The first FCC-ee TDAQ workshop

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Radboud University Nijmegen/Nikhef

FCC@Nikhef Meeting, May 6, 2026

Radboud University

Nikhef

The workshop

Slides from T. Wengler

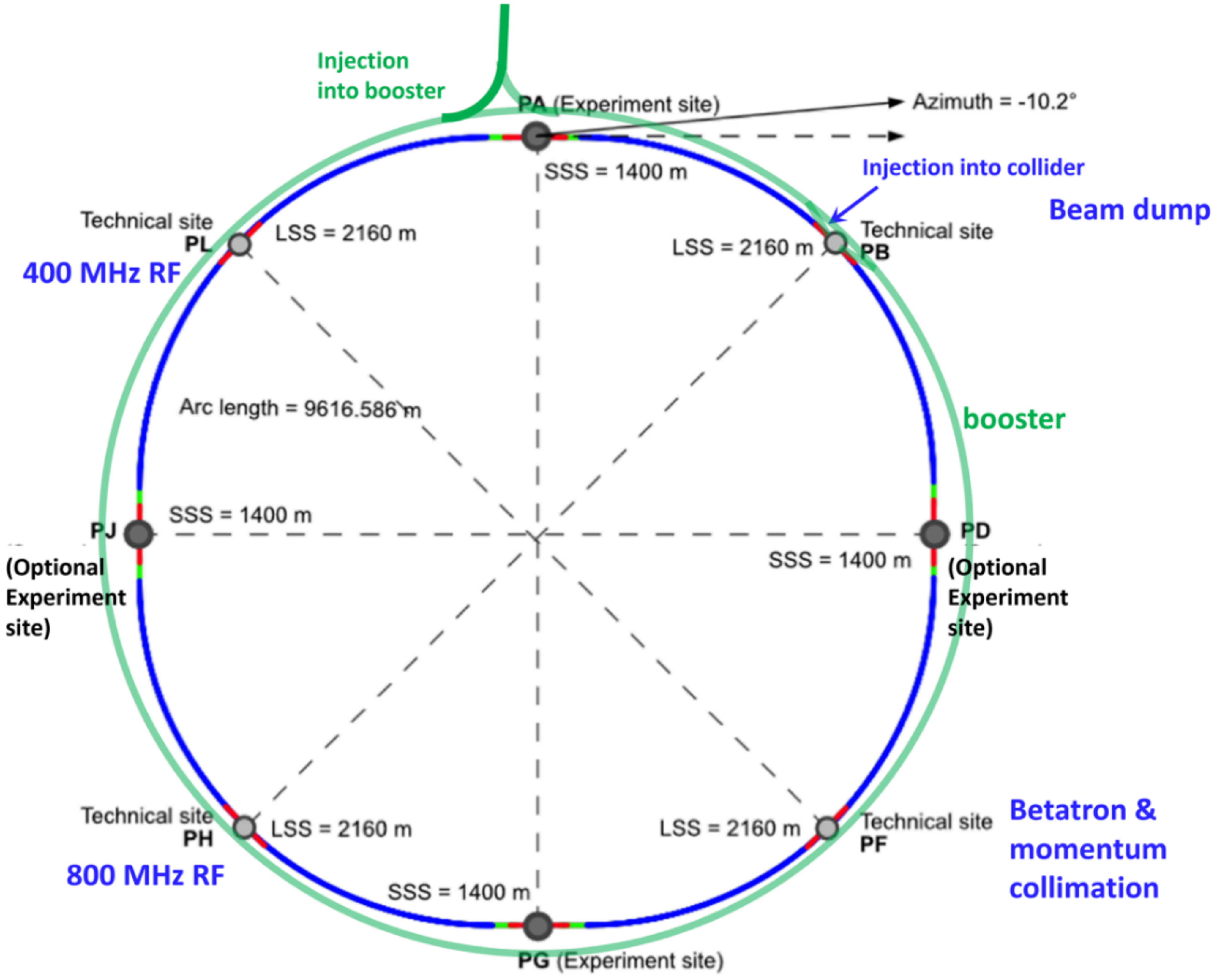
- First FCC-ee TDAQ workshop
  - Aim is to bring together the detector concept study groups with MDI, background and TDAQ groups to discuss:

https://indico.cern.ch/event/1583755/

  - What is the situation we will be dealing with, at different √s, considering both physics and, crucially, the beam induced background
  - Too far away for a concrete design of a TDAQ system - main aim is to identify the implication and constraints on the design of both TDAQ systems and the required capabilities of the subdetector systems
  - How to best contribute to our understanding of what is coming and what is needed

FCC-ee – a quick recap

Adapted contents from M. Dam



- Electron-positron collider covering 90-365 GeV energy range at very high luminosity
  - At Z-pole energy, luminosity x10^5 LEP !
- Factory for the four heaviest particles of the SM
  - Z, W, and Higgs bosons; top quark

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**140**	20	7.5	1.5

- Via >10^{12} Z decays (and >10^8 W decays) also factory for
  - Heavy quarks (b, c) and tau leptons

4 experimental areas / experiments
  - Experimental diversity - control of overall systematic uncertainties
  - Sustainability - physics/TWh

Trigger strategy at FCC-ee

Adapted contents from M. Dam & T. Wengler

- Very different running condition for Z, WW, ZH, tt
  - X-section goes down with energy, bunch spacing increases →lower rates
- Most challenging is running on the Z peak
  - Highest rate
  - Don't want to miss any!
  - 100 kHz interaction rate + the same again (or more) from background

⇩

1 of every 400 BCs with an interaction
(1 in 200 including BKGS)

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40MHz BC w/ 100kHz physics

→ Triggerless?
→ Minimally triggered?
→ Classical Triggered?

Trends in the discussion @ the workshop

A lightweight/minimised trigger plan?

Trends

- Triggerless?
- Minimally triggered?
- Classical Triggered?

The TDAQ system challenge

- The FCC-ee experiments are aiming to measure a range of processes with extreme accuracy (low systematic uncertainties).
- Therefore, the TDAQ system can not contribute to the systematic uncertainty more than about 10^{-5}.

