Good Timing

The development of high resolution 4D detectors

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Guidance towards the next revolution

"[Science is] a series of peaceful interludes punctuated by intellectually violent revolutions"
T. Khun, "The Structure of Scientific Revolutions", 1962

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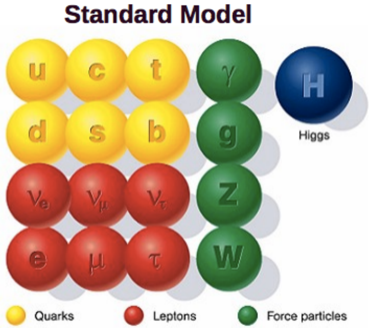
- HEP is in an interlude period, awaiting for the next revolution
- The Higgs boson discovery consolidated the Standard Model (SM) paradigm
- LHC is the current most powerful tool to directly probe SM anomalies
- So far direct searches of new physics beyond the SM have failed to bring the next revolution in HEP, but several *anomalies* have appeared
- Cross fertilization between different fields: intensity frontier, cosmic frontier, nuclear physics, etc.
- Theory cannot provide concrete directions on the energy scale at which the SM breaks down

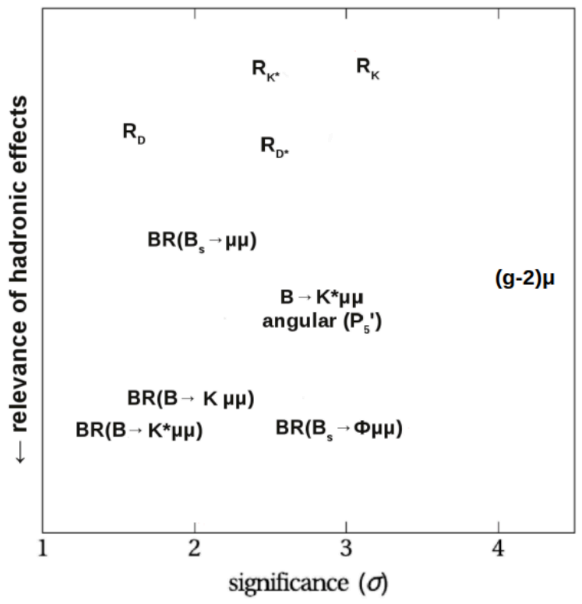
➔New experimental results will provide necessary guidance



Guidance towards the next revolution

- Guidance will come from direct searches, and systematic tests of the SM paradigm.
  See *g-2 and LHCb flavor anomalies*.
  - Are these anomalies evidence of the breaking of the SM paradigm in the lepton flavor sector?

by Wolfgang Altmannshofer



- ➢ New methodologies and technologies are critical
- ➢ HEP experiments are no longer table-top, preparation for the next generation of experiments must start decades ahead of time
  - ➢ A long term vision and planning is critical
- ➢ Impact of novel technologies extends beyond HEP

A Treasure Hunt...

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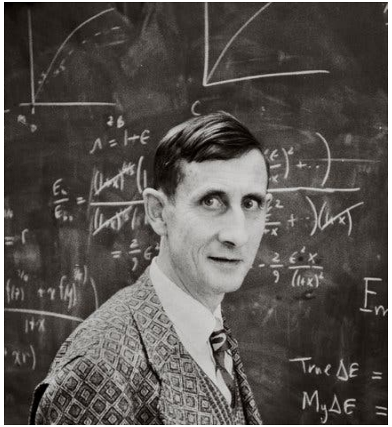
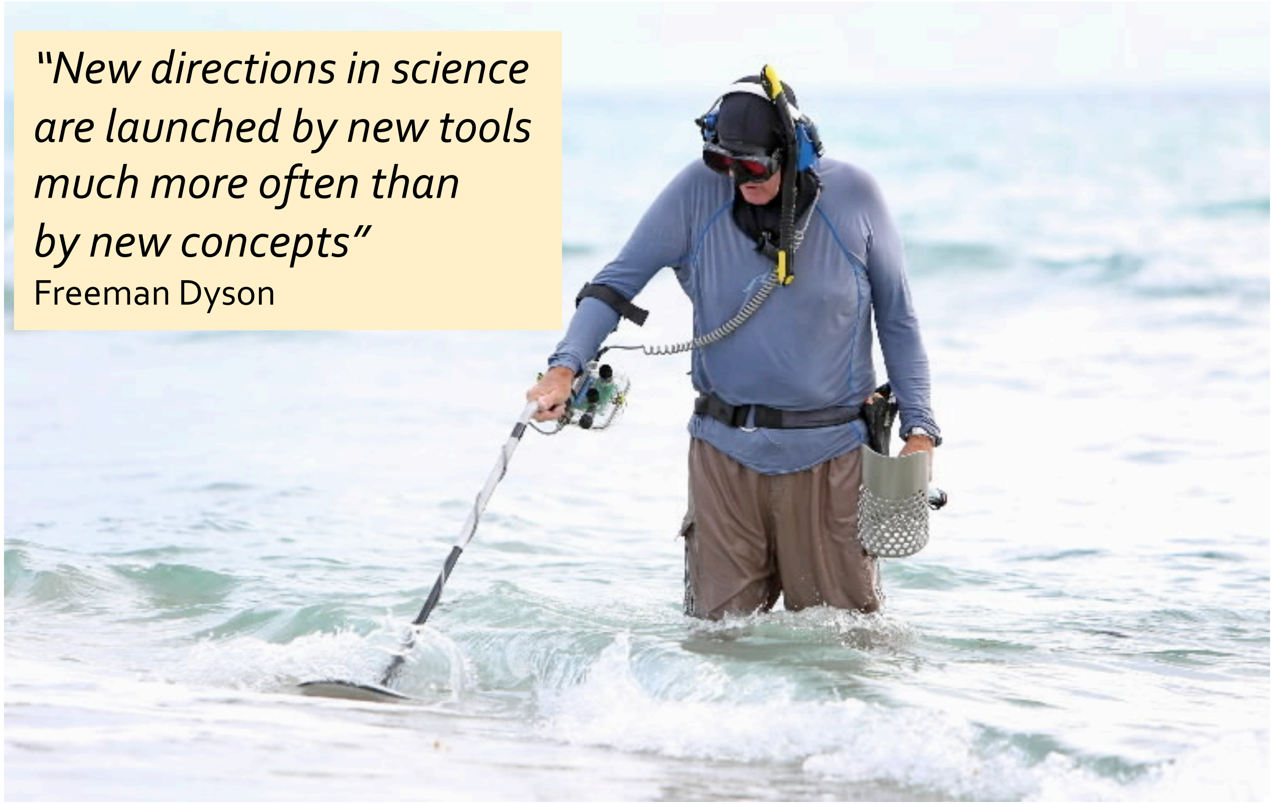




"New directions in science are launched by new tools much more often than by new concepts"

Freeman Dyson

LHC Beyond LHC Run-2 and -3…HL-LHC

- We are only at the beginning of the LHC program!
  - We only accumulated 5% of the total expected LHC data

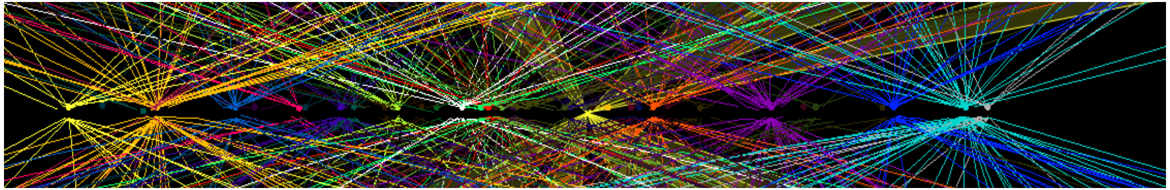
Current LHC key numbers:

- p-p collision energy: 13 TeV
- Peak luminosity: 2.1 x 10^{34} $cm^{-2}s^{-1}$
- Int. luminosity/exp.: 150 fb^{-1} at 13 TeV
- **Average Pileup in Run-II: 33 (peak ~65)**

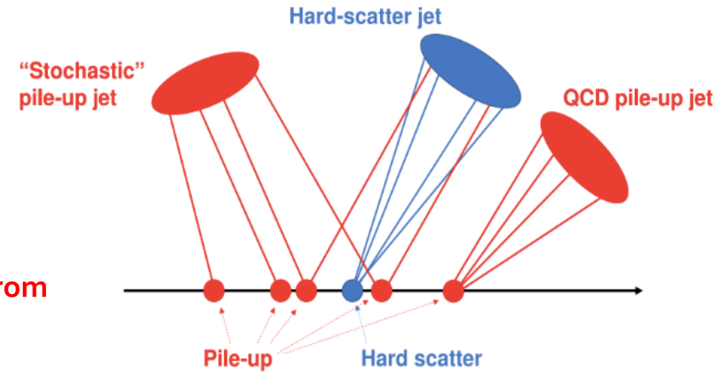
HL-LHC key numbers:

- p-p collision energy: 14 TeV
- Peak luminosity: 5-7.5 x 10^{34} $cm^{-2}s^{-1}$
- Int. luminosity: 3,000 – 4,000 fb^{-1}
- **Average Pileup: 200**

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**
    - Jets, b-jet tagging, missing E_T, lepton identification, …
  - **One of the key elements to mitigate the effect of pile-up is the precise assignment of tracks to vertices**
    - Extremely challenging in the forward region
    - **Common times for tracks nearby in space indicate that they are likely from the same vertex**
    - Time for hits to be linked with pixel/strip tracks and calorimeter clusters.



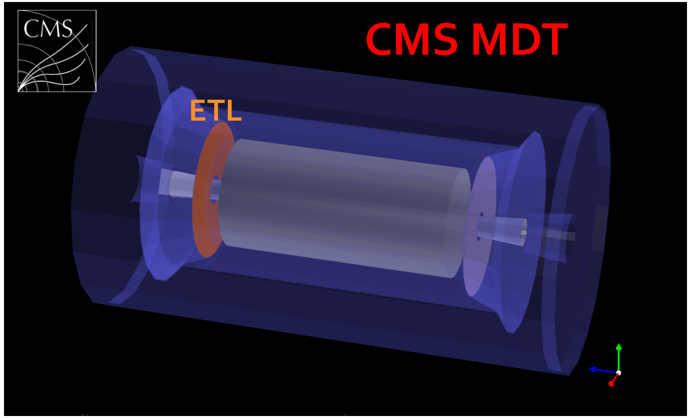
ATLAS and CMS upgrades for the HL-LHC

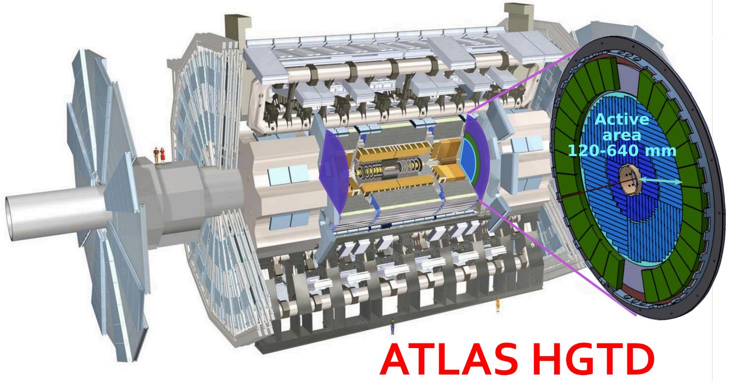
Major Detector Upgrades for HL-LHC

- Protect against high radiation
- Mitigate pileup rates and occupancy
- Keep low p_T requirements for main triggers
- Precise measurements up to large rapidity
- Lighten the detector, dropping material

- New silicon-based systems for timing to mitigate pileup
  - Goal: ~30 ps time resolution per hit

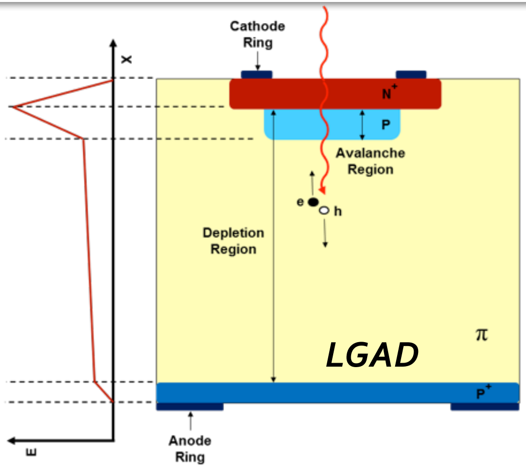
1. CMS MIP Timing Detector (MTD) in $-3 < |\eta| < +3$
   - Barrel: Crystal read out by SiPMs - Endcap: fast-time silicon (15.6 m^2 of LGADs)
2. ATLAS High Granularity Timing Detector (HGTD) in $2.4 < |\eta| < 4.0$
   - End-cap only: fast-time silicon (6.4 m^2 of LGADs)

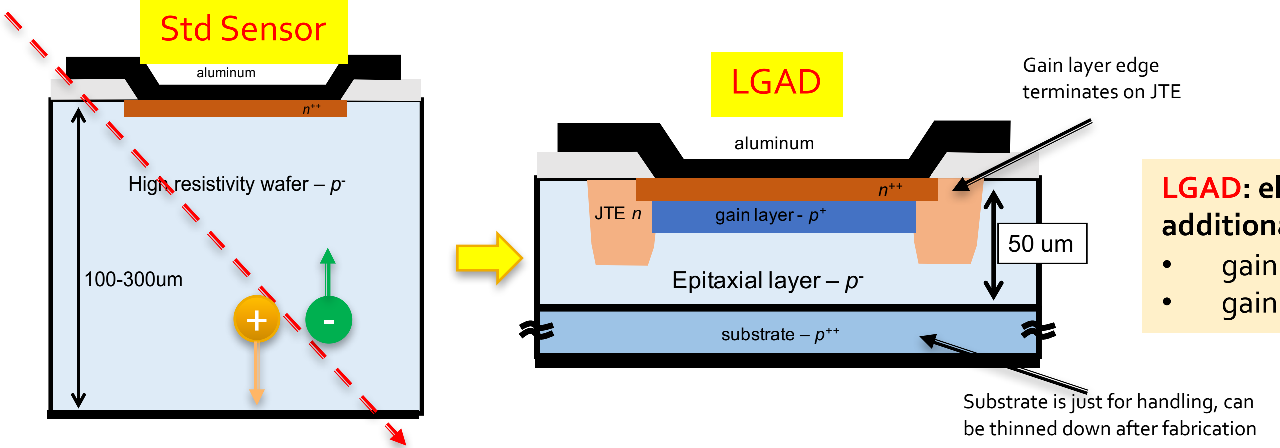




Fast-time silicon detector: LGAD

- Low Gain Avalanche Diode (LGAD) will be used at HL-LHC
- Process similar to standard n-in-p sensors + built-in multiplication
  - 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



