LHCb Heavy Ion and tracking upgrades

Contributions possibles du LLR à l'**upgrade II** de **LHCb**

F~ramework~ T~echnical~ D~esign~ R~eport~ : automne **2021**

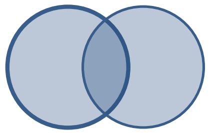
T~echnical~ D~esign~ R~eport~ : ~2024 – 2025

Installation (LS3): ~2031 – **2032**

fleuret@in2p3.fr

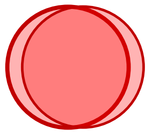
Current tracking limitation in Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV – 2015 data

Low Ecal Energy



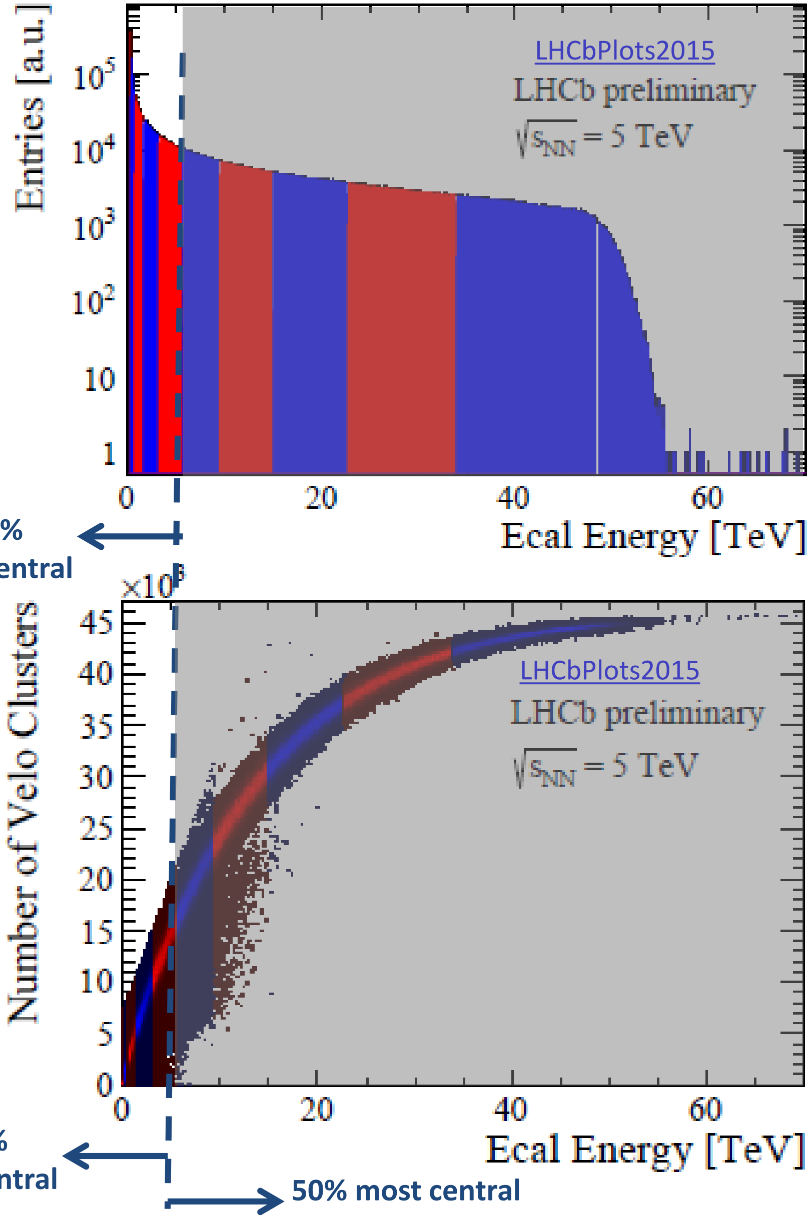
peripheral

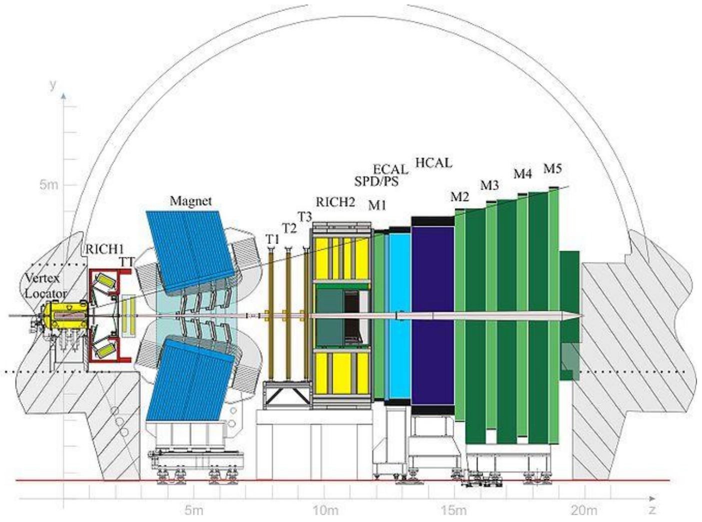
High Ecal Energy



central

- **LHCb centrality reach**
  - Detector limitation due to high occupancy in Pb-Pb collisions
  - No saturation of the calorimeter
  - But, saturation in the Vertex Locator (VELO)





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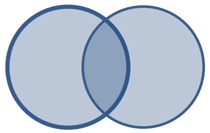
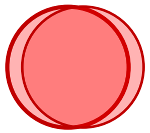


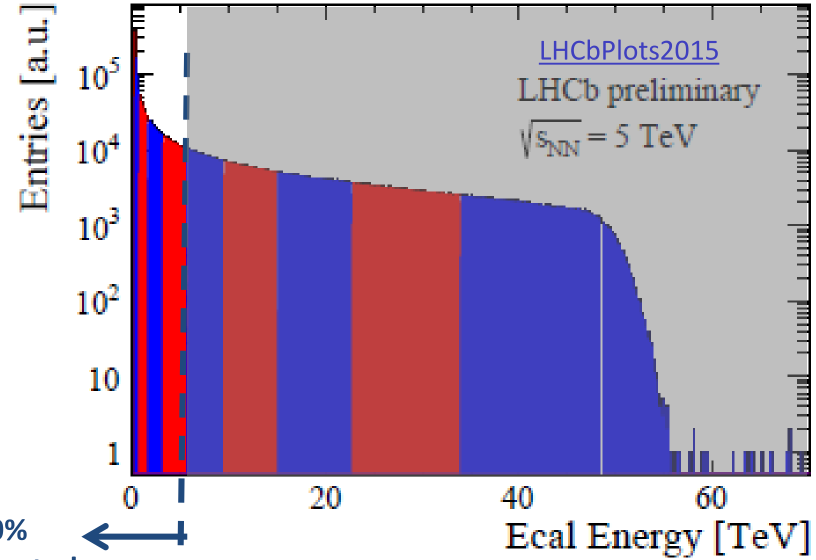
peripheral

High Ecal Energy

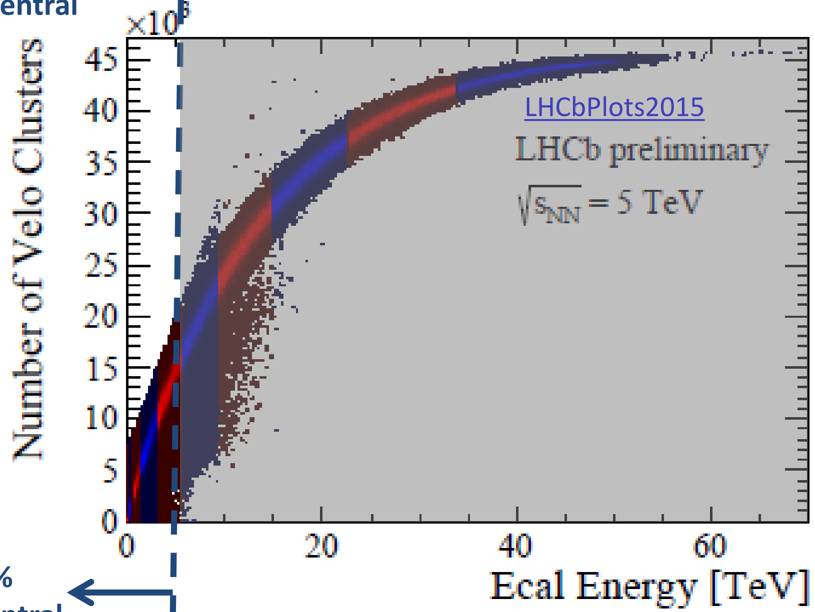


central

- **LHCb centrality reach**
  - Detector limitation due to high occupancy in Pb-Pb collisions
  - No saturation of the calorimeter
  - But, saturation in the Vertex Locator (VELO)
- **LHCb current limitations**
  - Current tracking algorithm efficient up to 50% most central
  - **Physics studies limited to 50% less central events**

