CEPC TDAQ study

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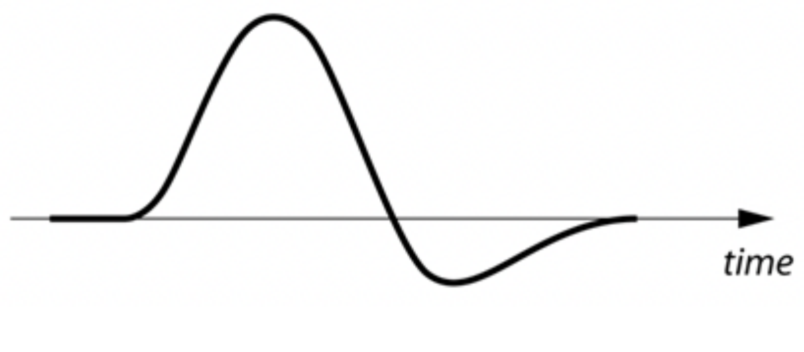
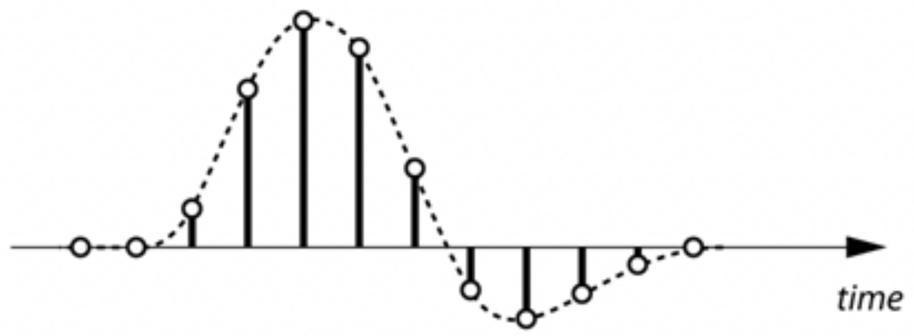
Introduction (1)

- Wikipedia: **Data acquisition** (DAQ) is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer

Sensor → **ADC** → **CPU/GPU/FPGA/…** → **Disk**





10000111000101
10100001000011
11011010110101

10010110
00111101

Introduction (2)

- Wikipedia: In particle physics, a **trigger** is a system that uses simple criteria to rapidly decide which events in a particle detector to keep when only a small fraction of the total can be recorded

