The rise of 4D detectors

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VERTEX 2022 Workshop
Tateyama Hotel Resort, Japan
24th -28th October, 2022

New Physics is a Treasure Hunt…

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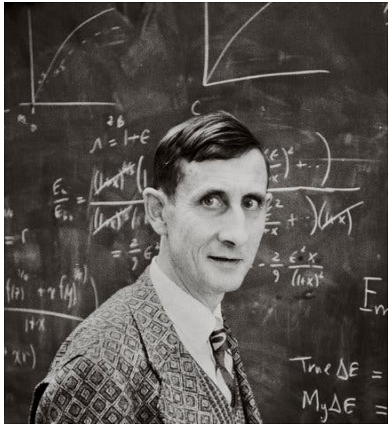
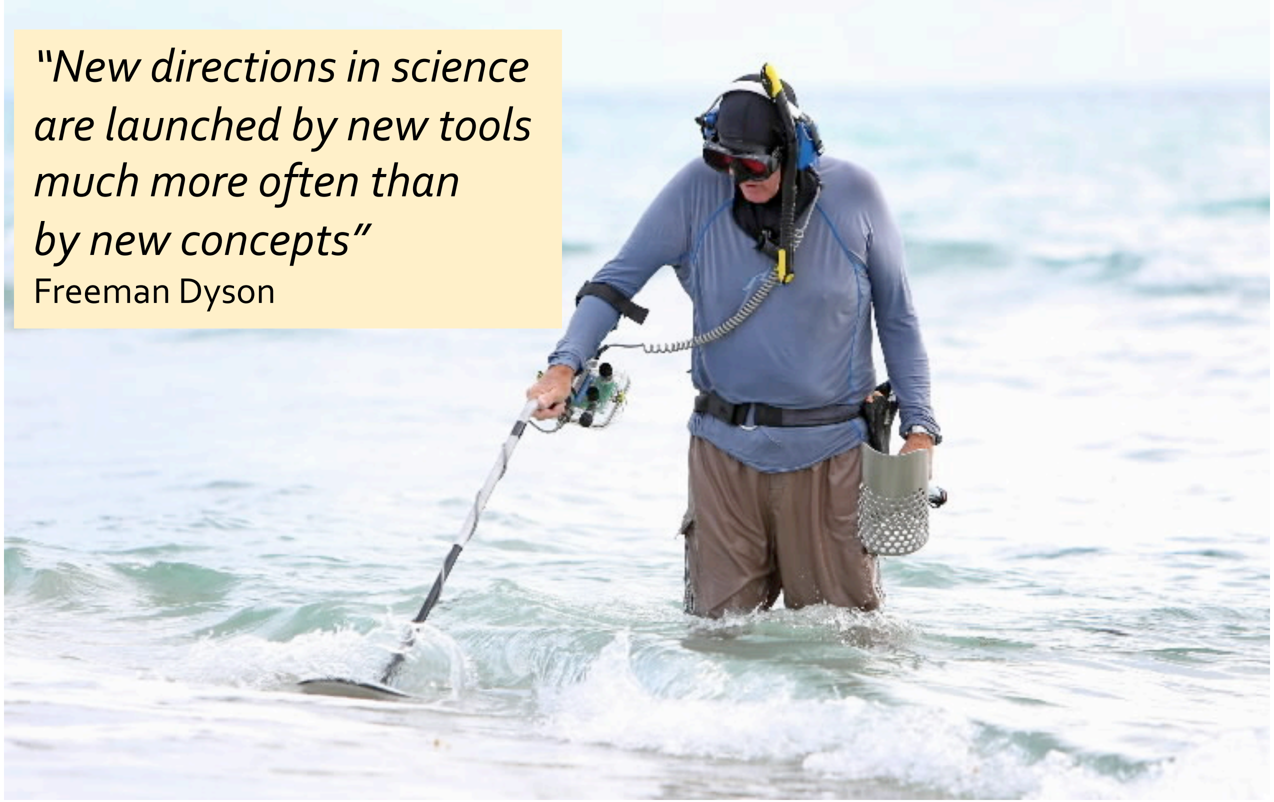
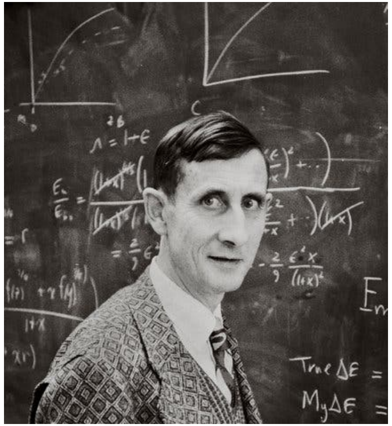




"New directions in science are launched by new tools much more often than by new concepts"
Freeman Dyson

New Physics is a Treasure Hunt…



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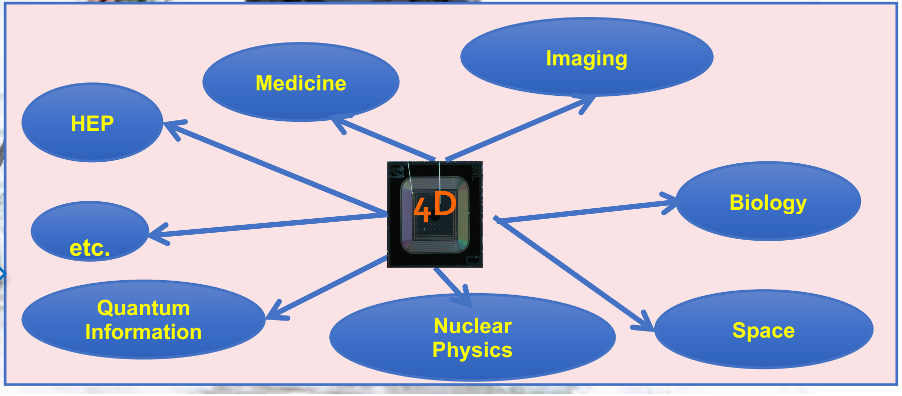
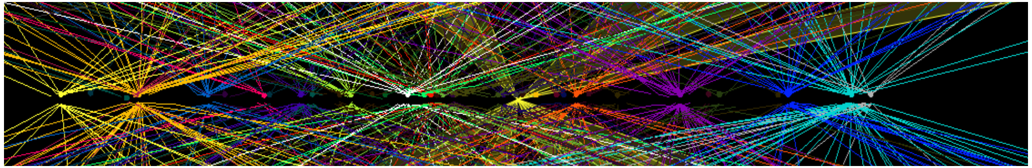
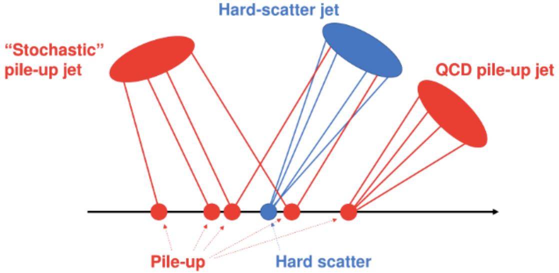
Detectors with high timing resolution in addition to high spatial resolution have attracted world-wide interest in several fields
➔ Several applications in a variety of scientific and commercial fields

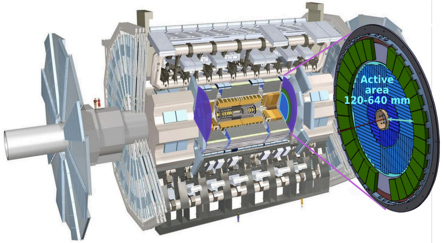


Pileup Challenge at HL-LHC

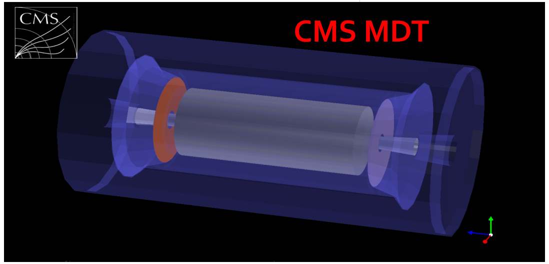


- The high number of interactions per bunch crossing (pileup 200) is one of the most serious challenges for the detectors
  - Reduced accuracy of most physics objects
- A key element to mitigate pileup effects is to assign precisely a track to a vertex
  - Track density too high for tracker system alone, especially in endcap
  - Common times for tracks nearby in space indicate that they are likely from the same vertex
  - ➔ ~30 ps timing resolution needed

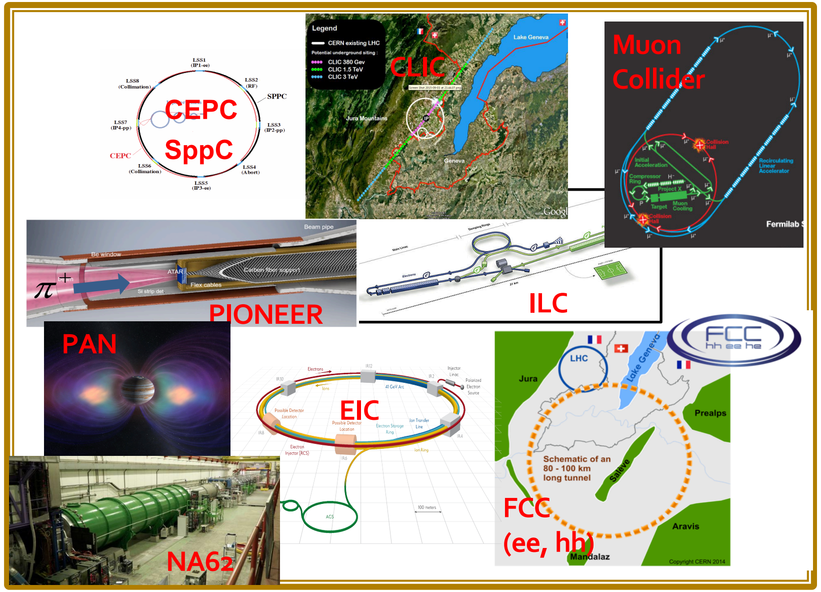




ATLAS HGTD



Beyond HL-LHC…



BRN:

Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2\times10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}]\ \sin^{\frac{3}{2}}\theta)^{-1}\ \mu m$ TR 1.1.3: Granularity : $25\times50\ \mu m^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5\times0.5\ \mathrm{cm}^2$, hadronic cells of $1\times1\ \mathrm{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and $3\times10^{16}\ (5\times10^{18})\ \mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8\times10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

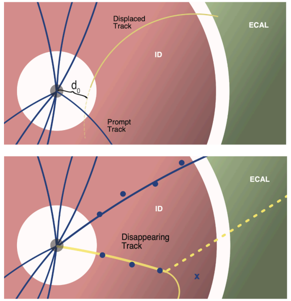
Strong demand for 4D detectors that provide in a single device fine space and time resolution

- US-DOE Basic Research Needs Study on HEP Detector R&D (**BRN**): https://science.osti.gov/-/media/hep/pdf/Reports/2020/DOE_Basic_Research_Needs_Study_on_High_Energy_Physics.pdf
- US-APS-driven HEP Planning Process (**Snowmass**): arXiv:2209.14111

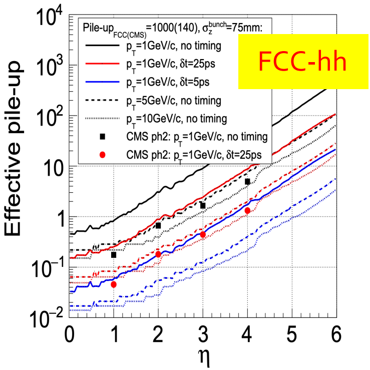
Technical Requirements:

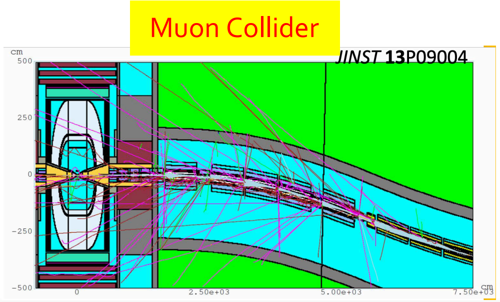
- 5-10 ps time resolution per track
- <5 µm space resolution per hit
- 8x10¹⁷ n/cm² radiation tolerance in hadron colliders
- Low mass
- Low power dissipation

4D detectors for lepton and hadron colliders



- **Future e+e- colliders (Higgs Factories)**:
  - low-mass detectors with high position accuracy for precision reconstruction of particle momentum, impact parameter, secondary vertices, and particle identification (Particle Flow)
    - **→ 4D detectors can enhance capabilities for particle identification and reconstruction, if material budget is low**
- **Future hadron colliders**:
  - Pileup (~1000) and radiation damage are main concerns as well as cost for a large tracker
    - **→ Track resolution < 10 µm per layer**
    - **→ Time resolution 5 – 10 ps**
    - **→ Radiation levels up to 8 x 10^{17} n/cm²**
- **Muon Collider**:
  - Beam induced background
    - **→ Tracker + 20-30 ps time resolution**

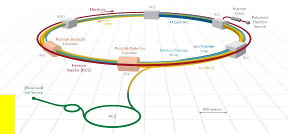




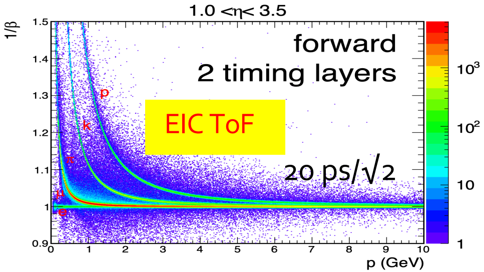
4D detectors for particle ID and Fwd Physics

- **Electron-Ion Collider (EIC) Time of Flight (ToF):** fine time and space resolution needed for π/K/p separation at low/medium momentum → 20-30 ps timing per hit
- **Proton tagging in Roman Pots:** smearing of proton momentum
  → 30 ps timing removes crab cavity rotation effect
  → ≤500/√12 μm space resolution mitigates angular divergence effects
- **Forward Physics at the (HL-)LHC and future hadron colliders:**
  - fine time and space resolution needed for precise proton momentum reconstruction and association to correct vertex (pileup suppression)
    → 5 ps timing to suppress pileup, 5 μm tracker resolution
    → Radiation hard detectors
- **PSI's PIONEER pion exp.:** charged lepton flavor universality in π decay
  - improve $R_{e/\mu}$ by an order of magnitude
  → fast timing and high segmentation

EIC

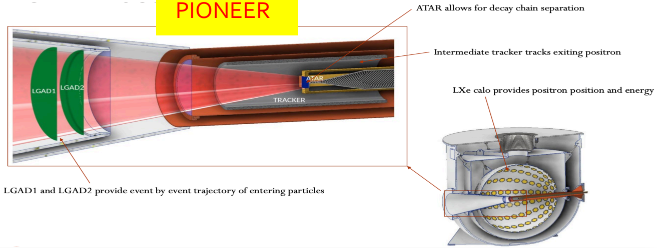


	Area (m^2)	Time resolution	Spatial resolution	Material budget
Barrel Timing Tracking Layer	11	30 ps	30 μm in $r \cdot \phi$	0.01 X_0
Endcap Timing Tracking Layers	1.2+2.2	25 ps	30 μm in x and y	0.08 X_0
B0 Tracker	0.07	30 ps	$500/\sqrt{12}\ \mu m$	0.01 X_0
Roman Pots	0.14	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.
Off-Momentum Detectors	0.08	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.



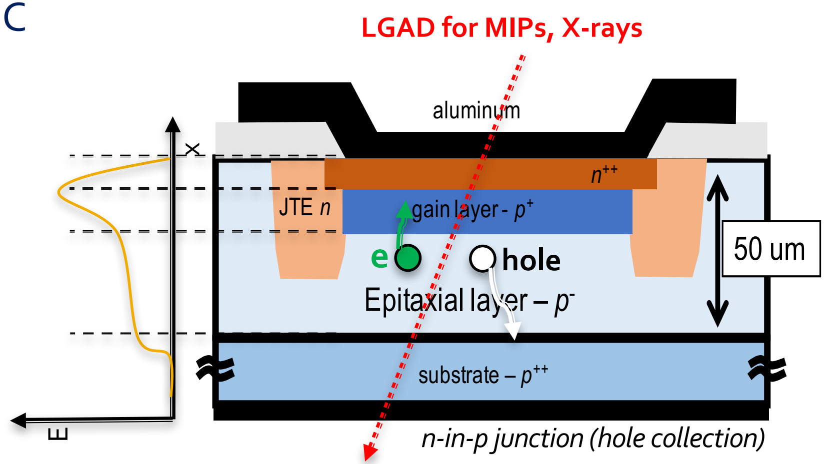
See talk by Xuan Li (Oct 27)

PIONEER

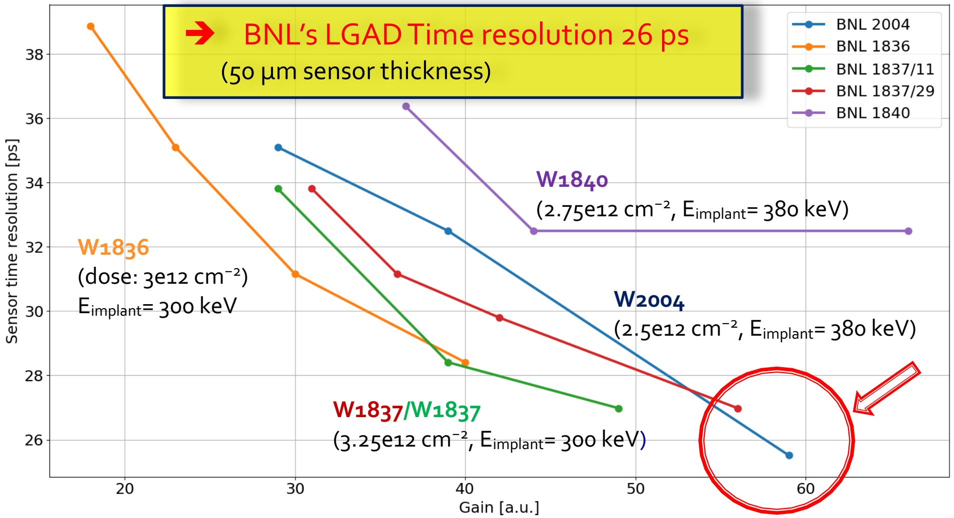


Developments towards 4D: Timing

- Low Gain Avalanche Diode (LGAD) will be used at HL-LHC
  - Process similar to standard **n-in-p** sensors + **built-in multiplication (gain)**
  - High and uniform electric field
    - 300 kV/cm over ~ 1 μm near junction → **Gain Layer**
    - Bulk field ~ 20 kV/cm saturates electron drift velocity (~ 10^7cm/s)
  - **High S/N** thanks to gain
  - **Moderate gain (10-100)** through electron impact ionization
  - **Time resolution: ~25 ps** with 50 μm active thickness
  - Radiation tolerance ~2.5×10^{15} neutrons/cm^2



Time resolution in LGAD



- LGADs for the LHC:
  - **50 µm thickness**
  - **1.3 mm pixel pitch**
  - **Space resolution limited by coarse pitch**
  - Several m² of sensors bump-bonded to **dedicated ASICs** (ALTIROC for ATLAS, ETROC for CMS)
  - **Time resolution pre-irradiation 30-40 ps** per hit
- Also proposed for ALICE, LHCb upgrades and used in TOTEM

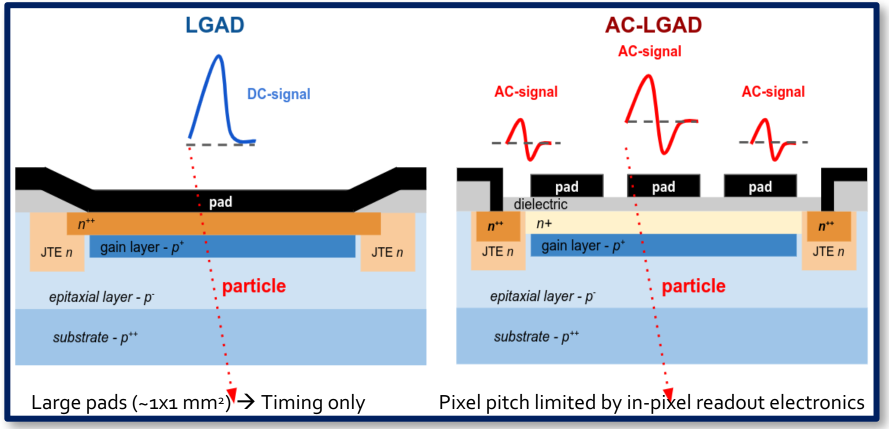
- **With 50 µm active thickness, resolution levels off at 25-30 ps because of Landau fluctuations**
  → Thinner sensors needed
  - **Landau fluctuations proportional to the detector thickness**
- **Jitter dominates in thin detectors**
  → to be minimized with low noise electronics and large signal (gain and voltage).

