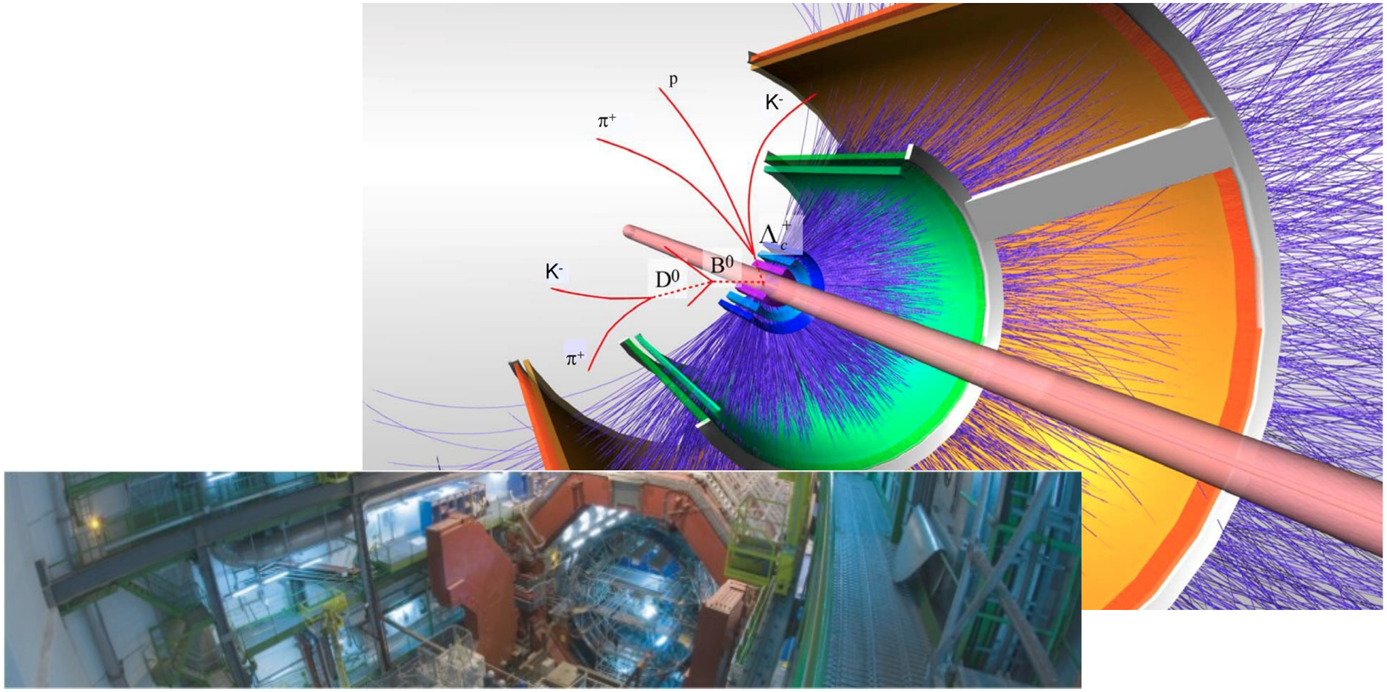
Antonin MAIRE – IPHC Strasbourg

Tues, 10 Dec 2019 – **QGP France prospectives 2019**

Towards a QCD+QGP physics at HL-LHC with ultra-low p_T detection :

ALICE ITS-3 + “all-Si experiment”



iPHC
Institut Pluridisciplinaire
Hubert CURIEN
STRASBOURG

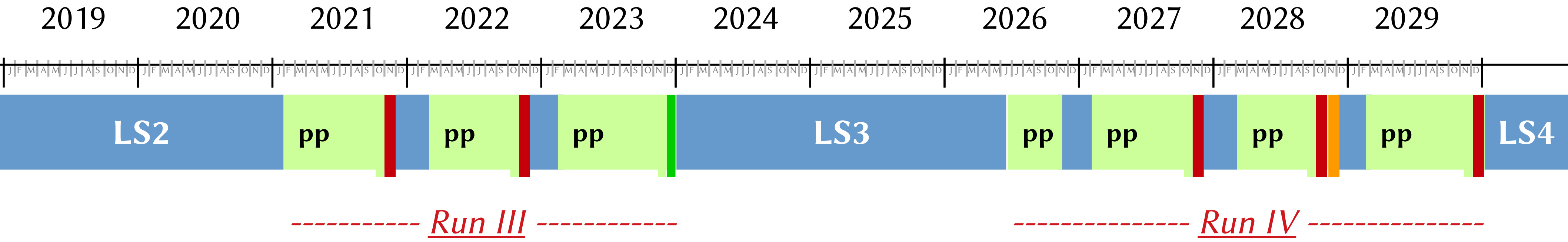
Foreword : brainstorming in progress…

FIELD	CONTACTS	Th/Exp	1st approach	Discussion
hydrodynamics	Jean-Yves Ollitrault	Th	√	√
hydrodynamics	Stefan Flörchinger	Th	√	√
hydrodynamics	Aleksas Mazeliauskas	Th	√	√
CNM	François Arléo	Th	√	√
CNM	Stéphane Peigné	Th	√	√
CGC	François Gellis	Th	√	TbD
jets	Grégory Soyez	Th	√	TbD
EFT	Jacopo Ghiglieri	Th	√	TbD
fluctuations	Derek Teaney	Th	√	TbD
fluctuations	Marlene Nahrgang	Th	TbD	…
net quantum numbers	Alice Ohlson	Exp	√	√
charm	Pol-Bernard Gossiaux	Th	√	√
ALICE TOF + light nuclei	Francesca Bellini	Exp	√	…
CMS MTD	Andre Stahl, Wei Li	Exp	√	√
$e^{\pm}$ p, ATLAS, CMS, H1	E. Sauvan, C. Diaconu, E. Perez, L. Schoeffel	Exp	√	√/…
BSM in HI	David d'Enterria	Exp	TbD	TbD
…	***+You ?***	**…**	**…**	**…**

Looking for contradictors
+ different perspectives…

√ = New since *GdR QCD 25/11/19*

Outline



A. Physics cases at HL-LHC (*runs IV + V*)

B. ≥2026, Run 4 (*ALICE ITS3*)

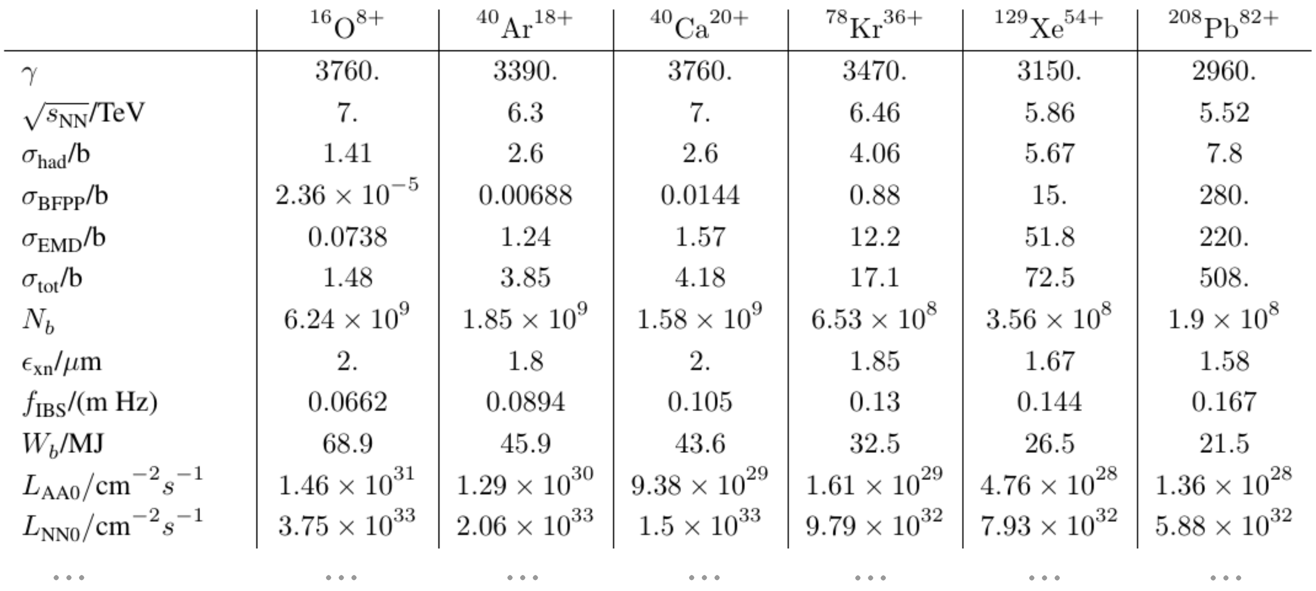
C. ≥2031, Run 5 (*All-Si experiment*)

Part A – some physics cases

I.0 – HL-LHC QCD+QGP : AA beyond 2029 ?

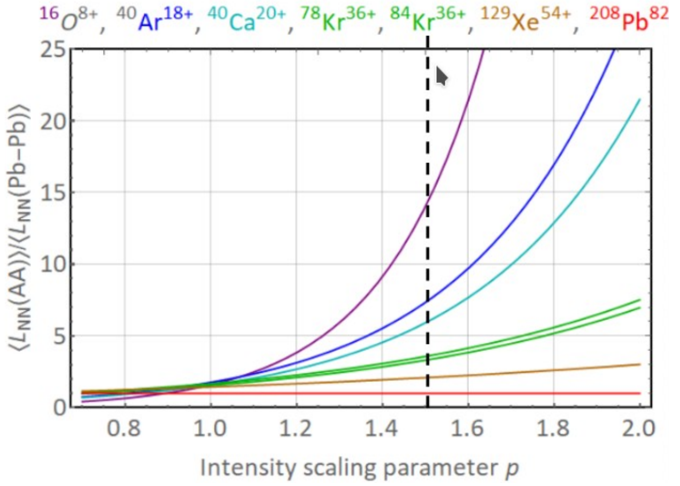
0. First things first : as of 2019 = no plan of “AA” runs after HL-LHC run 4

1. If AA in Run >V, likely *not* to be $^{208}Pb^{82+}$ - $^{208}Pb^{82+}$ but something of lower A
i.e. trade off to be found between (increased instanteneous luminosity) Vs. (QGP effects)



	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
σ_{BFPP}/b	2.36×10^{-5}	0.00688	0.0144	0.88	15.	280.
σ_{EMD}/b	0.0738	1.24	1.57	12.2	51.8	220.
σ_{tot}/b	1.48	3.85	4.18	17.1	72.5	508.
N_b	6.24×10^9	1.85×10^9	1.58×10^9	6.53×10^8	3.56×10^8	1.9×10^8
ϵ_{xn}/μm	2.	1.8	2.	1.85	1.67	1.58
f_{IBS}/(m Hz)	0.0662	0.0894	0.105	0.13	0.144	0.167
W_b/MJ	68.9	45.9	43.6	32.5	26.5	21.5
$L_{AA0}/cm^{-2}s^{-1}$	1.46×10^{31}	1.29×10^{30}	9.38×10^{29}	1.61×10^{29}	4.76×10^{28}	1.36×10^{28}
$L_{NN0}/cm^{-2}s^{-1}$	3.75×10^{33}	2.06×10^{33}	1.5×10^{33}	9.79×10^{32}	7.93×10^{32}	5.88×10^{32}
…	…	…	…	…	…	…

- *Table 4, Ch.2 WG5 Yellow Report*
  arXiv:1812.06772



- *WG5 Yellow Report, general meeting, 30/10/2018, Indico.cern.ch/758181*

I.1 – HL-LHC QCD+QGP : for which physics cases ?

1. Measuring QGP temperature = f(time) [low mass e^+e^-]

2. Nature of phase transitions (deconfinement + chirality) :
   Connecting to LQCD + asserting Hydrodynamics [ultra low p_T]

3. Understanding in-medium energy loss [Jets shapes and structures]

4. Challenging the flavour dependence of collectivity [*s*,*c*,*b*]

5. Searching for "SM/BSM" [...]

I.2 – HL-LHC QCD+QGP : low mass (e^+e^-) as virtual γ

1. QGP temperature = f(time) via thermal virtual photons ($m_{e+e-} \in [0;2.5]$ GeV/c^2)
   high m_{e+e-} = high T, i.e. early times

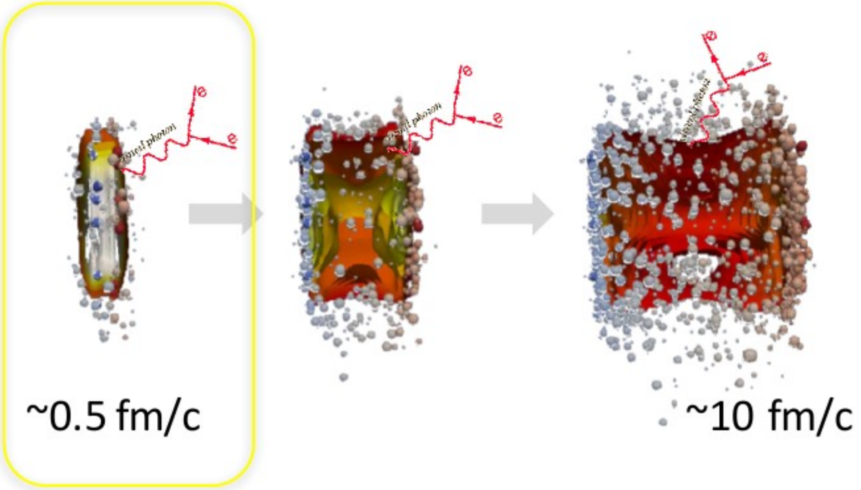
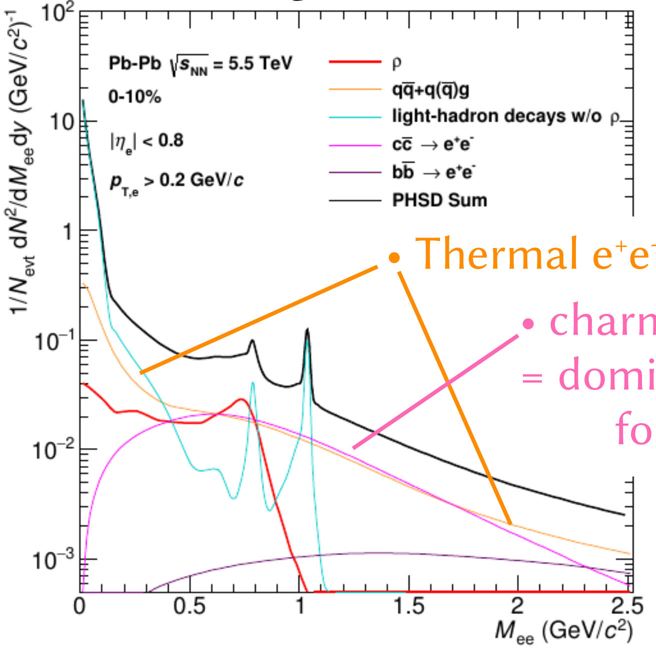


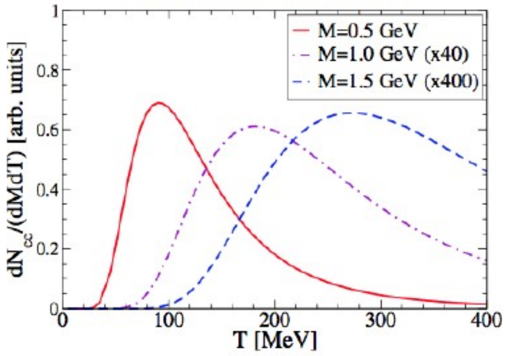
Fig. 54, YR WG5, arXiv:1812.06772



- Thermal e^+e^- signal
- charm semi-leptonic decays
  = dominant bckgnd
  for $m_{ee} > 1$ GeV/c^2

NB :
→ so, very good
control needed
on charm = a must

R. Rapp Acta Phys.Polon. B42 (2011)



I.3 – HL-LHC QCD+QGP : heavy-flavours facing collectivity

Λ_C^+ (m = 2.286 GeV/c² / cτ = 60 μm)

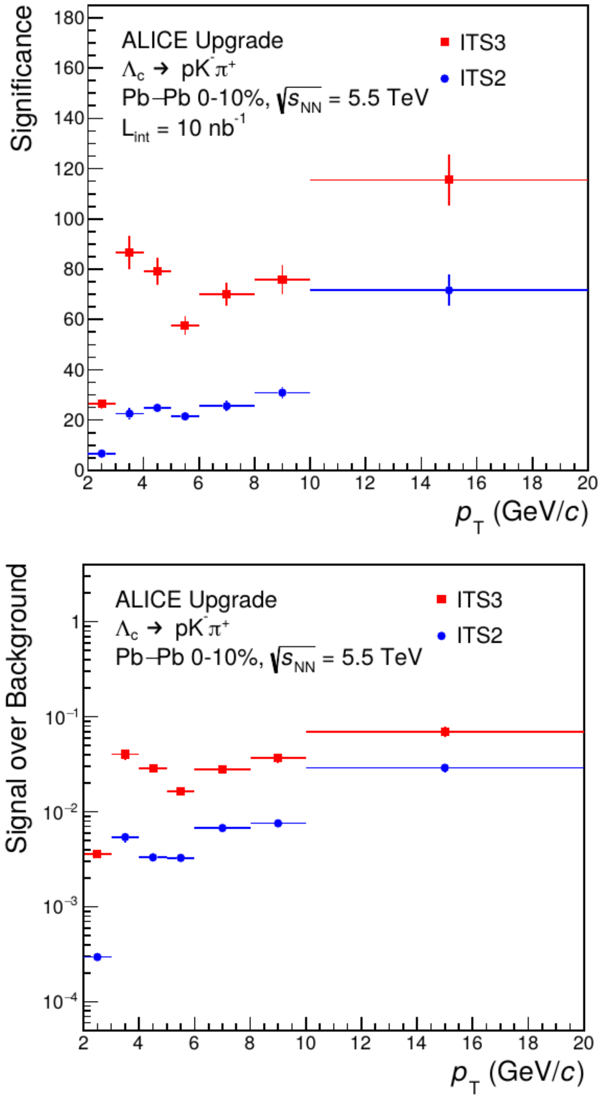


Fig. 13, EoI ITS3, ALICE-PUBLIC-2018-013

→ diffusion coefficient / hydrodynamization / in-medium energy loss / hadronisation