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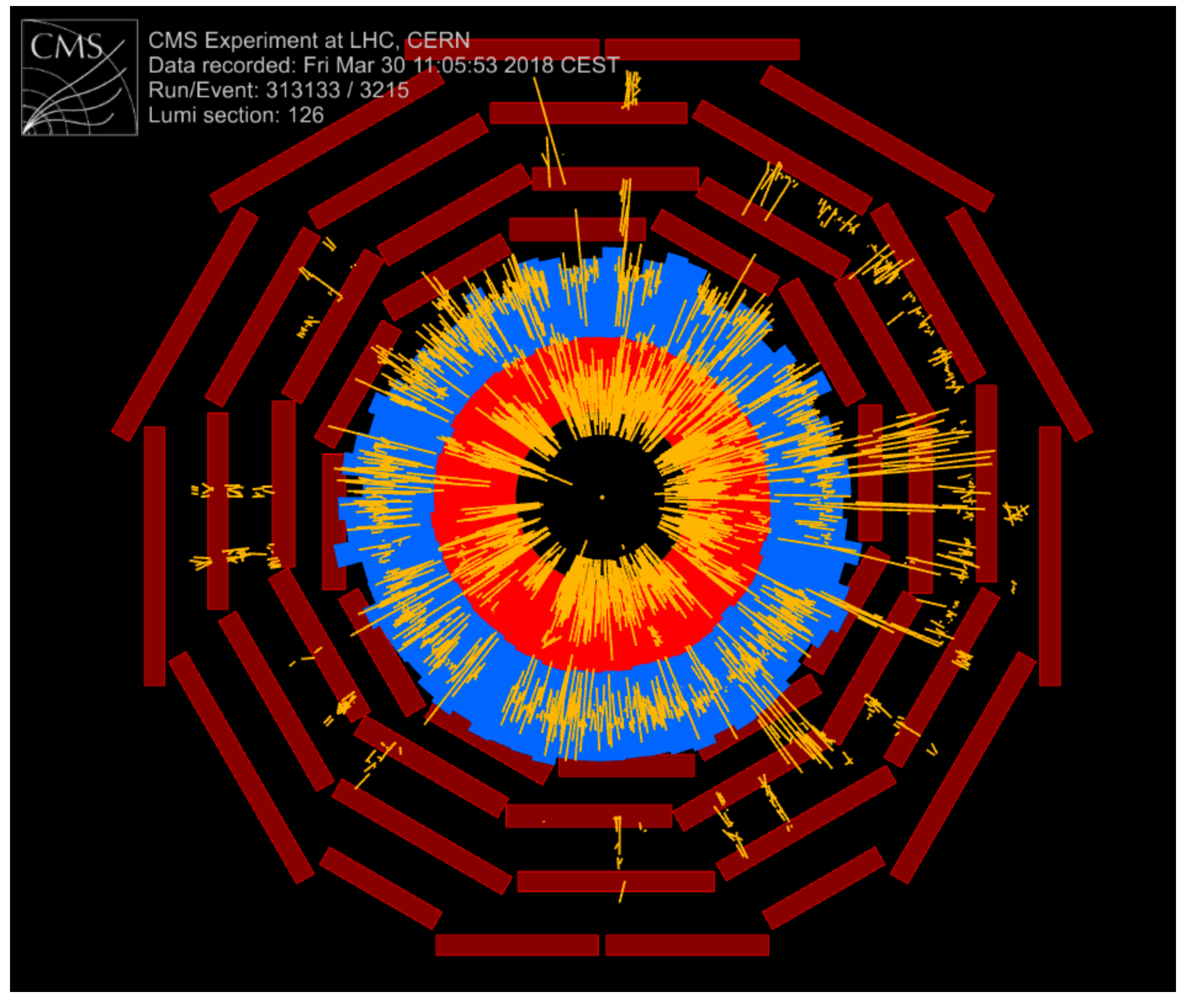
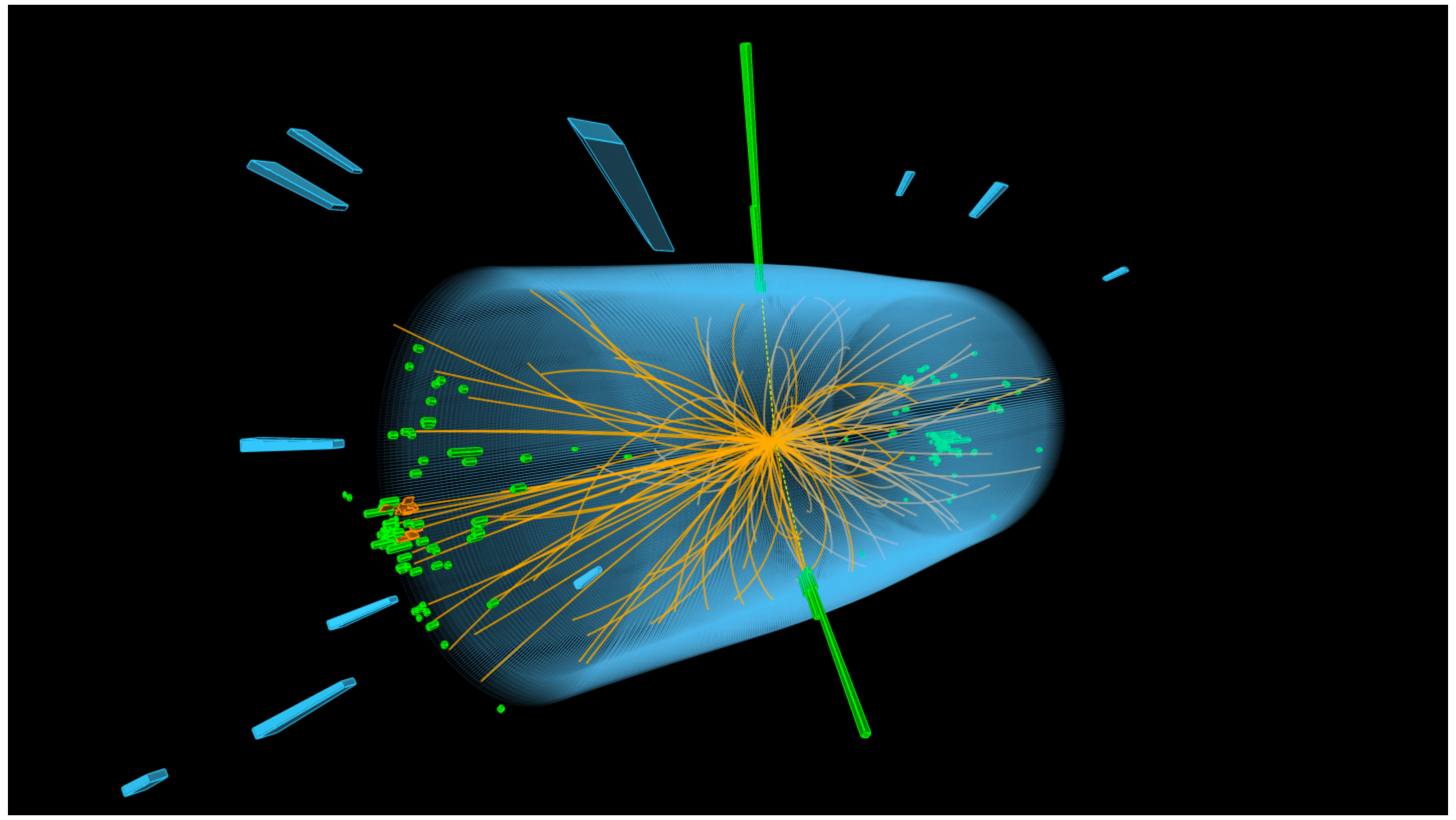


