Development of precision timing detectors for collider experiments and searches for di-Higgs boson production with the CMS experiment at the LHC

RA HES Committee Project: 22rl-037

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Introduction

Research program has two primary objectives:

- Advance the development of silicon detectors, focusing on the technology that achieves few tens of picoseconds time resolution with a spatial resolution of few tens or microns (4D Tracker).
- Establish a program of searches to discover pair-production of Standard Model Higgs bosons at the CMS experiment at the Large Hadron Collider (LHC).

Project starts in Dec 2022 and will span 5-years, in collaboration with:

- FermiLab, CERN, Caltech, DESY, JINR.

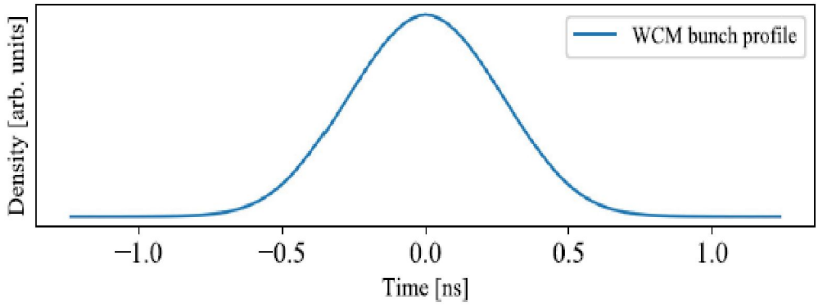
The goal is to establish a detector Lab at ANSL and create strong data analysis group:

- Implement a versatile testing system for prototype characterization, and to design readout electronics that can match the sensor layout and performance.
- Create strong data analysis group with skills of advanced machine learning methods and with expanded involvement in LHC physics focusing on objectives of HL-LHC.

4D Tracker: Motivation

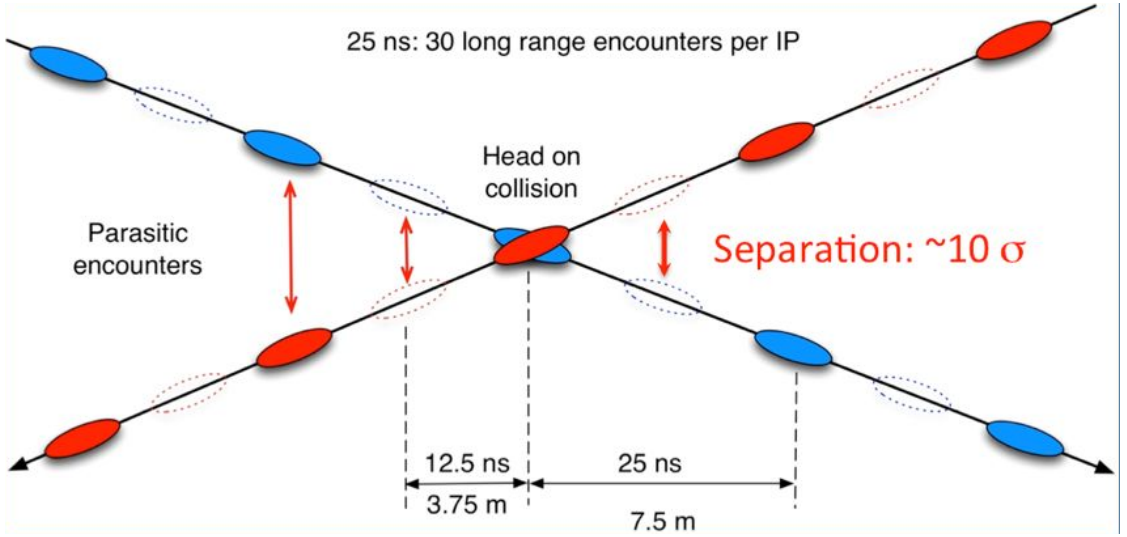
- Beam ~ 2800 bunches.
- Frequency 25 ns^{-1}.
- Bunch size → $\sigma_x \times \sigma_y = 16\ \mu m \times 16\ \mu m$.
- Bunch profile (few cm):

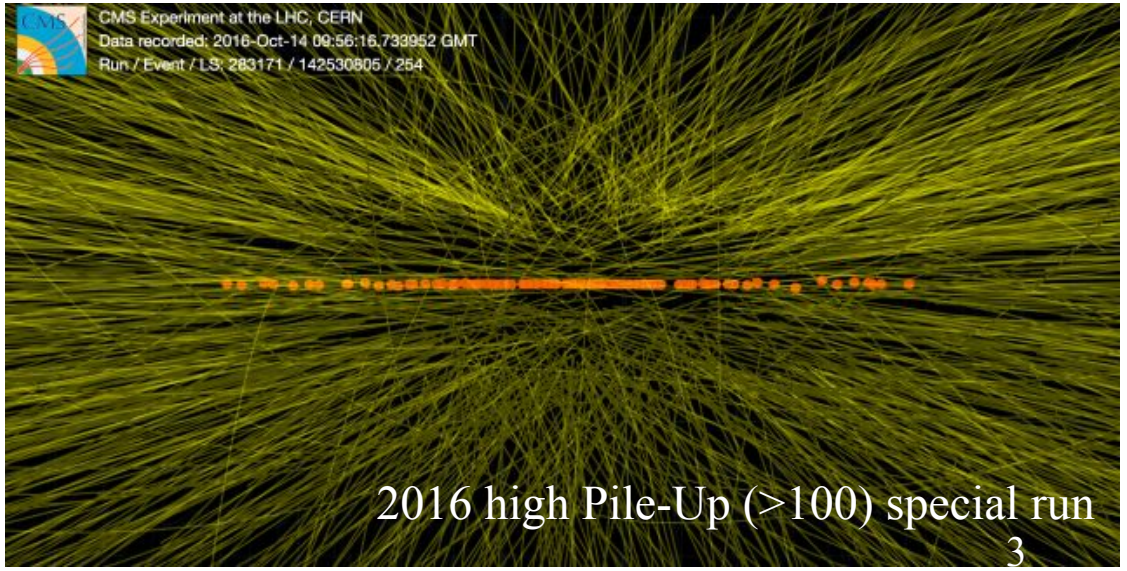
PHYS. REV. ACCEL. BEAMS 23, 062803 (2020)



- Crossing time ~ 1ns.
- Most of the collisions within 200 ps.
- Crossing half angle ~ 150 µrad.
- Up to 200 collisions per bunch crossing.

https://home.cern/news/news/accelerators/lhc-report-playing-angles

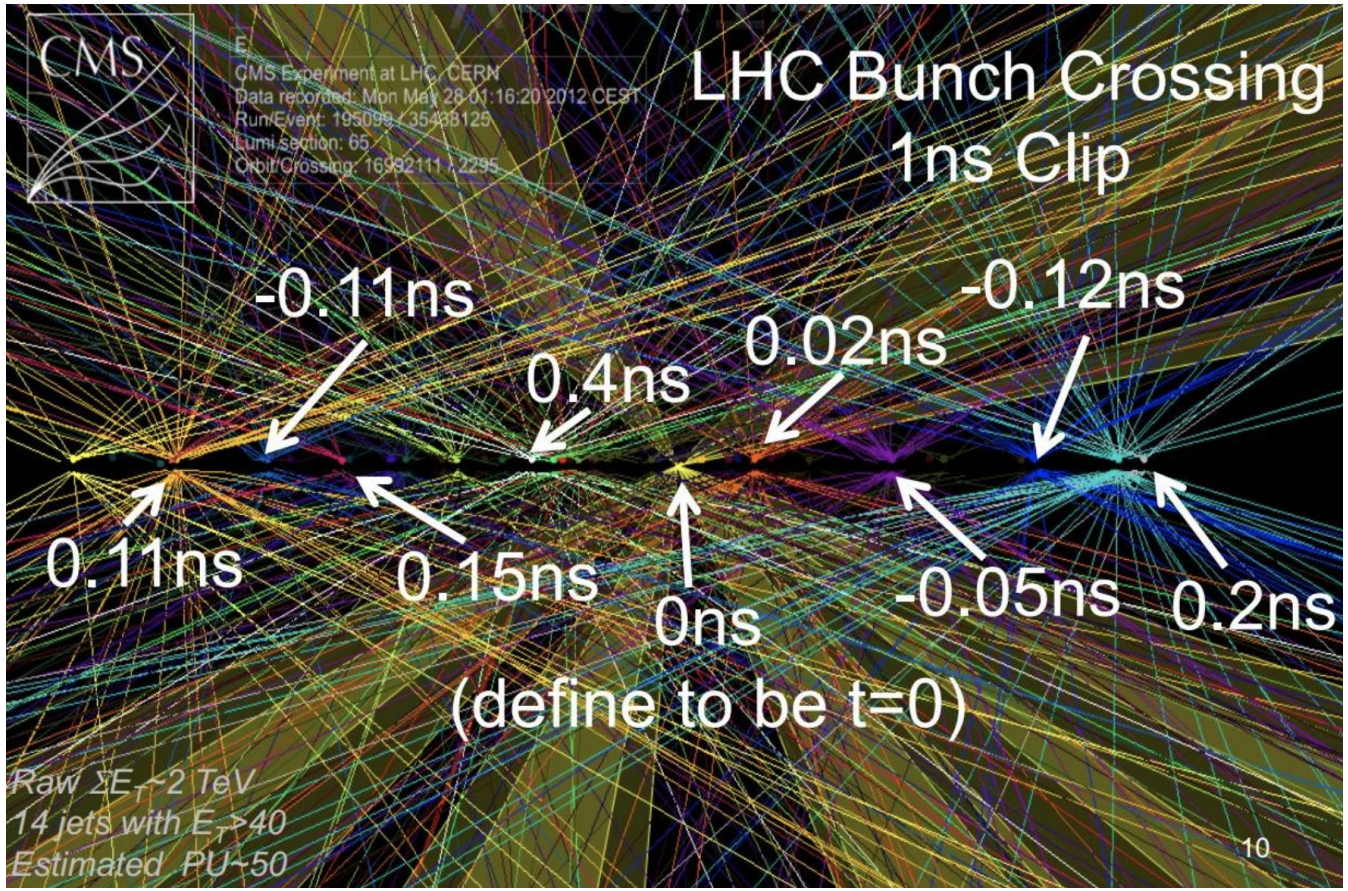




MIP timing detector for CMS at HL-LHC

- Existence of tracks timing detector with few 10 ps resolution will improve track separation: from 3D → 4D.
- If time resolution is ~ 30 ps, 4D tracker will perform at 200 PU as 3D at 50 PU.

- MTD will surround the entire Outer Tracker and will measure the time-of-arrival of charged particle with a time resolution of ~ 35 ps.
- MTD Barrel region: crystal scintillators (LYSO/LSO:Ce) with SiPMs (~40 m^2).
- MTD Endcap region: Low-Gain-Avalanche-Diodes (~9 m^2).



Requirements:

- Radiation and magnetic field tolerance.
- Low deadtime & high granularity.

Precision timing

Traditionally in collider experiments we measure very well:

- Position, charge and energy of particles.

