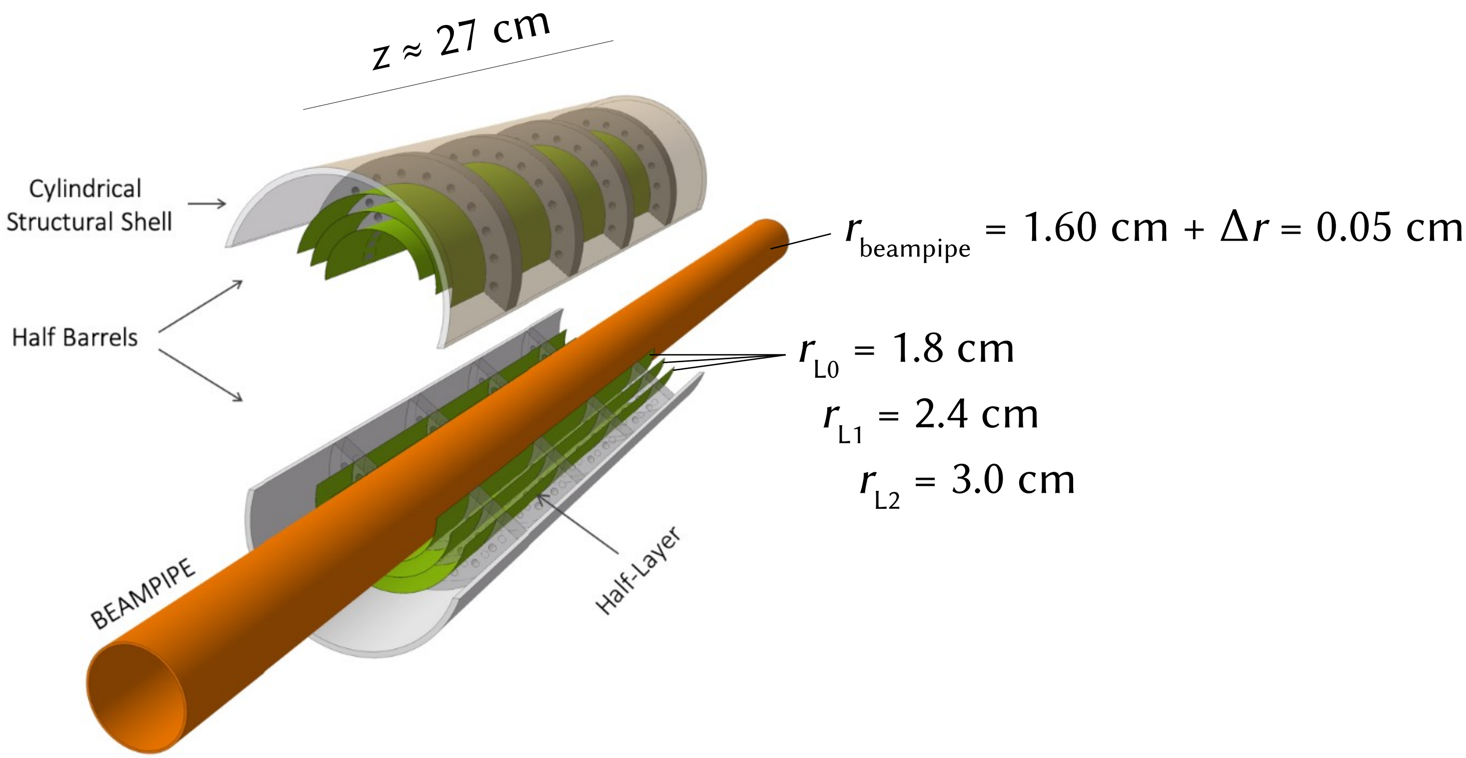
Antonin MAIRE – IPHC Strasbourg
Thursday, 27 Oct. 2022 – **Conseil Scientifique In2p3 2022**

Upgrade of the ALICE inner-tracker :
ITS3 for LHC run 4 (2029-2032)



Outline

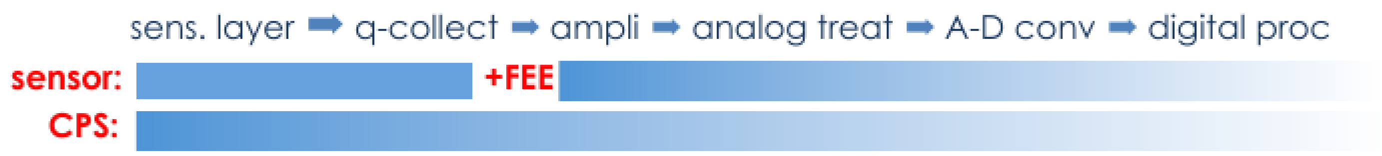
Part A - ITS3 as a project of the ALICE Collaboration

Part B - IN2P3 teams into the project

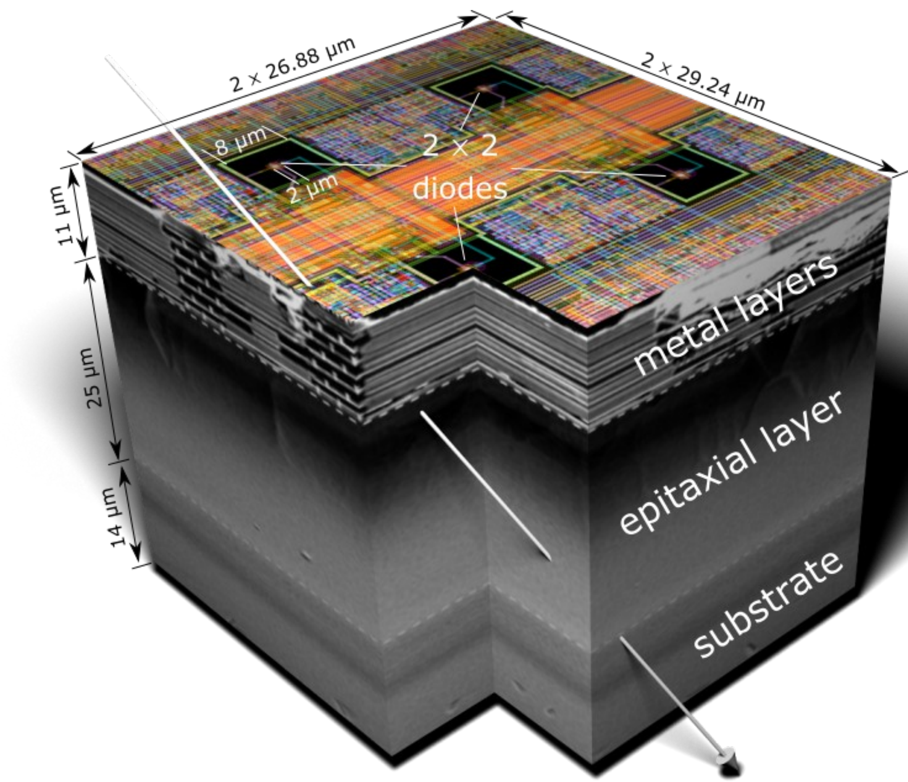
Part A – ITS3, an ALICE project

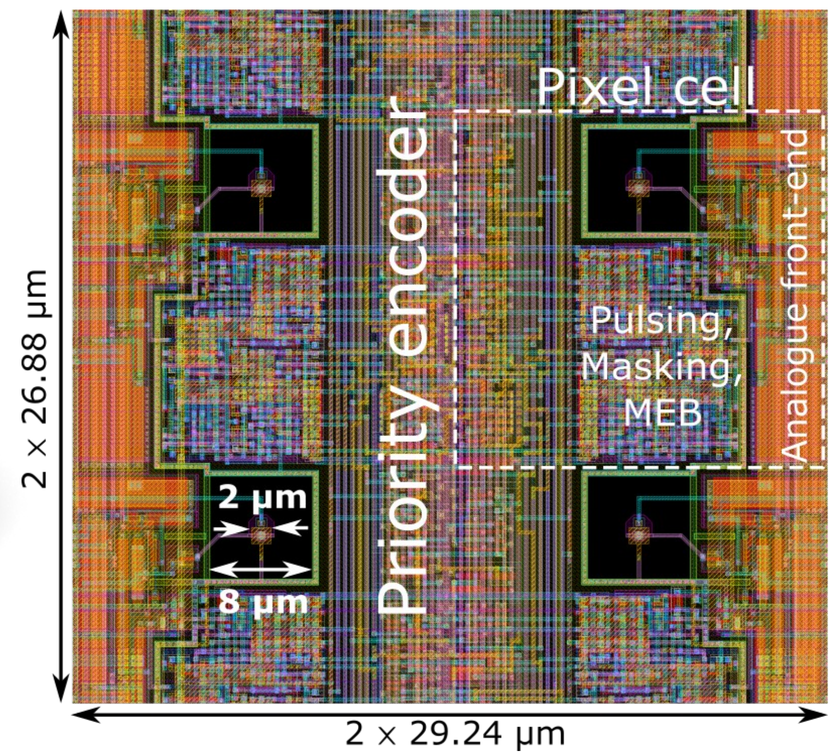
I.1 – Background: MAPS instrumental background

Hybrid pixel sensor ⟶
CMOS pixel sensor ⟶



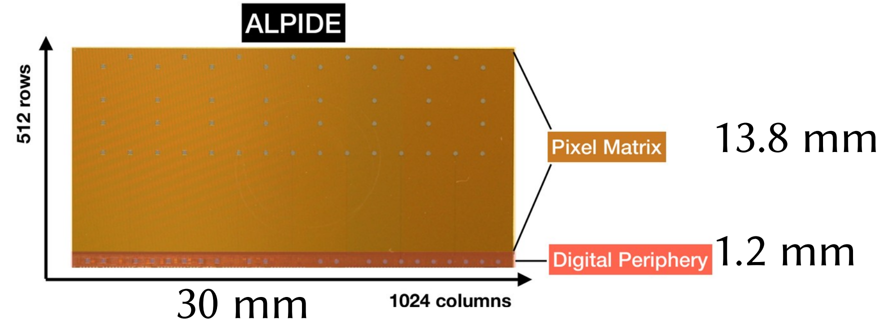
Ex: sensor using
TowerSemiconductor 180-nm CMOS Imaging Process





ITS2 ALPIDE – 3D and 2D views of 2x2 pixels
(Here, in the 50-µm-thick version...)

I.2 – Background : ITS2+MFT, MAPS-based detectors for Run 3

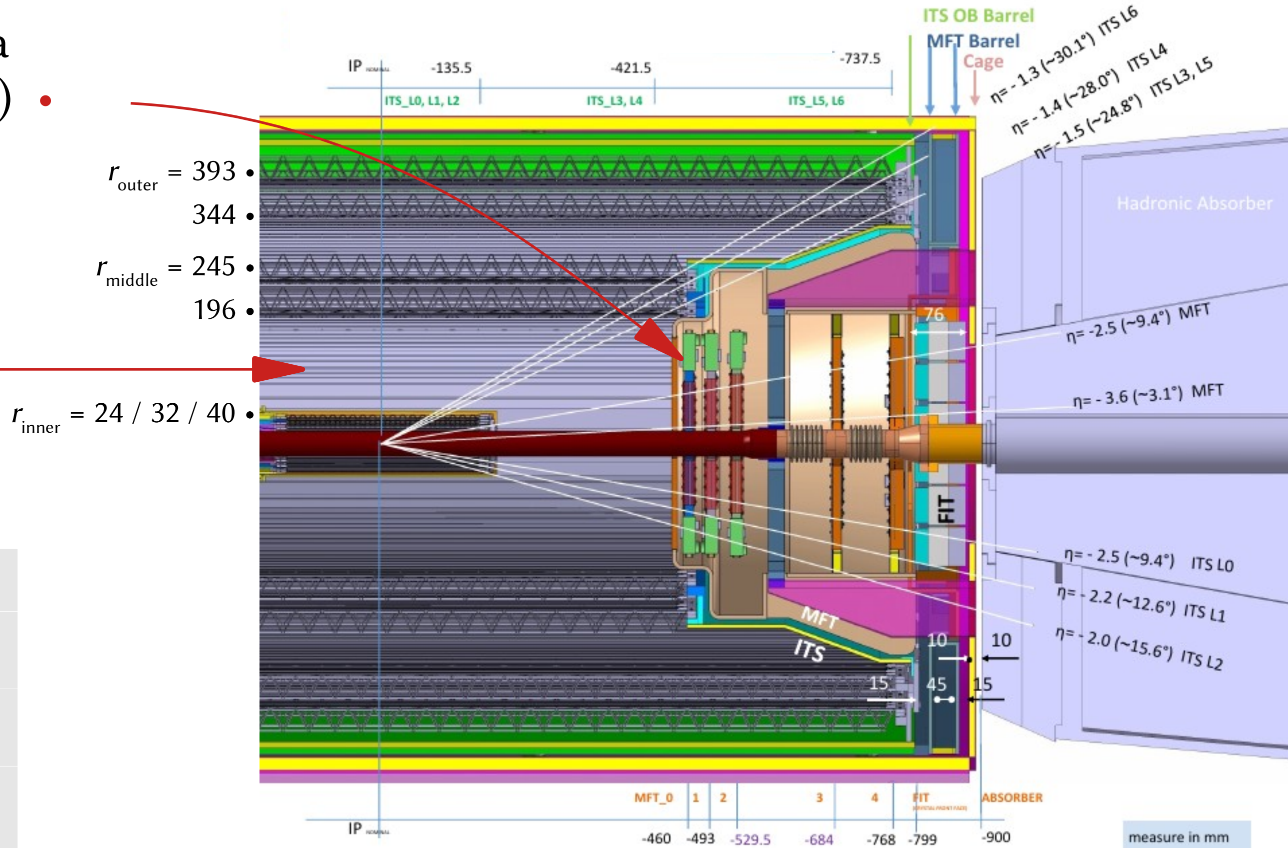


MFT

5 double-sided vertical discs
896 ALPIDE chips
0.47 x10^9 pixels
= 0.37 m² of active area
(3.7% of ITS2 area)

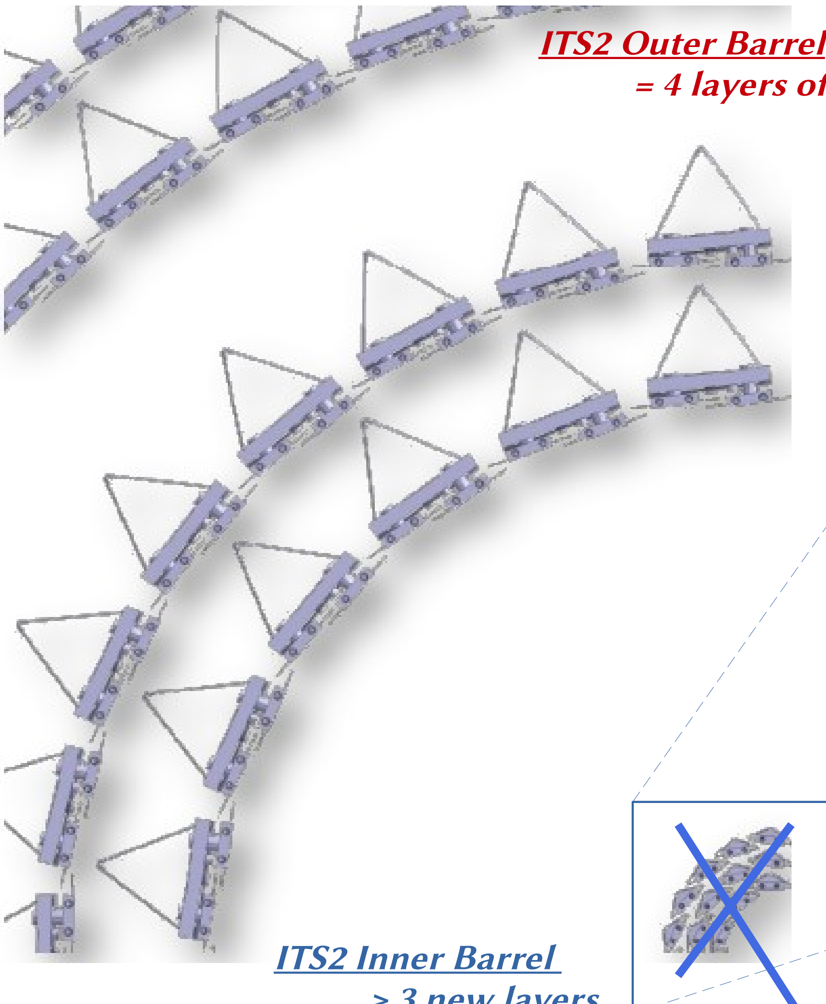
ITS2

7 layers as barrel structure
24120 ALPIDE chips,
12,6 x10^9 pixels
= 9.99 m² of active area



	L0,L1,L2	L3+L4	L5+L6
Layers	*Inner*	Middle	Outer
Chips	432	6048	17640
Active surface	0.18 m²	2.50 m²	7.30 m²
Fraction	1.8%	25%	73%

II.1 – ITS3 detector : the idea in one glimpse



ITS2 Outer Barrel
= 4 layers of ITS2 kept !

ITS2 Inner Barrel
≥ 3 new layers

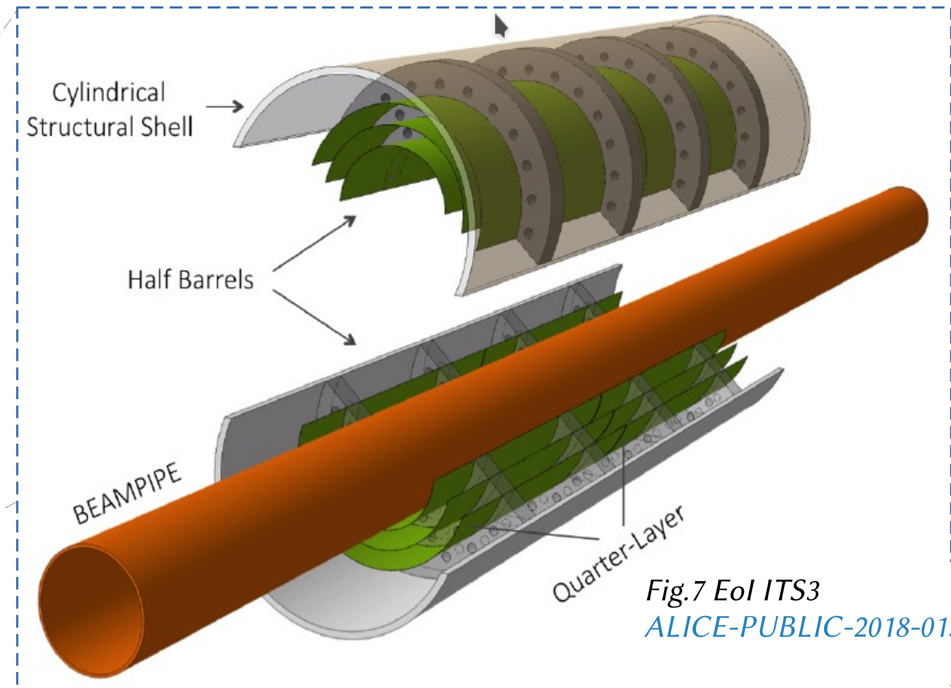


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013

II.2 – ITS3 detector : some key figures

Fig.5.8 TDR ITS2
CERN-LHCC-2013-024

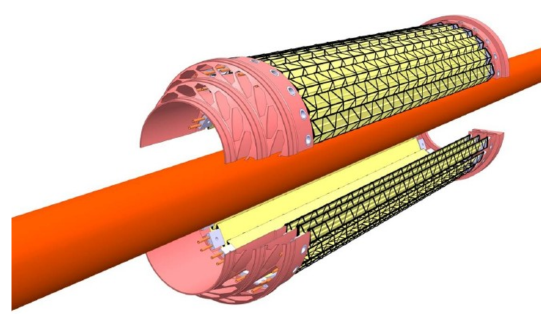
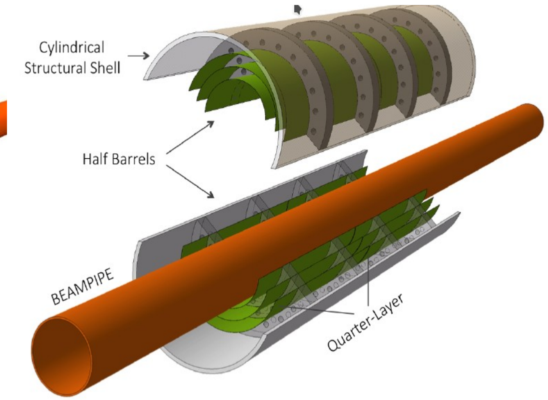


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013



ITS3 :
curled and lightweight wafer-scaled CMOS active silicon sensor
Active surface 0.12 m²

r_0 = 1.8 cm

r_1 = 2.4 cm

r_2 = 3.0 cm

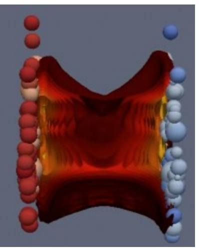
2. NEW keys	ITS2 IB	ITS3
Technology	180 nm	65 nm
Chips	432	6
Pixel size	27 x 29 μm²	≈ 20 x 20 μm²
Material /layer	0.35 % x/X°	≈ 0.05 % x/X°
r_{L0}	2.24-2.67 cm	1.80 cm
$r_{Beryllium\ pipe}$	1.82+0.08 cm	1.6+0.05 cm

1. (≈ preserved) keys :

- |η| < 2.2
- spatial resolution/layer ≈ 5 μm
- time resolution ≤ 2-5 μs
- Radiation hardness : NIEL: >3x10^{12} 1-MeV n_{eq}.cm^{-2} // TID: >0.3 Mrad

III.1 – Physics incentives : summary

$g + u,d,s,c,b\ (t)$ <=>



u,d,s

- $\pi^{\pm}\ \pi^{0}\ K^{\pm}\ K^{0}_{S}$ … $p\ \Lambda\ \Sigma^{\pm}(uus)\ \Xi^{\mp}(dss),\ \Omega^{\mp}(sss)$ …

  $\eta(547)\ \omega(782)$ … $K^{0}(892)\ \phi(1020)\ \Sigma^{\pm}(1385)\ \Lambda(1520)\ \Xi^{0}(1530)$

  + $d\ t\ {}^{3}He^{2+}\ {}^{4}He^{2+}$ …

  + ${}^{3}_{\Lambda}H,\ {}^{4}_{\Lambda}\overline{He}^{2+} \longrightarrow {}^{3}He^{2+}\ p\ \pi^{-}$.

c

- $(D^{0}\ D^{+}\ D^{*+}\ D_{S}^{+})$… $\eta_{c}\ J/\psi\ \chi_{Ci}\ \psi(2S)$ …

  $\Lambda_{C}^{+}(udc)$

  $\Xi_{C}^{+}(usc)$

  $\Xi_{C}^{0}(dsc)$

  $\Omega_{C}^{0}(ssc)$

  + *c*-deuteron $(\Lambda_{c}n)^{+}$, *c*-triton $(n\Lambda_{c}n)^{+}$?

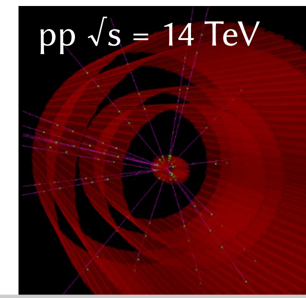
b

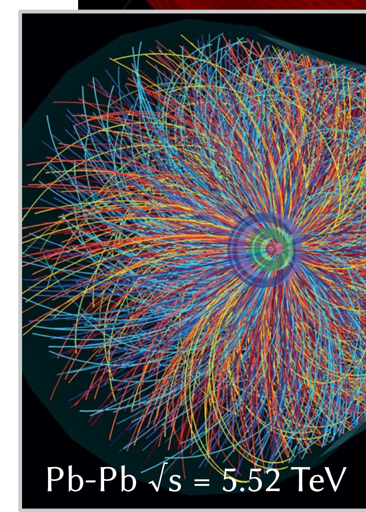
- heavy-flavour $(\mu^{\pm}, e^{\pm})$
- $B^{0}\ B^{\pm}\ B^{0}_{S}$ … $\Upsilon(1S,2S,3S)$…

  $\Lambda_{b}^{0}(udb)$ …

(• $e^{\pm}\ \mu^{\pm}\ \ \gamma$)

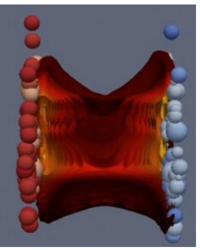
(• $W^{\pm}\ \gamma/Z^{\circ}$)





III.1 – Physics incentives : summary

g + u,d,s,c,b (t) <=>



Madai

u,d,s

- $\pi^{\pm}$ π^{0} $K^{\pm}$ K^{0}_{S} … p Λ $\Sigma^{\pm}(uus)$ $\Xi^{\mp}(dss)$, $\Omega^{\mp}(sss)$ …

  $\eta(547)$ $\omega(782)$ … $K^{0}(892)$ $\phi(1020)$ $\Sigma^{\pm}(1385)$ $\Lambda(1520)$ $\Xi^{0}(1530)$

  + d t $^{3}He^{2+}$ $^{4}He^{2+}$ …

  + $^{3}_{\Lambda}H$, $^{4}_{\Lambda}\overline{He}^{2+} \rightarrow {}^{3}He^{2+}\ p\ \pi^{-}$.

c

- $(D^{0}\ D^{+}\ D^{*+}\ D_{S}^{+})$… η_{c} J/ψ χ_{Ci} $\psi(2S)$ …

  $\Lambda_{C}^{+}(udc) \rightarrow pK^{-}\pi^{+}$ or $pK^{0}s$ $(c\tau \approx 60\ \mu m)$

  $\Xi_{C}^{+}(usc) \rightarrow pK^{-}\pi^{+}$ or $\Xi^{-}2\pi^{+}$ $(c\tau \approx 136\ \mu m)$

  $\Xi_{C}^{0}(dsc) \rightarrow \Xi^{-}\pi^{+}$ $(c\tau \approx 45\ \mu m)$

  $\Omega_{C}^{0}(ssc) \rightarrow \Omega^{-}\pi^{+}$ $(c\tau \approx 80\ \mu m)$

  + *c*-deuteron $(\Lambda_{c}n)^{+} \rightarrow dK^{-}\pi^{+}$? *c*-triton $(n\Lambda_{c}n)^{+}$?

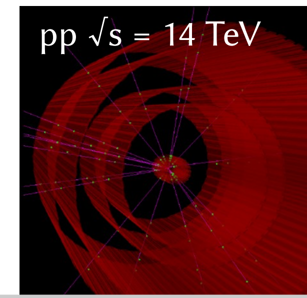
b

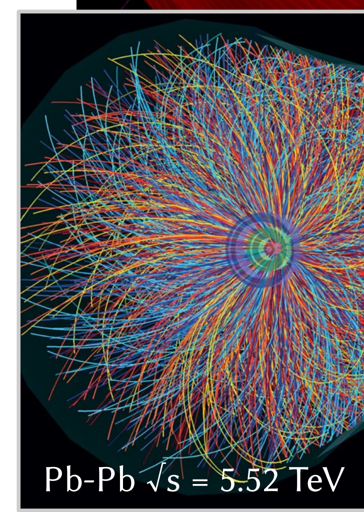
- heavy-flavour $(\mu^{\pm}, e^{\pm})$
- B^{0} $B^{\pm}$ B^{0}_{S} … $\Upsilon(1S,2S,3S)$…

  $\Lambda_{b}^{0}(udb)$ …

(• $e^{\pm}$ $\mu^{\pm}$ γ)

(• $W^{\pm}$ γ/Z°)

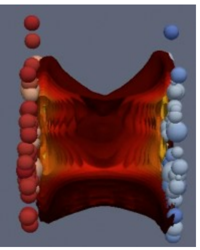




1. improve low-p_{T} Axε for stable particles

III.1 – Physics incentives : summary

g + u,d,s,c,b (t) <=>



Madai

u,d,s

- $\pi^\pm$ π^0 $K^\pm$ K^0_S … p Λ $\Sigma^\pm$(*uus*) $\Xi^\mp$ (*dss*), $\Omega^\mp$(*sss*) …

  η(547) ω(782) … K^0(892) ϕ(1020) $\Sigma^\pm$(1385) Λ(1520) Ξ^0(1530)

  + d t $^3He^{2+}$ $^4He^{2+}$ …

  + $^3_\Lambda H$, $^4_\Lambda \overline{He}^{2+}$ $\longrightarrow$ $^3He^{2+}$ p π^- .

c

- (D^0 D^+ D^{*+} D_S^+)… η_c J/ψ χ_{Ci} ψ(2S) …

  Λ_C^+(*udc*) $\longrightarrow$ $pK^-\pi^+$ or pK^0s ($c\tau \approx$ 60 μm)

  Ξ_C^+(*usc*) $\longrightarrow$ $pK^-\pi^+$ or $\Xi^-2\pi^+$ ($c\tau \approx$ 136 μm)

  Ξ_C^0(*dsc*) $\longrightarrow$ $\Xi^-\pi^+$ ($c\tau \approx$ 45 μm)

  Ω_C^0(*ssc*) $\longrightarrow$ $\Omega^-\pi^+$ ($c\tau \approx$ 80 μm)

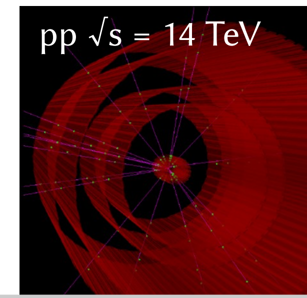
  + *c*-deuteron $(\Lambda_c n)^+$ $\longrightarrow$ $dK^-\pi^+$? *c*-triton $(n\Lambda_c n)^+$?

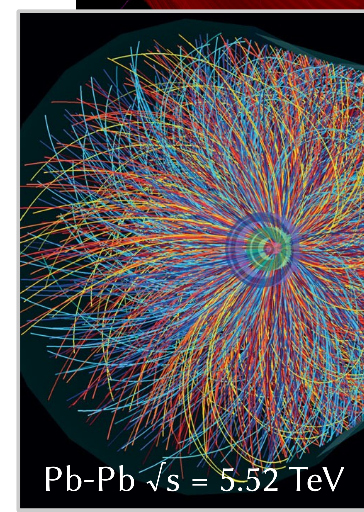
b

- heavy-flavour ($\mu^\pm$, $e^\pm$)
- B^0 $B^\pm$ B^0_S … Υ(1S,2S,3S)…

  Λ_b^0 (*udb*) $\longrightarrow$ $\Lambda_C^+\pi^-$ …

(• $e^\pm$ $\mu^\pm$ γ)
(• $W^\pm$ γ/Z°)





1. improve low-p_T Axε for stable particles

2. improve track pointing resolution : displaced vertexing, prompt/non-prompt

III.1 – Physics incentives : summary

$g + u,d,s,c,b\ (t)$ <=>

u,d,s

- $\pi^{\pm}$ π^{0} $K^{\pm}$ K^{0}_{S} … p Λ $\Sigma^{\pm}(uus)$ $\Xi^{\mp}(dss)$, $\Omega^{\mp}(sss)$ …

  η(547) ω(782) … $K^{0}(892)$ ϕ(1020) $\Sigma^{\pm}(1385)$ Λ(1520) $\Xi^{0}(1530)$

  + d t $^{3}He^{2+}$ $^{4}He^{2+}$ …
  + $^{3}_{\Lambda}H$, $^{4}_{\Lambda}\overline{He}^{2+} \rightarrow {}^{3}He^{2+}\ p\ \pi^{-}$.

c

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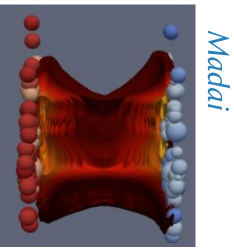
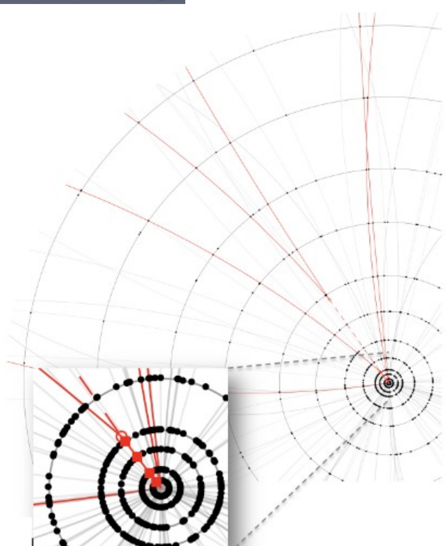
b

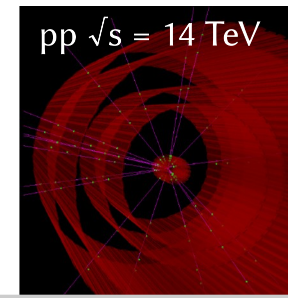
- heavy-flavour ($\mu^{\pm}$, $e^{\pm}$)
- B^{0} $B^{\pm}$ B^{0}_{S} … ϒ(1S,2S,3S)…

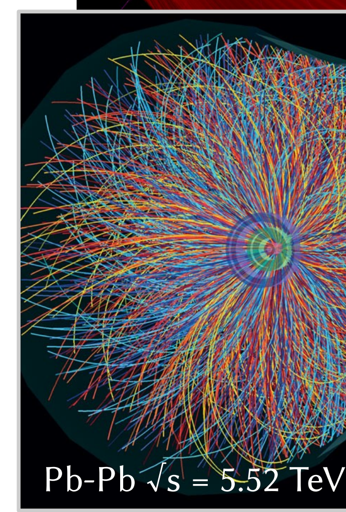
  $\Lambda_{b}^{0}(udb) \rightarrow \Lambda_{C}^{+}\pi^{-}$ …

(• $e^{\pm}$ $\mu^{\pm}$ γ)
(• $W^{\pm}$ γ/Z°)





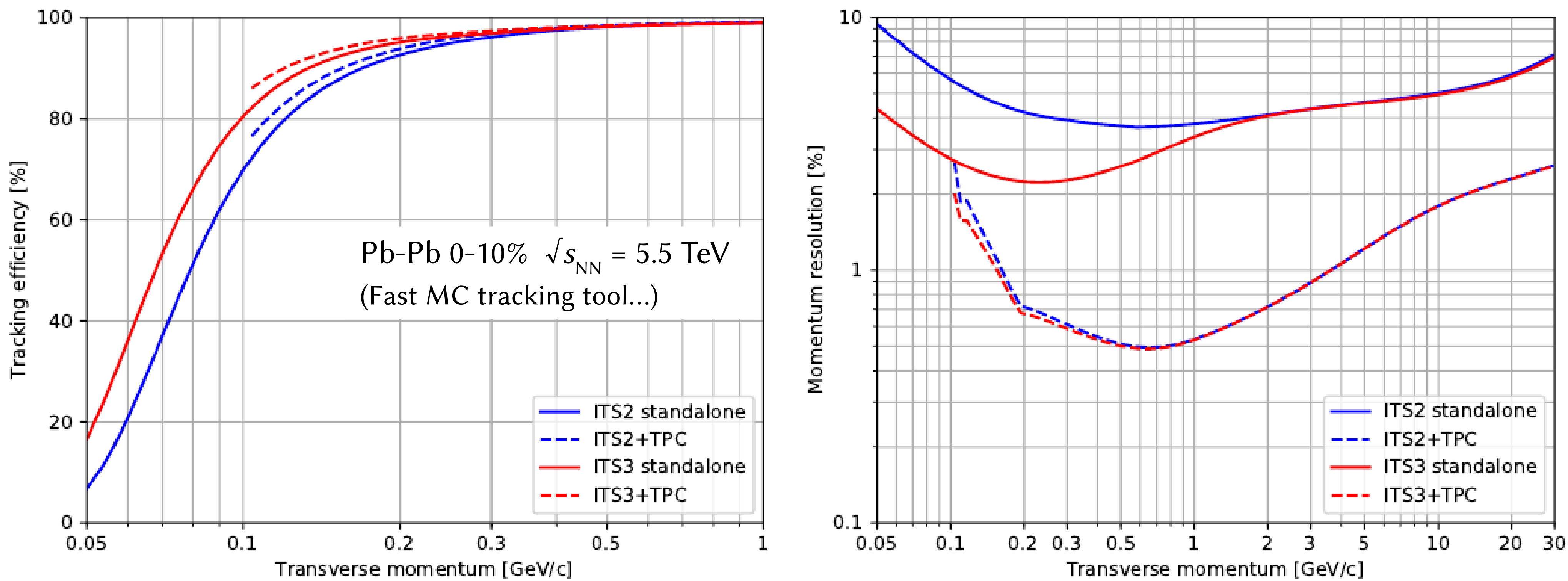




1. improve low-p_{T} Axε for stable particles
2. improve track pointing resolution : displaced vertexing, prompt/non-prompt
3. "strangeness tracking" [hits left by charged $\Xi^{\mp}(dss)$, $\Omega^{\mp}(sss)$, $\Sigma^{\pm}(uus)$]

III.2 – Physics incentives : improve low-p_T $A\times\varepsilon$

Fig.12, EoI ITS-3, ALICE-PUBLIC-2018-013



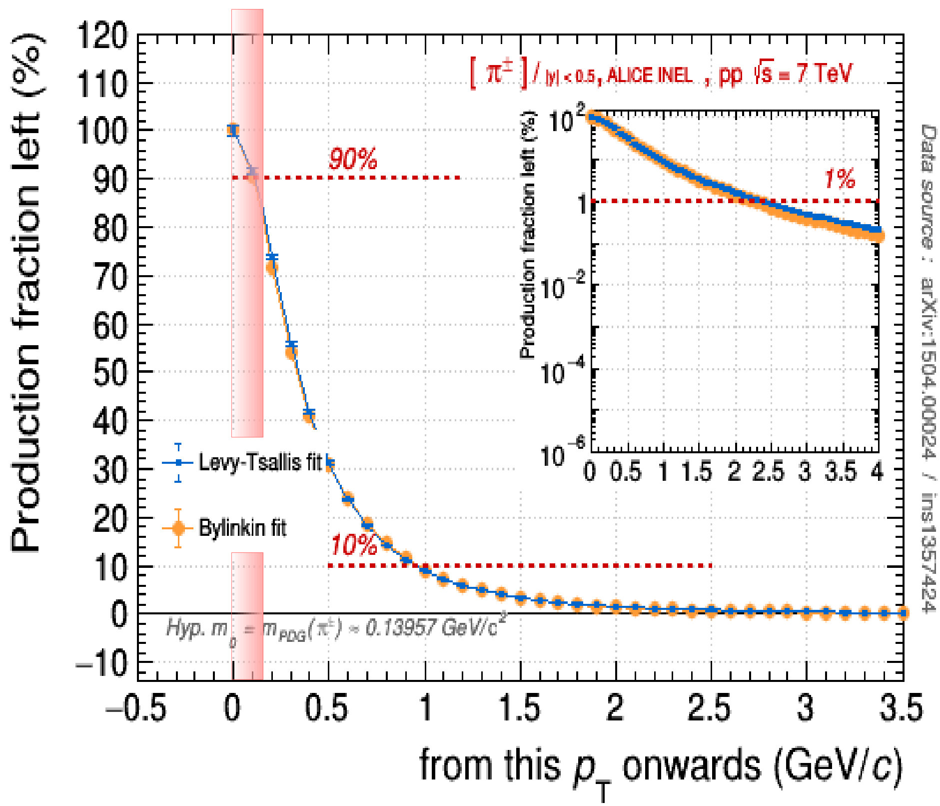
→ Importance to be as efficient as possible in low p_T detection, on an event-by-event basis …

Why ? crucial to study correlation between particles, get the particle of interest in its QCD context.
QCD+QGP physics happen essentially at *low* and *intermediate* p_T

… "Low p_T", but how low ?!

III.2 – Physics incentives : low-p_T $A \times \varepsilon$ for $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$

If your **$\pi^{+}(u\bar{d})$** measurements start above 0.0, 0.1, 0.2 … GeV/c,
how much (x%) of the total dN/dy in pp/in AA do you miss ?

