New Inner Tracking System (ITS) for open charm direct measurements by ALICE at the LHC: status and perspectives

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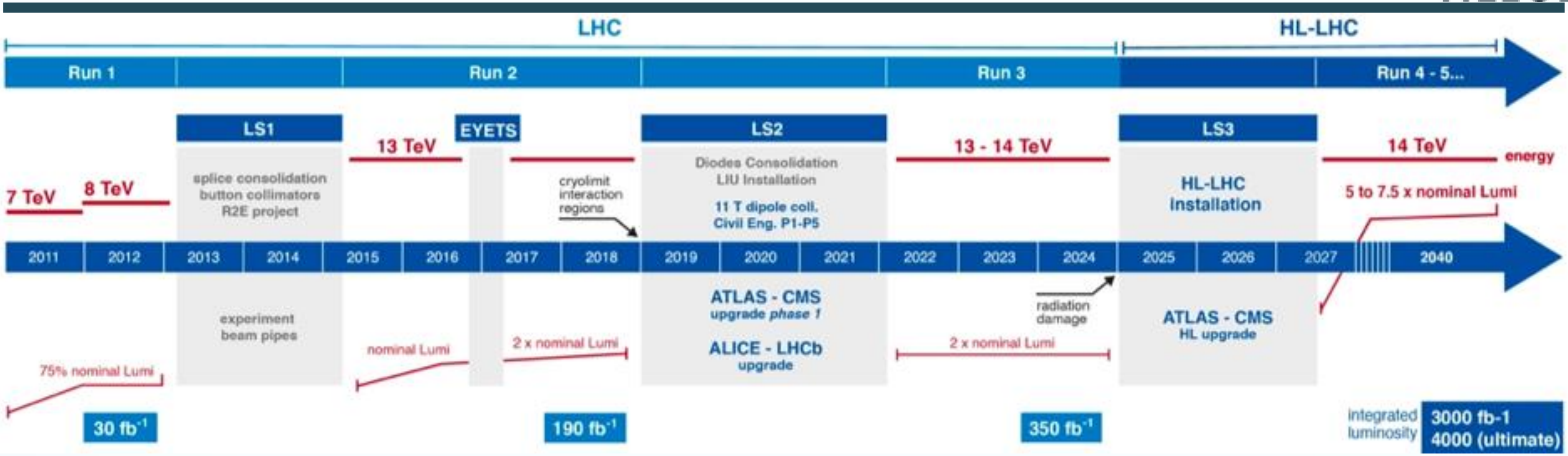
LXX International Conference NUCLEUS – 2020, October 11-17
https://events.spbu.ru/events/nucleus-2020?lang=Eng

Talk Layout

- LHC upgrade plans
- Open charm and beauty hadrons: why?
- Challenges for new Inner Tracking System for ALICE
- Design and status of the ITS-2
- Summary and Plans for the ITS-3

LHC upgrade plans
2018-2020 and 2024-2027



- 10 years of successful LHC operation 2008-2018, luminosity **in pp collisions** up to 1.2×10^{34} cm^{-2} s^{-1} has been routinely obtained in 2016.

- After the long shutdown 2 (LS2), **at the end of 2021,** the LHC is supposed to boost **the Pb--Pb collision rate in Run 3** from 10 kHz to **50 kHz**, corresponding to an instantaneous luminosity of 6×10^{27} cm^{-2} s^{-1}
  - **The upgrade of all detectors at the LHC is ongoing to meet the new HL-LHC high precision measurement era!**

[1] https://project-hl-lhc-industry.web.cern.ch/content/project-schedule

ALICE in Run 3 at the LHC

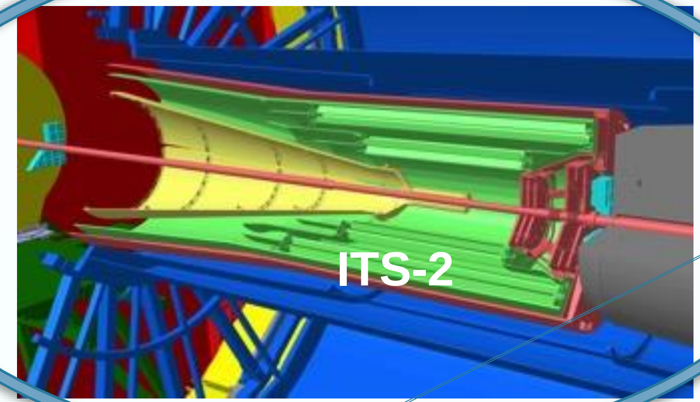
- Major upgrade of the ALICE detectors, data-taking and data-processing systems.
- **Collision rate of Pb-Pb collisions will be increased from 1 kHz to 50 kHz**
- **Data sample 100 times larger** than what has been obtained so far in Run 1+Run 2.

- **Precision measurements of strongly interacting matter**

ALICE upgrades

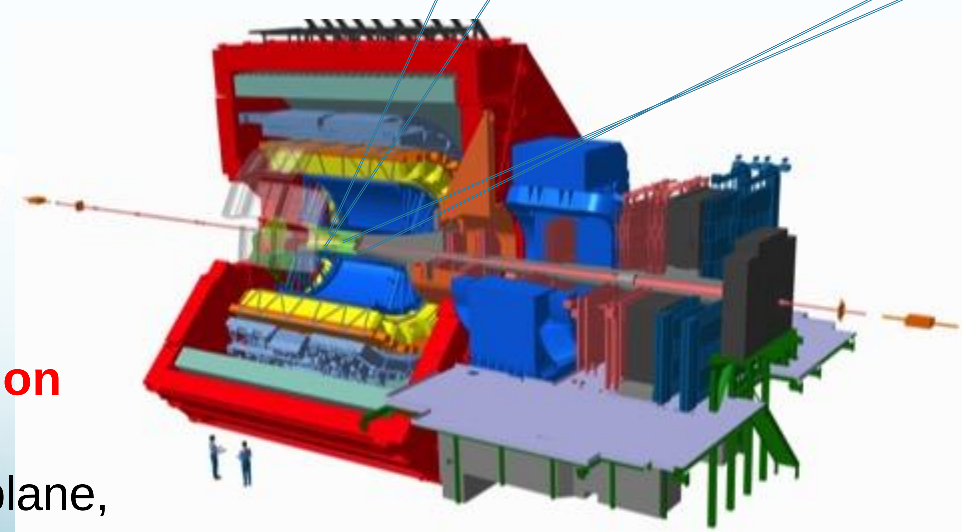
New Inner Tracking System (ITS-2)

- CMOS Active Pixel Sensors
- Improved resolution, less material, faster readout

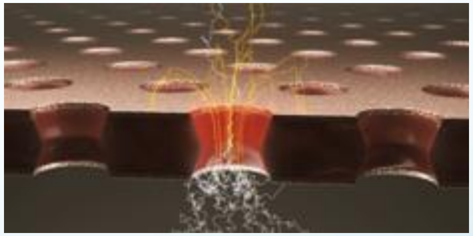


New Muon Forward Tracker (MFT)

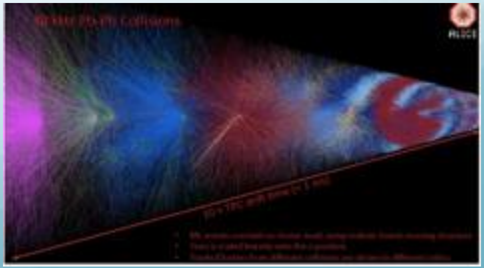
- CMOS Active Pixel Sensors
- Vertex tracker at forward rapidity



New TPC Readout Planes ---- 4 GEMs



Continuous readout



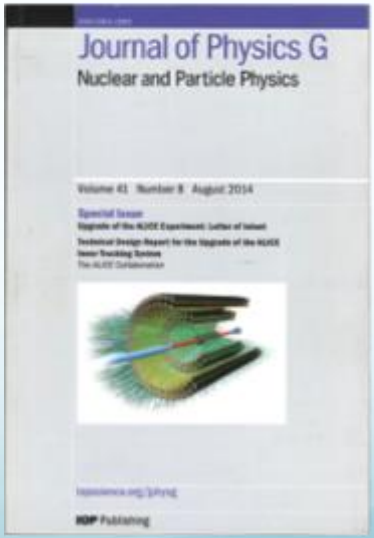
New Fast Interaction Trigger (FIT)

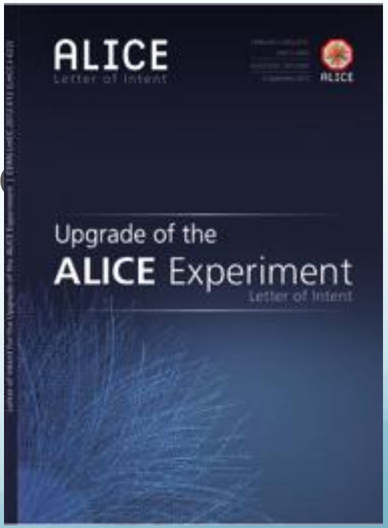
- Centrality, event plane, luminosity, diffractive processes

Focus on rare probes

Topics of interest:

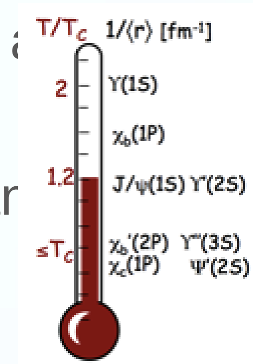
- **Heavy-flavour– heavy-quark interaction in QCD medium formed in AA collisions**
- **Quarkonium states, quarkonium melting and regeneration in QGP**
- Real and virtual photons, low-mass (thermal) dileptons – QGP radiation and chiral-symmetry restoration at $\mu_B = 0$
- Jet quenching – QGP tomography
- High-precision measurements and hyper-nuclei and states





Focus on rare probes

- Phase transition to deconfined QGP is expected a
  T_{crit}~150 MeV
- Ground state binding energies of charmonium ar
  bottomonium are ~ 500 – 1000 MeV
- Formation times are <~ 0.1 fm/c (depending on p_T)
- Masses are high
  (J/psi mass=3097 MeV/c^2, D0 mass =1864 MeV/c^2) and
  are well above the QGP temperatures reached in Pb—Pb
  collisions at the LHC
- **Therefore, thermal production of heavy quarkonia in QGP is strongly suppressed**
- **These rare probes are a nice tool to study the formation and evolution of the QGP!**

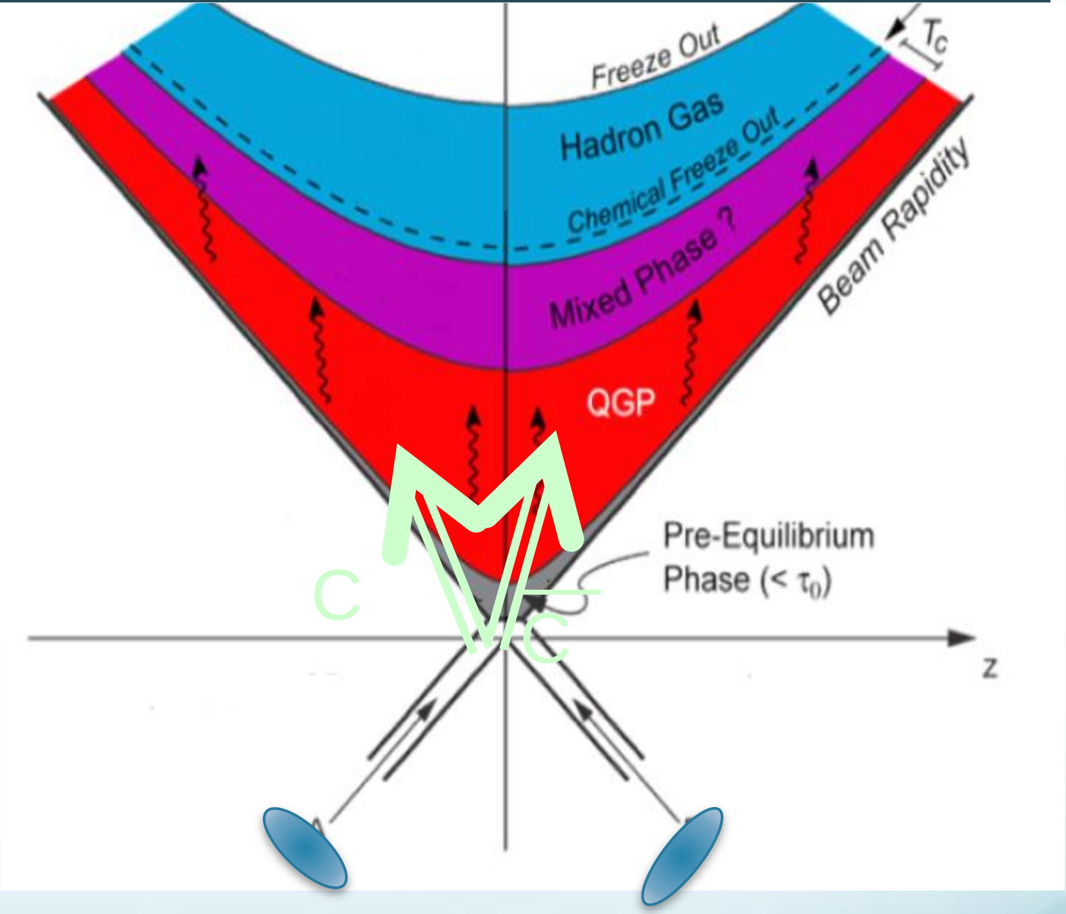


"Thermometer" for QGP [1]