A. Paramonov

Triggering has major implications

C. Paus @FCC-ee Vertex 2025

Positive implications

- Substantial reduction in output size
- Substantial reduction in processing and re-processing times

Problems that come with a trigger

- Some physics might not be possible (exotic things especially, you loose)
- Trigger hardware has to be able to identify the BX number per detector involved in the trigger to match information correctly: 1/(25 ns)
- Slew of implications of higher power budget with complex triggers running
- Trigger effects have to be very carefully modelled and implemented in the MC
- Early planning in the design is very important because trigger cannot be easily added after the fact

Preliminary conclusions

- Plan for a lightweight trigger to reduce rate but minimally affects physics

- Fixed-latency (aka "hardware") triggers may contribute to the systematic uncertainty.
- A trigger-less system (with data processing and filtering in an off-detector computer farm) may minimise the uncertainty

However:

Technological feasible? **to stream data from all the detector systems to commodity off-detector computing?**

Affordable? **to process, filter, and store the data with the commodity computing?**

A. Paramonov

Detectors

Physics programme to Detector challenges

Slides from M. Dam

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: s-channel $e^+e^- \to H$ at 125 GeV

→

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^8 WW events
- × 500 improvement of statistical precision on EWPO:
  $m_Z, \Gamma_Z, \Gamma_{inv}, \sin^2\theta_W, R_b, m_W, \Gamma_W$, ...
- 2×10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

→

- **Absolute normalisation of luminosity to 10^{-5} - 10^{-4} level**
- **Relative normalisation to $\lesssim 10^{-5}$ (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

→

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

→

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

Physics programme to Detector challenges

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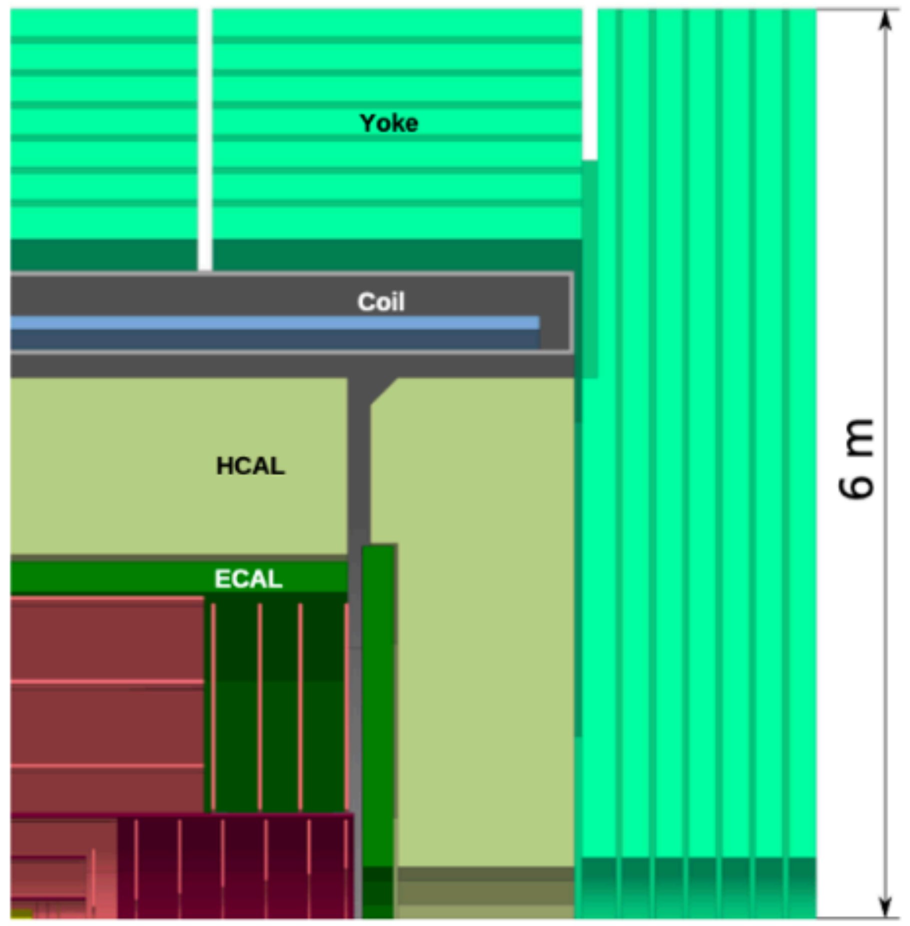
The 4 detector concepts

Contents from M. Dam

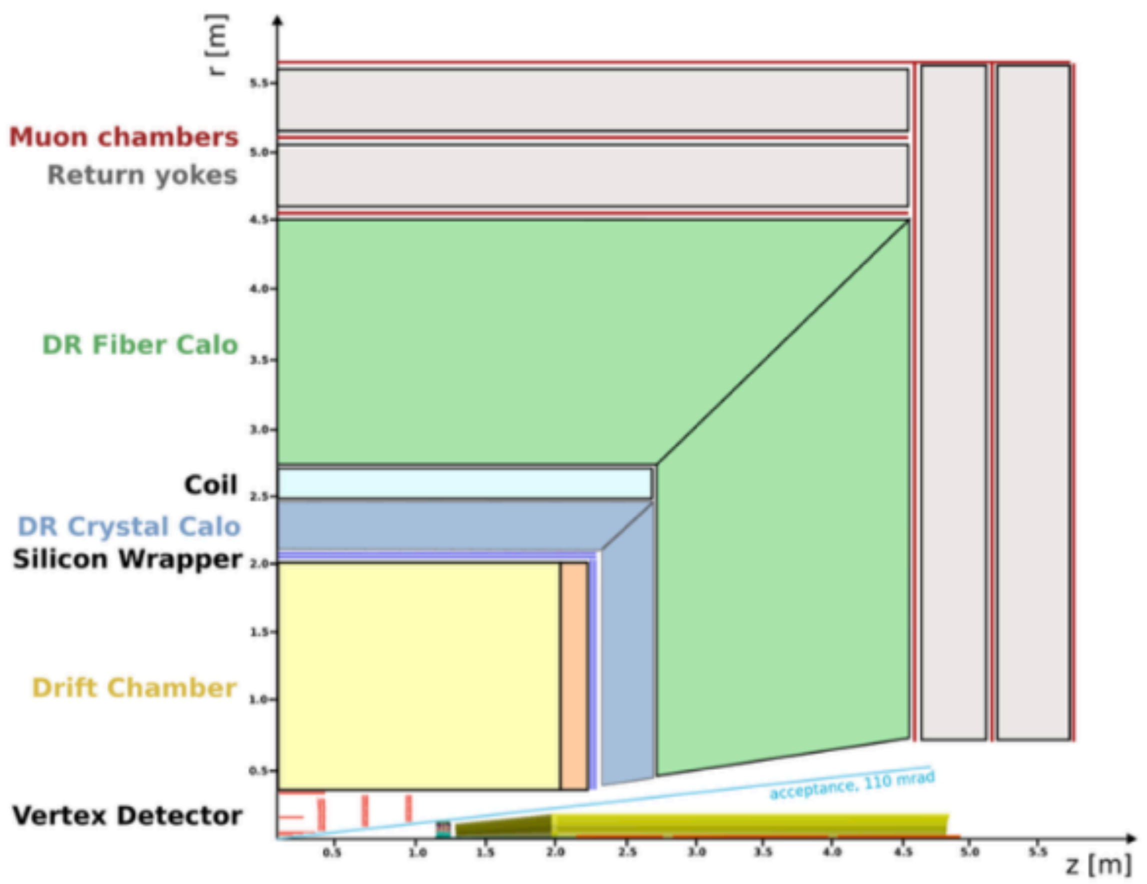
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

