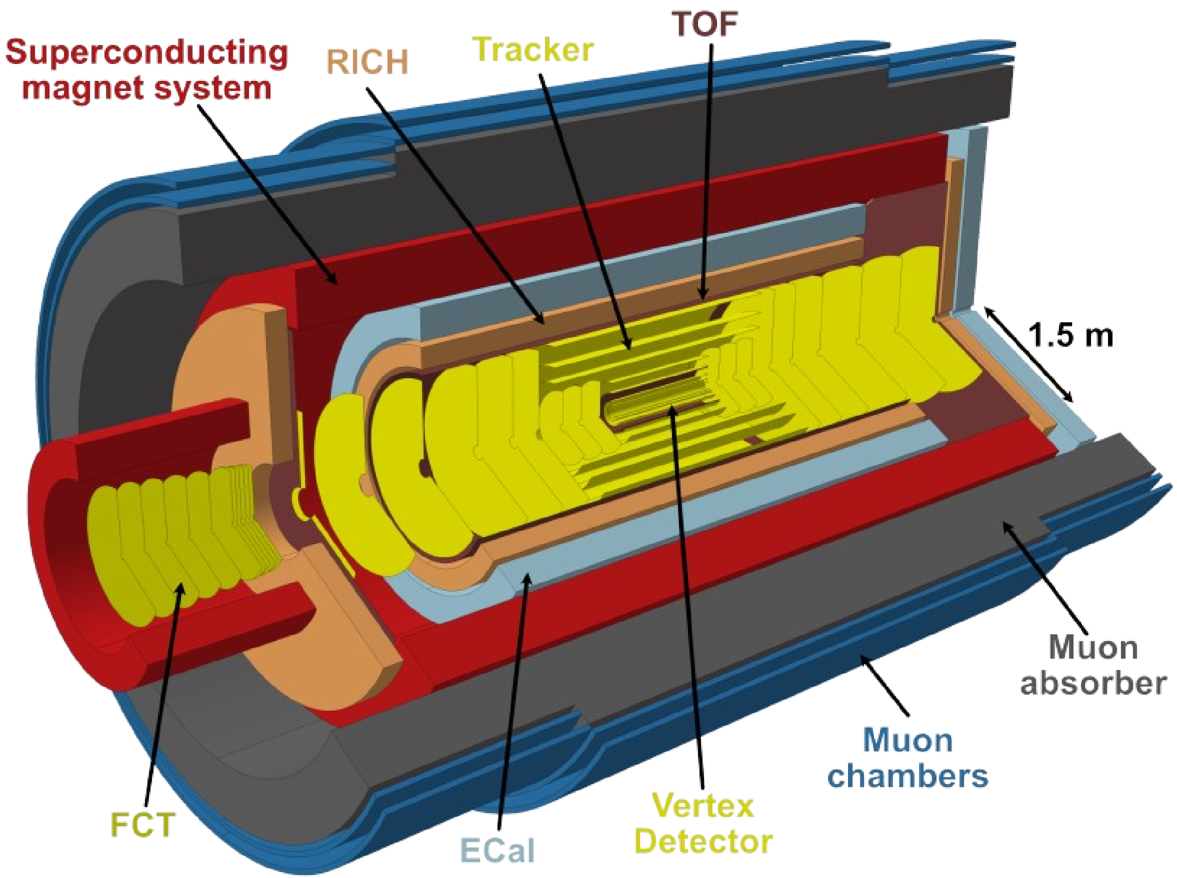
Antonin MAIRE – IPHC Strasbourg
Tuesday, 19 Sept 2023– **Pixel workshop within GdRs**



ALICE$_3$:
physics cases and specifications

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

Outline

A. Physics landscape

B. ALICE3 : *general layout*

C. ALICE3 sub-detectors : *vertexer and trackers*

I.1 – HL-LHC QCD+QGP : towards an ideal detector

By 2032, ≈ any inclusive identified measurements ≈ done.

⟶ Stakes = multi-differential and/or correlated measurements
(v$_n$, HBT, double-identified production, f(multiplicity), f(event activities) ...)

QGP physics = a particle of interest wrt to its ***context***,
i.e. QCD surroundings in the same event

⟶ Need a focus on :

- all identified particles (*u,d,s,c,b*)
- access to [ultra]low p_T ([0.05-0.15]- O(10) GeV/*c*)
- ∀ p_T, ∀ y, high AxEff(tracks) AxEff ≈ 100% ?
- ideally, done on an event-by-event basis,
- made available through huge integrated luminosities, both in AA and in pp

Criteria to define how the ideal experiment(s) should look like...

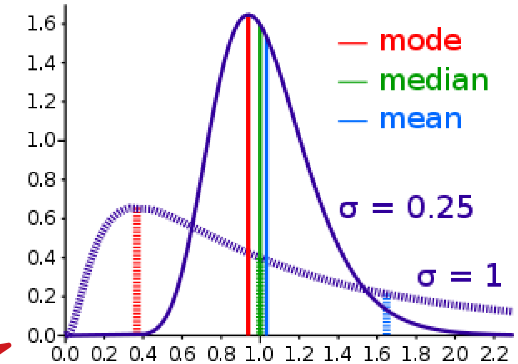
I.2 – HL-LHC QCD+QGP : for which physics cases ?

- Degrees of freedom within the QGP via LQCD (deconfinement dof + transition + chiral restoration) ?
  - net quantum-charge fluctuations at ($\mu_B = 0$)
    $\longrightarrow$ Q : ($h^+ - h^-$), B : ($p - \bar{p}$, $\Lambda - \bar{\Lambda}$, ...), S : ($K^+ - K^-$, $\Lambda - \bar{\Lambda}$, ...)
  - direct e^+e^- ($m_{inv} \in [2\text{-}5]$ GeV/c^2) to access initial state (cf. Ollitrault, Winn *arXiv:2104.07622*)
  - ....
- Probe the effect of chiral symmetry restoration ?
  - e^+e^- at $m_{inv} \approx m(\rho)$ (~0.8 GeV/c^2)
  - ultra-low p_T $\pi^\pm$ (p_T < 0.05-0.1 GeV/c)
  - ...
- Evolution of the thermodynamic param. (T, elec. conductivity, ...) within the system ?
  - Thermal e^+e^- (m_{inv} < 0.05-3 GeV/c^2) ?
  - ...
- Roots of collectivity (hydrodynamisation, chem. equilibration, thermalisation) ?
  - *u,d,s,c,b* = f[event-activity (mult, spherocity, R_T, ...) + system pp, pA, AA]
  - ...
- Alterations of parton shower by the medium ?
  - *PID* decomposition within *flavour-tagged* jets
  - ...
- Interplay between mechanisms of hadronisation ?
  - $\Xi_{cc}^{2+}(ucc)$, ... , $\Omega_{ccc}^{2+}(ccc)$
  - $\chi_{c1}(3872)(c\bar{c}u\bar{u})$, $T_{cc}^{+}(cc\bar{u}\bar{d})$
  - ...

I.3 – Phys. case : ex. 1 – net quantum fluctuations

Net quantum number fluctuations at ($\mu_B = 0$)

- **Q** : net charge (h^+ - h^-),
- **B** : net baryon (p - $\bar{\text{p}}$, Λ - $\bar{\Lambda}$, ...)
- **S** : net strangeness (K^+ - K^-, Λ - $\bar{\Lambda}$, ...)

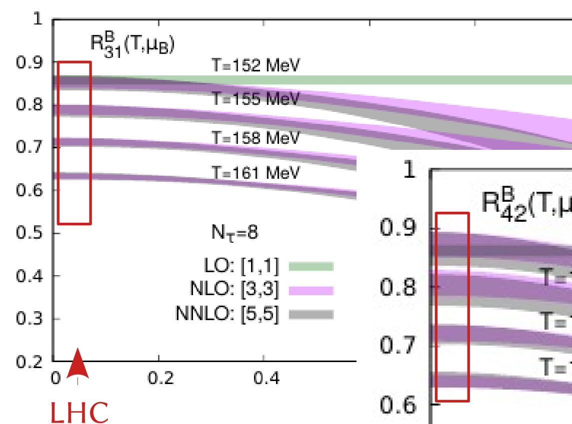


Wikipedia:Skewness

Measure event-by-event fluctuations into distributions with $p_T > 0$ GeV/c + over large y

(i.e. p_T-integrated quantities)

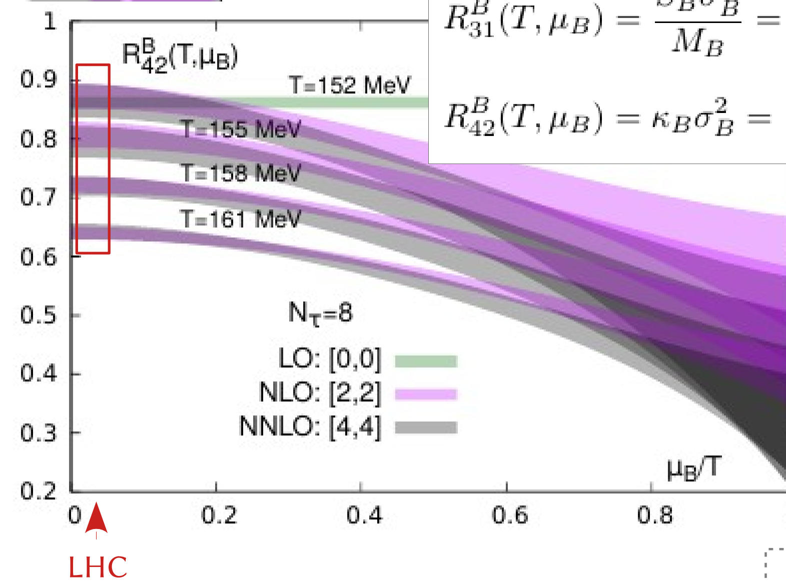
- 1st moment, m_1 : mean M
- 2nd moment, m_2 : variance σ^2
- 3rd moment, m_3 : ∝ skewness S
- 4th moment, m_4 : ∝ kurtosis κ
- 5th moment, m_5 : *no name*
- 6th moment, m_6 : ...
- 7th moment, m_7 : ...



HotQCD, arXiv:2001.08530

$$R^B_{31}(T,\mu_B) = \frac{S_B\sigma^3_B}{M_B} = \frac{\chi^B_3(T,\mu_B)}{\chi^B_1(T,\mu_B)}$$

$$R^B_{42}(T,\mu_B) = \kappa_B\sigma^2_B = \frac{\chi^B_4(T,\mu_B)}{\chi^B_2(T,\mu_B)}$$

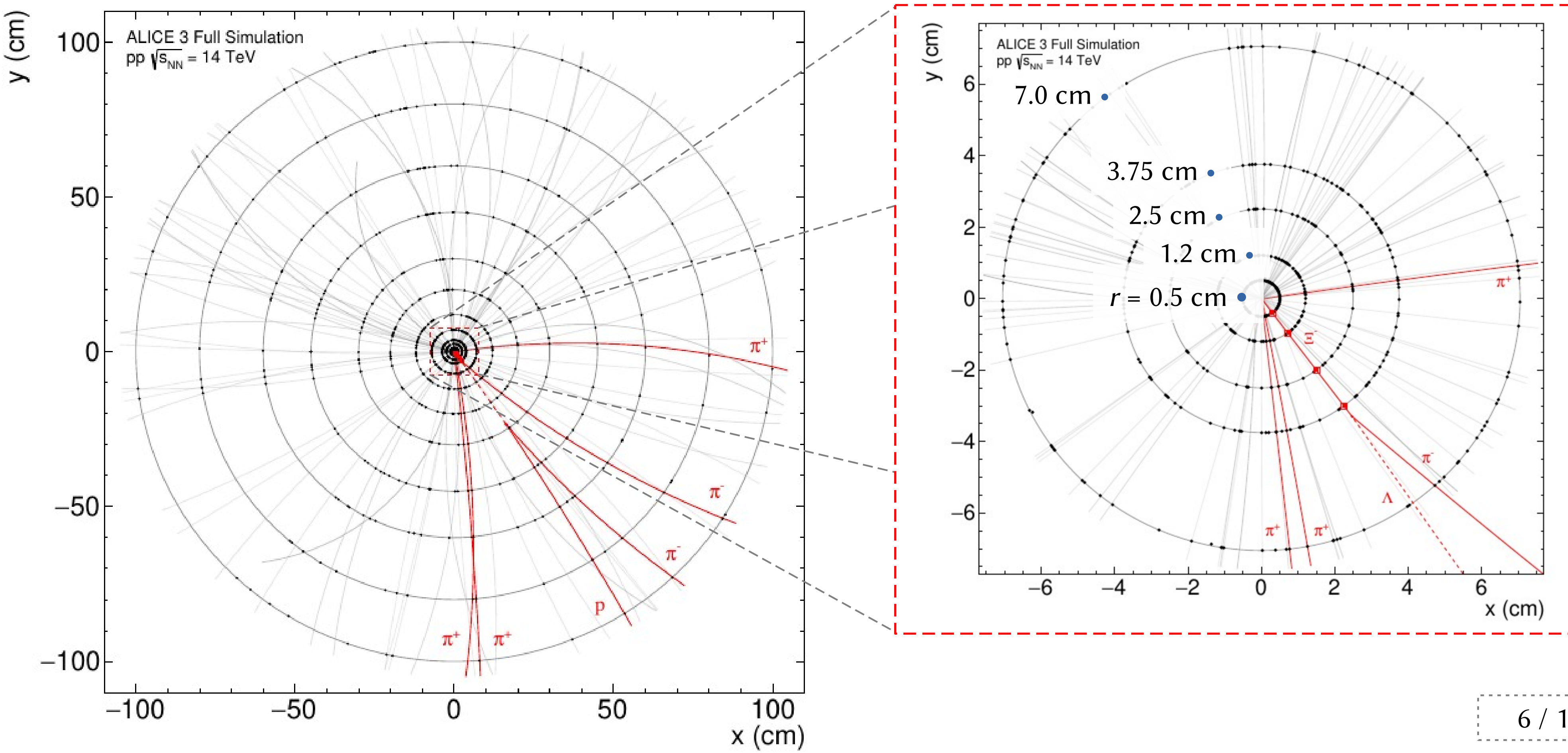


→ *key* : ratios m_j/m_i (e.g. $m_4{}^B/m_2{}^B$)
to access direct comparison to LQCD for
(deconfinement d.o.f.
\+ chiral restoration
\+ nature of transitions)

See also EMMI, arXiv:2001.08831

I.4 – Phys. case : ex. 2 – strangeness tracking in ALICE3

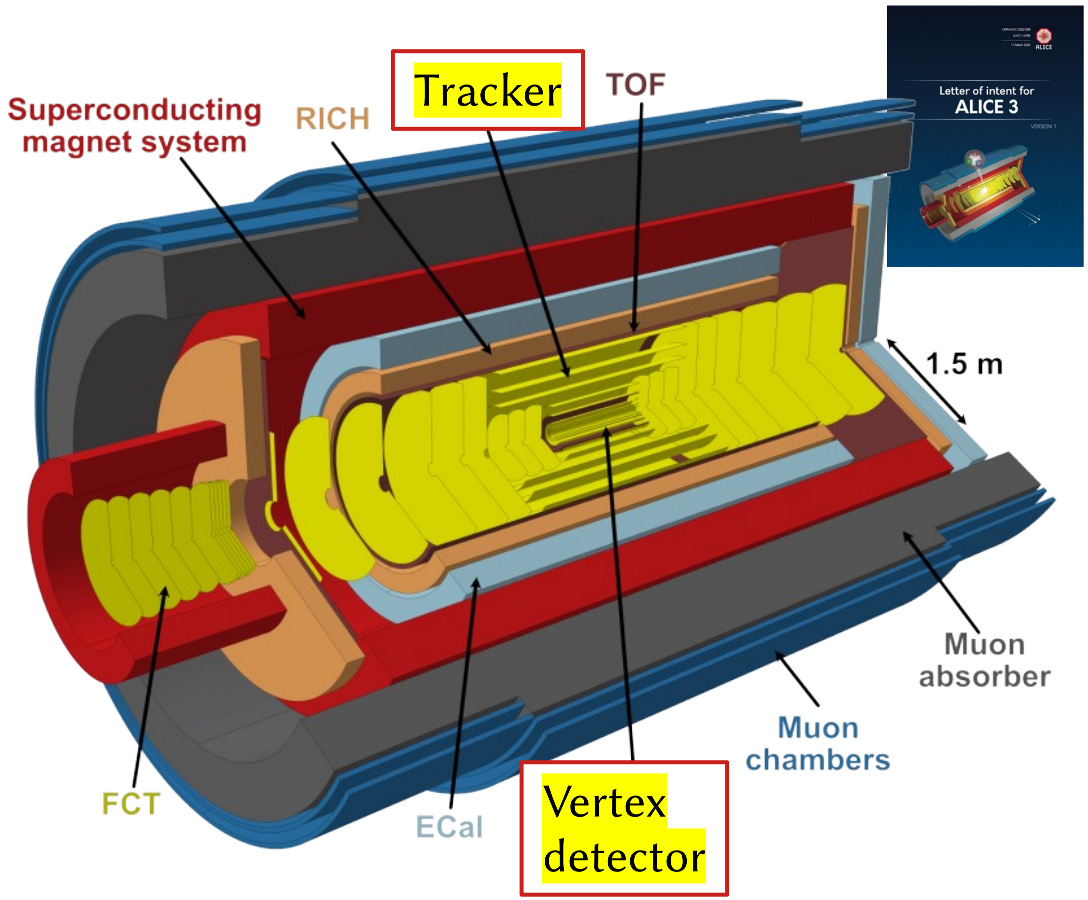
Figure 18: (left) Illustration of strangeness tracking from full detector simulation of the Ξ_{cc}^{++} decay into $\Xi_c^+ + \pi^+$ with the successive decay $\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$. (right) Close-up illustration of the region marked with a red dashed box in the left figure, containing 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*

II.1 – ALICE3 : LoI Layout (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

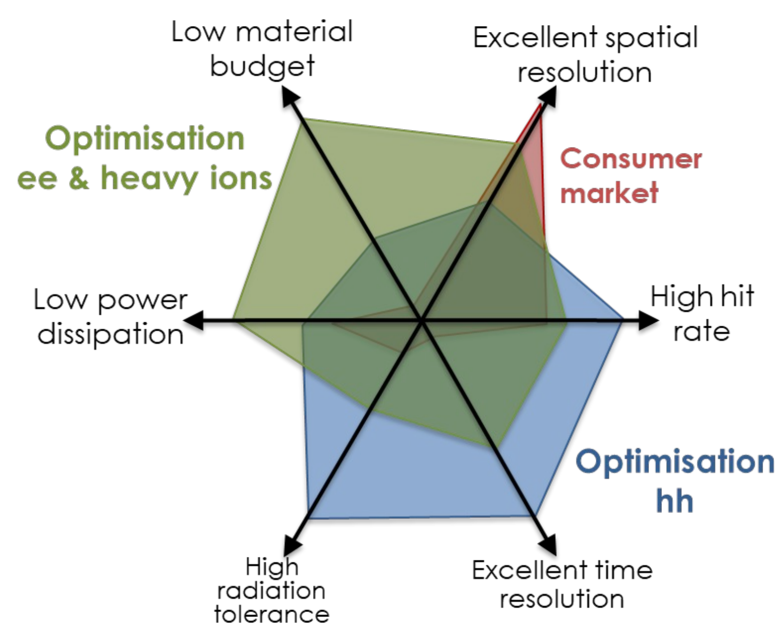
- $\mathcal{O}(0.5\ \text{fb}^{-1})$ / month pp
- $\mathcal{O}(5.6\ \text{nb}^{-1})$ / month Pb-Pb

II.2 – ALICE3 : proximity to (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

