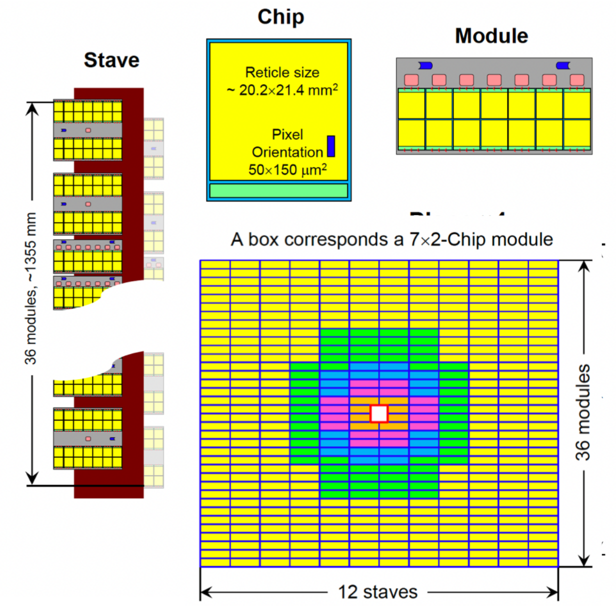
UP

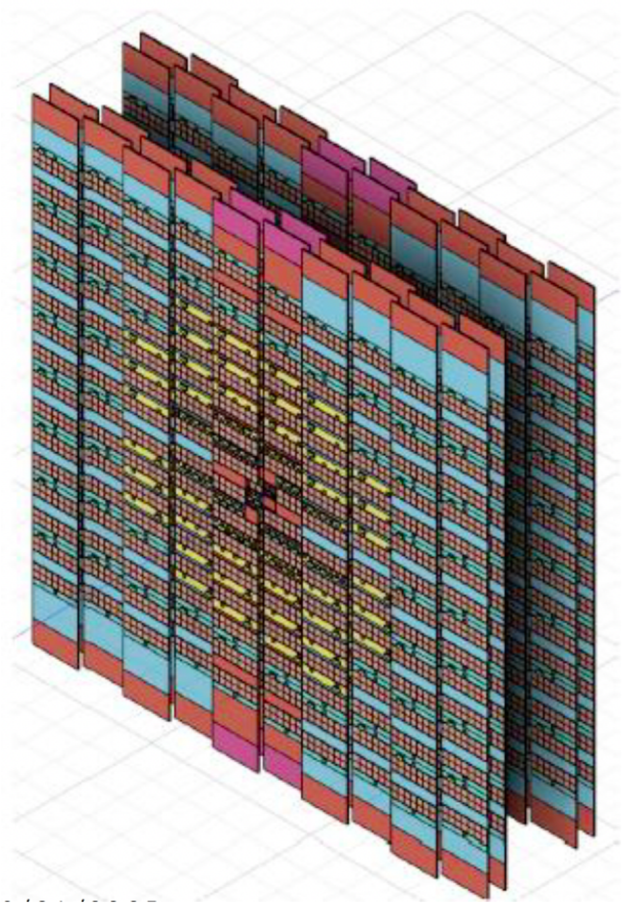
Upstream Pixel detector

- Challenges for UT due to higher luminosity
  - Increased track density (hit rate ~160 MHz/cm^2) → higher granularity
  - Higher bandwidth (up to 9 Gb/s on innermost chip)
  - Increased radiation level:
    NIEL up to 3×10^{15} n_{eq}/cm^2, TID up to 240 MRad
- A MAPS based pixel detector proposed
  - Sensor options: HVCMOS / small electrode CMOS



Ring	5	4	3	2	1	All
e-links / chip	1	1	1	1-3	2-7	
Gbps / e-link	0.32	0.64	1.28	1.28	1.28	
lpGBT / module	0.5	1	2	7	14/10	
Num of modules	1312	240	80	64	32	1728
Num of data lpGBTs	656	240	160	448	384	1888
Num of ctrl lpGBTs	656	240	80	192	144	1312

Dual-module



Upstream Pixel detector

- R&D collaboration formed mainly by Chinese and French institutes
- Leading development in all aspects
  - Simulation & performance
  - CMOS sensor R&D
  - Module and mechanics prototyping

The 1st UP mini-workshop @ Beijing, 22nd Jan 2025

PL: Jianchun Wang (IHEP, UT/UP)
DPL: Tomasz Skwarnicki (Syracuse, UT), Stefano Panebianco (IRFU, UP)

UT Management Structure

Yiming Li / IHEP
Fabrice Guilloux / IRFU
Franck Gastaldi / LLR
Sensor chip design and characterization

Charlotte Riccio / IRFU
Jiesheng Yu / HNU
Module stave and mechanical structure

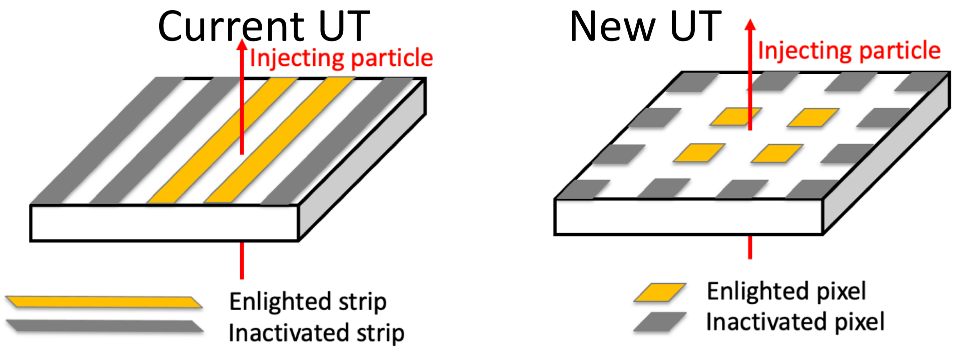
Benjamin Audurier / IRFU
Xuhao Yuan / IHEP
Simulation, reconstruction & performance

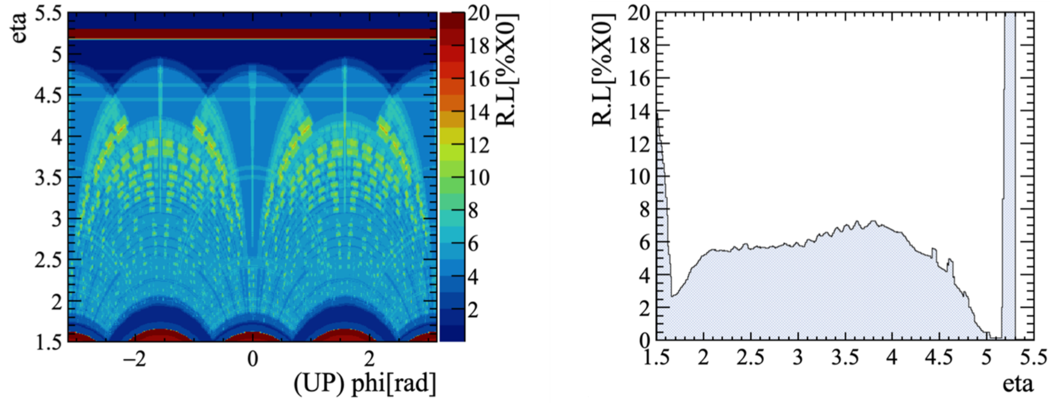
Manuel Guittiere / Subatech
Overall mechanics, integration & services

Kai Chen / CCNU
Readout scheme, DAQ firmware & software

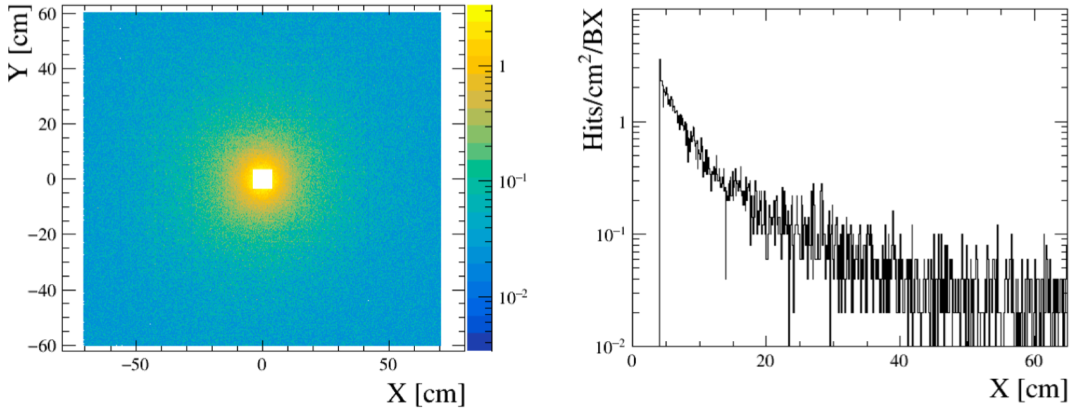
UP simulation

- UP geometry implemented for all scenarios in scoping document
  - Used for material scan, hit density studies etc
  - Hit digitization implemented for silicon pixels
- Tracking algorithms development
  - UP standalone / long track / up or downstream
  - Novel algorithms (GNN/ CAT/ MLP) for speedup





