can we exploit flexible nature of thin silicon ?

Chipworks: 30µm-thick RF-SOI CMOS

Silicon Genesis: 20 micron thick wafer

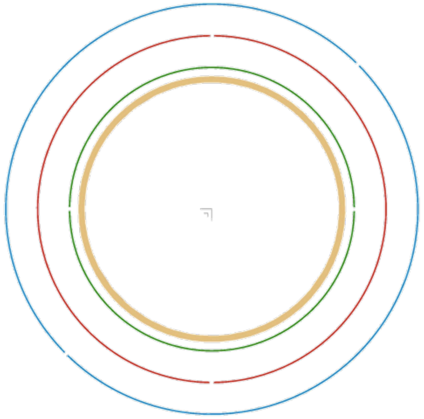
Ultra-thin chip (<50 um): flexible with good stability

Die type	Front/back side	Ground/polished/plasma	Bumps	Die thickness (µm)	CDS (MPa)	Weibull modulus	MDS (MPa)	$r_{\min}$ (mm)
Blank	Front	Ground	No	15–20	1263	7.42	691	2.46
Blank	Back	Ground	No	15–20	575	5.48	221	7.72
IZM28	Front	Ground	Yes	15–20	1032	9.44	636	2.70
IZM28	Back	Ground	Yes	15–20	494	2.04	52	32.7
Blank	Back	Polished	No	25–35	1044	4.17	334	7.72
IZM28	Back	Polished	Yes	25–35	482	2.98	107	24.3
Blank	Back	Plasma	Yes	18–22	2340	12.6	679	2.50
IZM28	Front	Plasma	Yes	18–22	1207	2.64	833	2.05
IZM28	Back	Plasma	Yes	18–22	2139	3.74	362	4.72

van den Ende DA et al. *Mechanical and electrical properties of ultra-thin chips and flexible electronics assemblies during bending*. Mircoelectron reliab (2014), http://dx.doi.org/10.1016/j.microrel.2014.07.125

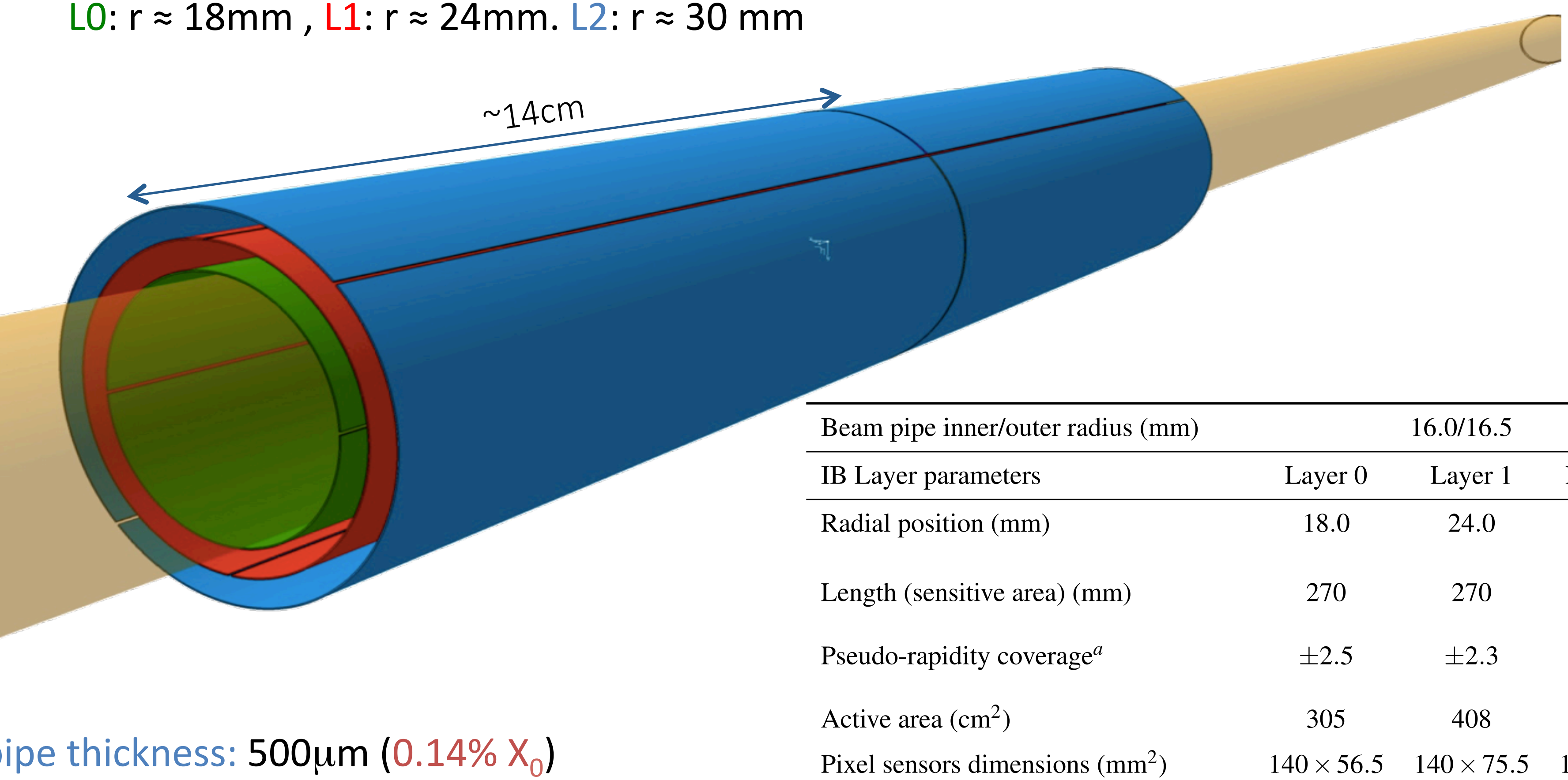
R&D with IZM ALPIDE started

Geometrical Parameters of ITS3



Pipe: r ≈ 16mm , ΔR = 0.5mm

L0: r ≈ 18mm , L1: r ≈ 24mm. L2: r ≈ 30 mm



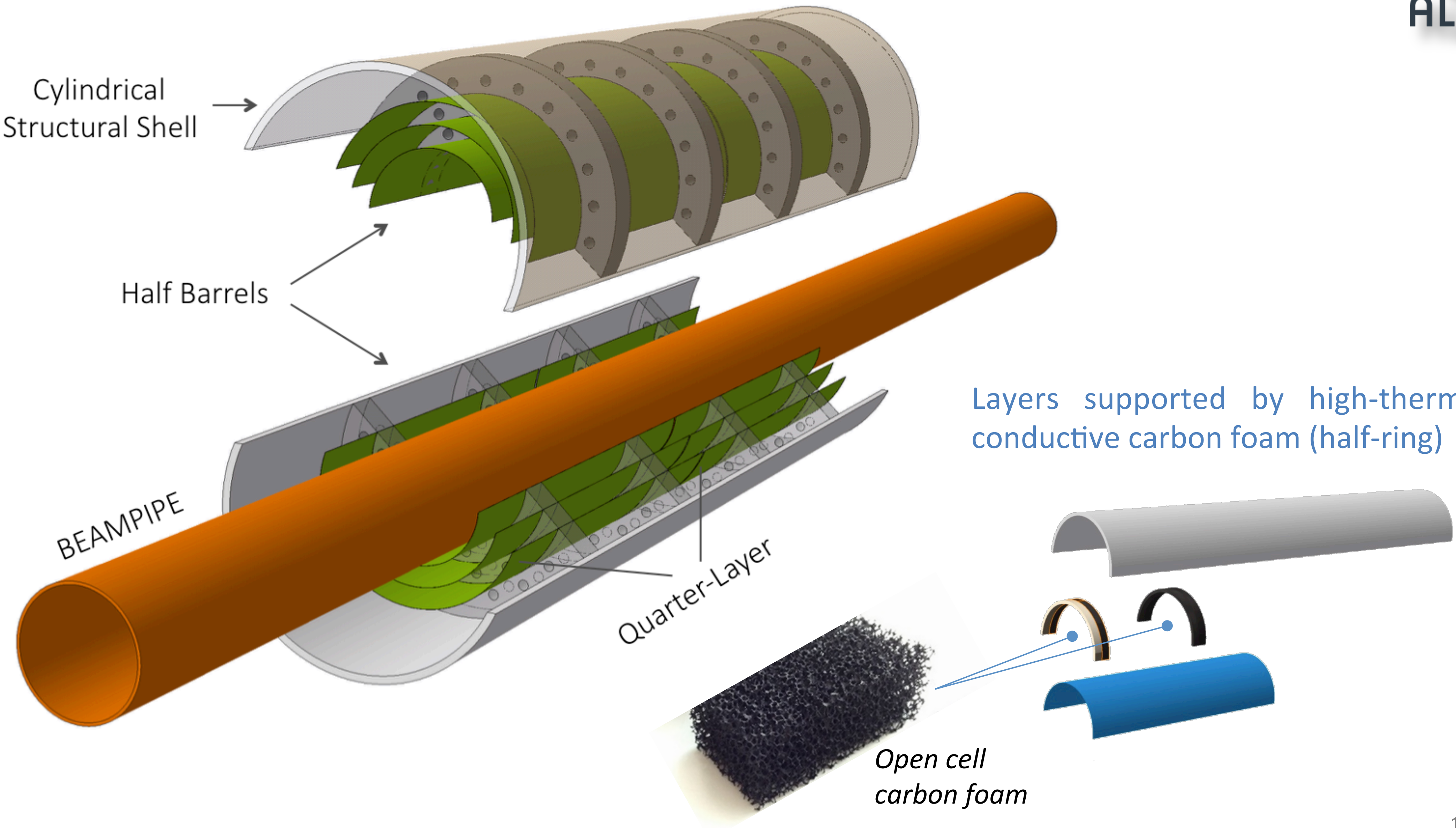
Beampipe
IR 16 mm
ΔR 0.5mm

Beam pipe inner/outer radius (mm)		16.0/16.5	
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	270	270	270
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	408	508
Pixel sensors dimensions (mm^2)	140 × 56.5	140 × 75.5	140 × 94
Number of pixel sensors / layer		4	
Pixel size (μm^2)		$O(30 \times 30)$	

Beam pipe thickness: 500µm (0.14% X_0)

Sensor thickness: 20 – 40µm (0.03 - 0.05% X_0)