- **Time resolution improves for thinner sensors!**
- **Productions at BNL with active thickness as low as 20 µm** → ongoing measurements

From Timing to 4D: AC-LGAD

- LGADs have opened up the possibility of excellent timing using silicon sensors for MIP signals

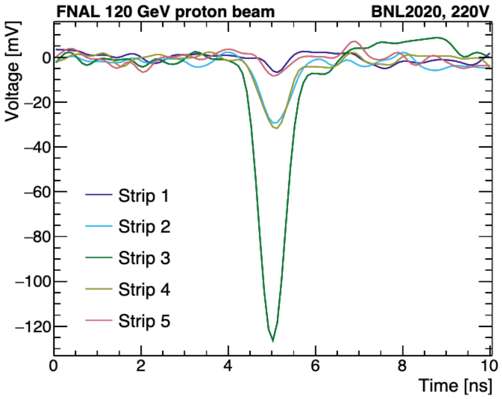
- LGAD have coarse segmentation (~ 1x1 mm²)
  - Lateral dimensions of Gain layer must be much larger than thickness of substrate, for a uniform multiplication.
  - Dead volume (gain~1) between the implanted region of the gain layer
- LGAD-based technologies developed to combine the good timing of LGADs with position resolution
  - **AC-coupled LGAD (AC-LGAD),** Deep Layer AC-LGAD, Deep Junction LGAD, Trench Isolation LGAD (TI-LGAD), Inverted LGAD (iLGAD)



- **AC-LGAD:**
  - One large low-doped / high-resistivity n⁺ implant over the all active area
  - A thin insulator over the n⁺ where electrodes are placed ➔ AC-coupling
    - **Signal is bipolar** and is still generated by drift of holes into the substrate, AC-coupled through dielectric
    - **Signal is shared between multiple electrodes**
  - 100% fill factor and fast timing information at a per-pixel level both achieved ➔ 4D

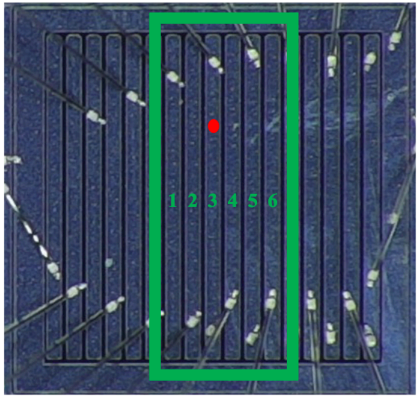
Signal Sharing in AC-LGAD

- Signal sharing depends on electrode geometry (pitch, gap size) and resistivity of n+ layer → tunable

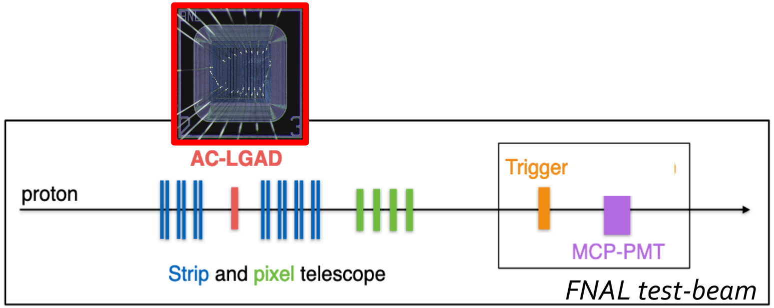


Signal from neighboring electrodes generated by ***120 GeV protons***

BNL Strip AC-LGAD*: 100 μm pitch, 20 μm gap, 1.7 mm long strip*



- *Apresyan et al., JINST 15 (2020) P09038*
- *Heller et al. JINST 17 (2022) 05, P05001*



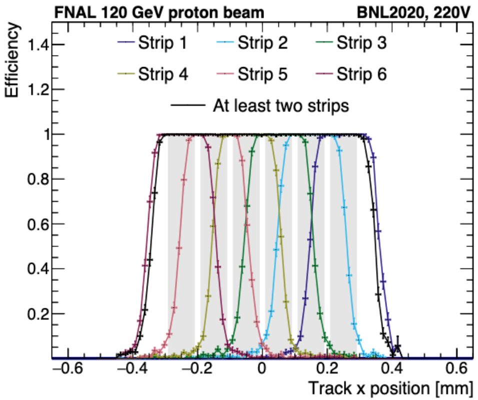
- **Signal decreases for electrodes farther away from hit position**
  - **To be exploited to improve space & time resolution**

Sparse electrodes in AC-LGAD

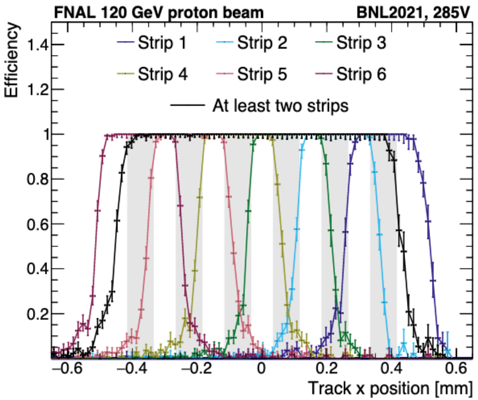
- **Sparse metallization results in lower capacitance (noise), and lower power by limiting channel count.**
  - Power in electronics is an important constraint on large tracker design and depends on the no. of channels

- Heller et al. JINST 17 (2022) 05, P05001

***BNL Strip AC-LGAD**: 100μm pitch, 80μm metal width, 1.7mm long strip*



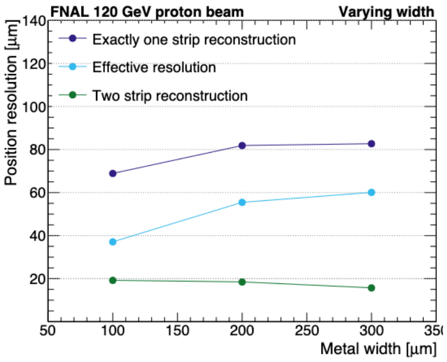
***BNL Strip AC-LGAD**: constant metal width (80μm) and variable pitch: 100,150,200μm, 2.5mm strip length*

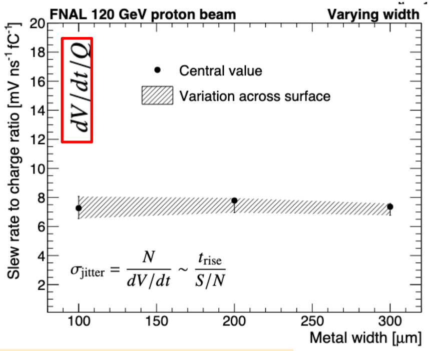


- **100% efficiency for varying pitches (100-200 μm)**
  - **Pitch and gap size can be adjusted to minimize number of channels and det. capacitance (thus noise)**

- **Position and time resolution unaffected by small strip metal size at fixed pitch**
  - **Tested in recent FNAL test-beam with 500 μm pitch strips and 100-300 μm strip metal width**

***BNL Strip AC-LGAD**: constant pitch (500 μm) and variable width: 100, 200, 300 μm*

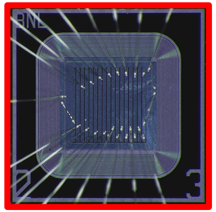


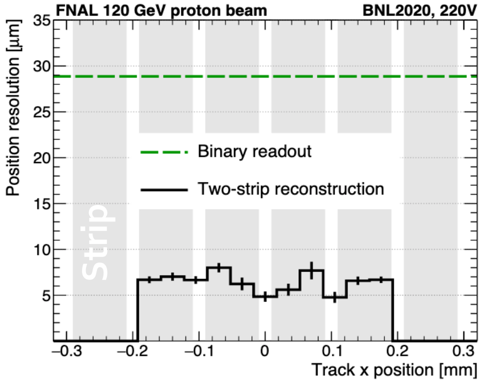


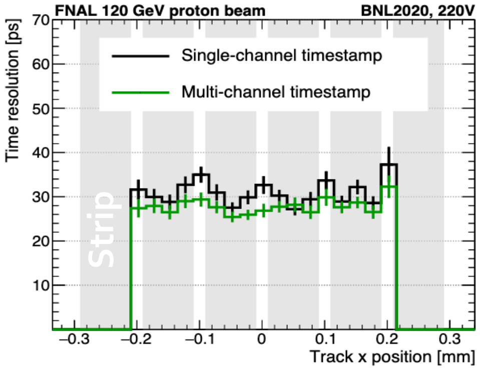
- FNAL, BNL, KEK, UCSC, UIC team work in progress

Position & Time with AC-LGAD (Strips, Pixels)

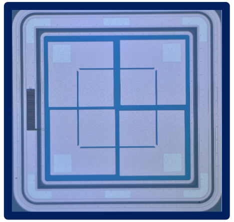
***BNL Strip AC-LGAD**:*
100 μm pitch, 80 μm metal width, 1.7 mm long strip



