Recent results by the CMS group

90th Meeting of the Physics Research Committee

Patrick L.S. Connor

on behalf of
the CMS group

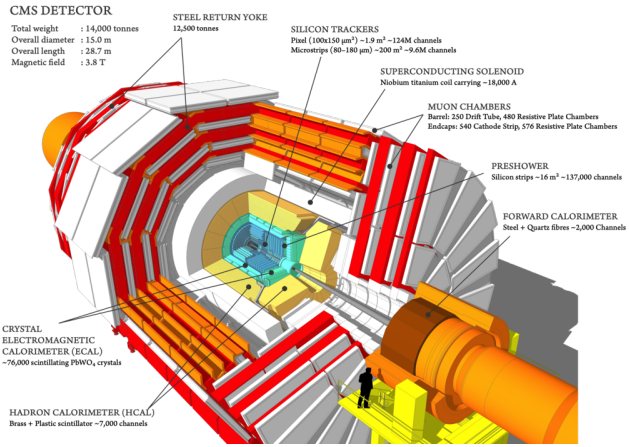
Deutsches Elektronen-Synchrotron
Hamburg

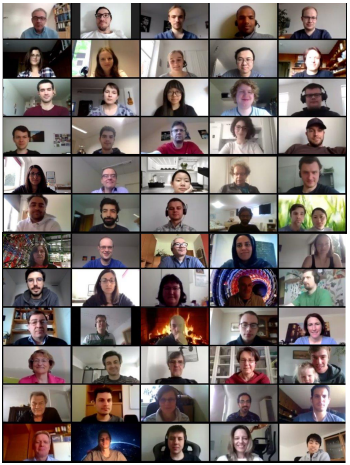
5 November 2020

Outline

- LHC status
- Physics analysis
- Tracker alignment
- Luminosity monitoring
- Generic R&D
- Phase-2 upgrade

Note: acronyms & references are clickable and defined in appendix.





LHC status.

LHC status

Schedule

- Beam test from 27 September to 10 October 2021.
- Injectors will have YETS from week 41 (2021) to week 4 (2022).
- ~~Early start in November 2021~~
- Close experimental caverns on 1 February 2022.
- Start with HL pp collisions in April.

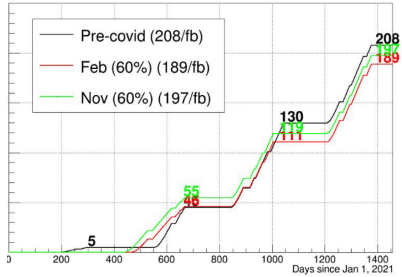
$\longrightarrow$ Review situation mid of March 2021.

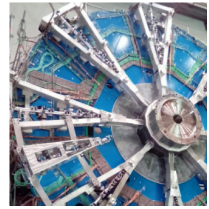
Goal for 2022

- Targeting $\mathcal{O}(50\ \mathrm{fb}^{-1})$
- Similar PU as in 2018

Impact on Detector upgrades

- ATLAS installs NSW
- CMS installs new shielding
- ALICE & LHCb complete their Phase-1 upgrades





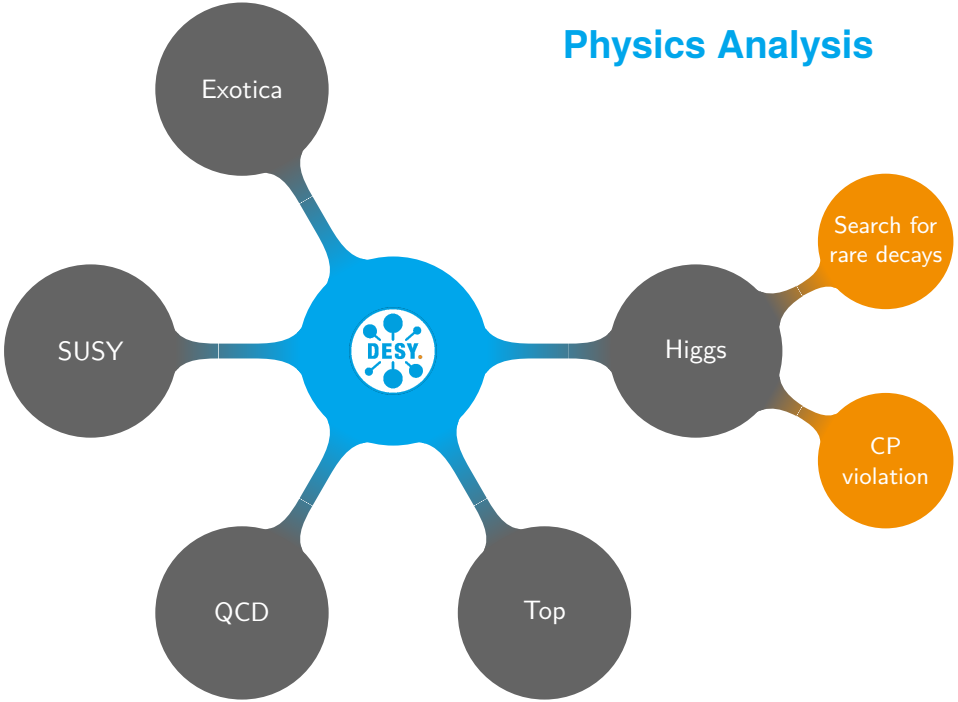
Physics Analysis.