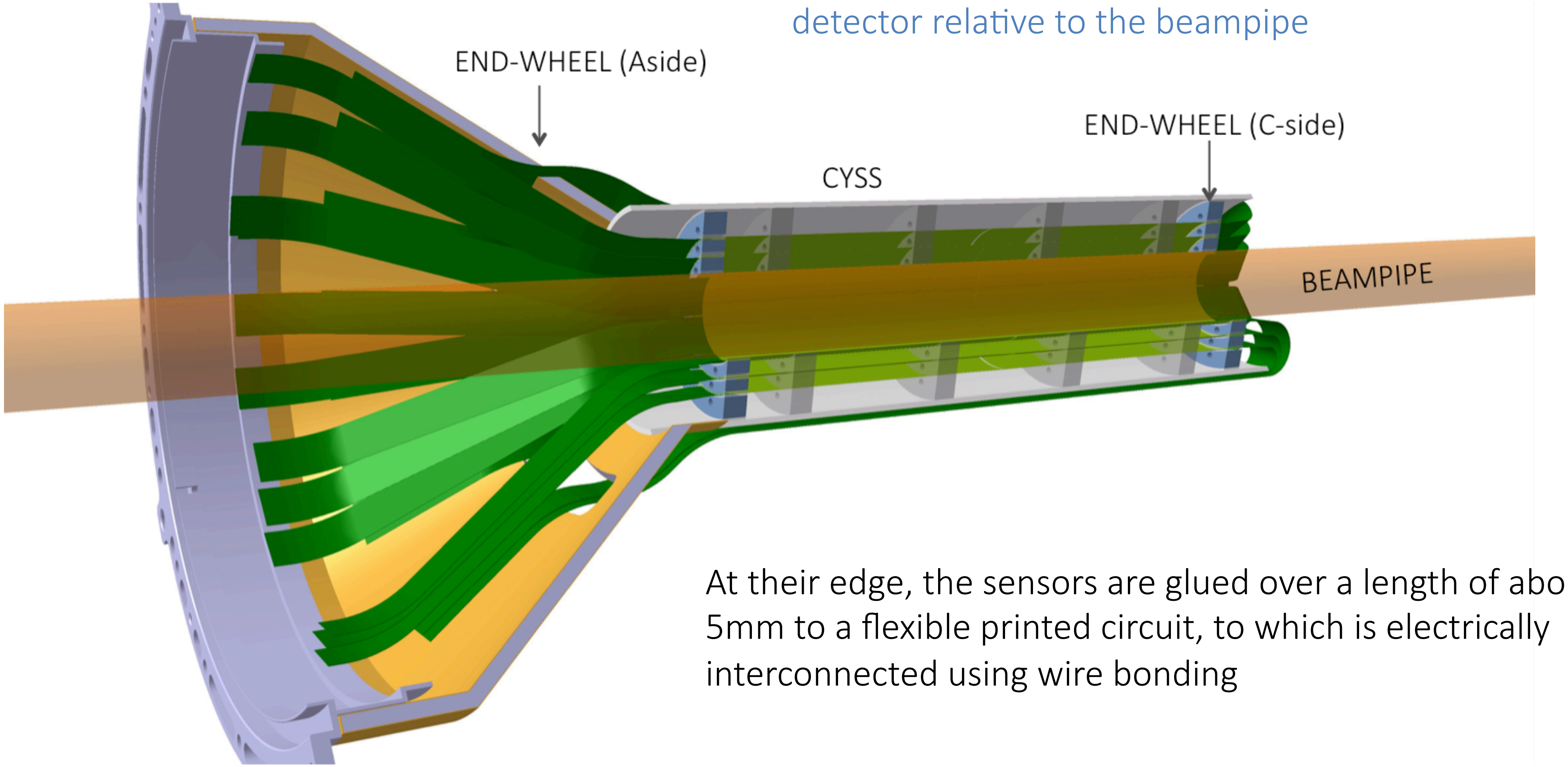
ITS3 Mechanical Layout



Layers supported by high-thermal conductive carbon foam (half-ring)

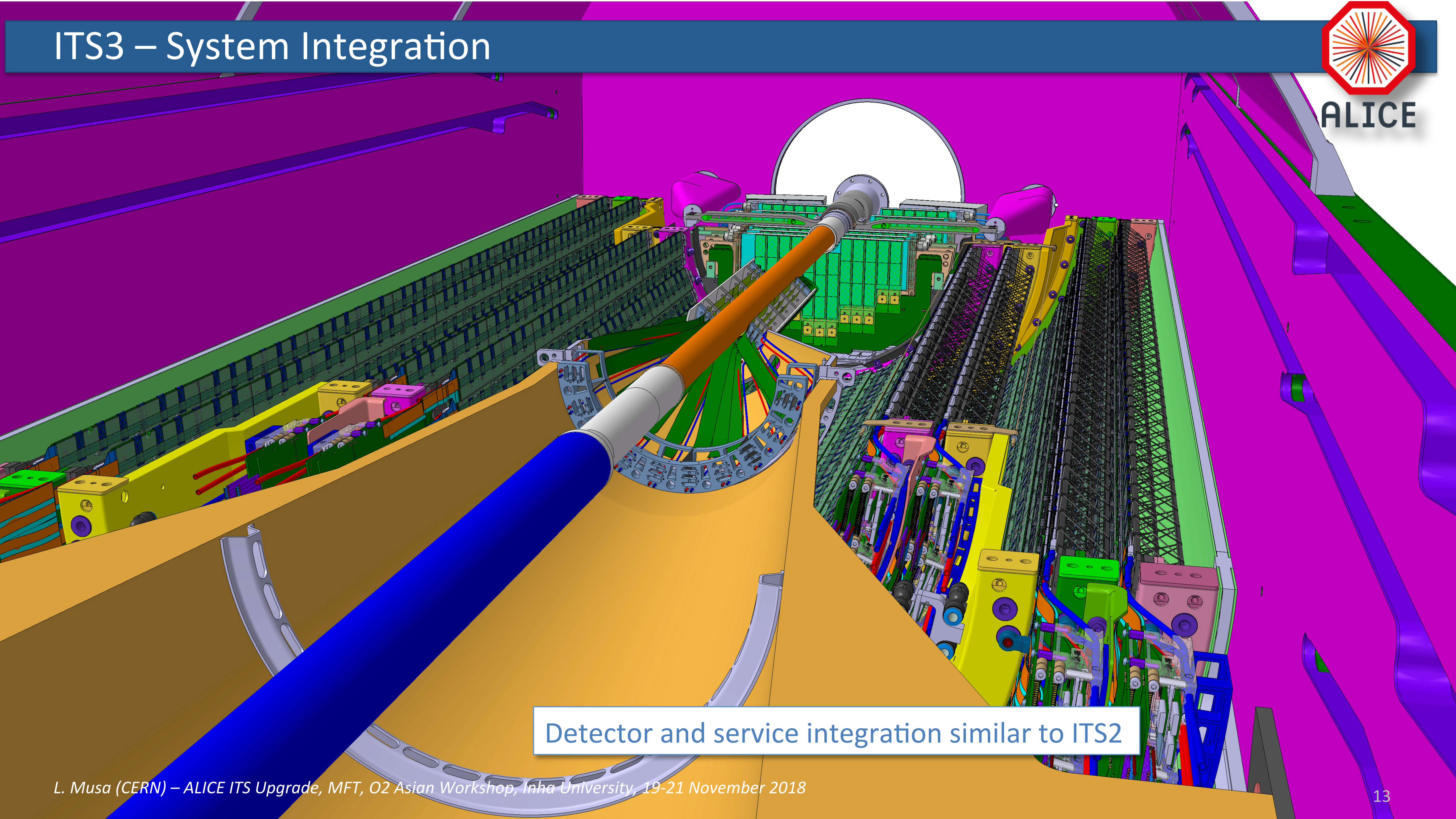
ITS3 Mechanical Layout

Two end-wheels provide precision and fixation of the detector relative to the beampipe



At their edge, the sensors are glued over a length of about 5mm to a flexible printed circuit, to which is electrically interconnected using wire bonding

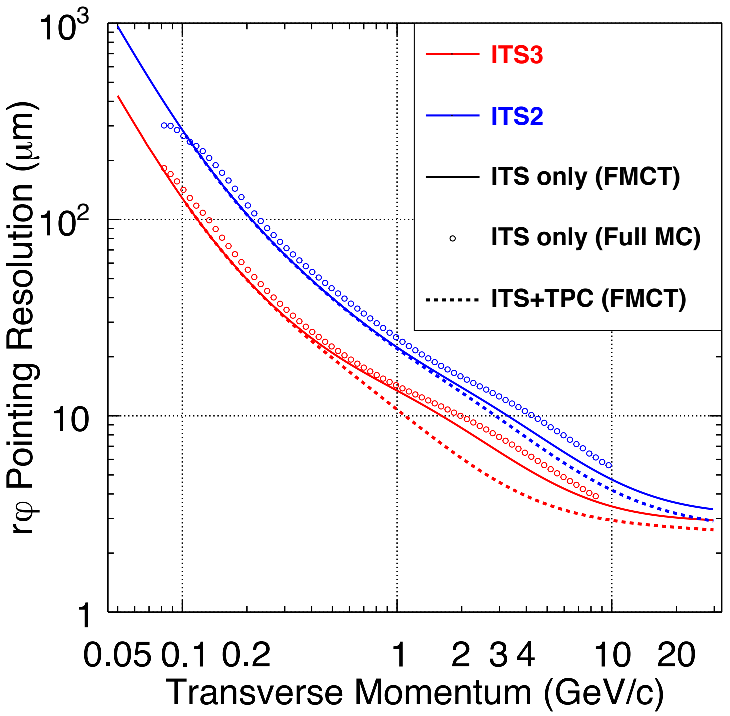
ITS3 – System Integration

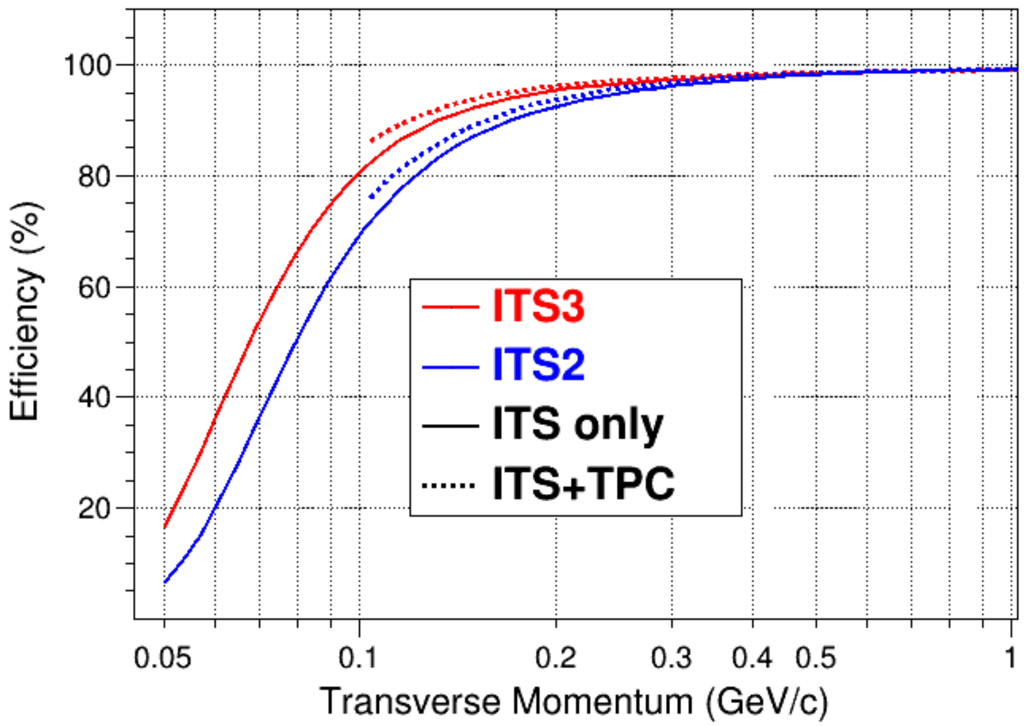


Detector and service integration similar to ITS2

Tracking Performance

Pointing resolution and tracking efficiency (charged pions) for ITS2 and ITS3





FMCT: semi-analytical, includes QED hits, but no energy loss fluctuations

Full MC: simplified ITS3 geometry, full MC simulation (GEANT3), Cellular Automaton ITS Tracker