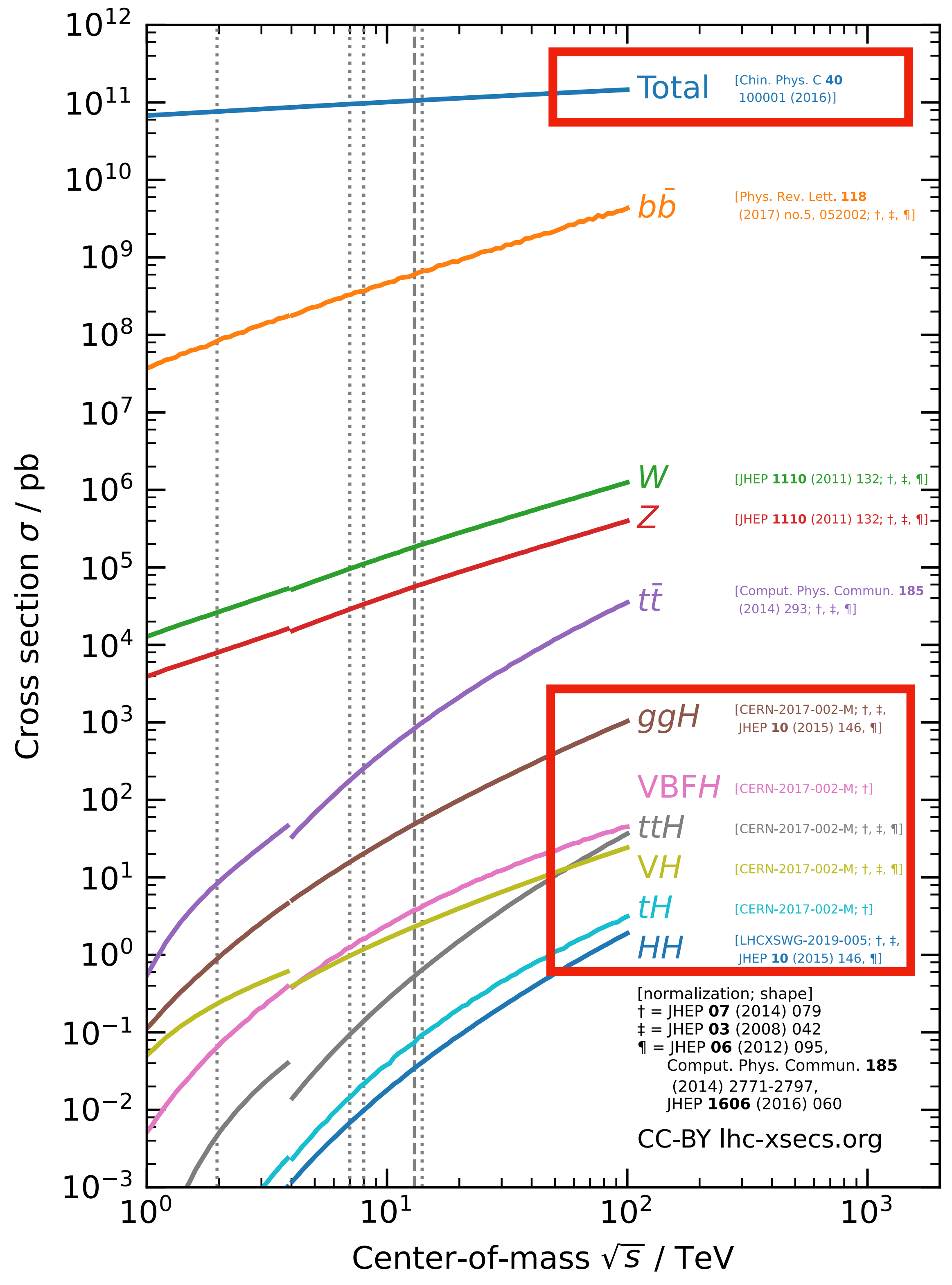


A pseudo-example

Left: uninteresting, don't keep

Right: $H \rightarrow \gamma\gamma$ candidate, keep

Introduction (3)



pp collision

- TDAQ architecture is driven by physics and resource limits
- When study rare physics processes (e.g. Higgs at ATLAS/CMS) at a hadronic collider (LHC), S/B can be extremely small (~$1/10^{10}$)
  - Impossible to store/process unfiltered data from all channels at the LHC collision frequency (40 MHz)
  - Often use a multi-tier trigger system
    - Level 1 (custom electronics) + high level trigger (software)

Introduction (4)