Ongoing analyses

$H \to Z\rho, Z\phi$

$H\tau\tau$ Yukawa coupling

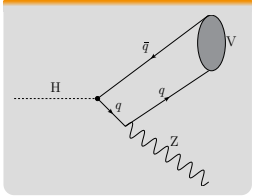
Physics Analysis



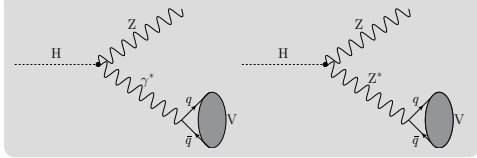
Physics Analysis

Search for rare decays in $H \to Z\rho, Z\phi$

Suppressed channel



Dominant channel



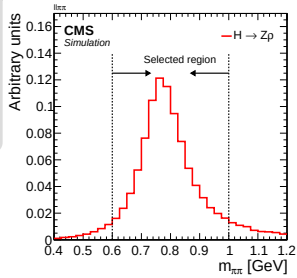
First experimental limits [1]

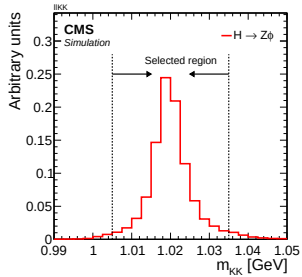
Novel analysis setting limits on BRs of decay modes $\rho \to \pi\pi$ & $\phi \to KK$.

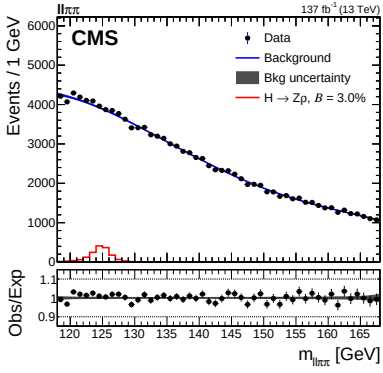
$\longrightarrow$ An enhancement would be an indication for physics BSM.

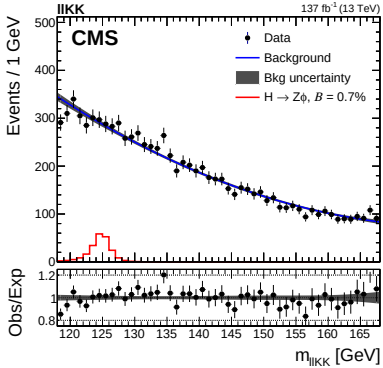
Selection

- Select di-lepton events with $60\ \text{GeV} < m_{ll} < 120\ \text{GeV}$
- Select track pairs of opposite charges with $\Delta R < 0.1$ ($p_T^{\text{leading}} > 10\ \text{GeV}$, $p_T^{\text{subleading}} > 1\ \text{GeV}$)
- Require track pair isolation.
- Apply meson mass window.









Physics Analysis

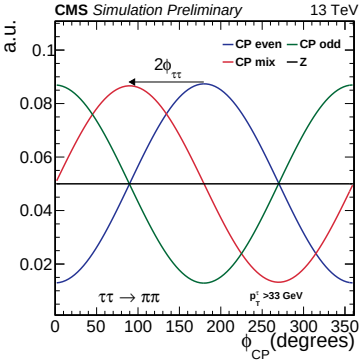
Search for rare decays in $H \to Z\rho, Z\phi$

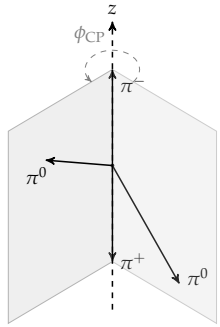
Procedure & result

- Fit $m(ll\pi\pi)$ and $m(llKK)$ to extract the signal.
- Upper limits on BR depend on polarisation.

