Searches for LLPs at CMS, and LLP-optimized detectors for future colliders

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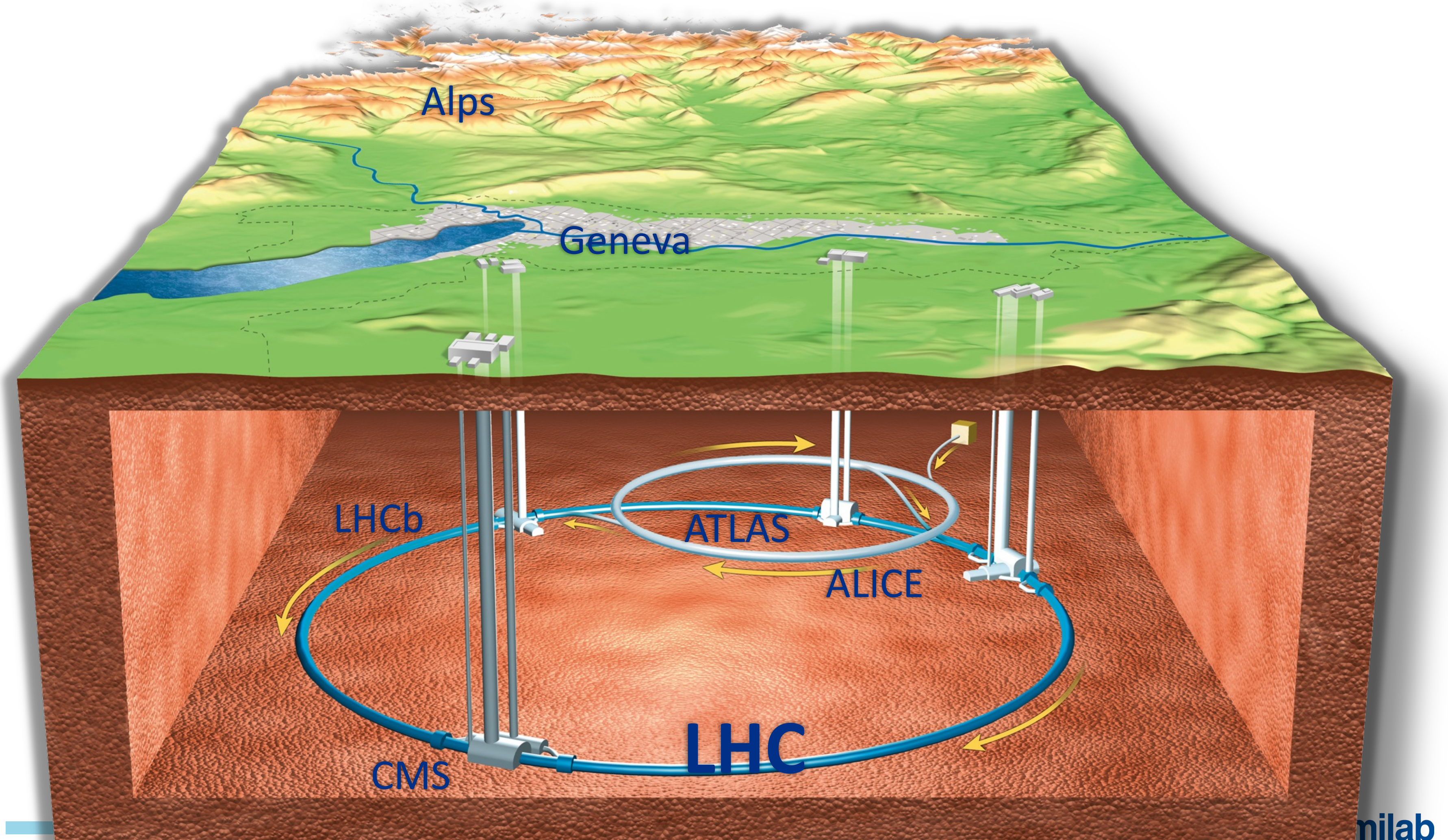
Conference On High Energy Physics

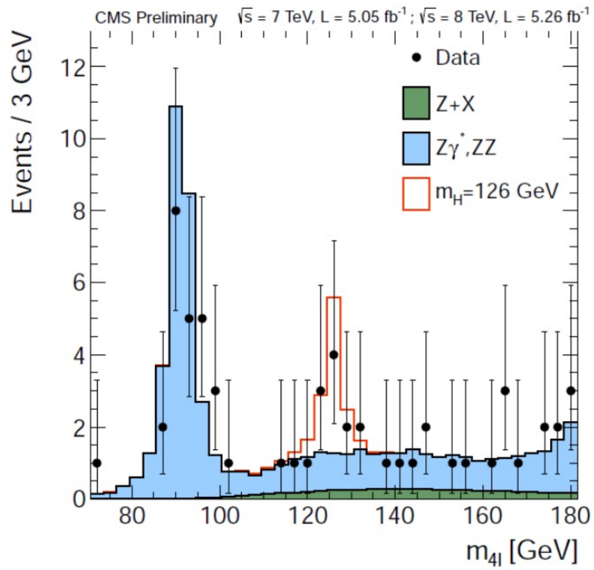
Sep 12, 2023

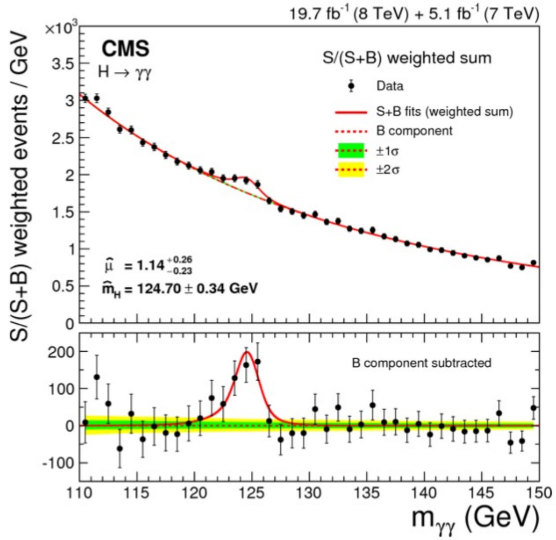
The Large Hadron Collider

Four large experiments: **ATLAS, CMS, ALICE**, and **LHCb**



Discovery of the Higgs boson: July 4, 2012



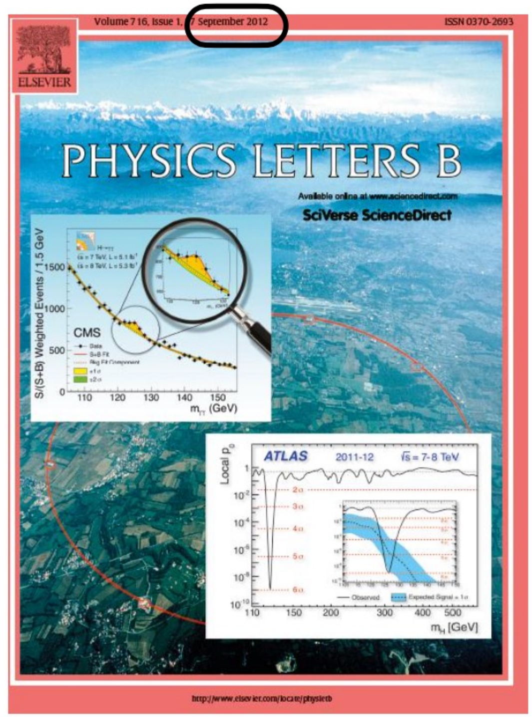


Volume 13, Number 16 PHYSICAL REVIEW LETTERS 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Discovery of first fundamental spin-0 particle: Higgs Boson



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

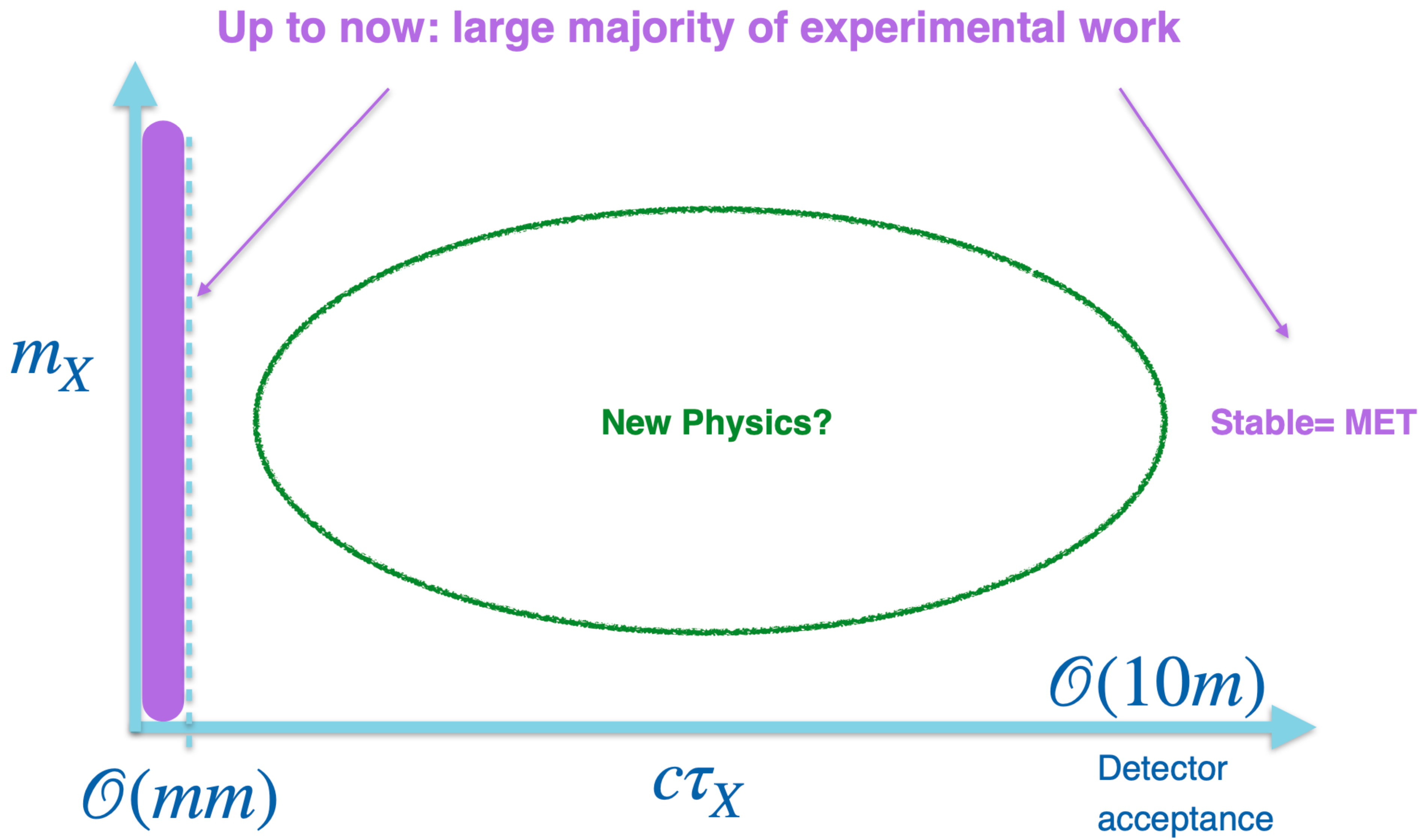
Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Searches for the unknown

https://en.wikipedia.org/wiki/Flammarion_engraving

New physics at the LHC



The Case for Long-lived Particles

- Small decay width (Γ) gives rise to sizable lifetimes

$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

- **Three general mechanisms:**
  1. Feeble coupling to SM
  2. Scale suppression
  3. Light new particle (m) — phase space suppression

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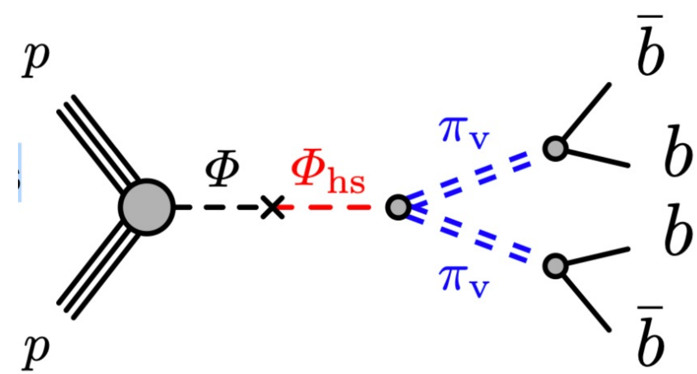
  – e.g: Higgs portal to hidden sectors
  – Accessing dark matter/sectors



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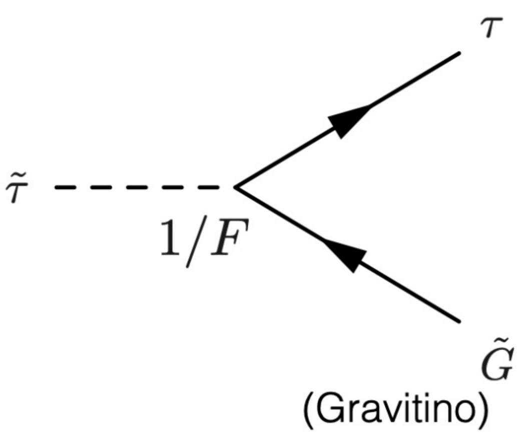
  - **e.g: Gauge mediated SUSY**
  - Decay to gravitino suppressed by SUSY-breaking scale (*F*)



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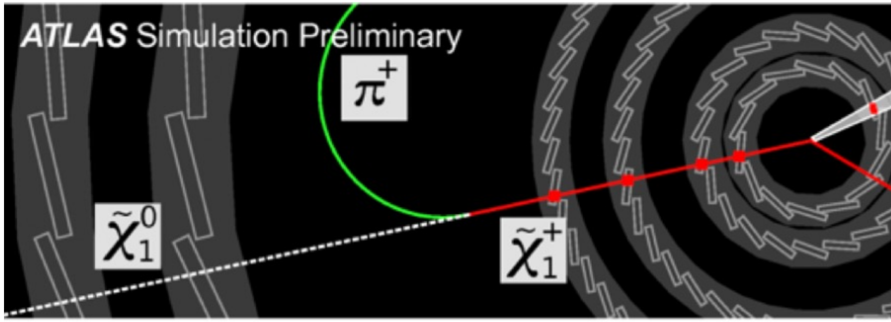
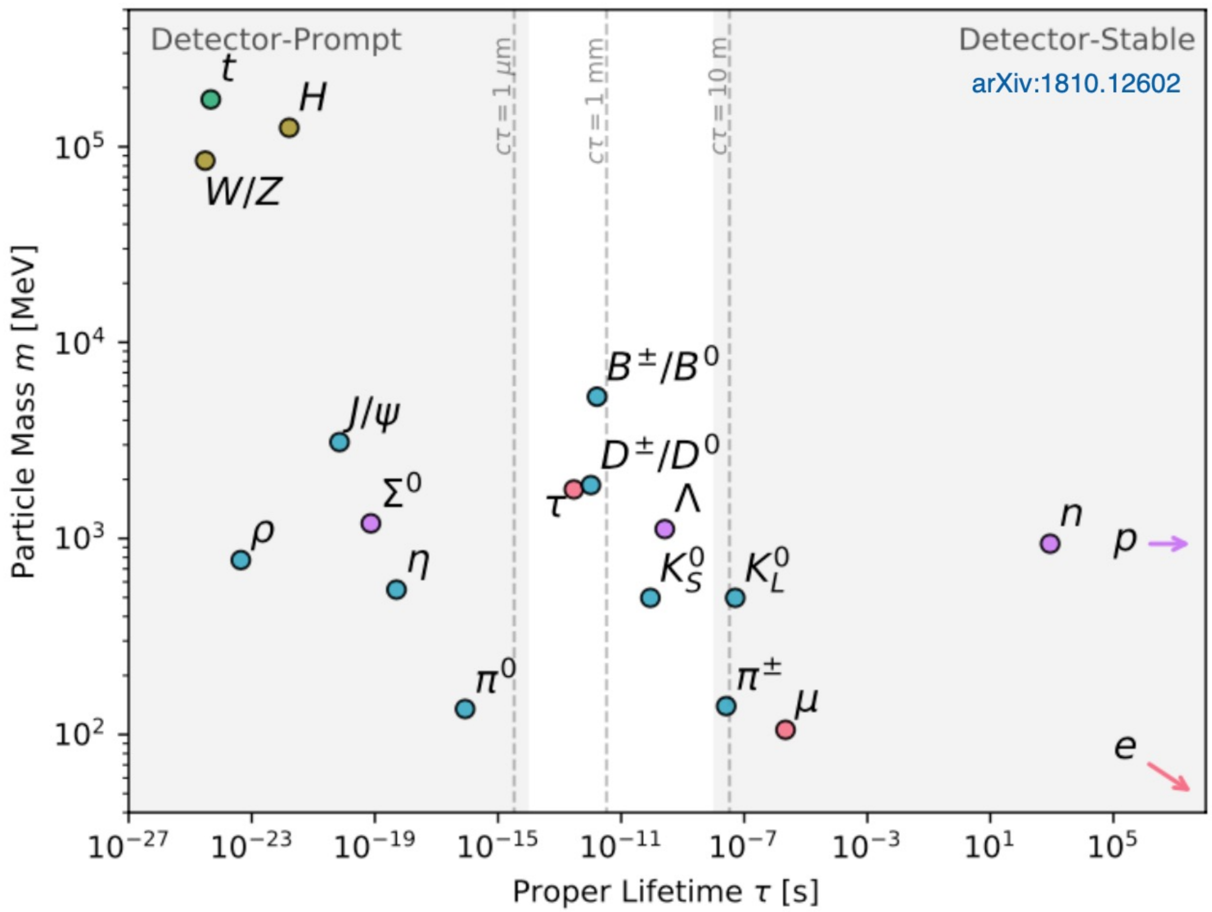
$$\Gamma \sim \frac{g^2}{8\pi}\left(\frac{m}{M}\right)^{2n} m$$