- total charm cross-section $c\bar{c}$:
  $\eta_C(1S)$, J/ψ, ψ(2S), χ_{Cj} + D^0, D^+, D_S^+, $D(2010)^\pm$ + Λ_C^+
- beauty :
  baryons $\Lambda_b^0 \longrightarrow \Lambda_C^+ \pi^-$
  mesons $B^0 \longrightarrow D^-\pi^+$, $B^\pm \longrightarrow D^0\pi^\pm$, $B_S^0 \longrightarrow$ non-prompt D_S^+
- recombination :
  $p/\pi^+ \longrightarrow \Lambda/K^0_S \longrightarrow \Lambda_C^+/D^+ \longrightarrow \Lambda_b^0/B^0$
- charm-strange baryons
  (cτ ~ 30-130 μm + 2-to-6 final states cascade decays) :
  = $\Lambda_C^+(udc)$, $\Xi_C^+(usc)$, $\Xi_C^0(dsc)$, $\Omega_C^0(ssc)$, $\Xi_{CC}^{2+}(ucc)$, … , $\Omega_{CCC}^{2+}(ccc)$

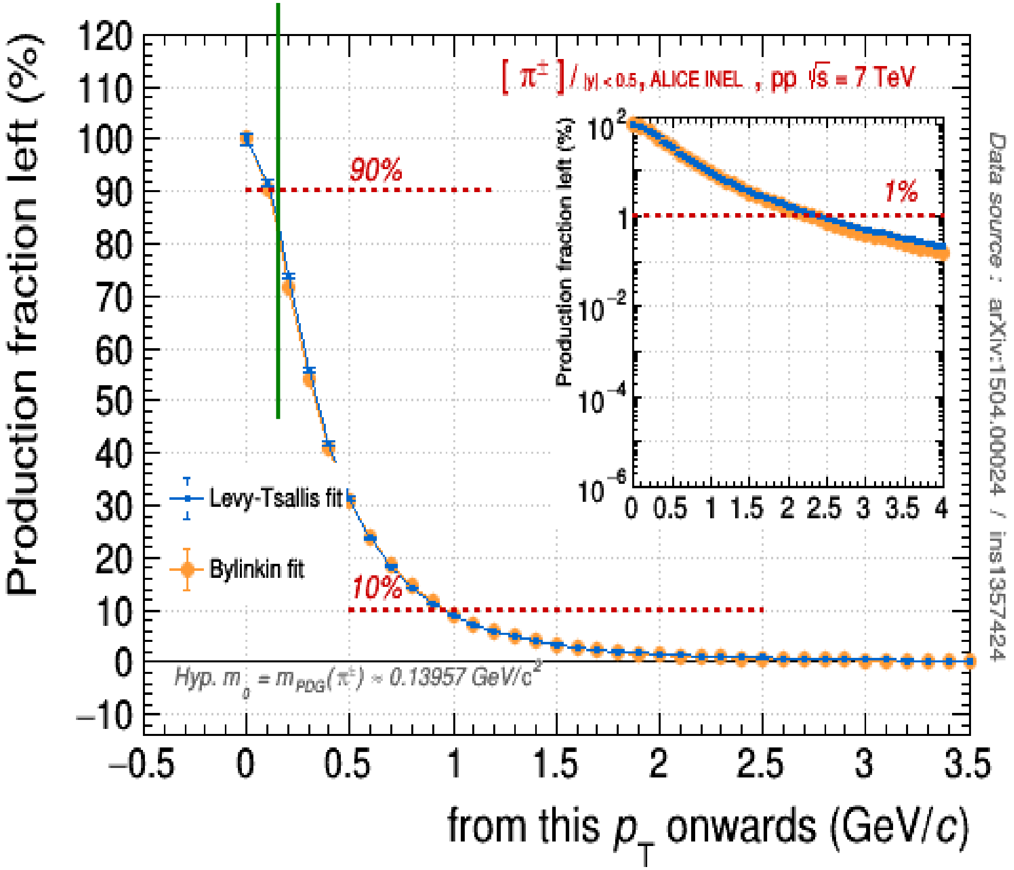
- charm hypernuclei, c-deuteron = $\Lambda_c n$ bound state
- tetraquark X(3872) ⟶ J/ψ $\pi^+ \pi^-$

See also QM 2019, G.-M. Innocenti for ITS-1 Pb-Pb or pp physics of Λ_C^+ …

I.4 – HL-LHC QCD+QGP : low-p_T $\pi^\pm$

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

For a given particle type of interest, can you claim a "precision measurement"
if you indeed miss x% of production ? → yes or no ? to be decided, case by case…

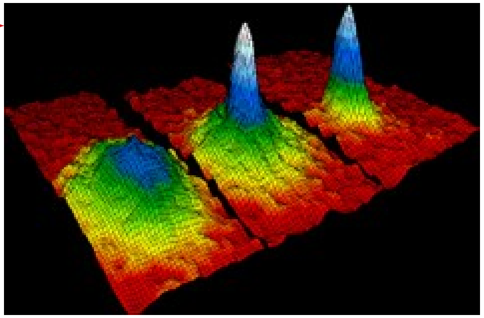


NB : ALICE pp 7 TeV arXiv:1504.0024
$h^\pm$ > 0.15 GeV/c → Missed cross-section ≈15%
$\pi^\pm$ > 0.10 GeV/c → Missed cross-section ≈10%

I.5 – HL-LHC QCD+QGP : why caring about the low-p_T $\pi^\pm$

1. Getting dN/dp_Tdy + $v_n(h^\pm)$ down to non-relativistic p_T (e.g. $p_T < 0{,}05$ GeV/c ⟶ $\beta_{\pi^\pm} \approx 0{,}34$)
⟶ change from non-relativistic (linear) to relativistic hydro. (quadratic behaviour)

2. Chiral disoriented condensate + π condensate
if present, $p_T < 1/2\ m_\pi$

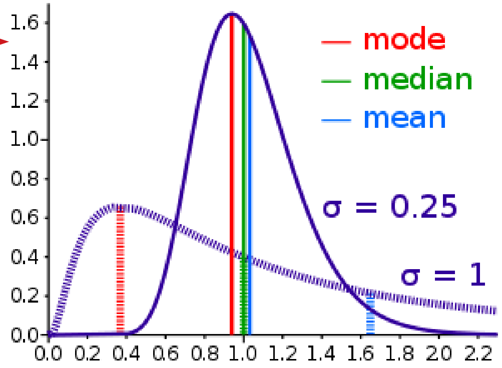


Wikipedia: Bose-Einstein condensate

3. Net quantum numbers 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 - $\bar{\Lambda}$, ...)

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

1st moment, m_1 : mean μ
2nd moment, m_2 : std deviation
3rd moment, m_3 : skewness
4th moment, m_4 : kurtosis
5th moment, m_5 : *no name*
6th moment, m_6 : ...
7th moment, m_7 : ...

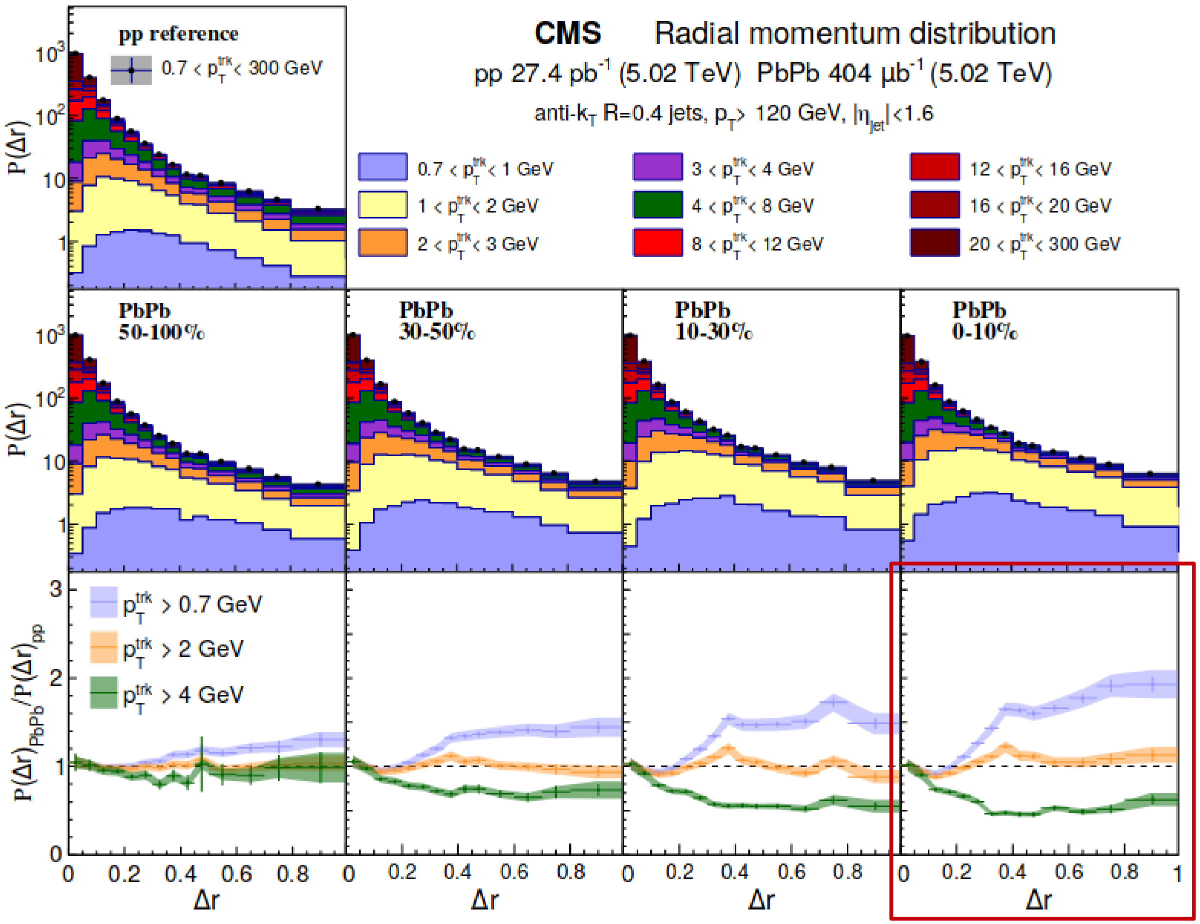


Wikipedia:Skewness

⟶ *one key (today)* : ratio m_6/m_4 to access direct comparison to LQCD for
(deconfinement dof + transition + chiral restoration)

I.6 – HL-LHC QCD+QGP : jet in charged jets...

CMS Pb-Pb 5.02 TeV arXiv:1803.00042



(0-10% AA)/pp diff = important at :

- large Δr (Δr >0.4)

← - low $p_{T,track}$ (p_T < 1 GeV/c)

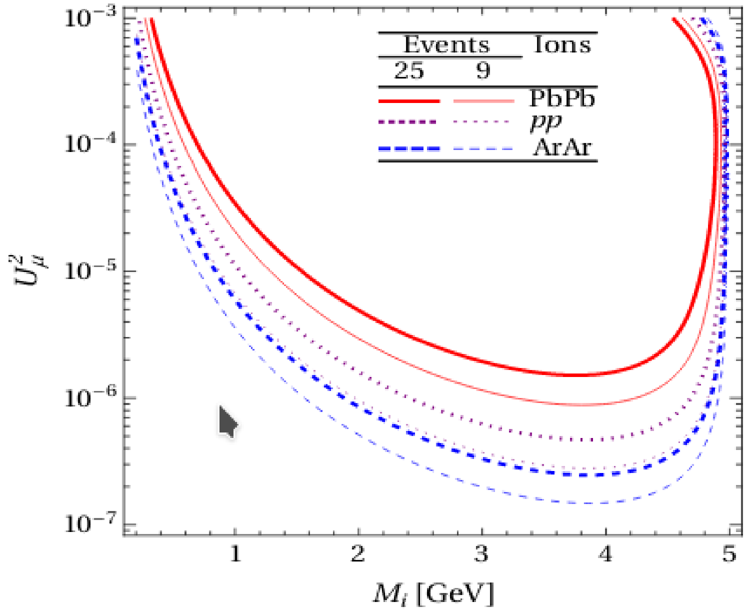
→ (hyper)fine structure/shape jets flavour jet-tagging (*g* Vs. *q*, *c* Vs. *b*)

I.7 – HL-LHC QCD+QGP : SM/BSM searches

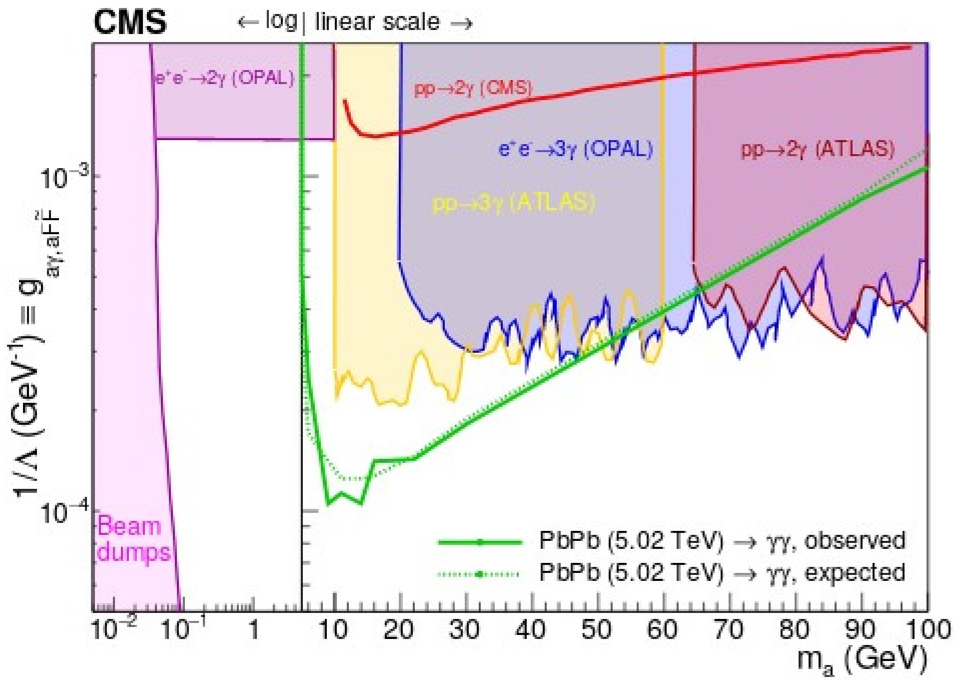
- axion-like particle (ALP) in UPC light by light,
- Long-lived particles,
- sexaquarks
- magnetic monopoles

…

d'Enterria ESPP, arXiv:1812.07688

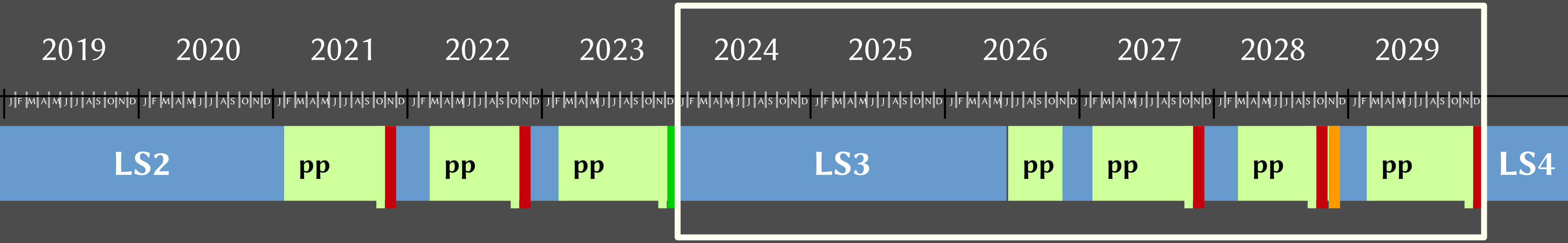


Heavy neutrino searches in B decays



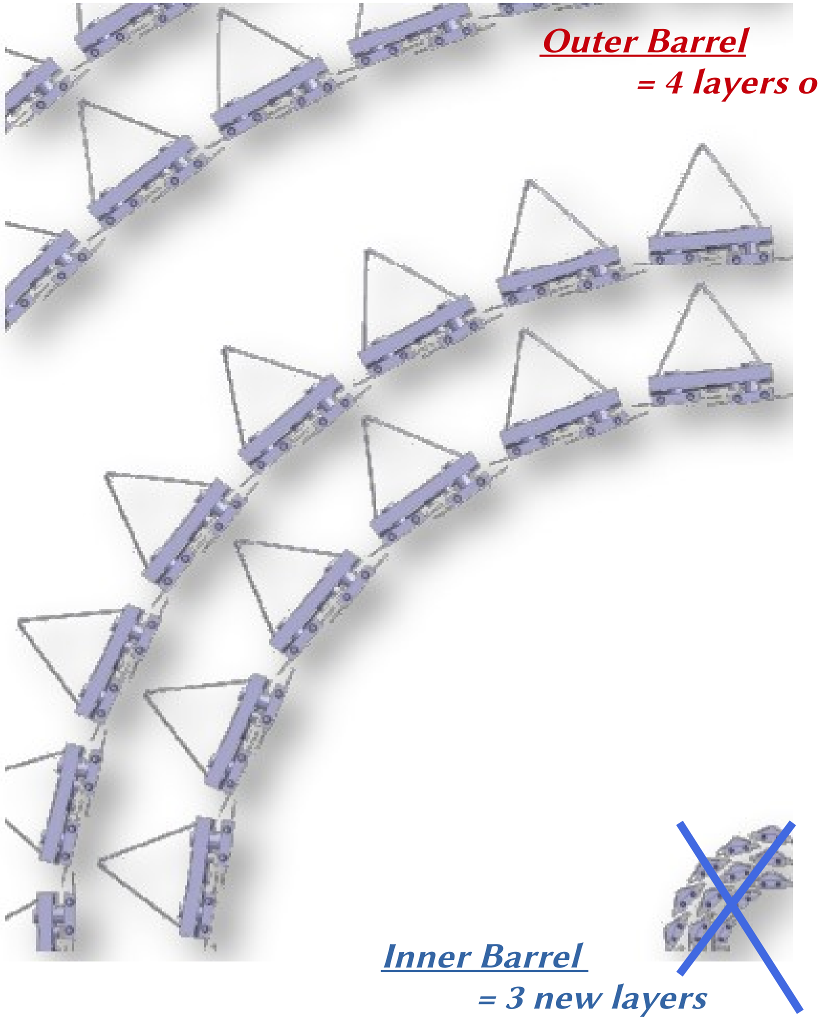
Current 95% CL exclusion limits
ALP coupling to γ Vs ALP mass

Part B – ITS-3 = after LS3 (≥2026, Run 4)



LHC running plan

III.1 – ITS-3 : first expression of interest



Outer Barrel

= 4 layers of ITS2 kept !