Material scan

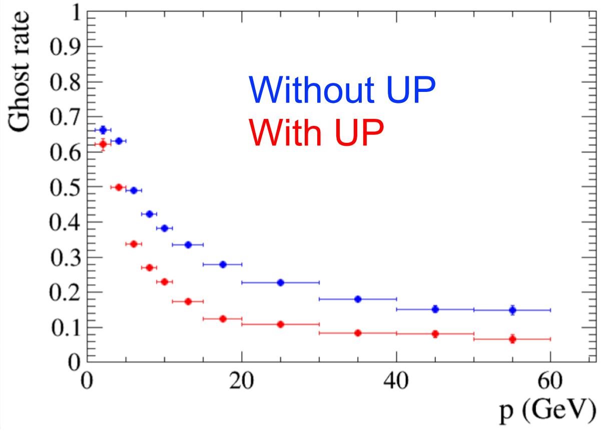


Hit density

UP performance

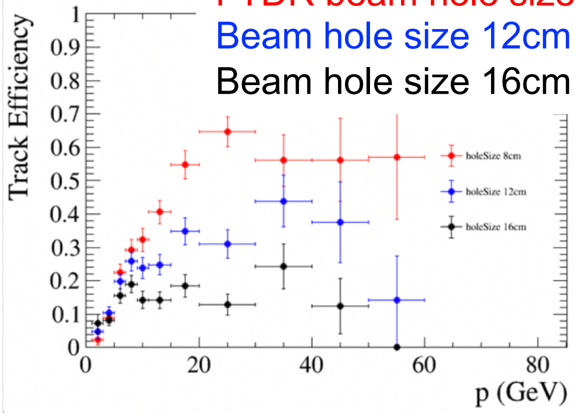
- Upstream and downstream tracks UP is crucial
  - Ensure tracking efficiency
  - Reduce ghost rate
  - Momentum resolution
- Improvements for long tracks
  - Low ghost rate
  - Better momentum resolution

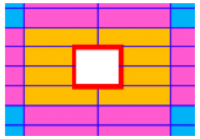
Long tracks – ghost rate

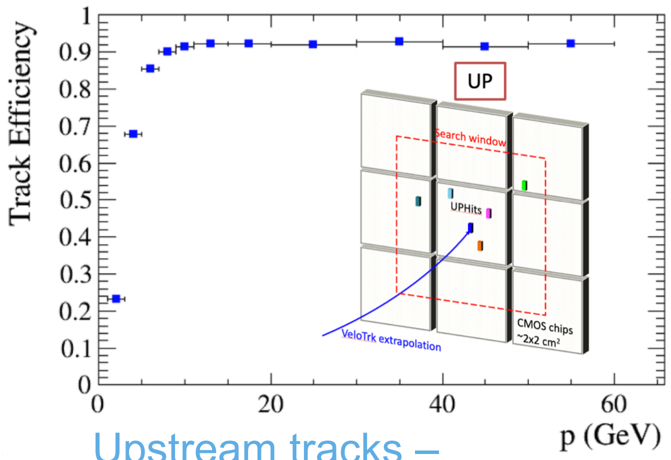


Downstream tracks – Tracking efficiency

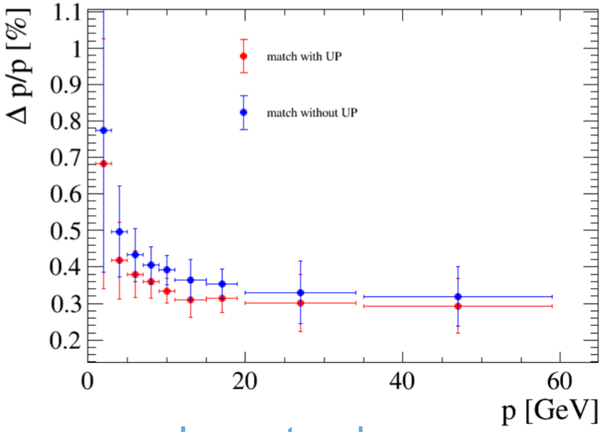
FTDR beam hole size 8cm
Beam hole size 12cm
Beam hole size 16cm



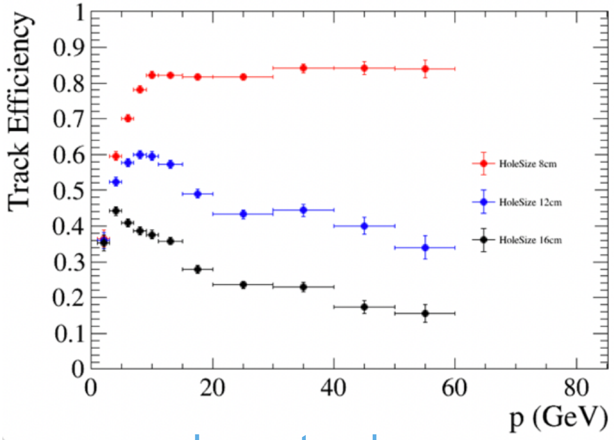




Upstream tracks – Tracking efficiency



Long tracks – momentum resolution



Long tracks – Tracking efficiency

UP sensor development

COFFEE
CMOS SENSOR IN FIFTY-FIVE NM PROCESS

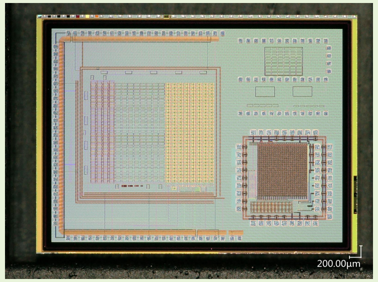
Parameter	UP Specification
Pixel size, square / rectangular	$\lesssim 85 \times 85\ \mu m^2$ / $\lesssim 50 \times 200\ \mu m^2$
Substrate thickness	$< 200\ \mu m$
Pixel orientation	x
Max. Particle Rate (R_{Part})	74(34) MHz/cm^2
Max. Hit Rate	150 Mhit $s^{-1}cm^{-2}$
Max. length of data word	32
Overall efficiency	>96%
In-time efficiency	>99% within 25 ns
Noise rate (End of life)	$\leq$ 400kHz/ cm^2
Transmission rate	$N \times 1.28$ Gbit/s
NIEL	$3 \times 10^{15} n_{eq}/cm^2$
TID	240 MRad
Power Consumption	$\leq$ 200 mW/ cm^2

- Development of High Voltage CMOS sensor with advanced process from domestic foundry
- Synergies with Mighty Tracker pixel part with other sensor candidates

COFFEE 2

First HVCMOS 55nm prototype chip

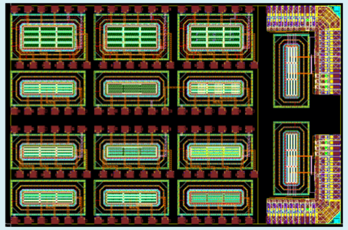
- Breakdown at -70V
- Responsive to laser, X-ray and beta-ray sources



… 2022 2023 2024 2025 …

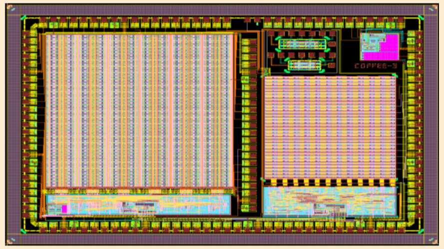
COFFEE1

- Prototype in LL process
- Validation of deep N-well structure
- Breakdown at -9V



COFFEE3

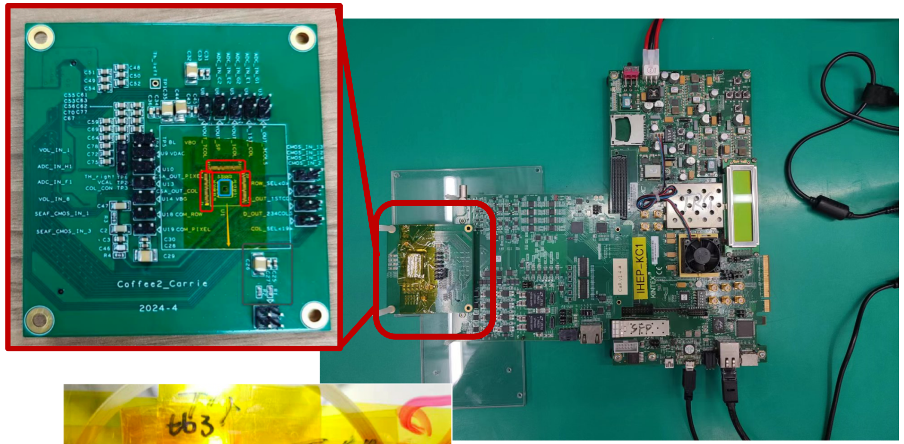
- Two pixel arrays with data-driven readout
- Designed for good timing resolution and moderate power consumption