- **Three general mechanisms:**
  3. Phase space suppression
  – **e.g: SUSY**
  – Small mass splitting between NLSP and LSP



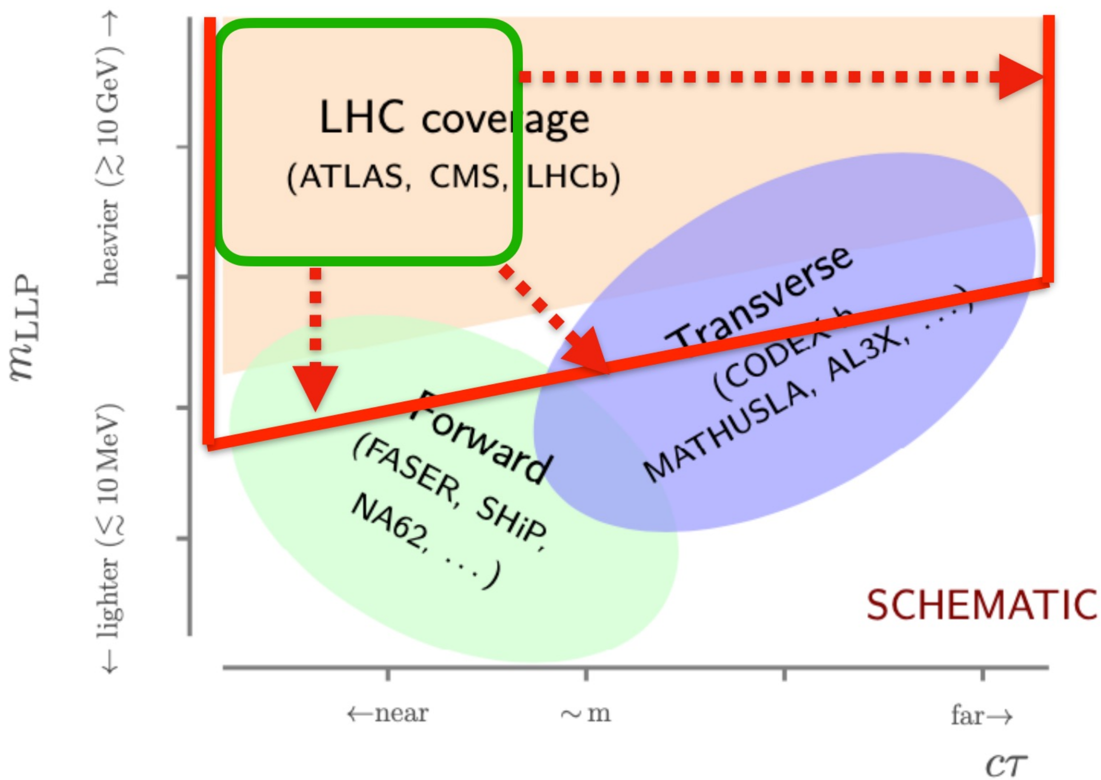
Long-Lived Particles (LLP) in SM



SM great example of fundamental laws giving rise to LLP

LLPs at CMS in Run2

arxiv:1911.00481 — CODEX-b

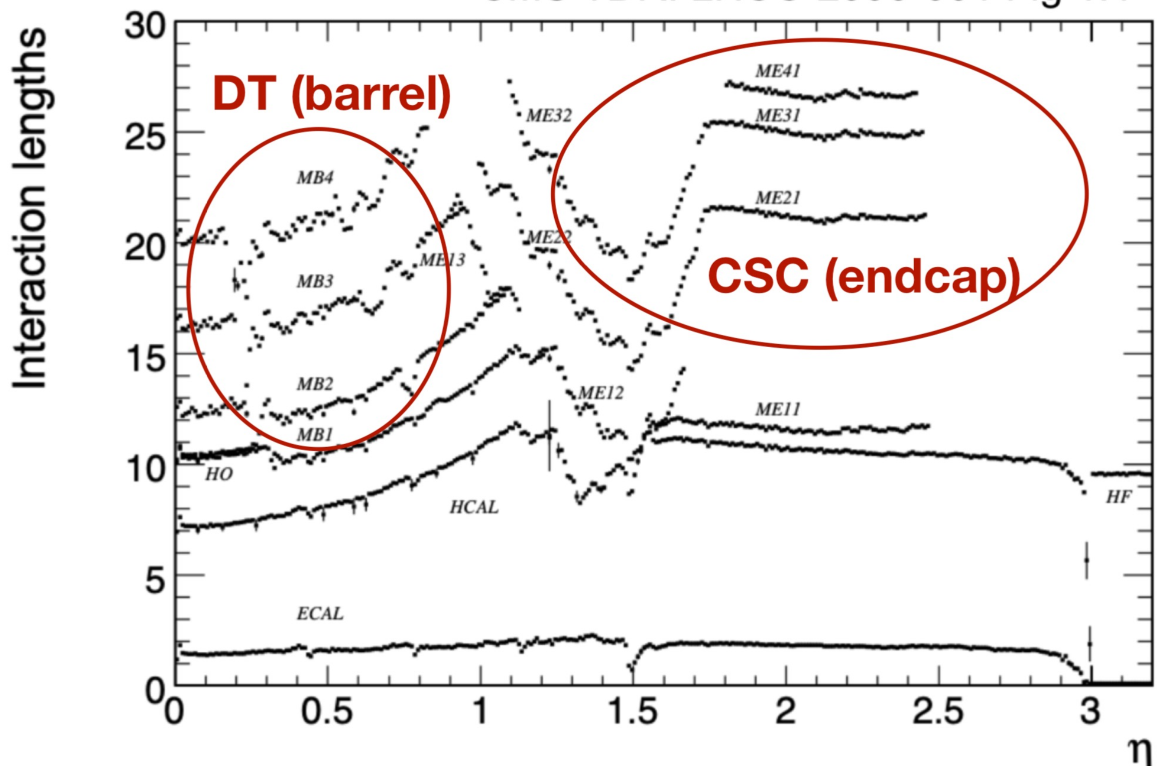


- How to unlock CMS' full LLP discovery reach?
- How far can we extend the mass and lifetime?

Opportunity for CMS

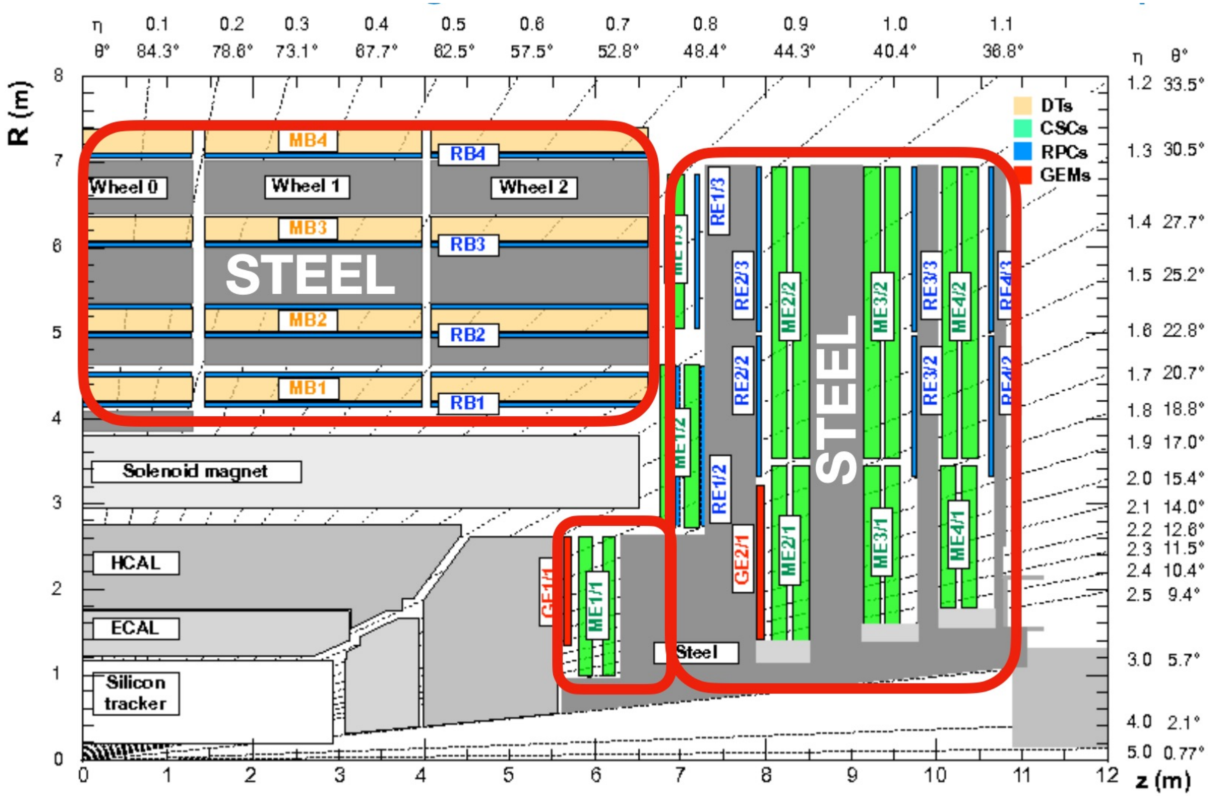
- CMS has **a lot of iron** to reject punch through jets
  - In the range of 12-27 λ lengths depending on the location
- Lots of STEEL → bkg suppression → Ideal for LLP searches ✅

CMS TDR: LHCC-2006-001 Fig 1.4



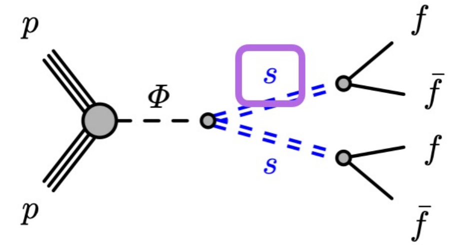
Compact Muon Solenoid

COMPACT Design + Small **$\pi \rightarrow \mu$ mis-ID** (10^{-3})