Inner Barrel

= 3 new layers

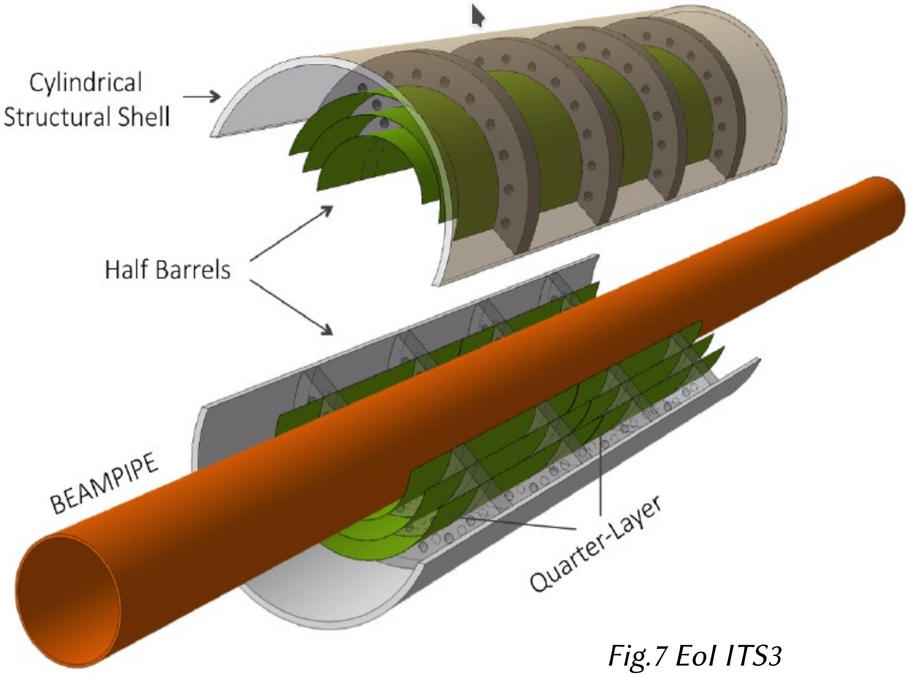


Fig.7 EoI ITS3
ALICE-PUBLIC-2018-013

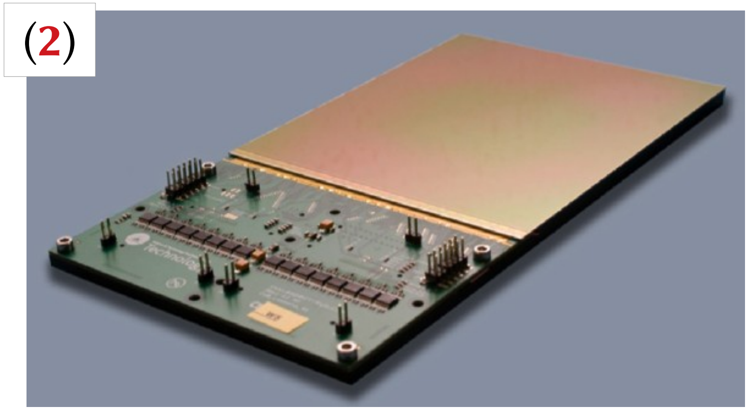
III.2 – ITS-3 : key foreseen features, “closer + lighter”

Keys :

(**1**) - shrinked beam pipe ($r_{\text{beam pipe}}$ = 1.6 cm)
⟶ inner most layer at r_{L0} = 1.8 cm

(**2**) - reticle-size sensor (O[15x10 cm^2])
+ (**3**) - ultra-thin Si CMOS (≤40-µm thick)
⟶ circuitry pushed to periphery (*stitching*), ~no extra services required
⟶ can be curved
⟶ homogeneous 0.05% X/X° per layer

(**2**)

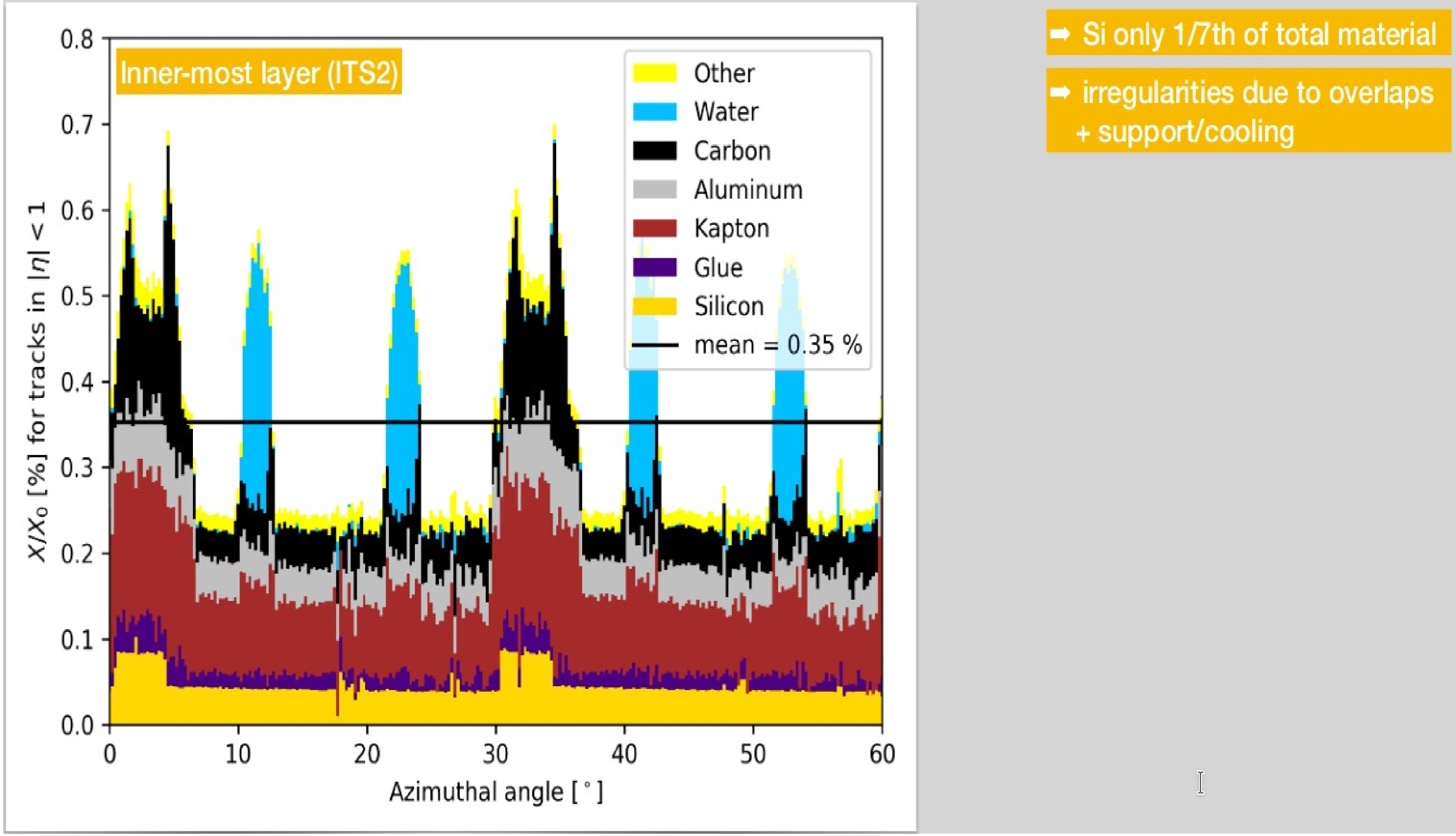


X-ray detector 13.9 x 12 cm² TowerJazz 0.18-µm

(**3**)

Silicon Genesis: 20 micron thick wafer

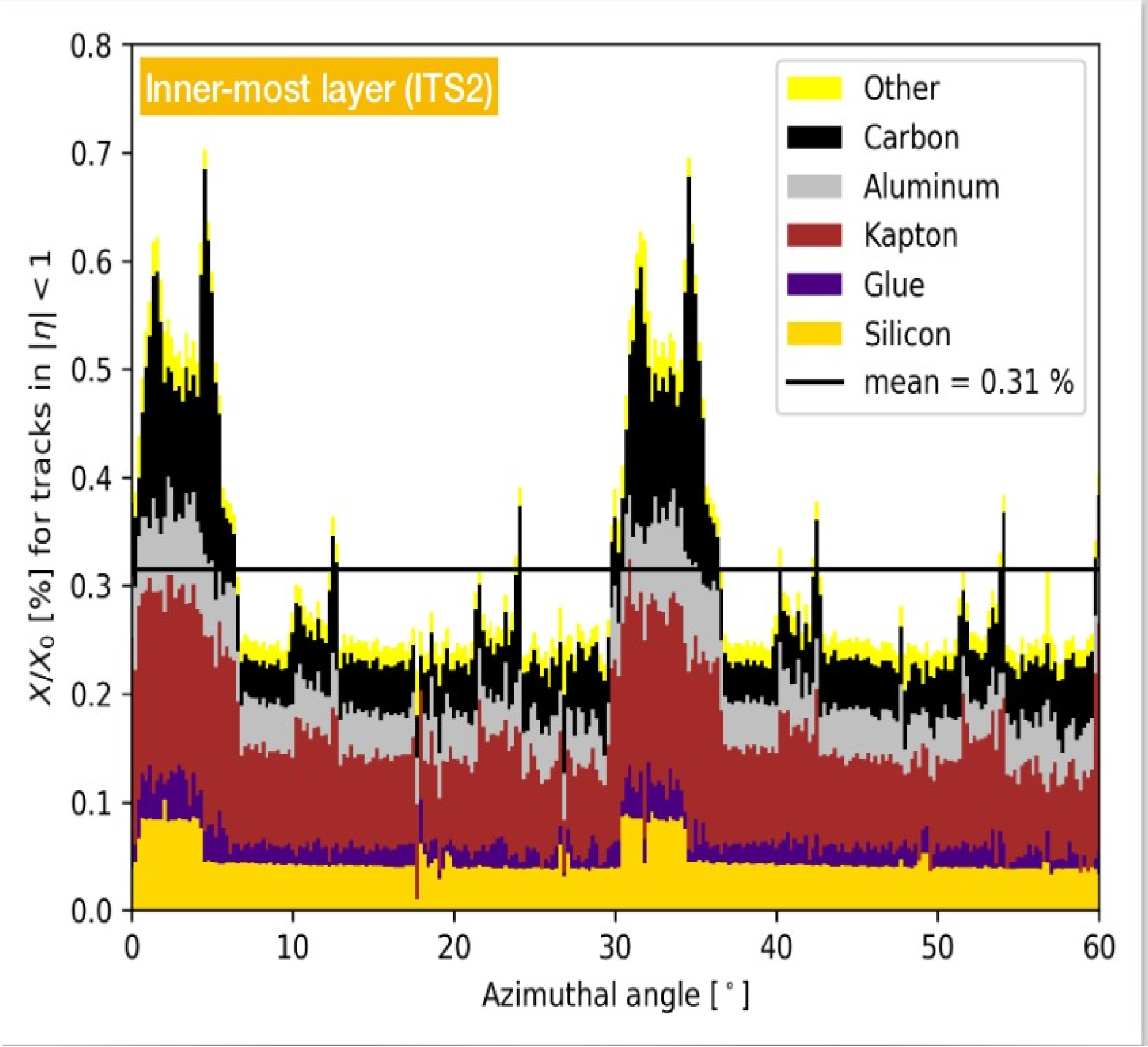
III.3 – ITS-3 : skimming material budget of ITS-2



- ➡ Si only 1/7th of total material
- ➡ irregularities due to overlaps + support/cooling

LHCc 2019-06 ALICE, M.Mager ITS3

III.3 – ITS-3 : skimming ITS-2



➡ Si only 1/7th of total material

➡ irregularities due to overlaps + support/cooling

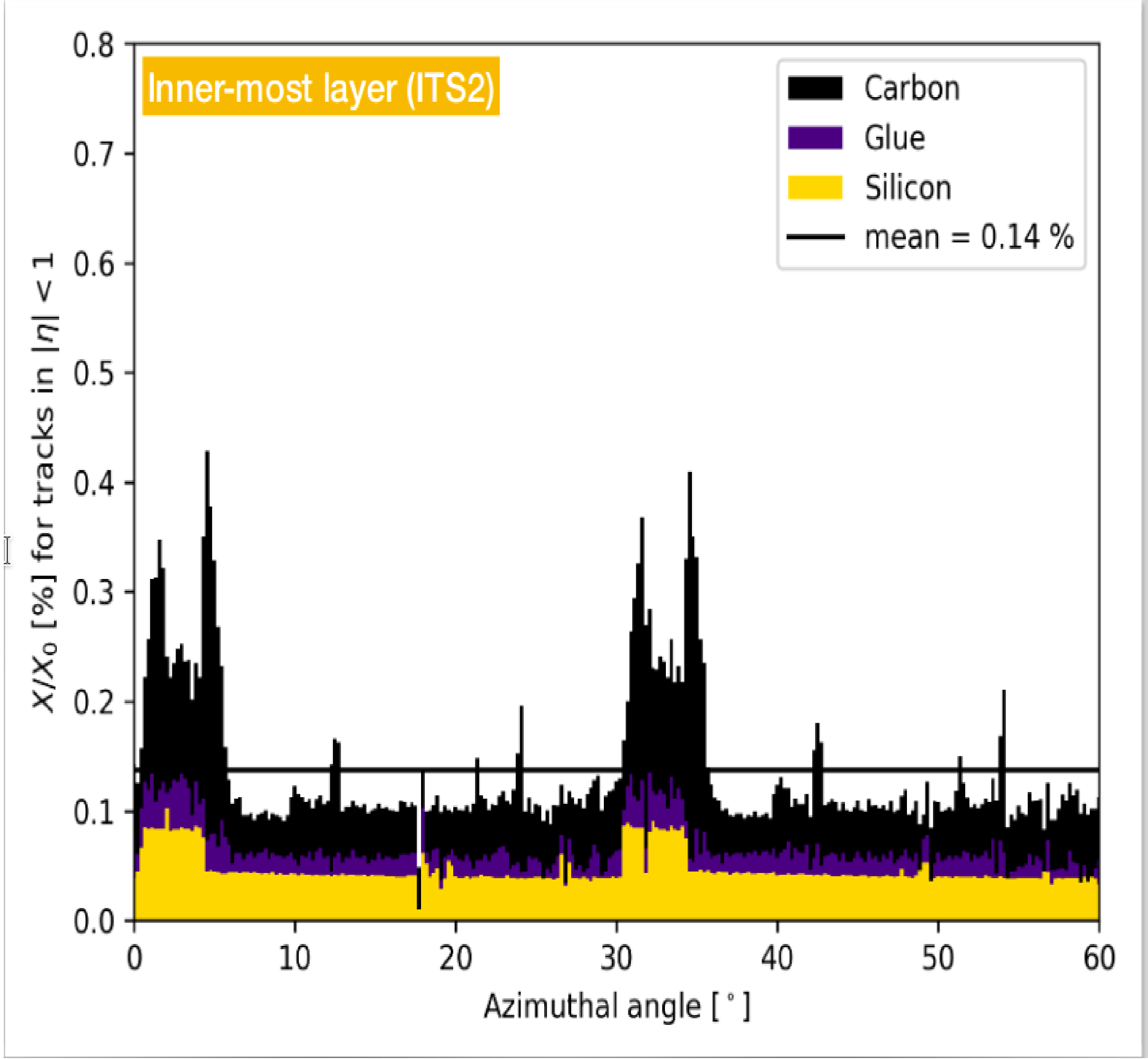
➡ remove water cooling

➡ possible by reducing power consumption in fiducial volume to <20 mW/cm^2

1.

LHCc 2019-06 ALICE, M.Mager ITS3

III.3 – ITS-3 : skimming ITS-2



➡ Si only 1/7th of total material

➡ irregularities due to overlaps + support/cooling

1.

