Time for High Luminosity – A New Detector for ATLAS

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RD50

ATLAS

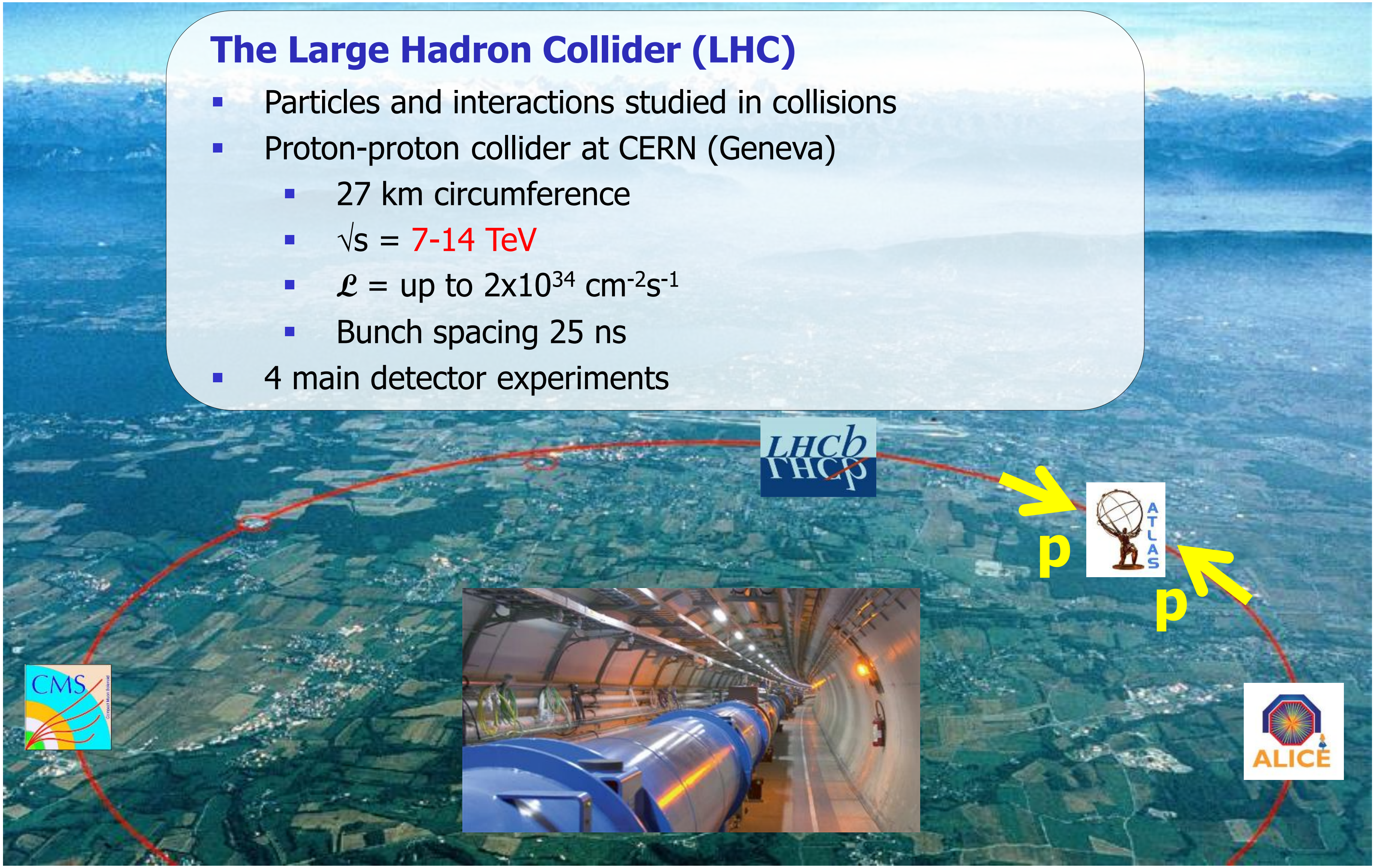
Overview

- LHC and High Luminosity upgrades
- High Granularity Timing Detector (HGTD)
  - Motivation and Concept
  - Performance and Physics Improvements
- Low Gain Avalanche Detector (LGAD)
  - Technology and Performance
- Other LGAD applications: HEP, photon science, medical
- Conclusions and Outlook

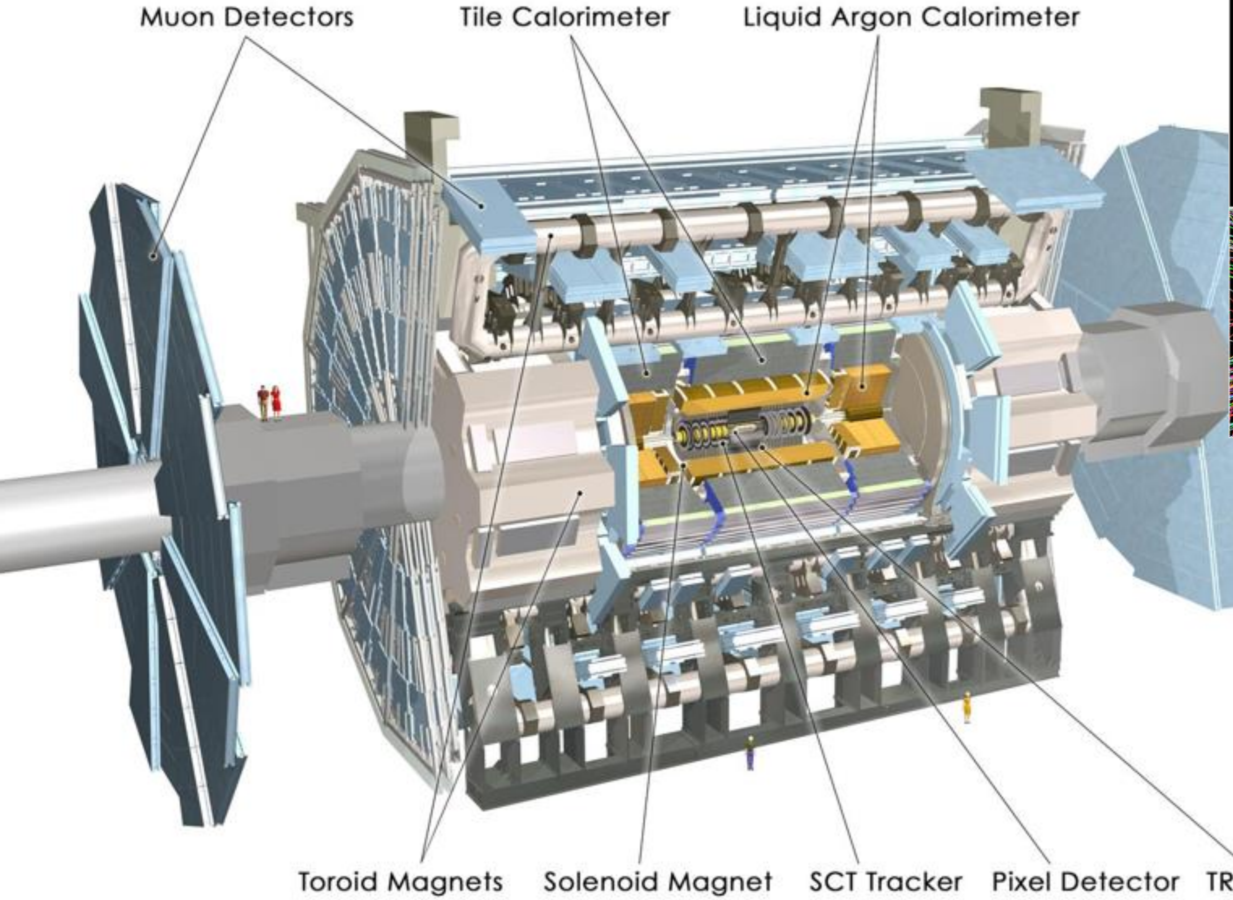
LHC Accelerator

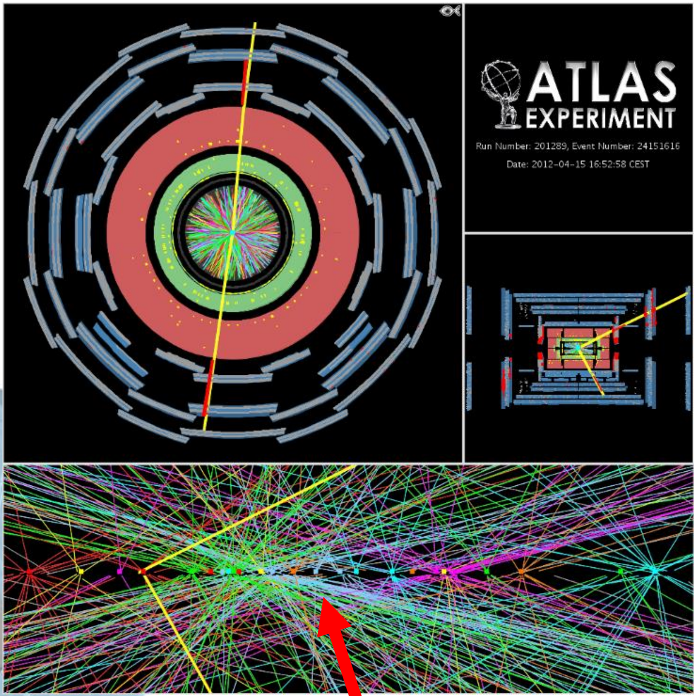
The Large Hadron Collider (LHC)

- Particles and interactions studied in collisions
- Proton-proton collider at CERN (Geneva)
  - 27 km circumference
  - $\sqrt{s}$ = 7-14 TeV
  - $\mathcal{L}$ = up to 2×10^{34} $\mathrm{cm^{-2}s^{-1}}$
  - Bunch spacing 25 ns
- 4 main detector experiments



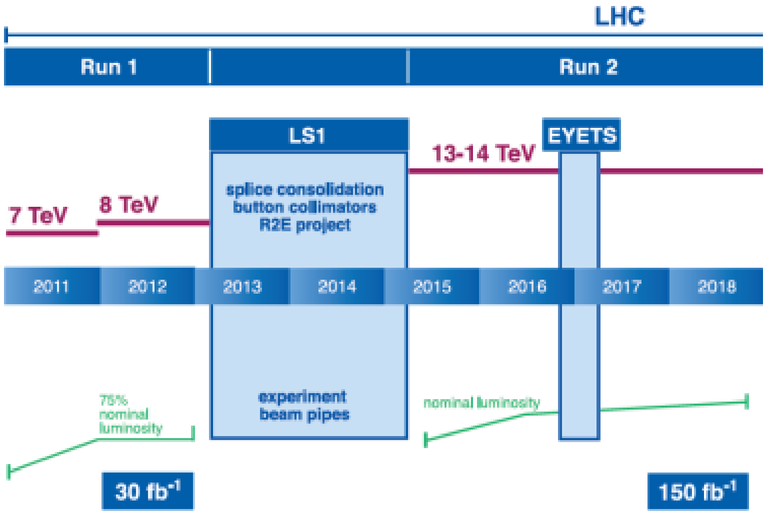
ATLAS: General Purpose Detector

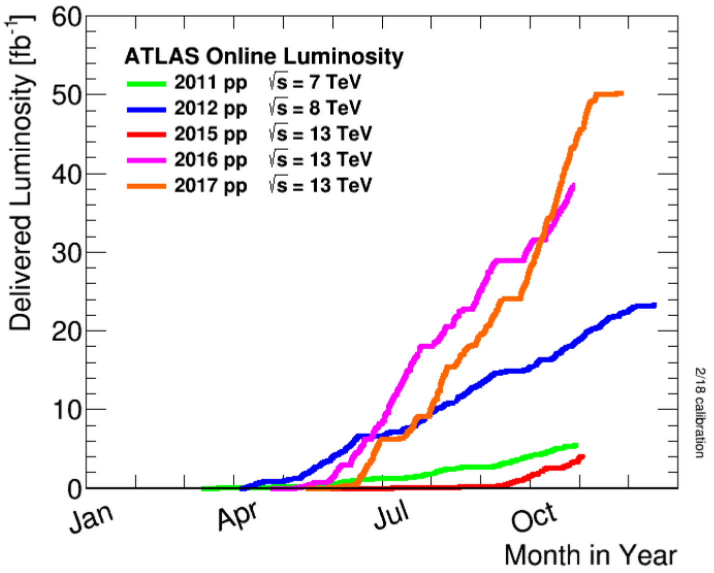




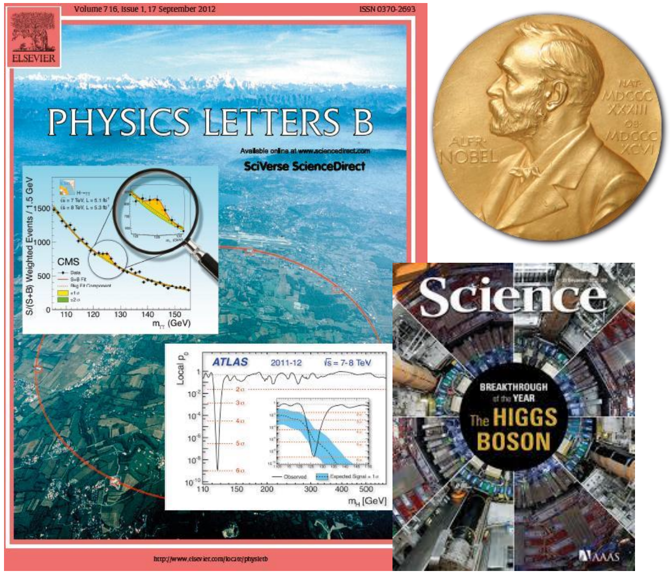
Pileup:
~50 interactions/bunch crossing

Where Are We? Outstanding Performance!

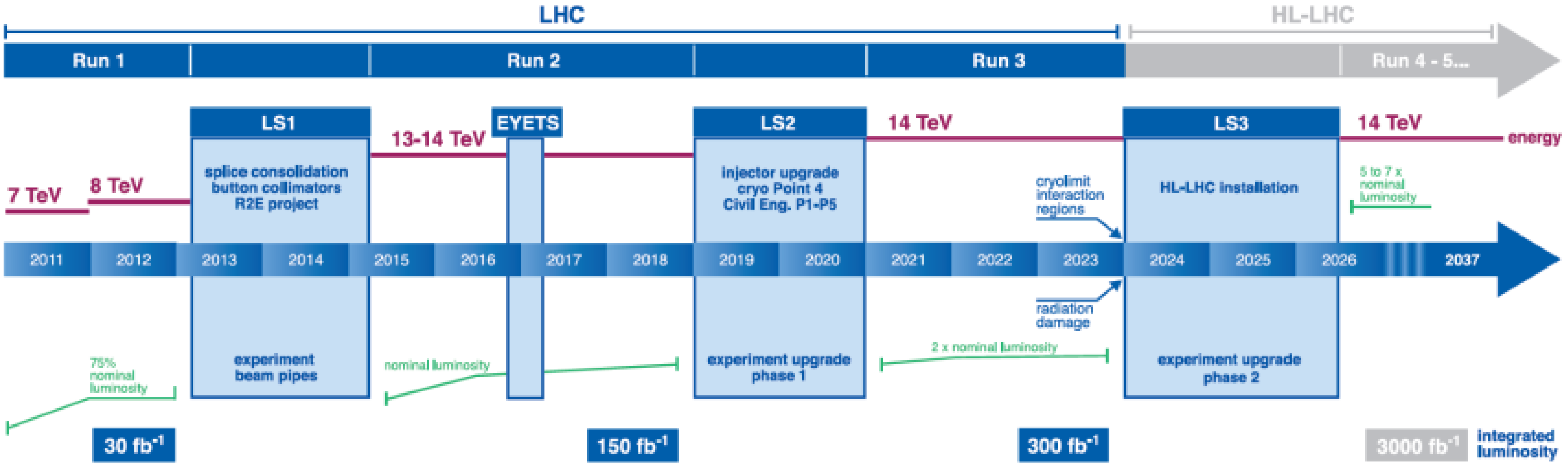




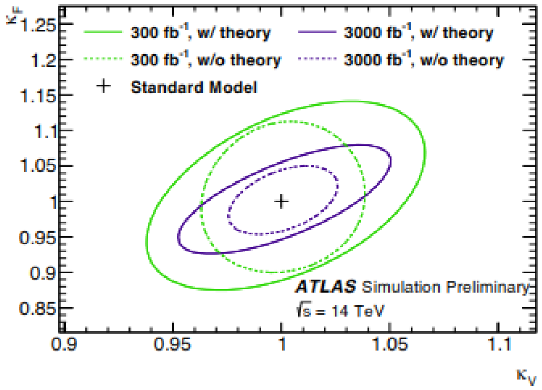
- Run 1+2 in 2011-2018
  - Energy ramp 7-13 TeV
  - Luminosity ramp up to 1.5x10^{34} cm^{-2}s^{-1}, μ~50
  - **Integrated luminosity 100 fb^{-1} now** + 60 fb^{-1} 2018
- Results
  - **Higgs discovery** 2012: m_H~125 GeV → Nobel prize!
  - Precise measurement of SM processes (always rarer!)
  - BSM searches → limits → excluding models/parameter space
  - 700 published papers each experiment ATLAS list

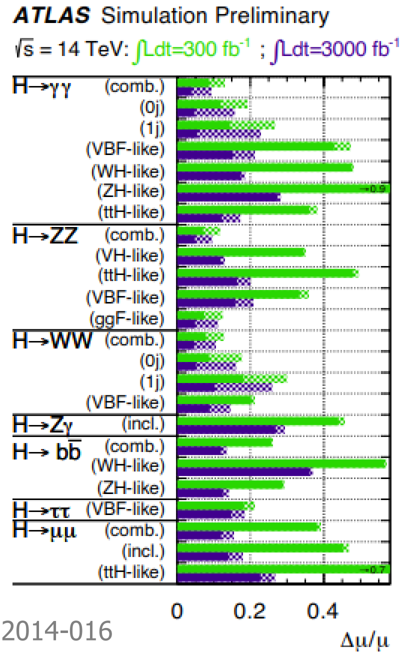


What is Next…? High Lumi!