Next generation detectors will have high granularity also in the time domain:

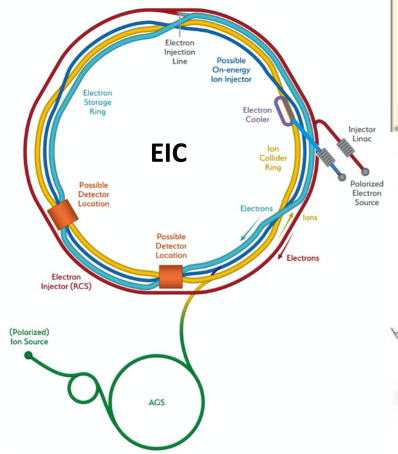
- At the tracker, calorimeter, muon detectors, and L1 trigger.

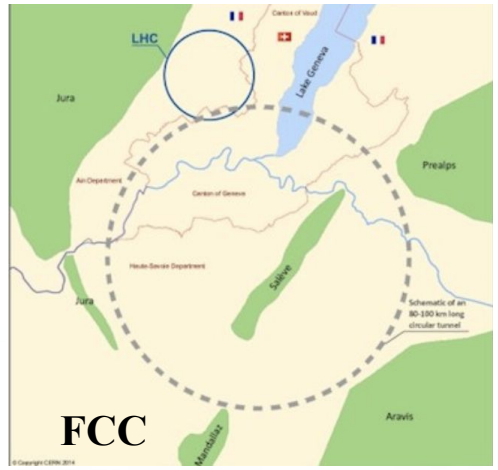
Precision timing information will radically change the capabilities of future experiments:

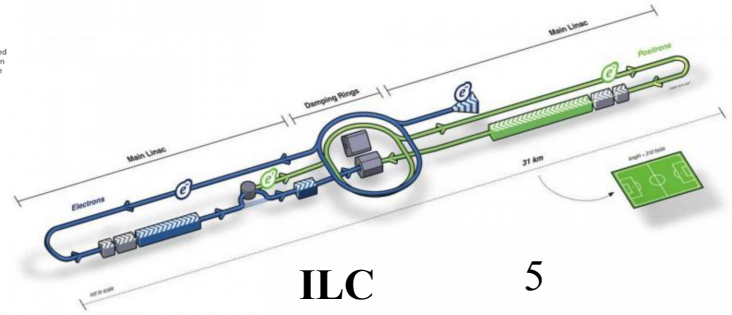
- Powerful tool to reduce the backgrounds.
- Improve event reconstruction at the Level 1 trigger.
- Completely new techniques in searches for long-lived particles.

The 4D-trackers will play a key role at the future machines:

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25 x 50 μm^2 pixels
	5 μm single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation tolerant up to 8 x 10^{17} n_{eq}/cm^2
	Per track resolution of 5 ps



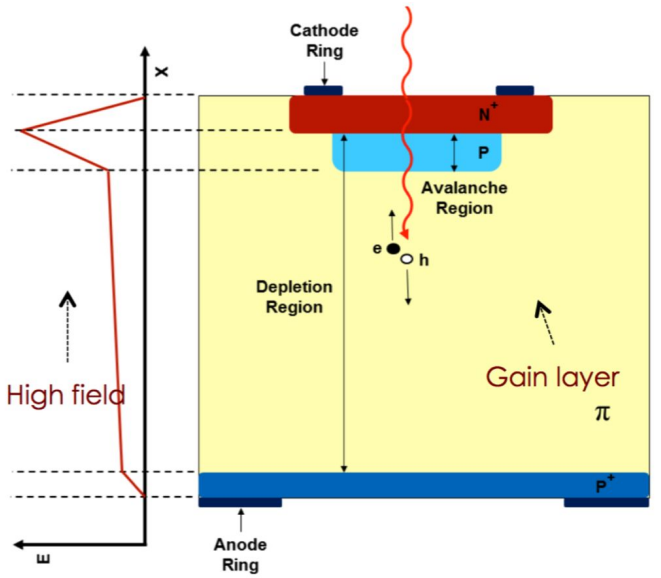




Low-Gain-Avalanche-Diodes (LGAD) detectors

Silicon sensors with specially doped thin region that produces high electric field

- Avalanche signal with 10-30 gain.

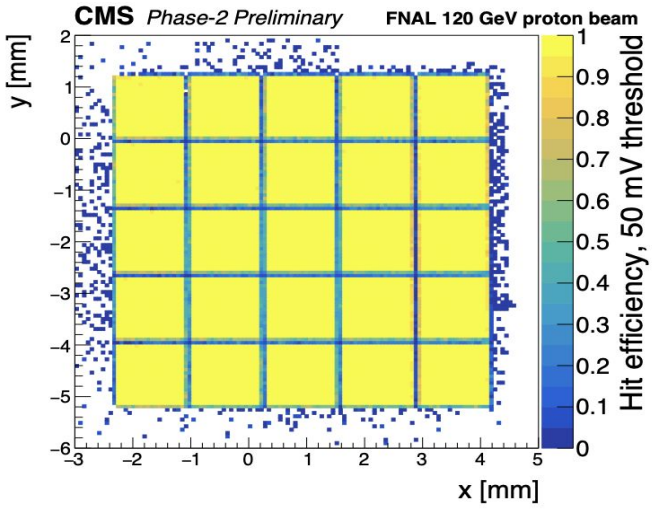


CMS/ATLAS will build detectors based on LGAD for HL-LHC:

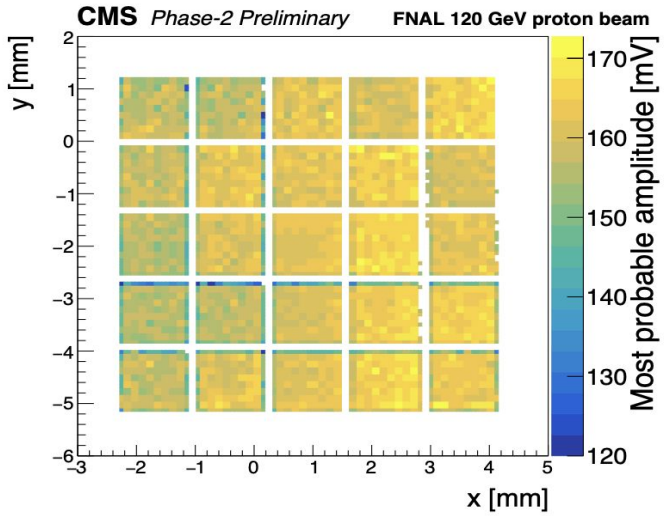
- Demonstrated time resolution ~ 30 ps up to 1.5 x 10^{15} n_{eq}/cm^2.

Each pixel is 1.3 x 1.3 mm^2

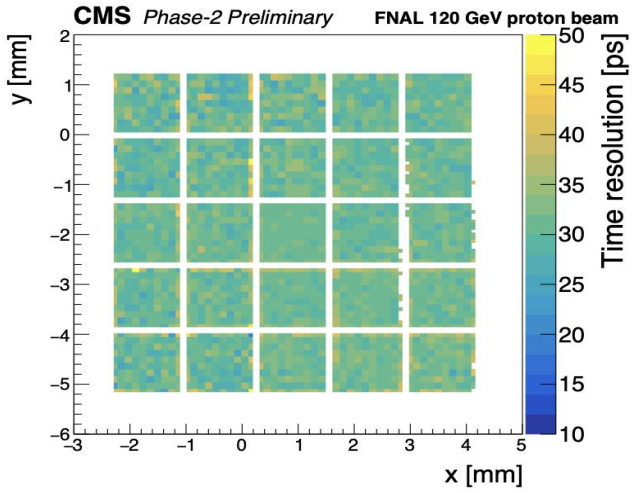
Hit efficiency

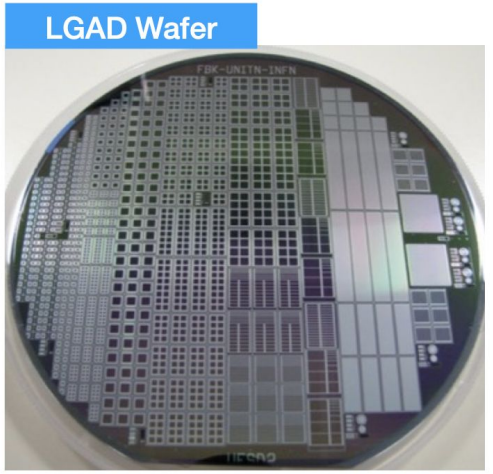


Signal size



Time resolution





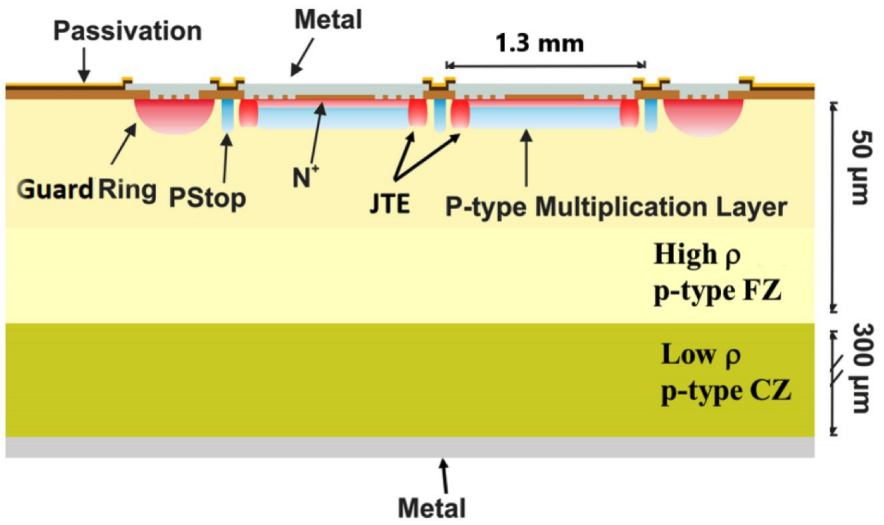
AC-coupled LGADs

Ongoing R&D to eliminate dead area

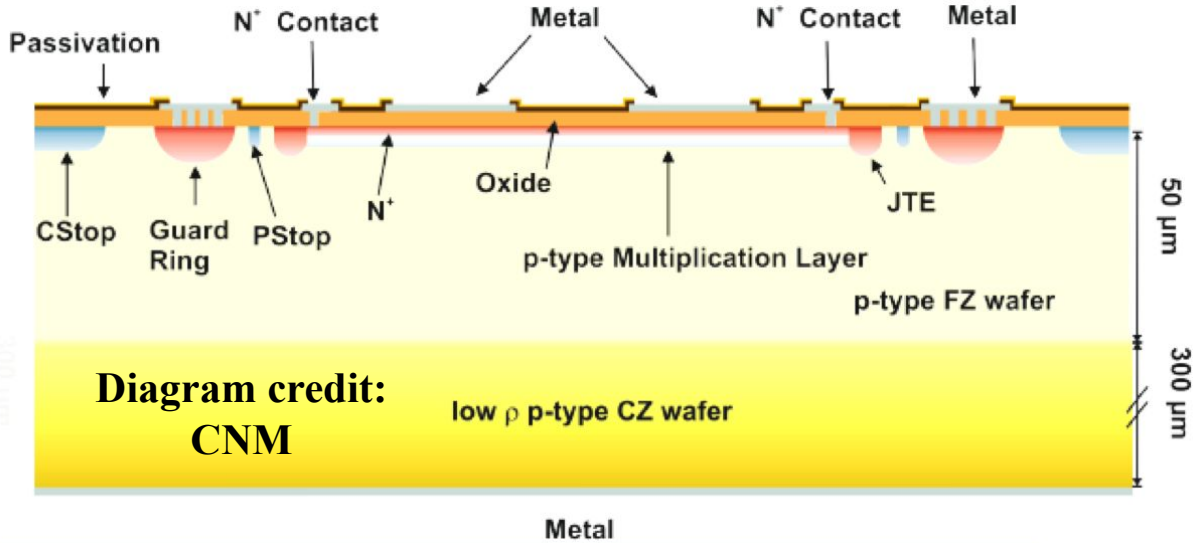
- Simultaneously improve position resolution via charge sharing.