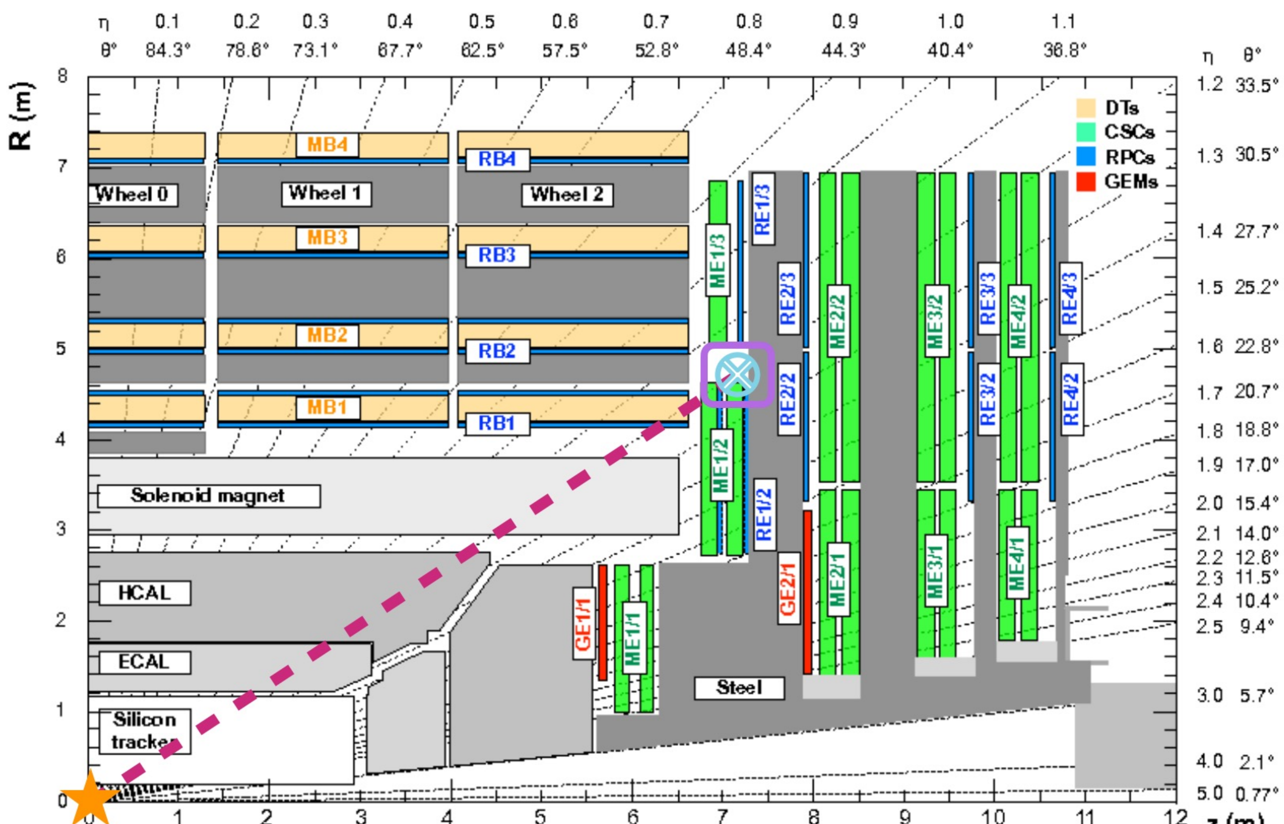


- 4-layers of highly segmented active elements → LLP signal ✅

Search for LLPs in Muon System

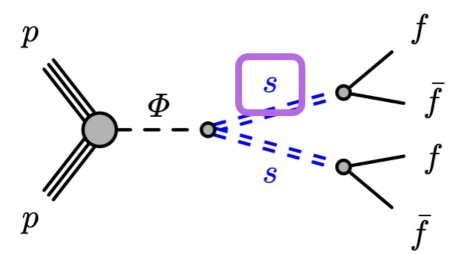


- LLP decays in MS cause a detectable shower



→ LLP (s) decay

Search for LLPs in Muon System



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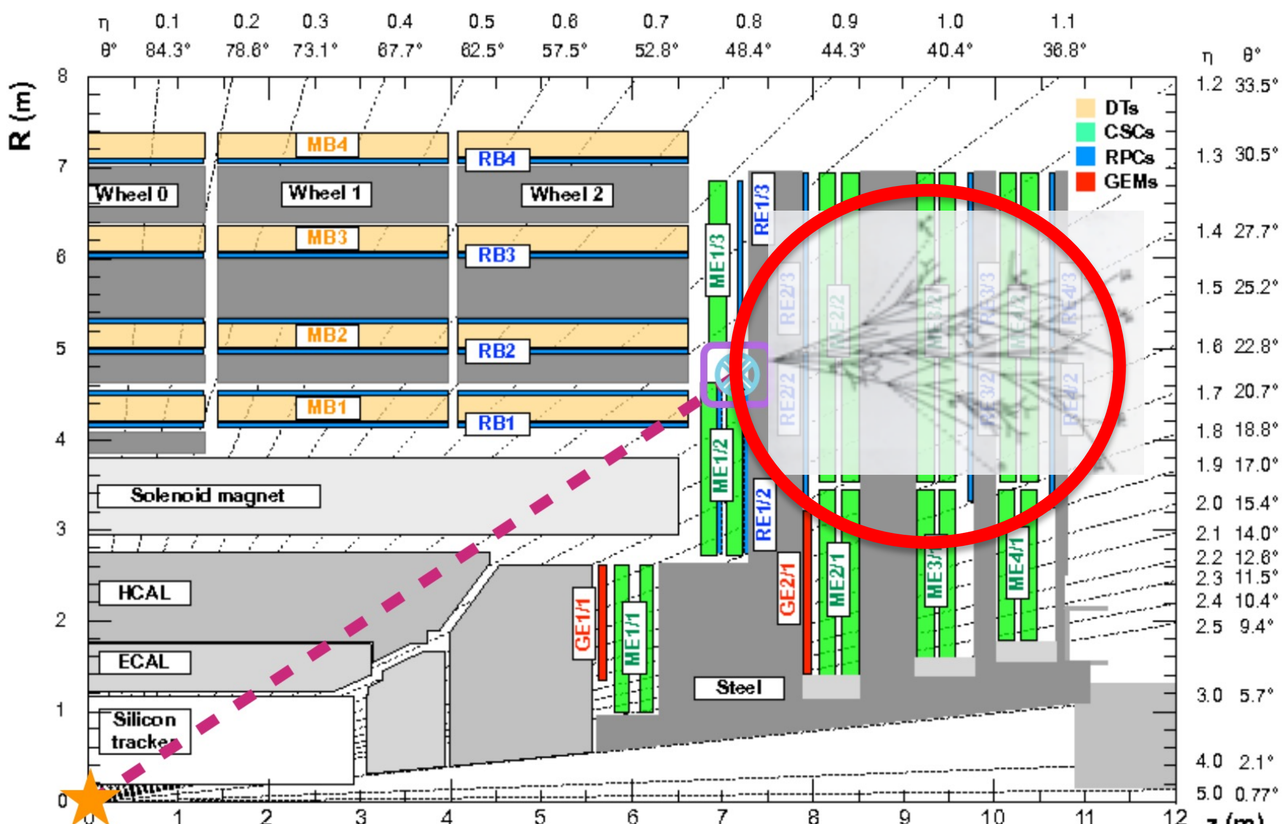
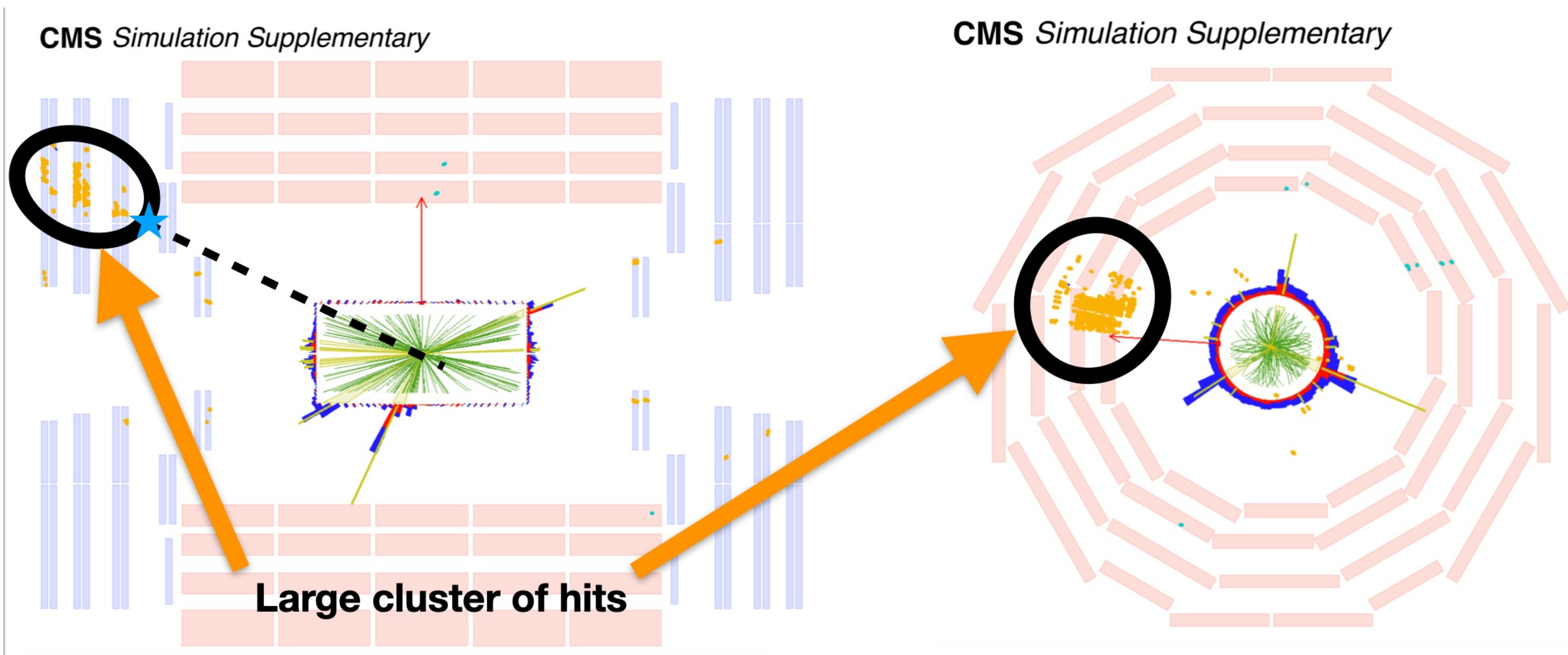


- Sensitive to a broad range of LLP decays

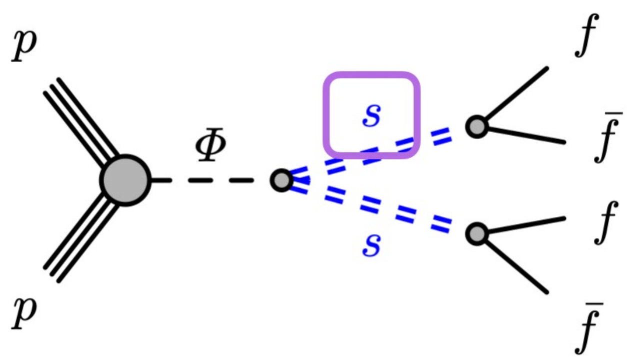
LLP Signature in Muon System

- **First time this signature is explored at the LHC**
- LLPs that decay in the muons system leave a signature of:
  - **Large cluster of hits** in the muon chambers (**MDS**)
- Muon system acts as a **sampling calorimeter**



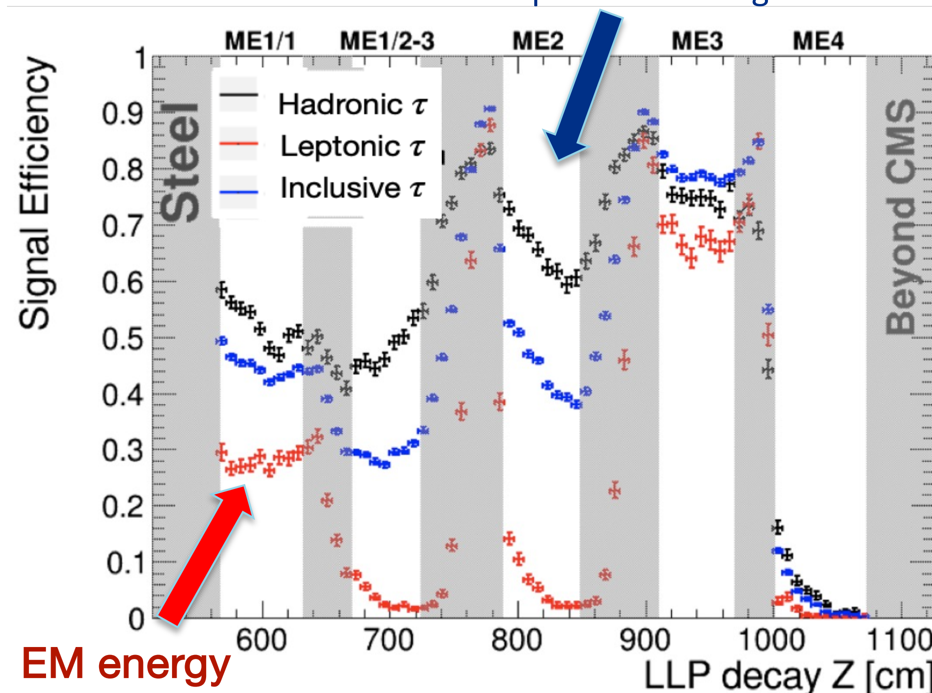
LLP Efficiency in Muon System

- Muon system acts as a sampling calorimeter



At least 50 hit reconstruction cluster

Hadronic energy punches through steel



EM energy stopped by steel

sensitive to hadronic, tau, photon, and electron decays

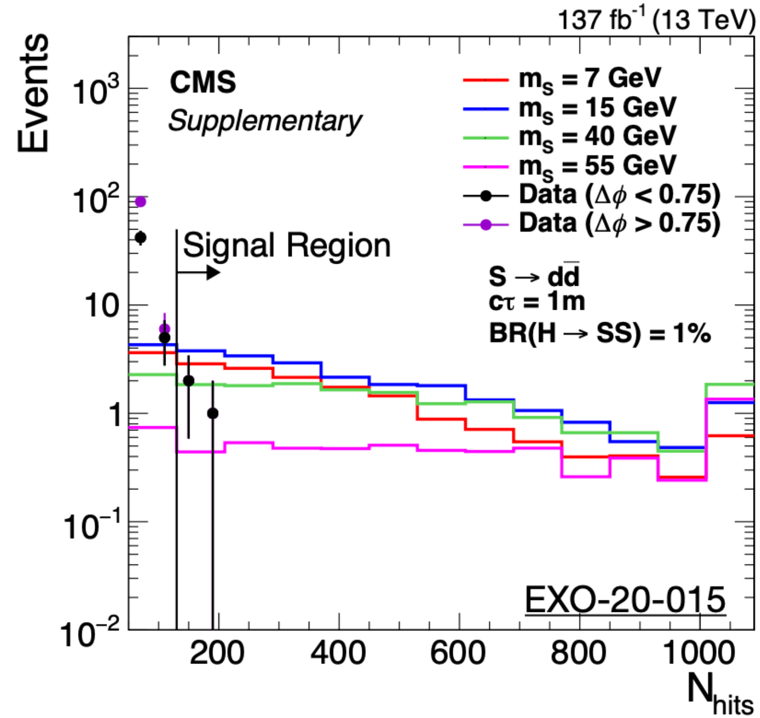
- Strong dependence on decay position (Z)
- Highly correlated with amount of steel in front of CSC

PRL 127 (2021) 261804

CSC/DT Cluster Reconstruction

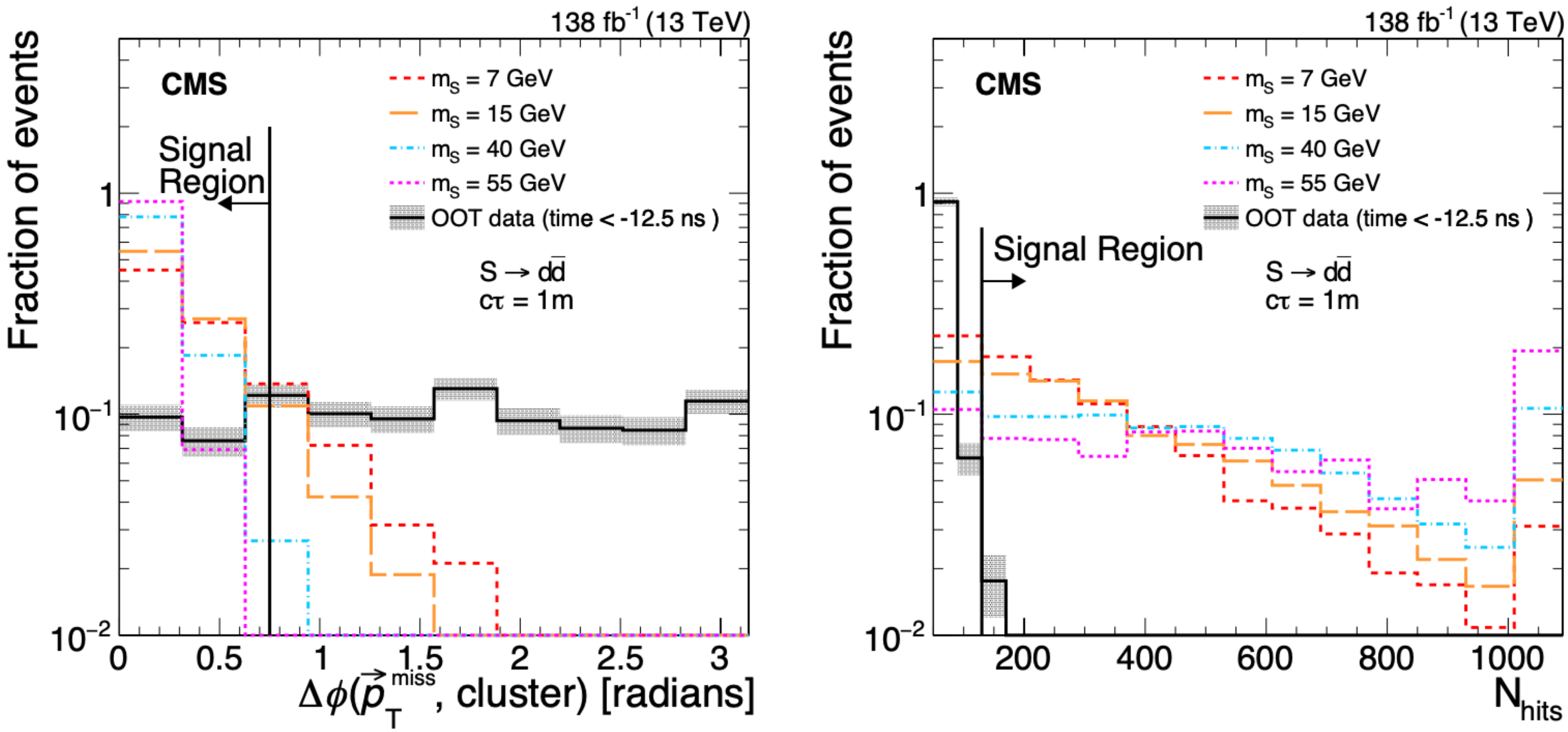
- Each CSC/DT RecHit is defined by their position, specified by η, ϕ
- Cluster RecHits with DBSCAN algorithm with distance parameter ΔR = 0.2
- Require > 50 RecHits per cluster
- Merge clusters if two clusters are within ΔR < 0.6