- LHC Run 3 after LS2
  - Design energy 14 TeV
  - Instantaneous luminosity 2x10^{34} cm^{-2}s^{-1}, μ~60
  - Integrated luminosity 300 fb^{-1}
- HL-LHC upgrade after LS3 (Run 4)
  - More data → higher precision/reach
  - Instantaneous luminosity 5-7.5 x10^{34} cm^{-2}s^{-1} , μ~200
  - **Integrated luminosity 4000 fb^{-1}** (was 3000 fb^{-1})
  - **Major upgrade** of accelerator and experiments needed!



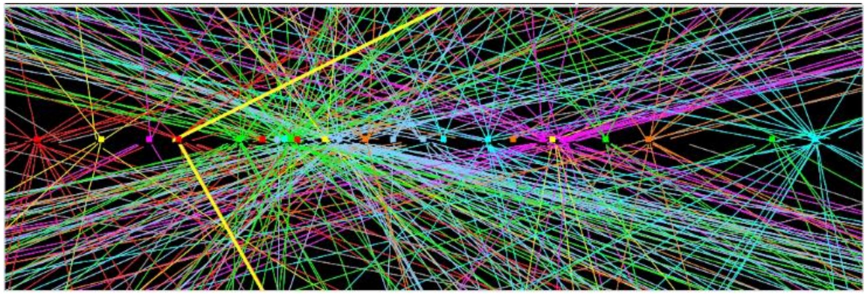


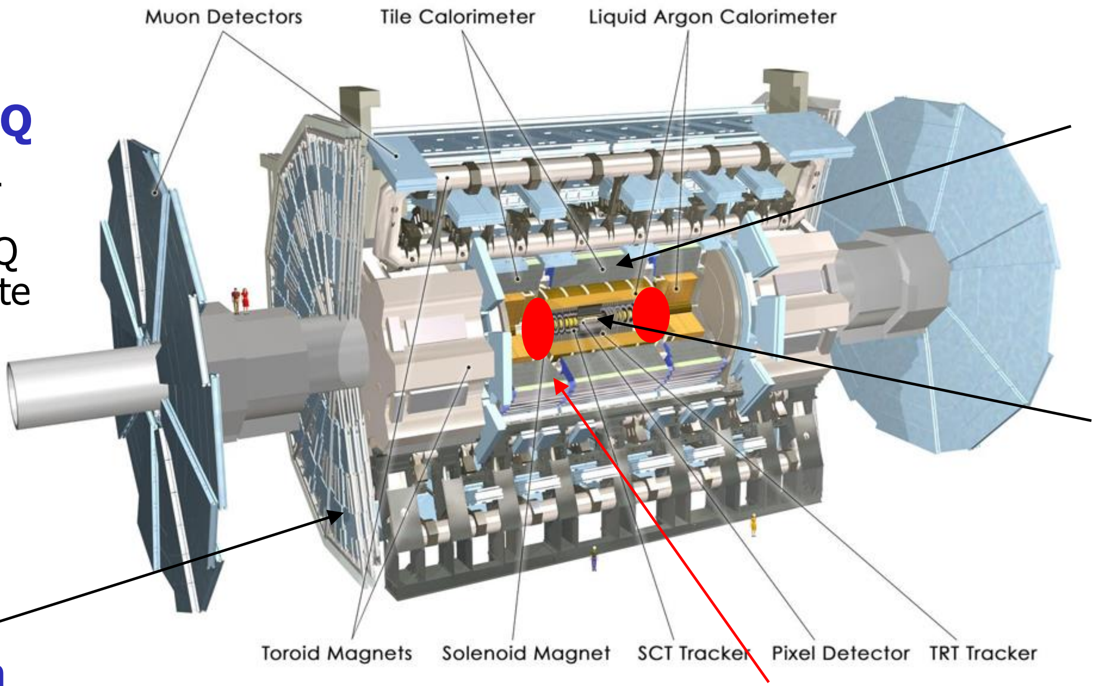
Higgs couplings/ signal strengths: x2 better

ATL-PHYS-PUB-2014-016

Price to Pay… Upgrade!

- **More pileup: μ~200**
  → increased particle density
  → higher data rate
  → higher occupancy
  → higher radiation damage





Trigger + DAQ

- Track trigger
- Upgrade DAQ for higher rate

Calorimeters

- Upgrade electronics

Inner Tracker

- Full replacement: all-Si extended to |η|=4

Muon System

- New trigger chambers in barrel

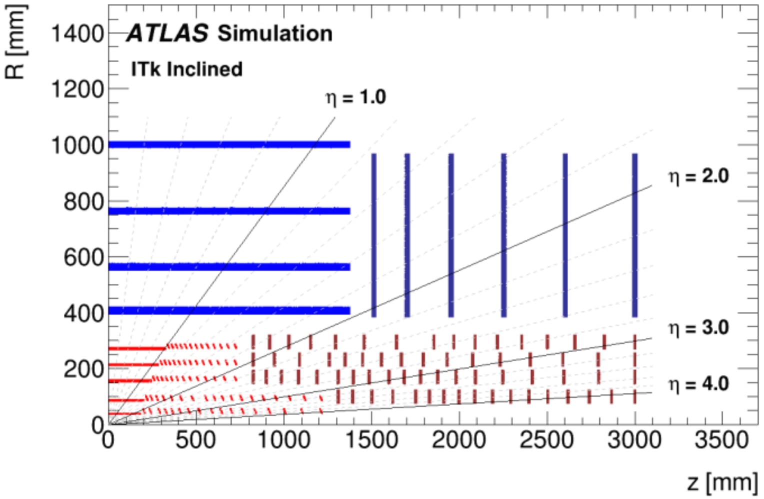
New

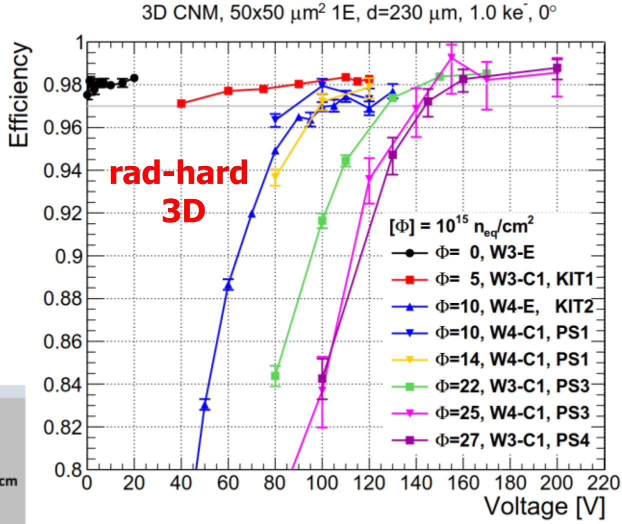
High Granularity Timing Detector

- Si timing for pileup rejection, 2.4<|η|<4

Biggest Project: Inner Tracker (ITk)

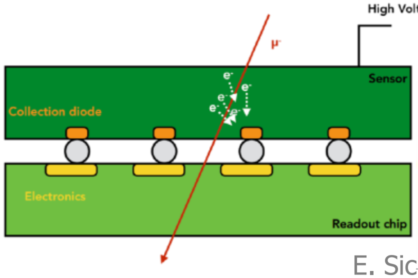
- **All-Silicon** 200 m²: Strips (outer) + Pixel (inner)
- Extended up to $|\eta|=4$
- Higher granularity
  - Pixel: 50x400 μm² → 50x50 μm² (or 25x100)
  - New FE chip in 65 nm (RD53A prototype)
- Optimised cost + radiation hardness
  → **new technologies!**
  - Intermediate layers: Thin planar hybrid detectors (100-150 μm)
  - Inner pixel layer: 3D sensors → rad-hard up to 3e16 n_{eq}/cm^2
  - Outer pixel layer: Possibly monolithic CMOS (low cost)



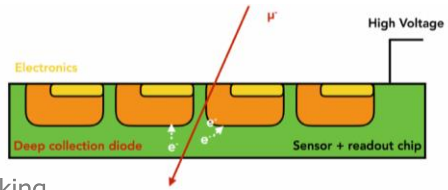


J. Lange et al., 13th Trento Workshop 2018, publ. in prep.

Planar hybrid

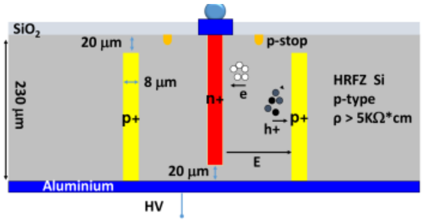


Monolithic CMOS



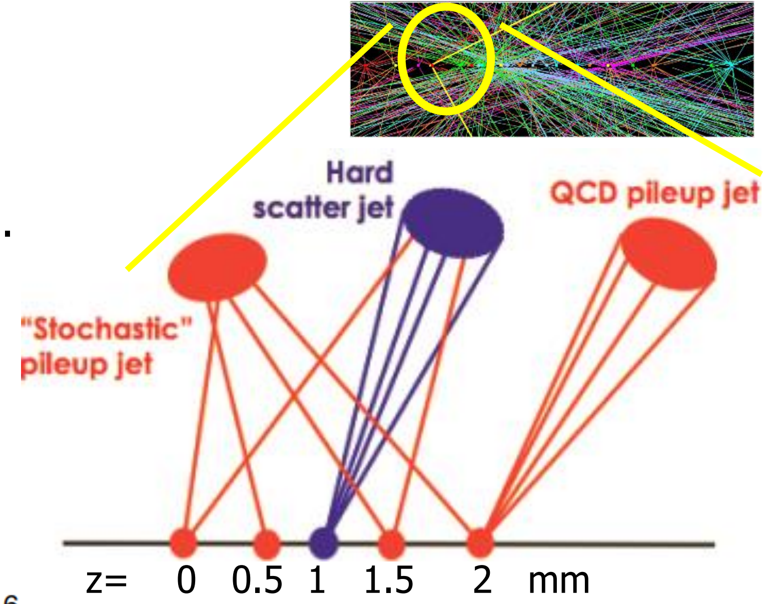
E. Sicking

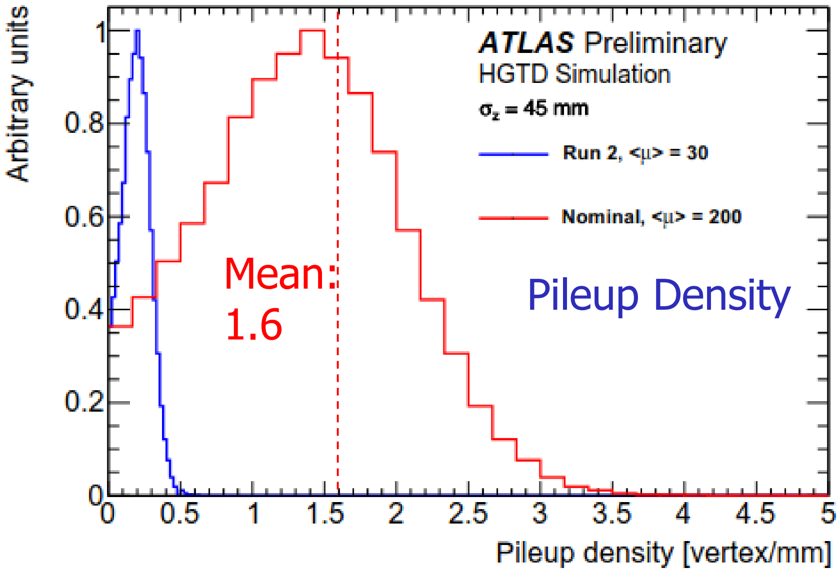
3D hybrid

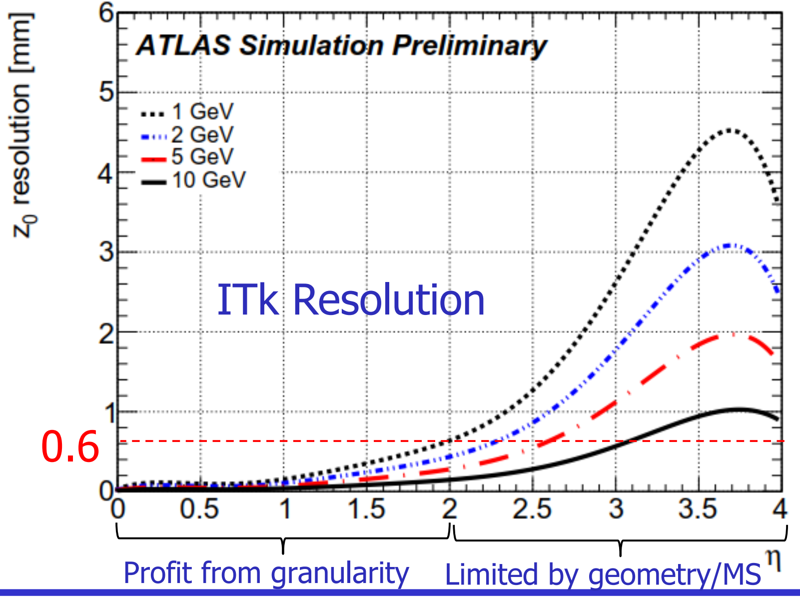


Is That Enough against 200 Pileups?

- Need to identify if particles or jets come from vertex of interest (hard scattering)
- MisID affects reconstruction performance:
  jet ID and energy, $E_{T,mis}$, b-tagging, lepton isolation, ...
- Vertices spread out with σ_z=45 mm + μ=200
  → 1.6 vertices/mm (mean)
  → need <0.6 mm ITk z_0 resolution
- **ITk performs well up to |η|~2-2.5, huge degradation beyond**

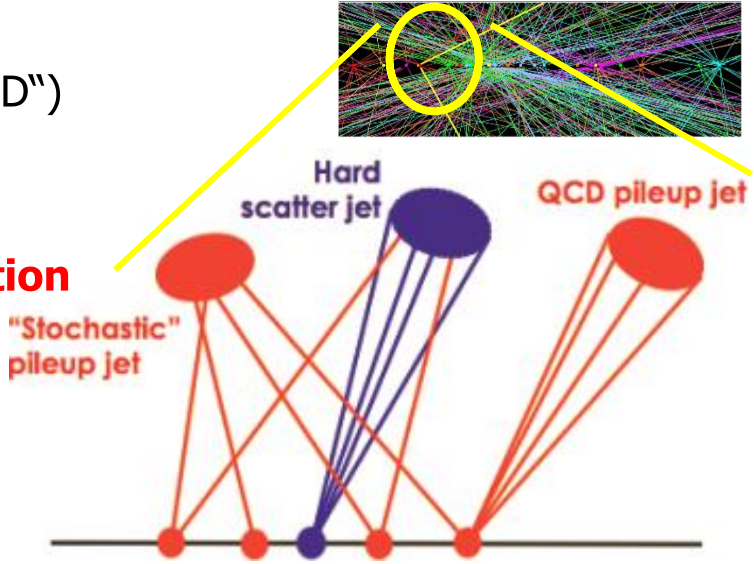




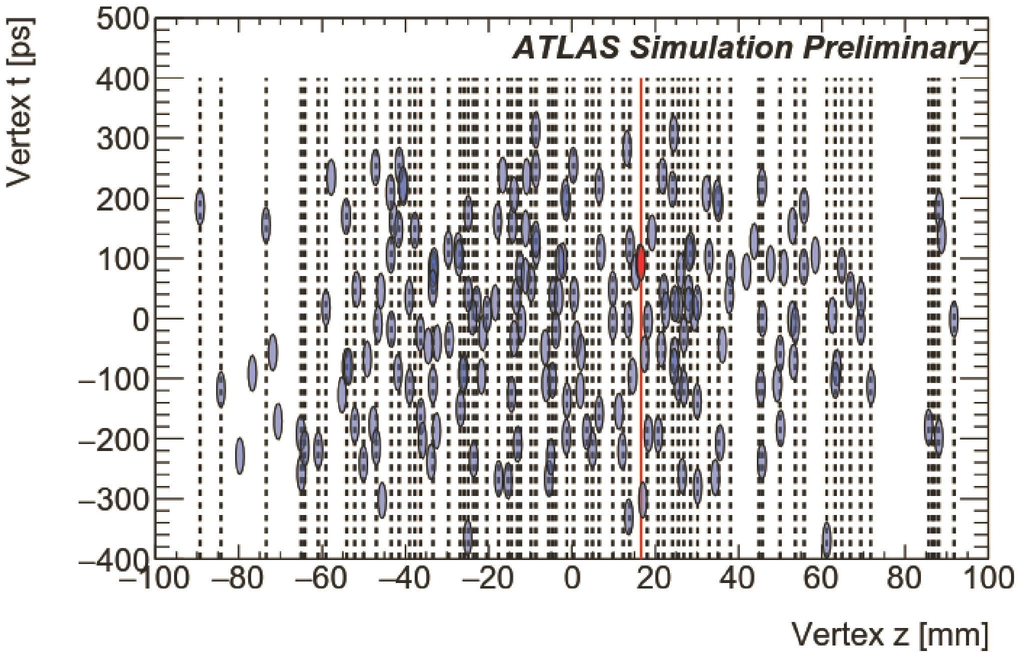


Time for Pileup!