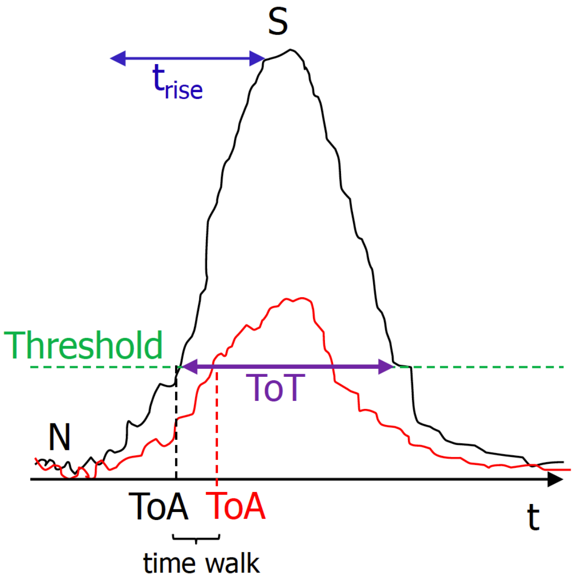


LGAD: electrons multiply in gain layer and produce additional e/h pairs (no hole multiplication)

- gain electrons have ~no effect on signal
- gain holes dominate signal

How to measure good timing

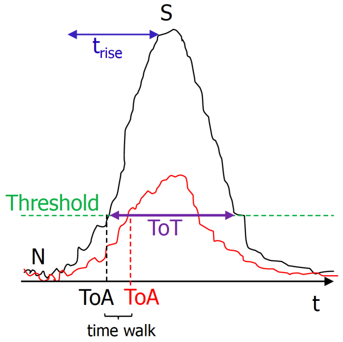
- **Time = Threshold Crossing (Time of Arrival)**



How to measure good timing

- **Time = Threshold Crossing (Time of Arrival)**

$$\sigma^2_{\text{det}} = \sigma^2_{\text{Landau}} + \sigma^2_{\text{jitter}} + \sigma^2_{\text{TW}} + \sigma^2_{\text{TDC}}$$



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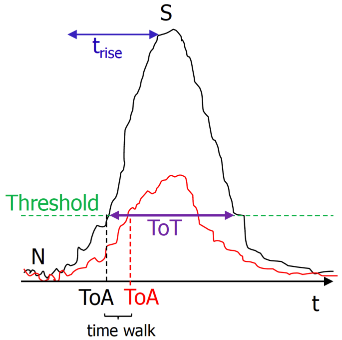
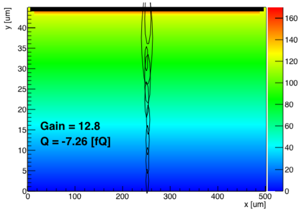


- **Landau fluctuations in the deposited charge in the sensor**



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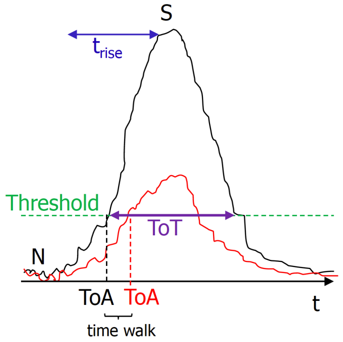

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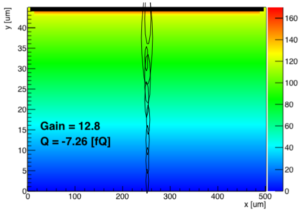
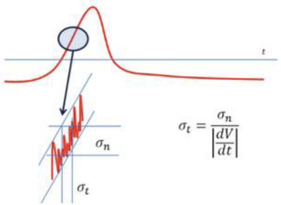


- **Jitter (noise in signal):**
  ➔ **high S/N and fast rise time**



$$\sigma_{\rm Jitter} = \frac{N}{(dV/dt)} \simeq \frac{t_{\rm rise}}{(S/N)}$$

How to measure good timing

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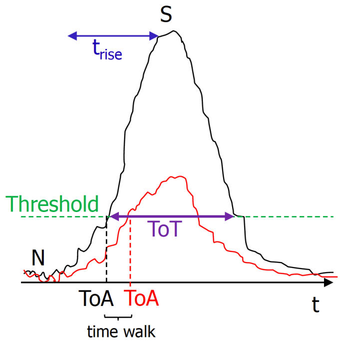
$$\boxed{\sigma_{\mathrm{det}}^2 = \sigma_{\mathrm{Landau}}^2 + \sigma_{\mathrm{jitter}}^2 + \sigma_{\mathrm{TW}}^2 + \sigma_{\mathrm{TDC}}^2}$$



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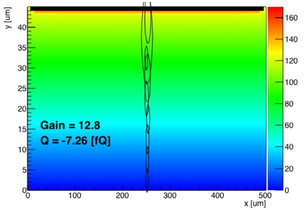

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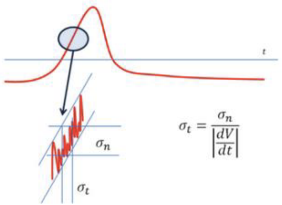
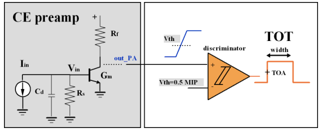
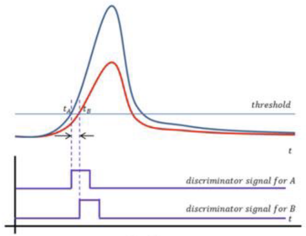


$$\sigma_{\mathrm{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\mathrm{rise}}}{(S/N)}$$

- **Time Walk (TW): differences in signal amplitudes**
  - negligible after offline TOT-based correction
    - ToT correction to account for TW [t_{corr} = ToA – f(ToT)]





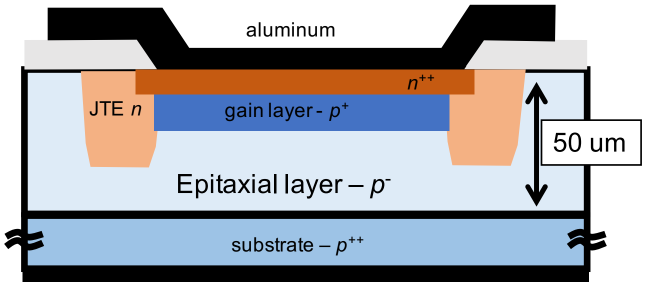
Time walk effect

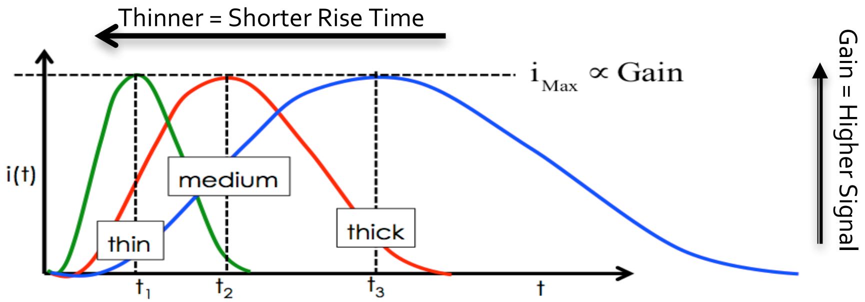
- **Fast/Low noise electronics, precise digitizer (TDC/oscilloscope), stable clock**

LGAD properties for HL-LHC

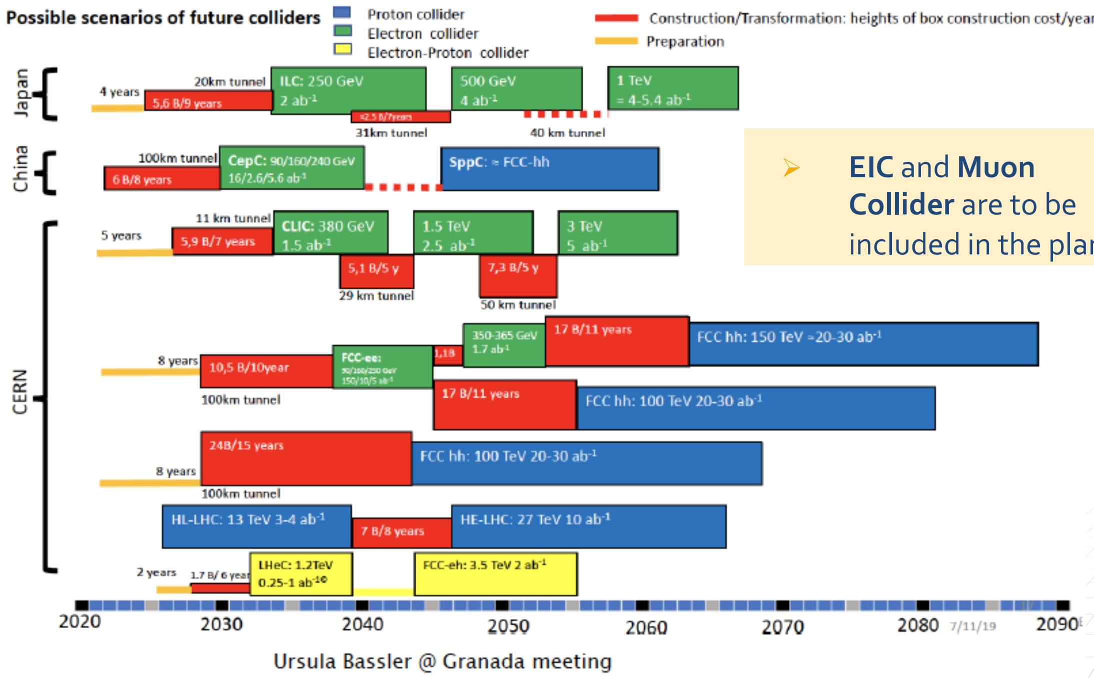
- **LGADs for ATLAS and CMS:**
  - **50 µm thickness**
  - **1.3 mm pixel pitch**
  - **Space resolution is limited by coarse pitch**
  - Several m² of sensors bump-bonded to dedicated ASICs (ALTIROC for ATLAS, ETROC for CMS)
  - **Time resolution pre-irradiation 30-40 ps** per hit
- Also proposed for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

- **Thin LGADs: 50 µm active thickness**
  - Fast charge collection (~1 ns) ← high repetition rate
  - Short rise time (~400 ps) ← minimizes jitter
  - Minimizes Landau fluctuations in charge generation ← faster
  - However, total charge is also reduced (smaller signal needs lower noise electronics), therefore higher gain is advantageous
- **Time resolution: ~25 ps with 50 µm active thickness**
- **Radiation tolerance ~2.5x10¹⁵ neutrons/cm²**

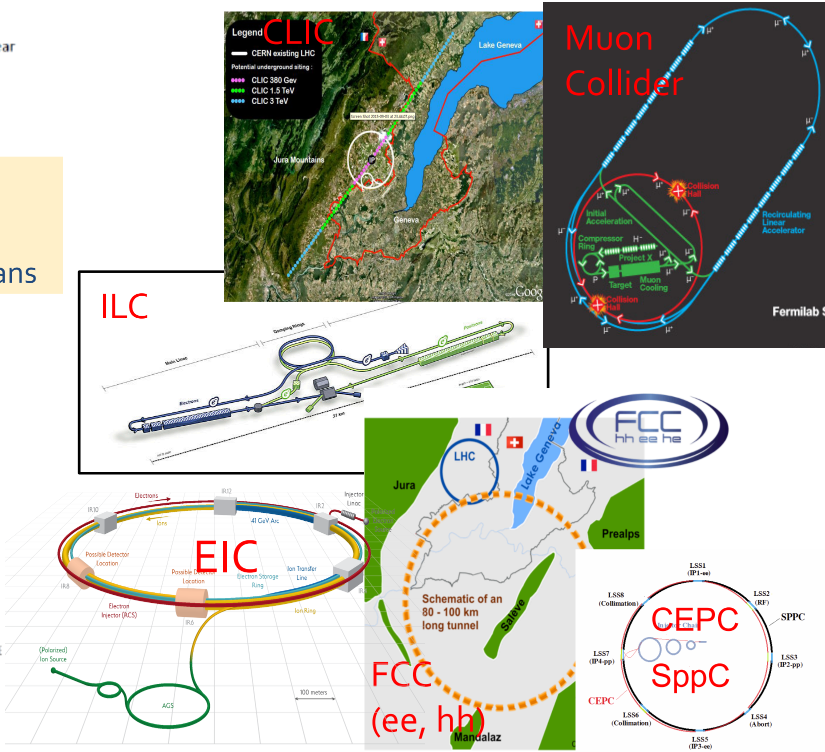




Beyond HL-LHC…

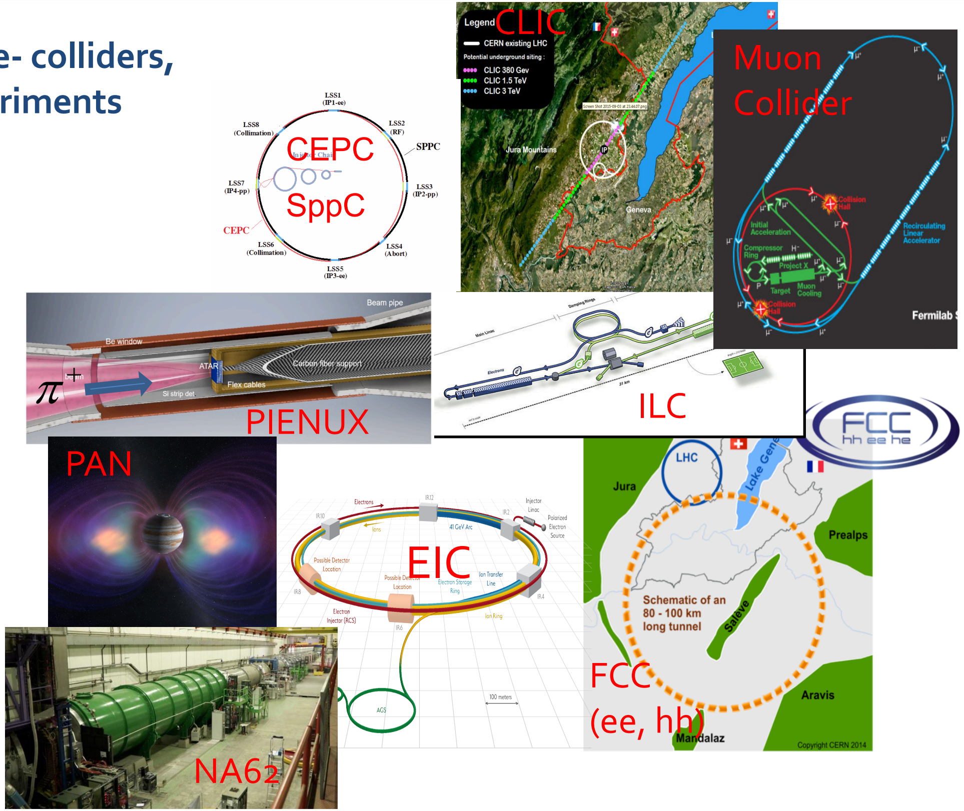


- **EIC** and **Muon Collider** are to be included in the plans



Good timing beyond HL-LHC

- Enhance capabilities for particle identification at e+e- colliders, and nuclear physics and rare process detection experiments
- Pileup mitigation at future hadron colliders
- Forward proton tagging at hadron colliders and EIC
- Beam background mitigation at Muon Collider
- Beam monitoring at colliders
- Space applications
- Photons science and photonics



- Demand for 4D detectors that provide fine space and time resolution in a single device

Basic Research Needs for HEP

- Technical requirements of future HEP experiments are driven by 4 main scientific goals
  - Higgs properties @ sub-% precision
  - Higgs self-coupling @ 5% precision
  - Higgs connection to Dark Matter
  - New particles and phenomena at multi-TeV scales
- Technical requirements based on existing proposals
  - Muon Collider's requirements still to be included

Technical Requirements:

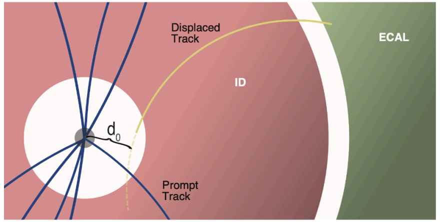
- 5-10 ps time resolution per track
- <5 µm space resolution per hit
- 8×10^{17} n/cm² radiation tolerance in hadron colliders
- Low mass
- Low power dissipation

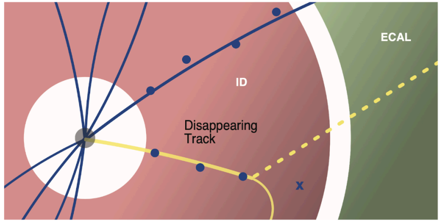
Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision; Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\text{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\text{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\text{m}^2$ 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 8×10^{17} $\text{n}_{\text{eq}}/\text{cm}^2$ 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 0.5×0.5 cm², hadronic cells of 1×1 cm² 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 3×10^{16} (5×10^{18}) $\text{n}_{\text{eq}}/\text{cm}^2$ 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 8×10^{17} $\text{n}_{\text{eq}}/\text{cm}^2$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	**16**, **17**, **21**, **26**

from DOE Instrumentation BRN, 2020

4D Detectors for e^+e^- colliders

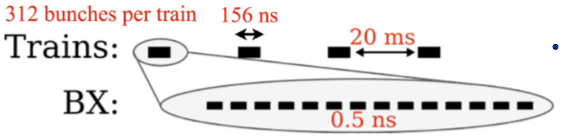
- **4D detectors can enhance capabilities for particle identification and reconstruction at e^+e^- colliders**
  - Measurements of Higgs boson properties, dark matter searches etc.