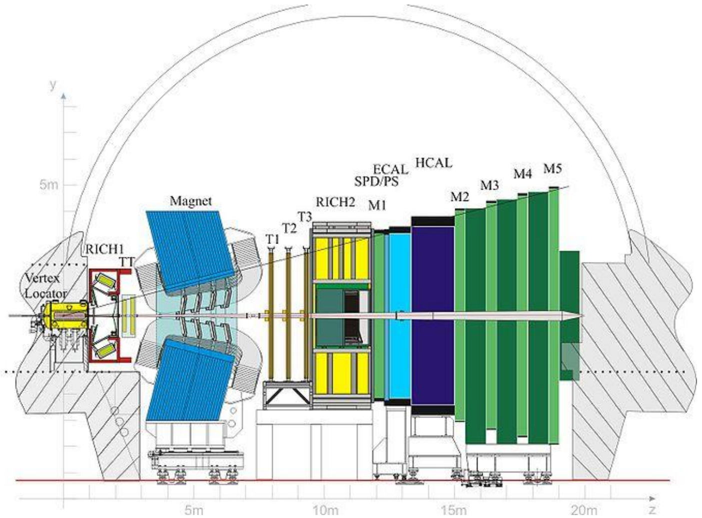


50% less central

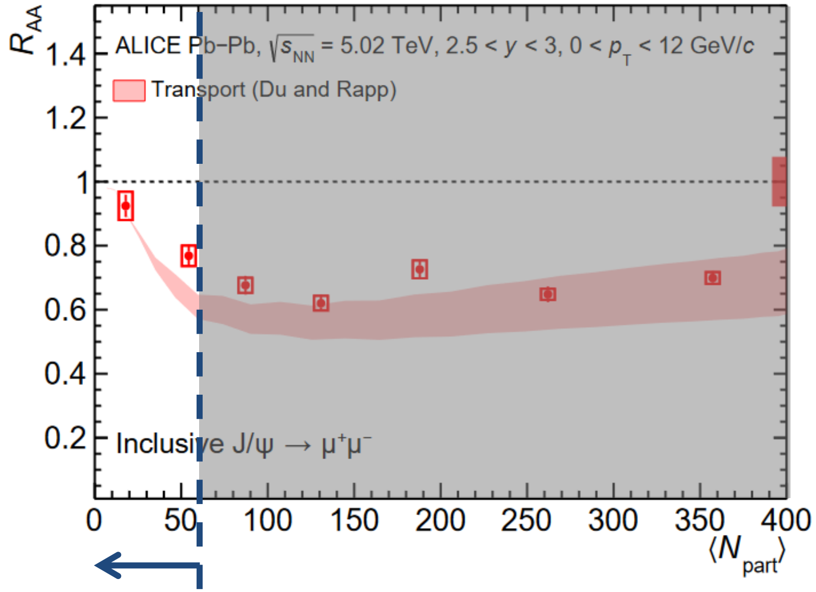


50% less central

50% most central



J/ψ production – PbPb – ALICE



50% less central

50% most central

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Detector upgrade – LHCb Upgrade I

9 fb^{-1} (Run 1 – Run 2) | Goal: 50 fb^{-1} (Run 3 – Run 4) | Goal: 300 fb^{-1} (Run 5 – Run 6) | Lumi *pp*

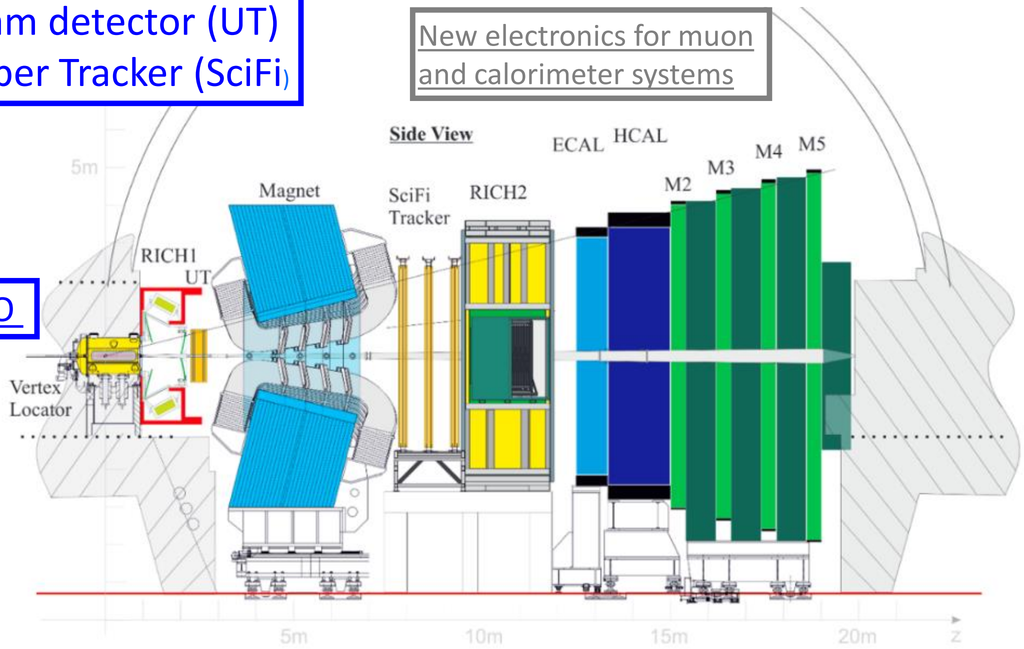
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6
2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024	2025 2026	2027 2028 2029 2030	2031	2032 2033 2034	2035	2036 2037 2038
			Upgrade I		Upgrade Ib		Upgrade II			

- **Upgrade based on pp collision requirements :**
  - Collision rate at 40 MHz.
  - Pile-up factor $\mu \approx 5$ (instead of $\mu \approx 1$ up to LS2)
  - Remove L0 triggers (software trigger)
  - Read out the full detector at 40 MHz.
  - Replace the entire tracking system.

New Tracking system :
- Silicon upstream detector (UT)
- Scintillating Fiber Tracker (SciFi)

New electronics for muon and calorimeter systems

New pixel VELO

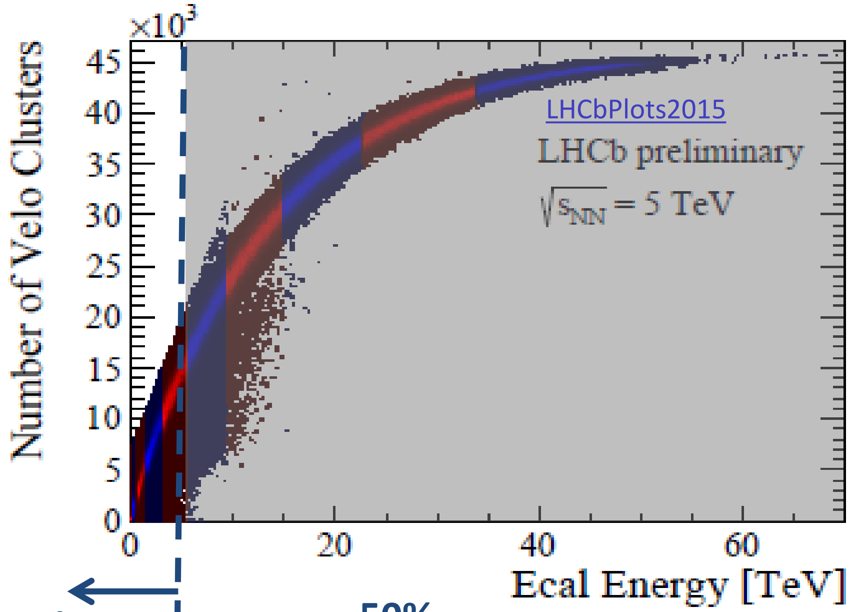


New RICH optics and photodetectors

- **Benefit for heavy ion physics**
  - Can reach more central PbPb collisions

- **Detector performances in Pb-Pb collisions**

Run2 : Vertex Locator saturates



50%
less central

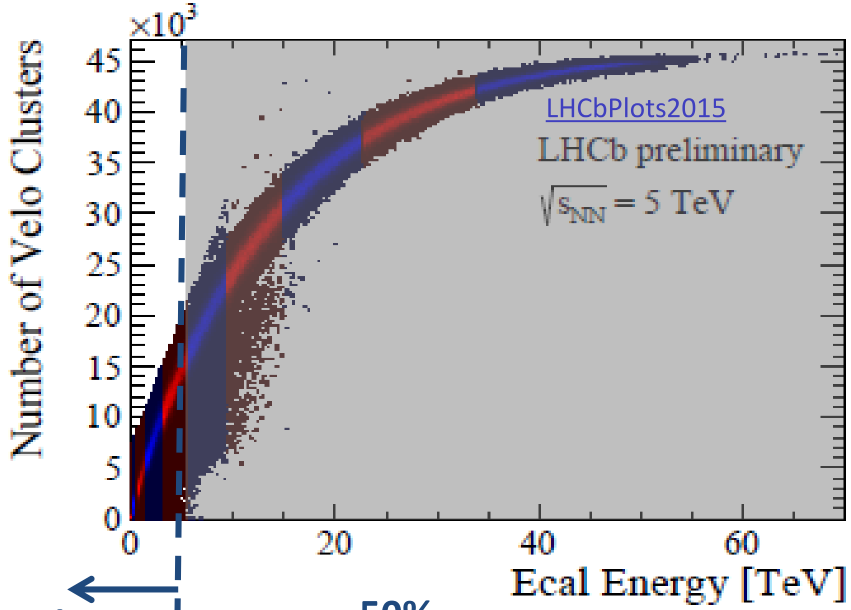
50%
more central

Reconstruction **limited to 50%** less central
Also **problematic for** FT **PbAr** (ok for PbNe)

- **Detector performances in Pb-Pb collisions**

(B. Audurier LHCb-INT-2020-004)

Run2 : Vertex Locator saturates



50% **less central** ← → **50%** **more central**

Reconstruction **limited to 50%** less central
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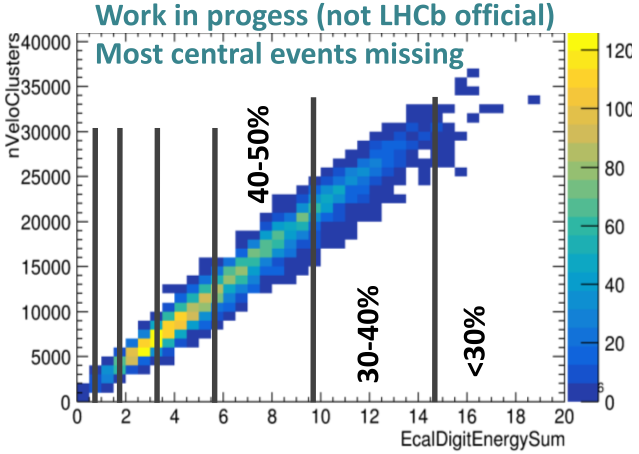
Run 3: **New Vertex Locator does not saturate**

MC PbPb UPGRADE (EPOS + PYTHIA)



Velo .vs. Ecal

*(Most central events missing because of LHCb software issues, currently under investigation, **work in progress**)*

