Silicon precision timing detectors for minimum ionizing particles

FNAL-LDRD-2017-027

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All Experimenters' Meeting

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LDRD Project description

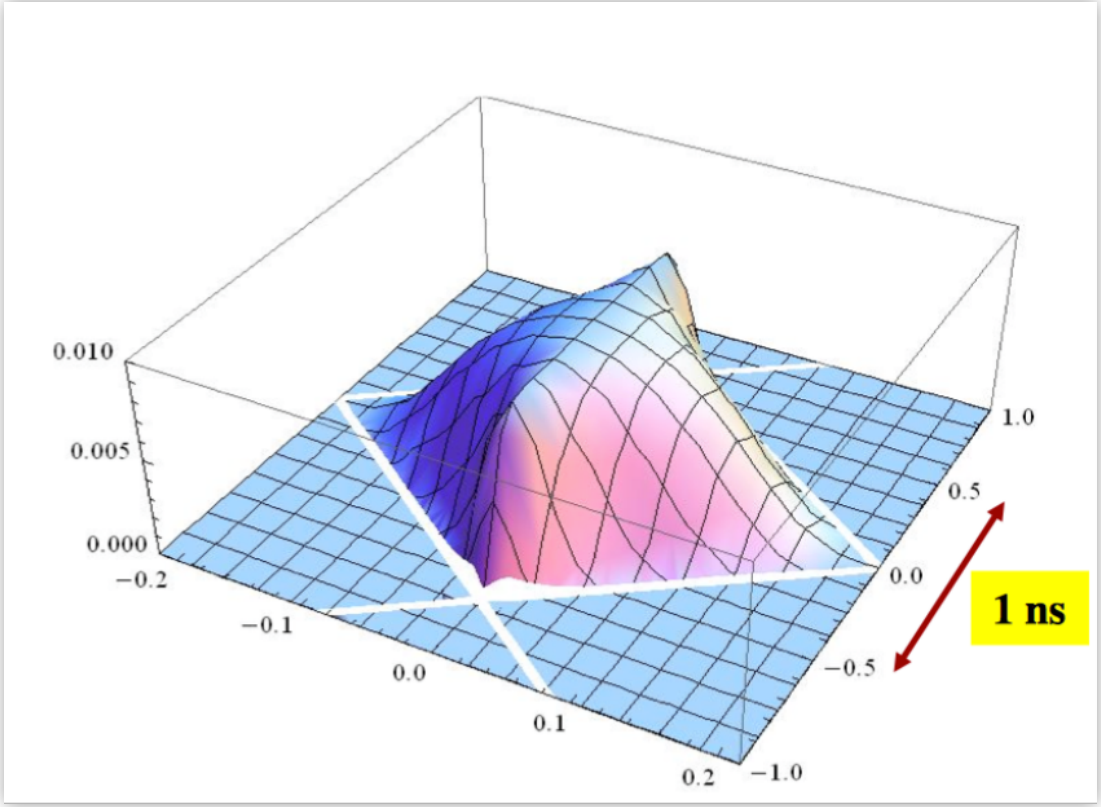
- The aim is to develop over two years the technology that achieves
  - Time-tagging at σ_t=20-30 psec for single MIPs,
  - Construct "large system" detector demonstrator, comprised of around 30-50 individual readout channels

- Next generations of detectors for hadron colliders will face enormously challenging experimental conditions
  - At HL-LHC: 140-200 overlapping interactions per bunch crossing
  - FCC or similar 100 TeV collider: up to 2,000 pileup interactions

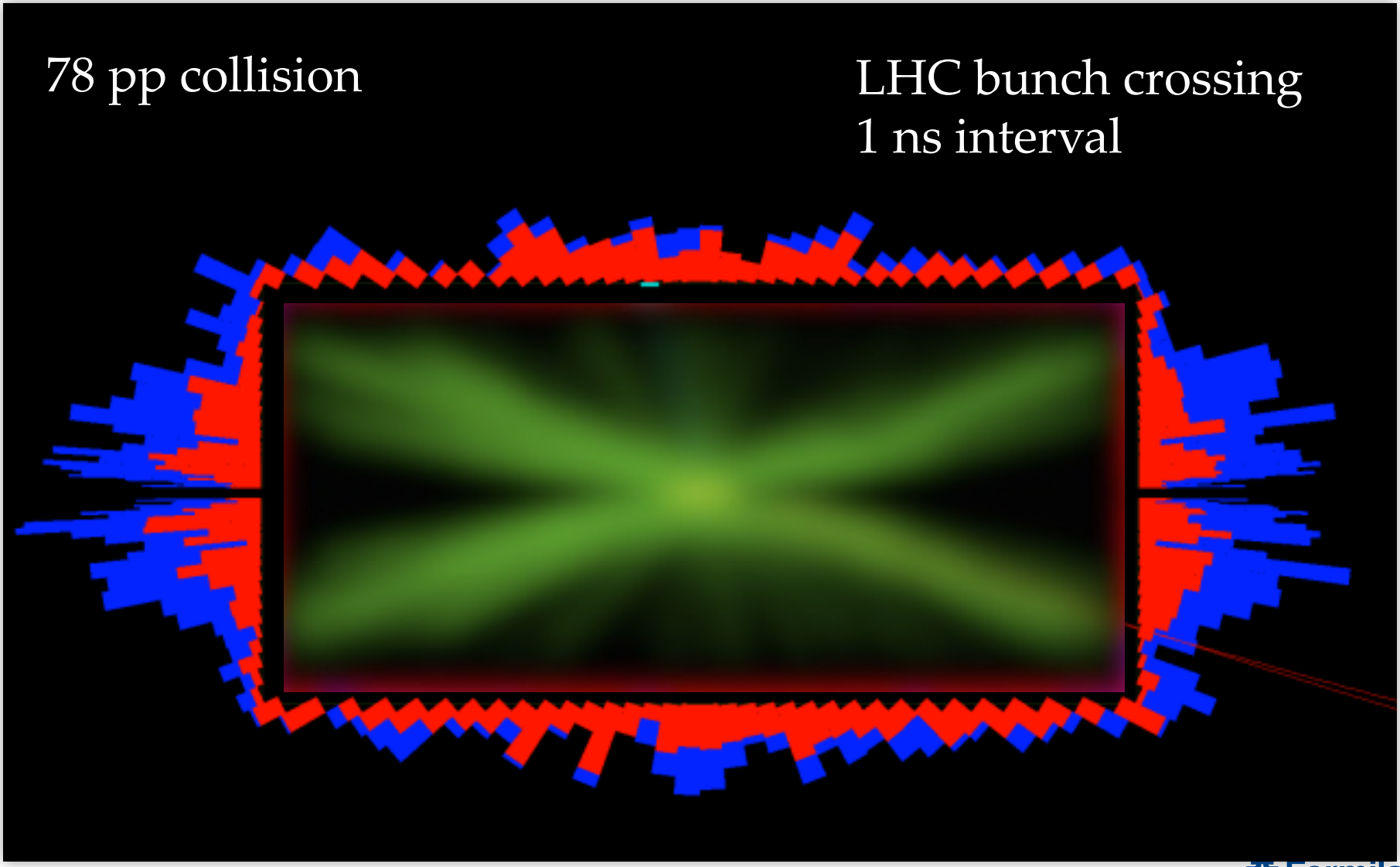
- Extreme density of charged particles severely degrades event reconstruction: *charged lepton eff., jets/MET resolution, etc..*