Collaboration with BNL, KEK on AC-LGAD developments

- 100% fill factor, and fast timing information at a per-pixel level.
- Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric.
- Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.



DC-LGAD

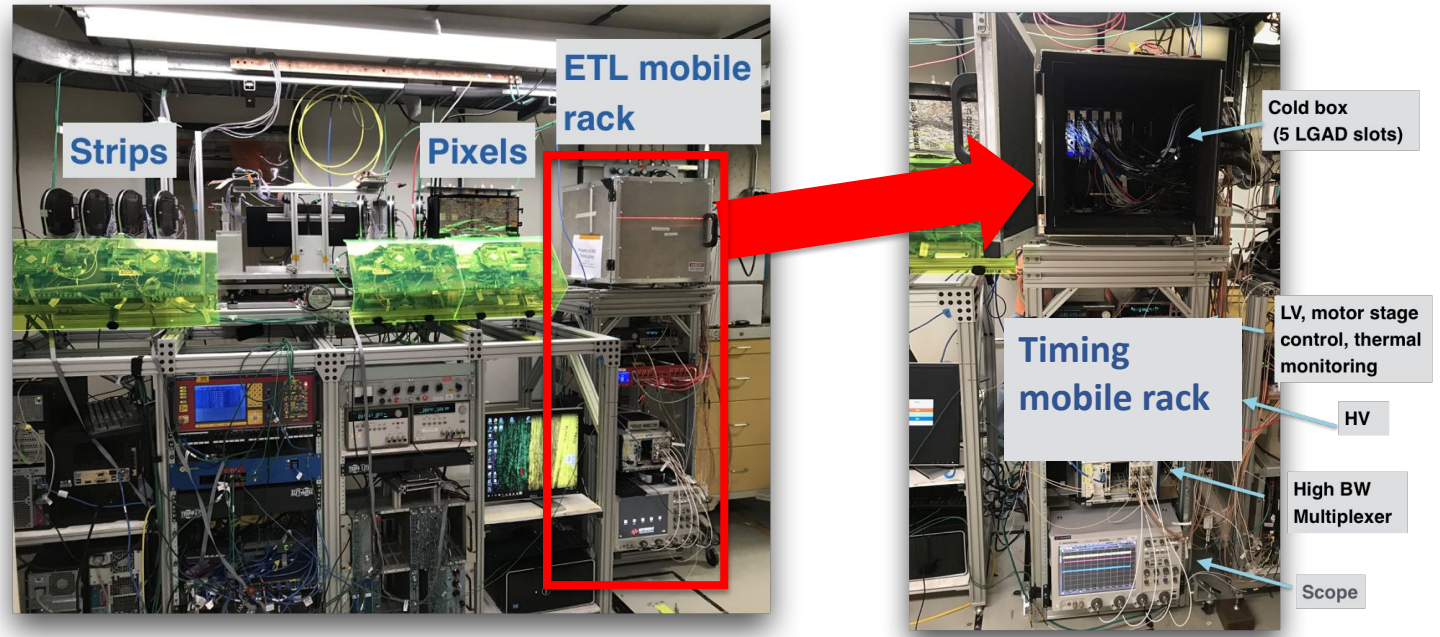


AC-LGAD

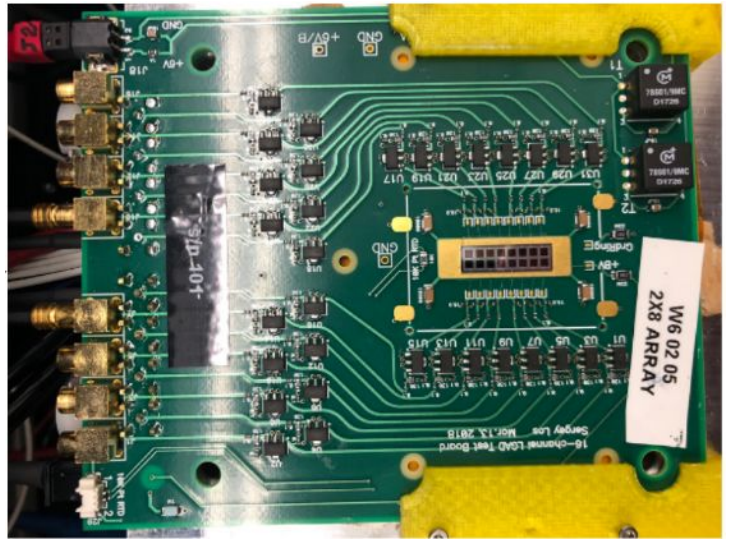
Test facilities

Permanent setup in FNAL test beam facility (FTBF):

- Movable: slide in and out of beamline as needed, parasitic use of beam.
- Environmental controls: sensor temperature (-25 C to 20 C).
- Remote control (stages, HV, LV), logging & reconstruction.
- σ_T ~ 10 ps time reference (MCP).
- Cold operation of up to 10 prototypes at the same time
- DAQ: high bandwidth, high ADC resolution scope 4 or 8 - channel oscilloscope.
- Record 100k events per minute, tracker with ~10 μm resolution.



PCB boards used for the data readout.

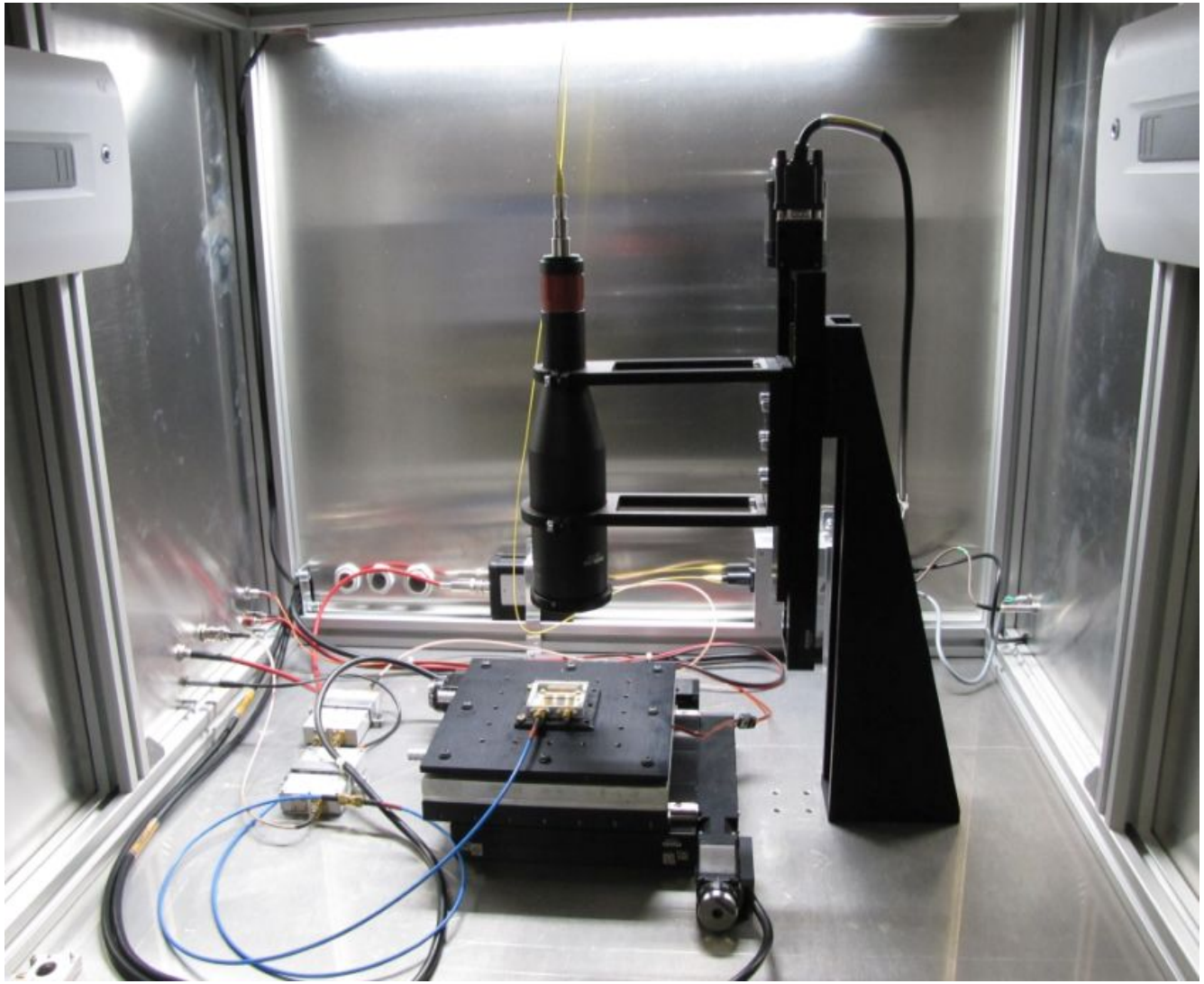


[eRD112/LGAD Consortium Meeting]

Test facilities

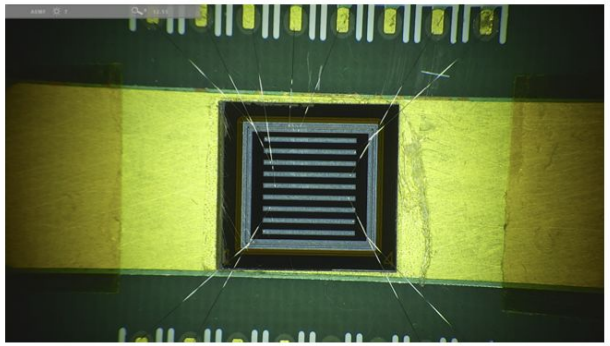
Large scanning TCT at AANL:

- Laser wavelength: 600 nm and 1024 nm.
- Pulse power: few m.i.p – 100 m.i.p.
- Beam spot (FWHM): < 11 μm.
- Computer controlled 3D translation with position resolution: < 1 μm.
- Complete DAQ system.
- Root based analysis software.