[1] Ágnes Mócsy, 2009,Eur.Phys.J,.C61,705–710; arXiv:0811.0337

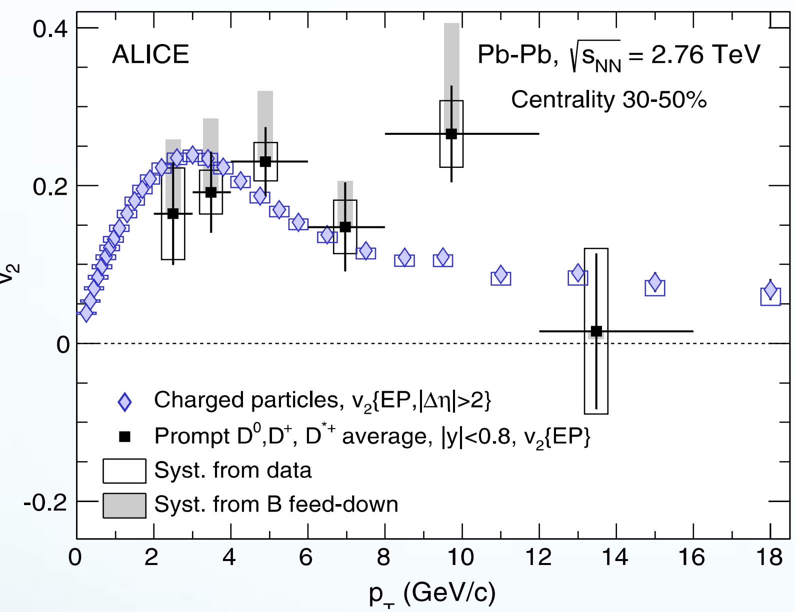
Why heavy-flavour particles in AA collisions?

- Study the early stages in heavy-ion collisions
- Understanding of charmonium production
- Probe to study thermalization of QGP:
  - measurements of flow of heavy quarks;
  - energy loss of charm quarks as an evidence of their thermalization, …etc.
- Microscopic insight into transport properties of the medium

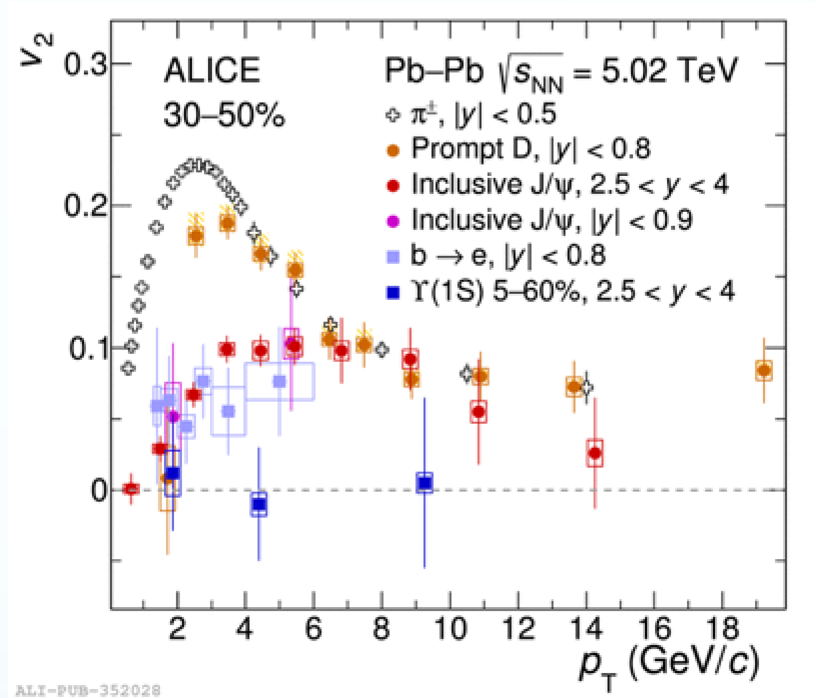


[1] T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.
[2] Helmut Satz, arXiv: 1303.3493
[3] Berndt Müller, arXiv:1309.7616

Some interesting results



PRL 111, 102301 (2013)



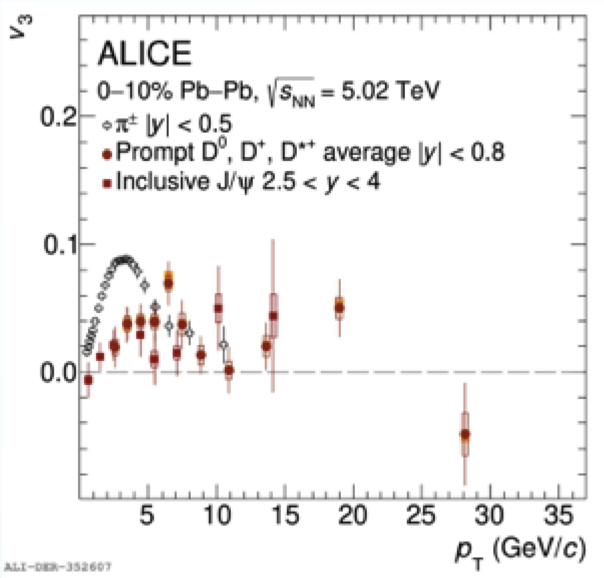
PRL 123, 192301 (2019)

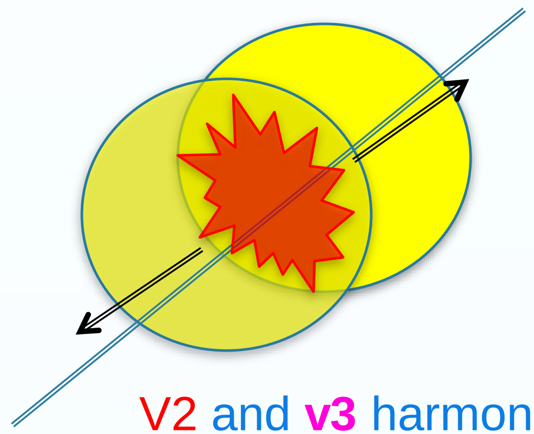
- ➢ *D* **mesons take part in the flow, i.e. participate in the collective motion?**

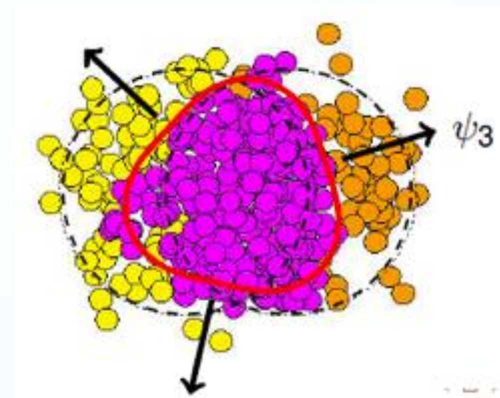
➢See also the report at this conference by Cristiane Jahnke: ”Measurements of heavy-flavour hadron production with ALICE at the LHC”

Some interesting results

D meson **triangular** flow similar to J/psi







V2 and **v3** harmonic anisotropic flows

JHEP 09 (2018) 006;
arXiv 2005.11131;
arXiv 2005.14518

- ***D* mesons take part in the flow, i.e. participate in the collective motion?**

- **See also the report at this conference by Cristiane Jahnke: "Measurements of heavy-flavour hadron production with ALICE at the LHC"**

Matter induced changes in the yield of quarkonia

1986: Charmonium suppression in AA collisions [1]

- **All charmonia are produced before QGP formation**
- **Suppression takes place in QGP**
- **Some charmonia may survive beyond T_c**

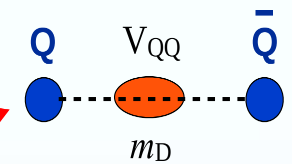
2013: Mechanisms contributing to matter induced changes in the yield of quarkonia [2]

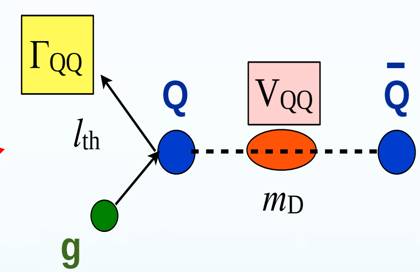
- Color screening
- Ionization by thermal gluons

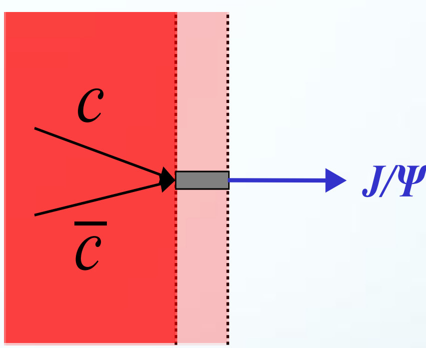
and

- **Recombination** (coalescense)

is a **competing mechanism** with screening







Challenges

[1] H.Satz and T.Matsui, Phys.Lett.B178(1986)416

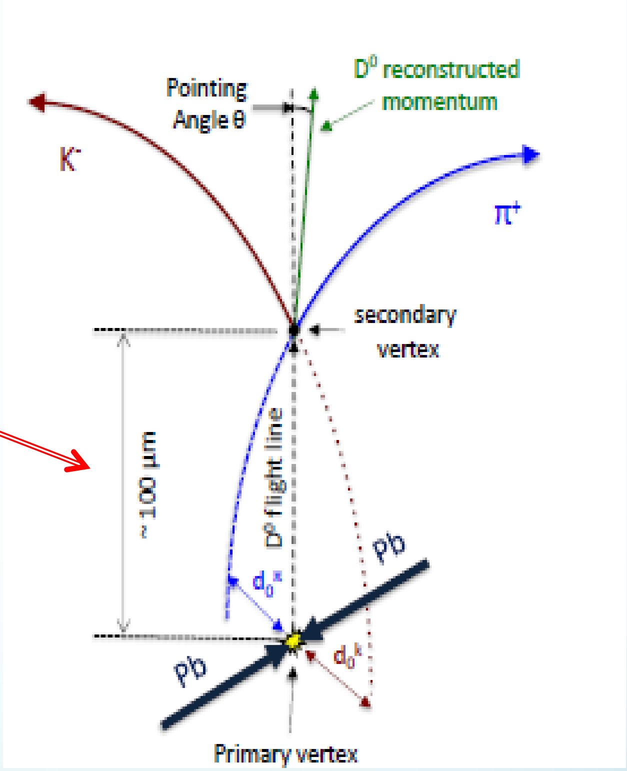
[2] Berndt Müller, arXiv:1309.7616

Challenges for open charm measurements

- **Challenge-1: Short life-time of D-mesons** ($< \tau > = 410.1 \pm 1.5) \times 10^{-15}$ s[1])

  Small mean decay length !

Reconstruction
from hadronic decay channels,
cτ ~100μm (!)



Meson	Decay Channel	Cτ	Branching Ratio
D^0	$D^0 \to K^- + \pi^+$	122.9μm	(3.91±0.05)%
D^0	$D^0 \to K^- + \pi^+ + \pi^+ + \pi^-$	122.9μm	(8.14±0.20)%
D^+	$D^+ \to K^- + \pi^+ + \pi^+$	311.8μm	(9.2±0.25)%
D^+_s	$D^+_s \to K^+ + K^- \pi^+$	149.9μm	(5.50±0.28)%
D^{*+}	$D^{*+} \to D^0 + \pi^+$	----------	(61.9±2.9)%

Vito Manzari,
LXV Conf.Nucl.Phys.,
29.06-03.07.2015, SPb

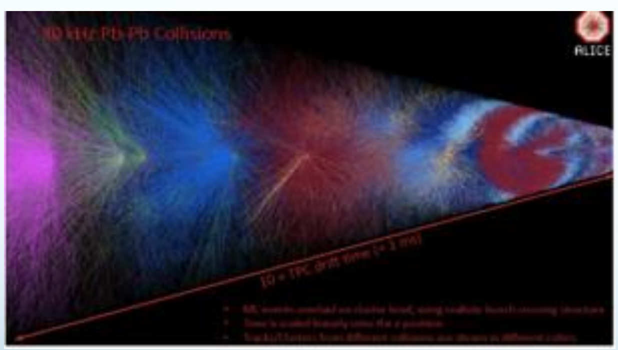
[1]PDG, PL B667, 1 (2008)

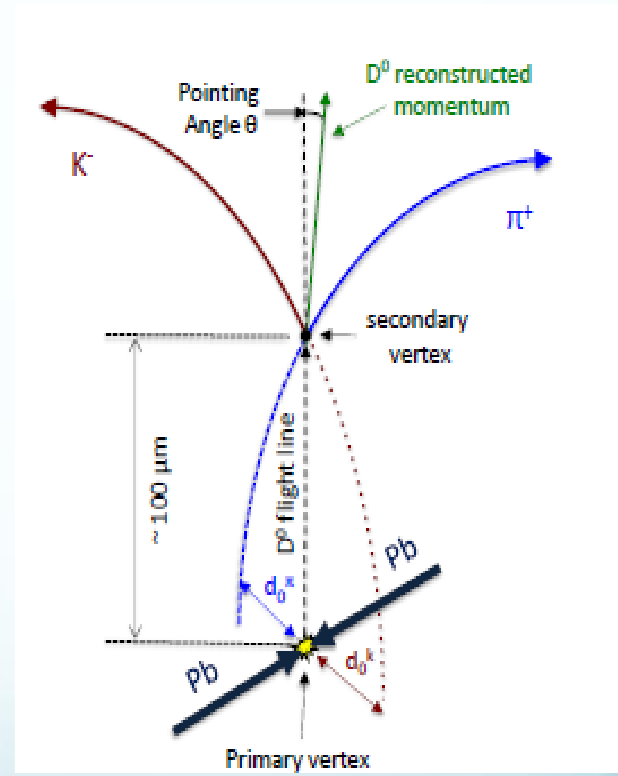
Challenges for open charm measurements

- **Challenge-2: high efficiency is needed for rare-probe registration**

- Coverage in transverse momentum to be as complete as possible, in particular down to very low momenta.