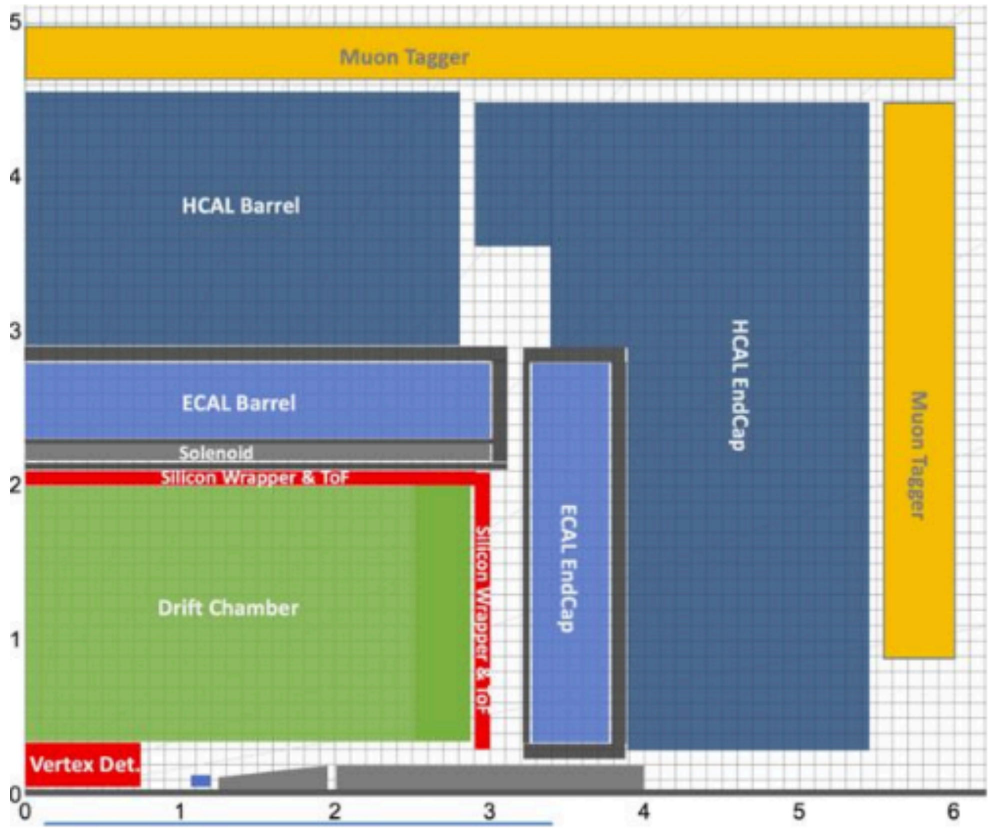
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

https://doi.org/10.48550/arXiv.2502.21223

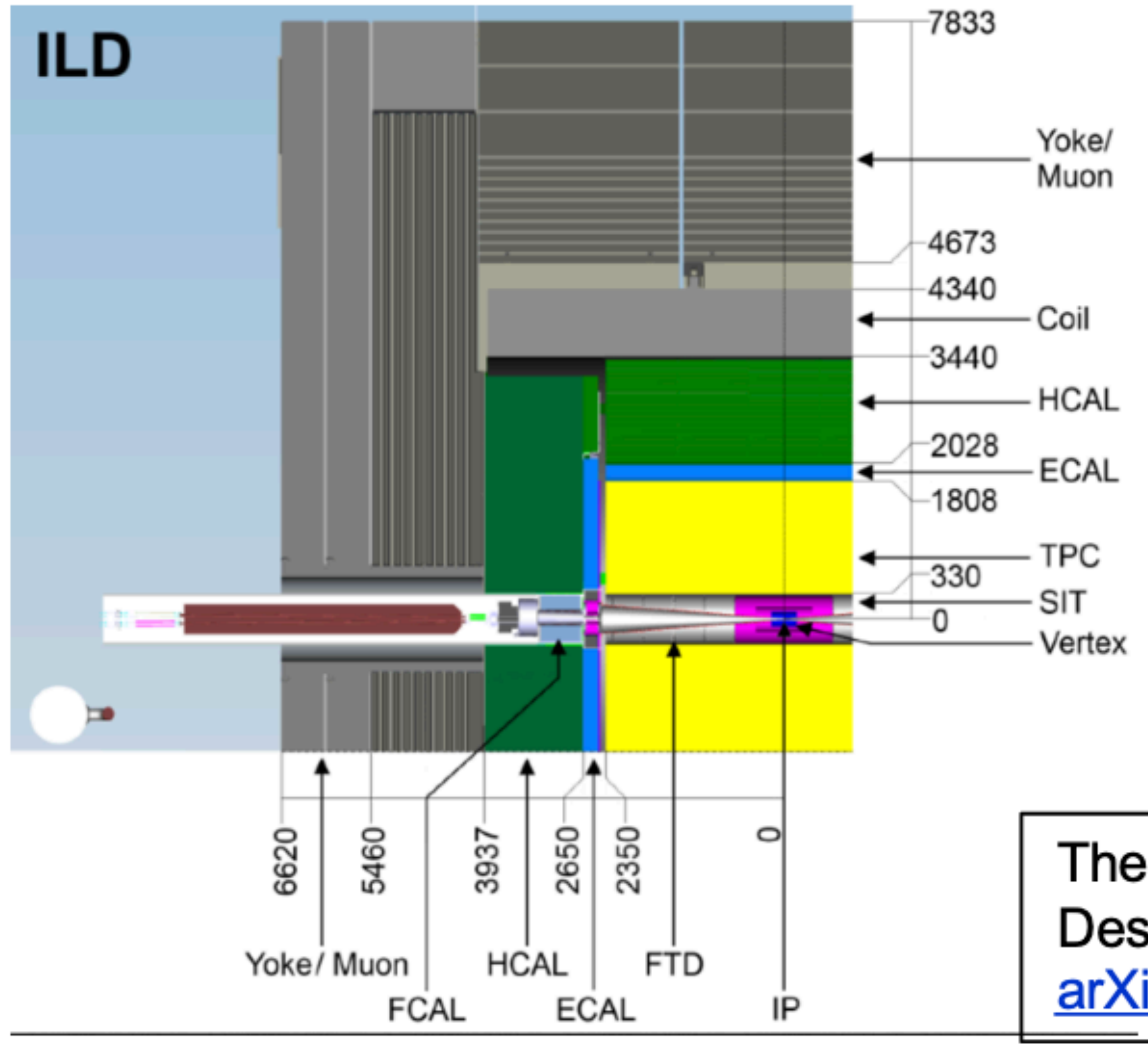
Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

ILD



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

TDAQ – from detector concept groups

Slides from M. Dam

Trigger(?) and Readout System

Slide from 2025 FCC Week

Goal of readout system

- *Full efficiency* to all SM annihilation physics events
  - Reminder: Aiming at $\mathcal{O}(10^{-5})$ (relative) normalisation
- No loss of potential BSM signatures
  - e.g., heavy (slow-movin) particles decaying late, LLPs

In particular at Tera-Z, challenging conditions

- 40 MHz BX rate
- Physics rate at $\mathcal{O}$(200 kHz)
  - Physics event in every 1/200 BX
- Example (perhaps the most challenging):
  - Pixel hit rate: ~200 MHz/cm² in VXD inner layer
    - Incoherent pairs from beam-beam interactions
    - Including cluster size of 5 and safety factor of 3
    - ⇒ **$\mathcal{O}$(5 Gbit/cm²/sec)**
    - Would saturate "standard" 1 Gbit/cm²/sec link

How to organise readout?