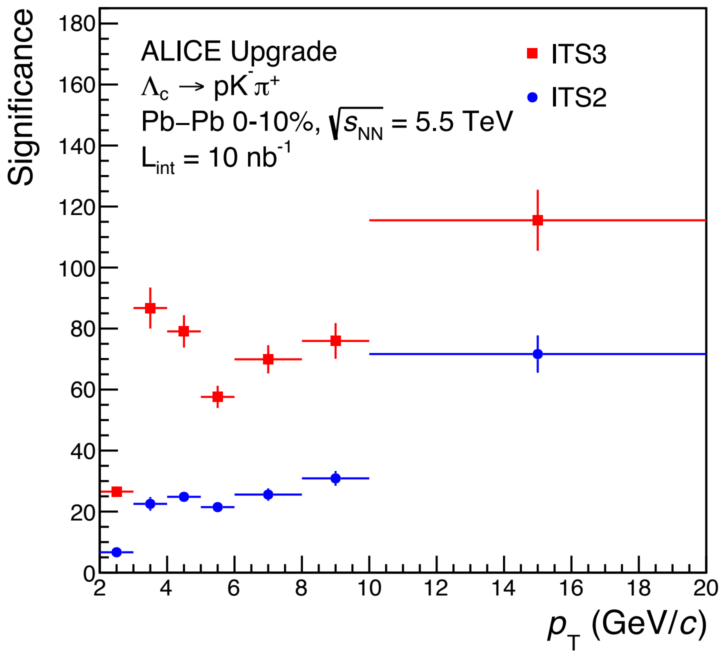
⇨ Improvement of ≈ factor 2 at all p_T's

Efficiency increases factor 1.2 – 2, for p_T < 100MeV

Physics Performance Studies – Λ_c and thermal dielectrons

Measurement of charm baryons (smallest $c\tau$)

⇨ vertexing precision



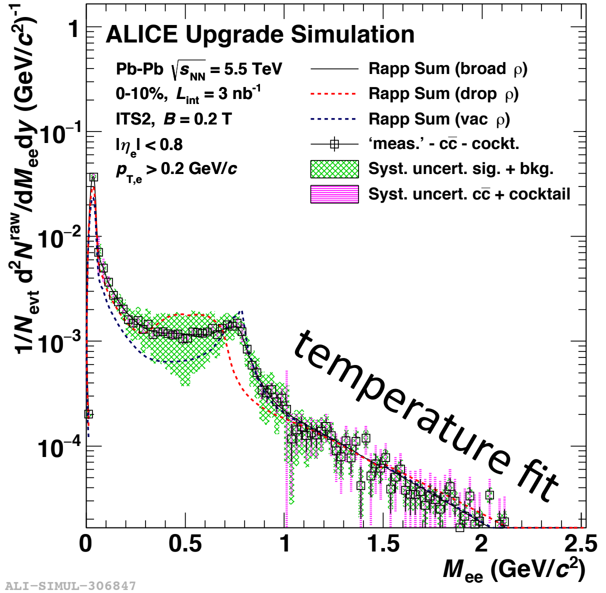
ITS3/ITS2 improvement
x 10 (S/B) , x 4 (significance)

Low-mass dielectrons

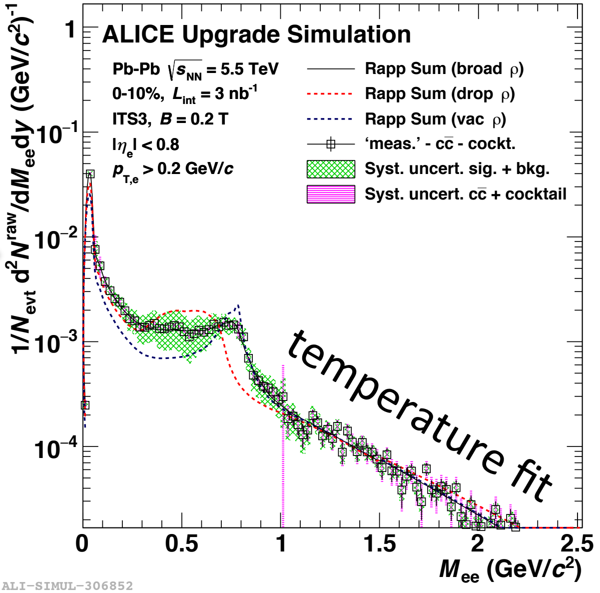
⇨ vertexing (better charm rejection)

⇨ material thickness (less conversion)

⇨ Higher low-p_T efficiency (better conversion rejection)



ALI-SIMUL-306847



ALI-SIMUL-306852

T (QGP)	Stat. error	Syst. (BG)	Syst. (Charm)
ITS3 / ITS2	1/1.5	1/1.3	1/2

Approximate Project Timeline & Cost Estimate

Forecast of the project probable costs and timeline

Table 3: Project Cost estimate.

Item	R&D (kCHF)	Construction (kCHF)	Total Cost (kCHF)
Total	2000	3300	5300
Beampipe	600	900	1500
Pixel CMOS Sensors	700	700	1400
Sensor test	100	150	250
Thinning & dicing	200	300	500
Hybrid printed circuit	100	100	200
Mechanics	150	350	500
Assembly & test	50	200	250
Installation tooling	0	200	200
Air cooling	100	150	250
Services	0	100	100
Patch panels	0	150	150

Tentative Project Time Line

2020 – 2023	R&D
2022	TDR
2024 – 2025	Construction
2025 – 2026	Pre-commissioning & Installation

Detailed cost breakdown and schedule will be defined in the TDR

Summary

Proposal for the construction of a novel vertex detector

- New beam pipe with IR = 16mm, ΔR = 0.5mm
- Three truly cylindrical layers based on curved ultra-thin sensors (⇨ $x/X_0 \approx 0.05\%$ per layer)
- The three layers differ only for their radii, with the innermost layer at 18mm radial distance from IP

The new vertex detector (ITS3) would be installed in LS3 to replace the innermost three layers of ITS2 (LS2)

The ITS3 will consist of two separate barrels: Inner Barrel and Outer Barrel

- The Outer Barrel (four outermost layers) will be that of ITS2
- The new Inner Barrel (three innermost layers) will instead replace the Inner Barrel of ITS2

The ITS3 will provide a large reduction of the material budget (close to IP) and an improvement of the tracking precision and efficiency at low p_T

The combination of these two improvements will lead to a significant advancement in the measurement of low p_T charmed hadrons and low-mass dielectrons

Next Generation HI Experiment at LHC

A new HI dedicated experiment beyond LS4?

With the LS2 upgrade, ALICE will reach the maximal rate with a spectrometer based on a TPC

- Maximum interaction rate limited by space-charge (ions) accumulated in drift volume (distortions ≈10cm) and track density (inner region signal occupancy ≈ 40%)
- Running at higher rates seems excluded with a TPC

Running ALICE beyond LS4 ⇨ Completely new detector without TPC?

The use of CMOS technologies opens new opportunities

⇨ **Vertex detectors, large area tracking detectors and digital calorimeters**

  - enhanced performance (very high-precision spatial and time resolution)

an "all-MAPS" detector

Can such a detector play a central role in HI physics at the LHC in the 2030's ?

See Andrea's talk at HI Town https://indico.cern.ch/event/746182/timetable/ - 20181024

A new HI dedicated experiment beyond LS4?

Design guidelines

- Increase rate capabilities (factor 20 to 50 wrt to RUN4): $<L_{NN}>$ ~ up to 10^{34} $cm^{-2}s^{-1}$
- Improve vertexing
  - Ultra-thin wafer-scale sensors with truly cylindrical shape, inside beampipe
  - spatial resolution ~ 1-3μm
  - material thickness < 0.05% X_0 /layer
- Improve tracking precision and efficiency
  - About 10 layers with a radial coverage of 1m
  - Spatial resolution of about 5μm up to 1m
  - whole tracker could be less than 6% X_0 in thickness (at mid-rapidity)
- Extended rapidity coverage (ideally up to 8 rapidity units)

Focus on relatively low p_T phenomena, $0.01 < p_T < 10$ GeV/*c*

Magnetic fields of < 0.5T would be sufficient but 1T (or higher) is to be considered

Which observables – some example

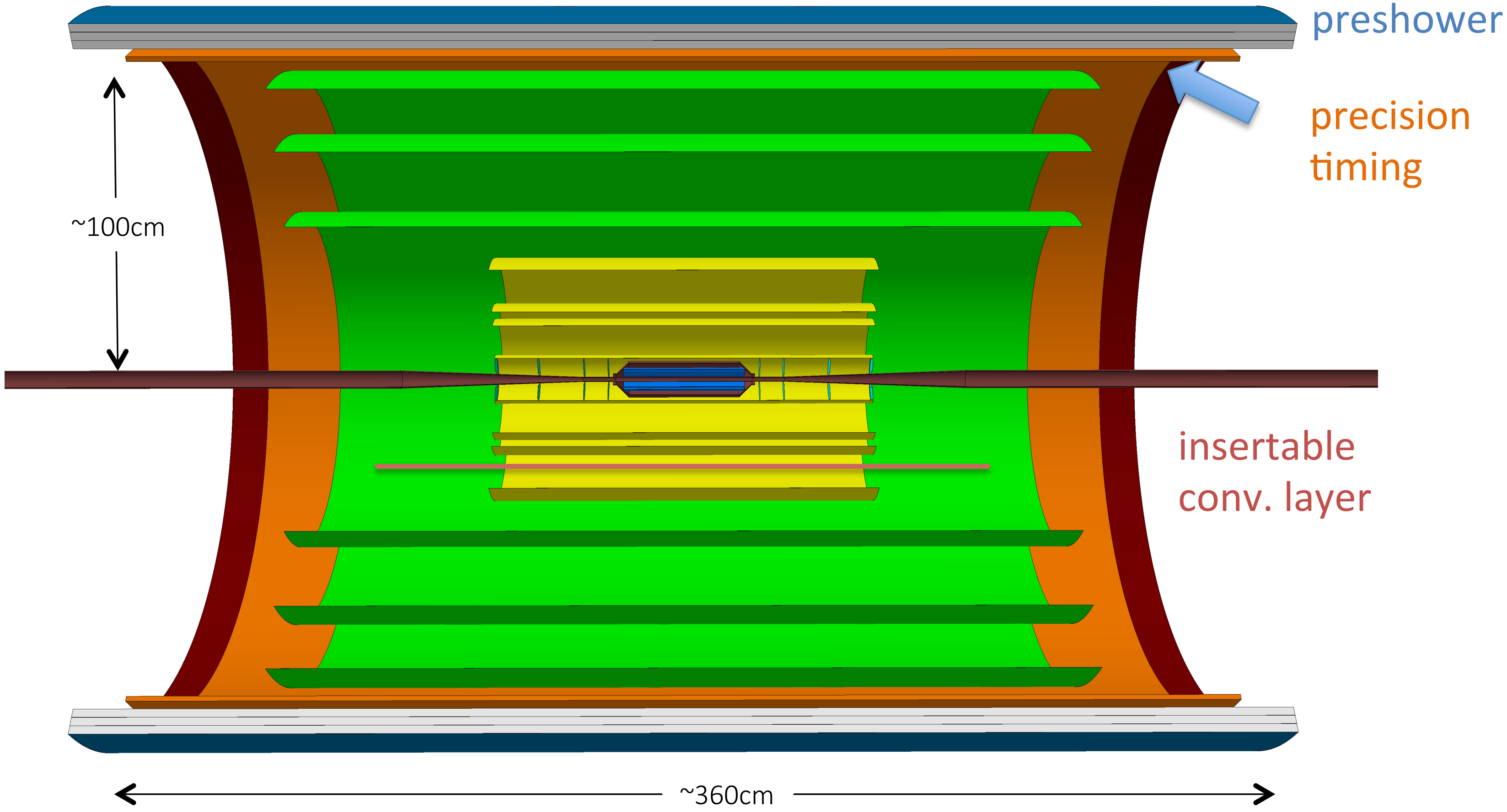
- Thermal radiation: dileptons and photons
  - ALICE unique measurement, measurement of electrons down to few tens of MeV
- Photons
  - ALICE could be unique due to low material budget and could do well at low energy using conversion technique (insertable converter)
- Open Heavy-flavor: single charmed and multiply charmed, charmed-beautiful, beautiful hadrons
  - At very low p_T ALICE still unique
- Quarkonia: e.g. $\chi_{c,b}$ (low p_T, ~200-300 MeV, photon in the final state)
  - ALICE competitive at very low $p_{T\,,}$
- Others (new in HI)
  - Exotic mesons: X(3872), Z_c (3900), Y(4140), … ⇨ compact multi-quark states / molecular states