HL-LHC beam spread

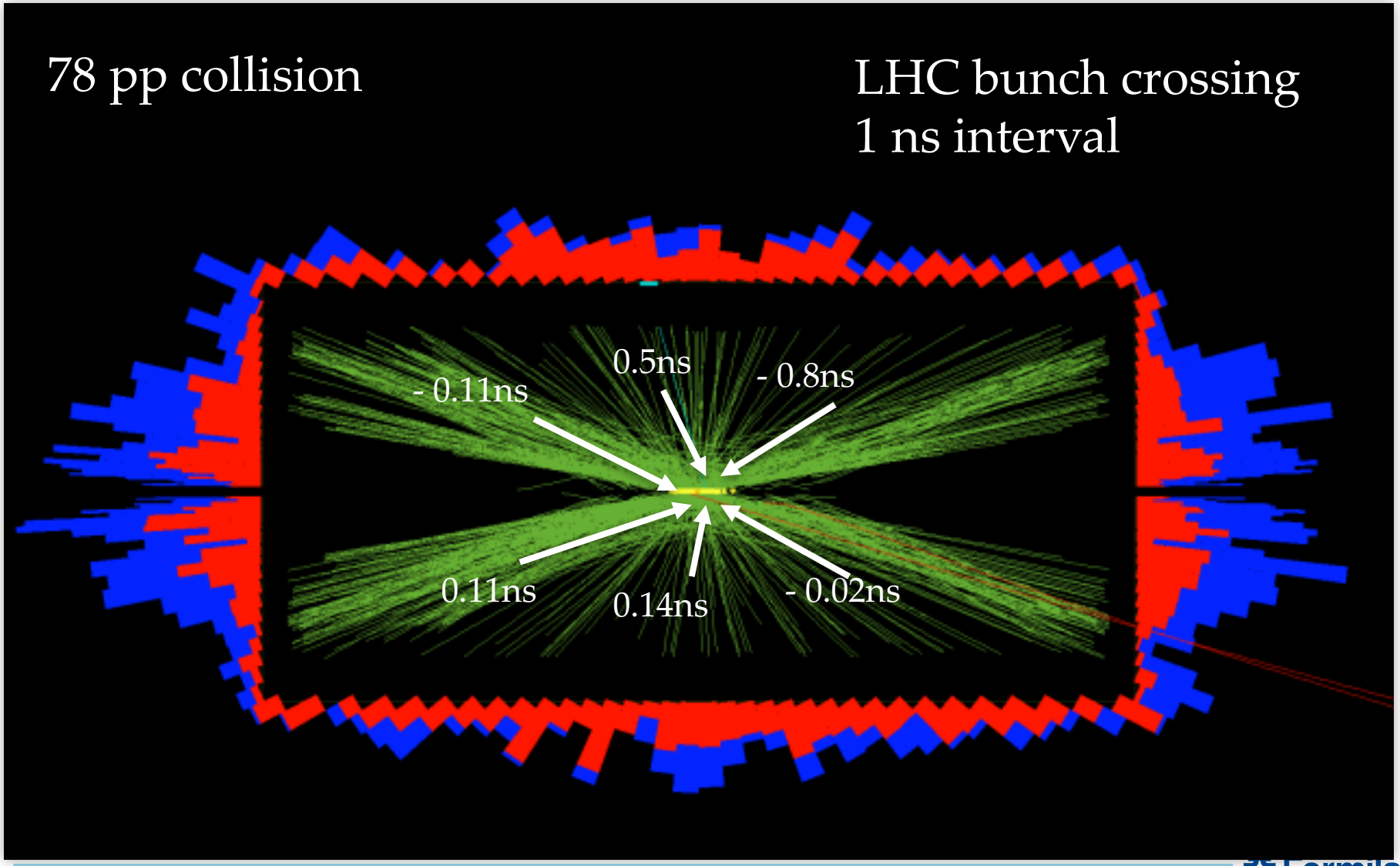
- Beamspot width in time is several hundred ps (**RMS = 200 ps**)
  - A detector with ~30 psec timing resolution could distinguish between interactions on the basis of timing