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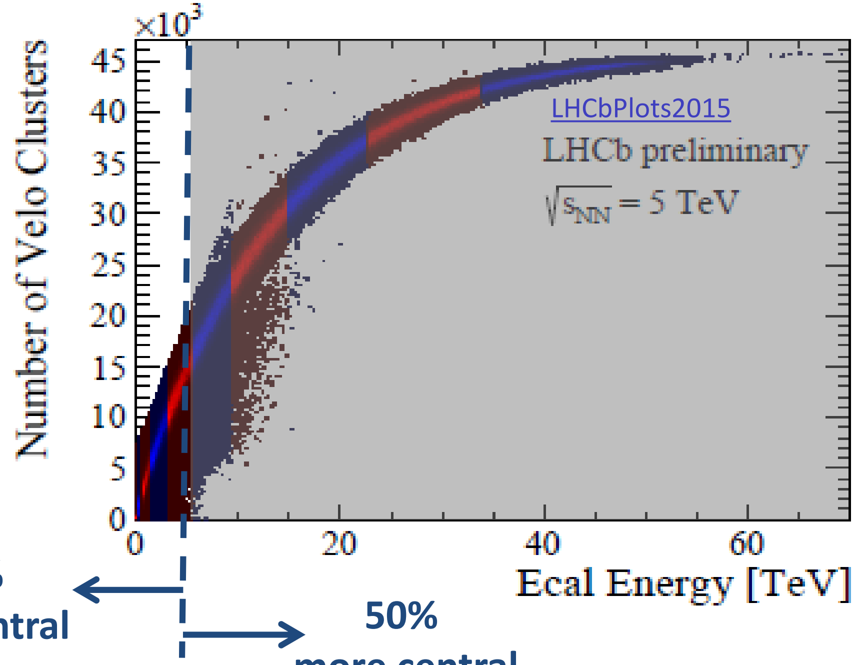
(B. Audurier LHCb-INT-2020-004)

Run2 : Vertex Locator saturates



Reconstruction **limited to 50%** less central
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Run 3: **New Vertex Locator does not saturate**
Expect SciFi to saturate in most central collisions

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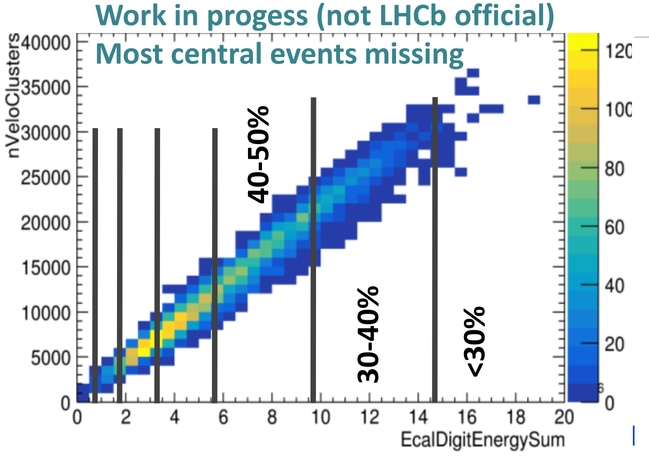

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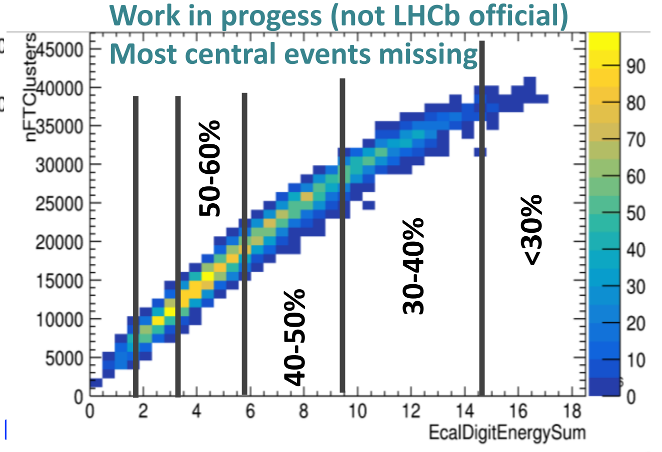
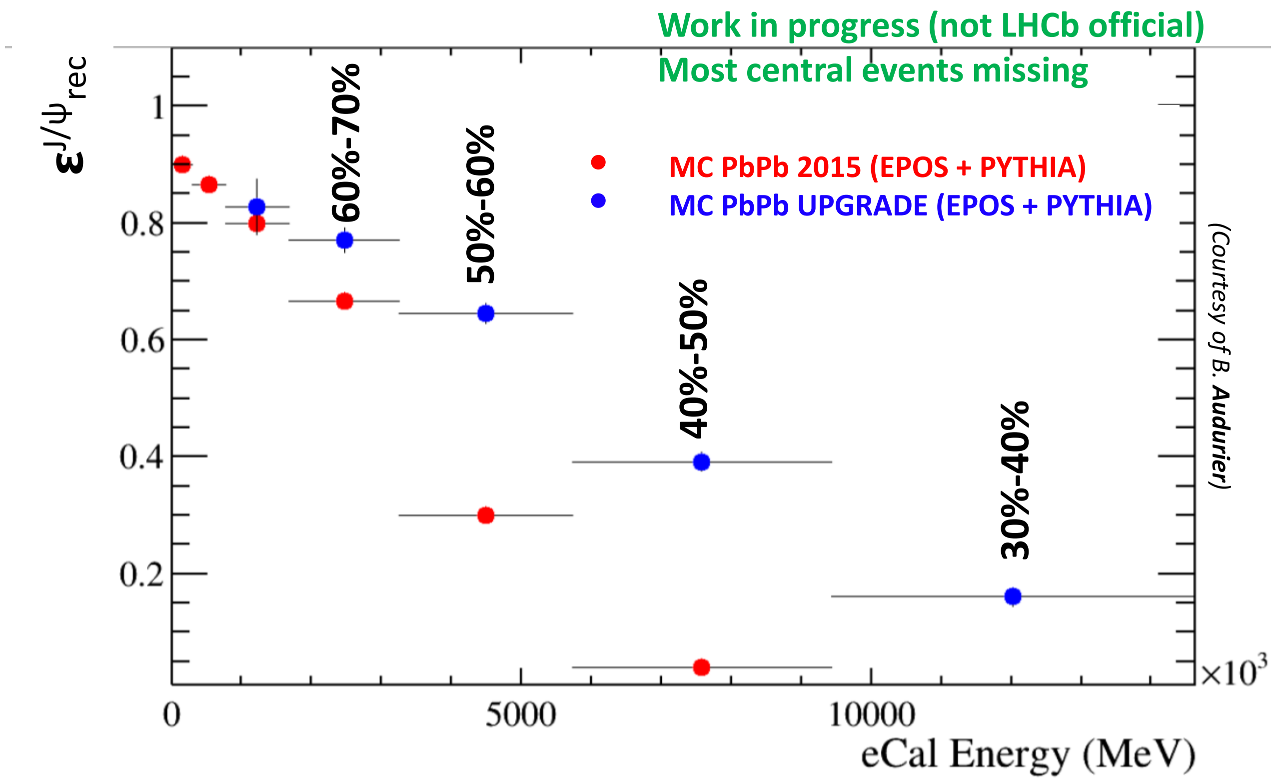


SciFi .vs. Ecal

*(Most central events missing because of LHCb software issues, currently under investigation, **work in progress**)*

Expect tracking limitation due to SciFi

- J/ψ reconstructible up to (at least) 30% centrality



- LHCb can play a significant role already in Run 3 Pb-Pb collisions
  - Can precisely study J/ψ, ψ(2S), χ_c, bottomonia, open charm, open beauty

Pb-Pb in Run 3

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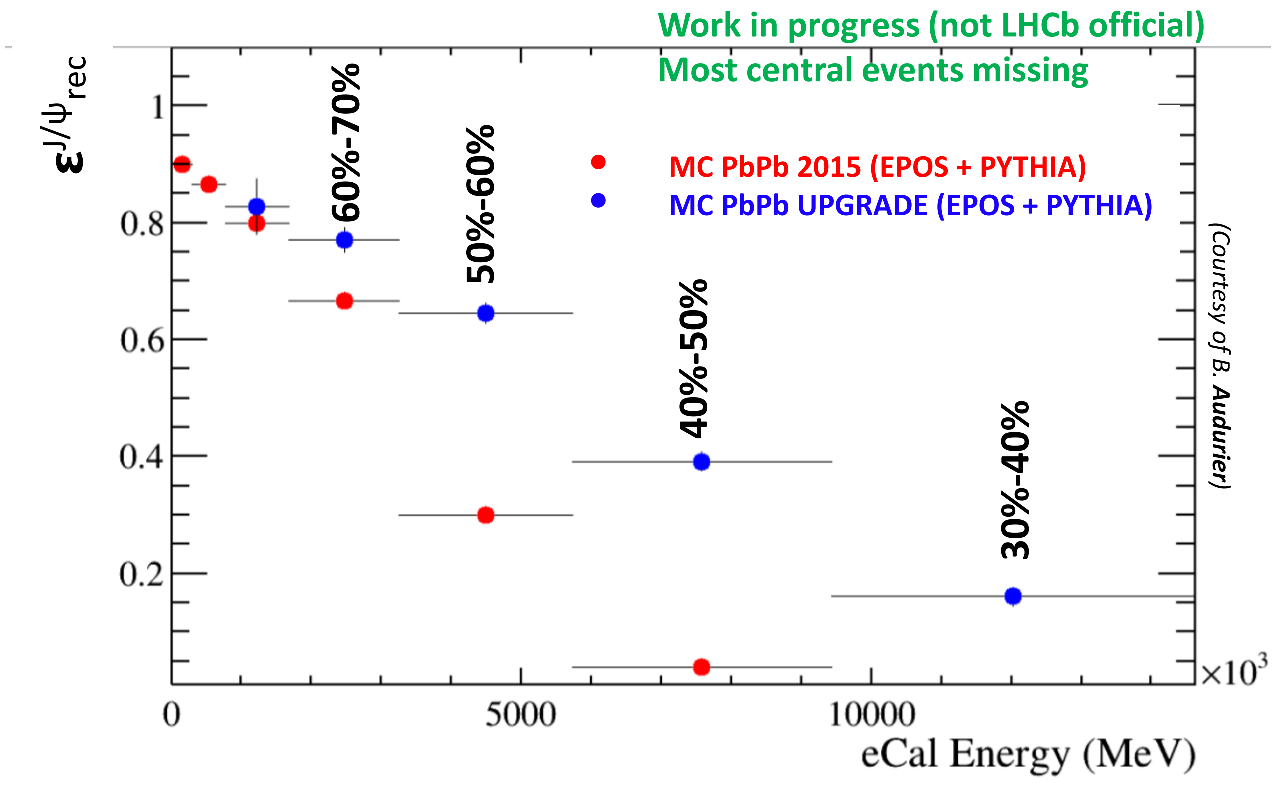