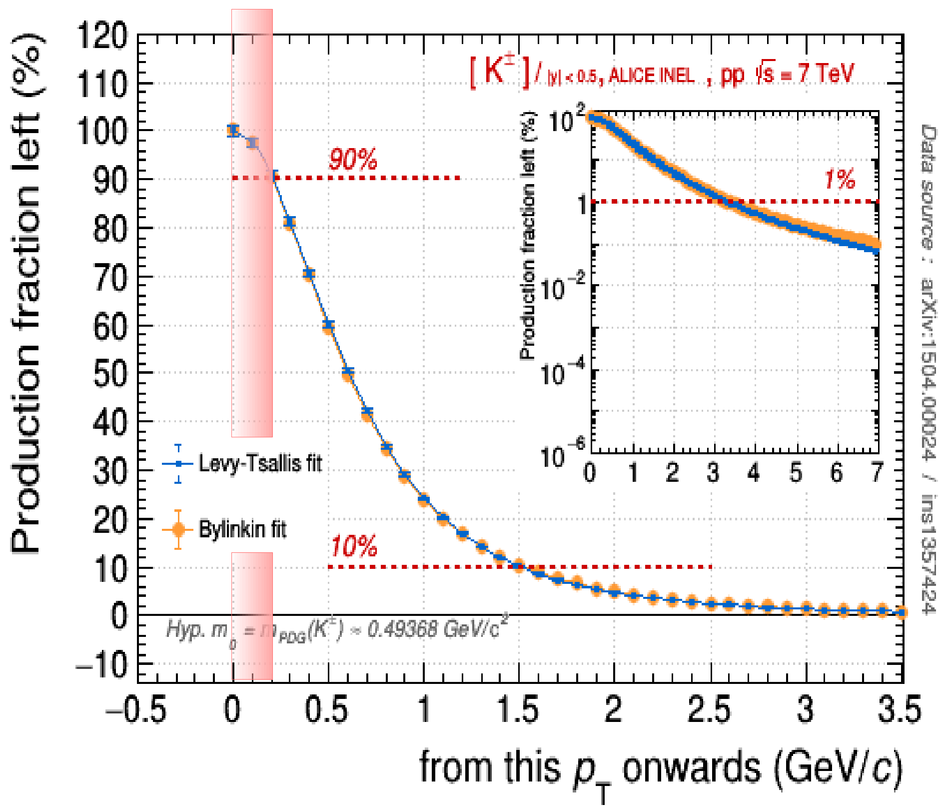


$\pi^{\pm} > 0.1$ GeV/c ⟶ Missed cross-section ≈10%
$h^{\pm} > 0.15$ GeV/c ⟶ Missed cross-section ≈16%
$\pi^{\pm} > 0.2$ GeV/c ⟶ Missed cross-section ≈26%

Ex: ALICE
pp 7 TeV *arXiv:1504.0024* $|y| < 0.5$, $\pi^{\pm} > 0.1$ GeV/c
Pb-Pb 5.02 TeV *arXiv:1910.07678* $|y| < 0.5$, $\pi^{\pm} > 0.1$ GeV/c

III.2 – Physics incentives : low-p_T $A\times\varepsilon$ for $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$

If your **$K^{+}(u\bar{s})$** measurements start above 0.0, 0.1, 0.2 … GeV/c,
how much (x%) of the total dN/dy in pp/in AA do you miss ?



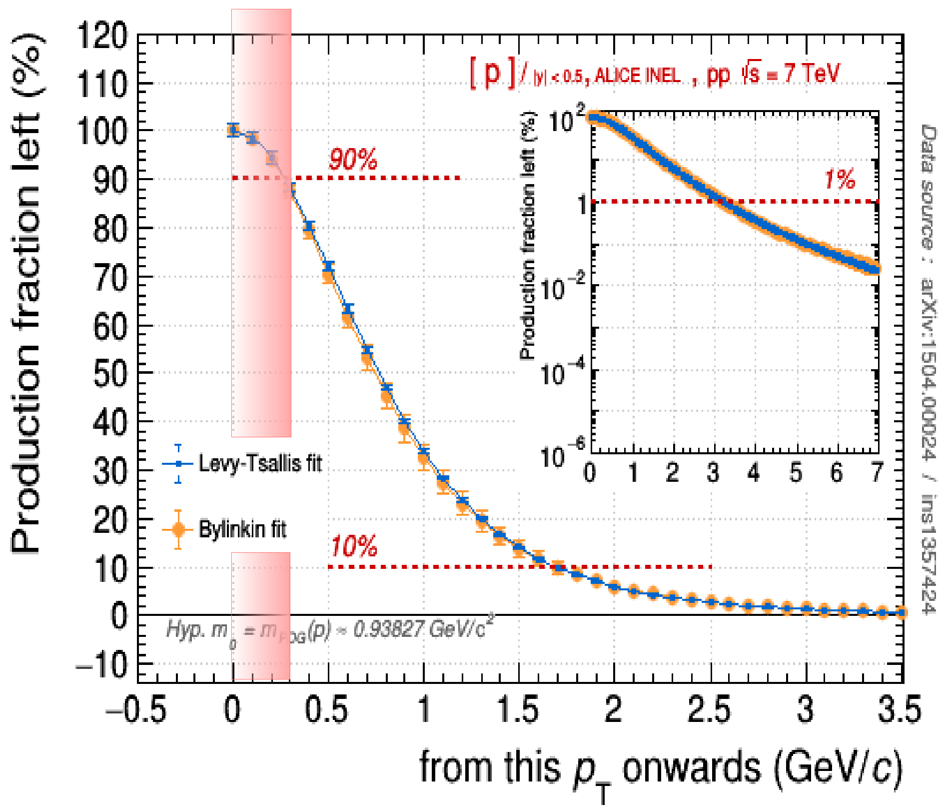
$K^{\pm}$ > 0.2 GeV/c ⟶ Missed cross-section ≈10%
$K^{\pm}$ > 0.5 GeV/c ⟶ Missed cross-section ≈40%

Ex: ALICE

pp 7 TeV *arXiv:1504.0024* $|y| < 0.5$, $K^{\pm} > 0.2$ GeV/c
Pb-Pb 5.02 TeV *arXiv:1910.07678* $|y| < 0.5$, $K^{\pm} > 0.2$ GeV/c

III.2 – Physics incentives : low-p_T $A \times \varepsilon$ for $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$

If your **p(*uud*)** measurements start above 0.0, 0.1, 0.2 … GeV/c,
how much (x%) of the total dN/dy in pp/in AA do you miss ?



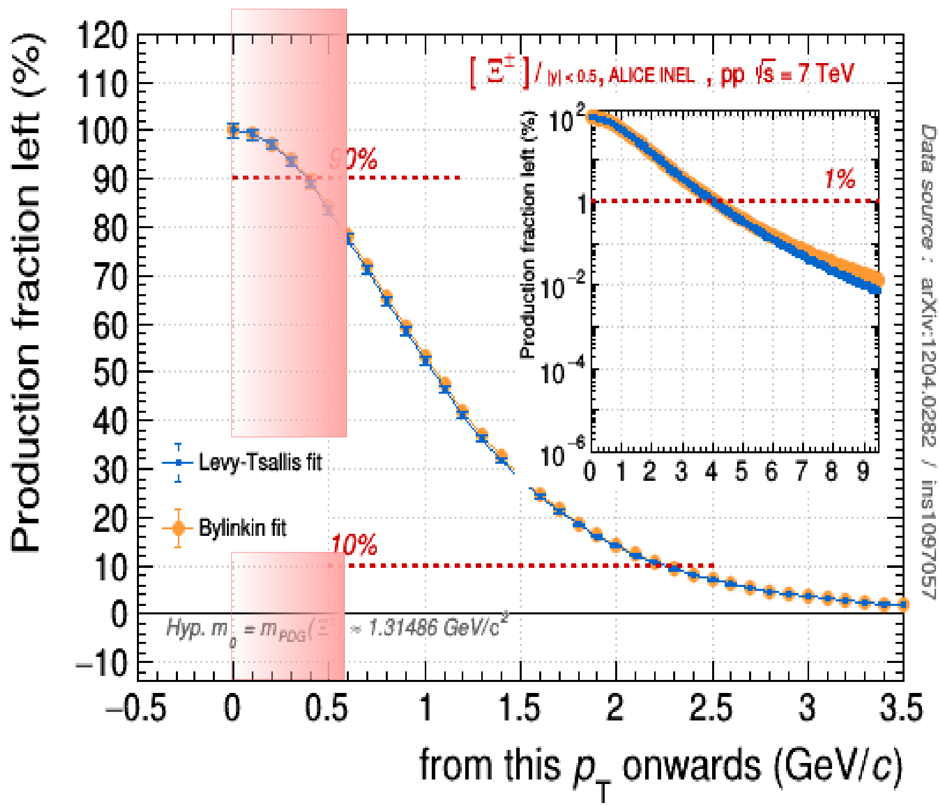
$p^{\pm} > 0.3$ GeV/c ⟶ Missed cross-section ≈14%
$p^{\pm} > 0.5$ GeV/c ⟶ Missed cross-section ≈30%

Ex: ALICE

pp 7 TeV *arXiv:1910.07678* $|y| < 0.5$, $p^{\pm} > 0.3$ GeV/c
Pb-Pb 5.02 TeV *arXiv:1910.07678* $|y| < 0.5$, $p^{\pm} > 0.3$ GeV/c

III.2 – Physics incentives : low p_T for $\Xi^{\pm}$

If your Ξ^{-}(*dss*) measurements start above 0.0, 0.1, 0.2 … GeV/c,
how much (x%) of the total dN/dy in pp/in AA do you miss ?



NB : $\Xi^{-} \longrightarrow \pi^{-} (\Lambda \longrightarrow p\ \pi^{-})$,
i.e. 3-(secondary)-particle final state

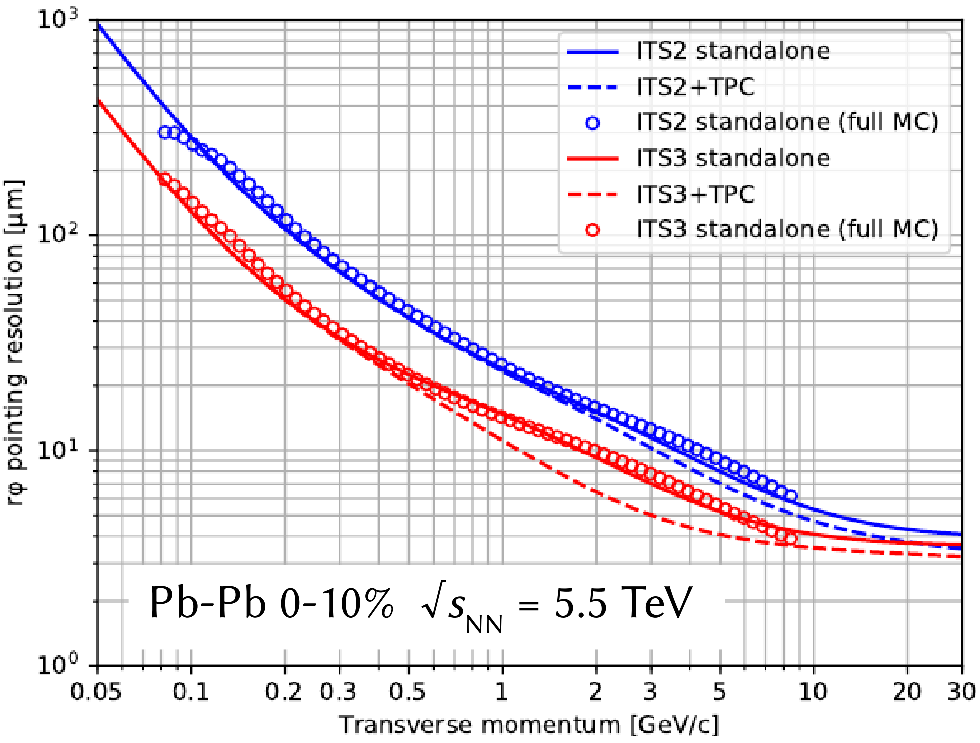
Ξ^{-} > 0.6 GeV/c ⟶ Missed cross-section ≈23%
Ξ^{-} > 1.2 GeV/c ⟶ Missed cross-section ≈45%

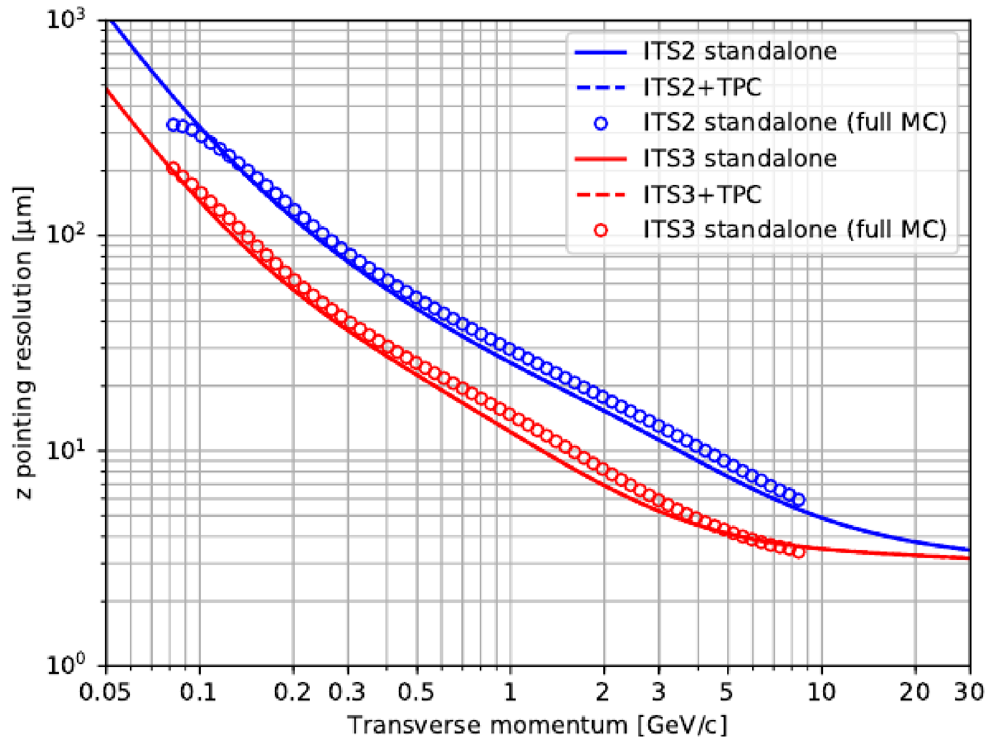
Ex: ALICE

pp 7 TeV	*arXiv:1204.0282*	$|y|$ < 0.5, $\Xi^{\pm}$ > 0.6 GeV/c
Pb-Pb 2.76 TeV	*arXiv:1307.5543*	$|y|$ < 0.5, $\Xi^{\pm}$ > 0.6 GeV/c

III.3 – Physics incentives : pointing resolution

Fig.11, EoI ITS3, ALICE-PUBLIC-2018-013





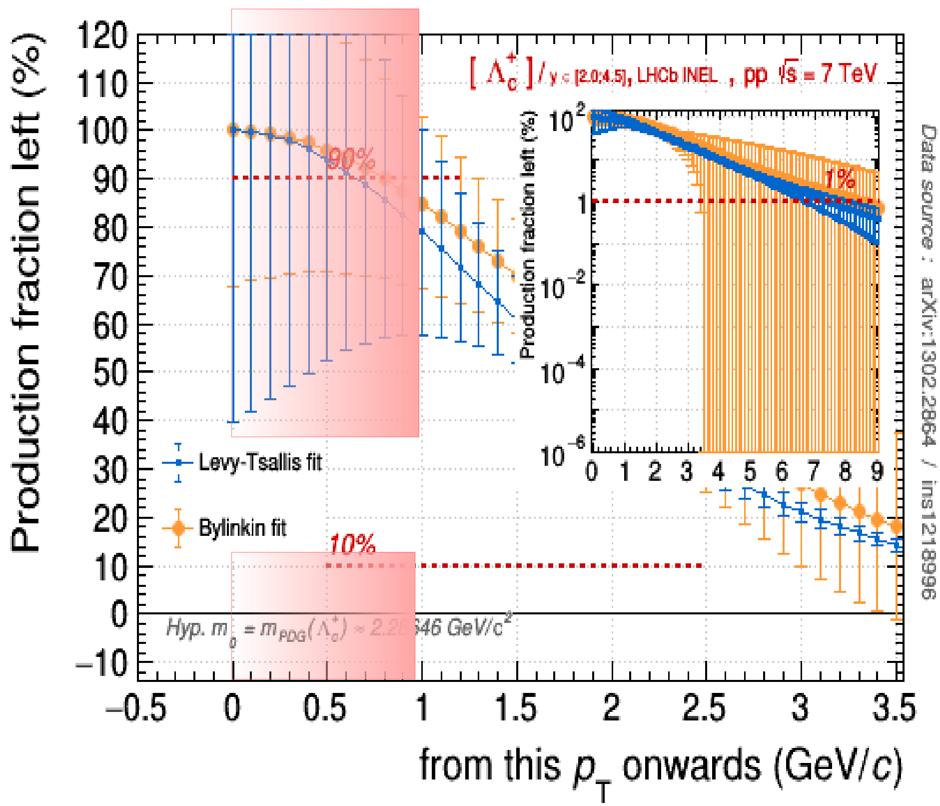
III.3 – Physics incentives : low-p_T signal for Λ_C^+

If your $\Lambda_c^+(udc)$ measurements start above 0.0, 0.1, 0.2 … GeV/c,

how much (x%) of the total dN/dy in pp/in AA do you miss ?

<u>*NB*</u> : $\Lambda_C^+ \longrightarrow$ p $K^- \pi^+$ or $\longrightarrow$ p(K^0s $\longrightarrow \pi^- \pi^+$)

i.e. 3-particle (primary-like) final state



Λ_C^+ > 0.0 GeV/c $\longrightarrow$ Missed cross-section ≈0%

Λ_C^+ > 1.0 GeV/c $\longrightarrow$ Missed cross-section ≈15%

Λ_C^+ > 2.0 GeV/c $\longrightarrow$ Missed cross-section ≈45%

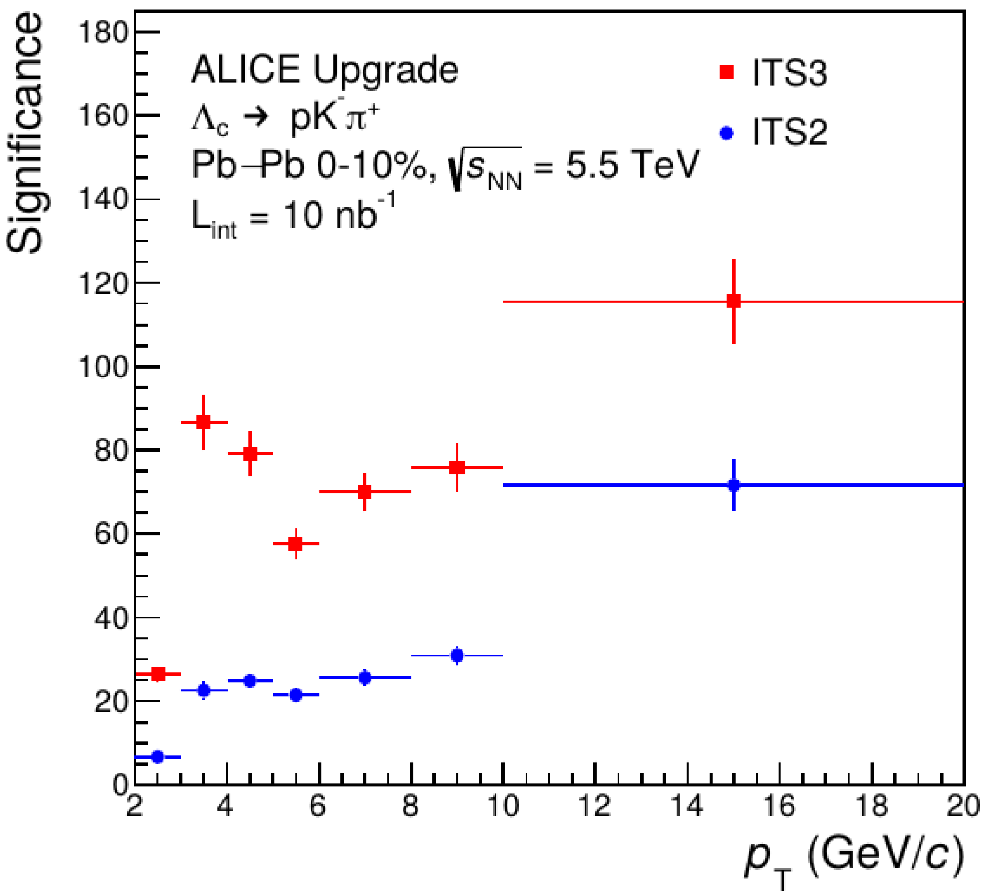
<u>*Ex:*</u>

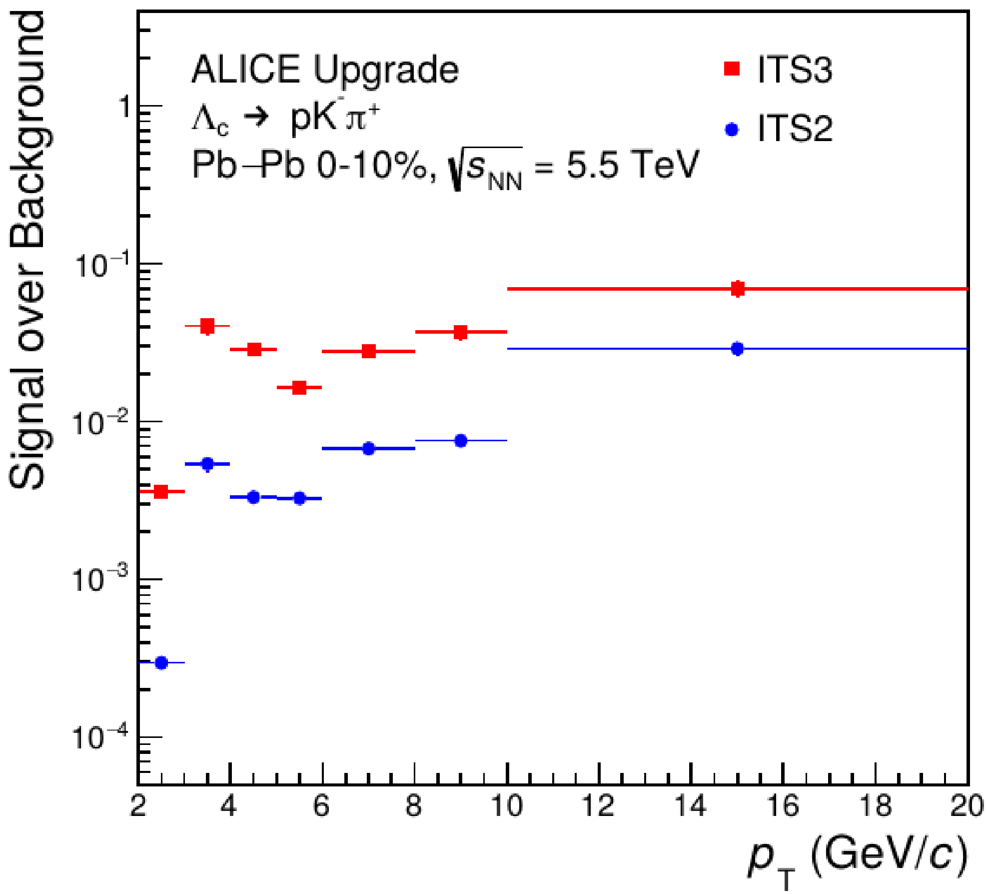
- LHCb pp 7 TeV *arXiv:1302.2864* y forward, Λ_C^+ > 0.0 GeV/c
- ALICE pp 7 TeV *arXiv:1712.09581* $|y|$ < 0.5, Λ_C^+ > 1.0 GeV/c
- ALICE Pb-Pb *arXiv:2112.08156* $|y|$ < 0.5, Λ_C^+ > 1.0 GeV/c

III.3 – Physics incentives : Λ_C^+ significance and S/B

Fig.13, EoI ITS3, ALICE-PUBLIC-2018-013
Public note : https://alice-notes.web.cern.ch/node/1327

Λ_C^+ (m = 2.286 GeV/c^2 ; $c\tau$ = 60 μm)

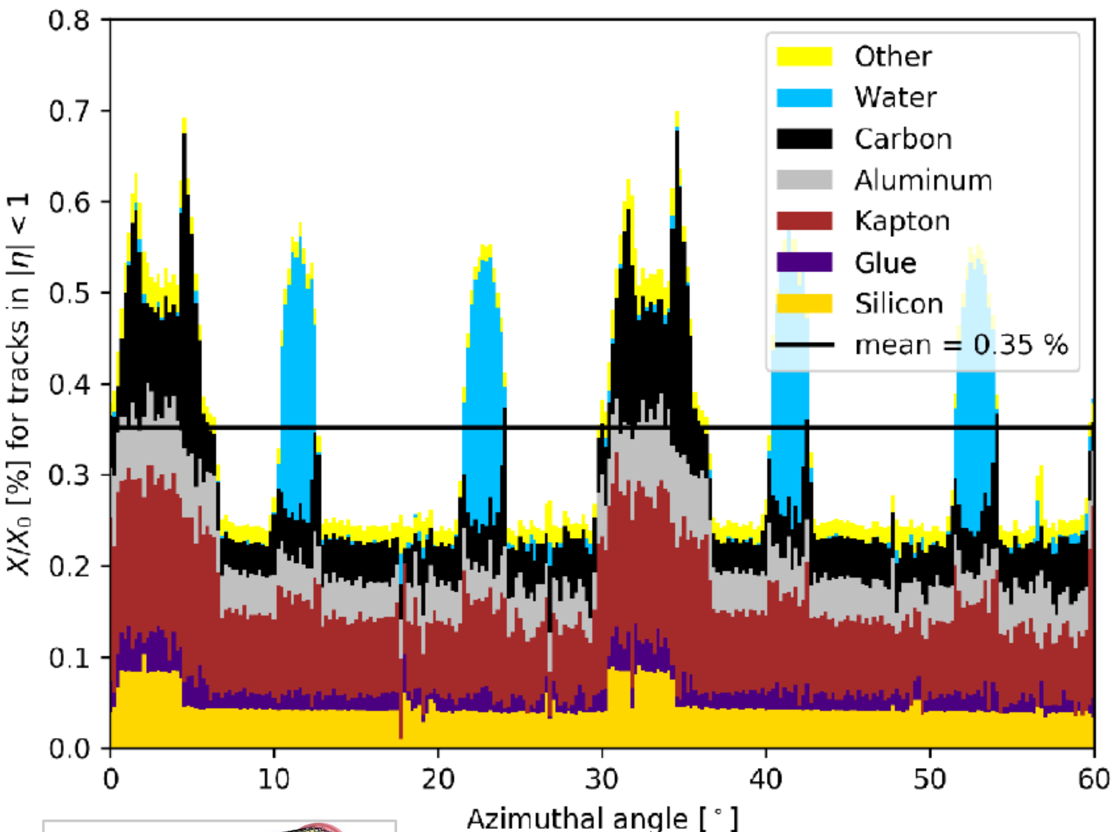


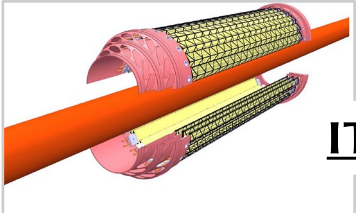


IV.1 – ITS3 project : characteristics and keywords

1./ Can we get closer to IP ?

2./ Can we get lighter in terms of material budget ?





ITS2 IB situation

Starting point : ITS2 Inner Barrel one layer
Statements :

- Si = 1/7 of the overall material budget
- Irregularities = from support + cooling…

1. Get rid of cooling ?

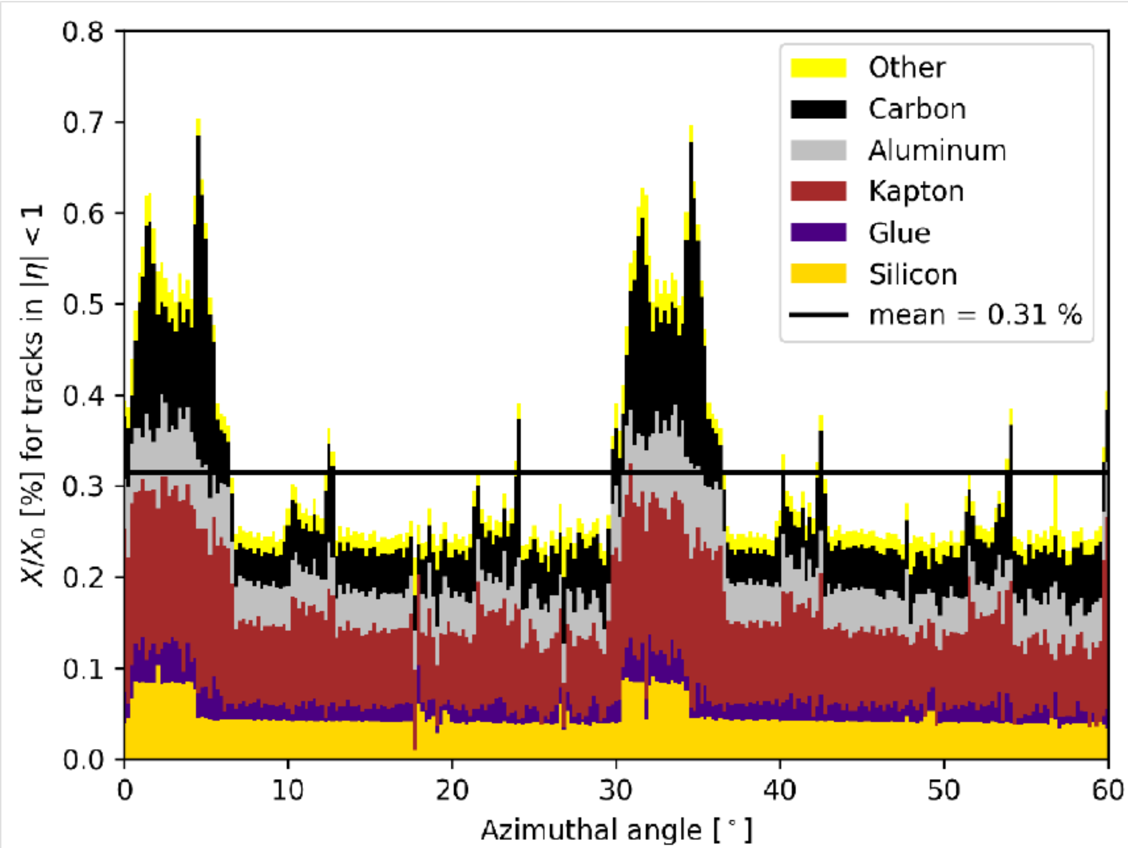
2. Remove the Flexible Printed Circuit (power+data transfer) ?

3. Shift the mechanical support to outside acceptance ?

IV.2 – ITS3 project : characteristics and keywords

1./ Can we get closer to IP ?

2./ Can we get lighter in terms of material budget ?



Starting point : ITS2 Inner Barrel one layer

Statements :

- Si = 1/7 of the overall material budget
- Irregularities = from support + cooling…

1. Get rid of cooling ?
⟶ Possible if reduction of power consumption i.e. < 20 mW/cm² on the pixel matrix

2. Remove the Flexible Printed Circuit (power+data transfer) ?

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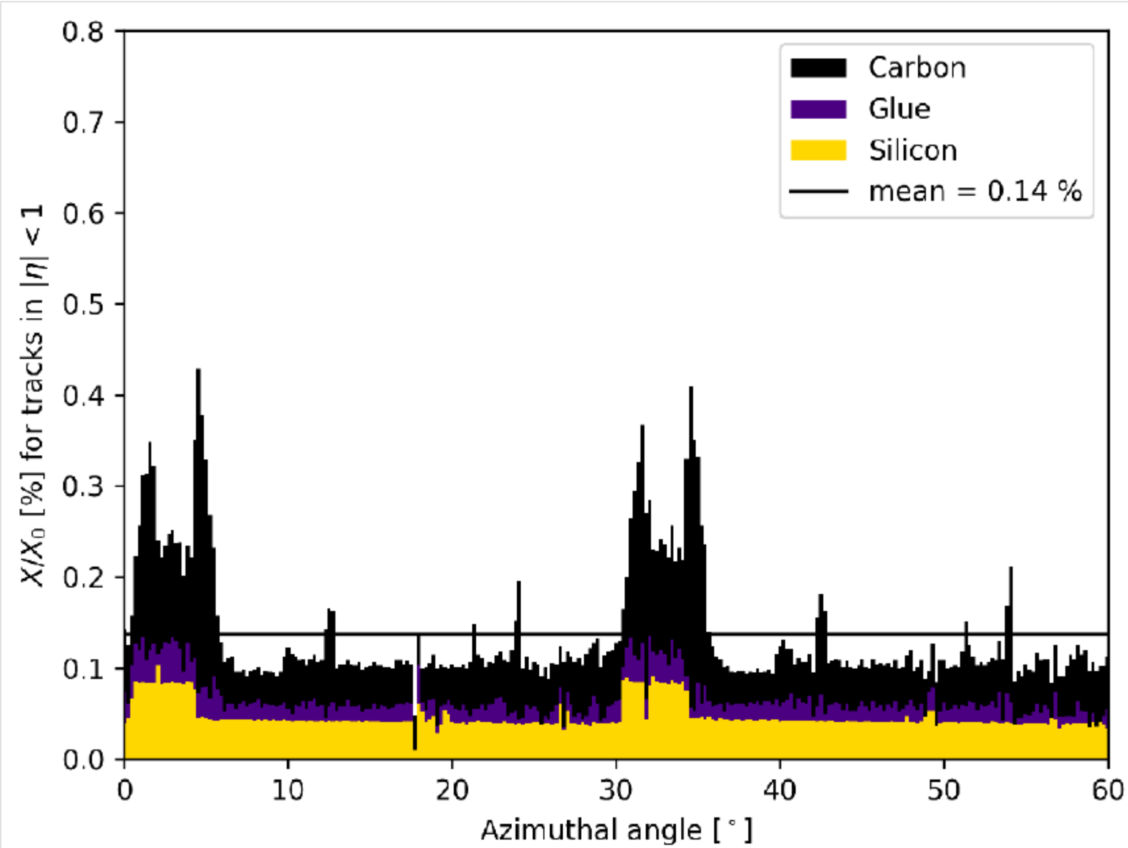
IV.3 – ITS3 project : characteristics and keywords

1./ Can we get closer to IP ? **2./ Can we get lighter in terms of material budget ?**



Starting point : ITS2 Inner Barrel one layer
Statements :

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→ integrate it on the metal layers of the chip itself

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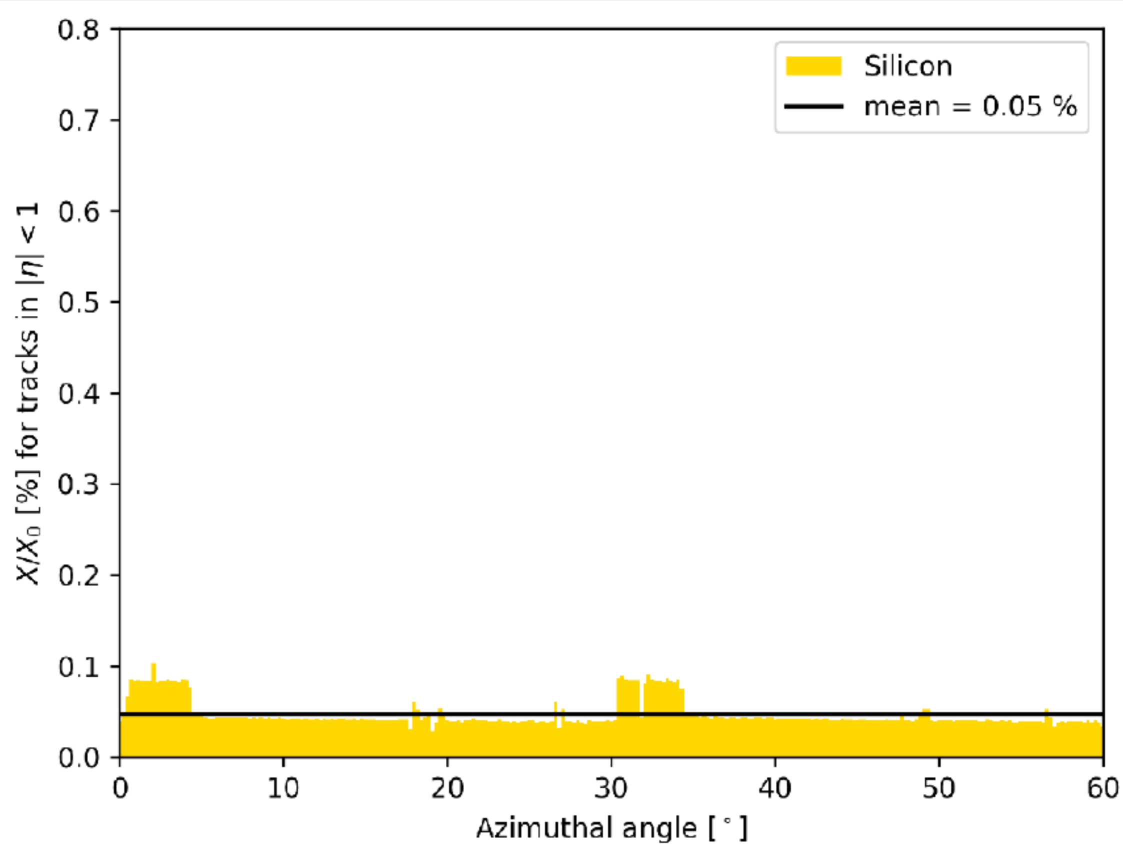

Starting point : ITS2 Inner Barrel one layer
Statements :

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→ thinned slicon [≤ 50 µm] → bending
Gain extra stiffness with curled sensor

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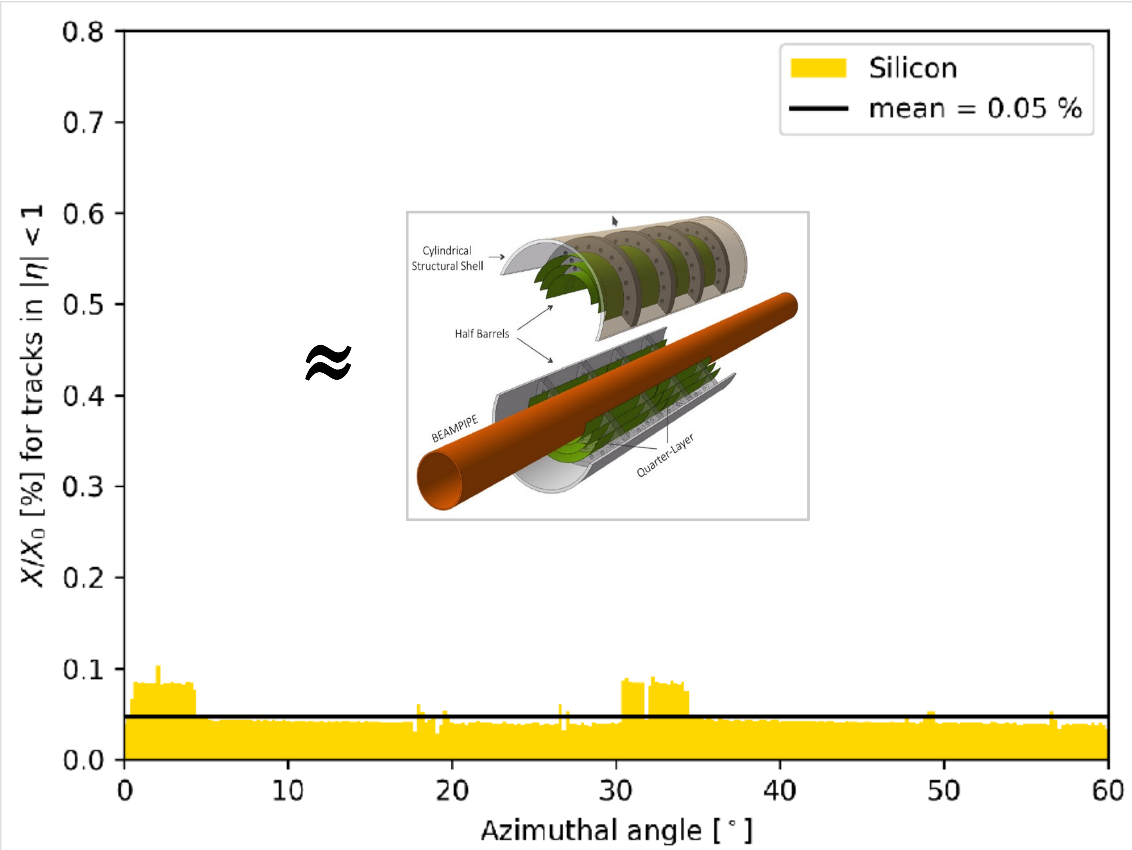