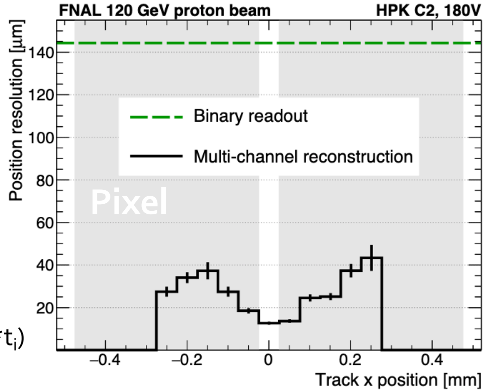




- *Heller et al. JINST* 17 (2022) 05, P05001



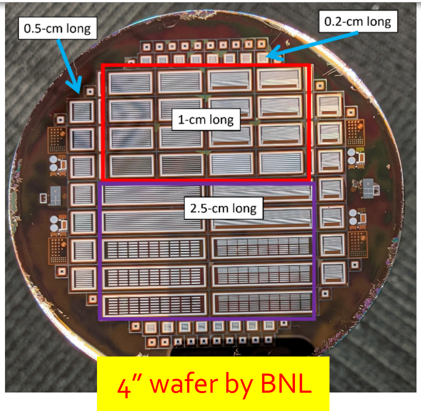
HPK Pixel:
500 x 500 μm^2



- **Space resolution:** Combination of 1st and 2nd largest *amplitudes*: param. of hit position vs $A_1/(A_1+A_2)$
  - a) **≲ 6 µm with 100 µm pitch** (limited by tracker resolution)
  - b) **~ 15 µm with 500 µm pixels**
  - Best space resolution in gap between electrodes
  - **Combination of electrodes improves spatial resolution**
- **Time Resolution ~28 ps:** Amplitude-weighted average time of 1st and 2nd largest *amplitudes*: $t_w=(1/\Sigma A^2_i)*(\Sigma A^2_i*t_i)$
  - Best time resolution per electrode is at center of electrode
  - **Combination of electrodes improves time resolution in gaps → improved uniformity**

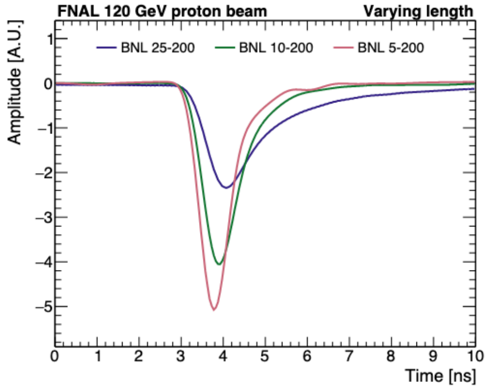
See more in talk by Sayuka Kita (Oct 27)

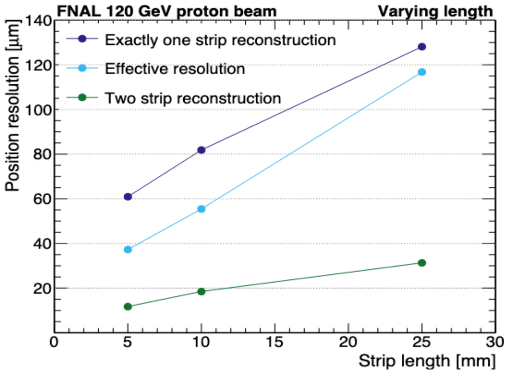
Electrode length dependence on AC-LGADs

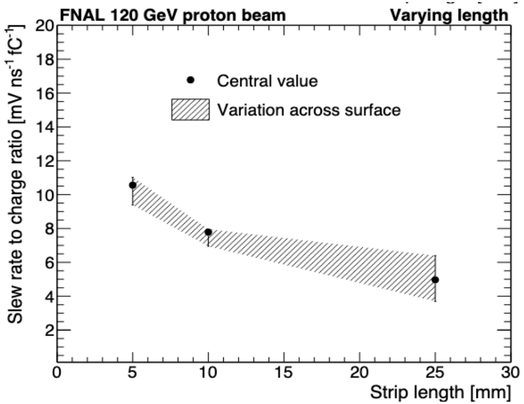


- FNAL, BNL, KEK, UCSC, UIC team work in progress

Name Unit	Pitch µm	Metal Width µm	Length mm	Thickness µm	Bias Voltage V
BNL 5–200	500	200	5	50	245
BNL 10–100	500	100	10	50	220
BNL 10–200	500	200	10	50	255
BNL 10–300	500	300	10	50	240
BNL 25–200	500	200	25	50	215





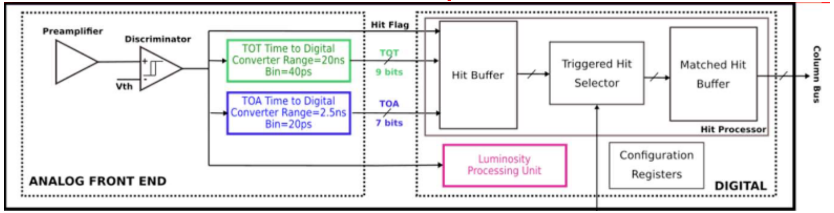


- **Strip Length important in large area detectors to minimize no. channels**
- **500 µm strip pitch planned at EIC**
- **Position and Time resolution are sensitive to strip length**

ASIC read out of AC-LGADs

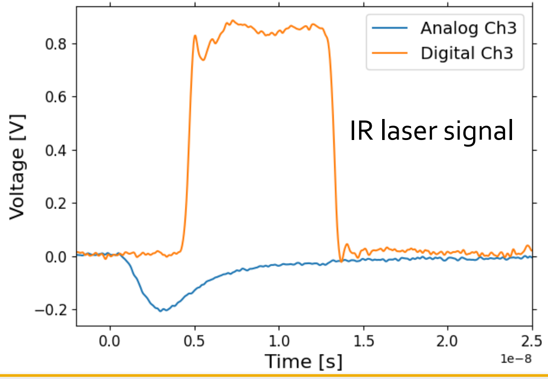
- **AC-LGADs will be read out by ASICs in most experiments**
- **In ATLAS HGTD, DC-LGADs are read-out by ALTIROC chip**
  - Designed in CMOS 130 nm
  - 2 TDC: TOT and TOA
- **Can it read out also AC-coupled LGAD?**
  ➔ Yes! a stepping stone for future ASIC developments
  - AC-LGAD strip wire-bonded to **ALTIROC0**

ALTIROC pixel

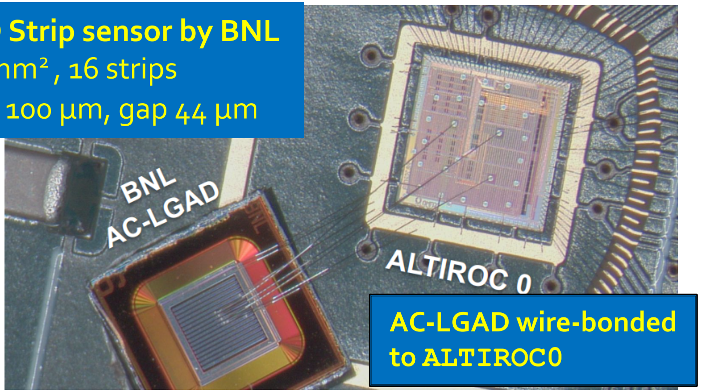


by Omega Electronics, IJCLAB (France), and SLAC (USA)
C. Agapopoulu et al., 2020 JINST 15 P07007, arXiv:2002.06089.

D'Amen et al., arXiv:2209.07329



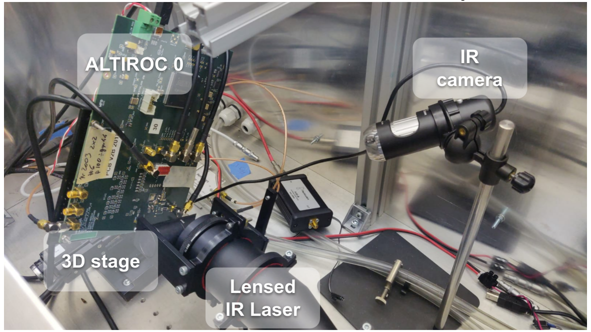
AC-LGAD Strip sensor by BNL
- 2x2 mm², 16 strips
- Pitch 100 µm, gap 44 µm

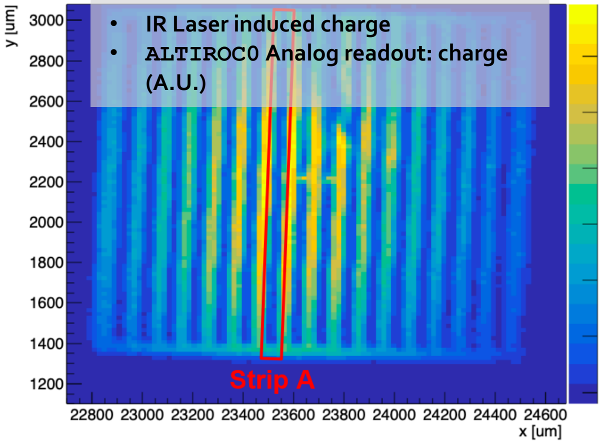


AC-LGAD wire-bonded to ALTIROC0

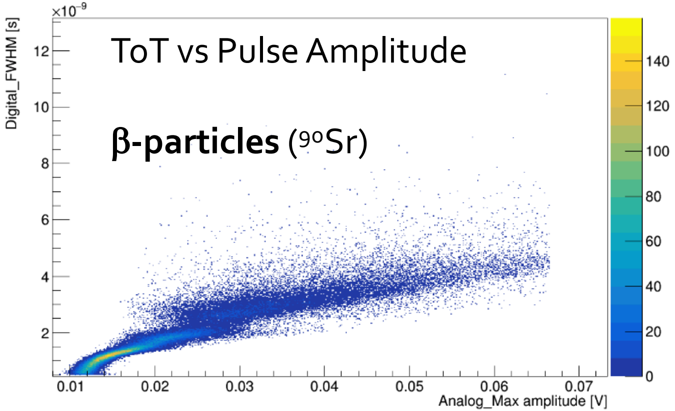
ASIC read out of AC-LGADs

BNL's TCT (Laser set-up)