Main discriminator for all analyses using MDS



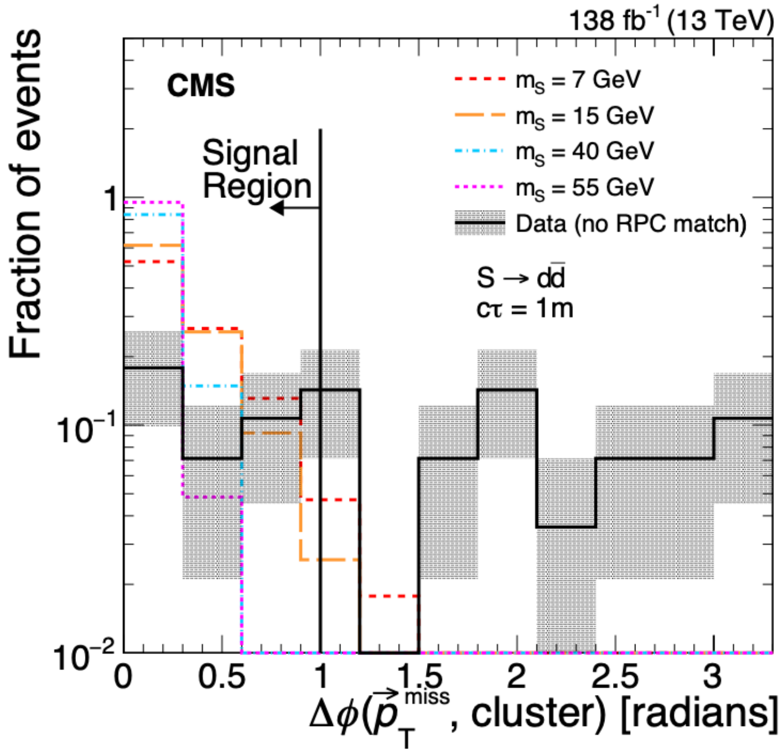
Fermilab

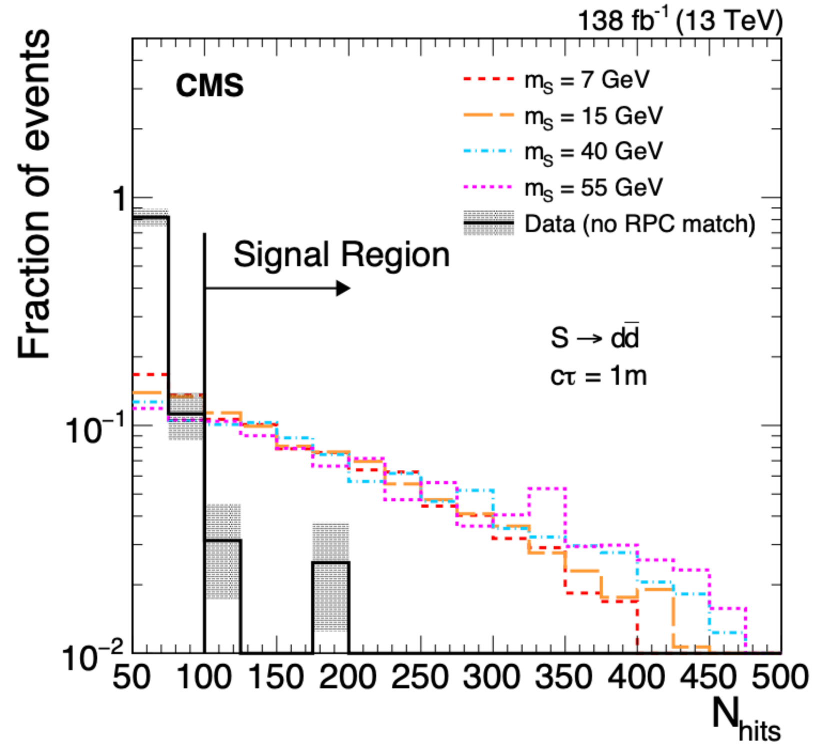
Cluster-level Selections (Single CSC Cluster)



- N_{hits} > 130: main discriminator against background
- $\Delta\phi$(MET, cluster) < 0.75: provides additional discrimination
  - For signal, MET and cluster are aligned
  - Provides a variable independent of N_{hits} for the ABCD method

Cluster-level Selections (Single DT Cluster)

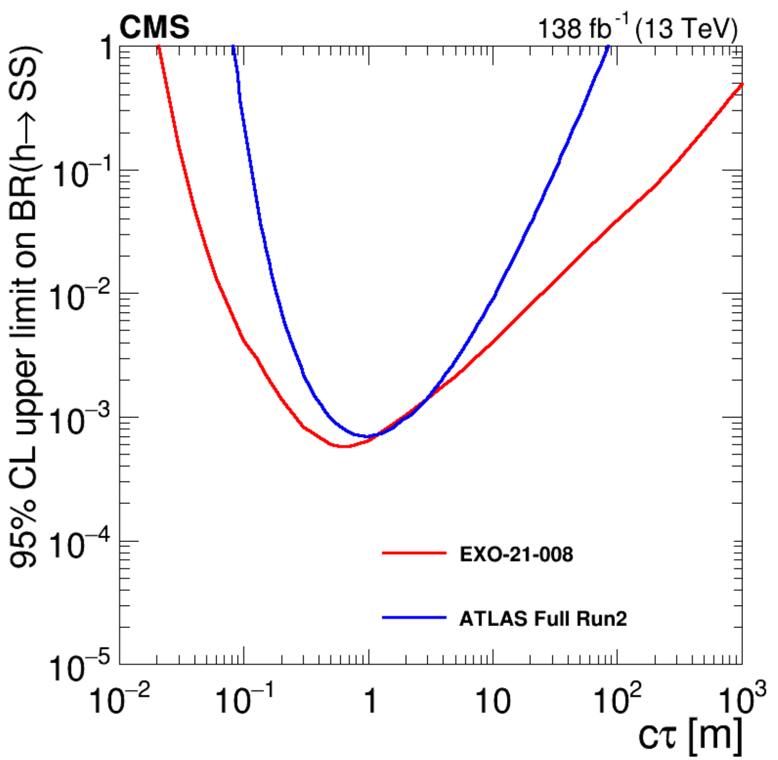


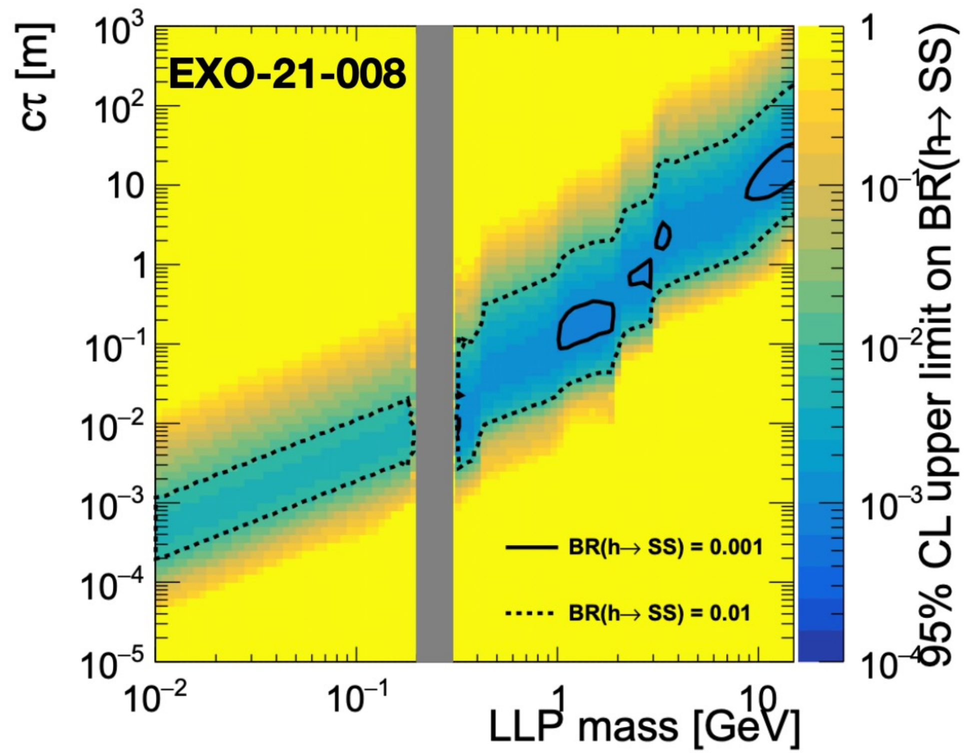


- Same variables as single CSC cluster category, except the thresholds are optimized separately
  - $\Delta\phi$(MET, cluster) < 1 & N_{hits} > 100

Search for new physics models in Higgs decays

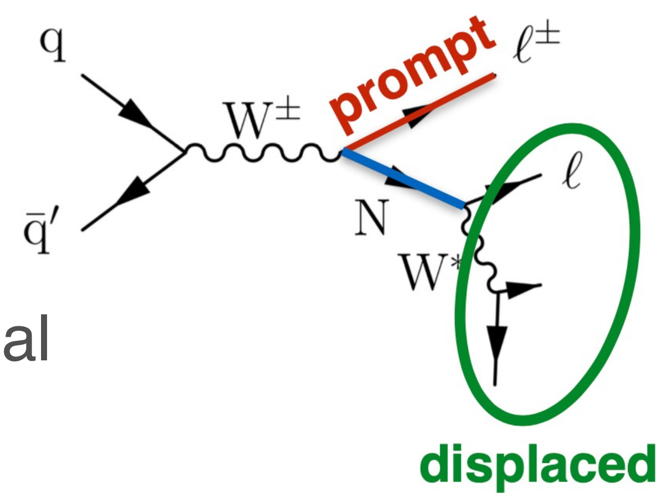
- Best sensitivity at LHC, reaching **Branching Fractions ~5x10^{-3}**
  - First-ever sensitivity for LLP **masses below 5 GeV**





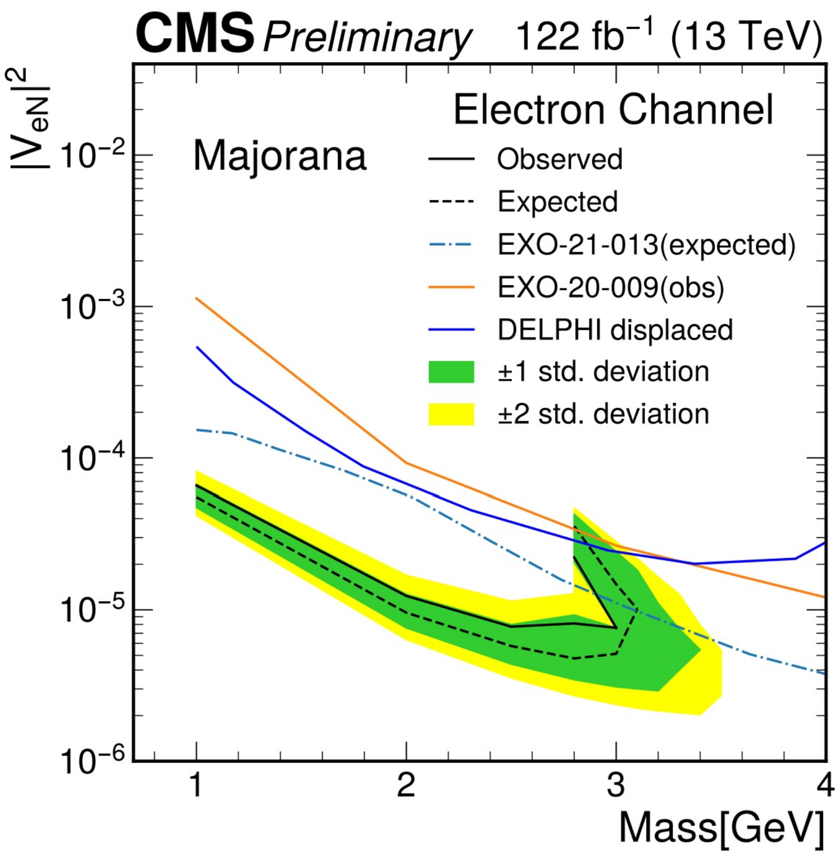
Search for Heavy Neutral Leptons with MDS

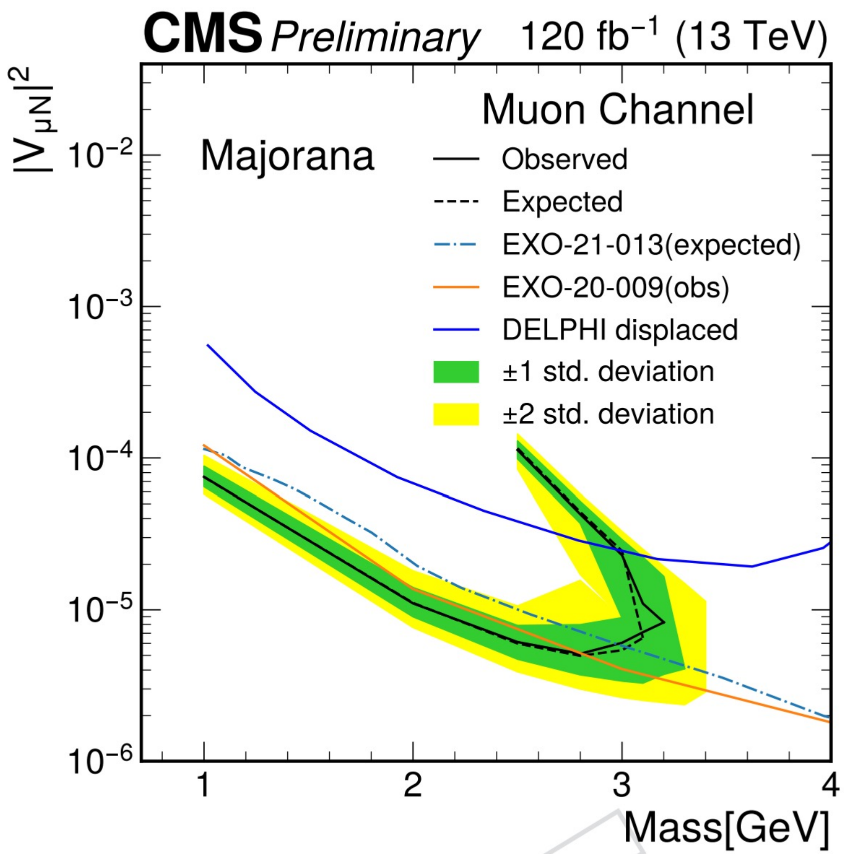
- Search for HNL with MDS with a prompt and triggering electron or muon
  - Sensitive to all visible HNL energy
  - Particle showers from the displaced lepton and inclusive W* decays
  - Extend sensitivity to smaller mass and mixing angle
- Cluster selections similar to Higgs portal searches



