Timing detectors at the EI

New generation 4D reconstruction and polarimetry

Speaker: Tommaso Isidori *

*PhD candidate at the university of Kansas

Overview

01. The timing era: why is the physics community investing in timing?

> Introduction: timing and 4D reconstruction
> Fast or Precise?
> ...A broad spectrum of applications

02. A casual guide to Timing

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> Read-out and Front end
> Current state and Results

03. A brave new world: Timing detectors at the EIC

> Particle ID with TOF
> Calorimetry
> Polarizing the beams

Conclusions

01

The timing era

why is the physics community investing in timing?

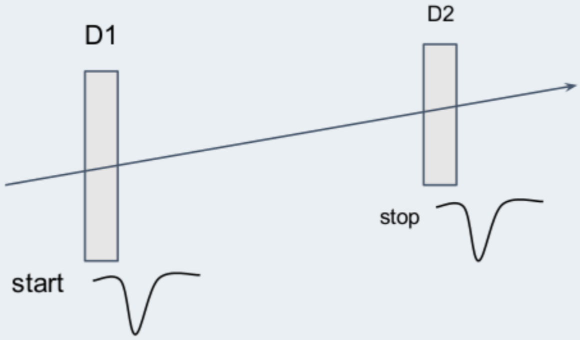
During the last decade, the increasing dem
detectors capable of accurate time resoluti
physics community to invest time and reso
upgrade and optimization of this technolog

The test performed on timing detectors of
proved their performance to be compatible
rates and radiation levels expected in HEP

Section 01 introduces the concept of timing
highlight its similarities and differences wit
fast detectors.

Introduction: timing and 4D reconstruction

When we talk about “Timing detectors” we usually refer to detecting devices optimized to accurately reconstruct partic
when collected from the sensor.



In the example of two devices (D1,D2) detecting the passage of a particle

$$L \approx |t_{start} - t_{stop}|\, v$$

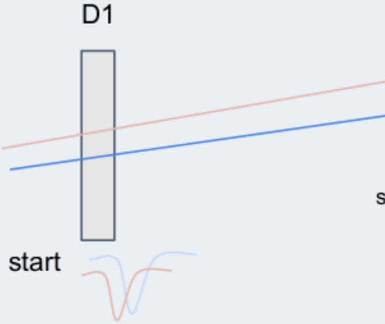
$$\sigma_z = \sqrt{\sigma_{t_1}^2 + \sigma_{t_2}^2} \cdot c$$

The precision of the measurement can be calculated as:

$$\sigma_{tot} = \frac{1}{N} \cdot \sqrt{\sigma_{det1}^2 + \sigma_{det2}^2 + ..} \approx \frac{1}{\sqrt{N}} \cdot \sigma_{det}$$

The example can be extended to include the passage of multiple particles...
In this case the Time of Flight (TOF) of different particle species can be used to perform an Identification of the detected object:

$$\Delta t = t_2 - t_1 = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) \approx \frac{Lc}{2p^2}\boxed{(m_1^2 - m_2^2)}$$



This class of detectors generally operates using high granularity sensors and, when paired with tracking apparatus, can provide a full **4D reconstruction** (x,y,z,t) of the event.

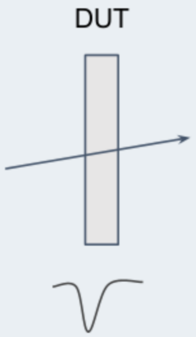
Fast or Precise?

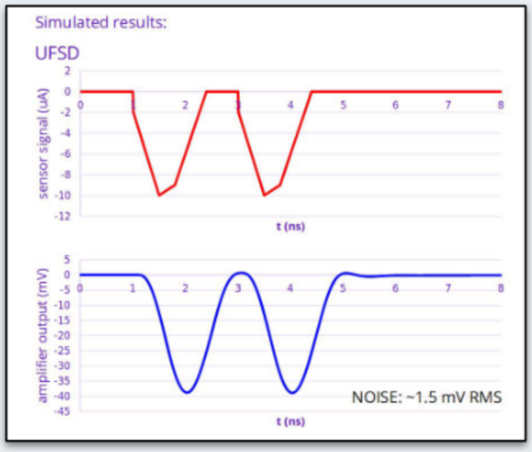
Precise Detector

- Output the timestamp of a particle's passage in the active volume with a small uncertainty.
- Suited for **TOF**, **difference of time of arrival**, **time reference for HEP detectors**...
- In new generation detectors, the time uncertainty can go as low as **σ ~ 10ps.**
- The accuracy of the timing measurement affect the spatial reconstruction accuracy $\sigma_L \propto \sigma_t$

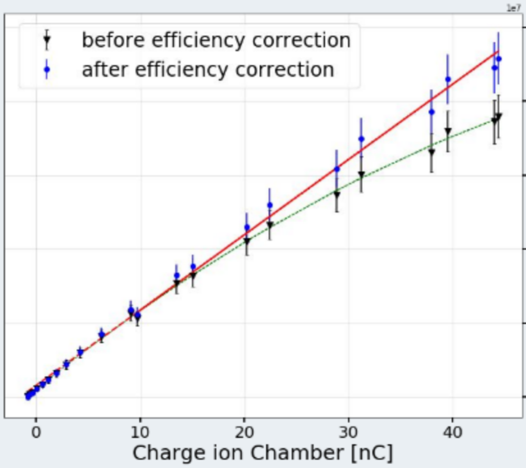
Fast detector

- Output a narrow pulse in response to the passage of a particle.
- Modern electronic components can be combined to develop circuit that outputs pulses as narrow as **~ few ns.**
- A fast integration of the signal reduces the dead time of the detector: **single particle resolution guaranteed up t**



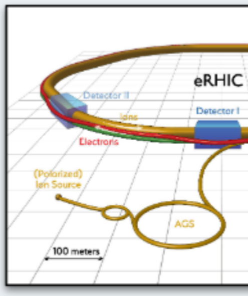


[1]