- New technique:
  Measure **time** of each particle in addition to space („4D")
- Vertices spread out with σ_t=175 ps
  → time is independent vertex property
  → 30 ps resolution gives additional ~x6 **pileup rejection**
- Especially crucial in forward region where ITk degrades
  → build timing detector at high |η|



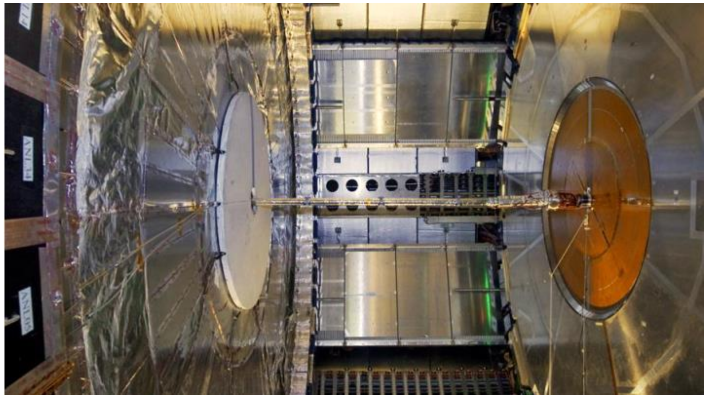
z= 0 0.5 1 1.5 2 mm
t= -200 40 100 300 -50 ps

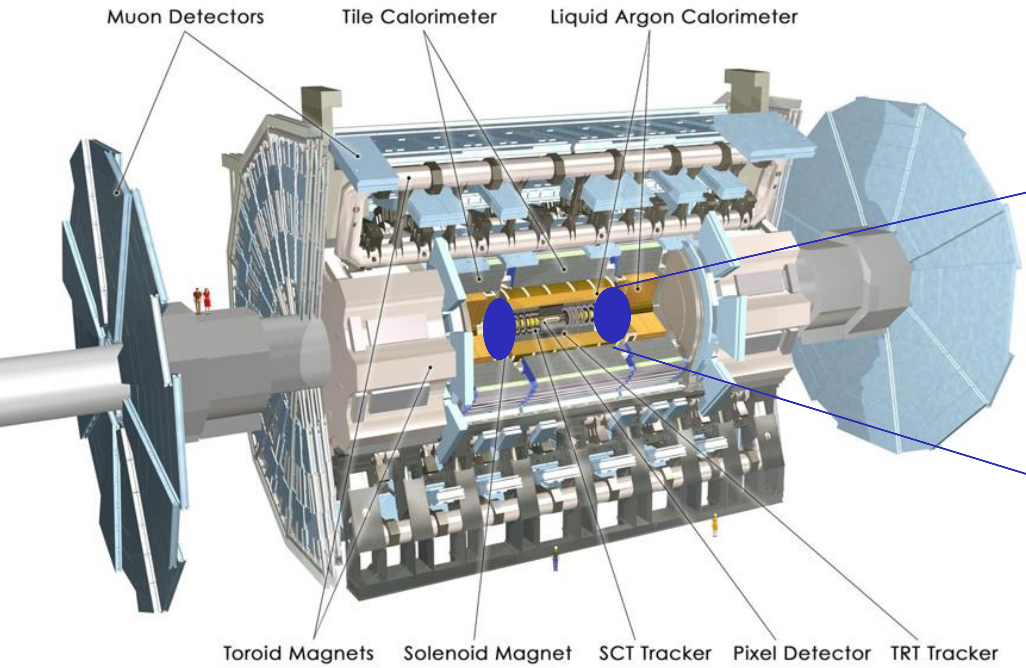


High Granularity Timing Detector (HGTD)

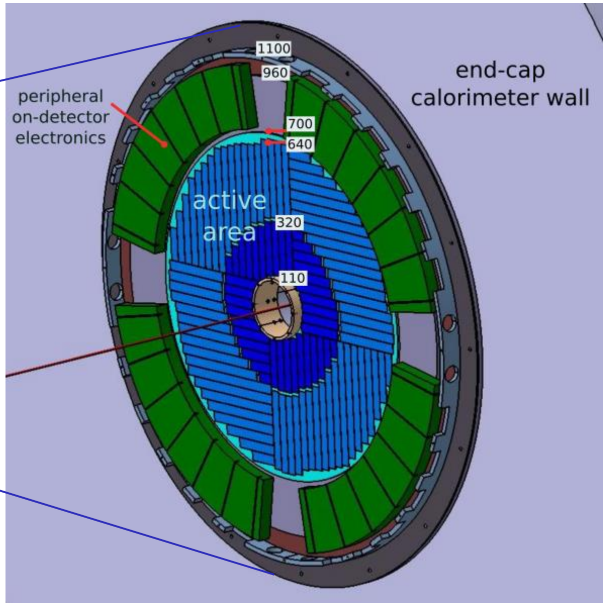
- **Forward region: 2.4 < |η| < 4.0**
- Replaces Minimum Bias Trigger Scintillator (MBTS)
- Only 7.5 cm space in z at ±3.5 m
- **Goal: σ_t=30 ps /MIP**
- 2-3 layers of Silicon LGAD, 1.3x1.3 mm² granularity, 6 m² Si
- Radiation hardness: 4e15 n_{eq}/cm² (replace inner region)
- Similar Endcap Timing Layer (ETL) for CMS

MBTS now





HGTD 2026

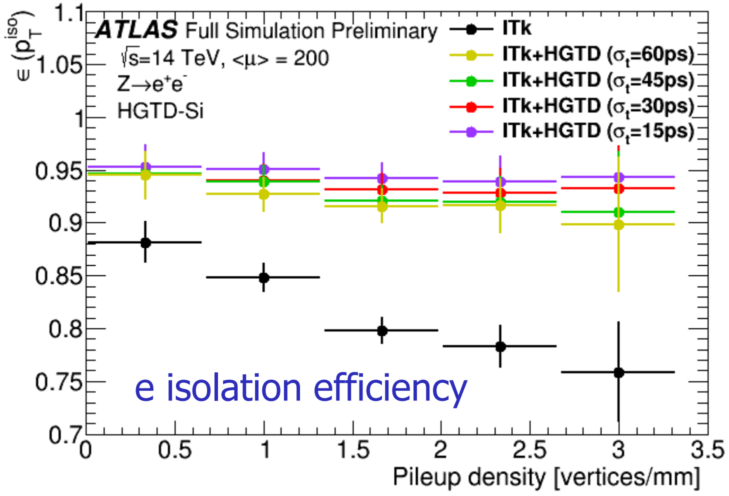


HGTD Performance Improvements

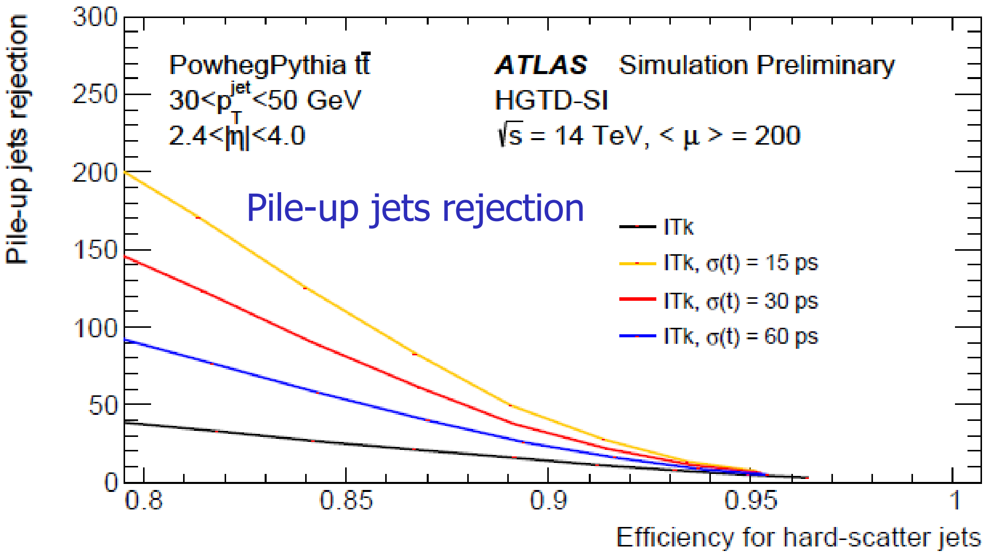
- **Big improvements of HGTD wrt. ITk-only** for
  - Pileup jet rejection
  - B-tagging (light-jet mistag)
  - Lepton isolation

→ brings back forward performance to central level

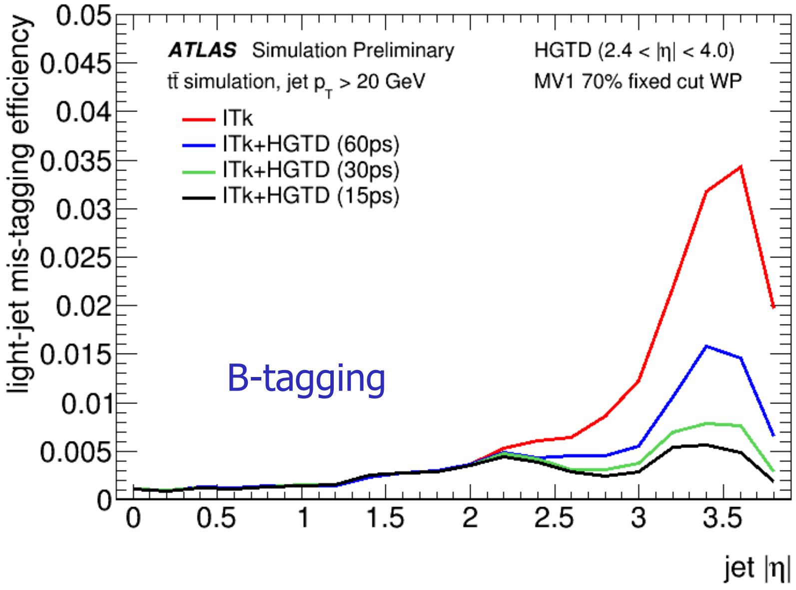
- No big further improvement for better than 30 ps



e isolation efficiency



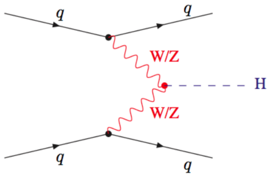
Pile-up jets rejection

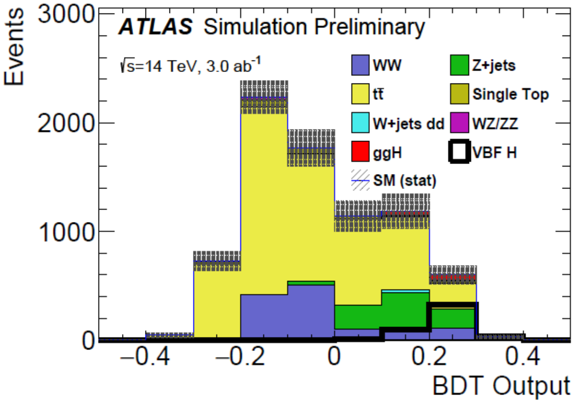


B-tagging

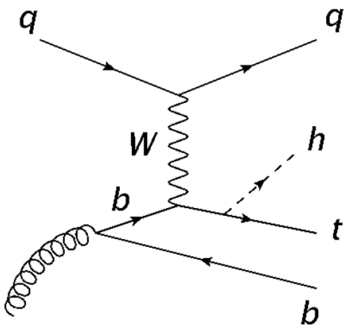
HGTD Physics Improvements

- **Better object performance/pileup rejection translates into physics improvements**
- Higgs production via vector-boson fusion (VBF)
  - E.g. VBF qqH → qqWW*
  - Forward jets → profits from forward pileup rejection
  - tt background rejection needs forward b-tagging
  - HGTD: 8% relative improvement in signal strength precision
  - VBF H→ττ, H→invisi. also studied with promising prospects





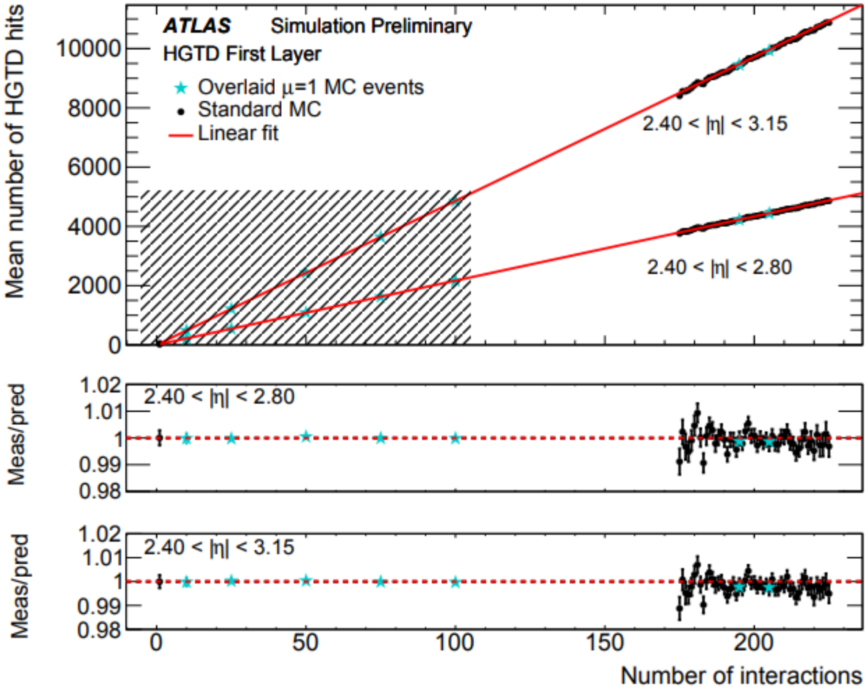
- tH with H → bb
  - Sensitive to top-Yukawa coupling
  - Light forward jet, a lot of b jets
    → profits from fwd pileup rejection and b-tagging improvement
  - HGTD: 11% relative improvement in signal significance



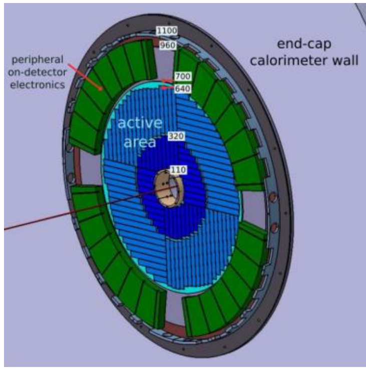
- Weak mixing angle $\sin^2\theta_{eff}$
  - HGTD: 5-10% relative improvement (due to e isolation)
- Further analyses studied
- Not yet fully incorporated all benefits from timing in analyses
  - Expected to be better exploited in the future

Luminosity and Trigger Capabilities

- Luminosity
  - Traditional luminometers challenged by high occupancies (saturation)
  - HGTD: High granularity → low occupancy
    - Count HGTD hits: linear with μ, i.e. luminosity
  - Fast+short signals → online bunch-per-bunch luminosity at 40 MHz



- Trigger at Level-0
  - Online estimate of μ for more precise pileup subtraction at trigger level
    (e.g. offset jet p_T correction)
    → could benefit all jets, not only forward
  - HGTD can be used as minimum bias trigger for low-μ runs (in fact it replaces MBTS!)



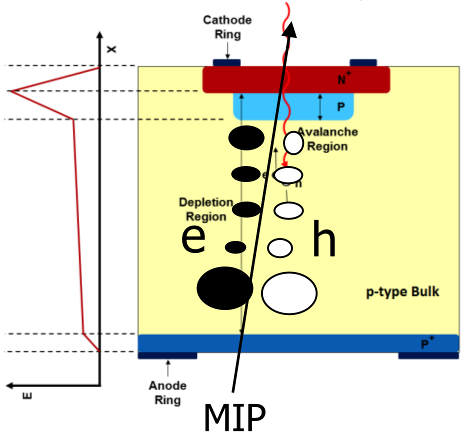
All physics analyses would profit (not only forward)!

