# Precision timing with the CMS ETL detector in the Phase 2 upgrade

# University of Science and Technology of China

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中国物理学会高能物理分会第十四届全国粒子物理学术会议





### HL-LHC upgrade and pileup challenge

Upgrade of the accelerator complex optics and injectors to increase the beam intensity

- 140 200 collisions / beam crossing, > 10000 tracks / beam crossing (40 MHz)
- target luminosity 3000 fb<sup>-1</sup>
- 1 year of HL-LHC equivalent to ~10 years of LHC!



CMS DP-2023-087









### **CMS MIP Timing Detector (MTD): New Precision Timing Measurement**



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### **Reduction of pileup tracks in charged** isolation cone of ΔR<0.3 around

Reduction of pile-up by MTD enhances physics object reconstruction ( $\mu$ ,  $\tau$ , b-tagged jets etc)

especially beneficial for multi-particle final states, e.g. 10 - 20% gain in SM di-Higgs significance significance

**Pileup mitigation with MTD** 





# **Charged hadron identification**

- Measurement of velocity for low *p*<sub>T</sub> hadrons, enabling particle identification:
  - $\pi/K$  separation up to 3 GeV
  - p/K separation up to 5 GeV



- Measurements of heavy flavor particles of interest to study evolution of QGP
- CMS, Alice and LHCb have complementary PID capabilities in terms of rapidity coverage

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### Mass reconstruction of long lived particles (LLP)

- Mass of LLP can be reconstructed with timing plus kinematics of visible part of LLP decay!
  Fundamentally changes how we carry out these searches
- Example: top-squark pair production and decay in gauge-mediated SUSY breaking scenario. The lightest neutralino  $\tilde{\chi}_0^1$  is long-lived, velocity could be measured with MTD:



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## **CMS MIP Timing Detector Overview**

the production time of MIPs



### **CMS-TDR-020** March 2019

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• MTD add completely new capability to CMS: measure precisely (30-70 ps resolution)

• Choice of sensor technologies for barrel and endcap timing layers driven by technology maturity, radiation hardness, power consumption, and cost and schedule considerations.





# **ETL detector layout**

Each endcap is comprised of 2 disks

- 16x16 LGAD, bump-bonded to the ETL read-out chip (ETROC)
- providing up to two measurements (50 ps/hit) per track (40 ps)

Coverage:

- z = 3 m from pp interaction, supported on HGC nose
- coverage  $1.6 < |\eta| < 3.0$
- 0.315 m < R < 1.2 m









# **ETL Detector Layout**



- 1: ETL Thermal Screen
- 2: Disk 1, Face 1
- Disk 1 Support Plate 3:
- Disk 1, Face 2 4:
- ETL Mounting Bracket 5:
- 6: Disk 2, Face 1
- 7: Disk 2 Support Plate
- 8: Disk 2, Face 2
- 9: HGCal Neutron Moderator
- 10: ETL Support Cone
- 11: Support cone insulation
- 12: HGCal Thermal Screen





### **ETL sensor: LGAD**

CMS ETL LGAD sensor requirements

- 1.3 x1.3 mm<sup>2</sup> pads for a total surface of 21.4 x 21.6 mm<sup>2</sup>
- 16 x 16 channel per sensor
- gain 10-30
- time resolution < 50 ps (per/hit) @  $1.7 \times 10^{15} n_{eq}/cm^2$
- depletion region thickness: 50 μm
- LGAD deliver > 8 fC
- ETL need 8.6 million channels
- ETL will comprise ~ 35k LGAD sensors (20% spare sensors included)

### A wafer of the FBK UFSD4 production









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## **Performance of prototype ETL detector**

Test results with ETROC1 wire-bonded to LGAD sensor demonstrate expected performance. 





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### **ETL sensor modules**



# between the module PCB and a baseplate

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ETL module: Four LGADs bump-bonded to the ETROC ASIC, arranged





### **USTC joined CMS-ETL since 2023**

- 依托核探测与核电子学国家重点实验室科大先进的LGAD研究测试平台





祥,张德,范北昆(研究生),鲁楠和胡雪野(教职工)



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### **CMS Large LGAD matrix characterization at USTC**

### Using existing 15x15 LGAD matrix IV/CV measurement setup designed by USTC







- Per channel IV/CV measurement enabled by probe card + switch board
  - all other channels are grounded
  - Switch board: <u>https://doi.org/10.1016/j.nima.2022.167008</u>