Search for new neutral leptons

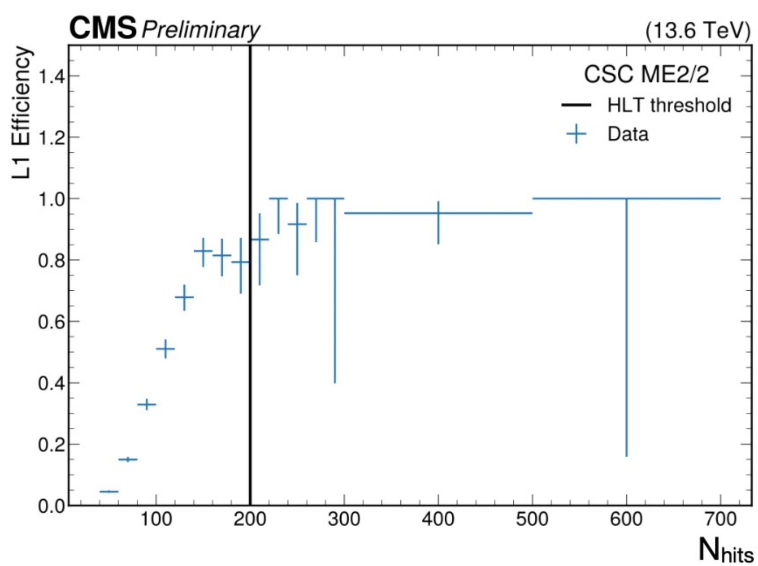
- **Best sensitivity for Heavy Neutral Leptons below 3 GeV**
  - 5-10x smaller mixing angle compared to previous results

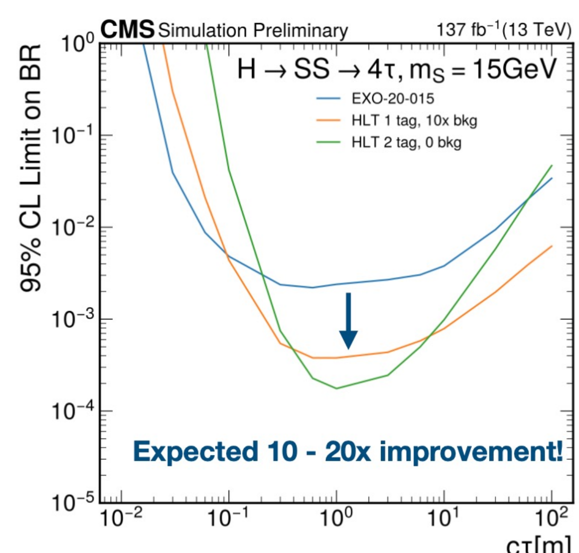




New triggers for MDS signatures

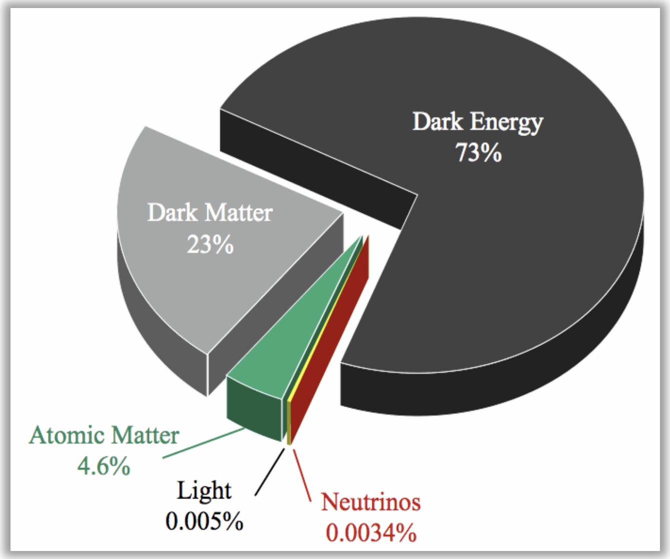
- Low signal efficiency in Run-2 analysis, triggering on prompt associated objects or MET
  - Only 1% efficiency for Higgs portal
- New Level-1 trigger developed and commissioned for Run-3
  - Require large number of cathode & anode-wire hits in CSC chambers
  - High L1 efficiency measured using first Run-3 data
- Improve sensitivity by x10-20 wrt Run 2 → reach BR below 1e-4 !

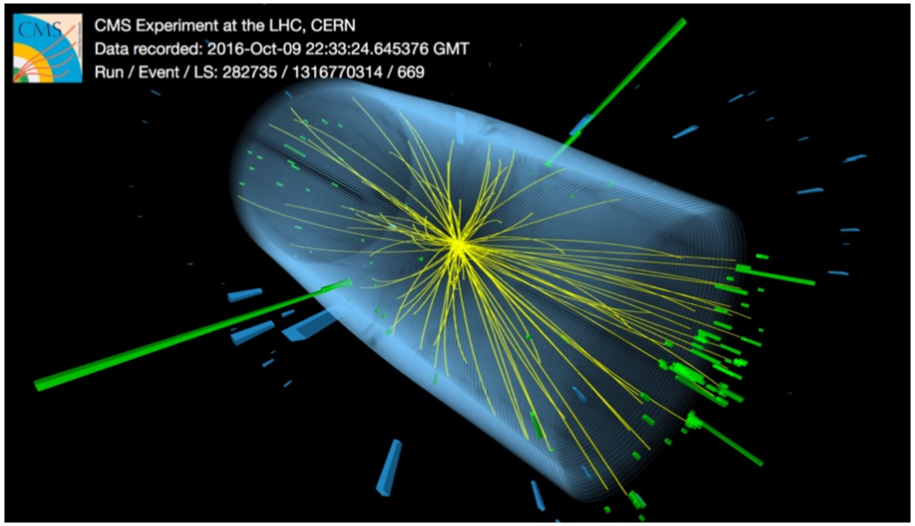




The grand challenges

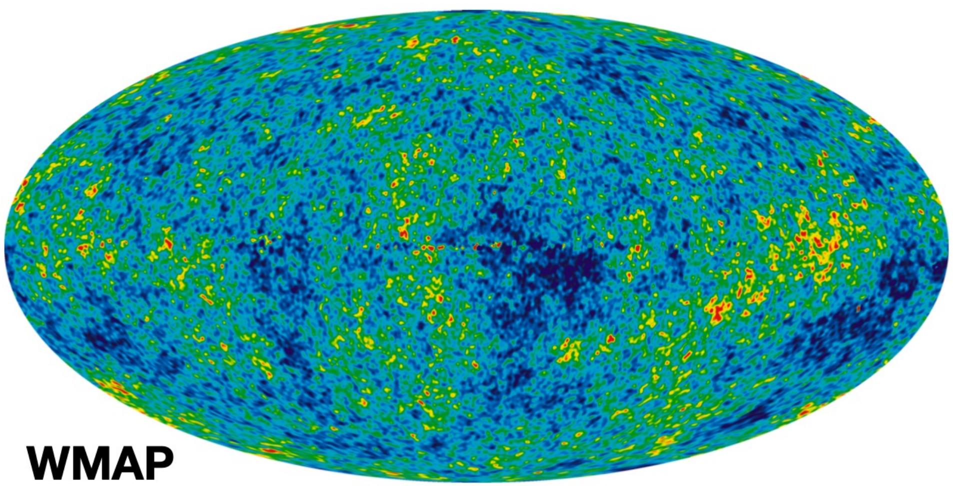
- Many fundamental questions remain in SM
  - Higgs boson: ”unnatural” mass
  - Dark matter: no candidate particle
  - Non-zero neutrino masses
  - Origins of the dark energy
  - Baryon asymmetry

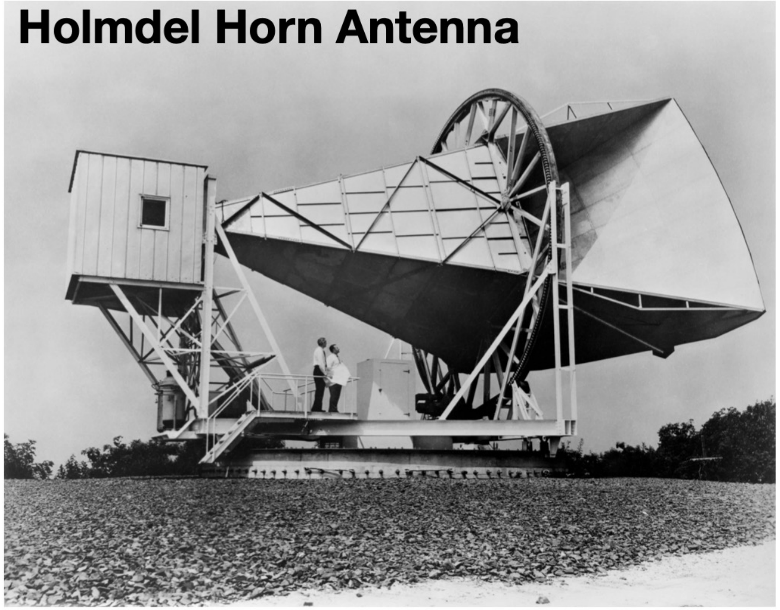




Transformative Physics Discoveries

- Explore nature at the frontier of detection-technology
  - New fundamental principles
  - Enable discoveries
  - New directions in science



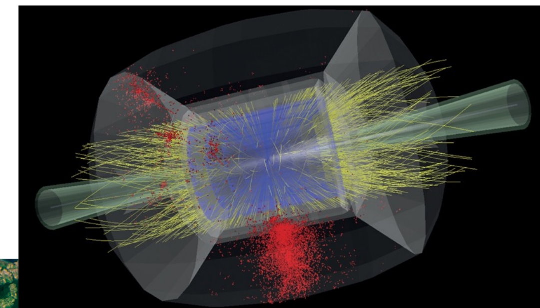


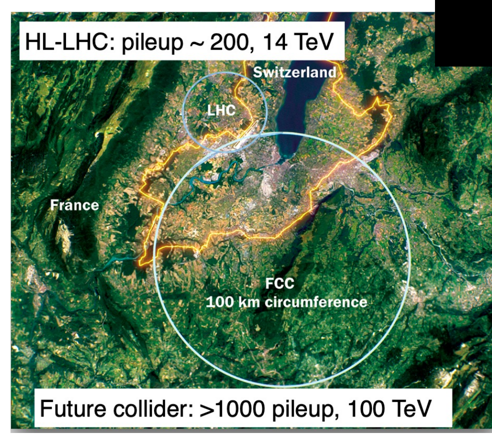
Future trackers need timing

- 4D-trackers will play a key role at future machines
  - Reduce backgrounds, track reconstruction, Level-1 triggering
  - New capabilities: PID and LLP reconstruction
  - All of these pose unique challenges and opportunities to detector design

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 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 toleran up to $8x10^{17}$ n/cm^2
	Per track resolution of 5 ps

Technical requirements for future trackers: from [DOE's HEP BRN]


Muon collider



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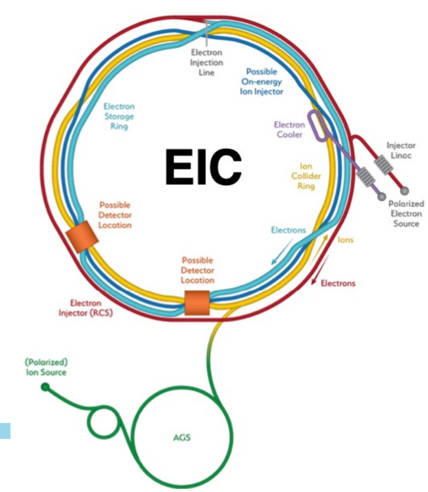
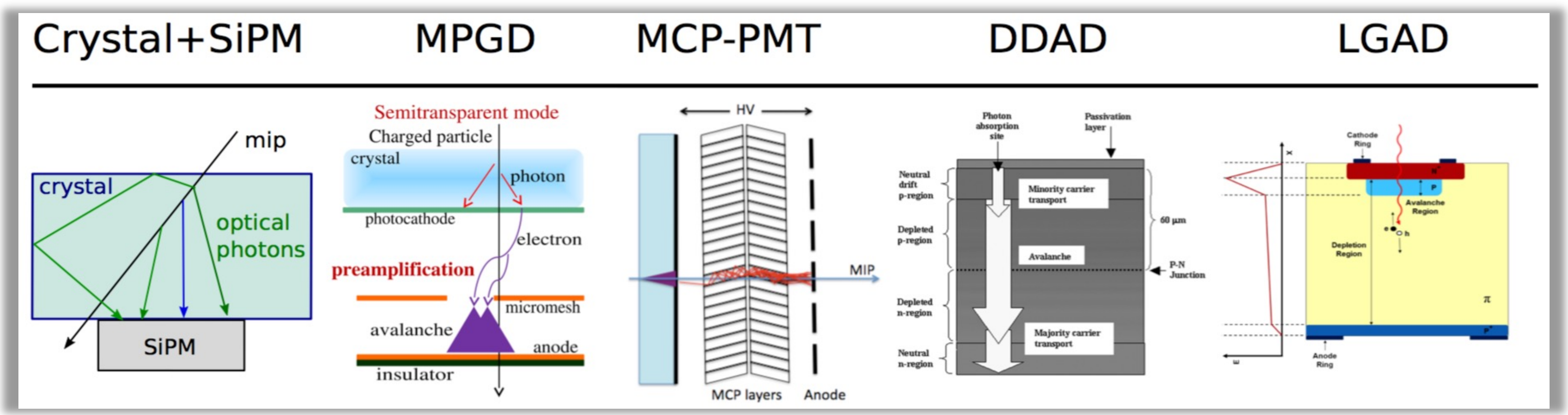


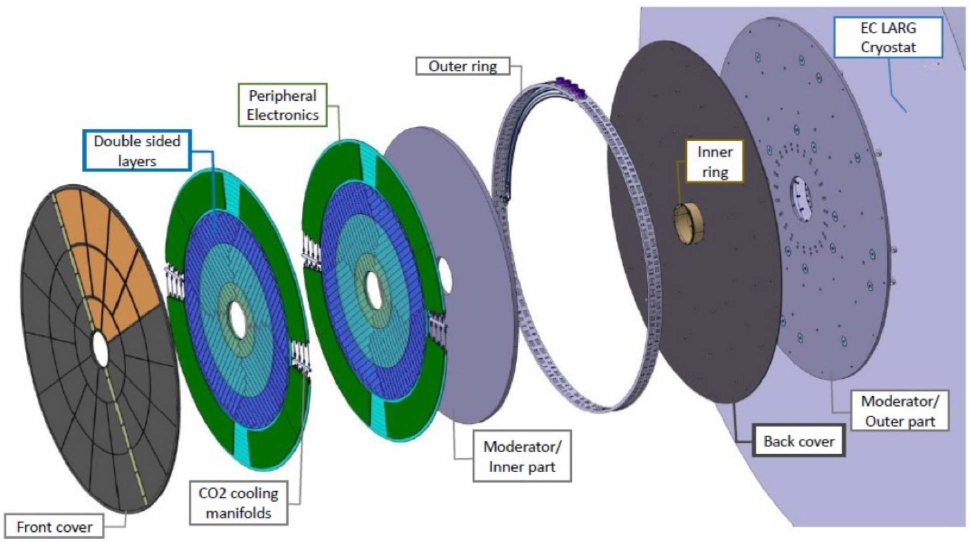
Technologies for precision timing detectors

- Active area of R&D for future collider experiments
  - One of the priority areas highlighted in DOE BRN, European Strategy for Particle Physics, and Snowmass
- Optimized solutions for various applications
  - Trackers: high granularity and low mass
  - Calorimeters: dense volume interspersed with fast detecting medium
  - Muon detectors: fast gas detectors with low mass