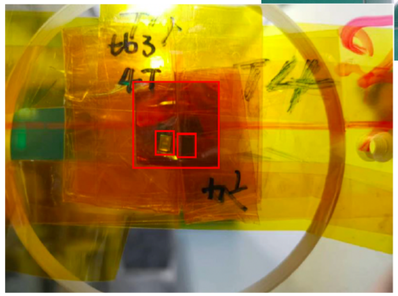
Large prototype planned around 2027

COFFEE2

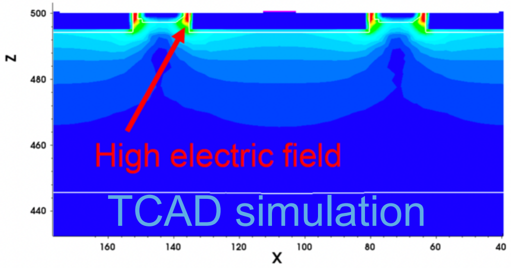
- COFFEE2 test verifies key functions of the process
  - IV shows breakdown at ~ - 70 V
  - Leakage current increased from 0.01 nA to ~1 nA after $10^{14} n_{eq}/cm^2$ radiation
  - Signals observed with in-pixel amplifier: laser / X-ray / beta-ray

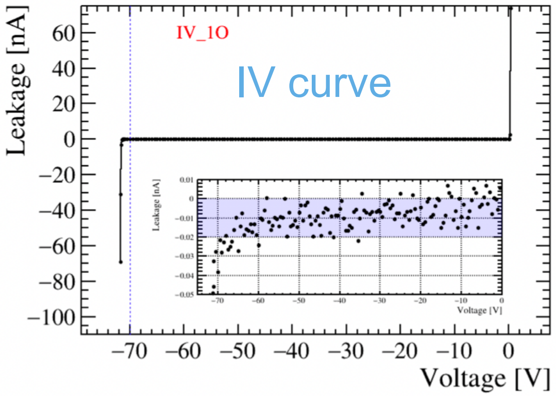


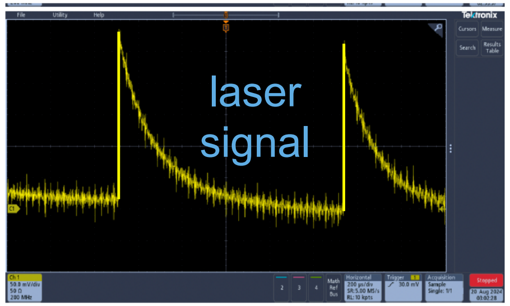
Lab test setup

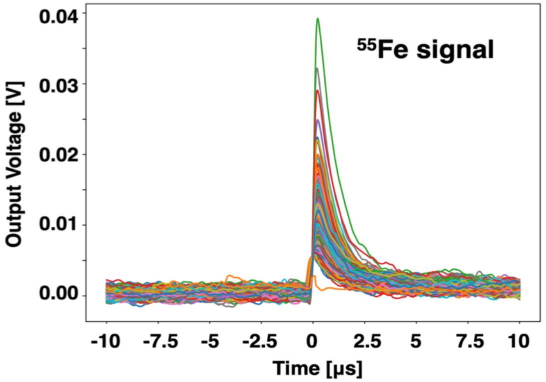


Irradiation setup



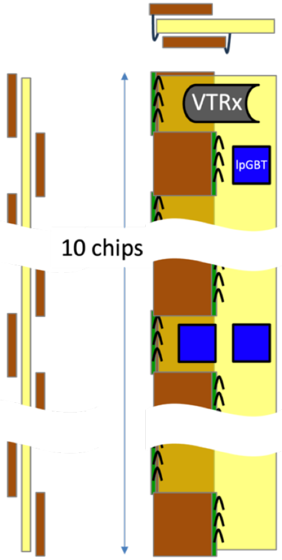






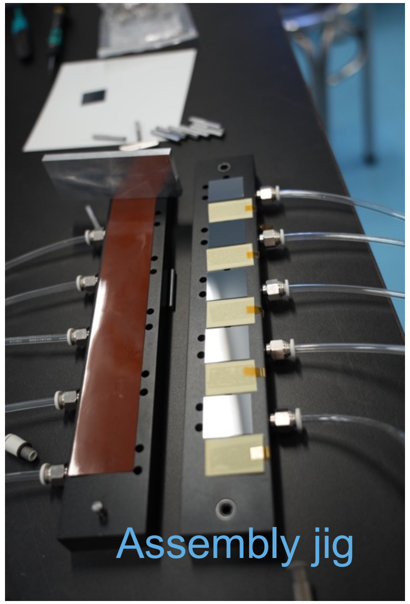
UP module and mechanics

- Module design updated to reduce dead area
- Prototyping starting with dummy components
  - Dummy silicon sensors produced with similar thermal mechanical properties
  - Tools designed for assembly procedure
  - Thermal simulation + market survey for realistic mechanical design

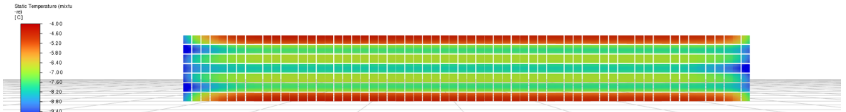


1st dummy sensor

1st dummy hybrid



Assembly jig



Thermal simulation of stave w. CO_2

1st dummy module assembled
Apr 2025

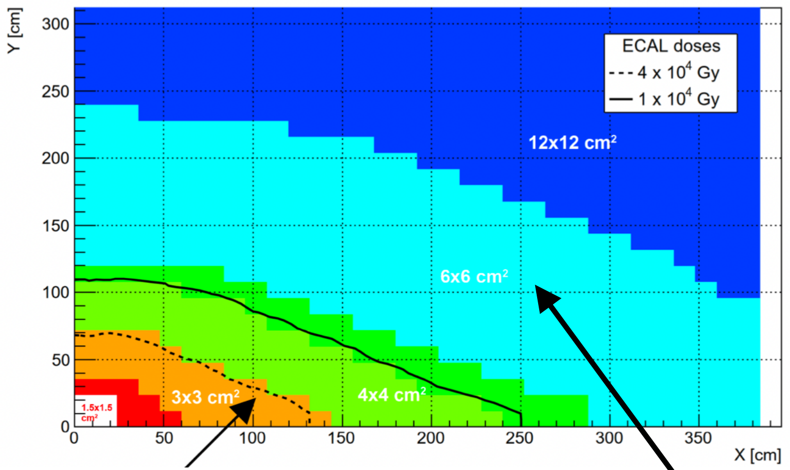
PicoCAL

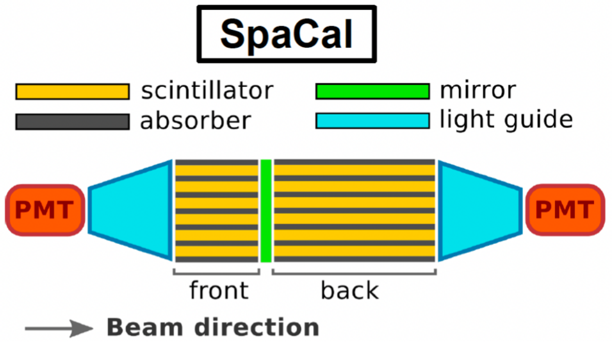
PicoCAL

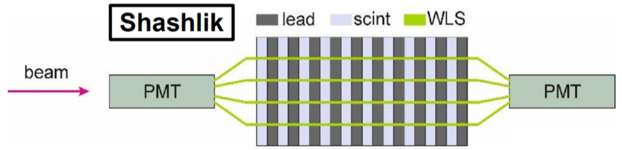
CERN-LHCC-2023-005

- Maintaining ECAL performance
- Inner part using SpaCal and outer keeps Shashlik technology
- Timing of O(10) ps expected

- Chinese groups active in the R&D:
  - Software and simulation
  - Fast GAGG crystal fibre development
  - 3D printed tungsten absorbers
  - Light-guide system development
  - LS3 SpaCal-W-Polystyrene module assembly
  - (just started) PMT R&D





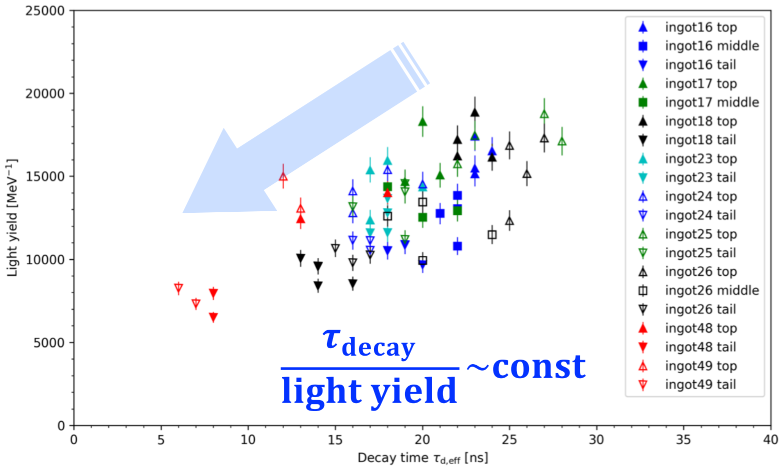


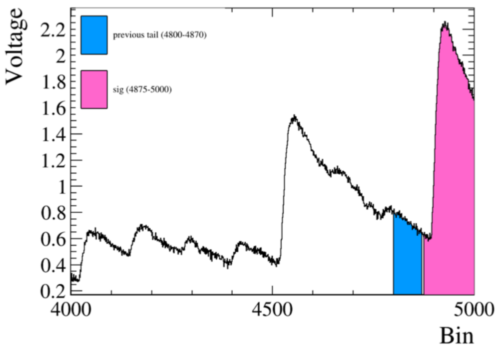
PicoCAL: progress

- Software and simulation
  - Performance studies for LHCb Upgrade II (U2) Scoping Document
  - Software development & optimization of reconstruction algorithm in full swing towards U2 TDR
- Fast GAGG crystal fibre development
  - Collaborating with SiPAT (电科芯片)+CERN starting from end of 2021
  - Gradually reducing effective decay time τ_{eff}: 50 ns (2022) → 20 ns (2024) → 8 ns (2025)
  - SpaCal-W-GAGG prototype with GAGG with $\tau_{\text{eff}} \approx 20\ \text{ns}$, testbeam at SPS+DESY in 2024
- 3D printed tungsten absorbers
  - Finalising details for PRR (Production Readiness Review) in June
- Light-guide system development
  - Light-guide design for LS4 and market investigation for material candidates in China
- LS3 SpaCal-W-Polystyrene module assembly
  - Module assembly starting from 1 cell, to 4 cells, and finally full-size (36 cells)
    - Many inputs for optimising the design and the assembly process
    - Beam-test planned at SPS end of May, results for EDR review in June
- PMT R&D: just started, collaborating with NNVT(北方夜视)+IHEP