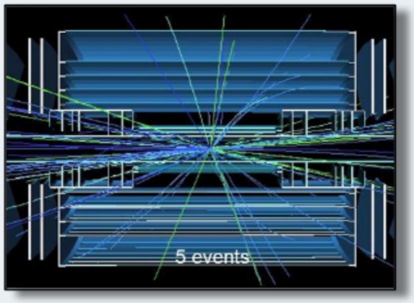
[1] Nicola Minafra - Precision Electron Polarimetry at EIC, EIC User Group Meeting, July 18-22 2017
[2] T.sidori, P. McCavana, B. McClean, R. McNulty, N. Minafra, N. Raab, L. Rock, C. Royon - arXiv:2101.07134

...A Broad spectrum of applications



HIGH RATE FACILITIES

Measurements that requires detectors capable of single particle resolution such as:
<u>Polarimetry</u>, **Luminometry**, **Dose evaluation...**



PRECISION

Measurements that requires detectors capable of high
Background rejection for exclusive events, **<u>Time of Flight</u>**, **<u>4D tracking, 5D</u>**

COMMERCIAL APPLICATIONS

Few other applications can be listed:
commercial sensors, **dosimetry in medical facilities**, **study of fluids interfaces...**

Note:
Part of the EIC physics program requires the use of different types of **fast(to operate with precisely polarized e-ion b** **precise (to identify the hadrons generated from the interaction)** timing detectors.

02

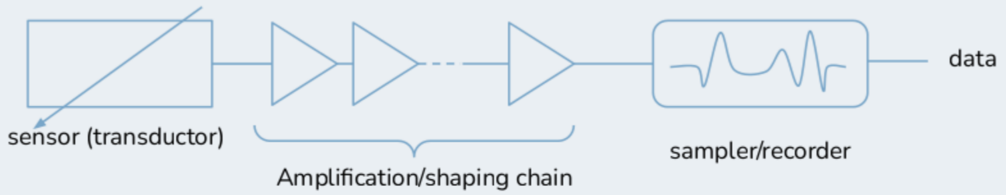
A casual guide to Timing

To optimize the timing accuracy and increa
for single particle reconstruction, the choic
sensor has to be combined with the develo
read-out.

The output signals are later digitized and r
use of high-bandwidth fast samplers.

This section will provide a rapid description
of operation of timing detectors as well as
some of the technologies proposed for 4D
reconstruction and particle ID at the EIC.

Principles of Operation



Example of

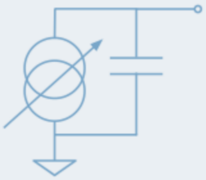
... The dE/dx of a particle produces a cu
active volume. The **read-out** electronics s
(if needed) the signal. A fast, high-bandwi
and s

Disclaimer: the detector technologies described are the ones proposed for the final design of the EIC central and forwa

Sensor

The choice of the sensor it's the first important step for designing a particle detector. The current state of the art timing detectors are based on **so**
state sensor.

Solid state (sCVD Diamond, LGAD, SiPM, MCP...)



- $\mu > 1000$ **(cm2/V)s** High **mobility** of the carriers
- $v_s > 10^7$ **cm/s** - High **saturation velocity**
- $C_{sensor} \propto \varepsilon_0 \varepsilon_d$ **(S/d)** the sensor capacitance is proportional to the dielectric constant (low capacitance means shorter integratio time)
- The **Displacement energy** in sensors of new generation drastically improved (lifespan up to 10^{15} n_{eq})
- **Low thickness** and **material budget.** Sensor size down to ~**50μm**
- **High granularity** on the active area

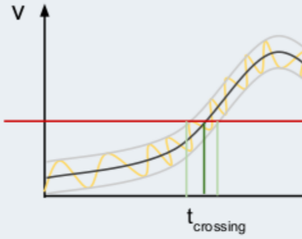
Note: some of the above mentioned detectors (**SiPM,MCP)** require an external active medium to collect (and often con the energy deposited by charged particles. The most common options are represented by the use of **Quartz** (Cěrenkov **scintillating polymers.**

Read-out and Front-end

The sources of uncertainty of a timing measurement can be expressed adding in quadrature the contributing factors:

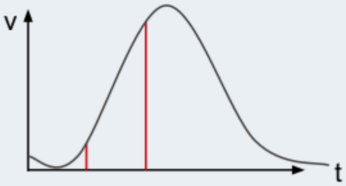
$$\sigma^2_t \sim \sigma^2_{jitter} + \overset{*}{\sigma}^2_{Landau} + \sigma^2_{TimeWalk} \overset{*}{+} \sigma^2_{Distorsion}$$

* contribution of the sensor



read-out

The predominant contribution introduced by the shaping and amplifying chain comes from the **noise fluctuations** that, in turn affect the Signal to Noise Ratio (SNR)



The choice of a performing sampler directly influence the timing precision of the instrumen depends on the slope of the signal's rising edge. The bottleneck of the rising time for fast d from the **sampler's bandwidth.**

$$\boxed{\sigma_{jitter} \simeq \frac{noise}{dV/dt} = 1.25\frac{\tau_{0.1} - \tau_{0.9}}{SNR} = 1.25\frac{t_{rise}}{SNR}}$$

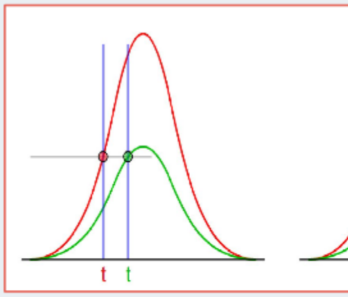
With

$$\boxed{t_{rise} = \frac{0.35}{Bandwidth}}$$

Note (post-processing data):

Some of the contributions come from effects that are intrinsic to the nature of the measurement and can only be corrected during the analysis procedure.

The **Time Walk** is the mis-reconstruction of the timestamp of simultaneous pulses with **different amplitudes**.