### **CMS Large LGAD matrix characterization at USTC**

### A1519 VBD hist Mean=157.41 RMS/Mean=0.1712 Unit: V

	170.68 A04 170.64	170.64 804 125.76	170.59 C04 170.56	170.12 D04	165.04 E04	165.85 F04	165.95 G04	145.31 H06 165.88	140 G27 165.86	165.87 F27	166.06 E27	165.92 D27 145.03	170.66 C27 170.66	170.57 B27	25.12 AUT 170.32		40
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	170.68 A05	170.61 805	170.57 C05	170.61 D05	165.05 E05	165.84 F05	165.96 G05	165.84 H25	165.87 G26	165.86 F26	130.07 E26	165.87 D26	170.69 C26	170.66 B26	52.04 A26		
5	170.66 A06	170.6 806	104.63 C06	160.01 D06	165.05 E06	160.02 F06	165.45 G06	165.84 H07	165.83 G25	165.85 F25	166.09 E25	155.1 D25	170.14 C25	170.64 825	170.59 A25		60
3	170.62 A07	170.64 807	165.43 C07	119.94 D07	165.05 E07	145.01 F07	165.11 G07	160.34 H24	130 624	165.45 F24	166.18 E24	165.93 D24	170.65 C24	170.69 824	170.67 A24		00
	170.62 A08	170.6 808	157.15 C08	101.02	155.01 E08	165.86 F08	165.92 G08	165.83 H09	60.01 623	165.84 F23	166.15 E23	165.79 D23	170.57 C23	170.67 823	170.63 A23		80
	170.61 A09	165.74 809	170.57 C09	170.39 D09	165.05 E09	165.89 F09	165.9 G09	165.84 H22	165.8 G22	165.81 F22	166.12 E22	120.34 D22	115.01 C22	170.62 822	170.29 A22		100
10	170.63	76.2	170.54	150.01 D10	165.04 E10	119.31 F10	165.78 G10	165.82 H10	165.85 621	165.88 F21	166.11 E21	165.95 D21	160.01	170.58 B21	166.74 A21		
10	143.28	170.36 B11	102.16	170.56 D11	165.04 E11	25,39	165.82 G11	165.81 H21	165.87 G20	165.87 F20	165.84 E20	165.89 D20	170.57 C20	170.59 B20	170.58 A20	-	120
	170.66	170.65 B12	166.78 C12	170.48 D12	165.05 E12	165.85 F12	165.82 G12	165.53 H11	165.85 G19	165.05 F19	166.13 E19	165.88 D19	170.56 C19	170.61 B19	160.01 A19		
	170.66 A13	170.66 B13	170.23 C13	166.16 D13	165.05 E13	165.86 F13	165.38 G13	165.78 H20	165.8 G18	165.85 F18	166.15 E18	165.22 D18	104.86 C18	170.57 B18	170.52 A18		140
	170.63 A14	170.51 B14	170.2 C14	121.34 D14	165.05 E14	165.28 F14	165.85 G14	136.34 H12	165.82 G17	165.86 F17	166.15 E17	165.52 D17	65.08 C17	25.01	140.02 A17		100
15	170.57 A15	170.55 B15	170.64 C15	165 D15	165.01 E15	165.9 F15	165.68 G15	115 H19	165.84 G16	165.84 F16	150.11 E16	165.95 D16	170.25 C16	170.49 B16	170.5 A16		160
	15 10 5	15 170.57 A15 170.63 A14 170.66 A13 170.66 A13 170.66 A13 170.66 A11 170.63 A11 170.63 A11 170.63 A11 170.63 A11 170.63 A11 170.63 A11 170.63 A11 170.66 A13 170.66 A16 A17 170.63 A10 170.66 A08 170.62 A08 170.66 A08	10 170.57 170.55 A15 B15 170.63 170.51 B14 170.66 170.66 A13 170.66 170.66 170.65 B12 143.28 170.36 A11 1811 170.63 76.2 B10 170.61 165.74 B09 170.62 170.6 B08 170.62 170.64 B08 170.66 170.65 B08 170.62 170.64 B08 170.68 170.61 B06	10     170.57     170.55     170.64       170.63     170.51     170.2       170.66     170.65     170.23       170.66     170.65     170.23       170.66     170.65     166.78       170.66     170.65     166.78       170.63     170.36     102.16       170.63     76.2     170.54       170.61     165.74     170.57       170.62     170.6     157.15       170.62     170.64     165.43       170.62     170.64     165.43       170.66     170.6     104.63       170.68     170.61     105.57	$10 \begin{bmatrix} 170.57 & 170.55 & 170.64 & 165 \\ 170.63 & 170.51 & 170.2 & 121.34 \\ 170.63 & 170.66 & 170.23 & 166.16 \\ 170.66 & 170.65 & 166.78 & 170.48 \\ 170.66 & 170.65 & 166.78 & 170.48 \\ 143.28 & 170.36 & 102.16 & 170.56 \\ 143.18 & 170.36 & 102.16 & 170.56 \\ 143.0 & 76.2 & 170.54 & 150.01 \\ 170.61 & 165.74 & 170.57 & 170.39 \\ 170.62 & 170.6 & 157.15 & 101.02 \\ 170.62 & 170.64 & 165.43 & 119.94 \\ 170.66 & 170.64 & 165.43 & 119.94 \\ 170.66 & 170.64 & 165.43 & 160.01 \\ 170.68 & 170.6 & 104.63 & 160.01 \\ 170.68 & 170.61 & 100.65 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 100.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 \\ 170.68 & 170.61 & 170.57 & 170.61 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  170.64     165     165.01     165.9       170.63     170.51     170.2     121.34     165.05     165.28       170.64     170.66     170.66     170.23     166.16     165.05     165.86       170.66     170.65     166.78     170.48     165.05     165.86       170.66     170.65     166.78     170.48     165.05     165.85       170.66     170.65     166.78     170.48     165.05     165.85       170.66     170.35     162.16     170.55     165.85     165.85       170.61     170.35     165.04     25.39     165.04     25.39       10     143.28     170.36     102.16     170.56     165.04     25.39       170.63     76.2     170.54     150.01     165.04     19.31       170.61     165.74     170.57     170.39     165.05     165.89       170.62     170.64     157.15     101.02     155.01     165.86       170.62	10   170.57   170.55   170.64   165   165.01   165.9   165.68     170.63   170.51   170.2   121.34   165.05   165.28   165.85     170.66   170.66   170.66   170.23   166.16   165.05   165.86   165.38     170.66   170.66   170.65   166.78   170.48   165.05   165.85   165.82     170.66   170.65   166.78   170.48   165.05   165.85   165.82     170.66   170.65   166.78   170.56   165.85   165.82   165.82     143.28   170.36   102.16   170.56   165.04   25.39   165.82     143.28   170.36   102.16   170.56   165.04   19.31   165.78     170.61   165.74   170.57   170.39   165.05   165.89   165.92     170.62   170.66   157.15   101.02   155.01   165.86   165.92     170.62   170.64   165.43   119.94   165.05   145.01   165.11     170.62   170.64   165.43	$10 \begin{bmatrix} 170.57 & 170.55 & 170.64 & 165 & 165.01 & 165.9 & 165.68 & 115 \\ 170.63 & 170.51 & 170.2 & 121.34 & 165.05 & 165.28 & 165.85 & 136.34 \\ 170.66 & 170.66 & 170.23 & 166.16 & 165.05 & 165.86 & 165.38 & 165.78 \\ 170.66 & 170.65 & 166.78 & 170.48 & 165.05 & 165.85 & 165.82 & 165.53 \\ 170.66 & 170.36 & 102.16 & 170.56 & 165.04 & 25.39 & 165.82 & 165.81 \\ 143.28 & 170.36 & 102.16 & 170.56 & 165.04 & 25.39 & 165.82 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170.57 & 170.61 & 165.05 & 165.94 & 165.95 & 165.84 & 165.83 \\ 170.68 & 170.61 & 170.57 & 170.61 & 165.05 & 160.02 & 165.45 & 165.84 & 165.83 \\ 170.68 & 170.61 & 170.57 & 170.61 & 165.05 & 160.02 & 165.45 & 165.84 & 165.83 \\ 170.68 & 170.61 & 170.57 & 170.61 & 165.05 & 165.94 & 165.95 & 165.84 & 165.83 & 165.87 \\ 170.68 & 170.61 & 170.57 & 170.61 & 165.05 & 160.02 & 165.45 & 165.84 & 165.83 & 165.87 \\ 170.68 & 170.61 & 170.57 & 170.61 & 165.05 & 165.84 & 165.96 & 165.84 & 165.87 & 165.87 & 165.84 & 165.85 & 165.84 & 165.84 & 165.87 & 165.84 & 165.85 & 165.84 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.84 & $	$10 \begin{bmatrix} 17\\ 170.57\\ 170.55\\ 170.63\\ 170.63\\ 170.63\\ 170.66\\ 170.65\\ 170.66\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.66\\ 170.65\\ 170.65\\ 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    170.57     170.55     170.64     165.01     165.9     165.68     115     165.84     165.84     165.84     165.84     165.85	10   170.57   170.55   170.64   165   165.01   165.9   165.68   115   165.84   165.84   150.11   165.85   170.25   170.55   170.55   170.25   170.55   170.24   121.34   165.05   165.28   165.85   136.34   165.82   165.85   16	$10^{10} \begin{bmatrix} 170.57 & 170.55 & 170.64 & 165 & 165.01 & 165.9 & 165.68 & 115 & 165.84 & 165.84 & 150.11 & 165.95 & 170.25 & 170.49 \\ 170.63 & 170.51 & 170.2 & 121.34 & 165.05 & 165.28 & 165.85 & 136.34 & 165.82 & 165.86 & 166.15 & 165.22 & 65.08 & 25.01 \\ 170.66 & 170.66 & 170.23 & 166.16 & 165.05 & 165.86 & 165.38 & 165.78 & 165.85 & 166.15 & 165.22 & 104.86 & 170.57 \\ 170.66 & 170.65 & 166.78 & 170.48 & 165.05 & 165.85 & 165.82 & 165.85 & 165.85 & 165.85 & 166.15 & 165.22 & 104.86 & 170.57 \\ 170.66 & 170.65 & 166.78 & 170.48 & 165.05 & 165.85 & 165.82 & 165.83 & 165.85 & 165.85 & 166.13 & 165.88 & 170.56 & 170.61 \\ 143.28 & 170.36 & 102.16 & 170.56 & 165.04 & 25.39 & 165.81 & 165.87 & 165.87 & 165.84 & 165.89 & 170.57 & 170.59 \\ 143.411 & 170.41 & 170.44 & 150.01 & 165.04 & 119.31 & 165.78 & 165.82 & 165.81 & 165.87 & 165.84 & 165.89 & 170.57 & 170.59 \\ 170.63 & 76.2 & 170.54 & 150.01 & 165.04 & 119.31 & 165.78 & 165.82 & 165.81 & 165.81 & 165.81 & 165.95 & 160.01 & 170.58 \\ 170.64 & 165.74 & 170.57 & 170.39 & 165.05 & 165.89 & 165.9 & 165.83 & 165.81 & 165.81 & 165.81 & 165.79 & 170.57 & 170.59 \\ 170.62 & 170.64 & 157.15 & 101.02 & 155.01 & 165.06 & 165.92 & 165.83 & 165.81 & 165.81 & 165.81 & 165.79 & 170.57 & 170.59 \\ 170.66 & 170.64 & 157.15 & 101.02 & 155.01 & 165.06 & 165.92 & 165.83 & 165.81 & 165.81 & 165.89 & 170.57 & 170.69 \\ 170.66 & 170.64 & 165.43 & 119.94 & 165.05 & 145.06 & 165.92 & 165.83 & 165.83 & 165.81 & 165.83 & 165.85 & 165.82 & 165.83 & 165.81 & 165.83 & 165.85 & 165.82 & 165.83 & 165.81 & 165.79 & 170.57 & 170.69 \\ 170.66 & 170.6 & 170.64 & 165.05 & 165.05 & 165.06 & 165.92 & 165.83 & 165.83 & 165.81 & 165.83 & 165.85 & 165.83 & 170.57 & 170.69 & 170.68 & 170.66 & 170.64 & 165.05 & 165.05 & 165.86 & 165.92 & 165.83 & 165.83 & 165.81 & 165.83 & 170.57 & 170.69 & 170.68 & 170.64 & 165.05 & 165.05 & 165.06 & 165.92 & 165.84 & 165.85 & 165.85 & 165.84 & 165.85 & 165.85 & 165.84 & 165.85 & 165.85 & 165.84 & 165.85 & 165.85 & 165.84 & 165.85 & 165.84 & 165.85 & 165.85 & 165.84 & 165.85 & 165.8$	170   170.57   170.55   170.54   165.01   165.9   165.91   165.91   165.91   165.91   165.92   165.84   165.84   165.85   180.34   165.82   165.85   165.85   180.34   165.82   165.85	10 = 10 = 10 = 10 = 10 = 10 = 10 = 10 =