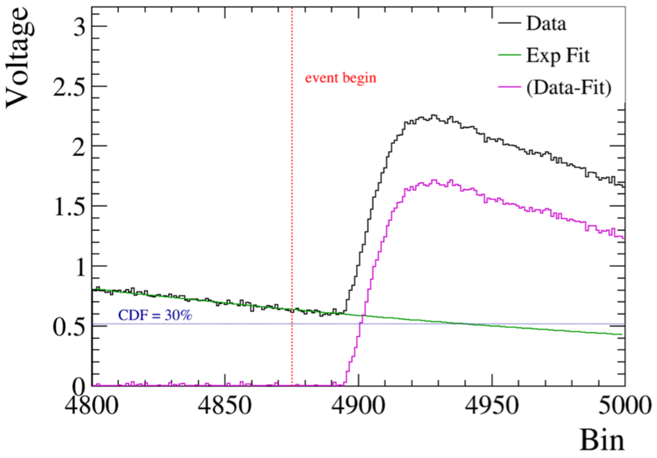
PicoCAL - simulation

- Material R&D: study of spill-over effect to identify target decay time of garnet crystal



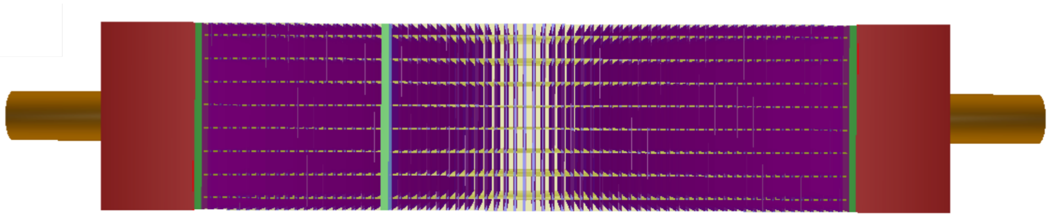


event train with bunch crossing of 25 ns

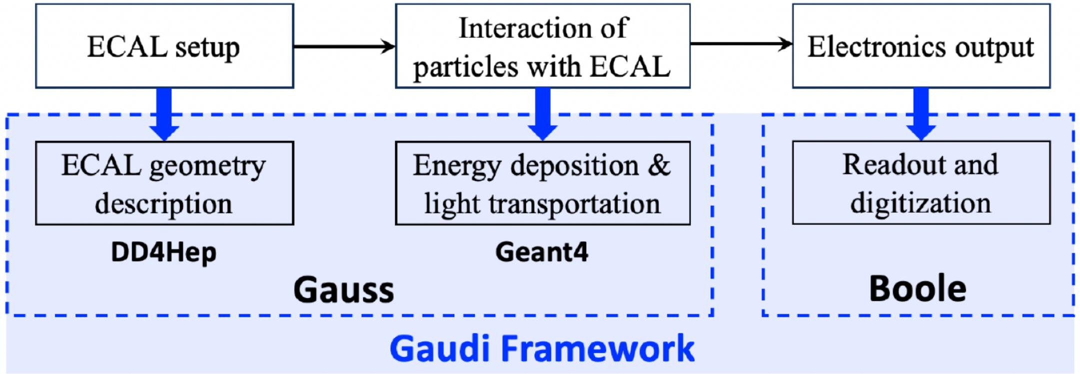


✓ spill-over effect on energy & time resolution being studied by subtracting contribution from previous events with exponential fit

- Construction of simulation in LHCb official framework

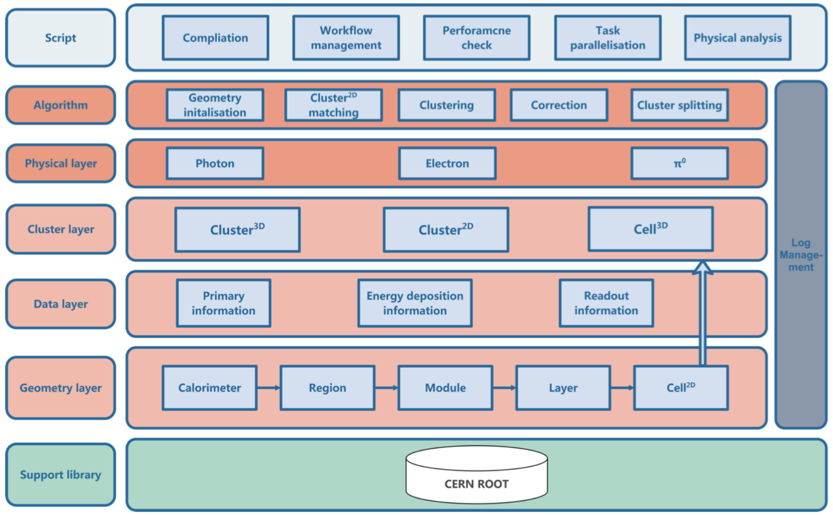


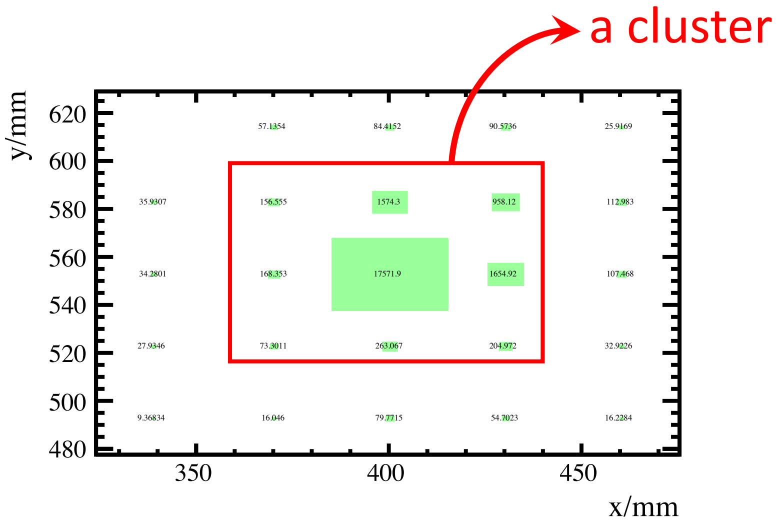
Shashlik module in DD4Hep



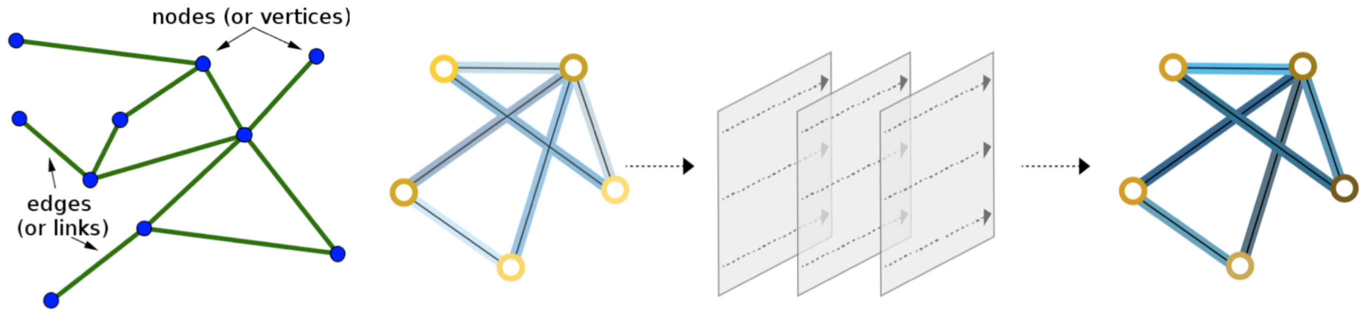
PicoCAL - reconstruction

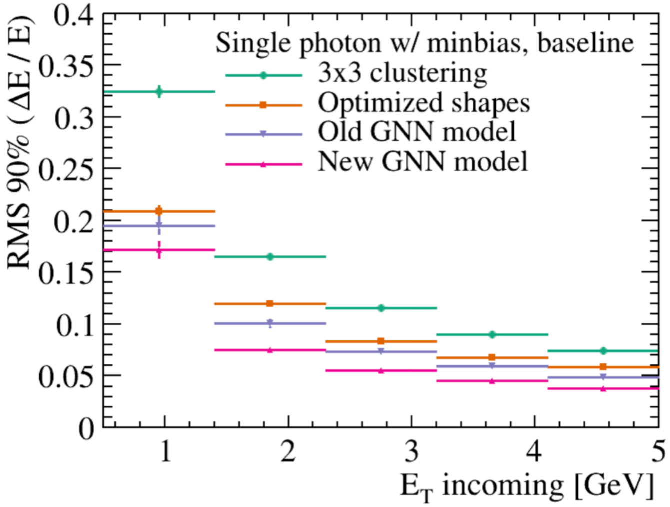
- Build-up of a working package based on ***layered*** ***3x3 (& optimized shapes) clustering***