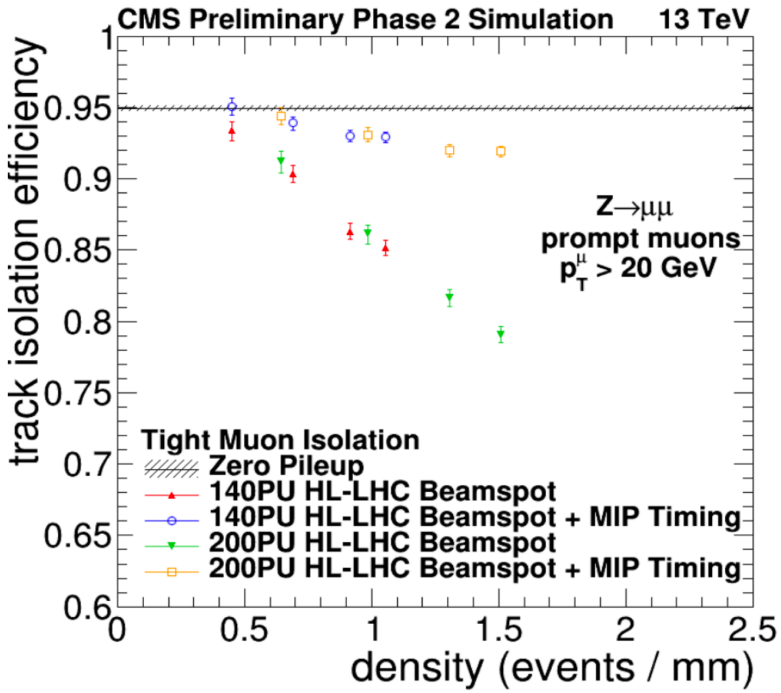
Event reconstruction at HL-LHC



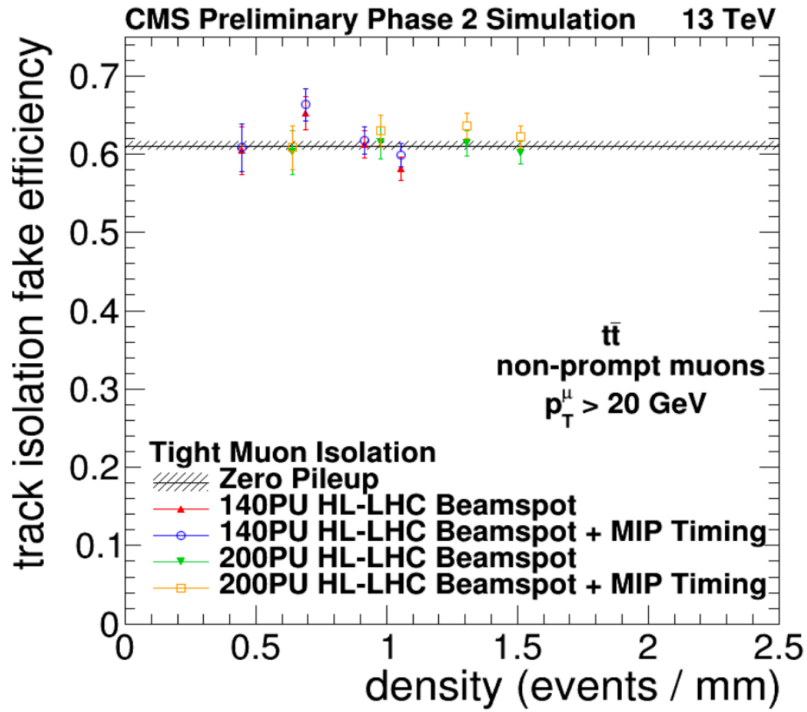
Event reconstruction at HL-LHC



Muon reconstruction



(a) Prompt μ Efficiency

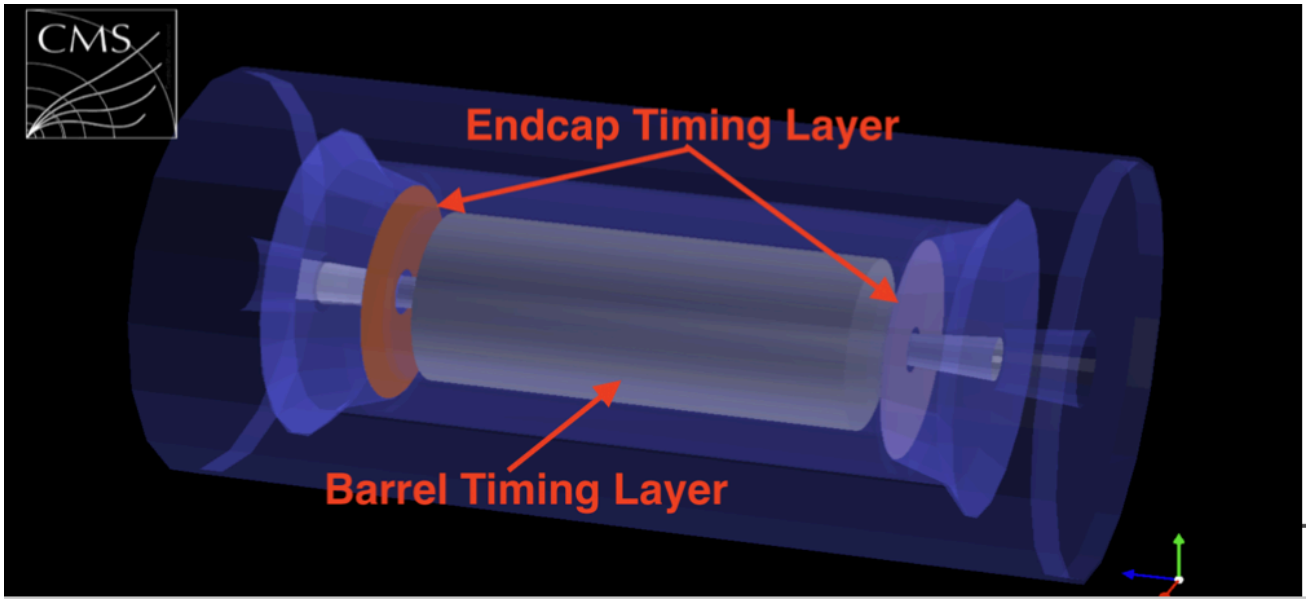


(b) Efficiency for fakes

- Muon charged isolation efficiency in Z → μμ and ttbar (fake) events
- Timing yields 10% improvement per muon

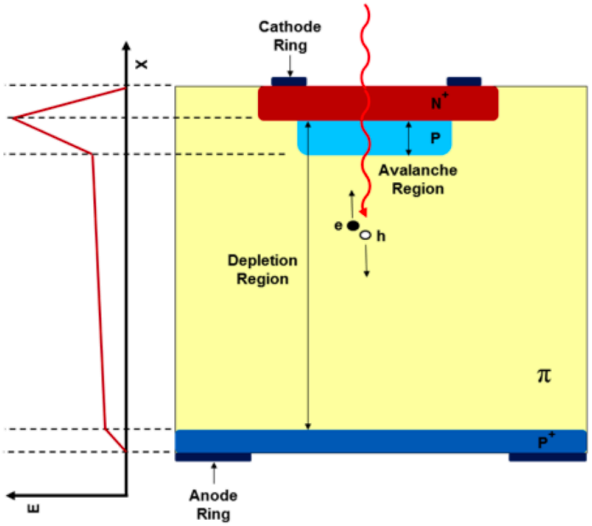
Precision Timing Detectors

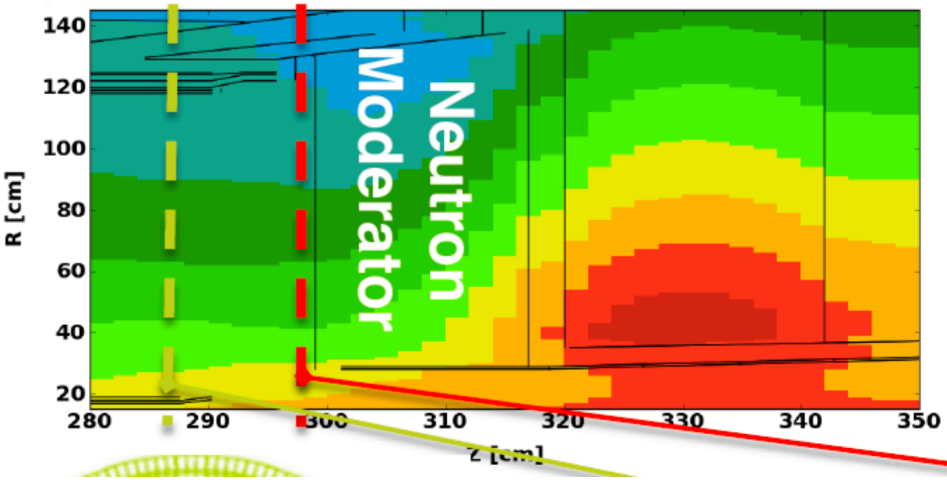
- **MIP timing detector:** cover up to |η|<3.0 to time stamp charged particles in the event: ~30 psec timing resolution
- Timing detector in the endcap:
  - High granularity detectors needed in the forward region due to particle density
  - Radiation tolerance up to ~$2x10^{15}$ n/cm^2 to survive 3,000 fb^{-1}
  - Time resolution of ~30 pse for single MIPs
- Barrel timing detector with SiPM+LYSOs



Timing layer in the endcap

- Silicon sensor with specially doped thin region that produces high electric field→ produces avalanche providing signal 15-30 gain
  - Large community: RD50 collaboration, several manufacturers (CNM, FBK, Hamamatsu)
- Key Challenges our LDRD tries to tackle:
  - Achieve radiation tolerance up to 2×10^{15} n_{eq}/cm^2 at $|\eta| = 3.0$ for 3,000 fb^{-1}
  - Develop a process to produce **large area**, **uniform gain**, **high production yield** LGAD sensors.