How to Do Good Timing?

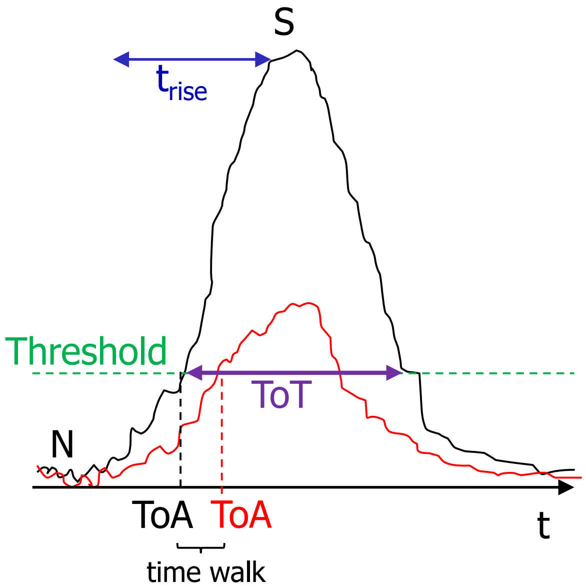
- Need a signal
  - Light based:
    Cherenkov, scintillator
  - Ionisation based:
    gas, diamond, silicon: standard planar, 3D, with gain (APD/LGAD)

Silicon Diode

Reversely biased p-n junction

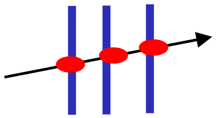


- Time measurement = threshold crossing („Time of Arrival“)
  - Uncertainties from fluctuations $\sigma_{\text{det}}^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TW}}^2 + \sigma_{\text{TDC}}^2$
  - For best resolution need to have
    - Low jitter: High S/N, short rise time $\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)}$
    - Fast+low noise electronics, precise digitiser (TDC or oscilloscope), stable clock
    - Time walk correction: Constant Fraction Discrimination (CFD) or Amplitude/ToT correction



- Multiple measurements improve single-hit resolution:

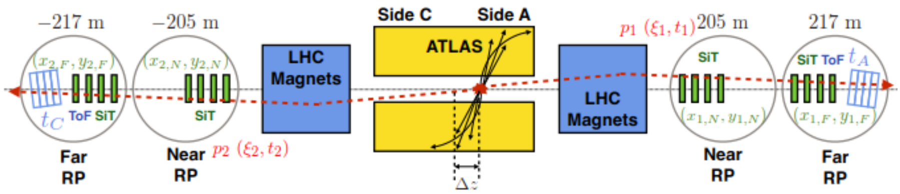
$\sigma_{N_{\text{layers}}} = \sigma_{\text{single}}/\sqrt{N_{\text{layers}}}$



Existing Fast Timing Detectors

- Forward Detectors: AFP + CT-PPS
  - Involvements of SBU, IFAE, UTA, Czech, Alberta,…
  - Measures intact forward p for diffractive physics
  - Need 10-20 ps for pile-up removal via Time-of-Flight of both p
  - AFP: Quartz-Cherenkov + MCP-PMT + PA + CFD + HPTDC → **20 ps**
  - CT-PPS: Diamond+PA+NINO+HPTDC → **80 ps**

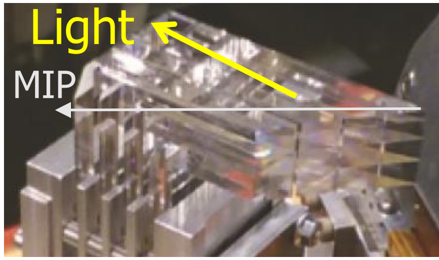
    V. Sola et al., 13th Trento Workshop 2018



I. Lopez Paz, PhD

L. Chytka, Opt. Ex. Vol. 26 No. 7 8028 (2018)
J. Lange et al., JINST 11 (2016) P09005

AFP ToF: Quartz

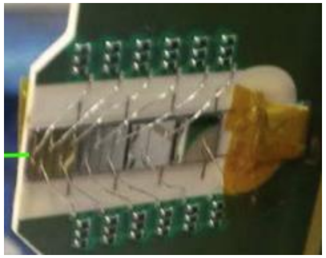


- NA62 Gigatracker
  - Measures rare kaon decays at CERN SPS (fixed target)
  - Standard planar Si pixel+TDCpix chip → **150 ps**

    G. A. Rinella et al., JINST 10 (2015) P12016

NA62 Gigatracker

CT-PPS ToF: Diamond



- R&D
  - Straight Quartz bar + SiPM → **10 ps**

    M. Albrow et al., JINST 7 (2012) P10027
  - Quartz window+MCP-PMT → **5 ps**

    M. Centis Vignali et al., RD50 Workshop 2016
  - Micromegas → **25 ps**

    E. Oliveri et al., BTTB6 Workshop 2018
  - 100 μm thin Si planar → **100 ps**

    L. Paolozzi et al., JINST 11 (2016) P03011
  - Si APD → **10 ps**

    M. Centis Vignali et al., 13th Trento Workshop 2018
  - Si LGAD (this talk) → **25 ps**

LGAD: HGTD baseline due to requirements on time resolution, granularity, radiation hardness, large area, thinness, …

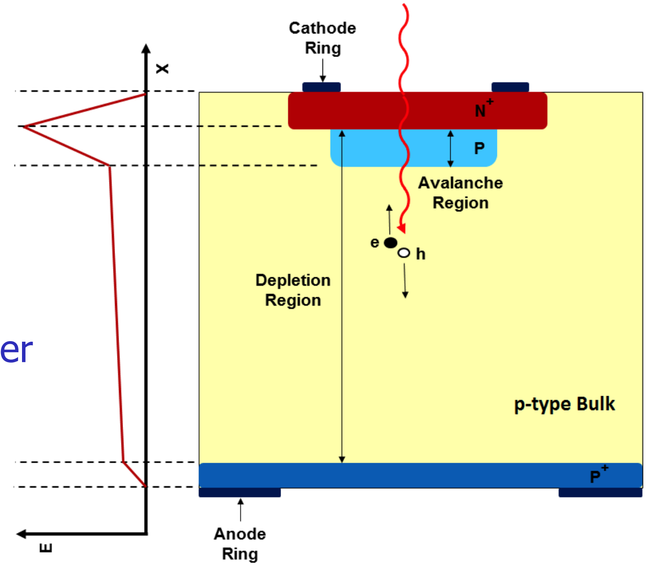
LGAD in a Nutshell

- Low Gain Avalanche Detectors (LGAD)

G. Pellegrini et al., NIM A765 (2014) 12
H. Sadrozinski et al., arXiv:1704:08666

  - Developed by CNM Barcelona (E) and CERN RD50 collaboration
  - Now also Hamamatsu (J), FBK (IT), BNL (US), Micron (UK)
  - Inspired by charge multiplication in irradiated Si detectors

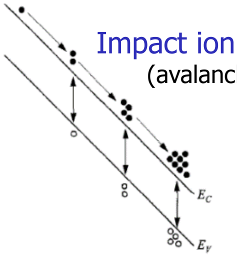
J. Lange et al., NIM A622(2010)49



- Standard segmented n-p silicon detector + built-in p multiplication layer (similar to APD/SiPM but for charged particle tracking + lower gain)

→ High E field
→ Impact ionisation
→ Moderate gain ~10-20
→ Increases signal
→ Keeps noise limited

Increased S/N



Impact ionisation
(avalanche)

- Multiplication allows thinner detectors (now 35-50 µm)

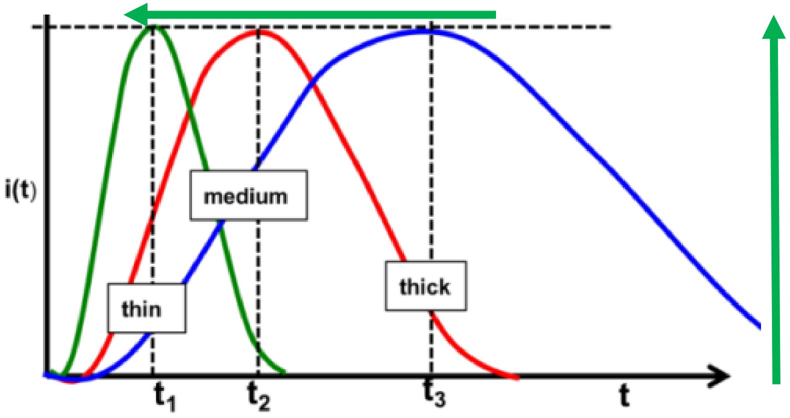
→ Fast charge collection (~1 ns)
→ Small rise time (~400 ps)

→ Excellent time resolution 25 ps

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

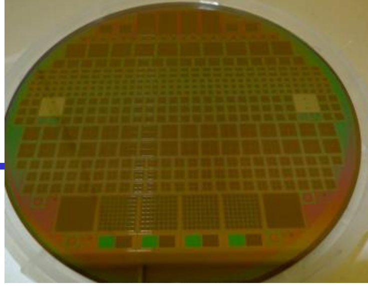
Thinner → lower t_{rise}

Gain
→ higher S



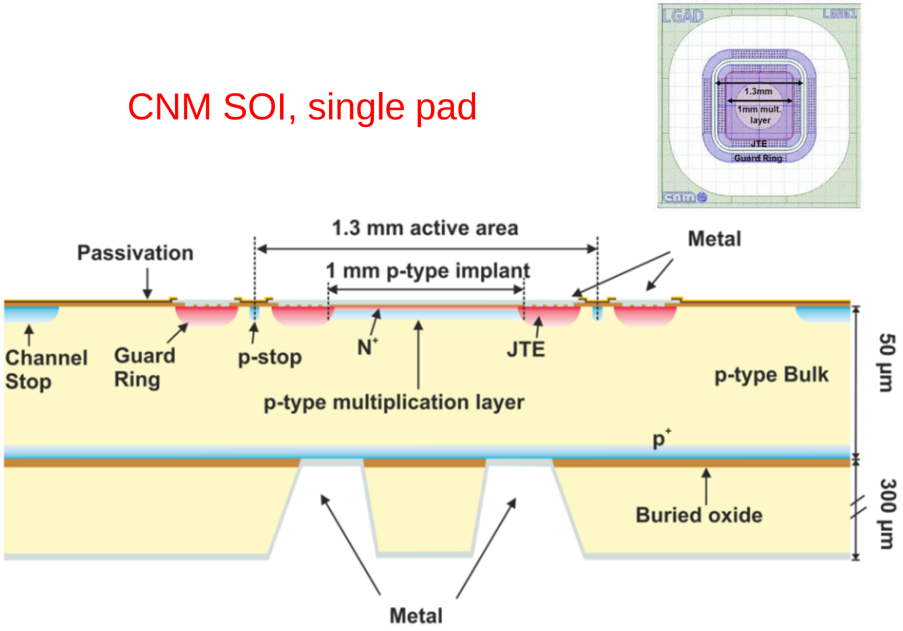
LGAD Signals

LGAD Technology

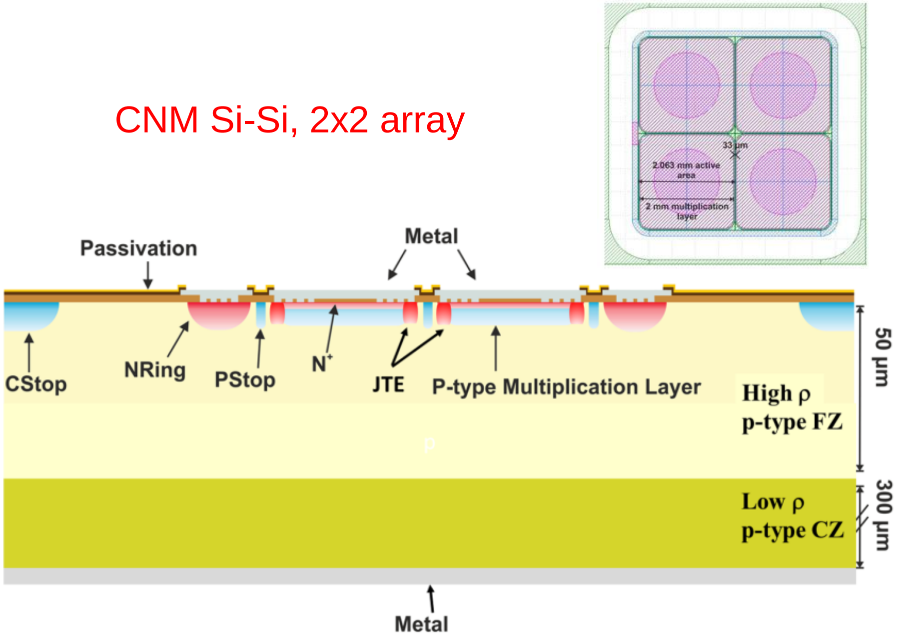


- 4 or 6” wafers
- 35-50 µm active thickness on substrate wafer: different technologies (Epi, SOI, Si-Si)
- Usually B used for highly doped p-type multiplication layer
  - Also Ga and additional C-spray under investigation for improved radiation hardness
- Junction terminations (e.g. JTE) needed to avoid local high fields and early breakdown at implant edges
  - Drawback: no-gain inter-pad gap

CNM SOI, single pad



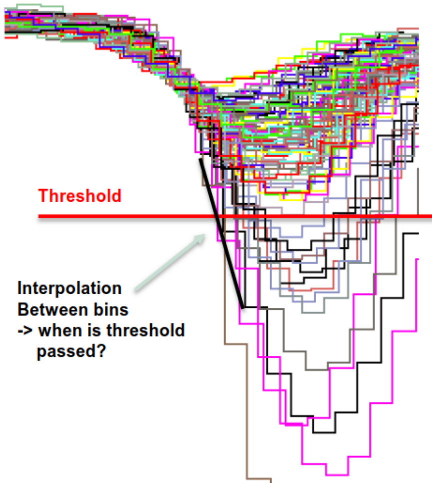
CNM Si-Si, 2x2 array



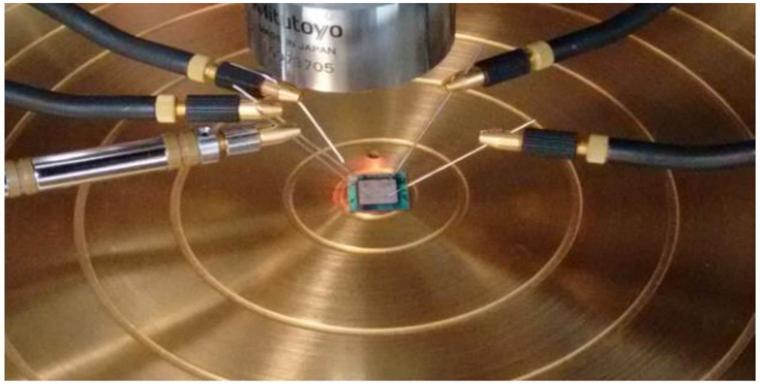
G. Pellegrini, 30th RD50 Workshop 2017

Performance Measurements

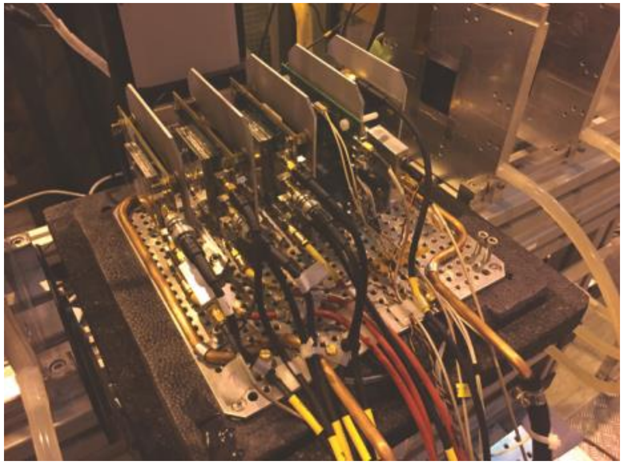
- Laboratory electrical testing (IV, CV)
- Laboratory dynamic testing (β, α, laser) and beam tests with MIPs
- Time resolution analysis
    - Measured from spread of time difference of ToA of different devices
    - Typically well-known reference device used (good LGAD or Quartz+SiPM ~10 ps)
    - Time walk corrected via amplitude/ToT correction or Constant Fraction Discrimination