➡ remove water cooling

➡ possible by reducing power consumption in fiducial volume to <20 mW/cm^2

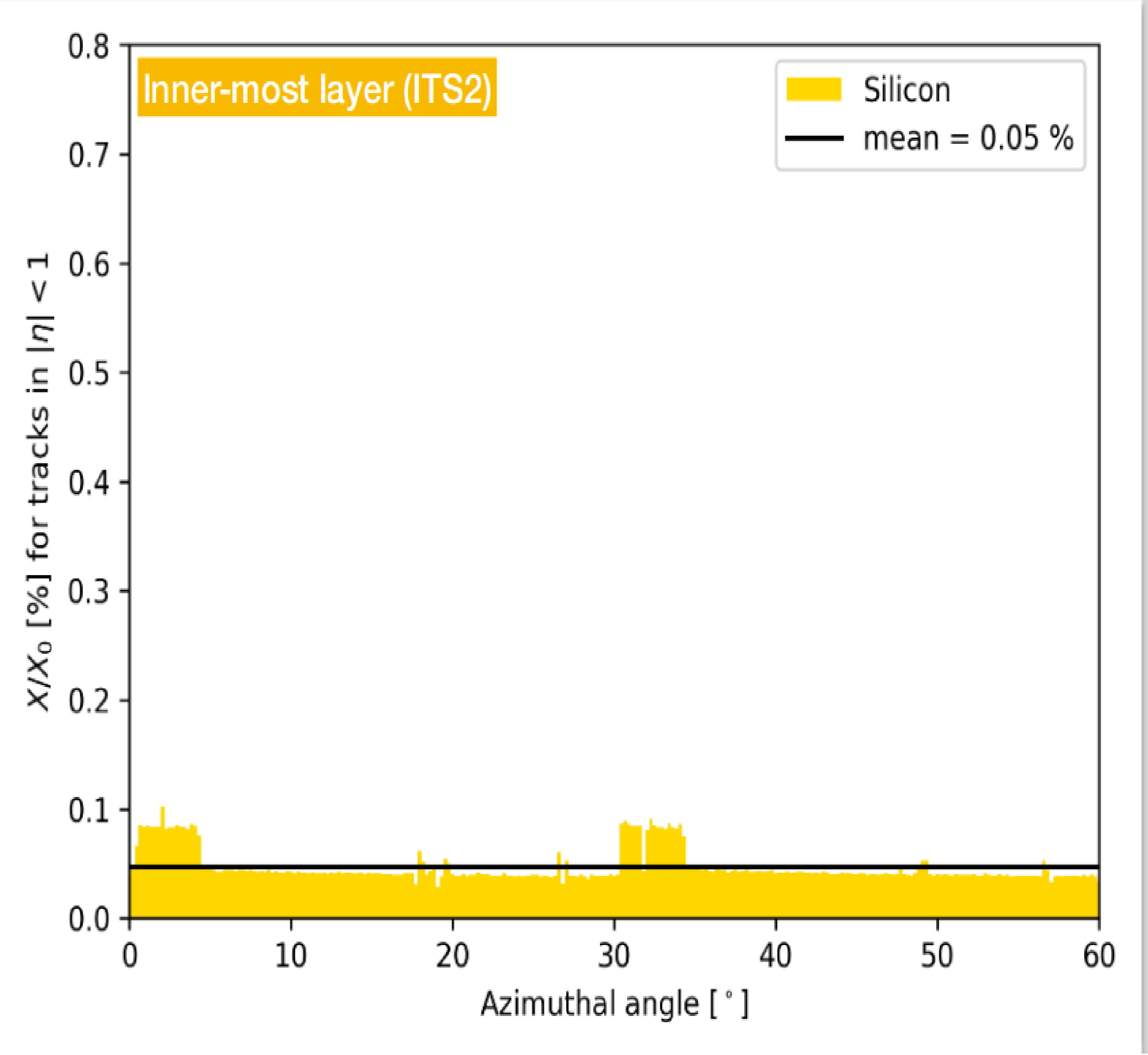
2.

➡ remove external data lines + power distribution

➡ possible by making a single large chip and that for distribution

LHCc 2019-06 ALICE, M.Mager ITS3

III.3 – ITS-3 : skimming ITS-2



- ➡ Si only 1/7th of total material
- ➡ irregularities due to overlaps + support/cooling

1.

- ➡ remove water cooling
  - ➡ possible by reducing power consumption in fiducial volume to <20 mW/cm^2

2.

- ➡ remove external data lines + power distribution
  - ➡ possible by making a single large chip and that for distribution

3.

- ➡ move mechanical support outside acceptance
  - ➡ benefit from increased stiffness by rolling Si wafers

LHCc 2019-06 ALICE, M.Mager ITS3

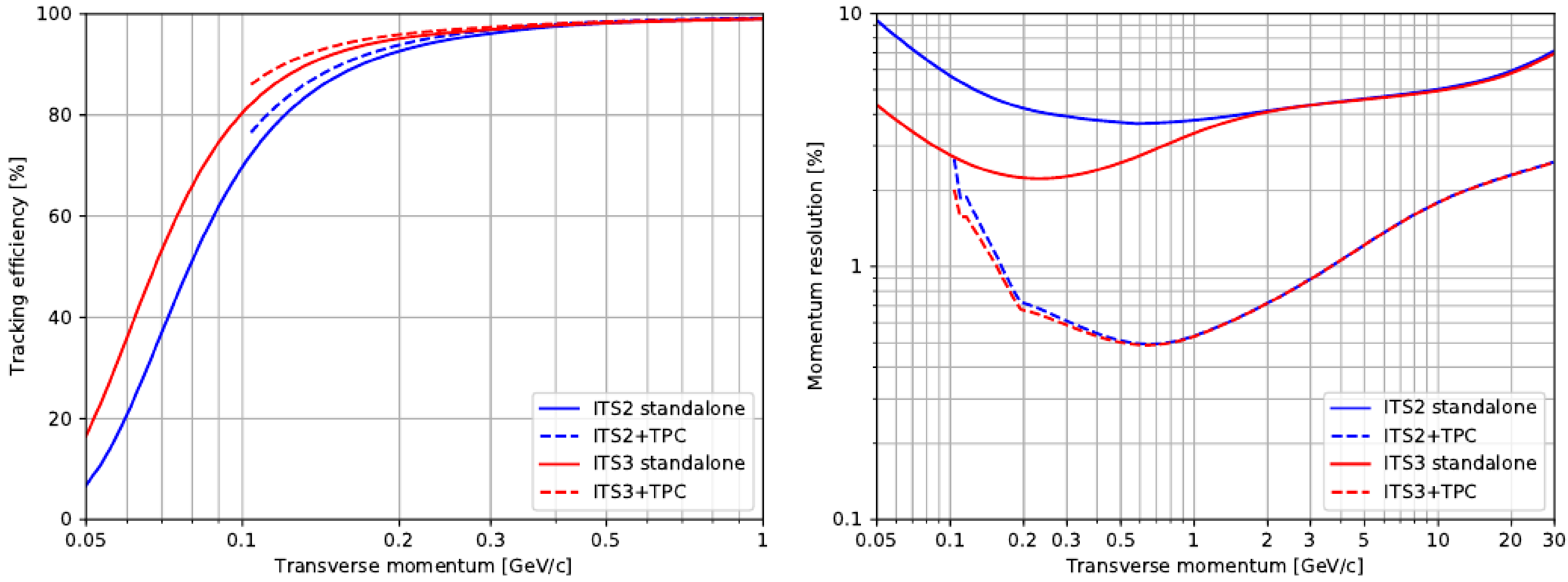
III.4 – ITS-3 : synoptic table

	ITS1 (SPD = 2 inner)	ITS2 (3 inner)	ITS3 (3 inner)
Beam pipe inner radius/thickness	3.0 cm/0.09 cm	1.82/0.08 cm	1.6/0.05 cm
First-layer radius	3.9 cm	2.3 cm	1.8 cm
X/X° per layer	1.1 %	0.35 %	0.05%
|η| coverage	> 1.4	> 2.0	> 2.0
Number of Sensors per layer	80+160	108+144+180	2* to 4
Technology	Hybrid pixels	CMOS	CMOS
Trigger ?	yes	no	not foreseen
Pixel size rφ x z	≈ 50x425 µm^2	≈ 30x30 µm^2	*≈ 15x15 µm^2
Intrinsic resolution rφ / z	12 µm / 100 µm	5 µm / 5 µm	≤ 5 µm / 5 µm
Readout frequency Pb-Pb	< 3 MHz > 300 ns (SPD)	< 50-100 kHz > 20-10 µs	≈ ≥ 1 MHz* ≈ ≤ 1 µs*
Power dissipation in the pixel *matrix*	≈ 550-736 mW/cm^2 i.e. liquid cooled	~40 mW/cm^2, i.e. liquid cooled	~7 mW/cm^2, i.e. air flow

* *if CMOS with the 0.065-µm technology, instead of the current (=ITS-2) 0.180-µm*

III.5 – ITS-3 : why would you invest into it ?

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

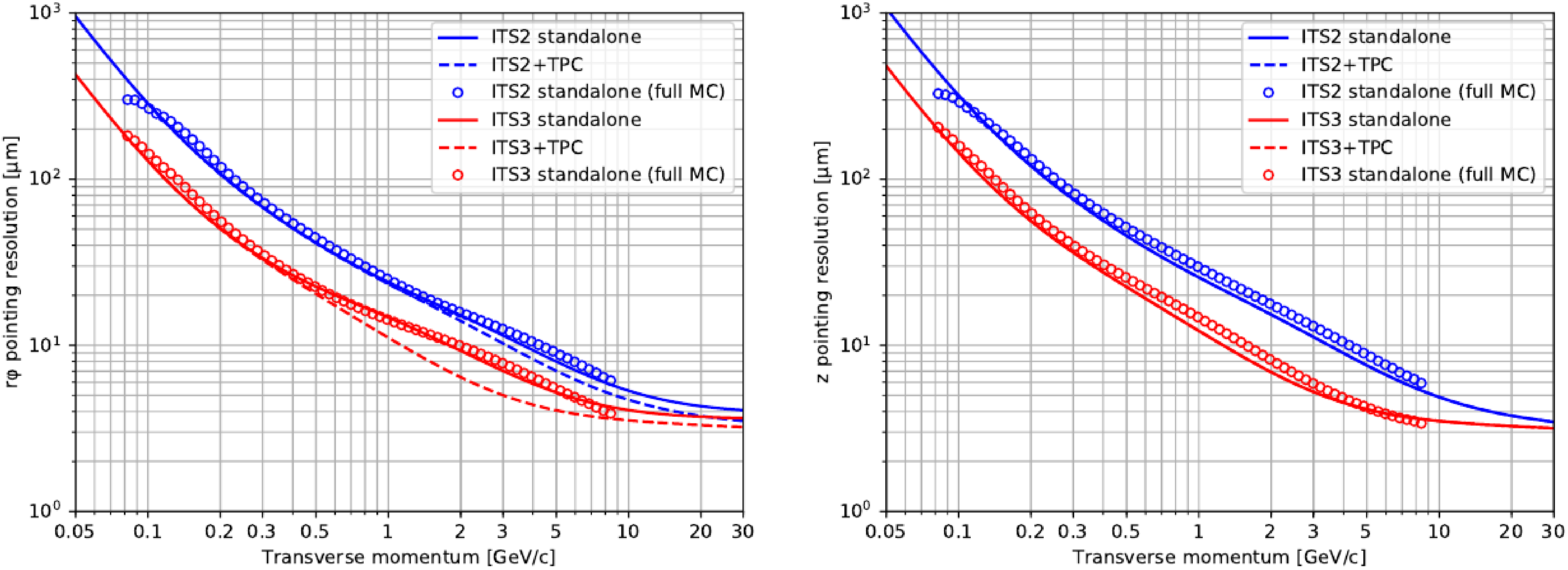


Pb-Pb 0-10% $\sqrt{s_{NN}}$ = 5.5 TeV

(Fast MC tracking tool…)

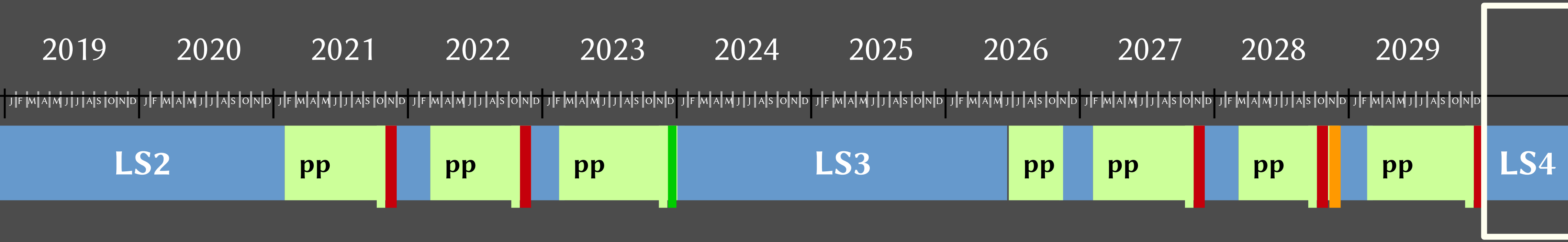
III.6 – ITS-3 : why would you invest into it ?

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



Pb-Pb 0-10% $\sqrt{s_{NN}}$ = 5.5 TeV

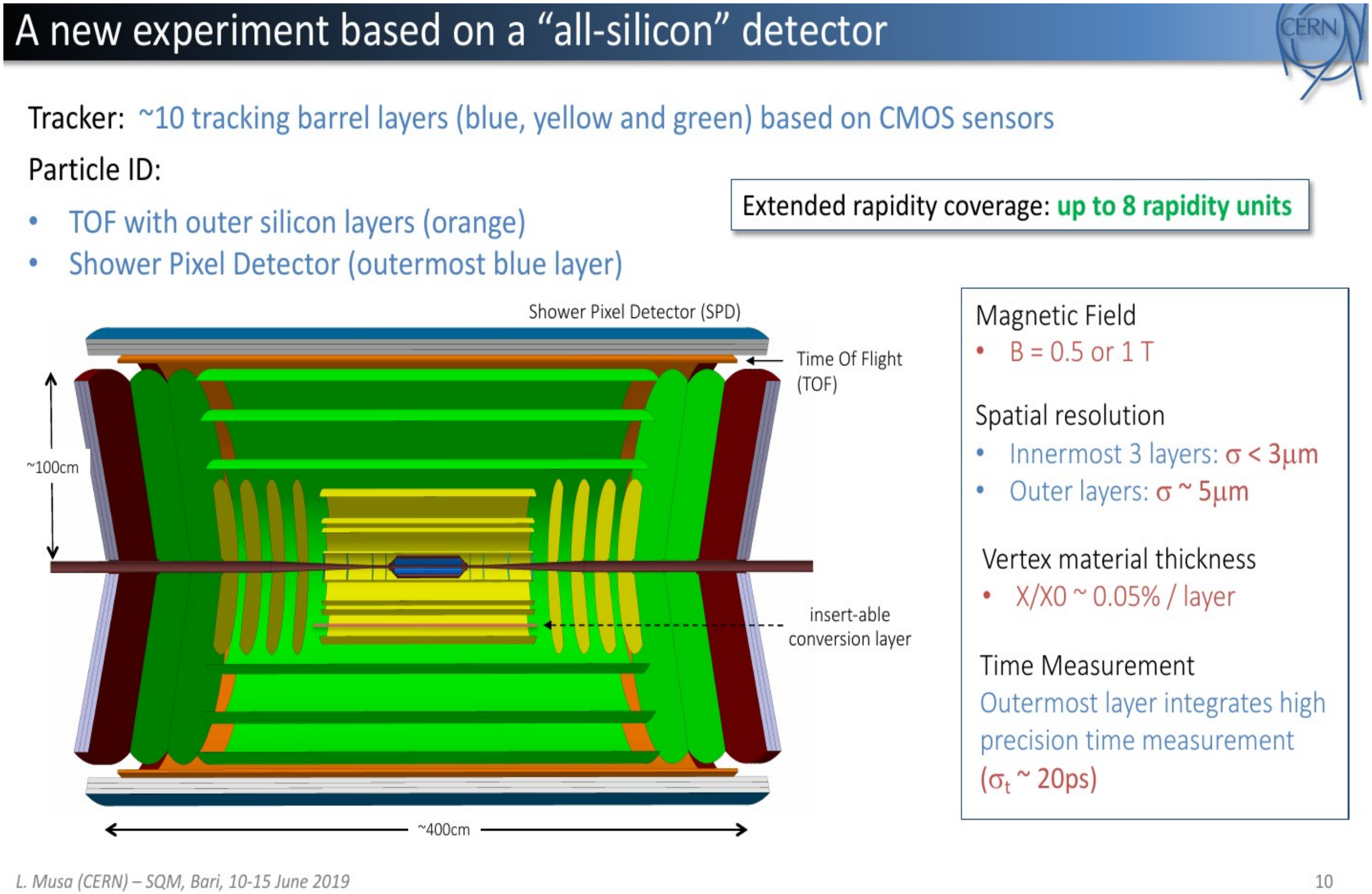
Part E – All-Si = after LS4 (≥2031, Run 5)



V.1 – All-Si : “LS4+” = “ITS4” = “ANGHIE”

EoI A Next Genreration lhc heavy-ion Experiment LS4+, arXiv:1902.01211
+ SQM 2019 L.Musa Indico.cern.ch/e/755366/c/3428151/

- Tracking over : $|\eta| < 4$ + (p_T > 30-50 MeV/c at y=0)
- space resolution ≈ < 5 μm
- $e^{\pm}$ and γ tag
  (p_T > 30-50 MeV/c)
- TOF PID



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

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

Particle ID:

- TOF with outer silicon layers (orange)
- Shower Pixel Detector (outermost blue layer)

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

Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: σ < 3μm
- Outer layers: σ ~ 5μm

Vertex material thickness
- X/X0 ~ 0.05% / layer

Time Measurement
Outermost layer integrates high precision time measurement (σ_t ~ 20ps)

L. Musa (CERN) – SQM, Bari, 10-15 June 2019

10

Conclusion

Now +10-year horizon = blur ?

→ future of QCD/QGP physics = via precision measurements for sure.

No escape.

ALICE choice : roadmap paved with LS2 upgrades (≥2021)

with a stress given to :

i) PID and low p_T ($\mathbf{0} < p_T < O(10)$ GeV/c)

ii) flavour mapping (Light/Heavy Flavours : differences ? Similarities ?)

