Applications of Detector Technology

DPF2019

Andy White
University of Texas at Arlington
Introduction

- An overview* of detector technologies as applied to a variety of experiments

- A technology/functionality approach:
  - Position measurement
  - Time measurement
  - Energy measurement
  - Particle ID measurement
  - Innovation/new ideas

- Perspectives on how technologies have moved us forward in our abilities to study physics.

- R&D Organizational Issues

*Note: this is personal selection; any mistakes are mine.
**ECFA Detector Panel Report**

P. Allport, A. Cattai, S. Dalla Torre, D. Eckstein, E. Koffeman, L. Linssen, L. Serin, A. Straessner

The ECFA Detector Panel
(http://ecfa-dp.desy.de/ - ecfadp@desy.de)

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?? NO Quantum Information Science listed ???
LHC – High Luminosity Upgrades
14 TeV, $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, $\langle \mu \rangle = 200$
$\int L \, dt = 3-4 \text{ ab}^{-1}$,
$\sim 10^{16} (1 \text{ MeV n eq})/\text{cm}^2$

**ATLAS Inner Tracker (Itk)**

- Barrel strip pitch 75.5$\mu$m
- Pixel pitch 50 x 50 or 25 x 100 $\mu$m$^2$

**RD50 Silicon Detectors for HL-LHC**

- **3D**
- **HV-CMOS**

- **Pixels and Strips**
- **Extended coverage**

- **RD53 readout chip**

Nathan Readioff
LHCP2019

M.Mandurrin CTD/WIT 2019
CMS Tracker Upgrade

Position Measurement

CMS Upgrade

https://doi.org/10.1016/j.nima.2018.11.023.

2S Modules
- Two strip sensors with 5 cm x 90 μm strips
- Sensor is 10x10 cm² - two sets of strips

PS Modules
- Module with one (Macro-)Pixel and one strip sensor

Significant material profile reduction

Luminosity measurement

Improved $P_T$ resolution

$\sigma(\delta P_T/P_T)$ [cm]

CMS Simulation

Simulated muons $p_T = 10$ GeV
- Phase-1 tracker
- Phase-2 tracker

Extended coverage

$\sigma(\delta \eta_p)$ [cm]

CMS Simulation

Simulated muons $p_T = 10$ GeV
- Phase-1 tracker
- Phase-2 tracker

G. Sgauzzoni, VCI2019

7/31/2019 A. White/UTA DPF2019
VELO Upgrade I (for Run 3):
Luminosity $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \rightarrow 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
No hardware trigger – 40 MHz r/o (was 1 MHz)
41M pixels, 3.5 mm from beam
Micro-channel cooling
VELOPix ASIC derived from TimePix3
130nm CMOS, $55 \times 55 \ \mu\text{m}$ pixels;
Sensor: Hamamatsu n-on-p 200$\mu$m

VELO Upgrade II:
Add 100ps timing for pixels
HL-LHC 50 PV/bunch
and $2 < \eta < 5$ acceptance

Recovered with $O(100\text{ps})$ timing measurements of pixel hits.
ALICE Inner Tracker Upgrade

**ALPIDE** is the core of the new ITS

Monolithic CMOS 180nm

**Goals:**
- High precision QGP studies esp. at low Pt
- Heavy flavor and quarkonia

**Position Measurement**

**New ITS layout**

- 7 layers of Monolithic Active Pixel Sensors (MAPS)
  - 3 Inner Layers (Inner Barrel)
  - 2 Middle + 2 Outer layers (Outer Barrel)
- Total area: ~10 m²
- $|\eta|$ coverage: $|\eta| < 1.22$
- $r$ coverage: 22 – 400 mm

**Run 3**

- Inner Barrel (IB)
- Outer Barrel (IB)

**Material budget:** $1.1\% X_0 \rightarrow 0.3\% X_0$ (inner layers)

**Pixel size:** $50 \times 425 \mu m^2 \rightarrow 30 \times 30 \mu m^2$

**Closer to the vertex** (first layer radius): $39 \text{ mm} \rightarrow 22 \text{ mm}$

*Inner Barrel Production completed and all layers assembled*

**Run 4**

- Ultra thin (< 30μm) wafer-scale CMOS sensors.
- Few μm spatial resolution.