- **Hardware** (or software?) **trigger** as at LEP and LHC ?
  - Which sub-detectors can a trigger decision be based on?
  - High BX rate: Need for local **latency buffering** a la LHC?
    - Space/power/cooling for on-detector buffering?
- **Free streaming** of "self-triggered" sub-detectors ?
  - Off-detector event building based on BX ID via time stamping ?
  - Potential enormous data rate out of sub-detectors
    - Easily Tbit/sec from VXD alone
    - Is that at all technologically feasibly? Power needs,...?
      - c.f.: EiC will be streaming at max of 100 Gbit/sec
- **Hybrid Solution** possible **?**

Need to consider TDAQ architecture as integral part of detector design

CLD as an example

Contents from A. Paramonov

- The beam backgrounds (incoherent pair production) are dominating the data rate from the 1st layer of the vertex detector. → **Arguably the hardest to readout!**

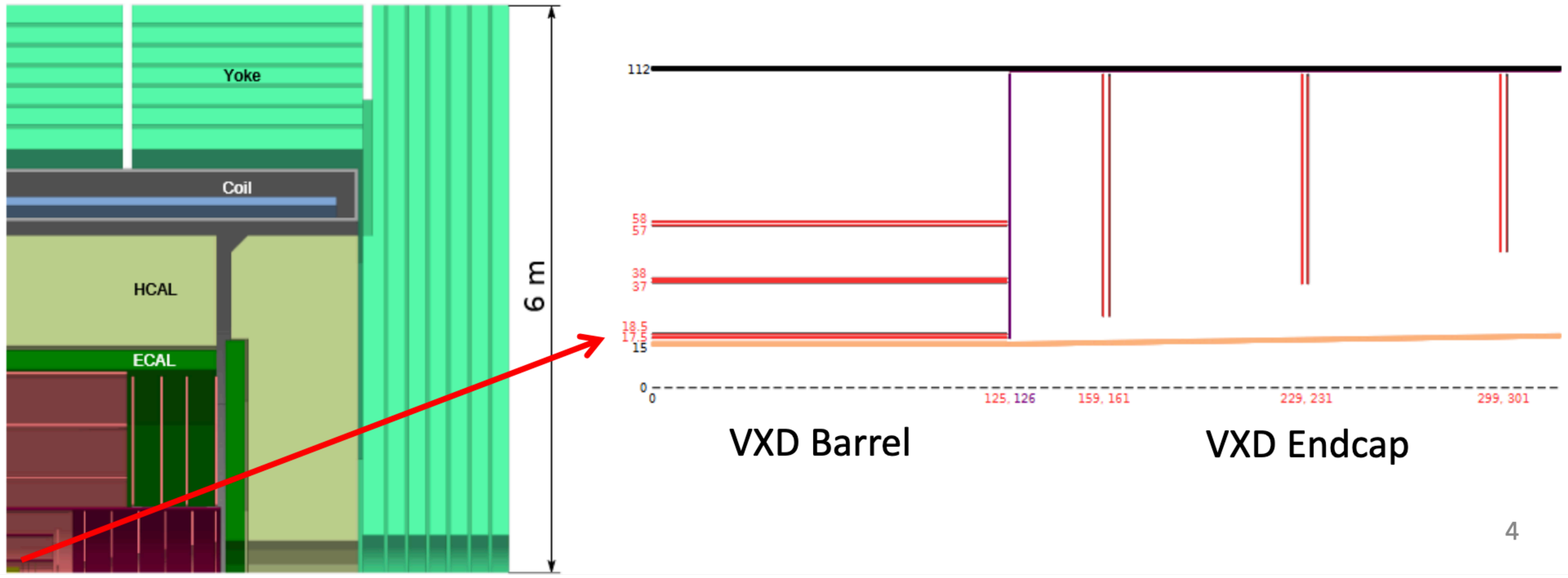
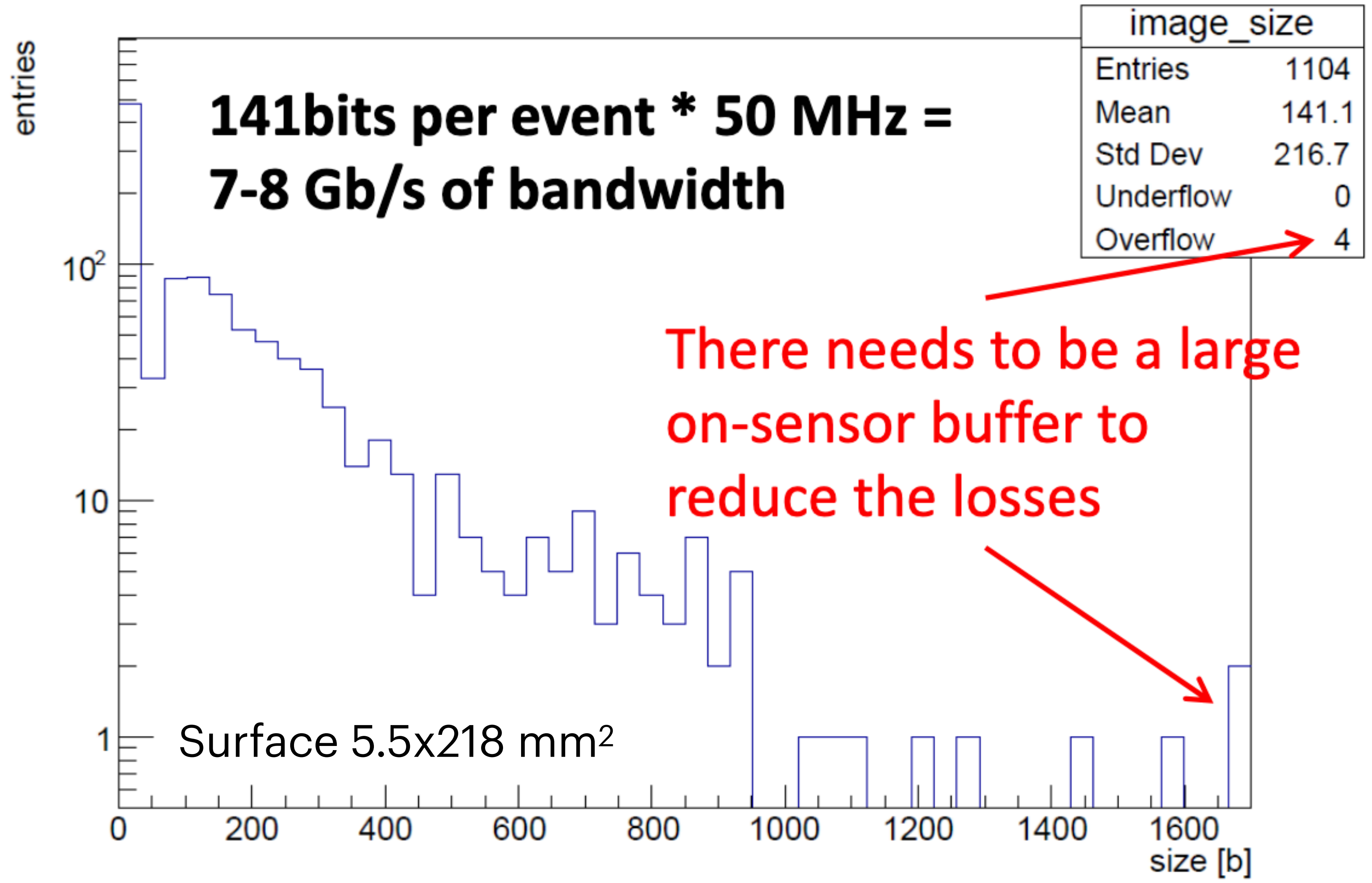