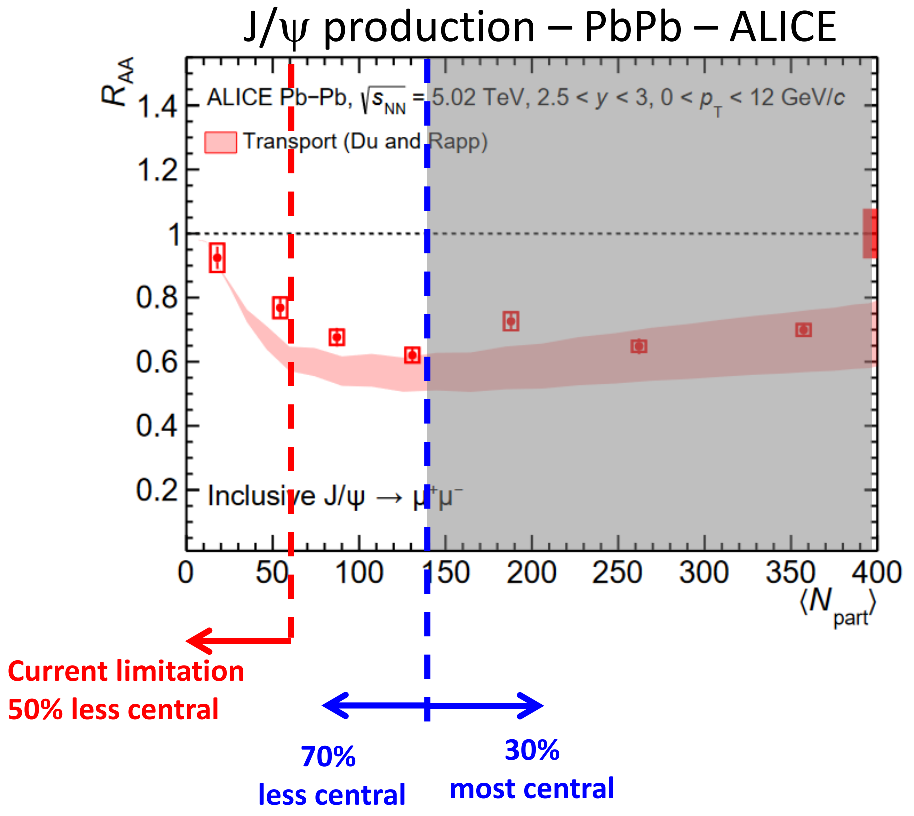

- **LHCb can play a significant role already in Run 3 Pb-Pb collisions**
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Improving LHCb capabilities in PbPb collisions

LHCb at Run 3:

- Inst. *pp* lumi = **2.10^{33} cm^{-2}s^{-1}** ➔ $\langle N_{pp} \rangle$ / BX ~ 5
- PbPb: should run **ok up to ~30-40% centrality**

Fixed Target ok up to PbAr (A=40)

Centrality	<dNch/dη> (Δη=1)	<dNch/dη> * 3	Eq. pp@13TeV Coll.	Eq. <pp@13TeV> / 5	Eq. <pp@13TeV> / 40
0-5%	1940	5820	366	73	9
0-10%	1777	5331	335	67	8
10-20%	1180	3540	223	45	6
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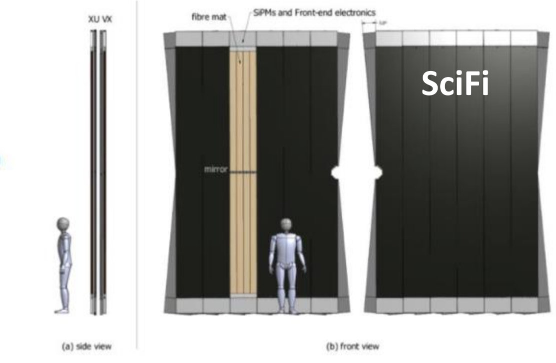
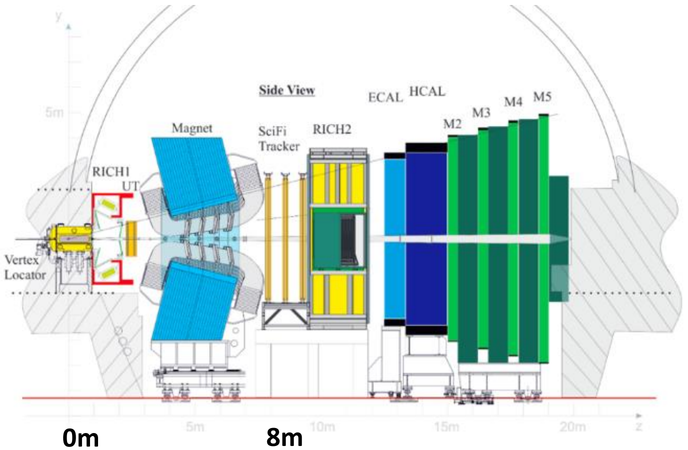
30-40%	512	1536	97	19	2

PbPb limit (30-40%)



Layout of one of three stations for the LHCb SciFi Tracker.



0m VELO

8m SciFi

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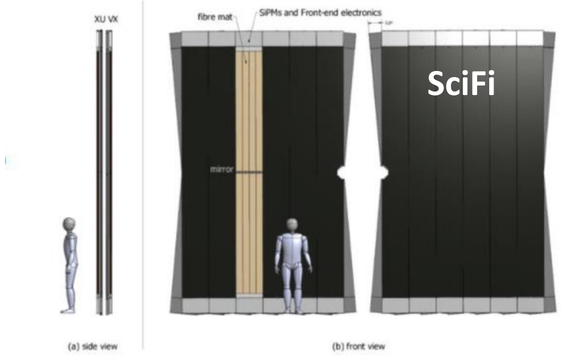

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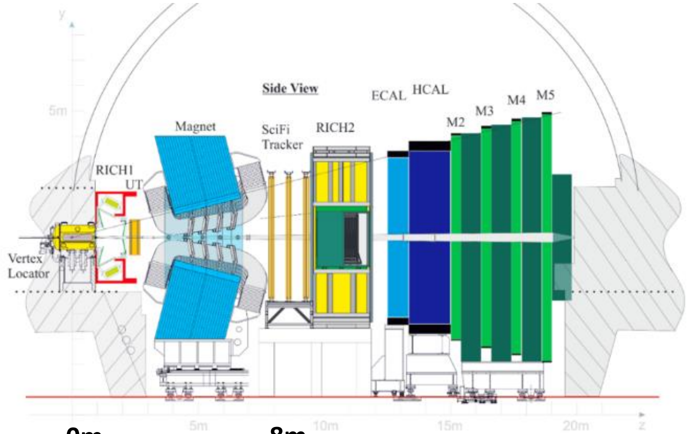

0m VELO

8m SciFi **IT**

LHCb at Run 4:

- Inst. *pp* lumi = **4.10^{33} cm^{-2}s^{-1}** ➔ $\langle N_{pp} \rangle$ / BX ~ 10
- PbPb: should run **ok up to ~10-20% centrality** (thanks to **IT**)

Fixed Target ok up to PbKr (A=84)

PbPb limit (10-20%)

Centrality	<dNch/dη> (Δη=1)	<dNch/dη> * 3	Eq. pp@13TeV Coll.	Eq. <pp@13TeV> / 5	Eq. <pp@13TeV> / 40
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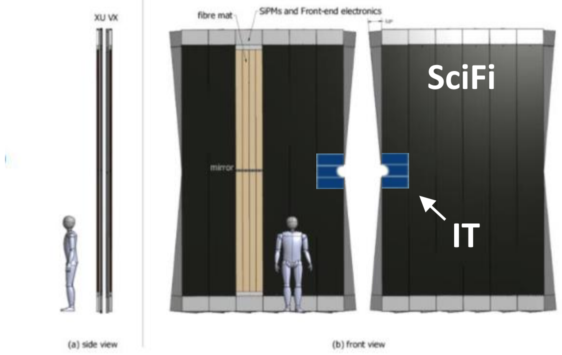

Layout of one of three stations for the LHCb SciFi Tracker.