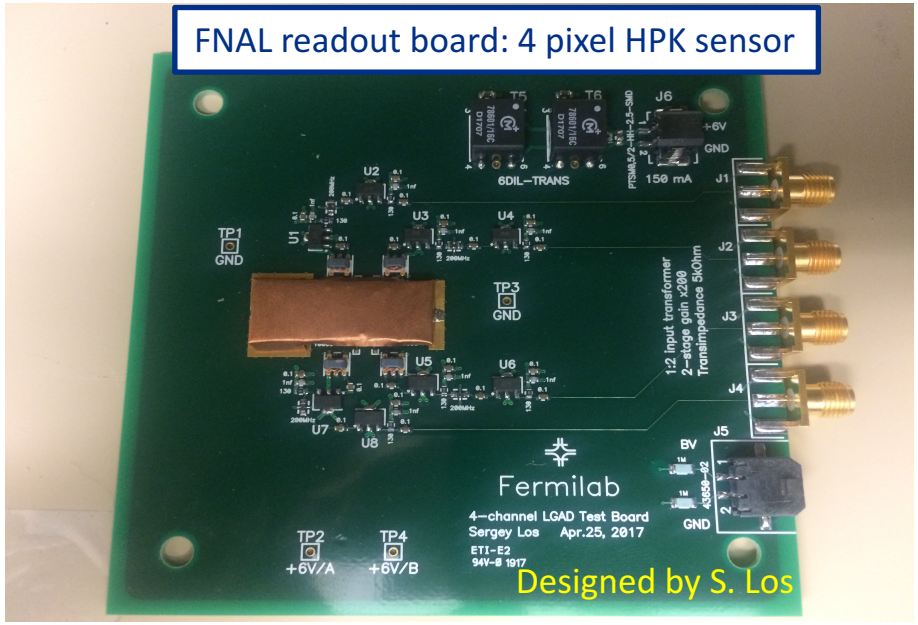


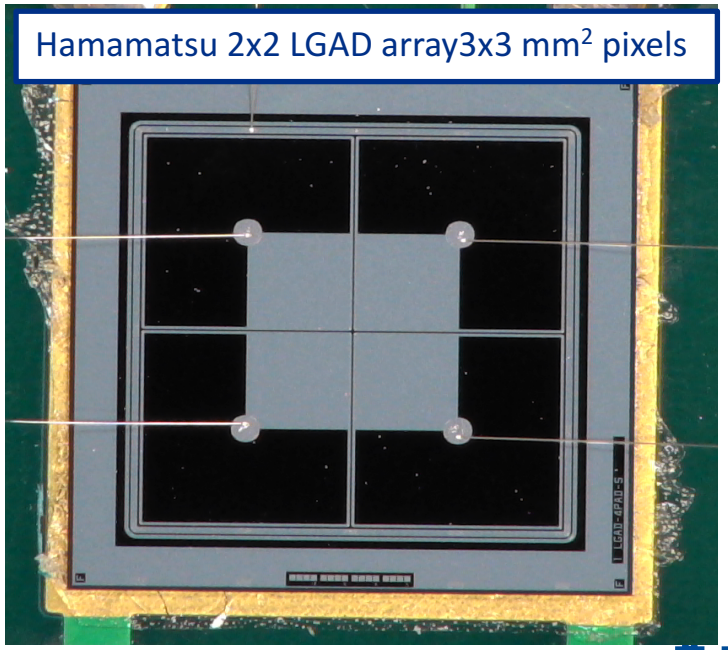


η	TK / HGCal nose
1.6	1.1×10^{14}
2.0	2.1×10^{14}
2.5	4.8×10^{14}
3.0	10.0×10^{14}

FNAL Readout Board

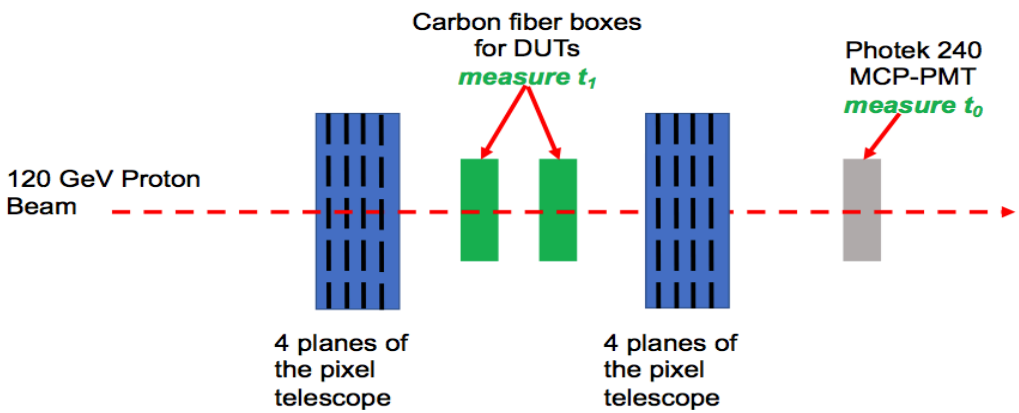
- Developed a readout board for the characterization of LGADs
  - Final goal is to have tens of channels on one board: need to learn!
  - Similar boards developed previously by others for 1- or 2-channels
  - FNAL 4-ch board is cheaper, simpler, and is as good as the alternatives
  - FNAL board is now being used at UCSB, UCSC, KIT, CERN, and more are being prepared





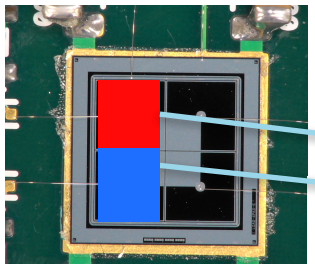
Sensor R&D and testing

- Collaborative effort with CMS & ATLAS institutes:
  - Caltech, FNAL, Univ. of Kansas, Univ. of Torino, UC Santa Cruz
  - Close collaboration with Hamamatsu, CNM, FBK
- Characterization of newest LGAD sensors: irradiated & unirradiated
  - Fermilab and LDRD was critical for the success of this campaign: FTBF, SiDet, support of technicians and engineers, readout board desing and production
  - Precision tracking detector available at FTBF: **unparalleled precision** of measurements