- Development of ***machine learning approaches*** for clustering – ***GNN*** method





✓ Improved energy resolution wrt classic clustering

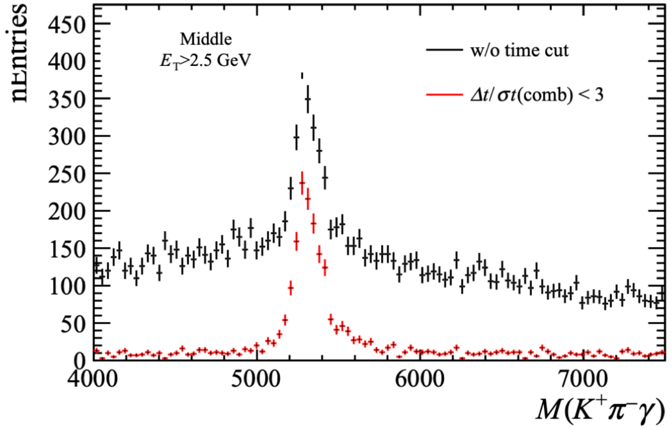
PicoCAL - performance

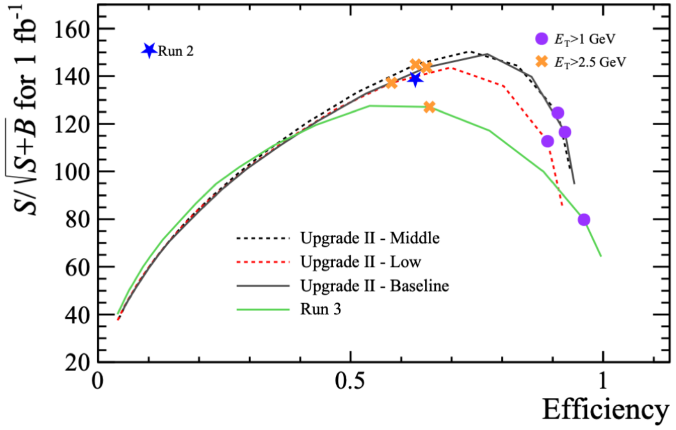
- Performance compared between different scenarios for benchmarking physics modes

Baseline	Middle	Low
$1.5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$	$1.0 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
	PicoCal	
40 SpaCal-W	40 SpaCal-W	40 SpaCal-W
408 SpaCal-Pb	408 SpaCal-Pb	408 SpaCal-Pb
2864 Shashlik	2864 Shashlik	2864 Shashlik
double R/O	double R/O	single R/O except 176 inner
30,976 channels	30,976 channels	20,224 channels

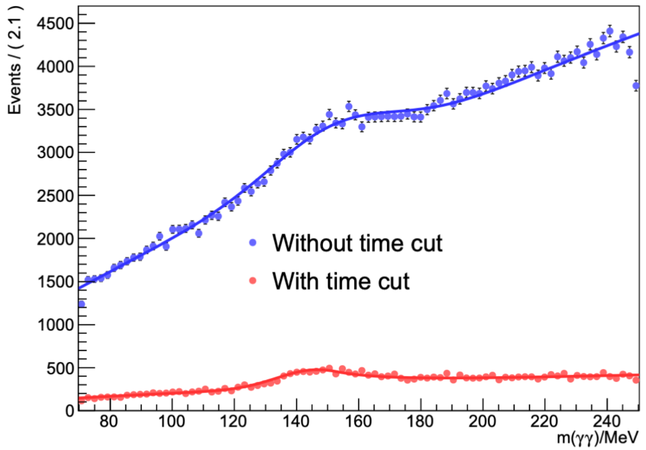
- Studies based on *3x3 clustering approach*
- ***Timing information*** plays a critical role in background reduction
- Results included in ***LHCb Upgrade II Scoping Document*** [CERN-LHCC-2024-010, LHCb-TDR-026]

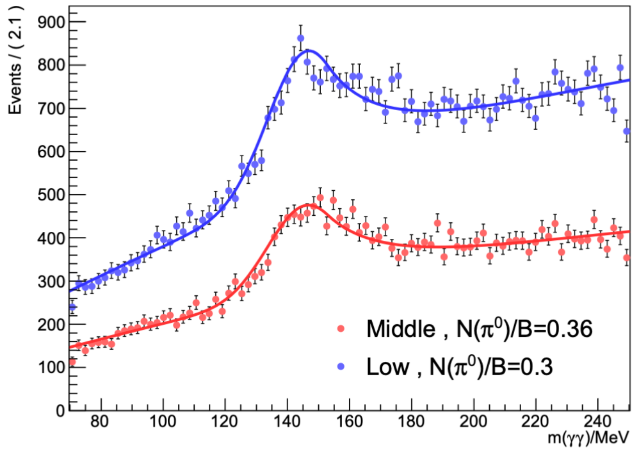
$B^0 \rightarrow K^{*0}\gamma$





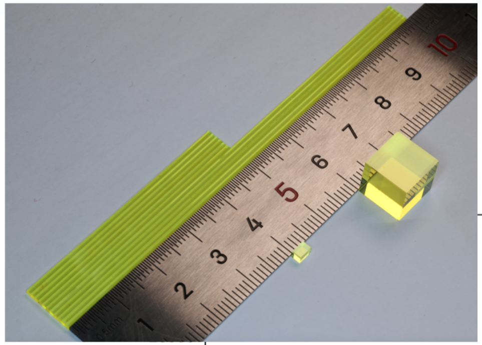
$D^0 \rightarrow \pi^+\pi^-\pi^0$

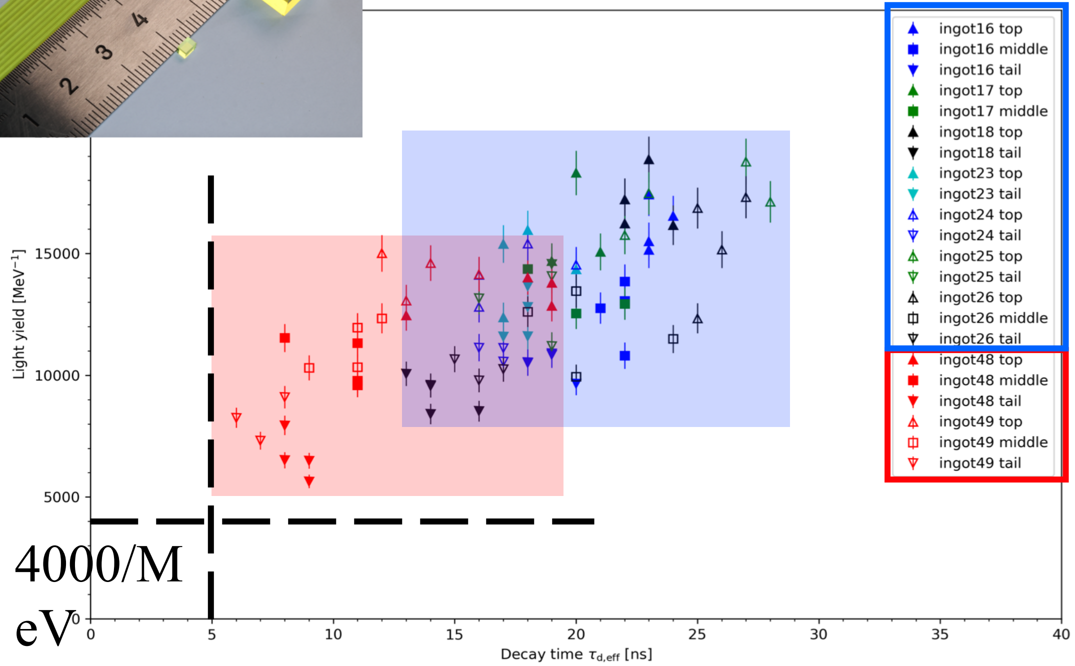




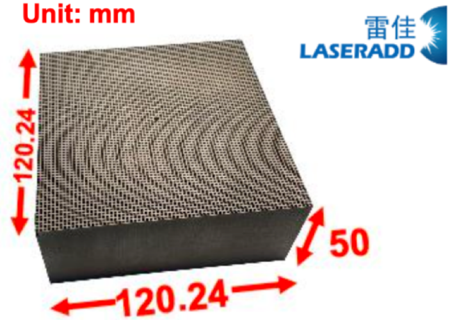
Fast GAGG R&D

- Continued progress on timing under close collaboration with SIPAT (电科芯片) and CERN
  - Started with $\tau_{d,eff}$ ~ 50 ns in end of 2021
  - Characterize at PKU and CERN
  - $\tau_{d,eff}$ down to 20 ns in Mar. 2024
  - Fibres produced/tested for testbeam with SpaCal-W-GAGG prototype (2024.06 at SPS + 2024.11 at DESY)
  - Latest GAGG samples: $\boldsymbol{\tau_{d,eff}}$ **~ 8 ns** with light yield ~7500 MeV^{-1} in Jan 2025
- Meanwhile, improving ingot growth process to for homogeneity