D'Amen et al., arXiv:2209.07329

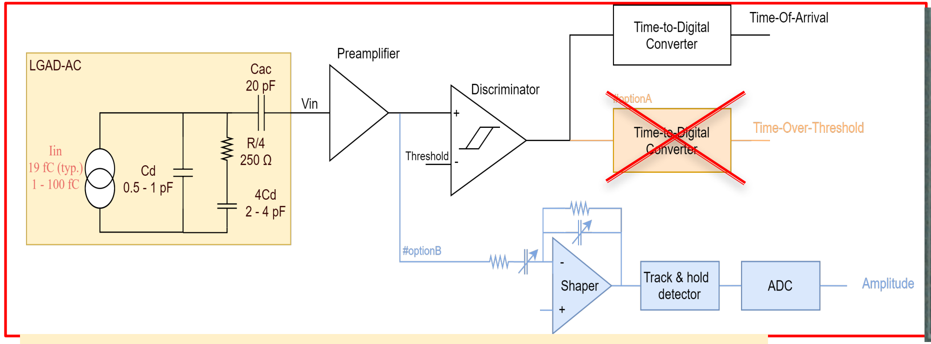


- ➢ **Signal sharing visible in ASIC output**
- ➢ **Approx. linear correlation between ToT and analog amplitude**
  - ➢ **ToT can be used as proxy for Amplitude when combining signals from neighboring electrodes in position and time measurements**

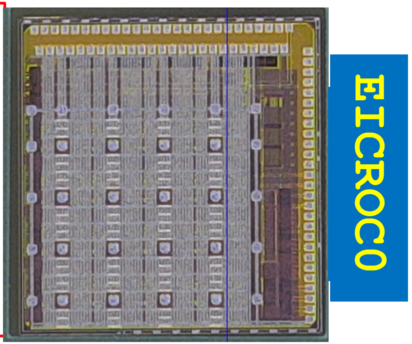
- ➢ Measurement of Time Resolution (jitter only) with **IR Laser as Δt(Laser Trigger, Digital Channel TOA)**
  - Digital output jitter ~14 ps for an injected charge of ~5 MIPs

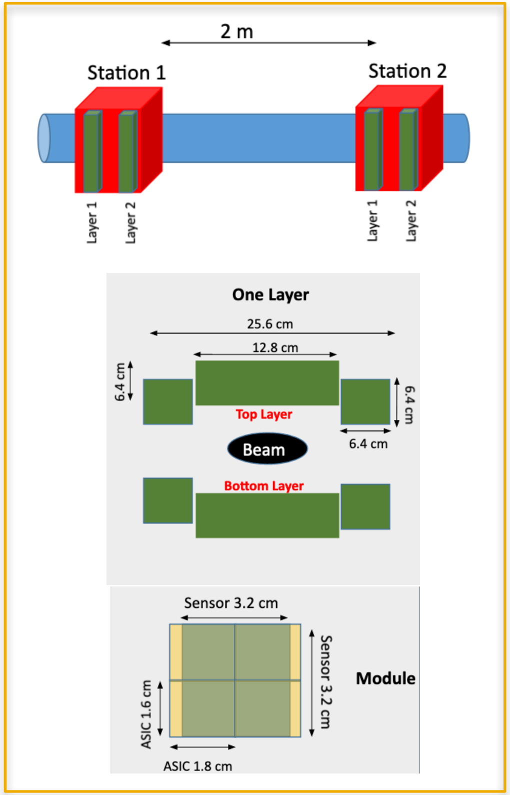
ASIC readout of AC-LGAD at EIC

- **EIC Roman Pots (RP): aim for 500 x 500 µm² pixels with ~30 ps time resolution**
  - 1,310 cm² silicon, 128 modules, 512 ASICs (32x32 channels), ~500k channels
  - Signal sharing between pixels to improve time and space resolution
  - Low occupancy
  - Low radiation environment
  - Triggerless system
- **1st ASIC prototype (EICROC0) for EIC RP, based on ALTIROC experience**
  - **TDC for ToA and ADC for amplitude measurements → exploit Signal Sharing**
- **Similar design may be used in EIC ToF detector**



by OMEGA, CEA-Saclay/Irfu, IJCLab (France) and AGH (Poland)

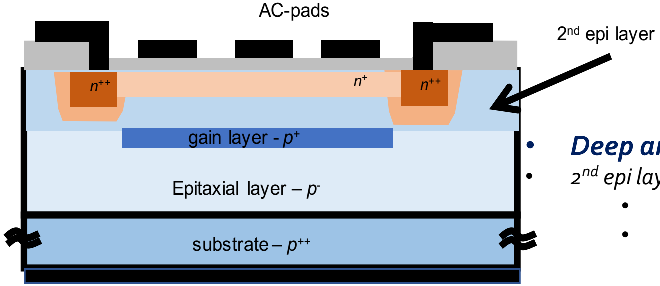




Radiation Tolerance Improvements

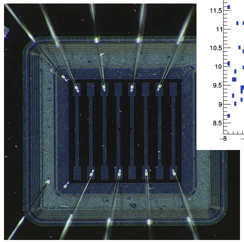
- **One of the biggest challenges is radiation hardness** (LGADs will operate up to 2.5 10^{15} n/cm² at HL-LHC)
- **Effective reduction of gain in LGADs at high fluence, and sudden death at high voltages**
  - Boron in gain layer loses effectiveness → raise voltage to maintain large enough net gain layer field
  - Death (crater) in HPK 50 μm LGADs at V_{bias} >600 V ($\gtrsim 10^{15}$ n/cm²)
- **AC-LGADs are subject to similar radiation damage as LGADs**
- **Several ideas and ongoing studies to improve radiation hardness**
  - Carbon infusion in gain layer (carbon ties up defects that otherwise would inactivate Boron)
  - **Thinner gain layer:** damage sites uniformly distributed over the silicon after irradiation → **thin gain layer reduces volume exposed to radiation**
  - **Deep gain layer e.g. ~ 2 μm**: amplification depends not only on the field but also its spatial extent

Deep-Layer AC-LGAD

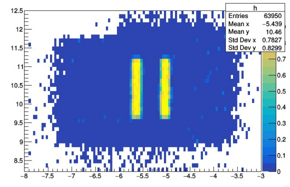


- ***Deep and thin gain layer***
- *2nd epi layer grown over the p+ implant*
  - *FNAL idea and BNL fabrication*
  - *Coll. with Cactus Material, Inc*

200 μm pitch AC-LGAD, 50 μm metal, 2x2 mm²



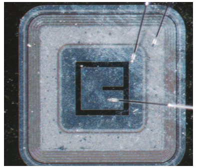
Efficiency for leading hit in strip 2 or 5

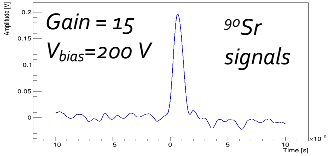


10 mV threshold

- Positive FNAL test-beam results

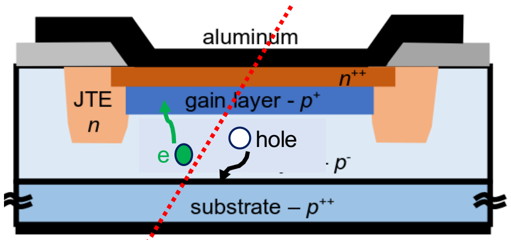
1x1mm², AC-LGAD by Cactus Inc.



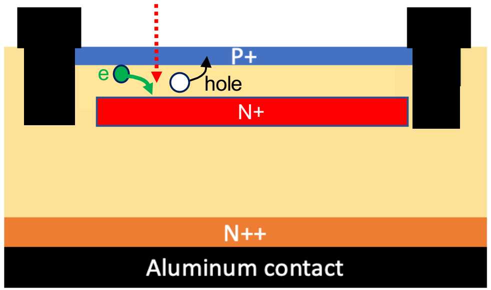


LGADs for Photon Detection

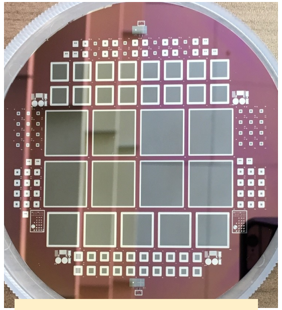
- **LGADs have great potentials for photon detection thanks to signal amplification**
  - Standard LGAD design aims at detecting charged particles, high energy photons (X-rays/γ), high energy electrons
  - Dedicated design for **soft X-rays** and **low-energy electrons** (*low-penetrating particles*)



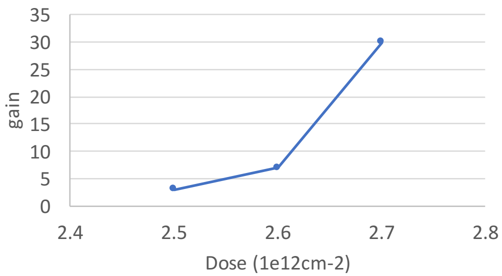
n-in-p junction (hole collection)



p-in-n junction (electron collection)
Pixelation possible in a double sided design



BNL production



- **Applications to Photon Science, Photonics, and photoelectron spectroscopy**
  - e.g. Soft X-rays for studies of nanoscale dynamics of materials, imaging in visible range

Conclusions

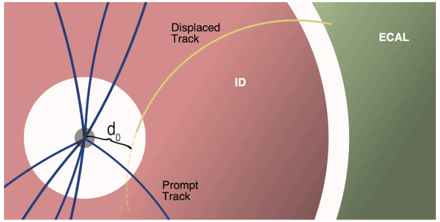
- New Physics exploration needs **novel fast-time silicon technologies with 4D capabilities**
- **4D detectors** will be the key for coping with the challenging HL-LHC environment (pileup) and at future collider experiments (hadron and lepton colliders)
- The impact of this novel silicon technologies can be vast: nuclear physics, measurements of rare processes, space science, photon science, imaging etc.