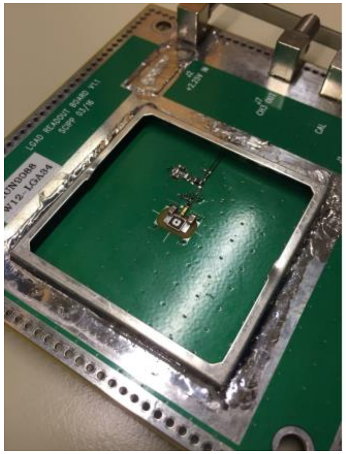
Electrical Testing



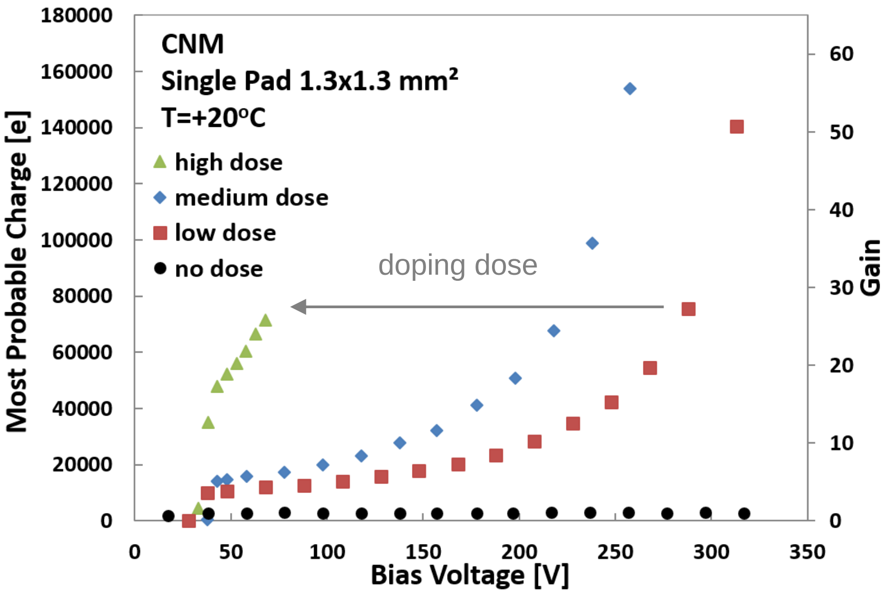
HGTD beam test



Fast Readout Board

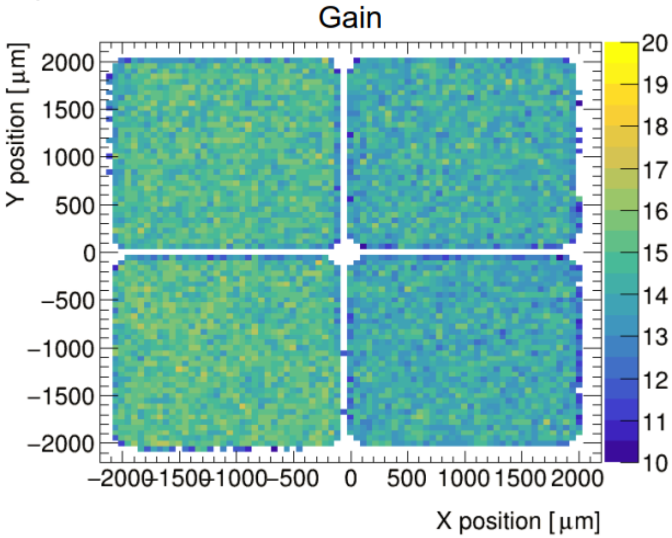


Gain and Efficiency



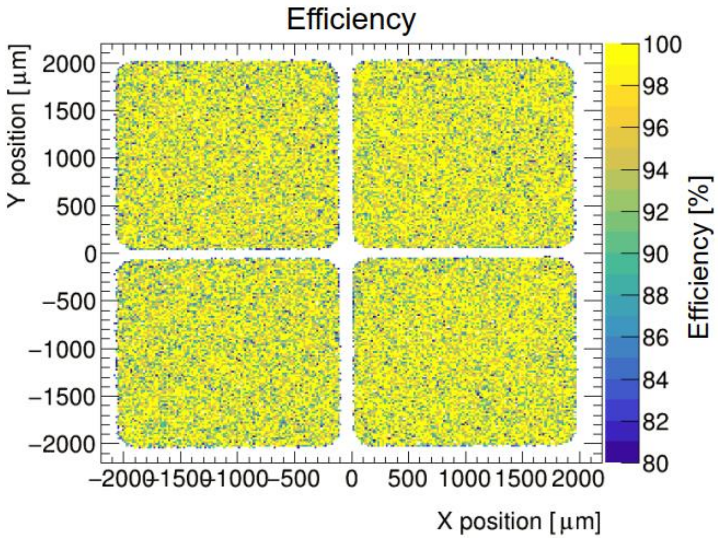
G. Kramberger et al., arXiv:1711.06003

- Break down and gain depend on dose of multiplication layer
- Gains of up to 50-100 reached (baseline 10-20)
  - Uniform over array
  - 70-100 µm no-gain inter-pad gap for current designs
- Hit efficiencies uniformly 96-99%

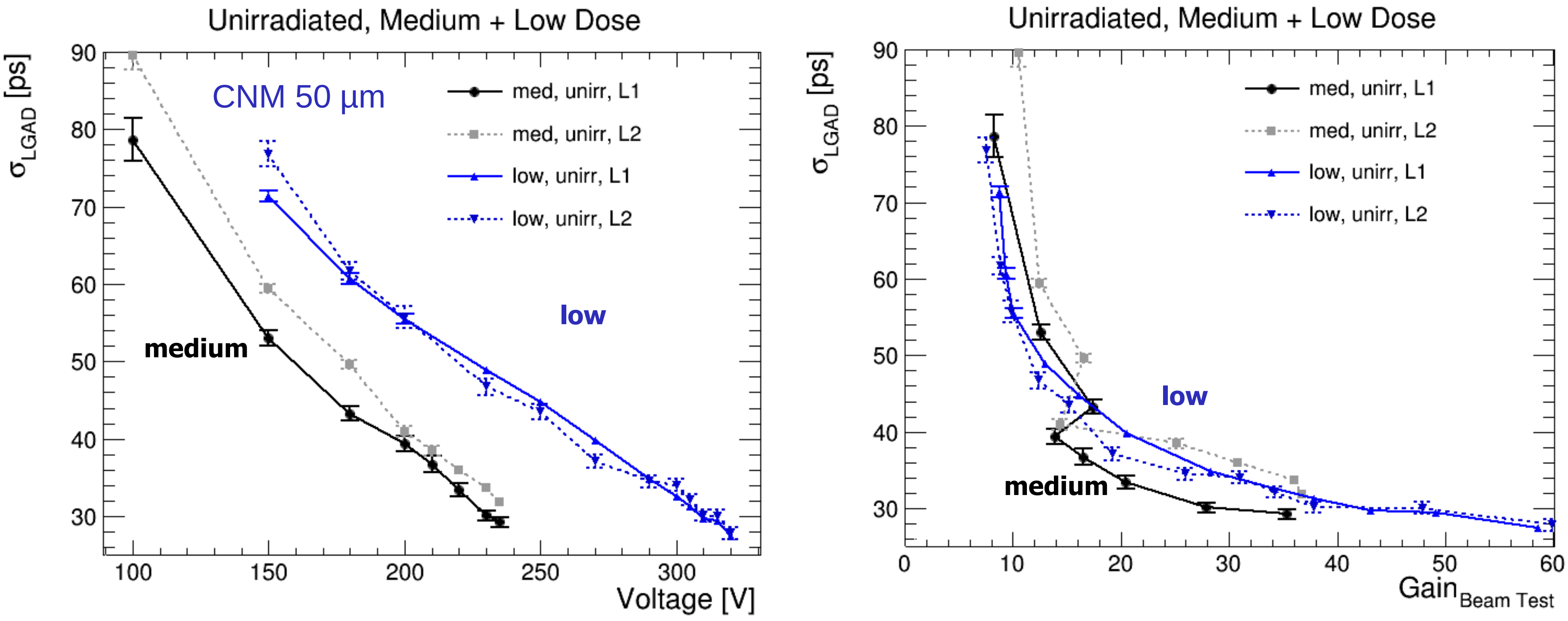


CNM
2x2 Arrays
HGTD Beam Tests

arXiv:1804.00622



Time Resolution Unirradiated

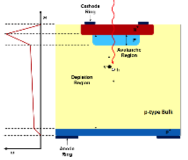


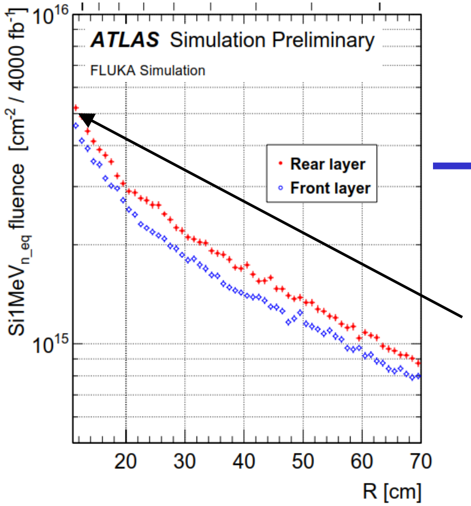
J. Lange et al., JINST 12 (2017) P05003

- Time resolution 20-30 ps / layer achieved
- Higher V needed for lower dose for same performance
- Universal behaviour as a function of gain
- Similar performance for all vendors and different groups

N. Cartiglia et al., NIM A850 (2017) 83
J. Lange et al., JINST 12 (2017) P05003
HGTD beam test, arXiv:1804.00622
Z. Galloway et al., arXiv:1707.04961

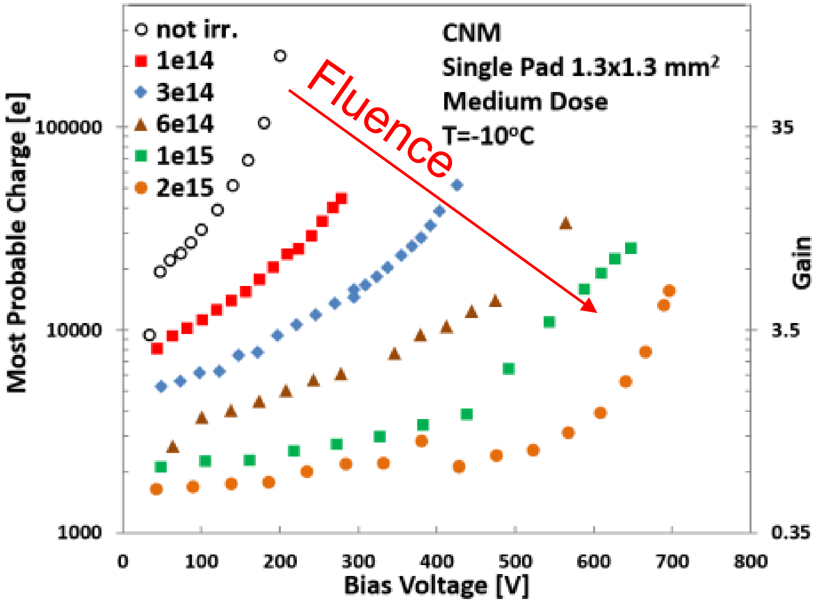
Radiation Effects



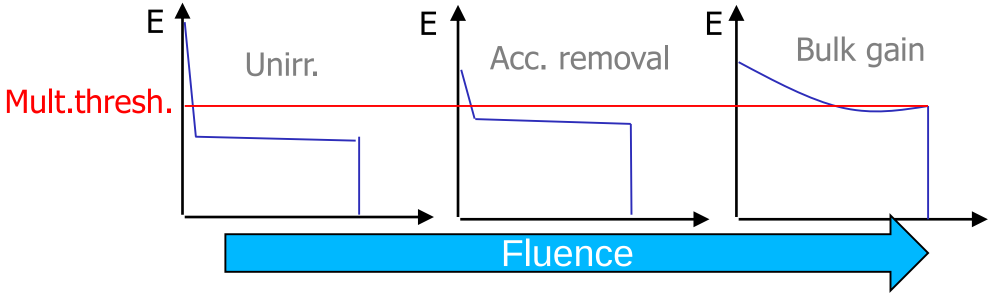


Max. fluence at inner radius:
4e15 n_{eq}/cm² (SF 1.5 + replace.)

G. Kramberger et al., arXiv:1711.06003



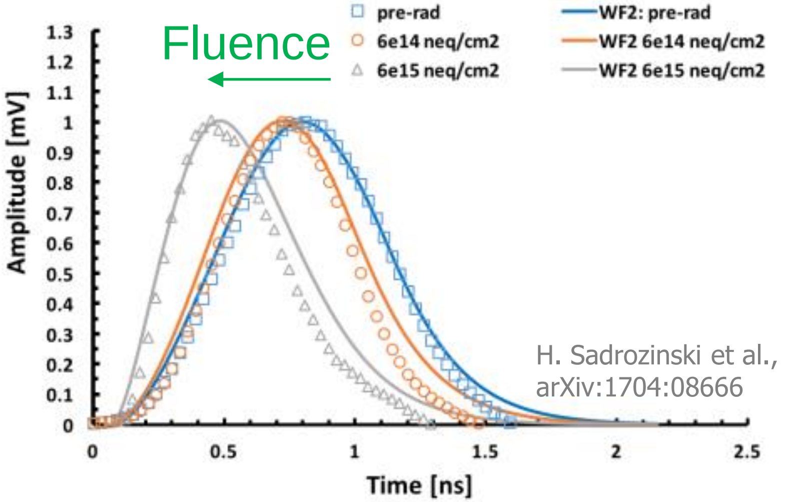
- Removal of initial dopants ("acceptor removal")
  → removes multiplication layer
  → degrades gain and time resolution



- Partly compensated by:
  - Higher break down voltage after irradiation
  - Radiation-induced acceptor-like defects in bulk

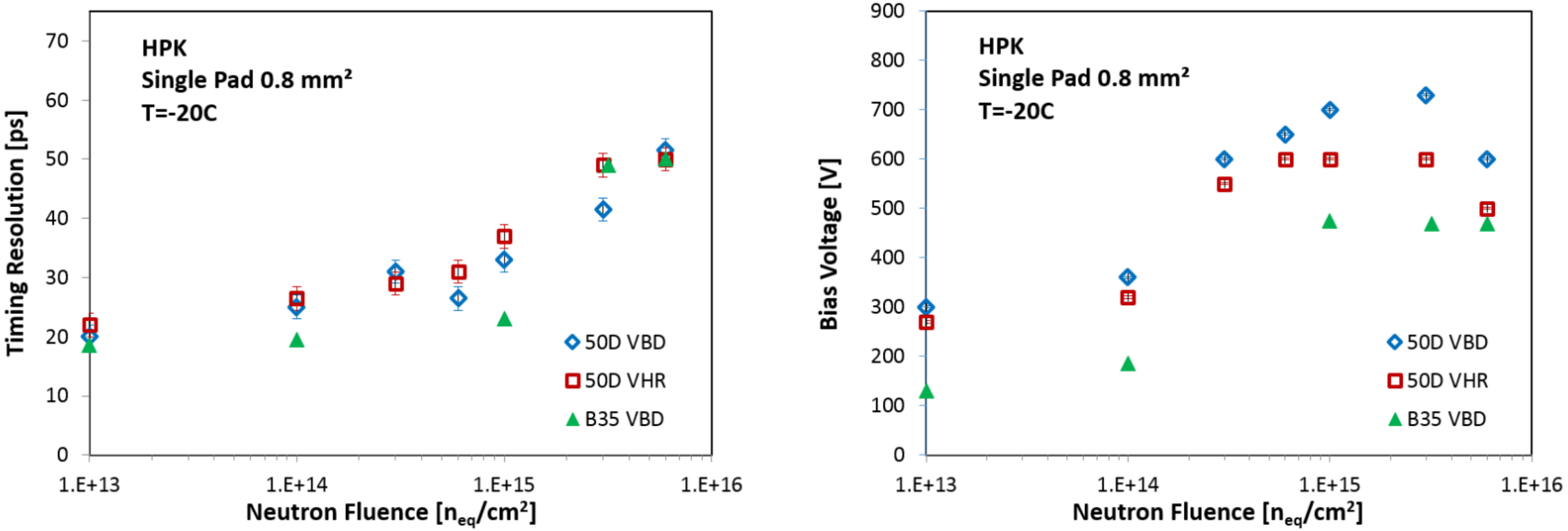
    → introduces gain in the bulk (even in PIN)
    → decrease in rise time