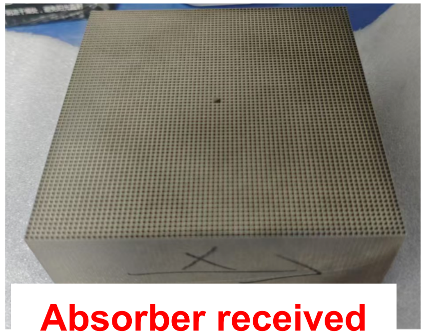




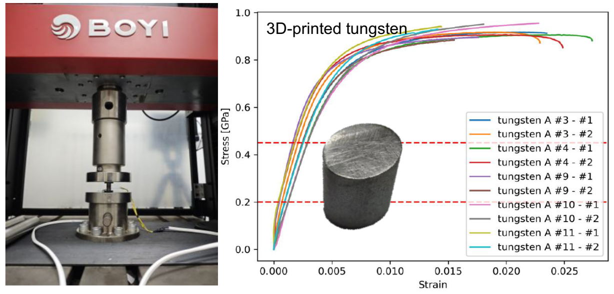
3D printed tungsten absorber



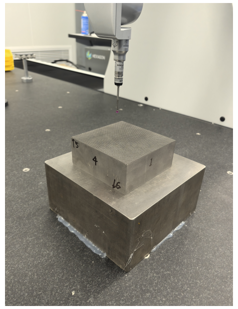
- Requirements
  - High density: close to $\rho_W = 19.3\ \mathrm{g/cm^3}$
  - Geometry: $120\times120\times50\ \mathrm{mm^3}$
  - 5180 square holes of $1.20\times1.20\ \mathrm{mm^2}$
  - Roughness $R_a < 5\ \mathrm{\mu m}$
- LaserAdd (雷佳) gradually improved the W absorbers
  - $\rho \approx 19.0\ \mathrm{g/cm^3}$, $R_a \approx 4\ \mathrm{\mu m}$
  - Young’s module measured at THU, WHU, CERN
- We are finalizing all tests and QA system for PRR in June



Absorber received 4 April 2025



Young’s module measurement at THU

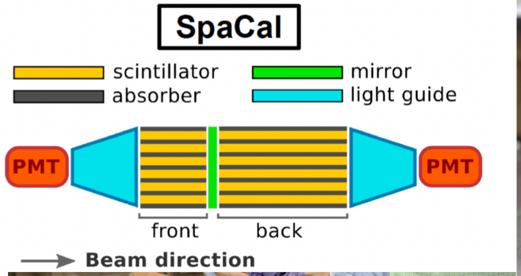


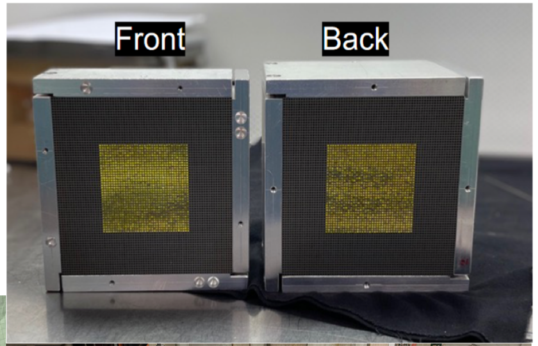
Plane	Angle (°)	
	5# at top	6# at top
1⊥2	89.9	90.1
2⊥3	90.0	90.0
3⊥4	90.0	90.1
4⊥1	90.1	89.9
5⊥1 or 6⊥1	90.1	90.0
5⊥2 or 6⊥2	90.0	90.0
5⊥3 or 6⊥3	90.1	90.0
5⊥4 or 6⊥4	90.1	90.0

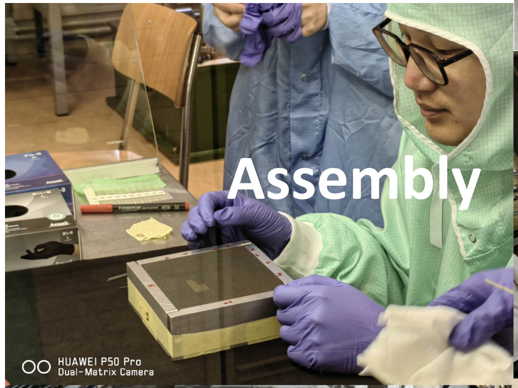
Perpendicularity measurement at WHU

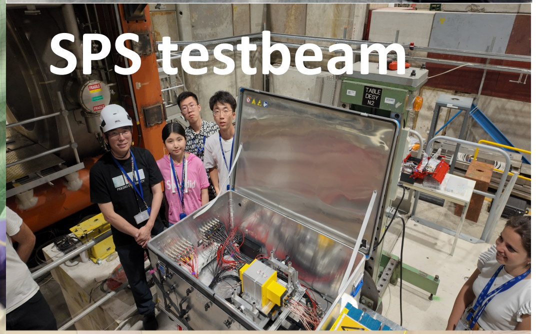
SpaCal-W-GAGG testbeam @ SPS & DESY

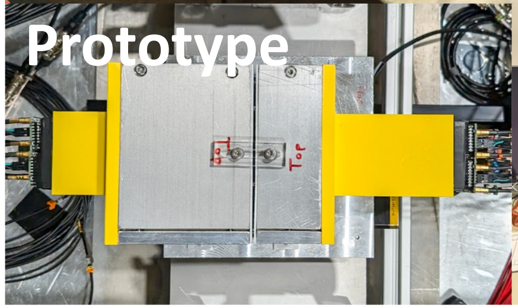
- First SPACAL-W-GAGG prototype assembled in May 2024
  - Size： $\mathbf{120.24 \times 120.24 \times 150\ mm^3}$, split with two halves (50mm front + 100 mm back)
  - $\mathbf{4 \times 4}$ cells with GAGG fibres from SIPAT (电科芯片), absorbers from LaserAdd (雷佳）
  - PMT and Light guides provided by CERN:
    - 8 x Multi-anode PMT R7600U-00-M4
    - Asymmetric LGs: square to square
    - double-side readout
- Performance of prototype tested in testbeams
  - DESY(Dec 2024): 1 – 5 GeV electron
  - SPS (May 2024): 20 – 100 GeV electron
  - Energy resolution and time resolution measured