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Statements :

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→ Possible if reduction of power consumption i.e. < 20 mW/cm² on the pixel matrix

2. Remove the Flexible Printed Circuit (power+data transfer) ?
→ integrate it on the metal layers of the chip itself

3. Shift the mechanical support to outside acceptance ?
→ thinned slicon [≤ 50 μm] → bending
Gain extra stiffness with curled sensor

V.1 – ITS3 project : milestones

4 Engineering Runs **(ER)**, all in 65-nm technology, "*no production phase only R&D*" :

1. **MLR1** tape out (2020-12) :

60 chips of 1.5x1.5 mm², (analog + digital blocks) + 3 prototypes : APTS, CE65, DPTS •

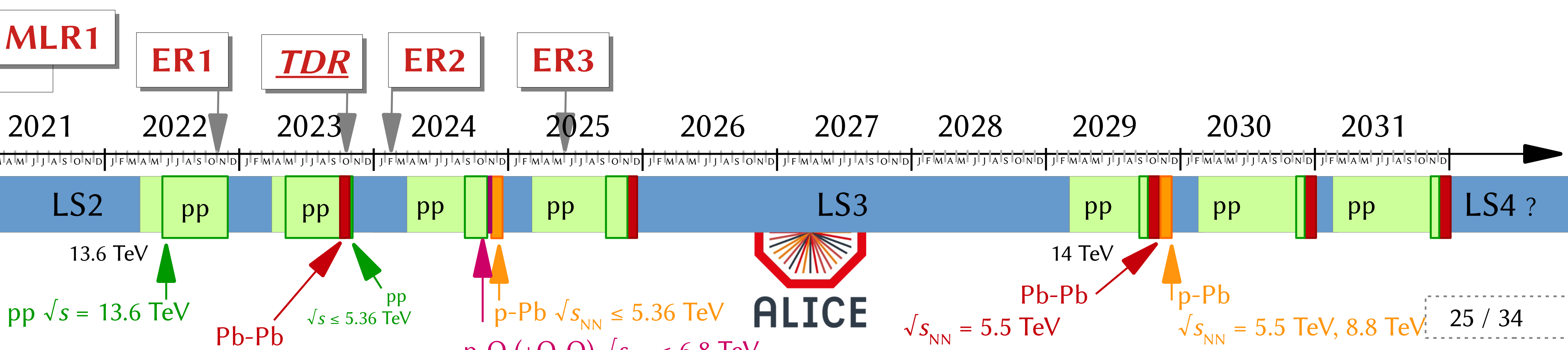
Main goals:
- Learn technology features of 65-nm node
- Characterize charge collection (cluster, timing, ...) and detection eff. (>99%)
- Validate radiation hardness

2. **ER1** tape out (2022-11) : stitching 1D (+ assess yields by the foundry)
sensors MOSS and MOST, with 18 and 22.5 µm pixel pitches

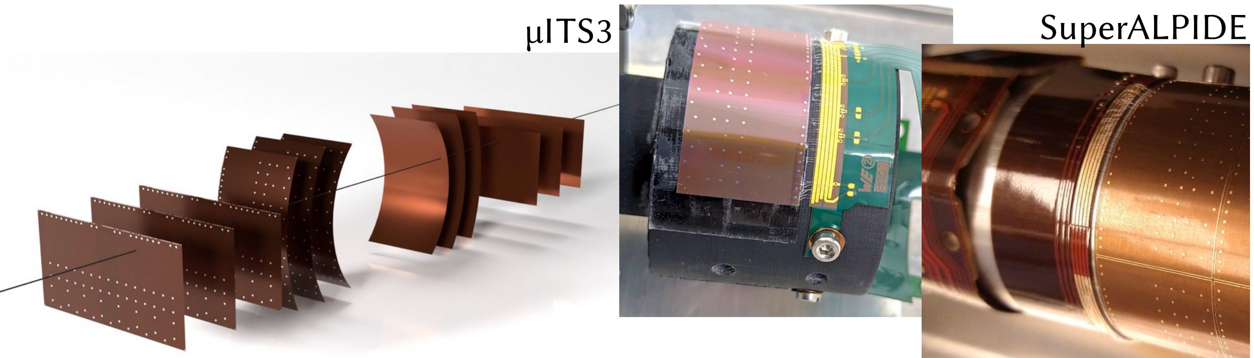
– Technical Design Report, **TDR** (2023-10) – *i*) bending MAPS, *ii*) 65-nm MAPS, *iii*) stitching –

3. **ER2** tape out (2024-02) : prototype with full functionalities (power, readout, ...) ITS3-like

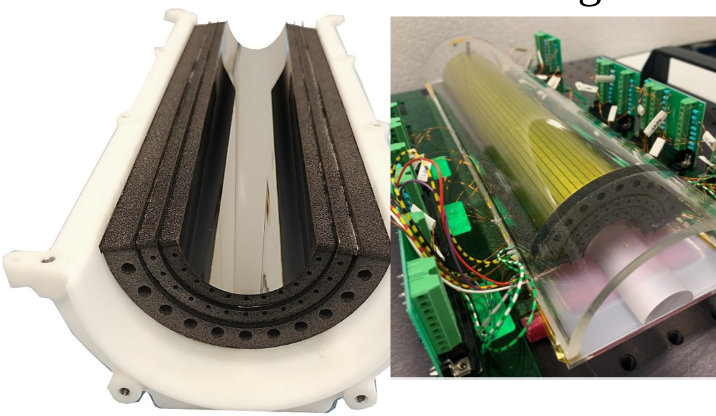
4. **ER3** tape out (2025-06) : final "production"



VI.1 – ITS3 project : state of the art 2022-10

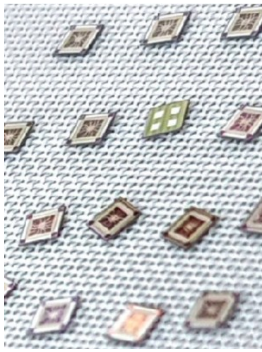


B. Mechanical integration, cooling test



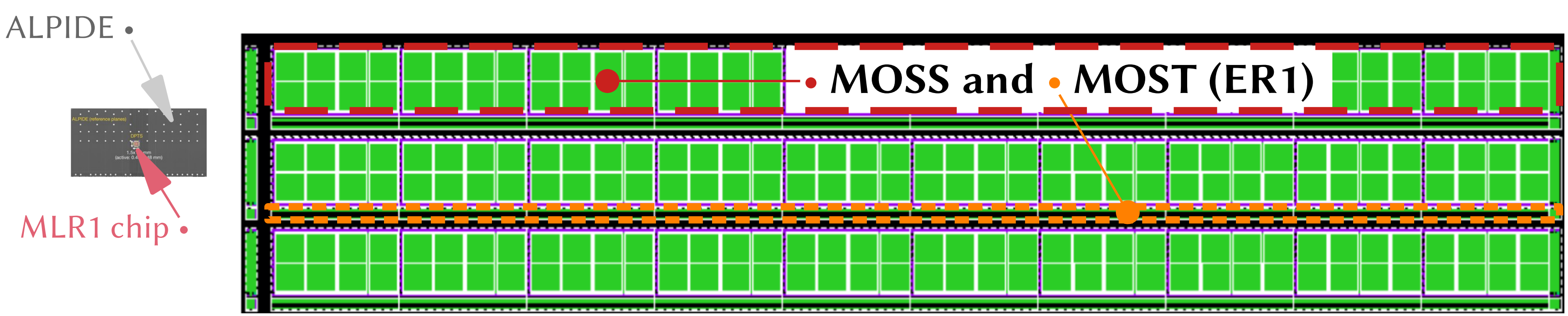
A.
- Beam tests of ***bent*** ALPIDE chips (*arXiv:2105.13000*)
- Beam tests with μITS3
- Construction of SuperALPIDE, ongoing

(i.e. ITS2 chip 50-μm thick, 180-nm technology)



C. from 180-nm CMOS technology to **65-nm** (Tower foundry) : MLR1

i) charge collection, **ok!** *ii*) ε **> 99%** *iii*) rad hard, **ok!**



D. 1D **Stitching** : wafer-scale "chip" (≈1.4x26 cm²), thinned (< 40 μm)

Part B – ITS3 among IN2P3 teams

VII.1 – ALICE France : ITS3 commitments under discussion

IPHC

- software :
  - . tracking, alignment, sensor response, simulations
  - . physics performances studies (*e.g. strangeness tracking*)
- electronic integration and microconnectivity (*SuperALPIDE*)
- sensor design (analog & digital)

©LaChaineMeteo

LPSC

- mechanics (*under definition*):
  - . support on integration R&D
  - . tooling (*e.g.* composite mandrels for assembly,
  - . cooling manifold (3D printing)
- readout back-end cards (*under definition*):
  - . unit (re)design, incl. firmware *(prototype in 2023-24, tested on ER2 sensors)*
  - . production

IP2I

- software :
  - . tracking
  - . physics performances studies (*e.g. jet tagging, strangeness tracking*)
- chip testing (*under definition*)
- beam test analysis (*under definition*)

- Signatories :
  >39 (physicists + engineers)
- budget request to IN2P3 :
  $\mathcal{O}$(500 k€)

VIII.1 – 1^{st} reason to commit : physics analyses

Heavy quarks (c,b) facing collectivity

- total cross-section of charm production for p_T>0 and $y \approx 0$ (baryons, mesons, quarkonia)
- single-charm baryons : $\Lambda_C^+(udc)$, $\Xi_C^+(usc)$, $\Xi_C^0(dsc)$, $\Omega_C^0(ssc)$ (with strangeness tracking)

→ hadronization of charmed quarks (recombination mechanisms)

\+ their sensitivity to the QGP medium (hydrodynamisation, chemical equilibration, thermalisation / transport coefficients)

ITS3 help : a drastic increase in the significance of the reconstructed signal + in the spatial precision

(increasingly complex decay topologies, typically ranging from 2 to 6 bodies)

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+ their sensitivity to the QGP medium (hydrodynamisation, chemical equilibration, thermalisation / transport coefficients)

ITS3 help : a drastic increase in the significance of the reconstructed signal + in the spatial precision (increasingly complex decay topologies, typically ranging from 2 to 6 bodies)

Interactions between hard partons and with medium constituents

- intra-jet modifications (jet shapes, jet structures, reconstructed using charged particles)
- interplay between jets and surrounding underlying-event
- di-jets with flavour-tagging (*i.e.* complete topological reconstruction of heavy mesons and baryons within the jets)

⟶ measurements on the energy losses of charm and beauty as a function of multiplicity/centrality

ITS3 help : high granularity + access to the tracks that make up the jets down to low p_T^{track}

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ITS3 help : high granularity + access to the tracks that make up the jets down to low p_T^{track}

Correlations between rapidity domains

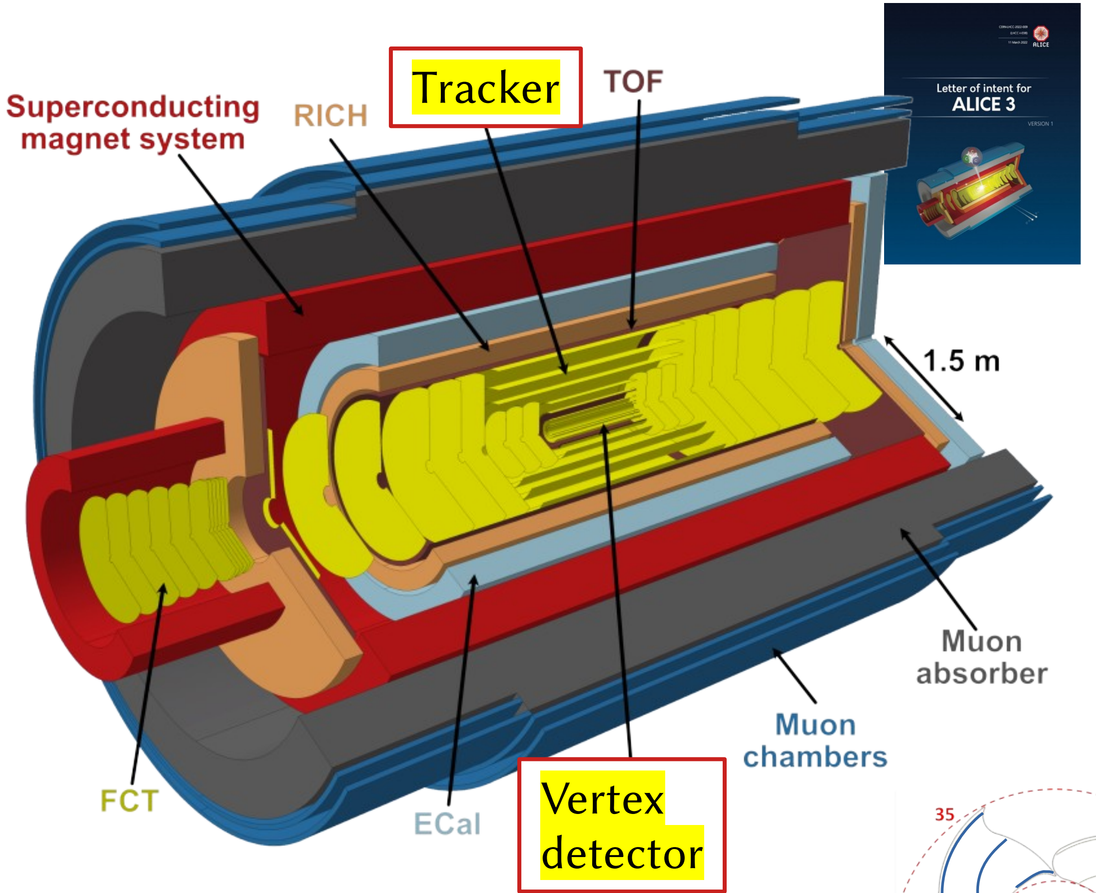
- correlation ITS3 ($|y|$ < 2.2) + MFT (y fwd)

→ map the event activity over a large y range

ITS3 help : ITS3 standalone tracking

VIII.2 – 2nd reason to commit : ALICE3 (Run 5, ≥ 2033)

ALICE3 LoI, *CERN-LHCC-2022-009*



Tracker,

Compact ($R_{\text{outer TOF}} \approx 85$ cm)

ultra-light (layer 0 ~ 0.1 % x/X_0)

All-Si (≈ 60 m²)

with high-performance tracking

(Axε, granularity, ...)

with **PID** capabilities

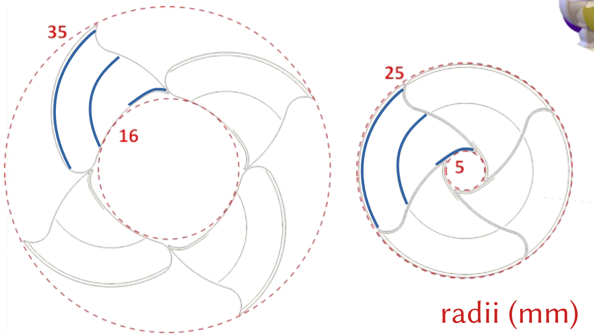
(iTOF, oTOF, RICH, ECal, μ)

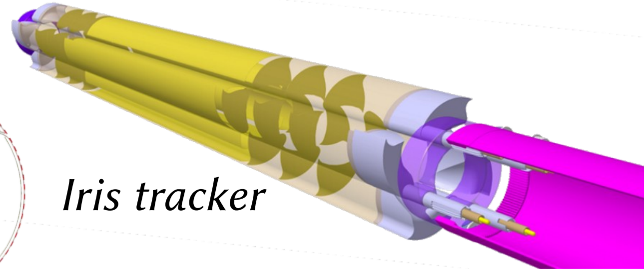
over wide **acceptance** :

- $|y| < 4$
- $p_T \in$ [**0.05** ; $\mathcal{O}(10)$] GeV/c

To collect integrated **MB luminosities** :

- ≈ 1 MHz recorded readout
- $\mathcal{O}(0.5\ \text{fb}^{-1})$ / month pp
- $\mathcal{O}(5.6\ \text{nb}^{-1})$ / month Pb-Pb





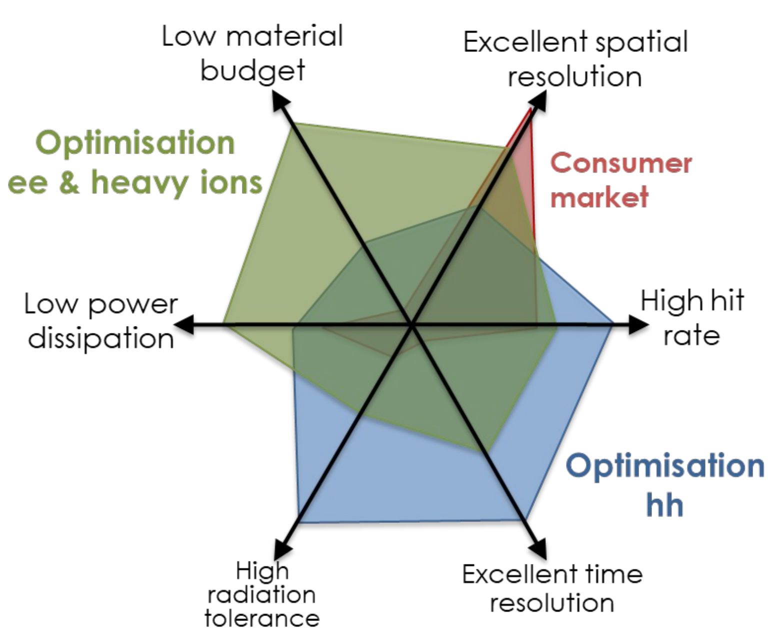
Iris tracker

VIII.3 – 3rd reason to commit : (e^+e^-) Higgs factories

A. Conclusion 1 out of 4 (*2021 ECFA roadmap*) :

"Develop cost-effective detectors matching the precision physics potential of a next-decade Higgs factory with beyond state-of-the-art performance, optimised granularity, resolution and timing, and with ultimate compactness and minimised material budgets"

B. Overlap of specifications : eA, pA, AA // e^+e^- !



Courtesy J. Baudot

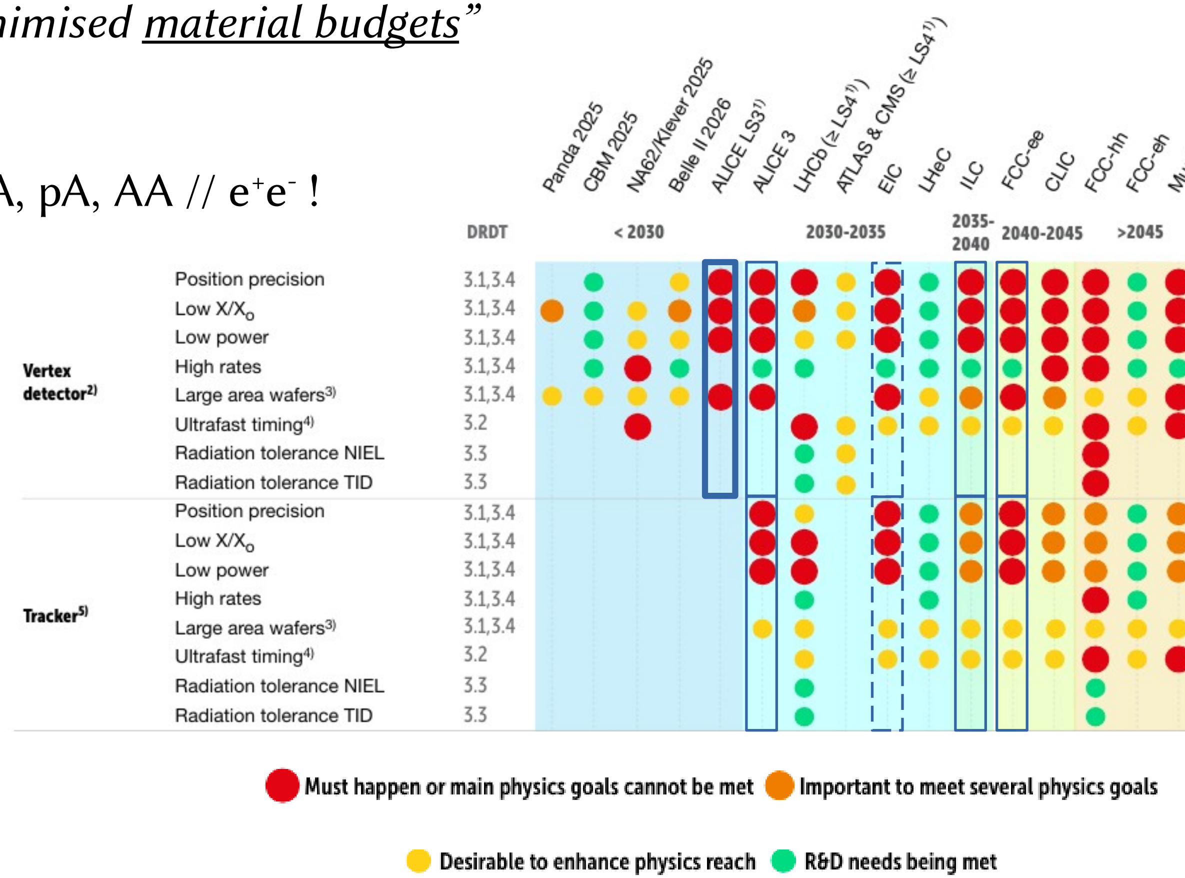


Fig. 3.1, 2021 ECFA roadmap

Conclusion : ITS3 triangulation

Peculiarities of the ITS3 project

- a continuous R&D project : ~R&D only, no construction phase per se.
- small surface to be equipped
- tightly bound logic of design, making mechanic design, sensor designs + physics perf. closely intertwined

ALICE-France in ITS3

- Expertises of the French community known, identified and recognised within the ALICE Collaboration :
  MAPS design, readout electronics, integration, tracking, data analysis
  ⟶ Something to build further upon.
- ITS3 project approached since its early stages (2019)
  ⟶ Strategic roles offered, on time and in position to take them

- unprecedented physics roads open for ALICE : hyper-granular, ultra-light, proximity to beam line.

  "finer, lighter, closer, cooler, (faster?) ... better"

  ⟶ higher $A \times \varepsilon$ at low p_T (fake hit rate under clean control) + better pointing resolution

  Important for event activity, 2 to 6 body decays of heavy hadrons, charged-jet, correlations mid-y / forward y

IN2P3 extra-interests in the enterprise

- ITS3 = instrumental driver paving the road for future trackers in HEP (e.g. ALICE3 but also FCC-ee, ILC, C^3, ...)
- ITS3 = unique opportunity in the decade to come to tackle and master :
  - the 65-nm technology node for a forefront project in a large HEP experiment
  - bending MAPS
  - stitching

Appendices

- A – ITS2 + MFT for Run 3 [2022-2025]
- B – ALPIDE chip
- C – ITS3 : MAPS bending R&D
- D – ITS3 : 65-nm technology + stitching
- E – ITS3 : mechanic R&D
- F – ITS3 as a project
- G – IN2P3 in the project
- H – ALICE3
- I – Template for QCD+QGP phys. cases

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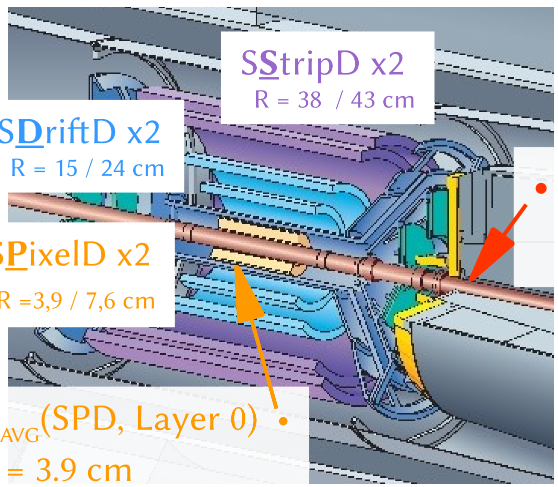
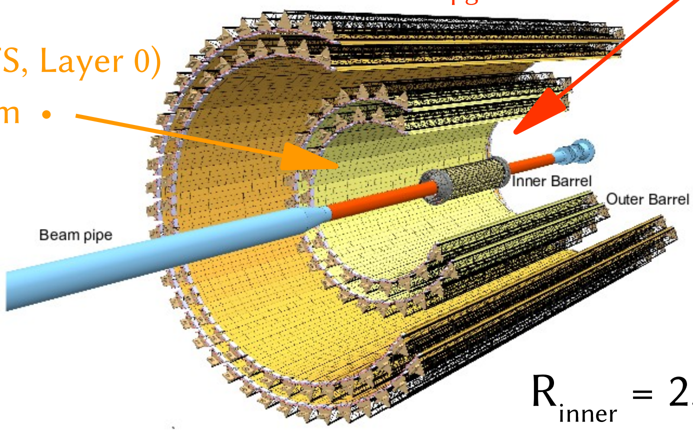
App. A – ITS**2** + MFT

A.1 – ITS2 : from ITS1 to ITS2

ITS Runs 1+2

ITS upgrade Runs 3+4





3 technologies : pixels, drifts, strips
6 layers

- x/X_0 (per layer) ≥ 1.1%

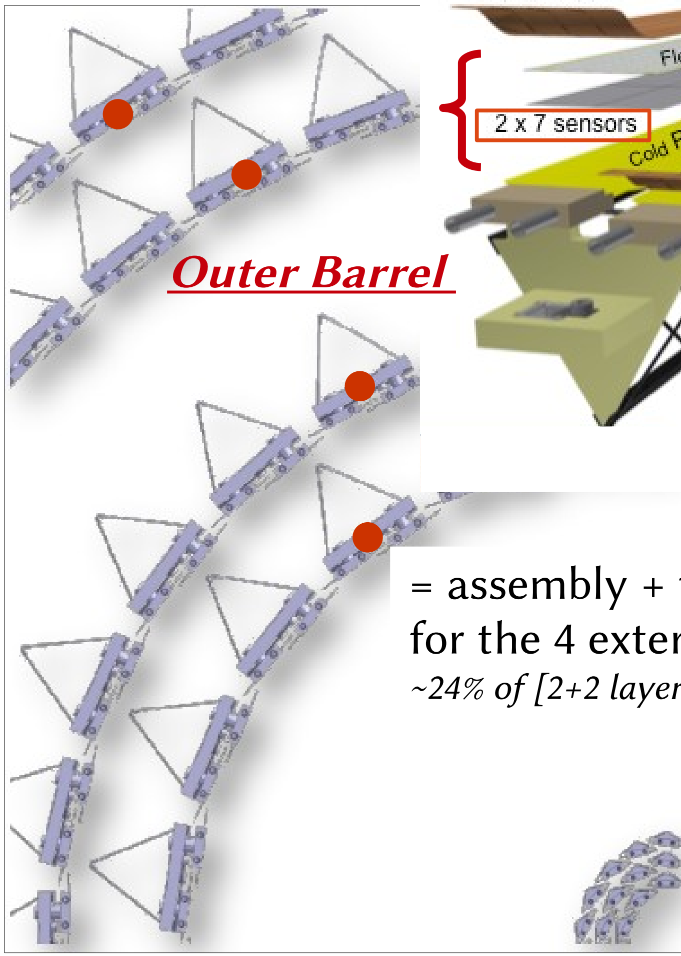
→ x/X_0 (ITS1) ~ 7.4%

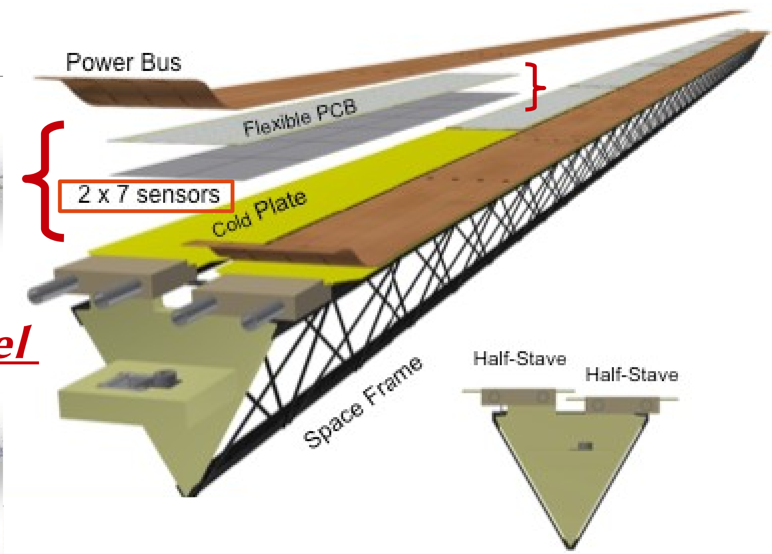
Single technology : CMOS (ALPIDE)
7 layers

- IB, Layer 0,1,2 : x/X_0(per layer) ~0.35%
- OB, Layer 3,4,5,6 : x/X_0(per layer) ~0.85%

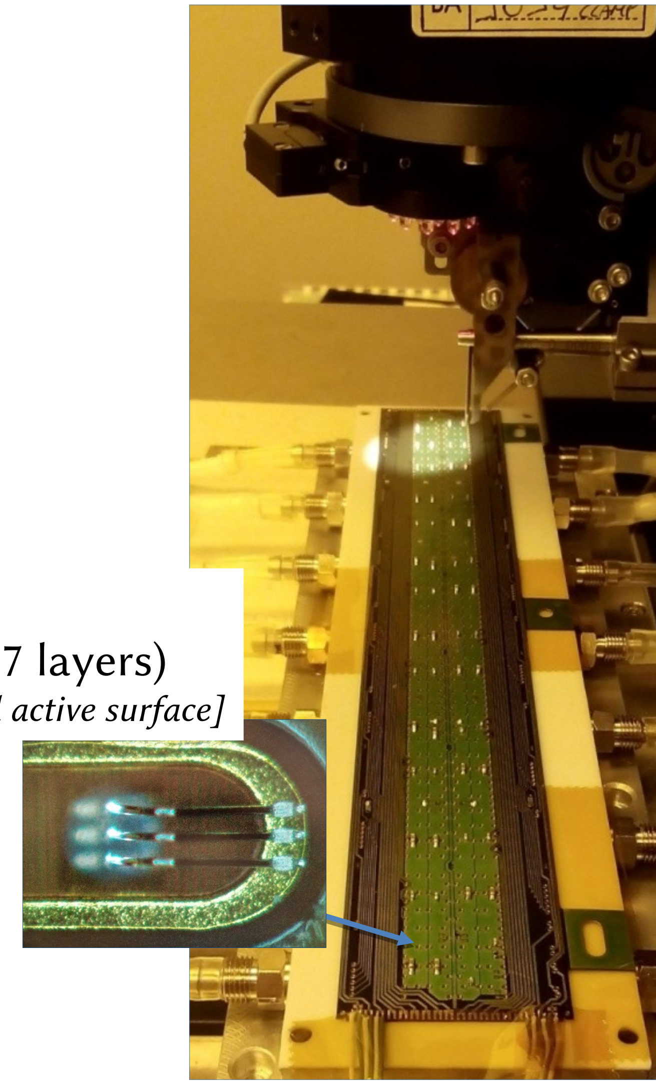
→ x/X_0 (ITS2) ~ 6.9%

A.2 – ITS2 : instrumentation, assembly ITS2





= assembly + tests of 2x7 CMOS sensors
for the 4 external layers of the ITS2 (out of 7 layers)
~24% of [2+2 layers = 2.3 + 6.9 m^2 = 25% +73% of the total active surface]



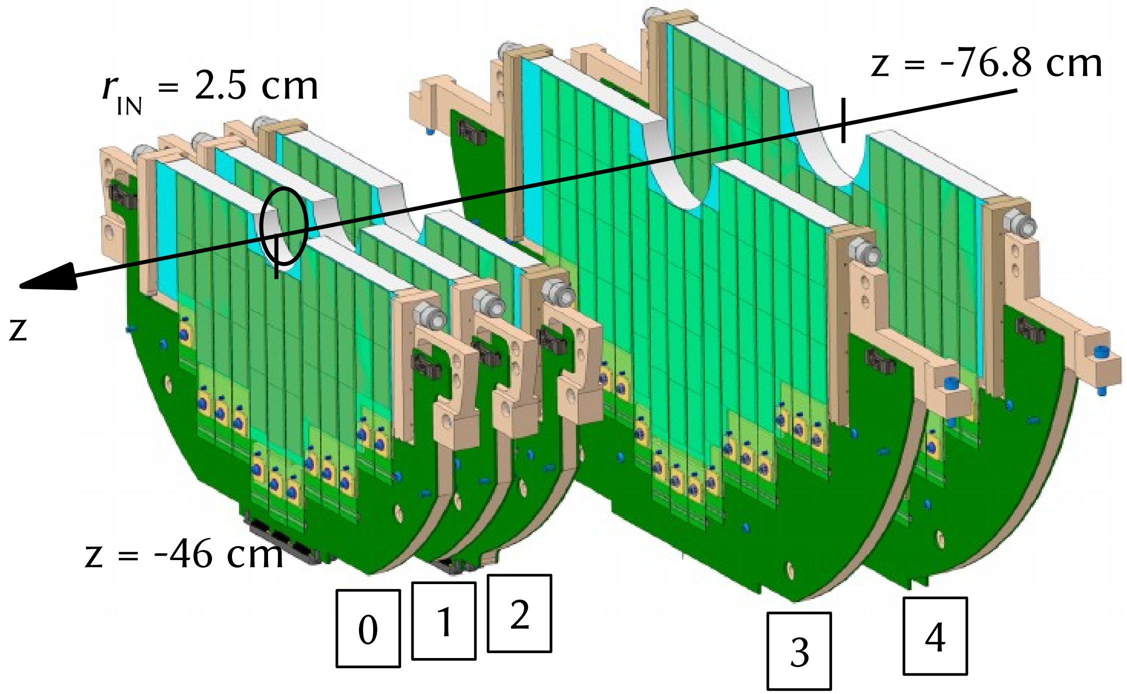
Bonding : YouTube

1. Production of ~585 modules (=25% of the total) (2017-11-2019-05)
2. Commissioning (2019-2021)
3. Data taking (2021-)

A.3 – MFT : layout

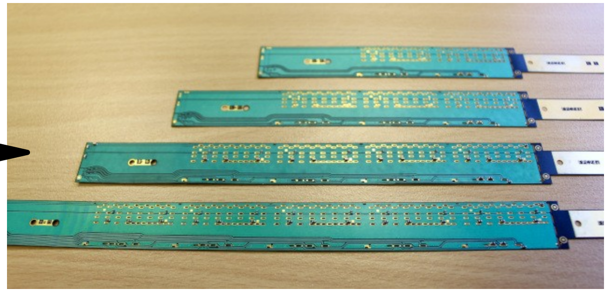
MFT = vertexing ahead of μ spectrometer
$-3.6 < \eta < -2.5$

(NB : in front of absorber,
no sensitive magnetic field)



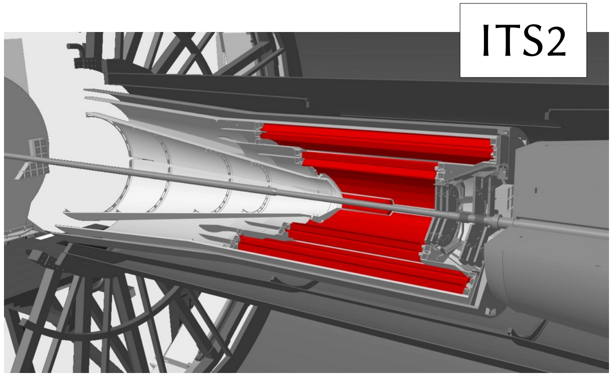
Components :
5 disks split into 2 halves
each disk = 2 sides of detection

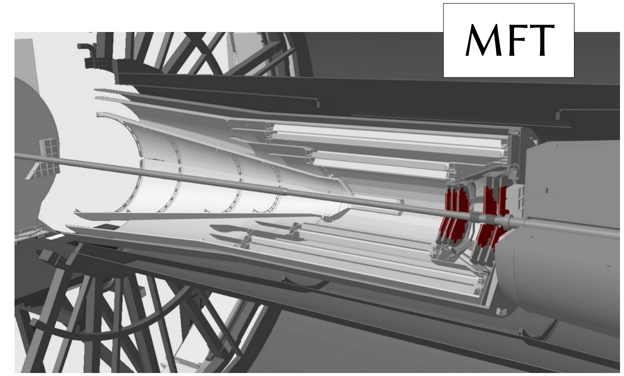
280 ladders out of 920 silicon sensors (2 to 5 chips/ladder) •
0.6 % x/X^0 per disk



NB : MFT doses (700 krad) over 10 years of operation,
~same ballpark as ITS inner layer

A.4 – ITS2+MFT : ALICE-France MAPS commitments

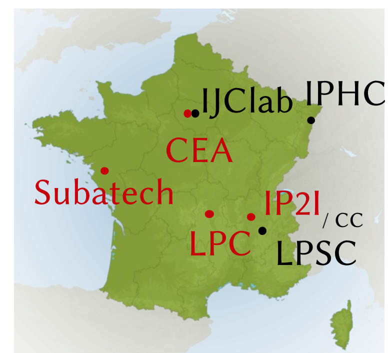




Total cost :
15.4 MCHF

In2p3 :
≈ 800 k€

LPSC : • assembly tool
IPHC : • module assembly
585 modules /~2500
(*2x7 chips glued, bonded on flexible circuit*)
• Coordination WG tracking/simul°/phys perf.