J. Lange et al.,
NIM A622 (2010) 49



H. Sadrozinski et al.,
arXiv:1704:08666

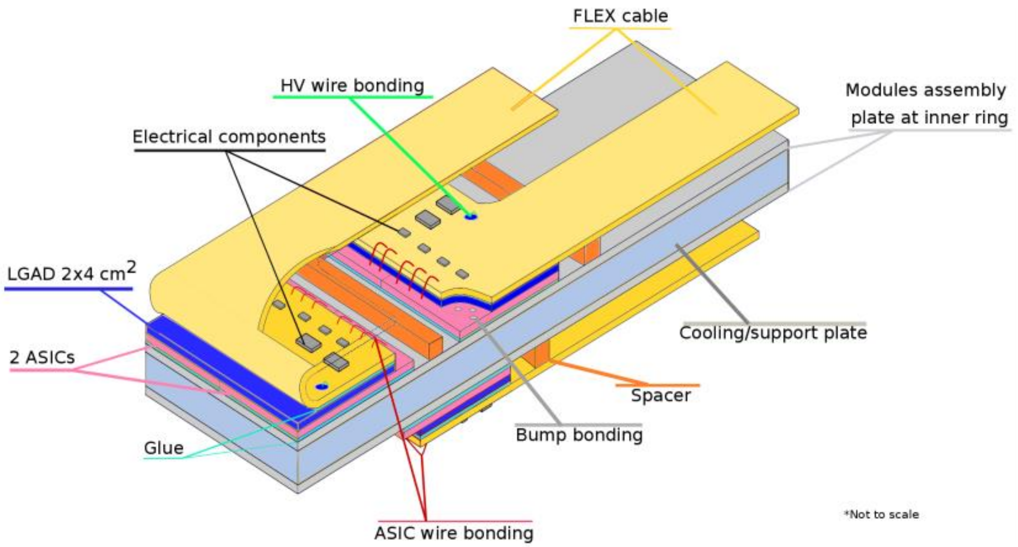
Time Resolution Irradiated HPK

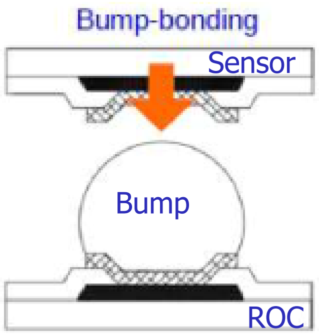


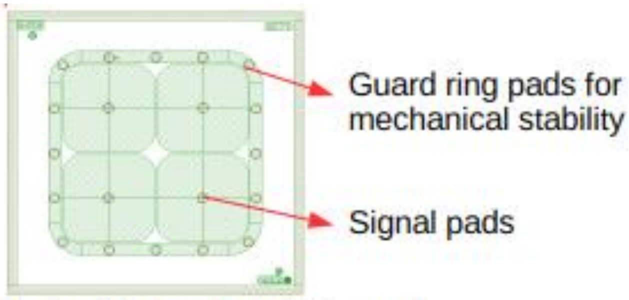
Z. Galloway et al., arXiv:1707.04961
Y. Zhao et al., arXiv:1803.02690

- Degradation of time resolution with fluence
- **50 ps/layer maintained up to 6e15 n_{eq}/cm²**
    - Can achieve HGTD target: 30 ps/MIP in inner radius for 3 layers + 1 replacement
- 2 operation points studied
    - Bias at break down VBD
    - Bias including “head room” VHR → can afford 10% less than VBD
    - V needs steady adjustment responding to radiation damage as a function of radius
- 35 µm: better σ_t up to 1e15 n_{eq}/cm²; also lower V

LGAD Module + Readout Chip





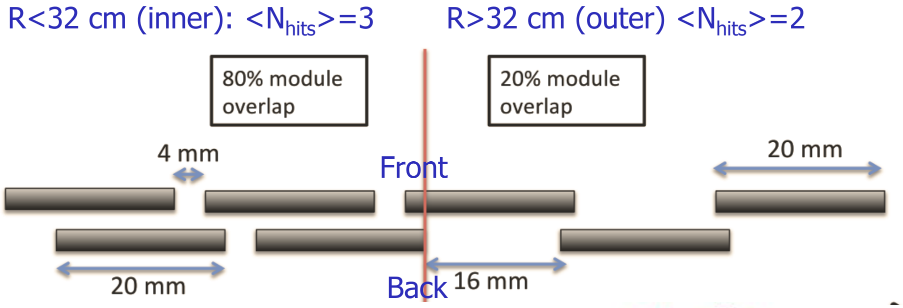


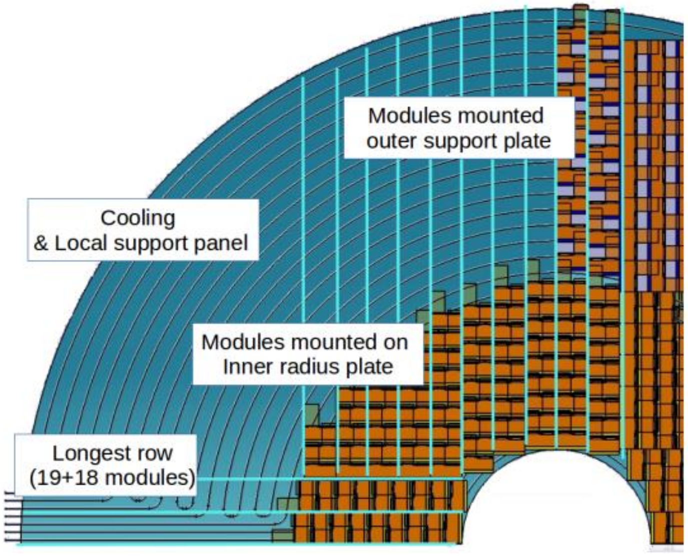
Matrix with 4 1x1 mm² channels

- Large size sensors + modules
  - 2x4 cm², 15x30 pixels of 1.3x1.3 mm²
- Sensor bump-bonded to 2 ALTIROC readout chips
  - Bump-bonding tests at IFAE and BNL
- Flex cable for data+power

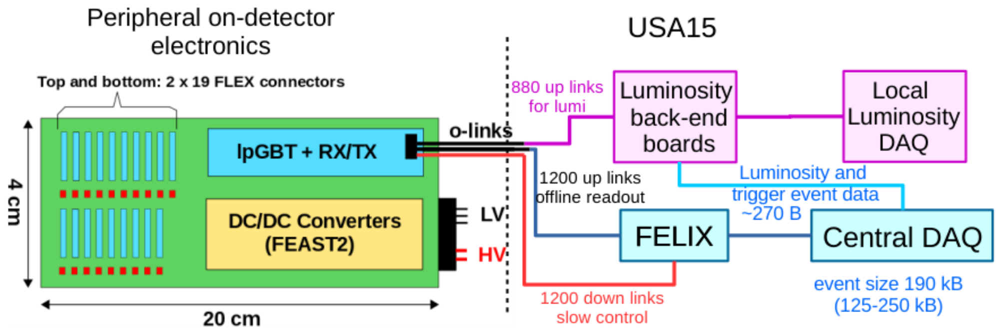
- ALTIROC readout chip
  - Developed at OMEGA, SLAC, IFAE
  - 130 nm TSMC
  - Measure signal, digitise and provide:
    - ToA + ToT at trigger (1 MHz)
    - Hit count for online lumi every BC (40 MHz)
  - Should keep good sensor timing
    - Low jitter, ToT correction for time walk, 20-40 ps TDC bins
    - Radiation hard to 4 MGy
  - Small prototype versions tested

Assembly + Full System





- Modules on front and back side of 2 disks
  - 20% overlap in outer region, 80% in inner
    → 2 hits in outer region, 3 hits in inner
    → keep 30 ps/MIP over full area and lifetime
- Cooling plate -30°C (CO_2 ITk solution)
- lpGBT Gigabit Transceivers, FELIX readout (BNL)
- Clock distribution+calibration
  - Need to assure max. 5 ps jitter + stable phase between clocks of different ASICs (AFP, SBU)
  - Time offset calibration+monitoring on data

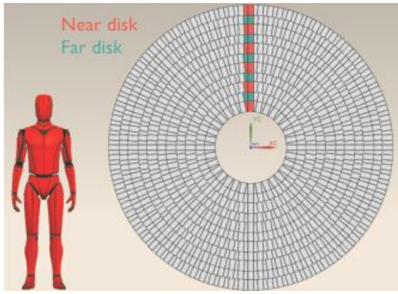


Other LGAD HEP Applications

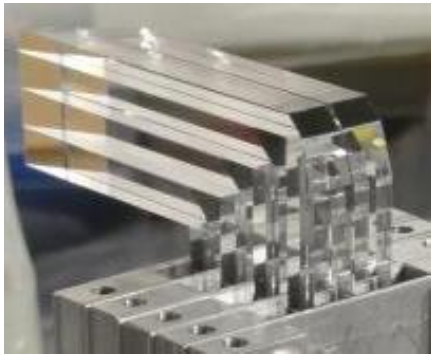
	ATLAS	CMS
Name	HGTD	ETL
$\|\eta\|$	2.4-4.0	1.6-3.0 +(barrel)
Layers	2-3	1
Resol. [ps]	30	30-35
Pixel [mm²]	1.3x1.3	1.0x3.0
Sensor size [cm²]	2x4	5x10
Max. Fluence [n_{eq}/cm²]	4e15 (1 repl.)	1e15

- CMS Endcap Timing Layer (ETL)
  - Same principle as HGTD but different details
  - Close collaboration within RD50
- Forward Physics: AFP + CT-PPS
  - AFP: now Quartz-Cherenkov, higher segmentation needed for Run3
  - CT-PPS: now diamond but better resolution needed
  - Exploratory LGAD already installed in CT-PPS (short lifetime)
  - **Biggest challenge: Non-uniform irradiation**
    → need different V in different sensor parts
  - Possible solution: separate pads or pre-irradiation to 1e15 n_{eq}/cm²

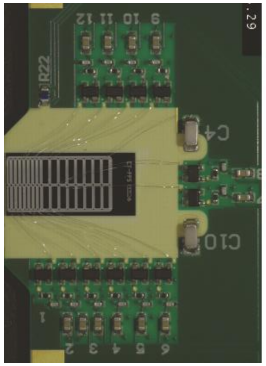
CMS ETL



AFP ToF

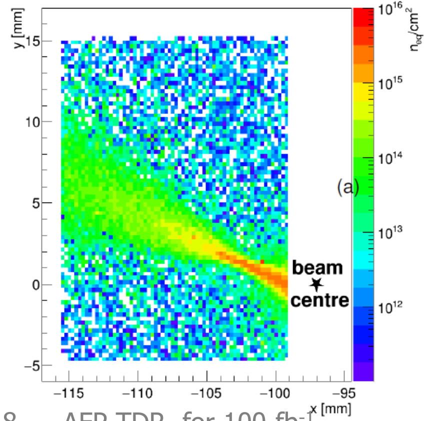


CT-PPS LGAD

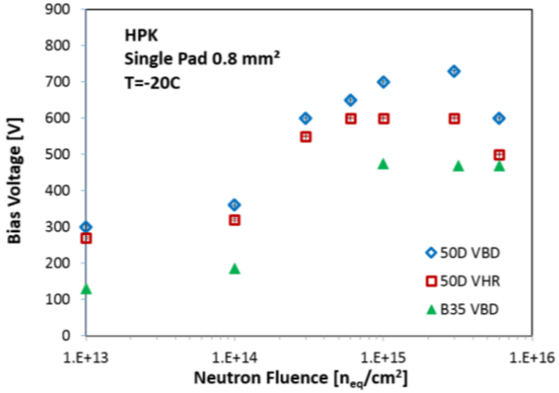


V. Sola, 13th Trento Workshop 2018

AFP Fluence

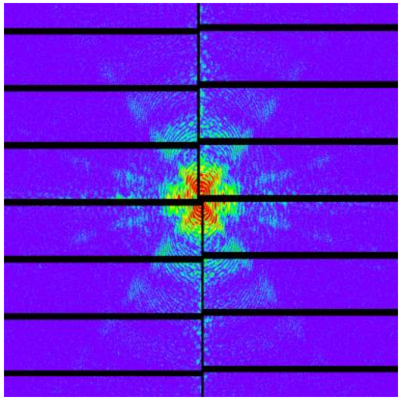


AFP TDR, for 100 fb^{-1}

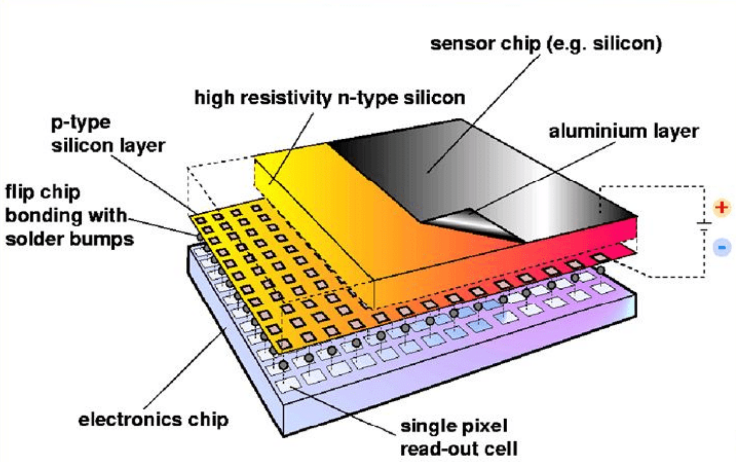


Photon Science LGAD Applications

AGIPD Image at DESY



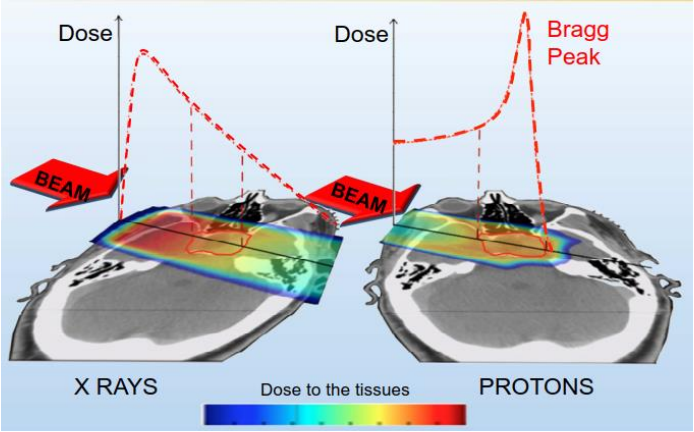
Hybrid Pixel Detector



- Photon science: Soft X-rays ~1 keV
  - Usually signal too low for threshold of ~700 e in hybrid chips
  - Possible solution: LGAD → Gain boosts small signal above threshold → Standard ASICs (AGIPD, Medipix) + infrastructure can be used
  - First results at PSI (CH) down to 3 keV promising: LGAD strips + Gotthard chip

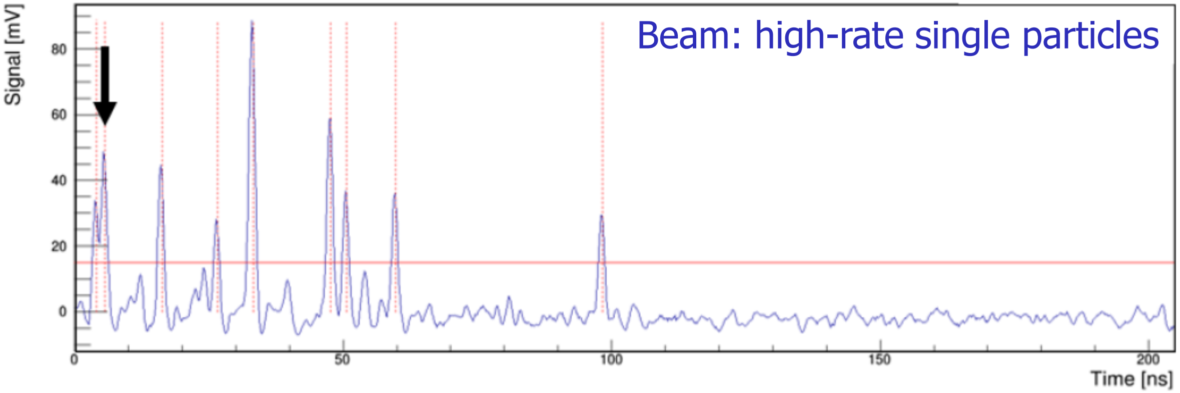
J. Zhang, Trento Workshop, Feb 2018

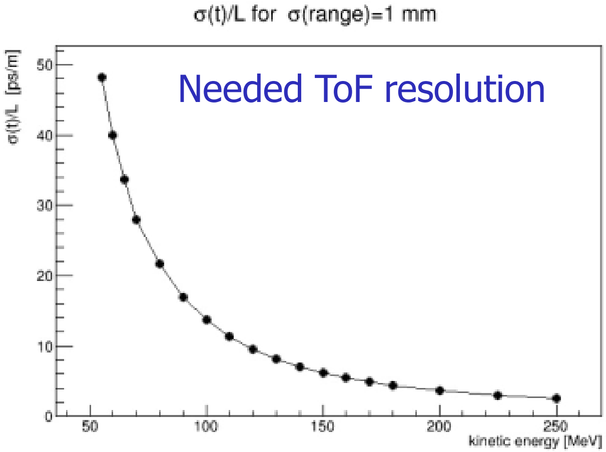
Medical LGAD Applications



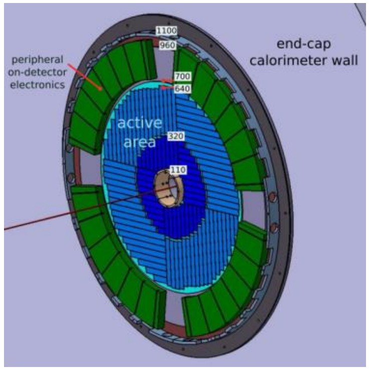
- Medical: Radiotherapy
  - First measurements in CNAO (Pavia) and Dublin
  - Beam monitoring crucial for treatment
  - E.g. p 60-250 MeV
  - LGAD
    - Fast (~1 ns duration)
      → measure high rate beams: single particle counting!
    - Good timing
      → ToF for precise beam energy (up to ~75 MeV p)