image size in bits for a VXD L1 sensor



- Let's round the bandwidth per a 5.5x218 sensor to 10 Gb/s.
- There are 32 sensors (links) in the Layer-1. => The total bandwidth is 32Gb.

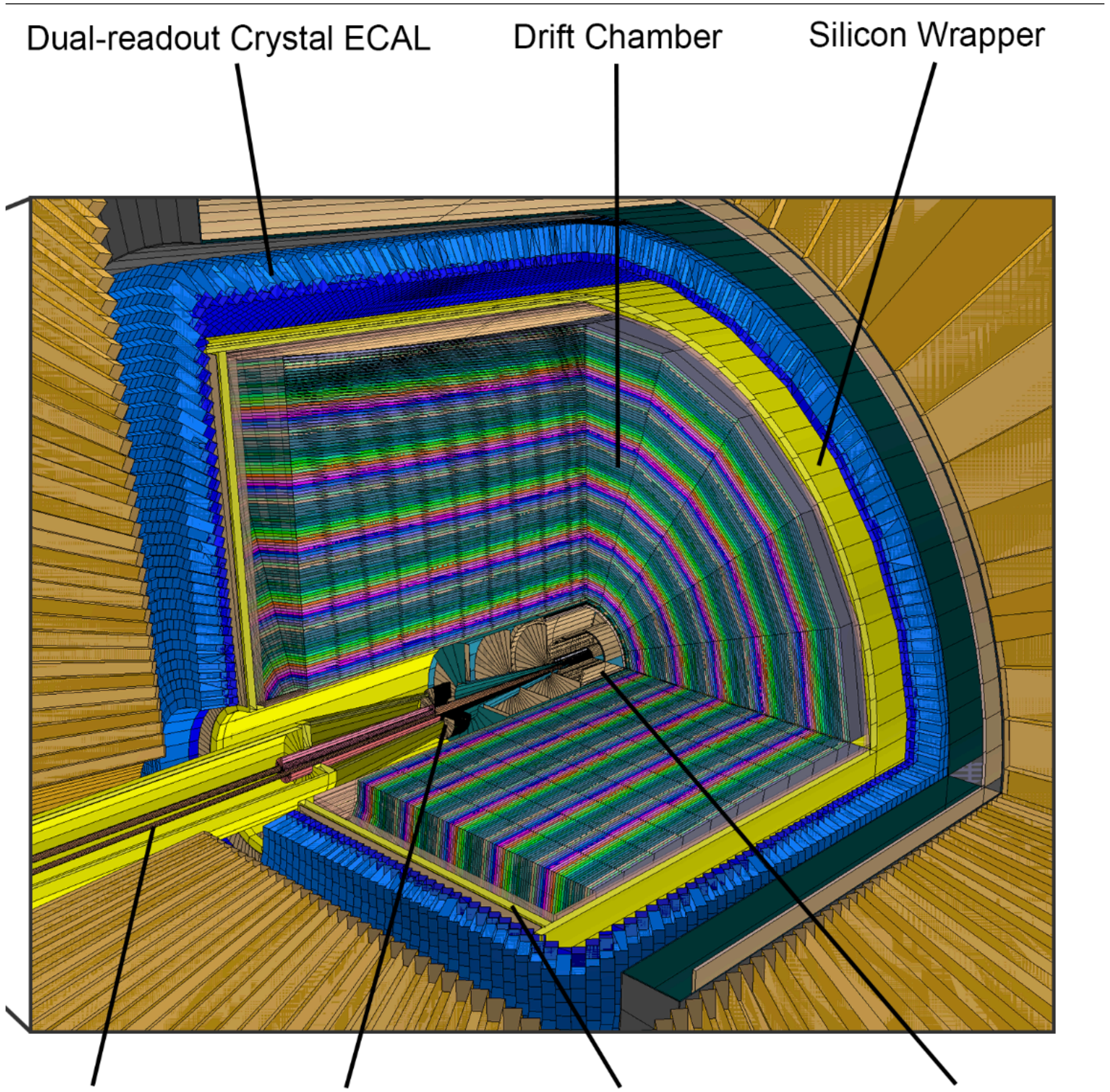
That's not hard to handle event with contemporary technology; e.g. with 1.5 of FLX155 cards

The other layers will suffer less from the beam backgrounds and the total bandwidth will not be a challenge. The whole tracker can probably the handled by a handful of FPGA cards like FLX-155.

However, with the numbers above, the triggerless readout seems possible even with the contemporary TDAQ technology. It will be easier in 10-20 years.

IDEA throughput summary – 2nd example

Slides from L. Capriotti



Q: how many seconds/year we will pull data out?