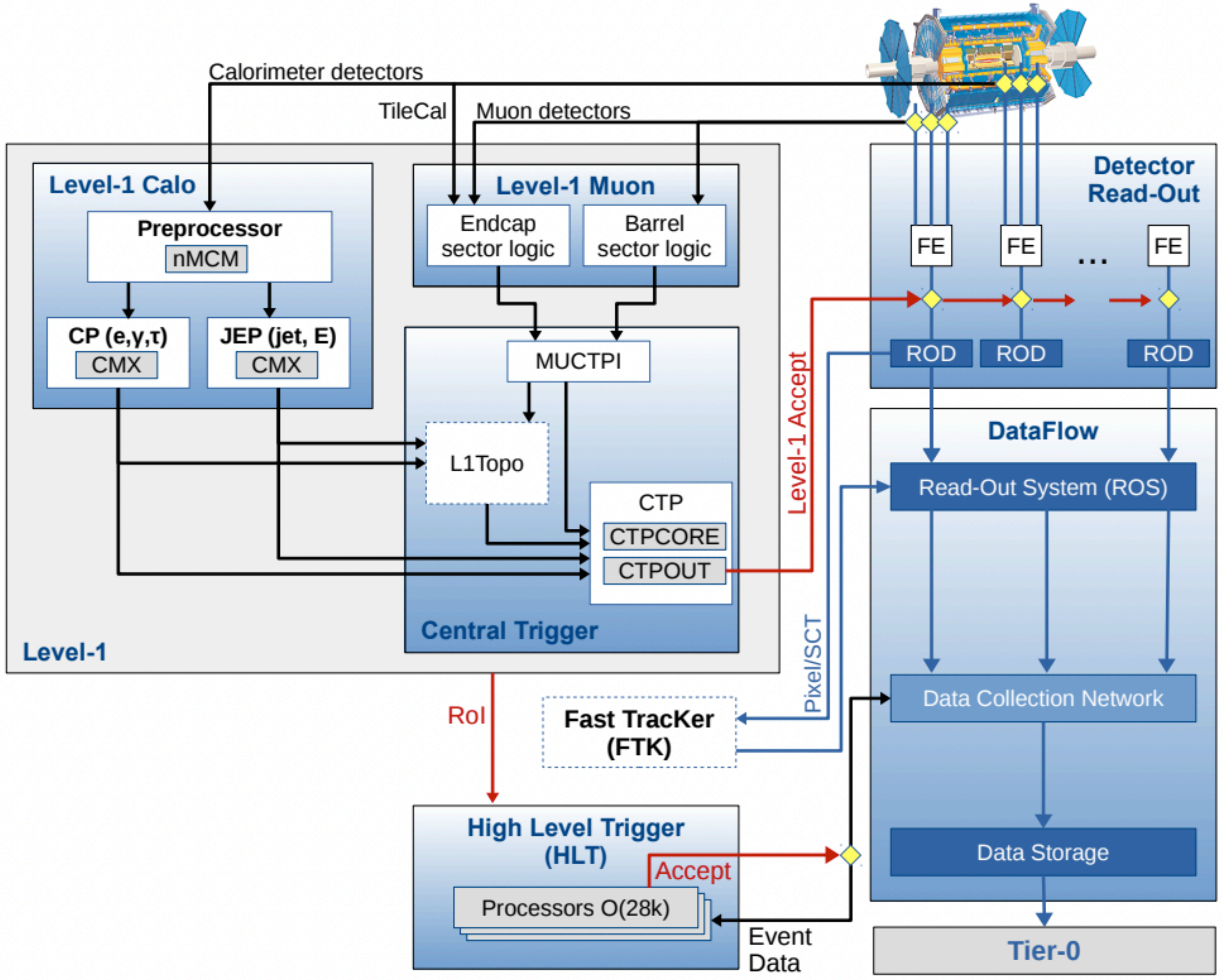


Figure 1: The ATLAS TDAQ system in Run 2 with emphasis on the components relevant for triggering. L1Topo and FTK were being commissioned during 2015 and not used for the results shown here. Eur.Phys.J.C 77 (2017) 5, 317

When operating at the design luminosity of $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ the LHC will have a 40 MHz bunch crossing rate, with an average of 25 interactions per bunch crossing. The purpose of the trigger system is to reduce this input rate to an output rate of about 200 Hz for recording and offline processing. This limit, corresponding to an average data rate of ∼300 MB/s, is determined by the computing resources for offline storage and processing of the data. It is possible to record data at significantly higher rates for short periods of time. For example, during 2010 running there were physics benefits from running the trigger system with output rates of up to ∼600 Hz. During runs with instantaneous luminosity $\sim 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, the average event size was ∼1.3 MB.

shown in Fig. 2. Detector signals are stored in front-end pipelines pending a decision from the L1 trigger system. In order to achieve a latency of less than 2.5 μs, the L1 trigger system is implemented in fast custom electronics. The L1 trigger system is designed to reduce the rate to a maximum of 75 kHz. In 2010 running, the maximum L1 rate did

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Key TDAQ parameters at future ATLAS/CMS

2030-?	ATLAS	CMS
Total readout channels		O(100) million
Collision rate	40 MHz	40 MHz
Peak luminosity	7.5×10^{34} $cm^{-2}s^{-1}$	7.5×10^{34} $cm^{-2}s^{-1}$
L1 trigger rate	750 kHz	1 MHz
L1 trigger latency	12.5 μs	10 μs
Max bandwidth per link at L1	28 Gb/s	30 Gb/s
HLT rate	7.5 kHz	10 kHz
Recording throughput (to disk)	51 GB/s	60 GB/s
Storage needed per day (*)	3.3 PB	5 PB
Event size (saved at disk)	5.9 MB	5.2 MB

* Assuming ~50 % LHC duty cycle

- Reviewed the phase II ATLAS and CMS detector TDAQ system for HL-LHC (TDRs: ref1, ref2, ref3)
- These detectors will work in much harsher environment than CEPC
- Numbers in table indicates the feasible technology limit (lower bound) in the next decade(s)

Key TDAQ parameters at ILC/FCC-ee

	FCC-ee	ILC
Reference	CDR (2018)	TDR (2013)
Center of mass energy (*)	91.2 GeV	1 TeV
Peak luminosity (*)	4.6×10^{36} cm^{-2}s^{-1}	$> 1.5 \times 10^{34}$ cm^{-2}s^{-1}
Trigger mode	With hardware trigger	Trigger-less readout
Hardware trigger rate	100 kHz	NA
Total output rate to disk	~100 GB/s	~100 GB/s

* The discussion of TDAQ in CDR/TDR is only done in the beam configuration most challenging for TDAQ

- According to CDR, FCC-ee is also exploring trigger-less readout
- ILC has two different detector designs in TDR (SiD/ILD), both have same baseline trigger strategy (trigger-less) and similar estimate in terms of data rate
- In both cases, reasonable zero suppression has been considered in estimating the rate

Trigger-less readout for CEPC?