Published results

	Prediction	Upper limits at 95% CL
$\mathcal{B}(Z\rho)$	$(1.4 \pm 0.1) \times 10^{-5}$	$0.0105 - 0.0131$
$\mathcal{B}(Z\phi)$	$(4.2 \pm 0.3) \times 10^{-6}$	$0.0031 - 0.0040$





Physics Analysis

CP structure of $H\tau\tau$ Yukawa coupling

Context & Methodology [2]

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}\left(\underbrace{\kappa_\tau \bar{\tau}\tau}_{\text{SM}} + \underbrace{\tilde{\kappa}_\tau i\bar{\tau}\gamma_5\tau}_{\text{BSM}}\right)$$

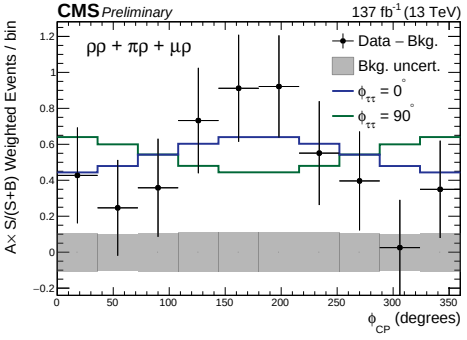
- Parameterise CP even and odd couplings via the mixing angle $\phi_{\tau\tau}$:

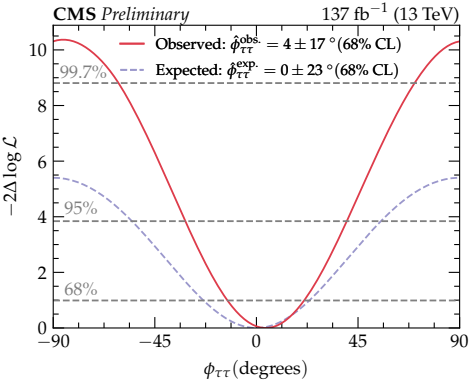
$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- The CP information is transferred to spin correlations of the two τs.
  $\longrightarrow$ Probe structure via angle ϕ_{CP} between the **decay planes** of the τs.
- Utilise ML techniques to optimise S/B.
  $\longrightarrow$ $Z \to \tau\tau$, $H \to \tau\tau$, fake τs.

Physics Analysis

CP structure of $H\tau\tau$ Yukawa coupling





Results

We distinguish CP-even from CP-odd with observed (expected) sensitivity of 3.2 (2.3) σ:

- Fully consistent with SM
- Excludes next-to-minimal SUSY model in this phase space

$\longrightarrow$ Leading uncertainty is statistical.

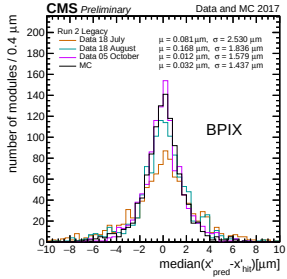
Tracker Alignment.

Run-2
Developments

$$\chi^2(\mathrm{p},\mathrm{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \left(\frac{m_{ij} - f_{ij}(\mathrm{p},\mathrm{q}_j)}{\sigma_{ij}^{\mathrm{m}}} \right)^2$$

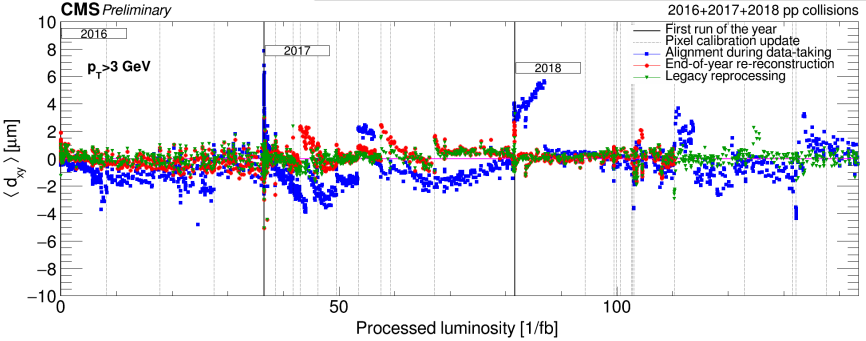
Tracker Alignment

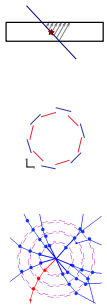
Run-2



Strategies & Performance [3, 4, 5]

- Significantly deeper understanding of alignment w.r.t. Run-1, in particular in context of high-radiation environment.
- Include a comparison to performance in MC.
- Describe **automated / online alignment**, **first high-precision alignment** (used for most published analyses) & **Legacy alignment** (for most upcoming measurements as well as Open Data).



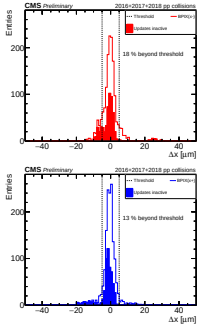


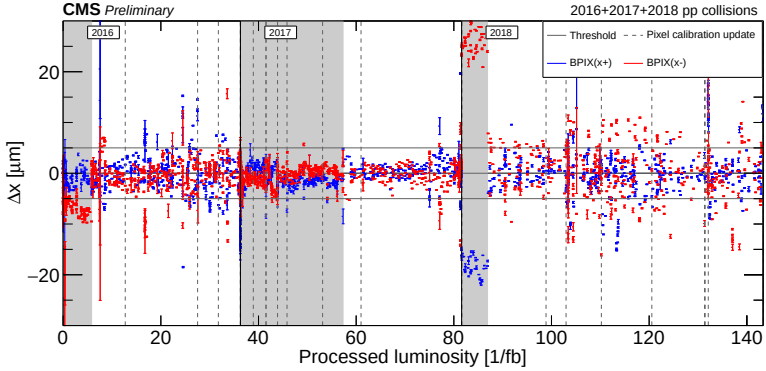
Tracker Alignment

Recent development with MillePede-II

Developments

- Re-organise part of the implementation (caching, sparsity, vectorisation)
- Parallelisation (in particular, porting to GPUs)