IT = (silicon pixel) Inner Tracker (replace central part of SciFi)

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PbPb limit

Centrality	$\langle dN_{ch}/d\eta \rangle$ ($\Delta\eta$=1)	$\langle dN_{ch}/d\eta \rangle$ * 3	Eq. pp@13TeV Coll.	Eq. $\langle$pp@13TeV$\rangle$ / 5	Eq. $\langle$pp@13TeV$\rangle$ / 40
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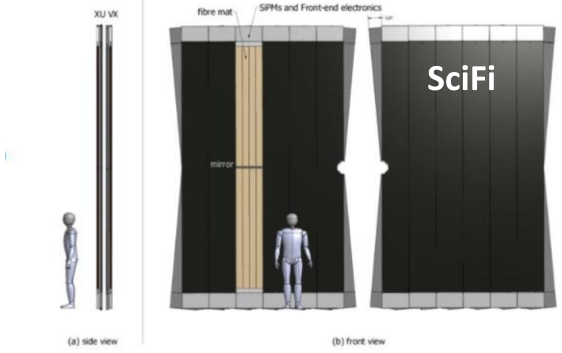

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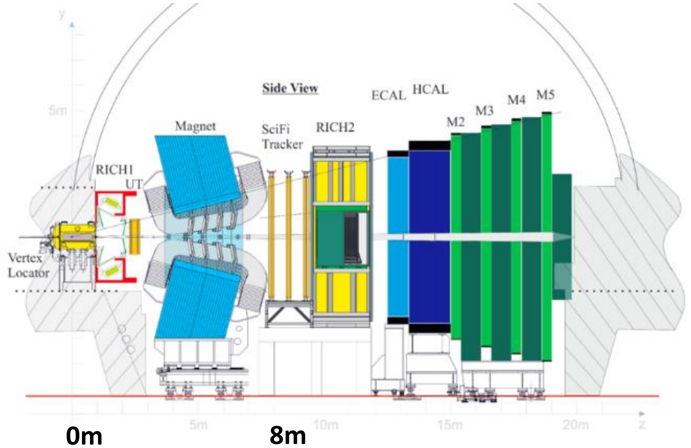

0m VELO

8m SciFi **IT** **MT**

LHCb at Run 4:

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- PbPb: should run **ok up to ~10-20% centrality** (thanks to **IT**)

Fixed Target ok up to PbKr (A=84)

PbPb limit

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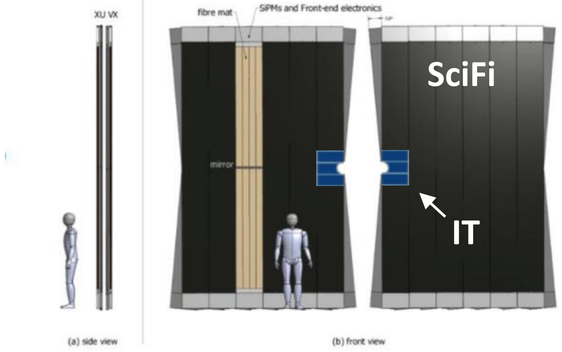

Layout of one of three stations for the LHCb SciFi Tracker.

IT = (silicon pixel) Inner Tracker (replace central part of SciFi)

LHCb at Run 5:

- Inst. *pp* lumi = **$1.5.10^{34}$ cm^{-2}s^{-1}** ➔ $\langle N_{pp} \rangle$ / BX ~ 40
- PbPb: should run **ok up to ~0-5% centrality** (thanks to **IT+MT**)

PbPb limit

Fixed Target ok up to PbXe (A=131)

Centrality	$\langle dN_{ch}/d\eta \rangle$ ($\Delta\eta$=1)	$\langle dN_{ch}/d\eta \rangle$ * 3	Eq. pp@13TeV Coll.	Eq. $\langle$pp@13TeV$\rangle$ / 5	Eq. $\langle$pp@13TeV$\rangle$ / 40
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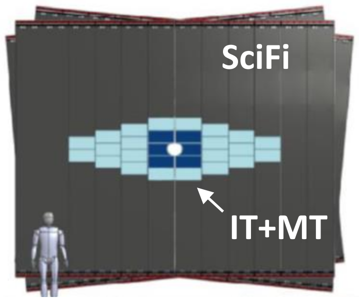

MT = (silicon pixel) Middle Tracker (replace central part of SciFi)

With Mighty Tracker (IT+MT) Tracking stations can cope with PbPb high multiplicity and fixed-target up to PbXe

Improving LHCb capabilities in PbPb collisions

LHCb at Run 3:

- Inst. *pp* lumi = **2.10^{33} cm^{-2}s^{-1}** ➔ $\langle N_{pp} \rangle$ / BX ~ 5
- PbPb: should run **ok up to ~30-40% centrality**

Fixed Target ok up to PbAr (A=40)

PbPb limit (row 30-40%)

Centrality	$\langle dN_{ch}/d\eta \rangle$ ($\Delta\eta$=1)	$\langle dN_{ch}/d\eta \rangle$ * 3	Eq. pp@13TeV Coll.	Eq. $\langle$pp@13TeV$\rangle$ / 5	Eq. $\langle$pp@13TeV$\rangle$ / 40
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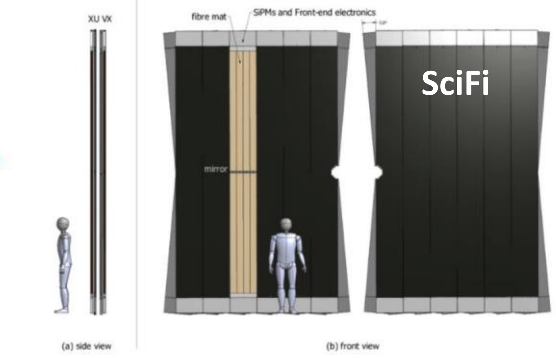

Layout of one of three stations for the LHCb SciFi Tracker.

LHCb at Run 4:

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Fixed Target ok up to PbKr (A=84)

PbPb limit (row 10-20%)

Centrality	$\langle dN_{ch}/d\eta \rangle$ ($\Delta\eta$=1)	$\langle dN_{ch}/d\eta \rangle$ * 3	Eq. pp@13TeV Coll.	Eq. $\langle$pp@13TeV$\rangle$ / 5	Eq. $\langle$pp@13TeV$\rangle$ / 40
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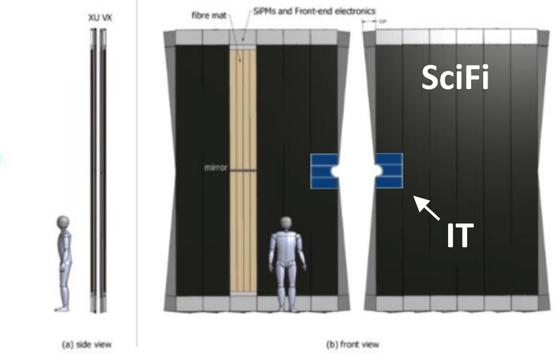

Layout of one of three stations for the LHCb SciFi Tracker.

LHCb at Run 5:

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- PbPb: should run **ok up to ~0-5% centrality** (thanks to **IT+MT**)

PbPb limit (row 0-5%)

Fixed Target ok up to PbXe (A=131)

Centrality	$\langle dN_{ch}/d\eta \rangle$ ($\Delta\eta$=1)	$\langle dN_{ch}/d\eta \rangle$ * 3	Eq. pp@13TeV Coll.	Eq. $\langle$pp@13TeV$\rangle$ / 5	Eq. $\langle$pp@13TeV$\rangle$ / 40
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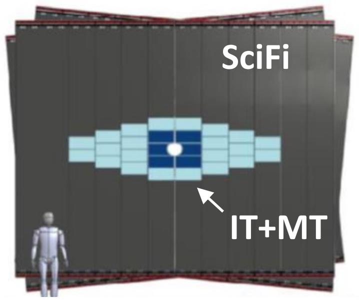
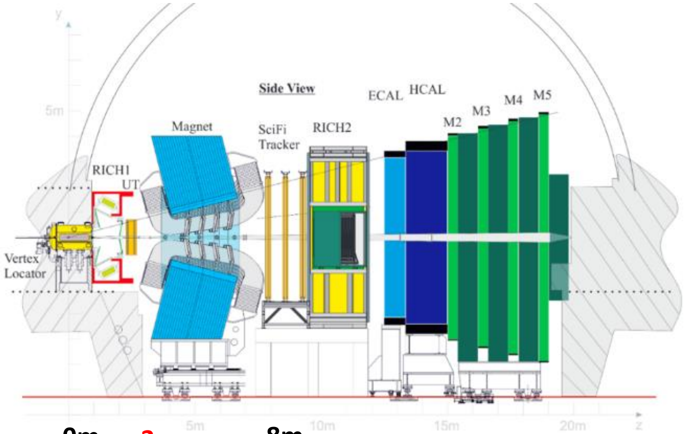
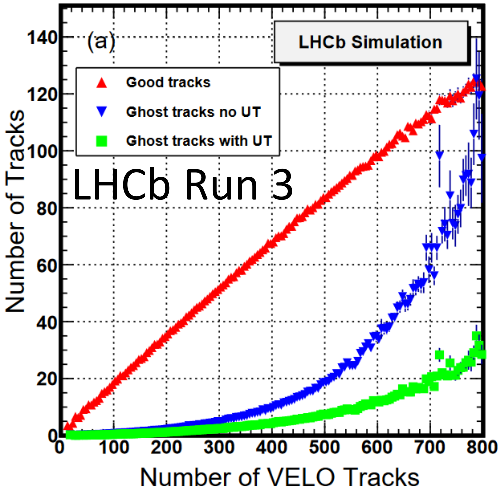




0m VELO | 3m UT | 8m SciFi, IT, MT

Upstream Tracker (UT)

Located upstream of the magnet



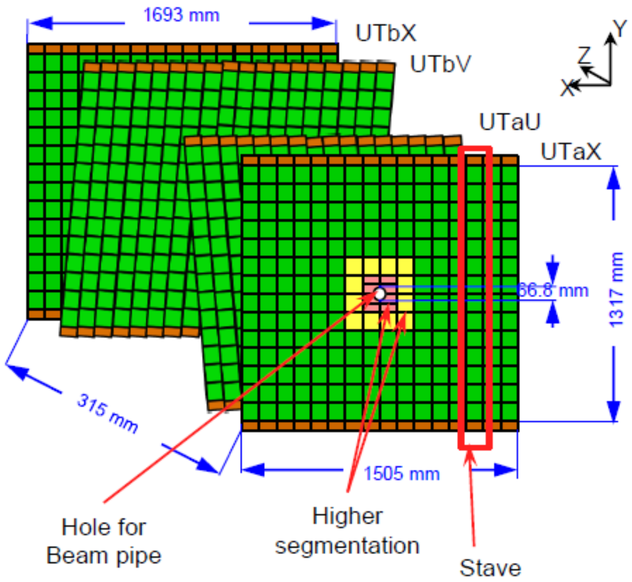
UT needed to deal with ghost (fake) tracks