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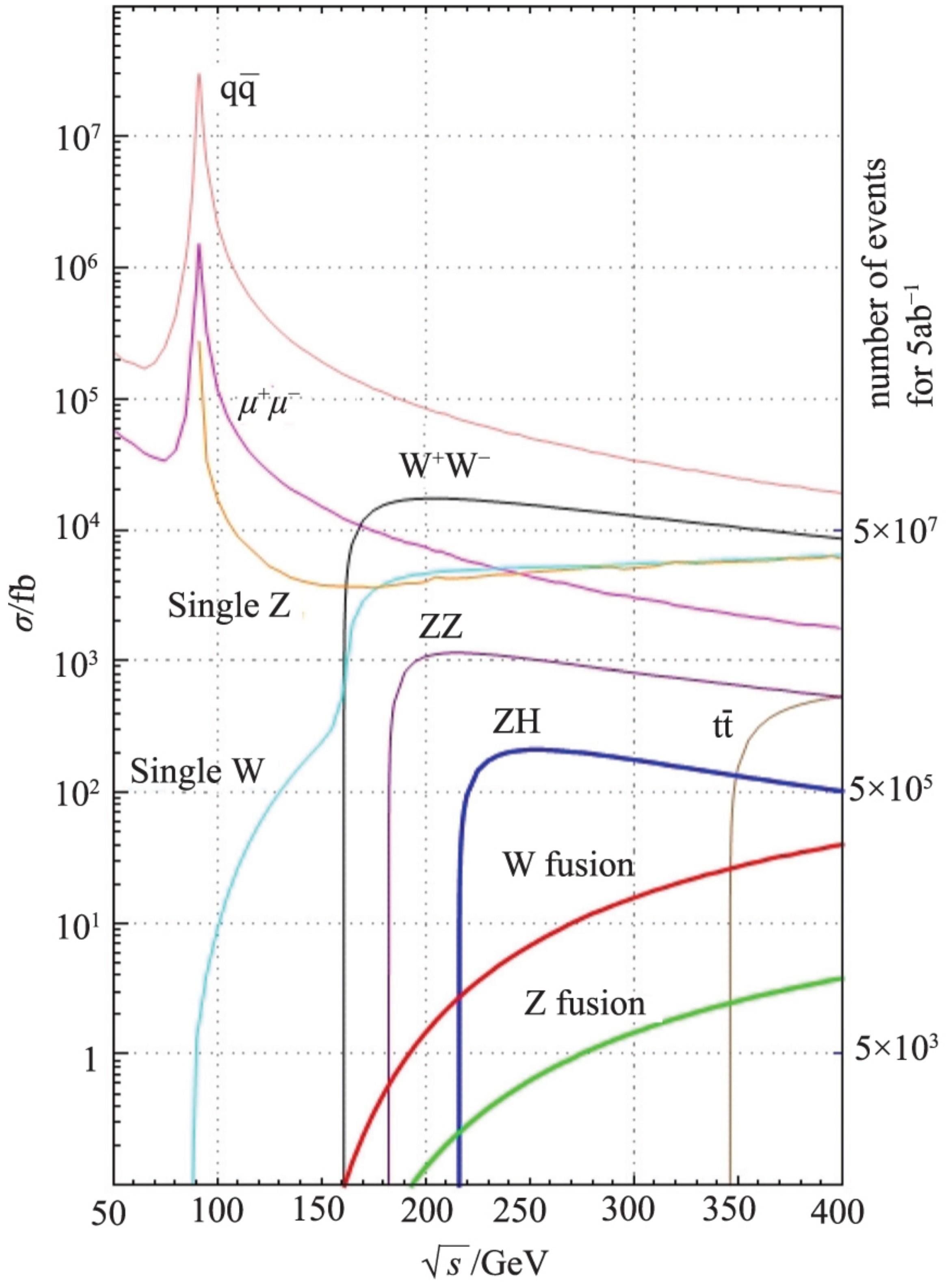


e+e- collision

- At lepton colliders, the background is not as difficult to deal with than hadron colliders (S/B~1/10^3 VS 1/10^{10})
- Trigger-less readout seems a very promising direction to explore
- Definition: All data in the front-end electronics above a programmable threshold is readout, no need to wait for hardware trigger decision

Pros and cons of trigger-less readout

- **Pros**
  - Flexible, unforeseen physics process won't be thrown away
  - Reduce the need to design custom hardware for trigger
  - Developing cycle is shorter, use high level programming language
- **Cons**
  - Not necessarily cost effective, if beam background dominates
  - Requires continuous calibration in ~real-time for robust zero-suppression

Feasibility study

- Reminder: limited output data rate/storage space => need trigger system
- As a first step, useful to know the expected data rate for detector readout at CEPC with/without hardware trigger system
- To develop the procedure of a proper rate estimate, start with Higgs and W mode from 2021 version of the CEPC design parameter

	Center of mass energy	**Luminosity per IP**
Higgs mode	240 GeV	5e34cm^{-2}s^{-1}
W mode	160 GeV	16e34cm^{-2}s^{-1}

Procedure

- **Data rate (bps) = event rate × trigger efficiency × detector occupancy × data size**
- Event rate (Hz)
  - Physics process (H, Z, WW, ZZ…) estimated from cross-section × luminosity
  - Beam background estimated from literature and dedicated studies

Procedure

- **Data rate (bps) = event rate × trigger efficiency × detector occupancy × data size**
- Trigger efficiency
  - **Trigger-less**: always 1 (assuming no 0-suppression in this iteration)
  - **Triggered**: based on simulation (physics process) and literature (beam background)
  - Trigger menu for triggered readout (details in backup)
    - Based on pT cut on single/double object (e/muon/photon/jet)
    - Efficiency > 95% for signal, ~50% for most background

Procedure

- **Data rate (bps) = event rate $\times$ trigger efficiency $\times$ detector occupancy $\times$ data size**
- Detector occupancy (active sensors per event):
  - Based on simulation (physics process) and previous studies (beam background)
- Data size (bits per active sensors):
  - From previous studies, use 4th conceptual design of detector