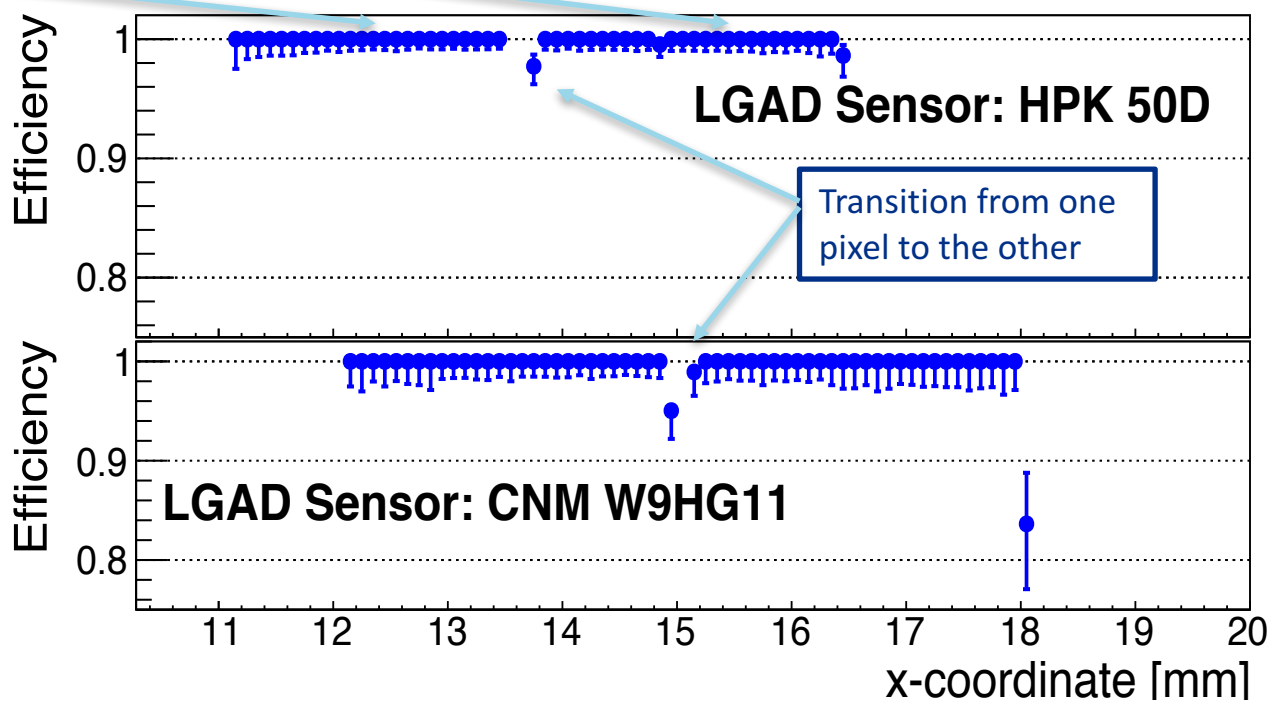


LGAD sensor uniformity

- We observe a flat 100% efficiency across the whole sensor area.
- A clear drop in efficiency is observed in the transition region between the two pixels



100% particle detection efficiency across the sensitive area



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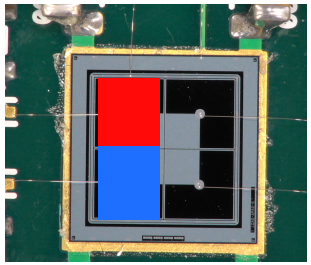
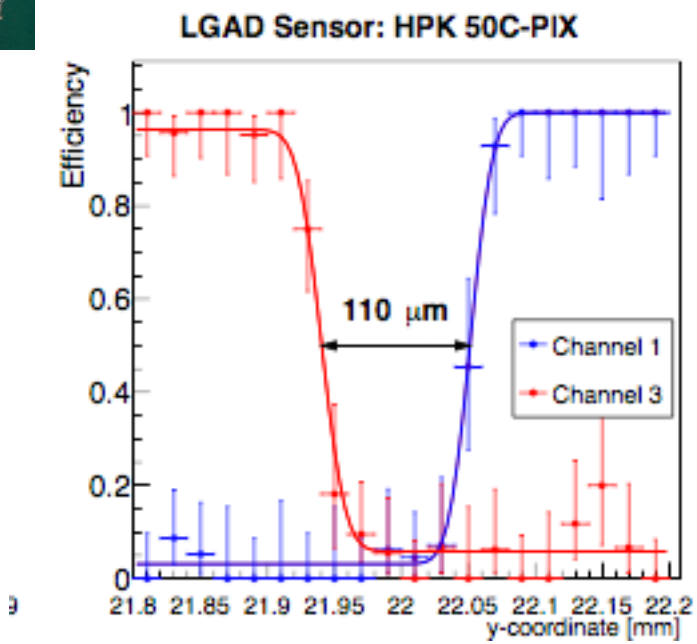
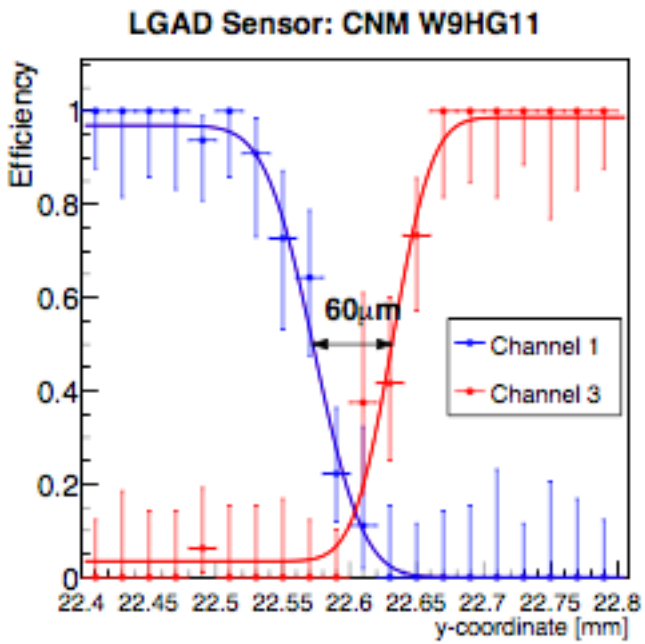
LGAD interpixel ”no-response area”

- Thanks to the pixel telescope in the FTBF, for the first time we can look into the LGAD behavior between pixels
  - We measure the no-response width to be around 110µm on the HPK sensor. And around 70 µm on CNM sensors.