A new experiment based on a “all-MAPS” detector

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Hadron ID: TOF with outer silicon layers (orange)

Electron ID: pre-shower (outermost blue layer)



Preliminary studies

Magnetic Field

- B = 0.5 or 1 T

Spatial resolution

- Innermost 3 layers: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Time Measurement

Outermost layer integrates high precision time measurement ($\sigma_t < 30ps$)

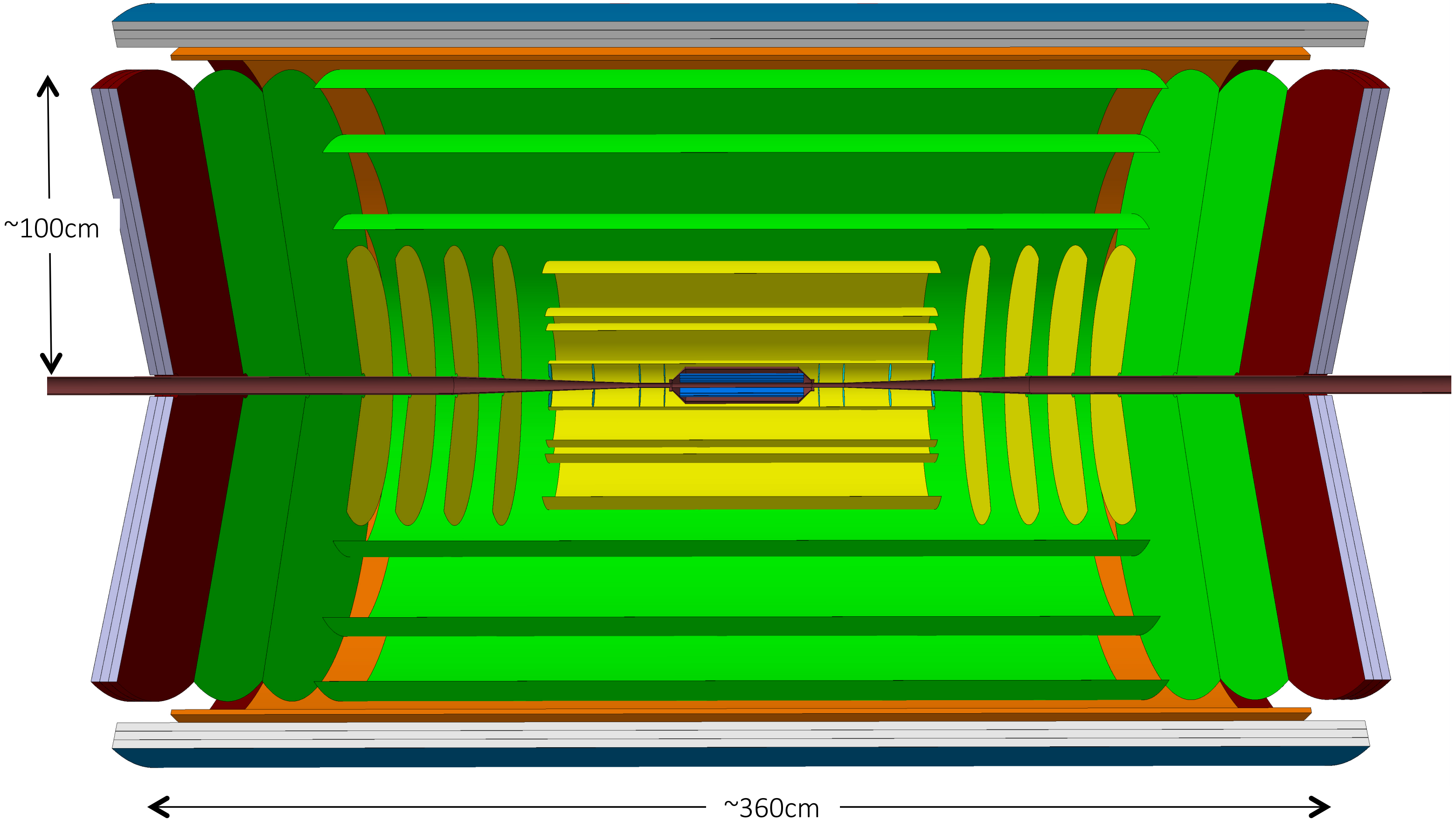
A new experiment based on a "all-silicon" detector

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Hadron ID: TOF with outer silicon layers (orange)

Electron ID: pre-shower (outermost blue layer)

Extended rapidity coverage: **up to 8 rapidity units**
+ FoCal



Preliminary studies

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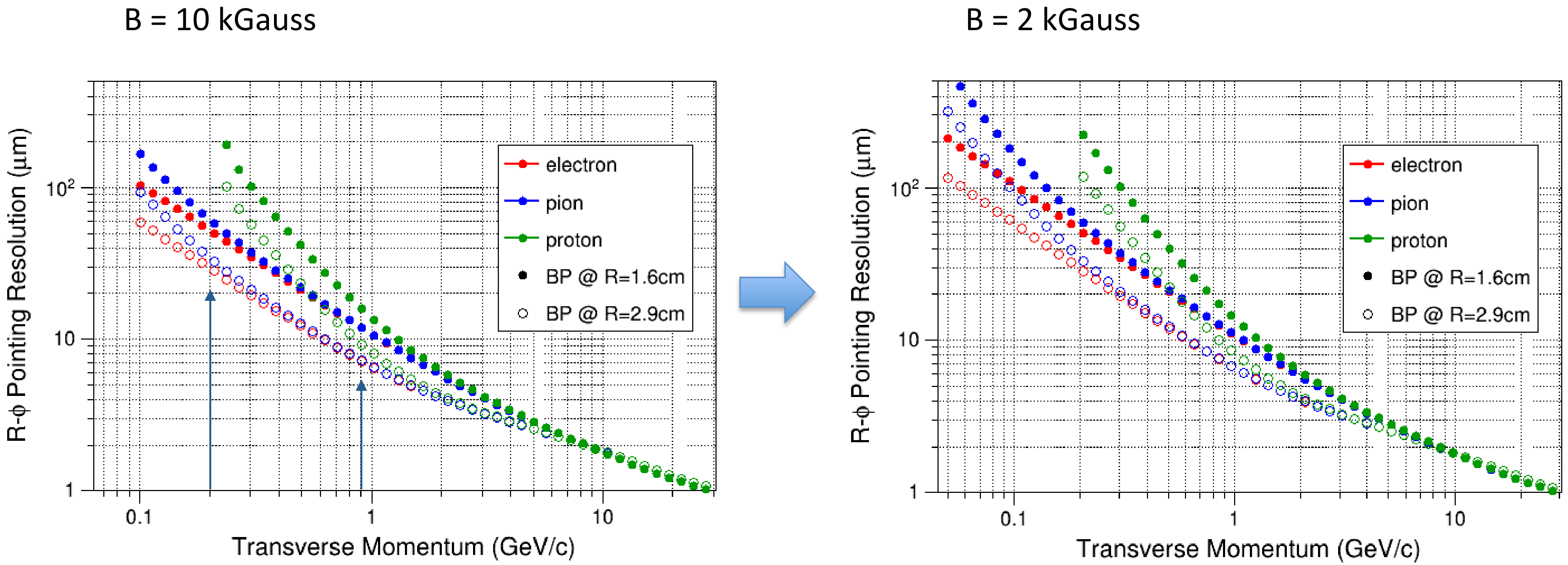
Operation at reduced B field for tracking low p_T particles



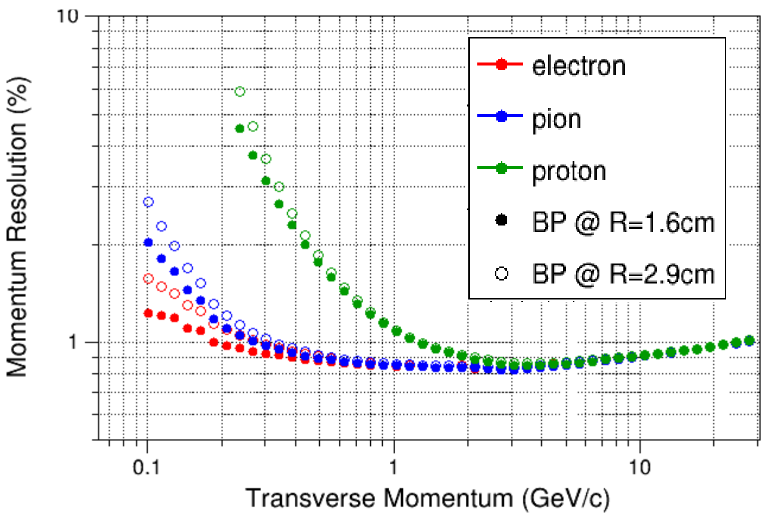
Pointing resolution (pions): ≈ 10 μm @ 1 GeV/*c*, <50μm @ 200 MeV/c

It does not depend on B field

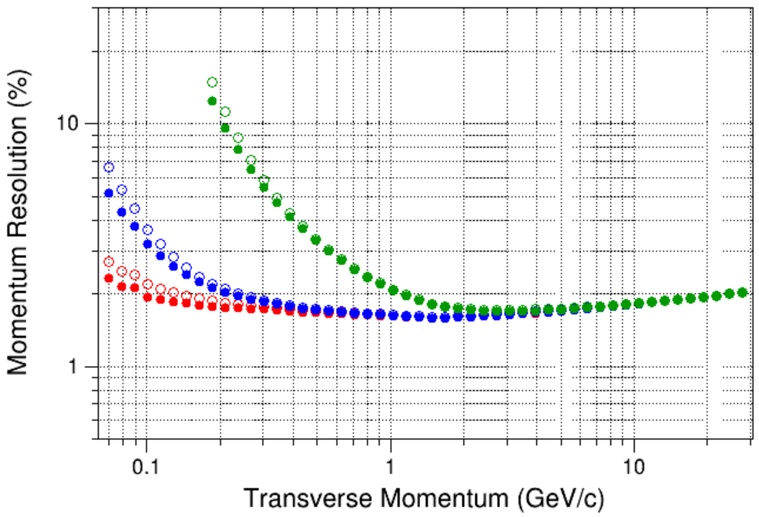
Operation at reduced B field for tracking low p_T particles

Compared to ALICE in Run3, same performance at high p_T, some improvement at very low p_T