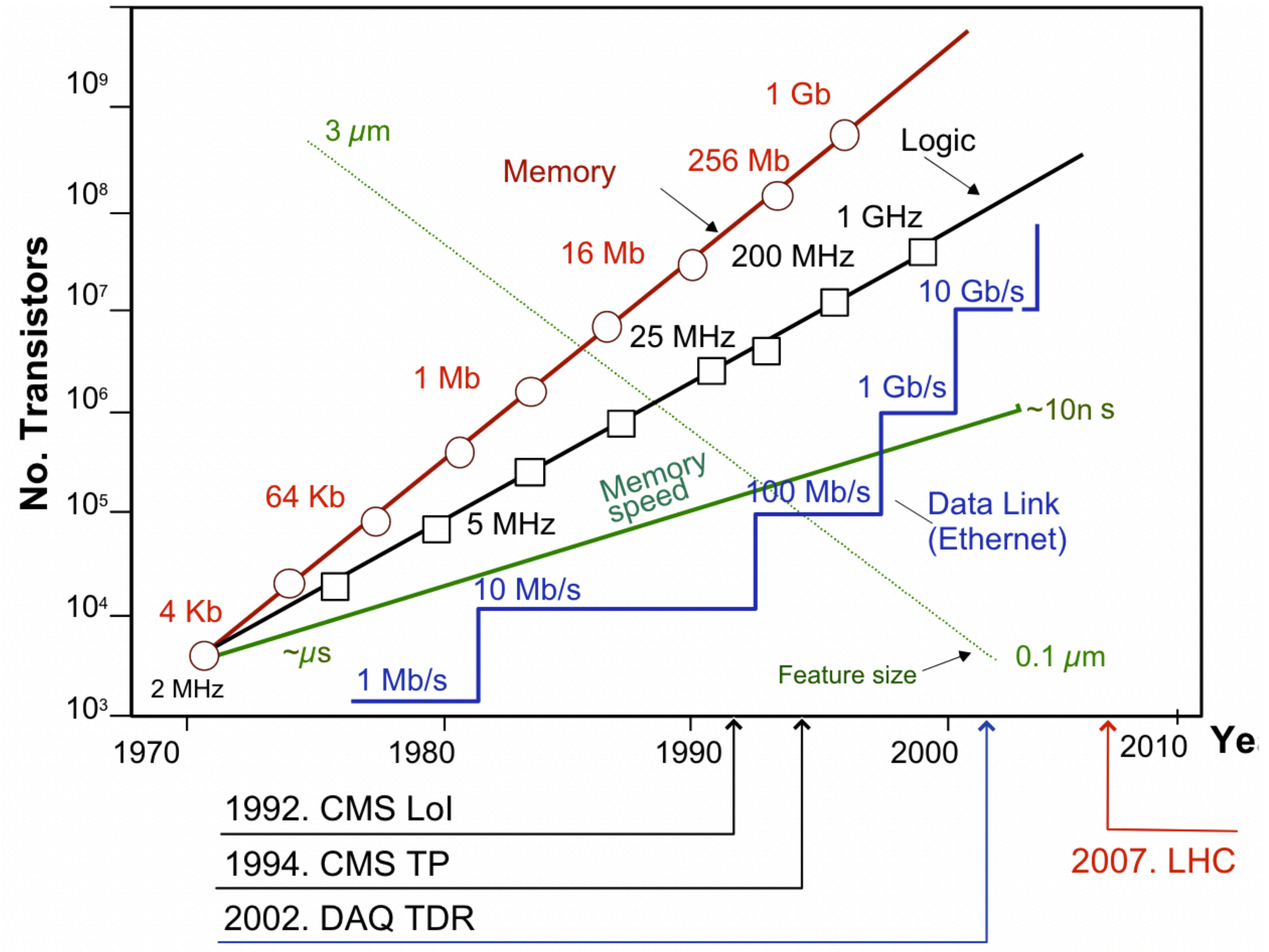
Preliminary rate result

	Trigger-less (H mode)	Triggered (H mode)	Trigger-less (W mode)	Triggered (W mode)
Vertex detector	1.5 Gb/s	3.9 Mb/s	3.8 Gb/s	9.8 Mb/s
Tracker	1.5 Gb/s	3.3 Mb/s	3.8 Gb/s	8.3 Mb/s
Drift chamber	0.3 Gb/s	261 Mb/s	1.2 Gb/s	948 Mb/s
ECAL	0.1 Gb/s	36 Mb/s	0.5 Gb/s	128 Mb/s
HCAl	0.04 Gb/s	25 Mb/s	1.2 Gb/s	87 Mb/s
Total	3.44 Gb/s	0.3 Gb/s	10.5 Gb/s	1.1 Gb/s