Such a physical roadmap = proposed to be extended with ITS3 (≥2026),

in order to bridge a gap towards an all-Si experiment (≥2030)

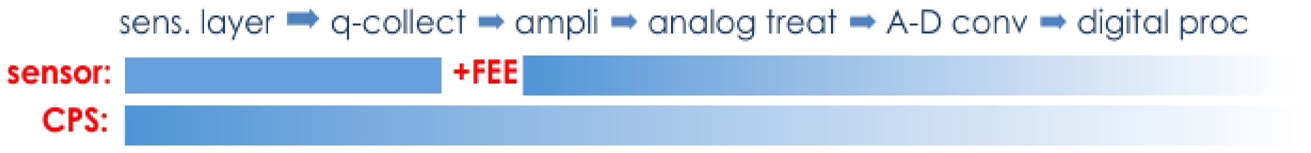
Appendices

Part A – CMOS, the basic tool

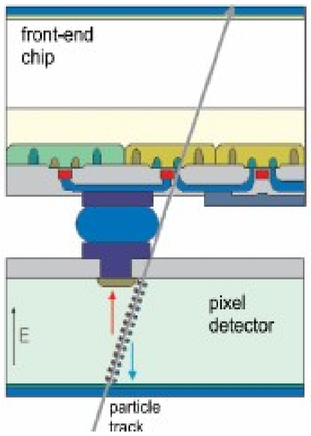
I.1 – Pixel detectors : Monolithic Active vs Hybrid techno.

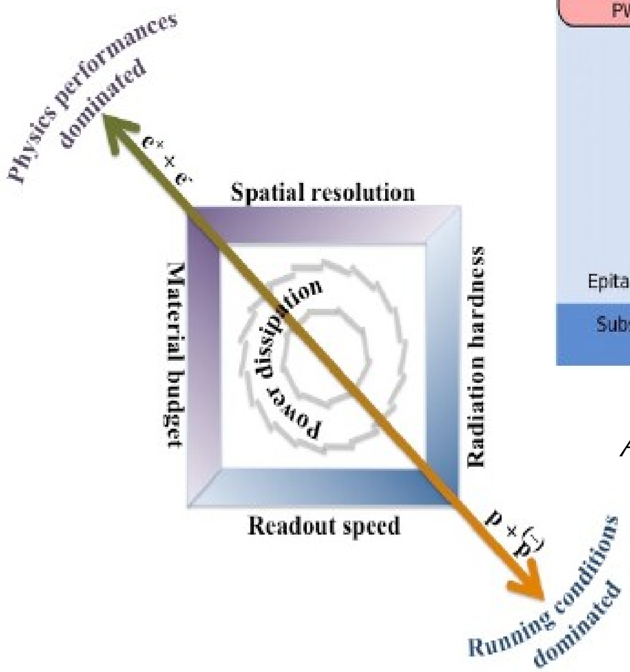
Hybrid pixel sensor →

CMOS pixel sensor →

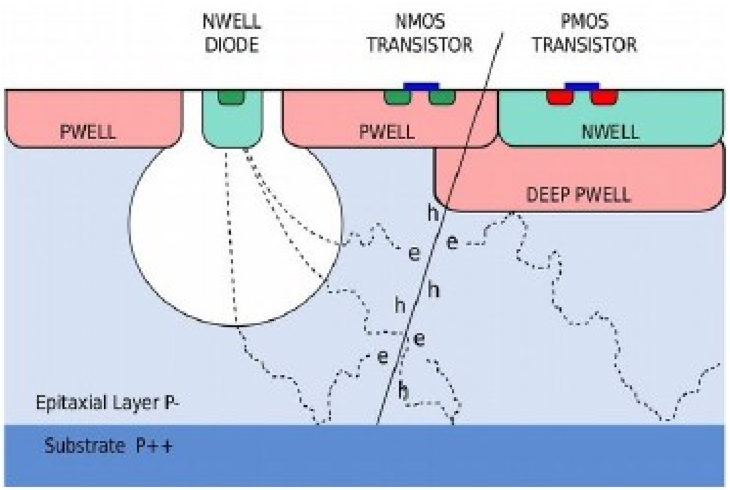


Hybrid pixel sensor





CMOS pixel sensor



Advantages :

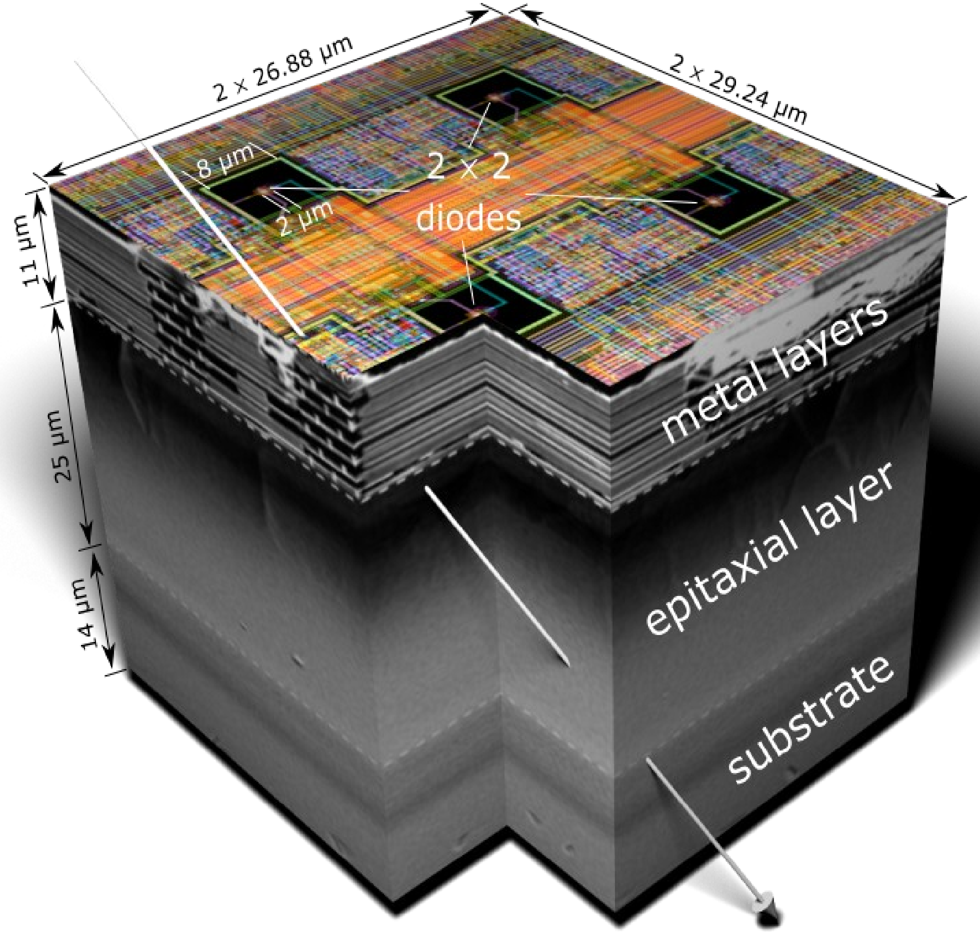
- faster readout
- better radiation-hardness
- …

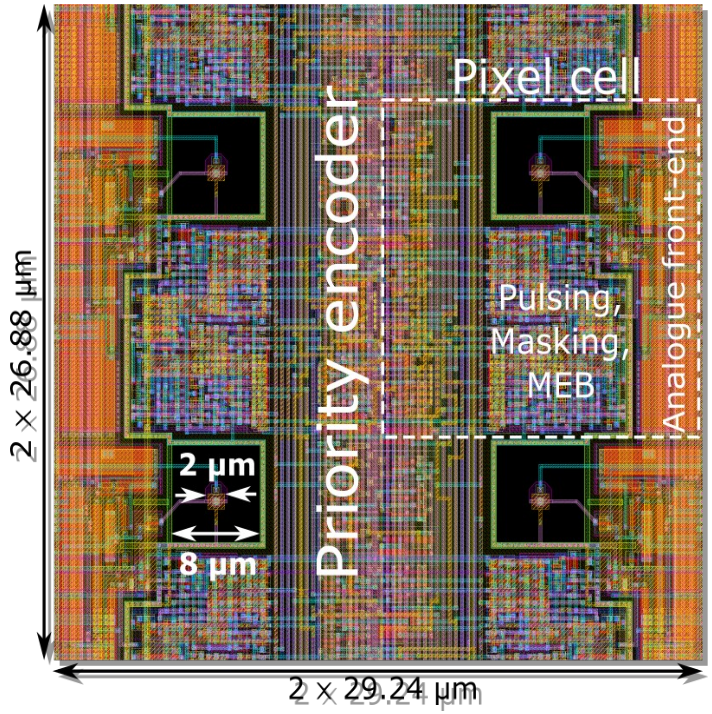
Advantages :

- thinner
- smaller pixel size accessible
- lower power consumption
- cheaper to produce
- …

I.2 – Pixel detectors : ALPIDE chip

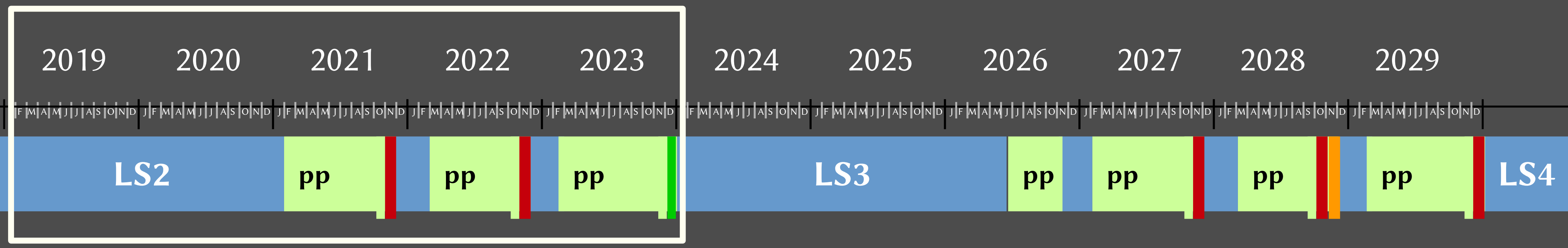
Sensor using
TowerJazz 0.18µm CMOS Imaging Process





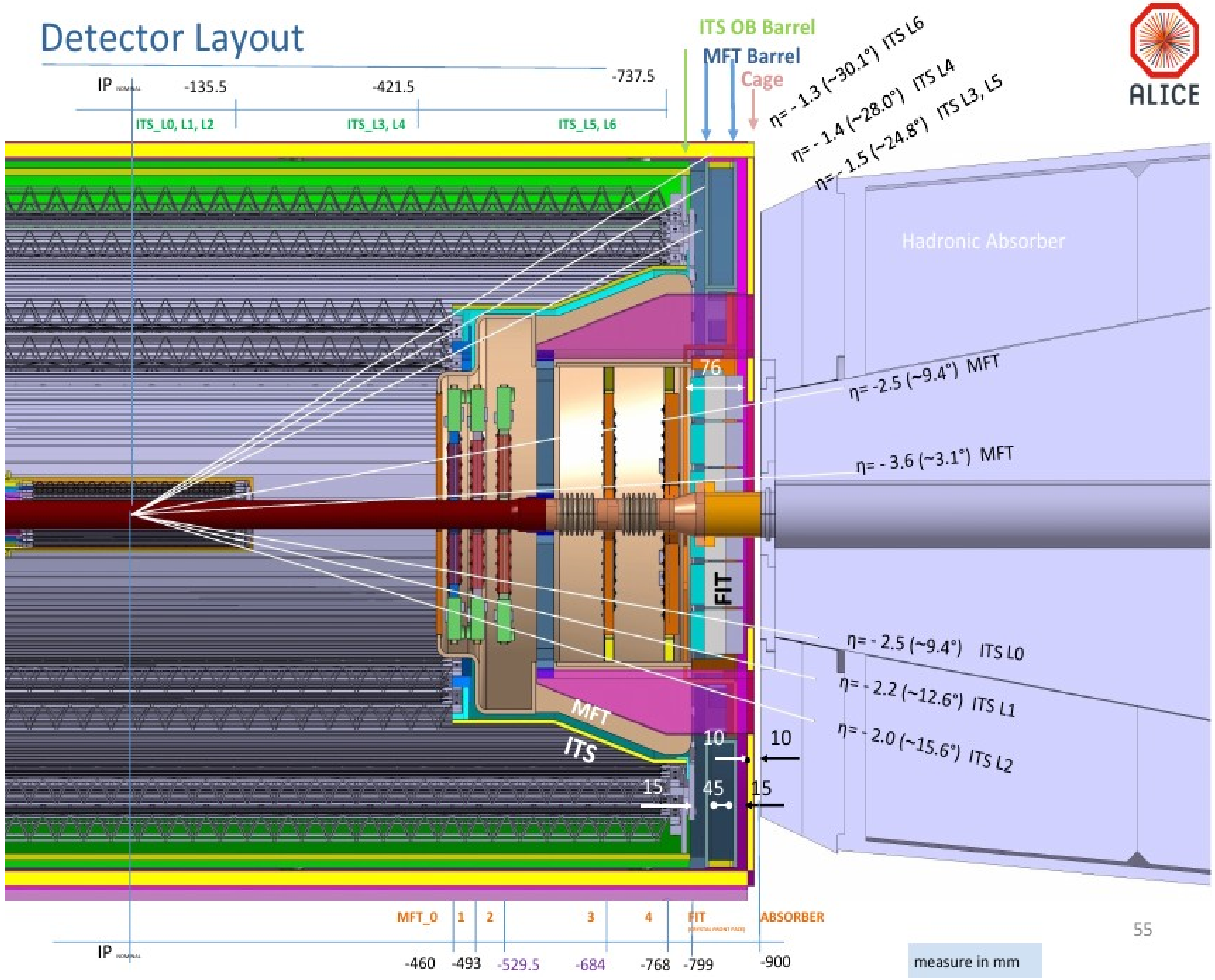
ALPIDE – 3D and 2D views of 2x2 pixels
(Here, in the 50-µm-thick version...)

Part B – ITS-2 = after LS2 (≥2021, Run 3)



LHC running plan

II.1 – ITS-2 + MFT : MAPS-based detector



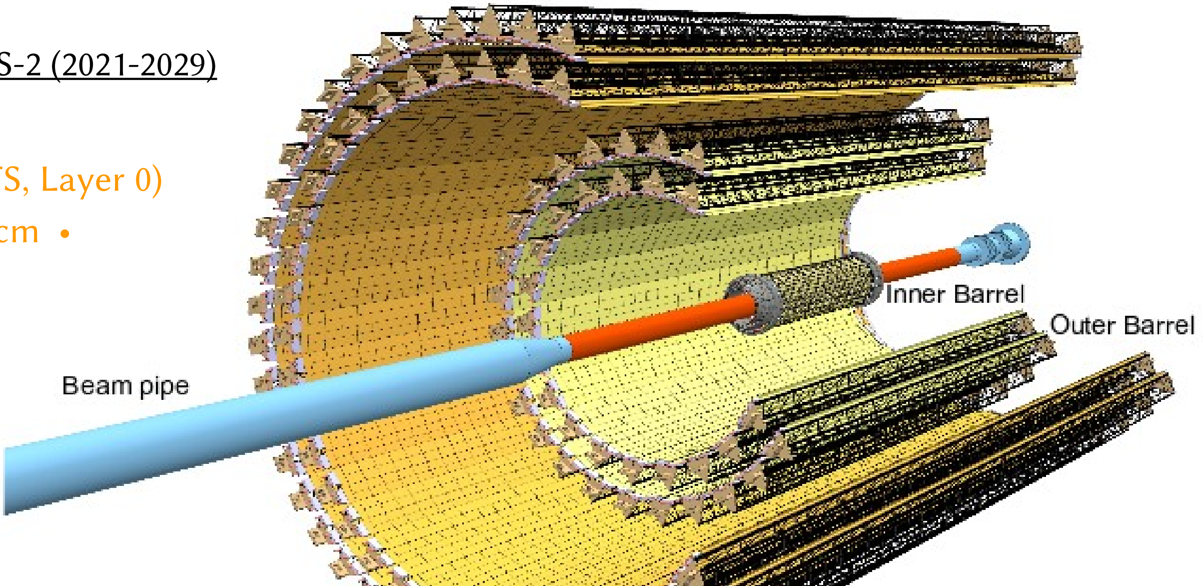
TDR ITS-2 Upgrade
- CERN-LHCC-2013-024

II.2 – ITS2 : ALICE upgrade ITS, few figures

Beam pipe : $R_{upgrade}$ 1.82 cm •

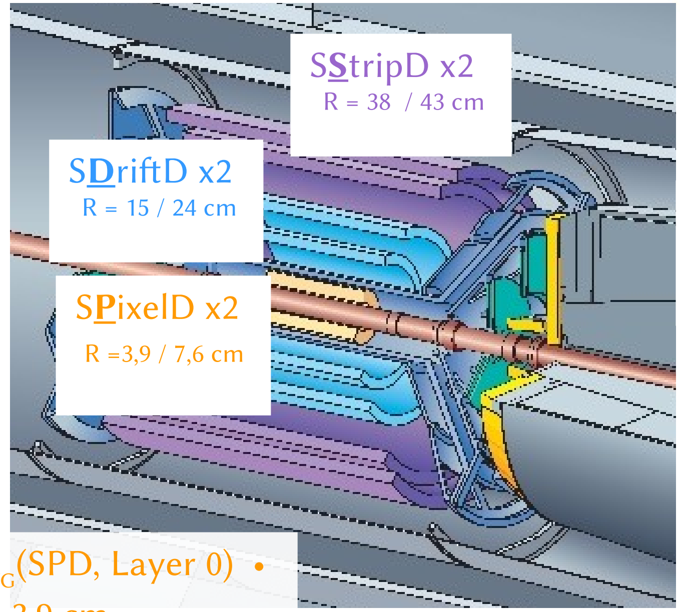
<u>ITS-2 (2021-2029)</u>

R_{AVG}(uITS, Layer 0) = 2.34cm •



- 7 pixel-only layers
- 12.6 x10^9 pixels,
- ~ 10 m² in total
- 13.6 x10^6 CHF (0.18-µm CMOS technology by TowerJazz)