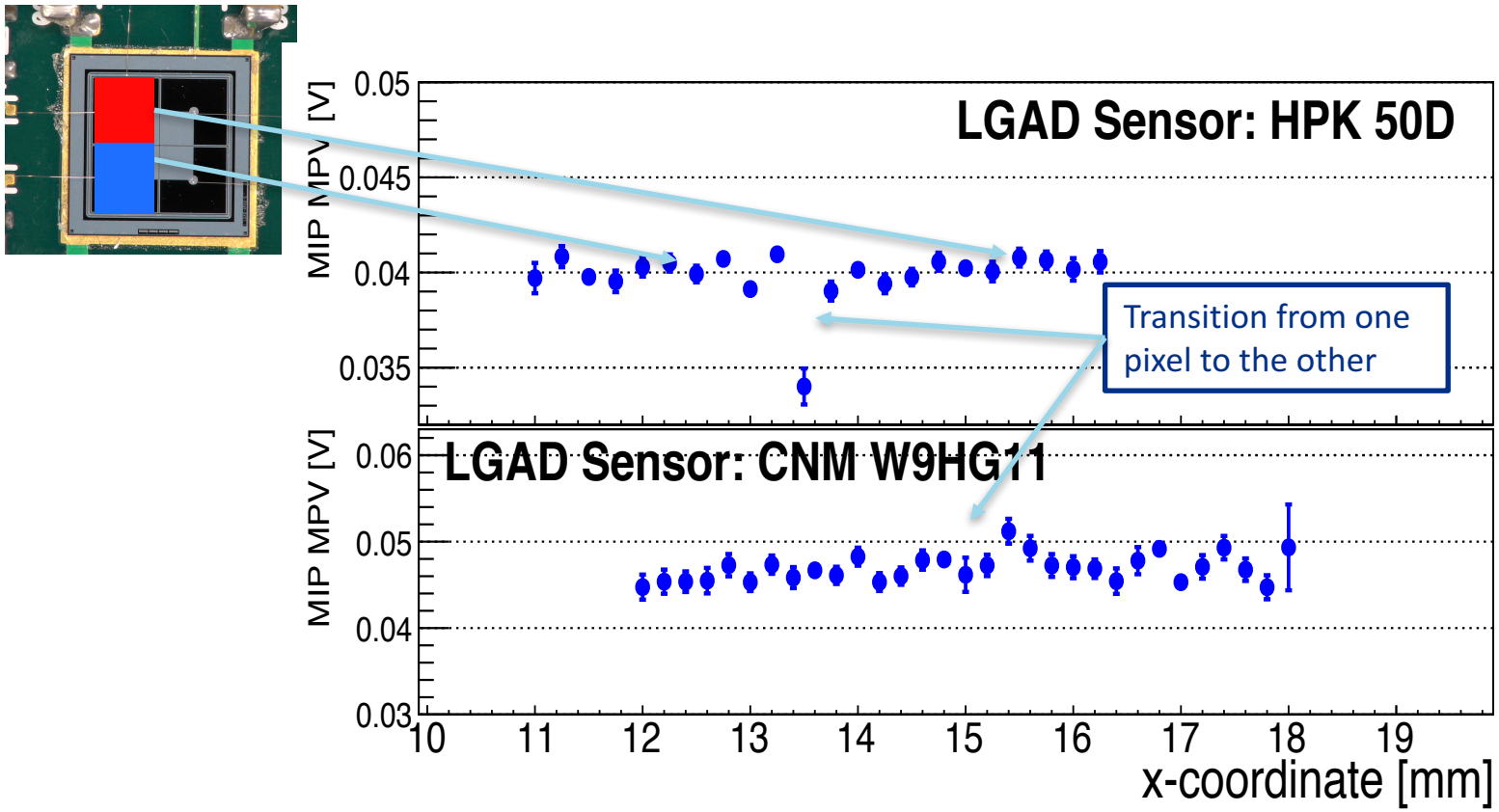






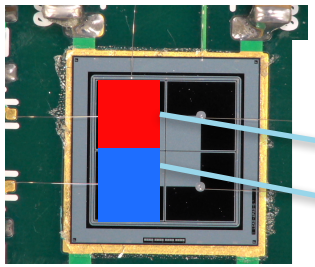
LGAD sensor uniformity

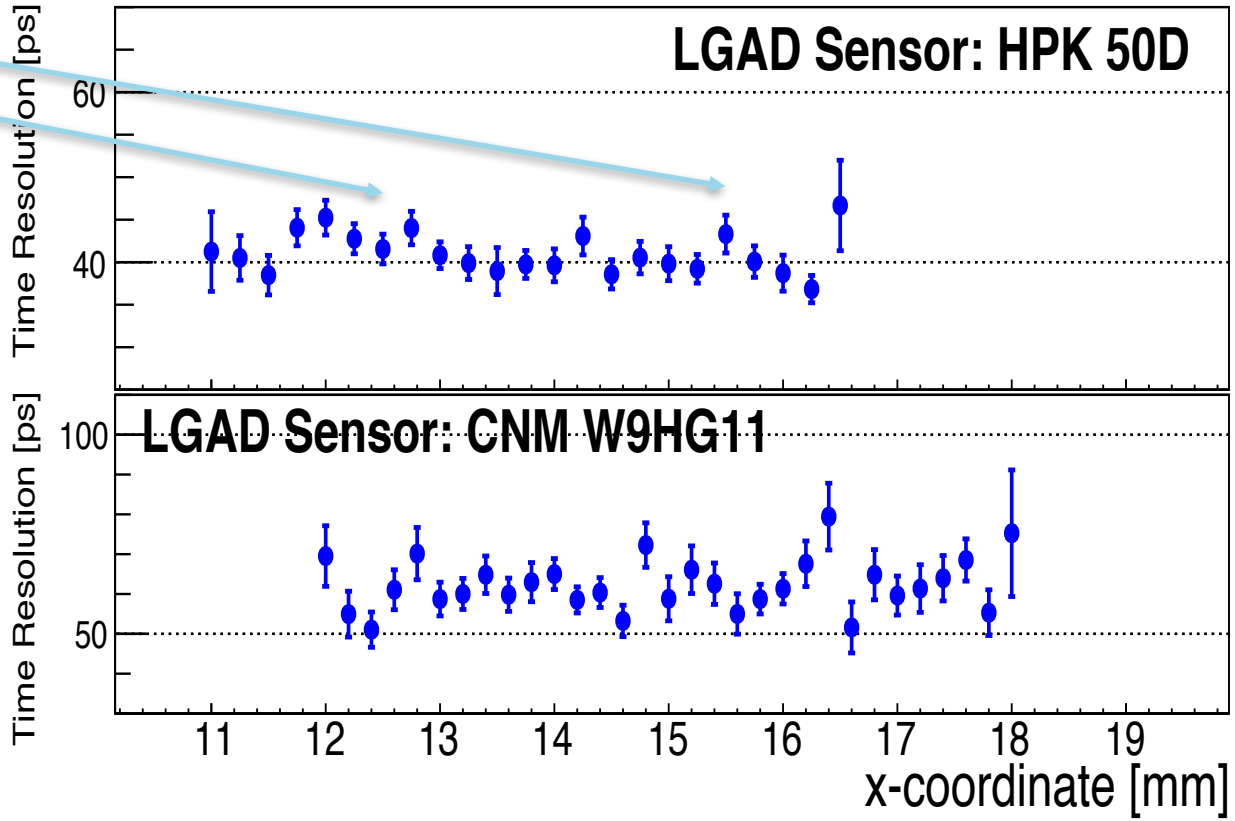
- Very uniform gain distribution across sensor surface
  - A flat response with a uniform signal size is observed over the whole sensor area



LGAD sensor uniformity

- We observe a uniform time resolution around 40 ps across the whole surface area for HPK, and around 55 ps for CNM sensors.