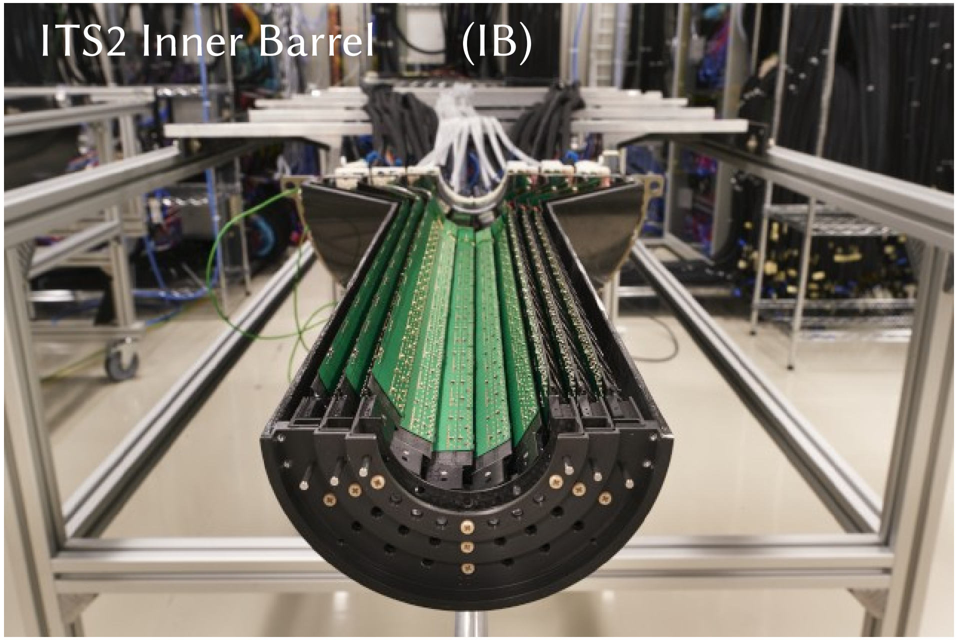
Total cost :
3.35 MCHF

In2p3 :
≈ 1.4 M€

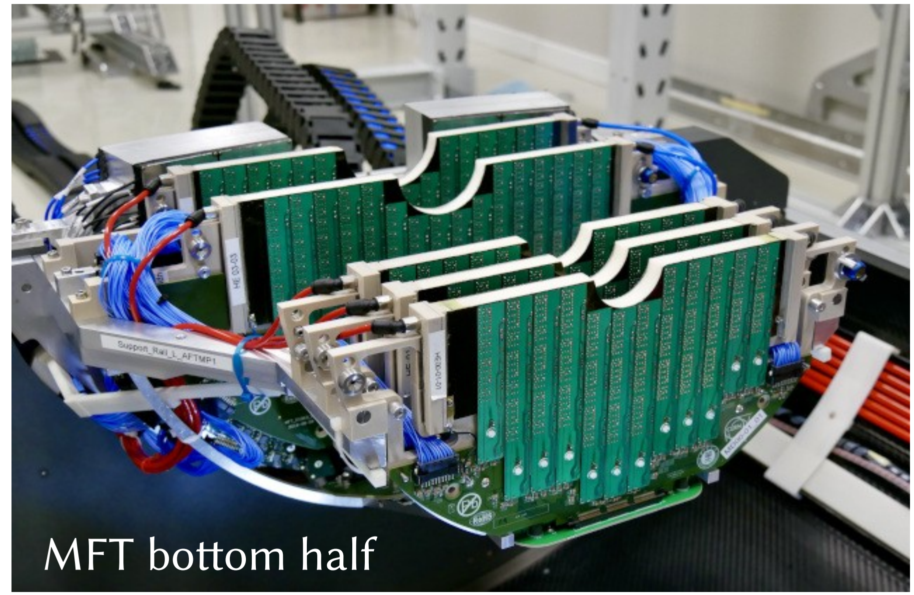
- Project leader
- Full detector construction
  → 8 out of 9 WG led by In2p3/CEA staff
- Coordination WG tracking/simul°/phys perf.

+ Read-out firmware of Common Readout Unit CRU (LPSC)

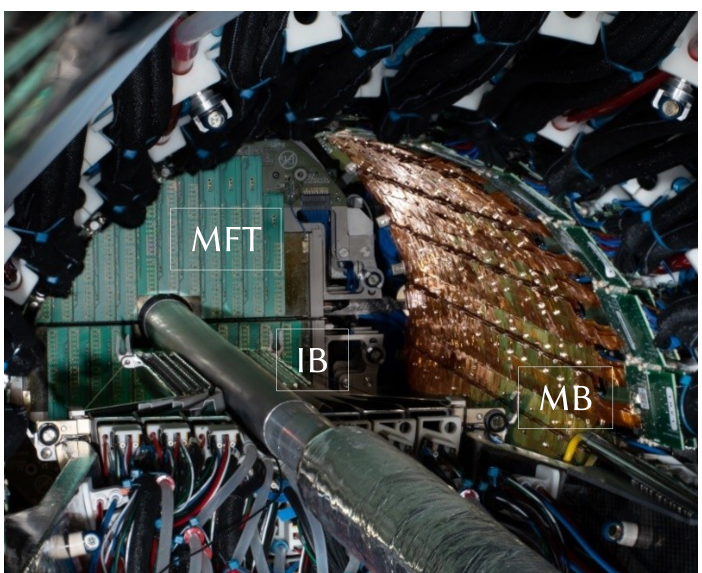
A.5 – ITS2+MFT : pictures



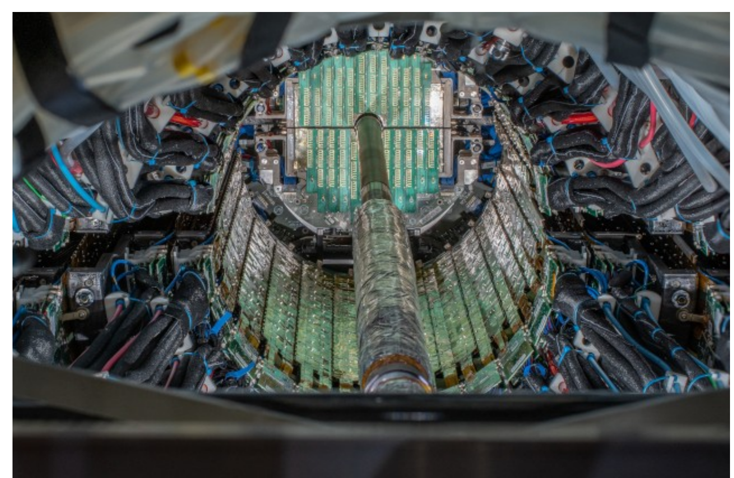
ALICE-PHO-GEN-2021-002



OPEN-PHO-EXP-2020-004



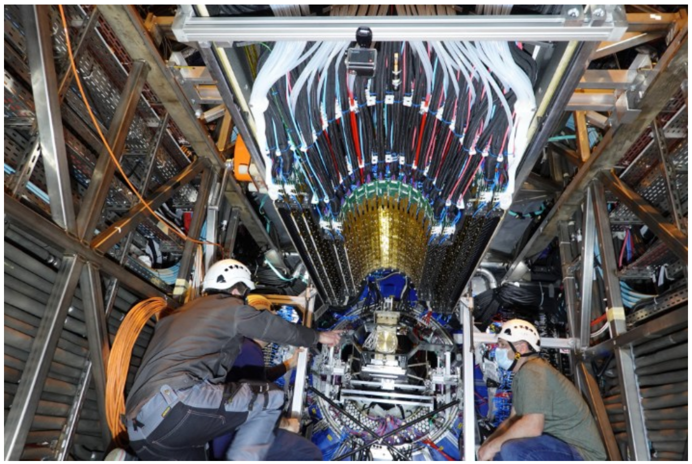
ALICE-PHO-GEN-2021-002



ALICE-PHO-ITS-2021-002

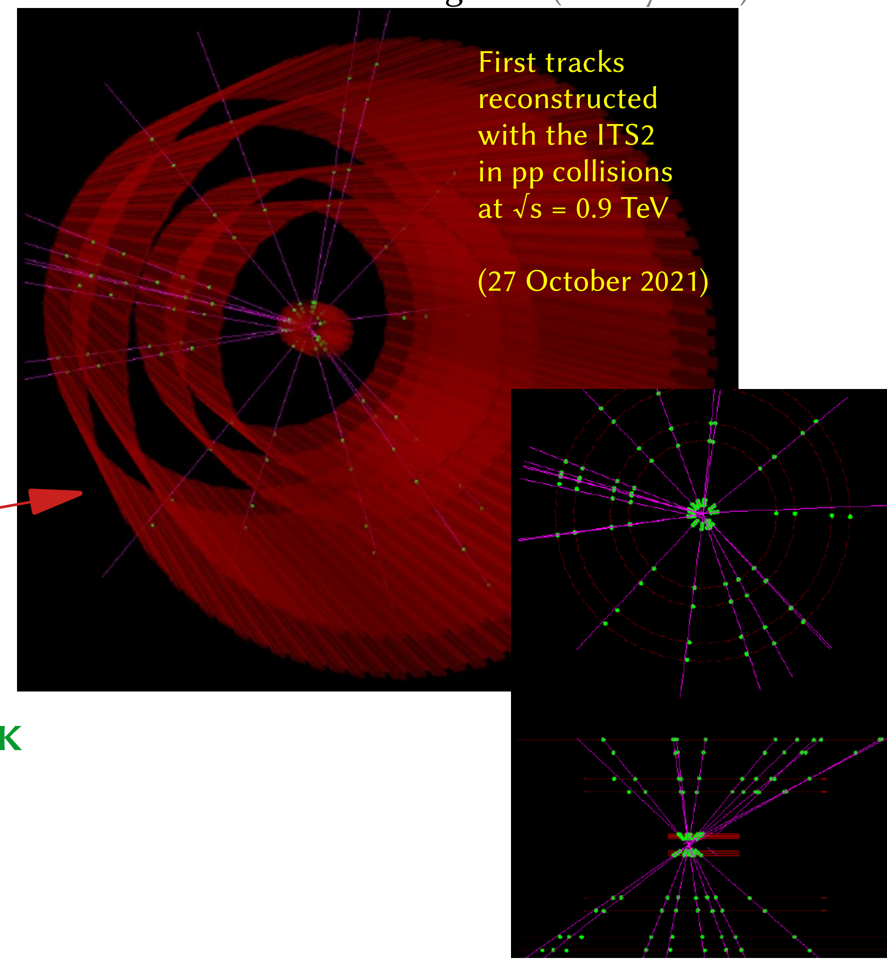
A.6 – ITS2 : installation+commissioning

ITS2 installation at LHC Point 2 (Jan. to May 2021)



- *Global commissioning ALICE* *(≥ July 2021)*
- *LHC pilot beam test* *(18-31 October 2021)*
- *Proton beams at 6,8 TeV* *(25 April 2022)*
- *Stable collisions pp $\sqrt{s}$ = 13,6 TeV* *(July 2022)*

Commisioning ITS2 (≥ May 2021)



Status point

- Power supplies, readout, Detector Control System, Cooling: **OK**
- Reconstruction algorithms + simulations, calibration: **OK**
  - . Acceptance (operational modules): **> 98%**
  - . Detection efficiency **> 99%** on average
- **Alignment:** 1st version + improvements, ongoing

Responsabilities ALICE-IPHC :

a) Coordination of the development/installation of **detector control system** and **cooling** for **ITS2**

b) **Installation** of readout electronics and detector cabling

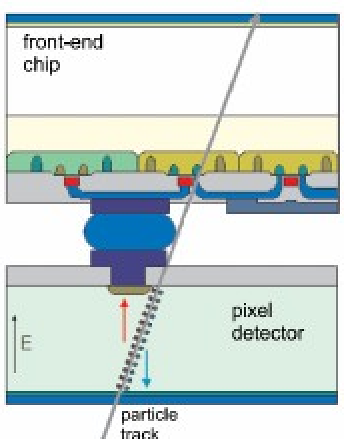
A.7 – MFT : installation+commissioning

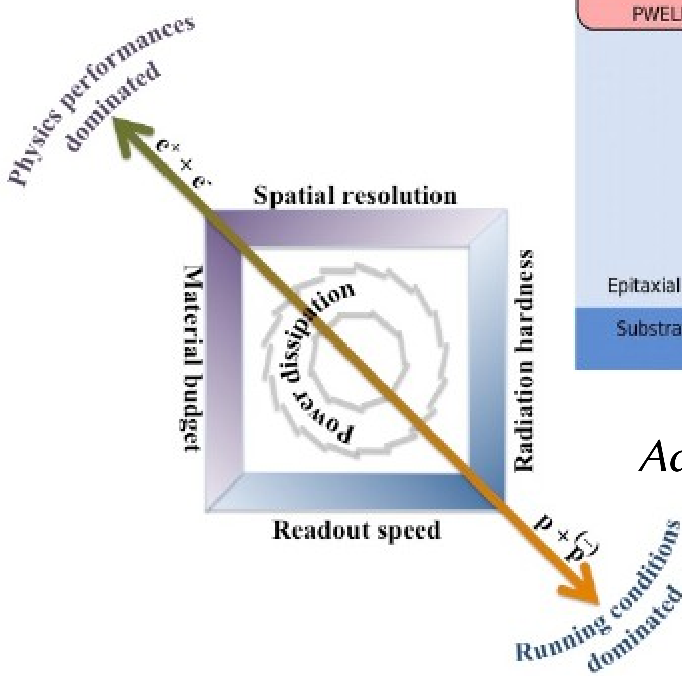
Back to App. TOC

App. B – ALPIDE chip

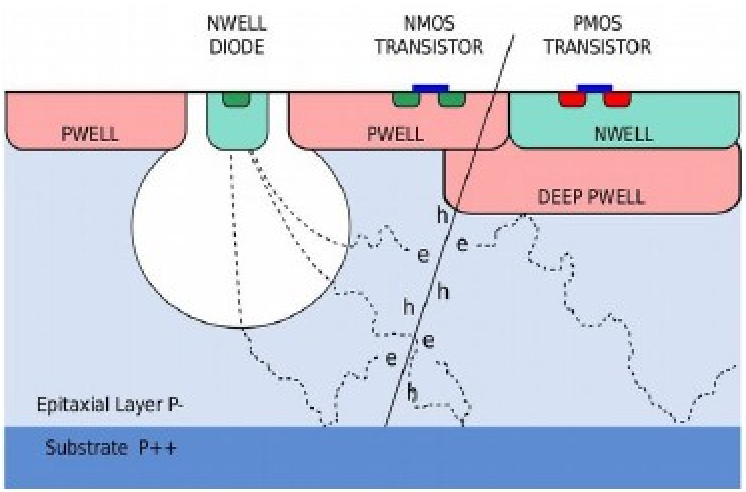
B.1 – Pixel detectors : Monolithic Active vs Hybrid techno.

<u>Hybrid pixel sensor</u>





<u>CMOS pixel sensor</u>

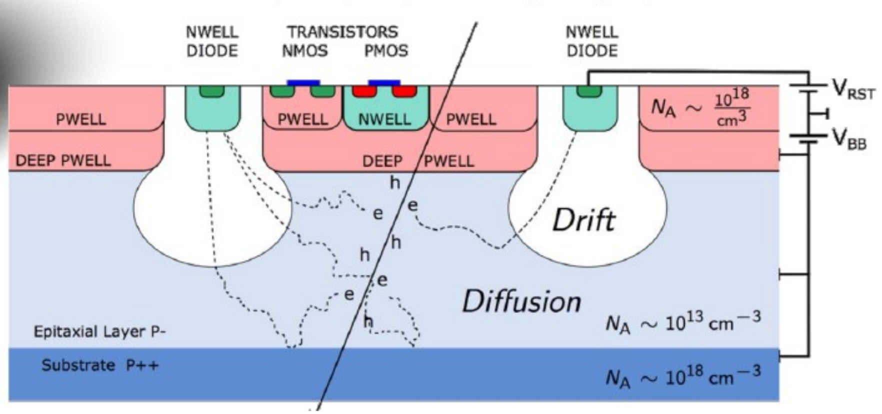


Advantages :
- faster readout
- better radiation-hardness
- ...

Advantages :
- thinner
- smaller pixel size accessible
- lower power consumption
- cheaper
- ...

B.2 – ALPIDE : chip characteristics

- **Process:** Tower Semiconductor 180 nm CIS
  - deep p-well to allow CMOS circuitry inside matrix
  - reverse-substrate bias
- **Detection layer:** 25 µm high-resistive (>1 kΩcm) epitaxial layer
- **Thickness:** 100 µm (OB) or 50 µm (IB)



- **Front-end:** (9 transistors, full-custom)
  - continuously active
  - shaping time: < 10 µs
  - power consumption: 40 nW
- **Multiple-event memory:** 3 stages (62 transistors, full-custom)
- **Configuration:** pulsing & masking registers (31 transistors, full-custom)
- **Testing:** analogue and digital test pulse circuitry (17 transistors, full-custom)
- **Readout:** priority encoder, asynchronous, hit-driven

O(200) transistors / pixel (wrt. 3T/4T)

M. Mager, CERN Detector Seminar 2021-09-24

B.3 – ALPIDE : ALPIDE chip

ALICE ITS, arXiv:2105.13000

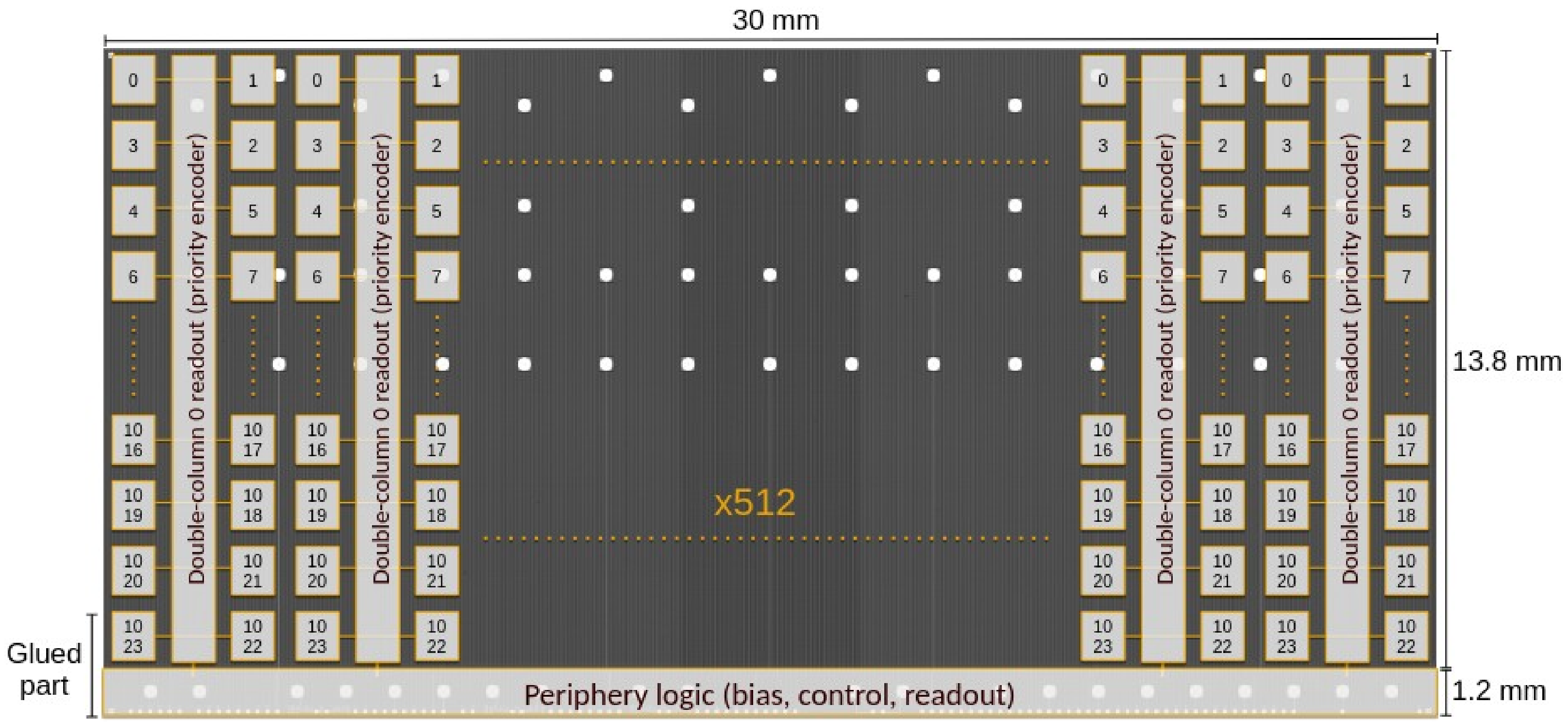
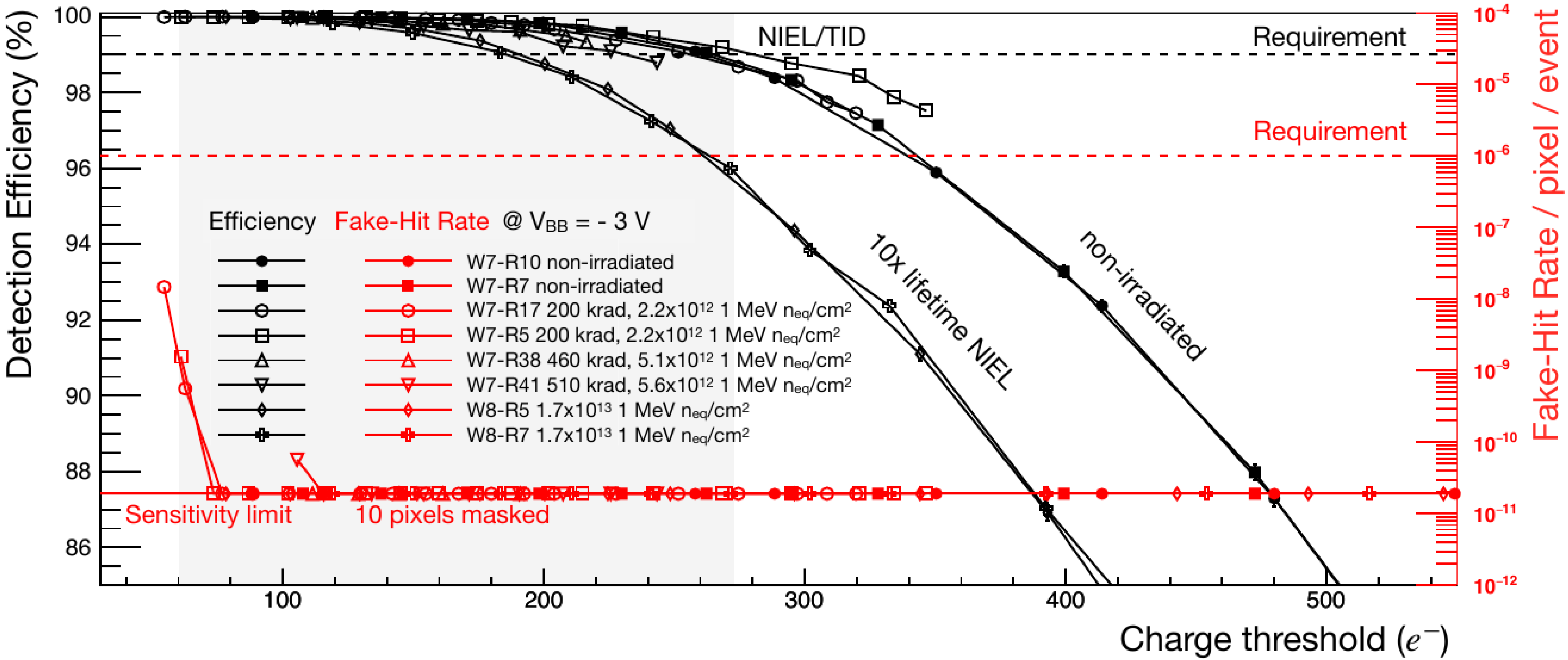


Figure 1: Layout of the ALPIDE pixel matrix. The pixels are organised in double-columns, each featuring a priority encoder circuit which propagates the addresses of the hit pixels to the periphery logic. The aluminum pads providing the electrical interface to the chip are located on the top of the periphery logic.

B.4 – ALPIDE : detection efficiency / Fake Hit Rate



10 pixels masked in 512 x 1024 = 2^{19} = 524 288 pixels/ALPIDE chip

⟶ 10/524 288 ≈ 2. 10^{-5} level

B.4 – ALPIDE : detection efficiency / Fake Hit Rate

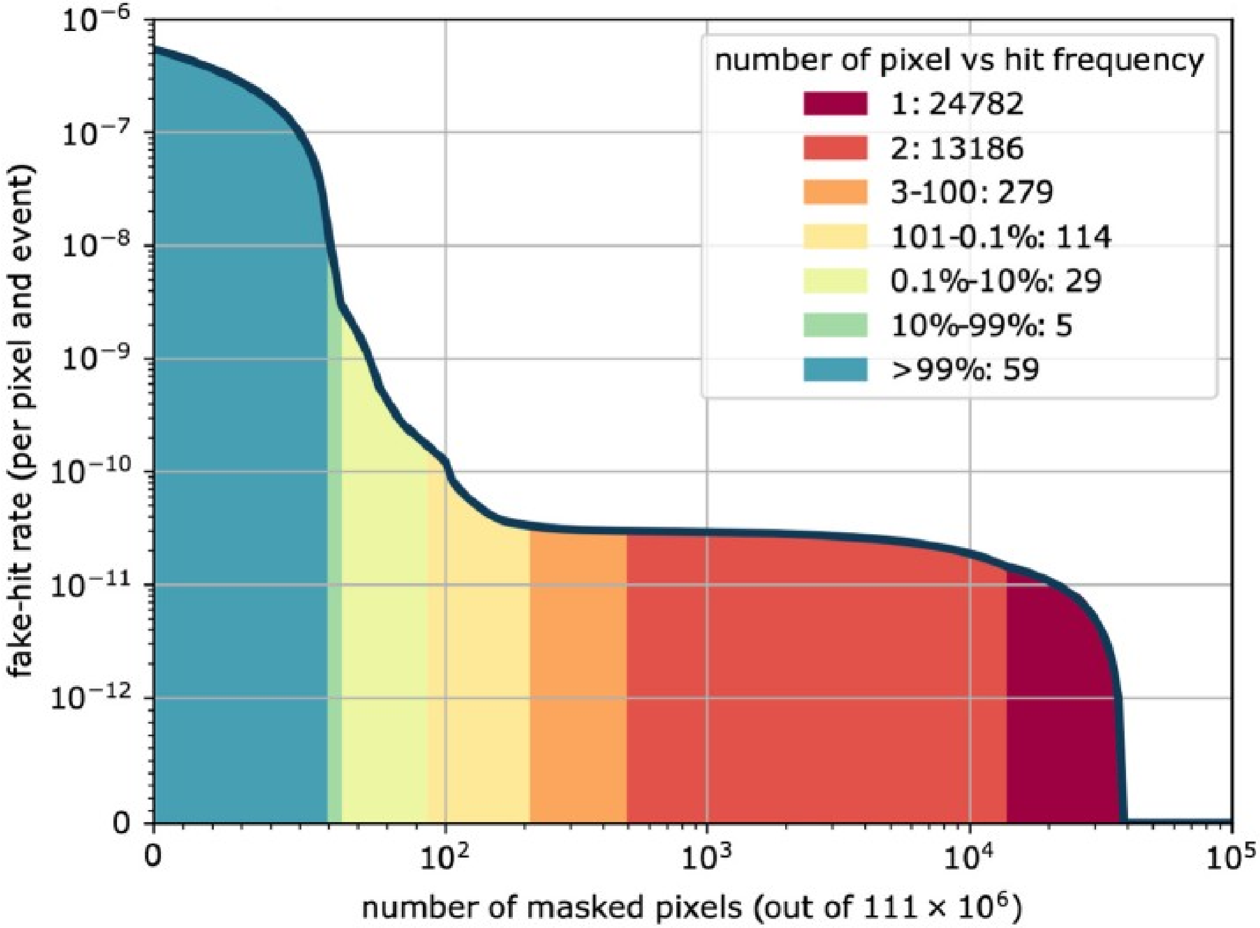


Figure 32: Fake-hit rate of an inner half-barrel as function of the number of masked pixels. Colors indicate how often a pixel fired in 15×10^6 events acquired at a trigger rate of 50 kHz using a charge threshold of $100\,e^-$, e.g. there were 24782 pixels which fired once in the sample.

B.5 – ALPIDE : spatial resolution / average cluster size

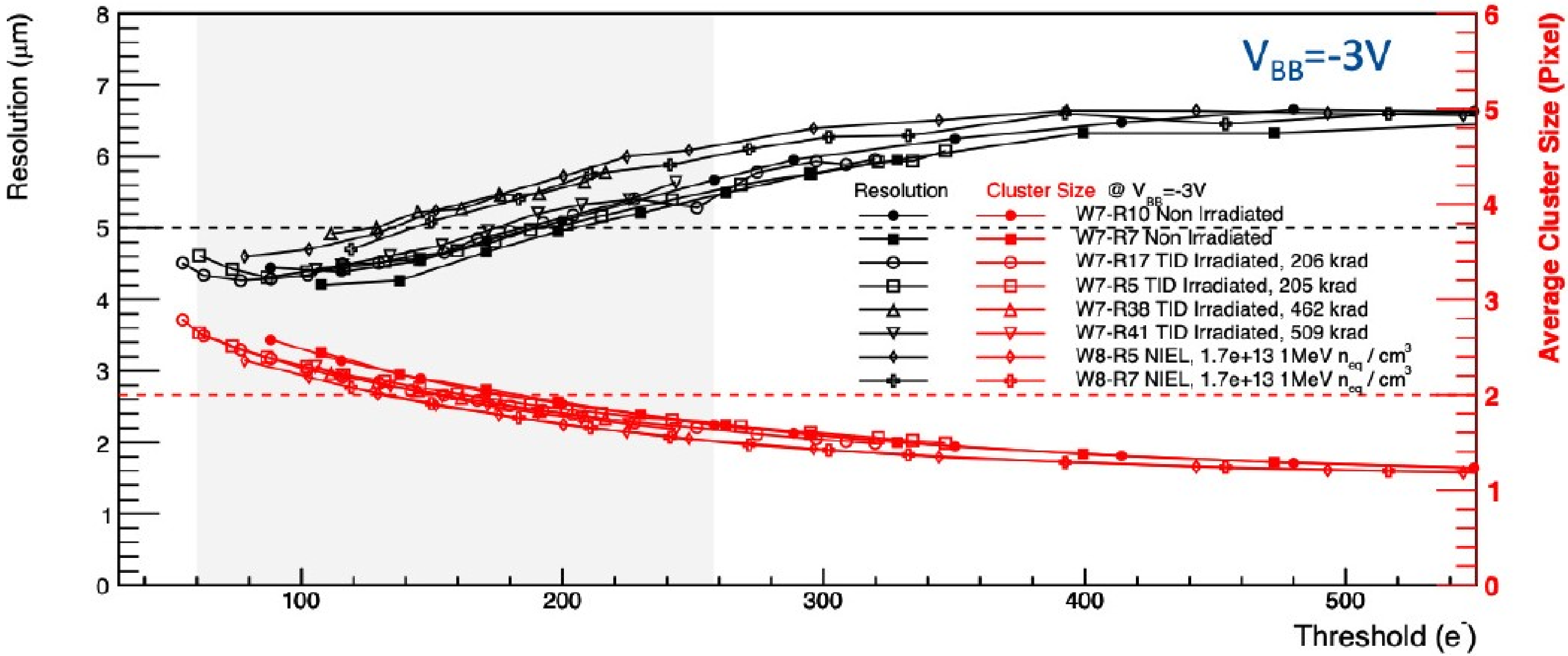
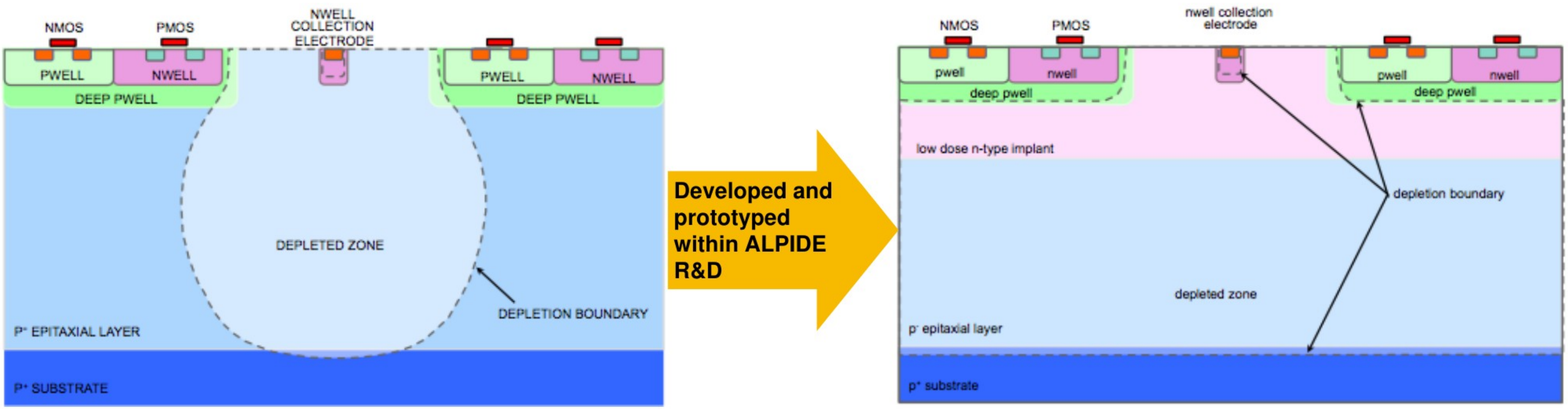


Figure 13: ALPIDE sensor chip hit-position resolution and average cluster size vs global threshold setting. Beam test results (6 GeV/c pions, orthogonal incidence). ALPIDE substrate reverse bias: −3 V.

process modification, depleted MAPS — ITS2 "side project"

ALICE

Foundry standard process | **Modified process CERN/Tower**



Partially depleted epitaxial layer
Charge collection time < 30 ns
Operational up to 10^{14} 1 MeV n_{eq}/cm^2

Fully depleted epitaxial layer
Charge collection time < 1 ns
Operational up to 10^{15} 1 MeV n_{eq}/cm^2

W. Snoeys et al, https://www.doi.org/10.1016/j.nima.2017.07.046

Courtesy Magnus Mager

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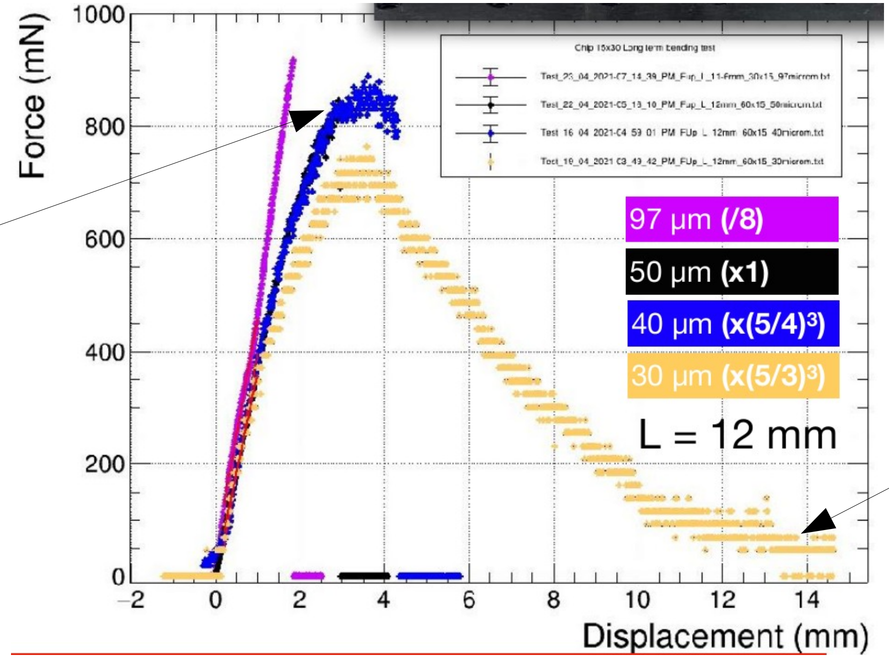
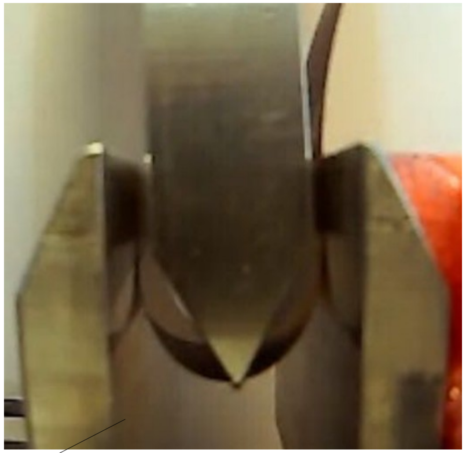
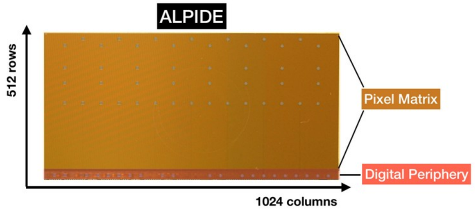
App. C – bending R&D

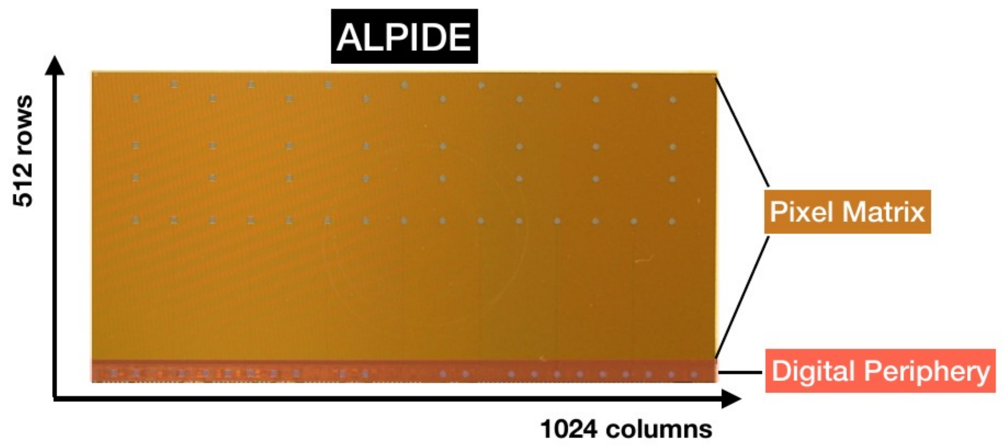
C.1 – MAPS bending : ALPIDE bending flexibility

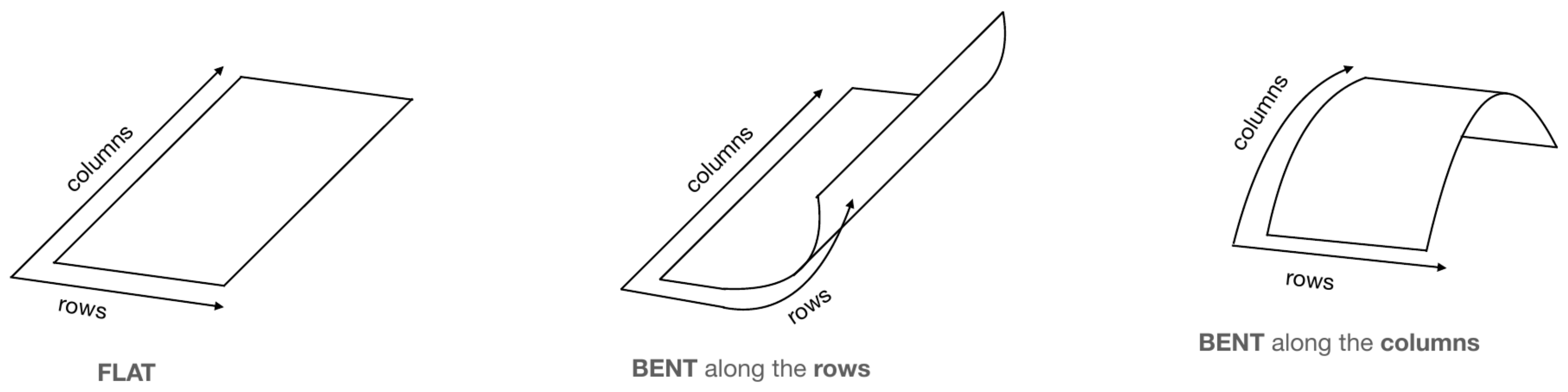






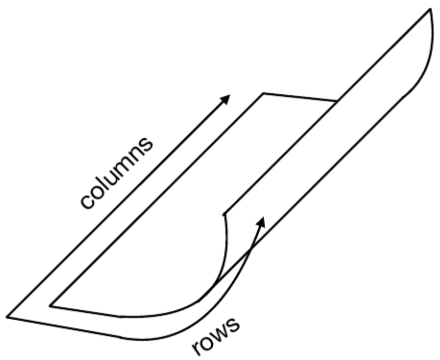
C.2 – MAPS bending : ALPIDE bent sensors





