# Timing for DAQ

## A physicist's perspective

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20 June 2023

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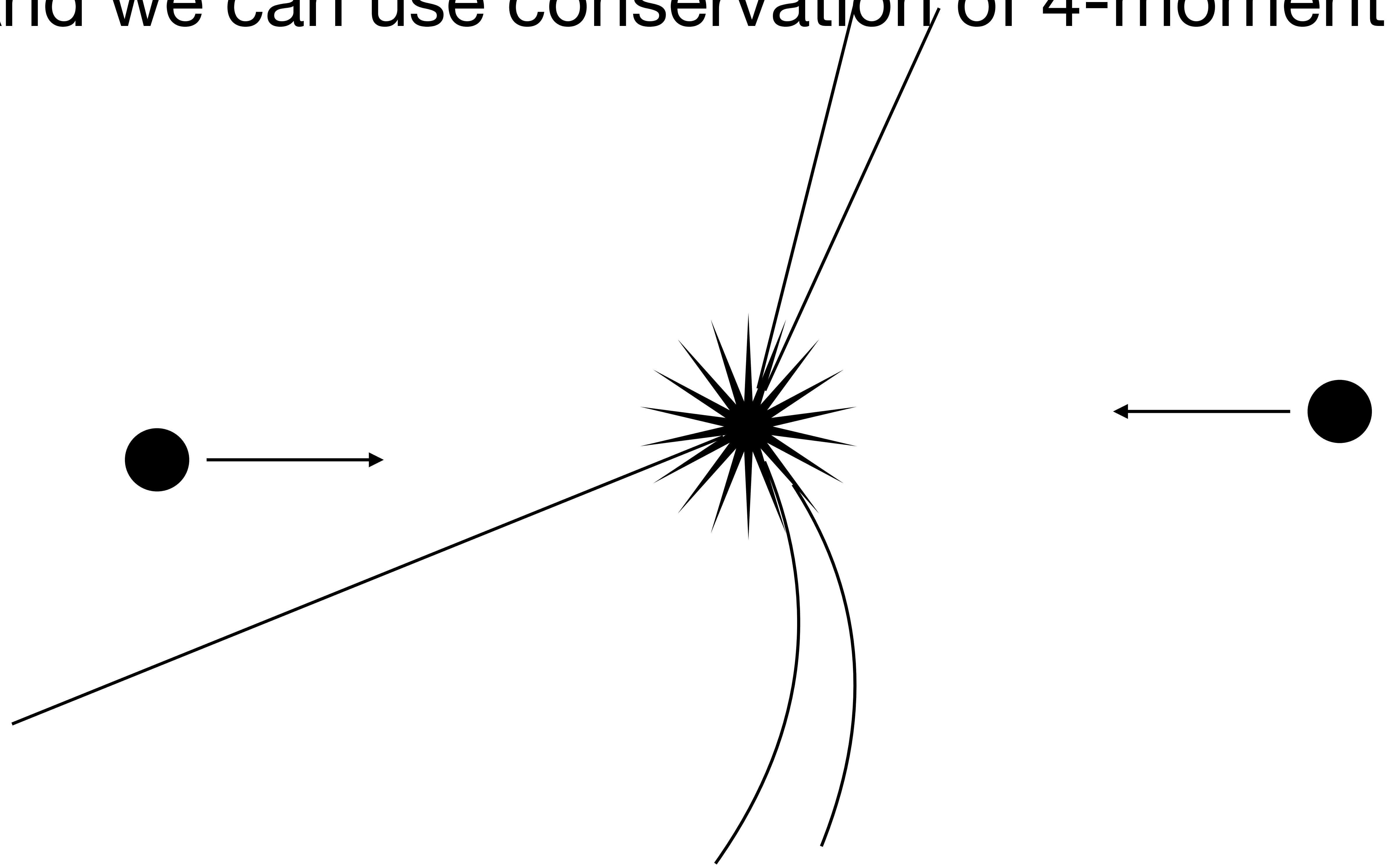
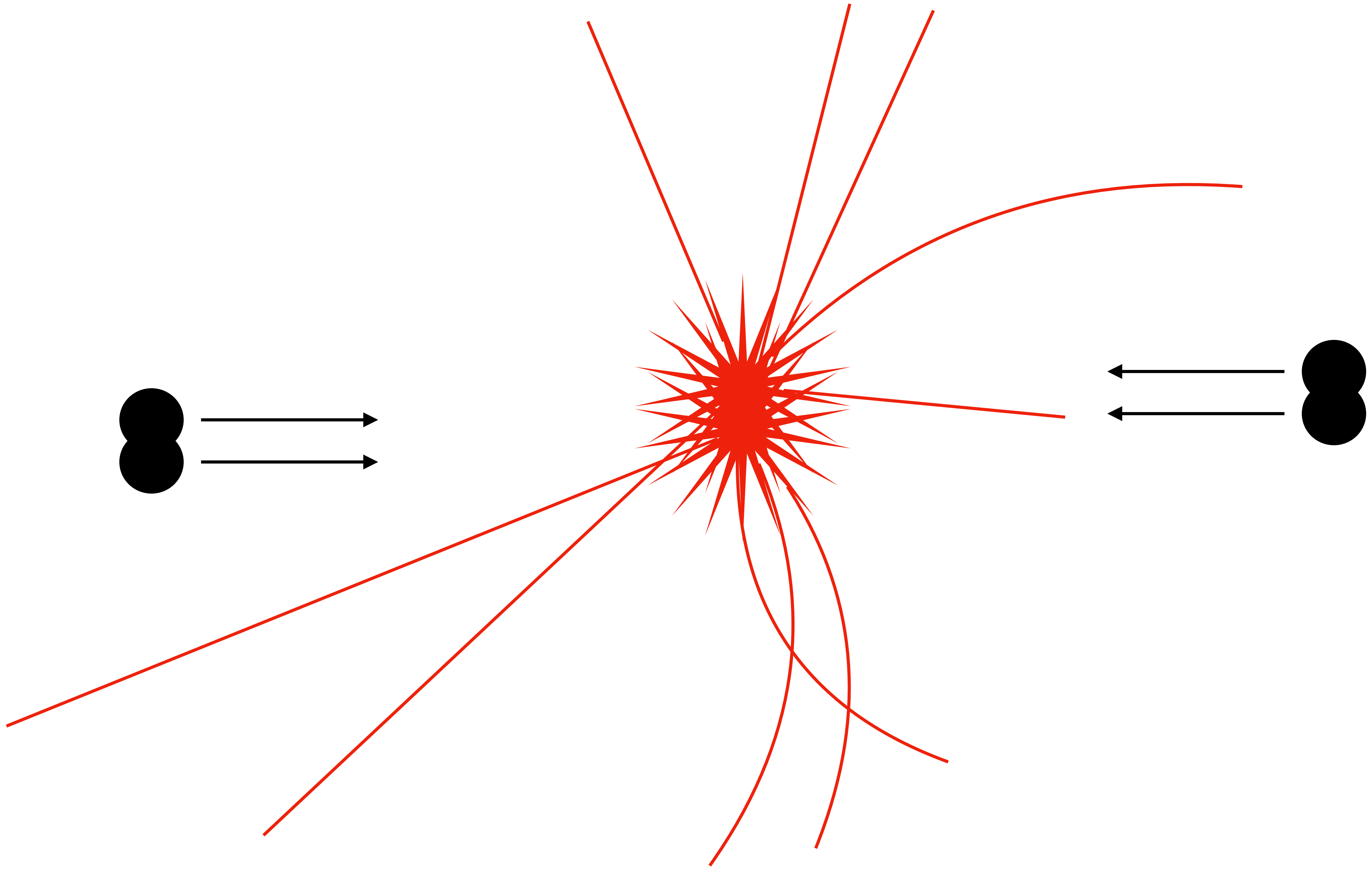
# Why do we need precision timing?