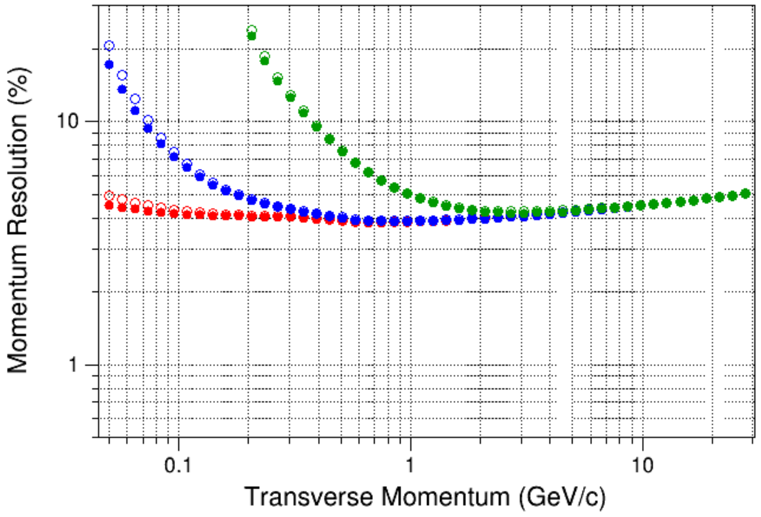
B = 10 kGauss



B = 5 kGauss



B = 2 kGauss



momentum resolution for 1GeV/c pions: ≈ 0.8% (10 kGauss), ≈1.6% (2kGauss), ≈ 4% (2kGauss)

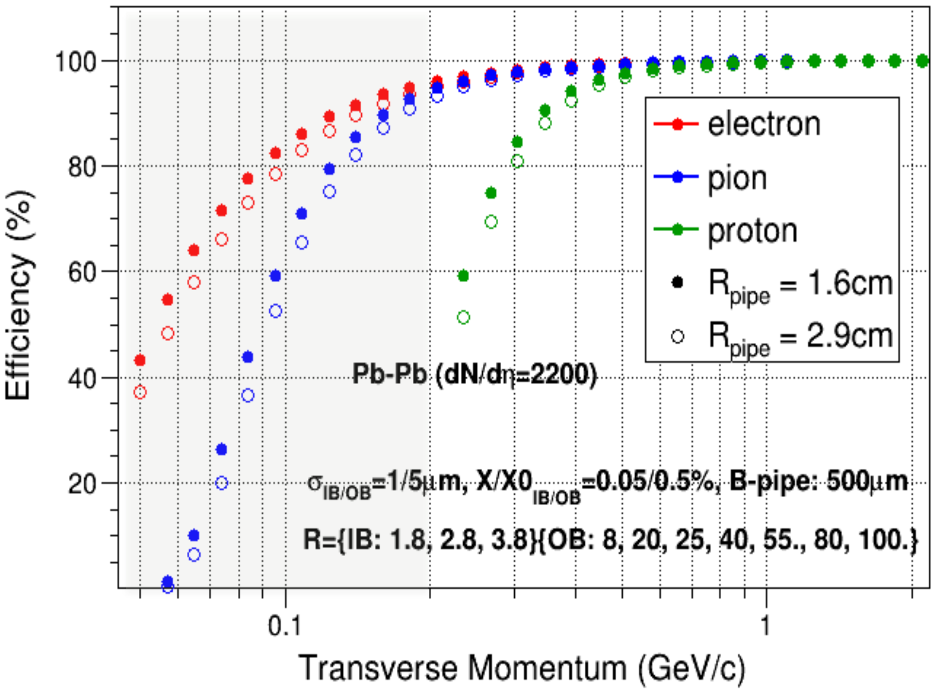
$$\boxed{\frac{\delta p}{p} = \frac{p}{0.3BL^2}\sigma \cdot \sqrt{C_N}}$$

$$C_N = \frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}$$

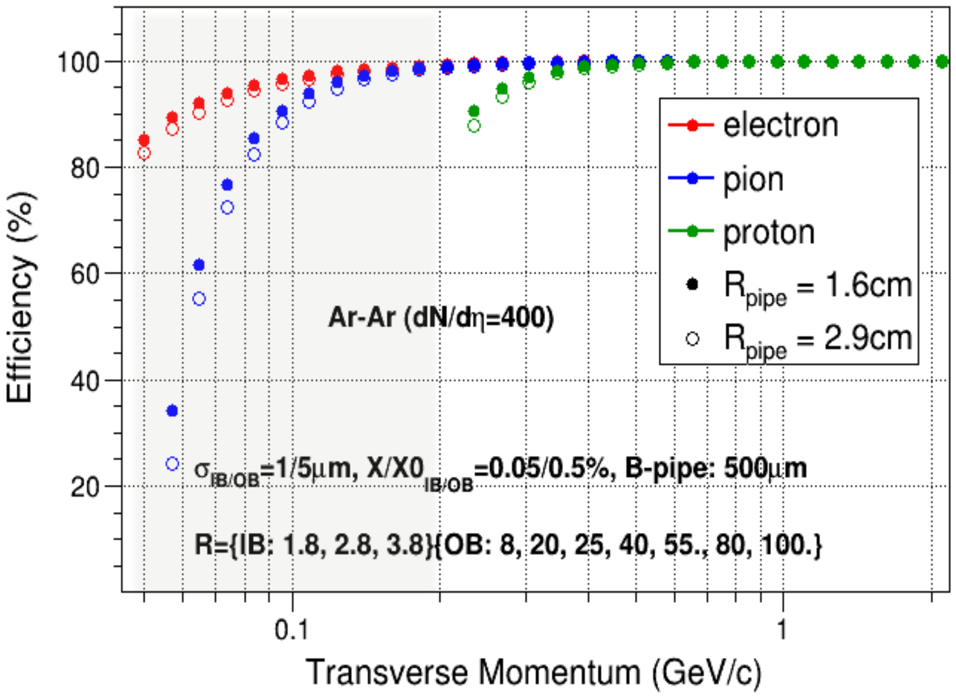
for layers equally spaced and neglecting multiple-scattering

Operation at reduced B field for tracking low p_T particles

Pb-Pb (dN/dy = 2200), B = 2 kGauss



dN/dy = 440, B = 2 kGauss



Efficiency requiring that all particles reach the outermost layer at 1m (10 layers)

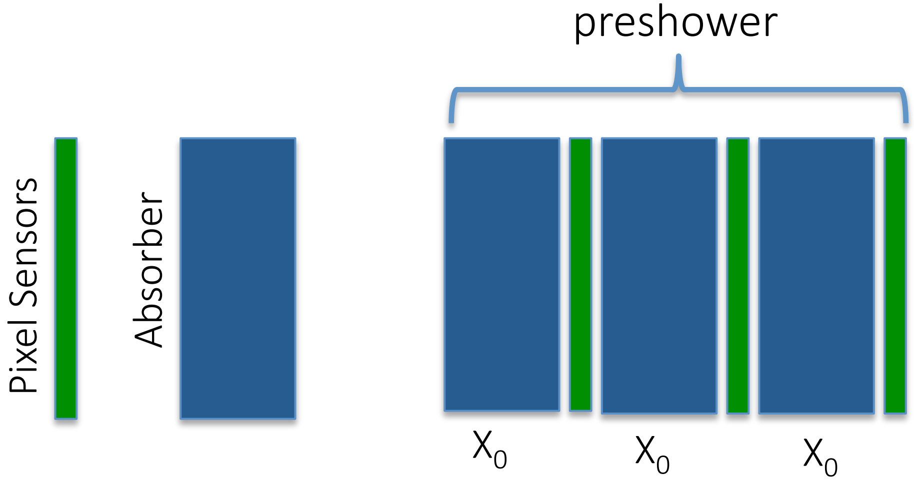
⇨ optimization possible (e.g. using only layers up to 40cm)

⇨ dramatic improvement for lower dN/dy

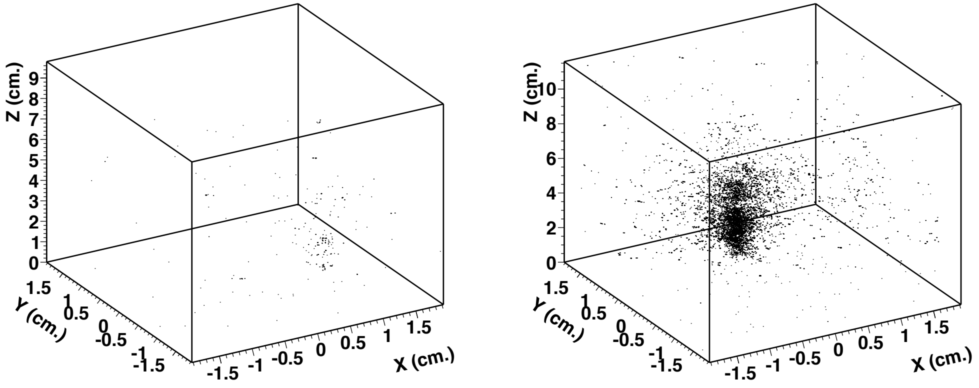
Particle Identification

Electron and hadron PID using dE/dx, TOF and pre-shower

- dE/dx in silicon (middle layers): PID at very low p_T (20 – 200 MeV)
- Time of Flight: $\sigma_{TOF} \approx$ 20-30ps, track length ~1m ➪ good e/π separation < 500 MeV
- Pre-shower (2-3 X_0) based on high-granularity (CMOS pixels) digital calorimetry
  - great potential to identify electrons down to few hundred MeV by detailed imaging (particle counting, geometry) of the initial shower