<u>ITS-1 (2009-2018)</u>



SStripD x2
R = 38 / 43 cm

SDriftD x2
R = 15 / 24 cm

SPixelD x2
R =3,9 / 7,6 cm

R_{AVG}(SPD, Layer 0) • = 3.9 cm

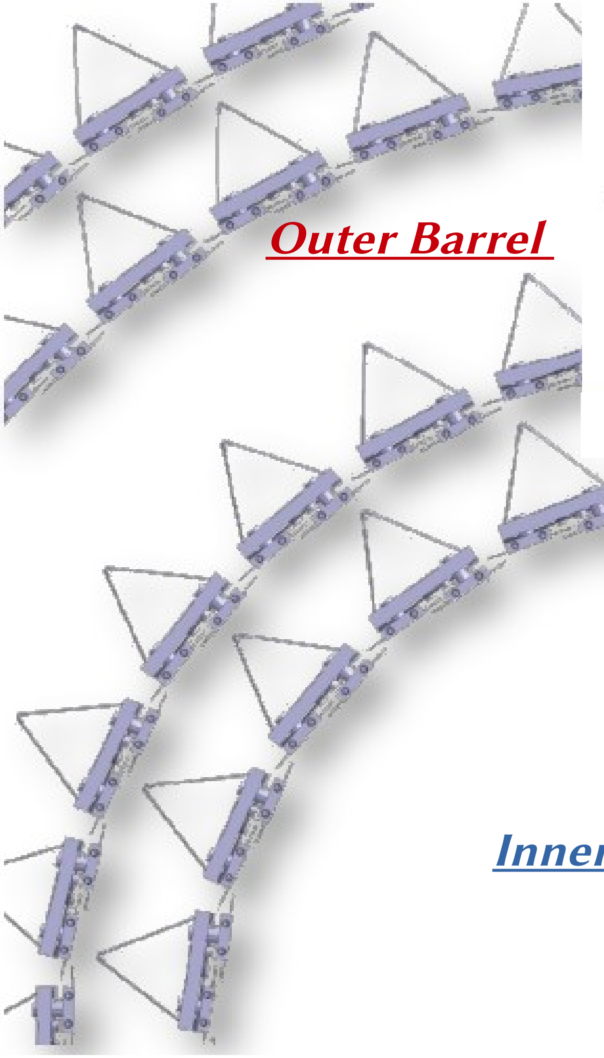
• Beam pipe : $R_{current}$ = 2.9 cm

- Chip = 1.5 x 3 cm²
- Pixel size = 29x27 µm² (current SPD : 50 x 425 µm²)

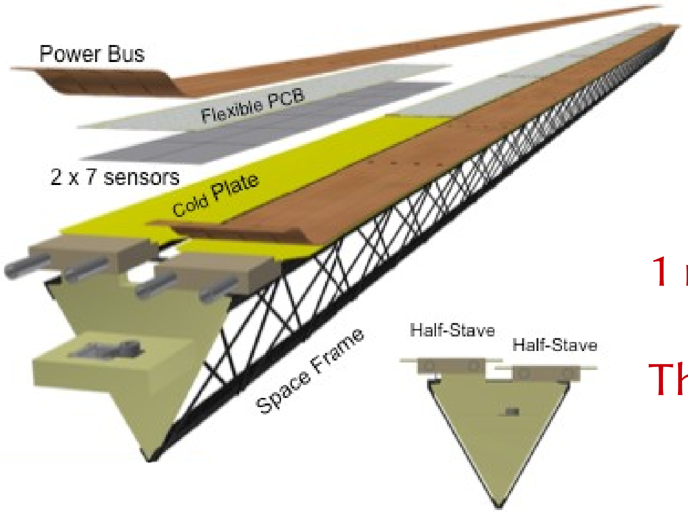
<u>Note :</u>
No d*E*/dx information, binary pixel readout "0/1"

Unlike "past" ITS-1 with SDD, SSD...

II.3 – ITS2 : “(half)-stave of modules of chips”

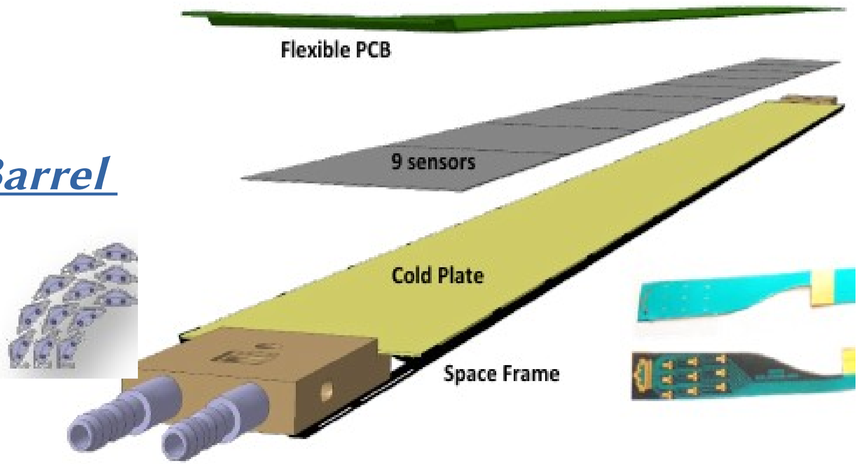


Outer Barrel



1 module = 2x7 chips
≈ 3 cm x 21 cm ,
Then, up to 7 modules to build half-stave

Inner Barrel



1 module
= 9 chips in a raw,
≈ 1.5 cm x 27 cm
directly put on stave

A.1 – Beyond LS2 : TDRs for run 3+4 detectors


ALICE

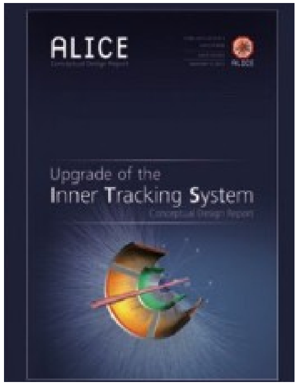
Upgrade of the
ALICE Experiment
Letter of Intent

CERN-LHCC-2012-012


ALICE

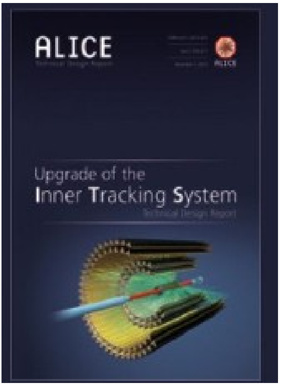
Upgrade of the
Time Projection Chamber
Technical Design Report

CERN-LHCC-2013-020


ALICE

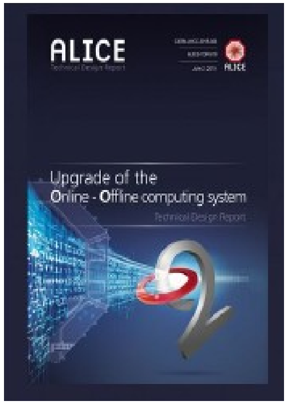
Upgrade of the
Inner Tracking System
Conceptual Design Report

CERN-LHCC-2012-005


ALICE

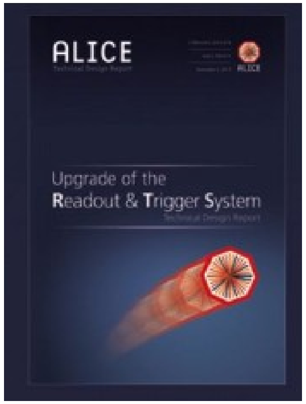
Upgrade of the
Inner Tracking System
Technical Design Report

CERN-LHCC-2013-024


ALICE

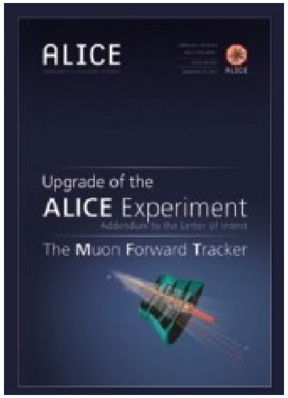
Upgrade of the
Online - Offline computing system
Technical Design Report

CERN-LHCC-2015-006


ALICE

Upgrade of the
Readout & Trigger System
Technical Design Report

CERN-LHCC-2013-019


ALICE

Upgrade of the
ALICE Experiment
Addendum to the Letter of Intent
The Muon Forward Tracker

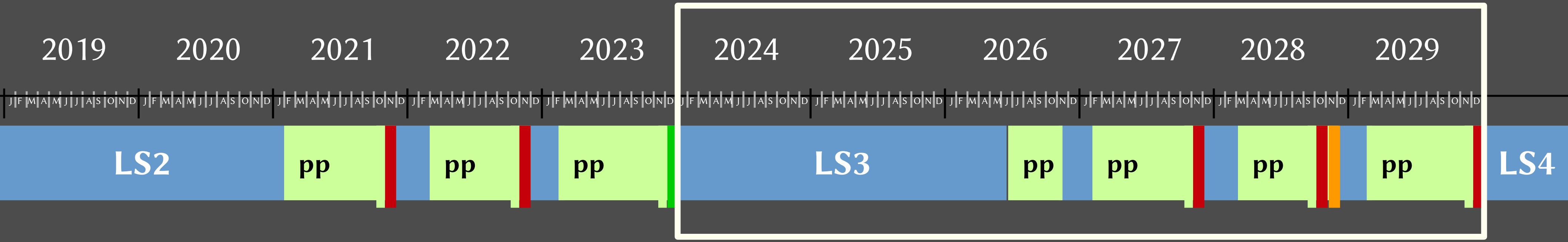
CERN-LHCC-2013-014


ALICE

Muon Forward Tracker
Technical Design Report

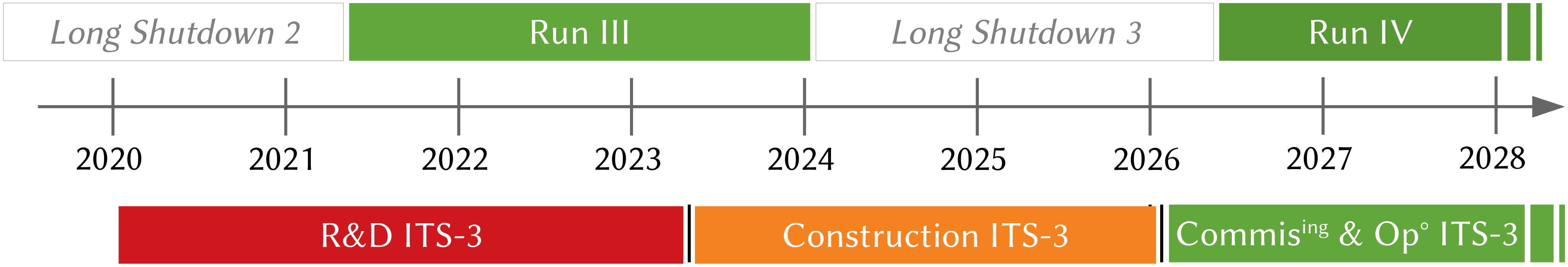
CERN-LHCC-2015-001

Part C – ITS-3 = after LS3 (≥2026, Run 4)



LHC running plan

III.4 – ITS-3 : 5.3 kCHF up to 2025



Long Shutdown 2

Run III

Long Shutdown 3

Run IV

2020 2021 2022 2023 2024 2025 2026 2027 2028

R&D ITS-3

Construction ITS-3

Commis^{ing} & Op° ITS-3

- **Wafer thinning and bending**
  2019: contact industry
  2019-20 : 1st prototype witj ALPIDE chips + wafers
  >2020 : specific prototype

- **Development of stitched sensor**
  2019-20 : technology test structures
  2020-22 : prototyping chips
  2022-23 : full-scale prototype + final chip

  → *Tech. Design Report + Physics Perf* = 2022

- **Construction** : 2024-25 = 3x2x2 sensors

Table 8: Project cost estimate breakdown (kCHF).

Item	R&D	Construction	Total Cost
Total	≈ 35% 1900	3400	5300
Beampipe	600	900	1500 ≈ 28%
Pixel CMOS sensors	600	800	1400
Sensor test	100	150	250
Thinning & bending	200	300	500
Hybrid printed circuit	100	100	200
Mechanics	150	350	500
Assembly & test	50	200	250
Installation & alignment	0	200	200
Air cooling	100	150	250
Services	0	100	100
Patch panels	0	150	150

LHCc 2019-06 ALICE, M.Mager ITS3

Part D – why physics with low p_T ?

LHC running plan

IV.2 – ITS*n* : admittedly… but, in more concrete terms, “why” ?

ALICE :

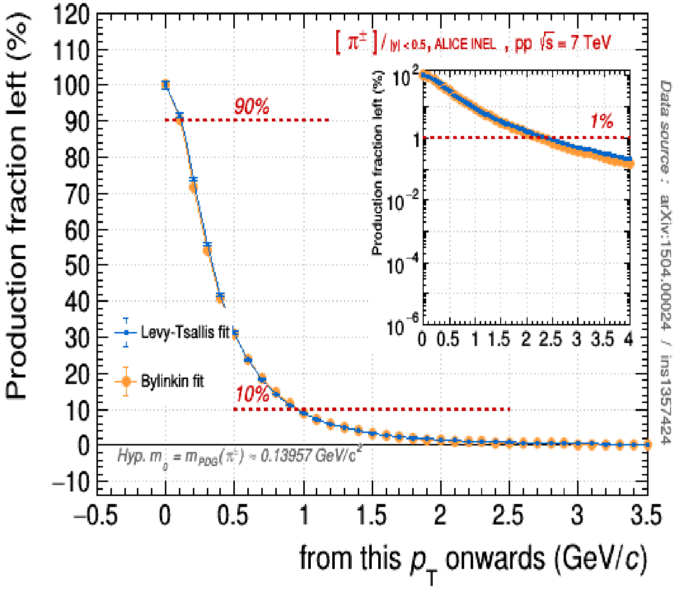
- for “low p_T charmed hadrons and baryons (Λ_C^+ to Ω_{CCC}^{++})”
- for “thermal radiation by the QGP via vitual photons (low-mass e^+e^- $m_{ee} < 2$ GeV/c)” !

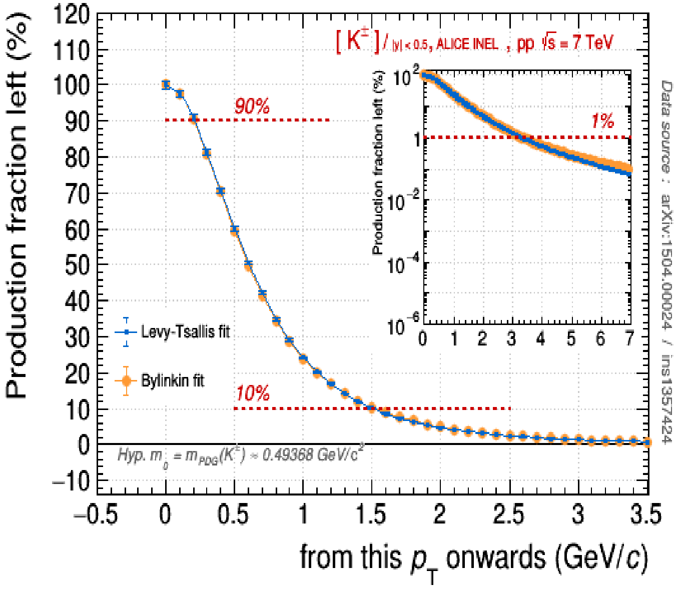
(Wo)man on the HEP street : “Seriously, that’s your physics case to be sold ?!”

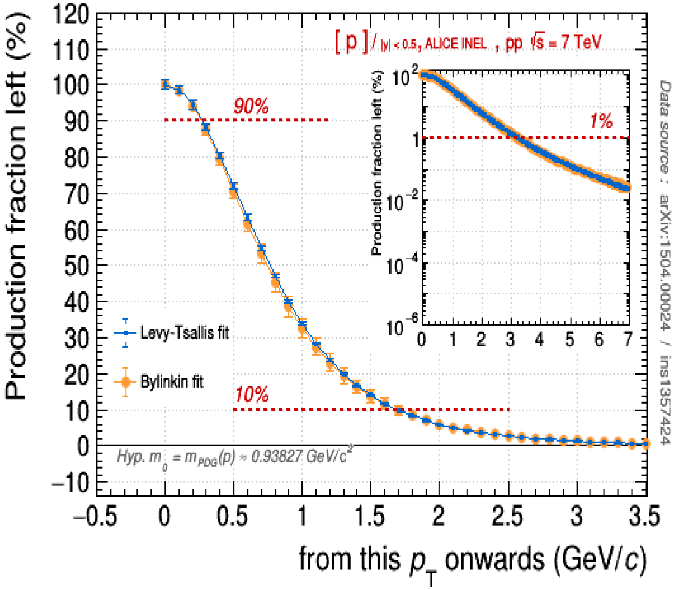
⟶ Consider them as <u>litmus tests</u> :
if one is able to do those two type of measurements,
then you can do many things on top of that.