Online alignment

- Run-2 automated alignment had very few degrees of freedom.
- Working on more elaborated online alignment to follow faster changes in the detector.

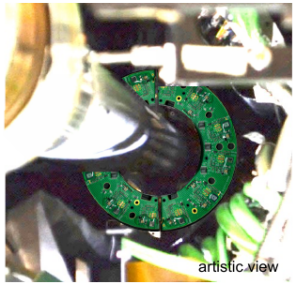
Luminosity monitoring.

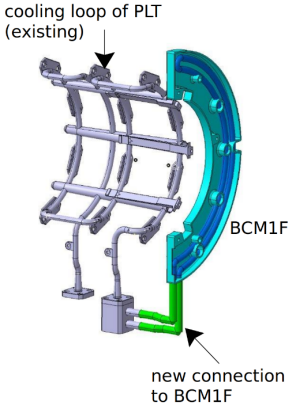
Context

Recent progresses

Luminosity monitoring

Context





Reminder

- BCM1F: bunch-by-bunch online luminosity measurement.
  - 2×2 *C-shape* PCBs directly surrounding the beam pipe at $1.8\ \mathrm{m}$ from the IP on each side.
  - Each C-shape PCB includes 6 sensors, *i.e.* 12 channels.
- Run-3 upgrade: replace diamond sensors by silicon sensors.
  - Better S/N.
  - Active cooling
  - AC-coupled read-out.

$\longrightarrow$ *collaboration with CERN*

DESY's contributions

- Dicing and testing sensors.
- SMD assembly.
- ASIC bonding on PCB.
- 3D-printed covers.

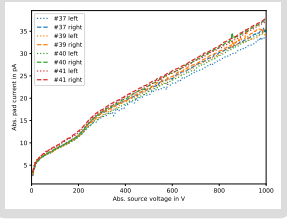
Luminosity monitoring

Recent progresses

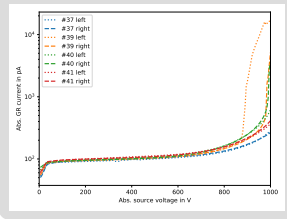
BCM1F upgrade for Run-3

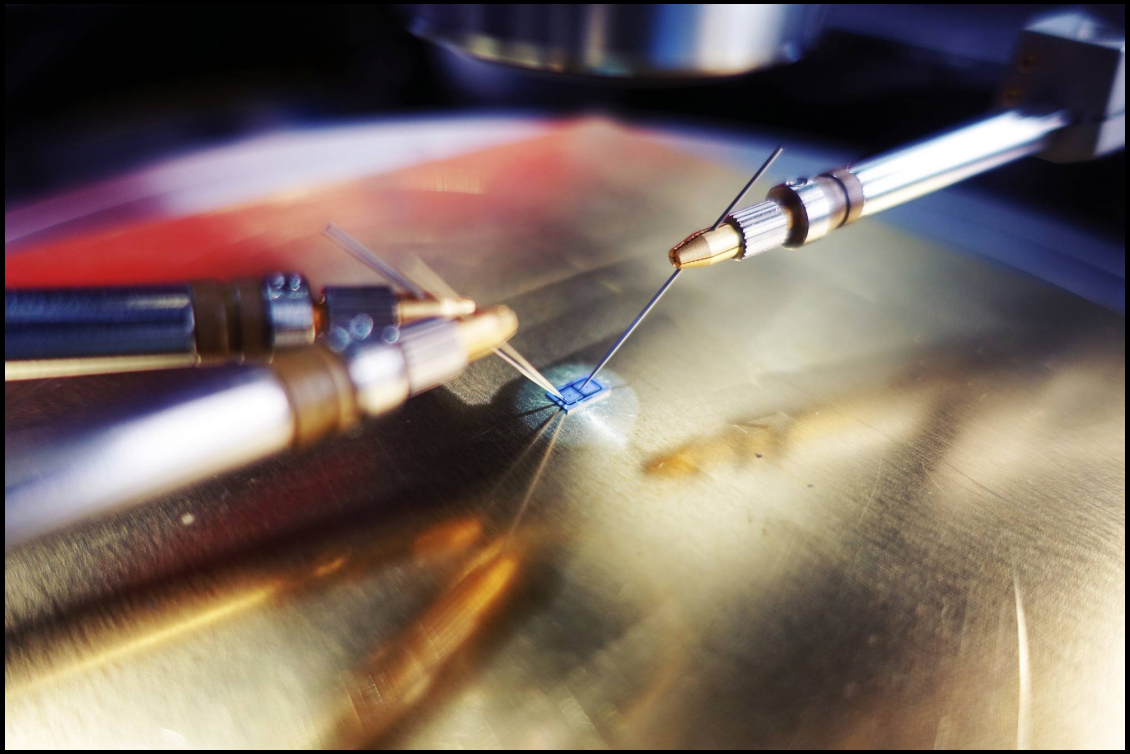
- Protection cover for transportation (upper left picture).
- Double-diodes produced on upgrade-tracker wafer « half-moons » (middle left picture).
- Sensor dicing (lower left picture) and characterisation at DESY (bottom right diagrams & picture on next slide)
  - 25 double-pad sensors tested so far: found similar behaviour.
  - ~ 50 more wafer half-moon sensors just shipped from Vienna.