A. Vignati, JINST 12 (2017) C12056
V. Monaco, BTTB Workshop, Jan 2018
N. Minafra, BTTB Workshop, Jan 2018

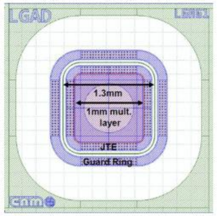

Beam: high-rate single particles


Needed ToF resolution

Conclusions and Outlook



- **ATLAS is proposing a new forward High Granularity Timing Detector for HL-LHC**
  - Pile-up removal and luminosity
  - Significant object performance and physics improvements
- **Successful development of fast silicon sensors in LGAD technology**
  - <30 ps / layer before irradiation
  - 50 ps / layer after 6e15 n_{eq}/cm^2



→ 30 ps / MIP timing requirements fulfilled

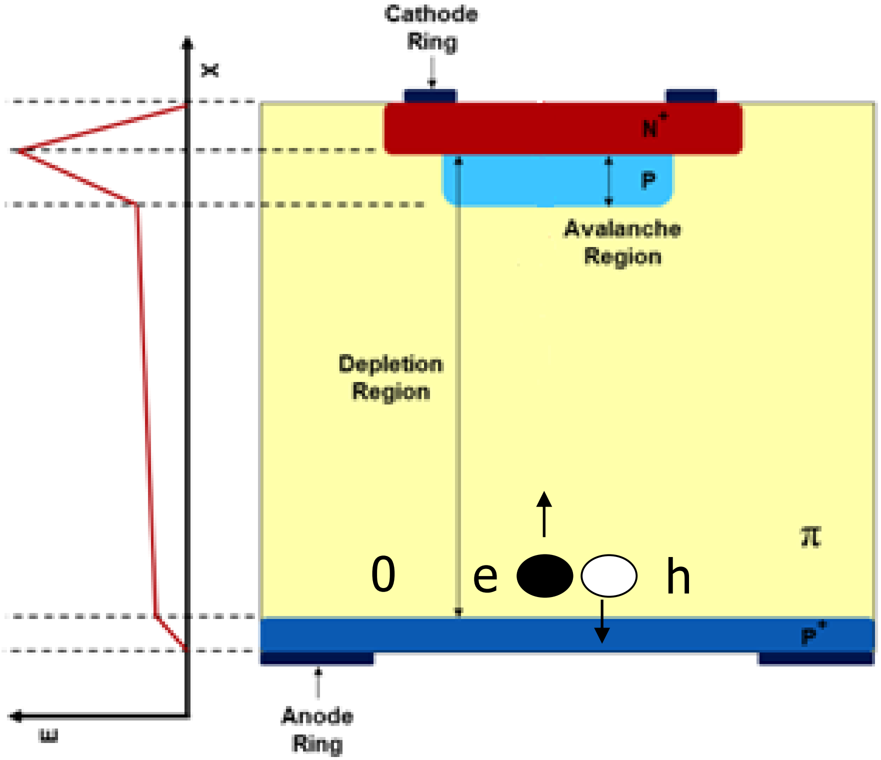
- Also LGAD applications for CMS, forward detectors, photon science, medical, …
- Very dynamic R&D field with intense development on-going
  - Improved radiation hardness (Ga, C-spray), thinner detectors, better fill factor, large devices, …
- Time line
  - HGTD Technical Proposal of ATLAS to be submitted to LHCC this week (!)
  - If approved in May, proceed to Technical Design Report (TDR) beginning 2019
  - (Pre)production + construction starts in 2021
  - Installation 2025

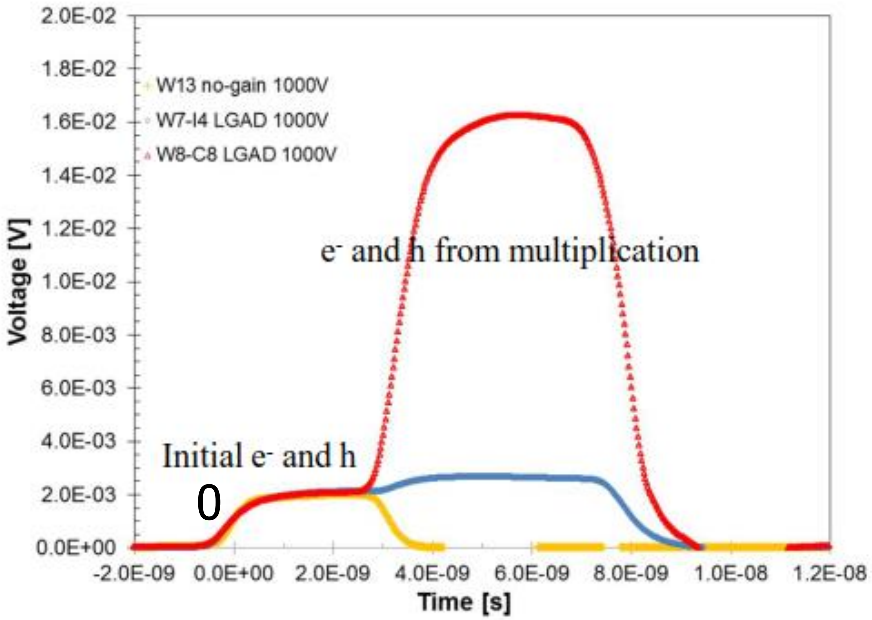
BACKUP

Signal Formation – Back Side Injection

- Measurable signal induced by Ramo theorem $I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$
- Back side charge injection (alpha or red laser) -> Follow charge carrier as probe of E field and multiplication

0) e-h pairs created at back side, h immediately collected





Hartmut Sadrozinski
23rd RD50 workshop

Signal Formation – Back Side Injection

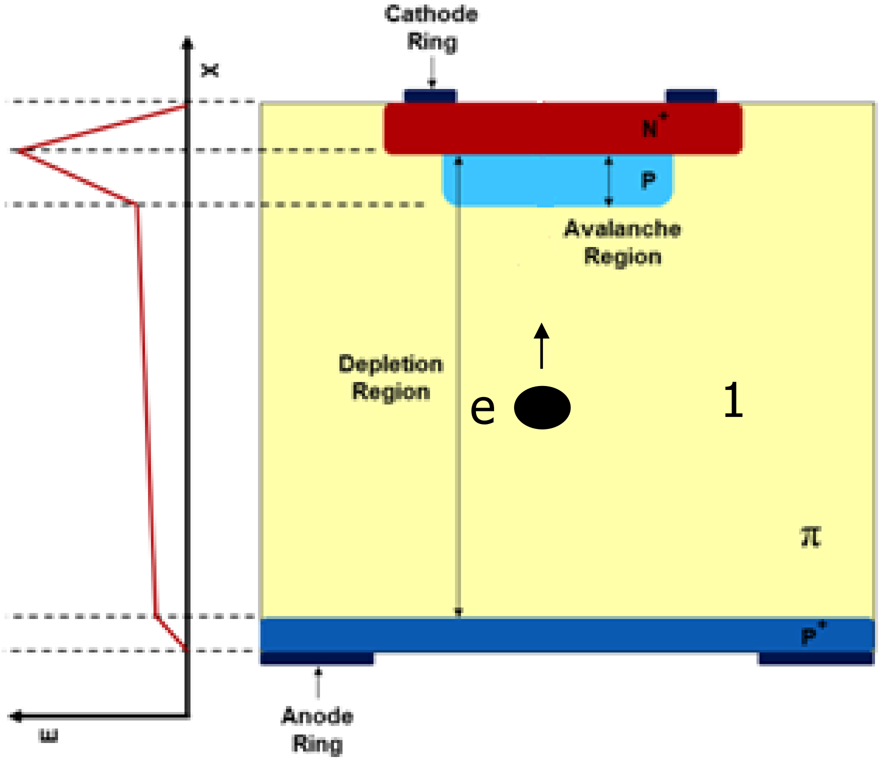
- Measurable signal induced by Ramo theorem

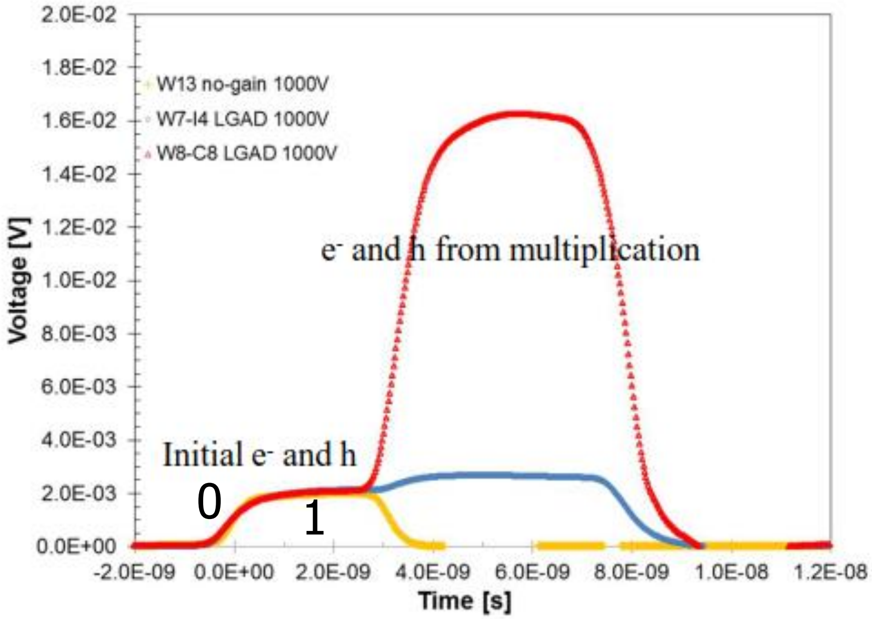
$$I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$$

- Back side charge injection (alpha or red laser) -> Follow charge carrier as probe of E field and multiplication

0) e-h pairs created at back side, h immediately collected

1) e drift towards high field from back to front





Hartmut Sadrozinski
23rd RD50 workshop

Signal Formation – Back Side Injection

- Measurable signal induced by Ramo theorem

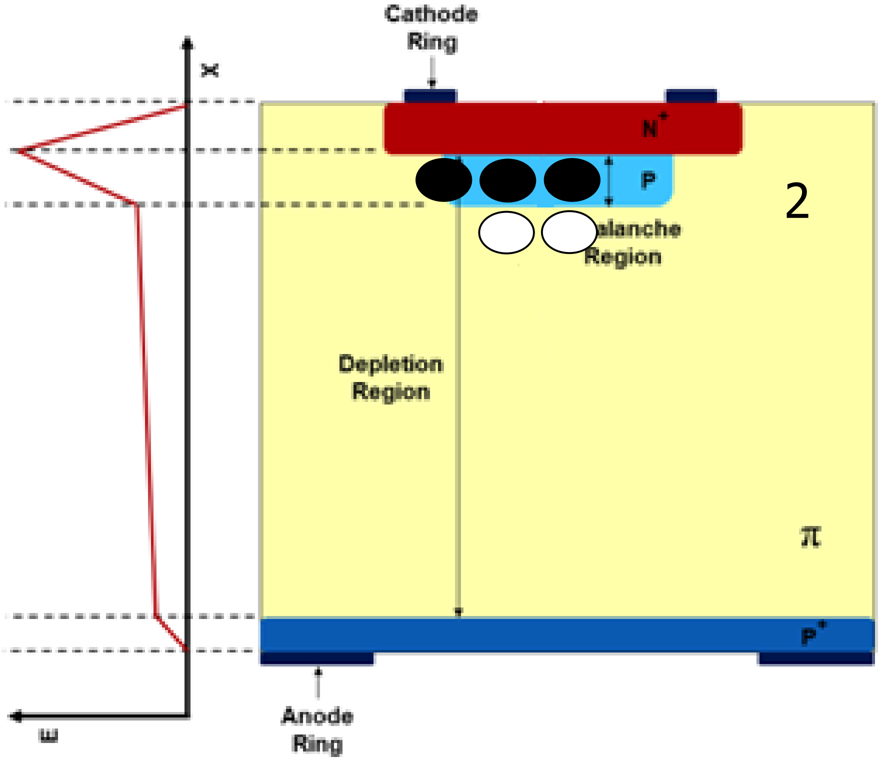
$$I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$$

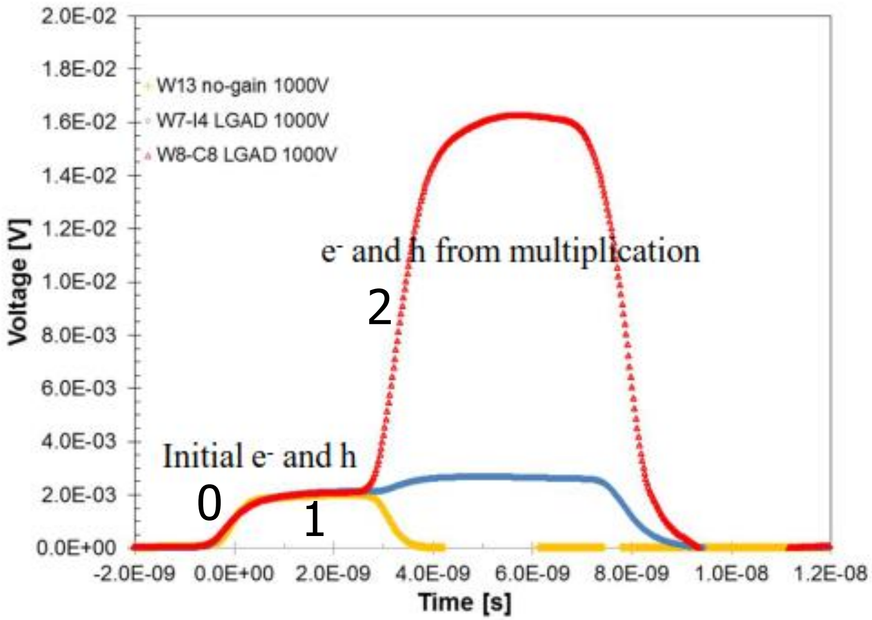
- Back side charge injection (alpha or red laser) -> Follow charge carrier as probe of E field and multiplication

0) e-h pairs created at back side, h immediately collected

1) e drift towards high field from back to front

2) e multiply in high field multiplication region





Hartmut Sadrozinski
23rd RD50 workshop

Signal Formation – Back Side Injection

- Measurable signal induced by Ramo theorem

$$I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$$

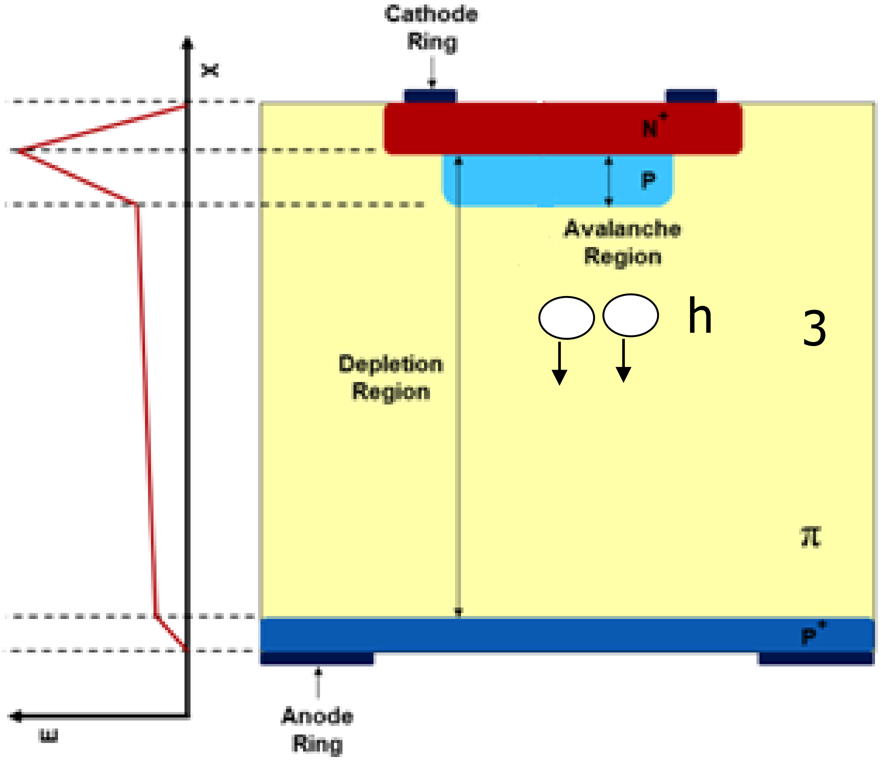
- Back side charge injection (alpha or red laser) -> Follow charge carrier as probe of E field and multiplication