= Focus given to “<u>ultra low p_T</u>” detection threshold (≥ 20-50 MeV/*c*),
i.e. push the logic of “scrutinise what is yet abundant” far to the end
in contrast to CMS/ATLAS strategy to fight for the “unseen/rarity”

IV.3 – ITS*n* : why low p_T ? Simple examples of π,K,p





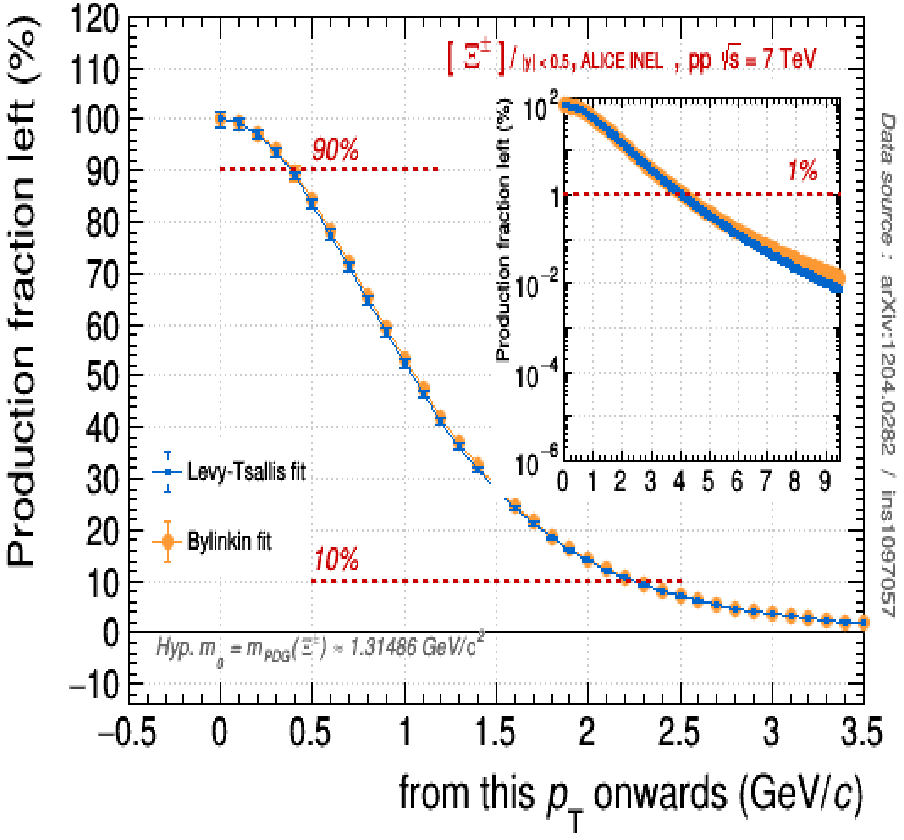


If your $\pi^+(u\bar{d})$ / $K^+(u\bar{s})$ / p(*uud*) measurements start above 0.0, 0.1, 0.2 … GeV/c,
you miss *x*% of the total d*N*/d*y* in pp.

For a given particle type of interest,
can you claim a “precision measurement” if you indeed miss *x*% of production ?
⟶ yes or no ? to be decided, case by case, but…

NB : ALICE arXiv:1504.0024 = $h^\pm > 0.15$ GeV/*c* // $\pi^\pm > 0.1$ GeV/*c* / $K^\pm > 0.2$ GeV/*c*, p > 0.3 GeV/*c*…

IV.4 – ITS*n* : why low p_T ? Example $\Xi^\pm$



If your Ξ^-(*dss*) measurement starts

above 0.0 GeV/c, you miss 0%

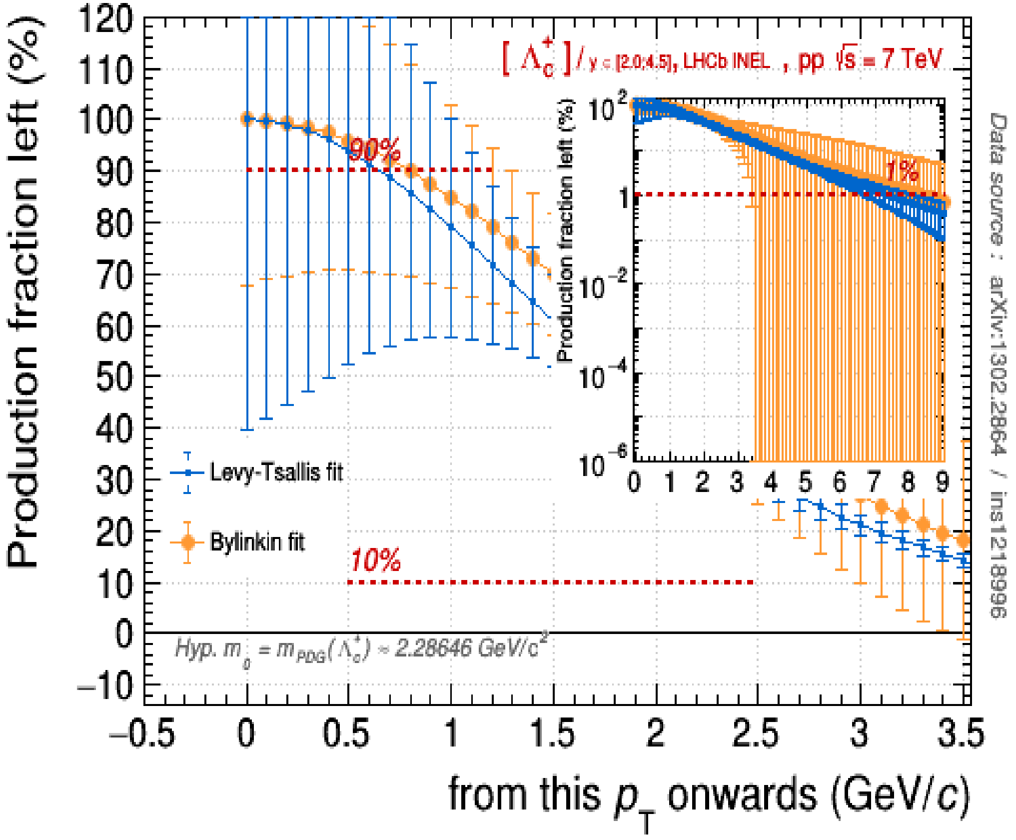
above 0.6 GeV/c, you miss ≈ 23%

above 1.2 GeV/c, you miss ≈ 45%

… of the total d*N*/d*y* in pp

NB :
ALICE arXiv:1204.0282, pp 7 TeV |y| < 0.5, Ξ > 0.6 GeV/*c*

IV.5 – ITS*n* : why low p_T ? Example of Λ_C^+

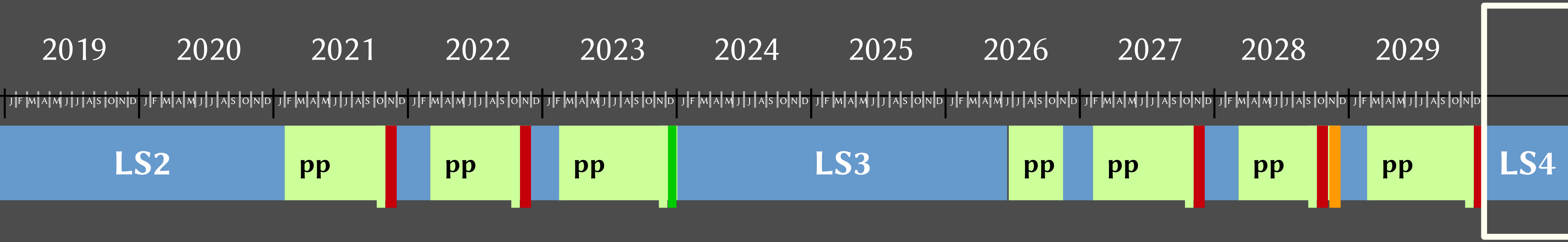


If your Λ_C^+(*udc*) measurement starts above 0.0 / 1.0 / 2.0 GeV/c,
you miss x% of the total d*N*/d*y* in pp

NB :

LHCb pp arXiv:1302.2864, $\Lambda_C^+ > 0.0$ GeV/c
ALICE pp arXiv:1712.09581, $\Lambda_C^+ > 1.0$ GeV/c

Part E – All-Si = after LS4 (≥2031, Run 5)



B.1 – ANGHIE : In2p3 prospectives, GT03 contribution

	ITS-2 [3]	ITS-3 [6]	ANGHIE [8]
Période LHC	Run III + IV (2021-29)	Run IV (2026-29)	≥ Run V (>2030)
Nombres de couches	3+*4*	3 (*+4 ITS-2*)	*O*(3+*7*)
R_{tube}	1,82 cm	1,6 cm	1,6 ou $2{,}9^2$
r_{L0} / r_{L1} / r_{L2} … r_{Last} (cm)	2,3 / 3,2 / 3,9 … *39,3*	1,8 / 2,4 / 3,0 … *39,3*	1,8 / … ≈ *100*
Champ magnétique $B_{\text{solénoïde}}$	0,2 ou 0,5 T	0,2 ou 0,5 T	0,2 à 1 T
Matière par couche (x/X_0)	0,3 % à *0,8 %*	0,07 % à *0,8 %*	0,05 % à *0,5 %*
Taille d'un pixel (μm^2)	≈ 30 x 30	≈15 x 15 (+ *30* x *30*)	≈10 x 10 (+ *30* x *30*)
Résolution temporelle	≥ 2-5 µs	2-5 µs	≤ 1 µs
Résolution spatiale	5 µm	5 µm	≈ 3-5 µm
Couverture en η	|η| < 2,0 à *1,3*	|η| < 2,0 à *1,3*	|η| < 4,0
$\varepsilon_{tracking}(p_T(h^{\pm})=X\ GeV/c)$	1 0,1 0,05	1 0,1 0,05	1 0,1 0,05
	98 % 60 % 10 %	98 % 75 % 20 %	98 % 75 % 20 %
Coûts totaux (R&D + Constr.)	≈ 10 MCHF	5,3 MCHF	≈ 80-100 MCHF
Nb d'instituts / Nb de pays	30 / 16	30 / 16	(>399 signataires)✋

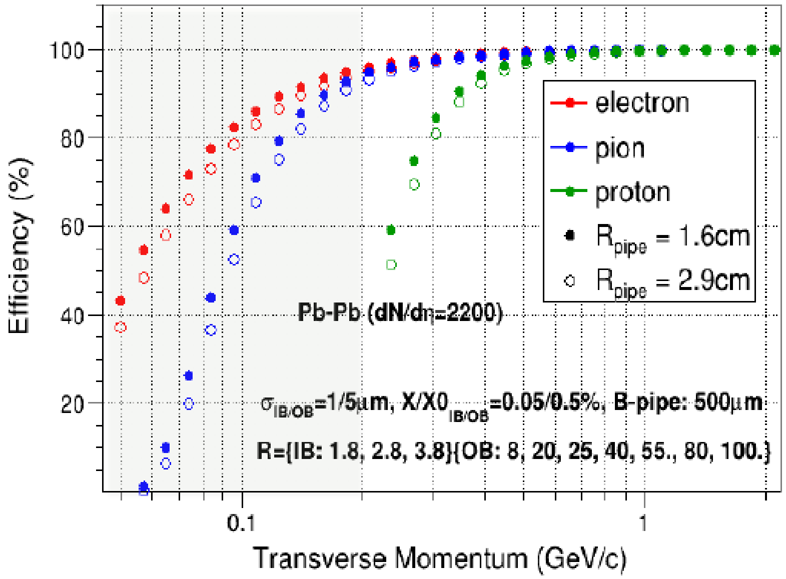
SQM 2019 L.Musa Indico.cern.ch/e/755366/c/3428151/

B.2 – ANGHIE : tracking efficiencies

Operation at reduced B field for tracking low p_T particles

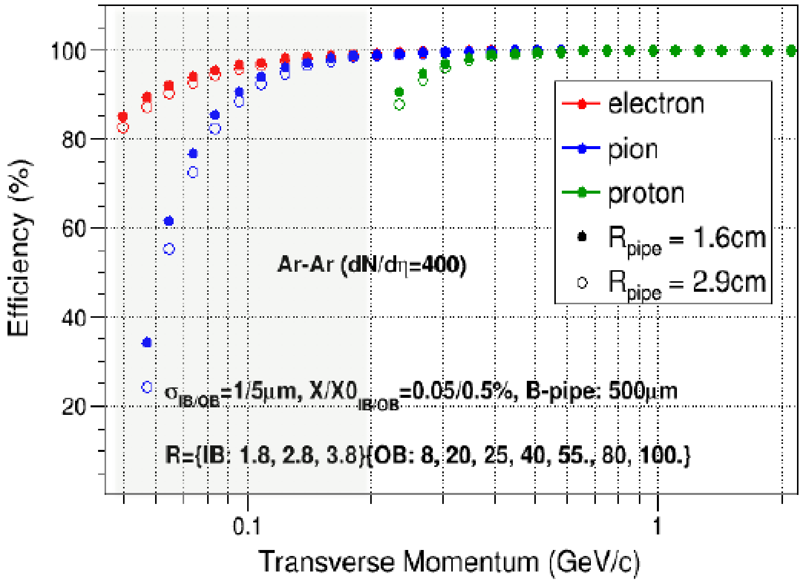
Pb-Pb (dN/dη = 2200), B = 0.2 Tesla

R. Shahoyan - 2018



dN/dη = 440, B = 0.2 Tesla

R. Shahoyan - 2018



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

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

⇨ improvement for lower dN/dη

Further layout optimization possible!

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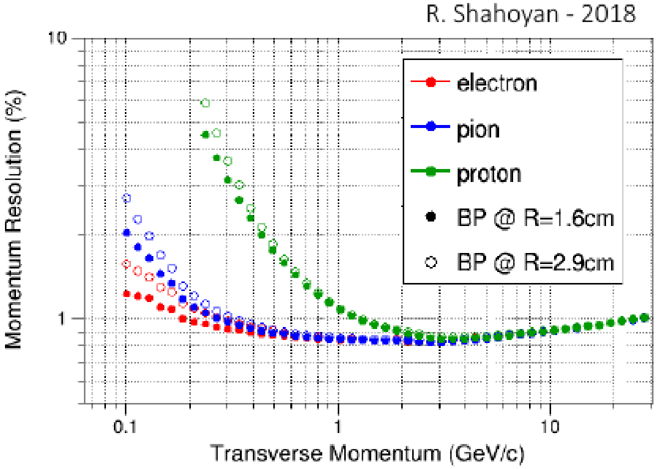
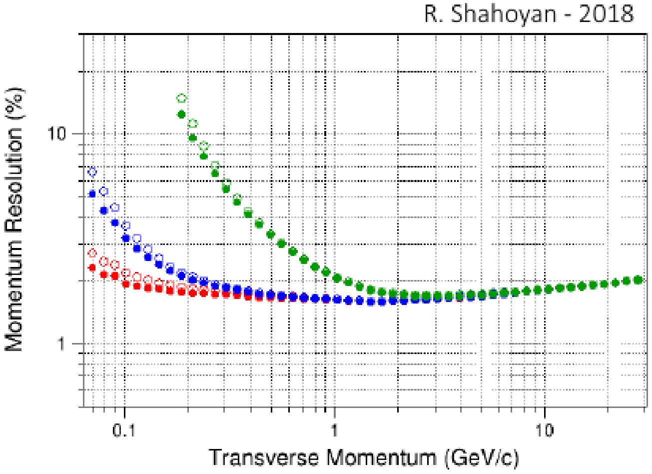
B.3 – ANGHIE : momentum resolution

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

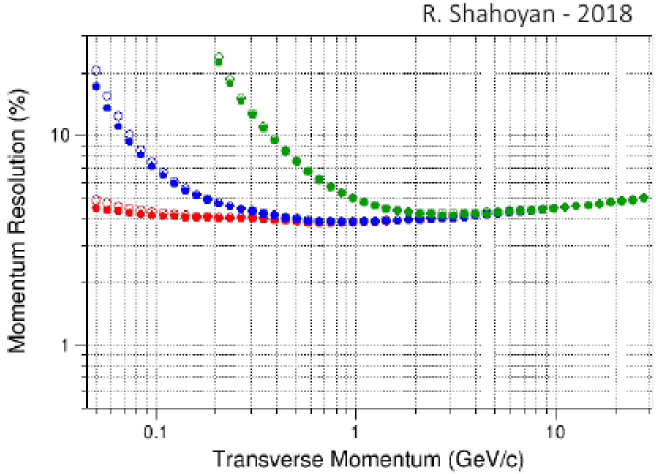
B = 1 T



B = 0.5 T

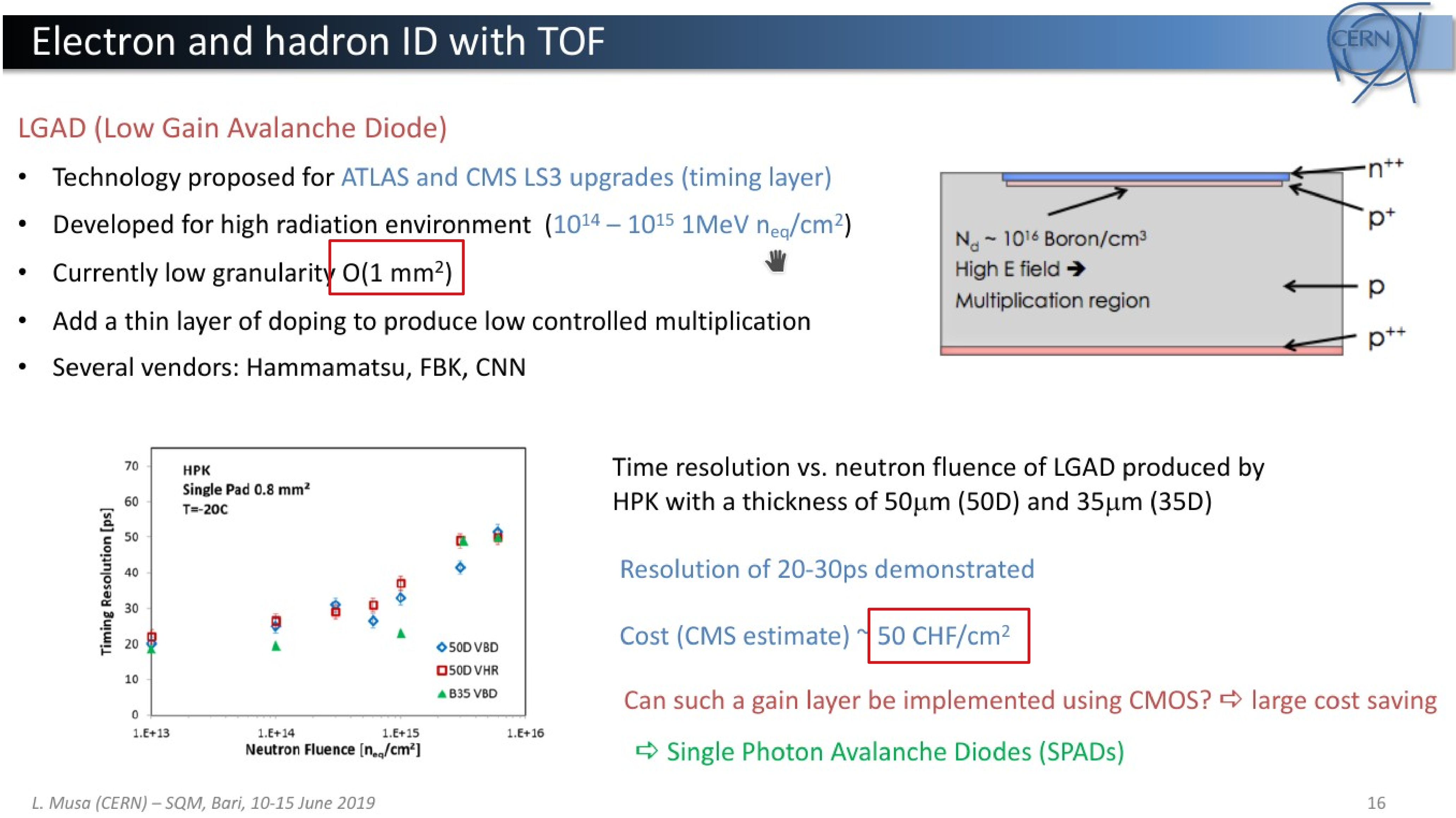


B = 0.2 T



momentum resolution for 1GeV/c pions: ≈ 0.8% (1 T), ≈1.6% (0.5 T), ≈ 4% (0.2 T)