Pads



Guard rings





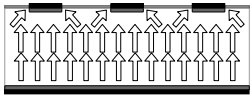
Generic Detector R&D.

Enhanced Lateral Drift Sensor

Electron CT

Generic Detector R&D

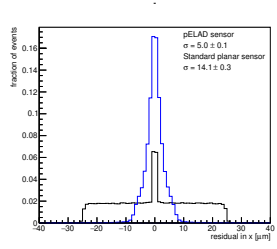
Enhanced Lateral Drift Sensor



Concept (developed in DESY)

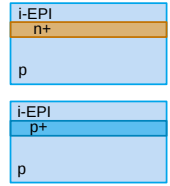
Modified electric field (⇑) in the **lateral** direction results in charge sharing at almost any MIP incident position.

⟶ Almost $3\times$ better position resolution at 150 µm detector thickness.

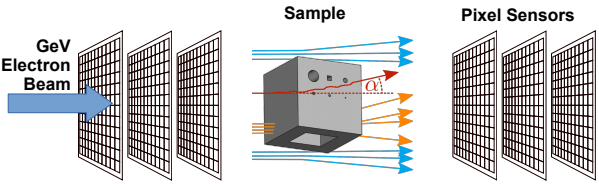


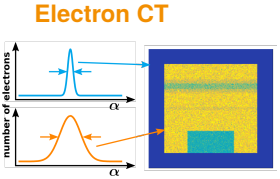
Status

- **Test structure** with one buried layer (produced in collaboration with the industry).
  ⟶ Doping profile within specifications.
- **Wafer layout** with three buried layers ready for production including different types of modules (pixels, strips, diodes).



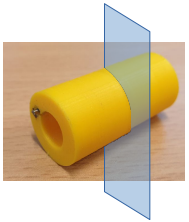
Generic Detector R&D





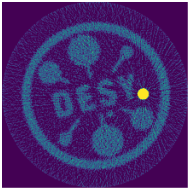
Concept (developed in DESY)

- Based on **multiple Coulomb scattering** in matter.
- Measure trajectory of electrons for $\neq$ incident angles (using GBL).
- Calculate width of angular distribution per pixel.
- **Iterative image reconstruction** using statistical method.



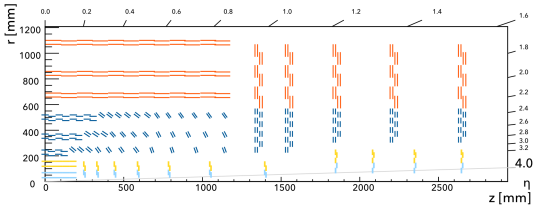
Applications

- This novel technique with electrons (instead of standard CT with photons) can be applied to objects with more material budget.
- The more material budget, the higher the beam energy should be.
- Investigating potential applications in medical physics with 200-MeV electrons.



Tracker Phase-2.

Reminder
2S module
PS module
Dee prototype
Disk integration

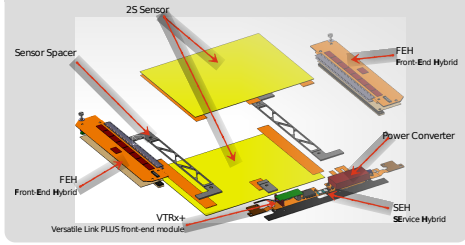


Tracker Phase-2

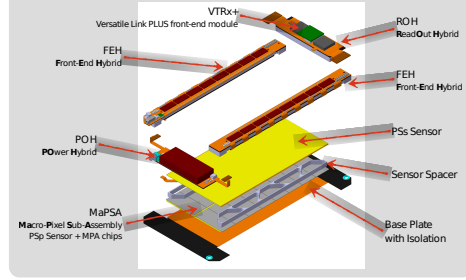
End-cap structure

end-cap 5 double-disks
double-disk 4 Dees
Dee (equipped with) PS + 2S modules

2S module (red)