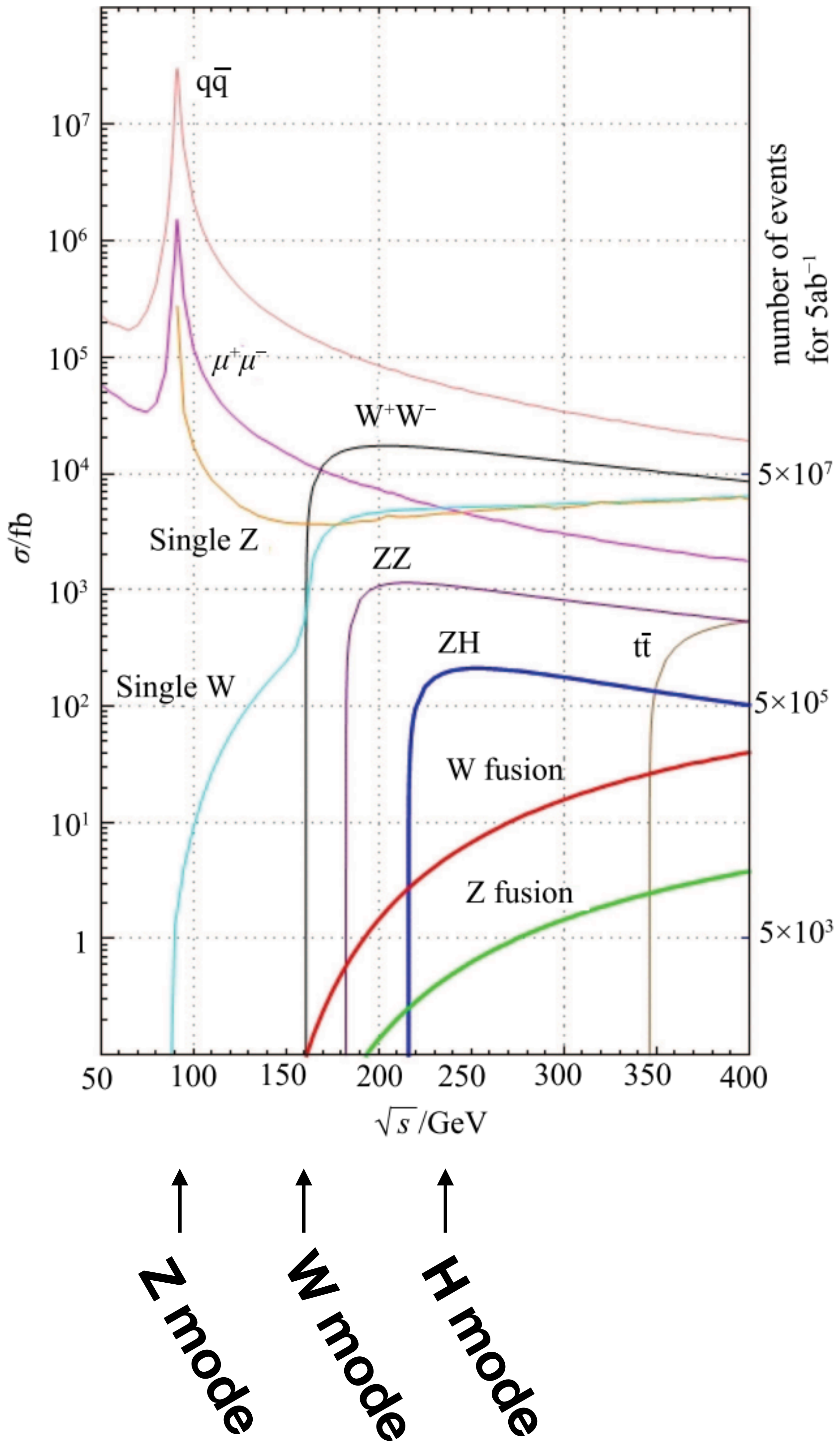
* Muon detector not considered in this iteration

- Beam background has a big impact on the rate of vertex detector
- Large data volume at drift chamber (DC) due to long drift time (~ 400 ns)
- Expect big rate reduction with proper 0-suppression (e.g. $\times$ 30 reduction at FCC-ee DC)

Other considerations



CMS TriDAS TDR
CERN/LHCC 02-26



- Technology develops rapidly over the years (Morse law)
- The biggest challenge in rate will be at Z mode
- Other design implications on front-end/backend electronics by trigger-less readout?

Summary

- The trigger and DAQ system is an important building block of the CEPC detector
- Evaluate the expected data rate at Higgs mode and W mode based on 2021 accelerator and 4th detector design
- The design of the TDAQ system still needs more careful evaluation, bearing in mind the fast development of the technology