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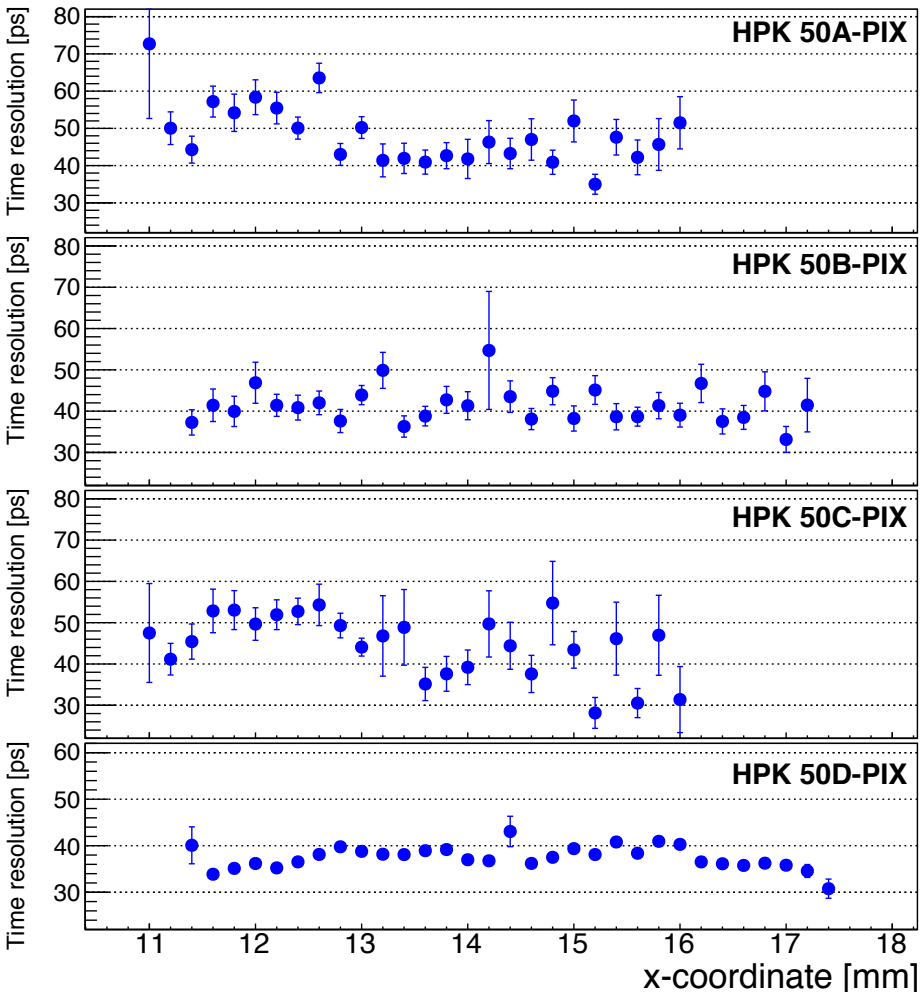
Comparison of HPK doping profiles

- Dependence of the sensors' characteristics on the doping concentrations were performed by comparing the 50 µm HPK sensors of different gain splits.
  - Difference between doping concentrations of adjacent splits is about 4%



We observe a uniform time resolution around 40 ps across the whole sensor area

Some difference between adjacent sensors due to KU board having variations on between channels

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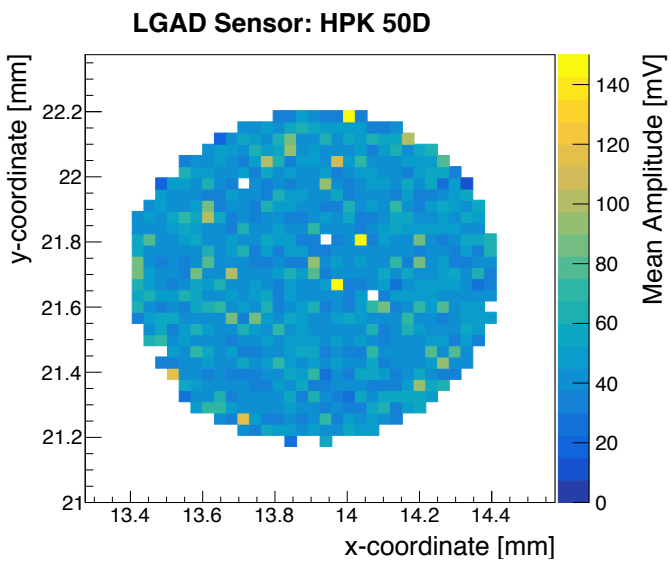
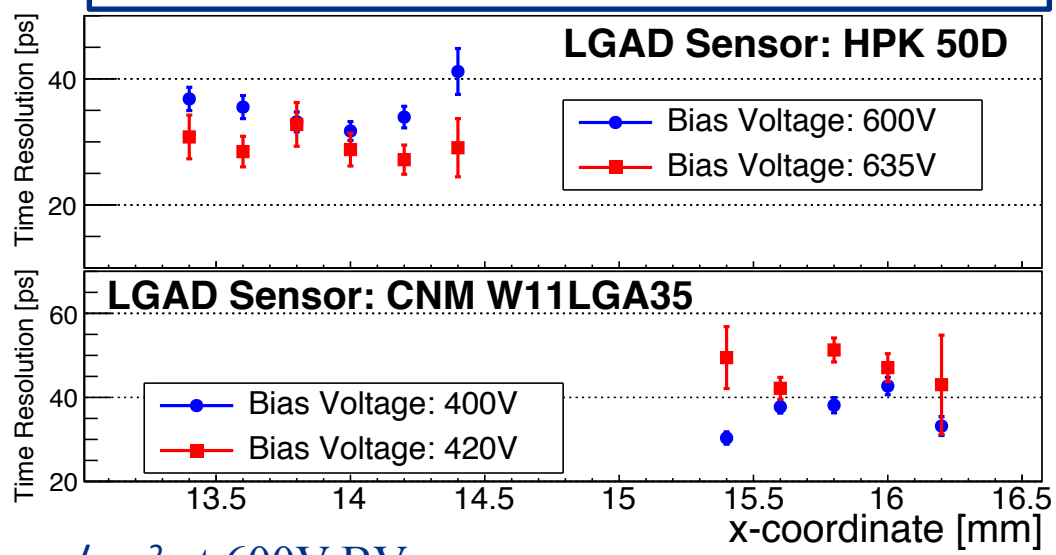
Irradiated HPK sensors performance

- Irradiation causes gain layer to fade
  - To preserve time resolution and gain, need to increase the operating bias voltage
  - Excellent uniformity of signal across the irradiated HPK sensor area
- Time resolution slightly improves with the increase of the bias voltage, and shows a uniform distribution across the sensor, around 30 ps