Throughputs summary table

Subdetectors	Throughput
Silicon Vertex Detector	~1 TB/s (untriggered) or ~10 GB/s (triggered)
Drift Chamber	< 1 TB /s (no clustering) or ~100 GB/s (w/ clustering)
Crystal calorimeter	< 1 GB/s
DR fibres calorimeter	10.2 TB/s (no threshold) - 4.2 GB/s (w/ threshold)
Luminometer	18 GB/s
Muon system	400 MB/s
Preshower (if no crystals)	350 MB/s

TDAQ R&D

DRD7

Slides from N. Neufeld

Assumptions

DRD7

TDAQ summary at FCC 2025 Vienna

- Basing following mostly on https://indico.cern.ch/event/1408515/contributions/6521330/attachments/3073372/5437820/jb_FCCee_TDAQ_22may25.pdf
- The most challenging scenario is the running at the Z-pole, which has a 40 MHz BC / 100 kHz "physics" rate
- From a claimed 1.7 EB / year and assuming 10^7 seconds of running for FCC-ee I derive an event-size of about 1.5 MB for a physics event (which seems large for a lepton machine, c.f. LHCb's event-size during LHC Run3 is about 100 kB)

Exabyte = 10^9 TB, a reference:

LHC at the end of HL (≈ 5 EB)

DRD7

Slides from N. Neufeld

DRD7: R&D Collaboration on Electronics and On-Detector Processing

WP7.1: Data density and power efficiency — Radboud University

WP7.2: Intelligence on the detector

WP7.3: 4D and 5D techniques — Nikhef, Radboud University

WP7.4: Extreme environments

WP7.5: Backend systems and COTS components — Nikhef

WP7.6: Complex imaging ASICs and technologies

WG7.7: Tools and Technologies

More on: https://drd7.web.cern.ch/

DRD7

Slides from N. Neufeld

Out of this vast menu the following seem relevant for FCCee-*DAQ

DRD7

- 7.1a: Silicon Photonics Transceiver Development — **Interested by a number of Nikhef colleagues,** including me
- 7.1c: WADAPT (Wireless Allowing Data and Power Transmission) — Radboud University
- 7.2b: Rad-tolerant RISC-V System-on-Chip
- 7.3c: Timing Distribution Techniques — Nikhef, Radboud University
- 7.5a: DAQOverflow
- 7.5b:From Front-End to Back-End with 100GbE — Nikhef

*: note the **deliberate** omission of the 'T' in TDAQ –
I do not see a need for any hardware trigger for FCCee

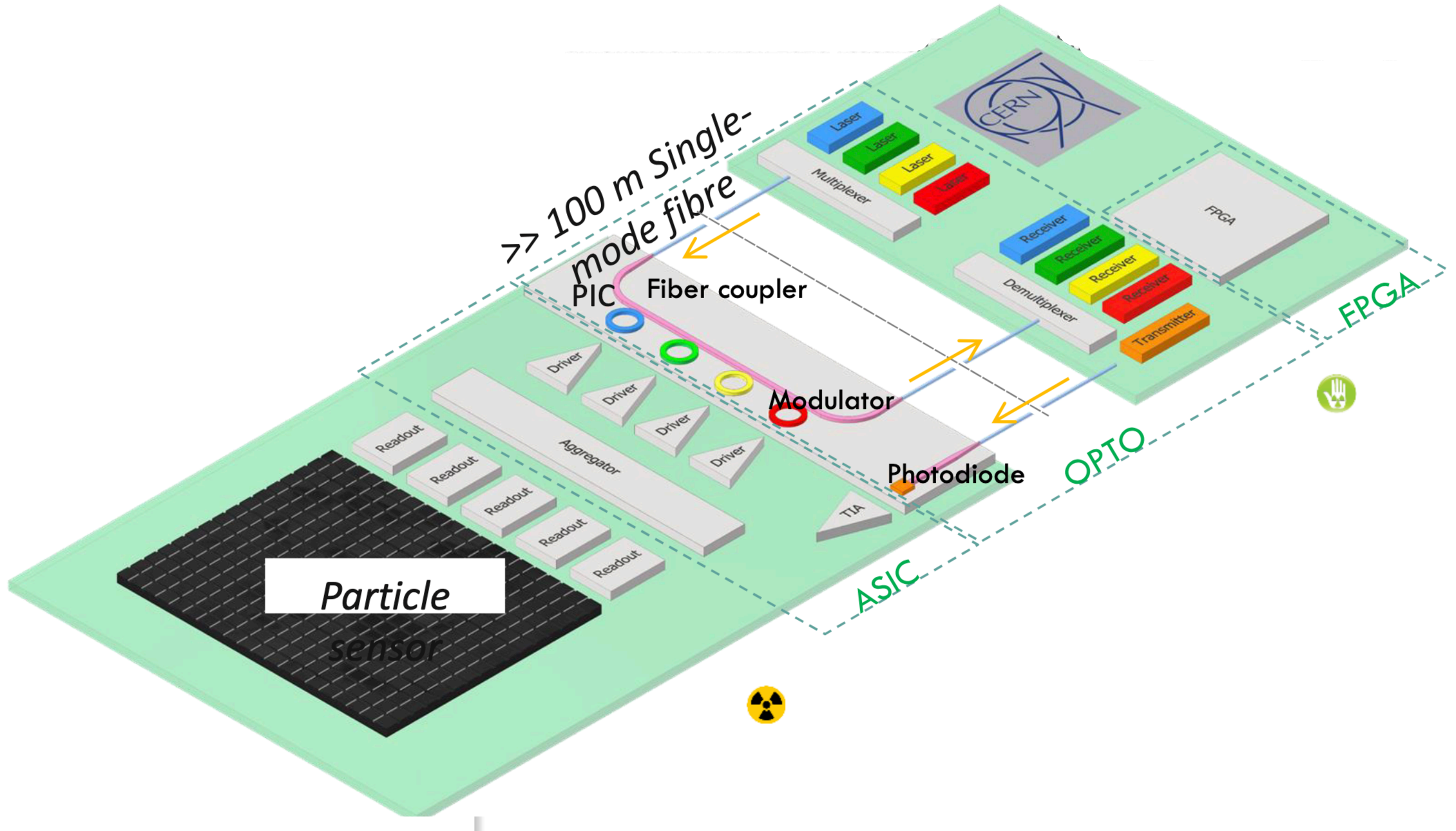
- LHCb is reading out the entire detector at BC rate (40 MHz) today
- From the numbers known so far, no requirement seems to go beyond what the LHC experiments have studied and solved
- Thus, for a trigger-less readout the question, for which DRD7 might offer answers, is mostly: *can we get the data out?*