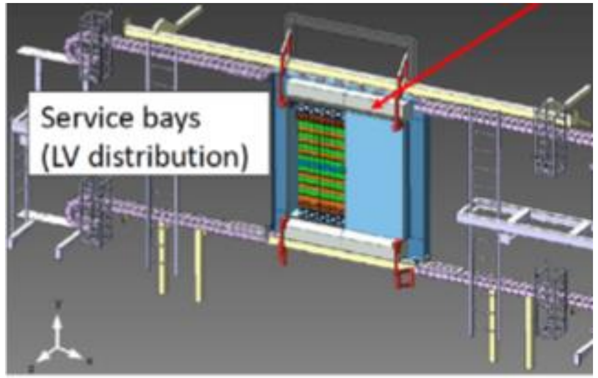
With Mighty Tracker (IT+MT) Tracking stations can cope with PbPb high multiplicity and fixed-target up to PbXe

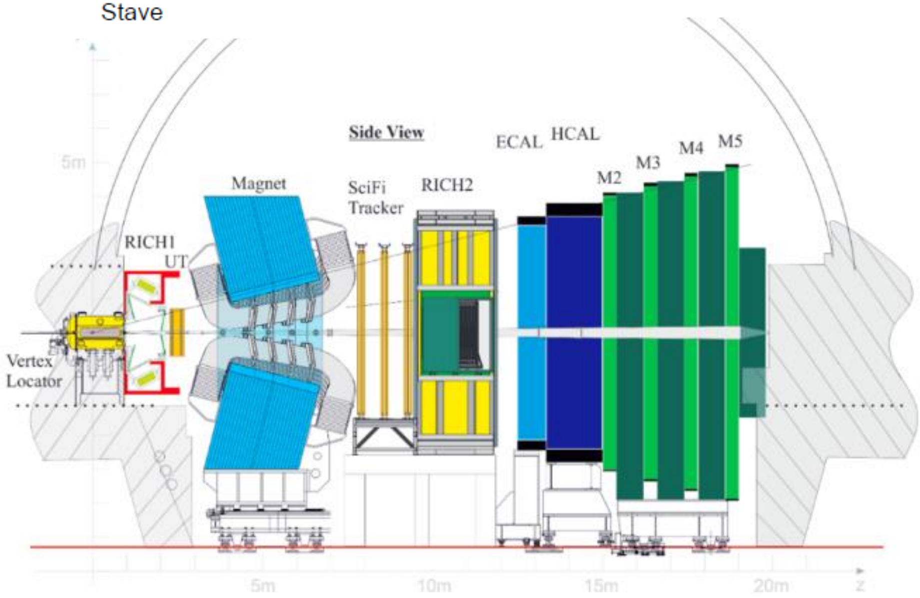
Current UT detector must be replaced

- **Current UT**
  - Silicon strips, oriented vertically
  - from 100µm×50**mm** to 187.5µm×100**mm**

Sensor	A	B	C	D
Pitch (µm)	187.5	93.5	93.5	93.5
Length (mm)	~100	~100	~50	~50
Strips/sensor	512	1024	1024	1024
Numbers	888	48	16	16







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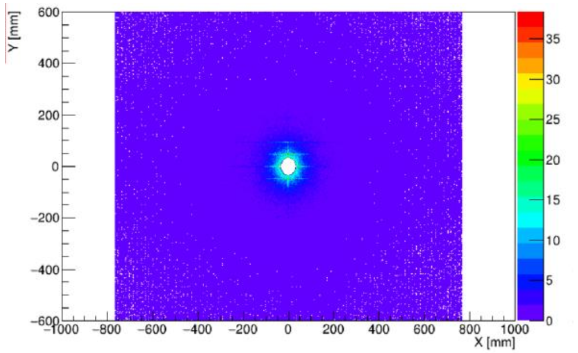
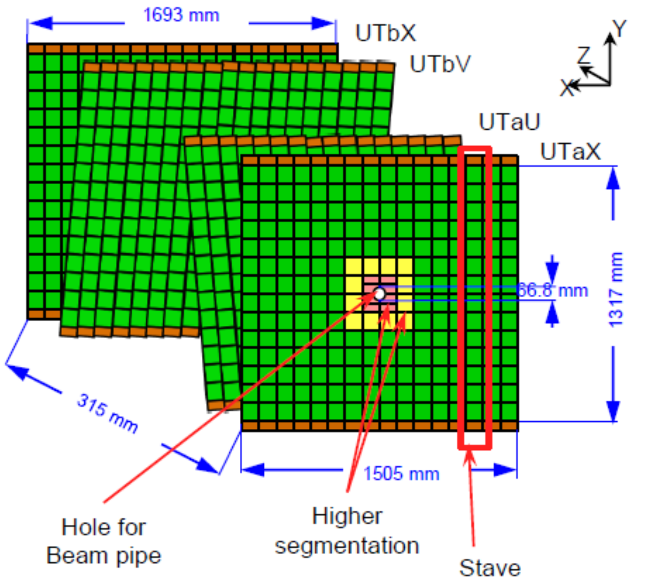
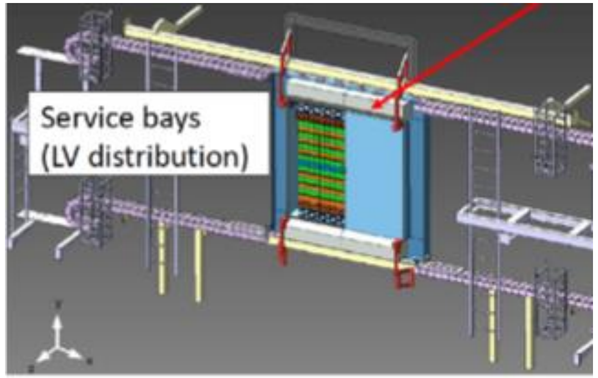
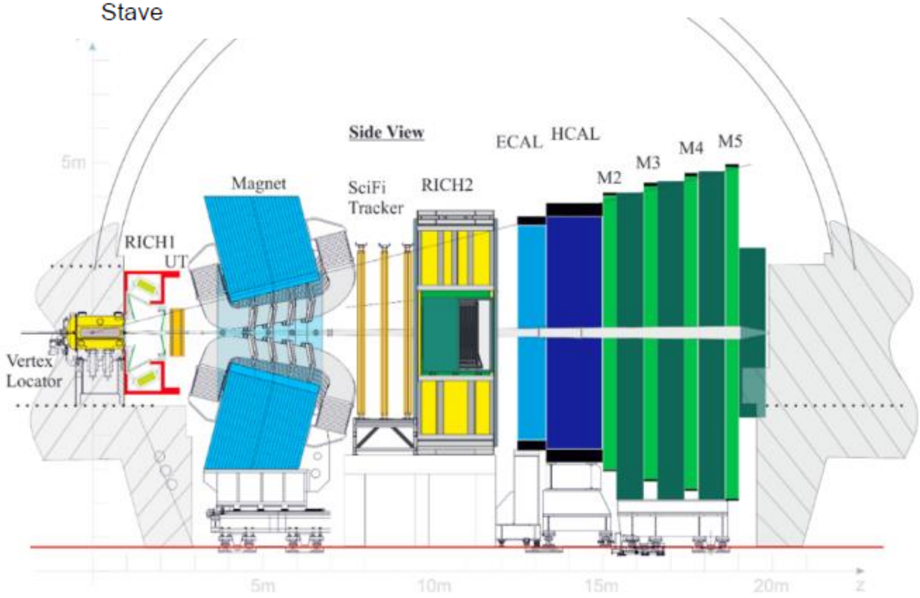
- **UT upgrade needed for LHC Run 5+:**
  - **High data rate** in pp high luminosity
  - **High hit density** in central PbPb collisions
    - ***Up to ~50 hits/cm² in central PbPb***



Occupancy [hit/cm² event] for PbPb in UT 1st plane







Possible french contribution to UT upgrade II

- **Several groups in France are interested in contributing to UT-U2**
  - ***LHCb members***
    - **LLR** – Palaiseau
    - **LPNHE** - Paris
  - ***Currently in ALICE***, willing to join LHCb for Run 5
    - **Irfu** - Saclay
    - **Subatech** - Nantes
  - Irfu/Subatech = leaders of ALICE Muon Forward Tracker
    - CMOS MAPS detector installed early 2021 based on ALPIDE towerJazz techno
  - Regular meetings since November with ~30 participants

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  - Institute of Particle Physics (CCNU) *Wuhan*
  - Physics and micro electronic college (HNU) *associated to Wuhan*
  - Institute of High Energy Physics (IHEP) *Beijing*
  - University of Chinese Academy of Science (UCAS), *Beijing*
  - Laboratory of Nuclear Science (SCNU), Guangzhou, *associated to Tsinghua*
  - School of Physics and technology (WHU), Wuhan, *associated to Tsinghua*

- Other groups (China, US) may join …

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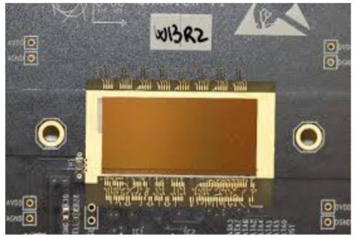
- **Technology currently envisioned to cope with *high data rate + high hit density***
  - *CMOS pixels*
  - *Specifications to be finalized*

LV-CMOS

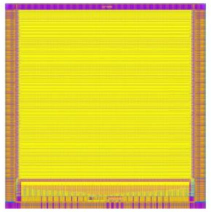
Example: TowerJazz chip (ALPIDE, MONOPIX)

Process	TJ 180 nm CMOS
Pixel size	33 µm x 33 µm
Time precision	25 ns
TID	100 MRad
Power	~150 mW/cm^2
Hit rate	100 – 200 Mhit/s/cm^2
Involved labs	Bonn Univ., CERN, CPPM, Irfu

TJ-ALPIDE (1.5 cm x 3 cm)



TJ-MONOPIX2 (2 cm x 2 cm)