- **Challenge-2:** Fast detectors and continuous readout[1] to ensure statistics

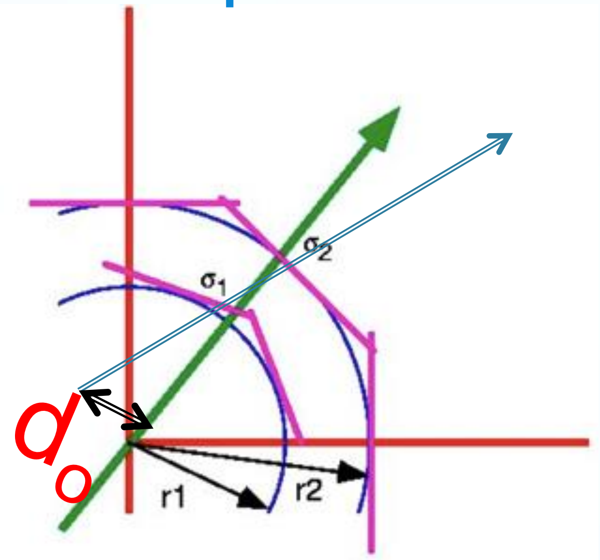




[1] David Rohr et al., arXiv:1811.11481

Impact parameter (d_0) resolution in particle tracking

- Example with two-layer setup:



$$\sigma_{d_0}^2 = \sigma_{MS}^2 + \sigma_{geom}^2$$

with

$$\sigma_{geom}^2 = \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2 \quad \text{and} \quad \sigma_{MS}^2 = \sum_{j=1}^{n_{scatt}} (R_j \Delta\Theta_j)^2$$

- Strong effect of Multiple Scattering (MS):

$$\sigma_{d_0} = \frac{r}{p} 13.6\text{MeV} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right]$$

REQUIREMENTS are very contradictory (!):

- Sensors with high coordinate resolution -- minimize σ_1 and σ_2 **(!)**
- The first layer close to interaction point (IP) --decrease r_1 **(!)**
- **The multiple scattering** should be minimized – apply low-mass, low-Z materials to provide **the minimal possible X/X_0 (!)**
- **Ensure high thermo- and mechanical stability ~10µm (!)**

Tracking of charged particles

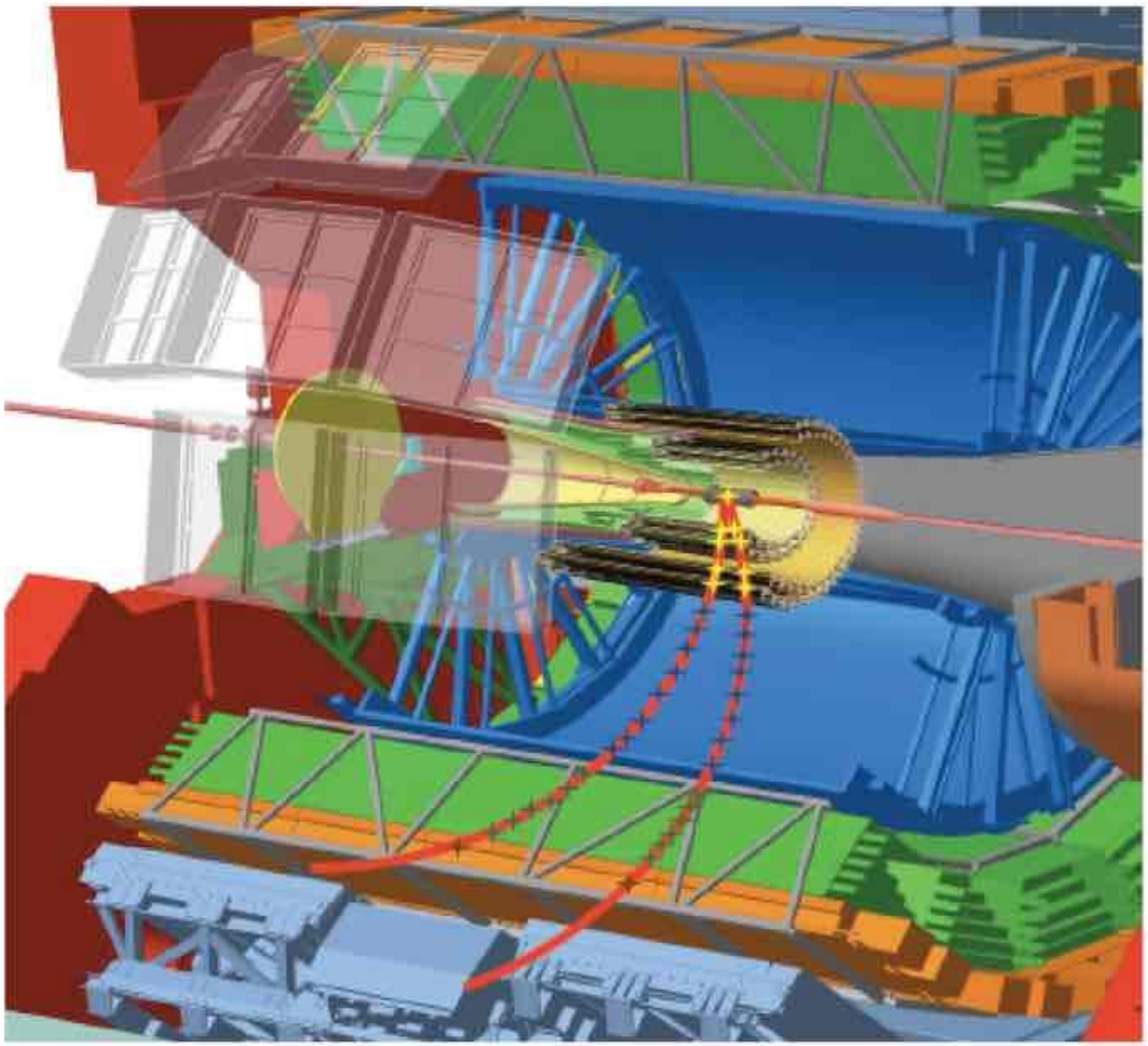


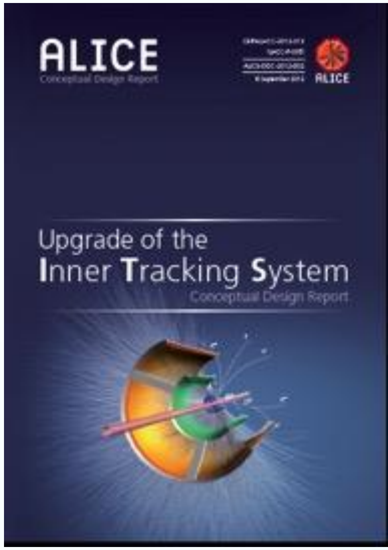
Illustration of ALICE detectors used in track reconstruction and particle identification[1]

- ITS
- TPC (blue)
- TRD (green)
- TOF(orange)

[1] "Track Reconstruction in the ALICE TPC using GPUs for LHC Run 3" , David Rohr et al., arXiv:1811.11481

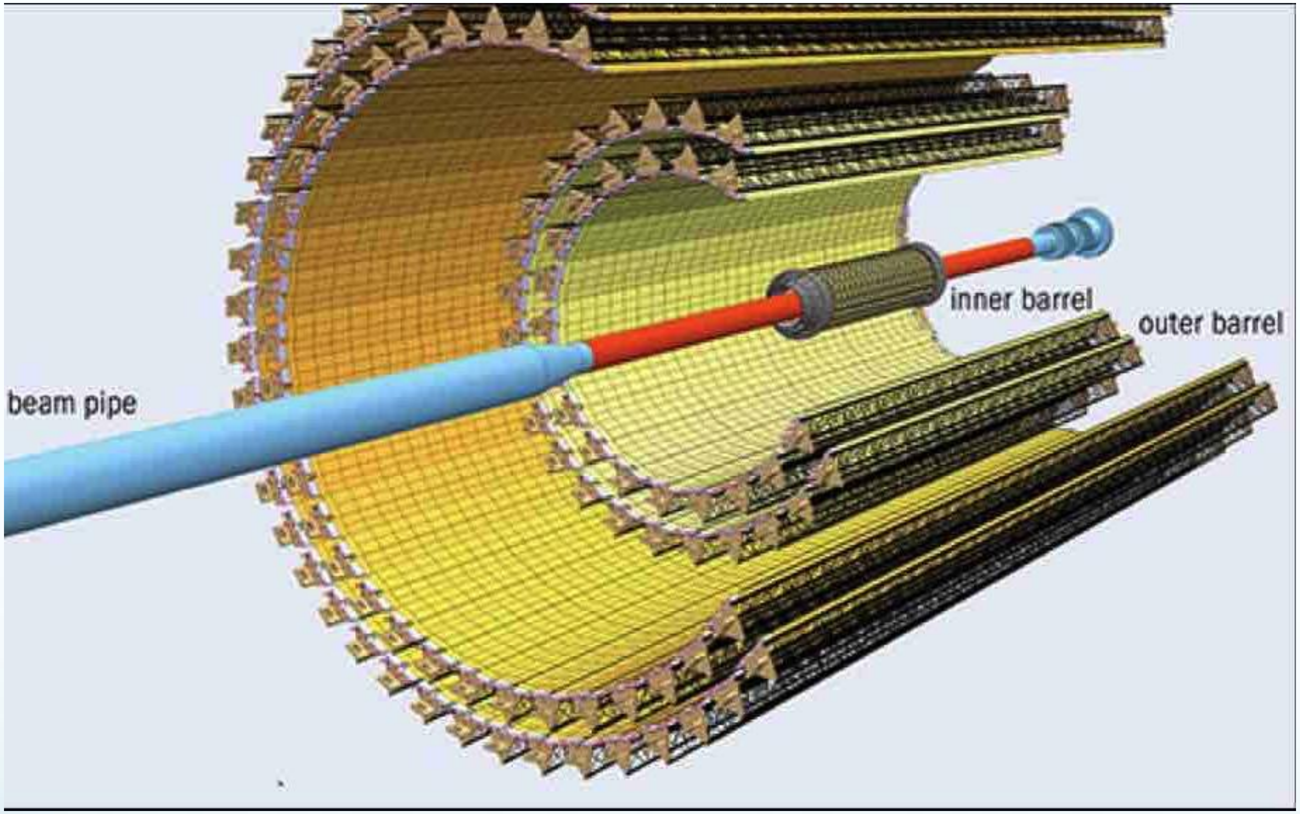
Summary of challenges and requirements:

- Improve impact parameter resolution factor of ~**3** in r-φ (z) at 500 MeV/c)
- First layer closer to interaction point: r0 = **39 mm → 22 mm**
- Smaller beam pipe radius: **29 mm → 18.2 mm**
- Smaller pixel size: **50μm x 425μm → 28μm x 28μm**
- Improve tracking efficiency and p_T resolution at low p_T: Increase the number of layers **6 →7**
- Easier maintenance – all services only from on one side!
- Fast readout : 1 kHz → 50 kHz in Pb-Pb, 200 kHz in pp
- Low-material budget (< 0.35% X_0 for 3 inner layers)
- **ITS-2 : New, high-resolution, low-material, Inner Tracker based on CMOS sensors!**