- In order to reconstruct an event at each collision, we need to match each track and deposit observed in the detector with the vertex from which it originates.
    - And we can use conservation of 4-momentum.



# Why do we need precision timing?

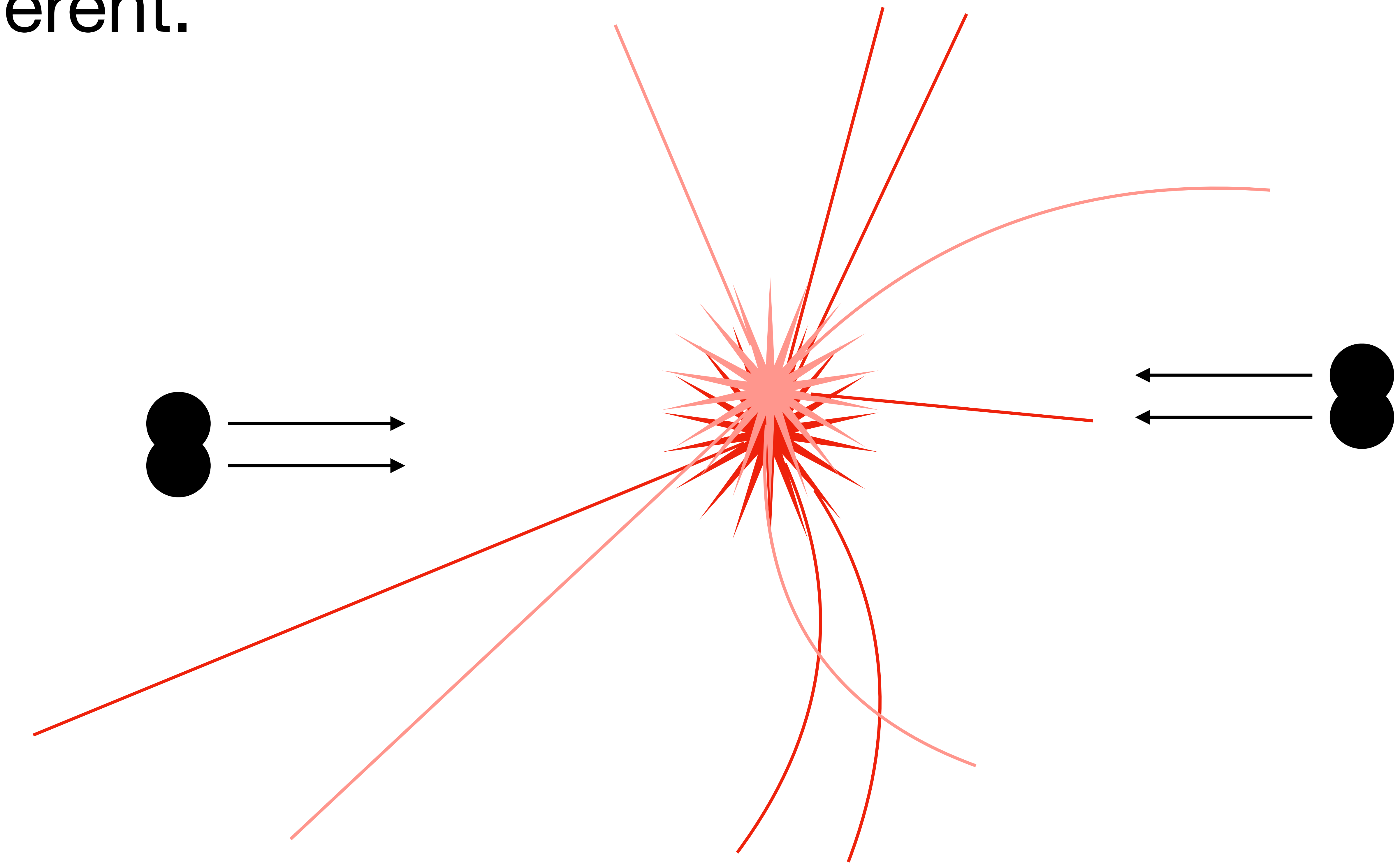
- Now we want to increase our chance of observing collisions.
  - Increase luminosity, more dense beams!



# Why do we need precision timing?

- When available dimensions are not enough, we can always look into photo in a different dimension (if it is available).

- For example the timing of these two collisions appear to be slightly different.



- By introducing precision timing we can distinguish between these events.

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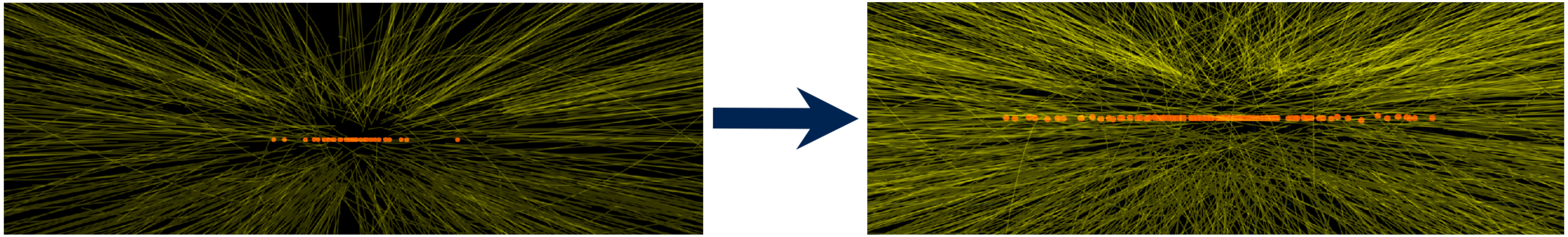
# Materializing the concept

- Starting from 2028, High Luminosity - Large Hadron Collider will deliver **10 times more integrated luminosity**.
  - Significant challenge for the detectors;
    - up to **5 times more simultaneous collisions, which will degrade the physics performance**.