- **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** ➔ ≲25 μm pixel pitch
  - Low material budget to minimize multiple scattering
    - <1% for Vertex Det./ Tracker ➔ **~100 μm si-tracker thickness**
  - Power dissipation 0.1-0.2 W/cm²
  - Timing < 1 ns – 100 ns

Timing needs



CLIC

- *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**

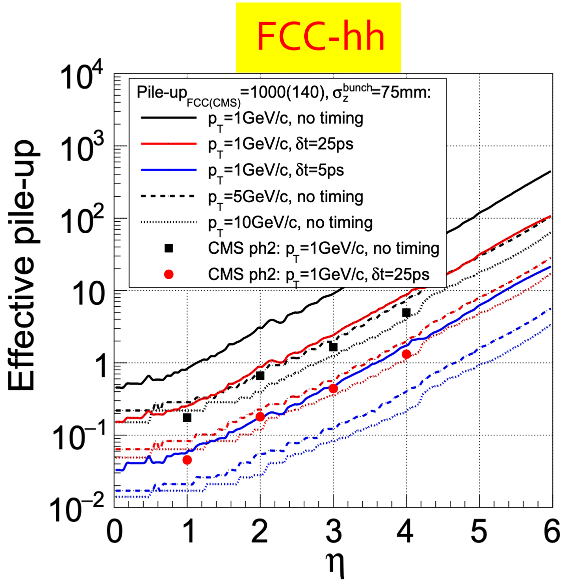
4D Detectors for Hadron colliders

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

- **Future Hadron colliders (FCC-hh): <u>pileup</u> (~1000), impact parameter resolution, and <u>radiation damage</u> are main concerns as well as <u>cost</u> for a large tracker**
  - ~430 m² of silicon (250 m² ATLAS/CMS at HL-LHC)
  - pixels as small as 25 x 50 μm → **Track resolution < 10 μm per layer**
    - 16 billion readout channels
  - Material budget ~1-2.5% X_0 per layer
  - **Radiation levels up to 8 x 10^{17} n/cm²**
  - Resolution on transverse impact parameter (d_0) ~5 μm: b-, τ- and c-tagging
  - Resolution on longitudinal impact parameter z_0 critical for pileup mitigation:
    - 125 μm spacing between vertices at |η|=1.5, 3 for p_T=1, 10 GeV

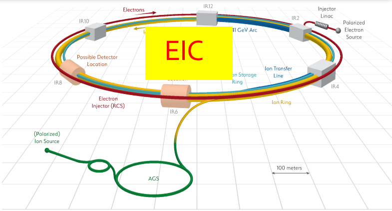
  → **Timing is necessary to correctly assign tracks to vertices**

- **Time resolution 5 – 10 ps needed at FCC-hh**
  - **5 ps → effective pileup of ≤1 at |η|<3.5**



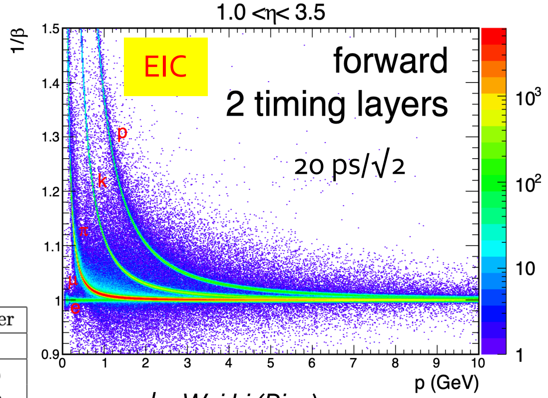
4D Detectors for Particle Identification

- **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**
  - Pixel/strip to extrapolate tracks from inner tracker and improve momentum resolution
  - Low material budget

	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05 X_0$ h-direction $< 0.15 X_0$

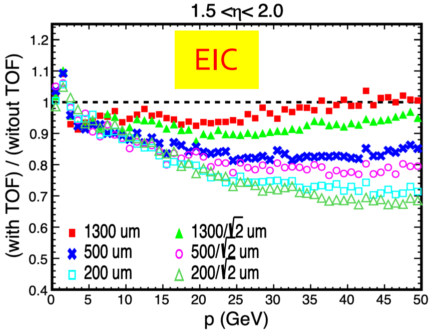


by Wei Li (Rice)

***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

***Track p_T resolution** improvement with fine ToF det. segmentation*

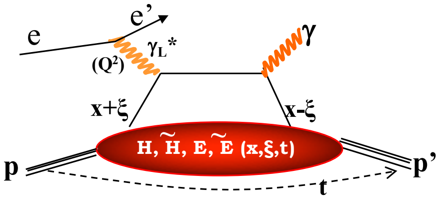


by Wei Li (Rice)

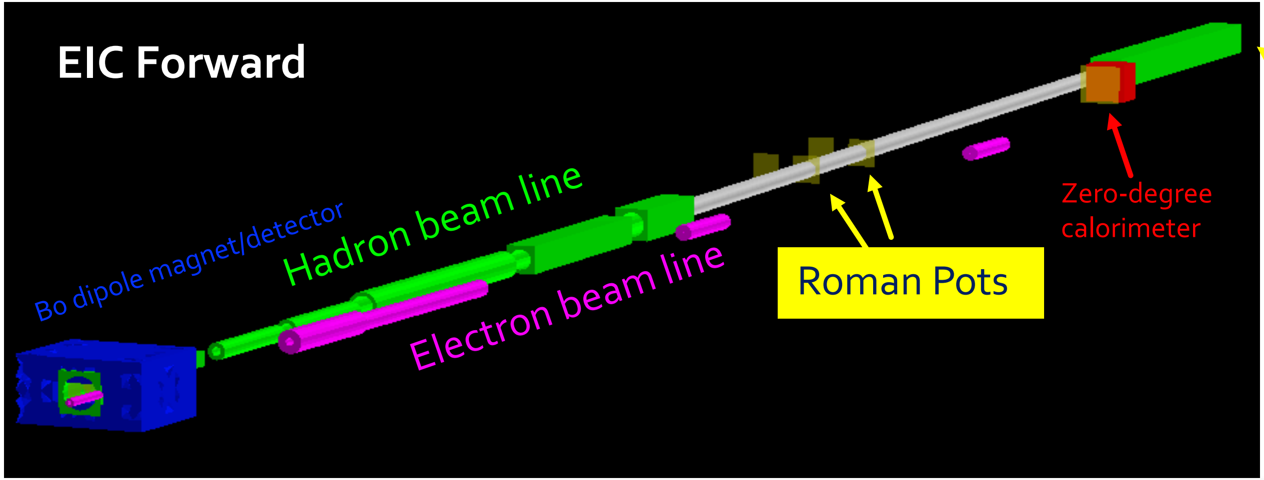
4D Detector for EIC Roman Pots

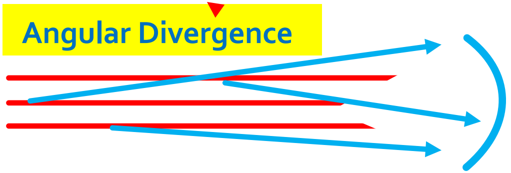
- **Forward proton tagging at EIC (e-hadron collisions)**
  - integral part of EIC physics programs

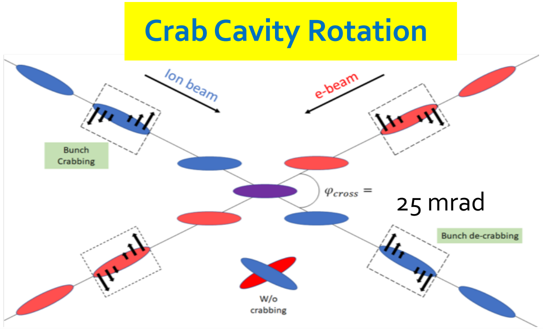
Deeply Virtual Compton Scattering at EIC



- **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 effect



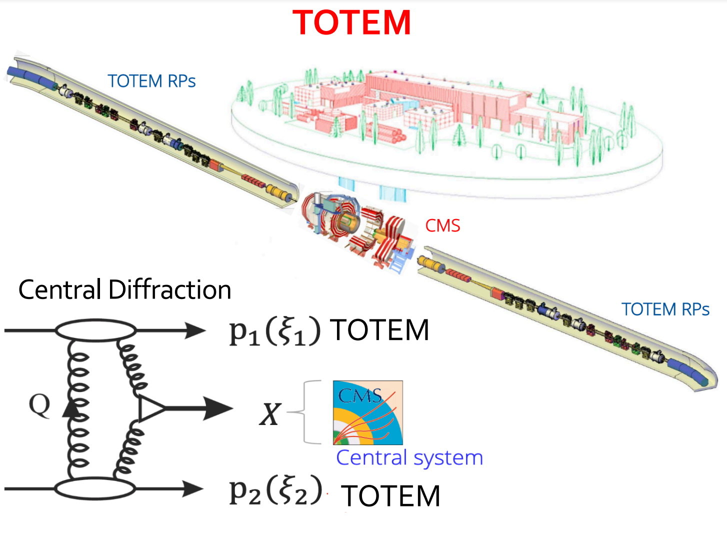




4D Det. for Forward Physics at Hadron Coll.

- **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.

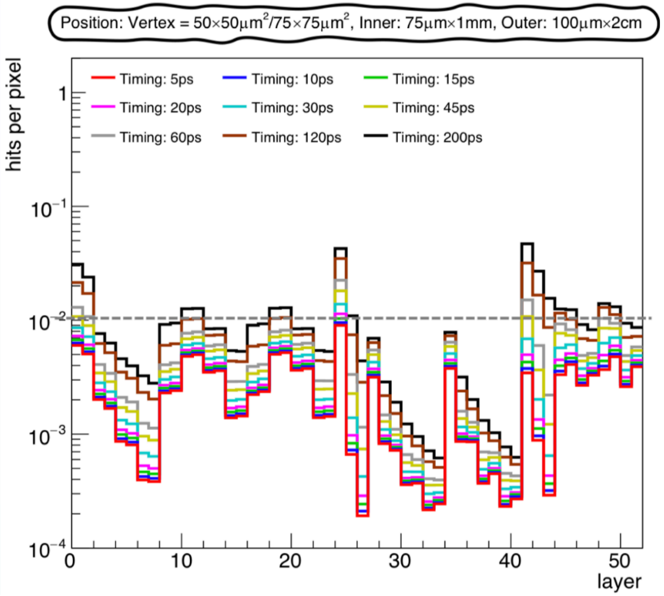
- **Forward Physics at the (HL-)LHC and future hadron collider: fine time and space resolution needed for precise proton momentum reconstruction and association to correct vertex (pileup suppression)**
  - **10-30 ps** timing to suppress pileup, **~10 μm** tracker resolution
  - Radiation hard detector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



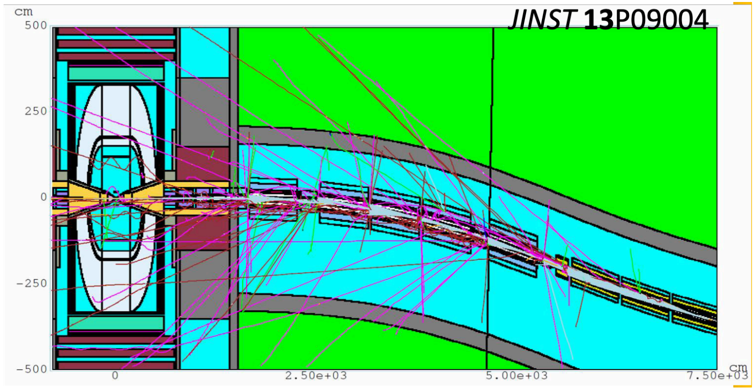
- Tracking (Pixels+Strips)
- Timing (LGADs)+SAMPIC chip

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



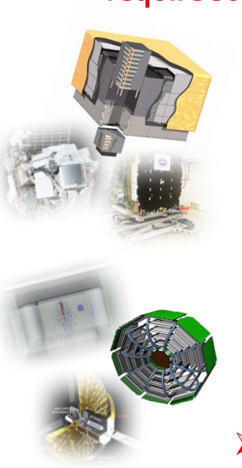
D. Lucchesi, S. Jindariani et al.