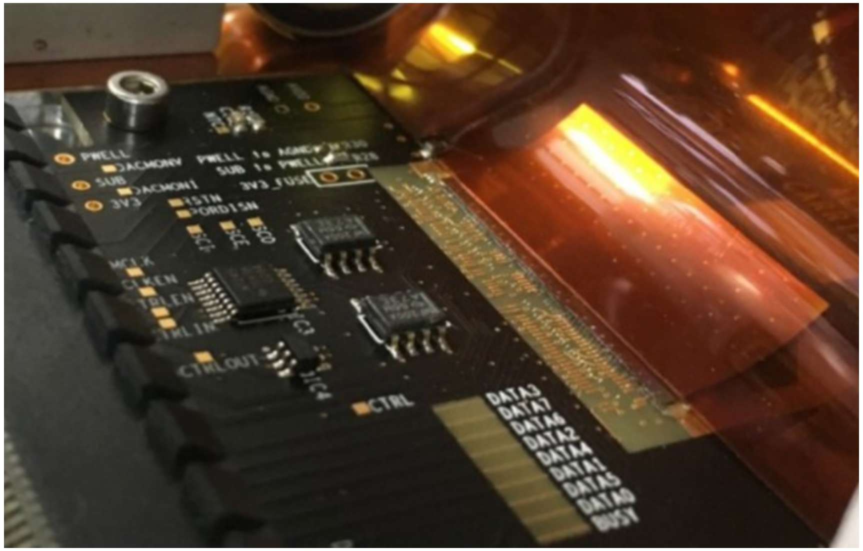
C.3 – MAPS bending : ALPIDE bent sensors, inefficiency

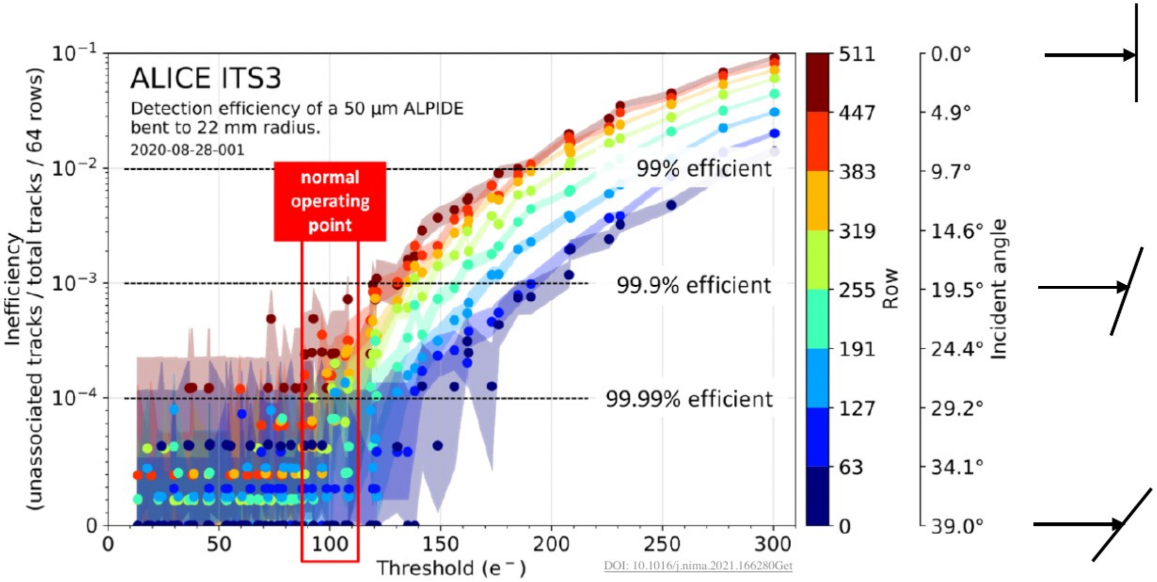
ALICE ITS, arXiv:2105.13000



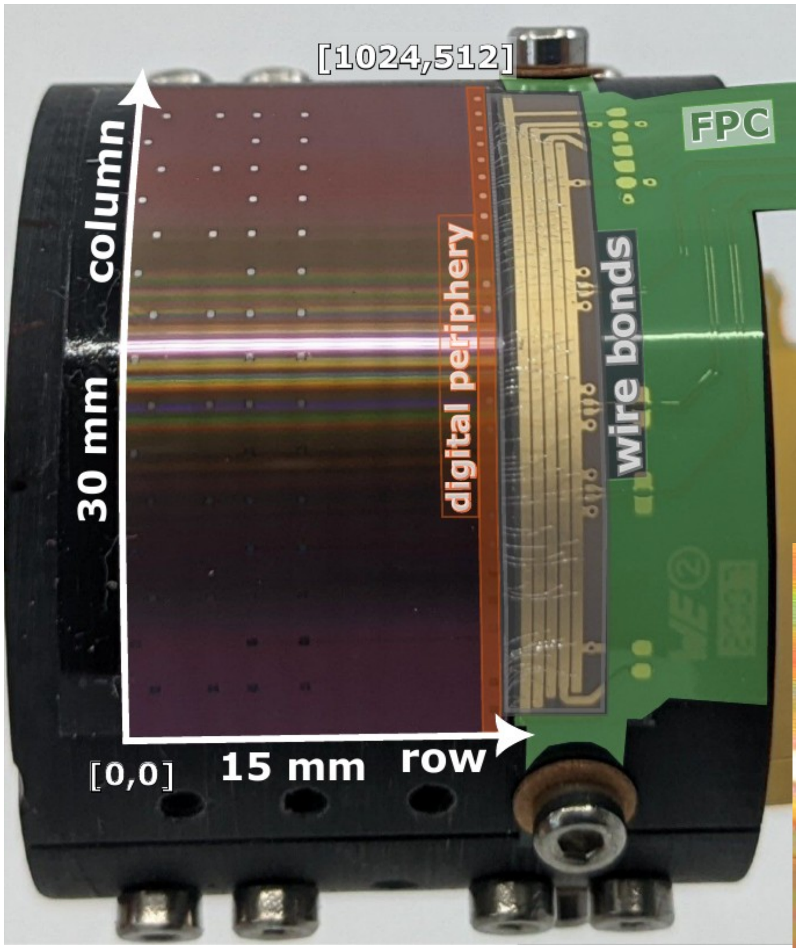
BENT along the **rows**

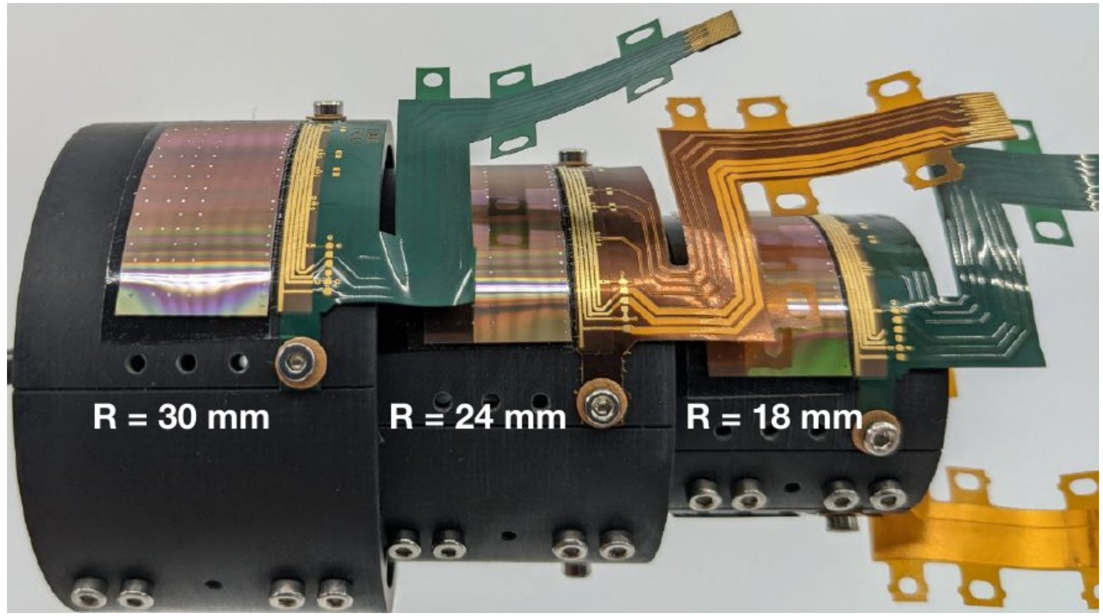
- ALPIDE bent along rows with flat digital periphery
- Demonstration : electric functionality and efficiency compatible with flat ALPIDE

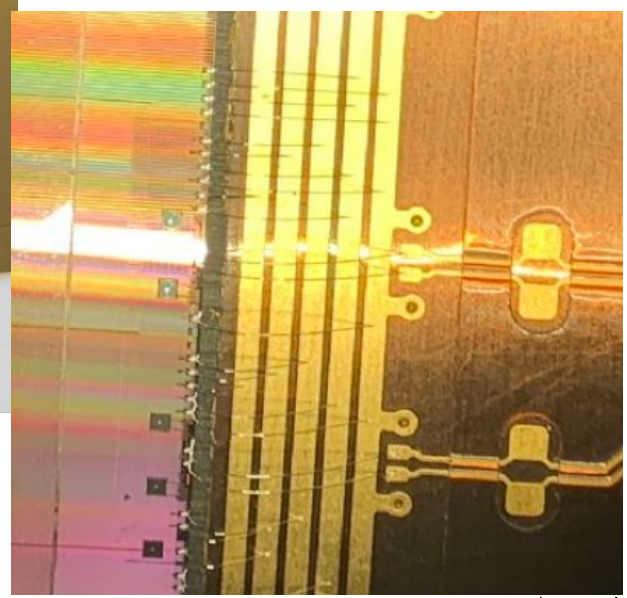




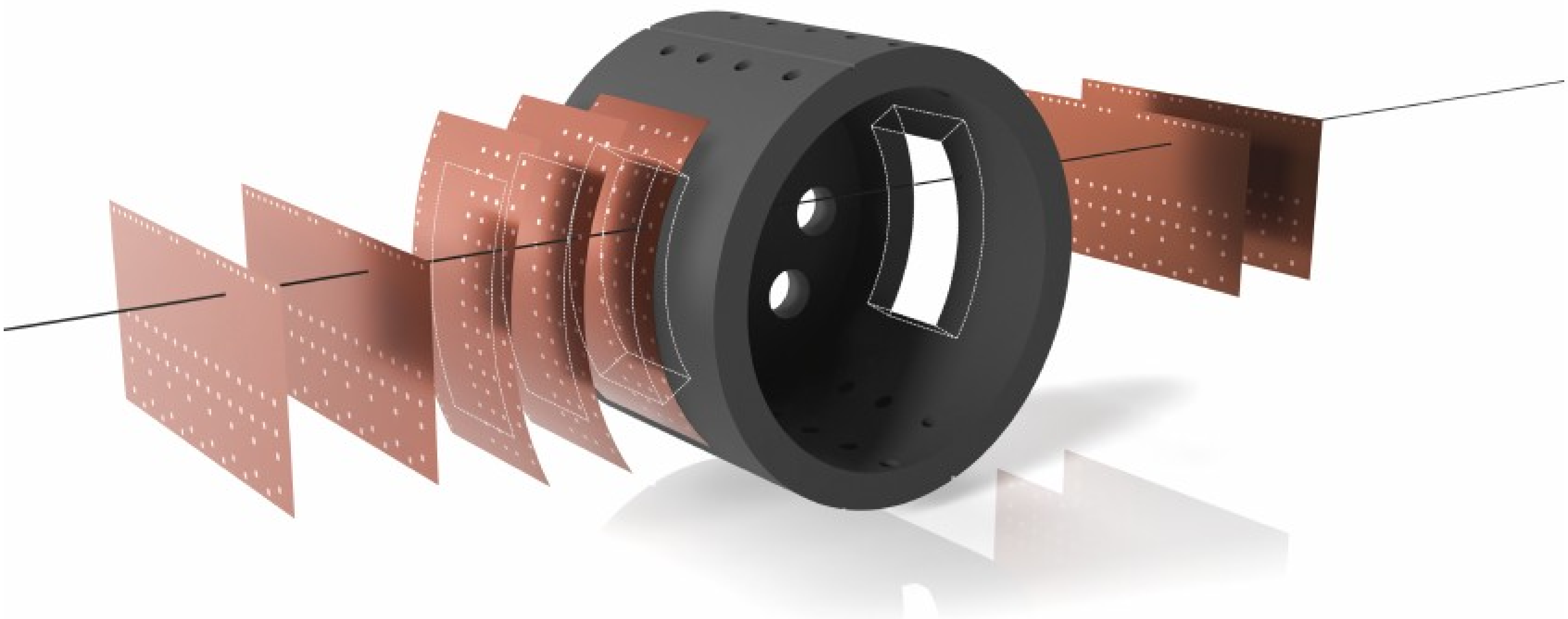
C.4 – MAPS bending : ALPIDE bent sensors, µITS3



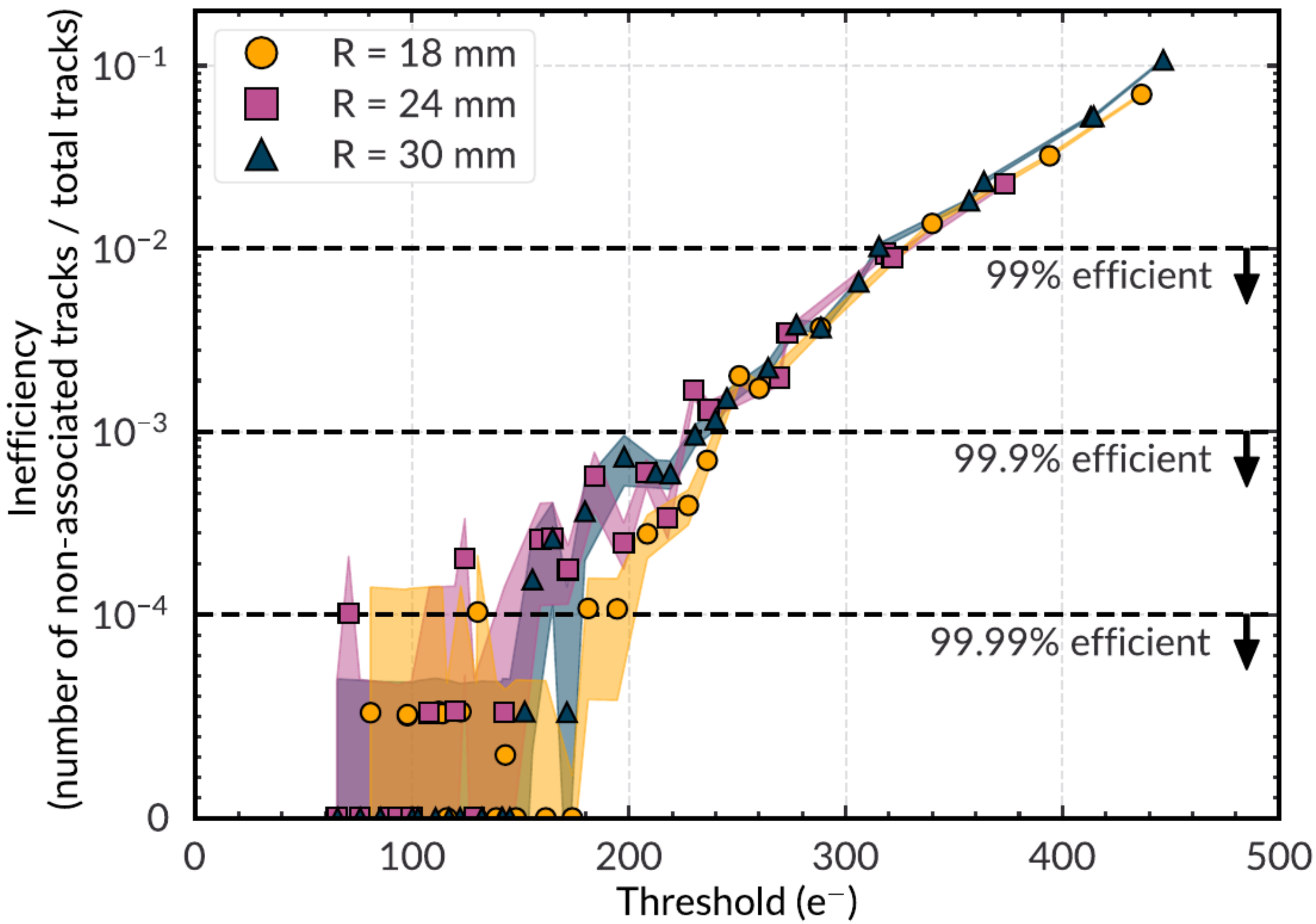




C.5 – MAPS bending : µITS3 under beams



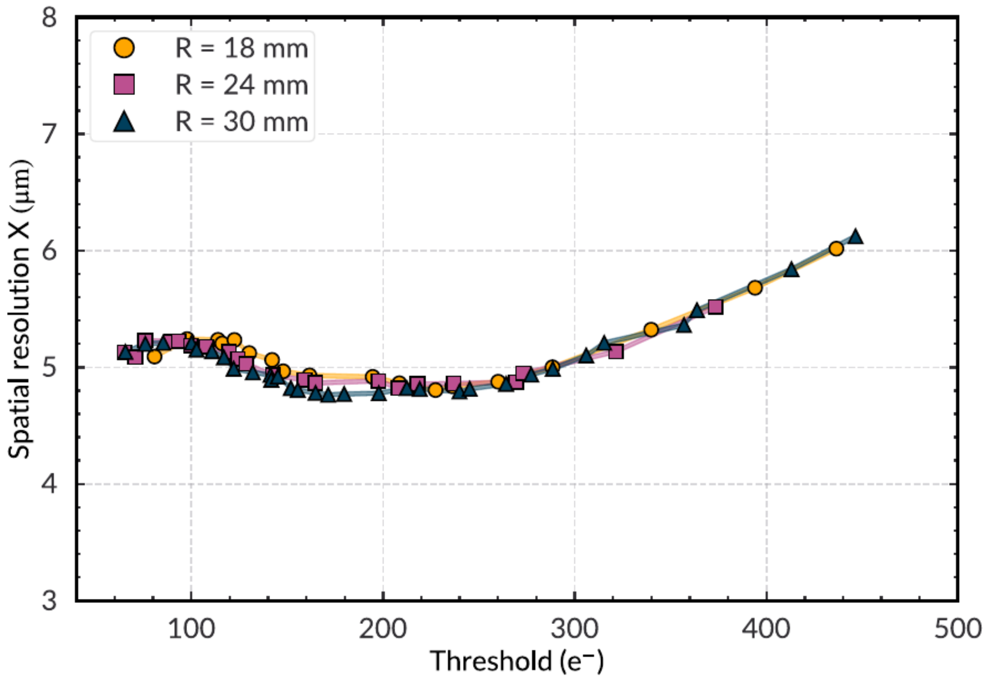
C.6 – MAPS bending : μITS3, detection inefficiency

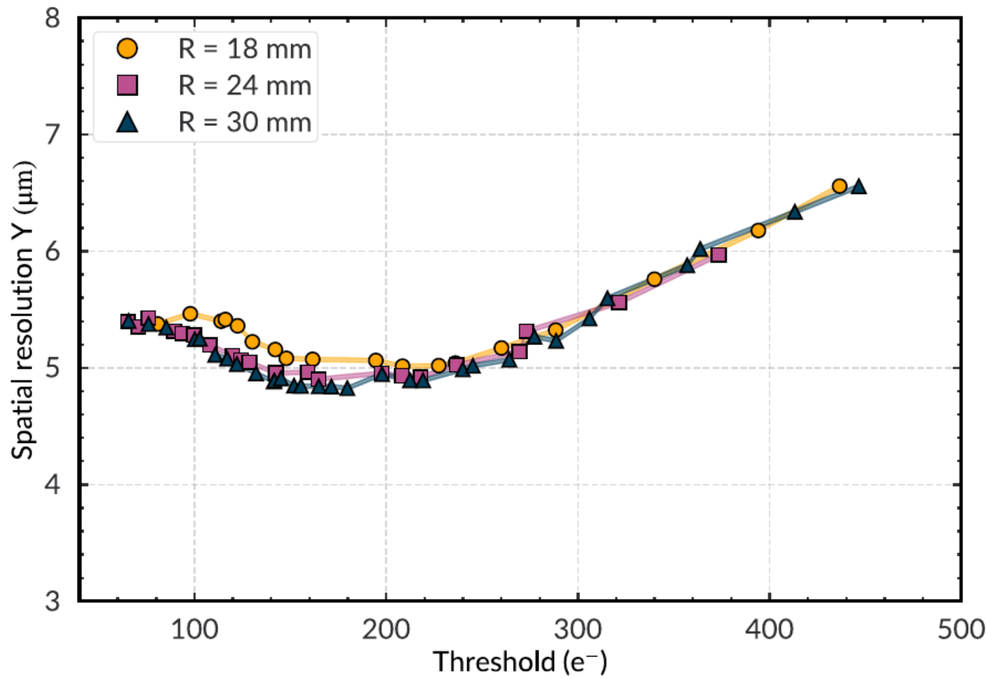


- No effects on bending radius observed
- Inefficiency compatible with flat ALPIDE
- Consistent with published results where chip was bent in the other direction

Lucas Lautner, ALICE Upgrade Week 2022-10
https://indico.cern.ch/event/1183733/contributions/5045649

C.7 – MAPS bending : μITS3, spatial resolution

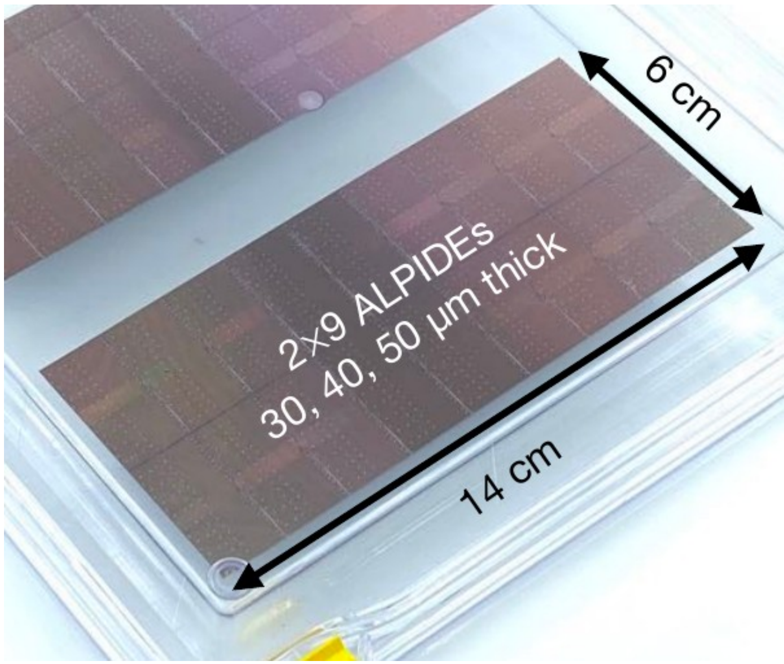


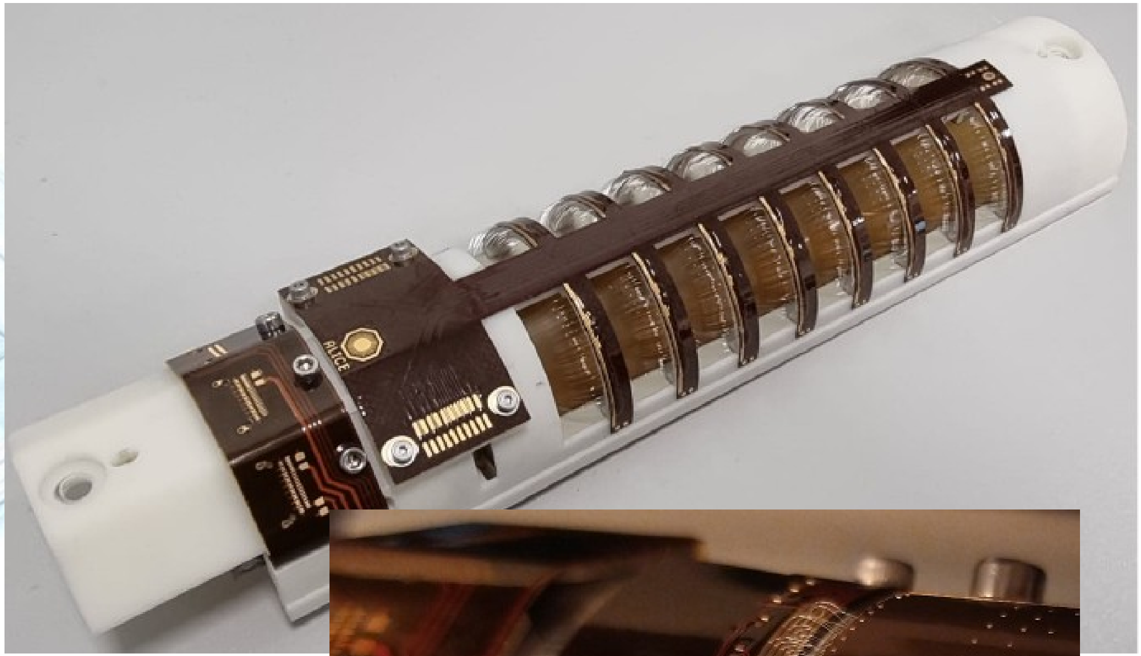


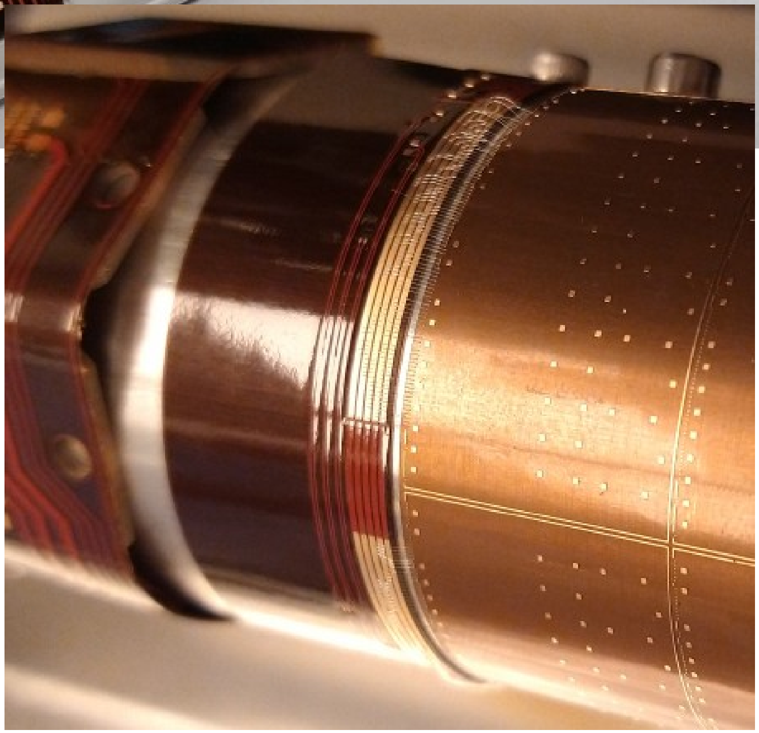
- No effects on bending radius observed
- Spatial resolution of 5 μm consistent with flat ALPIDE

Lucas Lautner, ALICE Upgrade Week 2022-10
https://indico.cern.ch/event/1183733/contributions/5045649

C.8 – MAPS bending : SuperALPIDE







- One silicon piece from ALPIDE *wafer* :
  9x2 dies, ≈ half an ITS3 layer L0
- Exoskeleton that mimics L1
  + allow for interconnection between dies

M. Mager, CERN Detector Seminar 2021-09-24

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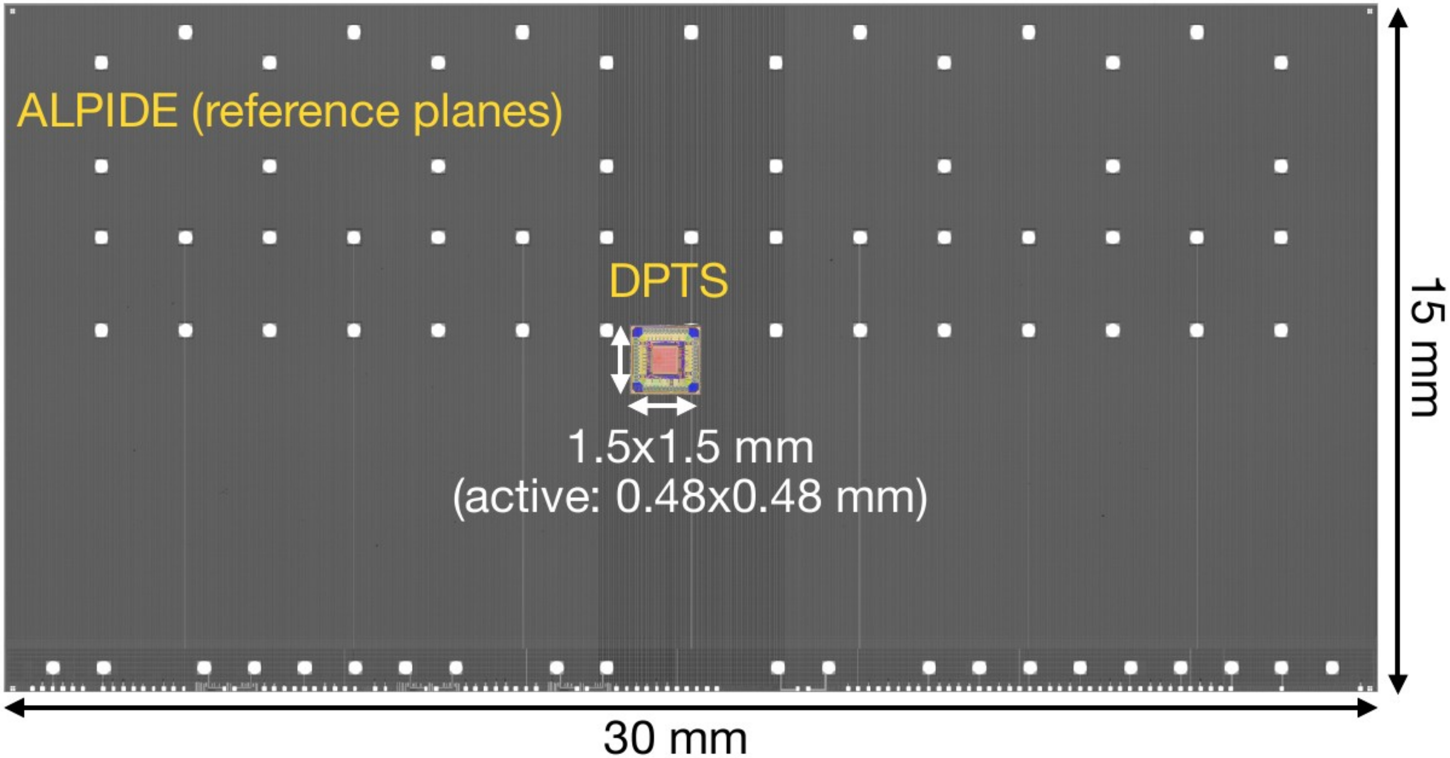
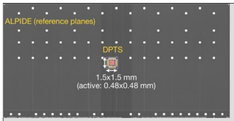
App. D – (65-nm + stitched) sensor design

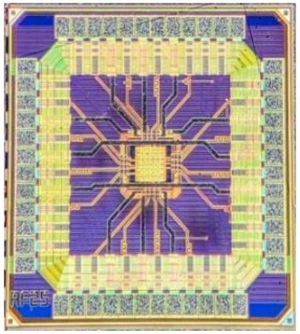
D.1 – 65-nm MAPS : tests of MLR1 65-nm sensors





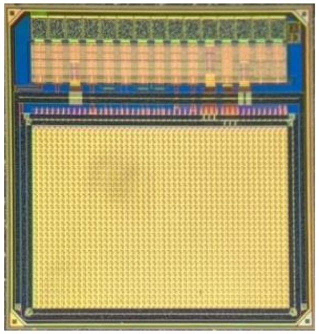
ITS3 1D-stitched sensor ≈ 1.88 x 28 cm^2

D.2 – 65-nm MAPS : MLR1 65-nm sensors



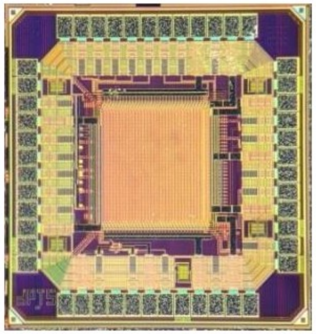
Analogue Pixel Test Structure (APTS)

- 6×6 pixel matrix
- Direct analogue readout of central 4×4 submatrix
- Two types of output drivers:
  - Source follower (APTS-SF)
  - Very fast OpAmp (APTS-OA)
- AC/DC coupling
- 4 pitches: 10, 15, 20, 25 µm
- 3 process variations



Circuit Exploratoire (CE65)

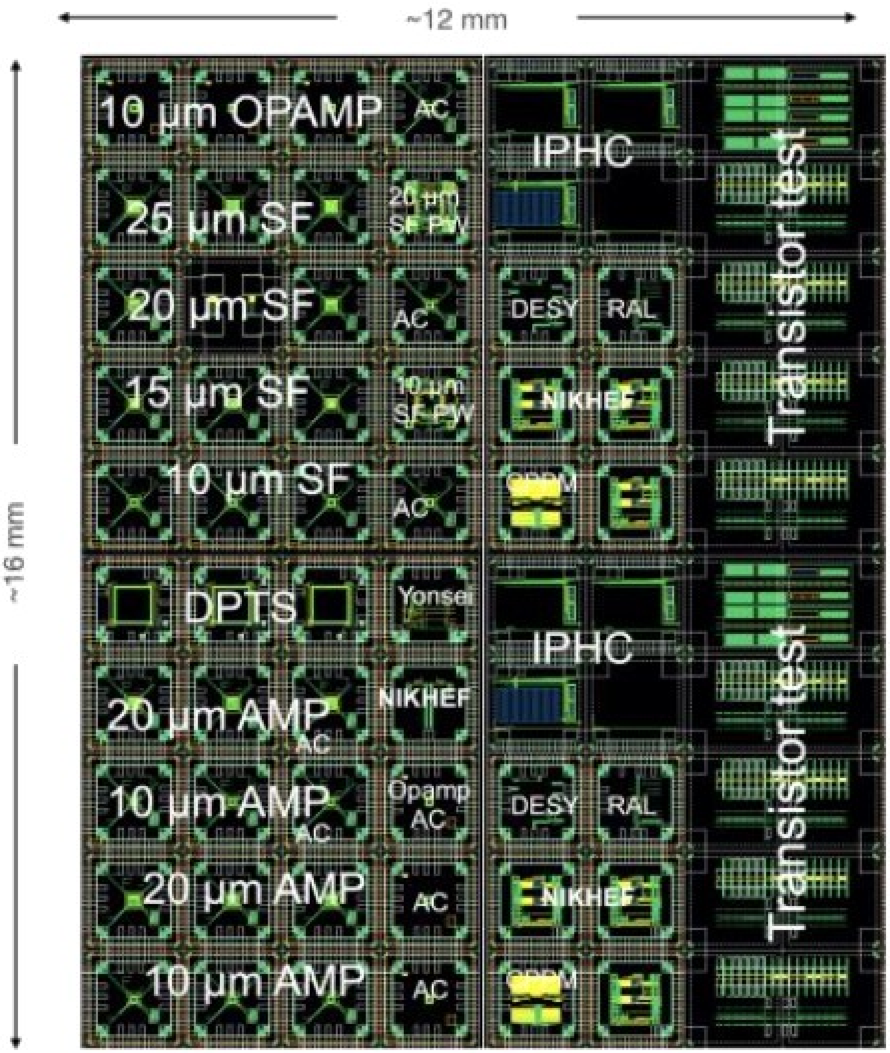
- 2 matrix sizes
  - 64×32 with 15 µm pitch
  - 48×32 matrix with 25 µm pitch
- Rolling shutter readout (50 µs integration time)
- 3 in-pixel architectures:
  - AC-coupled amplifier
  - DC-coupled amplifier
  - Source follower
- 4 chip variants:
  - **Standard process 15 µm pitch**
  - Modified process 15 µm pitch
  - **Modified process with gaps 15 µm pitch**
  - Standard process 25 µm pitch

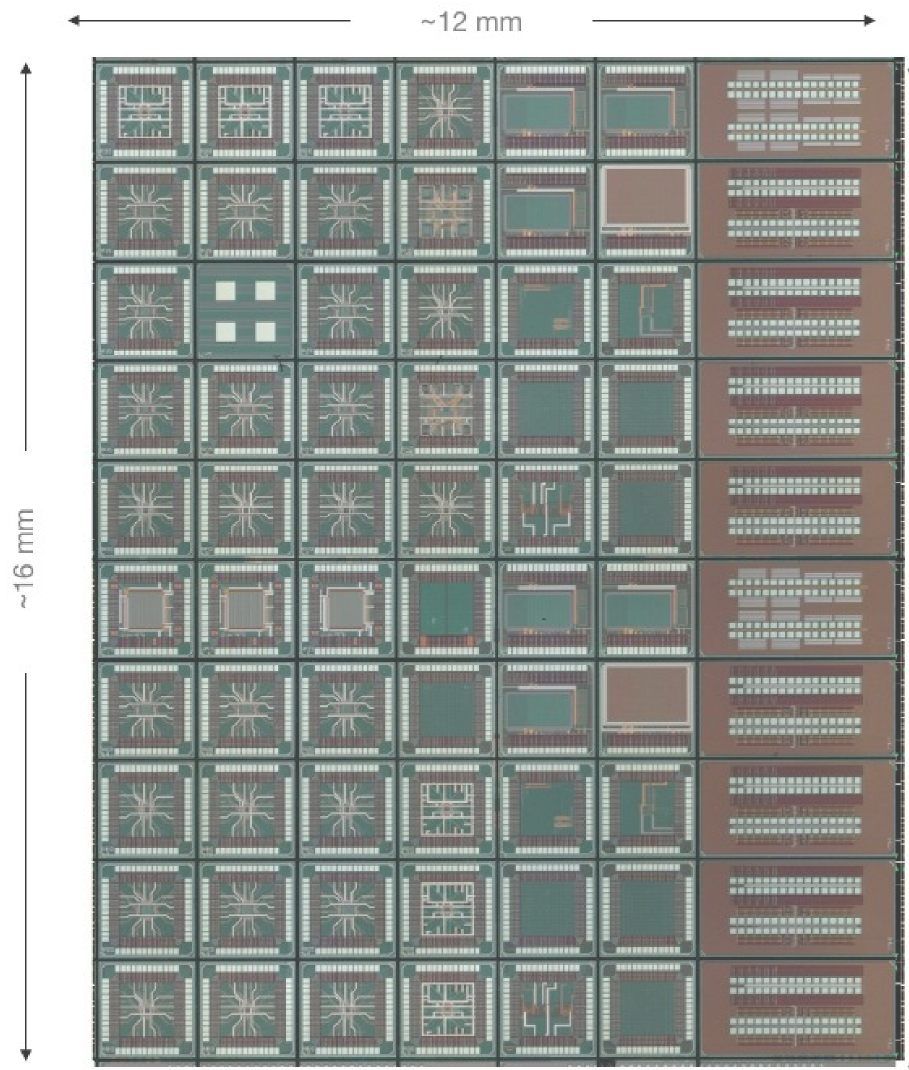


Digital Pixel Test Structure (DPTS)