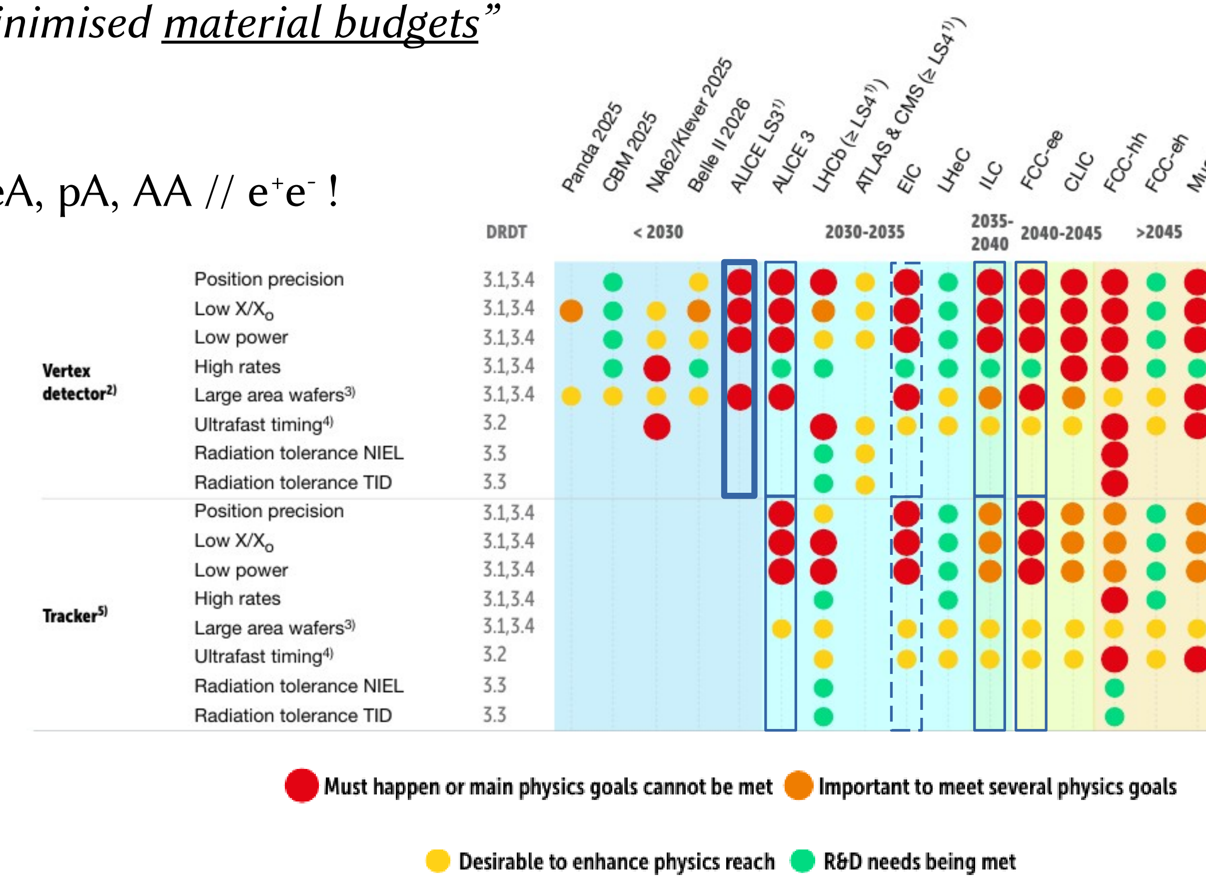
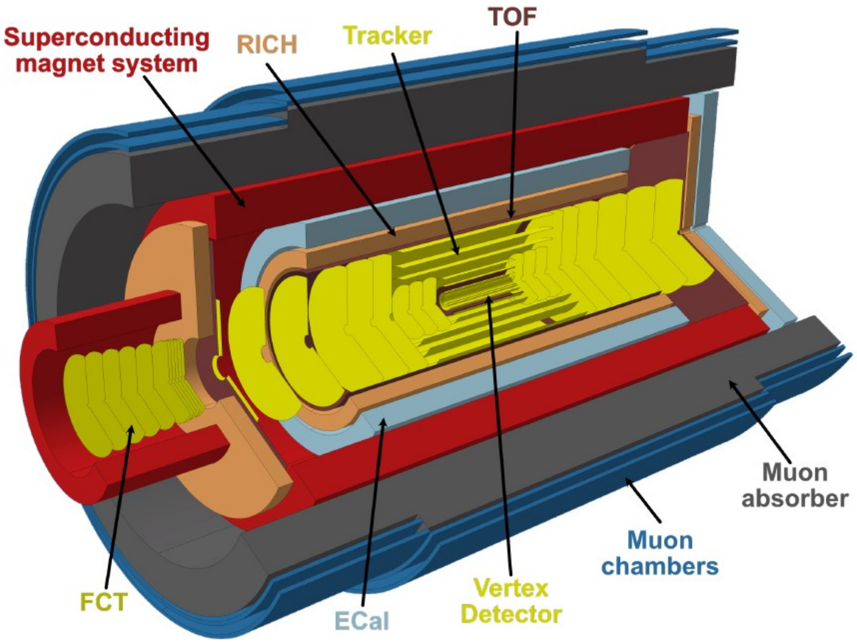
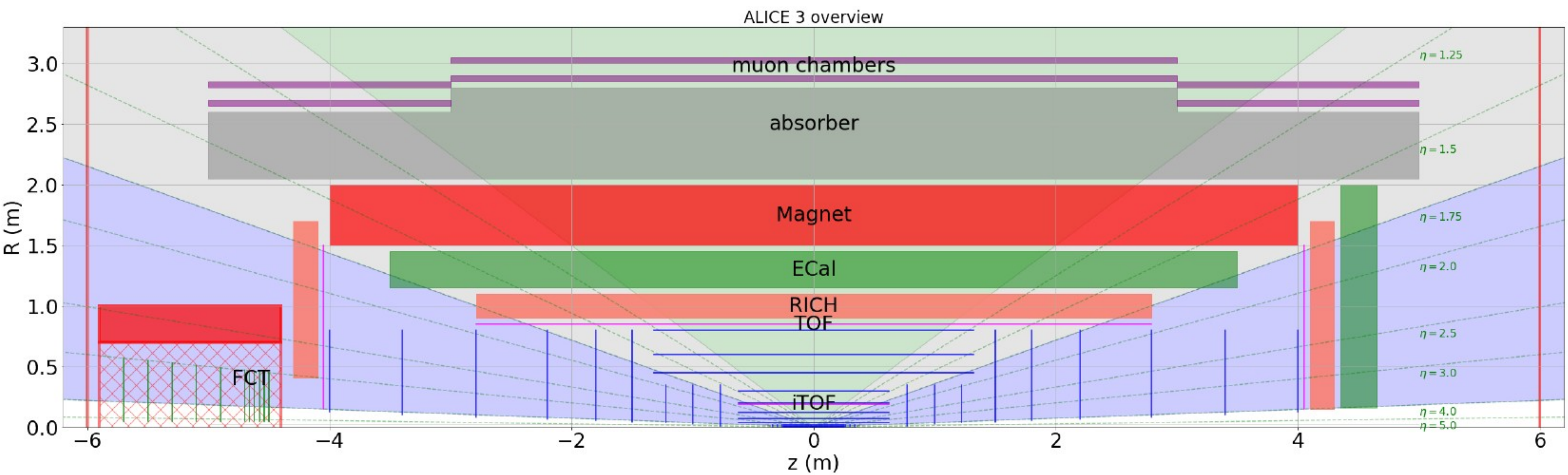


Fig. 3.1, 2021 ECFA roadmap

III.1 – ALICE3 : layout overvie



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



IV.2 – ALICE3 : PID with TOF + RICH

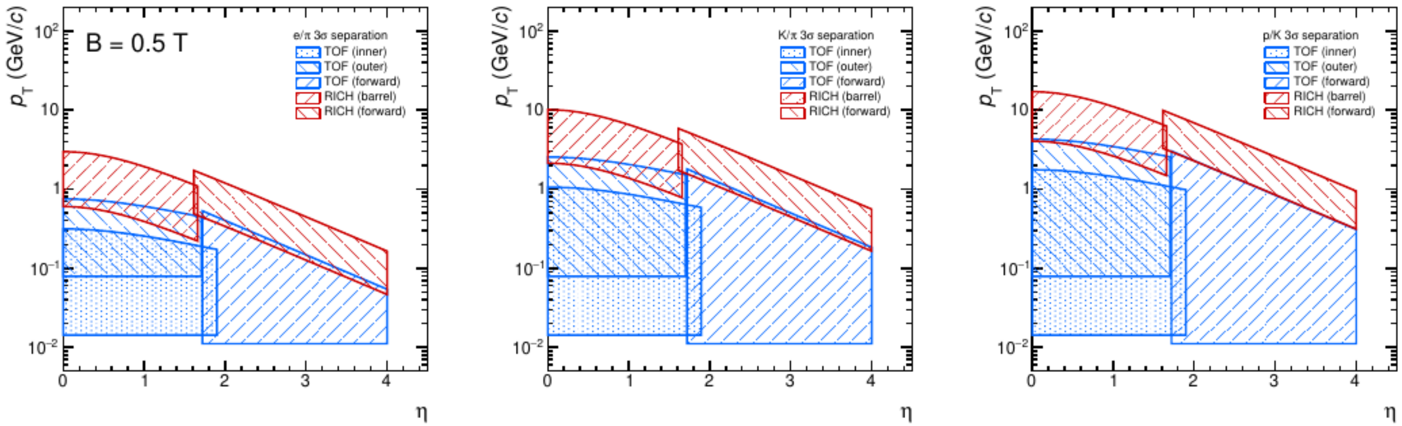


Figure 19: Analytical calculations of the $\eta - p_{\mathrm{T}}$ regions in which particles can be separated by at least 3σ for the ALICE 3 particle-identification subsystems embedded in a 0.5 T magnetic field. Electron/pion, pion/kaon and kaon/proton separation plots are shown from left to right.

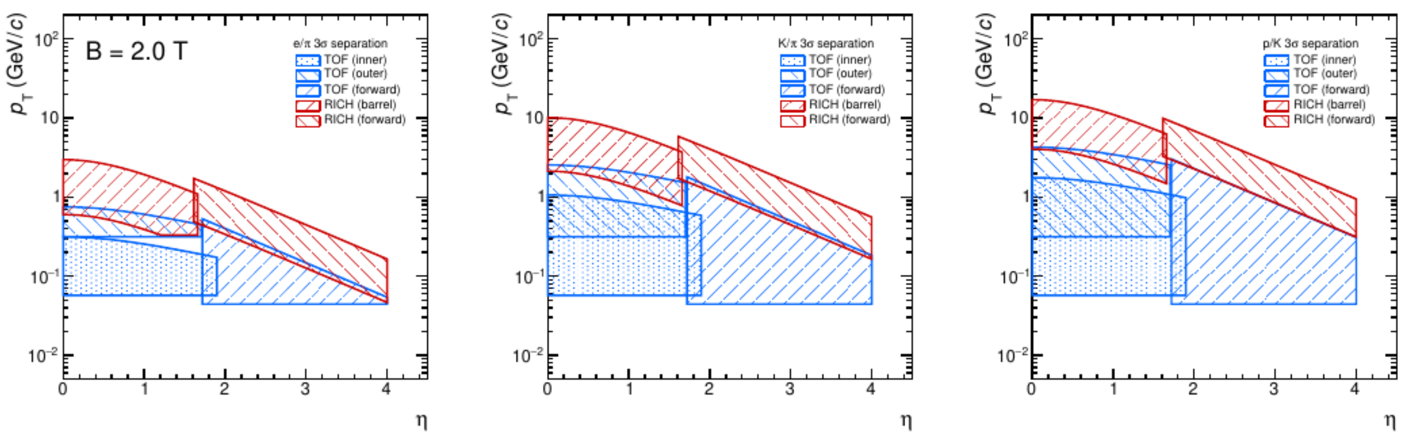


Figure 20: Analytical calculations of the $\eta - p_{\mathrm{T}}$ regions in which particles can be separated by at least 3σ for the ALICE 3 particle-identification systems embedded in a 2.0 T magnetic field. Electron/pion, pion/kaon and kaon/proton separation plots are shown from left to right.

ALICE3 LoI, *CERN-LHCC-2022-009*, *section 3.2.2*

IV.2 – 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*

V.1 – ALICE3 : vertexer and tracker, layout

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

. Outer
. Middle

. Inner

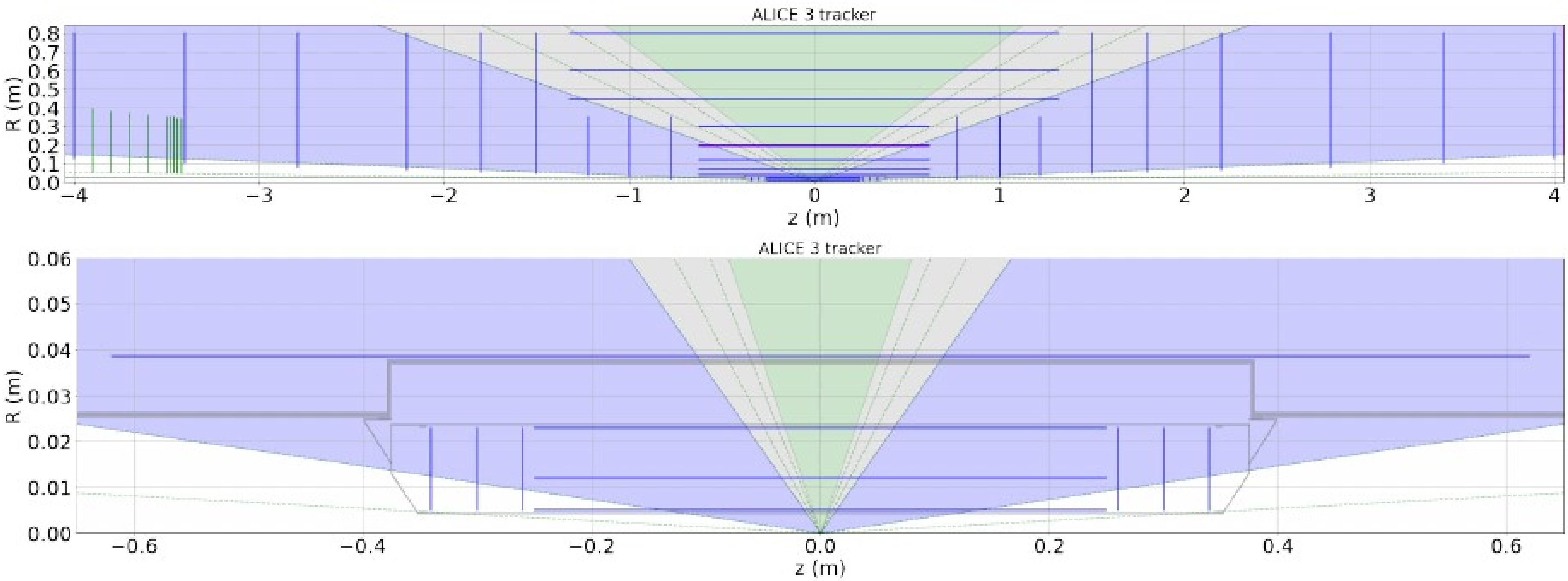


Figure 77: Schematic $R - z$ view of the full tracker (top) and of the vertex detector separately (bottom). The blue lines represent the tracking layers. The FCT disks are marked in green. In addition, the beampipe and vacuum vessel of the vertex detector are shown in grey.

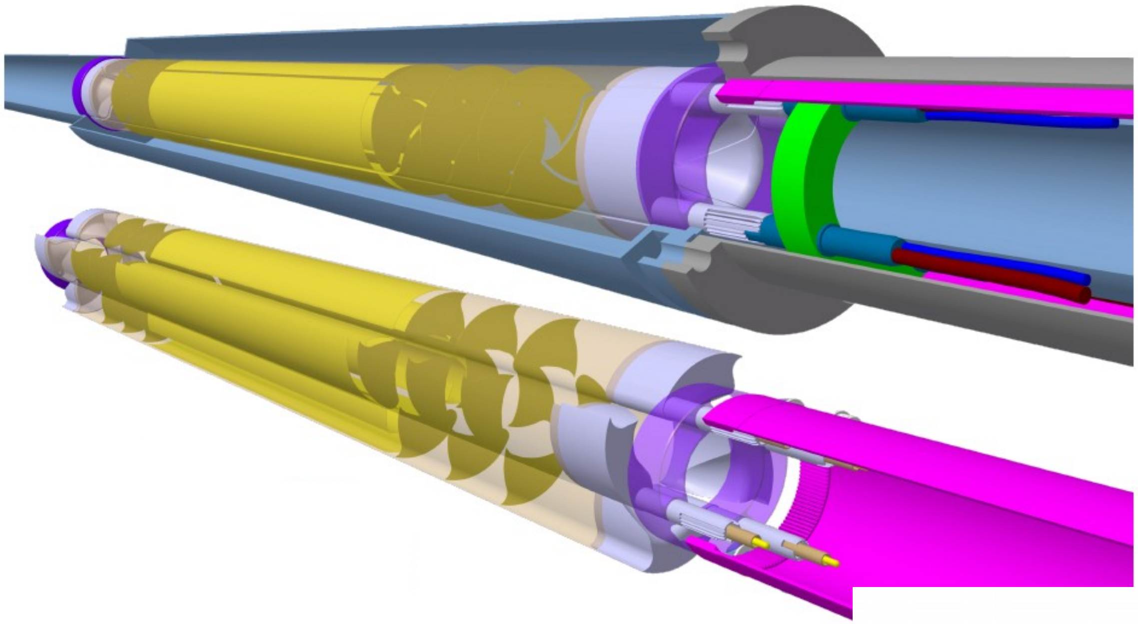
V.2 – ALICE3 : vertexer and tracker, location

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

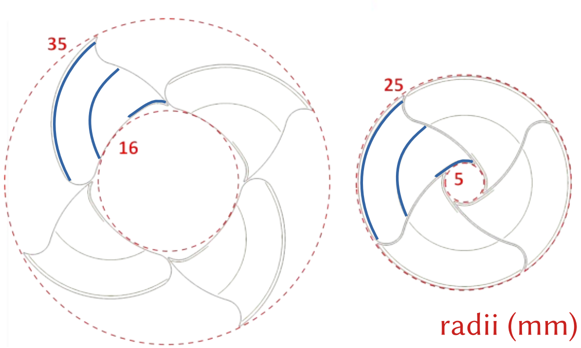
	Layer	Material thickness ($\%X_0$)	Intrinsic resolution (µm)	Barrel layers Length ($\pm z$) (cm)	Barrel layers Radius (r) (cm)	Forward discs Position ($\|z\|$) (cm)	Forward discs R_{in} (cm)	Forward discs R_{out} (cm)
Inner tracker	0	0.1	2.5	50	0.50	26	0.005	3
	1	0.1	2.5	50	1.20	30	0.005	3
	2	0.1	2.5	50	2.50	34	0.005	3
(Middle tracker)	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
Outer tracker	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.

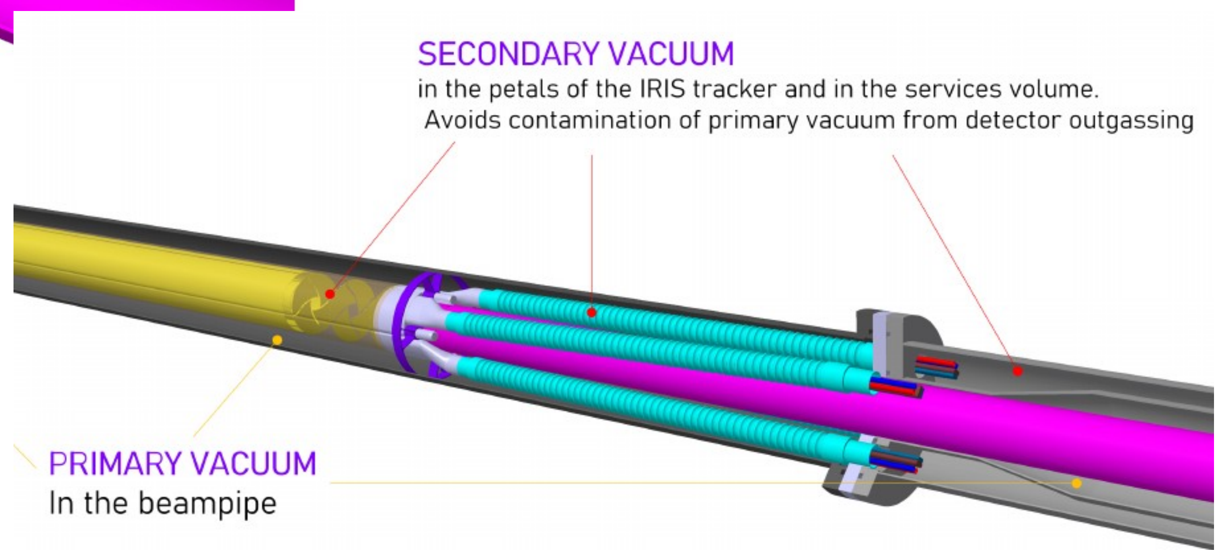
V.3 – ALICE3 : IRIS vertexer, 3D drawings



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



Iris tracker (transverse view)



V.5 – ALICE3 : outer tracker, drawings

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

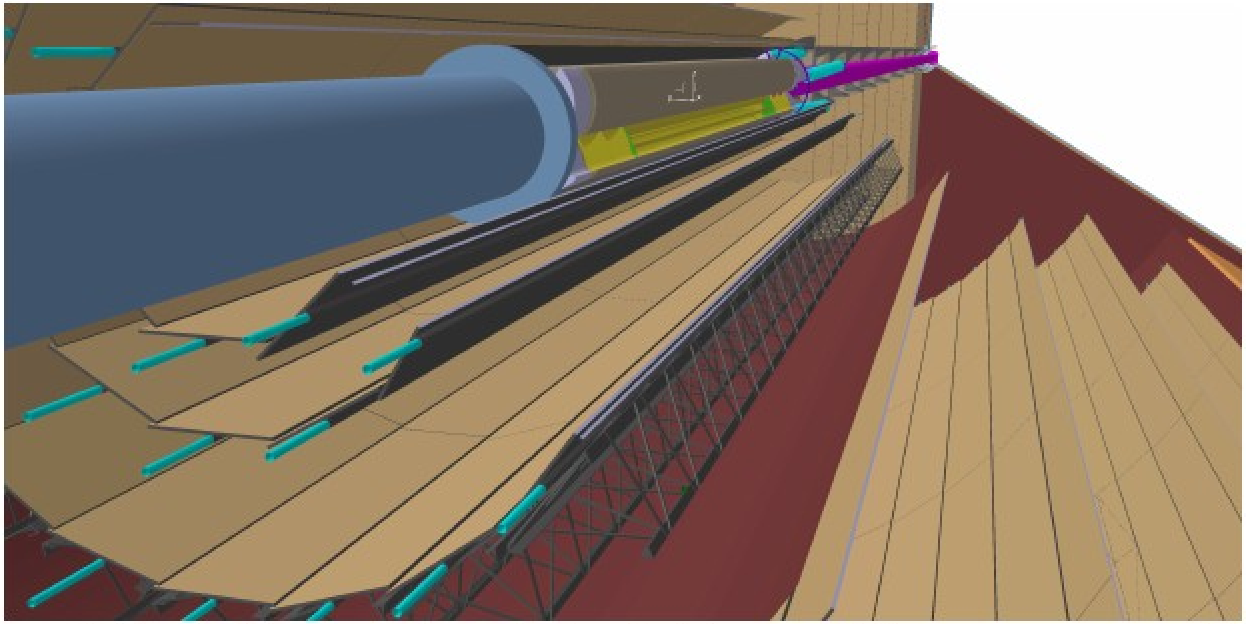


Figure 83: Sketch of the outer tracker mechanics. Modules assembled in staves structures are visible as well as services and power lines. Furthermore, the overlap of the staves can be seen.