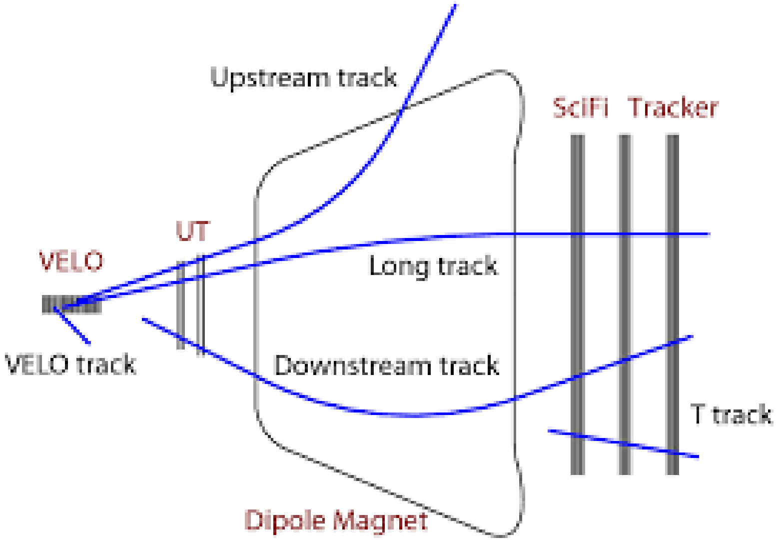


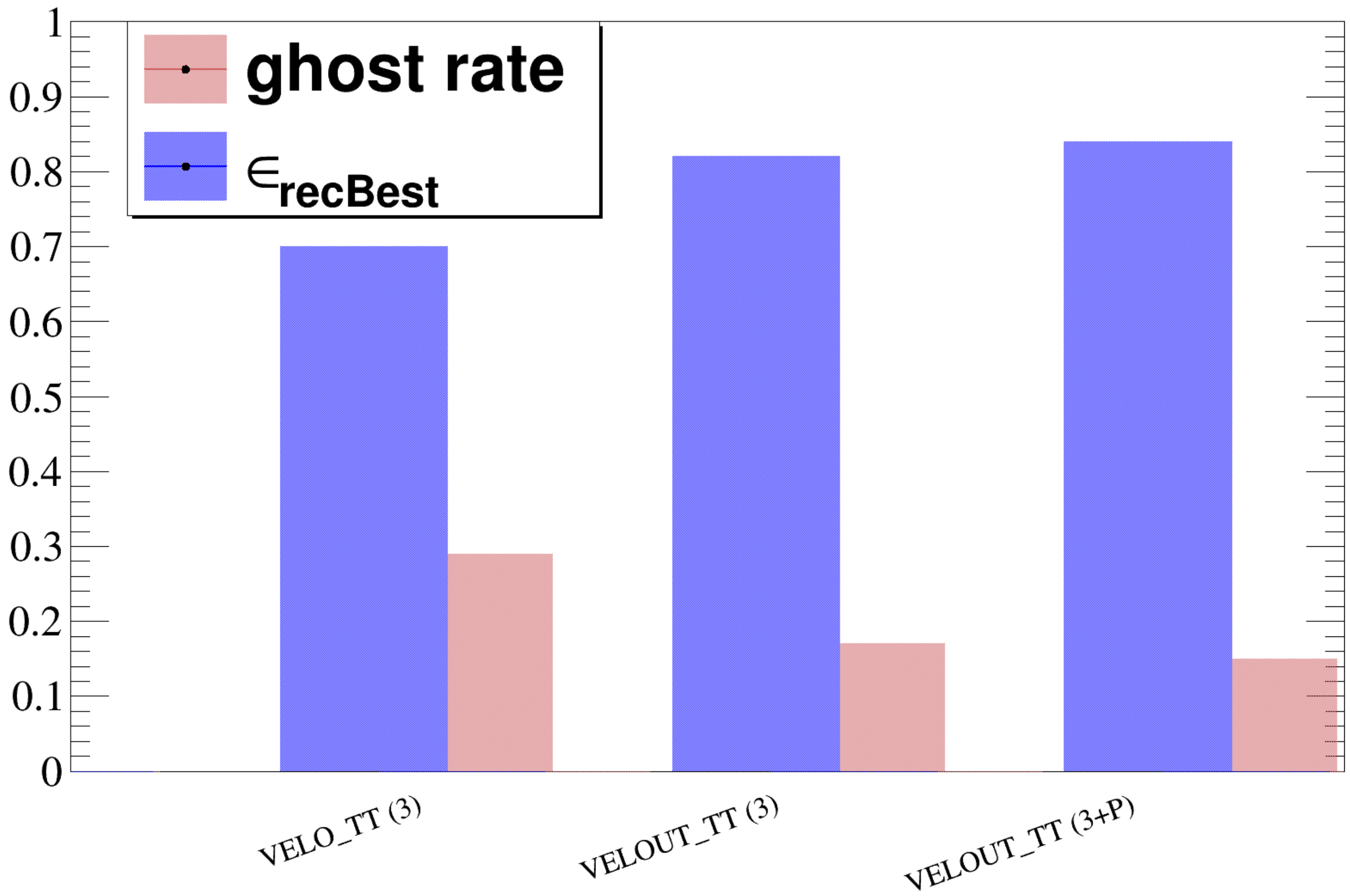
HV-CMOS

Example: VeloPix

Specification	VeloPix
pixel dimension	$55 \times 55\,\mu m^2$
matrix size	256×256
timewalk	< 25 ns
Time over Threshold range	6 bit (calibration mode only)
leakage current compensation (per pixel)	20 nA
Time stamp resolution	25 ns
Time stamp range	9 bit
average pixel hit rate	600 MHits/s
peak pixel hit rate	900 MHits/s
peak super-pixel packet rate	520 MHits/s
min. output bandwidth	18 Gbit/s
max. pixel hit loss at max. rate	1%
power consumption per ASIC	< 3 W
radiation hardness	> 400 Mrad
single event upset robust	yes

- **First performance estimates (~10 % most central PbPb) – B. Audurier**
  - Taking 100 µm x 100 µm pixels
  - Momentum resolution ~30% (Worst Case scenario)





With **No UT** information in track finding

With UT hit positions in track finding

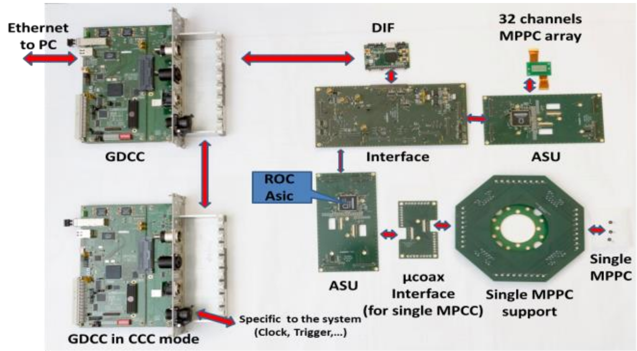
With UT hit positions + momentum in track finding

UT = key detector for central PbPb collisions

LLR possible contribution - electronics

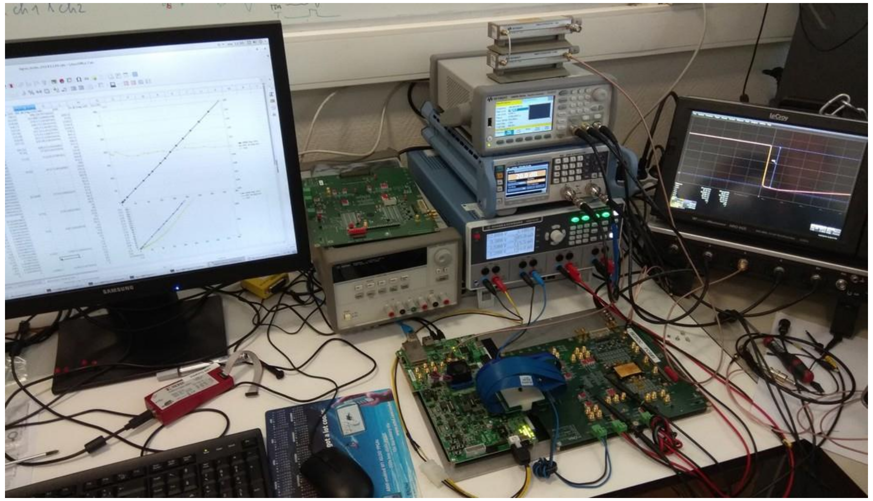
- **LLR expertise:** From sensor to data acquisition
  - Signal processing for the trigger algorithm
  - Processing and transmission of sensor data to the workstation (including board CAD)
  - Development and implementation of associated **test systems** (including board CAD)

Trigger algorithm bench
CMS HGCAL project

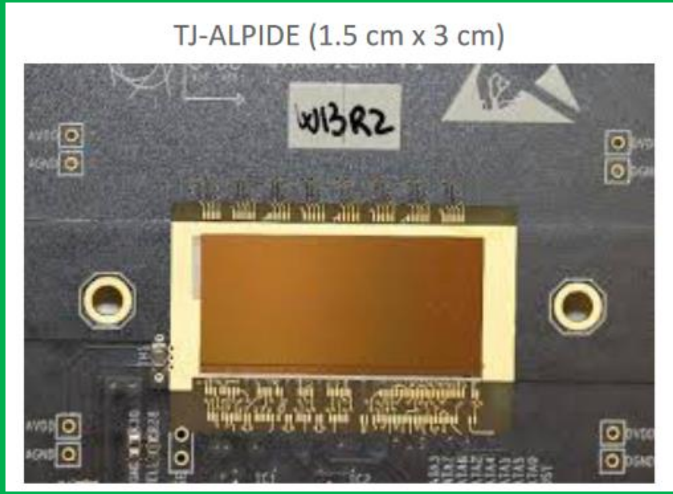


LLR DAQ system for T2K Wagasci project
(ND280 upgrade)

  - Put in place ***several platforms to characterize***, validate, or evaluate OMEGA ***ASICs*** (EasiRoc, T2K-SpiRoc, Calice-SkiRoc, Juno-CatiRoc, CMS-HGCRoc)
  - Program for 2021: study of ***ASIC mass production test*** (~100 k ASICs)