- **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 Space Science

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

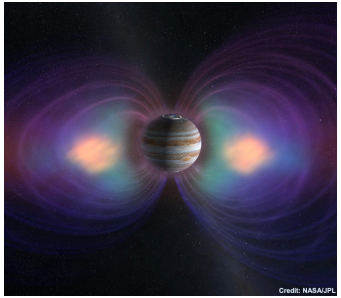


Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,\mathrm{m}^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu$m
AMS-02	2011	$\sim 7\,\mathrm{m}^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu$m
DAMPE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



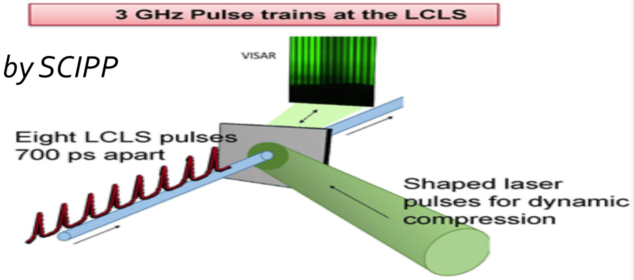
- **In-situ measurement of Jupiter's Radiation Belt (PAN- Penetrating Particle Analyser) : highly energetic and penetrating particles, i.e. ~100 MeV electrons, ~GeV/(n) ions** - *Elias Roussos et al.*
  - Spectrometer with successive tracking and timing layers

4D Detectors for Imaging

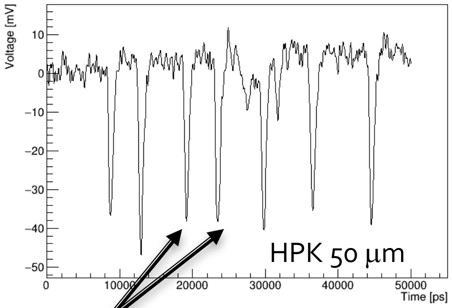
- 4D Photon detectors have multiple applications in visible and X-ray
  - Imaging:
    - **Low energy ion mass spectroscopy**
      ➔ LGAD increases camera sensitivity
    - **Single photon detection (quantum information)**
      ➔ LGAD with high multiplication (a new frontier for LGAD)
    - **Medical 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:
    - **Soft-X-rays**: 250 eV - 1.5 keV range is of considerable scientific interest (characteristic energies from Carbon, transition element L-edges, and rare-earth M-edges)

      ➔ LGAD with low noise and high signal improves sensitivity at such low energies

by SCIPP



X-ray Detection: speed is the goal
Excellent Rate capability for LGAD:
Signals in an 8 keV X-Ray beam

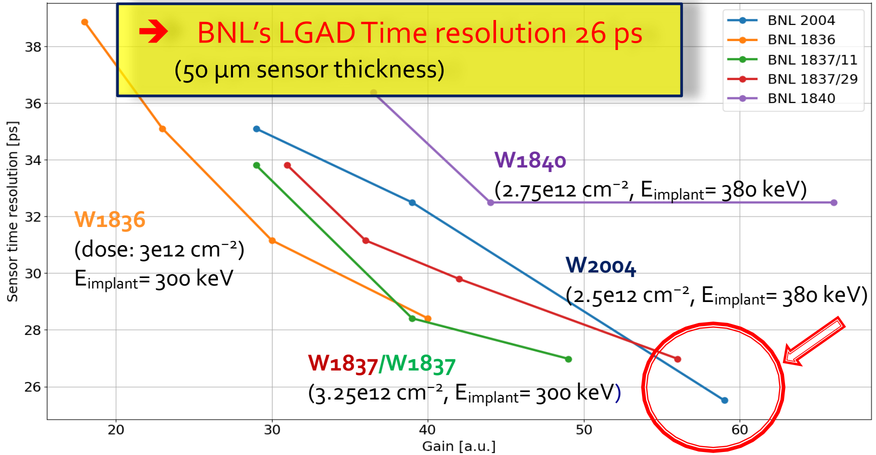


- **2 ns** between closest signals
- 20 μm thick sensor can reach 700 ps

Developments towards a 4D detector

- Several developments needed to meet requirements of future experiments in HEP, Nuclear Physics, Photon Science, Astro-particles, Imaging etc.
  1. Improve time resolution to 10-20 ps per hit
  2. Achieve space resolution of ≤ 5 micron
  3. Reduce power dissipation in readout electronics
  4. Reduce material budget
  5. Improve radiation hardness

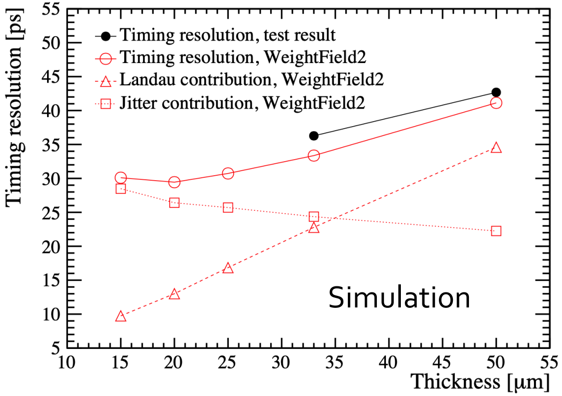
Time resolution improvement in LGAD



- Time resolution improves for thinner sensors!

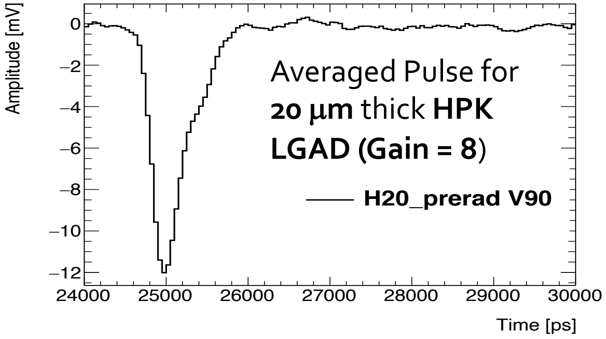
- With 50 μm thickness, resolution levels off because of Landau fluctuations at about 30 ps → Thinner sensors
  - Landau fluctuations proportional to the detector thickness
- Jitter dominates in thin detectors → to be minimized with low noise electronics and large signal (gain and voltage).

$$\sigma_{\mathrm{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\mathrm{rise}}}{(S/N)}$$

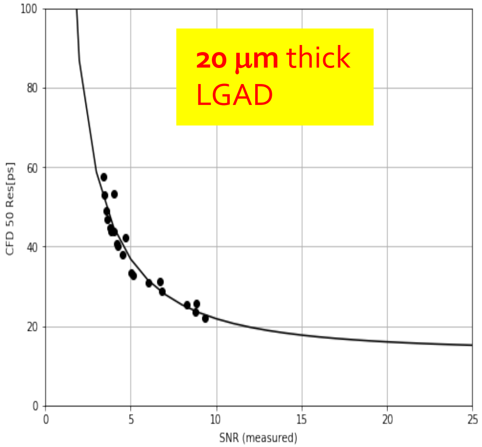


M. Li et al. (2021)
doi:10.1109/TNS.2021.3097746.

Time resolution improvement



- **LGAD with 20 μm thickness: produced by HPK**
  - **Rise time ~200 ps vs ~400 ps in a 50 μm LGAD**
  - **Very good S/N ratio with only Gain=8**



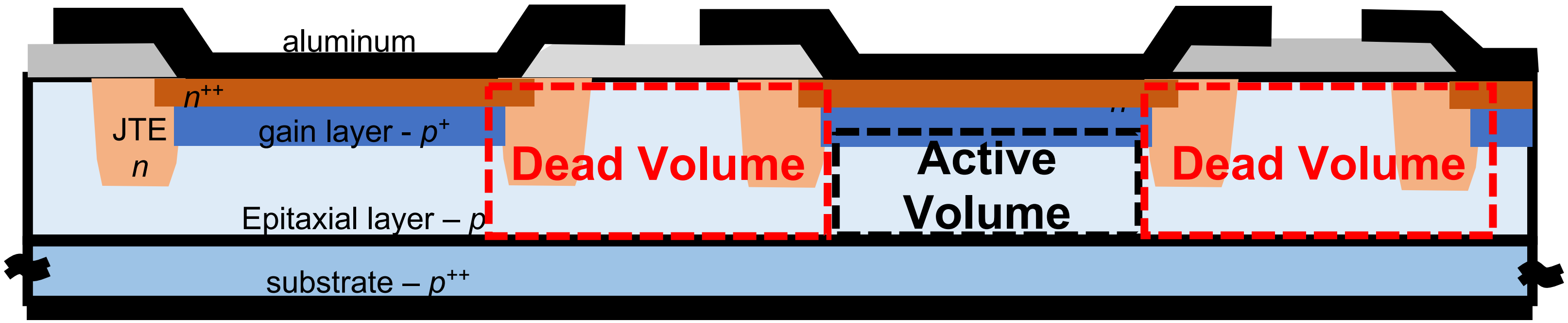
MIP Time resolution for thin LGAD versus S/N ratio

- **Signal height can be adjusted by changing detector voltage and gain.**
  - Modest value of S/N required to get to about 20 ps time resolution for the 20 μm thick sensor.
- **10 ps timing resolution with ~20 μm thick LGADs may be possible**

A. Seiden (UCSC), CPAD21

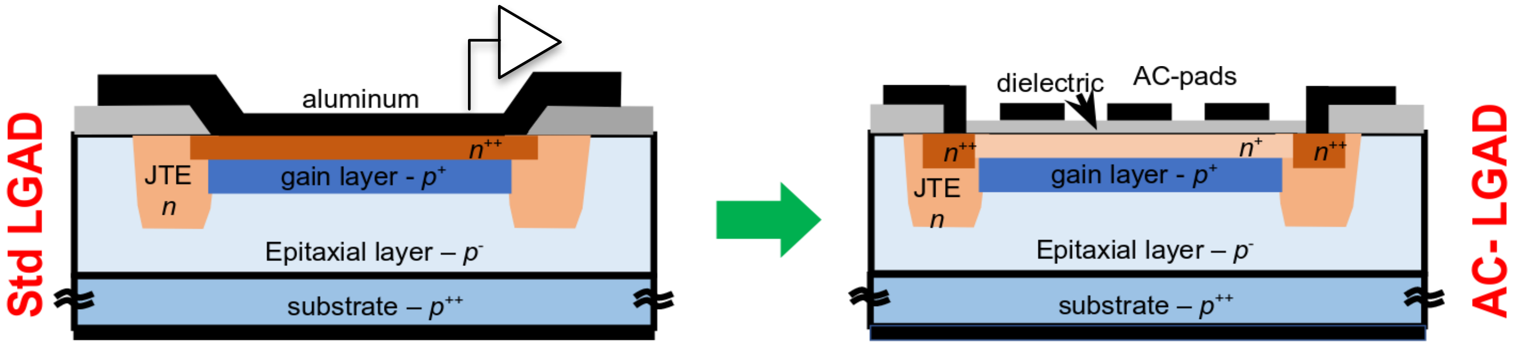
From Time (LGAD) to Time+Space (4D)

- 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!!!



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

- LGAD-based technologies have been developed to combine the good timing of LGADs with position resolution.
  - AC-coupled LGAD (AC-LGAD) ← Most advanced
  - Deep Layer AC-LGAD
  - Deep Junction LGAD
  - Trench Isolation LGAD (TI-LGAD)
  - Inverted LGAD (iLGAD)

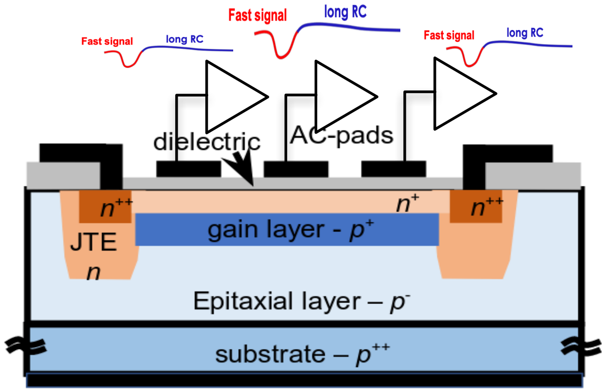


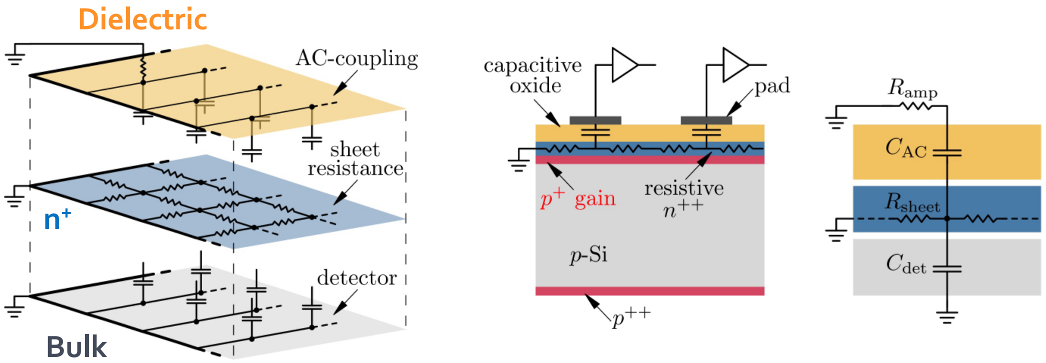
Large pads (~1 mm²) → Timing only

Can be finely pixelated → Time+Space (4D)

Pixel pitch mostly limited by in-pixel components in readout electronics

AC-LGAD





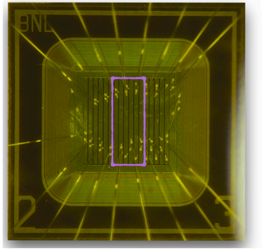
- **One large low-doped / high-ρ n⁺ implant over the all active area** (instead of a highly doped low-ρ n⁺⁺)
  - No p-stop, JTE, inter-pad gap
- **A thin insulator over the n⁺ where electrodes are placed ➔ AC-coupling**
  - **Signal is bipolar** and is still generated by drift of multiplied holes into the substrate, AC-coupled through dielectric
  - **Signal is shared between multiple electrodes**
  - Electrons collected at the resistive n⁺ and then slowly flow to an ohmic contact at the edge (n⁺⁺)
- **100% fill factor and fast timing information at a per-pixel level both achieved ➔ 4D**

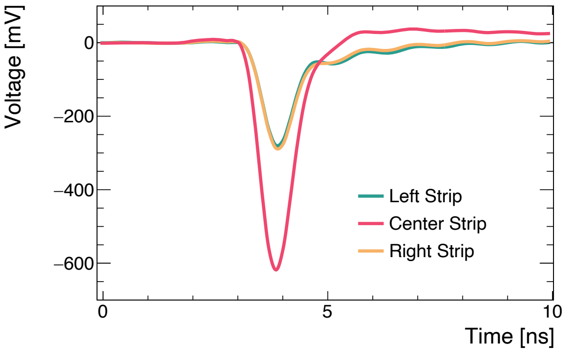
Position reconstruction with AC-LGAD

- Signal sharing can be exploited to improve space resolution beyond 1/√12 by combining signal from multiple electrodes
  - Signal sharing depends on electrode geometry (pitch, gap size) and resistivity of n⁺ layer ➔ tunable
  - Sparse metallization results in lower capacitance (thus noise), and lower power by limiting channel count.