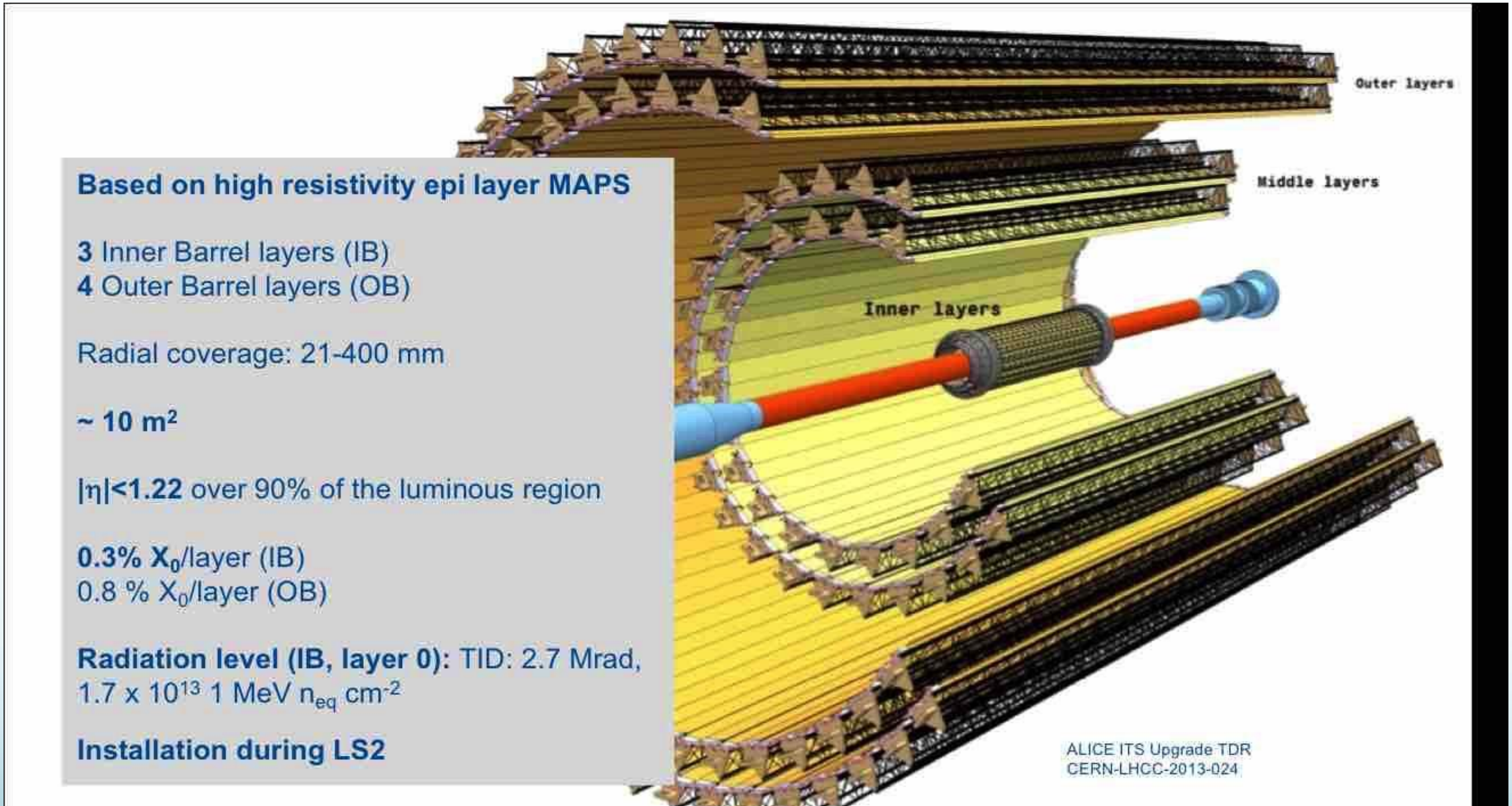
- **CDR: Endorsed by LHCC in Sept 2012**
- **ITS Upgrade TDR: in March 2014**

ITS-2 concept



- A schematic of the upgraded inner tracking system (ITS) showing 7 layers of the MAPS layers, carbon-fibre supports (black) and the beampipe in the central region (orange).

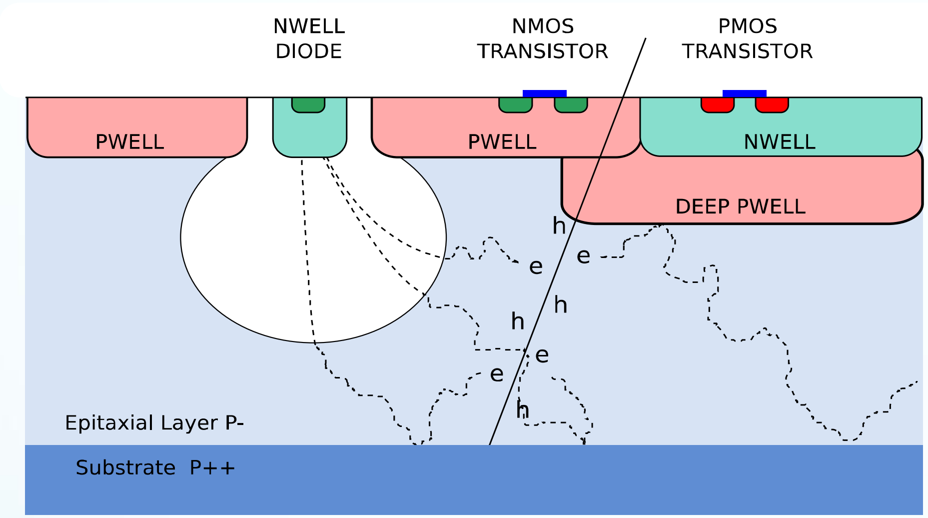
Upgraded ALICE ITS design



- **Based on Monolithic Active Pixel Sensors (MAPS)**

CMOS Pixel Sensor [1]

TowerJazz 0.18 µm CMOS Imaging Process

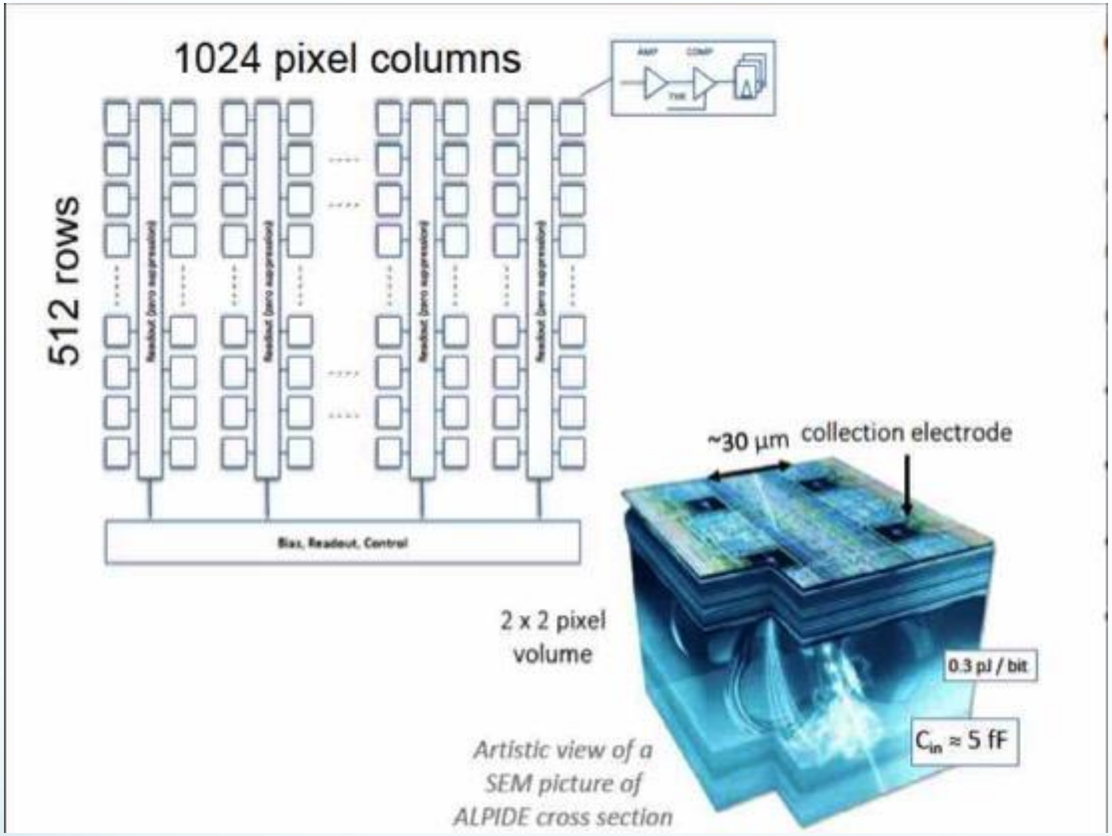


Schematic of MAPS pixel

- Pixel pitch ~ 30 µm
- High-resistivity (> 1 kΩ cm) p-type epitaxial layer (25 µm) on p-type substrate
- Small n-well diode (2 µm diameter),
  => low capacitance
- Reverse bias voltage to substrate (contact from the top) can be used to increase depletion zone around NWELL collection diode
- Deep p-well shields n-well L of PMOS Transistors
- Very low power dissipation (<300 nW/pixel)

[1] J. Phys. G: Nucl. Part. Phys. **41** (2014) 087002

ALPIDE chip

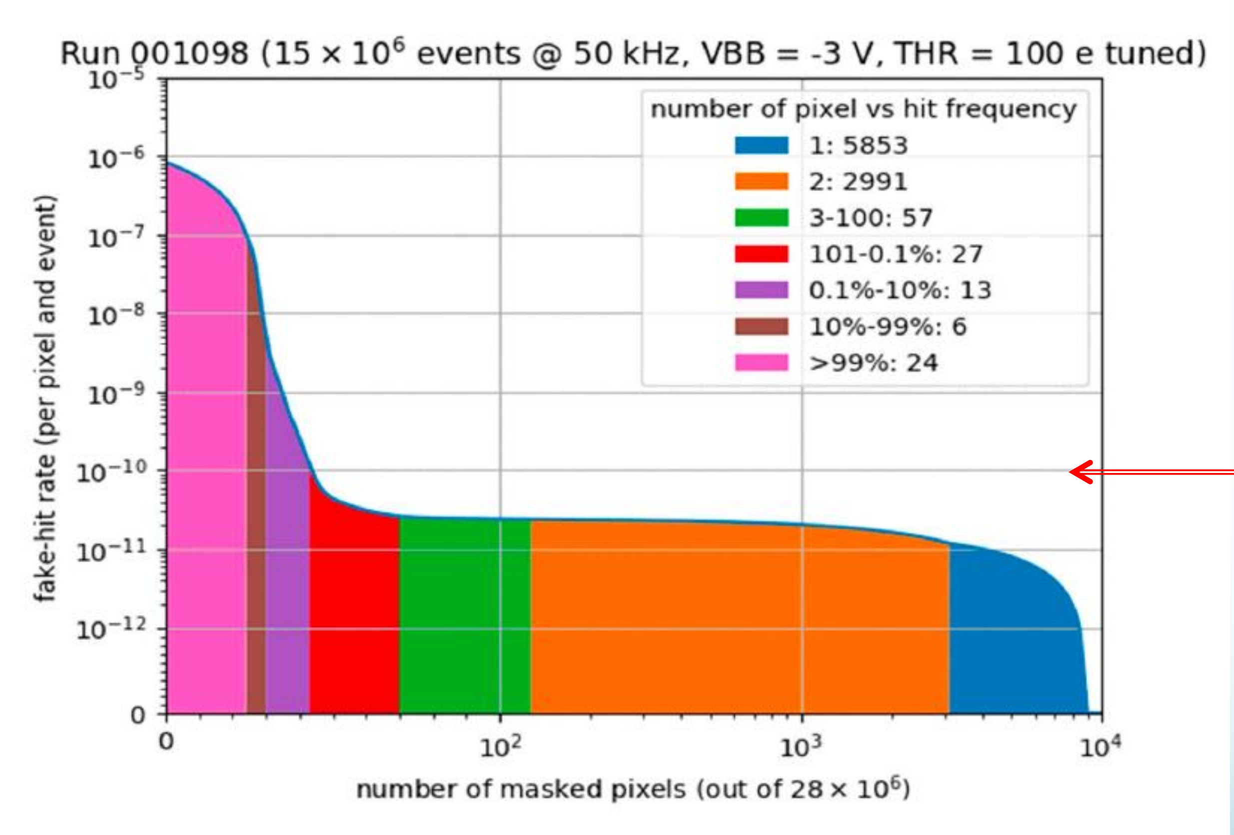


Each pixel:

- Amplification (always active)
- Discrimination
- Multiple hit buffer
- Data compression
- Common biasing settings
- Only digital outputs
- Triggering:
- Global shutter
- Continuous
  or triggered mode

- Characterization: Electrical tests (digital and analogue), noise, thresholds, fake hit rates vs. temperature, supply voltage, radiation, tests with γ- and β- sources, etc.