FoCal - R&D studies

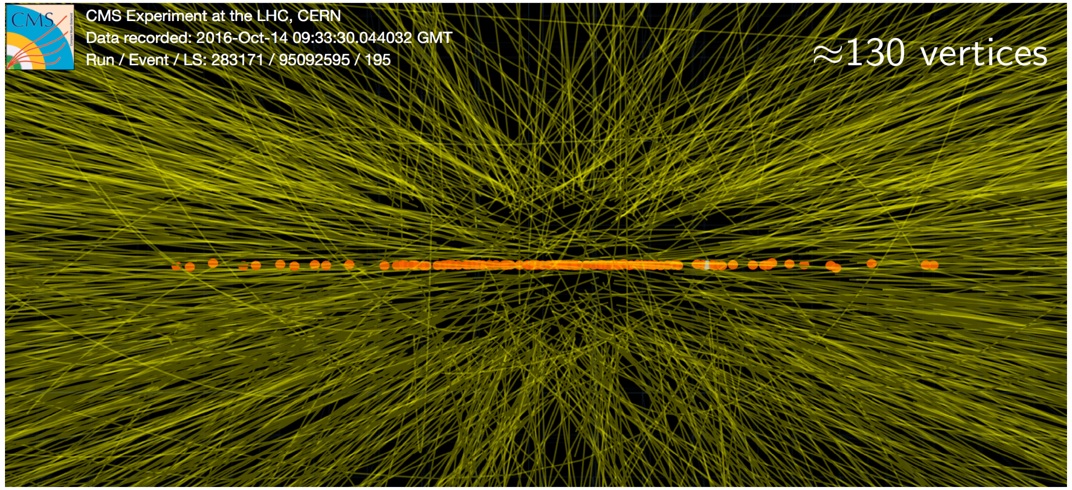


2 GeV/c positrons

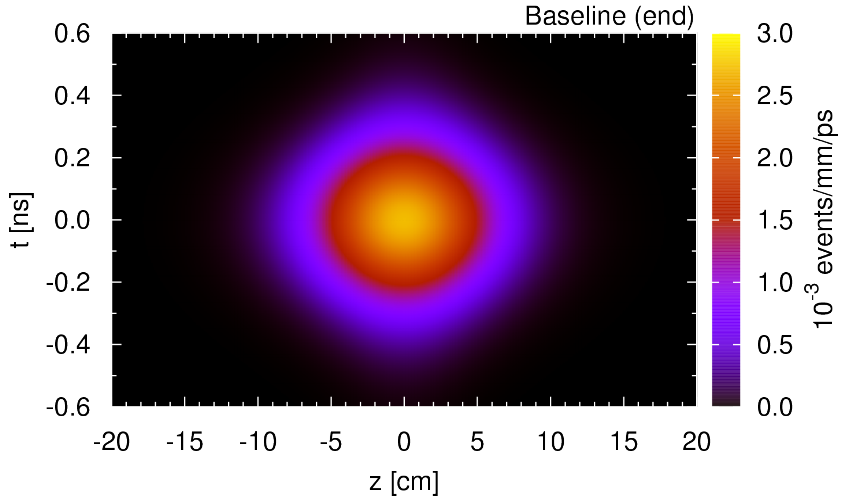
100 GeV/c positrons

Timing Layer for 4D tracking - CMS

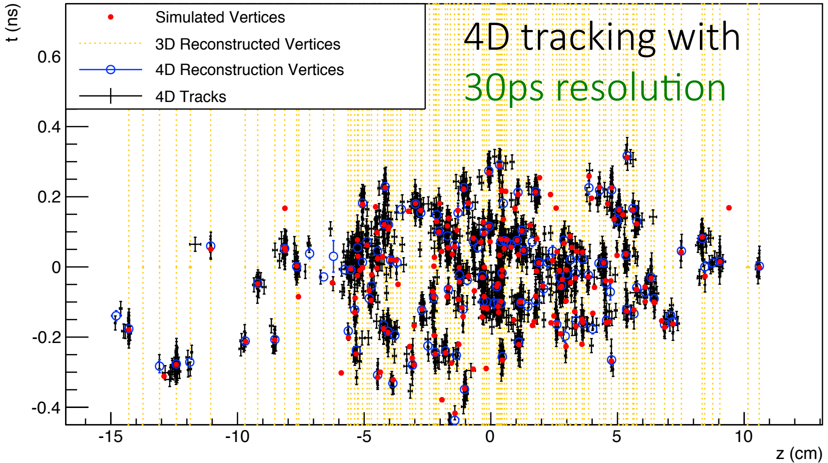
HL-LHC pp - z distribution of interactions within 1 BC



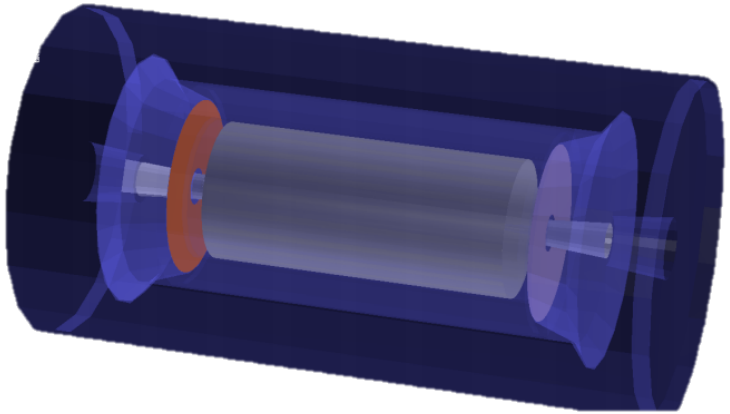
Interactions are also spread in time with a nominal RMS of 180ps, uncorrelated with z (σ_z ~4.5cm)



HL-LHC pp - z distribution of interactions within 1 BC



CMS Timing Layers for pile-up mitigation



LYSO crystals + SiPMs

Barrel (grey barrel)

between Tracker and ECAL

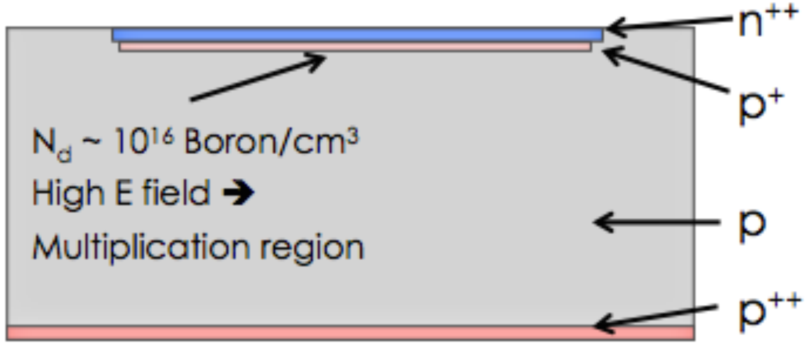
LGAD (Low-Gain Avalanche Diode)

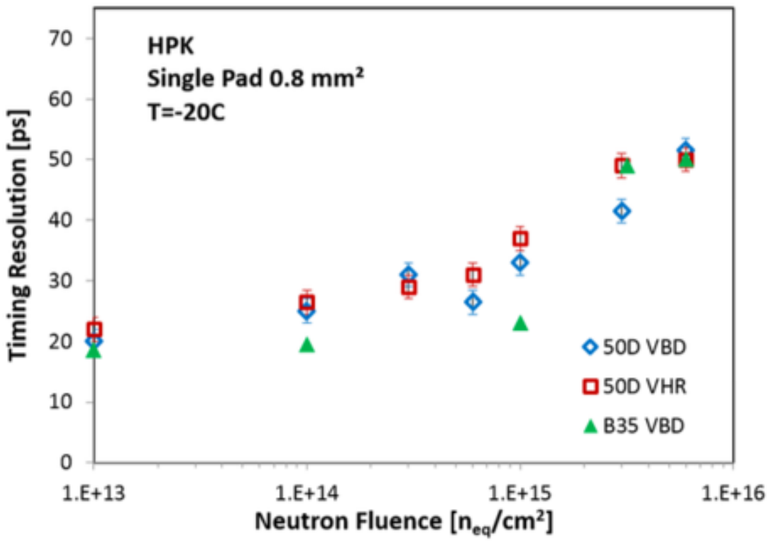
ENDCAP (orange disks) - 12m²

Timing Layer for 4D tracking - CMS

LGAD (Low Gain Avalanche Diode)

- Technology proposed for ATLAS and CMS upgrades (timing layer)
- Developed for high radiation environment (10^{14} – 10^{15} 1MeV n_{eq}/cm^2)
- Currently low granularity O(1 mm^2)
- Add a thin layer of doping to produce low controlled multiplication
- Several vendors: Hammamatsu, FBK, CNN





Time resolution vs. neutron fluence of LGAD produced by HPK with a thickness of 50μm (50D) and 35μm (35D)

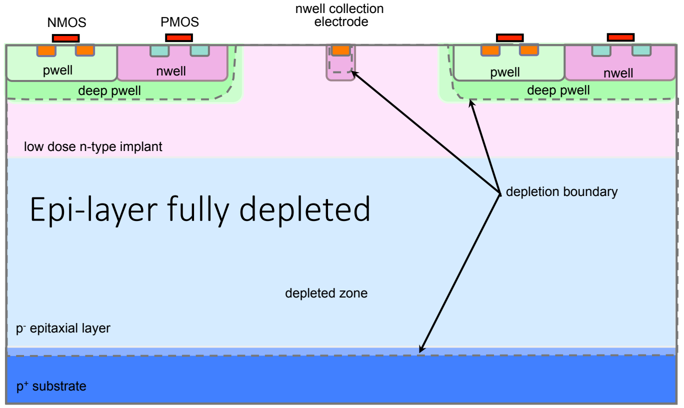
Resolution of 20-30ps demonstrated

Cost (CMS estimate) ~ 50 CHF/cm^2

Can such a low-gain layer be implemented in CMOS?

Hadron ID with silicon TOF detector

Time resolution of a fully depleted CMOS pixel sensors a la “ALPIDE”



Modified process CERN/Tower

R&D for the ALICE upgrade: developed in collaboration with Tower a process modification that allows full depletion of the high resistivity silicon layer

- Reduces charge collection time (<1ns)
- Enhances radiation hardness (~10^{15} n / cm^2)

First order approximation $\sigma_t = c\,\frac{t_r}{SNR}$

t_r: amplifier rise time
c = 0.4 – 0.6

In ultra-thin O(10μm) fully depleted CMOS sensors (e.g. INVESTIGATOR or ALPIDE with CERN/TJ modified process) with 10V reverse bias

- Charge (e) collection time T ≈ 170ps
- Standard deviation of signal centroid time $\Delta_T \approx$ 15ps
- noise ≈ few electrons
- Signal on seed pixel ≈ 1000 electrons

- $\sigma_{TDC} \approx$ 15ps
- jitter ≈ 10ps
- $T_0 \approx$ 10ps

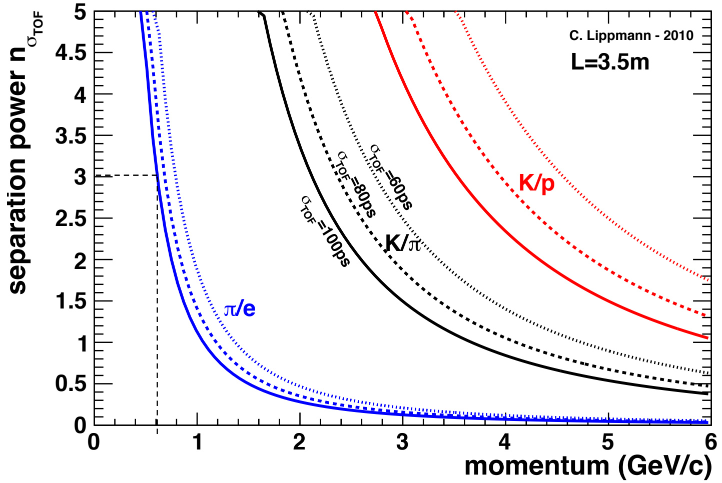
Single layer

$\boxed{\sigma_t < 27 ps}$

Time resolution might be further limited by signal shape fluctuations inside sensor