**Impact parameter resolution**

**Track reconstruction efficiency**

**B^− \rightarrow J/\Psi(\rightarrow ee) + K^+**
Position Measurement

SiD Detector for ILC

Very challenging requirements
• < 3 µm hit resolution
• Feature size ~20 µm
• ~0.1% X0 per layer material budget
• < 130 µW / mm²
• Single bunch time resolution

Chronopixel - Oregon, Yale

Chronopixel prototype 3 development board

• monolithic CMOS design
  90 nm feature size,
  7 µm epitaxial layer
  280 µm thick chip
  10 ohm-cm
  manufactured by TSMC
• store up to 2 hits per pixel, 12 bit per timestamps
• 25 µm pixel pitch
• implements 6 sensor diode options

Preliminary ideas for mechanical design.
Power pulsing, forced air cooling

Pair envelope study – Anna Schuetz (DESY)

Vertically Integrated (“3D”)
Position Measurement

SiD Detector for ILC Main Tracker

**Baseline**
- All Silicon Tracker
  - Using Silicon micro-strips
  - 25 µm pitch / 50 µm readout
  - v2 sensor prototype July 2017*
- 5 barrel layers / 4 disks
- Tracking unified with vertex detector
  - 10 layers in barrel
- Gas-cooled
- Material budget < 20% $X_0$ in the active region
- Readout using KPIX ASIC
  - Same readout as ECAL
  - Bump-bonded directly to the module

**Beam tests ongoing - DESY**

**Goal – full prototype test:**

**sensor + kPix + cables**

- Pixel tracker option and alignment methods (Bristol)
- Carbon fiber structures for low material, integrated services (Oxford, Lancaster, Liverpool)

**MAPS/Pixel tracker option**

kPixM – optimized for tracker, 40µm x 500µm pixels. Position resn. < 14µm, S/N >20
Position Measurement

Single phase
Active volume of 12m x 15m x 58m

Dual phase

ProtoDUNE hosted at CERN in a new facility

Stefan Söldner-Rembold

7/31/2019
Lepton flavor violation

\[ R_{\mu e} = \frac{\Gamma (\mu^- + N(A,Z)) \to e^- + N(A,Z)}{\Gamma (\mu^- + N(A,Z)) \to \text{all muon captures}} \leq 8 \times 10^{-17} \text{ at } 90\% \text{ C.L.} \]

10^4 improvement!

Tracker must measure momentum with better than 0.2% resolution to separate conversion electrons from normal muon decay products

Straws (15\(\mu\)m) account for only about half of the active detector mass, comparable to the drift gas inside

Straw and Sense Wire

Mu2e TDR

Low mass metalized Mylar
~20K straws, 5mm

Kate Ciampa, Fermilab 2018
Time Measurement

ATLAS High Granularity Timing Detector

LGAD Sensor

Precision timing:
Short rise time (thin)
Large signal
Low noise

Require $\Delta t \sim 30$ps
35ps achieved so far

Occupancy < 10%
1.3mm x 1.3mm pixels

After $5 \times 10^{15}$ n/cm$^2$
$\Delta t \sim 40$-50ps

e.g. Higgs $\rightarrow$ invisible analysis
Use correct VBF jet in q/g tagging.

VCI 2019, Bengt Lund-Jensen; A. Schwartzman, ICHEP2019
Time Measurement

CMS MIP Timing Detector

LYSO-Ce + SiPM

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<2.9$

Wrapping -> better time resolution

L. Masetti    CTD/WIT Valencia

Test beam results (LYSO-Ce)

LYSO: Ge 3x3x50 mm$^3$ - HPK 3x3 mm$^2$ (15 μm)

30 ps →

L. Masetti    CTD/WIT Valencia

Wrapping -> better time resolution

L. Masetti    CTD/WIT Valencia
Time Measurement

PICOssecond Collaboration (RD51 - MPGD)

Classic MicroMegas

New

MIPs

\[ \chi^2 / \text{ndf} = 73.26 / 45 \]
\[ \mu = 2.7451 \pm 0.0004 \text{ ns} \]
\[ \sigma_1 = 20.9 \pm 0.3 \text{ ps} \]
\[ \sigma_2 = 38.9 \pm 1.1 \text{ ps} \]
\[ \sigma_{\text{Tot}} = 24.0 \pm 0.3 \text{ ps} \]

Synchronous p.e. enter the 2nd stage

Time Resolution depends mostly on e-peak charge

Ioannis Manthos talk at MPGD2019

Best time resolution: 24ps 24.0±0.3 ps

Energy Measurement

Goal of ~3% jet energy resolution for ILC experiments, W/Z separation, high precision studies. (H. Videau, J-C Brient)