Noise performance of Inner Barrel Half-Layer 0 ALPIDE chips



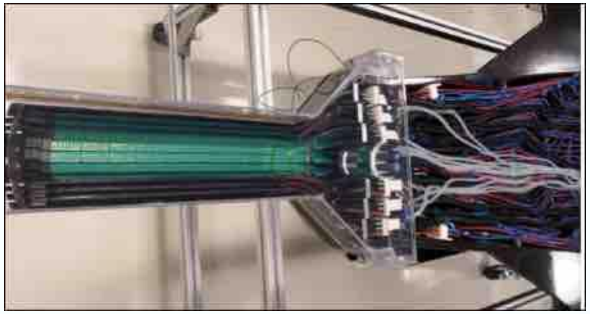


Photo of the Inner Barrel Bottom Assembly

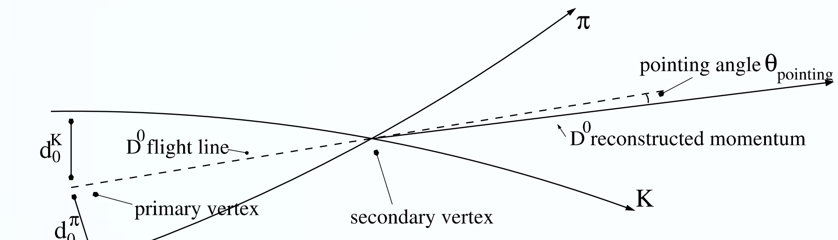
Noise level of 10^{-10} hits/pixel-event

- Performance is well exceeding the targeted ($\sim 10^{-5}$) value of the TDR[1]

[1] ALICE-TDR-017, CERN-LHCC-2013-024 02

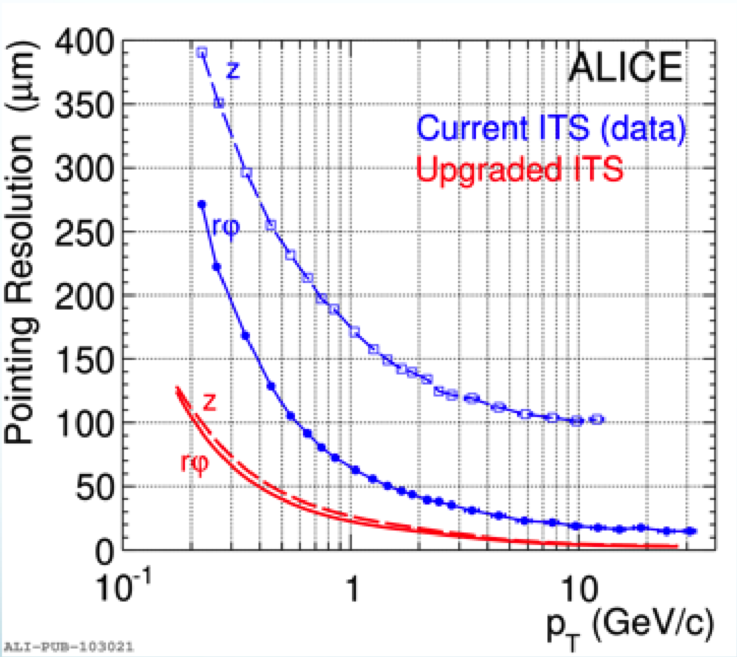
Identification of secondary vertices

CERN-PH-EP-2012-XXX March 6, 2012

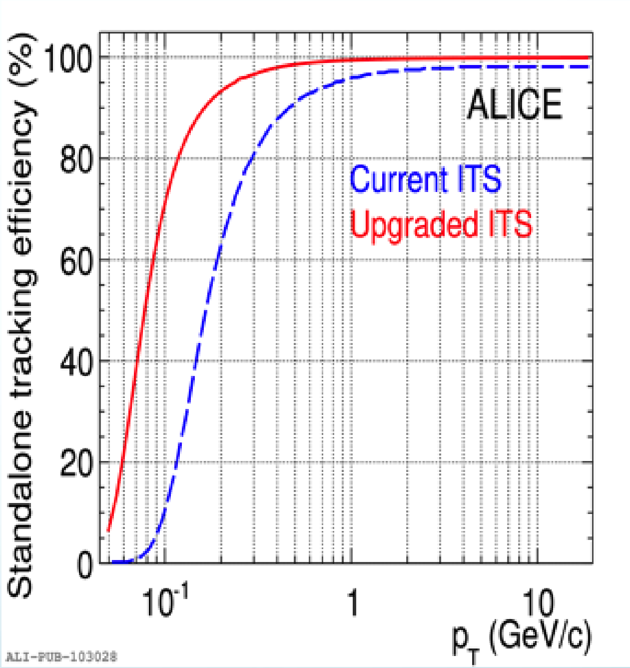


Schematic view of the D0 decay in the **D0 → K−π+** channel.

Impact parameter ~100 µm

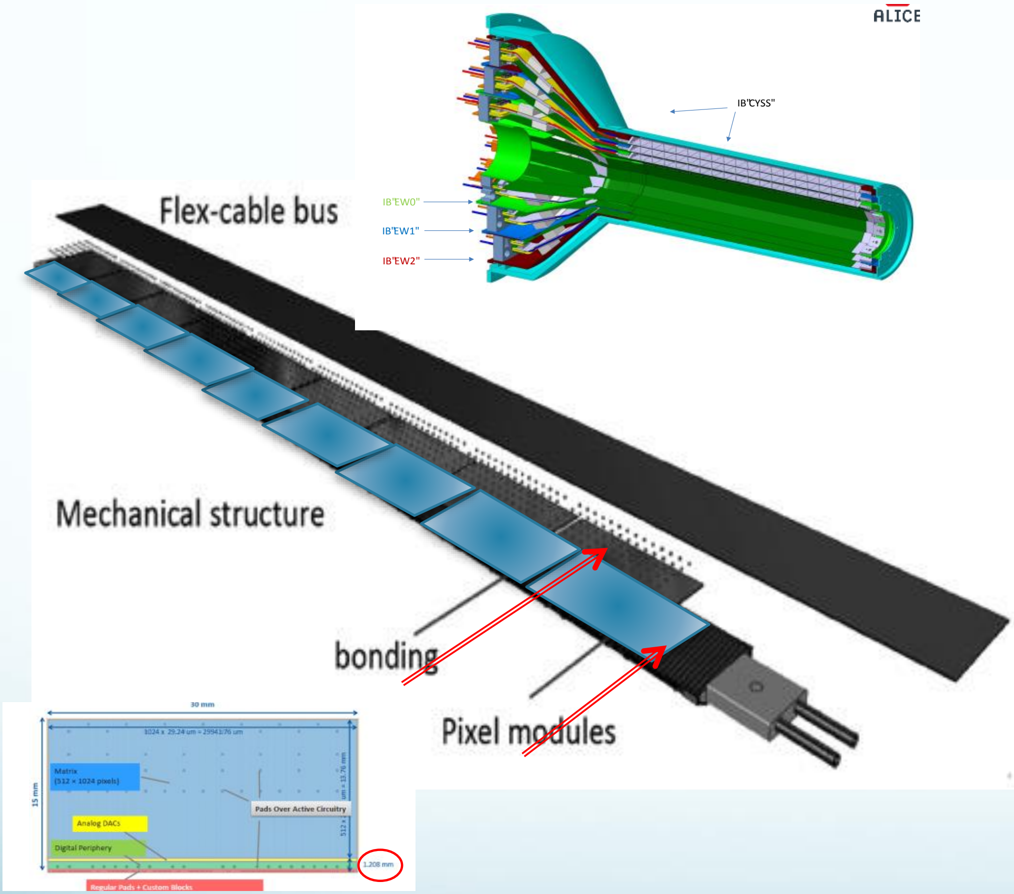


Impact parameter resolutions for ITS1 and ITS2



Stand-alone tracking efficiency

ALICE technology for Inner Barrel staves



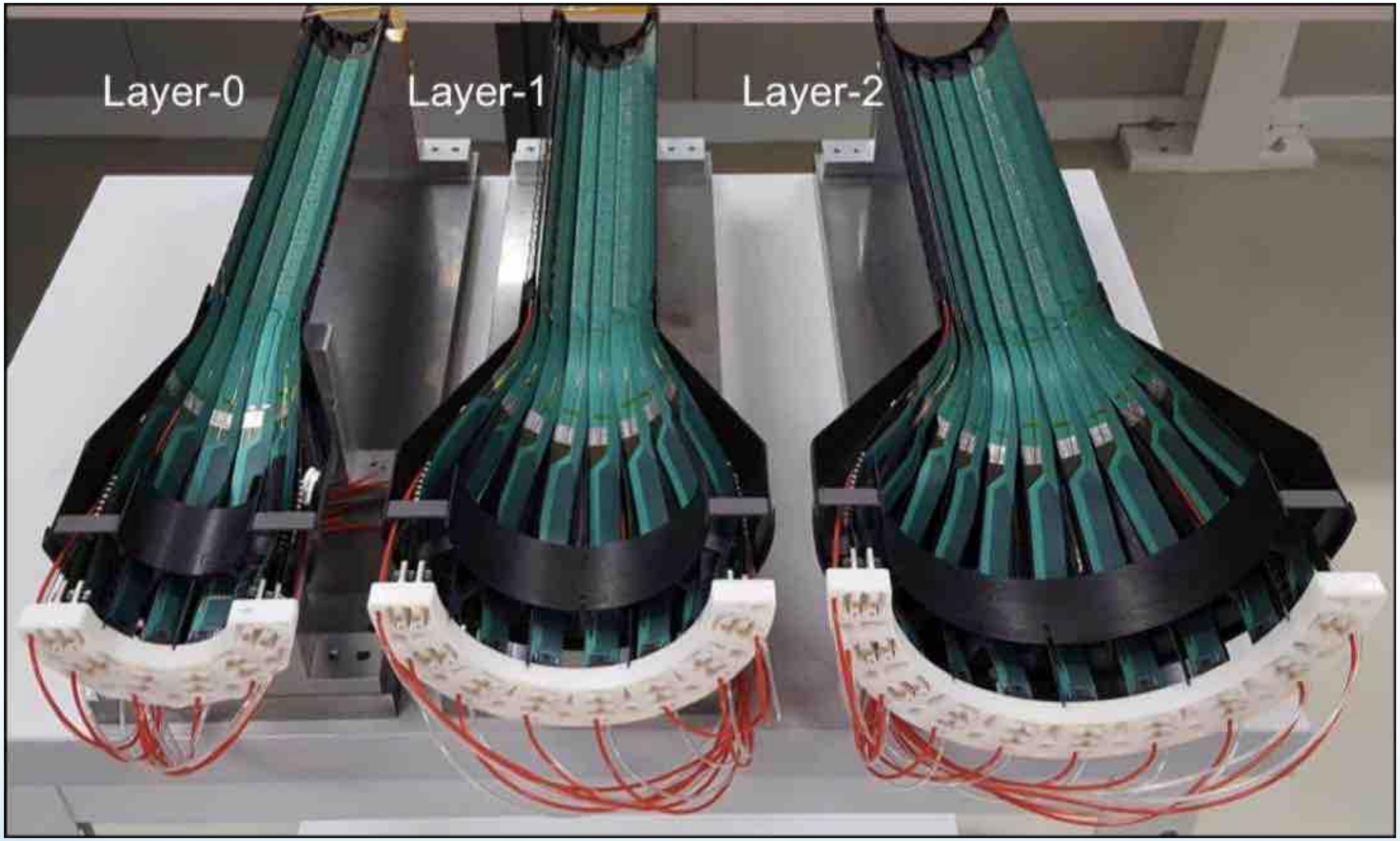
Thickness of detector components in terms of fraction of radiation length X/X_0 -

Material	Thickness (µm)	X_0 (cm)	X/X_0 (%)
Polyimide cooling pipe wall	25 µm	28.41	0.003
Carbon fleece	40 µm	106.8	0.004
Water	1mm	35.76	0.032
Carbon fiber plate K13D2U	70 µm	26.08	0.027
Graphite foil	30µm	26.56	0.011
Thermal greese (glue)	100µm	44.37	0.023
Si-sensor	50µm	9.36	0.064
Total (without FPC)			**0.164**
Total			**~0.3**