Electron ID

Time Of Flight



TOF PID – track length 3.5m

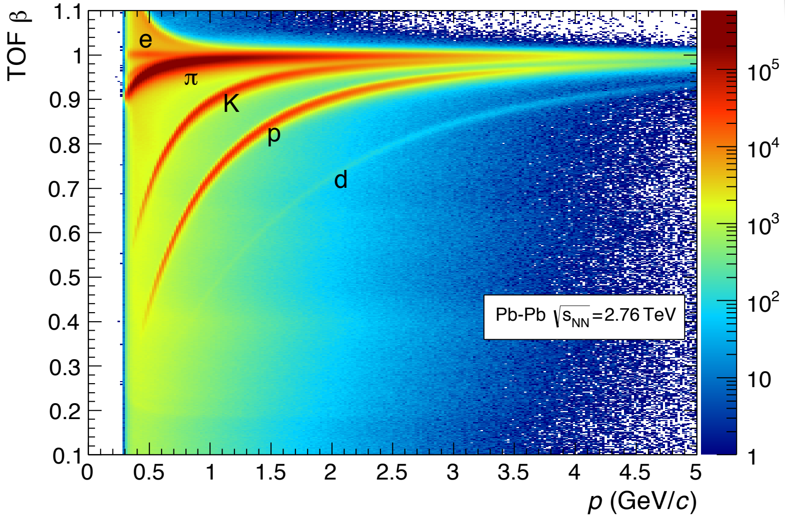
3 system time resolutions

60ps, 80ps , 100ps

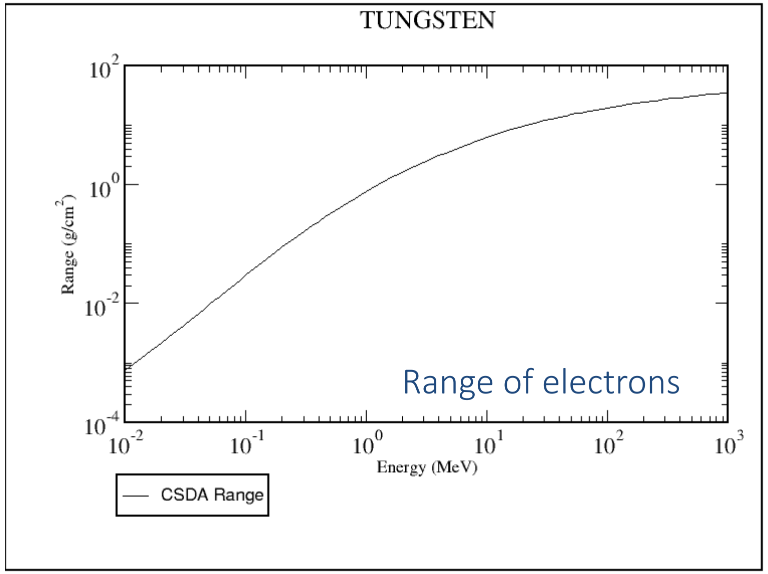
Ideal track length and p measurement

Good e/π separation < 600 MeV/c

ALICE TOF (current)



Range of electrons in W



Range of electrons

Absorption of electrons in W

- X_0 = 0.35 cm
- ρ = 19.3 g/cm^3

Range of e in W > 4.5X_0 for E> 500MeV

Energy (MeV)	10	50	100	200	500	1000
Range (cm)	0.33	0.79	1.02	1.26	1.58	1.81
Range (X_0)	0.92	2.27	2.90	3.60	4.52	5.18

Range of electrons in copper

Pixel Chamber Experiment

A pixel chamber as heavy-flavour imager

Studies on 3D Pixel Chamber Imager for measuring charm and beauty at a fixed target experiment

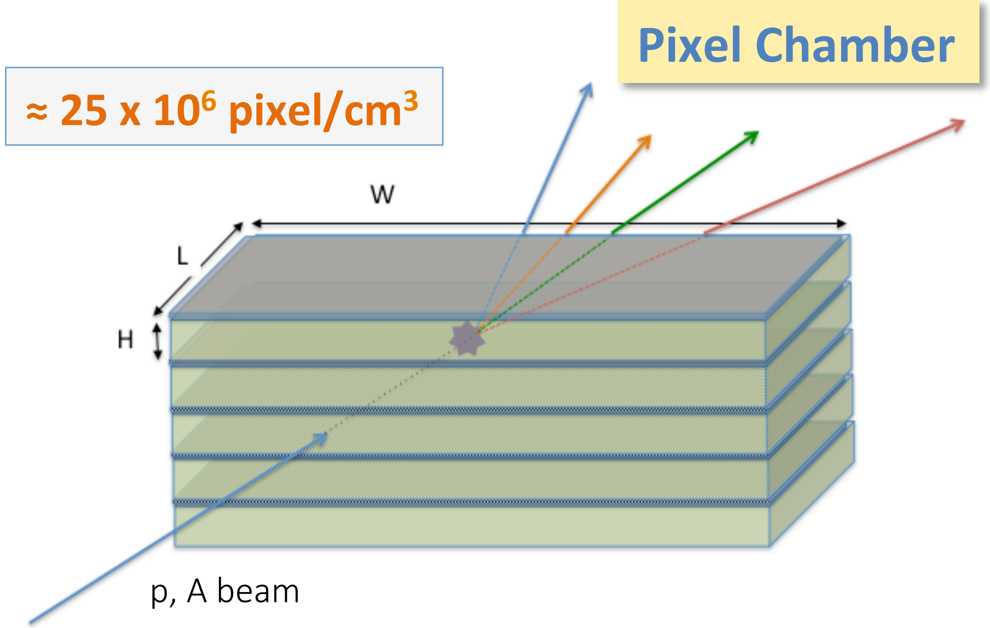
The heart is a **3D pixel chamber** used as active target

The idea is to have a detector able to provide the image of the proton-nucleus or nucleus-nucleus interaction and track the particles generated in the inelastic collision just starting at the interaction point

The pixel chamber is realized with a stack-up of thin CMOS sensors providing truly 3D (almost) continuous tracking with a precision of few microns for very high rate and multiplicity environment

Nuclear interaction inside a stack-up of N fine pitch pixel sensor

- N ≈ 100 , H ~ 50μm, L ≈ 0.1 nuclear collision length (≈30mm)



Pixel Chamber

≈ 25 x 10^6 pixel/cm^3

A pixel chamber as heavy-flavour imager

Using ALPIDE, Pixel Chamber Detector with a volume of about 15(w) x 30(L) x 5(H) mm^3

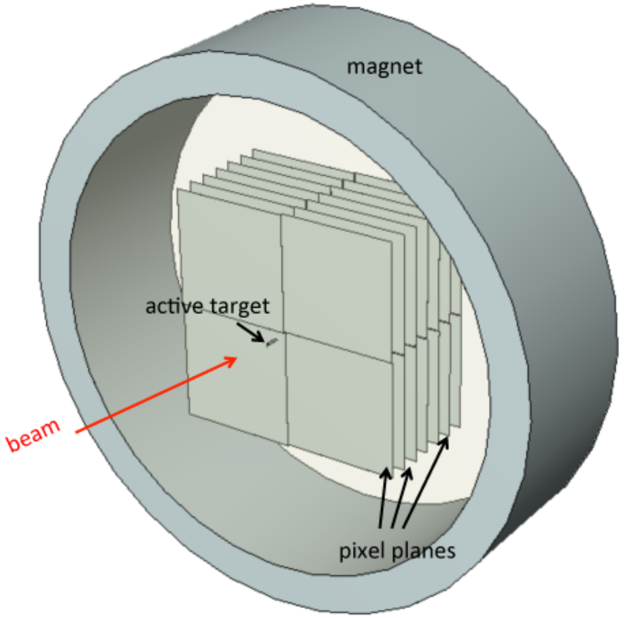
- segmented in pixels of about 27 x 29 x 50 μm^3
- providing the measurement of 25 x 10^6 space points / cm^3
- with a spatial resolution of ≈5μm in the three dimensions

Besides the huge granularity which ensures a three-dimensional image-like reconstruction of the event, this detector is sufficiently radiation hard (10^{14} - 10^{15} 1MeV n_{eq}) and fast for measurements in fixed-target mode (integration time O(1μs)).

The Pixel Chamber is coupled to a compact silicon telescope immersed in a magnetic filed of few tesla for precise measurement of particle momenta.

In this way a very compact instrument for imaging of heavy flavors with unprecedented precisions can be realized.

The detector could also be complemented with other detectors specialized for specific measurements (e.g. electrons, muons, photons)



Thank You

Particle Rates

Expected maximum particle density in the layers of the ITS Inner Barrel

EOI Sec. 4

	Particle density (cm^{-2})			
	LS2 Upgrade		LS3 Upgrade	
Layer	Hadronic[a]	QED electrons[b]	Hadronic[a]	QED electrons[b]
0	43	7	73	12
1	25	3	43	8
2	17	2	29	6

[a] *maximum particle density in central Pb-Pb collisions (including secondaries produced in material) for B = 0.2T*

[b] *for an integration time of 10μs, an* L_{int} *= 50 kHz and B = 0.2T*

Particle density at L0 increases by ≈ 70%

Sensor occupancy (fraction of pixel with a particle hit) ≈ 10^{-3} ⇨ no issues for the tracking

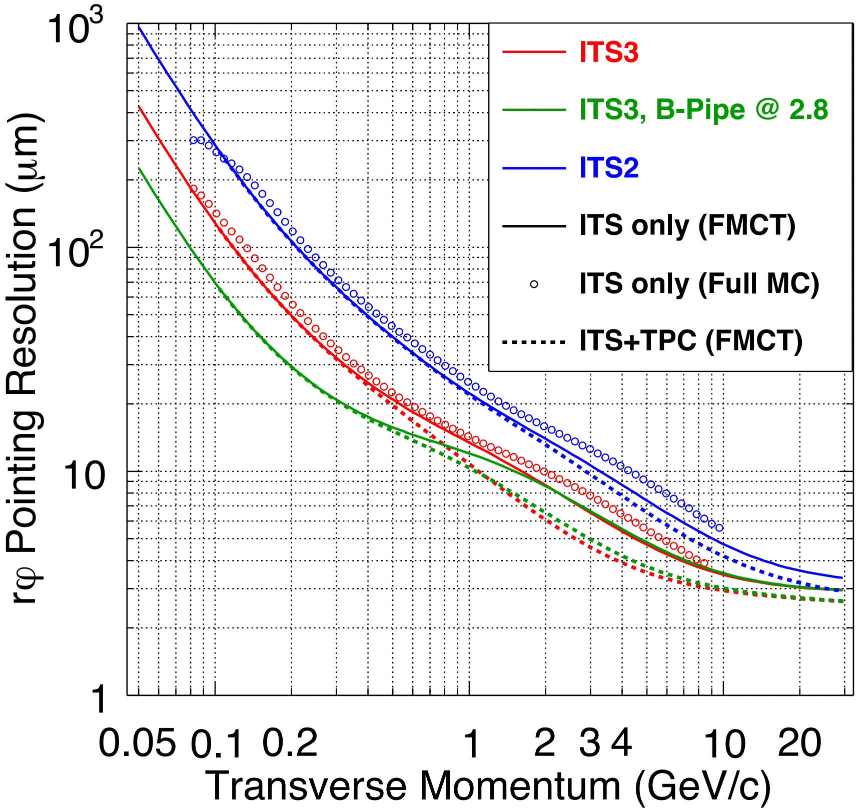
Particle flux (for 50 kHz Pb-Pb) < 4 MHz / cm^2 ⇨ well within the detector readout capabilities

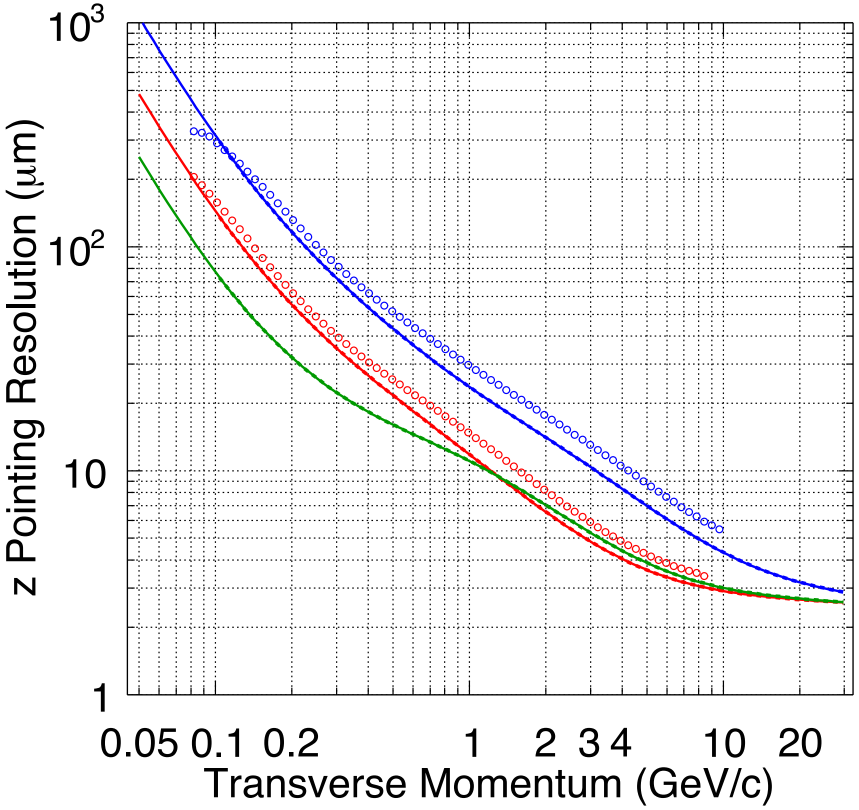
Radiation load increases by ≈ 70% ⇨ still well below the safety values