Light-weight readout-links

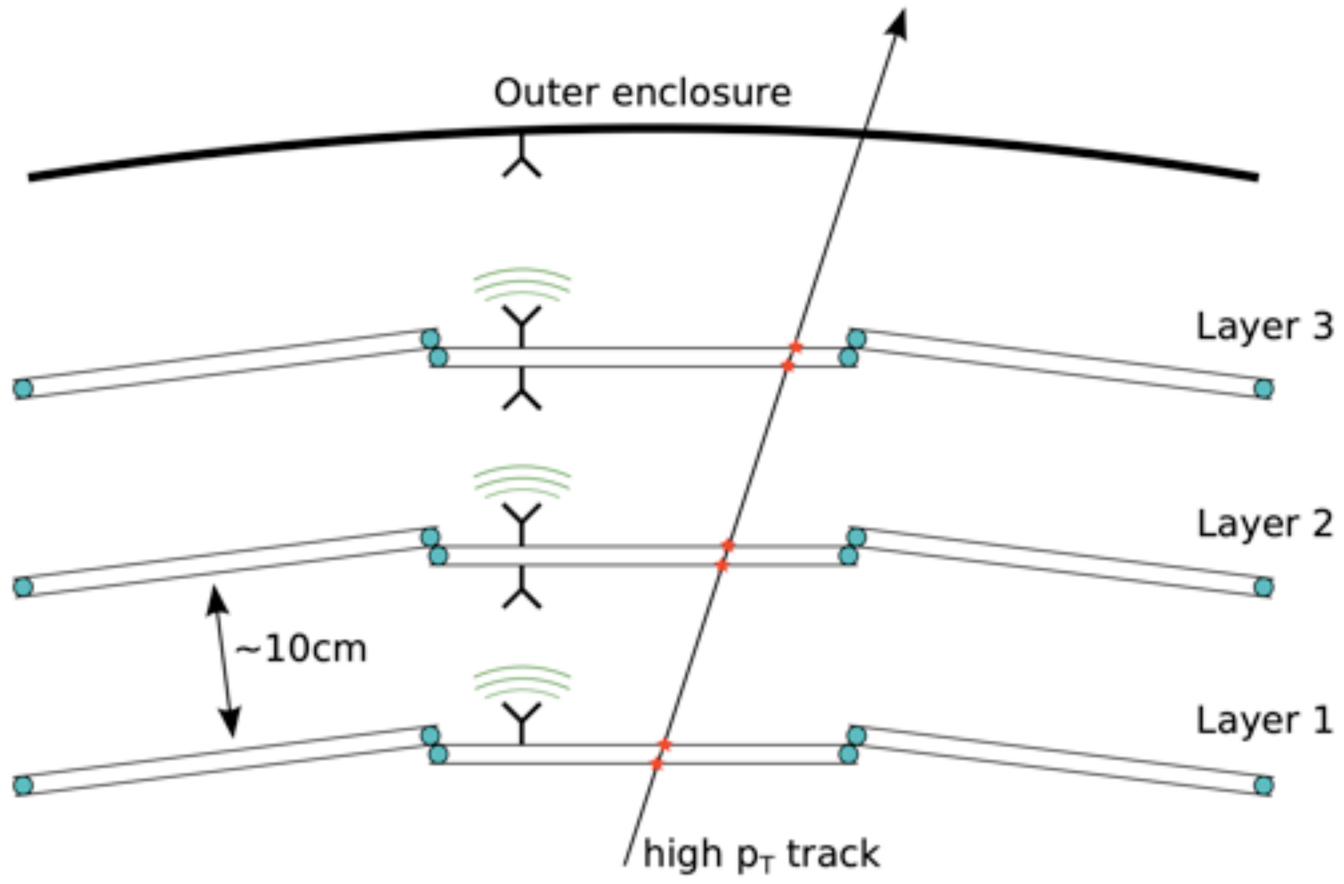
DRD7

Slides from N. Neufeld

- Silicon Photonics links (7.1a)
  - 100 Gbit/s, single single-mode-fibre, radiation-hard, might be used for VeloPix LHCb U2
  - This is also low-mass and relatively low-power, the laser itself is located outside the sensitive volume
  - These links might be “overkill” for sparse detectors. Depends on possibility to aggregate data locally. In any case even 100 Gigabit/s will be relatively slow compared to what the COTS technology in the further DAQ can do, so an aggregation layer will be useful in any case



- Work on a cost-effective back-end for such fast links is conducted in WP7.5, specifically in project 7.5b
- Wireless readout 7.1c is clearly more “experimental”, but potentially interesting for the innermost, high granularity detectors
  - At the time-scale of FCC-ee, there should be enough opportunity to establish the feasibility before final decisions on the front-end architecture need to be taken



System-building

Slides from N. Neufeld

DRD7

- The "core" DAQ for a larger experiment consists of
  - some receiving layer ("back-end") which might have some (additional) inline processing
  - Some kind of "event-building", where geographically dispersed fragments of the full collision data are assembled for further processing ("this need not be explicit: could be "file-based" like in CMS, or even with some kind of large global memory abstraction (PCIe, CLX etc…), but conceptually some kind of network will be involved
  - Possibly some storage, which at the very least is an operational convenience, as it allows buffering, derandomizing etc…,
  - Compute: which today looks to be a combination of CPU and GPU and might in the future include some more specialized "AI"-kind of hardware
- All but the first are COTS. Some novel possibilities for the compute are explored in 7.5a
  - But beware of the longevity of specific hardware solutions – HEP experiments today have long life-times, often longer than technology cycles with a few exceptions (PCIe, Ethernet, x86)
  - The "back-end" layer does conversion and is nowadays still custom-built
    - 7.5b studies possibilities to "remove" it or at least make it as much as COTS as possible, this reduces cost and makes it per definition more future-proof

Final touches

Some triggerless concerns

- Can we (and do we want to) afford triggerless readout?
  - Including 10x MC → could end up with ~ 20 x overall HL-LHC storage needs

- Affects the DAQ systems as much as the trigger of course
  - Precision measurements → low mass / low power systems
  - Deal with 10^{13} physics events without throwing any away

- The real question is the impact of beam related background
  - Can easily produce TB/s per region
  - Preliminary estimates vary easily by x10