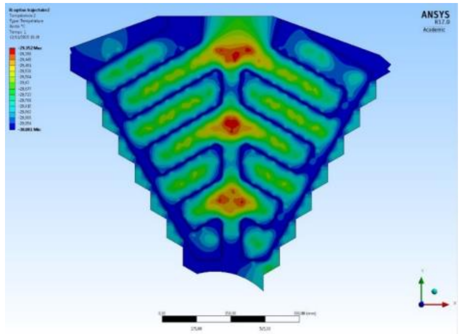
CMS HGCroc ***ASIC characterization*** system



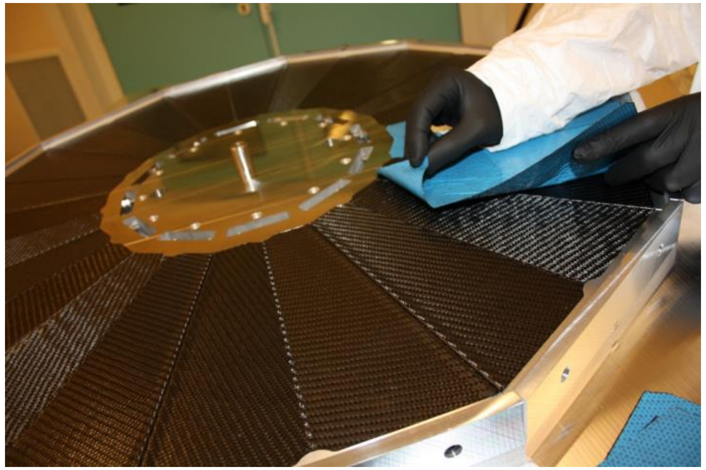
Discussion en cours avec Franck Gastaldi pour une possible contribution du LLR à la caractérisation des chips (banc test)

LLR possible contribution - mechanics

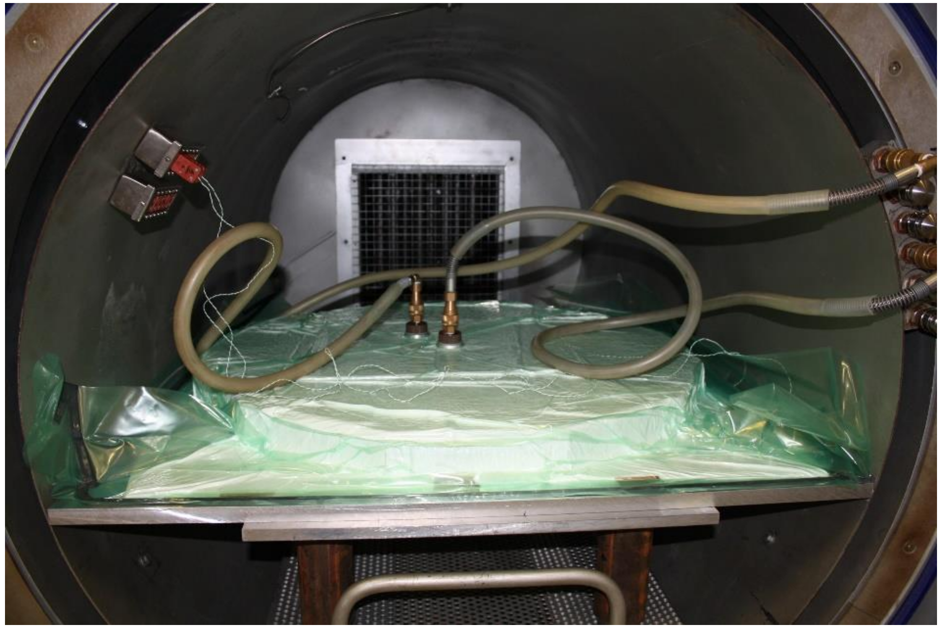
- **LLR expertise:** Studies and construction of physics particles detectors using a global approach:
  - detector design using CAD (Computer Aided Design) and FE (Finite Elements) softwares **CATIA_V5** & **ANSYS** (static, dynamic, thermal analysis)
  - prototypes definition and construction @LLR **mechanics workshop**, with specific machines and tools for carbon composite structures : **clean room** & **Autoclave**



Thermal simulation *of a cooling copper plate (HGCAL)*

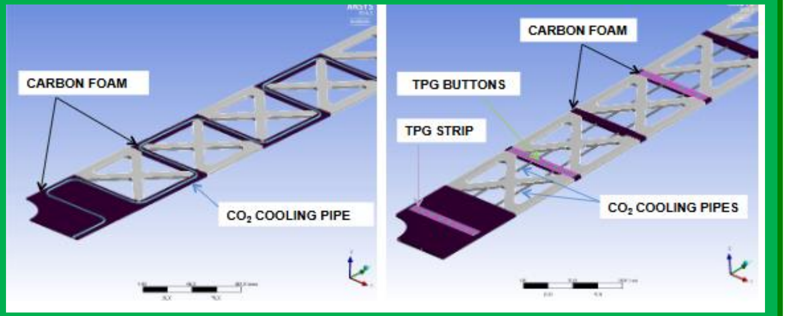


Alveolar wheel prototype for ECAL of HGCAL (CMS)
*Assembling process in **clean room (ISO7)***



*Curing step with an **autoclave***
(pressurized oven: 1m diameter - 1,7m long)

Current UT stave structure



Discussion en cours avec Oscar Ferreira, Thomas Pierre-Emile et Antoine Cauchois pour une possible contribution du LLR à la fabrication des structures en fibre de carbone

Upstream Tracker – Upgrade II – CMOS option

- **French team interests for the R&D phase (~4 years), towards TDR**

List of physicists

LPNHE – Paris:
- C. Agapopoulou,
- E. Ben Haim,
- M. Charles,
- L. Del Buono,
- V. Gligorov,
- F. Polci,
- P. Vincent

LLR – Palaiseau:
- B. Audurier
- V. Balagura,
- F. Fleuret,
- E. Maurice

Irfu – Saclay:
- A. Baldisseri,
- H. Borel,
- J. Castillo,
- A. Ferrero,
- S. Panebianco,
- A. Rakotozafindrabe,
- M. Winn

Subatech – Nantes:
- G. Batigne,
- M. Germain,
- M. Guilbaud

Work package	tasks	French teams Interests (estimated FTE)
WP0 – coordination		
WP1 – simulations and performances pp and PbPb	• Physics performances • Occupancy, Tracking and reconstruction • Geometry and material budget	**LLR** LPNHE Irfu Subatech (~2 – 2.5 FTE/y)
WP2 – chip design and characterization	• Pixel design and optimization • Chip design and simulation • Demonstrator and prototype production • **Test bench design and building** • **Characterization of prototypes**	**LLR** Irfu (~1.5 – 2 FTE/y)
WP3 – module stave and mechanical structure	• Flex (FPC) design and pototype production • **Structure design and prototype production** • **Cooling studies**	**LLR** Irfu Subatech (~1.5 – 2 FTE/y)
WP4 – overal mechanics, integration and services	• Global mechanics design • Integration in LHCb • Power, cooling and readout services design	Subatech (~0.5 – 1 FTE/y)
WP5 – readout	• Data throughput studies • Architecture design • Data links optimization • Frontend/backend card design and prototypes • Integration into LHCb DAQ	LPNHE Subatech (~1 – 1.5 FTE/y)

LHCb Upstream Tracker – Upgrade II

- **Bénéfices:**
  - **Performances optimales jusqu'aux collisions centrales PbPb (mode collisionneur) et PbXe (mode cible fixe)**
  - 2 nouveaux groupes Ions Lourds (**Irfu, Subatech :** ALICE->LHCb) viennent *renforcer la contribution française dans LHCb*
    - + 3ème groupe Ions Lourds français (**LPC** : ALICE->LHCb) – contribution en cours de définition
  - Participation du LLR à un projet technique de la collaboration LHCb
    - Conforme à nos engagements.
    - Participation des doctorants/postdoctorants/chercheurs du groupe à une activité technique du laboratoire.

- **Contributions LLR envisagées:**
  - **Électronique**: banc test de caractérisation des matrices de pixel (chips)
  - **Mécanique**: structure des échelles (fibre de carbone)

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- **Calendrier 2021 (pas d'engagement précis des laboratoires à ce stade)**
  - Soumission du FTDR au LHCC : *septembre 2021*
  - Discussion with Funding Agencies at the LHC Resources Review Board : *octobre 2021*
  - Aim for approval at LHCC/RB : *November/December 2021*

- **Demande**
  - Le groupe est actuellement impliqué dans
    - la rédaction du FTDR (Benjamin Audrier = co-éditeur de la section Upstream Tracker)
    - la coordination de la contribution française (Frédéric Fleuret + Eli Ben Haim – LPNHE)
  - Demande l'accord du laboratoire pour

- **Poursuivre notre contribution au FTDR** → LLR intéressé pour participer à l'upgrade II de LHCb
- **Continuer les discussions** (internes/externes au labo) et préciser notre possible contribution pour la phase R&D

backup

Large statistical increase of LHC run 3 and run 4 – precision era

- **Detailed (proposed) schedule for Heavy ion physics**

Physics of HL-LHC WG5: Future physics opportunities for high-density QCD at the LHC
arXiv1812.06772 - CERN-LPCC-2018-07

LHC

HL – LHC

LS2 → LHCb upgrade 1a

LHC Run 3

LS3 → LHCb upgrade 1b

LHC Run 4

LS4 → LHCb upgrade 2

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

LHCb is very well placed to have a **decisive contribution** to Heavy Ion Physics **in LHC run 3 and HL-LHC**

- **Best placed in pp and pPb** at forward rapidity
  - In pPb/Pbp: $\mathcal{L}$ ~ 30 nb^{-1} in run 2 (~1M J/ψ, ~8M D^0) ➔ $\mathcal{L}$ ~ 300 nb^{-1} in run 3 + 300 nb^{-1} in run 4
- **Well placed** (less limited) **in PbPb** at forward rapidity
  - Will benefit from **detector upgrade**
- Start **full physics** program in **fixed-target** mode (SMOG2) with H^2, D^2, He, Ne, Ar, Kr
  - Will benefit from target and detector upgrade

The LHCb Heavy Ion program – data taking for Heavy Ion physics

- **Heavy Ion Program started in 2015**