Among which : … IPHC (Institut Pluridisciplinaire Hubert CURIEN STRASBOURG), LPSC Grenoble, iP2i (LES 2 INFINIS LYON) …

V.6 – Overview : vertexer and tracker specifications

Time resolution: bunch tagging, *i.e.* O(100 ns)

A Large Ion Collider Experiment

ALICE 3 Vertex Detector and Outer Tracker — in numbers

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
Pixel size (μm^2)	÷ 9 O(10 x 10)	• 2.8 O(50 x 50)	• 2.8 O(50 x 50)	O(20 x 20)	O(30 x 30)
Position resolution (μm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm^2)	+ 75% 70	20	20	20**	47 / 35***
Particle hit density (MHz / cm^2)	• 20 94	1.7	67% 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm^2)	• 3000 1×10^{16}	• 100 2×10^{14}	≈ 5.6×10^{12}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000 300	• 10 5	≈ 0.2	0.3	0.3
Surface (m^2)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget ** Pixel matrix *** Innermost layers / outer layers

Table courtesy Felix Reidt

Appendix

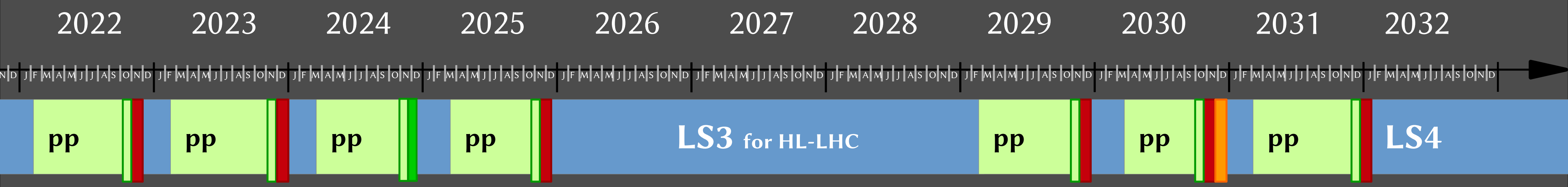
A. ITS2 in $ALICE_2$ in runs 3+4

B. ITS3 in $ALICE_2$ in run 4

C. Outer Tracker in $ALICE_3$ run 5

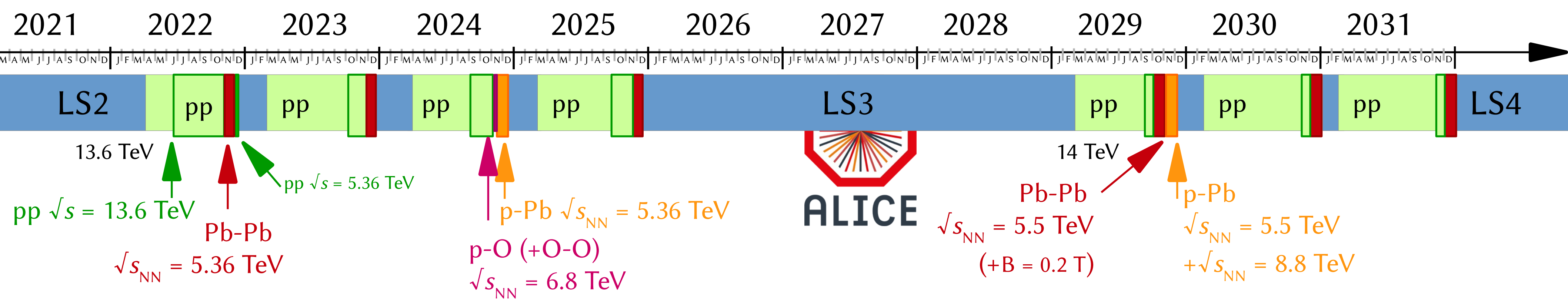
D. Template for QCD+QGP physics cases

A. – ALICE2 run 3+4



LHC running plan

A.1 – ALICE-2 : ALICE campaigns in LHC run 3+4



Runs 1+2
= 1 nb^{-1} MB Pb-Pb delivered
⟶ 0.1 nb^{-1} recorded

Runs 3+4
= 10+3 nb^{-1} MB Pb-Pb delivered
⟶ 10+3 nb^{-1} recorded

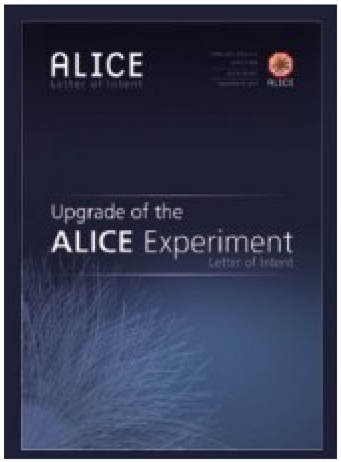
Consequence : **50 kHz in Pb-Pb** // ~200 kHz in pp, p-Pb

⟶ preserve ALICE features (PID, material budget, μ arm, ...)
+ improve tracking precision (ITS, MFT)
+ improve data rate (pile-up challenge)

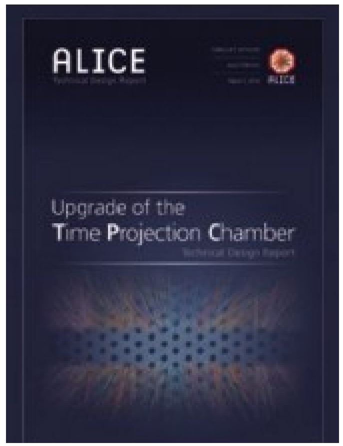
⟶ **specific data taking strategy** :

- "triggerless" readout (small S/S+B ⟶ ≈ no online trigger)
- *Readout+recorded : 50 kHz* Min Bias Pb-Pb
  + a *few 100 kHz* pp, p-Pb collisions
  Runs 3+4 = 100x Run 2
- no more 8-month/year of pp data taking...
  ALICE pp campaign = $\mathcal{O}$(weeks)
  (*main limit : computing capacity*)

A.2 – ALICE-2 : TDRs for run 3 detectors



CERN-LHCC-2012-012



CERN-LHCC-2013-020

CERN-LHCC-2013-024

CERN-LHCC-2012-005

CERN-LHCC-2015-006

CERN-LHCC-2013-019

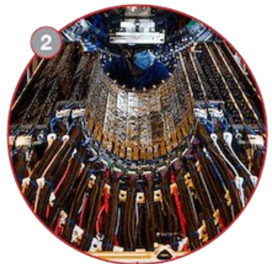
CERN-LHCC-2015-001

CERN-LHCC-2013-014

A.3 – ALICE-2 upgrades : overview

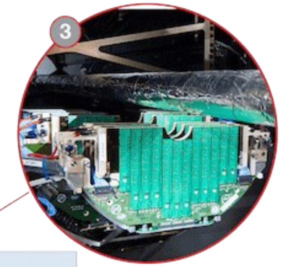
TIME PROJECTION CHAMBER (TPC) UPGRADE

New GEM (gas electron multipliers) technology replaced the old wire chambers to significantly increase the readout rate of the TPC.



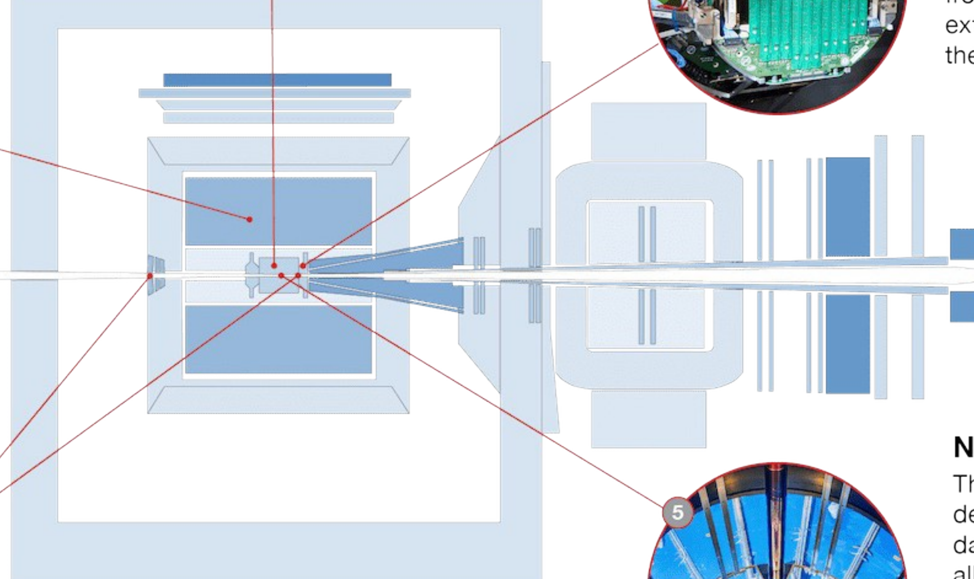
NEW INNER TRACKING SYSTEM (ITS)

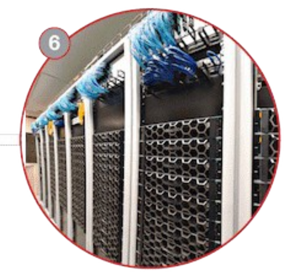
Seven layers comprising a total of 12.5 billion monolithic active silicon pixel sensors distributed over a 10m^2 surface area, the largest pixel detector ever built.



NEW MUON FORWARD TRACKER (MFT)

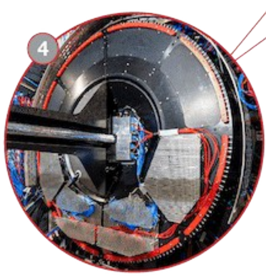
Five disks of monolithic active silicon pixel sensors, installed in front of the muon spectrometer to extend precision measurements to the forward rapidity region.





NEW READOUT SYSTEM

The new readout system is designed to handle increased data throughput by combining all the computing functionalities needed in the experiment.



NEW BEAMPIPE WITH A SMALLER DIAMETER (36.4 mm)

The vacuum tube that carries protons and ions to the collision point inside the detector has an 870-mm-long central beryllium section that has an inner radius of 18.2 mm and measures 0.8 mm in

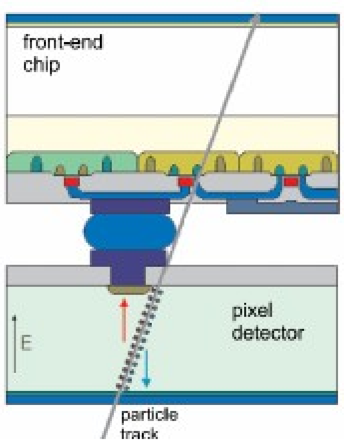
NEW FAST INTERACTION TRIGGER (FIT)

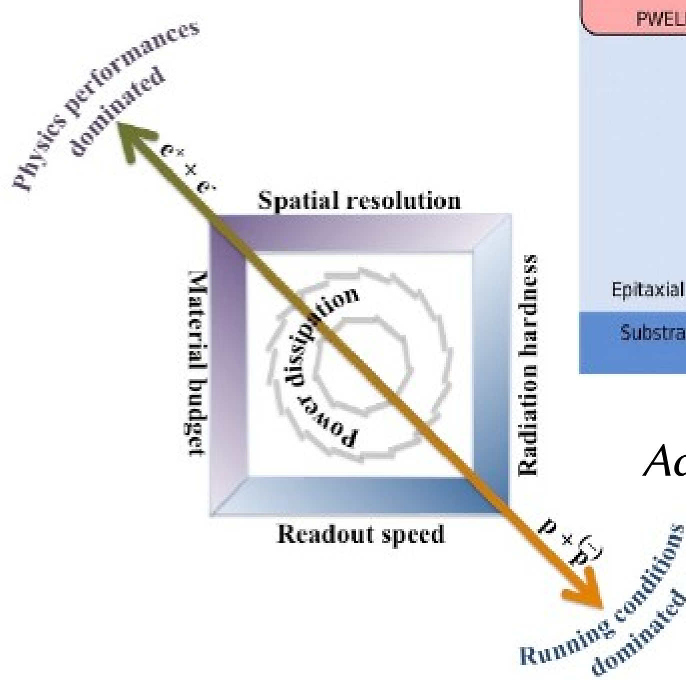
Combining three detector technologies, the FIT detector serves as an interaction trigger, online luminometer, indicator of the vertex position and forward multiplicity counter.

A.4 – Pixel detectors : Monolithic Active vs Hybrid techno.

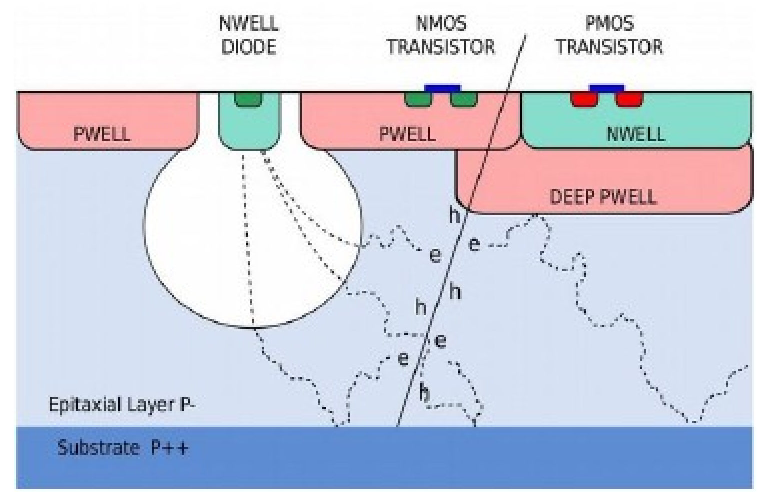
Hybrid pixel sensor ⟶
CMOS pixel sensor ⟶

<u>Hybrid pixel sensor</u>





<u>CMOS pixel sensor</u>



Advantages :

- faster readout
- better radiation-hardness
- ...

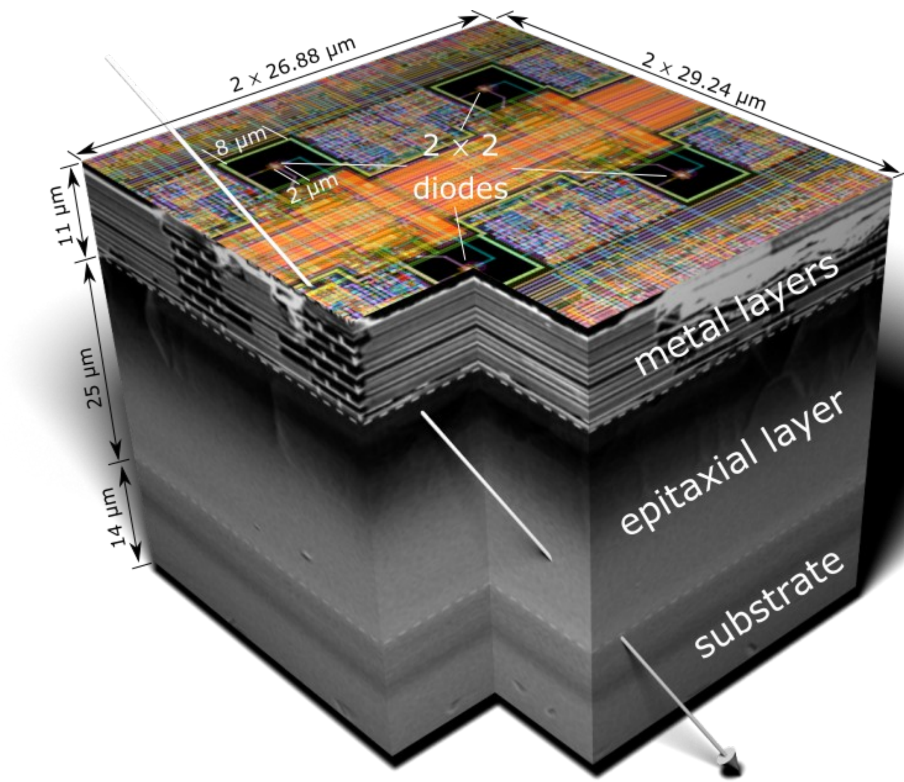
Advantages :

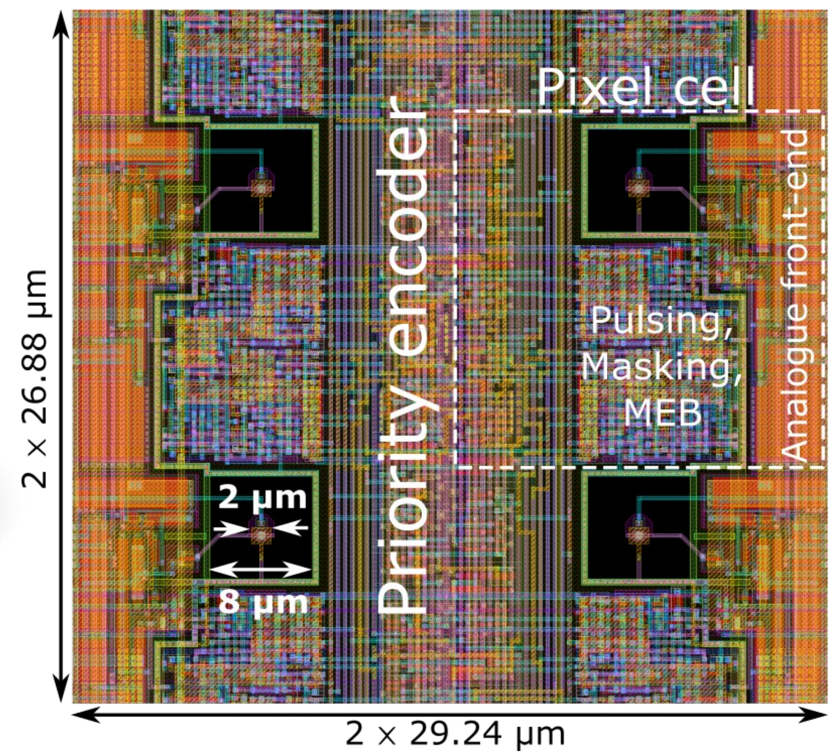
- thinner
- smaller pixel size accessible
- lower power consumption
- cheaper
- ...