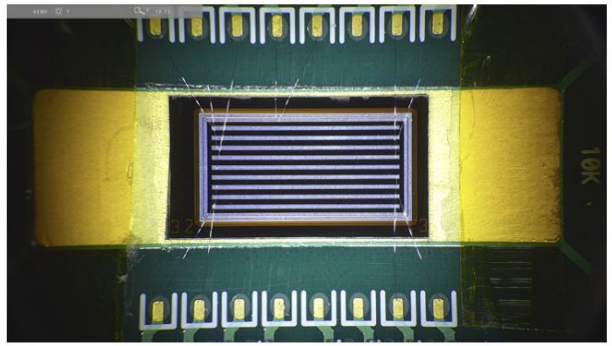


AC-LGAD measurements

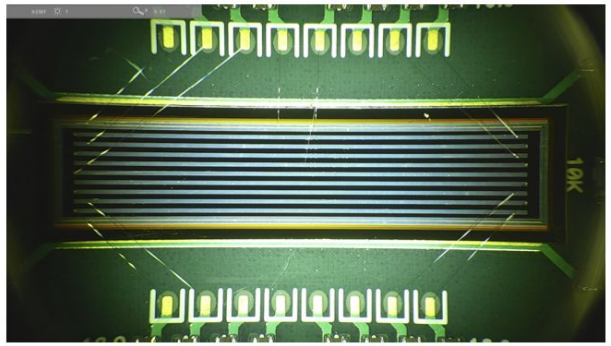
Examples of sensors recently tested at FNAL test beam and with β-source



5 mm

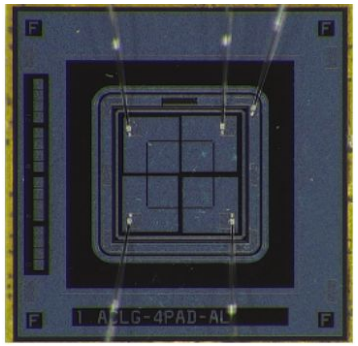


10 mm



25 mm

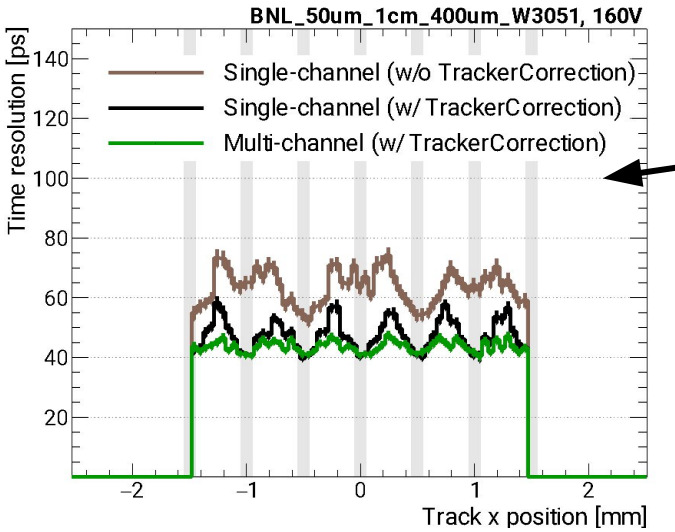
[First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam]

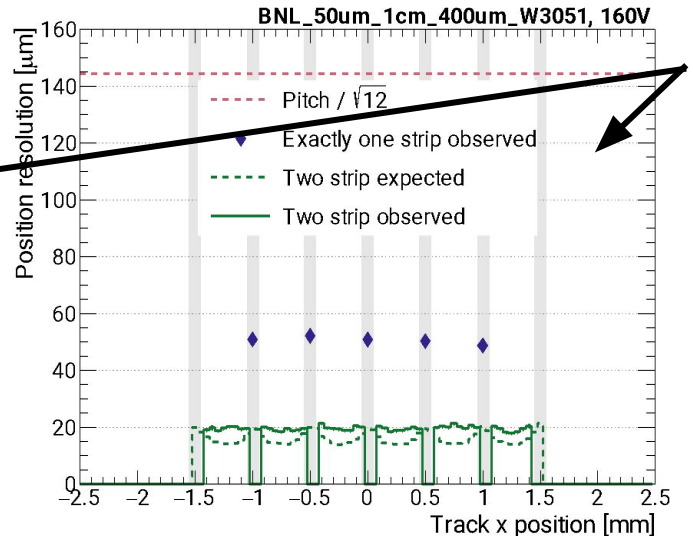


HPK 2x2, 500 µm pads Pixel sensors

Results:

Strip sensors

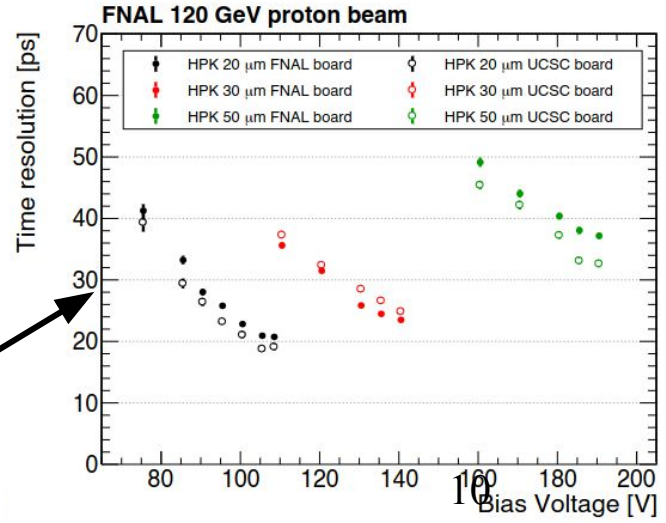




Best performing strip sensor: 50µm thickness 10mm length

[eRD112/LGAD Consortium Meeting]

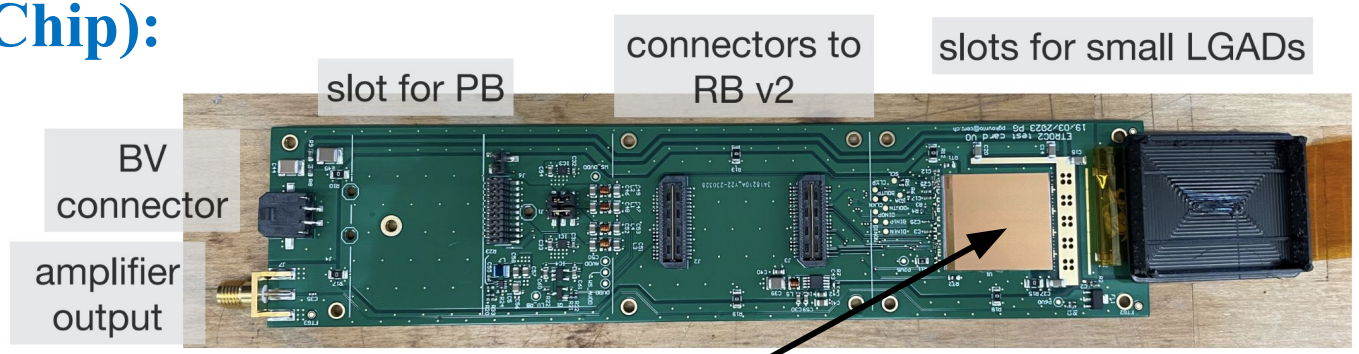
Time resolution of different pixel sensors



Novel readout chips for LGAD sensors

ETROC (Endcap Timing Layer ReadOut Chip):

- ETROC is used for the data readout from the LGAD sensors.
- The testing of the performance of ETROC chips and corresponding electronics is currently performed.



ETROC

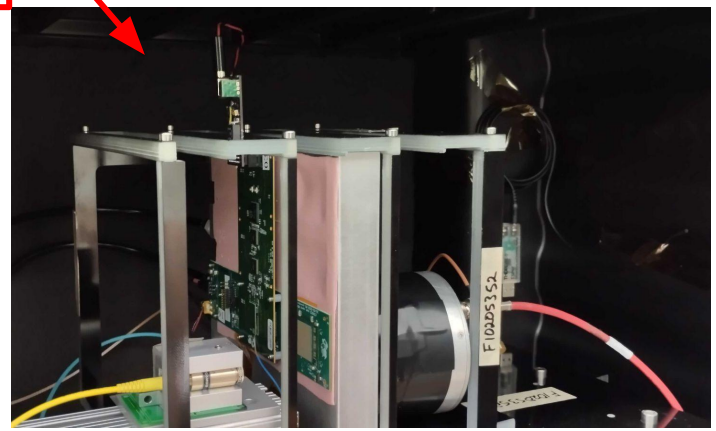
16 x 16 pixels

Size: 20 × 20 mm²

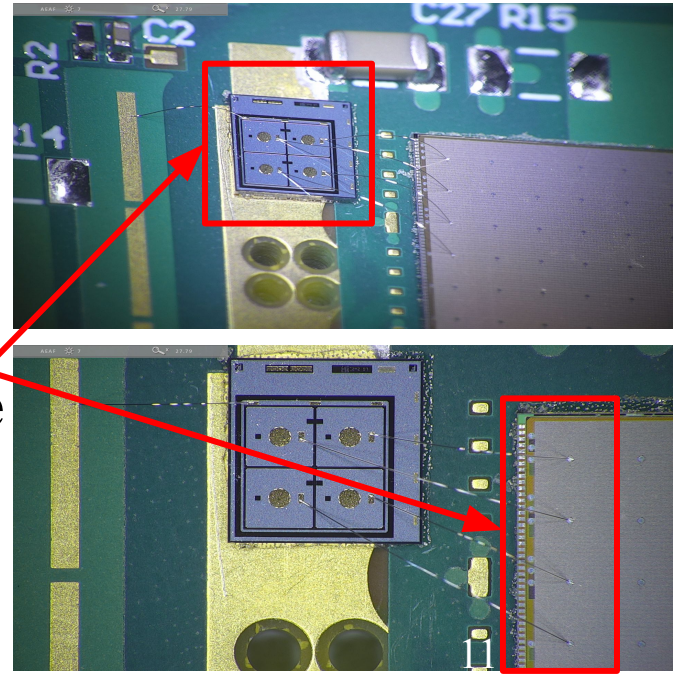
The setup for ETROC testing.

The testing is performed by:

- Charge injection into ETROC.
- Infrared laser illumination.
- Beta source radiation.



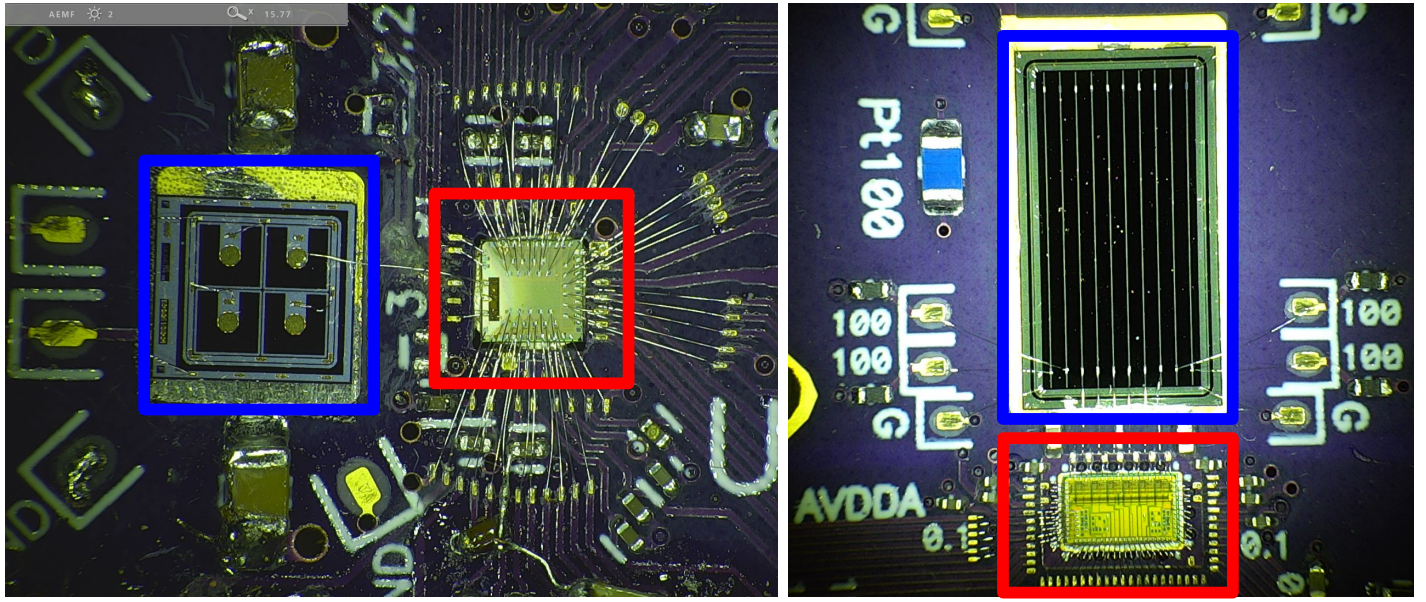
Wire bonded LGAD sensor, to the ETROC.