Apresyan et al., 2020 JINST 15 P09038

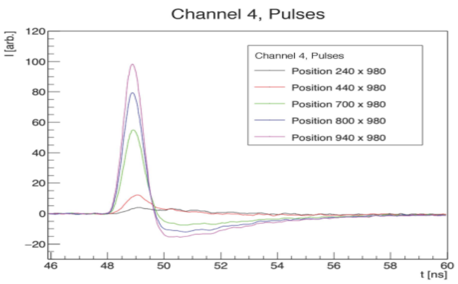
100 micron pitch, 20 micron gaps

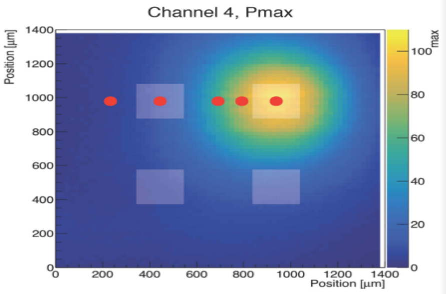




Signal from neighboring electrodes generated by ***120 GeV protons*** *(FNAL test-beam)*

Amplitudes generated by **IR laser** at varying distance from readout channel - *A. Seiden (UCSC) TIPP Conf.*



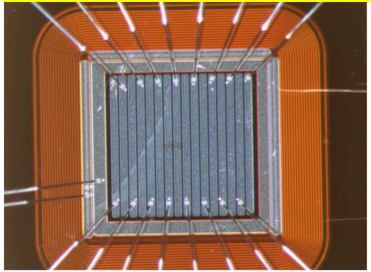


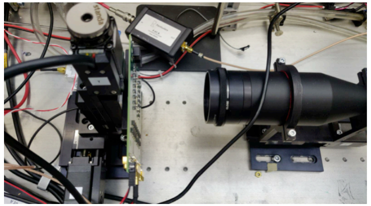
- **Signal decreases as we move away from hit position**
- **To be exploited to improve position resolution**

AC-LGAD’s space resolution

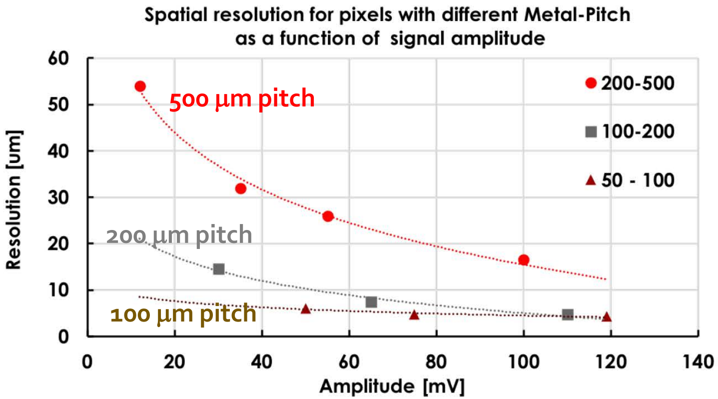
- Position resolution is improved interpolating between several electrodes
- At low signal, space resolution dominated by jitter
  - Low noise electronics needed
- Larger geometries have worse position resolution
  - Need high gain

BNL 16-strip AC-LGAD with pitch 100 μm, gaps 44 μm





- **1 μm space resolution with large signal (>400 mV, i.e. ~5 MIPs charge) injected by IR laser**
  - Spatial resolution computed via χ^2 minimization of signal fractions observed by adjacent strips



By Torino group

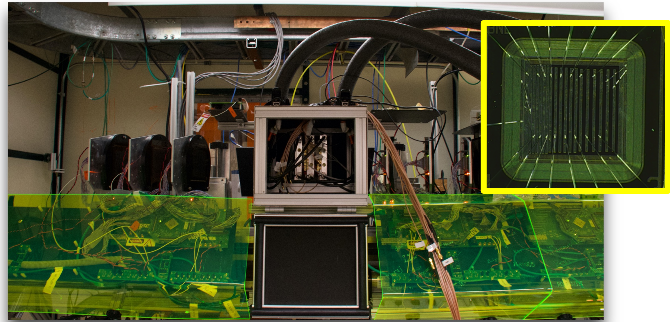
- **100 μm metal pixel, 200 μm pitch gives ~5 μm resolution without requiring very small pixels.**

- **~1 μm resolution is at reach with medium-size pixels**

Position reconstruction with AC-LGAD

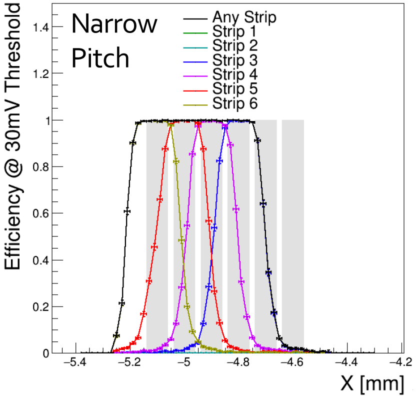
- Signal sharing can be exploited to improve space resolution beyond $1/\sqrt{12}$ by combining signal from multiple electrodes
  - Signal sharing depends on electrode geometry (pitch, gap size) and on resistivity of n^+ layer ➔ tunable
  - Sparse metallization results in lower capacitance (noise), and lowered power by limiting channel count.

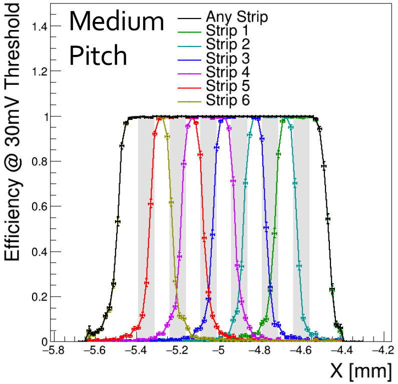
*FNAL test-beam with **120 GeV protons** and improved tracking resolution*

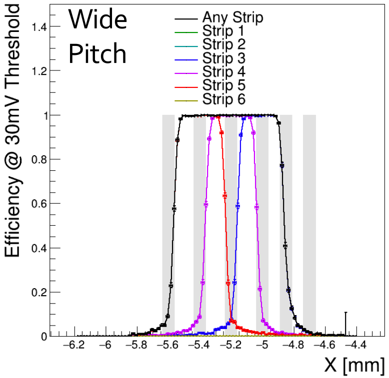


BNL strip sensor with constant metal width (80 μm) and variable pitch: 100, 150, 200 μm

<u>FNAL</u>: A. Apresyan, R. E. Heller, C. Madrid, C. Pena, S. Xie
<u>BNL</u>: W. Chen, G. D'Amen, G. Giacomini, A. Tricoli



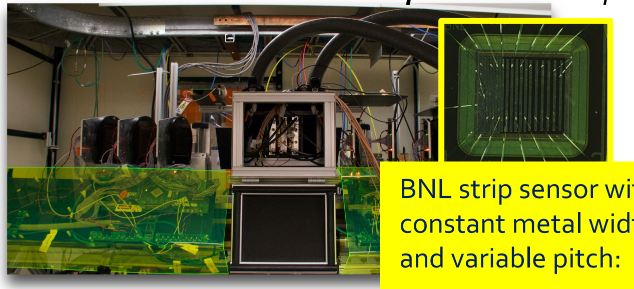




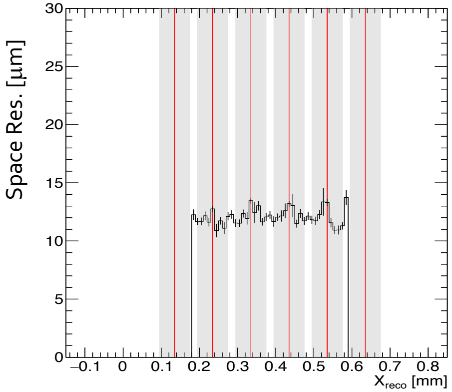
- **100% efficiency for all 3 geometries**
  - **Pitch and gap size can be adjusted to minimize number of channel and det. capacitance (thus noise)**
    - Power in electronics is an important constraint on large tracker design and depends on the no. of channels

Position & Time with AC-LGAD

*FNAL test-beam with **120 GeV protons** and improved tracking resolution*

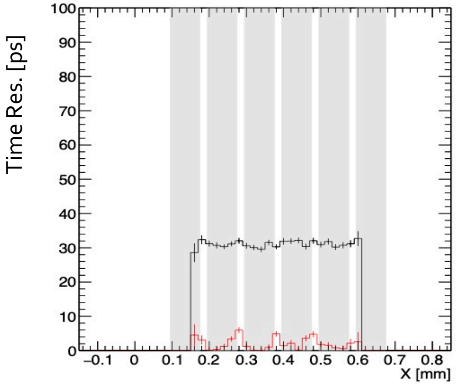


BNL strip sensor with constant metal width (80 μm) and variable pitch: 100, 150, 200 μm



<u>FNAL</u>: A. Apresyan, R. E. Heller, C. Madrid, C. Pena, S. Xie
<u>BNL</u>: W. Chen, G. D'Amen, G. Giacomini, A. Tricoli

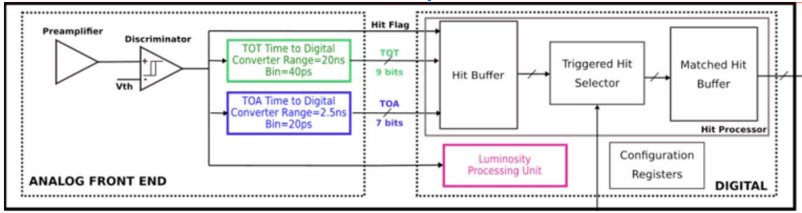
- **Space resolution: <12 μm (limited by tracker resolution) for all 3 geometries**
  - **Best space resolution in gap between electrodes**
  - **Combination of strips improves resolution on electrodes**
    - Combination of 1st and 2nd largest *amplitude* strips: parametrization of hit position vs $A_1/(A_1+A_2)$
- **Time Resolution: 30-33 ps for all 3 geometries**
  - **Best time resolution per electrode is at center of electrode**
  - **Combination of strips improves time resolution in gaps between electrodes**
    - Use amplitude-weighted average time of 1st and 2nd largest *amplitude* strips: $t_w=(1/\Sigma A^2_i)*(\Sigma A^2_i*t_i)$

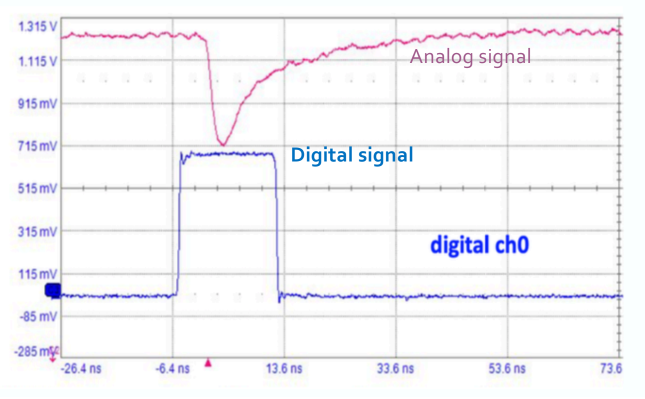


ASIC read out of AC-LGADs

- 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

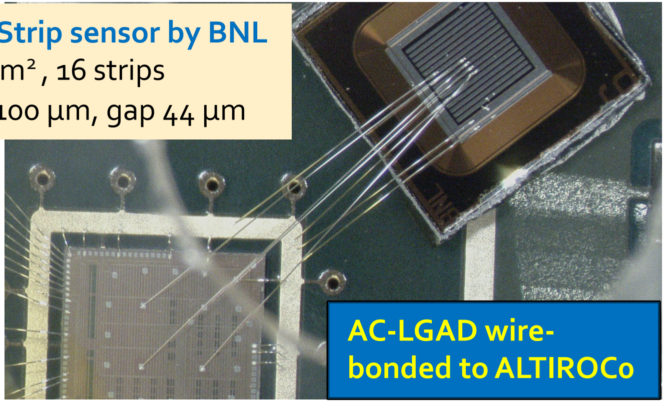
ALTIROC pixel



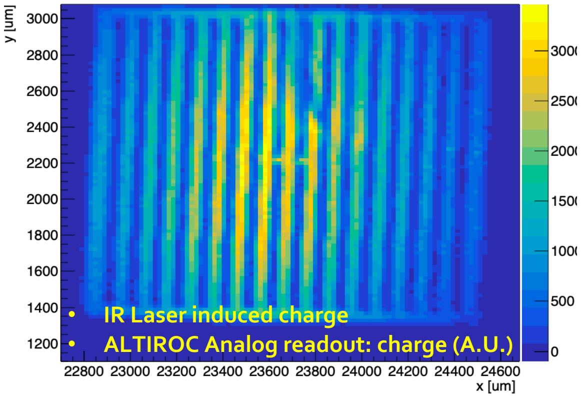


by BNL, IJCLAB, Omega team

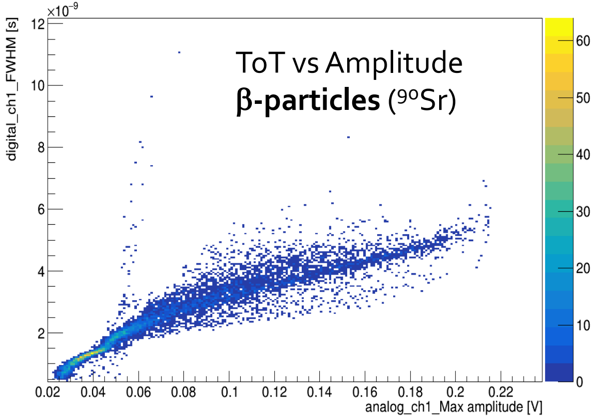
AC-LGAD Strip sensor by BNL
- 2x2 mm^2, 16 strips
- Pitch 100 µm, gap 44 µm



ASIC read out of AC-LGADs



- ➢ 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

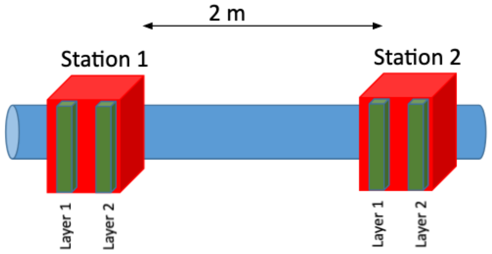


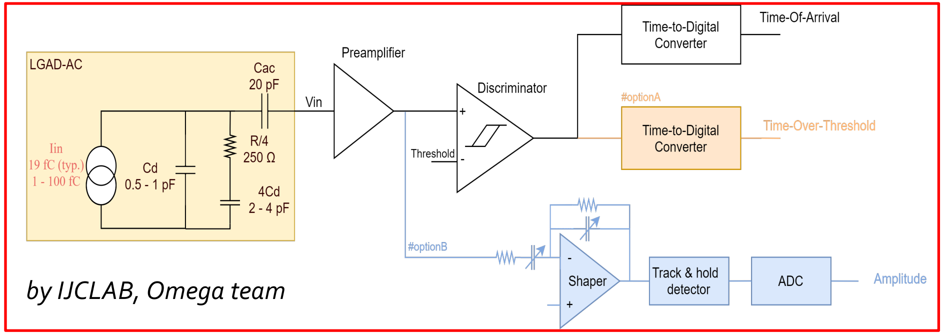
by BNL, IJCLAB, Omega team

- ➢ 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

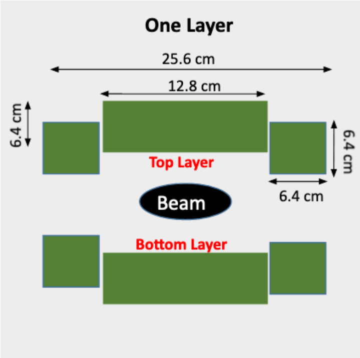
ASIC read out of AC-LGAD at EIC Roman Pots