A.5 – Background: MAPS instrumental background

Hybrid pixel sensor ⟶
CMOS pixel sensor ⟶

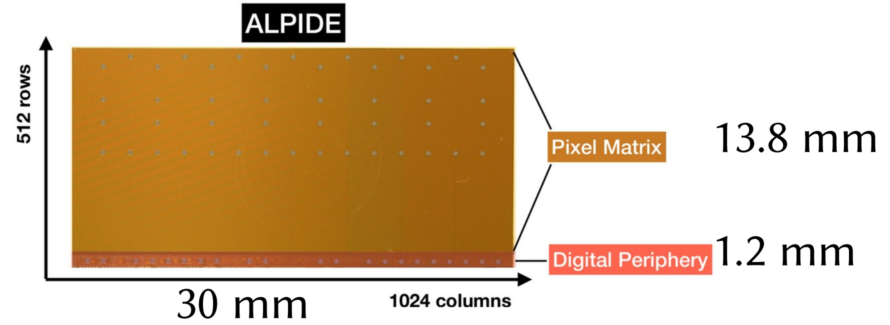
Ex: sensor using
TowerSemiconductor 180-nm CMOS Imaging Process





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

A.6 – Background : ITS2+MFT, MAPS-based detectors for Run 3

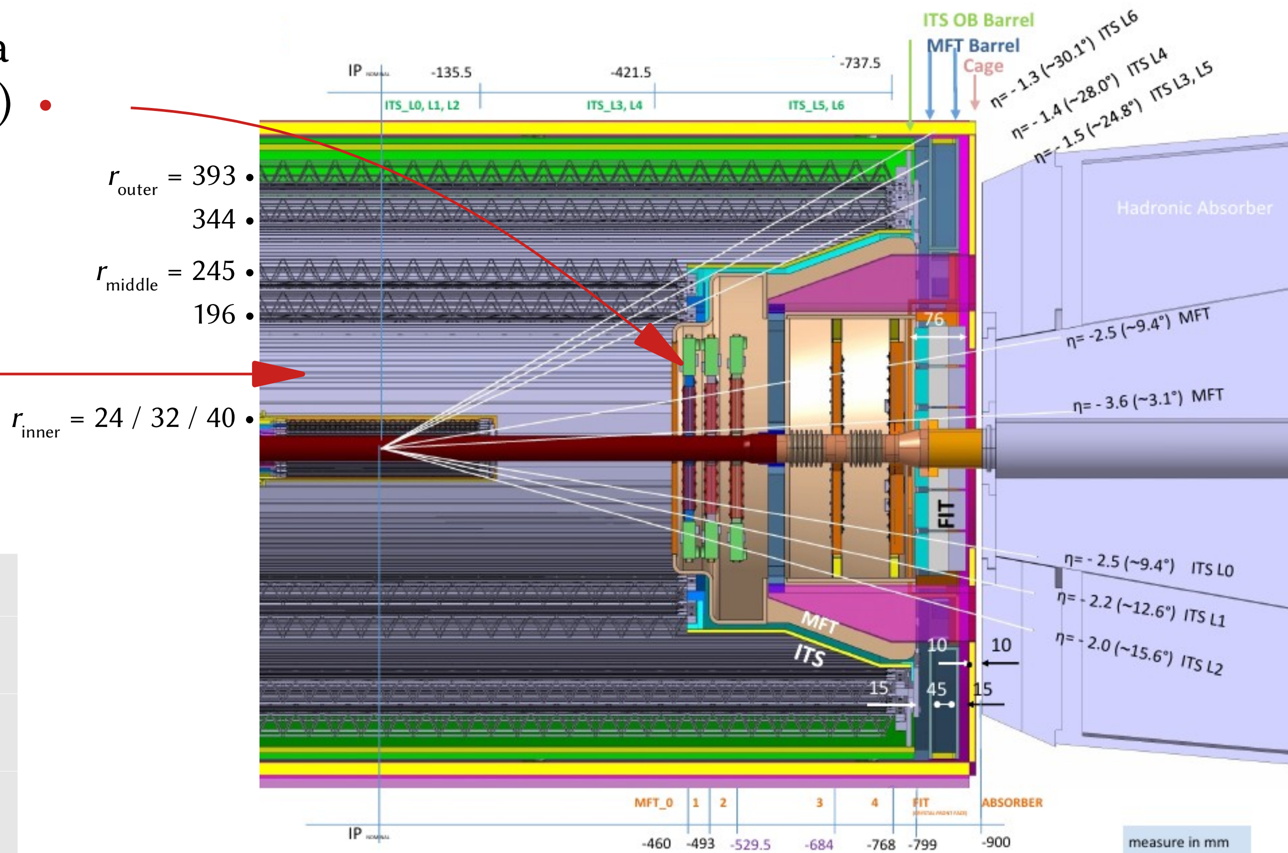


MFT

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

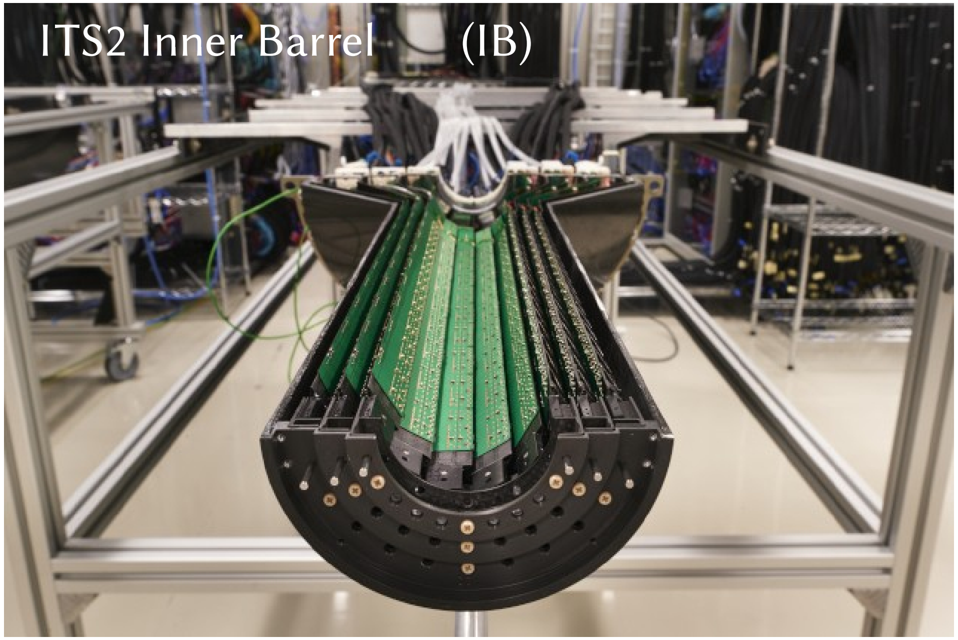
ITS2

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

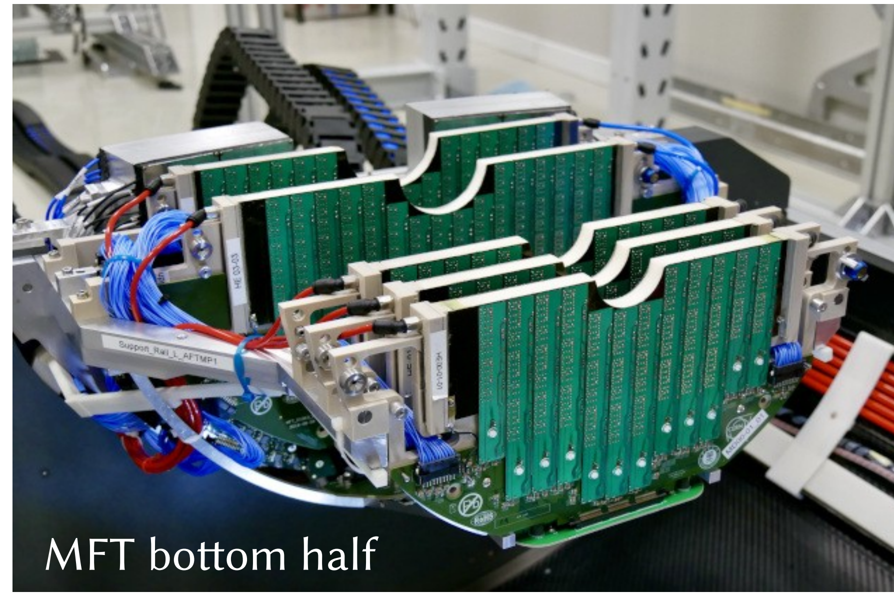


	L0,L1,L2	L3+L4	L5+L6
Layers	*Inner*	Middle	Outer
Chips	432	6048	17640
Active surface	0.18 m²	2.50 m²	7.30 m²
Fraction	1.8%	25%	73%

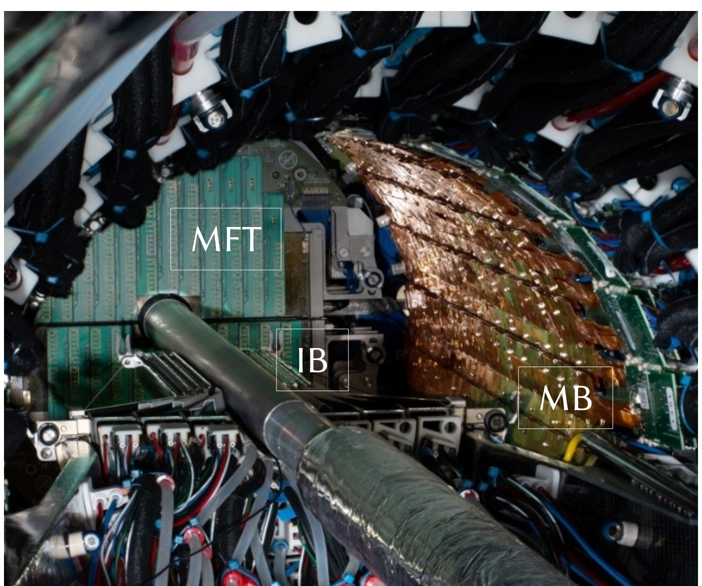
A.7 – ITS2+MFT : pictures



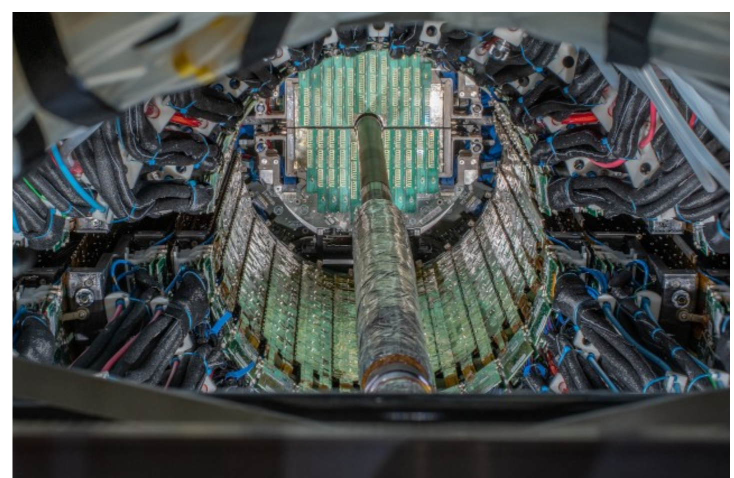
ALICE-PHO-GEN-2021-002



OPEN-PHO-EXP-2020-004



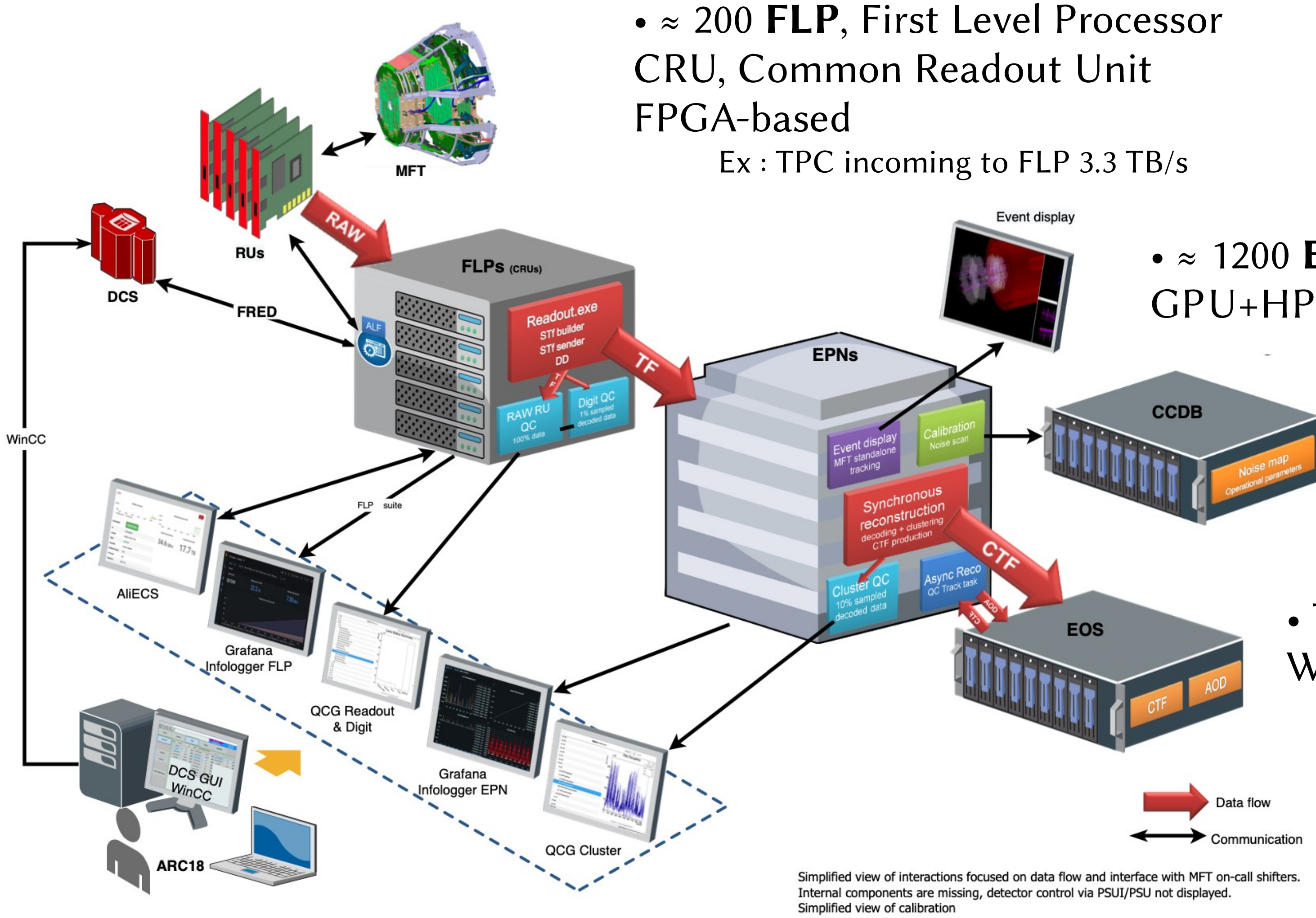
ALICE-PHO-GEN-2021-002



ALICE-PHO-ITS-2021-002

A.8 – ALICE-2 continuous readout ? : what it costs…

- ≈ 200 **FLP**, First Level Processor
CRU, Common Readout Unit
FPGA-based
  Ex : TPC incoming to FLP 3.3 TB/s

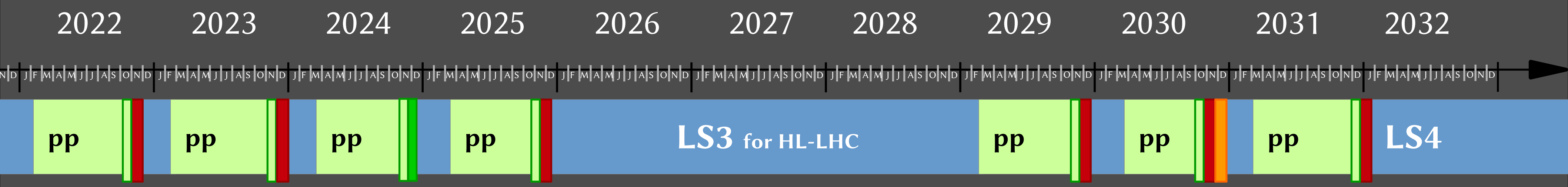


- ≈ 1200 **EPN**, Event Processing Nodes
GPU+HPC CPU based
  Ex : TPC incoming to EPN 570 GB/s

- Tier-0+Tier-1
Whole ALICE2 : 360 GB/s

NB : Time frames ≈ **<u>10 ms</u>** Vs bunch spacing at LHC ≈ **<u>25 ns</u>**

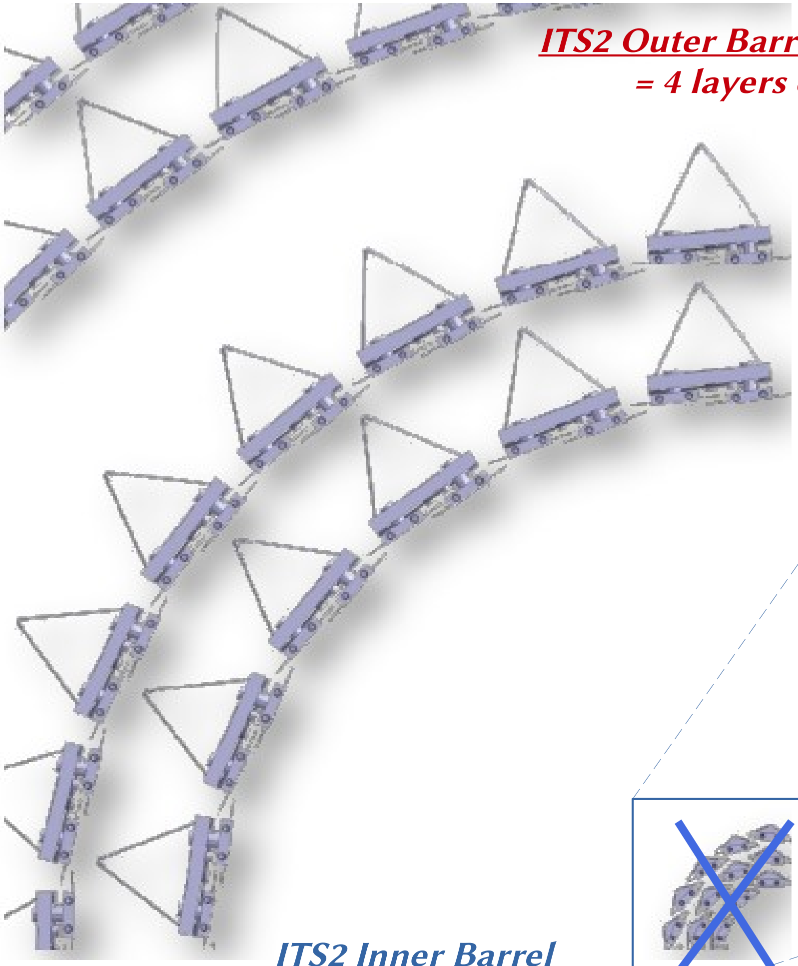
B. – ITS3 in ALICE2 run 4



LHC running plan

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

ITS2 Outer Barrel
= 4 layers of ITS2 kept !