- The LHC detectors will be upgraded (Phase II - HL upgrade)

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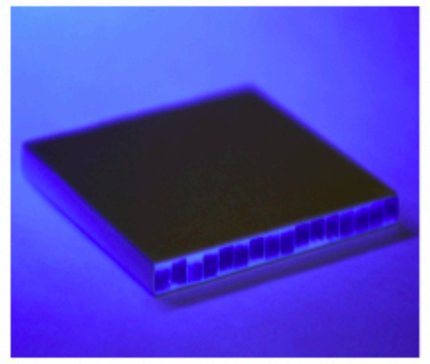
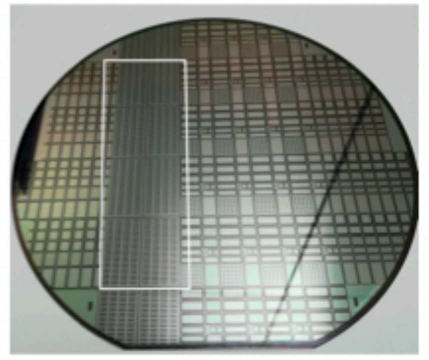
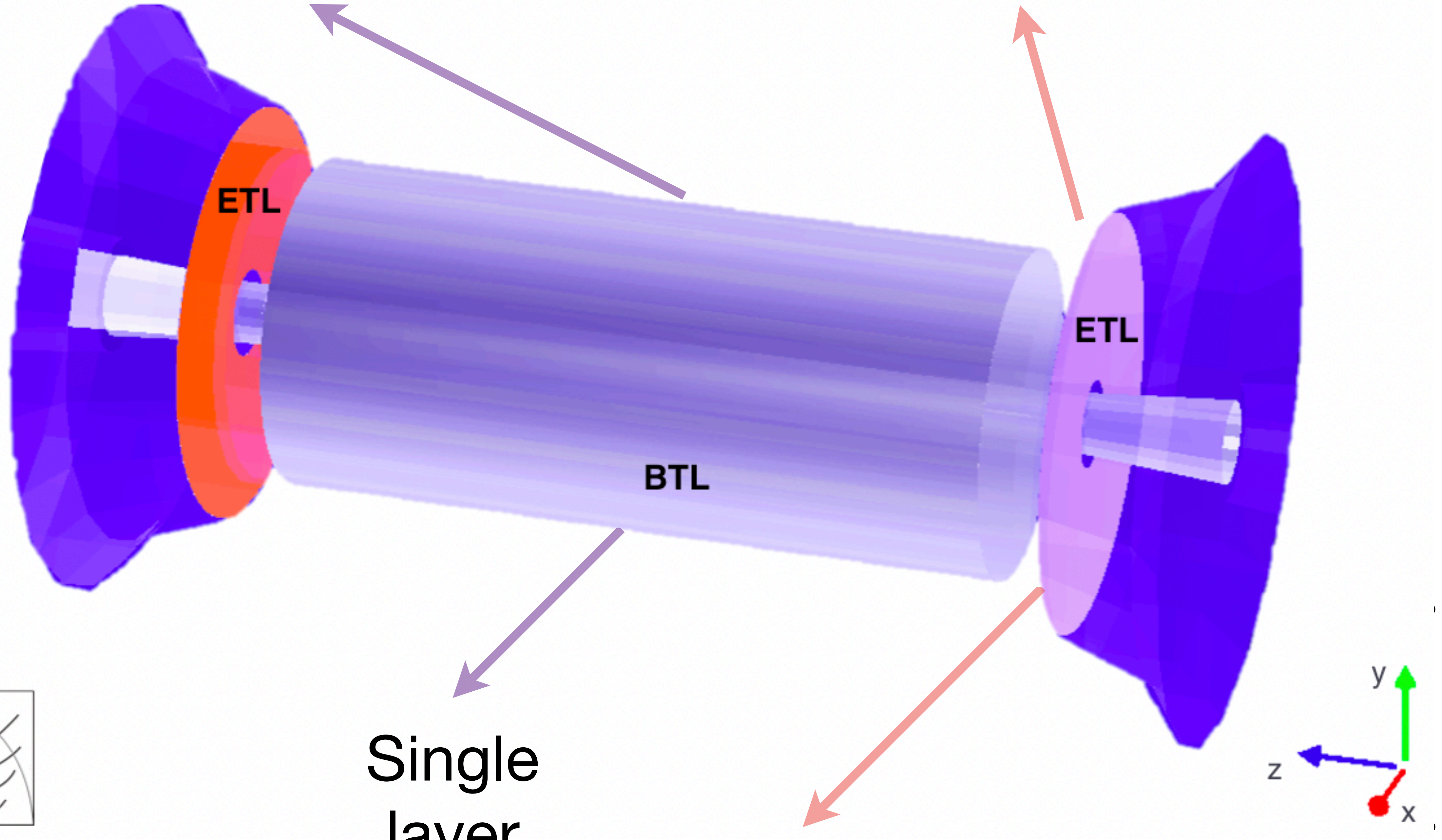
# An example solution