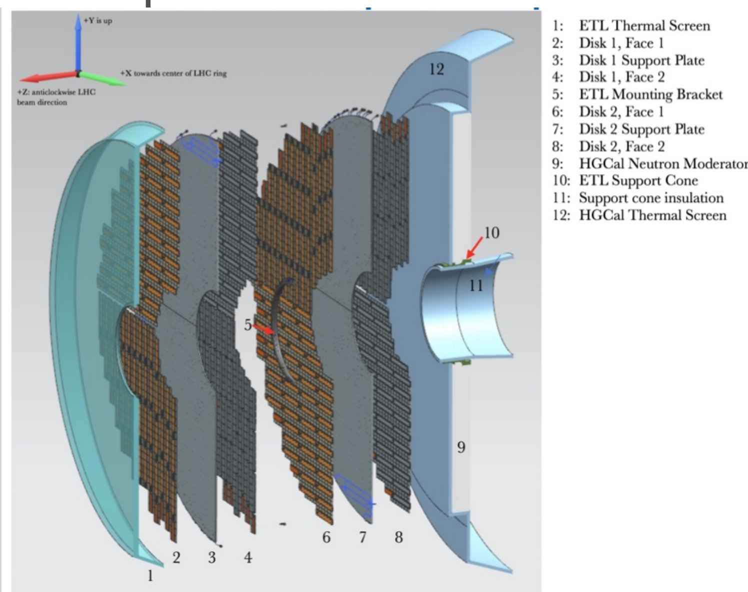


Precision timing

- CMS and ATLAS are building first-generation of 4D-detectors
  - Next-gen detectors will have high granularity also in **time domain**
  - At the tracker, calorimeter, muon detectors, and L1 trigger
- Future detectors moving towards full **5D Particle Flow**
  - Active R&D to achieve required performance for future experiments
  - Sensors, ASIC, front-end electronics developments



ATLAS timing detector

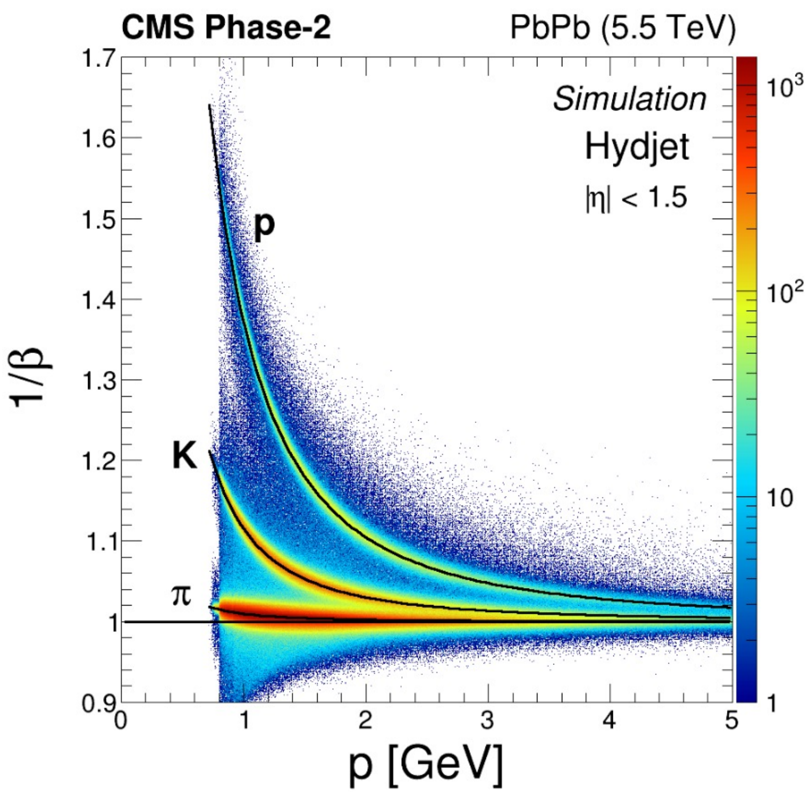


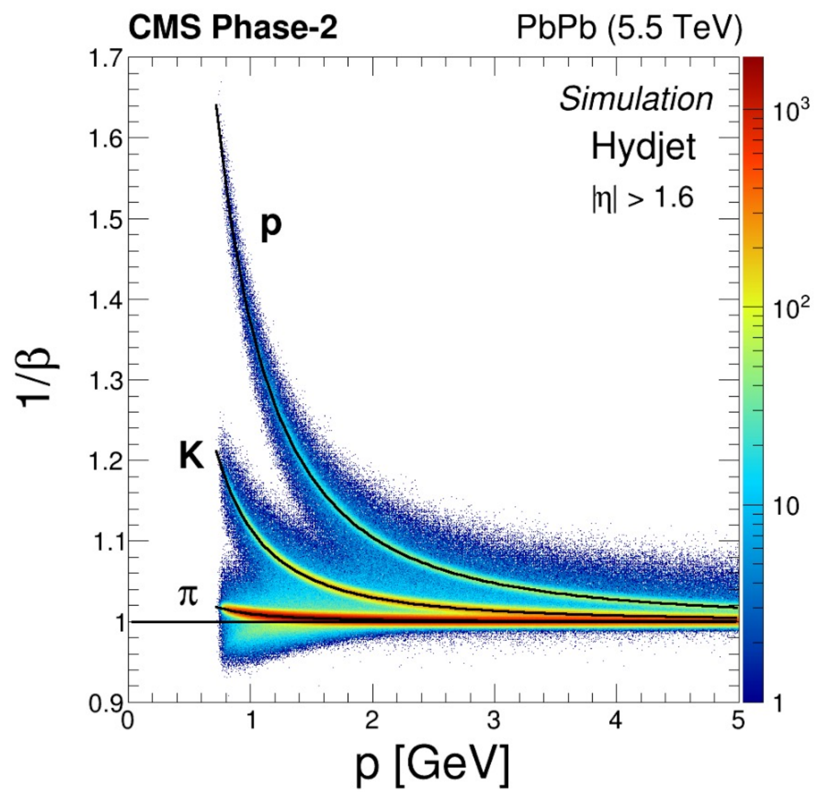
CMS timing detector

Time-of-flight Particle ID

- Time-of-flight particle identification: 2σ **π**/K separation up to p~2 GeV and K/p up to p~4 GeV
  - New handle for CMS for heavy flavor physics

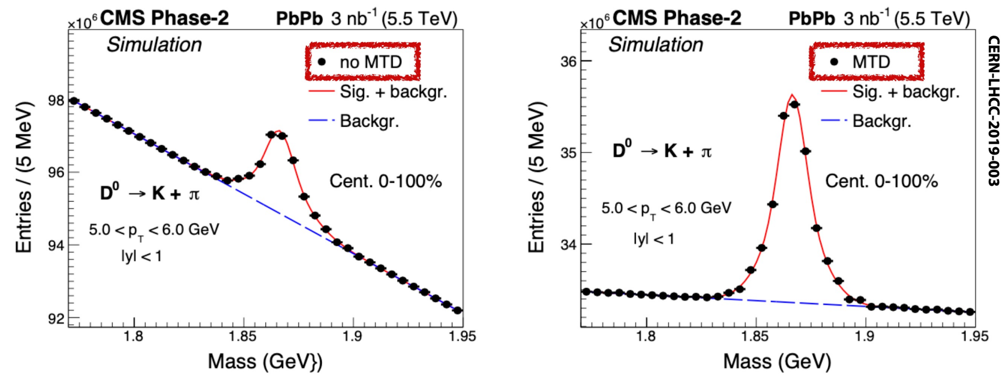
$$\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$$





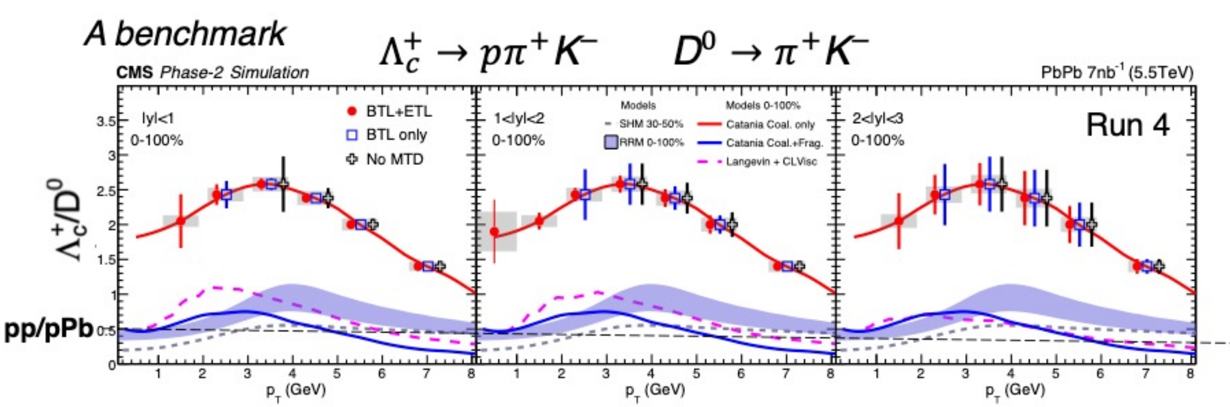
Physics impact: TOF Particle ID

- Competitive momentum coverage comparable to ALICE and STAR
  - Significantly suppressed background candidates
  - Signal significance is drastically improved
  - The region of $|\eta|>1$ is uncovered by other experiments



- Unique possibility to study charm and bottom hadrons production over a wide range of p_T and rapidity.

  Low p_T regions (inaccessible without MTD) should have the largest effect from QGP.



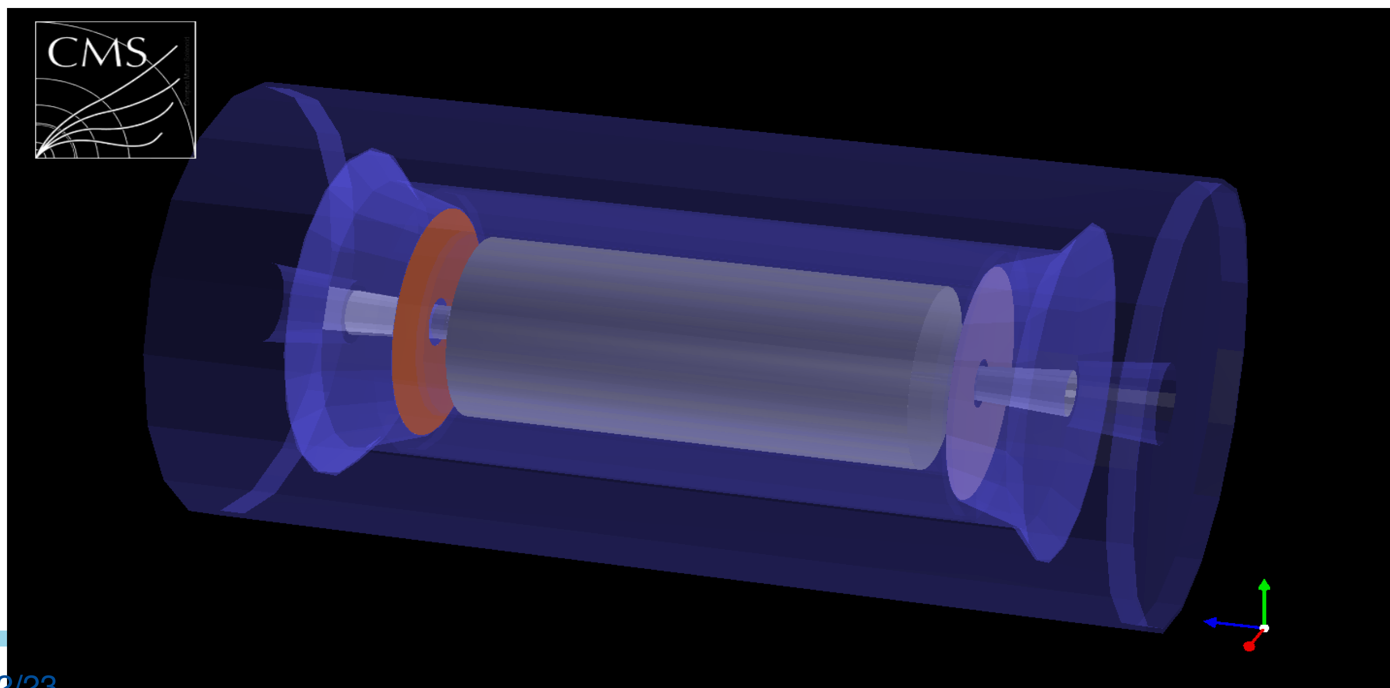
Comparison of performance with and without MTD

Technologies for precision timing detectors

- Complex systems need to be developed and implemented
  1. Rad-hard detecting **sensor** capable of high precision timing
  2. High precision, rad-hard, and low-power **readout electronics**
  3. Low noise detector system with high fidelity precision **clock**
  4. Integration into **trigger** and **event reconstruction**
  5. Continuous **monitoring** and **calibration**

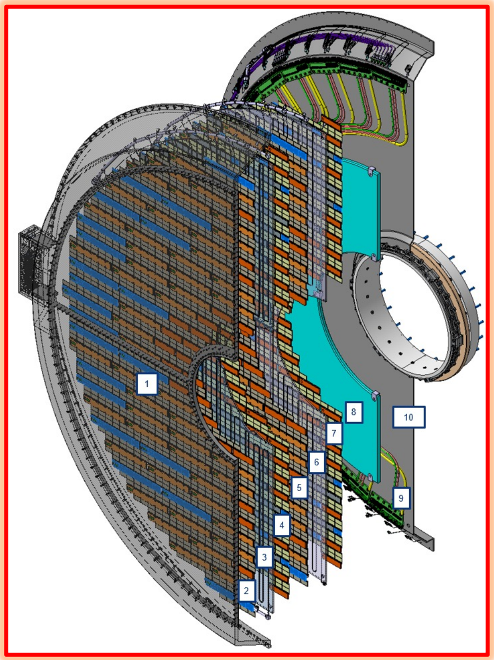
Precision timing for CMS in HL-LHC

- CMS Phase 2 upgrade aims to achieve high precision timing measurements
  - **In ECAL barrel**: new electronics to achieve ~30 ps resolution for photon/electron
  - **In HGCal**: design to achieve ~50 ps timing resolution per layer in EM showers, multiple layers can be combined
  - **MIP timing detector:** cover up to $|\eta|<3.0$ to time stamp charged particles in the event: ~30 psec timing resolution
    - **LYSO + SiPM** layer in the barrel,
    - **Low Gain Avalanche Detector** (LGAD) layer in the endcap

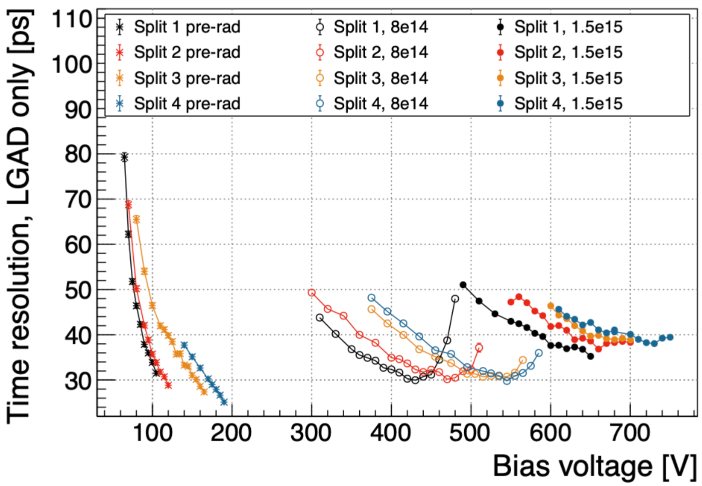


Endcap Timing Layer (ETL) design

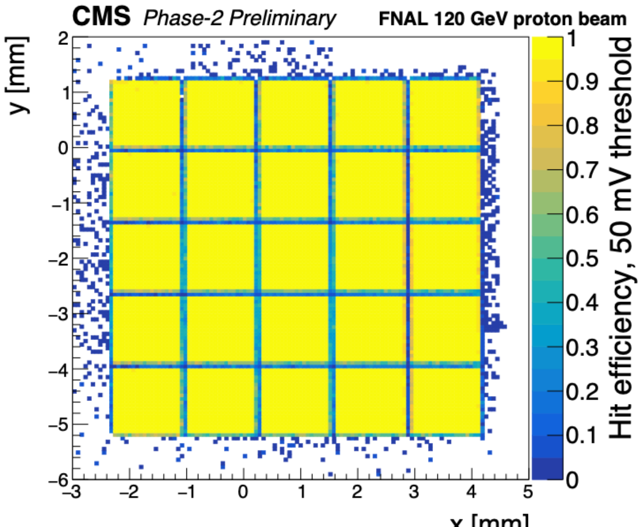
- Sensitive element are LGAD sensors
- Time resolution 30 ps at the beginning of life, 40 ps by the end
- Total silicon surface area of ~14 m^2 for the two Z-sides
  - Two hits for most tracks to improve per track efficiency and resolution