ITS2 Inner Barrel
≥ 3 new layers

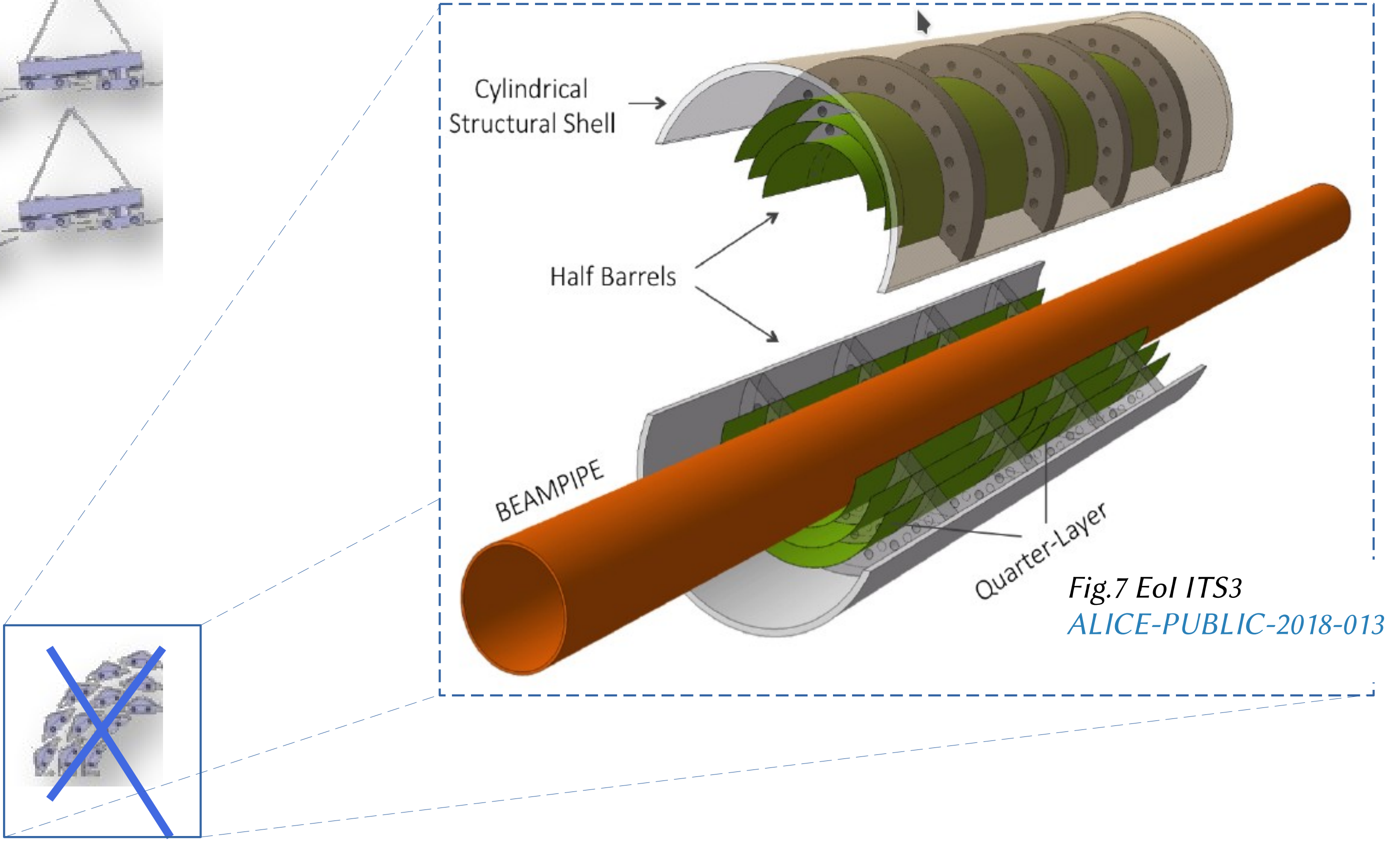


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013

B.2 – ITS3 detector : some key figures

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

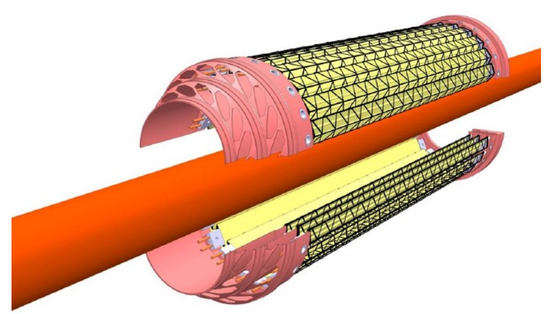
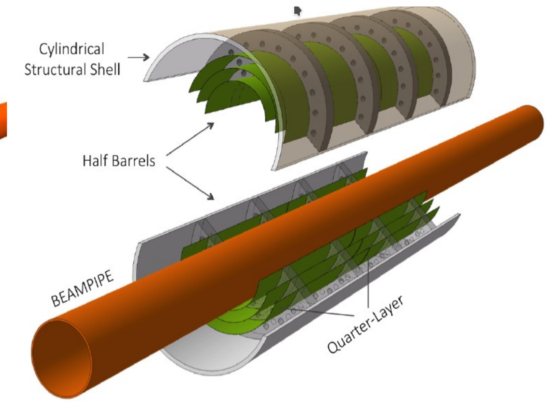


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013



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
$r_{\text{Beryllium pipe}}$	1.82+0.08 cm	1.6+0.05 cm

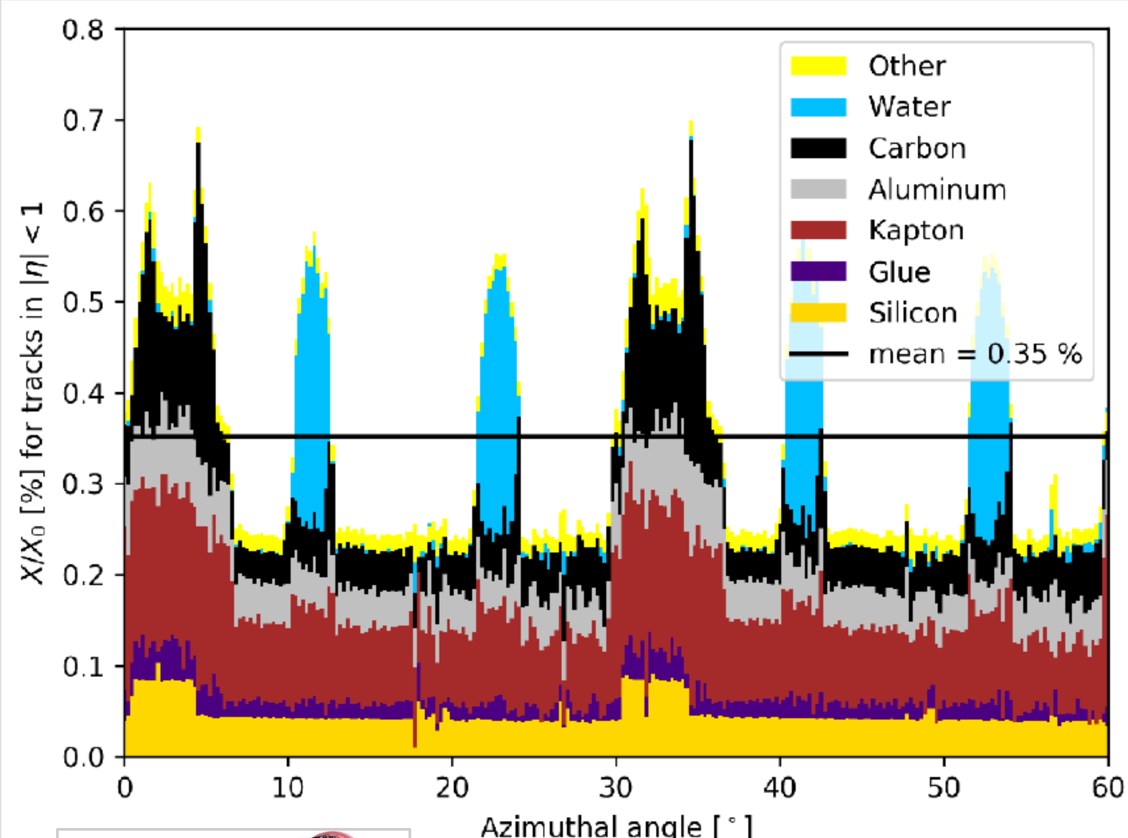
1. (≈ preserved) keys :

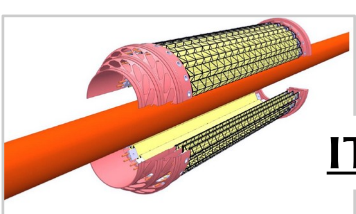
- |η| < 2.2
- spatial resolution/layer ≈ 5 μm
- time resolution ≤ 2-5 μs
- Radiation hardness : NIEL: >3x10^{12} 1-MeV n_{eq}.cm^{-2} // TID: >0.3 Mrad

B.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…

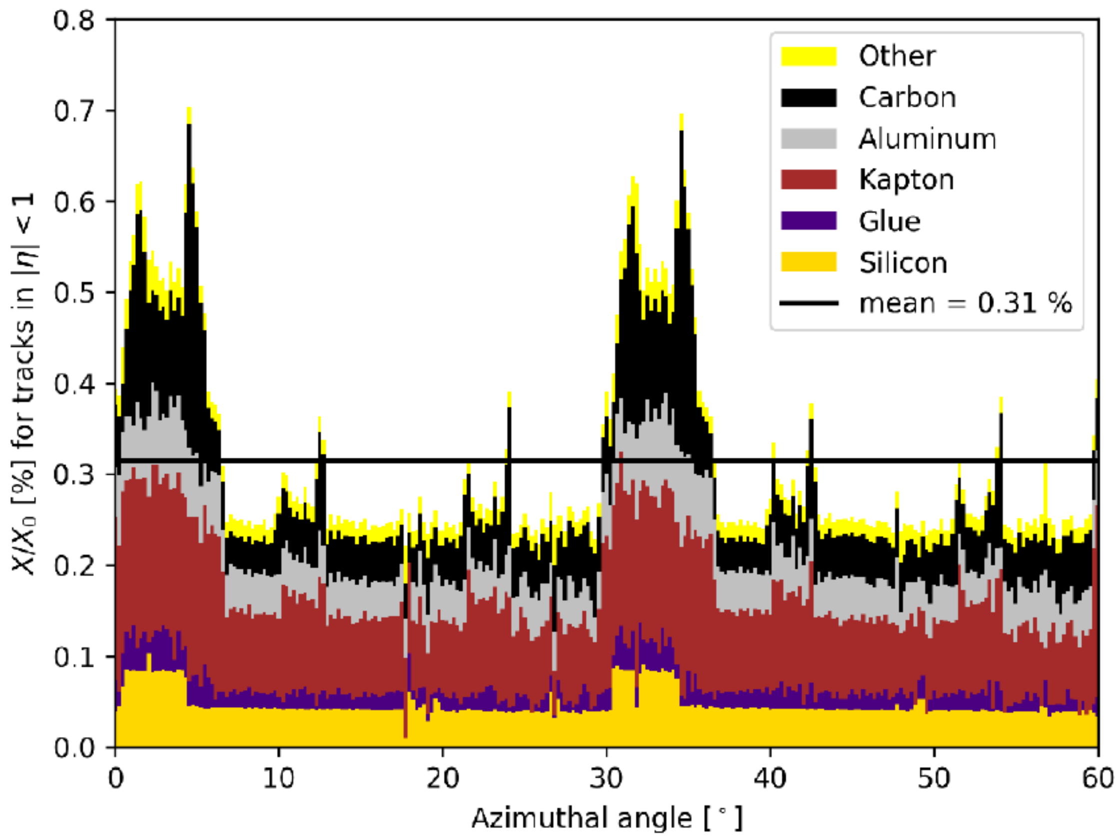
1. Get rid of cooling ?

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

3. Shift the mechanical support to outside acceptance ?

B.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...

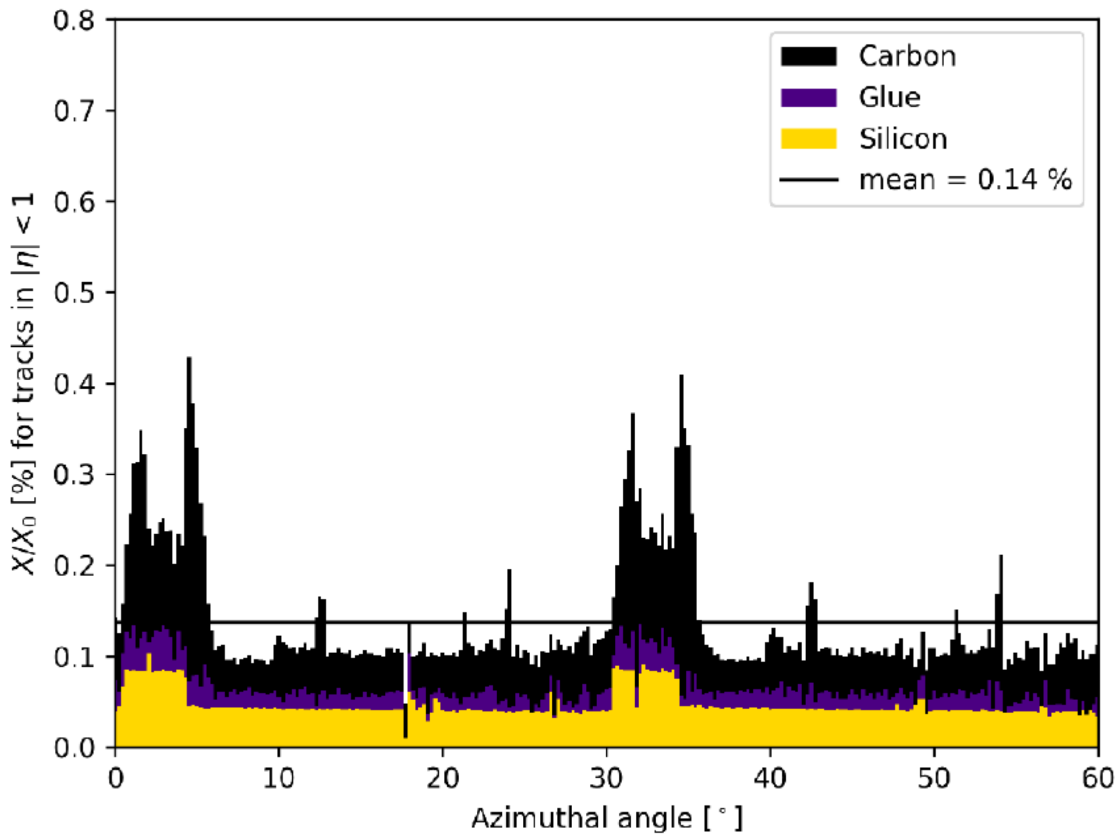
1. Get rid of cooling ?
→ Possible if reduction of power consumption i.e. < 20 mW/cm² on the pixel matrix

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

3. Shift the mechanical support to outside acceptance ?

B.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 :

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

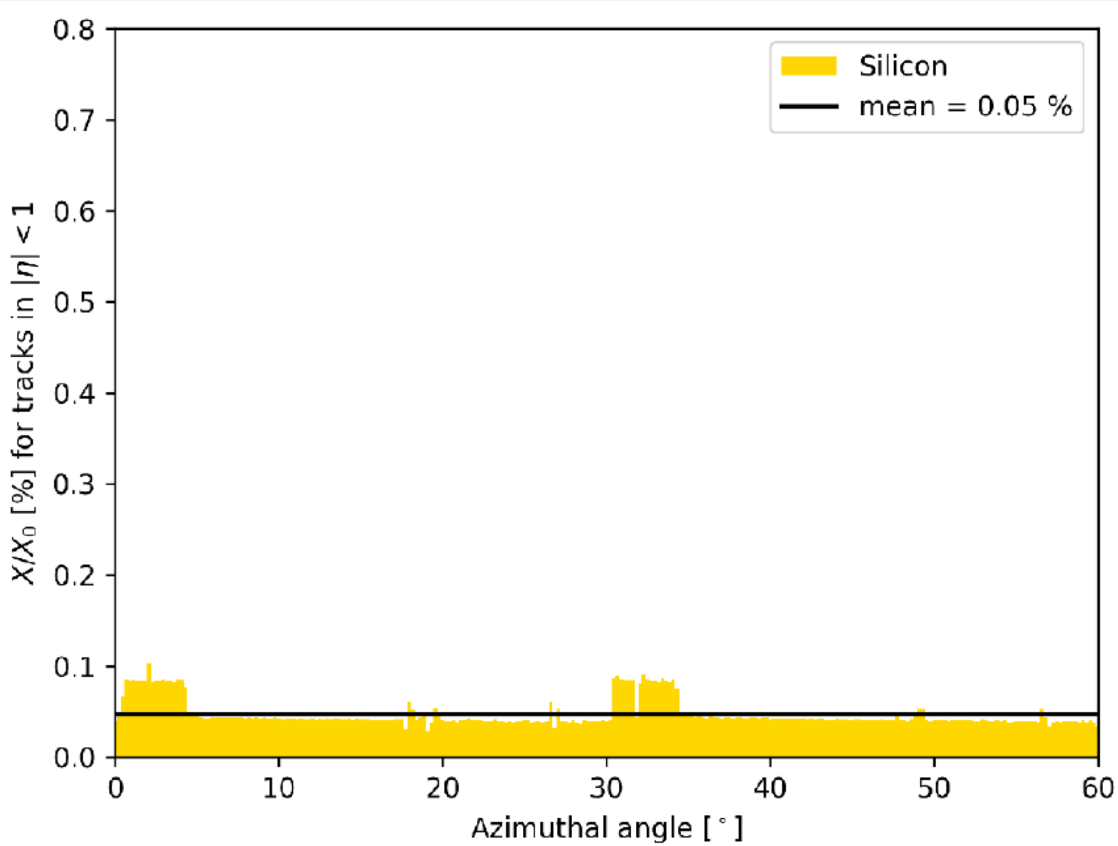
1. Get rid of cooling ?
⟶ Possible if reduction of power consumption i.e. < 20 mW/cm² on the pixel matrix

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

3. Shift the mechanical support to outside acceptance ?

B.4 – 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…

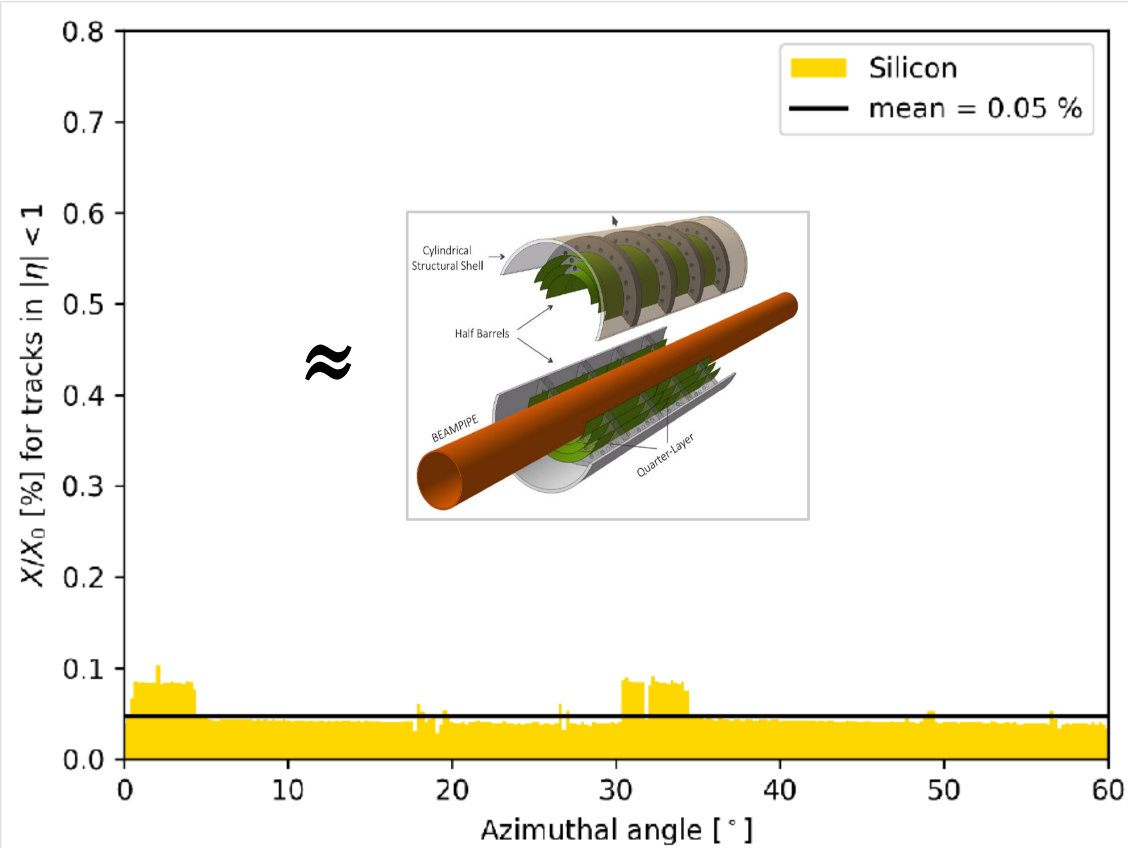
1. Get rid of cooling ?
⟶ Possible if reduction of power consumption i.e. < 20 mW/cm² on the pixel matrix

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

B.II.4 – 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 :

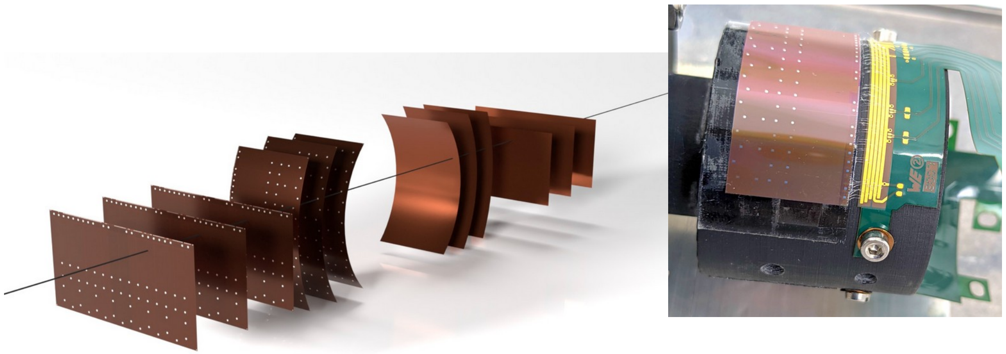
- Si = 1/7 of the overall material budget
- Irregularities = from support + cooling…

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) ?
→ 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