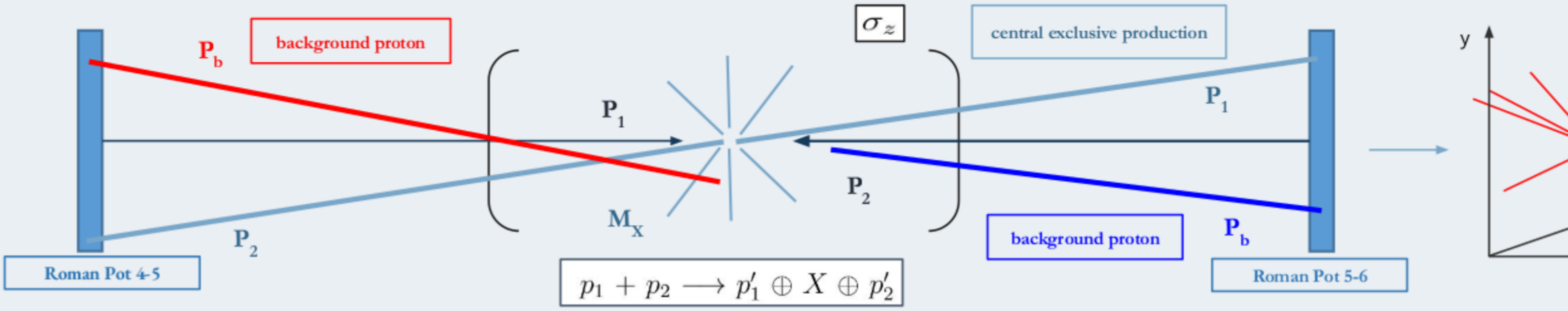


Current state and Results

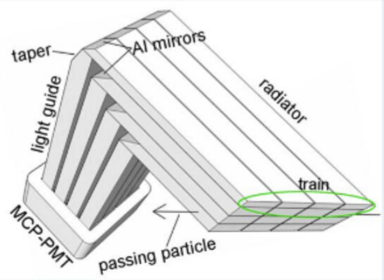
Particle ID and TOF

In preparation for future High Luminosity facilities, many HEP experiments are aiming to include fast timing sensor for
and identification. The request for pile-up removal for optimal discrimination pushed the research community in the de
top of the line solid state detectors.

ATLAS and CMS forward detectors represents a good example of TOF for pile up rejection (and not only)



The ATLAS Forward Proton Detector (AFP)



Quartic (Quartz bars + MCP readout)

- High fill factor (>85% per layer)
- Despite the crosstalk resolution **< 25 ps**
- requirement: spatial resolution of **2.12mm**
- requirement: rate **5 MHz** per channel

ATLAS Forward Proton (AFP) time-of-flight (ToF) detector: construction & existing experience - T.Sykora

CMS Proton Precision Spectrometer

4 Layers of **sCVD Diamond detectors**

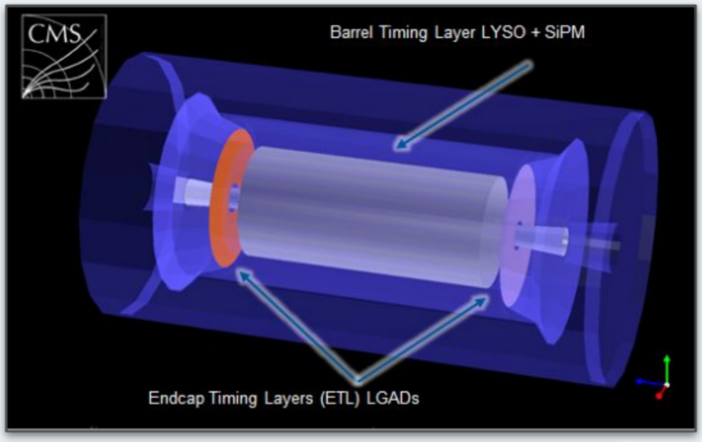
- Active area **~ 80 mm²**
- sustainable hit rate up to **few MHz/mm2**
- double sCVD design **~ 50 ps** resolution (per plane)
- resolution degradation ~ 20-50% (full 2018 data taking)
- stable time resolution in detecting 6-7 TeV protons

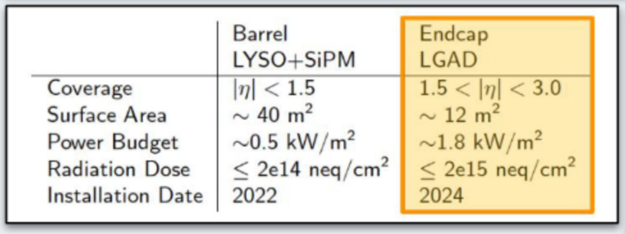
The CMS Precision Proton Spectrometer timing system: performance in R
future upgrades and sensor radiation hardness studies - E.Bossini

Current state and Results

Particle ID and TOF

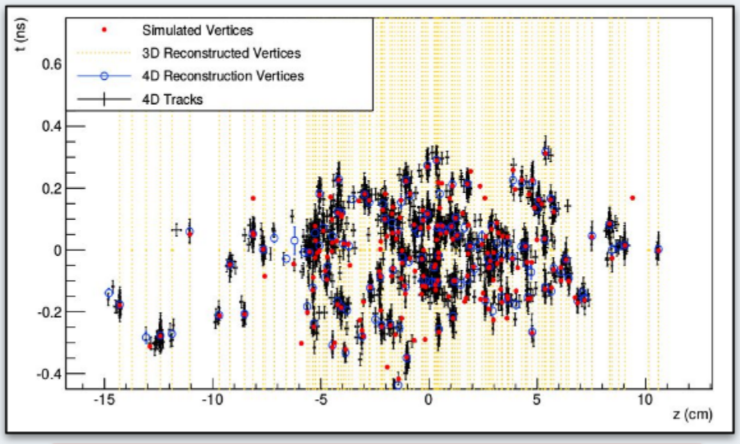
The CMS MIP Timing Layer





	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\lvert\eta\rvert < 1.5$	$1.5 < \lvert\eta\rvert < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024