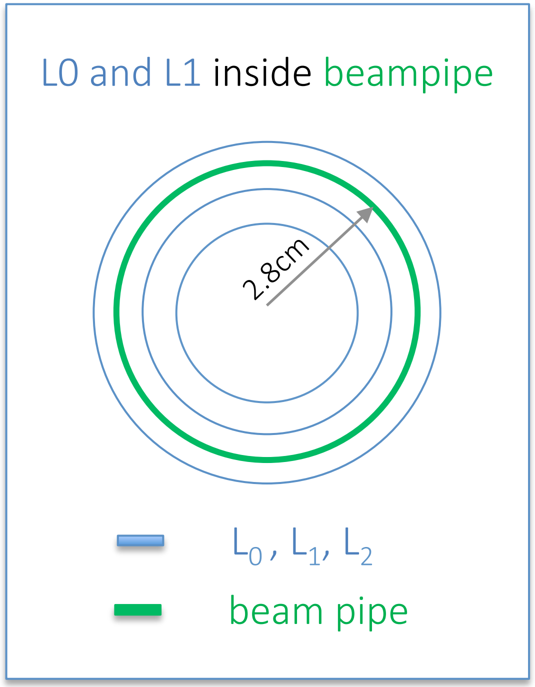
Tracking Performance

EOI Sec. 4

Impact parameter resolution (charged pions) for ITS2 and ITS3






L0 and L1 inside beampipe

FMCT: semi-analytical, includes QED hits, but no energy loss fluctuations

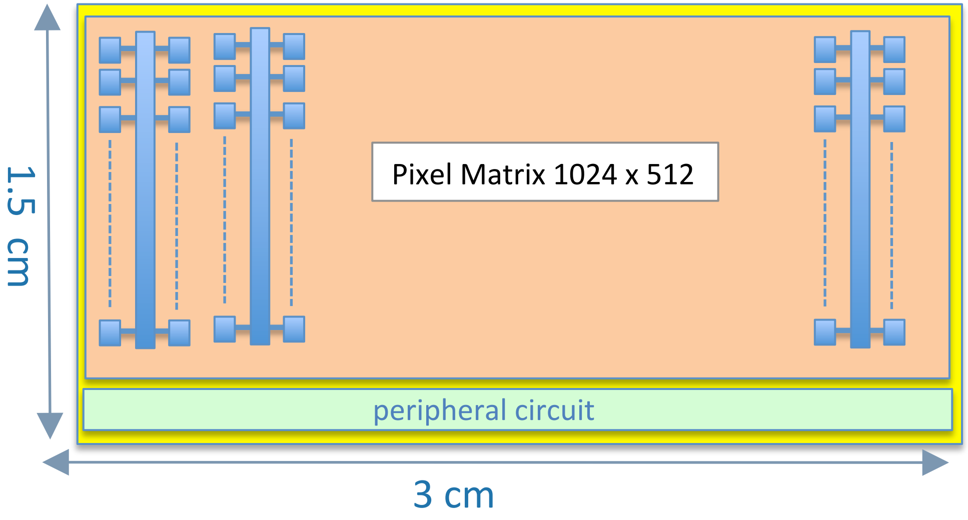
Full MC: simplified ITS3 geometry, full MC simulation (GEANT3), Cellular Automaton ITS Tracker

⇨ Improvement of ≈ factor 2 at all p_T's

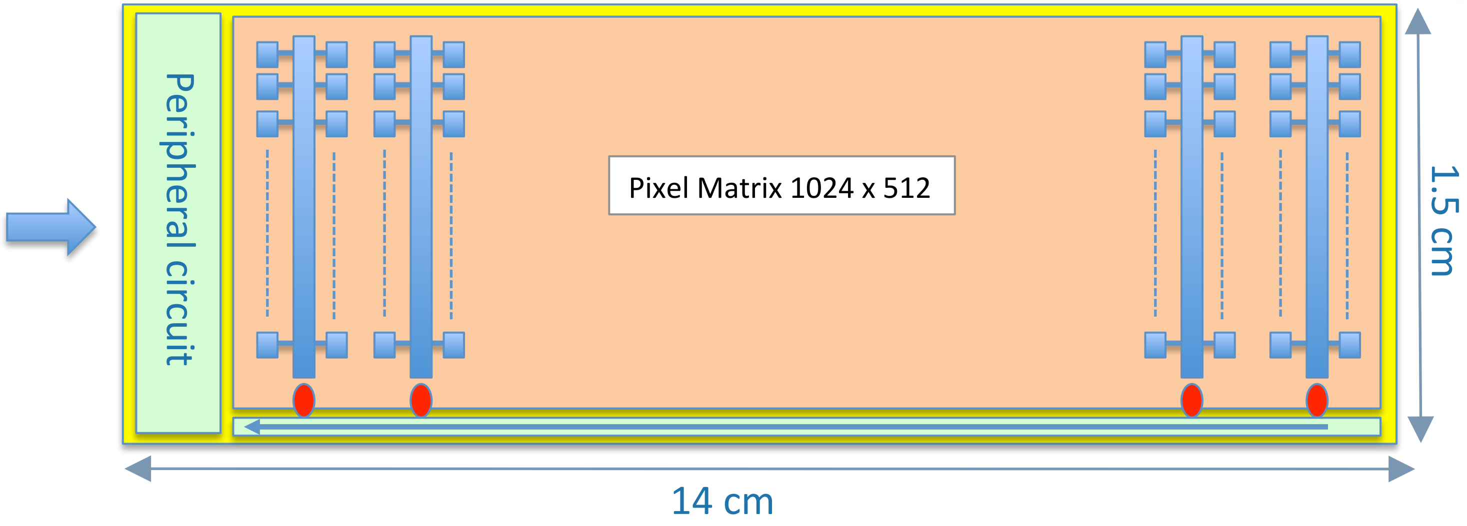
≈ factor 3 for $p_T < 500$MeV with pipe @ 28mm

Stitching allows the fabrication of wafer scale sensors

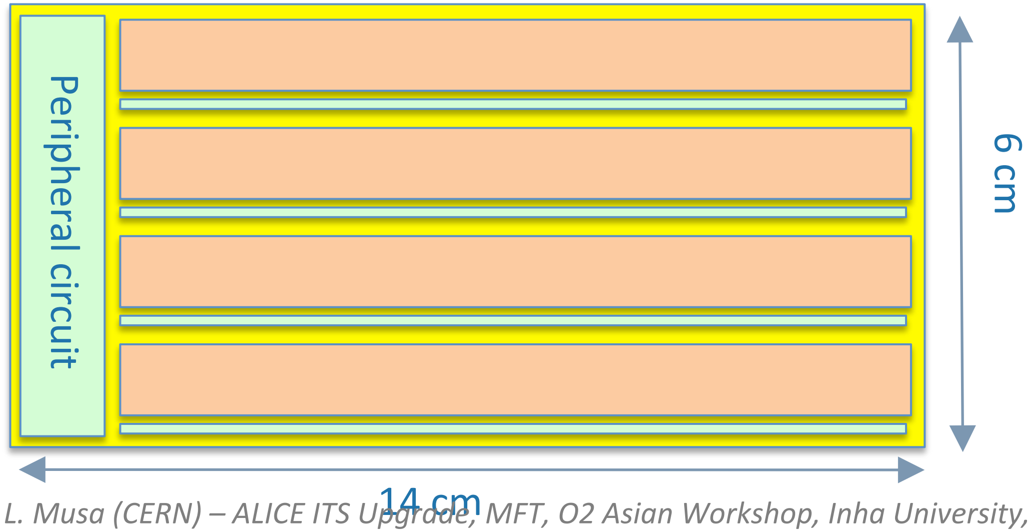
ALPIDE Chip



1D stitched sensor (z direction)



2D stitched sensor – wafer-scale



By instantiating multiple times the same circuits in the second dimension (ϕ) one can realize the sensors for the different layers. For example

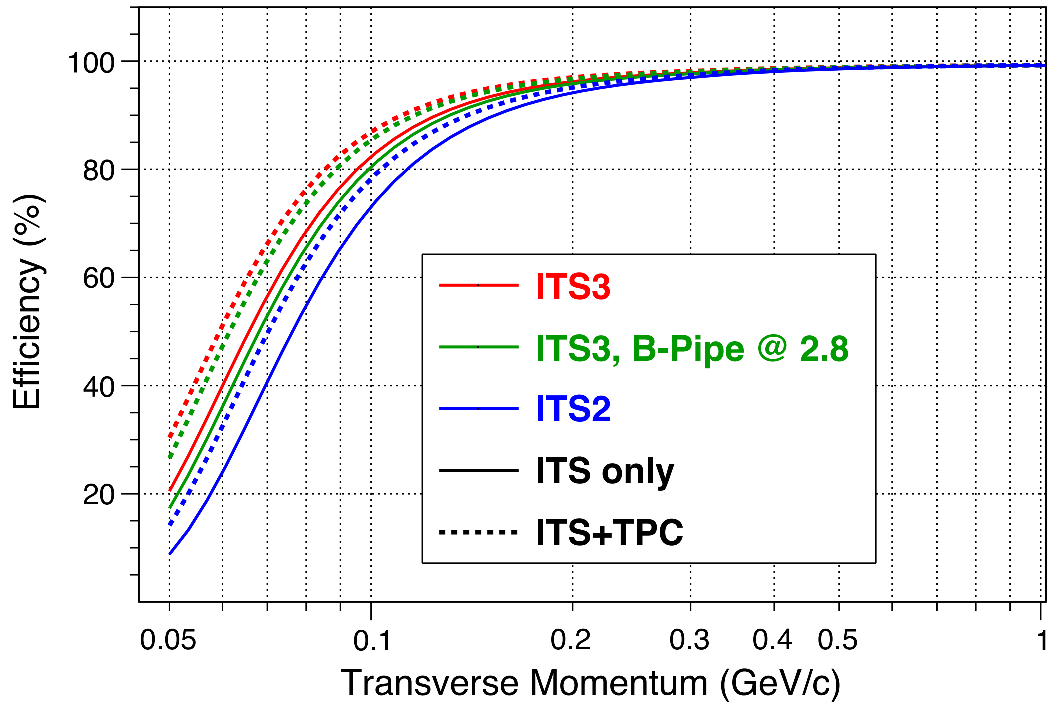
- L0 = 14 cm x 6.0 cm
- L1 = 14 cm x 7.5 cm
- L2 = 14 cm x 9.0 cm

Tracking Performance

Tracking efficiency and momentum resolution

Pb-Pb, B=0.2T

Tracking Efficiency



Momentum resolution