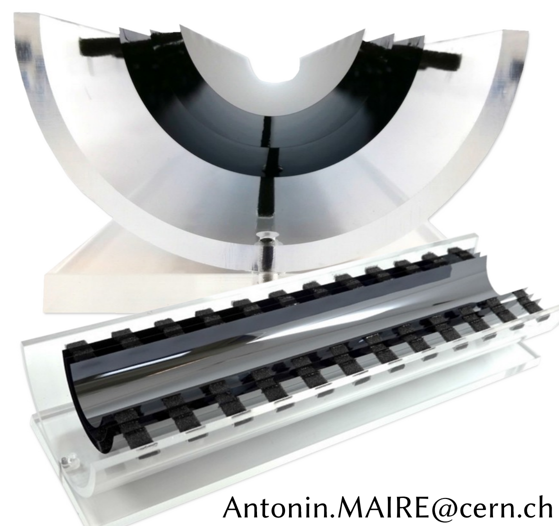
B.V.2 – ALICE 2.1 : ITS3

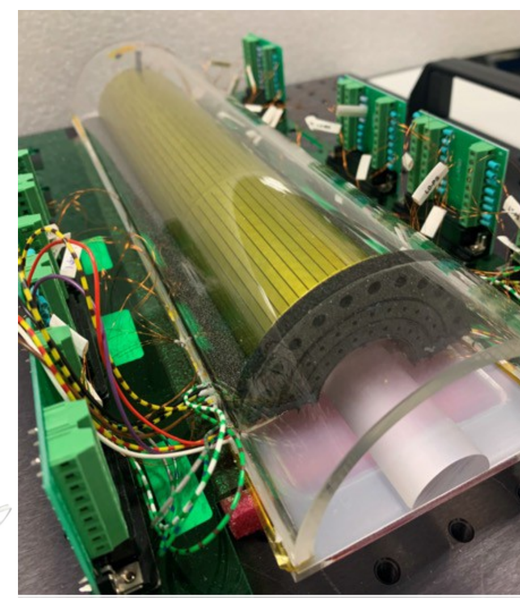


Beam test of ***bent*** ALPIDE chips
(i.e. ITS2 chip 50-µm thick, 180 nm technology)
(*arXiv:2105.13000*)

Move from 180 nm CMOS technology to 65 nm (Tower foundry)
→ Wafer-scale chip,
thinned (< 50 µm) + to be bent

Mechanical integration
cooling test

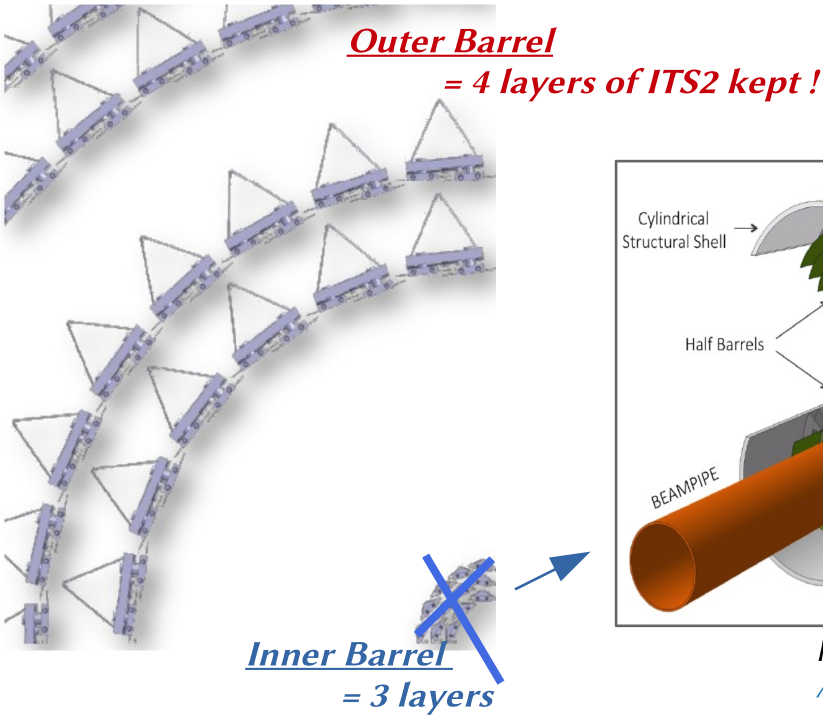




Project milestones :

. EoI *ALICE-PUBLIC-2018-013*
. LoI *CERN-LHCC-2019-018*
. 2019 : LHCc blessing for R&D
→ Engineering run 2 = 2022-05,
on-wafer stitching among chips
. TDR by spring 2023

B.V.2 – ALICE 2.1 : ITS-3, keys + physics cases



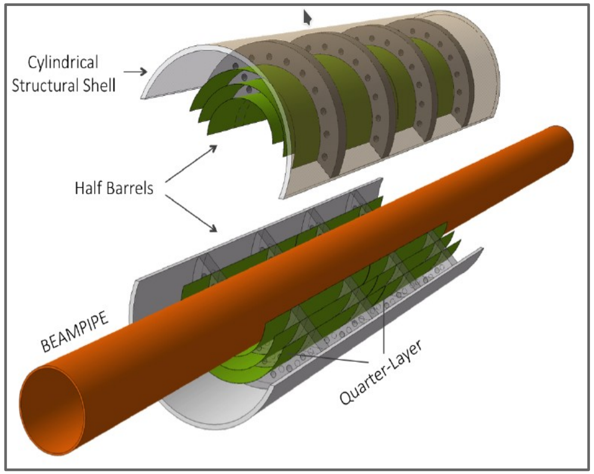


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013

Keys :

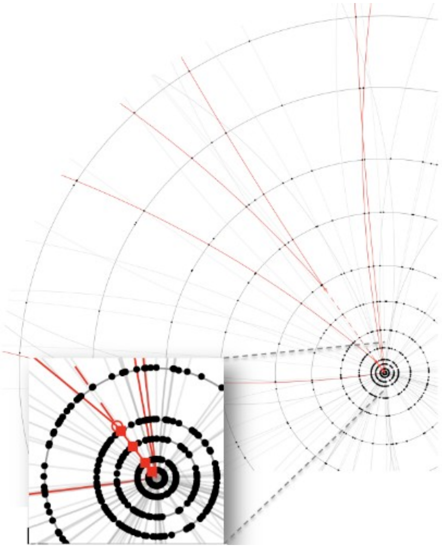
. |η| < 2.0

News wrt Run 3

. finer : $\mathcal{O}$(15x15) μm²

. lighter : ultra-low material budget (< 0.05% x/X° per layer)

. closer (r_{ITS3} > 1.8 cm)



- improve low p_T AxEff
- improve track pointing resolution
  (Heavy-flavour vertexing at low p_T)
  prompt/non-pr Λ_C^+, D_s^+, Ξ_C …
  + Λ_b° … + Λ_cn (c-deuteron), nΛ_cn (c-triton) ?
- "strangeness tracker", 1st implementat° ($\Xi^\pm$, $\Omega^\pm$, $\Sigma^\pm$)

c. – OT brainstorming

II.1 – Timing: …

Time resolution: bunch tagging, *i.e.* O(100 ns)

A Large Ion Collider Experiment

ALICE 3 Vertex Detector and Outer Tracker — in numbers

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
Pixel size (μm²)	÷ 9 O(10 x 10)	• 2.8 O(50 x 50)	• 2.8 O(50 x 50)	O(20 x 20)	O(30 x 30)
Position resolution (μm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm²)	+ 75% 70	20	20	20**	47 / 35***
Particle hit density (MHz / cm²)	• 20 94	1.7	67% 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm²)	• 3000 1×10^{16}	• 100 2×10^{14}	≈ 5.6×10^{12}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000 300	• 10 5	≈ 0.2	0.3	0.3
Surface (m²)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget ** Pixel matrix *** Innermost layers / outer layers

Table courtesy Felix Reidt

I.1 – Working hypotheses: playground

- **Foundry** : Tower (Intel…) / TPSco
- ~~**Bending**~~
- **Stitching** ? ≈ likely not (*e.g.* problem of foundry yield, inversely propto active surface)
- **Technological node**: 65 nm, 180 nm or… 28 nm ? $\longrightarrow$ very likely 65 nm

[65 nm] *positive things*

+ More transistors/surface unit
+ Intrinsic Radiotolerance
+ Larger wafer size (more chips)
+ Less power neeeded

[180 nm] *positive things*

+ More customisations allowed by foudnry (*nb of metal layers, thickness of epitaxial layer, …*)
+ Cheaper (Engineering Run ! + ~price/wafer)
+ Less current leakage
+ Maturity in HEP

II.1 – Timing: ...

Time resolution: bunch tagging, *i.e.* O(100 ns)

A Large Ion Collider Experiment

ALICE 3 Vertex Detector and Outer Tracker — in numbers

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
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Position resolution (µm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm^2)	+ 75% 70	20	20	20**	47 / 35***
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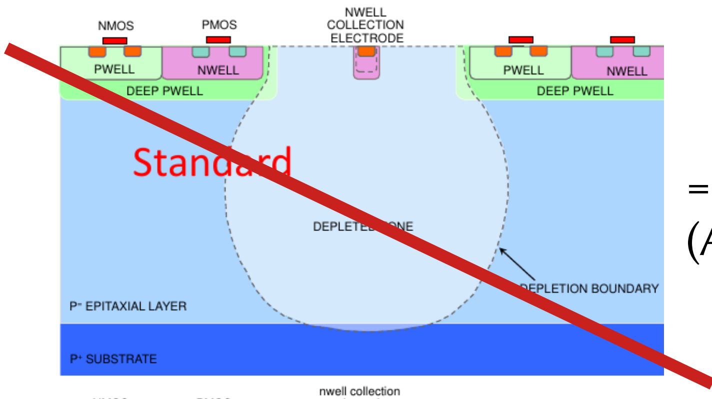
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget   ** Pixel matrix   *** Innermost layers / outer layers

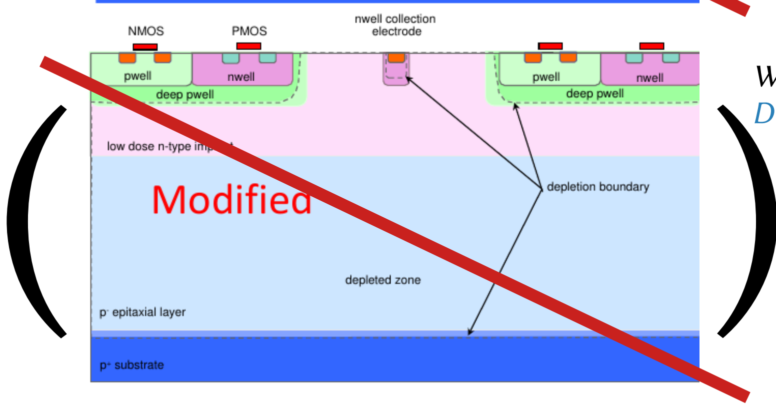
Table courtesy Felix Reidt

II.2 – Timing: time resolution, O(100 ns)

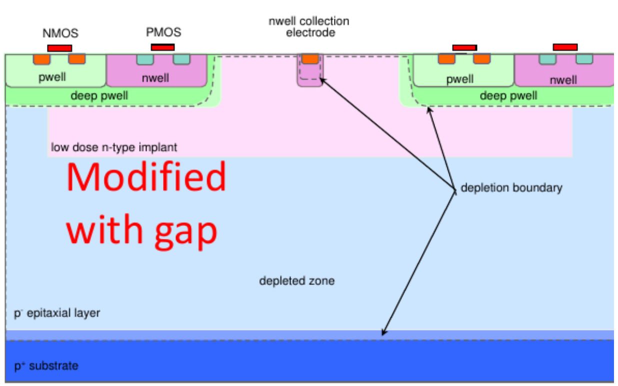
The most lilely path to reach this timing ?



= Default by Tower (ALPIDE ITS2)



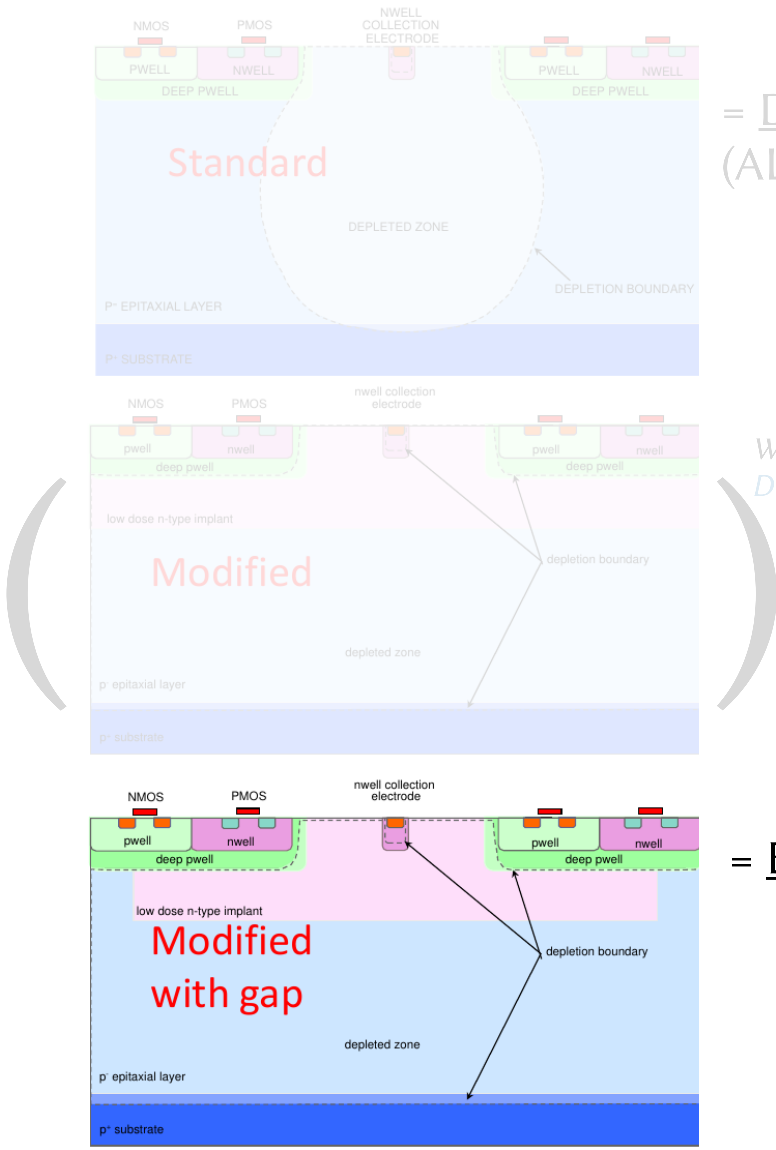
W. Snoeys et al,
DOI:10.1016/j.nima.2017.07.046



= Basis for ITS3

→ + to be improved/optimised even further !

II.3 – Timing: time resolution, O(100 ns) + spatial resolution…



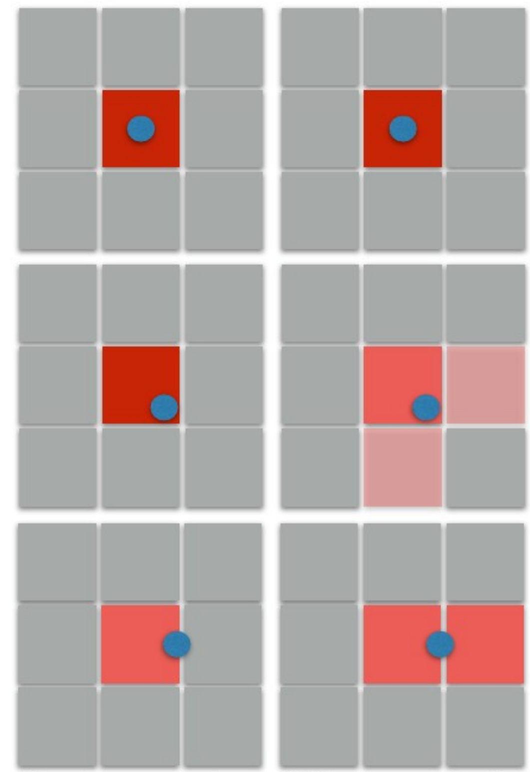
= Default by Tower (ALPIDE ITS2)

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

= Basis for ITS3

Spatial resolution ≈ (pixel pitch)/$\sqrt{12}$

(i.e. not better than this, due to ~~cluster shapes~~)



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

Courtesy Felix Reidt

II.3 – Timing: time resolution, *O*(100 ns) + <u>spatial</u> resolution…

Time resolution: bunch tagging, *i.e.* *O*(100 ns)

A Large Ion Collider Experiment

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Pixel size (μm²)	÷ 9 *O*(10 x 10)	• 2.8 *O*(50 x 50)	• 2.8 *O*(50 x 50)	*O*(20 x 20)	*O*(30 x 30)
Position resolution (μm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
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Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget   ** Pixel matrix   *** Innermost layers / outer layers

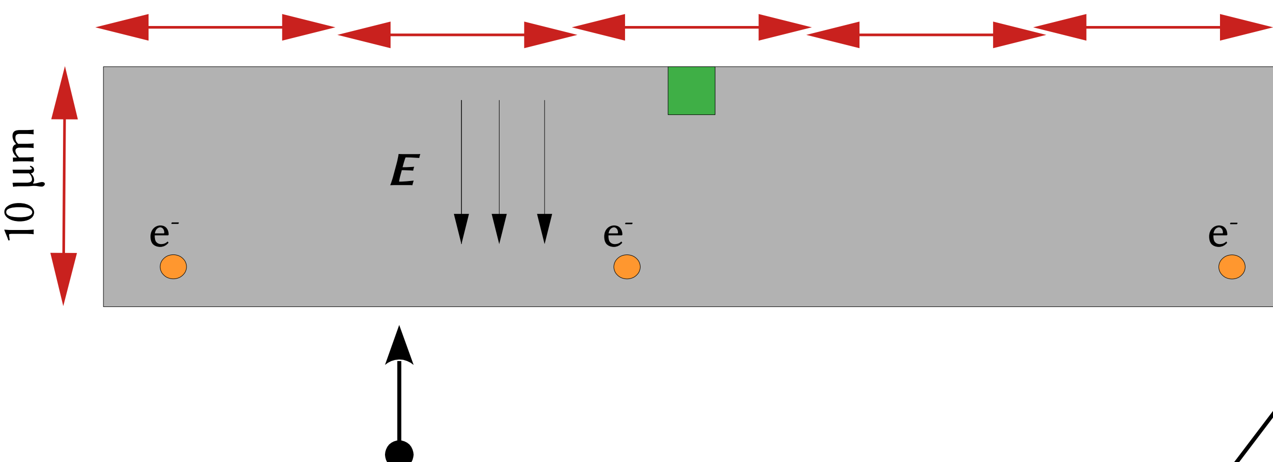
II.4 – Timing: time resolution, spatial resolution, efficiency…

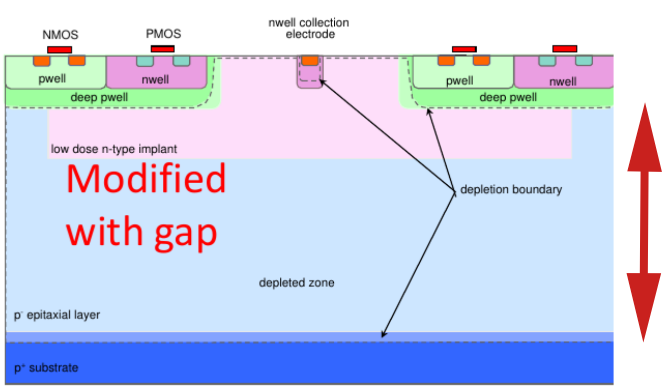
Issue of ***E*** field Vs *lateral* charge collection

+ local efficiency degradation = f(irradiation)

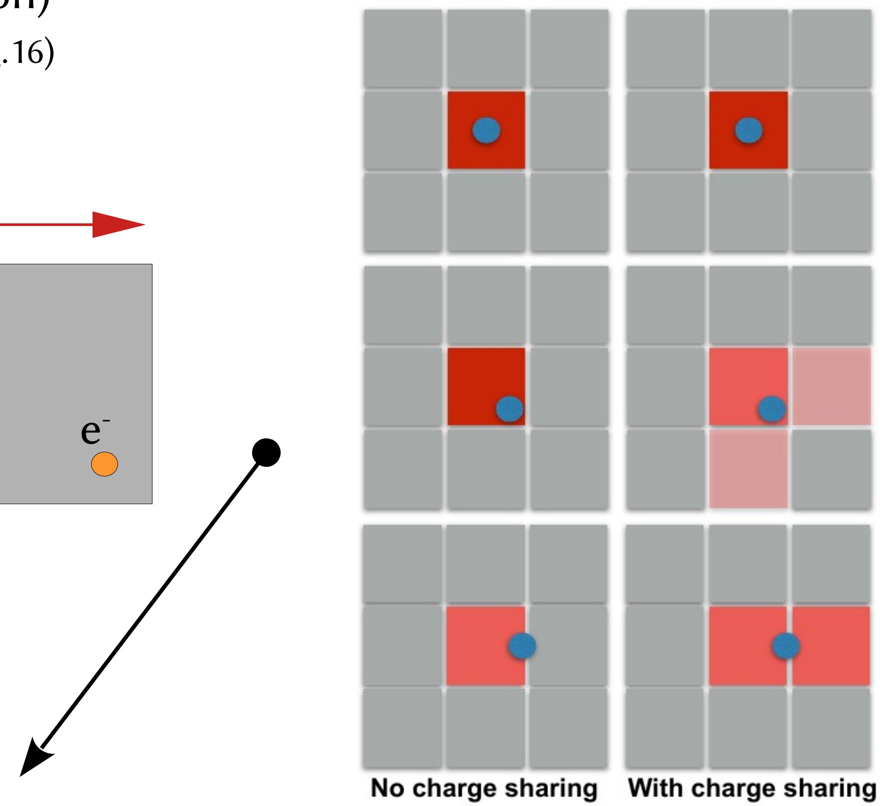
(See Miljenko presentation sl.10 = *arxiv:2212.08621*, Fig.16)

Pixel pitch ≈ **50 µm** ?