- **Record level of radiation transparency < 0.35% X_0 [1].**

[1] arXiv:1706.02110v2

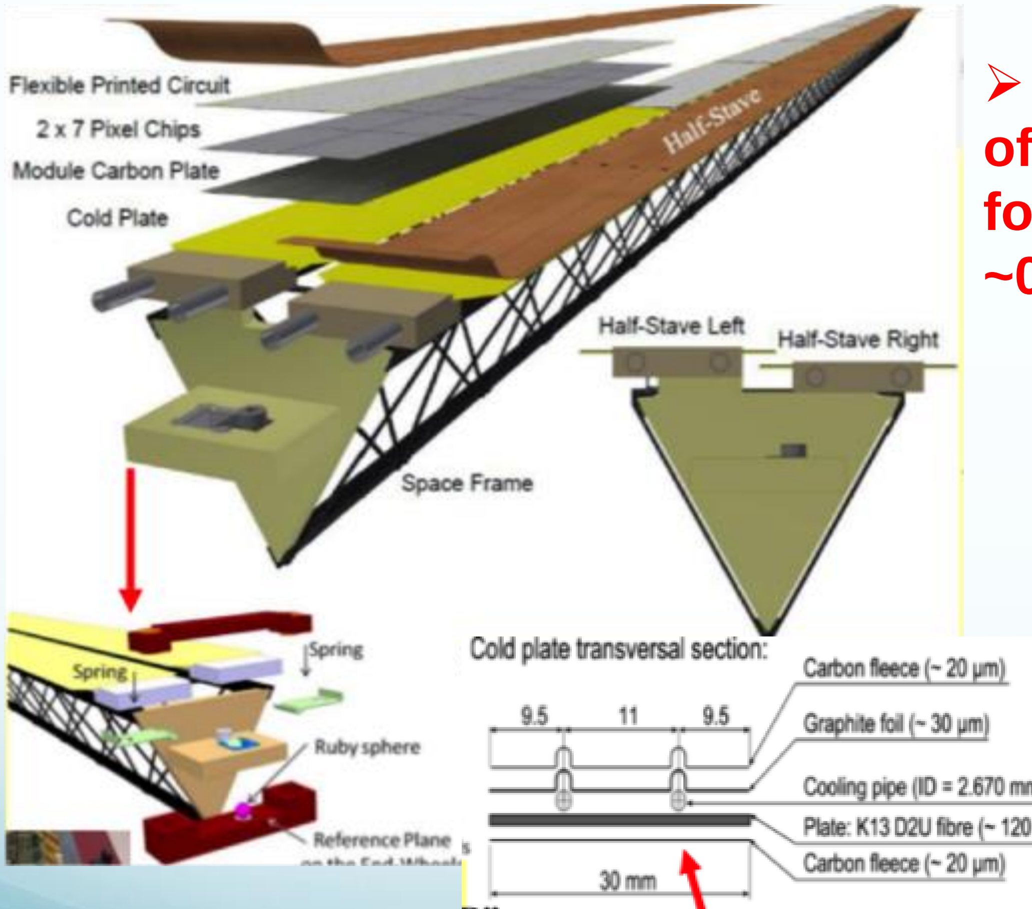
ITS-2 Inner Barrel



IB half-layers (Layer-0, Layer-1 and Layer-2).

[1] ALICE-PUBLIC-2018-013, CERN-LHCC-2019-018/LHCC-I-034, 01/12/2019

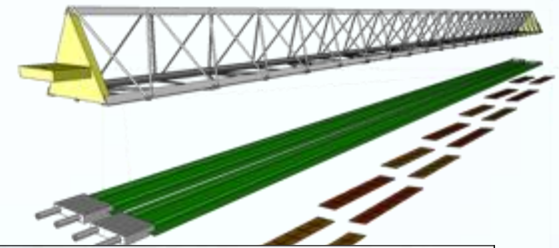
ALICE technology for ITS-2 0uter Barrel 1.5 m staves

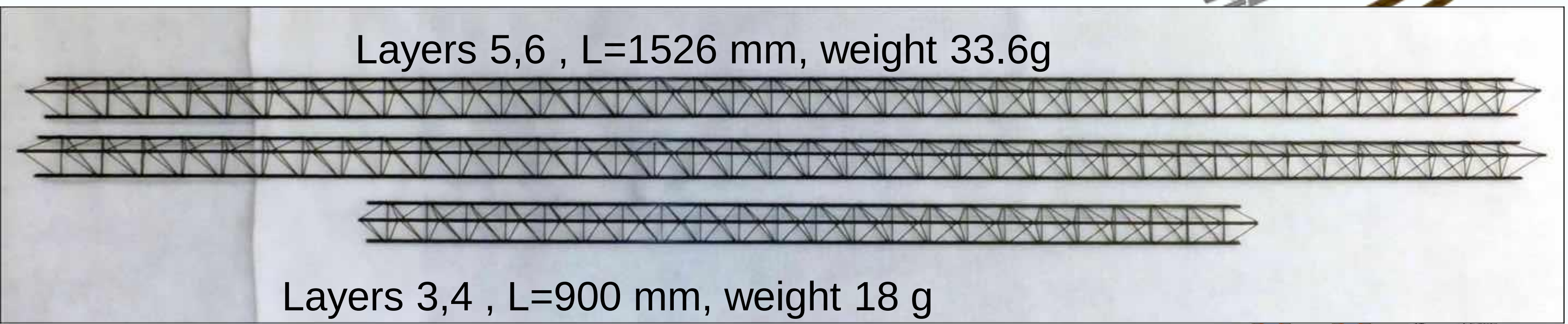


Cold plate

- **Record level of radiation transparency for 1.5 m length detector: ~0.8% X_0**

Carbon Fiber support and cooling extra-lightweight structures





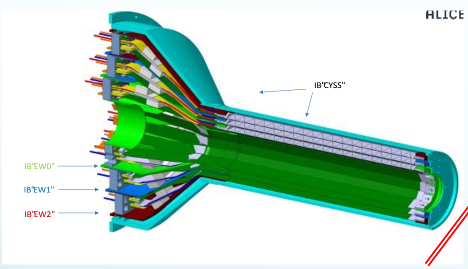
COLD PLATEs

End- PLATE fixators

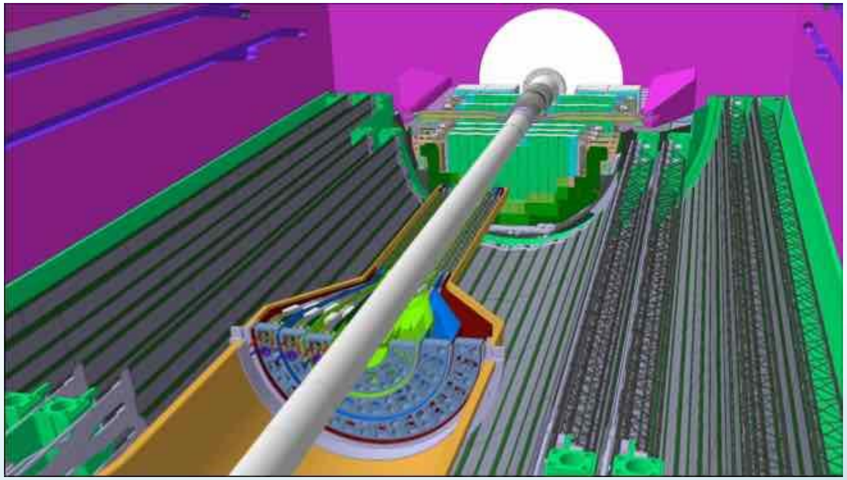
Ensures Material Thickness per detector layer for the Outer Barrel: ~ 0.8% X_0 (!)

Comparison with ATLAS and CMS upgrade

	current ALICE	ALICE upgrade	ATLAS upgrade	CMS upgrade
innermost point (mm)	39.0	22.0	25.7	30.0
x/X_0 (innermost layer)	1.14%	0,35%	1.54%	1.25%
d_0 res. $r\varphi$ (μm) at 1 GeV/c	60	20	65	60
hadron ID p range (GeV/c)	0.1–3	0.1–3	–	–



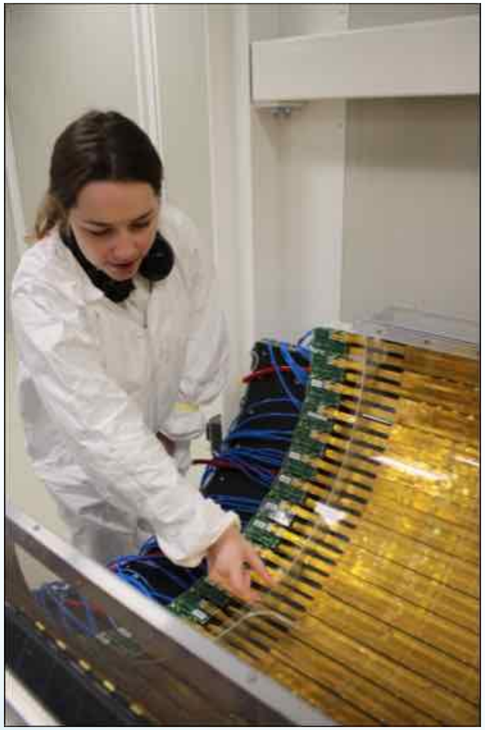
ALICE Inner Barrel

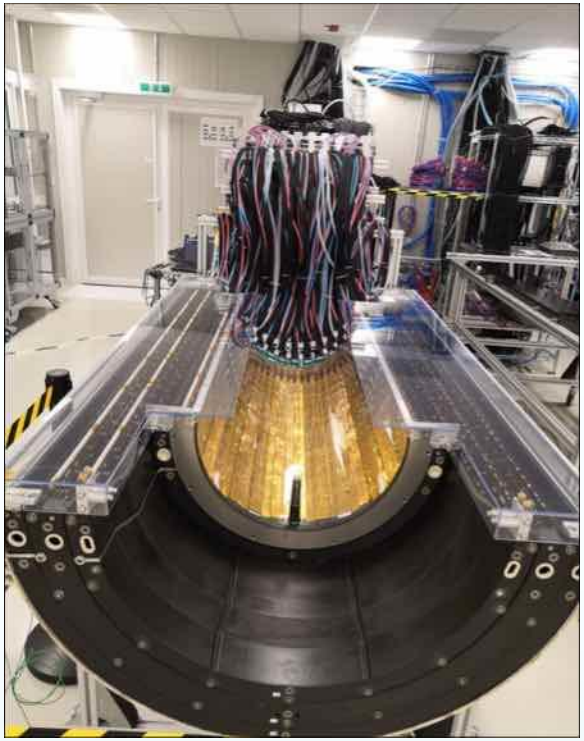


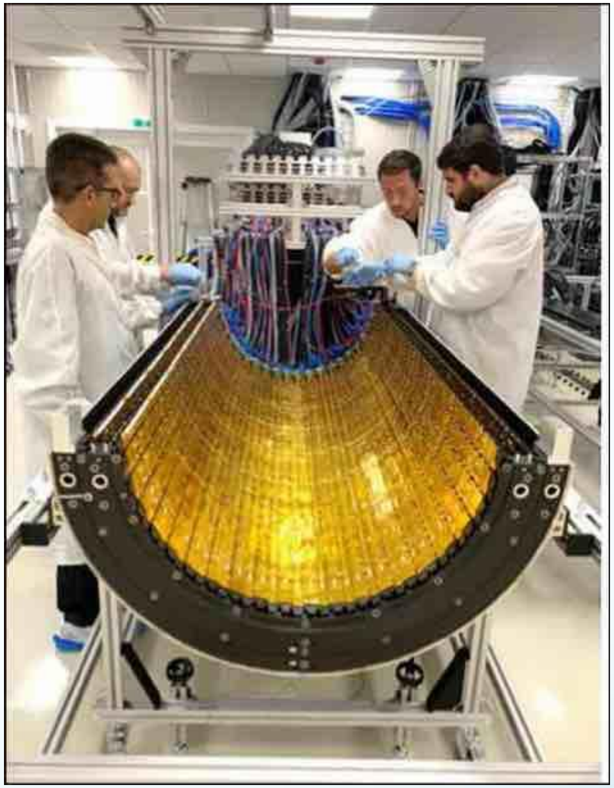
ALICE ITS-2 general design

CERN-LHCC-2012-013 (LHCC-P-005)

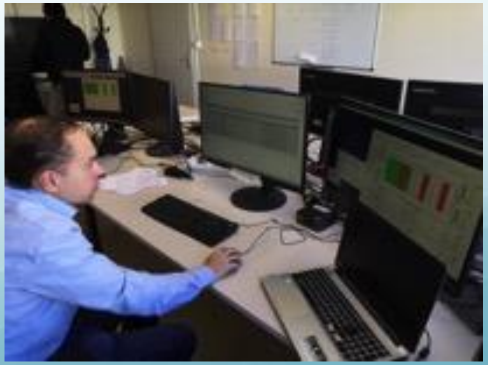
Commissioning of the ITS-2 at CERN







➢ Regular ITS-2 Commissioning Shifts at CERN in the period January 2019-March 2020. Shifts resumed in August and will be continued till the end of 2020



Construction steps

Construction Installation and Commissioning Timeline

May '19
Jun '19
Aug '19
Sep '19
Oct '19

Detector Construction and Assembly

- HIC production: completed!
- Stave production: 90% done
  continues until September 19
- Electronics production and testing:
  done!