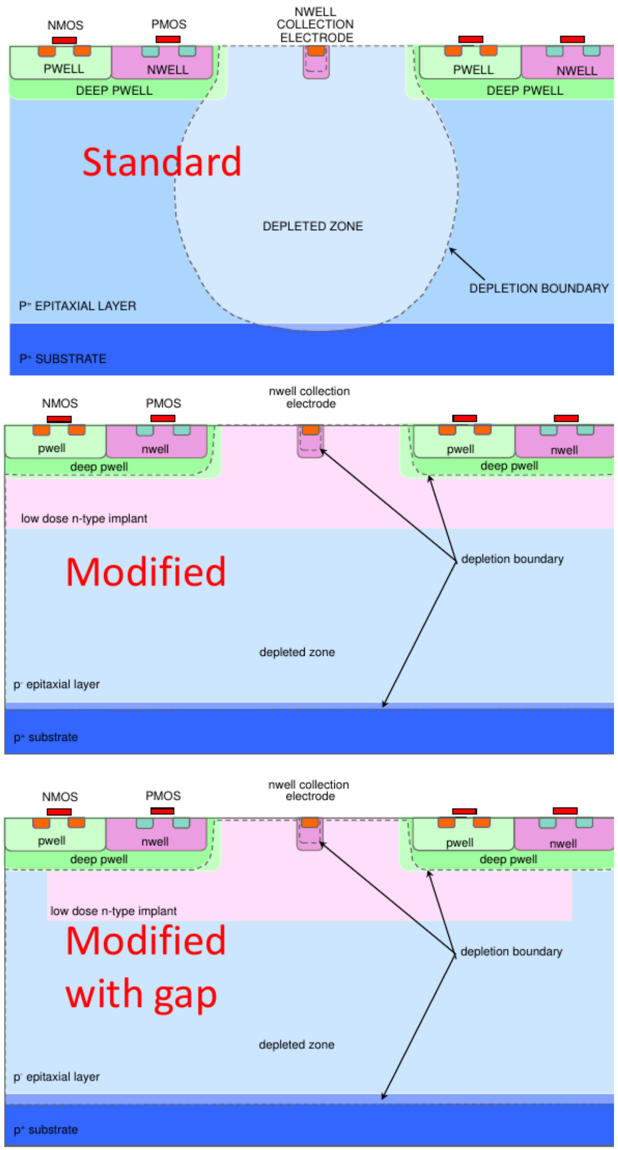
- 32×32 pixel matrix
- Asynchronous digital readout
- Time-over-Threshold information
- Pitch: 15×15 µm^2
- Only “modified with gap” process modification

D.3 – 65-nm MAPS : MLR1 65-nm sensors





D.4 – 65-nm MAPS : modified process and charge collection

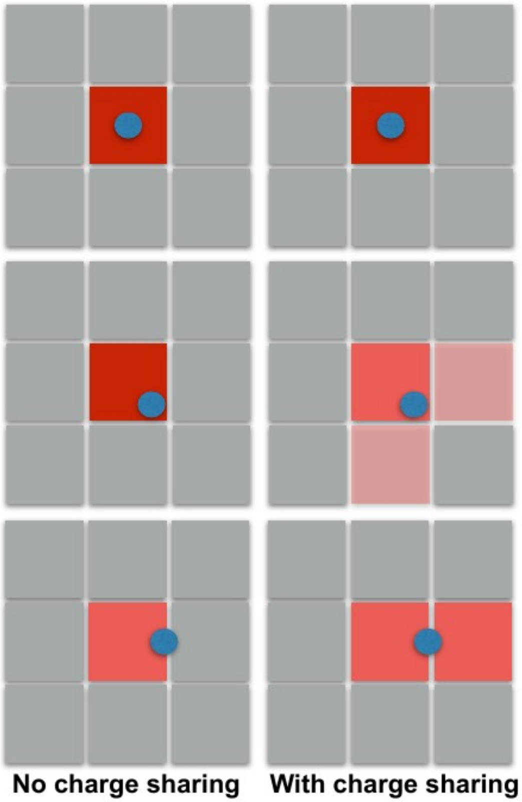


= Default by Tower

(Modified) W. Snoeys et al, DOI:10.1016/j.nima.2017.07.046

= Basis for ITS3

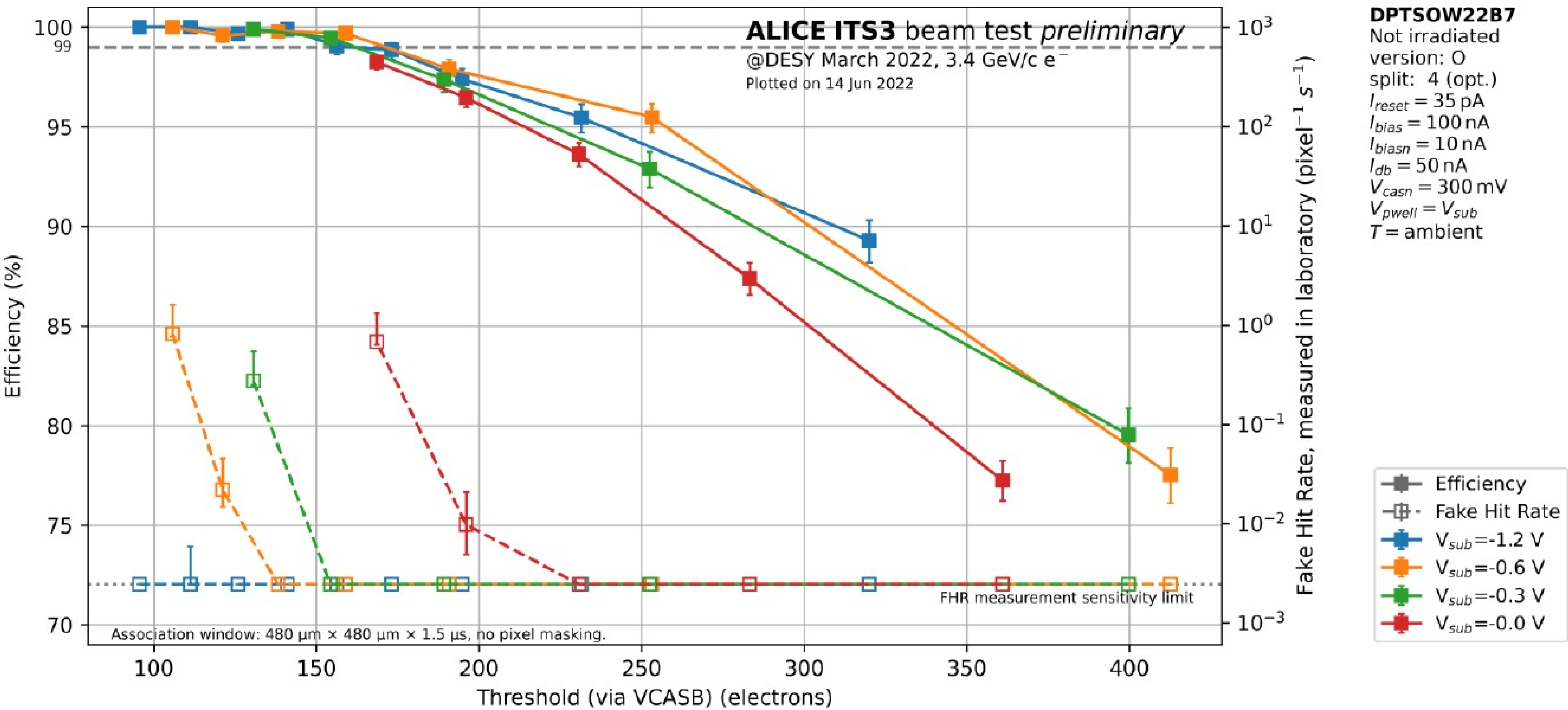
Sketches courtesy Serhiy Senyukov



Schematic comparison of cluster shapes without and with charge sharing Depending on the impinging point

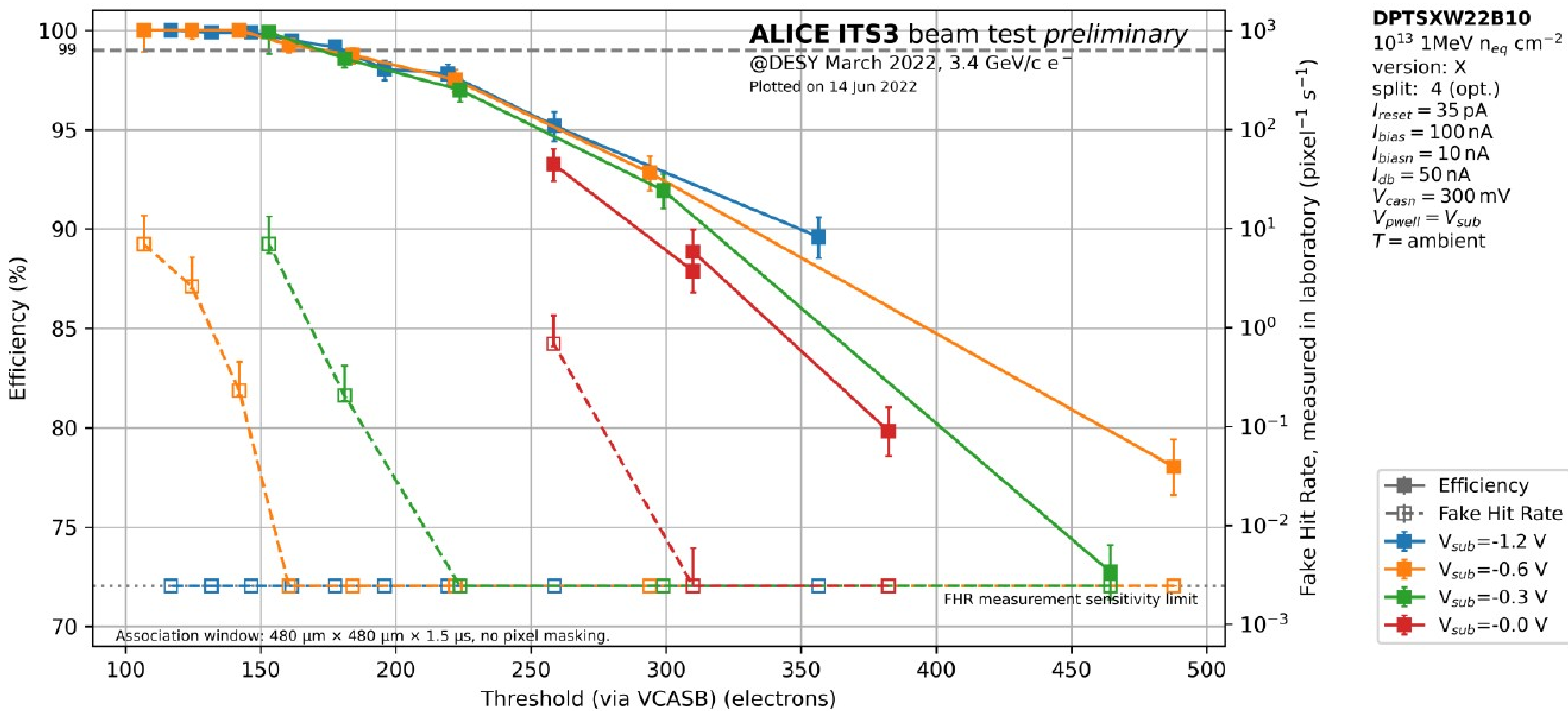
Courtesy Felix Reidt

D.5 – 65-nm MAPS : DPTS 65-nm, 0 radiation



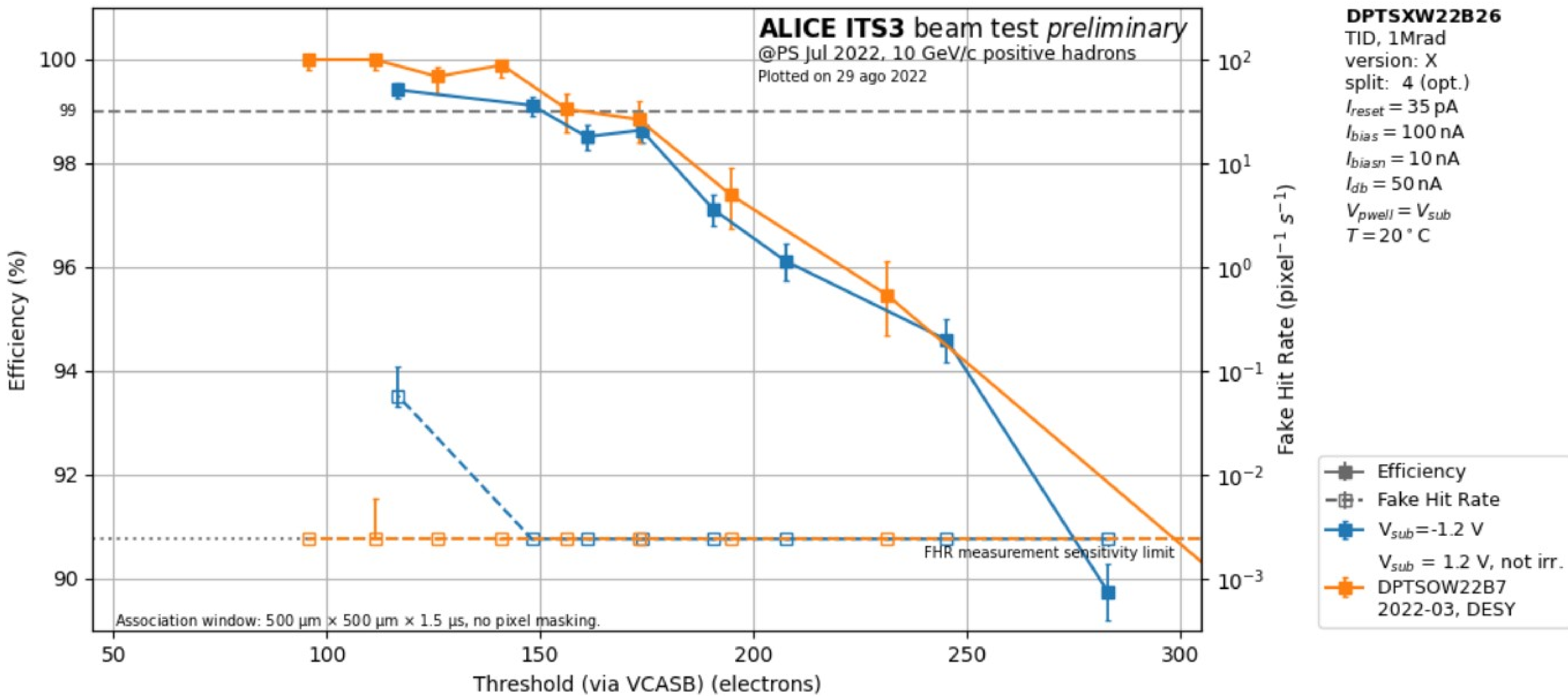
→ Excellent efficiency + low fake-hit rate

D.6 – 65-nm MAPS : DPTS 65-nm, $+10^{13}$ n_{eq} NIEL



→ larger fake-hit rate but still some margin

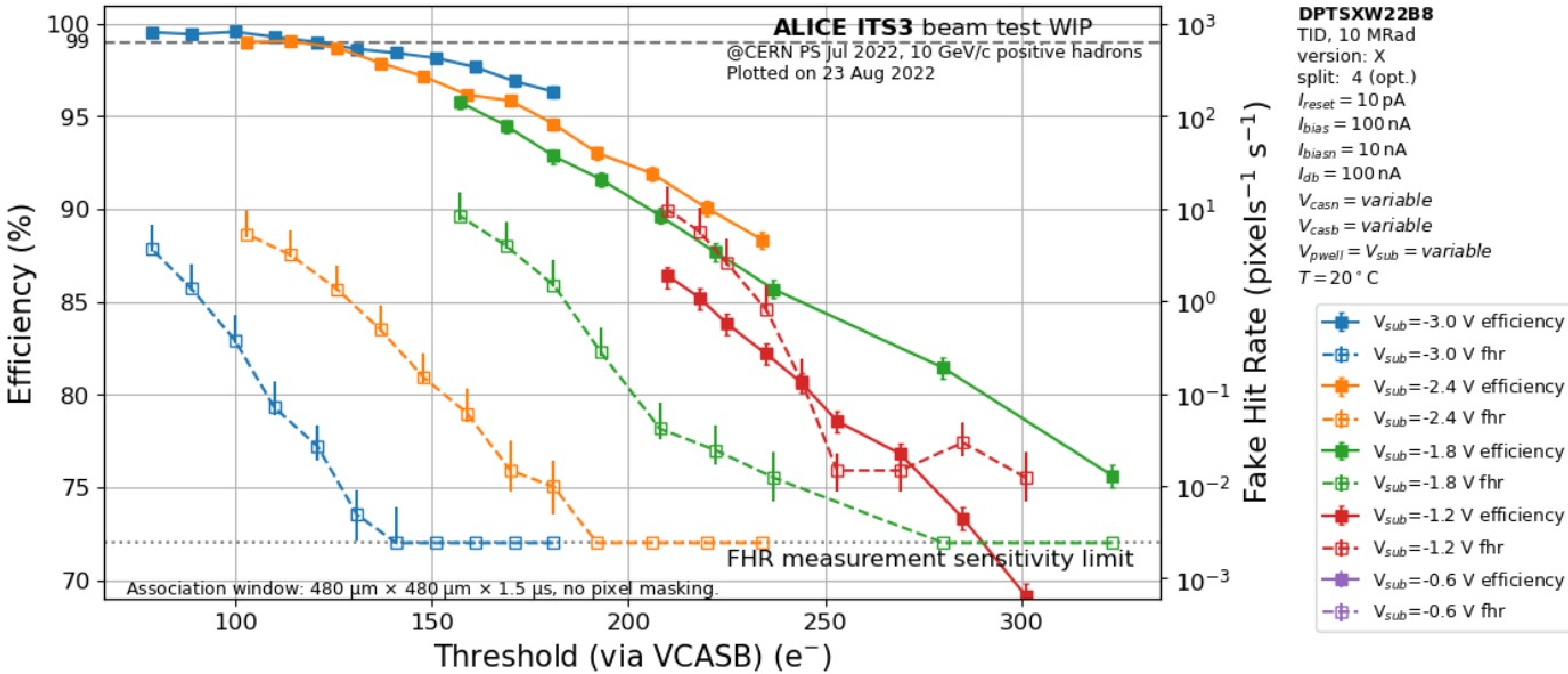
D.7 – 65-nm MAPS : DPTS 65-nm, +1 Mrad TID



→ Negligible effect

D.8 – 65-nm MAPS : DPTS 65-nm, +10 Mrad TID

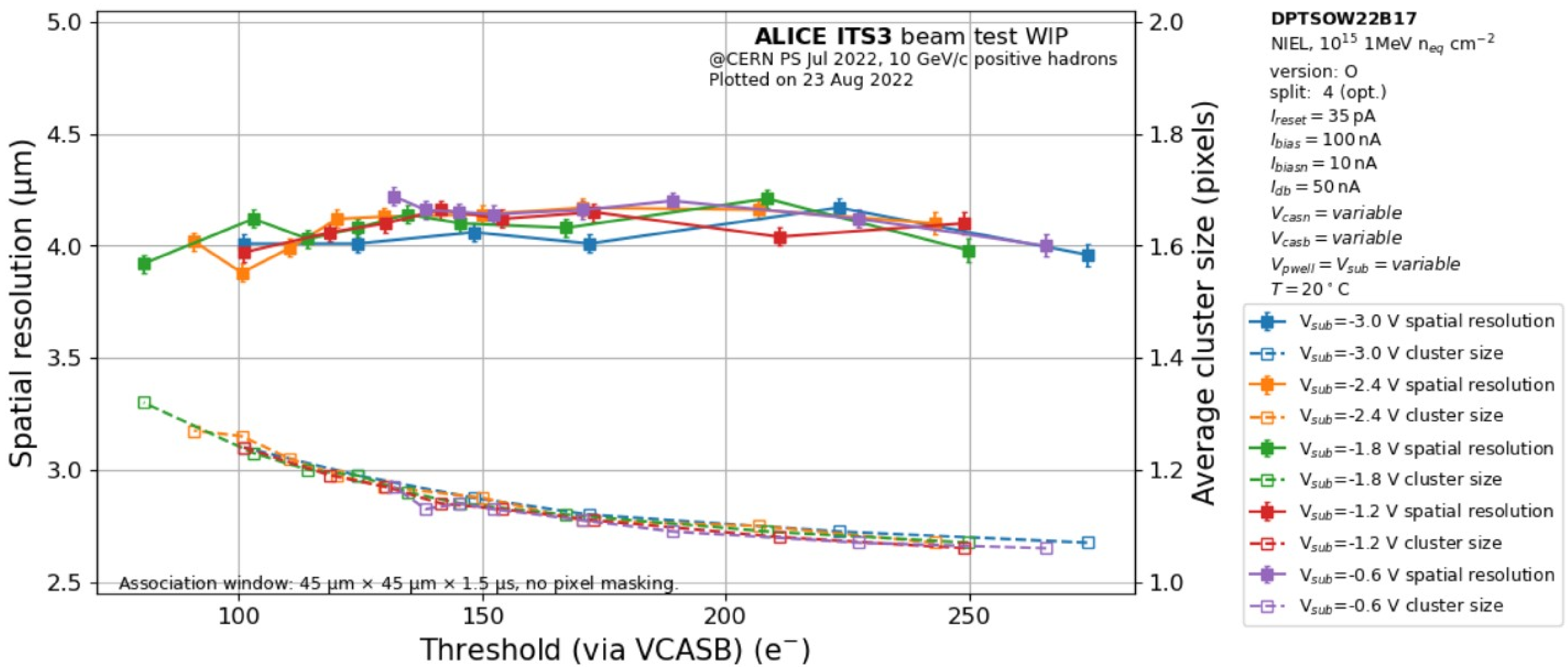
WORK in PROGRESS



→ reverse back bias, necessary

D.9 – 65-nm MAPS : DPTS 65-nm, +10^{15} 1-MeV n_{eq}.cm^{-2} NIEL

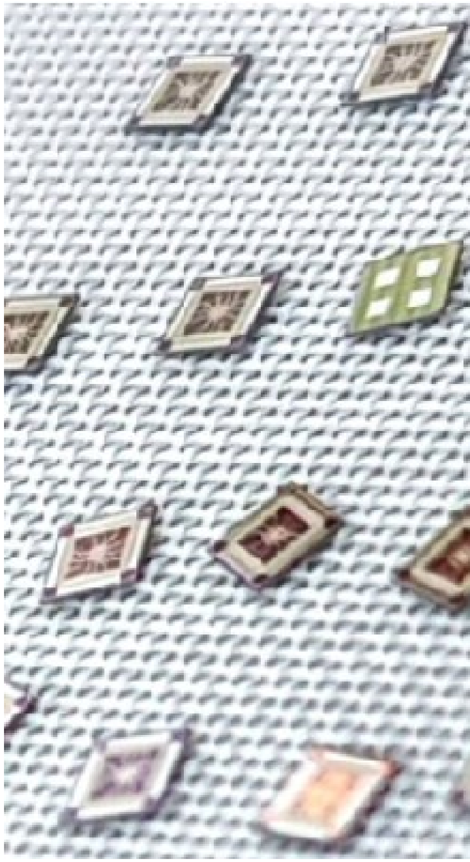
WORK in PROGRESS



D.10 – 65-nm MAPS : Analog chips 65-nm

Roadmap of (ongoing) characterisations :

Focus ≈ charge collection characteristics.
NB : rather small chips (*e.g.* 6x6 pixels) more difficult to bring to beam tests
+ full readout/steering to be deployed outside the chip itself



CE65

- Analogue signal distributions for 25 µm pitch
- Spatial resolution for 15 and 25 µm pitch

APTS-SF: analogue signal distributions, spatial resolution, cluster properties vs.

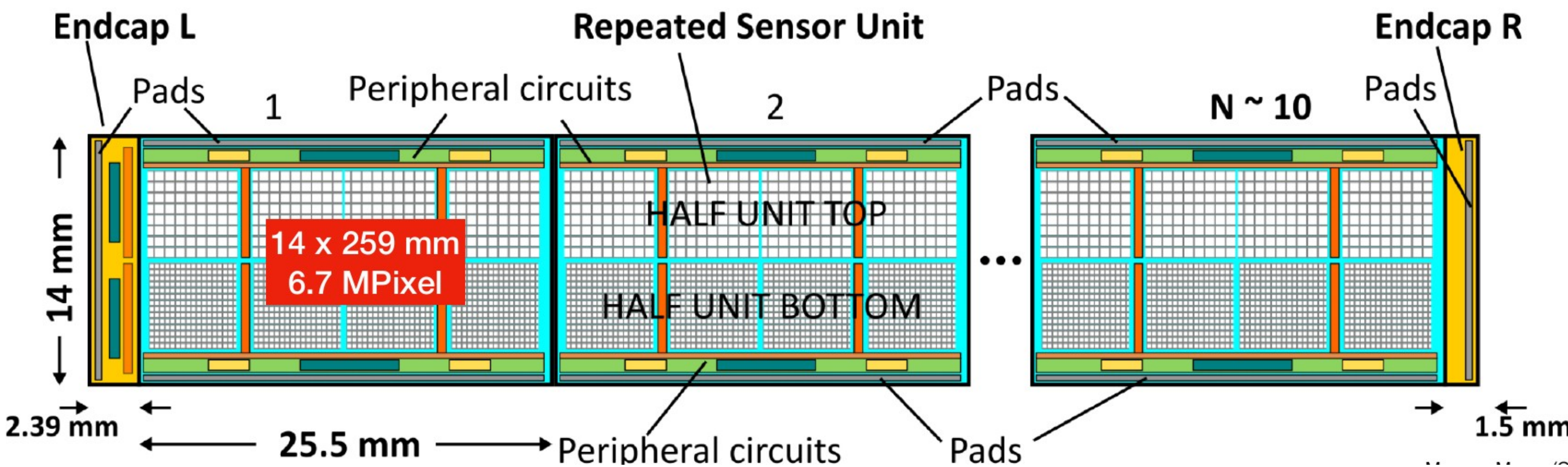
- Process modification: standard, modified, modified with gap
- Reverse back bias: -1.2, -2.4, -3.6, -4.8 V
- Pixel pitch: 10, 15, 20, 25 µm
- NIEL irradiation: 10^{13}, 10^{14}, 10^{15} 1-MeV n_{eq}/cm^2

APTS-OA

- Temporal resolution, efficiency and cluster properties

⟶ Dedicated publications for APTS-SF, APTS-OA and CE65 will follow

D.11 – 65-nm MAPS : ER1 submission, stitching



MOSS 2 pitches, 22.5 µm (top) + 18 µm (bottom)

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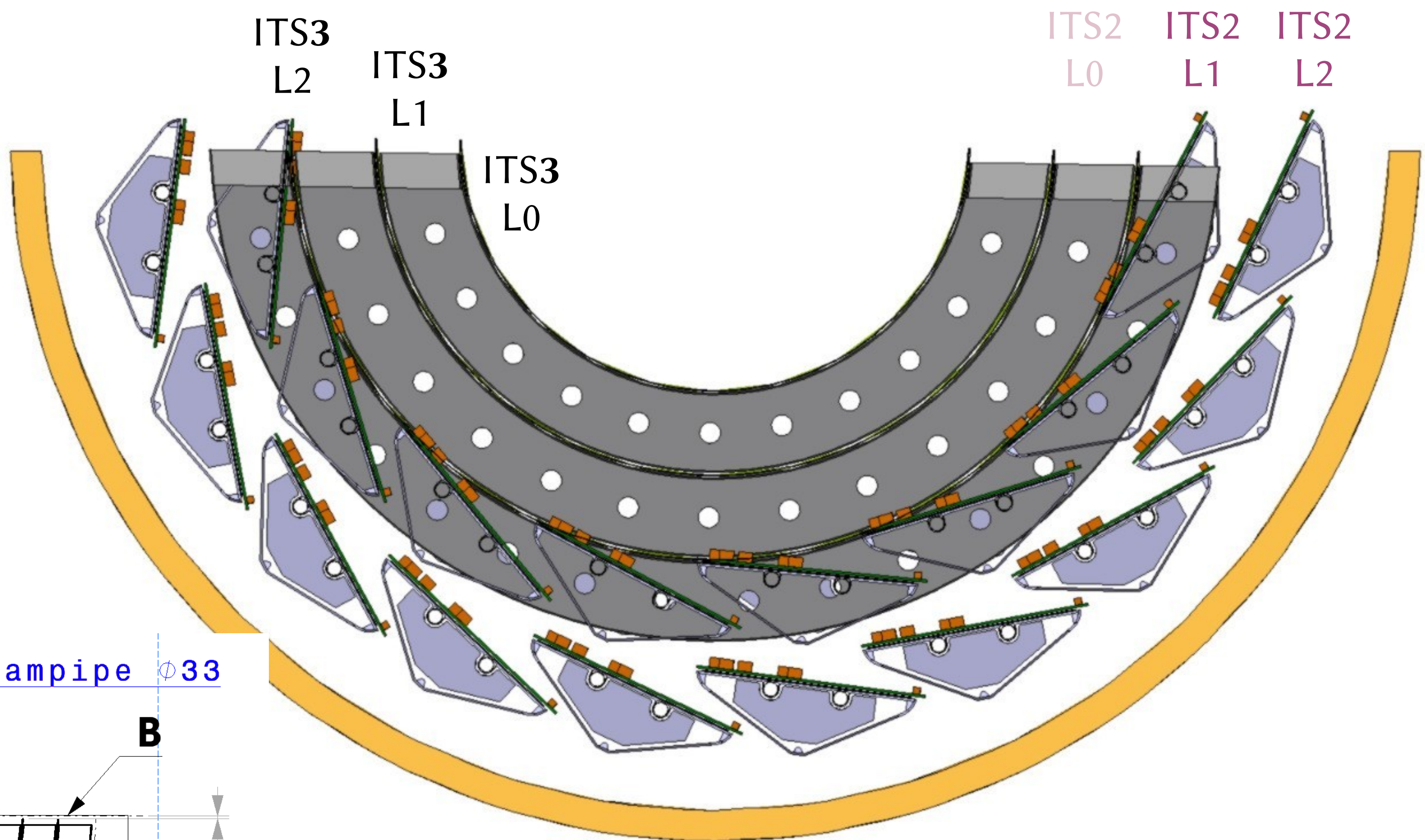
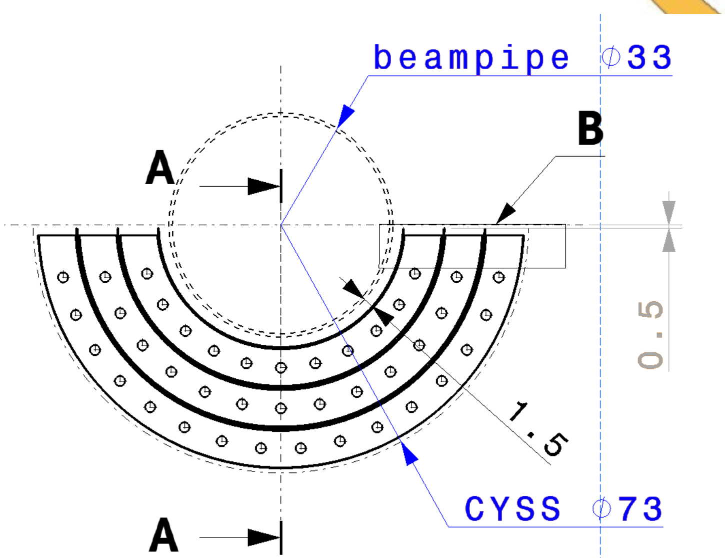
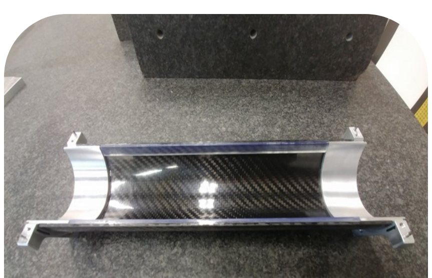
App. E – ITS3 mechanics

E.1 – ITS3 mechanics : layout sketch







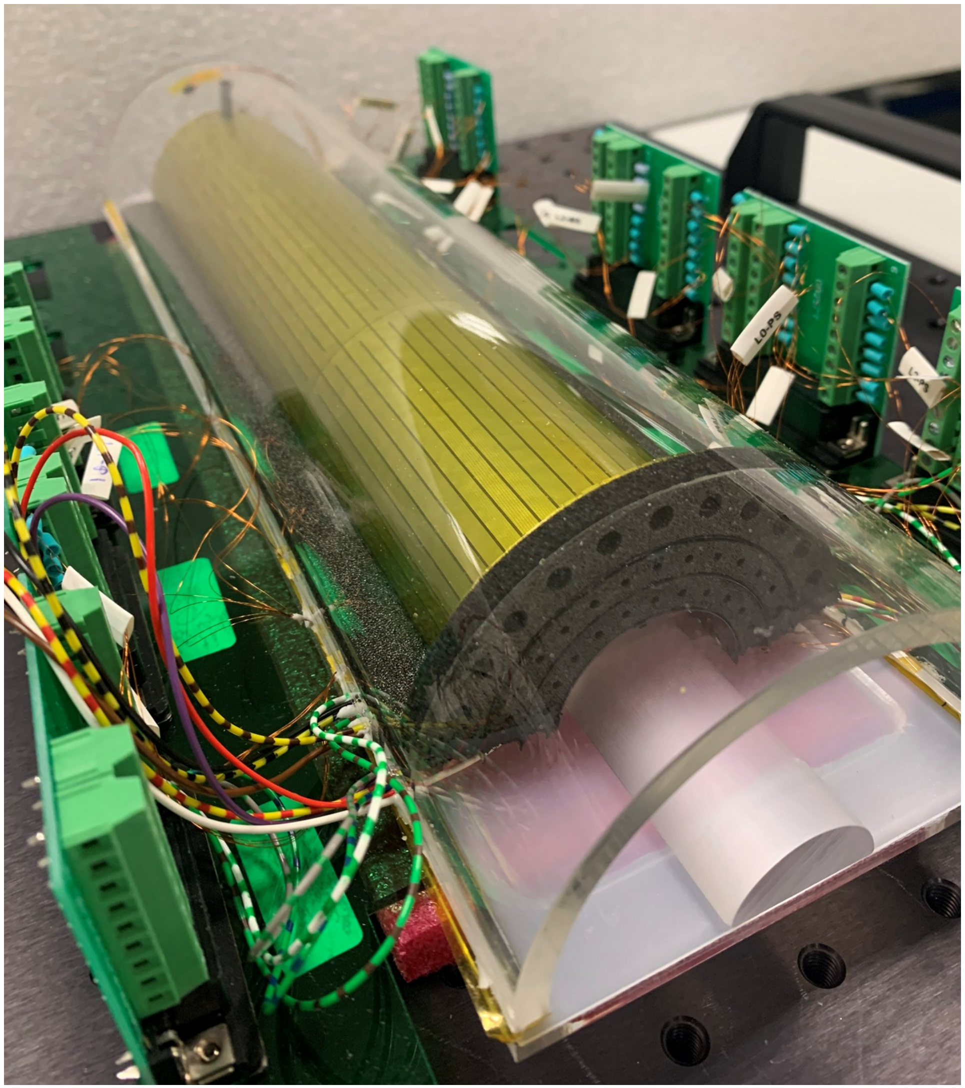
E.4 – ITS3 mechanics : mechanical integration

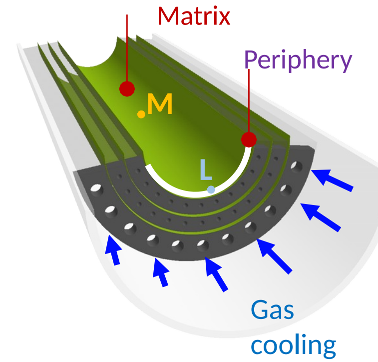
Engineering Model 2 (2022)

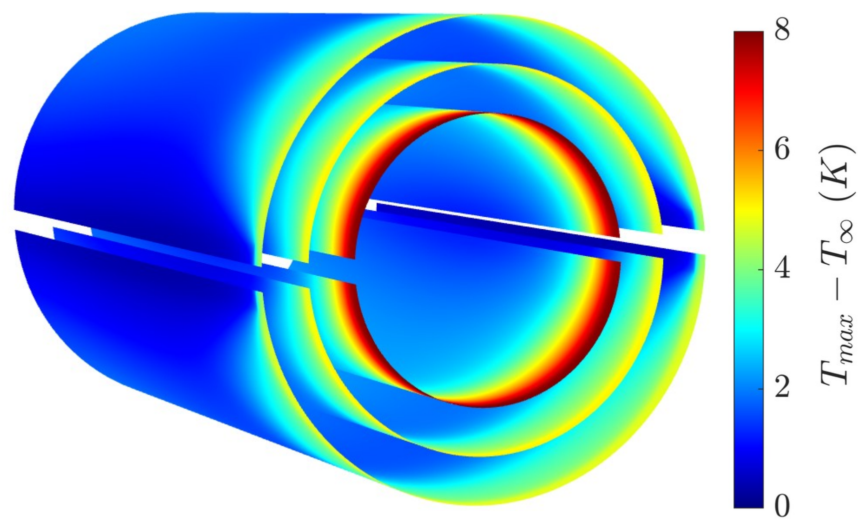
Items	Th. [µm]	L [mm]	Circ. [mm]
L0	40	280	56.5
L1	40	280	74.4
L2	40	280	93.2

Courtesy Corrado Gargiulo
ITS3 WP5

E.5 – ITS3 mechanics : wind tunnel

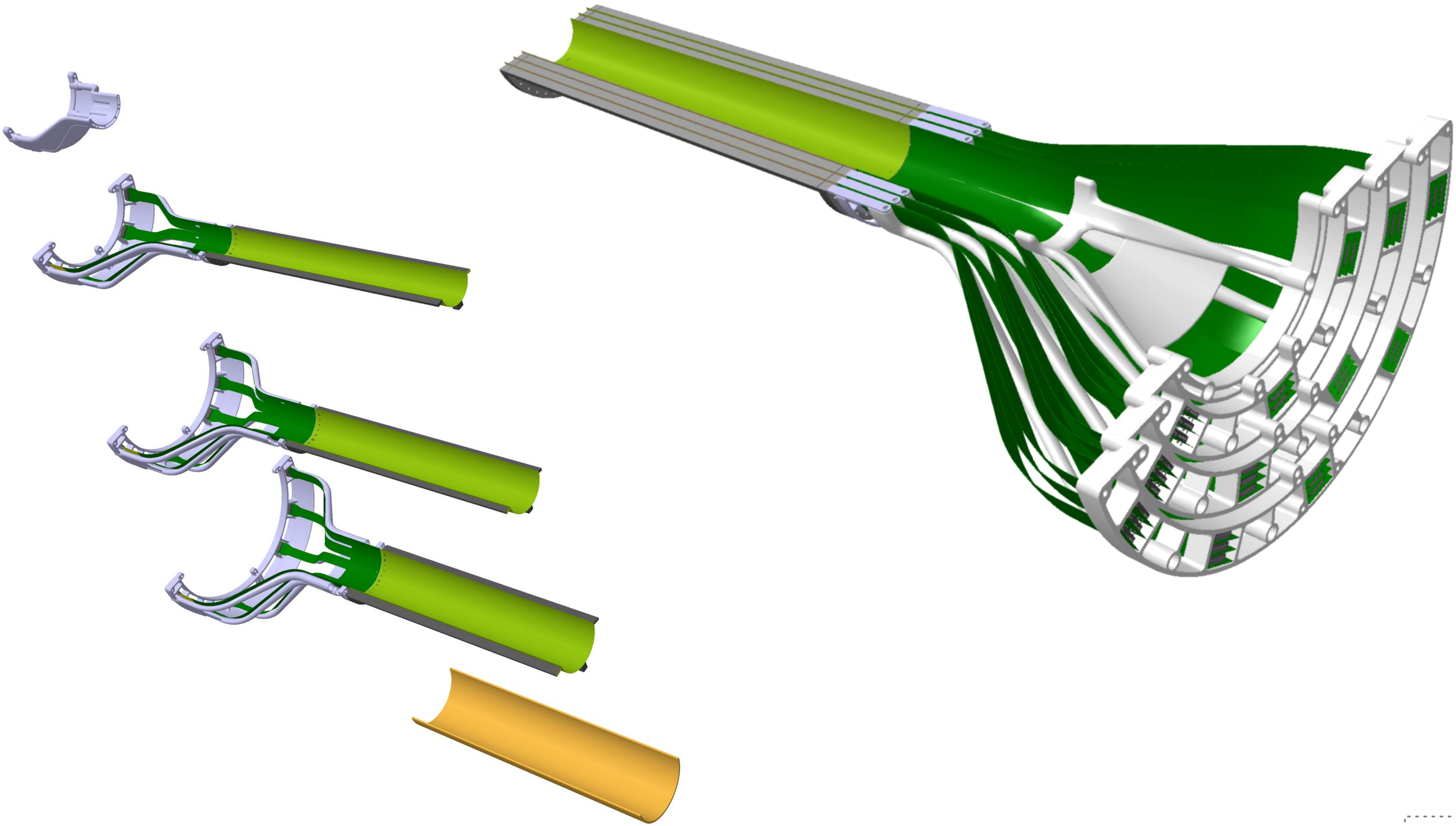




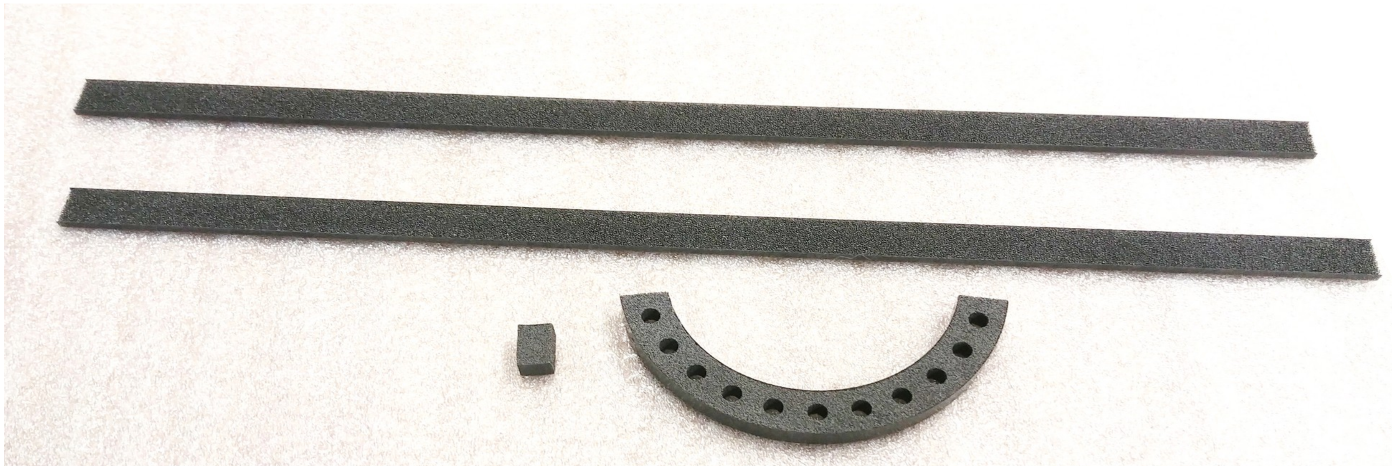


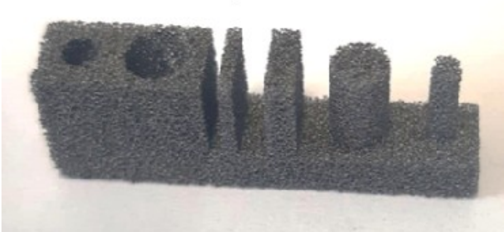
Temperature contours for v = 6 m.s^{-1}

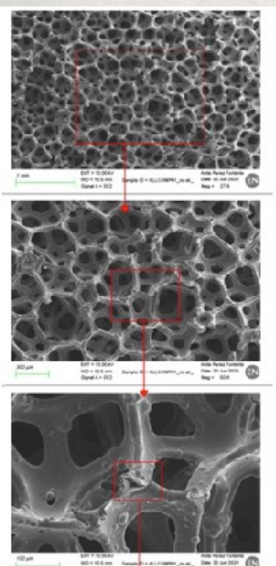
E.6 – ITS3 mechanics : Engineering Model 3