Epitaxial layer (65 nm)
≈ *10-µm* thickness



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

Courtesy Felix Reidt

II.5 – Timing: time resolution, O(100 ns) + PID…

What is about PID capabilities for MAPS (dE/dx) ?

1st : Why dE/dx PID ?

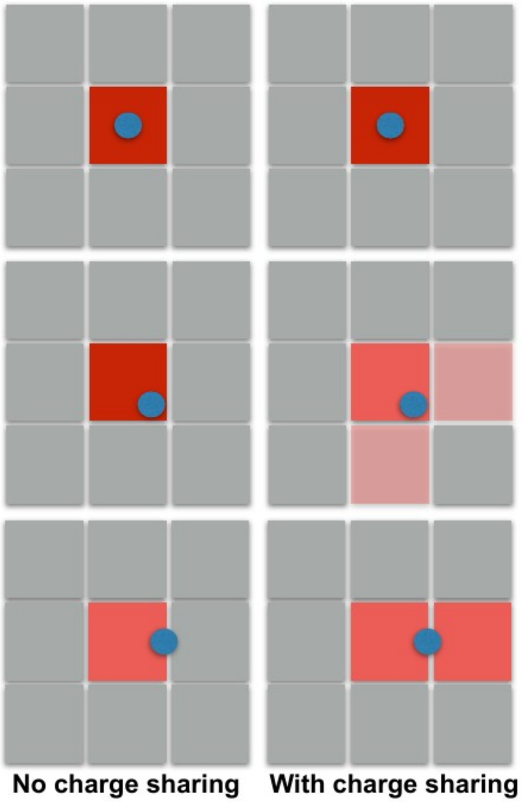
Charge separation momentum (p) Vs rigidity (p/Z)

→ p, d, t Vs $_3He^{2+}$, $_4He^{2+}$

ALICE3 dE/dx measurement = ∅ …

2nd PID how ?

- Provided binary information (pixel fired, 1 or not, 0)
  - ~~Number of hits per cluster~~
  - ~~Cluster shape~~
    - → = ideas for ITS2
- Sampling / characterising the signal differently ?
  - …



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

Courtesy Felix Reidt

III.1 – Timing Vs PID: …

Time resolution: bunch tagging, *i.e.* O(100 ns)

A Large Ion Collider Experiment

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Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
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Surface (m^2)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget ** Pixel matrix *** Innermost layers / outer layers

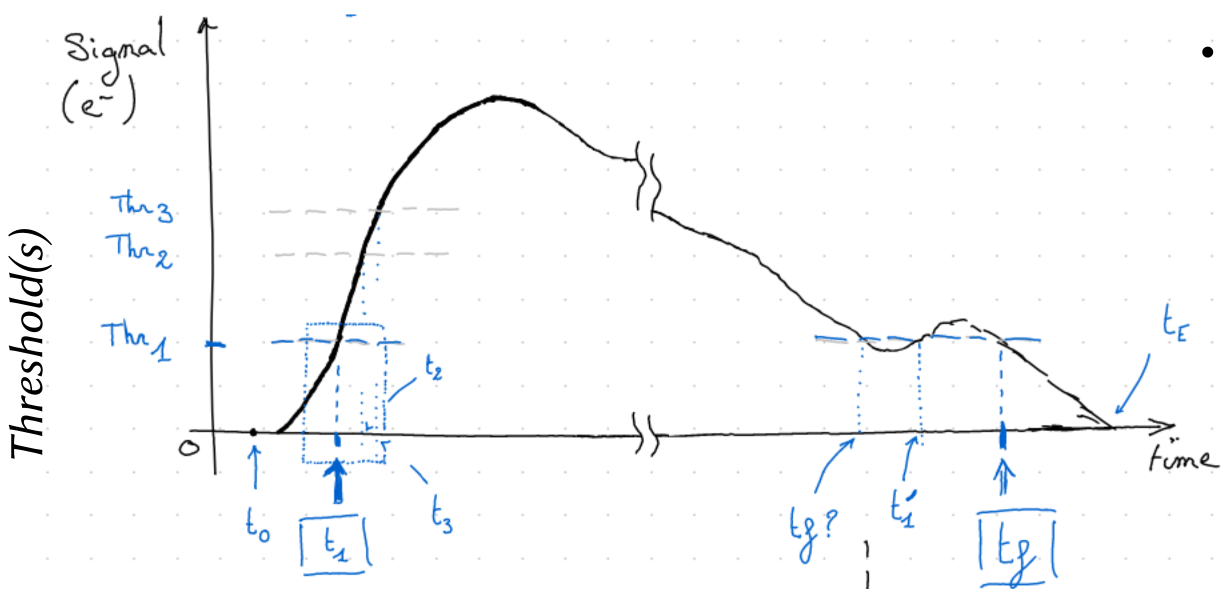
III.2 – Timing Vs PID: the analog signal and its challenges

Time : signal shaping / time shaping, O(200 ns)

A few figures

- ‹ t_1 › ≈ O[80 **ps**], nice ‼
  Including digital treatment ≈ O[1 **ns**]
- ‹ t_f › ≈ O[5-20 **µs**] …

- Thr1 ≈ 100-150 e⁻ typically (ITS2, MOSS)



Challenge[1] :

“Large” pixel 50 µm pitch,
+ Integration time (Time Frame) = ?
→ problem of **pile-up per pixel**

200 ns time shaping, implies that **dead time** to blind the pixel(s) = needed, at the pixel level at least.

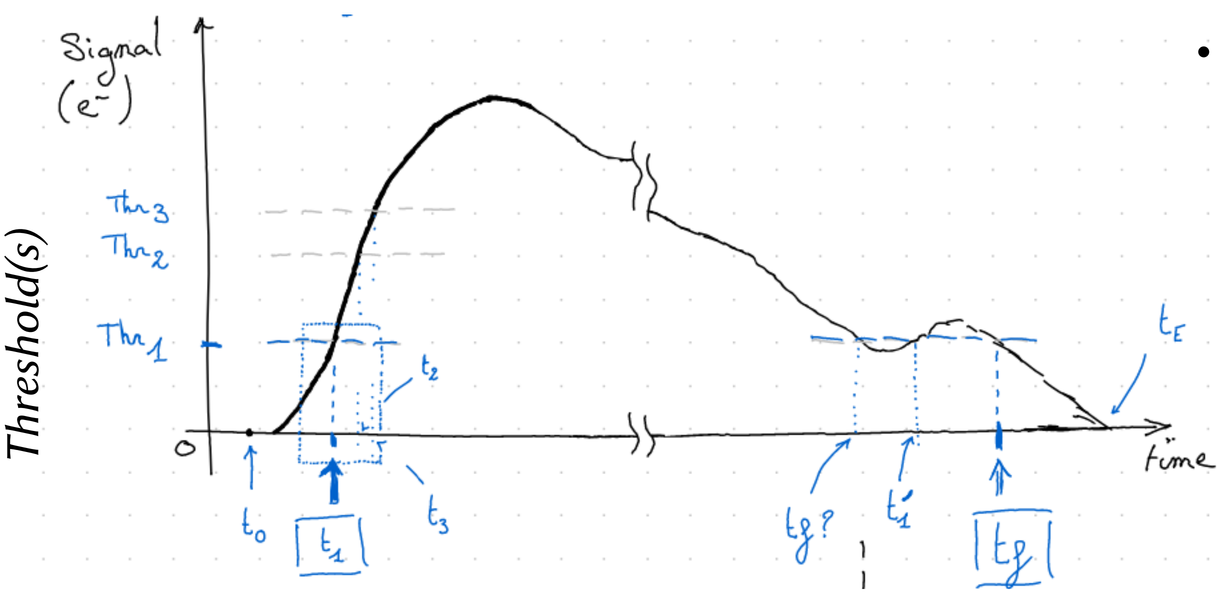
III.3 – Timing Vs PID: the analog signal and its challenges

Time : signal shaping / time shaping, O(200 ns)

A few figures

- ‹ t_1 › ≈ O[80 **ps**], nice ‼
  Including digital treatment ≈ O[1 **ns**]
- ‹ t_f › ≈ O[5-20 **µs**] …

- Thr1 ≈ 100-150 e^- typically (ITS2, MOSS)



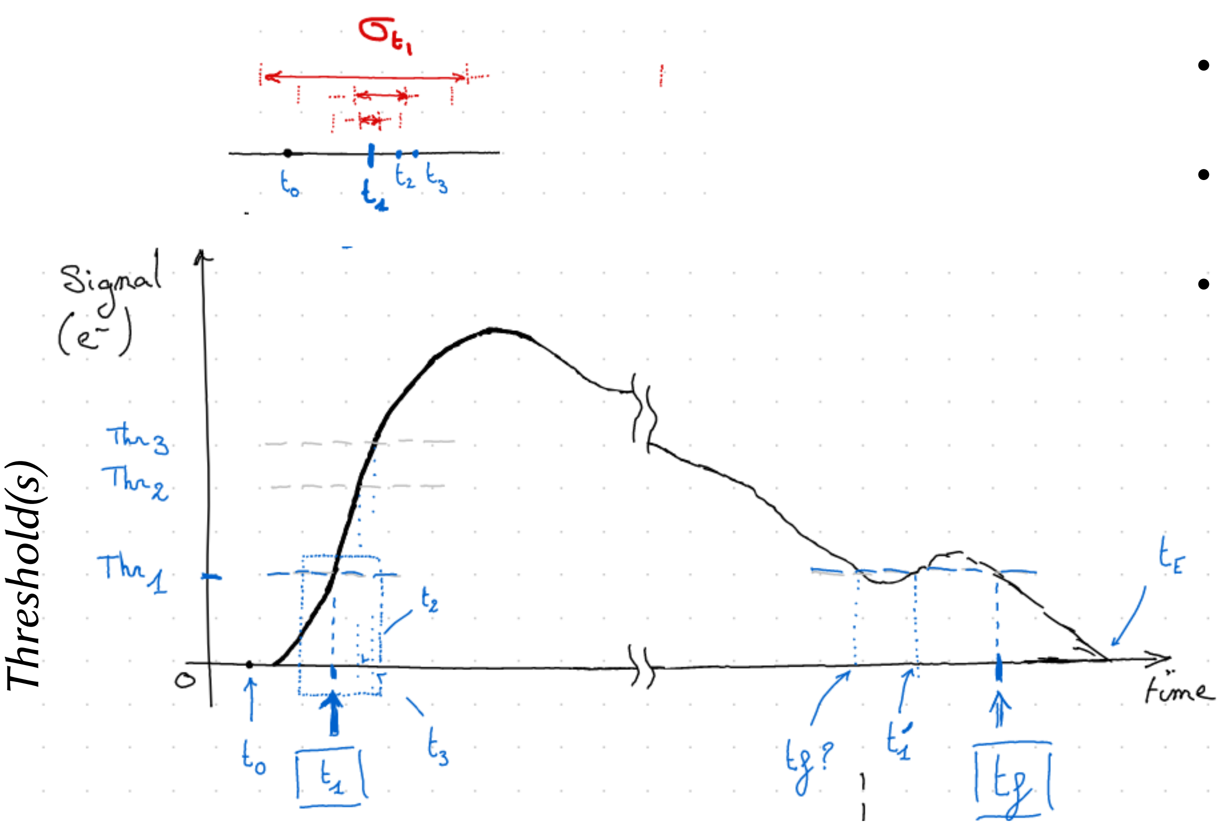
Challenge[2] :

Deal with **noise** around Thr1 level
(See t_f t_1')

NB : Suppress noise from the beginning as most as possible
(useless information to be shipped out of the sensors, layers, …
i.e. bandwidth)

III.4 – Timing Vs PID: the analog signal and its challenges

Time : signal shaping / time shaping, $\mathcal{O}$(200 ns)



A few figures

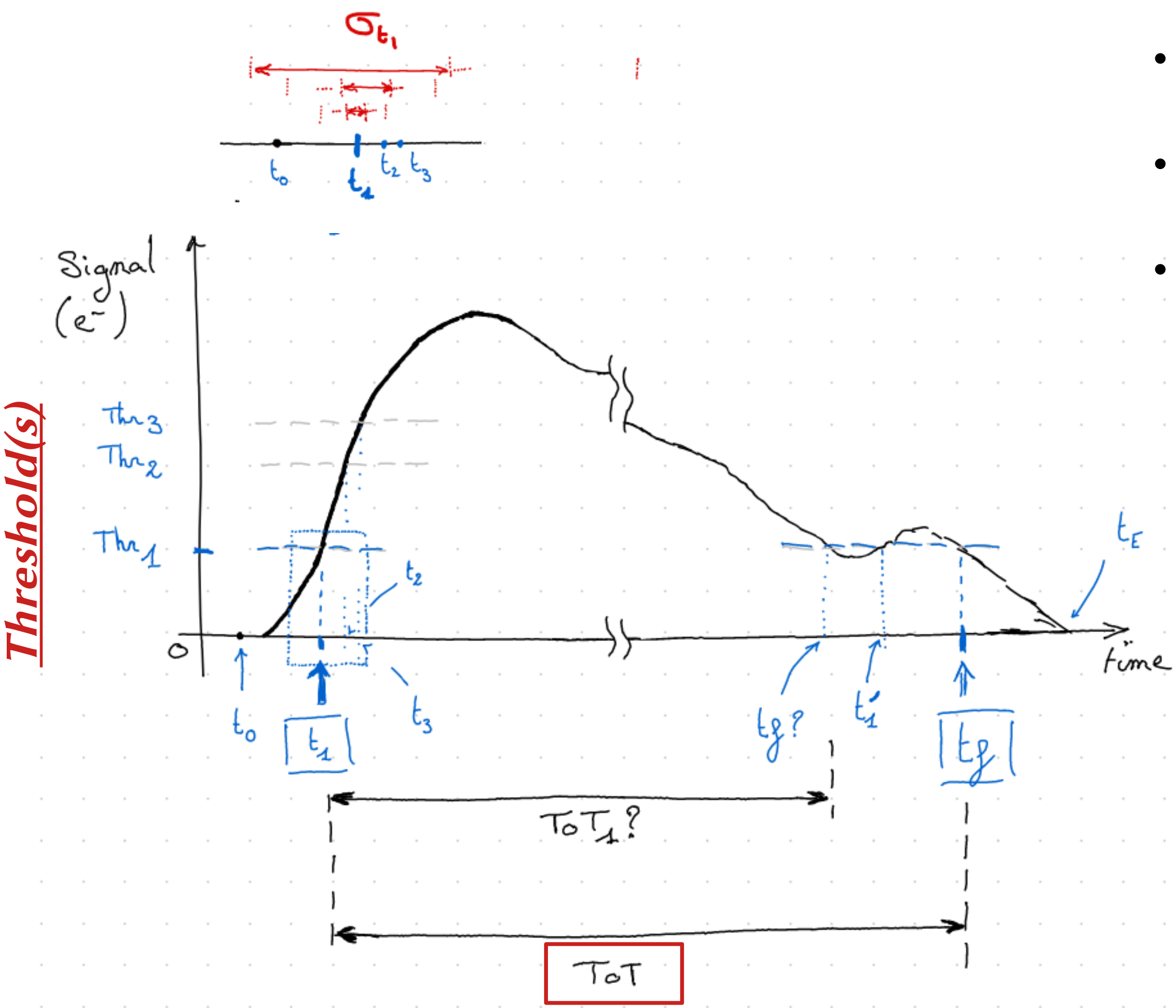
- ‹ t_1 › ≈ $\mathcal{O}$[80 **ps**], nice ‼
  Including digital treatment ≈ $\mathcal{O}$[1 **ns**]
- ‹ t_f › ≈ $\mathcal{O}$[5-20 **µs**] …
- Thr1 ≈ 100-150 e^- typically (ITS2, MOSS)

<u>Challenge[3]</u> :

Accuracy of the timing measurement, σ_{ti} resolution on a given instant t_i
(*related to sampling strategy, and jitter*)
⟶ Sampling for as long as 20 µs ?
Or stop sooner ?

III.5 – Timing Vs PID: the analog signal and its challenges

Time : signal shaping / time shaping, O(200 ns)



A few figures

- $\langle t_1 \rangle \approx O$[80 **ps**], nice ‼
  Including digital treatment $\approx O$[1 **ns**]
- $\langle t_f \rangle \approx O$[5-20 **µs**] ...

- Thr1 ≈ 100-150 e^- typically (ITS2, MOSS)

Challenge[4] : PID information

- ~~cluster shape~~
- Time over threshold measurement ?
- multiple threshold detect° on the rise ?
  (Thr1, Thr2, ...)

IV.1 – Timing Vs Power: …

Anything extra, anything fancy as MAPS functionalities = a extra price in terms of power
i.e. power consumption and/or power dissipation
i.e. integration problem, + material budget problem

~~Very detailed sampling of the signal~~
~~Collect fast thanks to extra depletion voltage~~

	Vertex Detector	Middle Layers	Outer Tracker	ITS3	ITS2
Pixel size (μm^2)	÷ 9 *O*(10 x 10)	• 2.8 *O*(50 x 50)	• 2.8 *O*(50 x 50)	*O*(20 x 20)	*O*(30 x 30)
Position resolution (μm)	÷ 2 2.5	• 2 10	• 2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	÷ 10 100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	÷ 25 200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm^2)	+ 75% 70	20	20	20**	47 / 35***
Particle hit density (MHz / cm^2)	• 20 94	1.7	67% 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm^2)	• 3000 1×10^{16}	• 100 2×10^{14}	≈ 5.6×10^{12}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000 300	• 10 5	≈ 0.2	0.3	0.3
Surface (m^2)	• 2.5 0.15	÷ 2 5	• 6 57	0.06	10
Material budget (% X_0)	0.1	1	1	0.05	0.36 / 1.1 ***

* goal, not crucial, like not possible due to power budget ** Pixel matrix *** Innermost layers / outer layers

V.1 – "Industrialisation" : ...

Industrialisation likely to happen at the "module" level ~ a few ALPIDE-like sensors

e.g. ITS2 Middle/Outer layers: module = 2x7 ALPIDE sensors

So industrialisation would mean :

lithographying, thinning, dicing, massive testing, placing, glueing, bonding, massive testing, ...

Clear retroactive consequences, upstream to CMOS design !

⟶ Fanciness and complexity can impair large-volume production

⟶ Needs something as *handy* as possible,
as *ergonomic* as possible

e.g. . no fancy bonds on some ill-located pad...
. easy to handle without breaking it
. plug, unplug for repair ? ... flexibility
. robustness (flux of inner information, power distribution, slow control design, ...)