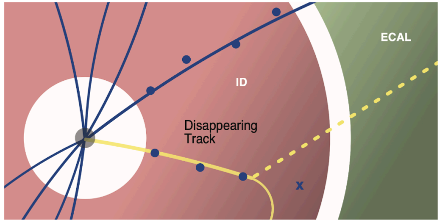
- LGADs are a stepping stone to develop **4D detectors**, and **AC-LGAD** is the most mature technology
  - Internal signal sharing combined with internal gain
  - 100% fill factor
  - Potential to reach <20 ps time resolution and ~1 μm space resolution → **4D detectors**
  - Sparse electrode metalisation with similar space/time resolution → **Power saving in electronics**
  - Available ASICs (ALTIROC) can be used for readout and dedicated ASICs (EICROC) that exploit signal sharing are being designed
  - Potential to combine AC-LGADs with readout circuitry in a monolithic detector → **Low-mass detector**
  - Longer term R&D is needed to optimize the **radiation hardness**

Backup

4D Detectors for e$^+$e$^-$ colliders

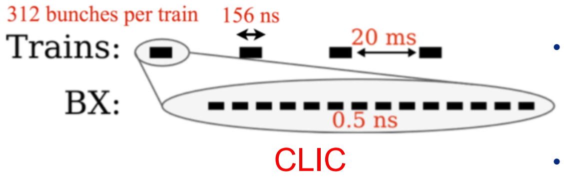
- **4D detectors can enhance capabilities for particle identification and reconstruction at e$^+$e$^-$ colliders**
  - Measurements of Higgs boson properties, dark matter searches etc.





- **Future Linear or Circular e$^+$e$^-$ colliders: <u>low-mass</u> detectors with <u>high position accuracy</u> for precision reconstruction of particle momentum, impact parameter, secondary vertices, and particle identification (Particle Flow)**
  - Space resolution **per track <3-5 μm**
  - Low material budget to minimize multiple scattering ➔ **~100 μm si-tracker thickness**
  - Low power dissipation 0.1-0.2 W/cm^2
  - Timing < 1 ns – 100 ns

Timing needs



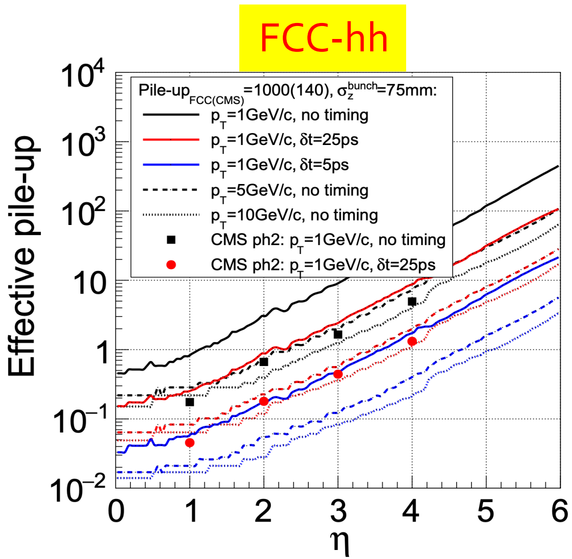
- *Bunch spacing 0.5 ns ➔ σ_t<500 ps for unambiguous track assignment to BC*
- *Good timing to suppress machine induced background (e.g. $\gamma\gamma$→hadrons) and improve mass reconstruction from jets (e.g. in HA→4b search)*
- *Good timing can impact particle flow*

- **4D tracker could be considered for e+e- if physics gain is significant with respect to increased material budget**

4D Detectors for Hadron colliders

- **Broad physics program at Hadron Colliders**
  - Long-Lived particle detection, Dark Matter searches, Higgs coupling and electroweak measurements etc.

- **Future Hadron colliders (FCC-hh): pileup (~1000), impact parameter resolution, and radiation damage are main concerns as well as cost for a large tracker**
  - **~430 m² of silicon** (250 m² ATLAS/CMS at HL-LHC)
  - **Track resolution < 10 μm per layer**
  - **Radiation levels up to 8 x 10¹⁷ n/cm²**
  - **Timing is necessary to correctly assign tracks to vertices: ~ 5 ps per track**

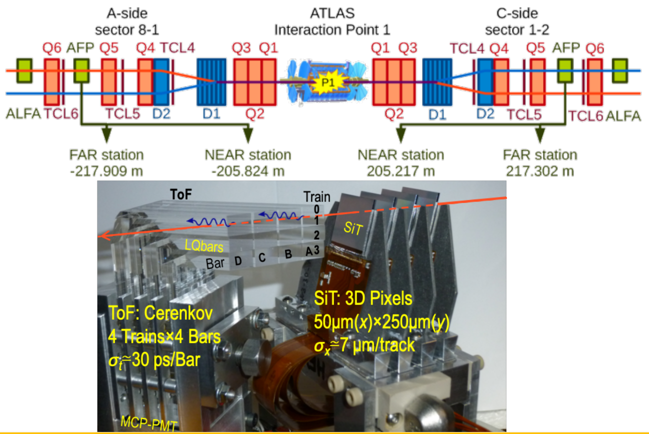


4D Det. for Forward Physics at Hadron Coll.

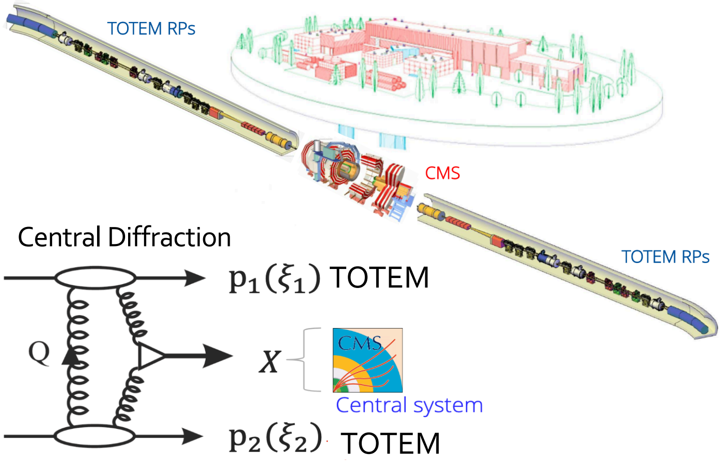
- **Forward proton tagging at hadron colliders**
  - Forward physics with proton tagging: central diffraction (e.g. exclusive jet production), exclusive γ–γ production, light-by-light scattering etc.

- **Forward Physics at the (HL-)LHC and future hadron collider: fine time and space resolution needed for precise proton momentum reconstruction and association to correct vertex (pileup suppression)**
  - 10-30 ps timing to suppress pileup, ~10 μm tracker resolution
  - Radiation hard detector needed

ATLAS AFP

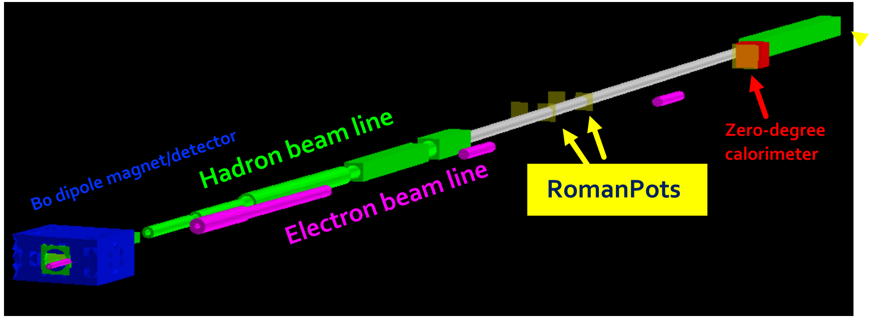


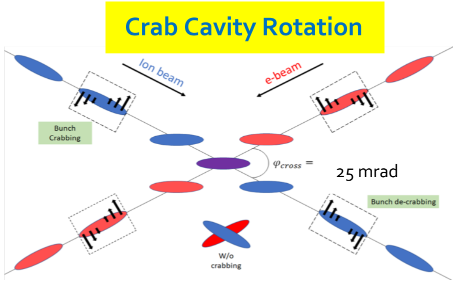
TOTEM

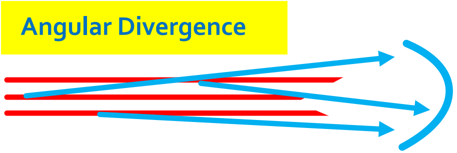


- Tracking (Pixels+Strips)
- Timing (LGADs)+SAMPIC chip

4D detectors for forward physics at EIC



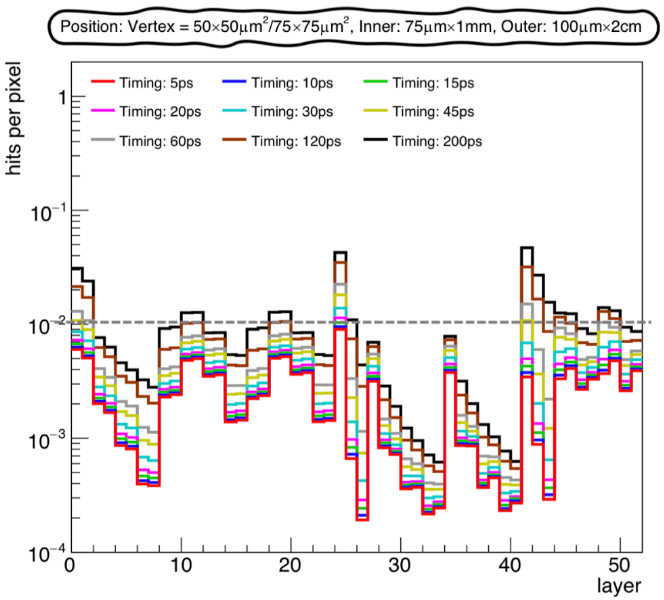




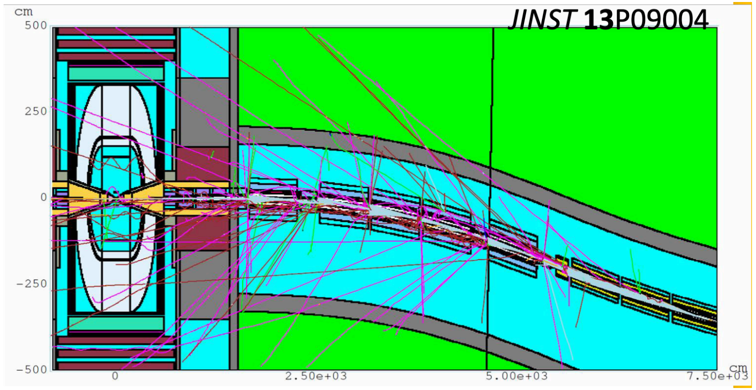
- **Forward proton tagging at EIC**
  - Roman Pots: physics impacted by smearing of proton momentum
    - → 35 ps timing removes crab cavity rotation effect
    - → Fine space resolution (≤500/√12 μm) mitigates angular divergence effects

4D detector for Muon Collider

- **Beam Induced background mitigation at Muon Collider**
  - Background from muon decays: multitude of particles from secondary interactions that hit the detectors



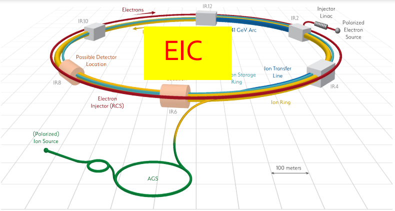
D. Lucchesi, S. Jindariani et al.