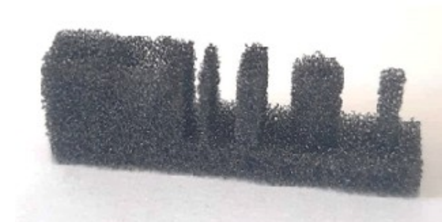
E.7 – ITS3 mechanics : mechanical integration

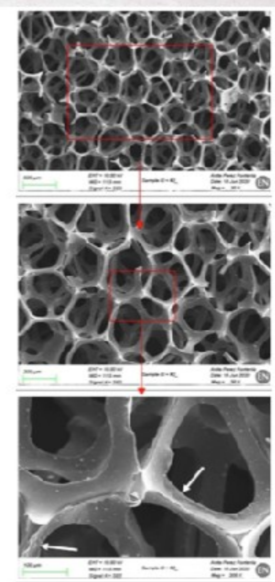






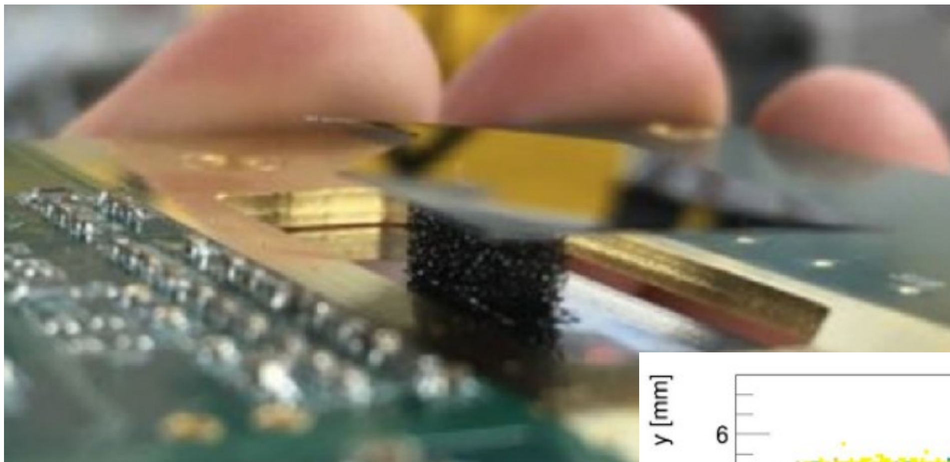
ngs :
.LCOMP LD foam
ρ = 0.2 kg/dm³
k = 20 W/m.K



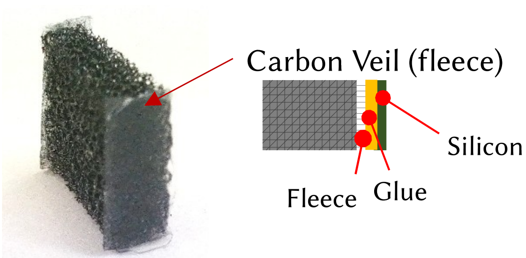


Longerons :
ERG DUOCEL foam
ρ = 0.07 kg/dm³
k = 0.05 W/m.K

E.8 – ITS3 mechanics : impact of carbon foam on material budget



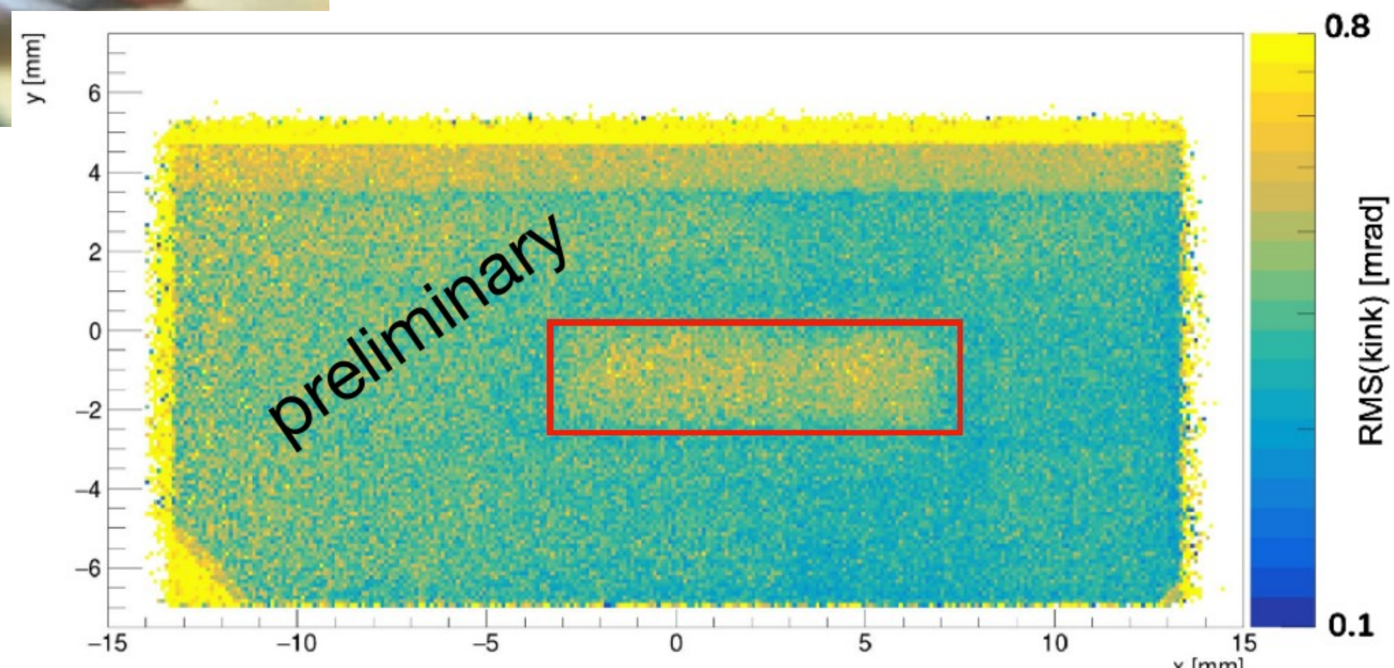
- A sandwich of chip-foam-chip was brought to beam
- Scattering angle due to carbon foam is measured
- Very small (but visible) effect, as expected



Araldite 2011

Minimized glue penetration
in the foam wedge

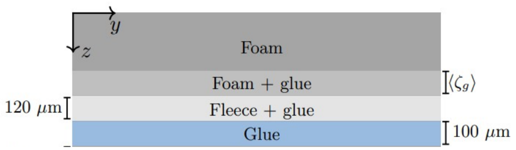
Fleece impregnated
with glue allows for glue control



M. Mager, CERN Detector Seminar 2021-09-24

E.9 – ITS3 mecha. : impact of carbon foam on material budget

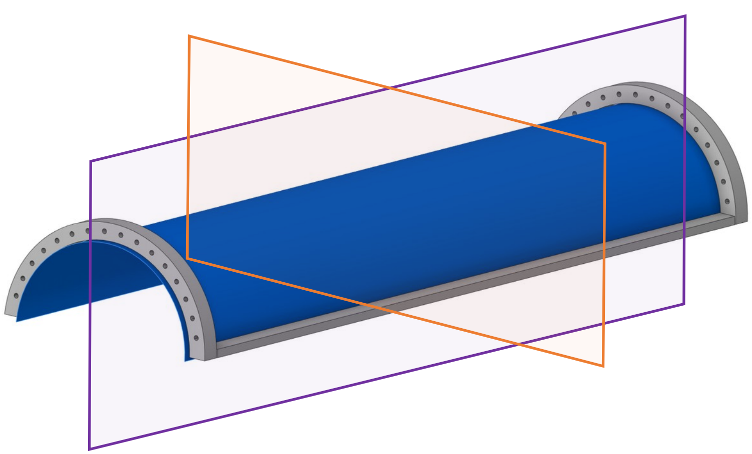
Thermal glue interface (less glue at the mechanical interface)



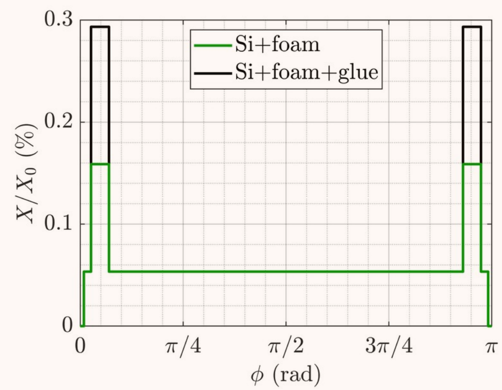
Baseline

180 um glue penetration
120 um Glue + Carbon Fleece
100 Glue (between Si-Carbon foam)

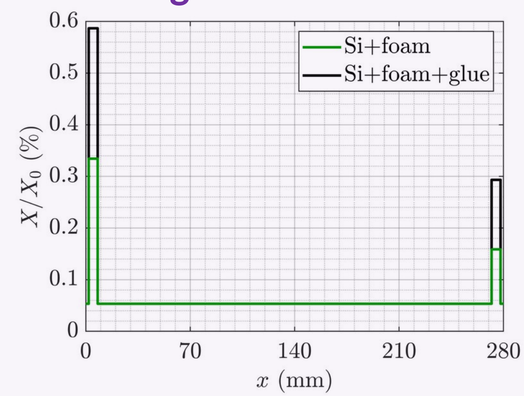
preliminary



Azimuthal direction



Longitudinal direction



Mean value : 0.07 % X_0

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App. F – ITS**3** as a project

F.1 – Synopsis : specifications (1), ITS2 vs ITS3

	ITS-2 (TDR)	**ITS-3** (LoI)
LHC period(s)	Run3 [2022-2025] + Run4	Run4 [2029-2032]
Number of layers	3+4	3 (*+4 ITS-2*)
beryllium pipe inner radius R_{pipe} (thickness ΔR)	1.82 cm [CERN-news] (0.08 cm, = 0.22% x/X_0)	1.6 cm (0.05 cm, = 0.14% x/X_0)
r_{L0} / r_{L1} / r_{L2} ... r_{Last}	2.3 / 3.2 / 3.9 ... *39.3 cm*	1.8 / 2.4 / 3.0 ... *39.3 cm*
Magnetic field $B_{solenoid}$	0.2 and 0.5 T	0.2 and 0.5 T
Material budget per layer	0.3 % to *0.8 %* x/X_0	0.05 % to *0.8 %* x/X_0
CMOS technology	180 nm	65 nm *(180 nm)*
Pixel size	≈ 27 x 29 μm^2	≈ 20 x 20 μm^2 (+ ≈ *27 x 29*) μm^2
Size of *unitary* base sensor	≈ 1.53 x 3 cm^2	≈ (5.6-9.5) x 27 cm^2
Nb of sensors to assemble 3 inner layers	432	6 (!)
Non-Ionising Energy loss radiation	> 3.10^{12} 1-MeV n_{eq}.cm^{-2}	> 3.10^{12} 1-MeV n_{eq}.cm^{-2}
Total Ionising dose	> 0.3 Mrad	> 0.3 Mrad

F.2 – Synopsis : specifications (2), ITS2 vs ITS3

	ITS-2 (TDR)	**ITS-3** (LoI)
Consumed power (in the active volume, i.e. over the pixel matrix, ≠ in the periphery…)	< 35 mW/cm²	< 20 mW/cm²
Time resolution on hits	2-5 µs	≤ 2-5 µs
Time for charge collection per pixel	< 10 ns	≤ 1 ns
Spatial resolution	5 µm	≤ 5 µm
Coverage in η	|η| < 2,0 to *1,3*	|η| < 2,2 to *1,3*
$\varepsilon_{\text{tracking ITS}}$ ($p_T(h^{\pm})$ = X GeV/c)	1 GeV/c : 98% 0.1 GeV/c : ~60%	1 GeV/c : 98% 0.1 GeV/c : ~75%
Fake hit rate	<< 10^{-6} event^{-1}.pixel^{-1}	< 10^{-7} event^{-1}.pixel^{-1}
Particle hit density	5 MHz.cm^{-2}	8.5 MHz.cm^{-2}
Total costs [R&D + Construction] (+ beam pipe, out of the given project)	≈ 15.2 x10^6 CHF (…)	≈ 6.0 x10^6 CHF (1.5 x10^6 CHF)
Nb of institutes / Nb of countries	30 / 16	(≥19) / (≥ 8)

F.4 – ITS3 project : validation points towards TDR

1. Bending chips : with ALPIDE 180-nm
2. (MLR1) 65-nm validation in terms of radiation hardness + detection efficiency
3. (ER1) : stitching + foundry yields

Ultra-light mechanics and cooling

- mechanical concept to hold thin sensors “without” material
  - development of assembly procedure
  - qualification of carbon foams
- verification and optimisation of air cooling concept

Thinning, bending, interconnection

- development of procedures to handle and bend large thin chips
- characterisation of electrical and mechanical properties of sensors after bending
- development of electrical interconnection to bent chips

Wafer-scale sensor development

- switch to 65 nm technology (TPSCo)
  - verification of the technology for radiation tolerance and charge collection
- stitched sensor design and test
  - chip architecture
  - optimisation for yield

Courtesy Magnus Mager

F.5 – ITS3 project : overall costs

Table B.2 - Project cost estimate breakdown for the whole ITS3 project (kCHF). The R&D column concerns activities around MLR1, ER1 and ER2, while Construction relates to ER3. Partial update of the estimate given in the Tab. 8 of the [ITS3-LoI].
Updates concern :

i) the rising costs around 65-nm Engineering Runs (foundry + tests)

- the costs of a foundry run which now amount to **650-700 k$ per run**, including post-processing like thinning and dicing (and not anymore 300-400 k$ like for the 180-nm technology node)
- **200-300 kCHF/run** for DAQ cards and tests

ii) beam pipe R&D (600 kCHF) and construction (900 kCHF) costs, which are now taken out of the ITS3 project itself and will be covered by the ALICE collaboration as a whole.

Item	*R&D*	*Construction*	*Total Cost*
TOTAL	≈ 3450 *(LoI: ~~1900~~)*	≈ 2500 *(LoI: ~~3400~~)*	≈ 5950 *(LoI: ~~5300~~)*
Beampipe	*(LoI: ~~600~~)*	*(LoI: ~~900~~)*	*(LoI: ~~1500~~)*
Pixel CMOS sensors	3x700 = 2100 *(LoI : ~~600~~)*	700 *(LoI : ~~800~~)*	2800 *(LoI : ~~1400~~)*
Sensor test	3x250 = 750 *(LoI: ~~100~~)*	250 *(LoI: ~~150~~)*	1000 *(LoI: ~~250~~)*
Thinning & bending	200	300	500
Hybrid printed circuit	100	100	200
Mechanics	150	350	500
Assembly & test	50	200	250
Installation & alignment	-	200	200
Air cooling	100	150	250
Services	0	100	100
Patch panels	0	150	150

F.6 – ITS3 project : institutional partners

- CERN
- Italy (INFN+)
- France (IN2P3+)
- the Netherlands (NIKHEF, Utrecht)

- Korea (Inha, Yonsei, Pusan)
- Sweden (Lund)
- Norway (Bergen, USN Vestfold)
- Tchech Republic (Prague Univ, Prague National Academy of Sci)

- USA (Berkeley, BNL ? LNL ? Stanford ? if happening, it will be in good part linked with instrumental synergies found with EIC collider and/or Cool Copper Collider
- … ?

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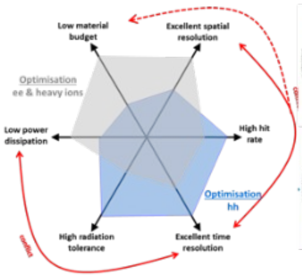
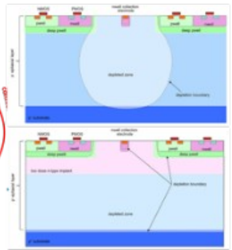
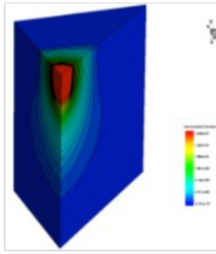
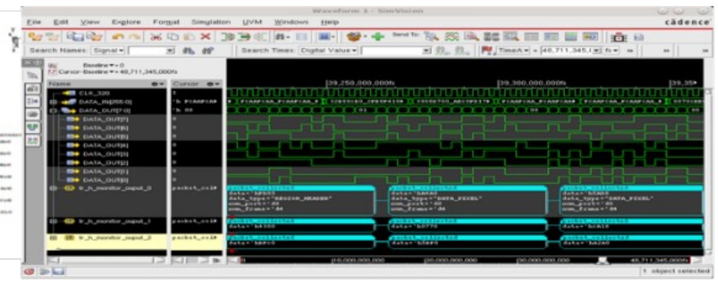
App. G – IN2P3 in the project

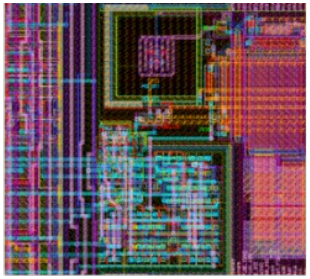
G.1 – IPHC C4π platform : from chip design to integration











Transcription of the experiment's constraints into electronics specs. & Architectures

Evaluation of suitable CMOS processes

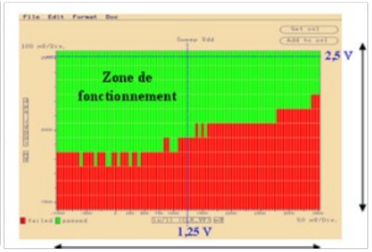
- TCAD Simulation & Optimization
  → Design validated by prototyping

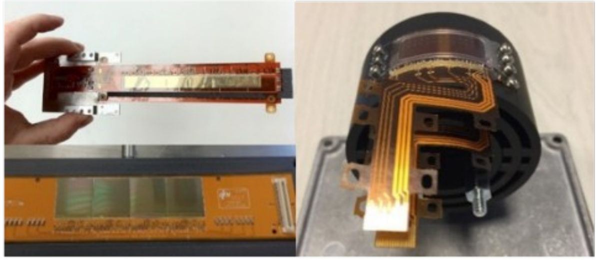
- Front-End Electronics Design
  - Very low noise and power
  - Robustness design (> 1M pixels), DfT
- Functional blocks (IP) for MAPS => SoC
  - A.w.a Complex Gates + Liberate Modelling

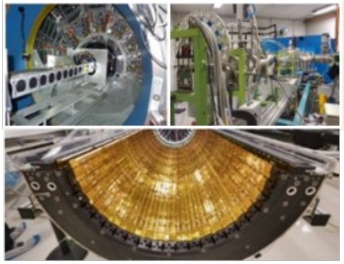
- System Design / Architecture of MAPS
  - Digital on Top Design & Verification Flow
  - Cadence Flowkit & UVM / systemVerilog
    - ✓ HDL modeling, synthesis,
    - ✓ Floorplan, IR-Drop, Routing + CTS , PostSim

Interaction with :

- CMOS foundries for specific manufacturing
- Post processing companies
  - ✓ Thinning, Dicing, ...







Design of Test and DAQ benches for:

- Functional test of sensors on probed wafers
- At Lab, Characterization :
- On Experimental Site

Characterization of Sensors and IP blocks

- At laboratory : X Fe55, Beta Sr90, laser
- On the experimental sites: beams, irradiations

Design, Integration and Test

- Detection systems based on MAPS (ladders)

Construction & Installation on sites

- STAR (USA)
- BEAST-BELLE2 (Japan)
- ALICE (Switzerland)

Courtesy Christine Hu

G.2 – IPHC C4π platform : from chip design to integration

Technical coordination

Architecture's definition

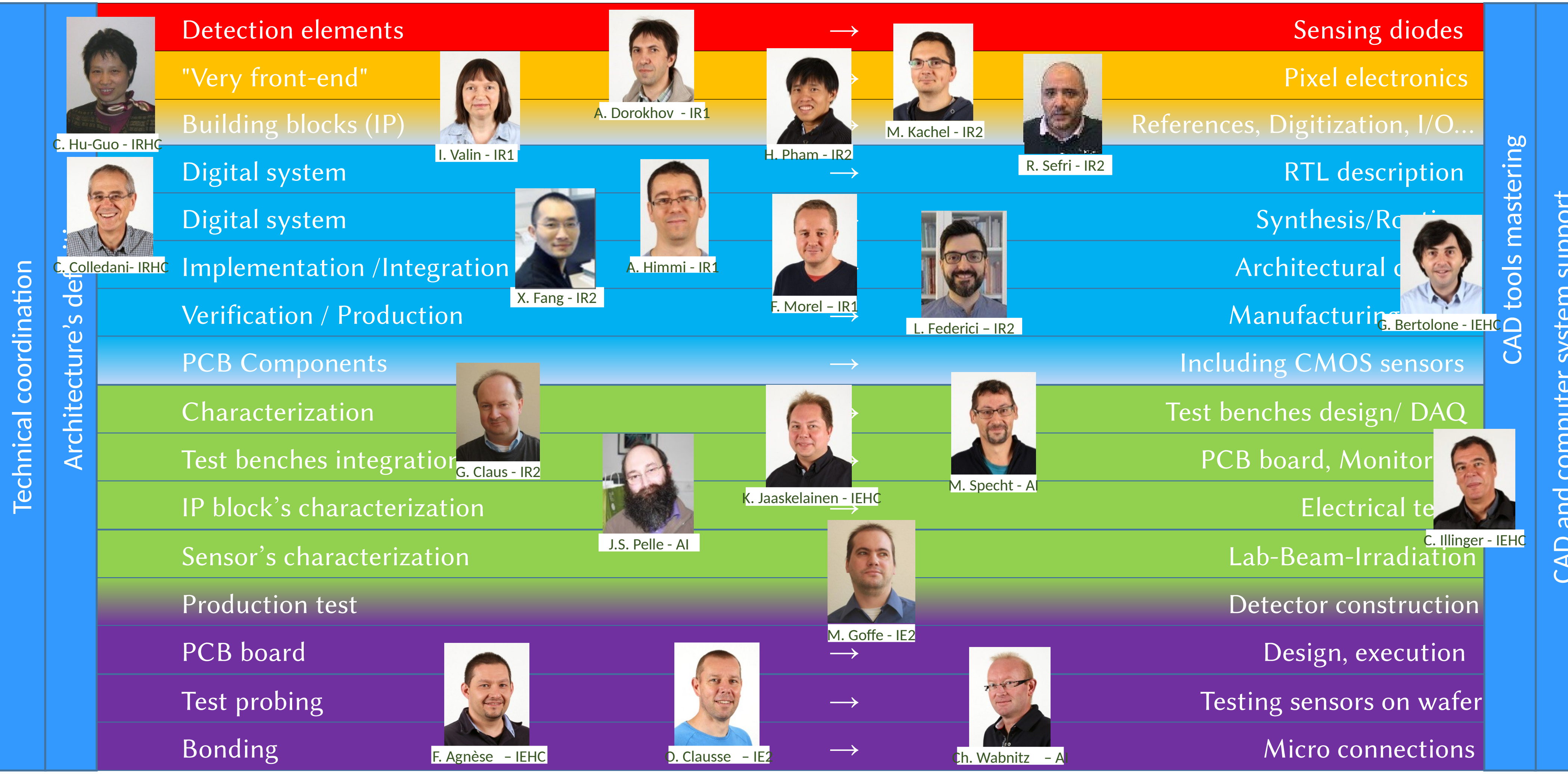
Detection elements	→	Sensing diodes
"Very front-end"	→	Pixel electronics
Building blocks (IP)	→	References, Digitization, I/O...
Digital system	→	RTL description
Digital system	→	Synthesis/Routing
Implementation /Integration (DoT)	→	Architectural design
Verification / Production	→	Manufacturing rules
PCB Components	→	Including CMOS sensors
Characterization	→	Test benches design/ DAQ
Test benches integration	→	PCB board, Monitoring
IP block's characterization	→	Electrical tests
Sensor's characterization	→	Lab-Beam-Irradiation
Production test	→	Detector construction
PCB board	→	Design, execution
Test probing	→	Testing sensors on wafer
Bonding	→	Micro connections

CAD tools mastering

CAD and computer system support

Courtesy Christine Hu

G.2 – IPHC C4π platform : from chip design to integration



21 persons

Courtesy Christine Hu

G.3 – ALICE-ITS3 & BelleII-VTX : simultaneously at C4π

Schedules overlap **BUT** Fits person-power & expertise available

- Sensor design: [2022-2024]
  - 3-4 FTEs for each project
  - ⟶ 7 FTEs in total for 10 available
  - leaving 3 FTEs for MAPS R&D (in synergy with ITS3)
- Sensor tests: [2023-2025]
  - Modest requirement ~1 FTE/project
  - thanks to commitment of Experiment collaboration teams
- Integration: [2023-2026/27]
  - ITS3 ~R&D tasks and small production
  - VTX, mostly production
  - Still close to saturate C4Pi staff in 2024-26
    ⟶ to be monitored closely

⟶ Detailed project planning for C4Pi under discussion with IPHC directorate, to be validated by platform COPIL – March 2023

Common slide J.Baudot (BelleII) and A.Maire (ALICE)

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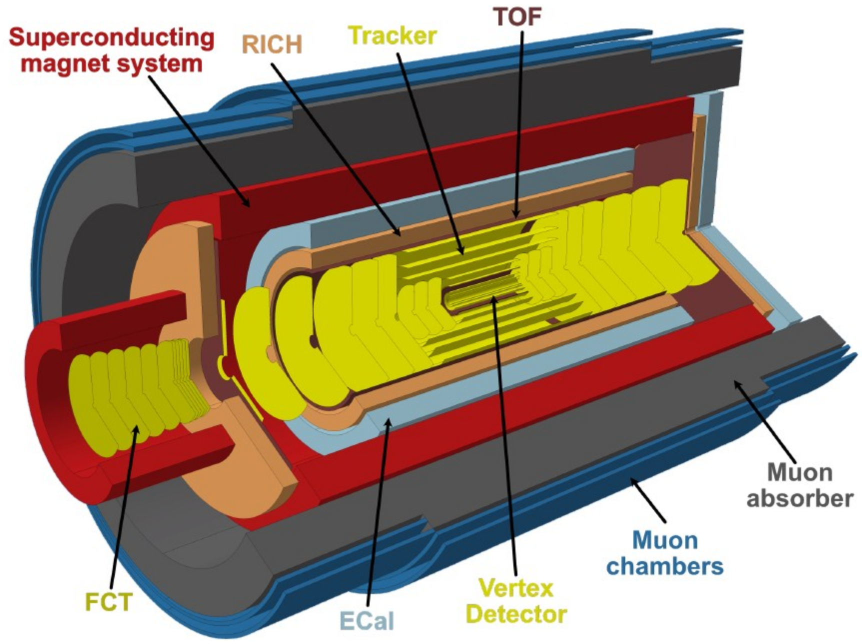
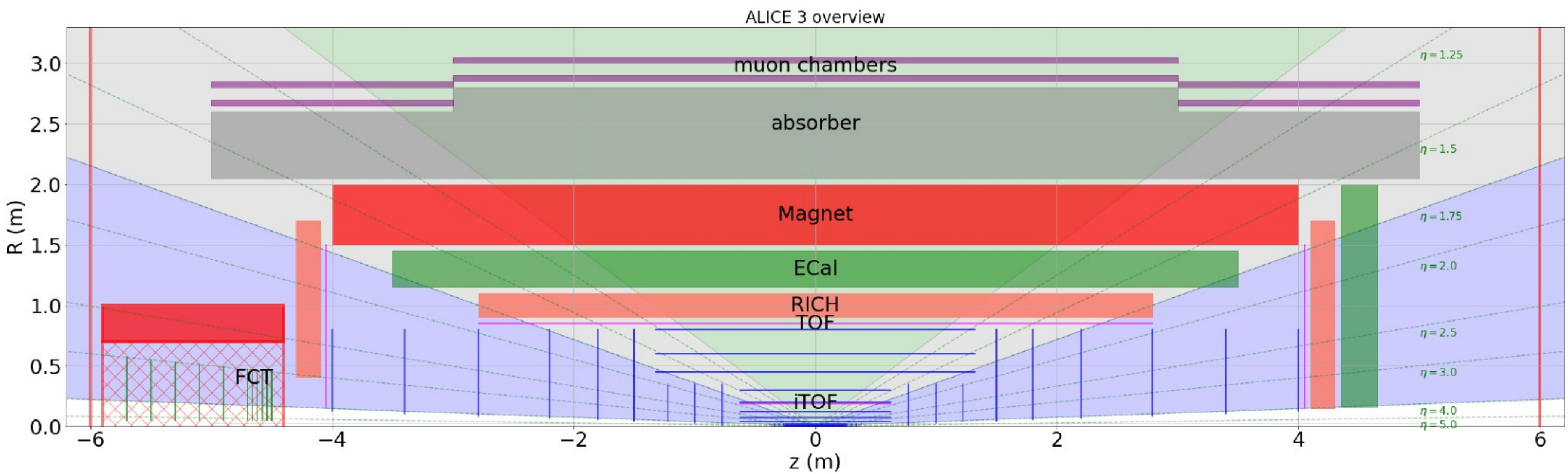
App. H – ALICE3

H.1 – ALICE3 : overview

ALICE3 LoI, *CERN-LHCC-2022-009*, *Fig. 1 + Fig. 2*





H.2 – ALICE3 : vertexer and tracker, layout

ALICE3 LoI, *CERN-LHCC-2022-009*

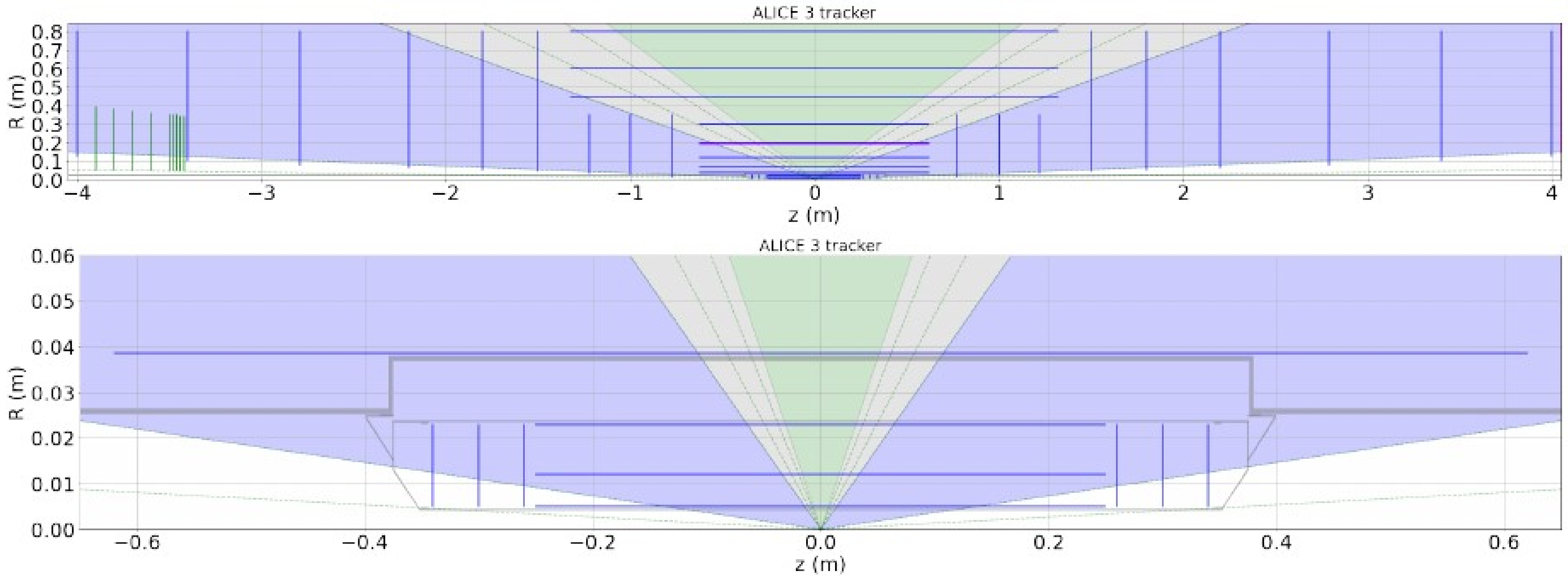


Figure 77: Schematic $R-z$ view of the full tracker (top) and of the vertex detector separately (bottom). The blue lines represent the tracking layers. The FCT disks are marked in green. In addition, the beampipe and vacuum vessel of the vertex detector are shown in grey.

H.2 – ALICE3 : vertexer and tracker, location

ALICE3 LoI, *CERN-LHCC-2022-009*

Layer	Material thickness (%X_0)	Intrinsic resolution (µm)	Barrel layers		Forward discs		
			Length ($\pm z$) (cm)	Radius (r) (cm)	Position ($\|z\|$) (cm)	R_{in} (cm)	R_{out} (cm)
0	0.1	2.5	50	0.50	26	0.005	3
1	0.1	2.5	50	1.20	30	0.005	3
2	0.1	2.5	50	2.50	34	0.005	3
3	1	10	124	3.75	77	0.05	35
4	1	10	124	7	100	0.05	35
5	1	10	124	12	122	0.05	35
6	1	10	124	20	150	0.05	80
7	1	10	124	30	180	0.05	80
8	1	10	264	45	220	0.05	80
9	1	10	264	60	279	0.05	80
10	1	10	264	80	340	0.05	80
11	1				400	0.05	80

Table 8: Geometry and key specifications of the tracker.