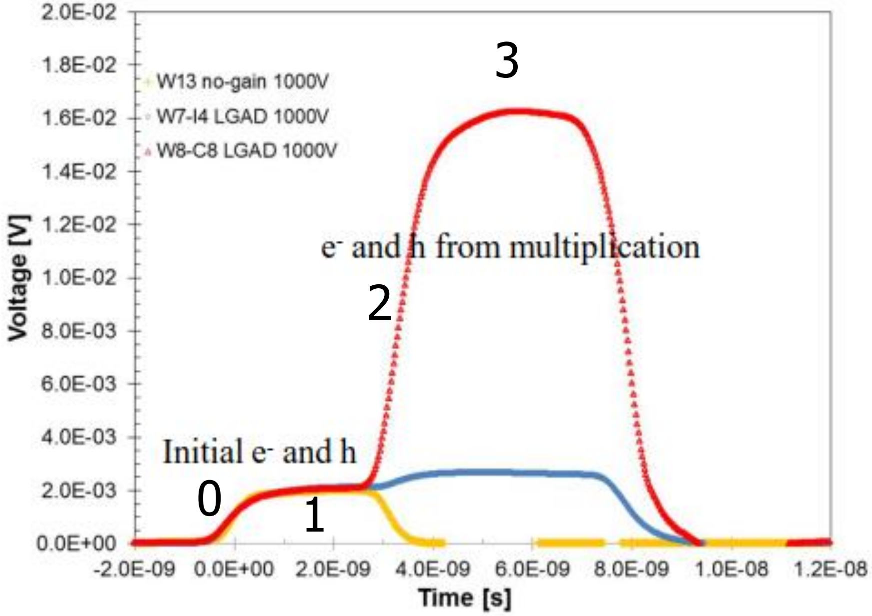
  0) e-h pairs created at back side, h immediately collected

  1) e drift towards high field from back to front

  2) e multiply in high field multiplication region

  3) multiplication h drift towards the back

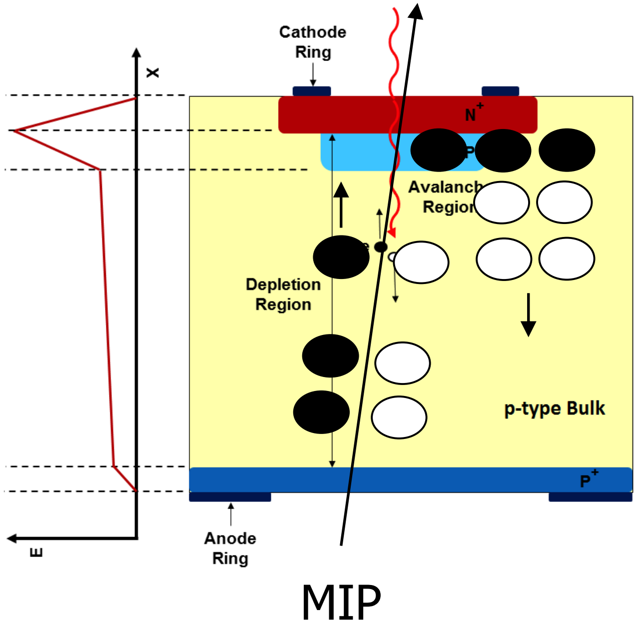


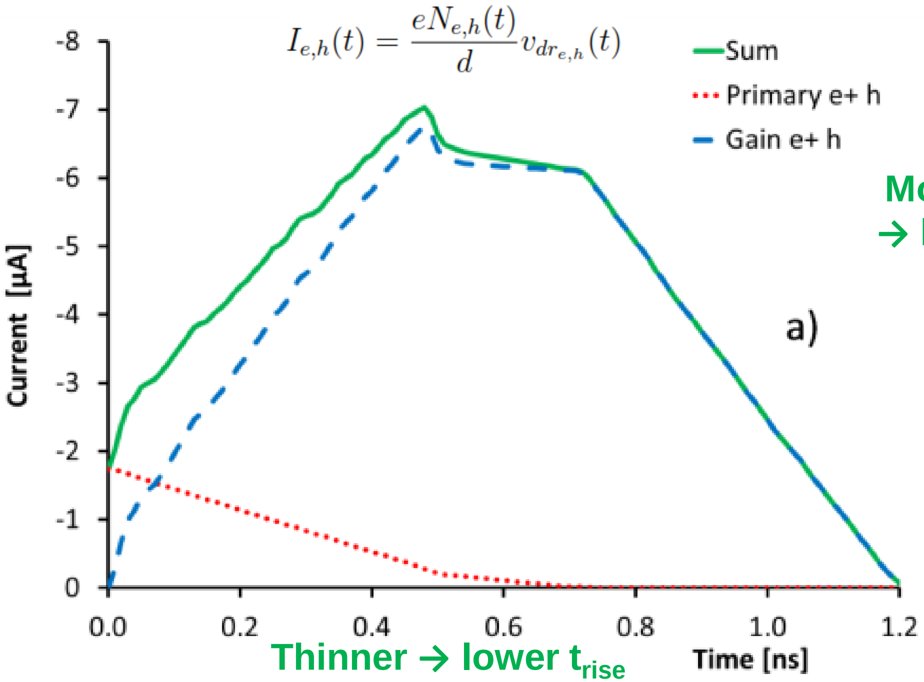


Hartmut Sadrozinski
23rd RD50 workshop

Signal Formation – MIP

- MIP is ionizing along its path
  - Rather uniformly in depth
  - But Landau fluctuations present
- Signal formation is sum of individual charge packages
  - Primary e+h
  - Constant multiplication until all e have reached front side (“gain e+h”)
  - Then only h signal





$$I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$$

More gain → higher S

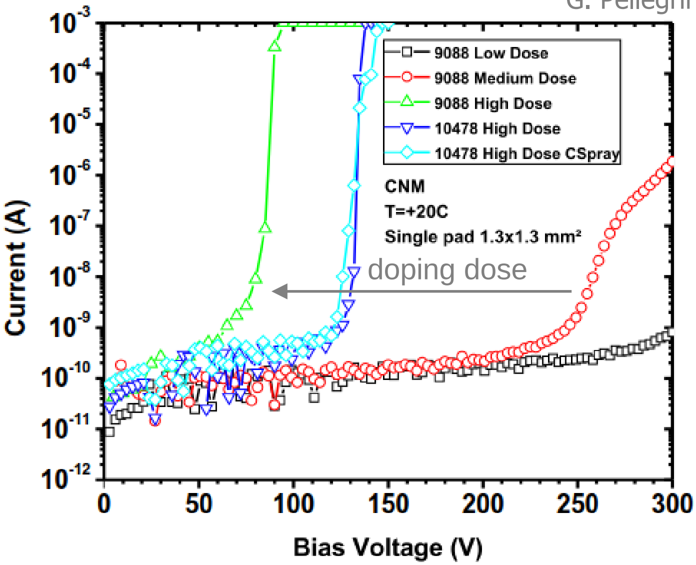
Thinner → lower t_{rise}

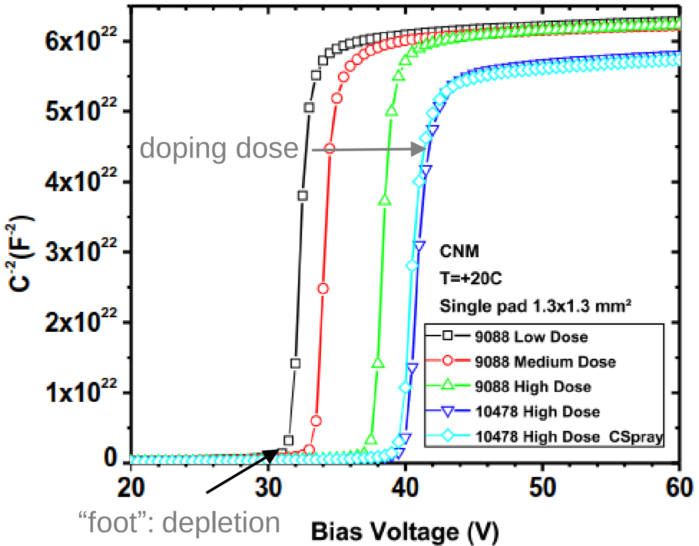
Weightfield2 Simulation

F. Cenna et al., NIM A 796

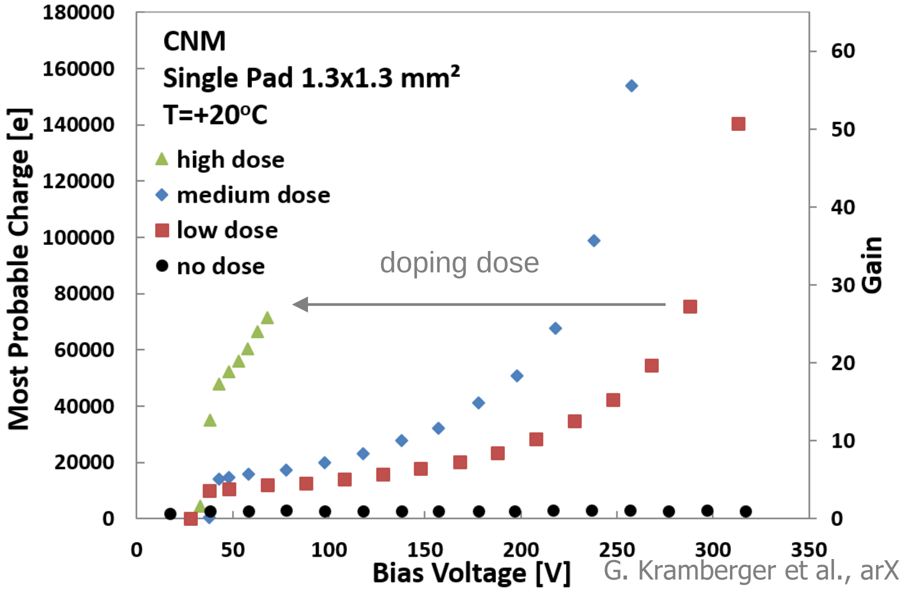
Electrical Characterization and Gain

G. Pellegrini, 30th RD50 Workshop 2017





"foot": depletion
of mult. layer



G. Kramberger et al., arXiv:1711.06003

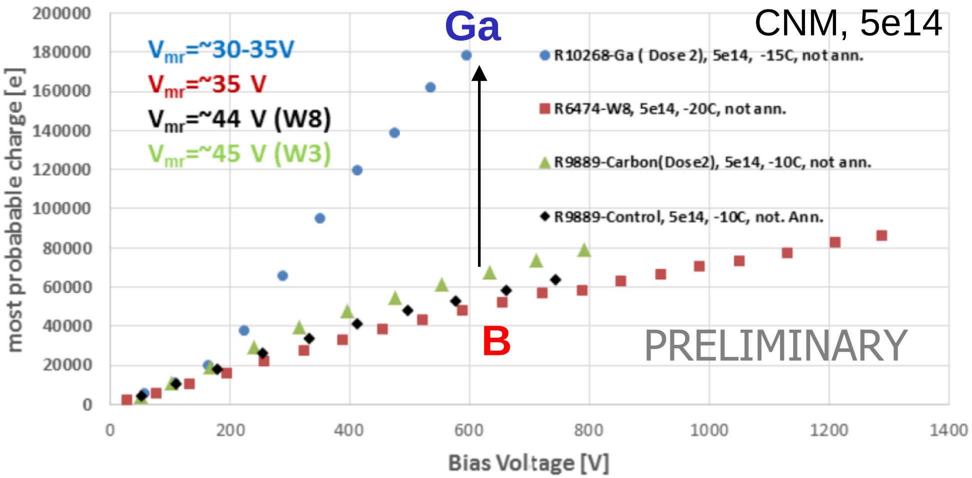
- Break down, depletion of multiplication layer ("foot") and gain depend on dose of multiplication layer
- Gains of up to 50-100 reached (baseline ~20)
  - Need less V for same gain at higher dose

Towards Higher Radiation Hardness

- Goal: reduce acceptor removal

  $$Si_i + B_s \rightarrow B_{i^-} \rightarrow B_i + O_{i^-} \rightarrow B_i - O_i$$

  1. Ga heavier than B → harder to remove
  2. C-spray: C easier to remove → sink for Si_i

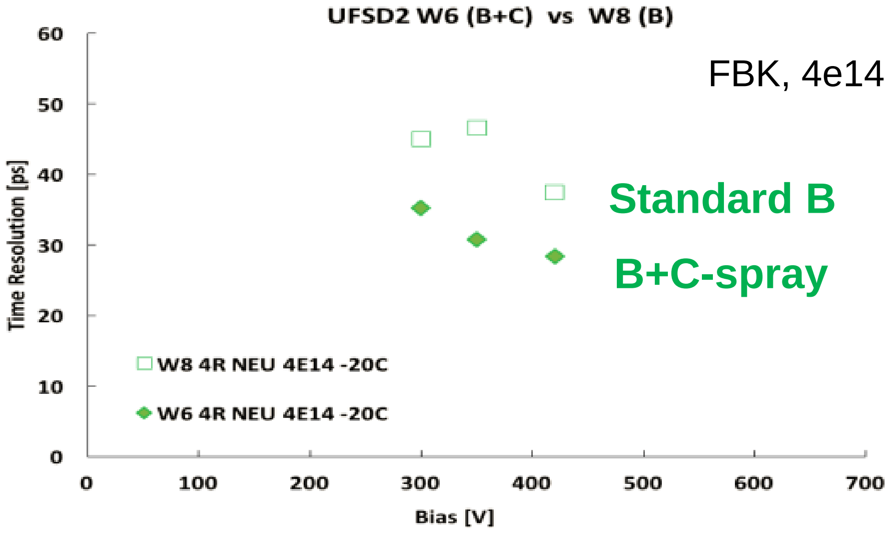


G. Kramberger, 30th RD50 Workshop

- Ga-LGAD
  - First results on CNM 300 μm Ga-LGAD test structures promising
    - But possible bias due to high initial doping
    - 50 μm run on-going
  - First results on FBK 50 μm Ga-LGAD: no effect

  → further studies on-going

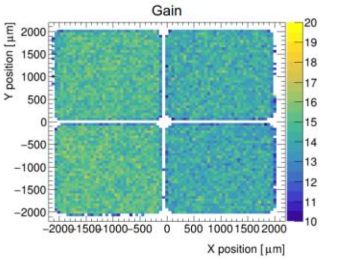
R. Arcidiacono, H. Sadrozinski, TREDI 2018



- C-spray
  - FBK C-spray LGADs have ½ acceptor removal rate than no-C
  - Better performance at intermediate fluences <1e15 n_{eq}/cm^2

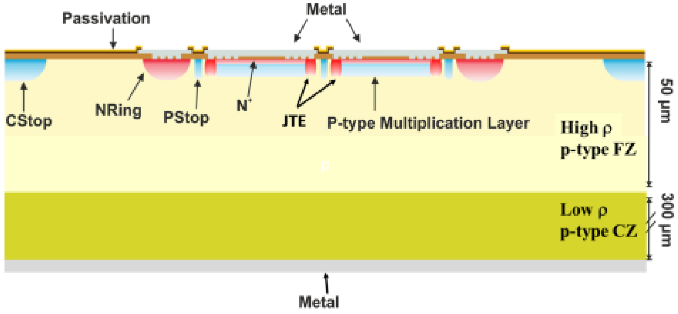
Better Fill Factor – Towards 4D

- First LGAD versions: no-gain inter-pad gap 70-100 μm
  - Only 85% fill factor for 1.3 mm large pads (HGTD) → inefficient region
  - Much worse for "real" pixels of ~50 μm pitch (e.g. Medipix)
    → needs to be much improved with final goal of 4D tracking

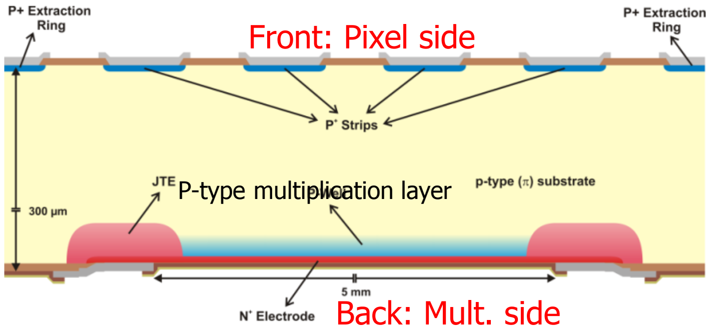


- Option 1: Standard LGADs with minimized inter-pad distance
  - Optimize or skip JTE around each pixel
    → expect degraded breakdown, but hopefully gain still enough

Pixel side = mult. side



- Option 2: inverted LGAD (iLGAD)
  - Homogeneous multiplication layer at back-side
  - p-in-p pixels at front side: hole collection
  - Already working devices produced



Front: Pixel side

Back: Mult. side

- Option 3: AC-LGAD
  - Homogeneous multiplication layer at front-side
  - Pixelation only in metal, AC-coupled to sensors via SiO_2
  - First prototype produced, new dedicated run starts soon

AC-LGAD