[1] Precision timing at CMS for HL-LHC - Artur Apresyan | TREDI 2017
[2] Test Platform for Automated Scan of Multiple Sensors - N.Minafra
[3] Timing detectors in the CMS experiment - T.Isidori



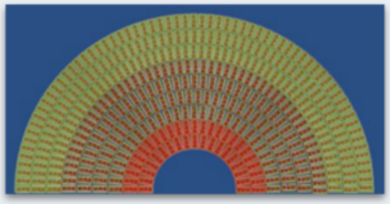
MIP Timin
of time pr

impact on th

> improved t
reconstructi
> lepton rec
> diphoton v
> missing tra
resolution
> reduction

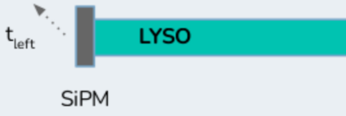
A closer look into the chosen technologies

ETL - LGAD



- Pad size: 1.3 x 1.3 mm^2
- High fill factor (>85% per layer)
- 16624 sensors of 2x4 cm^2

BTL - LYSO + Si

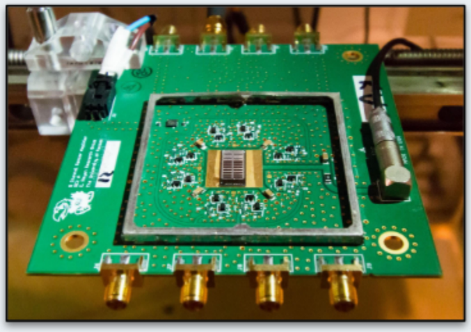


- Lutetium-yttrium orthosilicate
with cerium
- active volume (per strip) = 3 ×
- SiPM active area = 9 mm^2,
- SiPM light collection efficiency

Current state and Results

Fast detectors for high rates

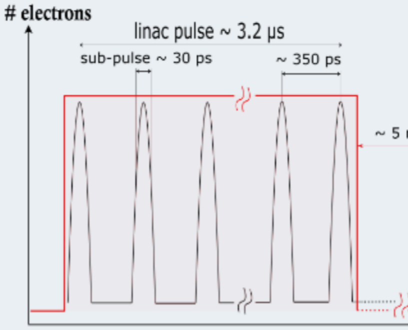
Many commercial (and research) applications require the use of fast detector for single particle resolution measuremen
precisely count the number of incident particle per unit of time (without distortions due to long integration time or effic
represents an invaluable tool for evaluating **radiation doses, study beams luminosities, calculate the polarization of p**

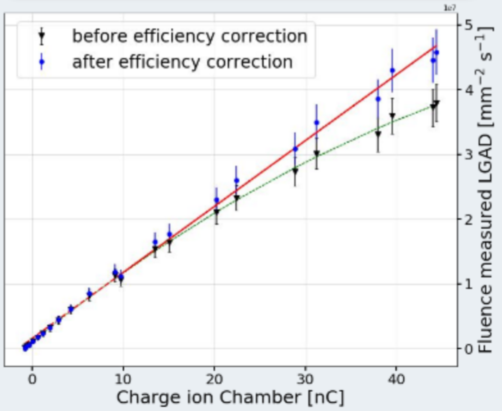


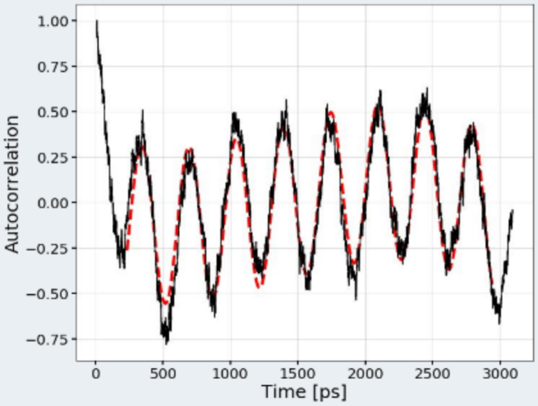
Example: monitor of a medical linac and characterization of the beam pr

Electronic board designed @ KU and characterized using a 50 µm UFSD

> Fast time integration of 5-10 ns
> Sensor's Area = 2.9 x 0.5 mm^2
> Time precision < 30 ps @ V_{bias} = 220V
> Tested with a 6 MeV electron beam
> Pulse repetition = 200 Hz
> Fine structure frequency is 2.858 GHz







Note:
The test works as a proof of concep
particle resolution in new generatio
detectors (up to **tens of MHz** with th
displayed).
The loss of efficiency due to multipl
can be corrected with the post-proc
procedures.

T.sidori, P. McCavana, B. McClean, R. McNulty, N. Minafra, N. Raab, L. Rock, C. Royon - arXiv:2101.07134

03

A brave new world

Timing detectors at the EIC

Every apparatus proposed for the final des
central detector include the use of fast and
detector.

The TOF of particles produced in the centra
for an accurate discrimination between ligh
same time, the energy measurement woul
use of the timestamps of the showers prod
calorimeter towers.

A last important subject that will be covere
section is the use of on-beam detectors to
polarization asymmetry of the beams.

Reminder: Timing detector Goals @ the EIC

Polarimetry

The EIC facility will provide fully polarized e-ion beams [1]. The collision of polarized particles constrains the final state of the collision, which in turn helps in constraining the angular momentum of the interacting protons.

Calorimetry

The central detector designs proposed for the EIC incorporate in their apparatus fine segmented imaging calorimeters [2,4]. The design is completed by the use of timing detectors for improving the particle discrimination capabilities [3].