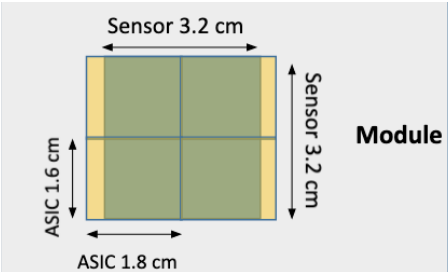
- EIC Roman Pots: aim for 500 x 500 μm² pixels with ~30 ps time resolution
  - 1310 cm² silicon, 128 modules, 512 ASICs (32x32 channels), ~500k channels
  - Signal sharing between pixels to improve time and space resolution
  - Low occupancy
  - Low radiation environment
  - Triggerless system
- ASIC design is ongoing based on ALTIROC experience
  - Option A: TDCs for ToA and ToT (a la HGTD)
  - Option B: TDC for ToA and ADC for amplitude measurements





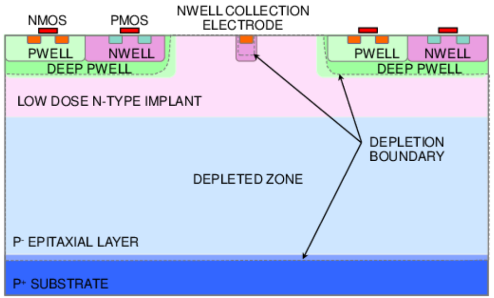
by IJCLAB, Omega team





Monolithic AC-LGADs

- Material budget and cost for large volume trackers is a concern for future collider experiments
- Monolithic Active Pixel Sensor (MAPS) are established technologies
  - Combine readout circuitry and sensing elements in a single and compact device (low mass)
  - Commercial CMOS foundries can be used
  - Cost savings, i.e. in bump-bonding, cooling
  - Used at STAR, LHC and planned to be used at EIC
  - New MAPS generation with TowerJazz (TJ) 65 nm technology

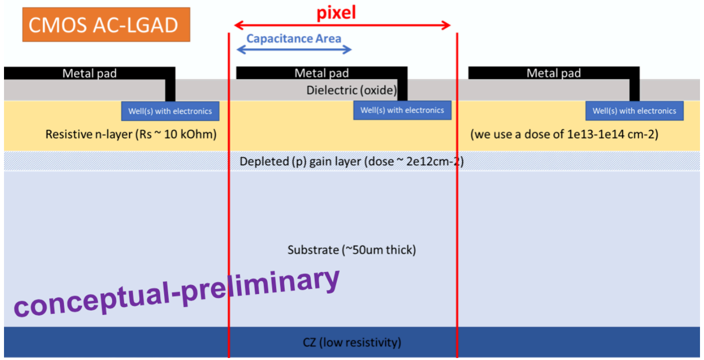


arXiv:1909.11987

Mini-Malta (DMAPS)

- TJ 180 nm CMOS
- Pixel 36.4 x 36.4 μm²
- High resistivity epitaxial p-type substrate
- Proposed for ATLAS ITk outer pixel layer

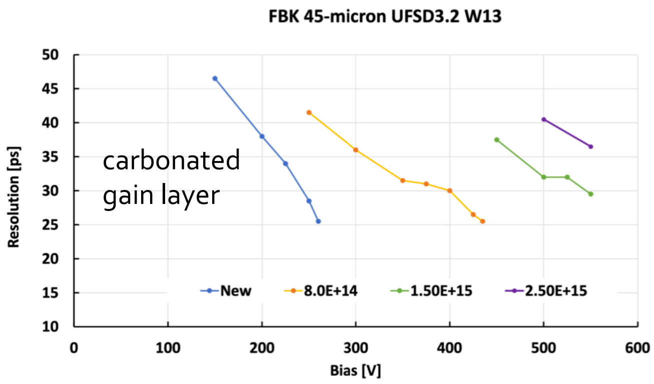
- Can we develop a Monolithic AC-LGAD?
  - Combining MAPS qualities with fast-timing capabilities
  - TowerJazz 65 nm processing as target

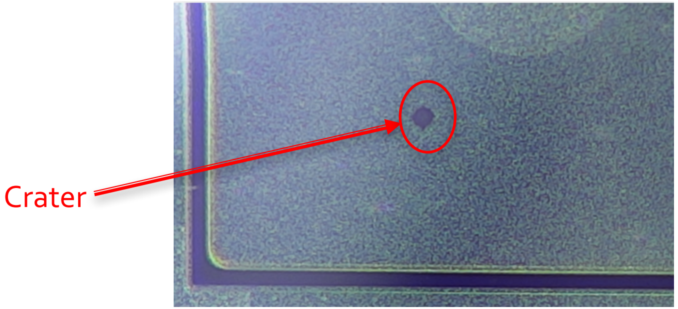


by BNL team (https://indico.fnal.gov/event/45625/)

Radiation Tolerance

- One of the biggest challenges is radiation hardness at hadron colliders
- 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 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/cm²)
    → Under investigation at FNAL testbeams
- AC-LGADs are subject to similar radiation damage as LGADs





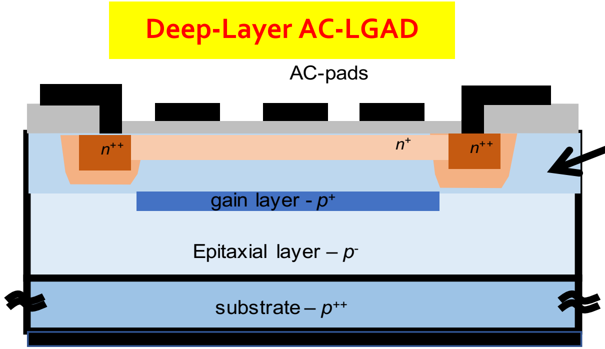
Single proton interaction with large ionization (40-50 MeV deposited energy)
- Excess charge leads to highly localized conductive path
- Large current in narrow path→ *"Single Event Burnout"*
- Critical field of ~12 V/µm

- More investigation is needed

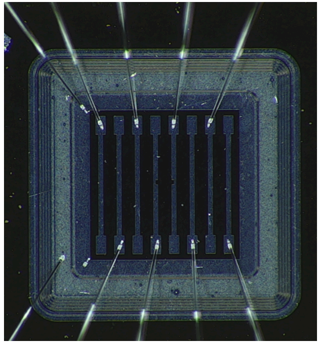
R. Heller (FNAL) at RD50 *https://indico.cern.ch/event/1029124/*

Radiation Tolerance Improvements

- **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 and narrow gain layer*
- *2^{nd} epi layer grown over the p^+ implant*
  - *FNAL idea and BNL fabrication*
  - *SBIR coll. with Cactus Material, Inc*



- Encouraging first results at FNAL test-beam

- **Significant R&D needed for future hadron colliders (~8x 10^{17} n/cm^2 !!)**
  - **Near goal: ~ 5E15 n/cm^2**
  - **Long term goal to combine gain in the bulk and in gain layer → sufficiently large signal from thin sensors**

Conclusions…

"Natural science […] describes nature exposed to our method of questioning."
W. Heisenberg, "Physics and Philosophy", 1962

- In HEP we are searching for **experimental** guidance for New Physics
- The LHC and future collider experiments aim at pushing further out the boundaries of exploration of HEP landscape
- This exploration needs **novel detectors**
- **Fast-time silicon technologies** will be the key for coping with the challenging HL-LHC environment (high radiation and 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.

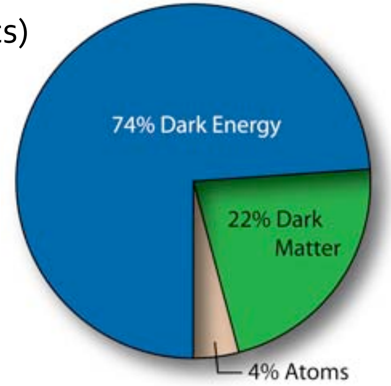
...Conclusions

- In just a few years **LGADs** have reached the level of maturity for use at the HL-LHC in timing detectors
  - 30 ps resolution with 50 μm active thickness
- LGADs are a stepping stone to develop **4D detectors**
- **AC-LGAD** is the most mature technology
  - Internal signal sharing combined with internal gain
  - 100% fill factor
  - Potential to reach <20 ps time resolution (with ~20 μm thickness) and <5 μm space resolution → **4D detectors**
  - Pixel size can be kept large (200 x 200 μm^2) to achieve 5 μm position resolution → **power saving in electronics**
  - 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**
- **Detectors have to be designed holistically from the start as all parts are interdependent:**
  - Coherent design of sensors, front-end electronics, services, cooling, power management, on/off-detector data-reduction, interplay with other subsystems etc.

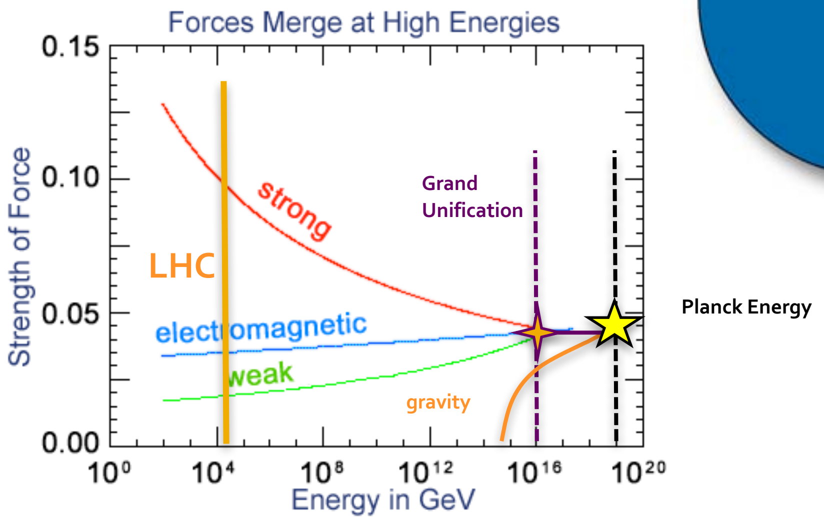
Backup

The Breaking of the SM paradigm

- Several indications that the SM is not the ultimate theory of particle physics
  - a more comprehensive theory is expected to emerge (a new revolution in particle physics)

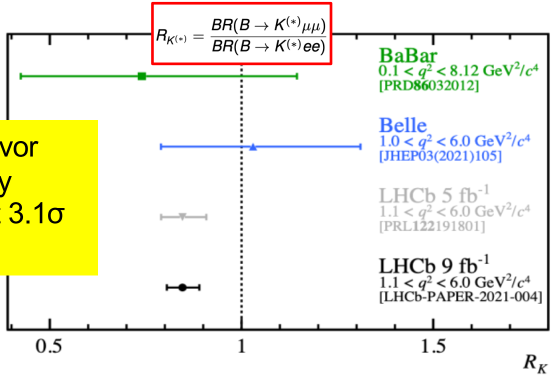


- SM only accounts for a small amount of energy of the Universe ~4%
- Apparent convergence of SM interaction couplings (strengths of forces) - Grand Unification ?
- SM does not account for gravity - unification at Planck Energy ?
- SM has many free parameters (particle masses, couplings etc.)
- Fine-tuning of Higgs mass



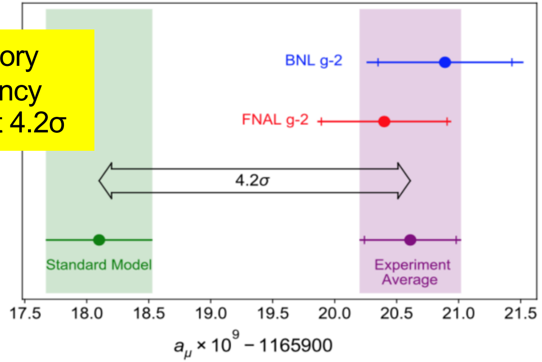
Guidance towards the next revolution

- Guidance will come from direct searches, and systematic tests of the SM paradigm.
  See *g-2 and LHCb flavor anomalies*.
  - Are these anomalies evidence of the breaking of the SM paradigm in the lepton flavor sector?



Lepton Flavor Universality violation at 3.1σ at LHCb

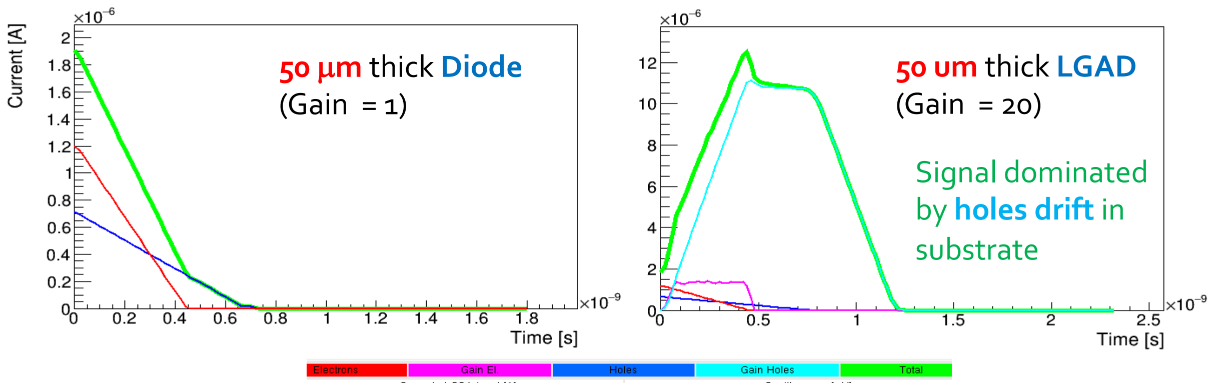
- New methodologies and technologies are critical
- HEP experiments are no longer table-top, preparation for the next generation of experiments must start decades ahead of time
- A long term vision and planning is critical
- Impact of novel technologies extends beyond HEP



Data-theory discrepancy on g-2 at 4.2σ

LGAD Signal

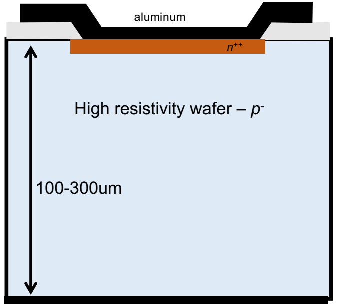
(V_{bias}= 200V)



- LGADs have larger amplitudes than Diodes
  - Higher S/N
  - Longer signal ~ 1 ns

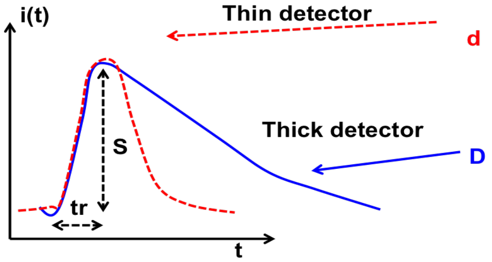
- LGAD pulse maximum is determined by the collection time of the last drifting electron
  - Determined by the detector thickness and the (saturated) drift velocity, i.e. providing a fixed time
  - At this point Gain Holes are still drifting
- So for constant weighting field & velocity, peak time is approx. independent of ionization and gain (determine tot. no. of drifting holes) and Landau fluctuations (determine clumping of ionisation)
  - Such uniformity of arrival time is very useful for time measurements

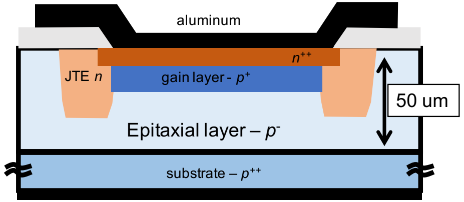
LGAD Signals

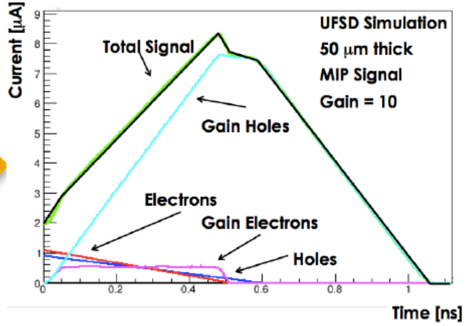


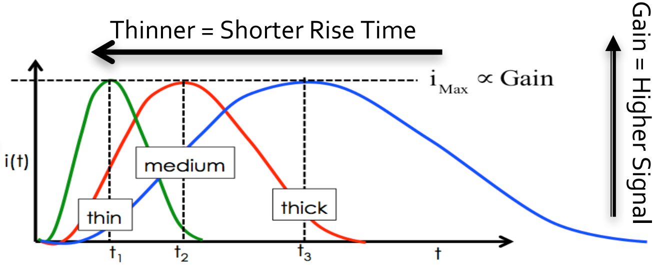
Conventional detector:

- **Rise time similar for thick and thin, same slew rate**: Ionization ~ D, weighting field ~ 1/D→ **D cancels out**.