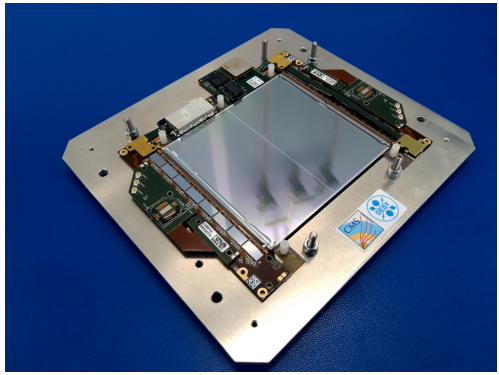
PS module (blue)



DESY's major contributions

- Design of 2S & PS modules.
- Production of 1250 PS modules.
- Integration of one TEDD.

$\longrightarrow$ *close collaboration with Karlsruhe, Aachen, Louvain & Lyon*



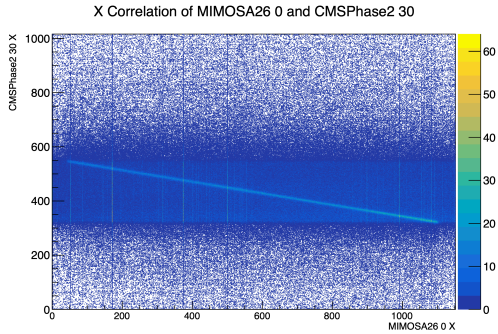
Tracker Phase-2

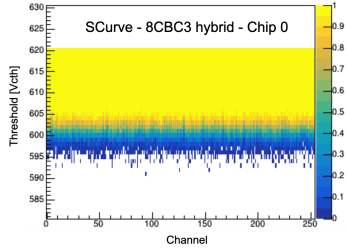
2S module

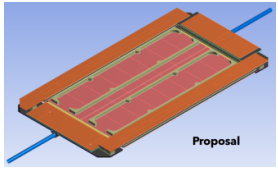
First functional 2S module built

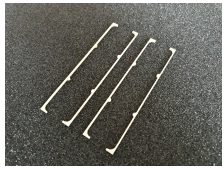
- Testing and tuning of module in DAF successful.
- Test beam measurements took place last week.
  $\longrightarrow$ correlation between module and telescope seen, but synchronization lost regularly.

$\longrightarrow$ Investigations will continue in the coming weeks!



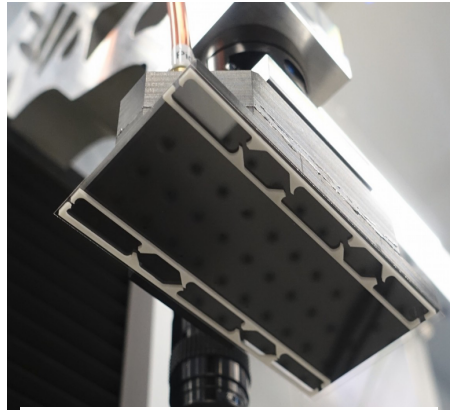






Tracker Phase-2

PS module



During assembly of glass prototype:
Lowering [PSs + 4 spacers] onto [MaPSA + baseplate]

Module design (top left pictures)

- Substantial increase of *power consumption estimates* for front-end electronics & expected fluences w.r.t. previous estimates.
  $\longrightarrow$ R&D effort in order to improve thermal performance of modules and support structures.
- New design includes four spacers (instead of two).
  $\longrightarrow$ More homogeneous heat transfer for nearly same material budget.

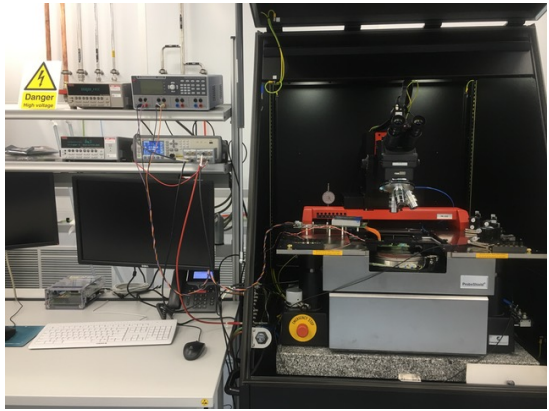
$\longrightarrow$ **Approved by CMS as baseline!**

Prototype (top right picture)

Successful PS sandwich assembly using four prototype spacers.