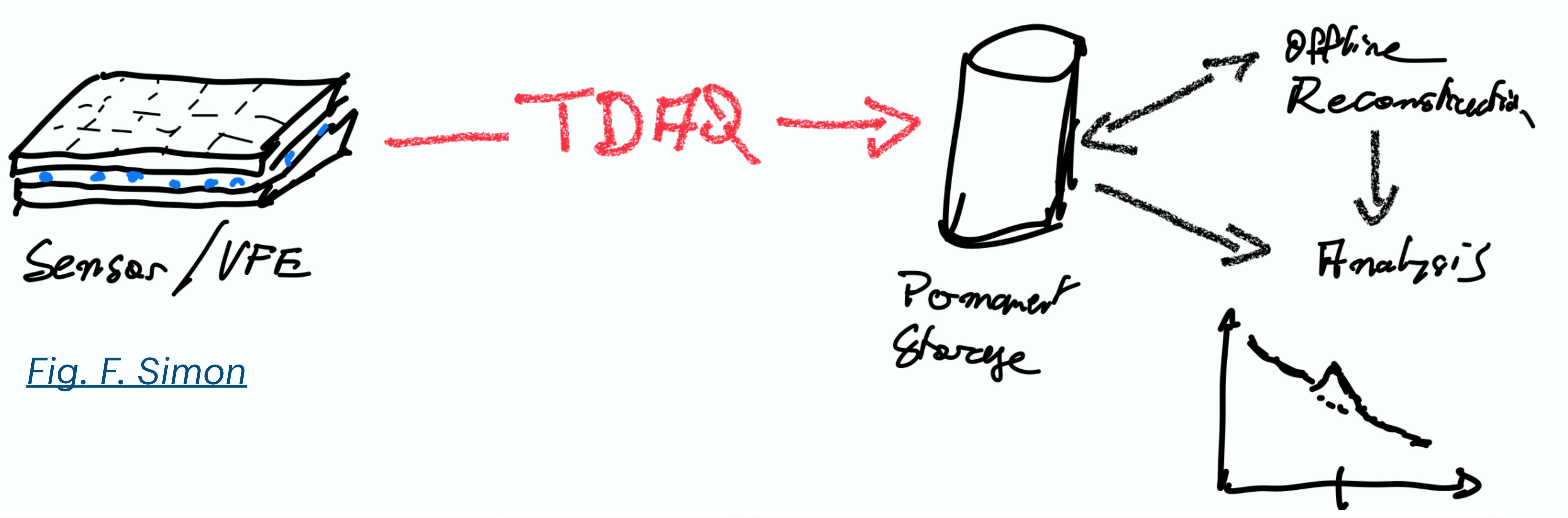
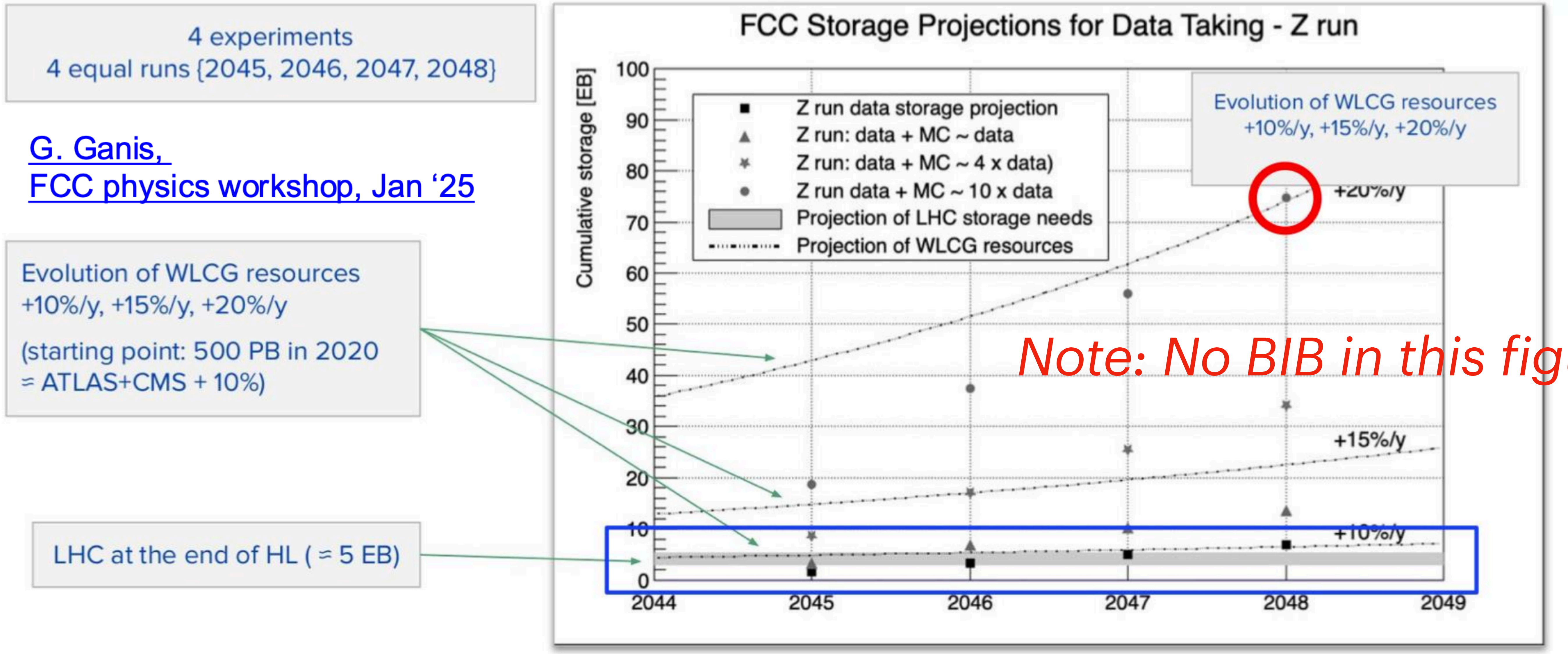


Fig. F. Simon



G. Ganis, FCC physics workshop, Jan '25

Challenge for off-line computing and long-term storage

Contents from T. Wengler

Data processing software – also a part of TDAQ

Contents from T. Wengler

Important to remember: TDAQ <-> Detector System Design

– The data rates, required transmission and processing impact the design of the subdetectors and their services

Lacunae

– Useful to have quick way of studying the implications of detector changes

Data processing

– Note we are considering digital readout so far of one BX – but we might need access to pulse shapes over several BX (e.g. LAr), several BX consecutive readout for LLP

→ fill in your favourite multiplication factor here: [ ] ✖ 

Common DAQ - long discussed steadily taking shape.
& Nikhef is part of it.

- It would seem to make sense to converge as much as possible on common elements in designing the TDAQ systems
  - See current TTC system, now White Rabbit, FELIX project …
  - Common designs need early understanding of requirements across detector concepts

Backup

DRD7

Slides from N. Neufeld

Timing

DRD7

- An enormous amount of work has been done on timing for the LHC experiments
- 7.3c continues and pushes this further – studying "pure" clock distribution, distribution of timing reference via White Rabbit, phase stability and reproducibility of commercial FPGA serializers and much more. Ambitious targets stated in terms of small number of *picoseconds*

Data-processing on detector

DRD7

- Inline data-reduction (common-mode, cluster-finding, etc…)
  - Depending on radiation levels could be done by COTS FPGAs (not part of DRD7)
  - More complex logic, also for control and monitoring, could use a micro-processor → 7.2b (RISC-V radiation hard CPU)
- Some more advanced processing possibilities are studied in 7.5a: "DAQOverflow" or "intelligence on/close to the detector". This focuses on the use of (novel) COTS hardware, so radiation issues are not considered though. Your Mileage May Vary ™ .

Hybrid/minimal trigger

Slides from L. Capriotti

Trigger or triggerless?

There is also a third possibility:

Triggerless readout → buffering → triggering/filtering → storage

- Delaying data filtering allows for simplicity
- Applying a filter limits data storage and allows synchronising in time different parts of the event
- The whole procedure facilitates user access

Example: **LHCb experience with use of a large buffer** (**weeks of data**) between HLT1 and HLT2

Each detector can use their own protocal for writing to the buffer (even triggered, if so desired)

- Delayed filtering can take advantage of run-dependent information, not just event-based
- Can account for aligments, variable beam conditions, background...
- **May be an option to consider**