CMS Endcap Timing Layer



Time resolution for different fluences

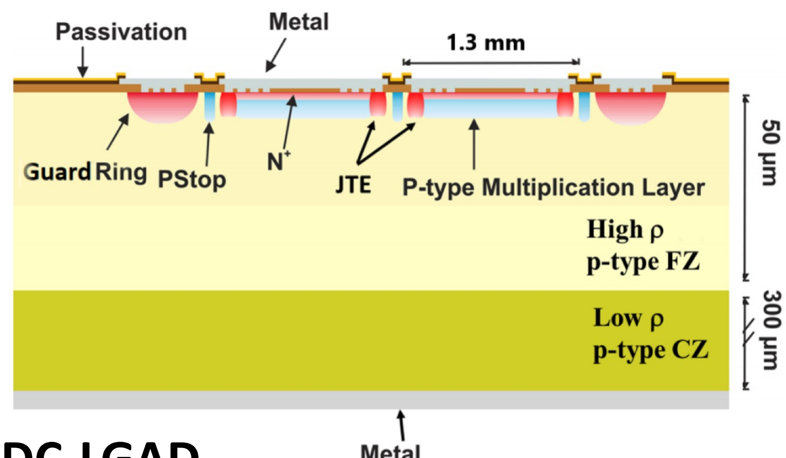


Hit efficiency across sensor area

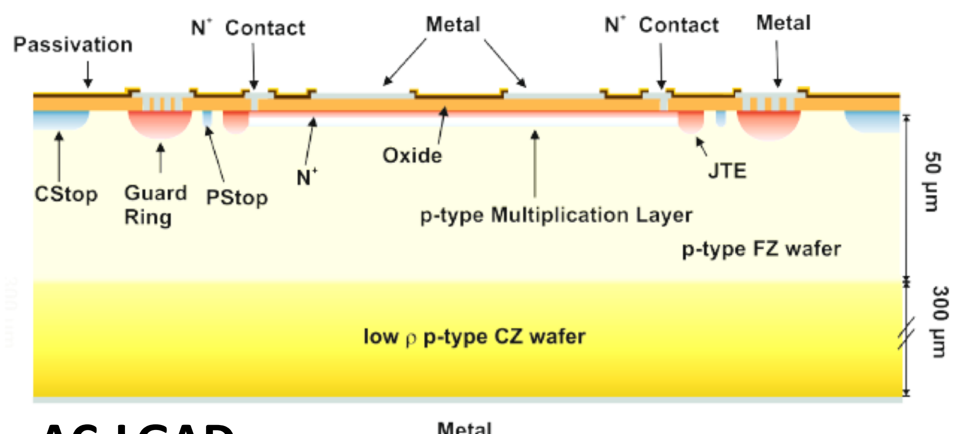
AC-coupled LGADs

- **Improve 4D-trackers to achieve 100% fill factor, and high position resolution**
- Active R&D at different manufacturers (FBK, BNL, HPK, etc)
  - 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.

Diagram credit: CNM



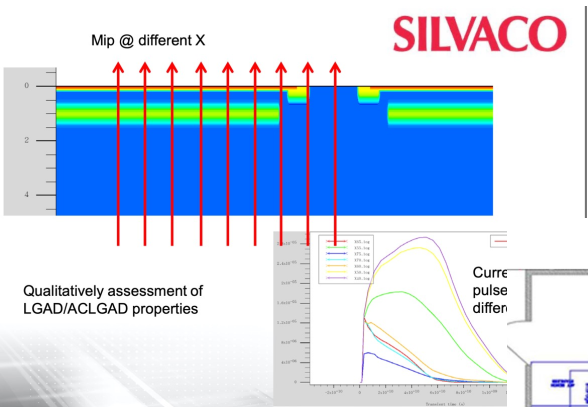
DC-LGAD



AC-LGAD

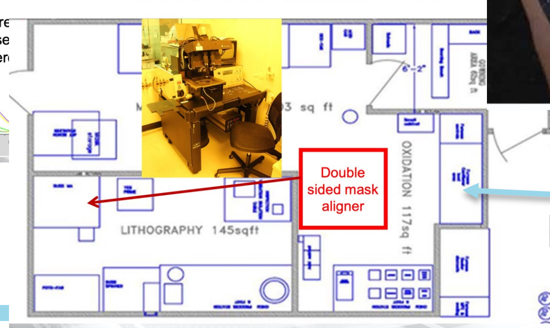
Development directions

- Next gen detector R&D requires a lot of infrastructure, expertise, and development cycles
  - Design, manufacture and test **sensor** prototypes
  - Our group and collaborators developed dedicated **readout boards and testing infrastructure** for characterization of prototypes,
  - Design, manufacture and test **full systems** integrating sensors and readout electronics

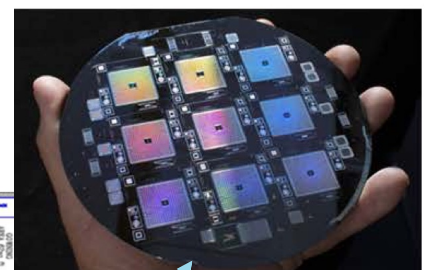


Design

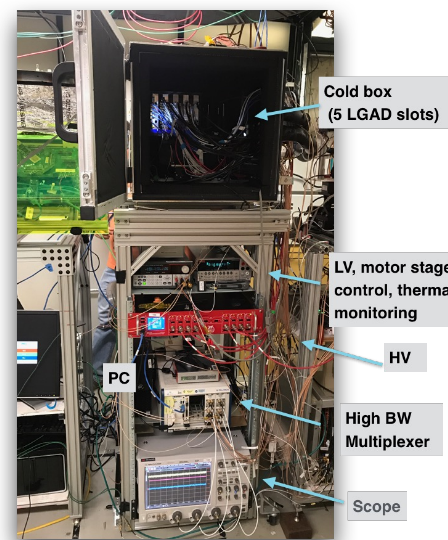
Class 100 Cleanroom



Finish Processed Wafer



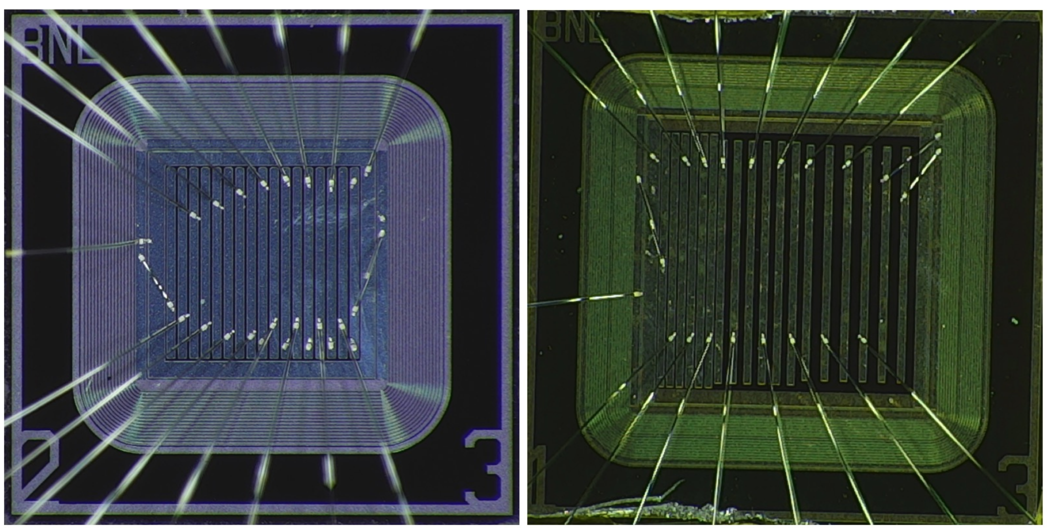
Fabrication



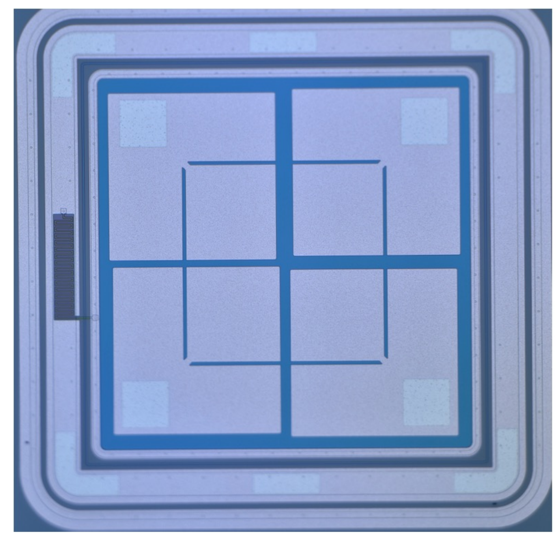
Testing in beams

AC-LGAD sensors prototypes

- Several rounds manufactured over the last few years
  - R&D benefiting from developments for HL-LHC
  - Optimization for AC-LGAD sensors has unique challenges
  - Can optimize position resolution, timing resolution, fill-factor, …
- Extensive characterization and design studies
  - Optimize the geometry of readout, and sensor design for performance



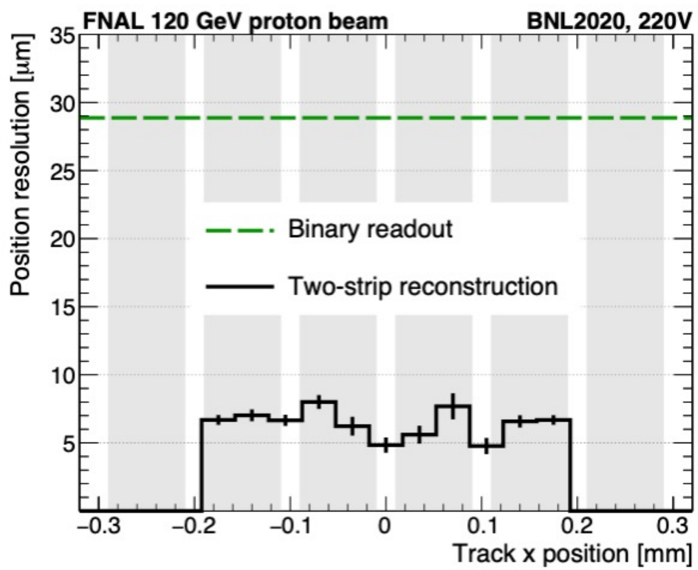
BNL strip AC-LGAD

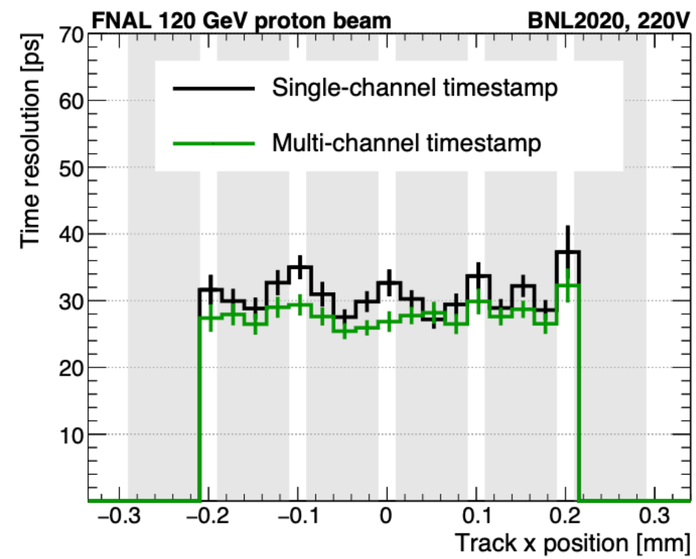


HPK pads AC-LGAD

Strip-sensor AC-LGADs (short sensors)

- Excellent performance from several strip prototypes
  - 100% particle detection efficiency across sensor surface
  - Signal shared between neighbors: measure position based on signal ratio
  - Well-tuned signal sharing → uniform 5-10 μm resolution

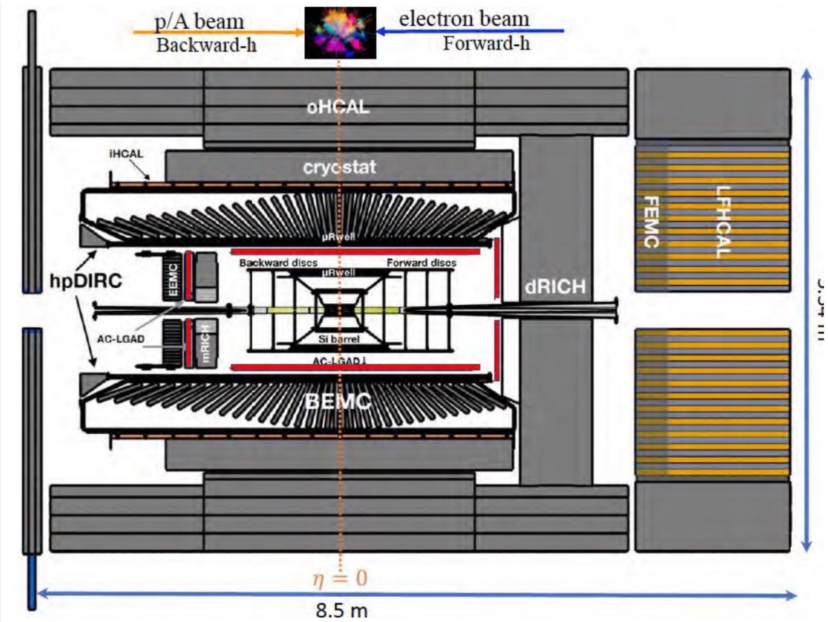




- **First demonstration of simultaneous ~5 μm, ~30 ps resolutions in a test beam: technology for 4D-trackers!**

Studies of long AC-LGAD strip sensors

- Technology demonstrator for 4D-tracking and detectors for **EIC**
  - First studies of large AC-LGAD sensors
  - Multiple sensors, geometries and designs studied
- Key insights for larger sensors
  - Sensor provides 100% efficiency, 15-20 µm resolution in large sensors,
  - Time resolution 30-35 ps for 1 cm strips

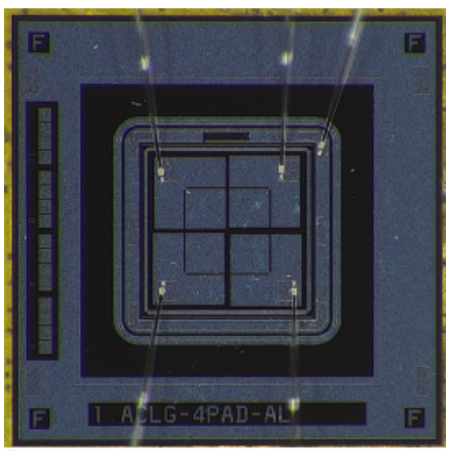


Name	Time resolution
	High gain
Unit	ps
BNL 5–200	30 ± 1
BNL 10–100	35 ± 1
BNL 10–200	32 ± 1
BNL 10–300	36 ± 1
BNL 25–200	51 ± 1