Tracker Phase-2

PS module

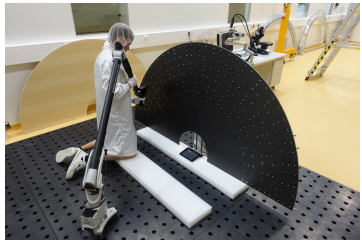


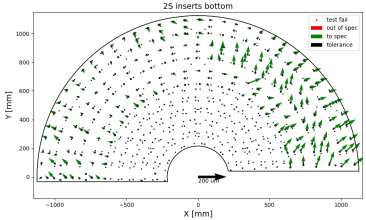
MaPSA test stand

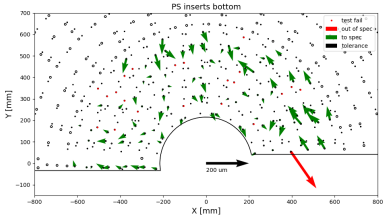
- Semi-automatic probe station in DAF.
- Development of the code to auto-control the probe station and DAQ system.

Toward first half PS module

- Prototyping with FEH only on RHS (instead of two as in design).
- DESY is involved in DAQ software & firmware developments for PS module.
- Most of Outer Tracker hybrid test systems are ready for procurement.







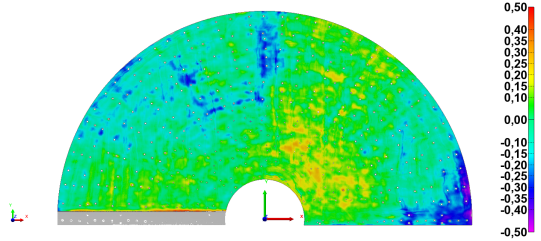
Tracker Phase-2

Dee prototype

Position of inserts (arrows)

- Mostly **within** 200 µm **tolerance**
- **One outlier**

Note: Some PS inserts were filled with glue
⟶ production process will be improved for future production.

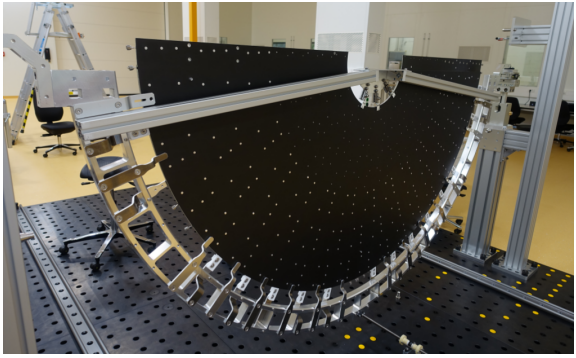


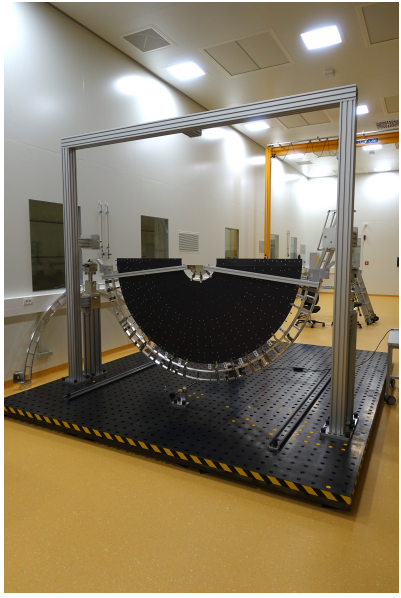
Flatness

- Within specifications
- Total min/max < 1.0 mm

Tracker Phase-2

Disk integration





Test

- DESY & Lyon full-size prototypes combined with our integration tooling.
- Originally planning tests in autumn with Lyon's Dee prototype

$\longrightarrow$ preparing for back-up solution due to constraints related to the pandemic, probably taking place early next year.

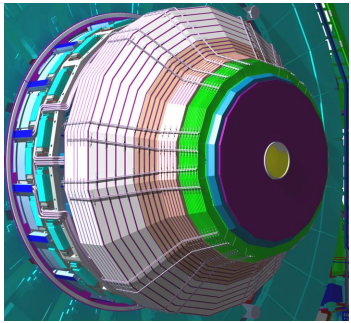
HGCAL.

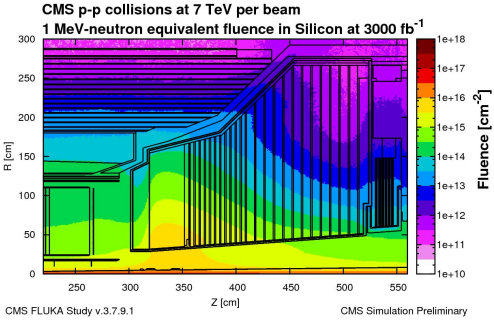
Reminder

Recent activity

HGCAL

Reminder





Context

Replace current pre-shower + ECAL + HCAL in forward region in order to face Phase-2 conditions.

$\longrightarrow$ Take advantage of experience developed in the context of detectors at future e^+e^- colliders (CALICE).