- **Muon Collider Tracker: 1% occupancy goal to mitigate Beam Induced Background with high resolution in position and time measurements**
  - No timing in tracker requires 25 x 25 μm pixels
    ➔ 5 billion channels
  - Tracker with 20-30 ps timing
    ➔ 1-2 billion channels (similar to CMS at HL-LHC)

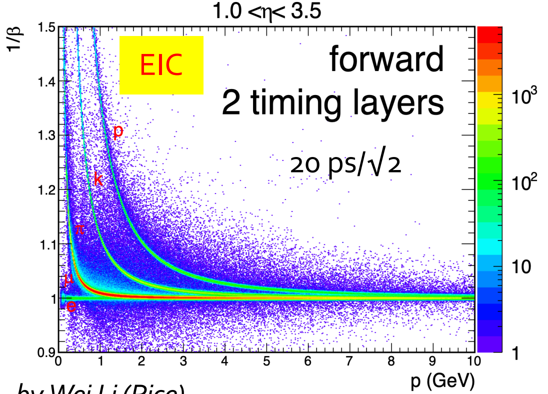
4D Detectors for Particle Identification

- **Particle identification at EIC and rare-process detection experiments**



- **EIC Time of Flight (ToF): fine time and space resolution needed for p/K/π separation at low/medium momentum**
  - **20-30 ps timing per hit needed**
  - Strip + TOF to improve momentum resolution
  - Low material budget

	Area (m^2)	Time resolution	Spatial resolution	Material budget
Barrel Timing Tracking Layer	11	30 ps	30 μm in $r \cdot \phi$	0.01 X_0
Endcap Timing Tracking Layers	1.2+2.2	25 ps	30 μm in x and y	0.08 X_0
B0 Tracker	0.07	30 ps	$500/\sqrt{12}\ \mu m$	0.01 X_0
Roman Pots	0.14	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.
Off-Momentum Detectors	0.08	30 ps	$500/\sqrt{12}\ \mu m$	no strict req.



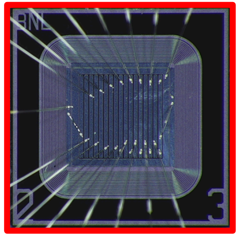
by Wei Li (Rice)

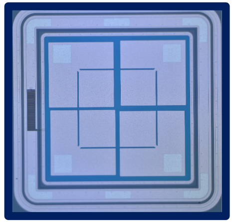
***π/k separation**: 0.1~4-5 GeV;*
***k/p separation**: 0.1~7-8 GeV*

- **CERN's NA62** GigaTracker for rare Kaon decays: **timing to remove accidental background to $K^+ \rightarrow \pi^+ + \nu\bar{\nu}$**
  - 30 ps timing per track, 300 μm pixel pitch, high rates

Position & Time with AC-LGAD (Strips, Pixels)

BNL Strip AC-LGAD:
100 μm pitch, 80 μm metal width, 1.7 mm long strip





HPK Pixel:
500 x 500 mm²

Name Unit	Pitch µm	Primary signal amp. mV	Position res. µm	Time res. ps
BNL 2020	100	101 ± 10	≤6	29 ± 1
BNL 2021 Narrow	100	104 ± 10	≤9	32 ± 1
BNL 2021 Medium	150	136 ± 13	≤11	30 ± 1
BNL 2021 Wide	200	144 ± 14	≤9	33 ± 1
HPK C–2	500	128 ± 12	22 ± 1	30 ± 1
HPK B–2	500	95 ± 10	24 ± 1	27 ± 1

- *Heller et al. JINST* 17 (2022) 05, P05001

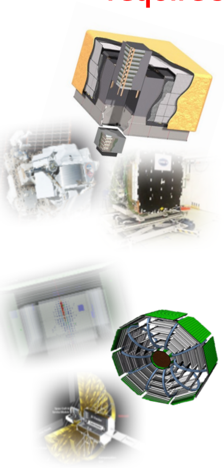
ALTIROC Chip

TID tolerance	Inner region: 4.7 MGy Outer region: 2.0 MGy
Pad size	$1.3 \times 1.3\,\mathrm{mm}^2$
Voltage	1.2 V
Power dissipation per area (per ASIC)	$300\,\mathrm{mW\,cm^{-2}}$ (1.2 W)
e-link driver bandwidth	$320\,\mathrm{Mbit\,s^{-1}}$, $640\,\mathrm{Mbit\,s^{-1}}$, or $1.28\,\mathrm{Gbit\,s^{-1}}$
Temperature range	−40 °C to 40 °C
SEU probability	$< 5\%/\mathrm{hour}$

Maximum leakage current	5 μA
Single pad noise (ENC)	$< 1500\,e^- = 0.25$ fC
Cross-talk	$< 5\%$
Minimum threshold	1 fC
Threshold dispersion after tuning	10%
Maximum jitter	25 ps at 10 fC
TDC contribution	< 10 ps
Time walk contribution	< 10 ps
Dynamic range	2.5 fC–100 fC
TDC conversion time	< 25 ns
Trigger rate	1 MHz L0 or 0.8 MHz L1
Trigger latency	10 μs L0 or 35 μs L1
Clock phase adjustment	100 ps

4D Detectors for Space Science

Space detectors for charged cosmic ray and γ-ray measurements require solid state tracking based on silicon microstrip sensors

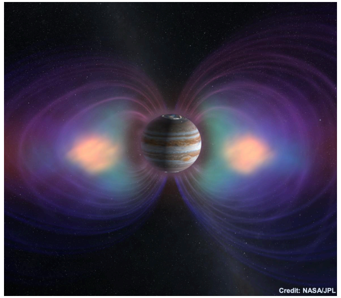


Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,\mathrm{m}^2$	38 cm	$\sim 880 \cdot 10^3$	$228\,\mu m$	$\sim 66\,\mu m$
AMS-02	2011	$\sim 7\,\mathrm{m}^2$	29–62 cm	$\sim 200 \cdot 10^3$	$110\,\mu m$	$\sim 7\,\mu m$
DAMPE	2015	$\sim 7\,\mathrm{m}^2$	38 cm	$\sim 70 \cdot 10^3$	$242\,\mu m$	$\sim 40\,\mu m$

Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,\mathrm{m}^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

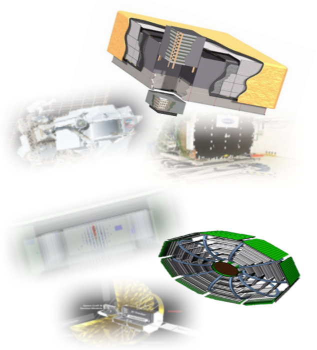
- **Timing for astro-particle detection : <100 ps timing to separate hits from primary particles and secondary backsplash, and for particle spectroscopy via ToF**
  - Radiation hard detectors
  - Low mass and low power electronics
  - Compact detector

A. Seiden at TIPP '21

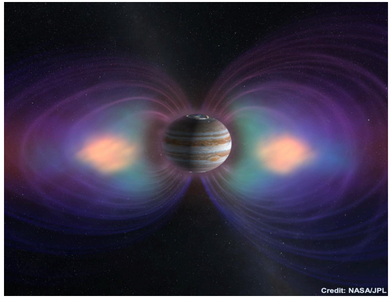


- **In-situ measurement of Jupiter's Radiation Belt (PAN- Penetrating Particle Analyser) : highly energetic and penetrating particles, i.e. ~100 MeV electrons, ~GeV/(n) ions** - *Elias Roussos et al.*
  - Spectrometer with successive tracking and timing layers

4D detectors in space and photon science

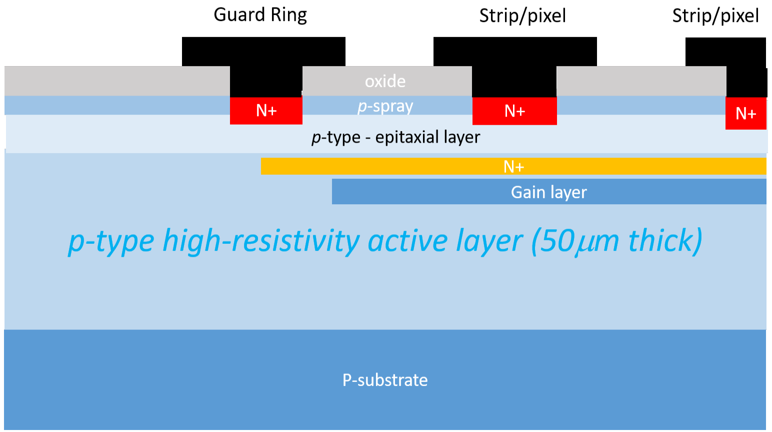


- **Charged cosmic ray and γ-ray measurements require solid state tracking based on silicon microstrip sensors + timing**
  - <100 ps timing to separate hits from primary particles and secondary backsplash, and for particle spectroscopy via ToF (spectrometers with successive tracking and timing layers)
- **Photon Science, QIS, Biology, Medicine**
  - Imaging in visible range:
    - Low energy ion mass spectroscope: increases camera sensitivity
    - Single photon detection (QIS)
    - Medical imaging (PET): timing improves ToF resolution hence extend application to children
    - Biology: sub-ns timing allows to study fast evolving samples
  - Soft X-rays for studies of nanoscale dynamics of materials:
    - 250 eV - 1.5 keV: improve sensitivity to characteristic energies from Carbon, transition element L-edges, and rare-earth M-edges