Backup

More on beam background

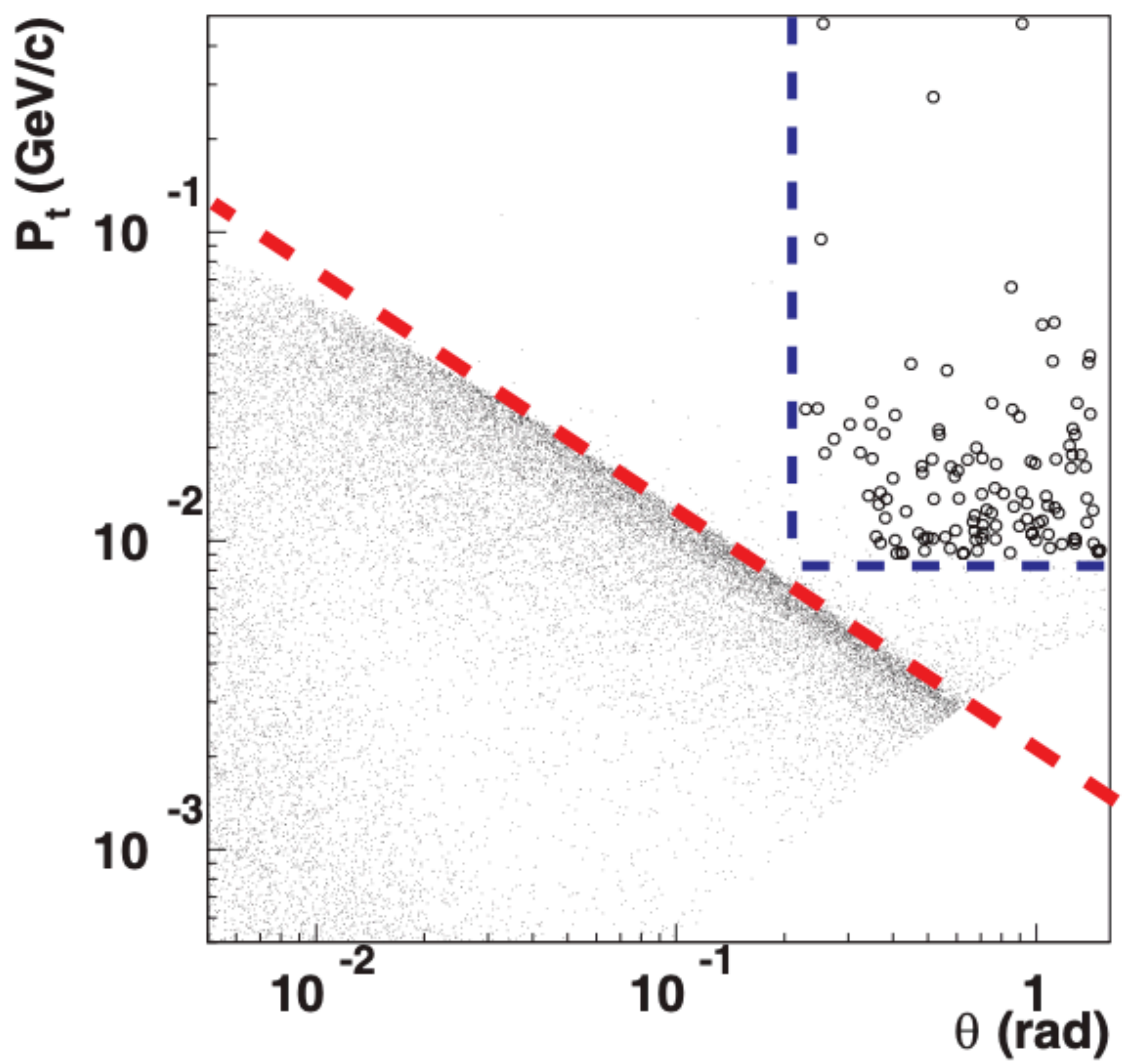


FIG. 7. (Color) Distribution of P_t versus θ for electrons from IPC processes. The region corresponding to particles reaching the VD (circles) is indicated with the two dashed lines for the detector configuration described in the text. A thick dotted line highlights the edge of the beam-beam deflection induced accumulation zone.

https://journals.aps.org/prab/pdf/10.1103/PhysRevSTAB.9.034402

TABLE V. Cross sections for incoherent pair production, $\sigma_{e^+e^-}$, and for the pair background reaching the VD, σ_{VD}, predicted by GUINEA-PIG, with the "beam-size effect" activated and using $Q_{\max} = m_e$ for the maximum virtuality in the equivalent photon spectrum instead of the default value.

GUINEA-PIG	$\sigma_{e^+e^-}$ (mb)	σ_{VD} (μb)
All processes	51.8	32.0 ± 4.3
Breit-Wheeler	1.09	5.7 ± 1.8
Bethe-Heitler	35.2	16.5 ± 3.1
Landau-Lifshitz	15.6	9.7 ± 2.4

With a drift chamber, all digitised hits generated on the occurrence of a trigger are usually transferred to data storage. The IDEA drift chamber transfers 2 B/ns from both ends of all wires hit, over a maximum drift time of 400 ns. With 20 tracks/event and 130 cells hit for each track, the size of a hadronic Z decay in the DCH is therefore about 4 MB, corresponding to a bandwidth of 400 GB/s at the Z pole. The contribution from $\gamma\gamma \rightarrow$ hadrons amounts to 60 GB/s. As reported in Section 7.4.4, the IPC background causes the read-out of additional 1500 wires on average for every trigger (including a safety factor of 3), which translates into a bandwidth of 250 GB/s. A similar bandwidth is taken by the noise induced by the low single electron detection threshold necessary for an efficient cluster counting. Altogether, the various contributions sum up to a data rate of about 1 TB/s.

FCC-ee CDR

Details

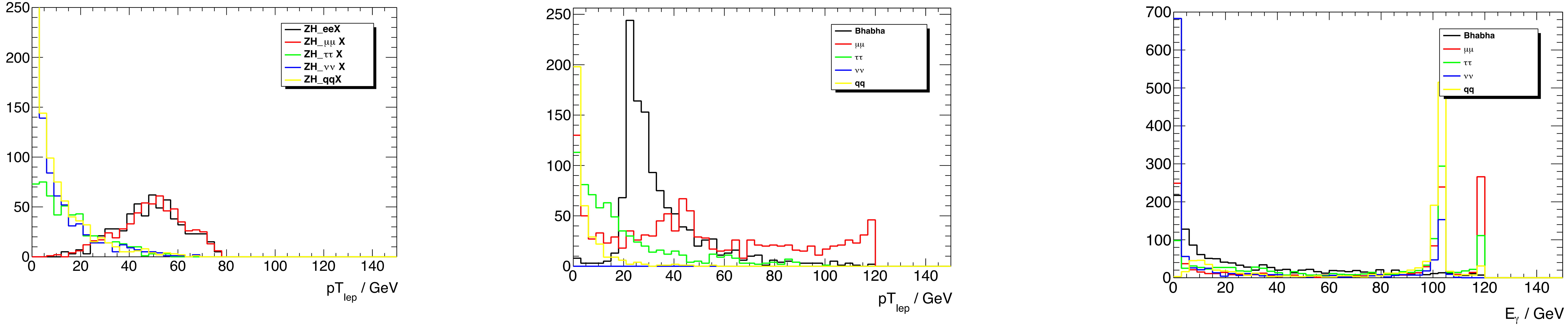
- Use several typical physics process with full MC simulation
  - Higgs signal (ee->ZH->ffH), 2-fermion background (ee->ff), bhabha
  - Events generated with Whizard 1.95
  - Detector based on CEPC 4th conceptual detector design
- Important beam backgrounds
  - Breamstrahlung, radiative Bhabha, incoherent pair production, coherent pair production, neutrons/other hadrons

Various analysis details

Pseudo trigger menu

	Single e	Single mu	Single gam	MET	Single jet	e-e	mu-mu	gam-gam	di-jet	e-mu	e-jet	mu-jet	gam-jet
Threshold [GeV]	20	20	20	20	40	10,10	10,10	10,10	20,20	10,10	15,20	15,20	15,20

Basic distributions



References from previous workshop

- https://indico.ihep.ac.cn/event/11444/session/14/contribution/228/material/slides/0.pdf
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