Particle ID wit

The central barrel is thou
equipped with timing det
particle ID. Combined
high-granularity tracking s
studies of the difference in ti
within the inner barrel p
substantial aid in discrir
pions-kaons-proton

[1] Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all
[2] M. Chadeeva -CALICE highly granular calorimeters: imaging properties for hadronic shower analy
[3] José Repond -TOPSiDE: Concept of an EIC Detector
[4] SiD concept: http://www.linearcollider.org/P-D/ILC-detector-concepts/SiD

Polarizing the beams

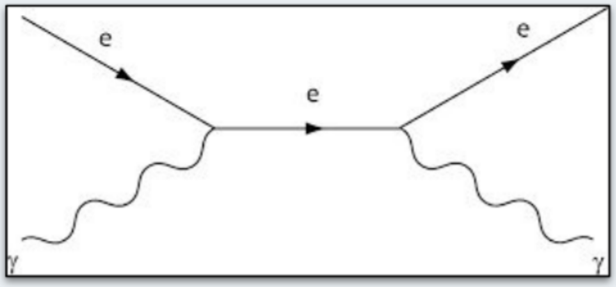
Polarimetry

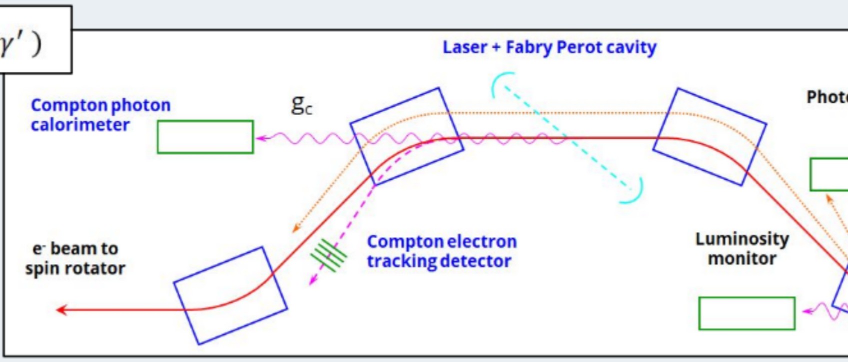
Compton polarimeters represent the best option for measuring the polarization asymmetry of high energy particle beams.

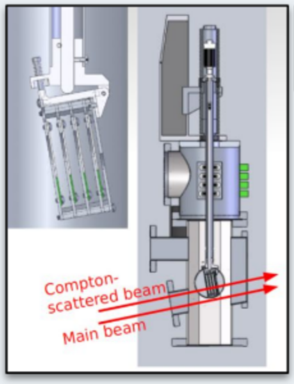
After every interaction @ the EIC, the level of polarization is verified using on-beam detectors. Starting from the photons polarization
laser+Fabry Perot cavity (measurable) and estimating the predicted QED asymmetry, the apparatus constraints the electrons polariza

$$\sigma(\ \vec{e} + \gamma \ \rightarrow \ e' + \gamma'\ ) \quad \neq \quad \sigma(\ \overleftarrow{e} + \gamma \ \rightarrow \ e' + \gamma'\ )$$

[1]



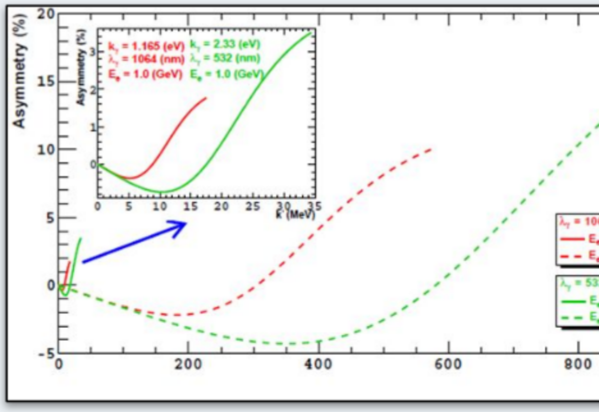




$$A_{EXP} \equiv \frac{N^+ - N^-}{N^+ + N^-} = \boldsymbol{P_e} * P_\gamma * A_{QED}(E_e, k_\gamma, k_{\gamma'})$$

Roman pots: solid state detectors (in the primary vacuum) approaching the beam using a movable support

Resolves the shape of the expected asymmetry by measuring the strip-by-strip asymmetry.
> Compton edge and zero needed to fit $\mathbf{P_e}$ to
$\mathbf{A_{measured} = P_e A_{theory}}$



[1] N. Minafra- Precision Electron Polarimetry at EIC, July 18-22 2017

Polarizing the beams

Polarimetry

Let's take a look at some of the worst case scenario: High-Lumi @ EIC

High luminosity
560 MHz RF
1320 bunches
10 ns between bunches
Electron current up to 2.4 A
Ion current up to 0.92 A

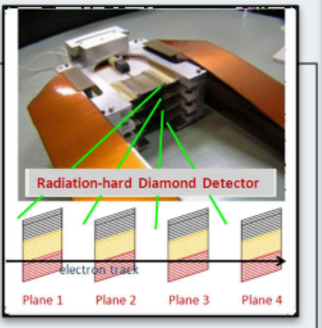
Note: Aiming for 1
electron polarizati
0.5 % for parity vi

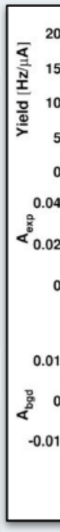
!! Need a fast, efficient and precise detector capable of single particle resolution for 10 ns spaced bunches (uniquely associate a detected particle with the correct bunch crossing**) !!**

Current technology [2]

The electron detector

> set of four diamond planes each with 96 "microstrips" of metal alloy etched on the Surface.
> Each strip is 0.180 mm wide separated by 0.02 mm.