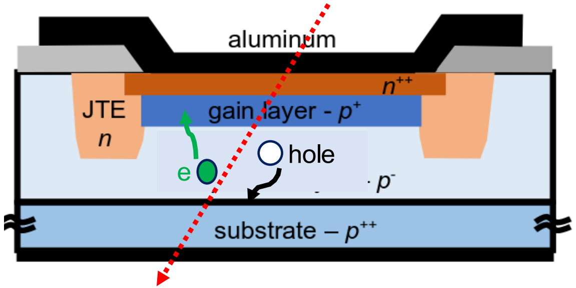
LGADs:

- **Rise time (and slew rate) are different for thick and thin detectors**: t_{Rise} ~ electron collection time ~ D
  → fast signals with thin sensors.

LGADs for Photon Detection

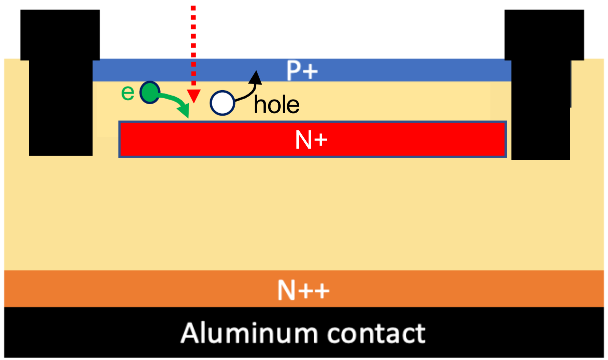
- **LGADs** have great potentials for **photon detection** thanks to signal amplification
  - Standard LGAD design aims at detecting charged particles, high energy photons (X-rays/γ), high energy electrons
  - Dedicated design for **soft X-rays** and **low-energy electrons (low-penetrating particles)**

LGAD for MIPs, X-rays

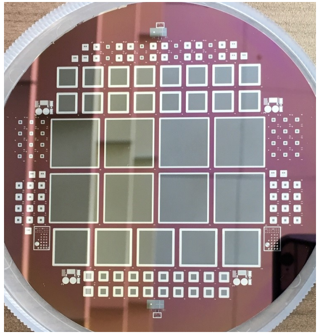


n-in-p junction (hole collection)

LGAD for low-penetrating particles



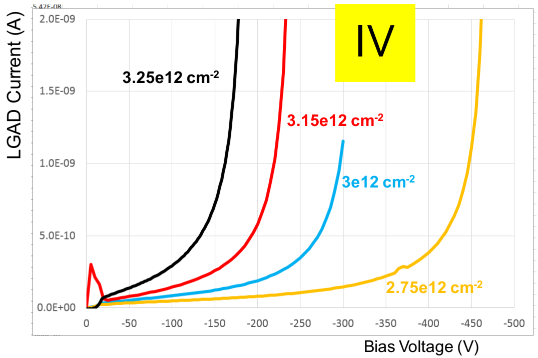
p-in-n junction (electron collection)
Pixelation possible in a double sided design

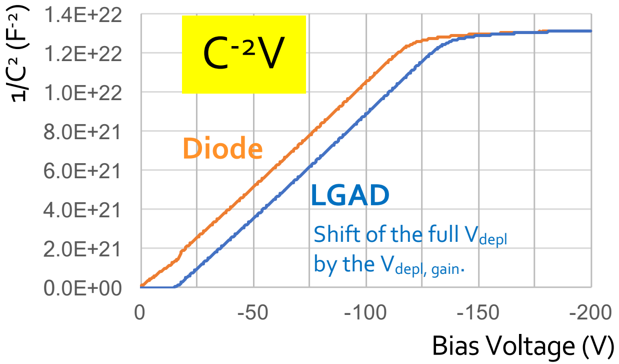


by BNL

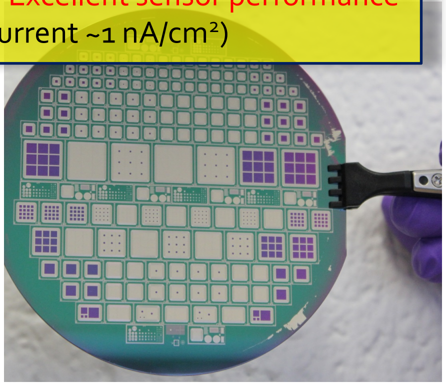
➢ **Applications to Photon Science, Photonics, and photoelectron spectroscopy**

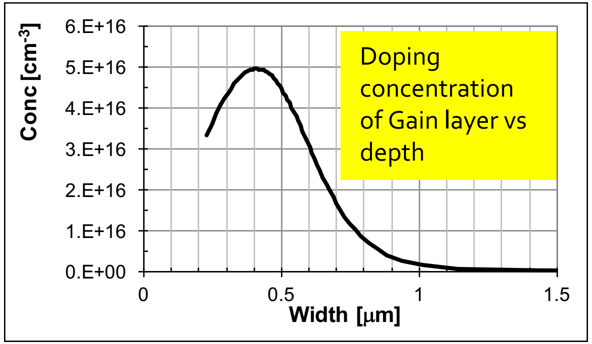
LGAD production at BNL





➔ Excellent sensor performance (current ~1 nA/cm²)



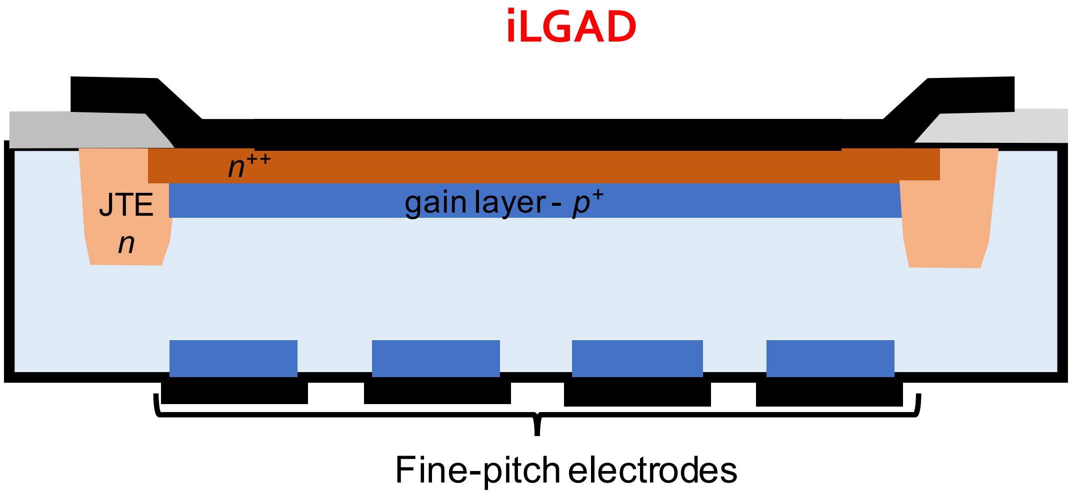


All silicon process done in BNL Instrumentation Division Class-100 Clean Room

Furnaces for dry oxidations and annealings	Double-sided mask aligner	Wet bench (HF, RCA I & II, piranha, polyetch, …)	Sputtering (Al, Al1%Si, Ti)	RTA for sintering	Laser dicing

➢ **CNM (Spain), FBK (Italy), HPK (Japan), IHEP-NDL (China) are also producing LGADs.**

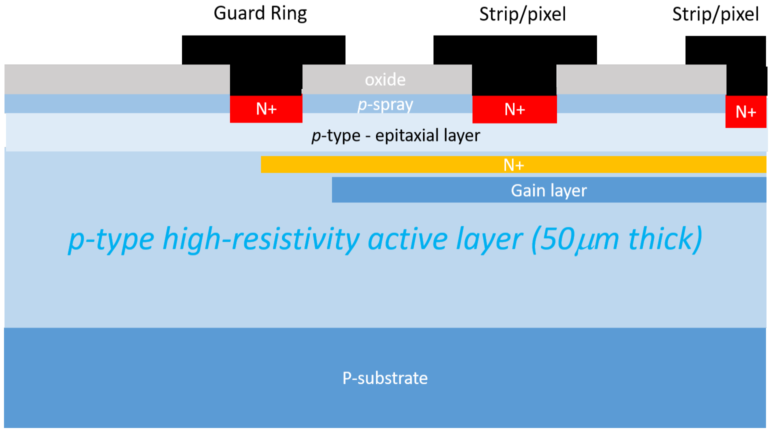
From Time (LGAD) to Time+Space (4D)



- ➢ Closely-spaced electrodes can be put on the opposite of the wafer (CNM, Spain), **but** wafers must be thick to be processed.
- → not possible to associate fast-time information on a per-pixel level
  - 100% fill factor
  - signal in single pixel (no sharing)

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

Deep-Junction LGAD

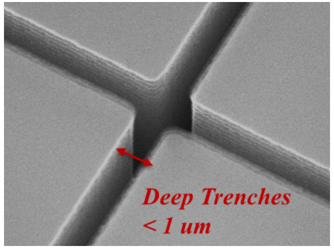


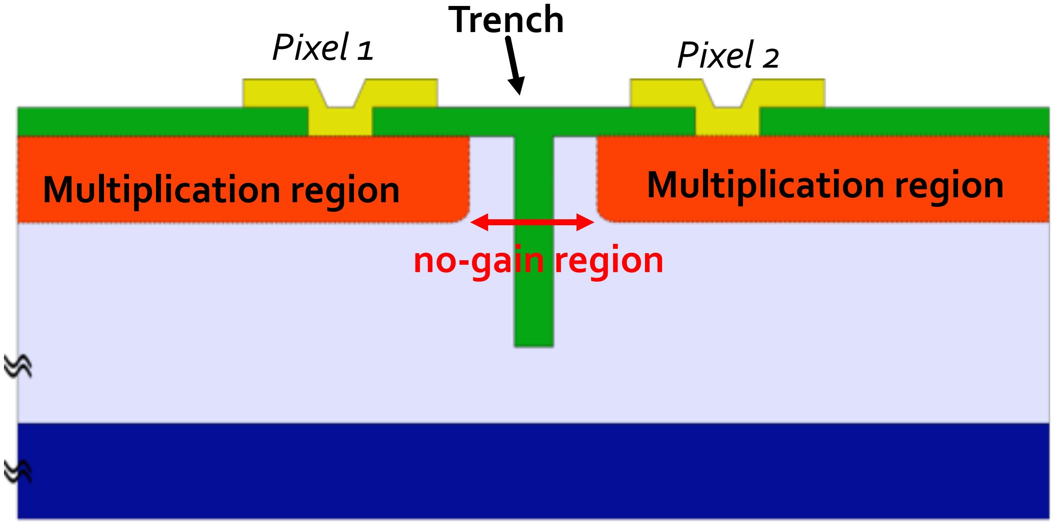
Under processing at BNL

- **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)

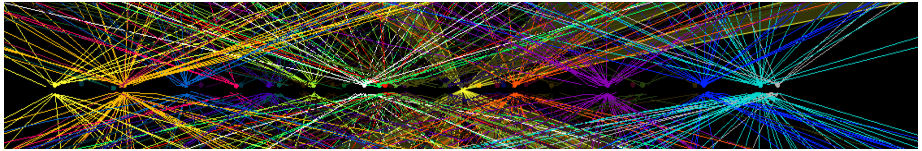
- JTE and p-stop, which limit fill-factor, are replaced by a single trench in DC-LGADs.
  - Trenches act as a drift/diffusion barrier for electrons and isolate the pixels.
  - ~100% fill factor
  - Signal in single pixel (no share)

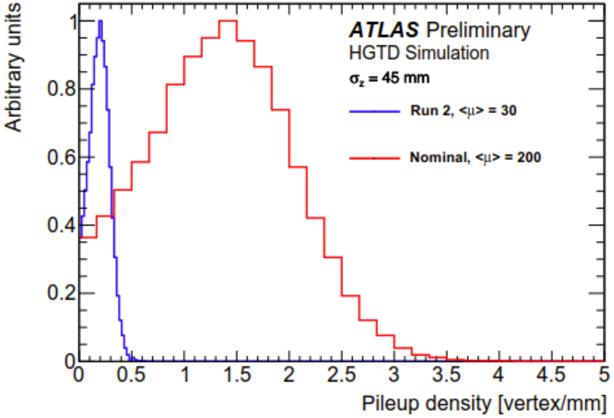
- Trenches are a few microns deep and < 1μm wide, filled with Silicon Oxide
- Fabrication process of trenches is compatible with the standard LGAD process flow.

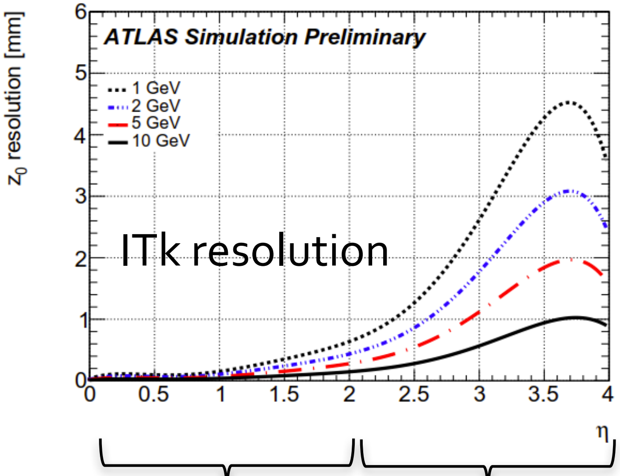
by Torino and FBK groups

Is ITk enough against 200 pileup?