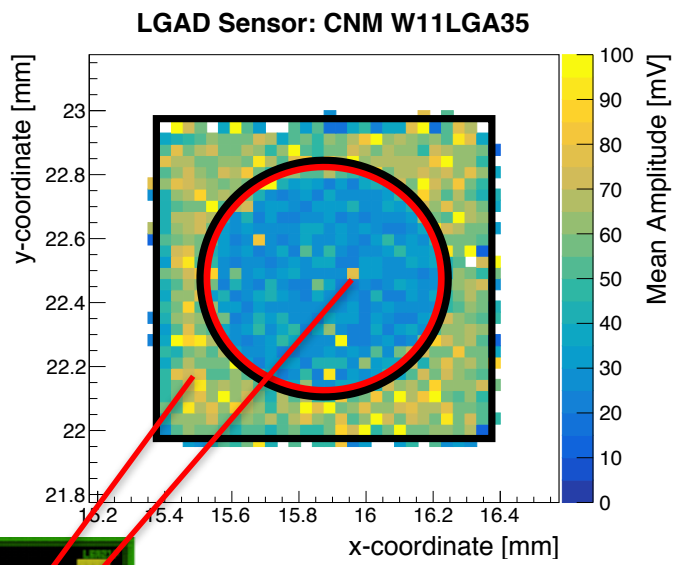
High uniformity of signal over irradiated sensor area



HPK 6 x 10^{14} n.eq/cm^2 at 600V BV

Irradiated CNM sensors performance

- Two distinct regions can be identified on the sensor based on the signal amplitude:
  - Different behavior under the aluminum metallization, and the region in the center
- The highest bias voltage reached is –420 V and the timing resolution is 30 ps for the metallized part and 40 ps for the non-metallized area.



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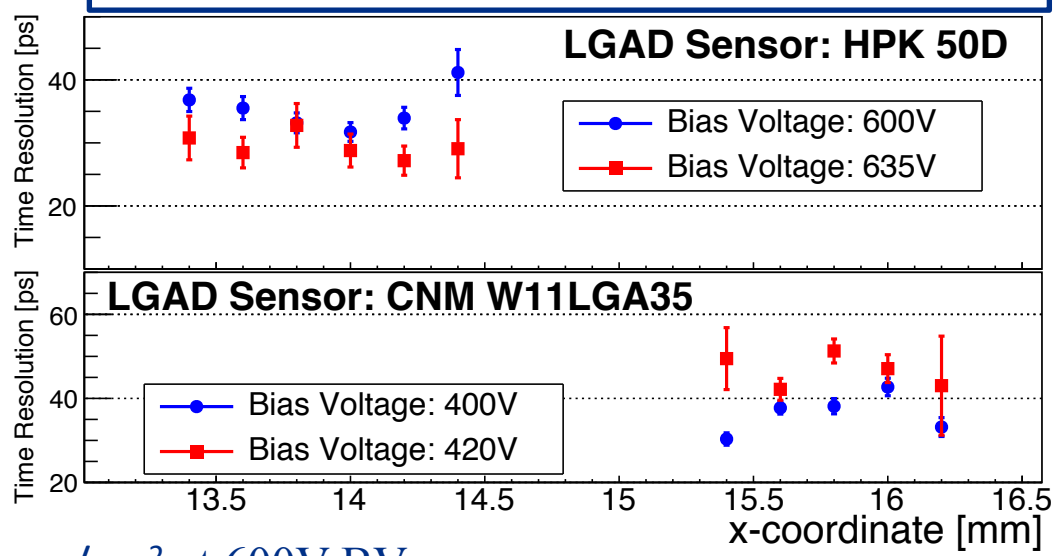

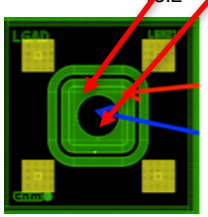

HPK 6 x 10^{14} n.eq/cm^2 at 600V BV

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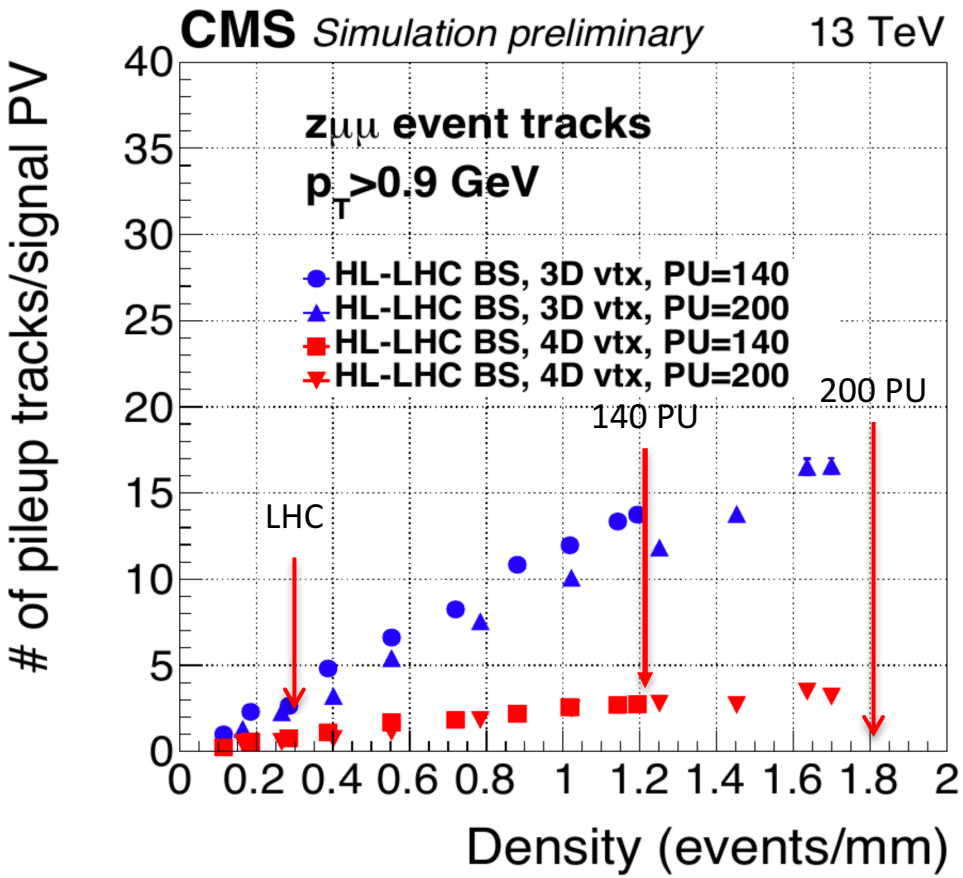
Summary

- Excellent start to the LDRD program
  - Extremely successful test beam campaign, many first measurements
  - 1st paper on sensor performance is to be submitted by end of August. 2nd paper on board performance to follow soon
- Measurement presented (will be) at several conferences
  - RD50 collaboration meeting, AWLC2017, Hiroshima symposium
  - Collaborations with various institutes established
- We have contacted the manufacturers (CNM, HPK, FBK) to proceed to the next stage of the R&D targeting larger sensor arrays
  - Expect next batch of production within 6-8 months

Backup

Vertex reconstruction with timing



- ~ 5x reduction in effective pileup in terms of charge multiplicity

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