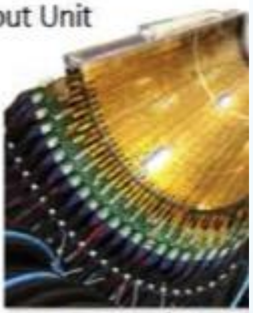
Commissioning on ground with final services ongoing (operation 24/7)

OB Layer Assembly: >50% done

Stave

Readout Unit

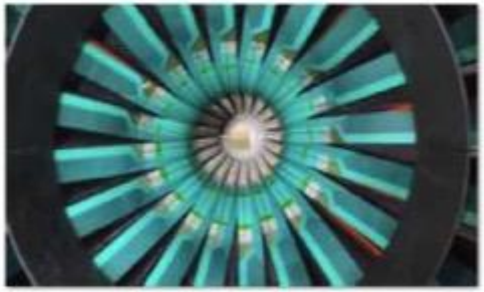
Inner Barrel Assembly

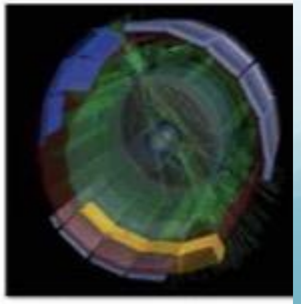


Outer Barrel Assen

Jan '20 – 100% assembly done
--Cosmic -ray registration,
--On-surface commissioning is ongoing

Jan '21 – start of moving to P2, assembly and commissioning





New technologies [1]

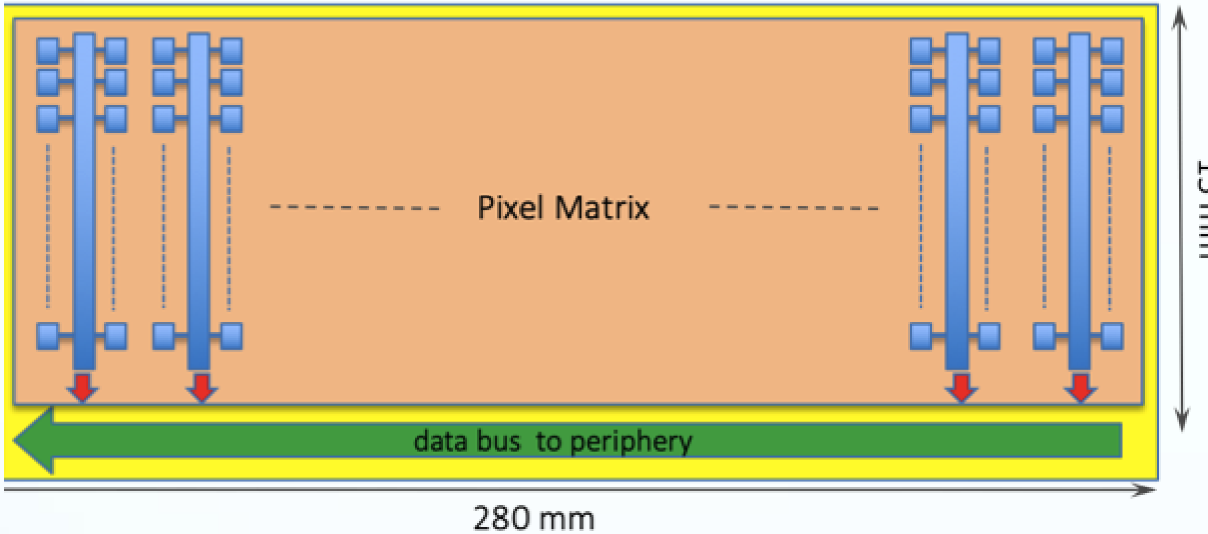


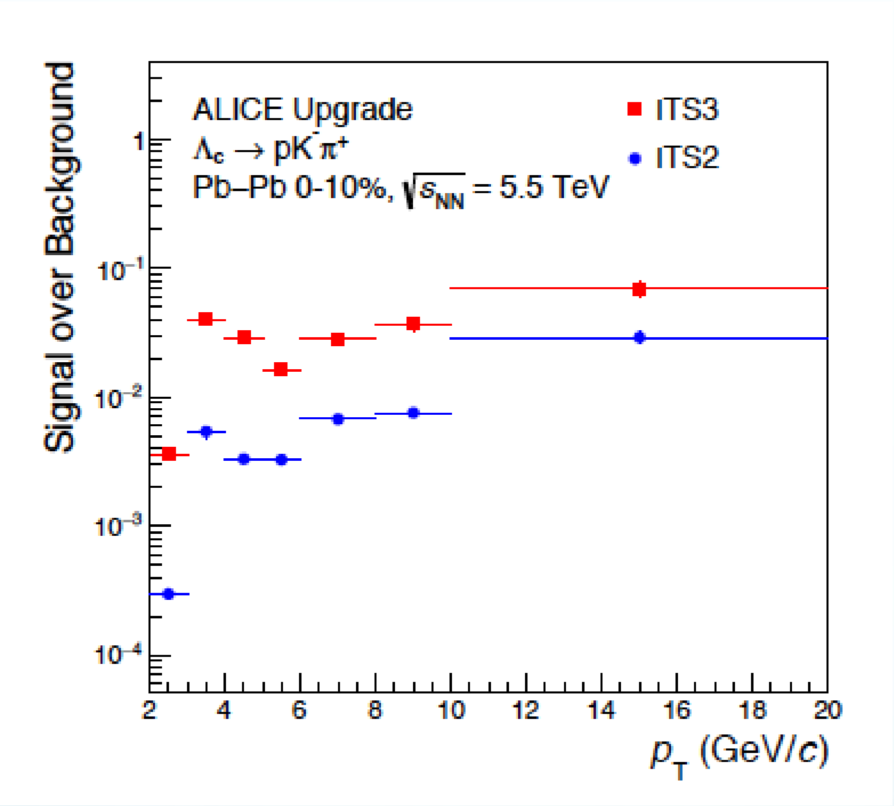
Diagram of sensor **15x280 mm^2** stitched in one direction (dimensions are not to scale).

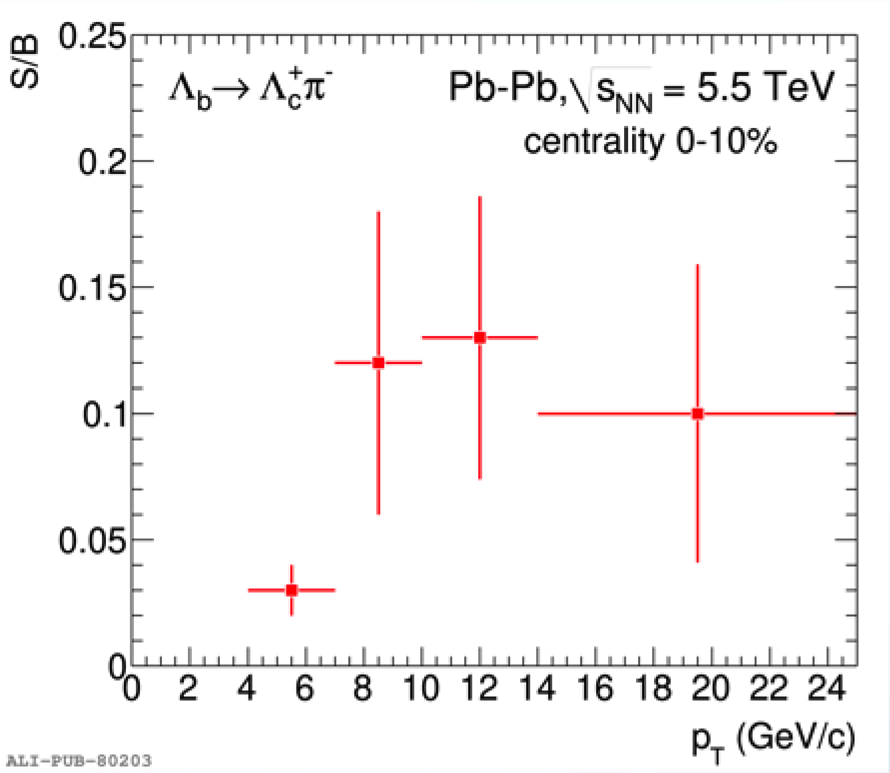
Ultra-thin wafers

- **Technology of stitching**
- **Thinning to 20** μm **– allows bending to cylindrical shape**
- **MAPS sensors could be curved to radius 10-20 mm**
- **Power ~20 mW/cm^2 – it is possible to use gas-flow cooling**
- **Eliminate electrical substrate**
- **~ 0.05% X/X_0 per layer (!!!)**

[1] ALICE-PUBLIC-2018-013

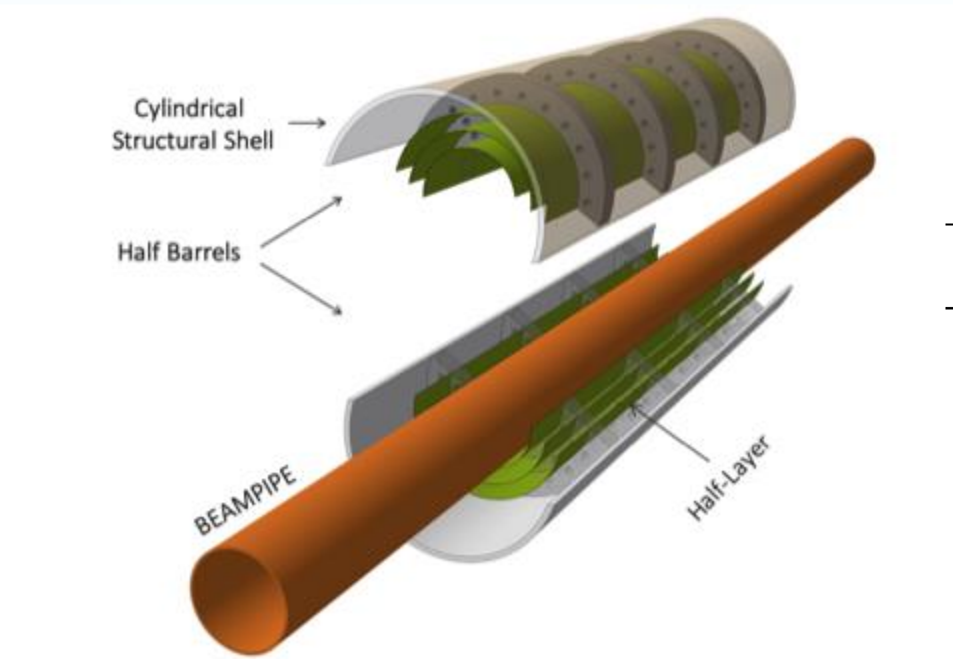
ITS-3: improved performance for Λ_c and Λ_b measurements

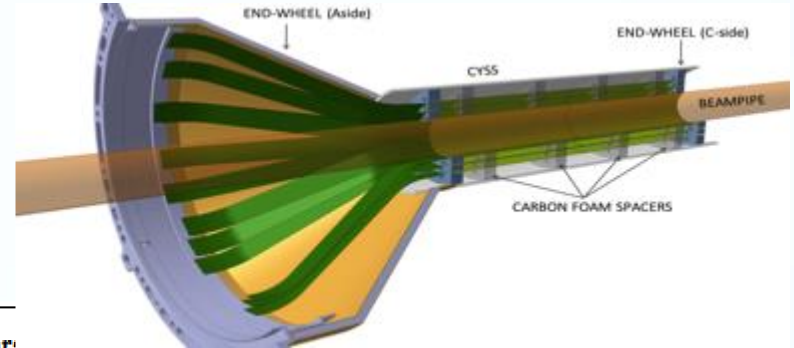




ALICE-PUBLIC-2018-013

Concept of ultra-light ITS-3[1]





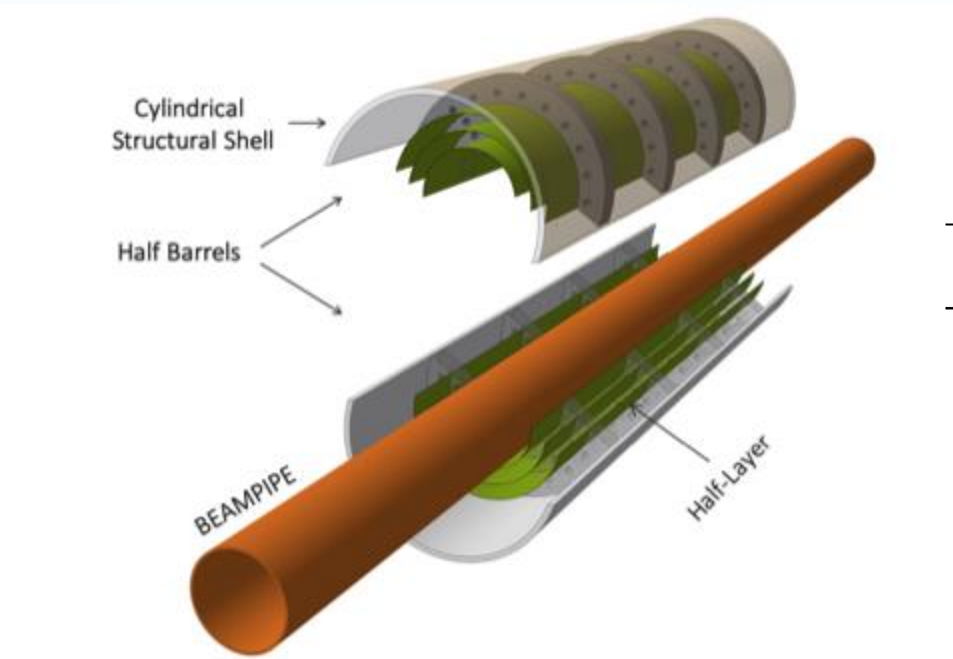
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	18.0	24.0	30.0
Length (sensitive area) (mm)	270	270	270
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	408	508
Pixel sensors dimensions (mm^2)	280×56.5	280×75.5	280×94
Number of pixel sensors / layer		2	
Pixel size (μm^2)		$O(15 \times 15)$[b]	

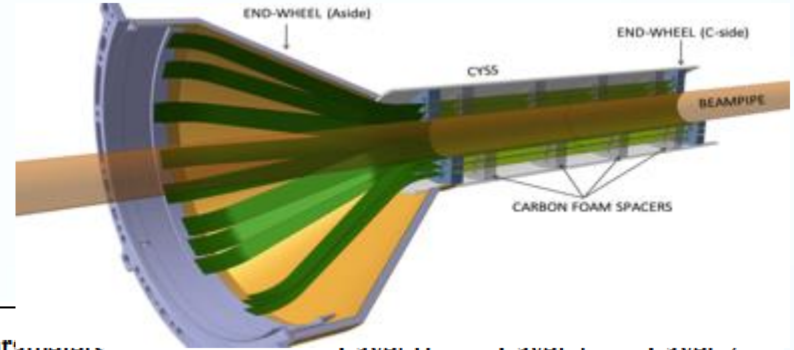
[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).