From Time (LGAD) to Time+Space (4D)

Deep-Junction LGAD

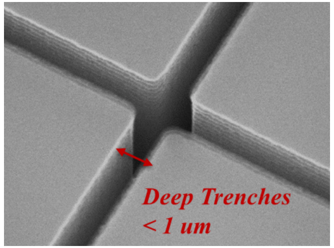


Under processing at BNL

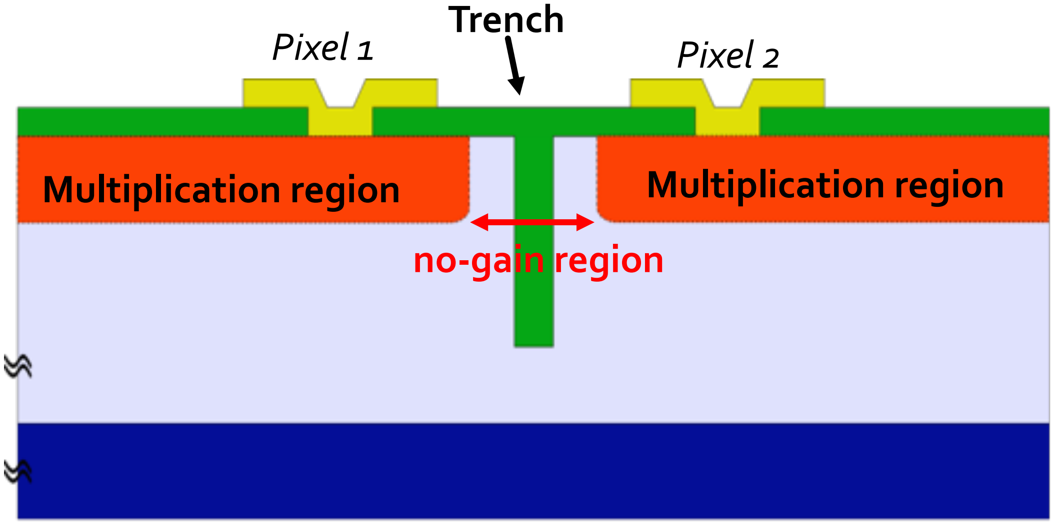
- **Bury the p-n junction (Deep Junction)** so that fields are low at the surface, allowing conventional *segmentation*
- Deep junction is depleted under the applied voltage.
- Over the junction, a few μm thick p-type HR epitaxial layer is grown.
- n+ electrodes (strip and pixels) are then implanted and DC-contacted by aluminum.
- **It is a DC-LGAD**, signal induced in the strips/pixels by drift of the multiplied holes in the substrate; spatial resolution as in conventional silicon strip detectors.

- *Concept developed at SCIPP*
- *Prototypes under development through a Cactus/BNL/SCIPP collaboration SBIR and LDRD funding*

From Time (LGAD) to Time+Space (4D)



Trench Isolation LGAD (TI-LGAD)



- **JTE and p-stop, which limit fill-factor, are replaced by a single trench in DC-LGADs.**
  - **Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.**
  - **~100% fill factor**
  - **Signal in single pixel (no share)**

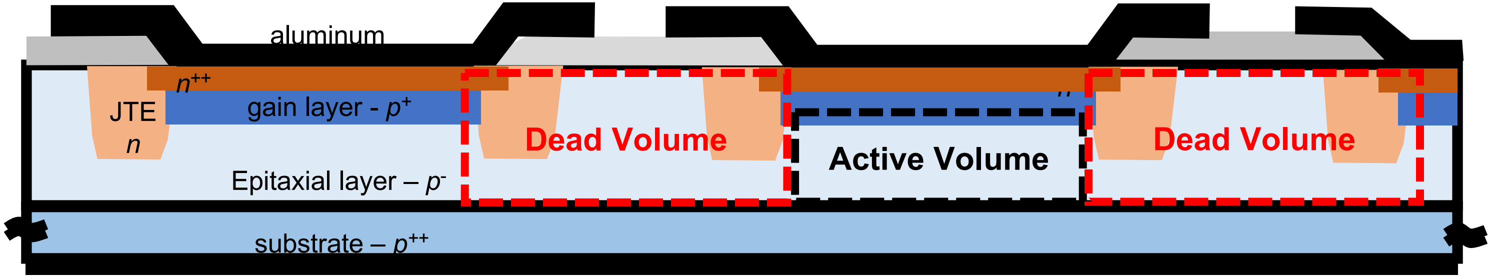
- Trenches are a few microns deep and < 1μm wide, filled with Silicon Oxide
- Fabrication process of trenches is compatible with the standard LGAD process flow.

by Torino and FBK groups

From Time (LGAD) to Time+Space (4D)

- LGADs have opened up the possibility of excellent timing using silicon sensors for MIP signals.

- LGAD limitation is the coarse segmentation, ~ 1x1 mm² pads
  - Lateral dimensions of Gain layer must be much larger than thickness of substrate, for a uniform multiplication.
  - Dead volume (gain~1) between the implanted region of the gain layer
    - pixels/strips (pitch ~ 100 μm) have a Fill Factor <<100% and is Voltage dependent
    - large pads are preferred (~ 1 mm); e.g., HGTD of ATLAS and MTD of CMS
    - **4D detector not possible!!!**

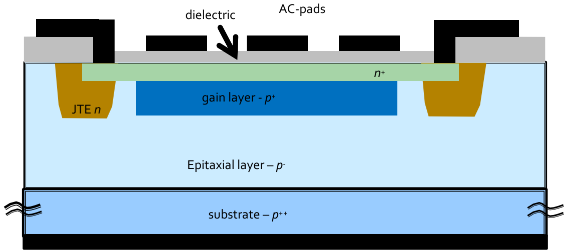


LGAD Families

As spatial resolution is poor in LGAD, an R&D towards a 4D detector is needed → modification of the original LGAD concept

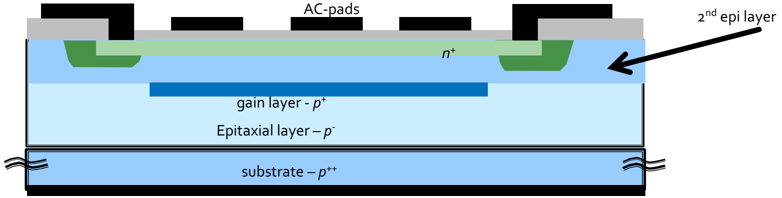
AC-LGAD

Excellent spatial resolution with smart position reconstruction algorithms, possibly for low interaction rates



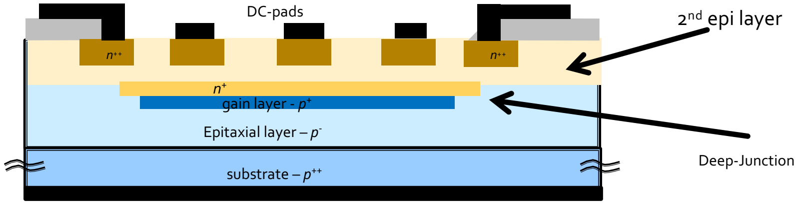
Deep-Layer AC-LGAD

(FNAL, Cactus, UCSC): an AC-LGAD with a higher rad-hardness



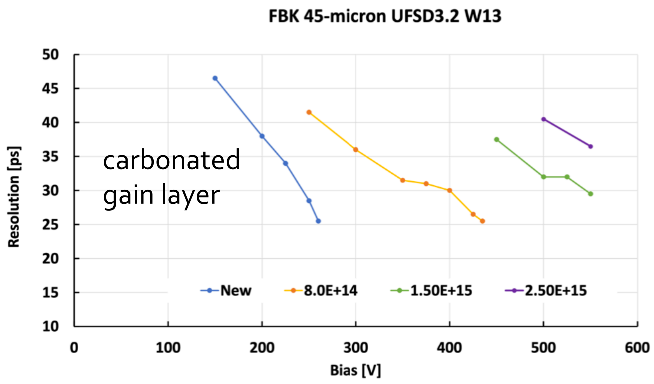
Deep-Junction LGAD

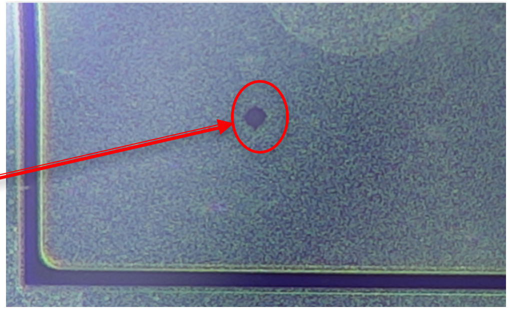
(UCSC, Cactus) Position resolution given by pitch, as in std pixel/strip detector



Radiation Tolerance

- One of the biggest challenges is radiation hardness at hadron colliders
- LGADs will operate up to 2.5 10^{15} n/cm^2 at HL-LHC
- Effective reduction of gain in LGADs at high fluence, and sudden death at high voltages have been observed
  - Boron in gain layer loses effectiveness
    → raising the voltage to maintain a large enough net gain layer field
  - Death (crater) in HPK 50 μm LGADs at V_{bias} >600 V ($\gtrsim 10^{15}$ n/cm^2)
    → Under investigation at FNAL testbeams
- AC-LGADs are subject to similar radiation damage as LGADs





Crater

Single proton interaction with large ionization (40-50 MeV deposited energy)

- Excess charge leads to highly localized conductive path
- Large current in narrow path→ *"Single Event Burnout"*
- Critical field of ~12 V/μm

R. Heller (FNAL) at RD50 [*https://indico.cern.ch/event/1029124/*](https://indico.cern.ch/event/1029124/)