H.2 – ALICE3 : outer tracker, drawings

ALICE3 LoI, *CERN-LHCC-2022-009*

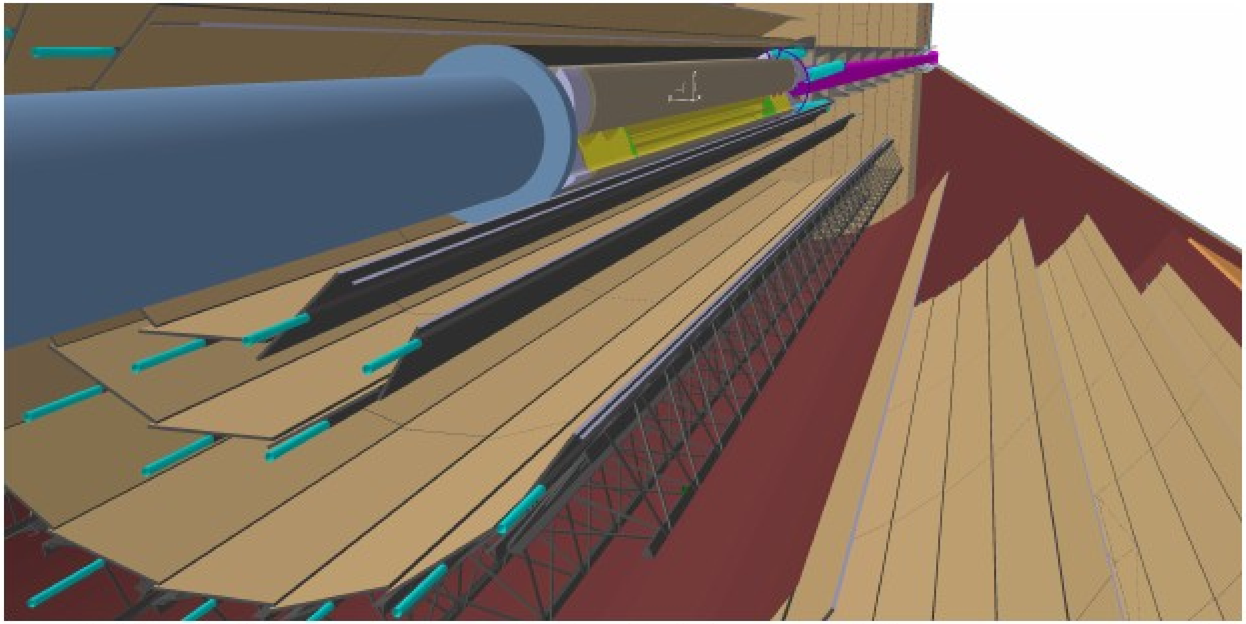
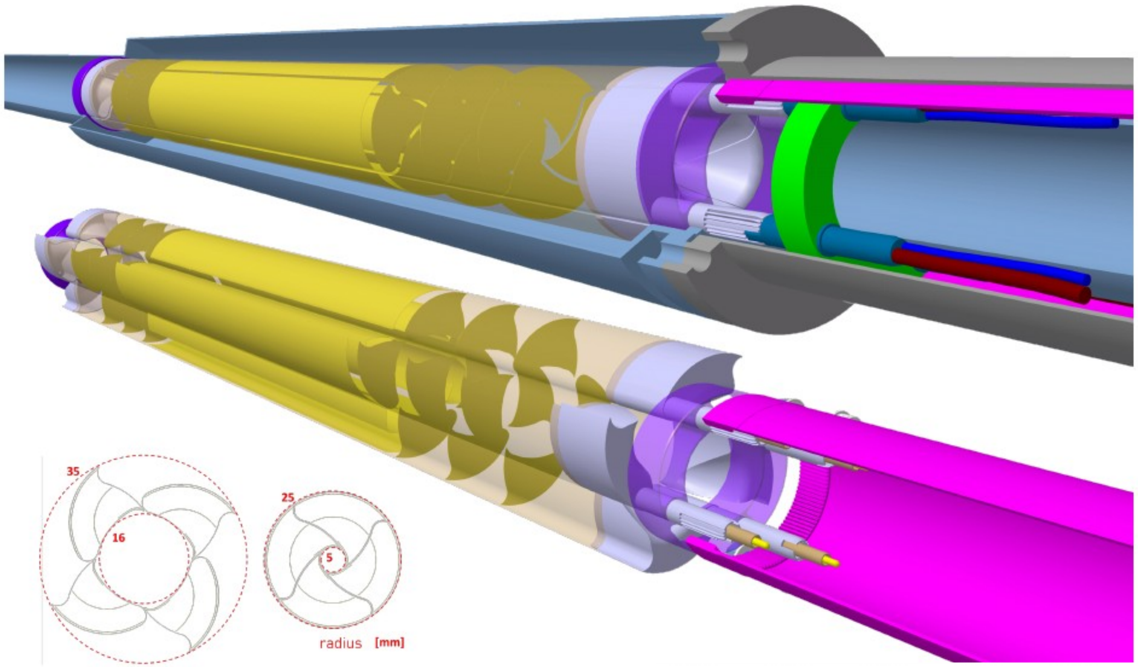
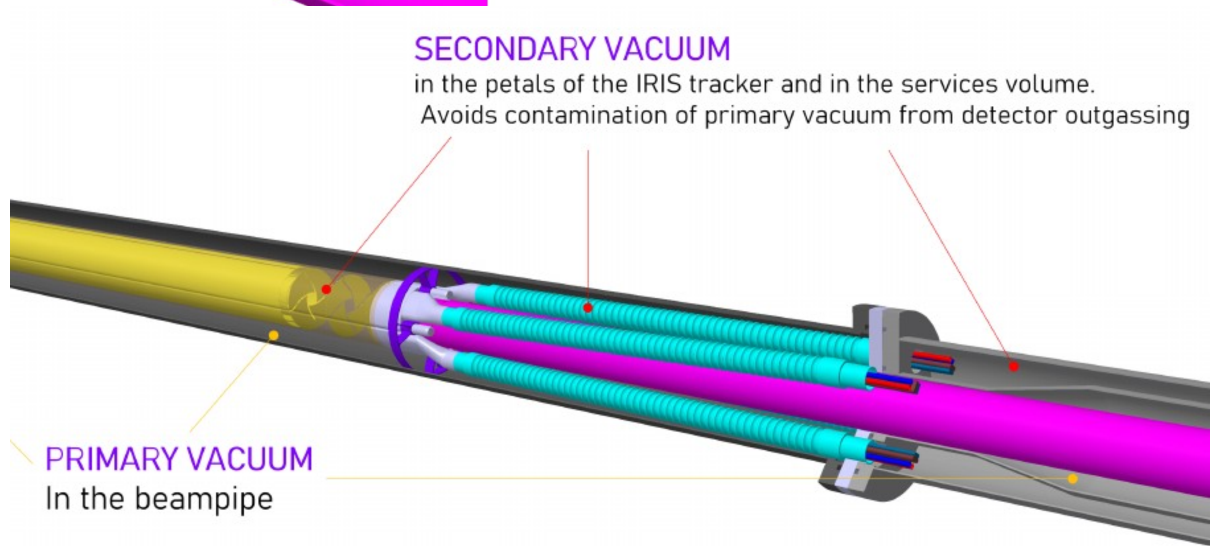


Figure 83: Sketch of the outer tracker mechanics. Modules assembled in staves structures are visible as well as services and power lines. Furthermore, the overlap of the staves can be seen.

H.2 – ALICE3 : IRIS vertexer, 3D drawings

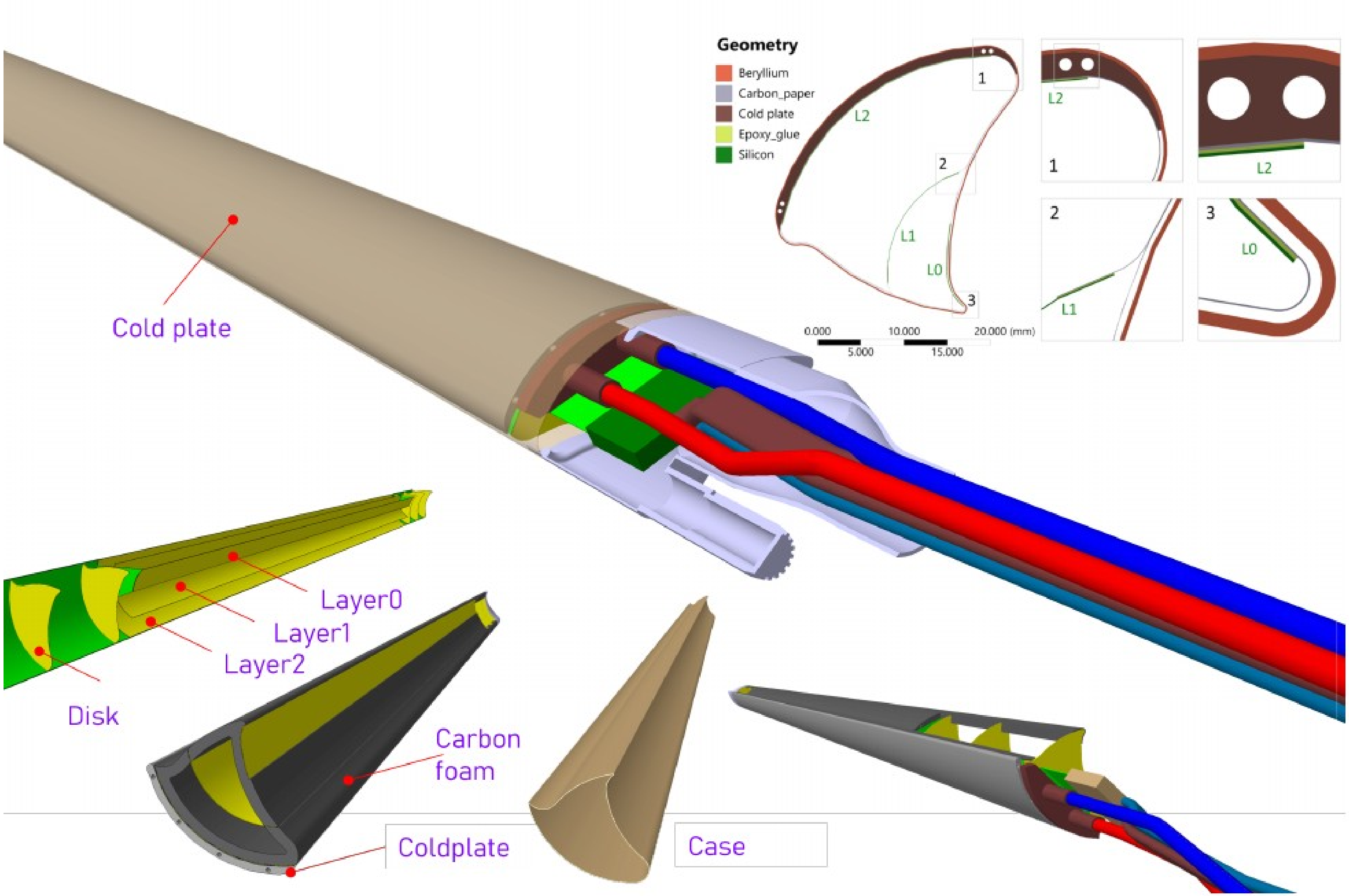
ALICE3 LoI, *CERN-LHCC-2022-009*
Fig.80





H.2 – ALICE3 : IRIS vertexer, 3D drawings

ALICE3 LoI, *CERN-LHCC-2022-009*
Fig.80



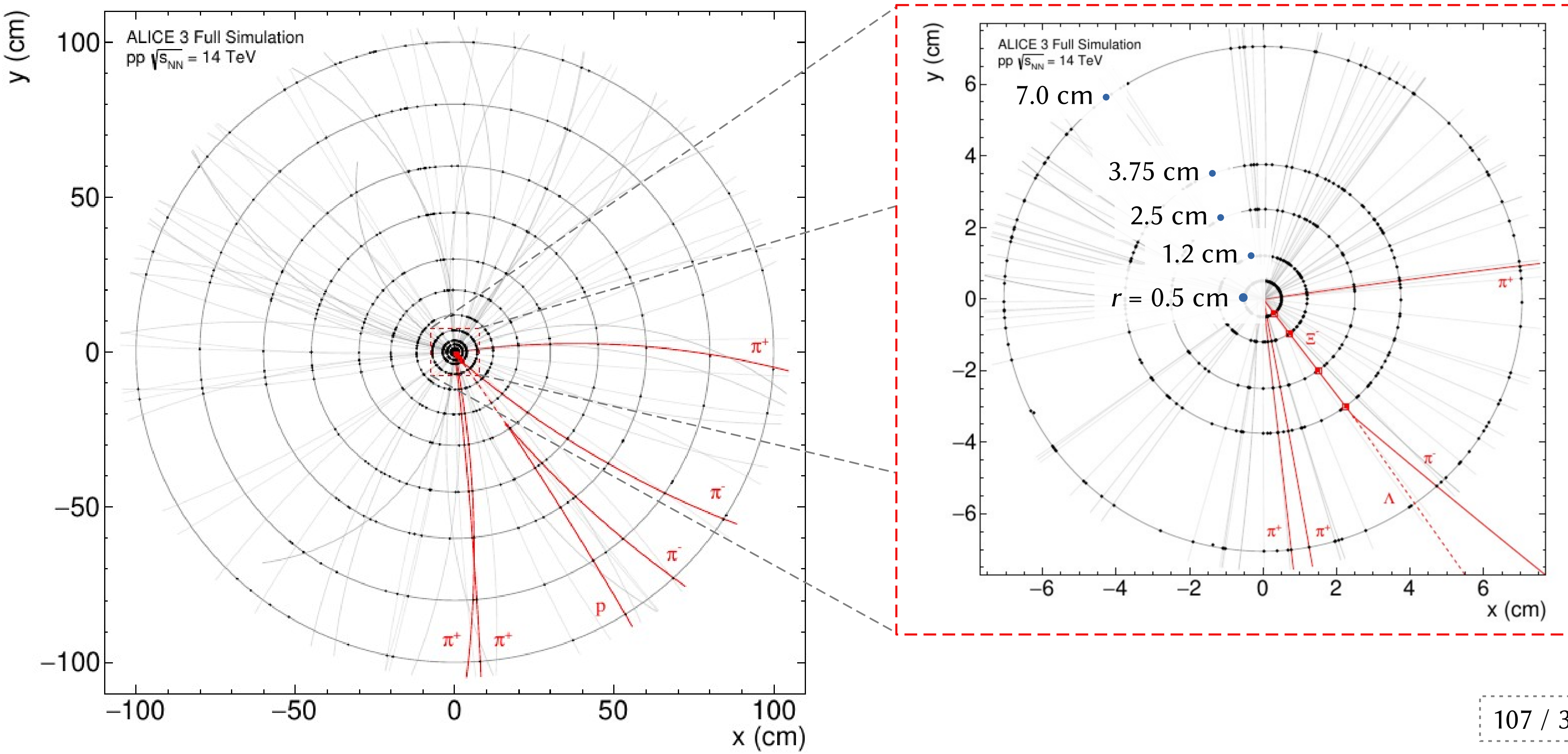
H.2 – ALICE3 : vertexer and tracker specifications

ALICE3 LoI, *CERN-LHCC-2022-009*

1. **Radial distance of first detection layers.** The radial distance of the first measured hit position must be as close as possible to the interaction point, which is fundamentally limited by the required aperture for the LHC beam (~ 5 mm).
2. **Material budget.** The vertex detector and the outer tracker target low material thicknesses of 0.1 % and 1 % of a radiation length, respectively.
3. **Intrinsic spatial resolution.** The layers of the vertex detector and of the outer tracker shall provide intrinsic position resolutions of 2.5 µm and 10 µm, respectively. Depending on the amount of charge sharing between neighbouring pixels, this translates to pixel pitches of about 10 µm and 50 µm, respectively.
4. **Hit time resolution.** To achieve a time binning of 500 ns in the vertex detector and the outer tracker, the sensors must provide a timing resolution (r.m.s) of $\sim$100 ns.
5. **Rate capability.** The sensors in the most exposed region of the vertex detector must be able to read out average hit rates of 35 MHz cm^{-2} in order to record all events in continuous readout. In the outer tracker, the expected rates are significantly lower, e.g. 1–5 kHz cm^{-2} in the outermost layers.
6. **Data throughput.** Assuming an encoding with 2 bytes/hit and a fake hit rate of $\sim 10^{-8}$ per pixel and event, a total data rate of $\sim$1 Tbit s^{-1} is expected.
7. **Power consumption and powering scheme.** In order to keep the material thicknesses within budget, the power consumption of the sensors must stay below 70 mW cm^{-2} for the Vertex Detector and around 20 mW cm^{-2} for the Outer Tracker.
8. **Radiation hardness.** The maximum radiation load per operational year will be about $1.5 \cdot 10^{15}$ 1 MeV $\mathrm{n_{eq}/cm^2}$ on the first tracking layer at a radial distance of 5 mm from the interaction point.

H.3 – Physics : strangeness tracking, example of ALICE3

Figure 18: (left) Illustration of strangeness tracking from full detector simulation of the Ξ_{cc}^{++} decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing the five innermost layers of ALICE 3 and the hits that were added to the Ξ^- trajectory (red squares).



ALICE3 LoI, *CERN-LHCC-2022-009*

H.4 – ALICE3 : PID with TOF + RICH

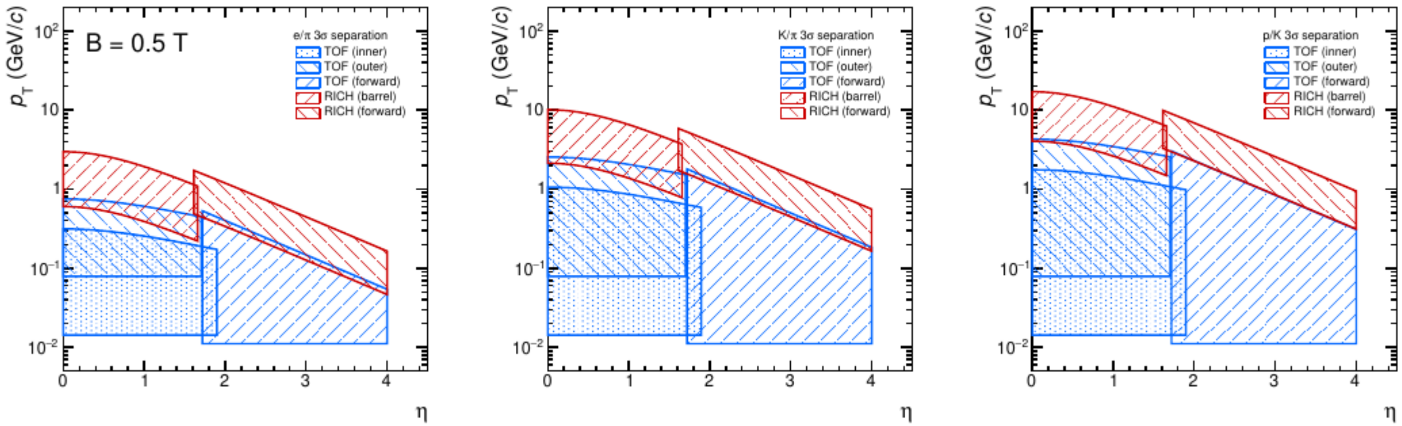


Figure 19: Analytical calculations of the $\eta - p_T$ regions in which particles can be separated by at least 3σ for the ALICE 3 particle-identification subsystems embedded in a 0.5 T magnetic field. Electron/pion, pion/kaon and kaon/proton separation plots are shown from left to right.

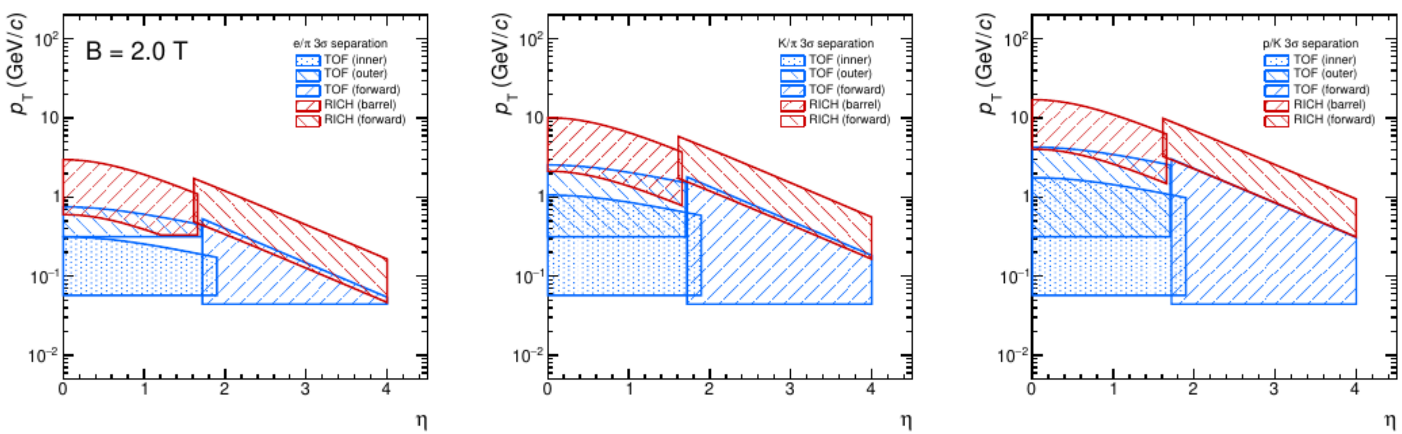


Figure 20: Analytical calculations of the $\eta - p_T$ regions in which particles can be separated by at least 3σ for the ALICE 3 particle-identification systems embedded in a 2.0 T magnetic field. Electron/pion, pion/kaon and kaon/proton separation plots are shown from left to right.

H.4 – ALICE3 : PID with (CMOS) TOF

	Inner TOF	Outer TOF	Forward TOF
Radius (m)	0.19	0.85	0.15–1.5
z range (m)	−0.62–0.62	−2.79–2.79	4.05
Surface (m^2)	1.5	30	14
Granularity (mm^2)	1×1	5×5	1×1 to 5×5
Hit rate (kHz/cm^2)	74	4	122
NIEL (1 MeV n_{eq}/cm^2) / month	$1.3 \cdot 10^{11}$	$6.2 \cdot 10^{9}$	$2.1 \cdot 10^{11}$
TID (rad) / month	$4 \cdot 10^{3}$	$2 \cdot 10^{2}$	$6.6 \cdot 10^{3}$
Material budget ($\%X_0$)	1–3	1–3	1–3
Power density (mW/cm^2)	50	50	50
Time resolution (ps)	20	20	20

Table 11: TOF specifications.

3 options :
- MAPS with gain layer (≈ ARCADIA project)
- Low Gain Avalanche Diodes (LGAD) (CMS MTD fwd, ATLAS HGTD)
- Single Photon Avalanche Diode (SPAD)

ALICE3 LoI, *CERN-LHCC-2022-009*, *section 4.3*

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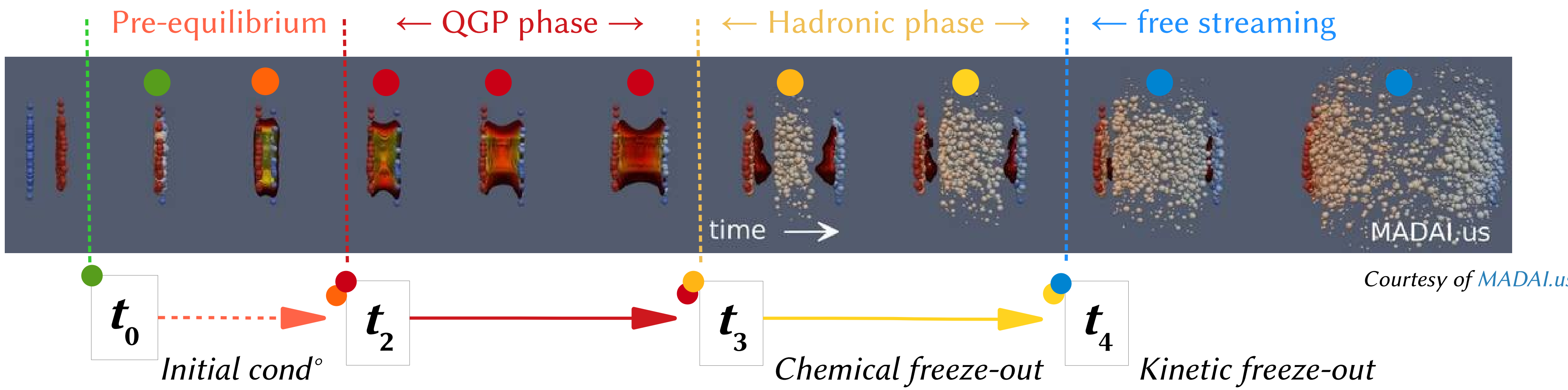
App. I – Template for QCD+QGP phys. cases

I.1 – Observables : Layer 1 / as a function of the collision time



0.
- Coherent E_{loss}
- nPDF
- shadowing
- CGC
+ fluctuations
…

1.
- Level of :
  . Hydrodynamisation
  . Chemical equilibration
  . Thermalisation

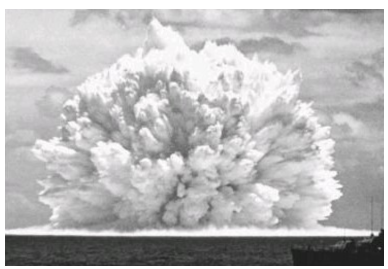
via
Multi-Parton Interactions
+ Colour Reconnections
+ Multiple parton scatterings
+ Rope shoving
+ Glasma
…

2.
- Degrees of freedom
- Phase transitions :
  . Chiral symm. restoration
  . Deconfinement
- Eq° of State
- Transport coefficients
- Radiative/Collisional E_{loss}
…

3+4.
. Sudden freeze-out
. HBT/Femtoscopy
. Recombination/
coalescence
. Hadronic re-interactions
…

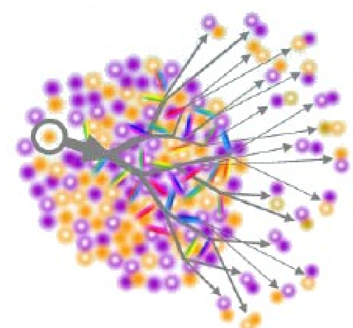
I.2 – Observables : Layer 2 / as a function of *momentum*

A. low-p_T "collectivity" ($p_T \leq$ 2-3 GeV/c)



≈ relativistic hydrodynamics,
barely viscous

B. high-p_T "collectivity" ($p_T \geq$ 6-8 GeV/c)

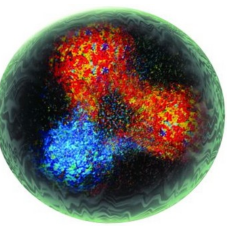


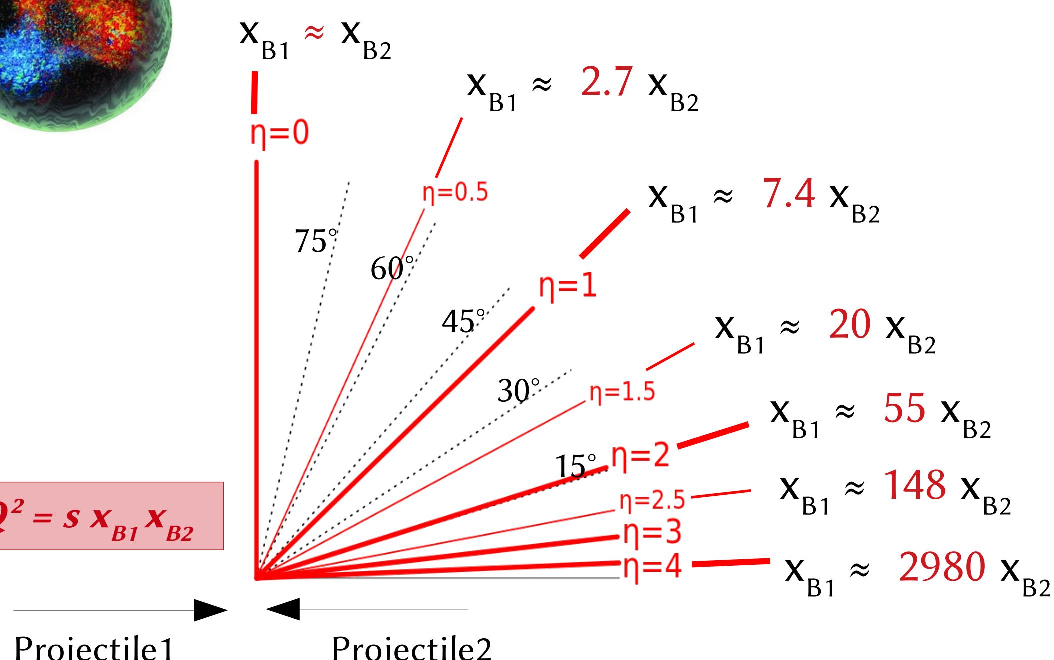
≈ in-medium energy losses for energetic particles

I.3 – Observables : Layer 3 / as a function of y (twice)

Initial state			*Longitudinal dynamics*		
I.	ultra-low x_B	($x_B \leq 10^{-5}$)	I'.	$\lvert y \rvert < 2$	: max = rapidity plateau in $dN_{ch}/d\eta$
II.	low x_B	($x_B \in [10^{-5} ; 10^{-3}]$)	II'.	$\lvert y \rvert \approx 3.5$	: 75% $(dN_{ch}/d\eta)_{max}$
III.	moderate x_B	($x_B \in [10^{-3} ; 10^{-1}]$)	III'.	$\lvert y \rvert \approx 5.0$	: 45% $(dN_{ch}/d\eta)_{max}$

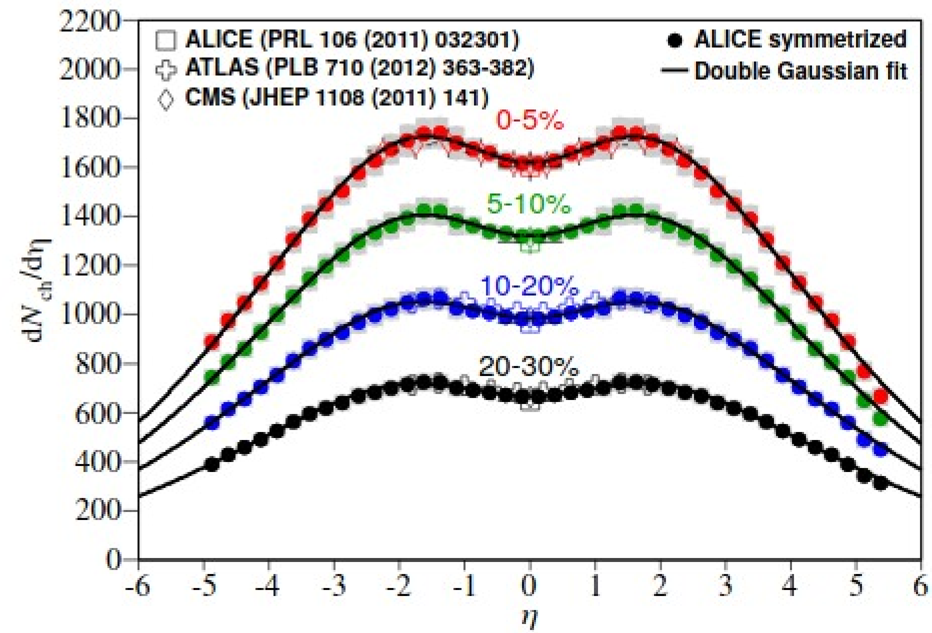
JLab





$Q^2 = s\, x_{B1} x_{B2}$

ALICE, arXiv:1304.0347

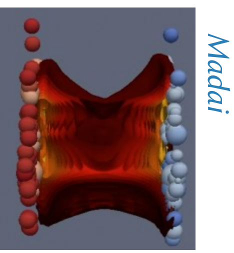


* if y ≈ η (m << p)
+ same type of beams (A_i/Z_i)

I.4 – Observables : Layer 4 / as a function of flavours

« hadron-quark duality »

g + u,d,s,c,b (t) <=>



u,d,s

- $\pi^{\pm}$ π^{0} $K^{\pm}$ K^{0}_{S} … p Λ $\Sigma^{\pm}$(*uus*) $\Xi^{\mp}$ (*dss*), $\Omega^{\mp}$(*sss*) …

  η(547) ω(782) … K^{0}(892) ϕ(1020) $\Sigma^{\pm}$(1385) Λ(1520) Ξ^{0}(1530)

  + d t $^{3}He^{2+}$ $^{4}He^{2+}$ …

  + $^{3}_{\Lambda}H$, $^{4}_{\Lambda}\overline{He}^{2+}$ $\longrightarrow$ $^{3}He^{2+}$ p π^{-} .

c

- (D^{0} D^{+} D^{*+} D_{S}^{+})… η_{c} J/ψ χ_{Ci} ψ(2S) …

  Λ_{C}^{+}(*udc*), Ξ_{C}^{+}(*usc*), Ξ_{C}^{0}(*dsc*), Ω_{C}^{0}(*ssc*)

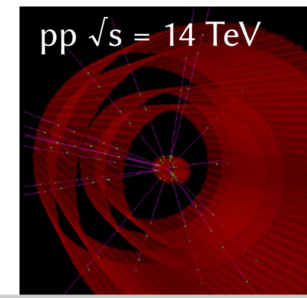
  + *c*-deuteron $(\Lambda_{c}n)^{+}$, *c*-triton $(n\Lambda_{c}n)^{+}$?

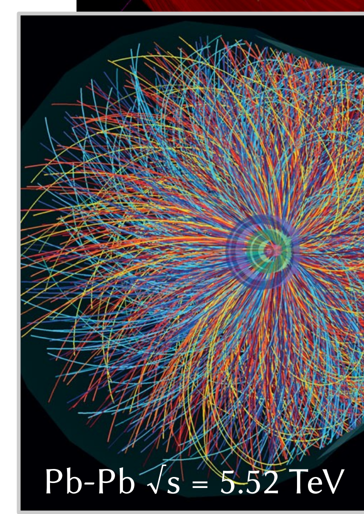
b

- heavy-flavour ($\mu^{\pm}$, $e^{\pm}$)
- B^{0} $B^{\pm}$ B^{0}_{S} … Υ(1S,2S,3S)…

  Λ_{b}^{0} (*udb*)…

(• $e^{\pm}$ $\mu^{\pm}$ γ)
(• $W^{\pm}$ γ/Z°)

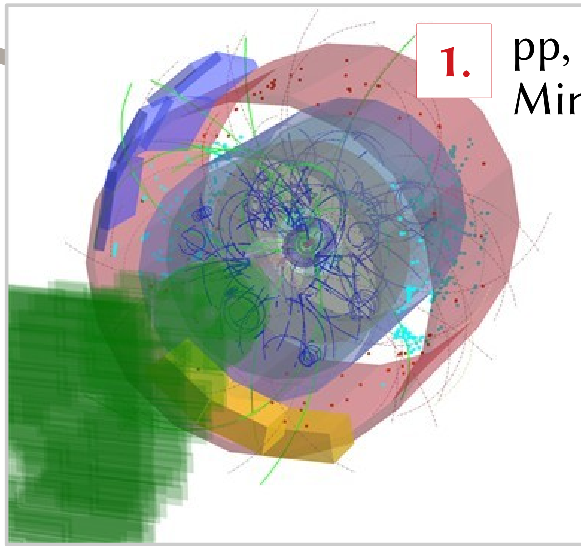




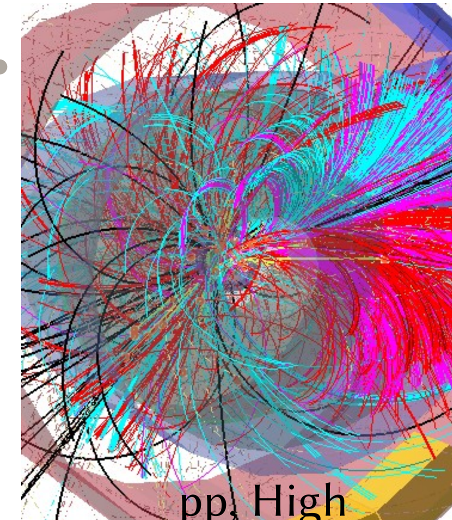
NB :

baryons Vs mesons
mixed flavours (s+c, s+b, … c+b …)

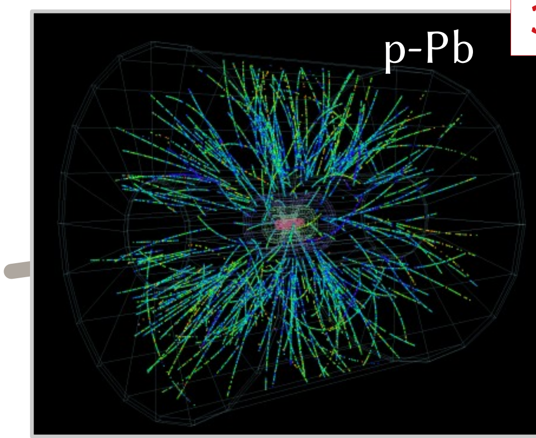
I.5 – Observables : Layer 5 / as a funct° of the collision system



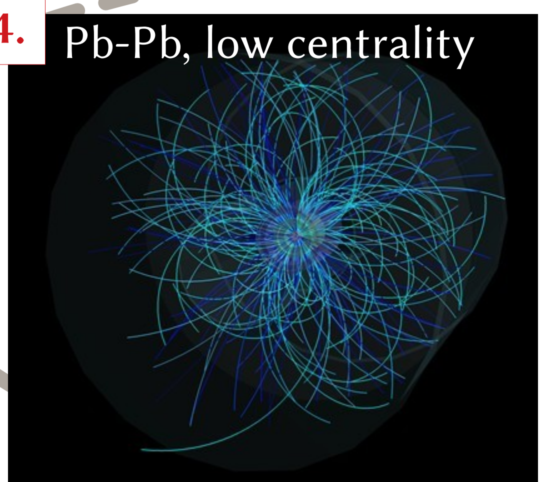
1. pp,
Min. Bias



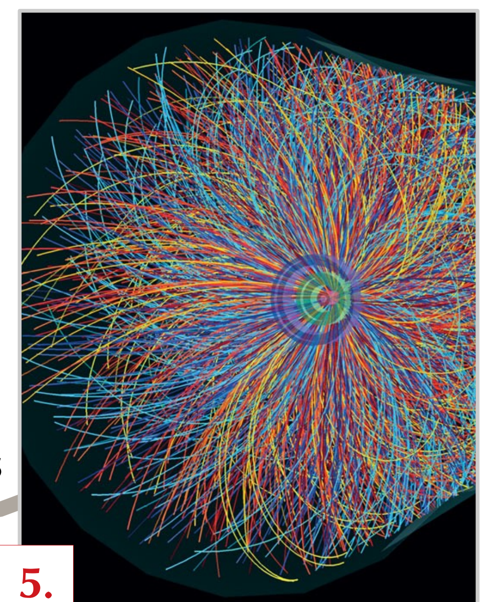
2. pp, High
Multiplicity



3. p-Pb



4. Pb-Pb, low centrality

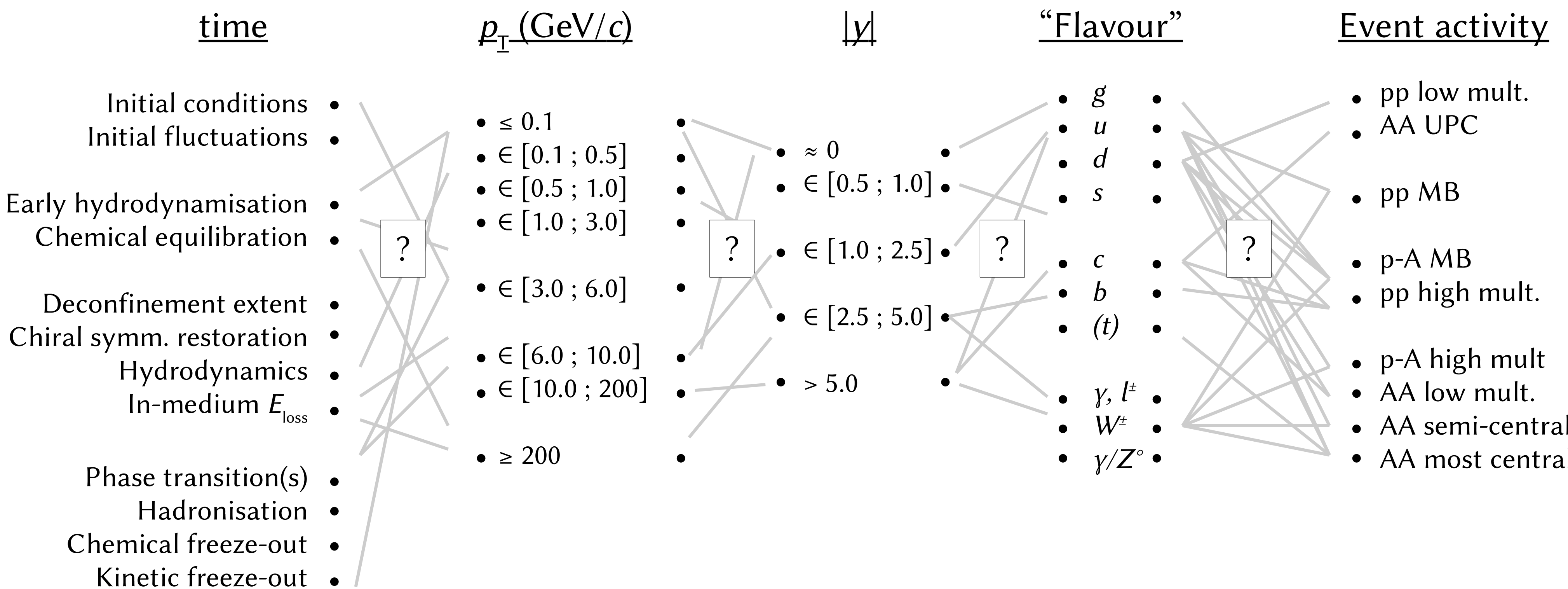


5. Pb-Pb,
most central events

CDS/record-1305398

I.6 – Observables : paths through the multi-layer mesh

The multi-variate and interleaved families of QCD+QGP observables :



(HL-)LHC watchword for (≥Run III) : "precision era" pushed on many fronts

i.e. fight for (σ_{stat} ≈ negligible) ⊗ (σ_{syst} ≤ 1-5%) as much as possible

Note : QCD+QGP physics is both i) a bulk physics + ii) a rare-probe physics
⟶ Nowadays, precision then implies extreme cases on both fronts ... (*i.e.* also for abundant observables)
(e.g. *multi-differential, multi-correlated probes, ≤ 1 High-Mult. evt every [10^6-10^9] MB pp evts ...*)

I.7 – Phys. incentives : some open questions left after Runs 1+2

Initial state
- What is the fundamental nature of the initial state ?
  Can hard probes reveal it ?

Equilibration
- Which mechanisms drive a (quantal QCD system) into a (high-T ~equilibrated medium) ?
- such an equilibration, possible in small systems ?
- or are there elementary QCD mechanisms that mimic the observed collective behaviour ?

In-medium dynamics
- What does the apparent collective behaviour of c+b tell us ?
- What is the fundamental nature of degrees of freedom
  relevant for QCD at finite T (partons, quasi-particles, ...) ?

Hadronisation
- Which processes do create hadrons, flavour by flavour ?