High Granularity Calorimetry

CMS HGCAL + CALICE AHCAL

CALICE combined physics prototype

Towards an engineering design

ILD HCal

SiD

CALICE SiW ECAl

CALICE Test Beam AHCAL results vs. SiD Simulation

A. White/UTA  DPF2019
Energy Measurement

CMS Endcap Calorimeter Replacement

R. Yohay
VCI 2019

Great detail – 80 GeV electron!
**Energy Measurement**

Tests of a dual-readout fiber calorimeter with SiPM light sensors

2 Cu modules

Pb 3×3 matrix

![Image 2x324 to 505x482]
![Image 13x313 to 197x435]
![Image 223x350 to 360x435]
![Image 509x316 to 700x434]

C ↔ S crosstalk measured ~0.3-0.4%

Using beam muons

112 cm long, 15 x 15 mm² wide

IDEA Detector for FCCee Dual Readout Calorimeter

Evolution from DREAM-RD52

Massimiliano Antonello - FCC week 2018
Lorenzo Pezzotti - CALOR 2018

7/31/2019 A. White/UTA DPF2019
Energy Measurement

Neutrino experiments – need **good measurement of initial flux** (low systematics ~1%) to preserve CPV discovery potential and physics understanding

The ENUBET project

- Fully instrumented decay region
- $K^+ \rightarrow e^+ \nu_e \pi^0 (K_{e3})$
- Large angle $e^+$ (~90 mrad)
- $\nu_e$ flux prediction = $e^+$ counting

**e+ tagging: challenging task**

- Injecting $10^{10}$ $n^+$ in a 2 ms spill

**Shashlik “UCM”**

Ultra Compact Module

- WLS fibers; FBK SiPMs

**Polysiloxane calorimeter**

- No drilling of scintillator
- Pour over fibers
- Soft solid at room temp.
- X10 rad. Hardness
- ~30% light yield
- Best optical contact w/fibers


G. Ballerini et al, JINST 13 (2018) P01028
Particle ID

Belle II aerogel RICH detector, Imaging TOP

Target performance: K/π separation at > 4σ C.L. @ 0.5 < p < 4 GeV/c

Rare B-decays (NP sensitive) require good K/π separation up to 4 GeV/c

Micro-channel plate (MCP) photon sensors

Silica aerogel dual focusing radiator

Imaging TOP (Time Of Propagation)
Very limited space (2cm!)

Channel:
\( D^* \rightarrow D^0 \pi^+_\text{S} \) with \( D^0 \rightarrow K^- \pi^+ \)

\( \phi \) decaying to kaons
TOP particle identification only

Single photon timing \( \sigma \sim 100 \text{ ps} \)

Martin Bessner
VCI 2019

NIM A907 (2018) 46-59
A. White/UTA DPF2019

Leonid Burmistrov VCI2019
Particle ID

LHCb – TORCH
Time Of internally Reflected Cerenkov light

10m path ~35ps → Need $\sigma_t \sim 10-15$ps
(70ps/photon, 30 photons/charged track)
Quartz (1cm) – fast signal
Micro-Channel Plate PMTs

Goal: distinguish $\pi/K/p$ 2-10 GeV
(Currently no positive kaon or proton identification below 10 GeV/c)

Simulation – heavy flavor production
arXiv:1812.09773v1

Long-term test of MCP-PMT

5 GeV/c pion beam
Best achieved is $88.8 \pm 1.3$ ps

Thomas H. Hancock – VCI2019
Innovation

Carbon nanotubes for HEP?

HEP goal ~1µm?
CNT pixels...how small?

~1M CNT FETs
Initial use – gas molecule detection
-> X-ray imaging
?-> HEP particles?
$0\nu\beta\beta$ - Barium Tagging

(N. Byrnes – talk at this meeting)

- Detection of neutrinoless double beta decay with background <0.1 counts per ton per year in the ROI is a formidable experimental challenge.
- Energy resolution better than 1% FWHM coupled with detection of a single barium ion in Xe has long been recognized as a background-free method.
- Recent important progress in “barium tagging” has yielded single ion sensitivity.

Novel dry chemosensor development


Innovation - QIS

Exploiting small quantum level changes for new particle/field detection?

How to improve precision measurements using spin state “squeezing”?