B.4 – ANGHIE : Particle Identification



Electron and hadron ID with TOF

LGAD (Low Gain Avalanche Diode)

- Technology proposed for ATLAS and CMS LS3 upgrades (timing layer)
- Developed for high radiation environment (10^{14} – 10^{15} 1MeV n_{eq}/cm^2)
- Currently low granularity O(1 mm^2)
- Add a thin layer of doping to produce low controlled multiplication
- Several vendors: Hammamatsu, FBK, CNN

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

Resolution of 20-30ps demonstrated

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

Can such a gain layer be implemented using CMOS? ➪ large cost saving

➪ Single Photon Avalanche Diodes (SPADs)

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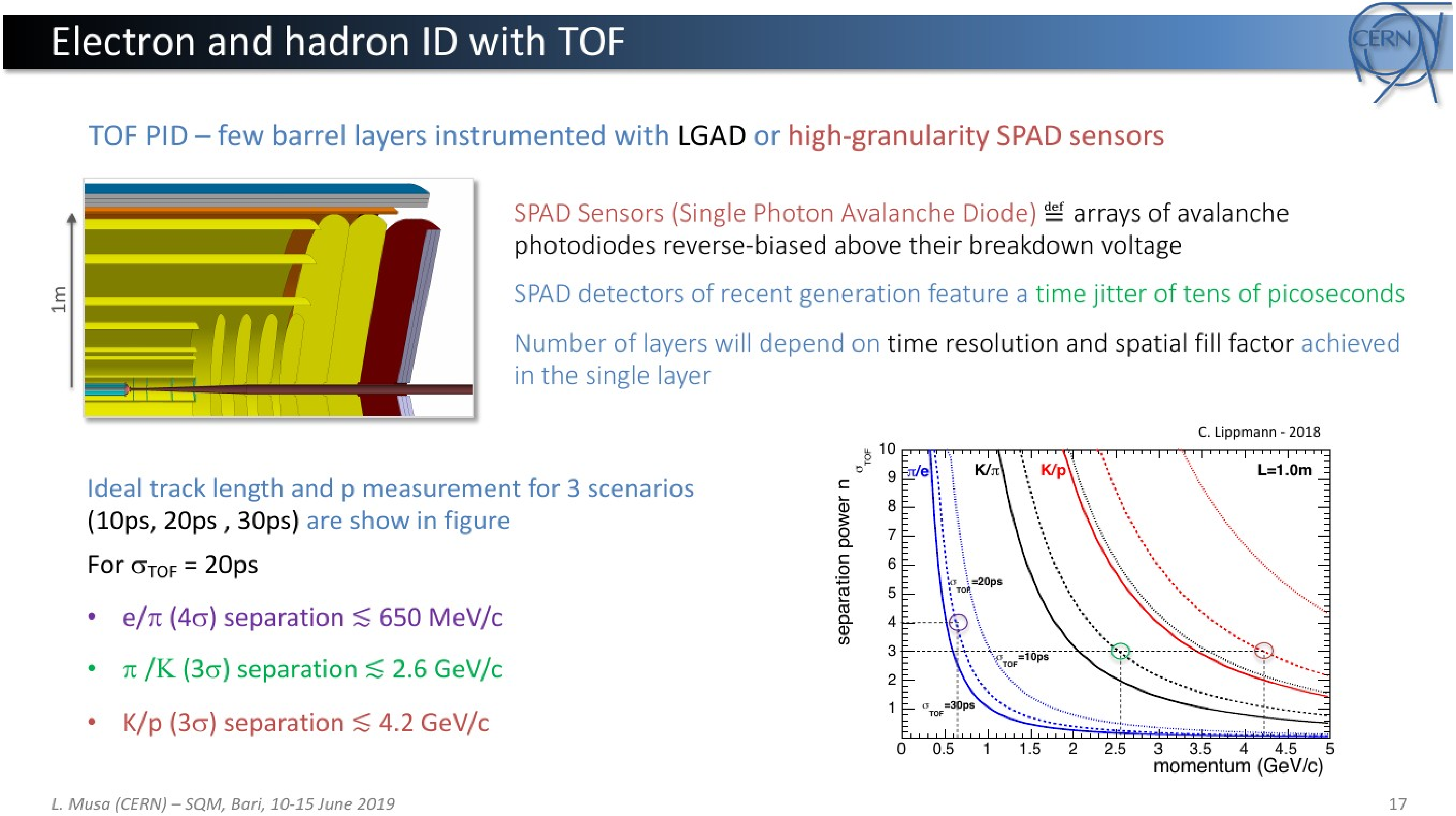
B.5 – ANGHIE : TOF



Electron and hadron ID with TOF

TOF PID – few barrel layers instrumented with LGAD or high-granularity SPAD sensors

SPAD Sensors (Single Photon Avalanche Diode) $\overset{\text{def}}{=}$ arrays of avalanche photodiodes reverse-biased above their breakdown voltage

SPAD detectors of recent generation feature a time jitter of tens of picoseconds

Number of layers will depend on time resolution and spatial fill factor achieved in the single layer

Ideal track length and p measurement for 3 scenarios (10ps, 20ps , 30ps) are show in figure

For σ_{TOF} = 20ps

- e/π (4σ) separation ≲ 650 MeV/c
- π /K (3σ) separation ≲ 2.6 GeV/c
- K/p (3σ) separation ≲ 4.2 GeV/c

C. Lippmann - 2018

L. Musa (CERN) – SQM, Bari, 10-15 June 2019

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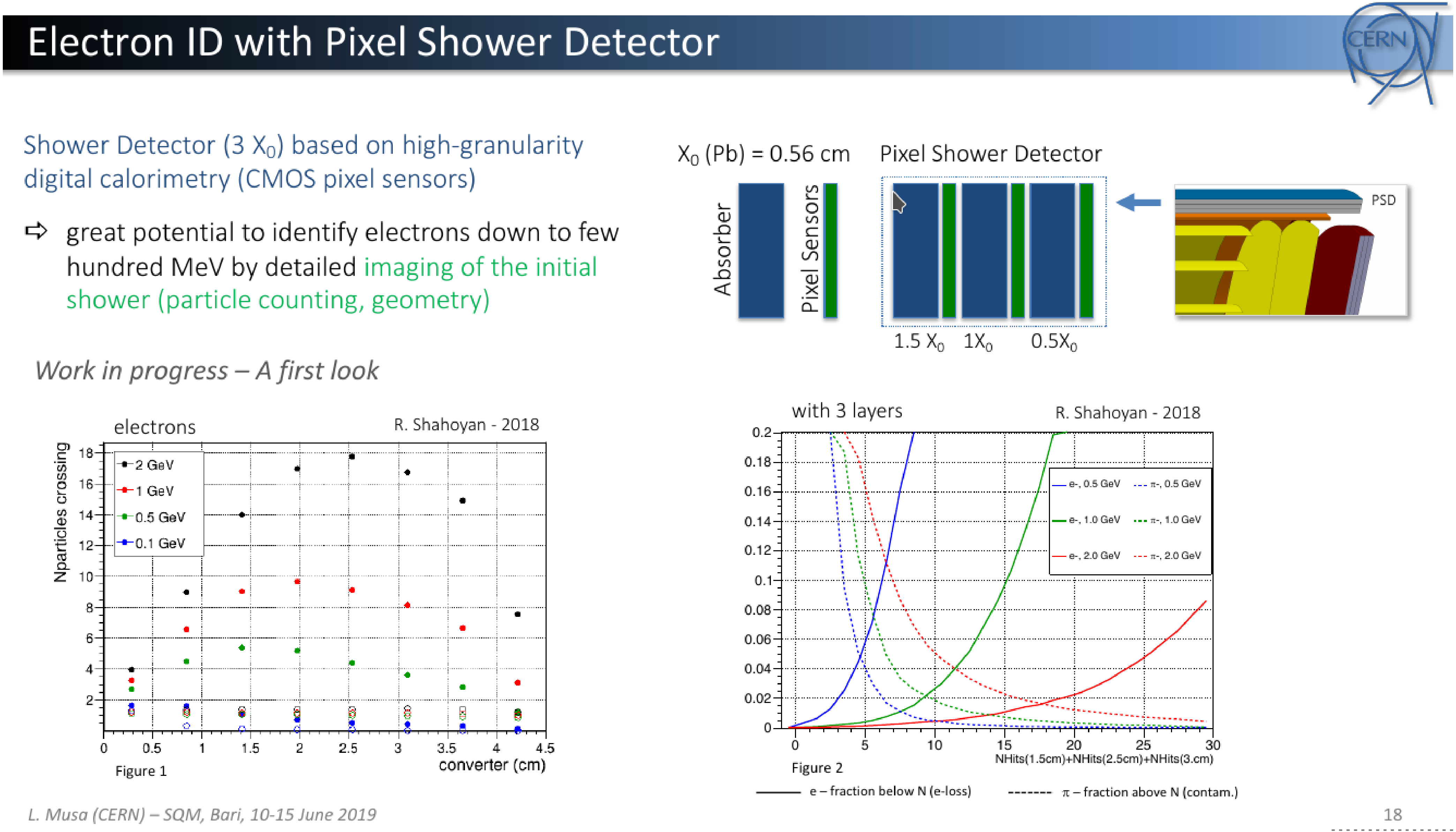
B.6 – ANGHIE : electron pre-shower, PSD…



Electron ID with Pixel Shower Detector

Shower Detector (3 X_0) based on high-granularity digital calorimetry (CMOS pixel sensors)

⇨ great potential to identify electrons down to few hundred MeV by detailed imaging of the initial shower (particle counting, geometry)

Work in progress – A first look

Figure 1

Figure 2

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C.2 – CMS : LHC alternative options possibly on the table

In Run 4+5, after LS3, beware CMS opportunities...

a) tracking on very large η coverage as well ($|\eta| < 4$)

CMS tracker, CERN-LHCC-2017-009

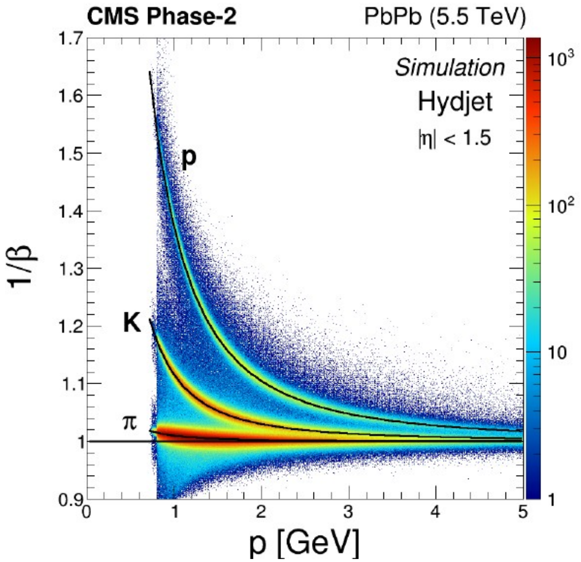
b) unique calorimetry ($PbWO_4$ EmCal + HGCal SiPM sampling)

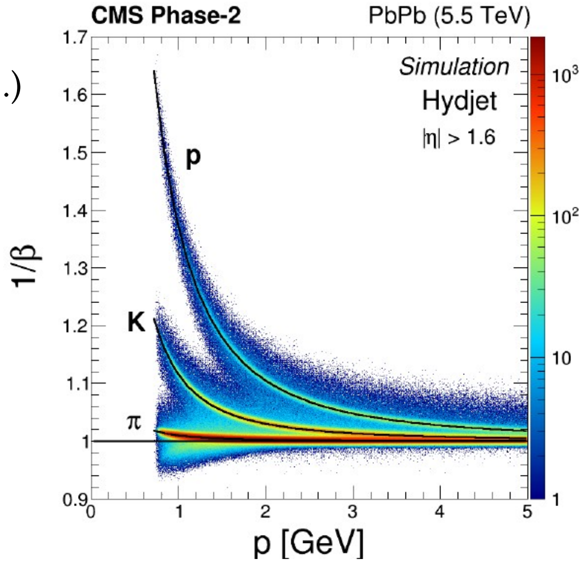
CMS HGCal, CERN-LHCC-2017-023

c) MTD = pile-up tagger + TOF ...

CMS MTD = "pile-up tagger", Fig 1.5 + Fig 5.23 - TDR CERN-LHCC-2019-003

(LGAD in endcap or SiPM in barrel ⟶ $\sigma_{\text{time stamp}} \approx 30$ ps),





NB : all this, really expensive (quite more than the All-Si exp...), but ~funded already (112 MCHF tracker, 67 MCHF HGCal, 21 MCHF MTD, DAQ 12 MCHF ...)

⟶ Could all this be ~bearable (?) for "low-p_T" purpose ?

(*i*) in any (?) or at least low pile-up condition (NB : TOF in Pb-Pb = ok !)

(*ii*) preferentially with moderate B field,

(*iii*) given material budget in the tracker

(phase-2 ≈ 30-40% X/X° as currently at $|\eta| < 1$ + improved at $|\eta| > 1.5$. See Fig 6.2 +12.1)

⟶ Decisive but open questions :

- influence of pile-up (pp) / running time negociated within CMS in (very) low pile-up ?
- running with (B field < 3.8 T) Vs max. number of hysteresis cycles authorised for the CMS magnet ?

SQM 2019 L.Musa Indico.cern.ch/e/755366/c/3428151/

C.3 – CMS : MTD aging

Fig B.10 - TDR CERN-LHCC-2019-003

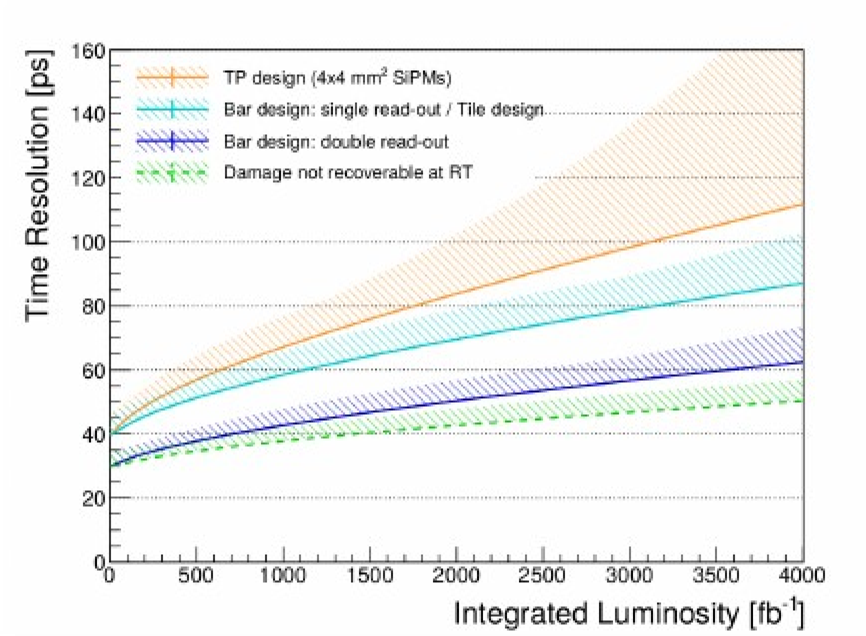


Figure B.10: Expected time resolution as a function of integrated luminosity for the TP reference design (orange); the TDR bar design from single-ended and tile design (light blue); the TDR reference design with crystal bars combining double-ended readout (blue); and the TDR reference design assuming all damage recoverable at room temperature (RT) is annealed. The bands show the expected performance for different sets of SiPM parameters.

D.1 – LHCb : LHC alternative options possibly on the table

In Run 5, beware LHCb opportunities…

LHCb, EoI upgrade LS4, arXiv:1808.08865

a) Profiting from boost for forward geometry,
→ LHCb will remain a serial heavy-flavour tagger…
Sitting forward makes life easier than at mid-rapidity in that respect

b) Readout/tracking/PID capabilities likely to work by then
in all systems (pp, p-O, Ar-Ar, Xe-Xe, …)
and under any event activity (Pb-Pb 0-5%)…