**BTL: LYSO bars + SiPM readout:**
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 $m^2$; 332k channels
- Fluence at 4 $ab^{-1}$: $2 \times 10^{14}$ $n_{eq}/cm^2$



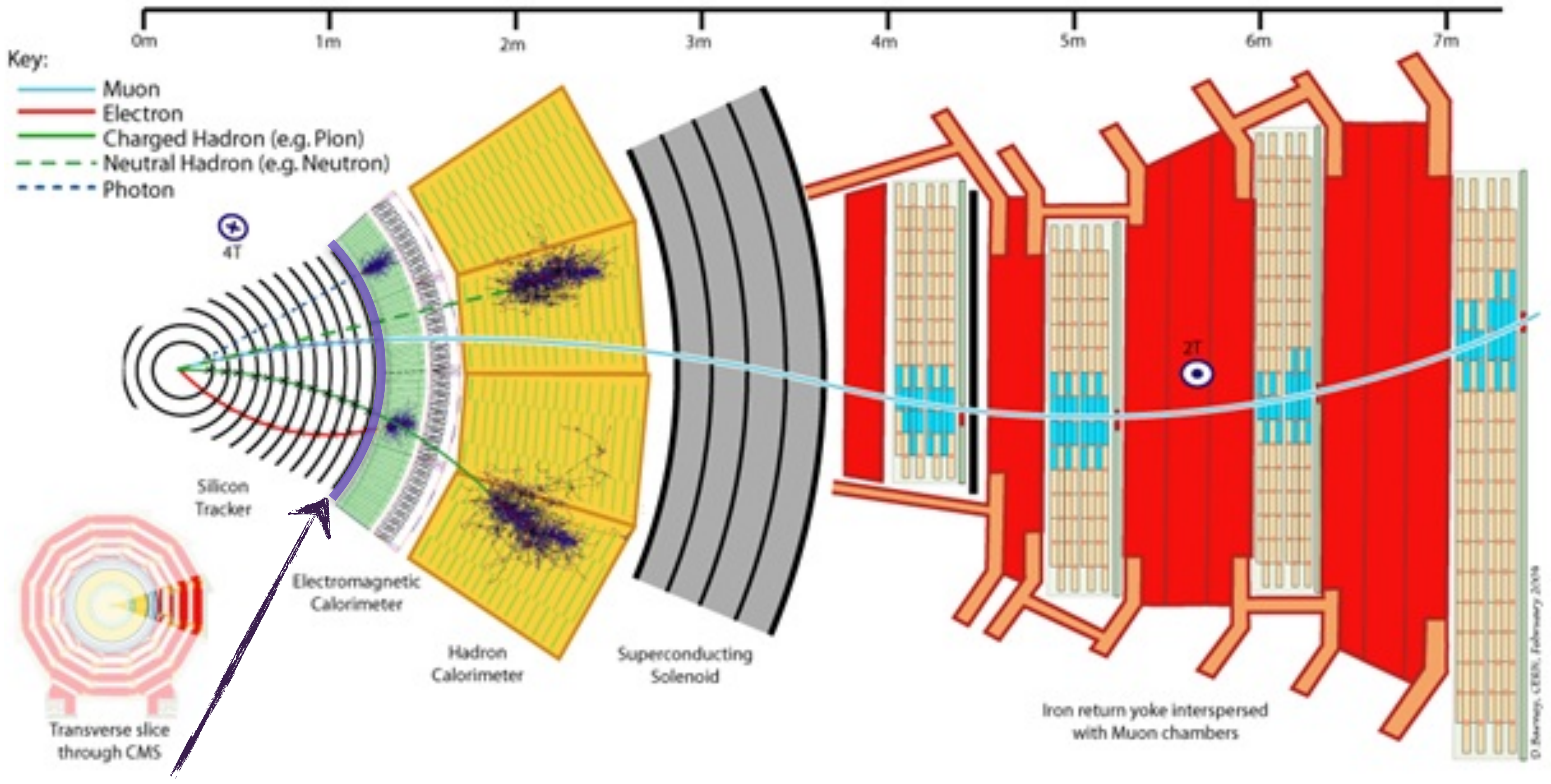
**ETL: Si with internal gain (LGAD):**
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 $m^2$; ~8.5M channels
- Fluence at 4 $ab^{-1}$: up to $2 \times 10^{15}$ $n_{eq}/cm^2$