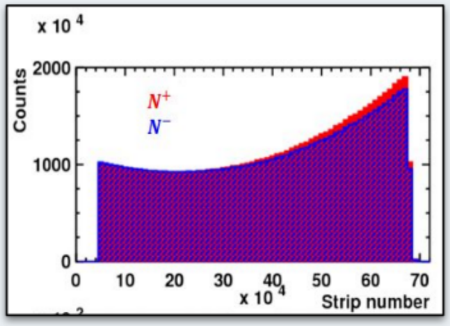


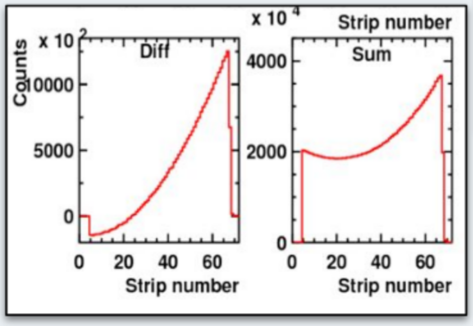
[1] ...Fast

- Single particle every bunch crossing per channel
- expected rate for 10 kW laser power >3 GHz per 5 cm^2
- Sensor, amplifier, digitizer, DAQ to be designed

... And Precise

- Increased segmentation
- Less challenging detector requirements, but more channels
- Digitizer, DAQ to be designed





[1] N. Minafra- Precision Electron Polarimetry at EIC, July 18-22 2017

[2] A. Narayan et al. - Precision Electron-Beam Polarimetry at 1 GeV Using Diamond Microstrip Detectors

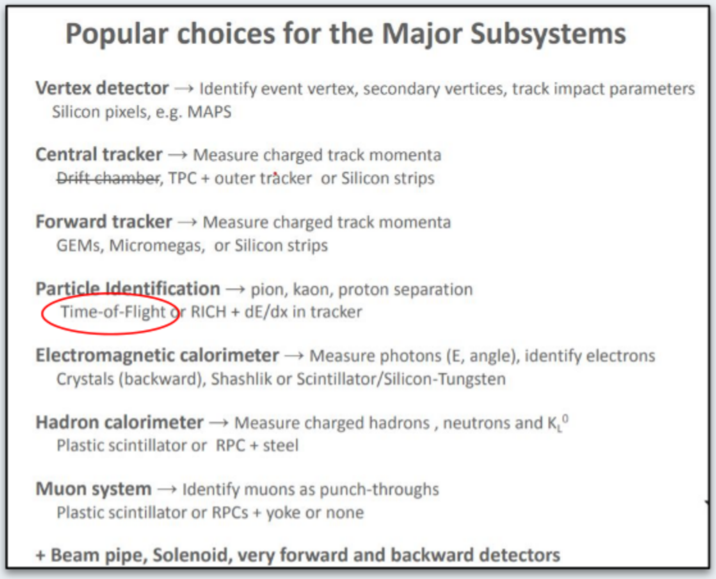
Particle ID with TOF

Multiple detector designs were proposed (BEAST,ePHENIX,TOPSIDE).
The scheme below, gathered from **[1]**, summarized layer by layer the technologies under study.

Design reque

Pion/kaon/proton se

Central barrel $\mathbf{p}_{\mathbf{hadrons}}$
Forward zone $\mathbf{p}_{\mathbf{hadron}}$



Popular choices for the Major Subsystems

Vertex detector → Identify event vertex, secondary vertices, track impact parameters
Silicon pixels, e.g. MAPS

Central tracker → Measure charged track momenta
~~Drift chamber~~, TPC + outer tracker or Silicon strips

Forward tracker → Measure charged track momenta
GEMs, Micromegas, or Silicon strips

Particle Identification → pion, kaon, proton separation
Time-of-Flight or RICH + dE/dx in tracker

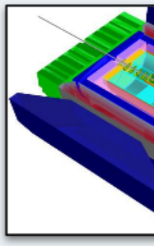
Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten

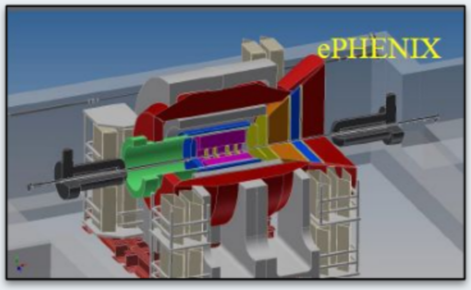
Hadron calorimeter → Measure charged hadrons , neutrons and K_L^0
Plastic scintillator or RPC + steel

Muon system → Identify muons as punch-throughs
Plastic scintillator or RPCs + yoke or none

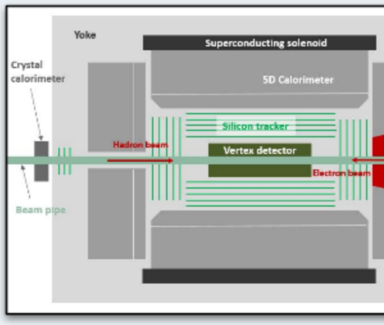
+ Beam pipe, Solenoid, very forward and backward detectors

BEAST (Brookhaven eA Solenoidal Tracker)
Low momenta (p < 1 GeV/c)
>dE/dx in tracker or time-of-flight with **moderate resolution**
Intermediate momenta (1 < p < 3 - 4 GeV/c)
>Ring Imaging Čerenkov with Aerogel (n~ 1.05)





ePHENIX
RICH + DIRCs for particle ID
DIRC performances studied by eRD1

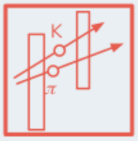


TOPSiDE
tracker + calorimeter equipped with timing
>Silicon sensors with time resolution of about 10 ps

[1] José Repond- EIC Detectors: An Overview
13th International Workshop on high-pT Physics in the RHIC/LHC Era University of Tennessee, Knoxville, TN March 19 - 23, 2019

Particle ID with TOF

[1] Particle identification for a future EIC detector - Ilieva, Y.; Allison, L.; Barber, C.; Cao, T.; Del Dotto, A.; Gleas
McKisson, J.; Nadel-Turonski, P.; Park, K.; Rapoport, J.; Schwarz, C.; Schwiening, J.; Wong, C. P.; Zhao, Zh.; Zorr

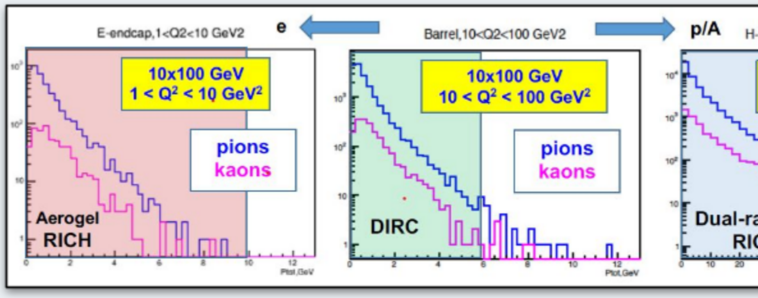


In the 2018 publication [1], a combination of RICH, DIRC and a dual radiator RICH is simulated to evaluate the particle ID capabilities

> **e-endcap:** aerogel RICH with **TOF** (or dE/dx) for lower momenta

> **h-endcap:** combined gas and aerogel RICH to cover the full range with **TOF**

> **barrel:** a DIRC is the most compact and cheapest way to cover the full momentum range for the barrel area.