NB :

ITS3 High-risk, high gain... for a crucial ($r \geq 1.8$ cm)
but for a very little active surface at the end of the day

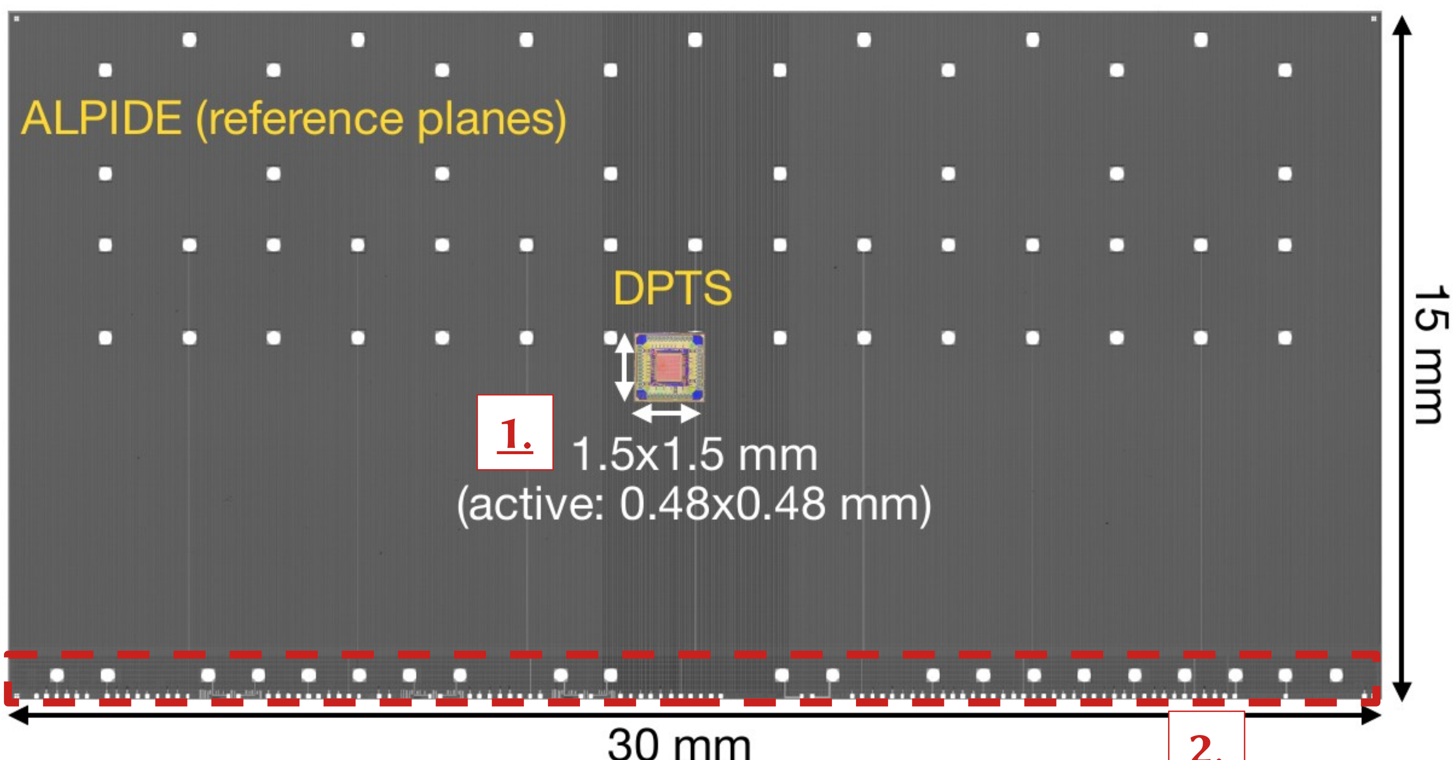
(ALICE2 ITS3 ≈ **0.12 m²**) Vs (ALICE3 OT ≈ **57 m²**)

VI.1 – Integration: to keep in mind from the very beginning

Ratio of **active surface** to **periphery surface**,

to pull out "O[MB.s^{-1}.cm^{-2}]"

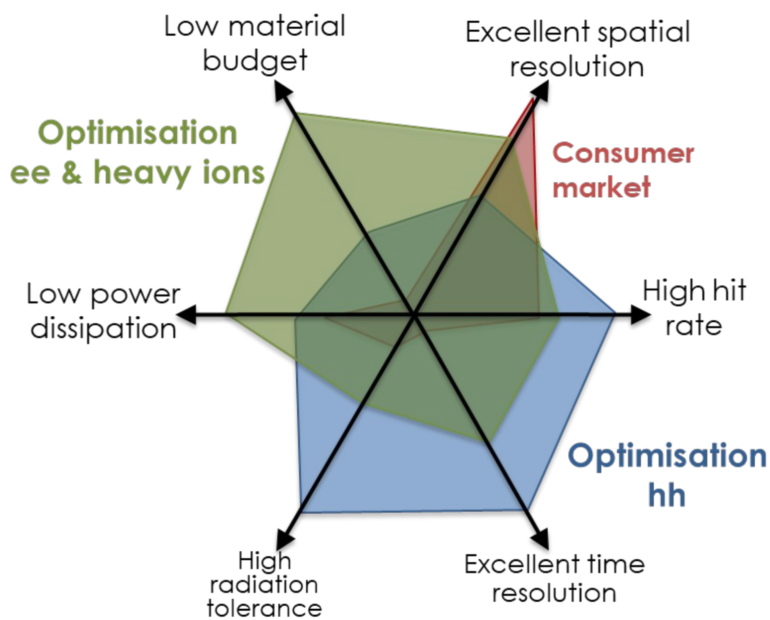
to ship (even low) current/voltages over sensor distance, not even talking about ladder length



Pixel matrix
13.8 mm

Periphery
1.2 mm

Conclusion: map of parameters



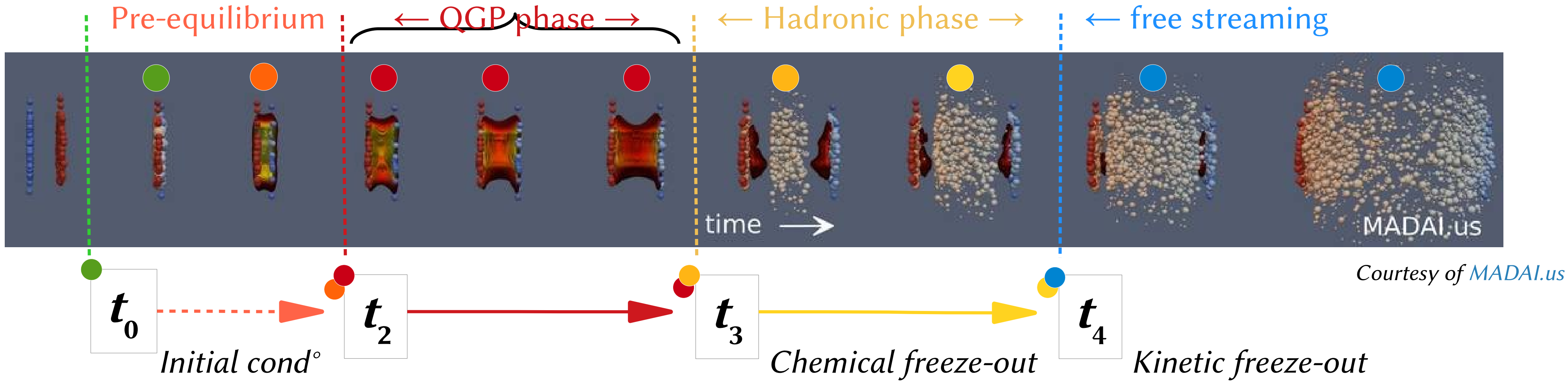
Courtesy J. Baudot

Outer Tracker in 2 keywords ?

≈ (LHC bunch-tagging) timing ***Vs*** power

D. – Template for physics cases

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



Courtesy of MADAI.us

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

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

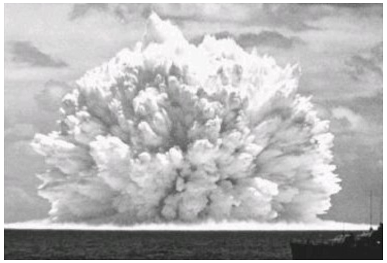
via
Multi-Parton Interactions
+ Colour Reconnections
+ Multiple parton scatterings
+ Rope shoving
+ Glasma
…

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
…

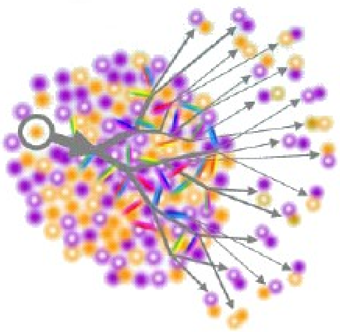
D.2 – Observables : Layer 2 / as a function of *momentum*

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



≈ relativistic hydrodynamics

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



≈ in-medium energy losses for energetic particles

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

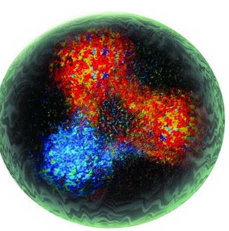
Initial state

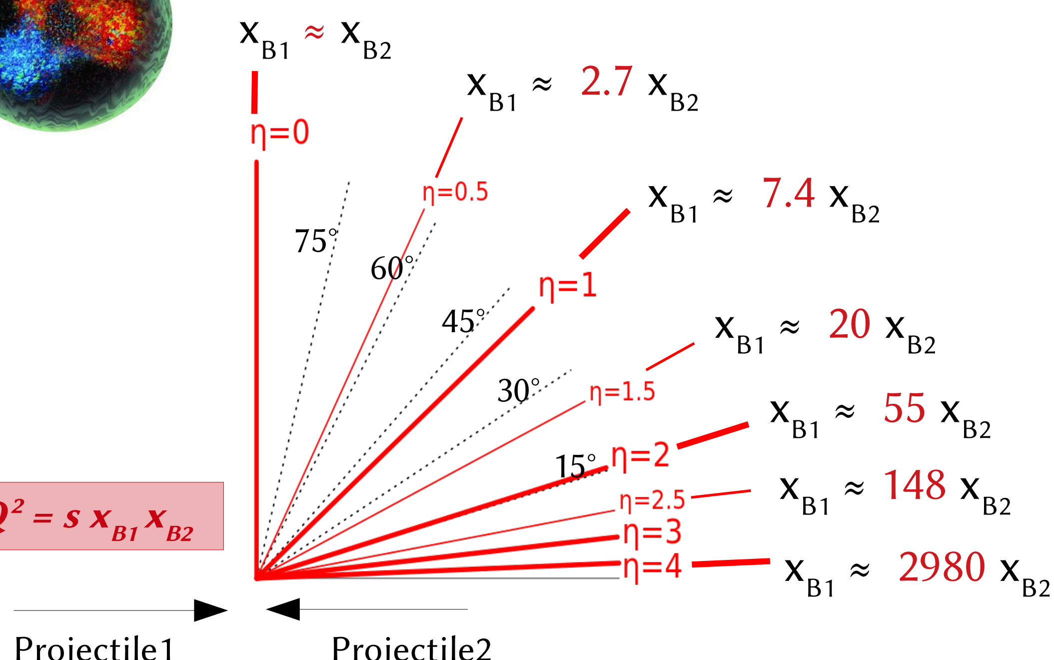
I.	ultra-low x_B	($x_B \leq 10^{-5}$)
II.	low x_B	($x_B \in [10^{-5} ; 10^{-3}]$)
III.	moderate x_B	($x_B \in [10^{-3} ; 10^{-1}]$)

Longitudinal dynamics

I'.	$|y| < 2$	: max = rapidity plateau in $dN_{ch}/d\eta$
II'.	$|y| \approx 3.5$	: 75% $(dN_{ch}/d\eta)_{max}$
III'.	$|y| \approx 5.0$	: 45% $(dN_{ch}/d\eta)_{max}$

JLab

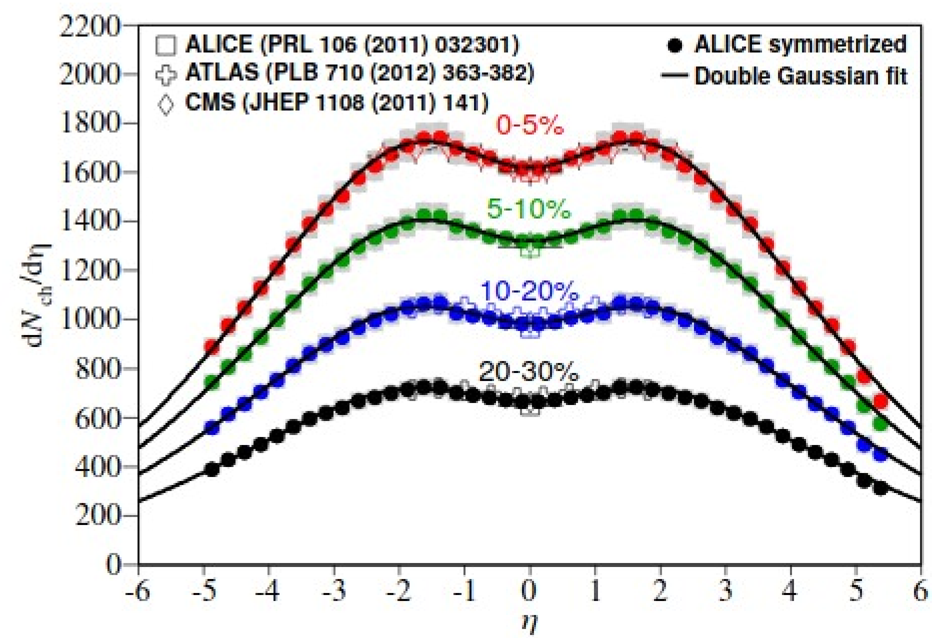




$Q^2 = s\, x_{B1} x_{B2}$

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

ALICE, arXiv:1304.0347



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

« hadron-quark duality »

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

- $\pi^{\pm}$ π^0 $K^{\pm}$ K^0_S … p Λ Ξ^- Ω^- …
  $\eta(547)$ $\omega(782)$ … $K^0(892)$ $\phi(1020)$ $\Sigma^{\pm}(1385)$ $\Lambda(1520)$ $\Xi^0(1530)$
  + d t ^3He ^4He …
  + $^3_\Lambda H$ …
  } *u,d,s*
- D^0 $D^{\pm}$ $D^{*\pm}$ D_S^+ … η_c J/ψ χ_{Ci} $\psi(2S)$ … Λ_C^+ Ξ_C^0… } *c*
- B^0 $B^{\pm}$ B^0_S … $\Upsilon(1S,2S,3S)$ … Λ_b^0 … } *b*

\+

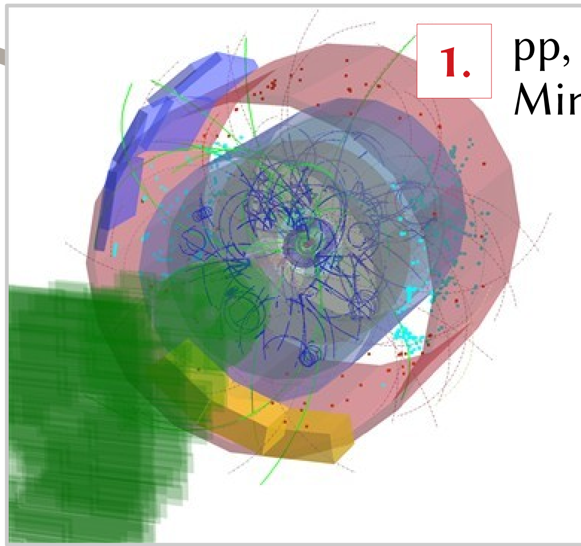
(• $e^{\pm}$ γ)
(• $W^{\pm}$ γ/Z°)

NB :

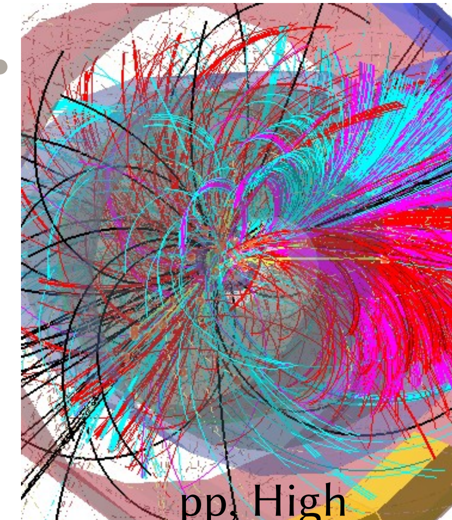
baryons Vs mesons
mixed flavours (s+c, s+b, … c+b …)

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

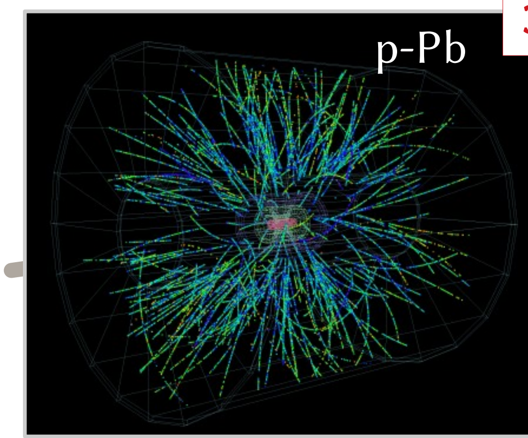
1. pp, Min. Bias



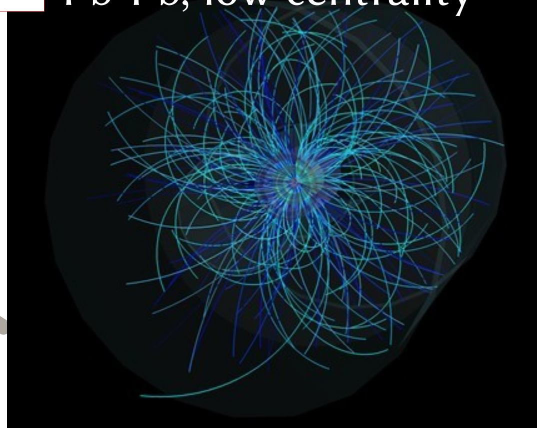
2. pp, High Multiplicity



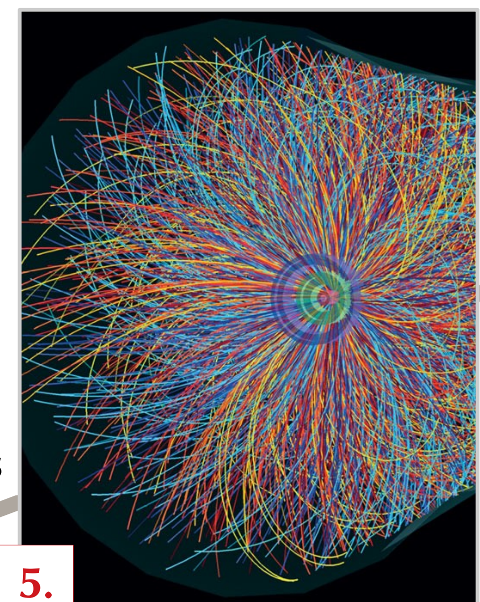
3. p-Pb



4. Pb-Pb, low centrality



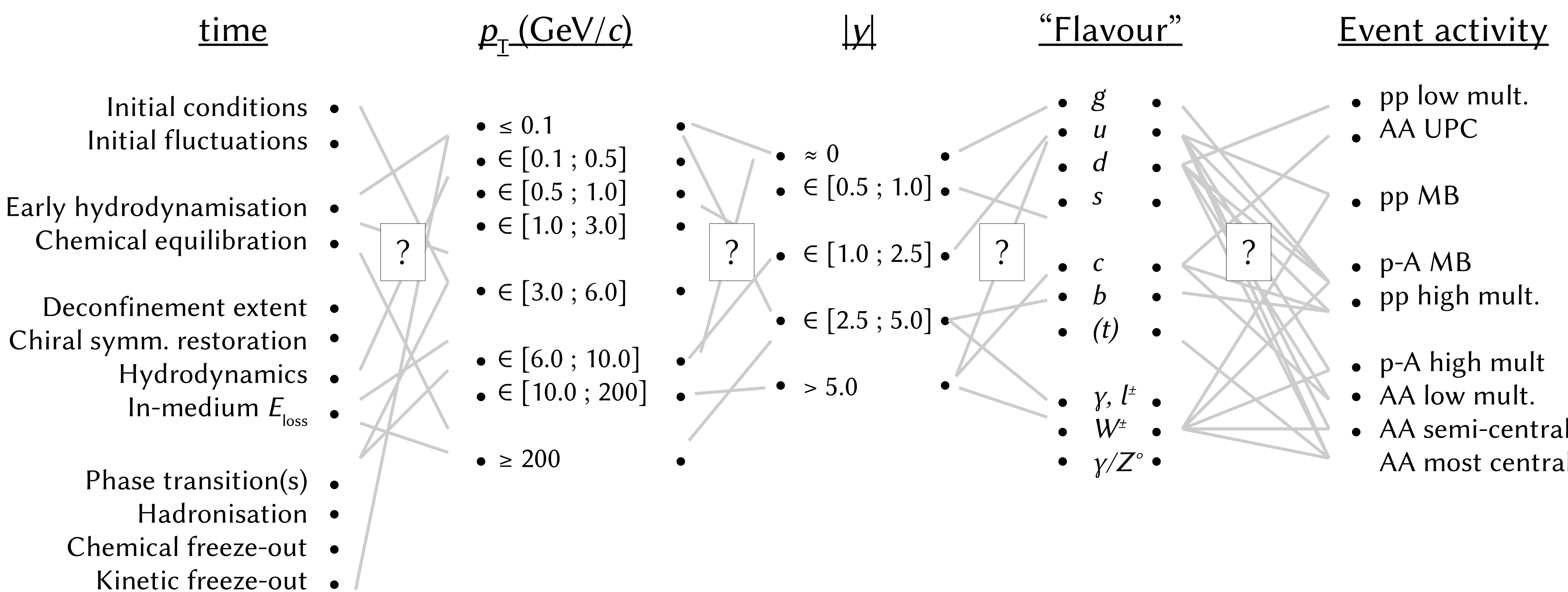
5. Pb-Pb, most central events



CDS/record-1305398

D.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 …*)