How to use entanglement to couple across arrays of quantum systems?

How to leverage use of QIS for HEP?
Perspectives on the Development and Applications of New Technologies

Technology has taken us to a new level of detector functionality for high energy physics (high precision tracking, track triggering, precise timing, imaging calorimetry,...)

1) Need driven solutions
   - e.g. LHC environment – radiation and pile-up
     Enabling new physics studies at heavy ion colliders

2) Availability of new device(s)
   - e.g. use of SiPM’s to enable practical designs for HG and DR calorimetry
     Wide use of CMOS technology – moves into monolithic CMOS

3) Solutions for new physics
   - e.g. detectors for high precision Higgs studies (ILC, CLIC,...)

4) Extension(s) of existing technologies
   - e.g. adding a Cerenkov component to MicroMegas for fast timing

5) Import technology(s) from other fields
   - e.g. Chemical barium-tagging
     WLS nano-particles, carbon-nanotube pixels?
6) **Going further** – once we have a new technological solution for a HEP application we should always ask what else could be enabled by this technology.

7) **Keep monitoring developments** – delay technology choices

8) **“Blue sky”**
   - always need this component
   - imagine solutions even if technology does not (yet) exist
   - what could we achieve by further extension of existing technologies (e.g. what would be enabled by sub-picosecond timing, sub-micron pixels?)

9) **What collaborative/administrative structures** best support detector R&D?
Detector R&D - Issues

U.S.

Coordinating Panel for Advanced Detectors

CPAD: to promote, coordinate and assist in the research and development of instrumentation for High Energy Physics nationally, and to develop a detector R&D program to support the mission of High Energy Physics for the next decades.

CERN

CERN – future detector R&D
Organize into 8 Work Packages
Target specific R&D challenges

- RD50 radiation tolerant n-in-p Si-sensors (ATLAS/CMS/LHCb), LGADs (Timing ATLAS/CMS)
- RD51 MPGD GEMs, Micromegas (ATLAS/CMS/LHCb/ALICE)
- RD18 Crystals (Barrel Timing Layer CMS)
- Electronics common components: 130 & 65 nm radiation tolerant technologies for ASICs, LpGBT, Optical Links, DCDC & serial powering
- RD53 Pixel detector ASIC first version with all features fully functional (ATLAS/CMS)
- Mechanics: new light material structure for trackers, CO₂ cooling with modularity toward detector needs
- Qualification: Gf11 Irradiation and rate facility

Can we benefit from more specific collaboration/coordination?
Some parallelism/competition is good, but resources are limited.
Basic Research Needs (BRN) Study

- Assess the present status of the HEP technology landscape
- Identify key enabling capabilities and associated performance requirements in pursuit of the P5 Science Drivers
- Identify strategic technology areas
- Formulate a small set of high-impact instrumentation “Key Challenges”
- Set up study Working Groups:

  - Physics-focused WGs
    - Higgs: Jim Hirschauer (FNAL), Gabriella Sciolla (Brandeis)
    - Neutrinos: Ornella Palamara (FNAL), Kate Scholberg (Duke)
    - Dark Matter: Jodi Cooley (SMU), Dan McKinsey (Berkeley)
    - Dark Energy and Inflation: NN, NN
    - Explore the Unknown: Monica Pepe Altarelli (CERN), Sarah Demers (Yale)

  - Technology-focused WGs
    - Quantum Sensors: Andy Geraci (Northwestern), Kent Irwin (SLAC)
    - Noble Liquids: Roxanne Guenette (Harvard), Jocelyn Monroe (RHUL)
    - Photodetectors: Peter Krizan (IJS), Lindley Winslow (MIT)
    - Solid State and Tracking: Marina Artuso (Syracuse), Carl Haber (LBNL)
    - Calorimetry: Francesco Lanni (BNL), Roger Rusack (Minnesota)
    - T/DAQ: Darin Acosta (UFlorida), Tulika Bose (Wisconsin)
    - Readout and ASICs: Gabriella Carini (BNL), Mitch Newcomer (UPenn)

“Technology Perspectives Factual Document”
Workshop in the DC area December 11-14, 2019
Detector technology has enabled a new generation of detectors and detector upgrades for HEP.

BSM physics is proving hard to find – requires refined, precise, and innovative technology solutions!

There are great opportunities waiting for the application of new technologies to HEP!

Fostering the development of new detector technologies deserves major attention, and support, and it pays off!
Thank you!