Single layer

Two layers




**MTD**

The MIP timing detector (MTD) will have 35 ps resolution at the beginning of its lifetime.

It will have an hermetic coverage up to $\eta$=3.

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# Timing detectors

- But there are more for Phase II:
    - In ATLAS: we will have HGTD
    - In CMS: In addition to MTD, we will have HGCAL, ECAL
- Furthermore, LHCb and ALICE will also introduce new precision timing detectors.

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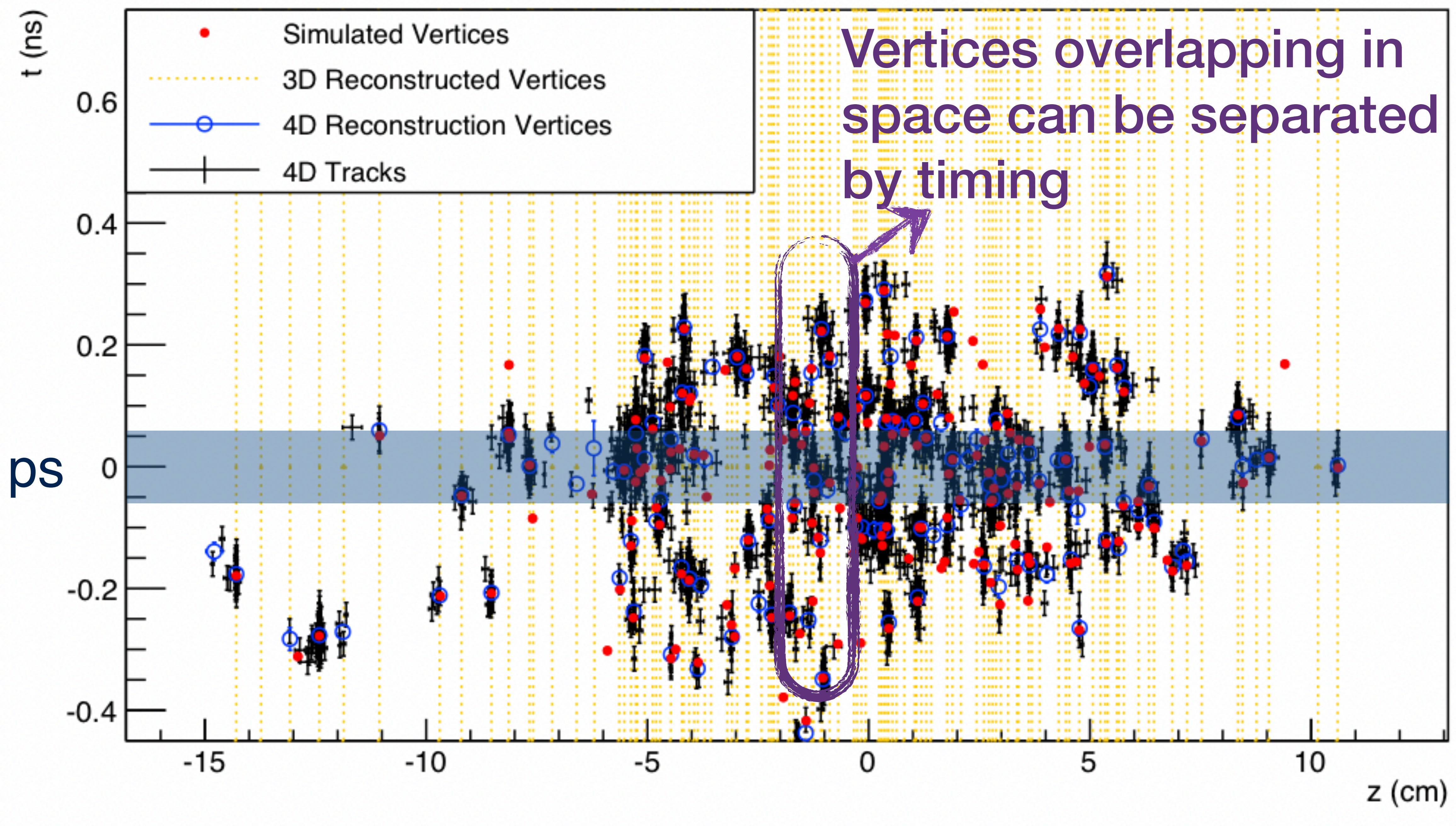
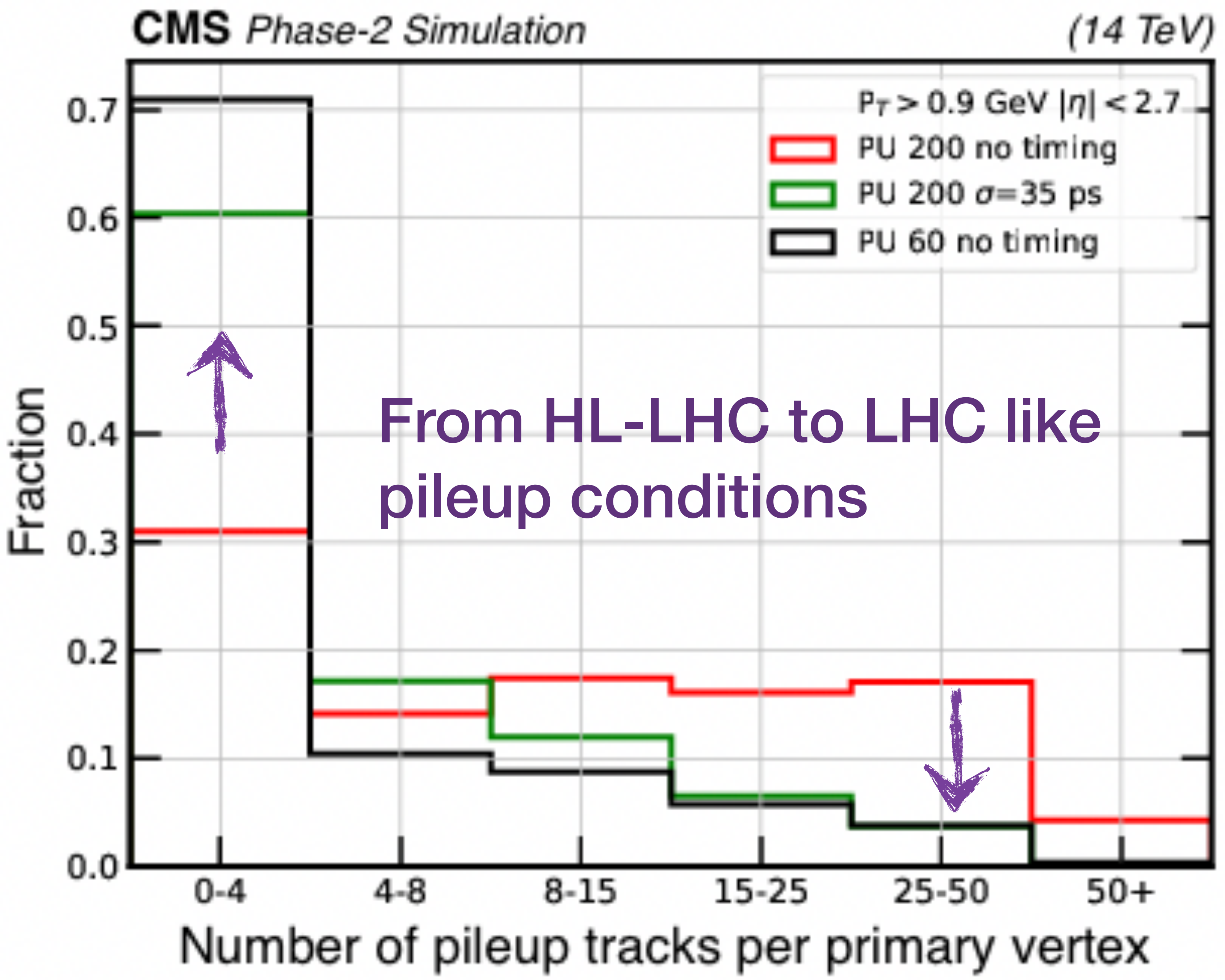
# Mitigating the pile up