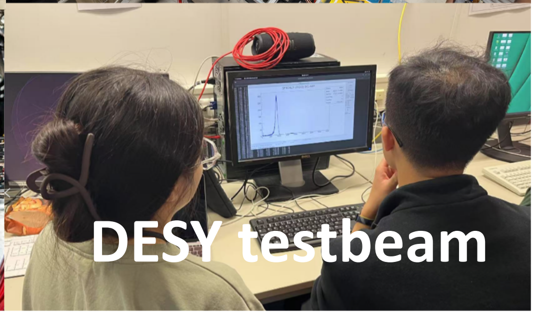










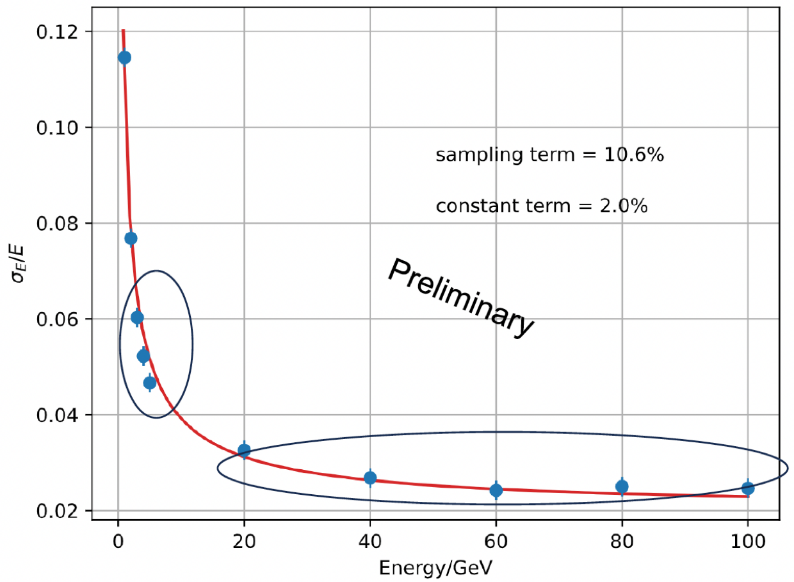


SpaCal-W-GAGG testbeam @ SPS & DESY

Energy resolution

$\sigma_E/E = 10.6\% \oplus 2\%$

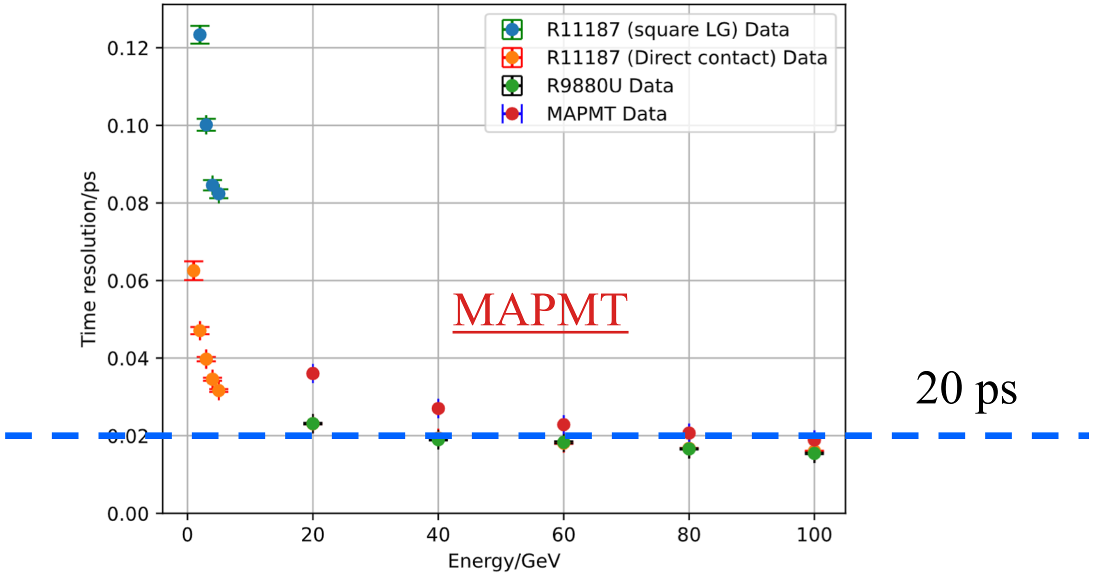
(Target: $\sigma_E/E = 10\% \oplus 1\%$)



Time resolution with different PMTs

R11187 (Direct contact) and R9880U have similar performance (**<20 ps for E > 20 GeV**)

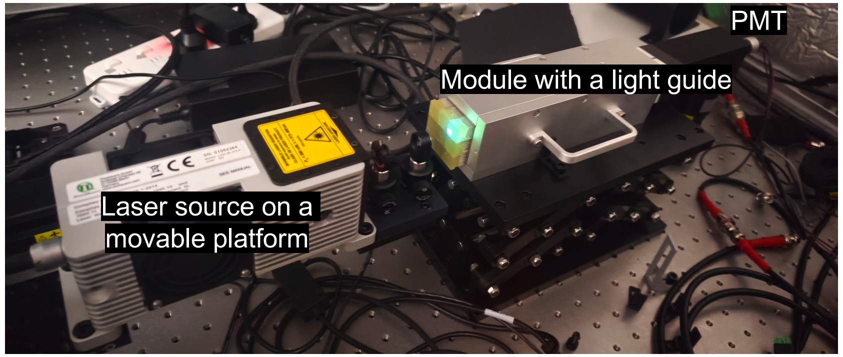
MAPMT and R11187 (square LG and only front part) much worse in time resolution



Could be improved with more suitable PMT and light guides

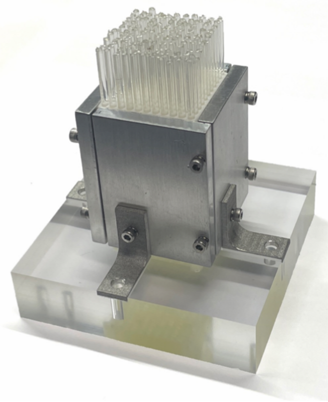
SpaCal-W-Poly module assembly

- Preparation for assembly of SpaCal-W-Polystyrene in China started in the end of 2024
  - PKU + THU + WHU +SCNU
- From Dec. 2024 to Apr. 2025, a series of modules were made to test and optimize the assembly procedures
  - Gluing, bundling, milling, ...
- In Mar. 2025, a module response uniformity test system was established at PKU

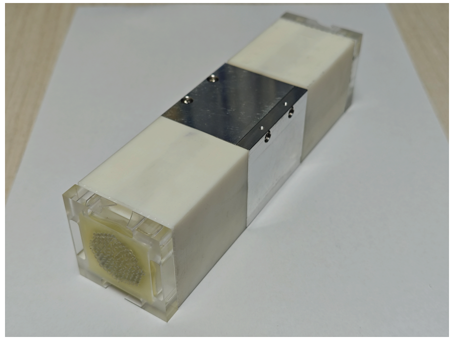


Module response uniformity test system

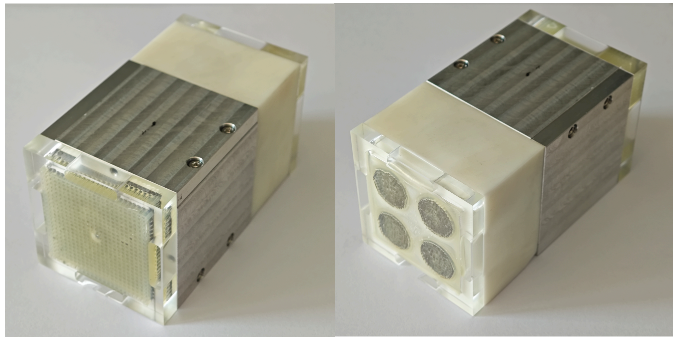
Module for gluing test



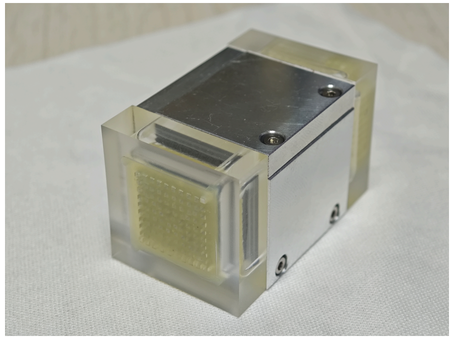
1-cell module for bundling and milling test