TOPSiDE LGAD

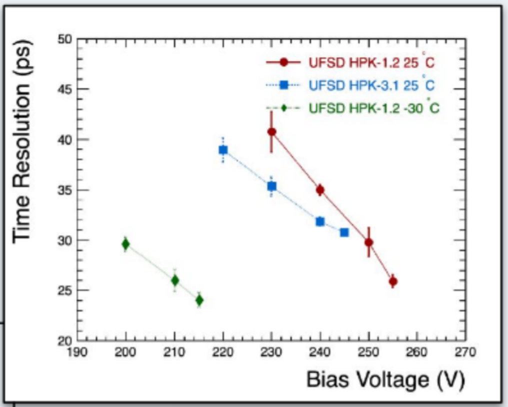
> Easier designed, inspired by the SiD collaboration

> Avoid the use of RICH, DIRC in the barrel (bulky and delicate)

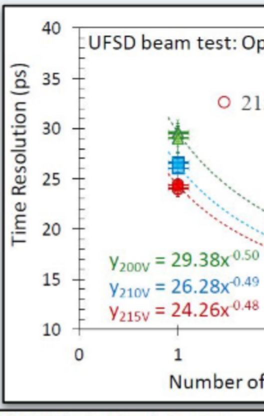
But...

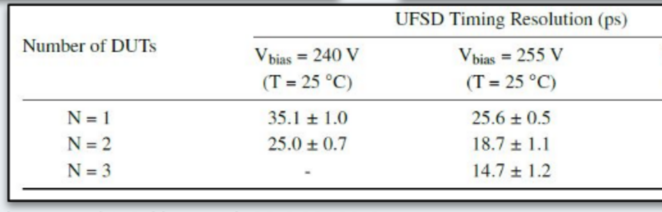
energy resolution of single particles, timing resolution requirement for time-of-flight identification of hadrons, reconstruction of kinematical variables, and reconstruction of the F2 structure function.... Are achievable with **σ_t~ 10 ps !!**

TOPSiDE design
barrel (-3 < η < 3)
The electromagnetic section utilizes LGAD as active medium for the calorimeter (treated in the next section)
Forward region (3 < η < 5)
RICH counter provides particle ID for **$p_{hadrons}$ 10 - 50 GeV/c**
TOF with LGAD for **$p_{hadrons}$ < 10 Gev/c**



[2]





Number of DUTs	UFSD Timing Resolution (ps)	
	V_{bias} = 240 V (T = 25 °C)	V_{bias} = 255 V (T = 25 °C)
N = 1	35.1 ± 1.0	25.6 ± 0.5
N = 2	25.0 ± 0.7	18.7 ± 1.1
N = 3	-	14.7 ± 1.2

[2] M. Jadhav, W. Armstrong, I. Cloet, S. Joosten, S. M. Mazza, J. Metcalfe, Z.-E.,Meziani, H.F.-W. Sadrozinski, B. Schumm, and A. Seiden - arXiv:2010.02499v3

Calorimetry

Each one of the detector designs encloses the entire solid inside the EM and Hadronic Calorimeters

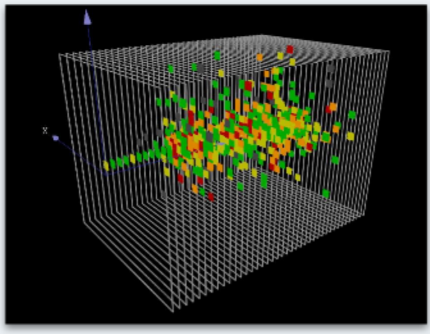
While ePHENIX and BEAST employ most common technologies....

Electromagnetic calorimeter
($\eta < -2$) → PbWO4 crystals with ~2%/√E energy resoluti
($-2 < \eta < 3.5$) → Tungsten powder + scintillating fiber w
Hadron calorimeter
Scintillator plate + lead absorber with ~50%/√E (Not pr
barrel)

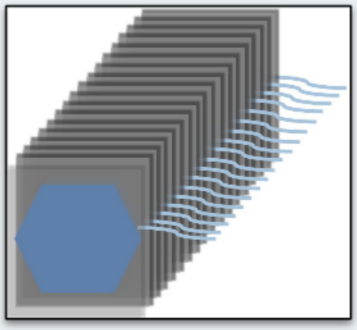
...TOPSiDE most innovative feature is the employment of:

5D Calorimetry

Very fine lateral and longitudinal granularity
10^7 channels



ElectroMagnetic Calorimeter
> Ultra fast silicon sensors (0.16 cm2 to 1.00 cm^2) + scintillator (4.5 x 0.5 cm^2)
Hadronic Calorimeter
> Scintillator pads (3 x 3 cm^2) + Resistive Plate Chambers (RPCs) with readout pads of 1 x 1 cm^2



Structure
20
layers
1 wafer/layer
Interleaved with tungsten (smallest Molière radius) plates
Data: position (x,y,z), precision time

Assumptions
8" wafers
Area ~ 324 cm 2
1 x 1 mm
2 pixels → 32,400 pixels/wafer
Total number of readout channels ~ 650,000

Advantages:
> The particle ID becomes trivial (from the precise s
> Software compensation
> Leakage corrections
> Gain monitoring
> Identification of underlying events
> Application of Particle Flow Algorithms

TOPSiDE combines imaging calorimetry with precision
measurement to provide pion-kaon-proton separation.