Testing of a readout chip at FNAL

A readout chip (FNAL Constant Fraction Discriminator, FCFD) has been developed:

- This chip performs time of arrival measurements of an incoming signal at a given fraction of the signal's amplitude.
- AANL CMS group members have participated in the testing of this chip:
  - Development of a DAQ and environment control software.
  - Data analysis.
- This method allows more flexible triggering of signals compared to fixed threshold method.



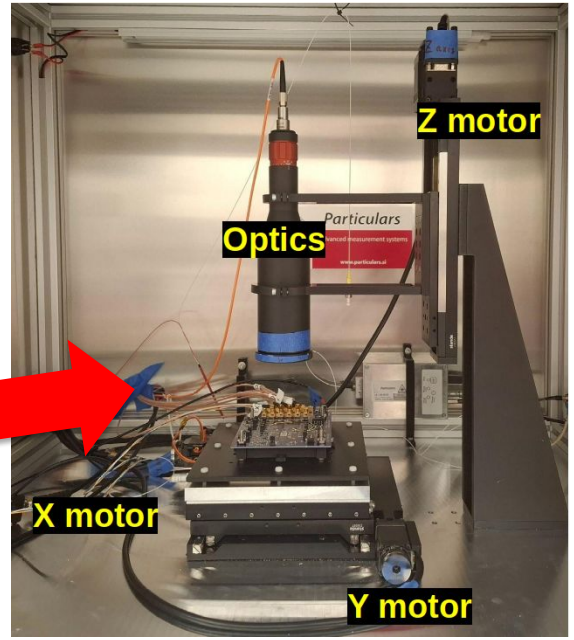
The first and second versions of FCFD chip attached to an LGAD sensor.

[Design and performance of the Fermilab Constant Fraction Discriminator ASIC]

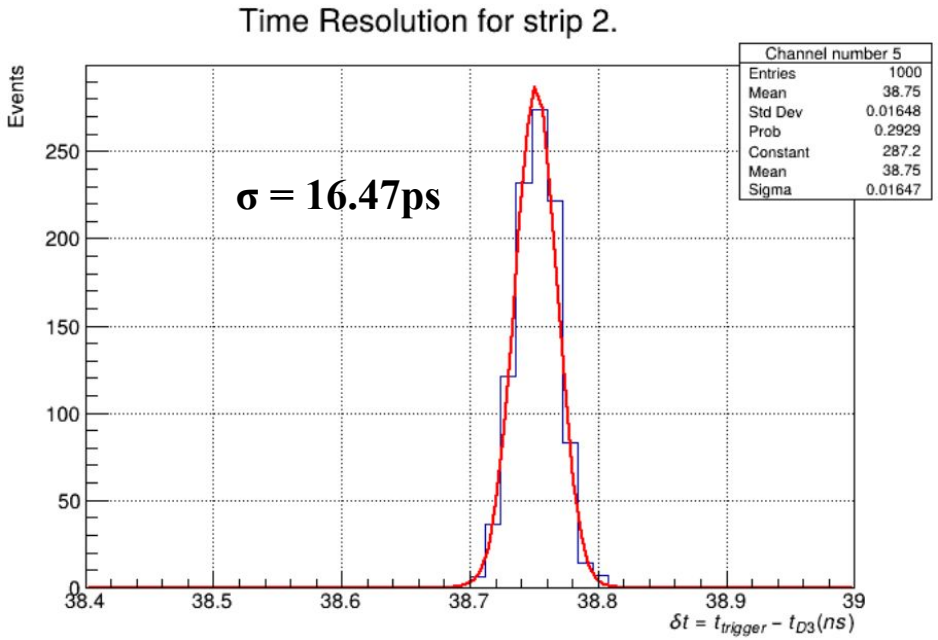
Testing of a readout chip at FNAL

The setup for tests assembled at FNAL

The setup from the inside



The results of the first tests at FNAL



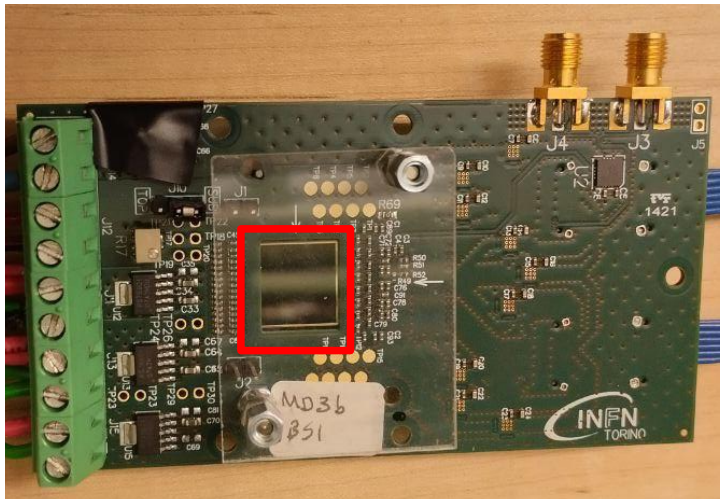
The AANL CMS group members have recently performed measurements using a laser setup in recent measurements.

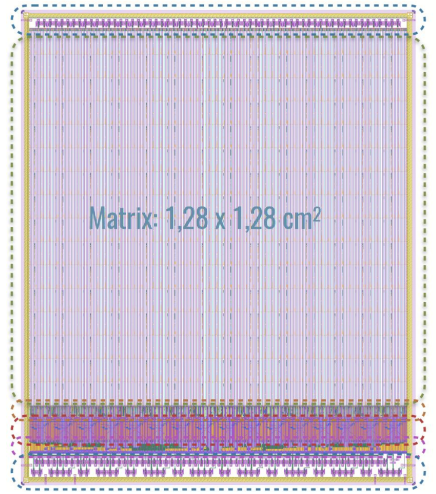
Testing of Monolithic Active Pixel Sensors (MAPS) at FNAL

Tests of MAPS sensors had been performed at FNAL with a group from INFN.

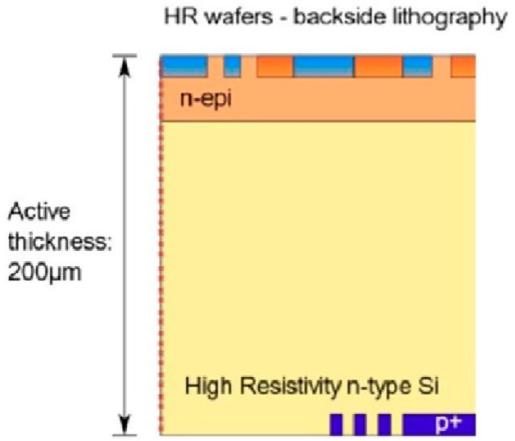
- MAPS sensors allow to combine the readout chip and a silicon sensor.
- Lithography is performed on one side of the silicon sensor.
- This technique allows to include thousands of pixels on a cm scale sensors (1.28 x 1.28 cm^2 and 262144 pixels in this case).
- AANL group members took part in the beam test at FTBF with 120 GeV proton beam.

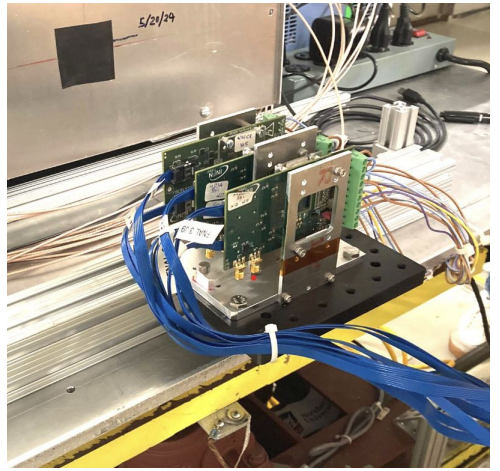
[ARCADIA fully depleted CMOS MAPS development with LFoundry 110 nm CIS]





An example of a MAPS sensor attached to a readout board (left) and the scheme of it's pixel structure (right).





Search for di-Higgs production

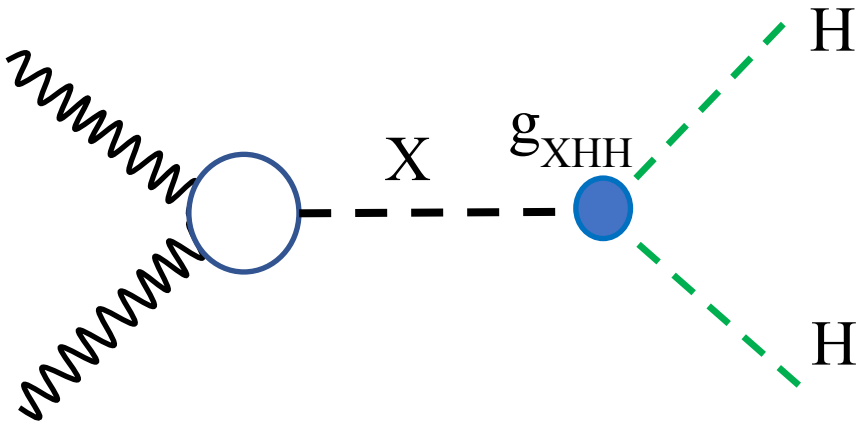
- One of the important tasks of LHC physics for coming years (especially at HL).
- Allows to probe the BSM hypothesis and SM trilinear coupling.

Resonant

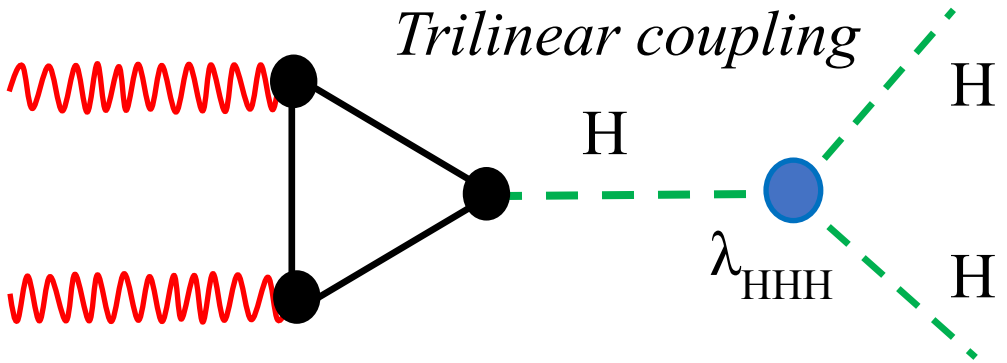
- Two-Higgs-doublet model (2HDM)

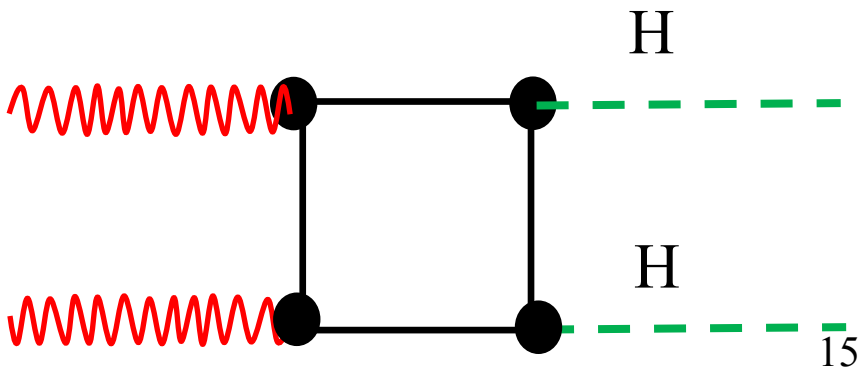
  with have scalar resonant.