- Primary collision vertices spread out with σ_z=45 mm
- Pileup will reach μ=200
  - → 1.6 vertices/mm (mean)
  - → need <0.6 mm ITk z_0 resolution





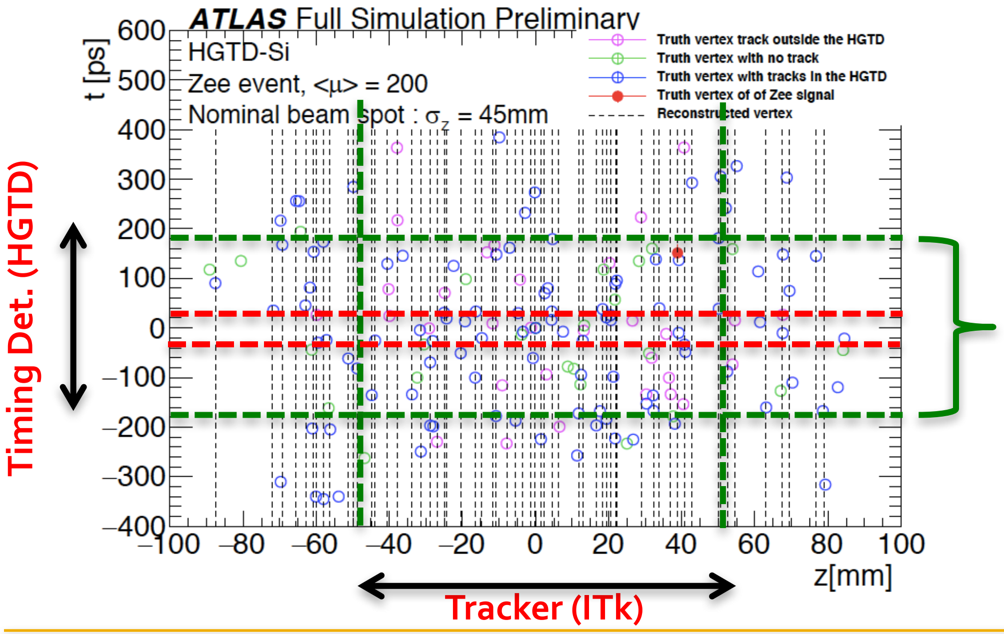


Limited by granularity
Limited by geometry

- ITk performs well up to |η|~2-2.5
- huge degradation beyond that

Pileup mitigation with Time Detector

- New technique: measure time
- ATLAS Timing Det. (HGTD) complements ITk by exploiting the time spread of collisions and reduce pile-up contamination

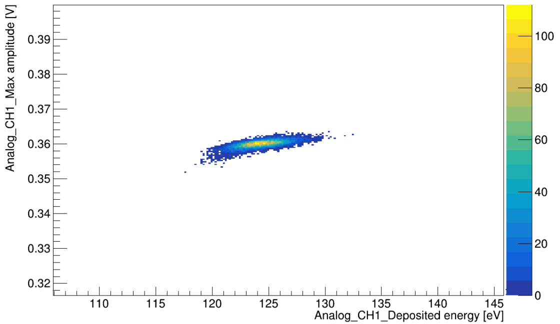


- With 30 ps time resolution
- ➔ 30/180 = 6x pile-up rejection than with tracker alone

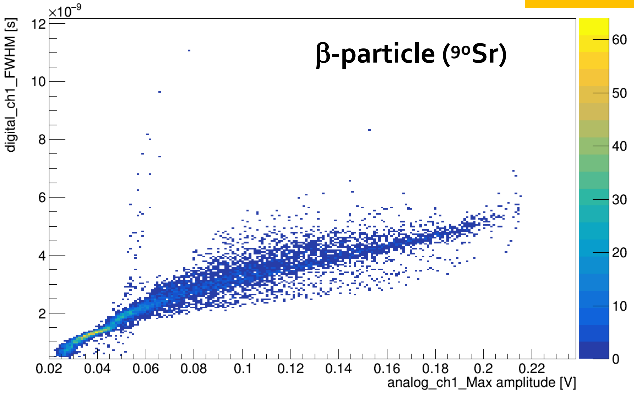
Beamspot size:
z ~50 mm
t ~175 ps

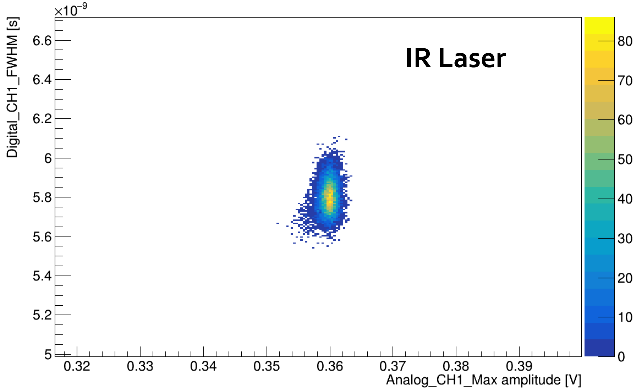
ASIC read out of AC-LGADs

- Linear correlation between Amplitude and collected charge
- 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



ToT vs Amplitude





- β-particle: Jitter & Landau contributions to signal
- Laser: only Jitter contribution
  - laser intensity corresponding to signal deposited by ~5 MIPs

by BNL, IJCLAB, Omega team

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	$< 5\%$/hour

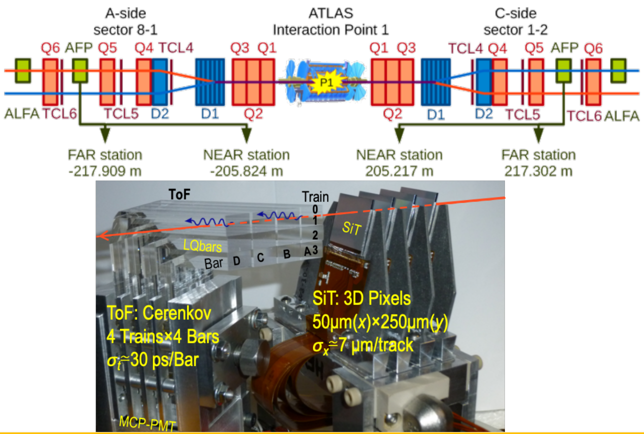
Maximum leakage current	5 μA
Single pad noise (ENC)	$< 1500\ e^- = 0.25$ fC
Cross-talk	$< 5\%$
Minimum threshold	1 fC
Threshold dispersion after tuning	10%
Maximum jitter	25 ps at 10 fC
TDC contribution	< 10 ps
Time walk contribution	< 10 ps
Dynamic range	2.5 fC–100 fC
TDC conversion time	< 25 ns
Trigger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

4D Det. for Forward Physics at Hadron Coll.

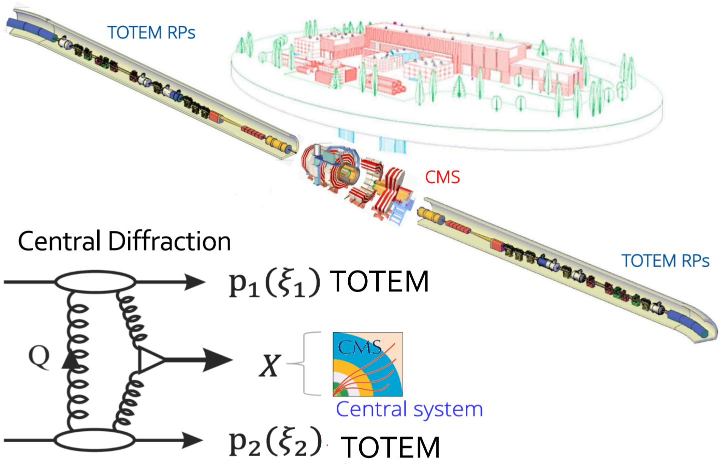
- **Forward proton tagging at hadron colliders**
  - Forward physics with proton tagging: central diffraction (e.g. exclusive jet production), exclusive γ–γ production, light-by-light scattering etc.

- **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

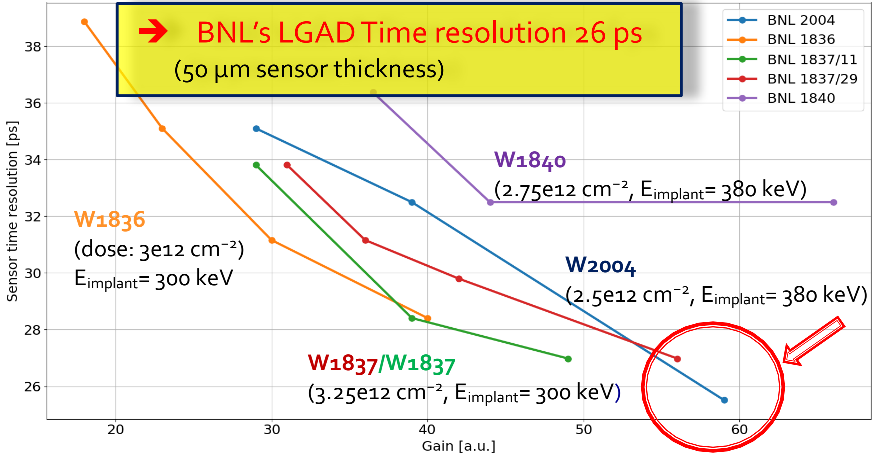


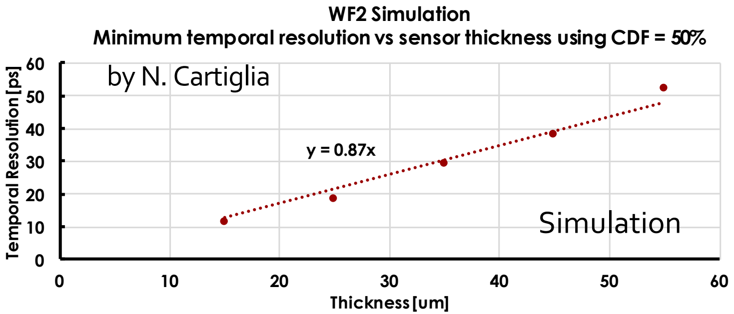
TOTEM



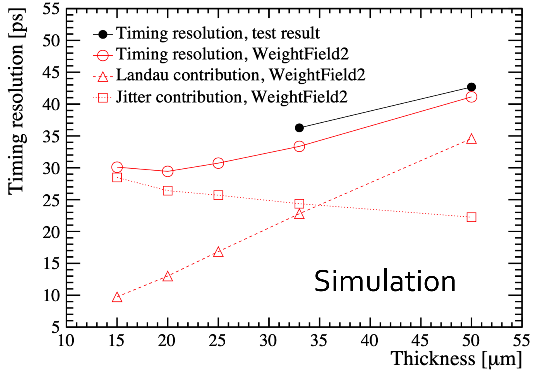
- Tracking (Pixels+Strips)
- Timing (LGADs)+SAMPIC chip

Time resolution improvement





- With 50 μm thickness, resolution levels off because of Landau fluctuations at about 30 ps → Thinner sensors
  - 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).



$$\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)}$$

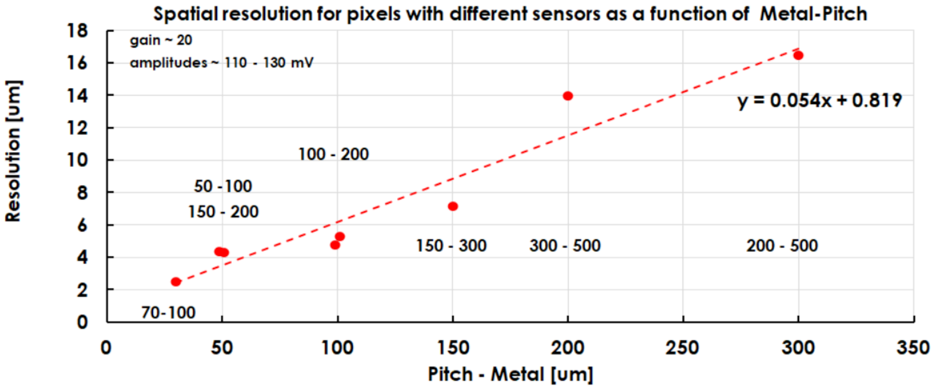
M. Li et al. (2021) doi:10.1109/TNS.2021.3097746.

- **Time resolution improves for thinner sensors!**

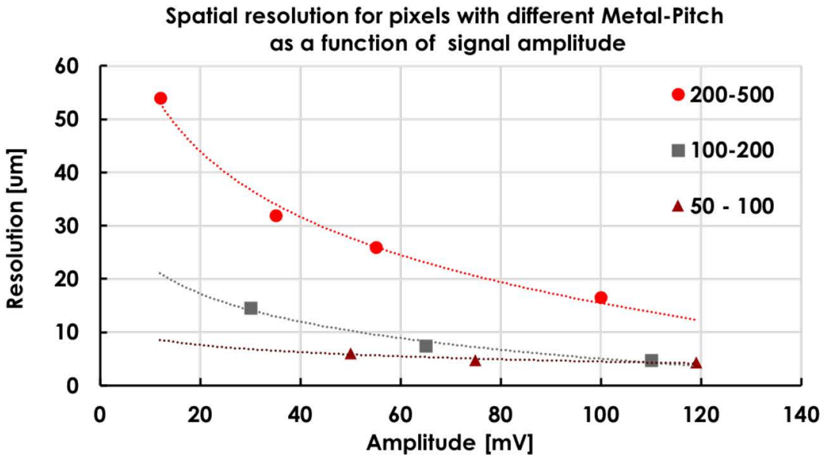
AC-LGAD's space resolution

- Position resolution is improved interpolating between several electrodes
  - E.g. 100 µm metal pixel, 200 µm pitch gives better than 10 µm resolution without requiring very small pixels.
- few µm resolution is at reach with medium-size pixels

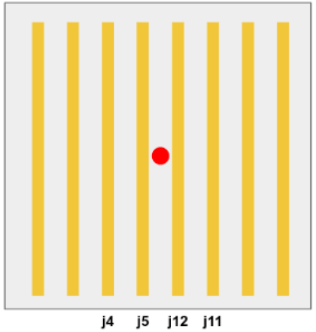
- At low signal, space resolution dominated by jitter
  - Low noise electronics needed
- Larger geometries have worse position resolution
  - Need high gain and lower n^+ resistivity to improve sharing



By Torino group



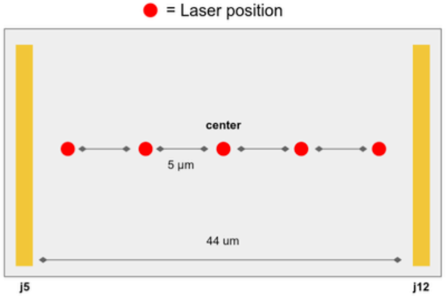
AC-LGAD's space resolution with IR laser



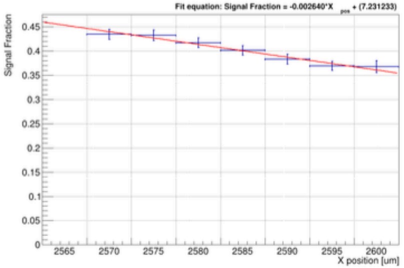
$$\chi^2 = \sum_{i=strips} \left(\frac{m^i * x + q^i - f^i}{\sigma^i} \right)^2$$

- x: laser position
- m^i, q^i: calibration params
- f^i: amplitude fraction observed by i^{th} strip

- Use data points and TCT position information (x_{TCT}) to find **linear calibration parameters** (m^i, q^i) for each strip
- Spatial resolution computed via χ^2 **minimization of signal fractions** observed by multiple strips
- Space resolution reconstructed from **difference between laser focusing position** (from TCT) **and position obtained from** χ^2 **minimization**



calibration - strip j5



by Gabriele D'Amen (BNL), PSD21, Sept '21