Conclusions

>The effort of the physics community brought to the development of **increasingly more accurate timing detectors**.

> In order to explore new physics or study rare events, HEP facilities are forced to increase the delivered luminositie
need for **fast and radiation hard devices** to comply with the expected rates.

> Precise timing detectors are often an important tool to employ when the pile-up doesn't allow a simple simple 3D reconstruction.

> The timing precision requested for particle ID @ the EIC is **stringent (~10ps) but achievable**: new results on solid state detectors are promising.

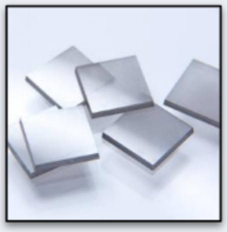
> The **sub-1% accuracy in the electron polarimetry** needed for the EIC operation at high lumi can be achieved improving the time integration and response of current detectors. The results presented (KU board) can work as a benchmark for detectors with single particle resolution in high rate environments.

Thank you for your

Backup

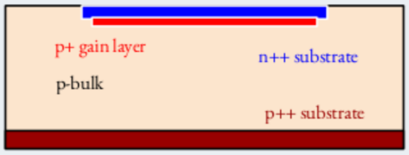
Principles of Operation

A bit of jargon and technicalities..



Chemical Vapor Deposition (sCVD) diamond

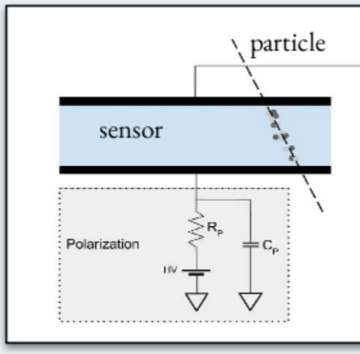
> low dielectric constant (low capacitance)
> high carriers mobility
> incredibly low dark currents
> The complicated production process limits the size to few mm^3
> intrinsically radiation hard

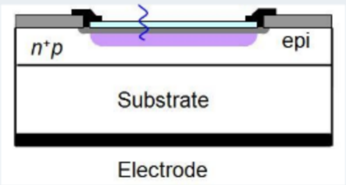


Low Gain Avalanche Diode (LGAD)

> low gain(compared to APDs) → necessity to add an additional gain layer
> fast rise time (dark currents' electron don't cause avalanche processes)
> low dark currents
> the thickness is substantially reduced (> 50 µm)
> Can be produced with Carbon insertion to reduce the radiation damages

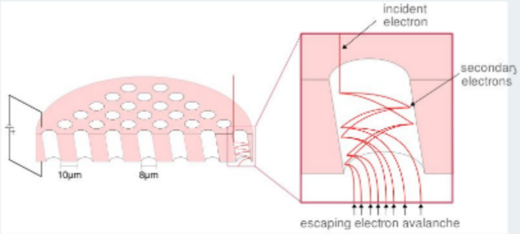
Standard opera





Silicon PhotoMultiplier (SiPM)

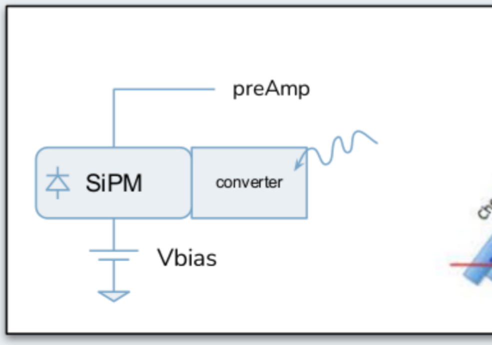
> Photo detection efficiency (PDE) ranges from 20 to 50%
> Gain ~ 10^6
> Low timing jitter
> not sensitive to external magnetic fields
> Small dimensions and low voltages required for bias



Multi Channel Plate (MCP)

> avalanche transit time ~100 ps range
> Gain ~ 10^{4} - 10^{8}
> fast rise time
> exceptionally low dark current < 0.5pA/cm2
> 0.4-3.0 mm thick plates
> up to ~1M channels/cm^2 of 5-15 m m diameter

Standard operati



Used in DIRC, RICH...

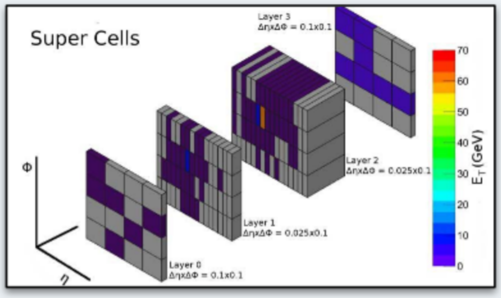
Current state and Results

Timing in Calorimetry

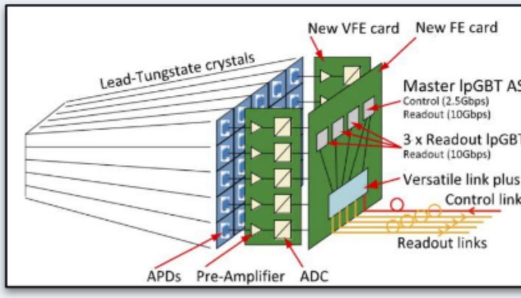
When used together with the Energy reconstructed by a calorimeter tower, the time information provides a fundamental tool to **dis**
in high rate environment.

Note: Whenever the granularity of the read-out allows a fine segmentation of the signal, the measurement takes the name of **5D r**

The need for pileup mitigation in high-Luminosity facilities affects the design of experiments EM and Hadronic calorimeters.



Liquid Argon
Faster shaping
Reduced out-of-time pile-up
Better discrimination scintillation vs spikes
Faster rise time
timing resolution ~ 0.5 ns (high-energy tail)
bunch-crossing ID resolution << 25 ns



Lead-Tungstate crystal read by APD

Faster shaping
Reduced out-of-time pile-up
Better discrimination scintillation vs spik
Faster rise time
30 ps timing resolution