- Randall-Sundrum Graviton.



Non-Resonant (σ_{HH} ~ 40 fb, main production mode is ggF: ~ 90%)





Search for di-Higgs production in *bb*-decay channel: Current status

Development of Analysis strategy:

Boosted, Semi-boosted, resolved analysis categories. Definition of signal and control regions (SR and CR).

Study of online triggers:

Set of online selections in CR and SR, Triggers Scale-Factors calculation and validation.

Contribution in MC and Data samples production:

Inclusion of trigger objects and filters in centralized production of data and MC samples.

CMS (LHC) Run3 data processing:

2022-23 data of pp-collisions at 13.6 TeV (~35 fb^{-1} and ~27 fb^{-1}), MC samples, Data-MC comparison in CR and SR regions.

Optimization of offline selection, Study and validation of signal search variables:

Set of offline selections in CR and SR, ML-classification for Signal-Background discrimination.

b, double-b taggers, regressed mass of FatJets or invariant mass of 2-jets system.

Development of signal and background models, Estimation of systematic uncertainties:

Data-derived QCD model development, development and validation of MC TTbar model, study of signal and other background processes, e.g. Higgs boson production in other all-hadron final states, study and estimation of theoretical and experimental systematic uncertainties.

Statistical analysis and results:

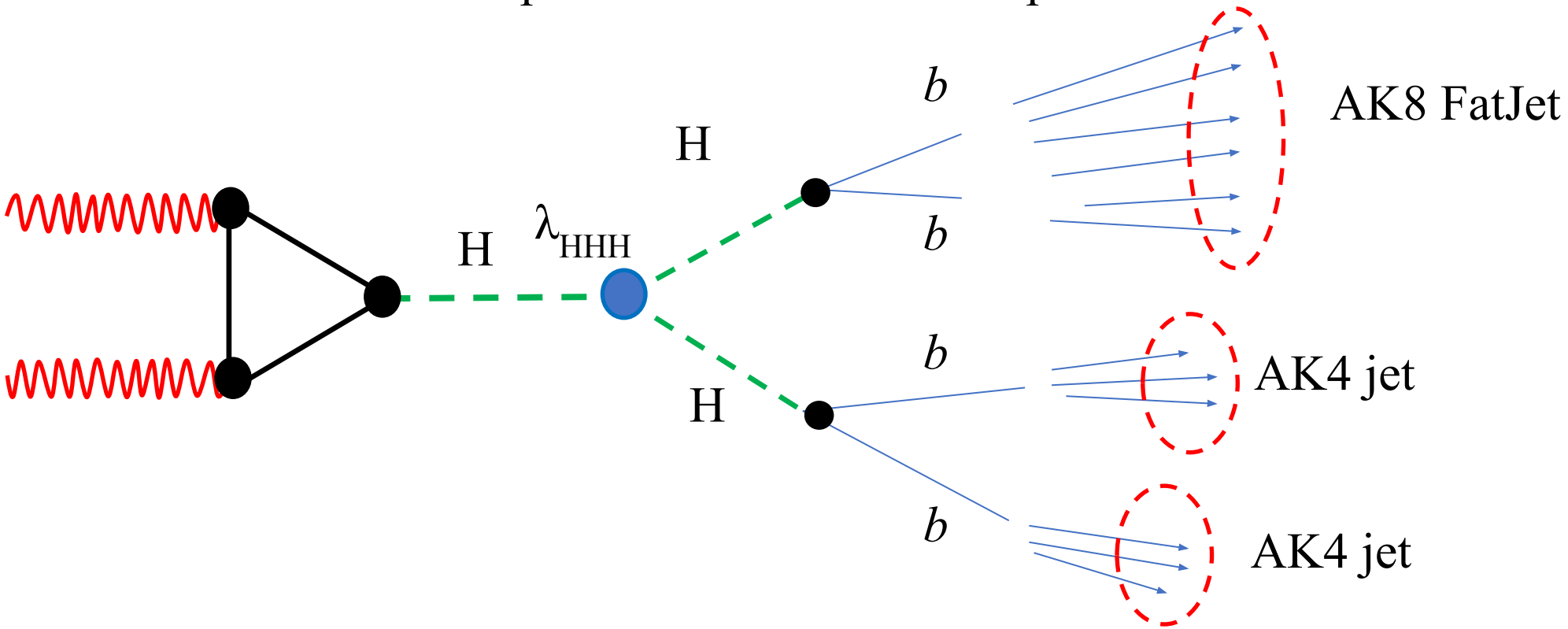
With 95% CL the expected upper limit on XSec × BR is $\mathbf{4.51\sigma_{SM}}$ while observed upper limit is $\mathbf{4.53\sigma_{SM}}$.

CMS (LHC) 2024 data processing:

2024 data of pp-collisions at 13.6 TeV (~109 fb^{-1}), MC samples,Triggers efficiency measurements, Data-MC comparison in CR and SR regions.

Search for di-Higgs production in *bb*-decay channel

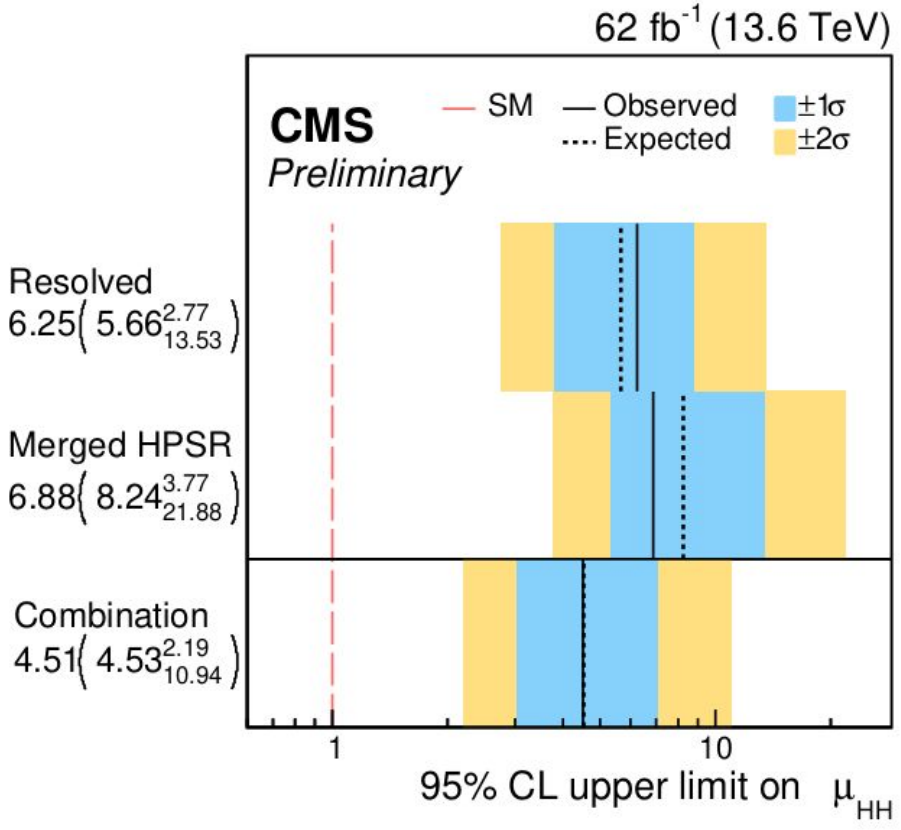
- Analysis was carried out in two categories: resolved and boosted.
- In resolved channel Signal scan was performed using invariant mass distribution of AK4 jets.
- In boosted channel Signal scan was performed using distribution of FatJet Mass.
- Upper limit in terms of SM expected cross section was provided.



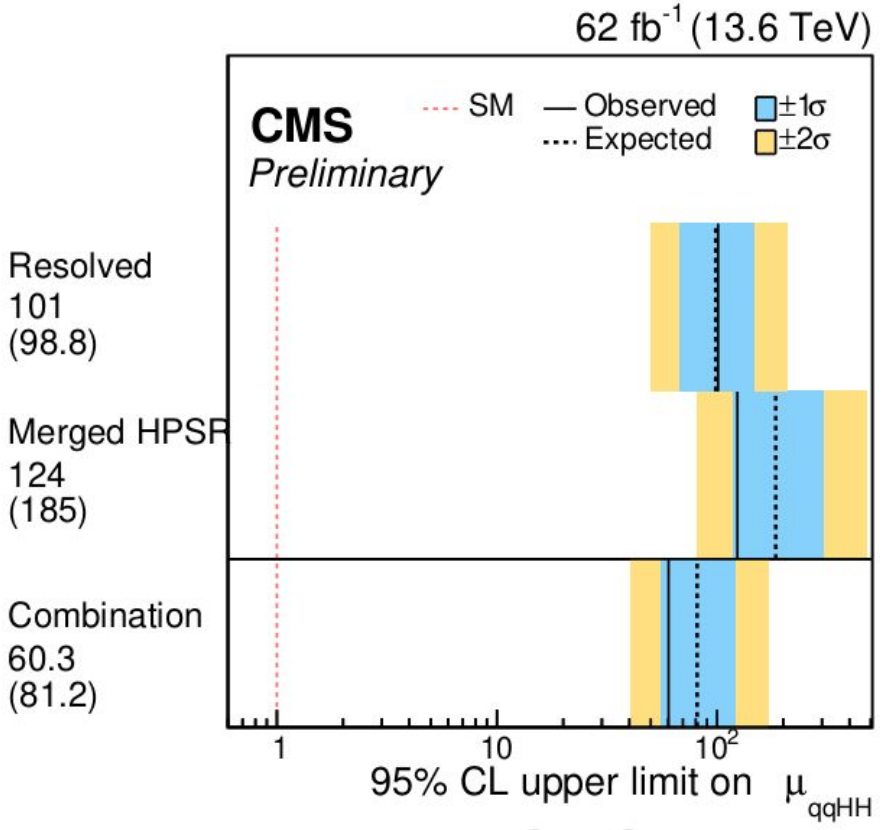
Search for di-Higgs production in *bb*-decay channel: Current status

- Main contribution comes from ggF production mode, VBF is the sub-leading.
- Preliminary results with CMS 2022-23 data are presented.

ggF



VBF

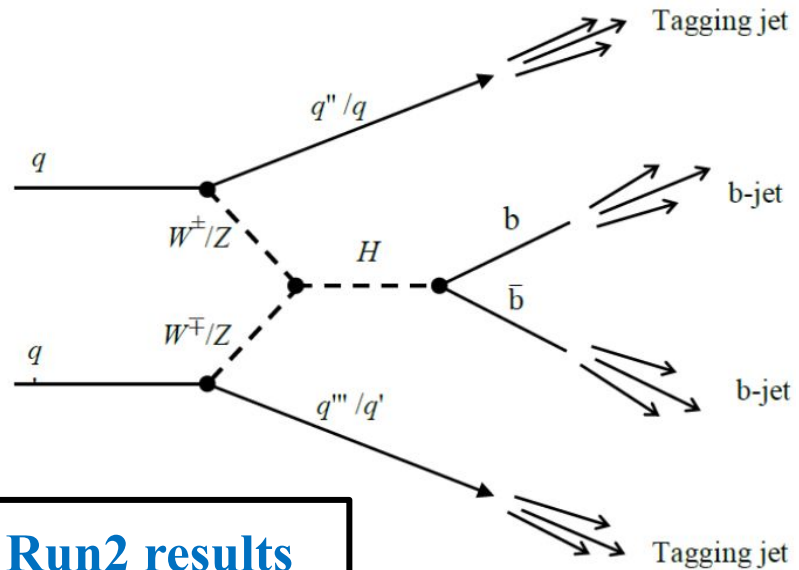


Article for journal publication is ready and is in CWR: HIG-24-010 Search for non-resonant HH production in 4b final state in 13.6 TeV data.