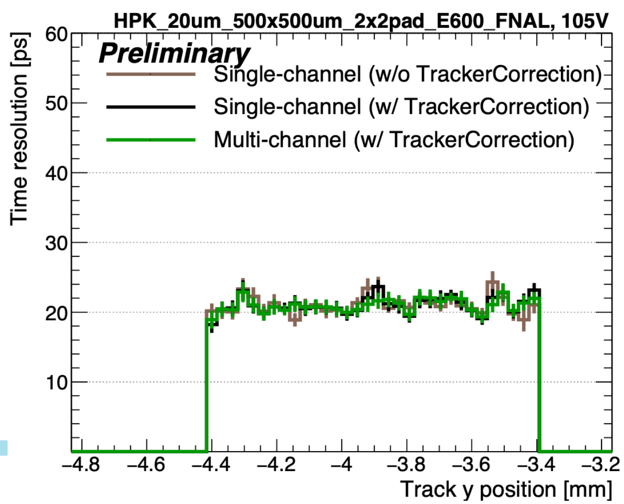
EIC experiments: TOF PID and tracking

Towards better time resolution

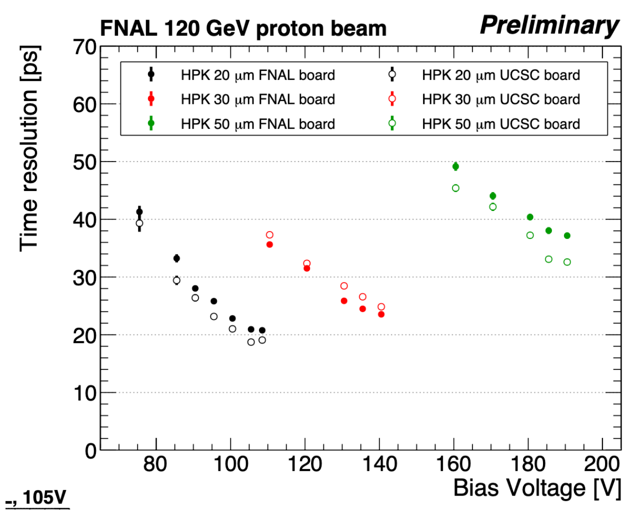
- How do you get better time resolution?
  - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
- Uniform time resolution across full sensor area
  - 25 ps for 30 µm thick sensor, **20 ps** for 20 µm thick sensor



HPK 2x2, 500x500 µm² pixel size



20 ps across full sensor surface



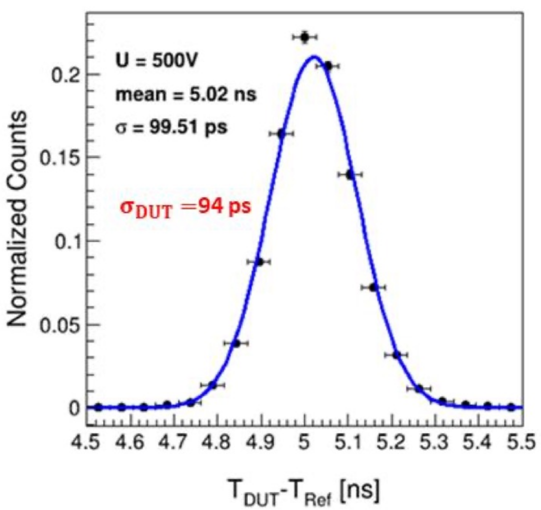
Time resolution for **20**, **30** and **50** µm-thick sensors

LGADs with SiC sensors

T. Yang: 40th RD50 Workshop
P. Gaggl: 41st RD50 Workshop
C. Haber: CPAD 2022

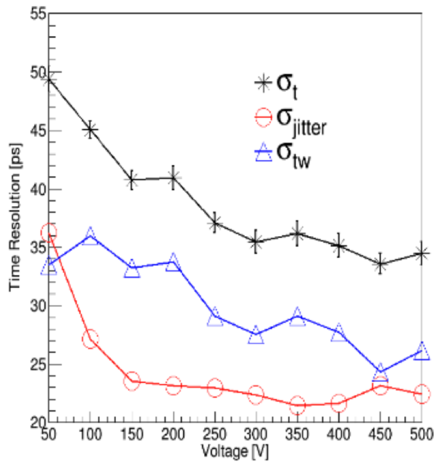
- Wide Band Gap Materials offer potential advantages
  - Enhanced radiation resistance
  - Reduced cooling requirements → reduced detector material mass
  - Increased commercial interest in wide band gap materials for power applications, HEP can benefit from these developments
- Several prototype runs recently produced
  - Early results look promising! Several new rounds of productions coming up

100 µm 4H-SiC PIN for MIPs (measurement)



doi: 10.3389/fphy.2022.718071

3D 4H-SiC Detector for MIPs (simulation)



doi: 10.3390/mi13010046

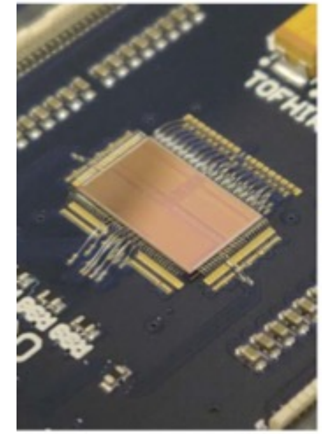
Electronics needs

- The developments of the current CMS and ATLAS detectors are demonstrating the challenges of the electronics designs
  - For HL-LHC: pixel size is 1.3x1.3 mm^2, ~2 mW/pixel
  - Going to small pixels for muon colliders, e.g. 50x50 μm^2: need to reduce power consumption per pixel by ~x680 to stay within cooling budgets similar to CMS/ATLAS timing detectors.

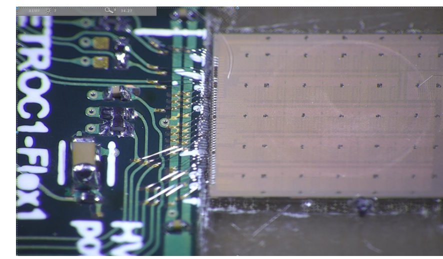
- Significant advancements will be needed:
  - More power/cooling budget,
  - Larger pixel size: AC-LGAD is one potential way to get precision position resolution with relatively large pixel sizes
  - Advanced detector concepts, new materials, AI/ML processing on chip
  - Advanced technology nodes (e.g. 28 nm) to reduce power consumption

Electronics for timing detectors

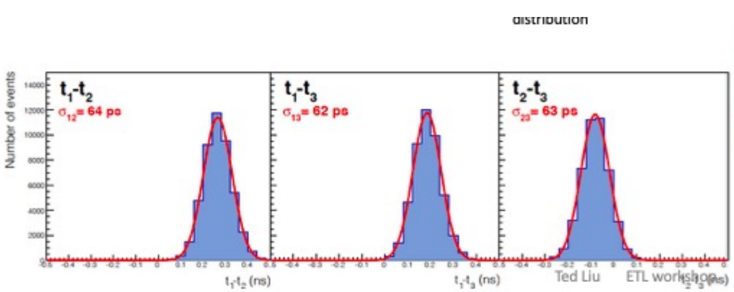
- BTL TOFHIR
  - minimize impact of DCR noise and pileup on time resolution
  - cope with very high rate of low energy hits per channel
  - Inverted and delayed pulse subtract from the input pulse
    - Restores baseline at the rising edge of the pulse.
  - Improves time resolution by about a factor 2 at EOL
- ETROC and ALTIROC
  - bump-bonded to LGAD, with 1.3 mm x 1.3 mm pads
  - Requirement: ASIC contribution to time resolution < 40ps
  - Deal with small signal size (~6fC, at end of operation)
  - Power consumption < 1W/chip



TOFHIR for CMS



ETROC for CMS



From preliminary analysis of the data from ongoing beam test at FNAL, the time resolution of each LGAD+ETROC1 layer has reached:

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)} \quad \sim 42 - 46 \text{ ps}$$

(with LGAD HV=230V for all three channels)

*This measured time resolution includes all **four contributions** in the table*

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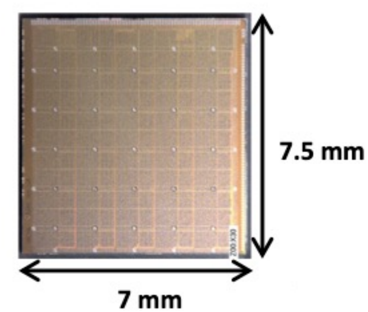
For more details, see ETROC1 testing results by Zhenyu Ye

Prototypes performance validated in test beam

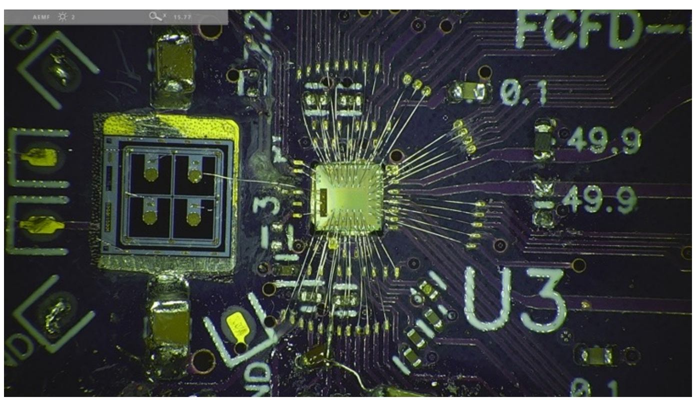


ALTIROC for ATLAS

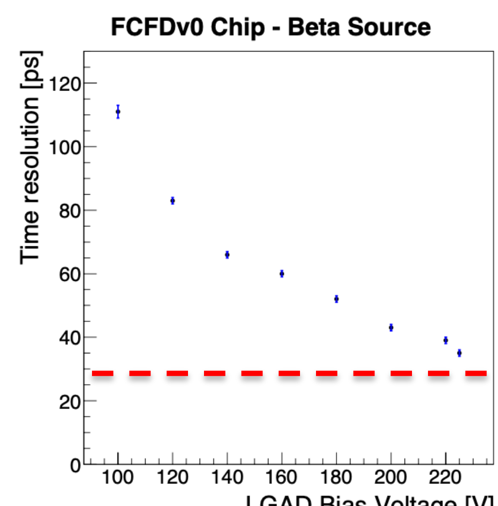
NIM A 1056 (2023), 168655

Timing ASIC with CFD

- A novel ASIC based on CFD for LGAD fast timing readout
  - Expect better performance for low S/N after irradiation, no need for time-walk correction, stability, simplicity of operation,
- The IC form an attenuated and a delayed version of the amplified input pulse
  - These two signals then directly feed a fast differential amplifier.
  - The single-ended output of the differential amplifier feeds a very simple output comparator that compares it to an internal DC threshold voltage



FCFD0 chip mounted to LGAD



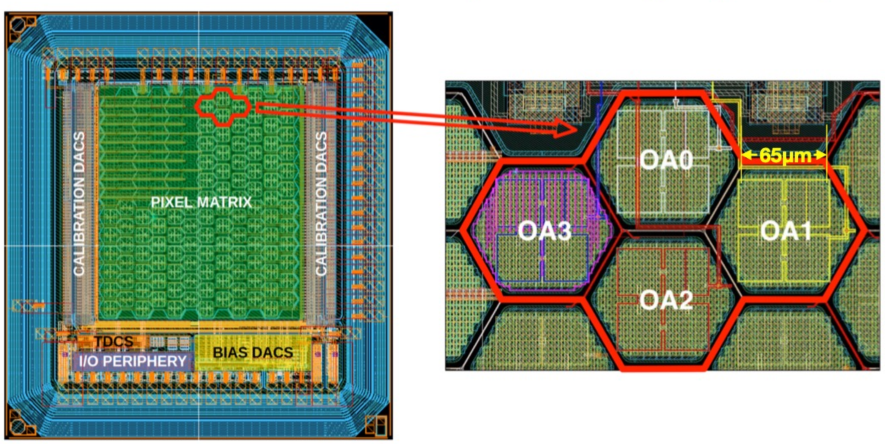
Time resolution with 1.3x1.3 mm^2 LGAD sensor

Monolithic sensors

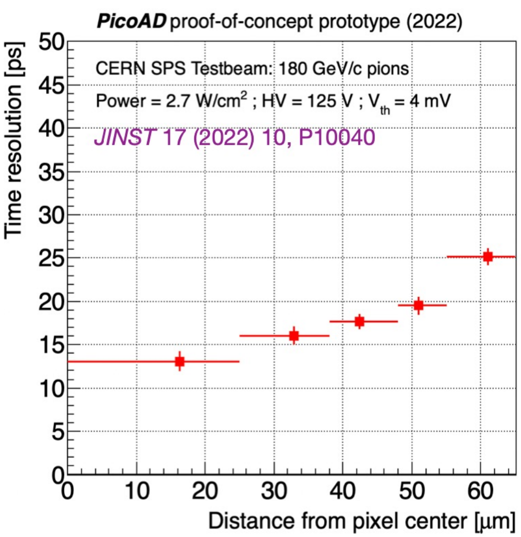
JINST 17 (2022) P10040

- Monolithic sensors with embedded readout
  - Take advantage of electronics on top layer, good signal-to-noise
- Promise to be paradigm-shifting for next-gen detectors
  - MONOLITH project: several prototypes produced over last few years
  - Continuous and deep gain layer, high pixel granularity and full fill factor
  - Time resolution from ~13 ps at the center to ~25 ps at the edge

PicoAD Proof-Of-Concept Prototype (2021)



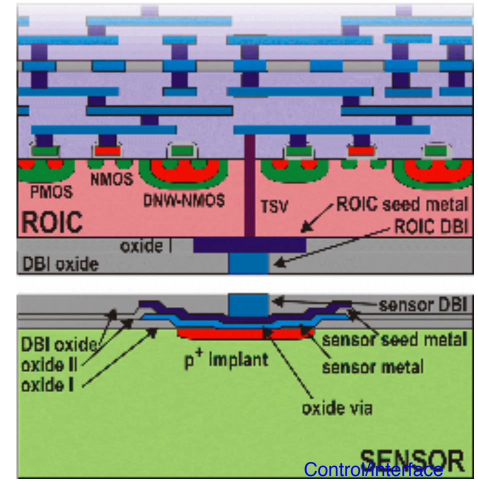
Time resolution

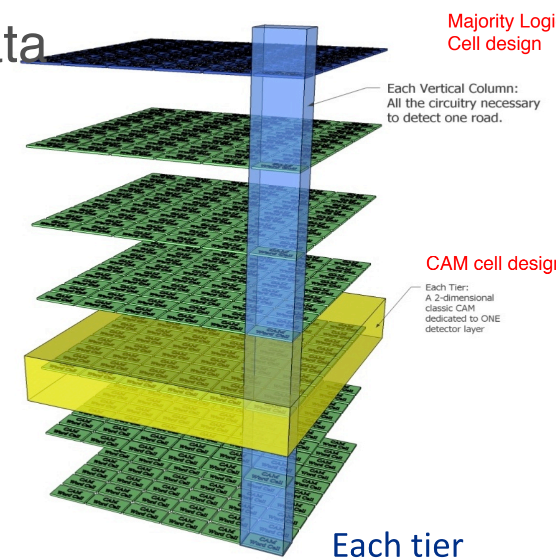


(13.2 ± 0.8) ps at the pixel center

Possibilities

- Advanced integration of technologies on the front-end
  - AI/ML on-chip to extract features for fast tracking and L1 triggering, on chip clustering to readout reduce data volume
  - Wireless communication between chips/layers of trackers to form tracks/stubs/vertices
  - Novel materials to design more power-efficient data processing on the front-end
- Extensive 3D integration
  - Very fine pitch possible, multiple layers of electronics for sophisticated signal processing, vertically integrated
  - Possible to integrate different technologies, each optimized for separate tasks





Summary

- Great Actively advancing LLP lifetime frontier by using existing CMS Muon detectors in new and unanticipated ways

- Already setting world best sensitivity for LLPs for lifetime larger than ~few meters
  - x20 improvement yet to come from new Run3 triggers

- Advent of the new tools are spawning lots of new and exciting ideas