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Nan Lu (USTC)

CNM is exploring in-kind contribution to ETL sensors

CNM provided us 15x15 sensor (ATLAS conditions) to measure breakdown voltage via IV measurement:

- Rate of good channels: 85% obtained from left plot
- The result is very well received: CNM very impressed by our characterization capability, they haven't seen such measurements before!
- CNM provided us 16x16 sensor (CMS condition with) better expected uniformity and performance) to characterize













### **CMS Large LGAD matrix characterization at USTC**

- Design and build the setup for 16x16 LGAD matrix at USTC
  - Zheng De design and produce switch matrix, based on 15x15 LGAD characterization experience
  - order 16x16 probe card with collaboration with INFN Torino group
  - Chengjun is leading students on commissioning the full system right now at USTC lab







LGAD Timeline:

- 2024: Freeze LGAD specifications + define quality management (QA/QC) procedures for the sensors production  $\rightarrow$  Invitation to Tender and final selection of the vendor(s)
  - decision if LGAD post-processing at vendor
- 2025: Beginning of the sensor production for ETL

Our ongoing work:

- To provide post-processed sensors for bump-bonding and module assembly + technology validation of CMS LGAD post-processing by vendor in China
  - four FBK 8 inch LGAD wafers will be post-processed by NCAP in late August
- Build LGAD QC centers in China USTC and SCNU

### ETL LGAD post-processing and preparation of QA center in China





### Summary and outlook

CMS MTD ETL, based on the LGAD technology, at last stage of detector prototyping and soon moving ahead to pre-production&production

- sensor production to start in 2025
- detector installation in CMS in 2027 2028

USTC contributed to LGAD characterisation during prototyping phase:

- Excellent measurement capability for 15x15 and 5x5 CMS LGAD sensors
- Work progress to design and build the 16x16 setup

Our ongoing&future work:

- validation of CMS LGAD post-processing by vendor in China
- Build LGAD QC centers in China USTC and SCNU

Close collaboration with SCNU, Shandong University and INFN Torino

To provide post-processed sensors for bump-bonding and module assembly + technology





# Thank you!

Nan Lu (USTC)







# backup slides

Nan Lu (USTC)







# **Tagging jets originating from bottom-quark**

- by reducing spurious secondary vertices
- caused by tracks from pileup interactions.



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• Improve b-jet tagging efficiency by 4–6% barrel (5–7% endcap)





# **MTD Physics Potential**



• 10 - 20% gain in di-Higgs significance

35  ps BTL, 35  ps ETL								
Channel	No MTD	ETL Only	BTL Only	MTD				
bbbb	0.88	0.90	0.93	0.95				
bb au au	1.30	1.38	1.52	1.60				
$bb\gamma\gamma$	1.70	1.75	1.85	1.90				
Combined	2.31	2.40	2.57	2.66				

**DP-Update\_MTD\_physics\_case\_v7:** https://twiki.cern.ch/twiki/bin/viewauth/CMS/AN-22-060





### **Requirements of the MIP timing detector**

	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Coverage	$ \eta  < 1.5$	$1.6 <  \eta  < 3.0$
Surface Area	38 m <sup>2</sup>	$12 m^2$
Power Budge	$0.5  kW/m^2$	$1.8 \ kW/m^2$
<b>Radiation Rose</b>	$\leq 2\times 10^{14} \ n_{eq}/cm^2$	$\leq 2\times 10^{15} \; n_{eq}/cm^2$

ETL: two disks of Low Gain Avalanche BTL: lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) crystal **Detectors (LGAD)**, same sensor read out with Silicon Photomultipliers technology as ATLAS High Granularity (SiPM) Timing Detector.







# Low Gain Avalanche Detectors (LGADs)

- LGAD: ultra-fast silicon detectors with a highly doped p+ gain layer for charge  $\bullet$ multiplication. Gain ~10-30



E field Traditional Silicon detector

### LGAD silicon sensors:

- maintaining very low noise
- fine segmentation
- thin sensor

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Technology choice of ATLAS High-Granularity Timing Detector (HGTD) and CMS ETL



• signals that are a factor of 10-20 larger than traditional silicon detectors







### **Precision timing at low power: ETROC ASIC**



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### **Performance specifications**:

- TSMC 65nm technology, 100 MRad (TID spec)
- Low noise and fast rise time
- Low power:  $\leq 4 \text{ mW}$  / channel at end-of-life
- ASIC contribution to time resolution  $\leq$  40 ps at endof-life

ETROCO: single analog channel ETROC1: with TDC, 4x4 channel-clock tree ETROC2: full size, full functionality, testing now! ETROC3: final chip, submit next year