Search for H-boson produced via VBF mechanism and decaying to b,*anti*b quarks: Current status

Features of VBF H→bb̄: (σ ≈ 2.2 pb at 13 TeV)

- Two b-quark jets from Higgs boson decay mainly in central region of CMS.
- Two light-quark jets from scattered quarks with large Δη and inv. mass and forward-backward tend.
- Low additional hadron activity.
- Well suppressed background.



CMS Run 3 status update (2025)

- Improvement of analysis strategy for Run3.
- Development of new online triggers for Run3 data collection with better b-tagging algorithms.
- Measurement of trigger efficiencies.
- Beginning of the analysis and preliminary results.
- CMS AN-2025/170 - Measurement of the Higgs production via VBF process with subsequent decay of the Higgs boson into a pair of bottom quarks using Run3 data.

CMS Run2 results

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μ = **0.99** (+0.48 / - 0.41)

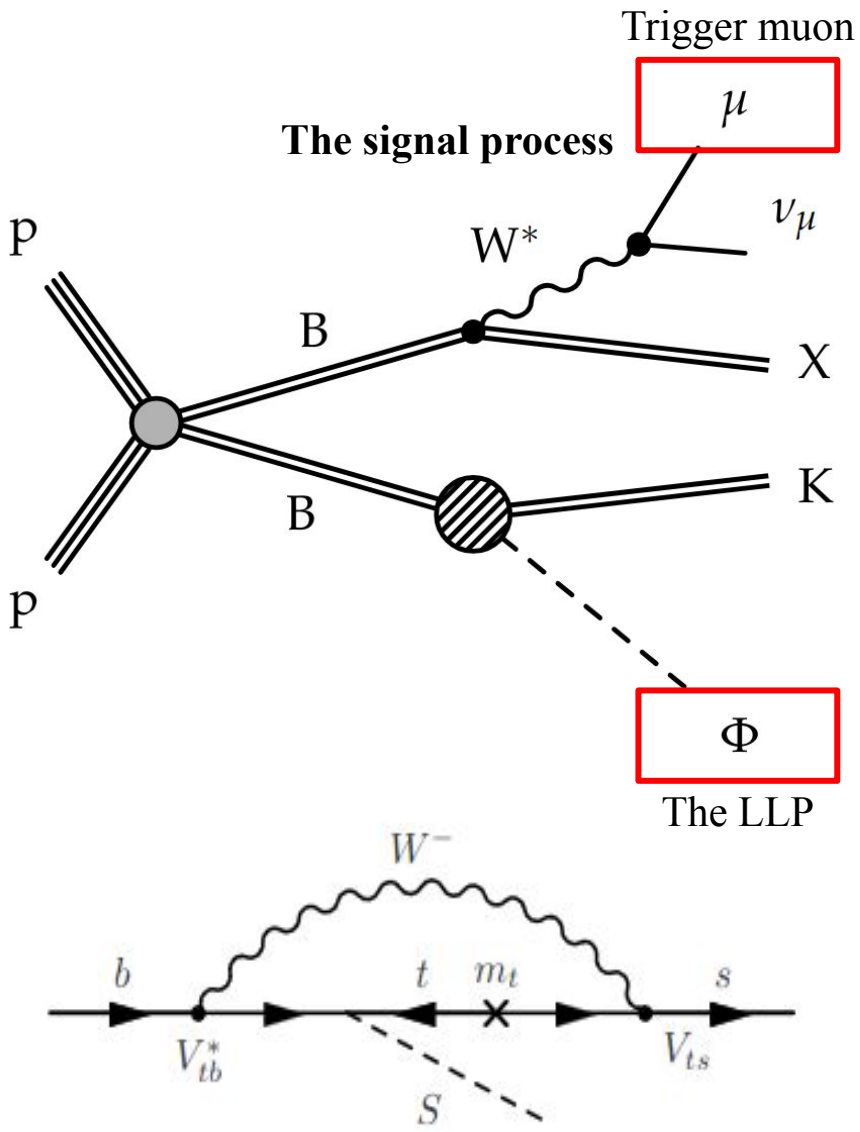
σ_{obs} = **2.6**

Search for LLP-particles with CMS Run2 data

The search for Long-lived particles (LLP) is done in pp collisions with energies of 13 TeV.

- The "Scalar Higgs Portal" has been used as a theoretical model for the search for LLPs.
- According to the theoretical model the LLPs are produced in B meson decays.
- Two scenarios of LLP particle decay are observed: $\pi^+\pi^-$ and $\pi^0\pi^0$ mesons.

The search is performed in the muon system (MS) of the CMS detector.



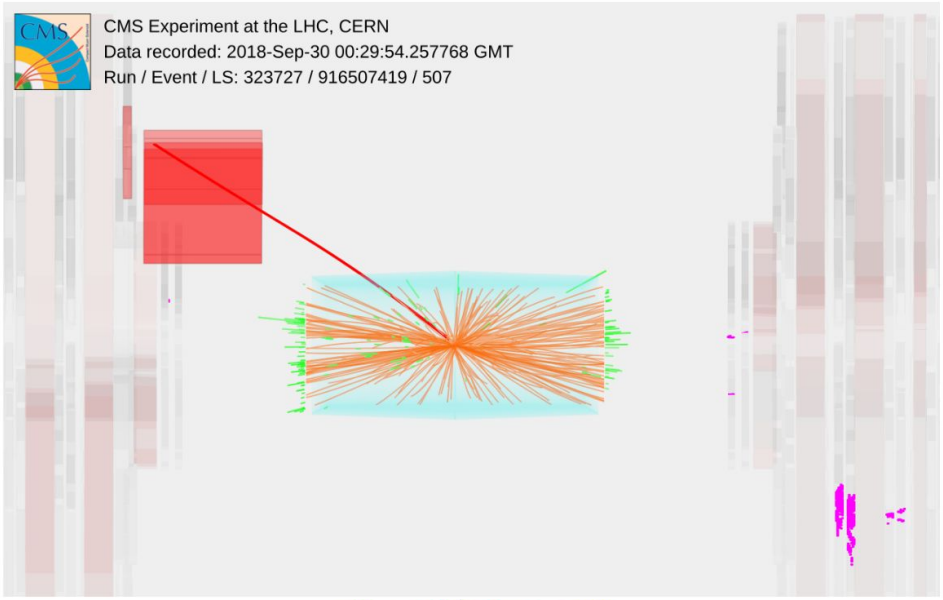
[Search for b hadron decays to long-lived particles in the CMS endcap muon detectors]

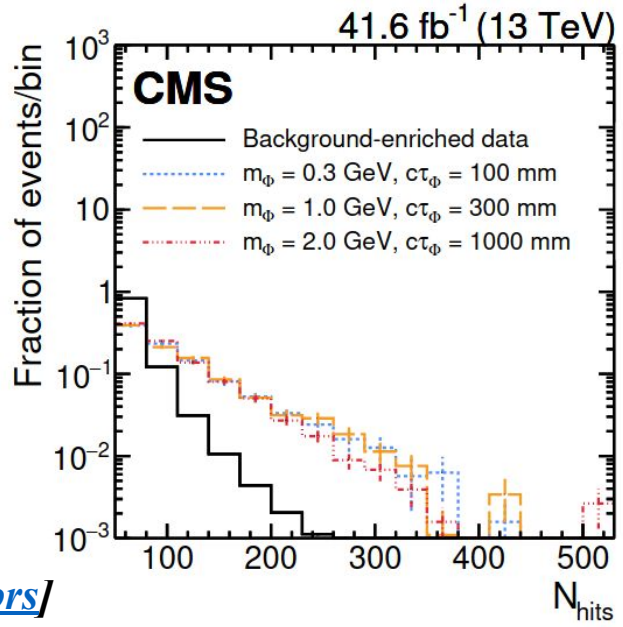
Search for LLP-particles with CMS Run2 data

- Hits in the MS are clustered using DBSCAN algorithm.
- The search is performed in two data categories: in **cathode strip chambers (CSC, endcap)** and in **drift tubes (DT, barrel)**.
- An analysis strategy has been developed based on the cluster's parameters like: **multiplicity, position, size and reconstruction time**.
- The signature of LLPs is the presence of high multiplicity clusters from electromagnetic showers caused by pions.

Used data:

- Simulated data of LLP production.
- Experimental data from acquired in CMS 2018.