4-cell module for bundling and milling test

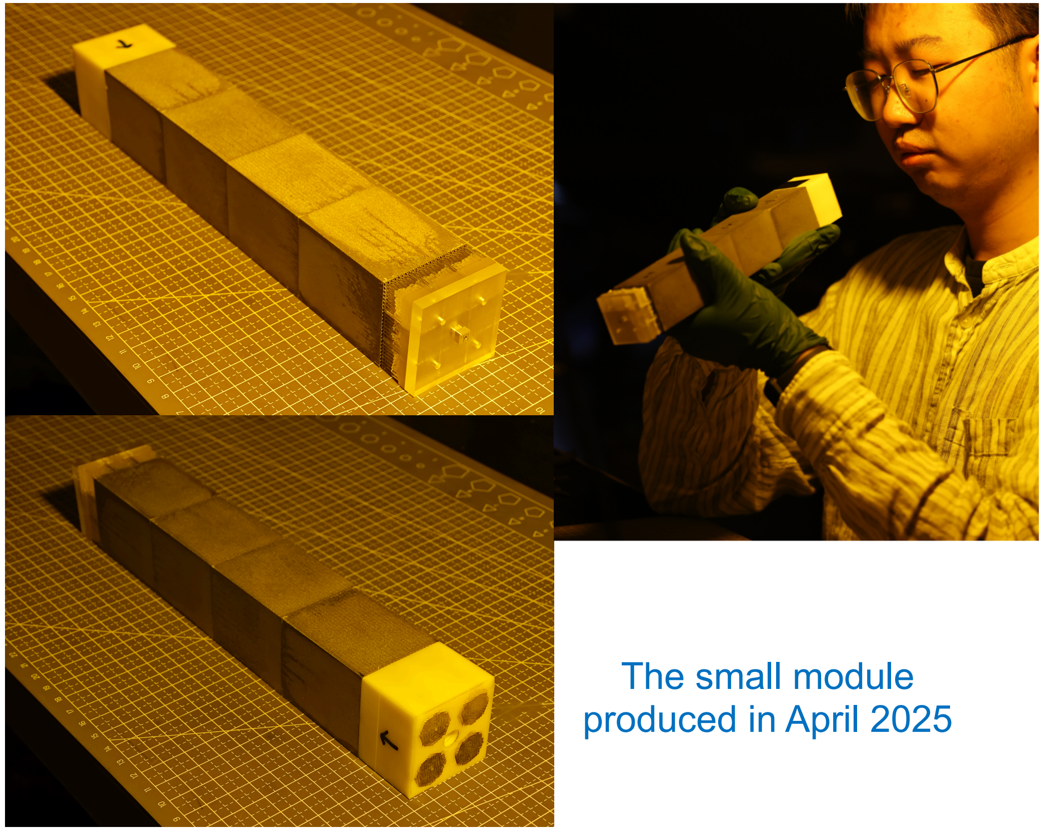


Module for milling quality inspection

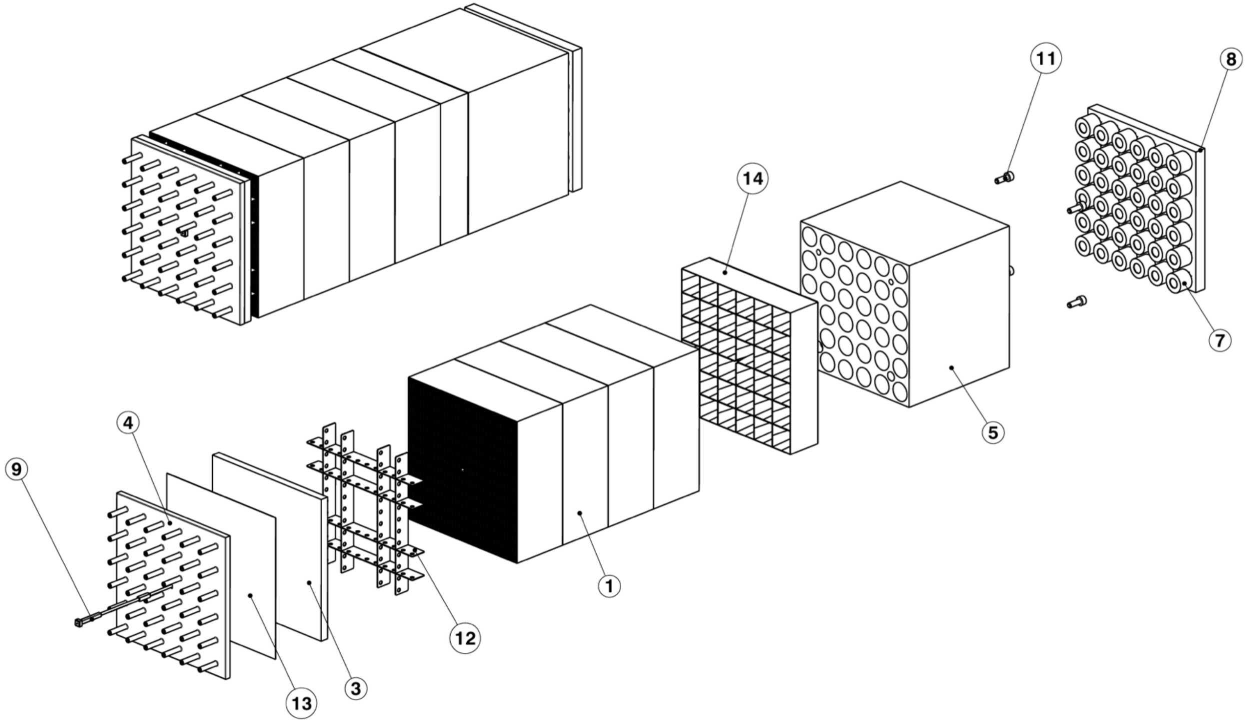


SPACAL-W-Poly module assembly

- Getting ready for the mass production in the second half of 2025
  - April 2025: a small module containing most of the designed elements was produced in Beijing.
  - May 2025: a full-size module will be produced and to be tested at CERN SPS testbeam.



The small module produced in April 2025



The structure design of the SPACAL-W-Poly module

To conclude …

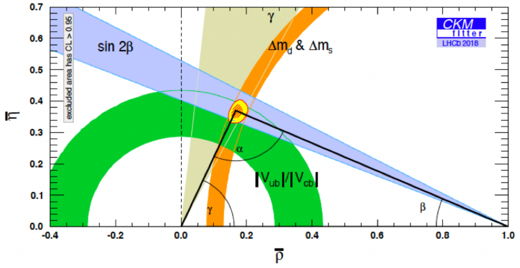
Physics Prospects

- Statistics is powerful
- Some gain can be expected

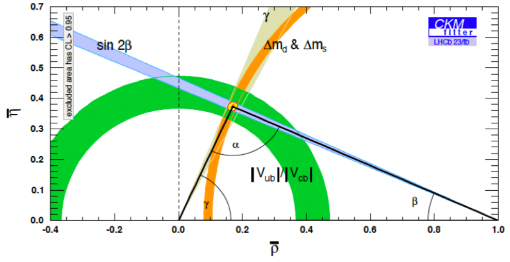
Observable	LHCb current	LHCb (23 fb^{-1})	LHCb (300 fb^{-1})
CKM tests			
γ (all modes)	4° [784, 931]	1.5°	0.35°
γ ($B_s^0 \to D_s^+ K^-$)	$(^{+17}_{-22})^\circ$	4°	1°
$\sin 2\beta$	0.04 [932]	0.011	0.003
ϕ_s ($B_s^0 \to J/\psi \phi$)	49 mrad [933]	14 mrad	4 mrad
ϕ_s ($B_s^0 \to D_s^+ D_s^-$)	170 mrad [825]	35 mrad	9 mrad
$\phi_s^{s\bar{s}s}$ ($B_s^0 \to \phi\phi$)	154 mrad [936]	39 mrad	11 mrad
a_{sl}^s	33×10^{-4} [938]	10×10^{-4}	3×10^{-4}
$\lvert V_{ub}\rvert / \lvert V_{cb}\rvert$	6% [847]	3%	1%
Charm			
$\Delta\mathcal{A}^{CP}$	2.9×10^{-4} [790]	1.7×10^{-4}	3.0×10^{-5}
A_Γ	1.3×10^{-4} [877]	4.2×10^{-5}	1.0×10^{-5}
$B^0_{(s)} \to \mu^+\mu^-$			
$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}$	71% [661, 662]	34%	10%
$\tau_{B_s^0 \to \mu^+\mu^-}$	14% [661, 662]	8%	2%
EW penguins			
R_K ($B^+ \to K^+ \ell^+ \ell^-$)	0.044 [703]	0.025	0.007
R_{K^*} ($B^0 \to K^{*0} \ell^+ \ell^-$)	0.10 [709]	0.031	0.008
LFU tests			
R_{D^*} ($B^0 \to D^{*-} \ell^+ \nu$)	0.026 [941, 942]	0.007	0.002
$R_{J/\psi}$ ($B_c^+ \to J/\psi \ell^+ \nu$)	0.24 [943]	0.07	0.02

Physics case for Upgrade II, CERN-LHCC-2018-027, arXiv:1808.08865
Chen et al, Frontiers of Physics 18 (2023) 44601

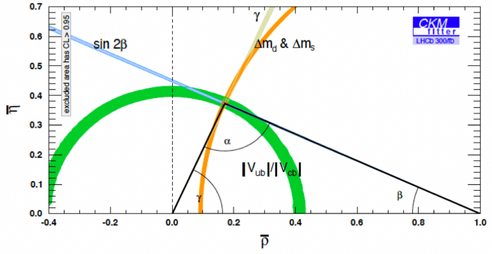
Run 2



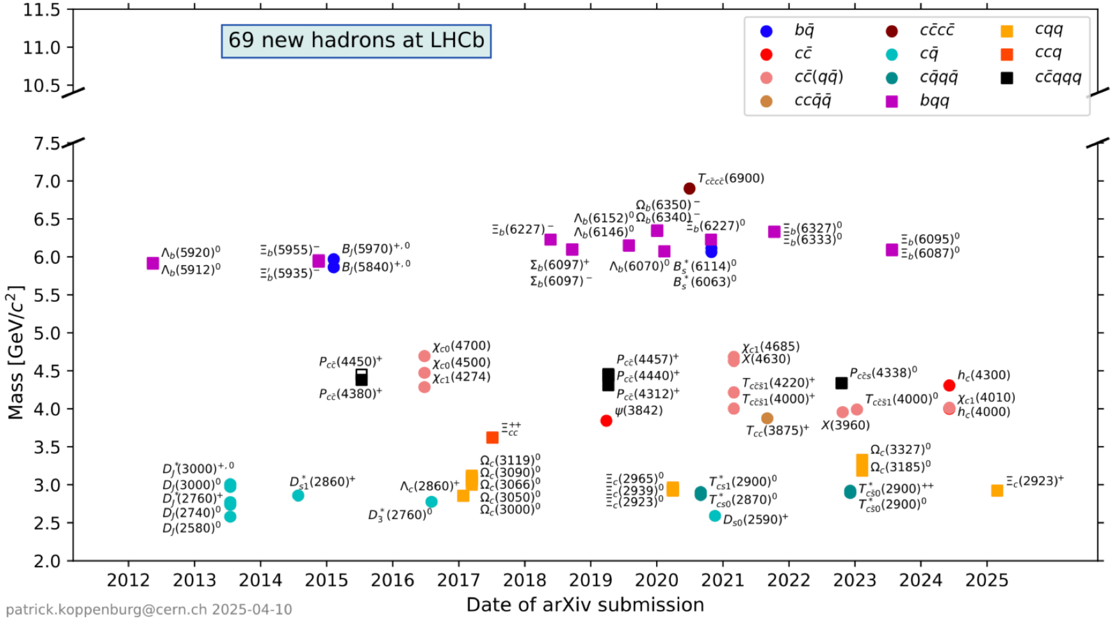
Run 3



Upgrade II



- Some not



https://www.nikhef.nl/%7Epkoppenb/particles.html

??

Baryons?
(bqq, ccq,
bcq, bbq,…)

Tetraquark?

Pentaquarks?

Summary

- LHCb upgrade I is completed and continues to take high-quality physics data
- R&D ongoing for Upgrade II, LHCb-China are key players in UP and PicoCAL
- A lot more data and potential for physics output, interplay with theory community more important than ever

Thank you for your time!

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Reference

- LHCb探测器及升级计划，科学通报 2024,69（31）：4529
- The LHCb Upgrade I, JINST 19 (2024) P05065
- LHCb Upgrade II Scoping Document, CERN-LHCC-2024-010
- LHCb Framework TDR for the LHCb Upgrade II, CERN-LHCC-2021-012
- Physics case for an LHCb Upgrade II – Opportunities in flavour physics, and beyond, in the HL-LHC era, arXiv:1808.08865