[b] For the fallback solution the pixel size is about a factor two larger ($O(30 \times 30)$ μm^2).

[1] ALICE-PUBLIC-2018-013

Concept of ultra-light ITS-3[1]





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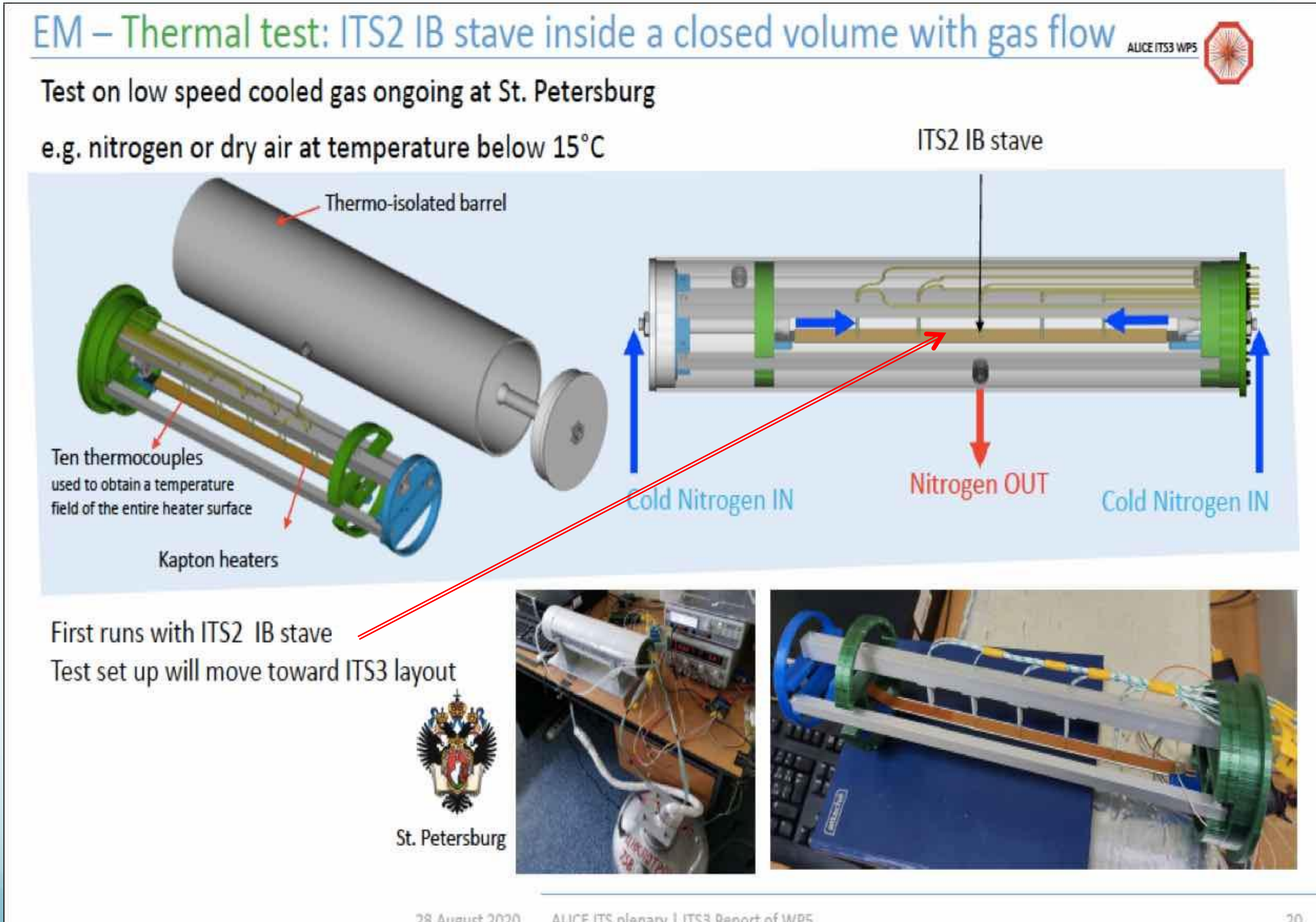
[b] For the fallback solution the pixel size is about a factor two larger ($O(30 \times 30)$ μm^2).

- ➢ Gaseous cooling and vibrations of 20 micron thick large area sensors?

[1] ALICE-PUBLIC-2018-013

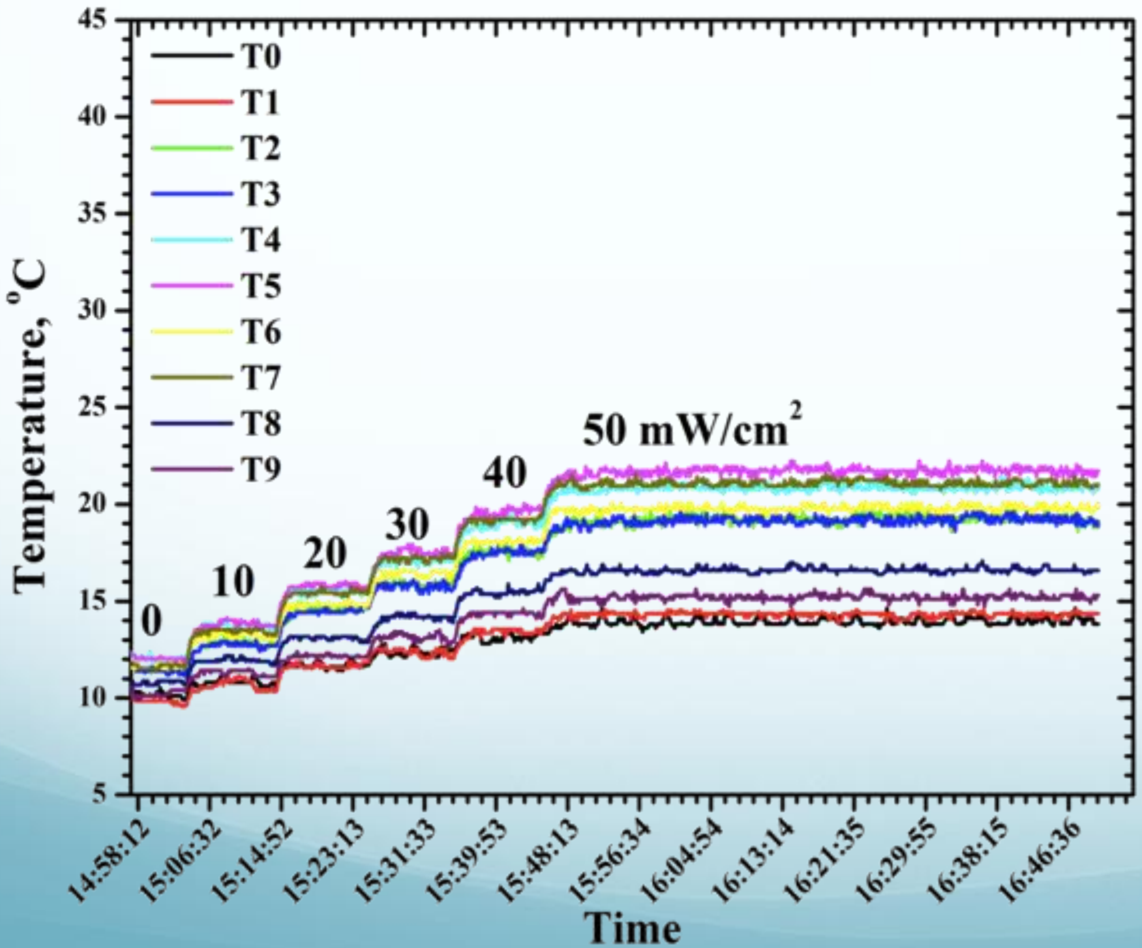
→see next slide

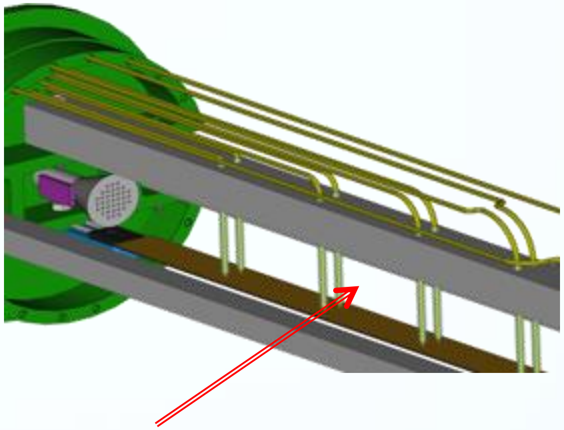
Thermal tests with ~zero-flow cold Nitrogen



Thermal tests with ~ zero-flow cold Nitrogen

- Heat power **up to 50 mW/cm²**
- Ten double thermocouples: T0,T1…T9





30 cm stave
with 10 thermocouples (T0,T1…T9) mounted along the heater

The first results are good:

- Temperature<25 °C for all heat loads
- Speed of N_2 gas flow ~0

Summary

The impressive amount of progress in the last decade for the ITS-2

- 2012–2014: the ITS-2 R&D is completed
- 2014–2016: evaluation of technologies & prototypes, selection of technologies, engineering, design, TDR, final design are done
- **2017–2020: production, tests, assembly are completed, commissioning is in progress**
- The new ITS-2 will provide:

–high accuracy of secondary vertex determination due to the extremely low-material budget (below 0.35% X/X_0 for 3 innermost layers). Impact parameter resolution will be better by a factor of 3.

–low p_T registration starting from 50 MeV/c

–charm and beauty mesons will be measured down to zero p_T.

–the rate of ALICE data taking in Pb–Pb collisions will be increased from 1 kHz to 50 kHz

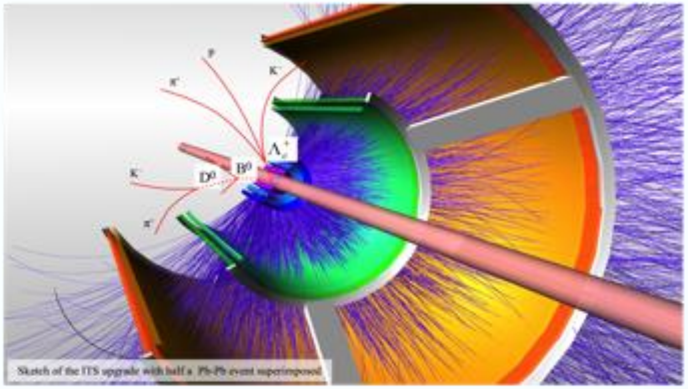
–opens new physics opportunities in study of strong interaction

- **The project is well on track to meet the very challenging and ambitious LHC schedule (in spite of COVID-19)!**

New physics possibilities with high luminosity Pb beams

ALICE

- Study of thermalization of partons in the QGP, with the focus on charm and beauty



Will be accessible for the first time:

- Production of D mesons, including D_s, down to zero p_T .
- Charm and beauty baryons Λ_c and Λ_b. The last one will be measured via the decay $\Lambda_b \rightarrow \Lambda_c + X$.
- Baryon/meson ratios for charm (Λ_c/D) and for beauty (Λ_b/B)
- The elliptic flow of charmed and beauty mesons and baryons down to low p_T
- Measurement of beauty via displaced D0 $\rightarrow$ Kp
- Measurement of beauty via displaced J/psi $\rightarrow$ e^+e^- will also be accessible.

Technical Design Report for the Upgrade of the ALICE Inner Tracking System
J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

Gain a factor **100** in statistics over the original physics program (Run 1 + Run 2)

Thank you for your attention!