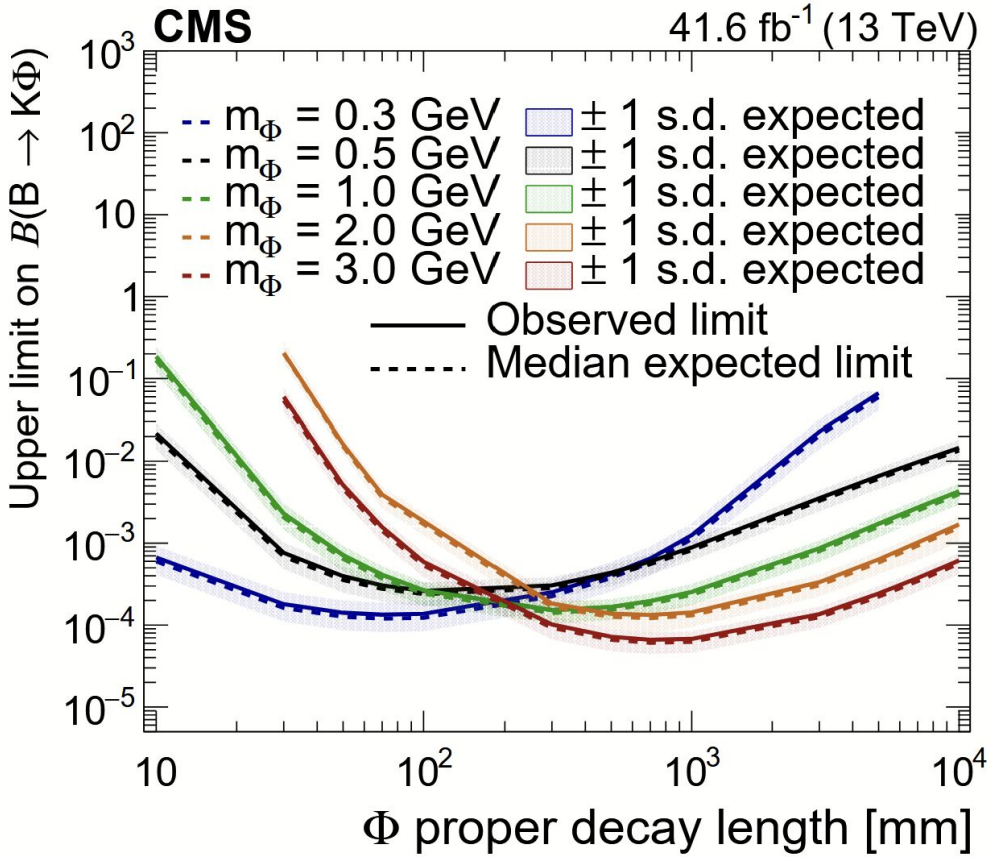


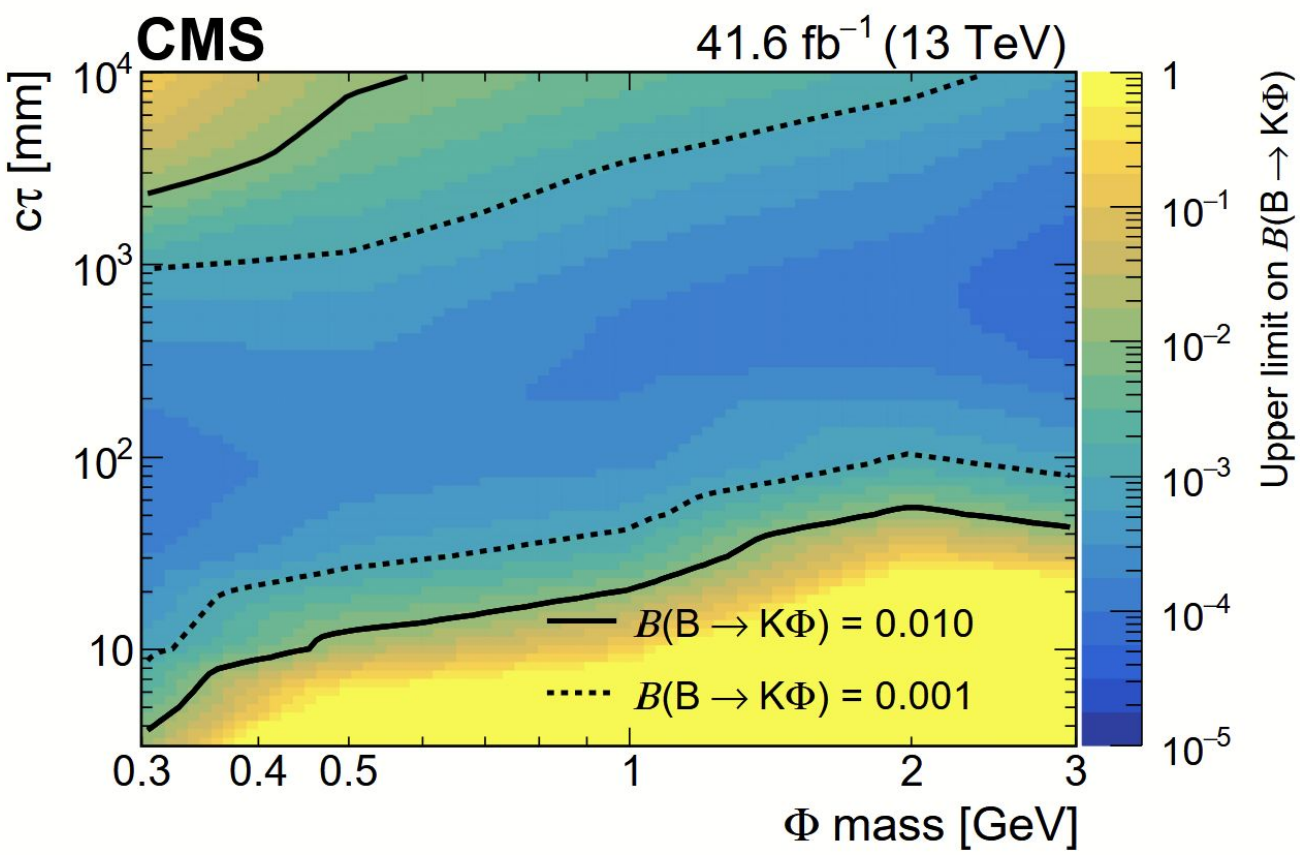
The multiplicity of the reconstructed clusters in the MS.

[Search for b hadron decays to long-lived particles in the CMS endcap muon detectors]

Search for LLP-particles with CMS Run2 data: RESULTS

- Main contribution comes from CSC category so DT category has been dropped.
- Final results with CMS 2018 data are presented.





The results of the analysis has been approved and the article for journal publication has been submitted: EXO-24-004 Search for LLP in 2018 B-Parking dataset using Muon Detector Shower.

[Search for b hadron decays to long-lived particles in the CMS endcap muon detectors]

RESULTS

- In Experimental Physics Division of AANL the “Compact Muon Solenoid” group is founded.
- Rooms for data analysis, LGAD sensors test, and control room are prepared and equipped.
- Search for Di-Higgs production with CMS 2022-23 data is completed.
- Search for Long lived particles with CMS Run2 data is completed.
- Measurement of VBF Hbb process with CMS 2022-24 data is ongoing.
- Search for Di-Higgs production with CMS 2024 data is ongoing.

Thank you

RESULTS: PUBLICATIONS

PUBLICATIONS

- CMS collaboration, Search for b hadron decays to long-lived particles in the CMS endcap muon detectors, Physical Review D, 8 Aug 2025. https://arxiv.org/abs/2508.06363
- HIG-24-010 (not available yet).
- Aram Hayrapetyan. “Реконструкция долгоживущих частиц в эксперименте CMS (LHC)”. Известия НАН РА. Физика 59.4 (February 2025), p. 8.
- Budkovsky, D.V., Lapushansky, I.V., Tumasyan, A. *et al.* The Potential for Observing Hadron Jets in the SPD Experiment at NICA. *Phys. Part. Nuclei* **56**, 784–789 (2025). https://doi.org/10.1134/S1063779624702290

TALKS

- D. Budkouski, A. Tumasyan, S. Shmatov, "Cluster particle production @SPD experiment. Pythia vs Herwig" https://indico.jinr.ru/event/5000/overview
- A. Hayrapetyan, “Search for Long-Lived Particles with CMS Experiment at LHC”, CHEP-Yerevan-2025, September 29 - October 3, 2025. https://chep-2025-yerevan.yerphi.am/

ONGOING

- CMS AN-2023/151 -- Search for nonresonant Higgs boson pair production in the four b quark decay channel with Run 3 data.
- CMS AN-2022/152 -- Search for hadronic LLP decays in the muon system using the B-parking dataset.
- CMS AN-2024/243 -- Search for VBF H $\rightarrow c\bar{c}$ with Run3 2023 data.

RESULTS: COLLABORATION PUBLICATIONS

1. CMS Collaboration, Aram Hayrapetyan (Yerevan Phys. Inst.) et al., Operation and performance of the CMS silicon strip tracker with proton-proton collisions at the CERN LHC, e-Print: 2506.17195 [hep-ex], DOI: 10.1088/1748-0221/20/08/P08027 Published in: JINST 20 (2025) 08, P08027.
2. CMS Collaboration, Aram Hayrapetyan (Yerevan Phys. Inst.) et al., Measurement of WWZ and ZH Production Cross Sections at s=13 and 13.6 TeV, e-Print: 2505.20483 [hep-ex], DOI: 10.1103/6z3d-zjw4, Published in: Phys.Rev.Lett. 135 (2025) 9, 091802
3. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Search for dark matter produced in association with one or two top quarks in proton-proton collisions at $\sqrt{\text{s}}$= 13 TeV, e-Print: 2505.05300 [hep-ex], DOI: 10.1007/JHEP08(2025)085 Published in: JHEP 08 (2025), 085.
4. CMS Collaboration, Aram Hayrapetyan (Yerevan Phys. Inst.) et al., Measurements of inclusive and differential Higgs boson production cross sections at $\sqrt{\text{s}}=13.6$ TeV in the H → γγ decay channel, e-Print: 2504.17755 , DOI: 10.1007/JHEP09(2025)070, Published in: JHEP 09 (2025), 070, JHEP 09 (2025), 070.
5. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Search for jet quenching with dijets from high-multiplicity pPb collisions at $\sqrt{{s}_{\text{NN}}}$ = 8.16 TeV, e-Print: 2504.08507 [hep-ex], DOI: 10.1007/JHEP07(2025)118, Published in: JHEP 07 (2025), 118, JHEP 07 (2025), 118.
6. CMS Collaboration, Aram Hayrapetyan (Yerevan Phys. Inst.) et al., Observation of a pseudoscalar excess at the top quark pair production threshold, e-Print: 2503.22382, DOI: 10.1088/1361-6633/adf7d3 (publication), Published in: Rept.Prog.Phys. 88 (2025) 8, 087801.
7. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Observation of nuclear modification of energy-energy correlators inside jets in heavy ion collisions, e-Print: 2503.19993 [hep-ex], DOI: 10.1016/j.physletb.2025.139556 (publication) Published in: Phys.Lett.B 866 (2025), 139556.
8. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Search for dark matter production in association with a single top quark in proton-proton collisions at $\sqrt{{\varvec{s}}}$=13 TeV, e-Print: 2503.20033 [hep-ex], DOI: 10.1007/JHEP09(2025)141, Published in: JHEP 09 (2025), 141.
9. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Search for vector-like leptons with long-lived particle decays in the CMS muon system in proton-proton collisions at $\sqrt{\text{s}}$ = 13 TeV, e-Print: 2503.16699 [hep-ex], DOI: 10.1007/JHEP08(2025)156, Published in: JHEP 08 (2025), 156.
10. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Probing Gluon Fluctuations in Nuclei with the First Energy-Dependent Measurement of Incoherent J/ψ Photoproduction in Ultraperipheral PbPb Collisions, e-Print: 2503.08903 [nucl-ex], DOI: 10.1103/w9kp-f8xr (publication), Published in: Phys.Rev.Lett. 135 (2025) 11, 112301.
11. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Observation of the Charged-Particle Multiplicity Dependence of σψ(2S)/σJ/ψ in p-Pb Collisions at 8.16 TeV, e-Print: 2503.02139 [nucl-ex], DOI: 10.1103/c9wp-5tq3 (publication), Published in: Phys.Rev.Lett. 135 (2025) 9, 092301.
12. CMS Collaboration, Vladimir Chekhovsky (Yerevan Phys. Inst.) et al., Search for medium effects using jet axis decorrelation in inclusive jets from PbPb collisions at $\sqrt{{s}_{\text{NN}}}$ = 5.02 TeV, e-Print: 2502.13020 [nucl-ex], DOI: 10.1007/JHEP06(2025)120 Published in: JHEP 06 (2025), 120, JHEP 06 (2025), 120.
13. …

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