Design

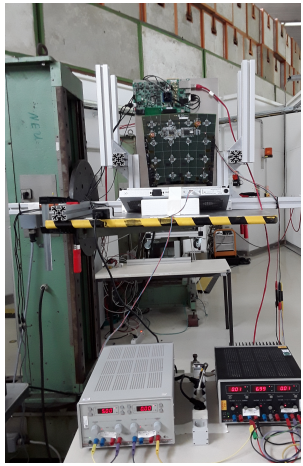
CMS design dictated by radiation levels:

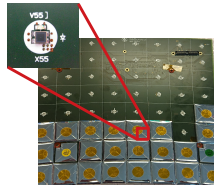
- scintillator: SiPM-on-Tile technology (with intrinsic amplification) wherever possible
- silicon: radiation-harder elsewhere

$\longrightarrow$ common read-out ASIC, namely **HGCROC**

HGCAL

Recent activity





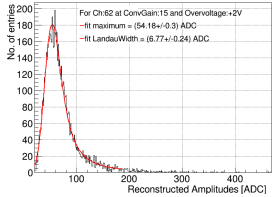
Development & assembly of tile-modules at DESY

ASICs, DCDC converters, scintillators

Tile-module prototype in DESY test beam

- Custom SiPMs from Hamamatsu in thermally conductive package
  $\longrightarrow$ Dedicated to CMS.
- Injection-moulded tiles from Russia, wrapped in reflector foils at DESY
  $\longrightarrow$ Automation for massive production in DAF.

$\longrightarrow$ **First particle signals** recently recorded with HGCROC!



Summary & Conclusions.

Summary & Conclusions

Physics analysis

- First experimental limits on Higgs rare decays.
- CP violation in Higgs production.

+ Many results in Higgs, Top, QCD, SUSY & Exotica on their way to publication!

Detector development

tracker alignment preparing reference for Run-2, preparing automation for Run-3;

luminosity measurement refurbishment of detector with silicon-based technology to face higher radiation;

generic detector R&D new design for silicon detector, electron tomography;

tracker upgrade 2S & PS modules, mounting in Dees, disk integration test;

HGCAL preparation for automated massive production, first beam tests.

Vielen Dank für Ihre Aufmerksamkeit!

Back-up.

Acronyms I

2S 2-Strip (module). 22, 23, 32

AC Alternative Current. 15
ALICE A Large Ion Collider Experiment. 4
ASIC Application-Specific Integrated Circuit. 15, 29, 30
ATLAS A Toroidal LHC ApparatuS. 4

BCM1F Fast Beam Conditions Monitoring. 15, 16
BR Branching Ratio. 7, 8
BSM searches Beyond the SM. 7

CALICE CAlorimeter for LInear Collider Experiment. 29
CERN European Organisation for Nuclear Research. 15
CL Confidence Level. 8
CMS Compact Muon Solenoid. 4, 24, 29, 30
CP Conjugation-Polarity. 9, 10, 32
CT Computed Tomography. 20

DAF Detector Assembly Facility. 25, 30
DAQ Data Acquisition. 25
DCDC Direct-Current to Direct-Current. 30
DESY *Deutsches Electroknen-Synchrotron*. 15, 16, 19, 20, 22, 25, 27, 30

ECAL Electromagnetic CALorimeter. 29

Acronyms II

FEH Front-End Hybrid. 25

GBL General Broken Lines. 20
GPU Graphical Process Unit. 13

HCAL Hadronic CALorimeter. 29
HGCAL High-Granularity Calorimeter. 32
HGCROC HGCAL ROC. 29, 30
HL High-Luminosity. 4

IP interaction point. 15

LHC Large Hadron Collider. 2
LHCb LHC beauty. 4

MaPSA Macro Pixel Sub-Assembly. 25
MC Monte Carlo. 12
MIP Minimum-Ionising Particle. 19
ML Module Level (actually sensor level). 9

NSW New Small Wheels. 4

PCB Printed-Circuit Board. 15
PS Pixel-Strip (module). 22, 24–26, 32
PS Parton Shower. 22

Acronyms III

QCD Quantum Chromodynamics. 32

RHS Right-hand side. 25

SiPM Silicon Photo-Multiplier. 29, 30
SM Standard Model. 10
SMD Surface-mounted device. 15
SUSY Super Symmetry. 10, 32

TEDD Tracker End-cap Double Disk. 22

YETS Year-End Technical Stop. 4

References I

CMS Collaboration. *Search for decays of the 125 GeV Higgs boson into a Z boson and a ρ or ϕ meson*. 2020. arXiv: 2007.05122 [hep-ex].

Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV. Tech. rep. CMS-PAS-HIG-20-006. Geneva: CERN, 2020. URL: https://cds.cern.ch/record/2725571.

"CMS Tracker Performance results for full Run 2 Legacy reprocessing". In: (Feb. 2020). URL: http://cds.cern.ch/record/2713208.

"CMS Tracker Alignment Parameter Errors performance results for full Run 2 Legacy reprocessing". In: (Apr. 2020). URL: https://cds.cern.ch/record/2717927.

"Additional Run 2 CMS Tracker Alignment Performance Results". In: (July 2020). URL: https://cds.cern.ch/record/2727090.