σ 30 ps

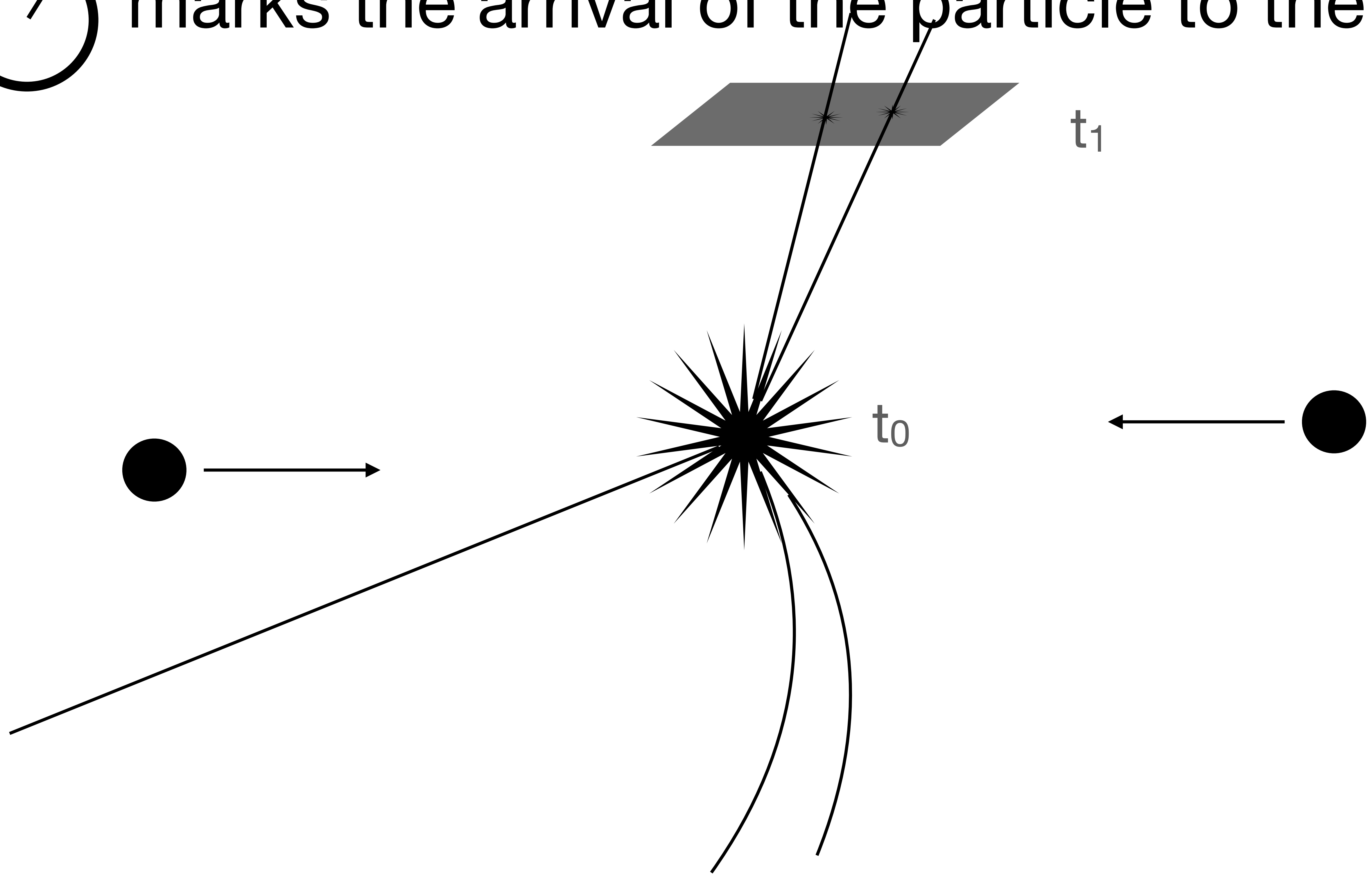



- We can use to mitigate the negative impact of the pile-up interactions.
- A precision of around 30 ps would recover Run3 (current) operation conditions.

# How do we measure the timing?

- One can imagine the timing in the detector as a stopwatch measurement.
- $t_0$ marks the beginning of the measurement, collision instance.
- $t_1$ marks the arrival of the particle to the detector.




- $\Delta t = t_1 - t_0$

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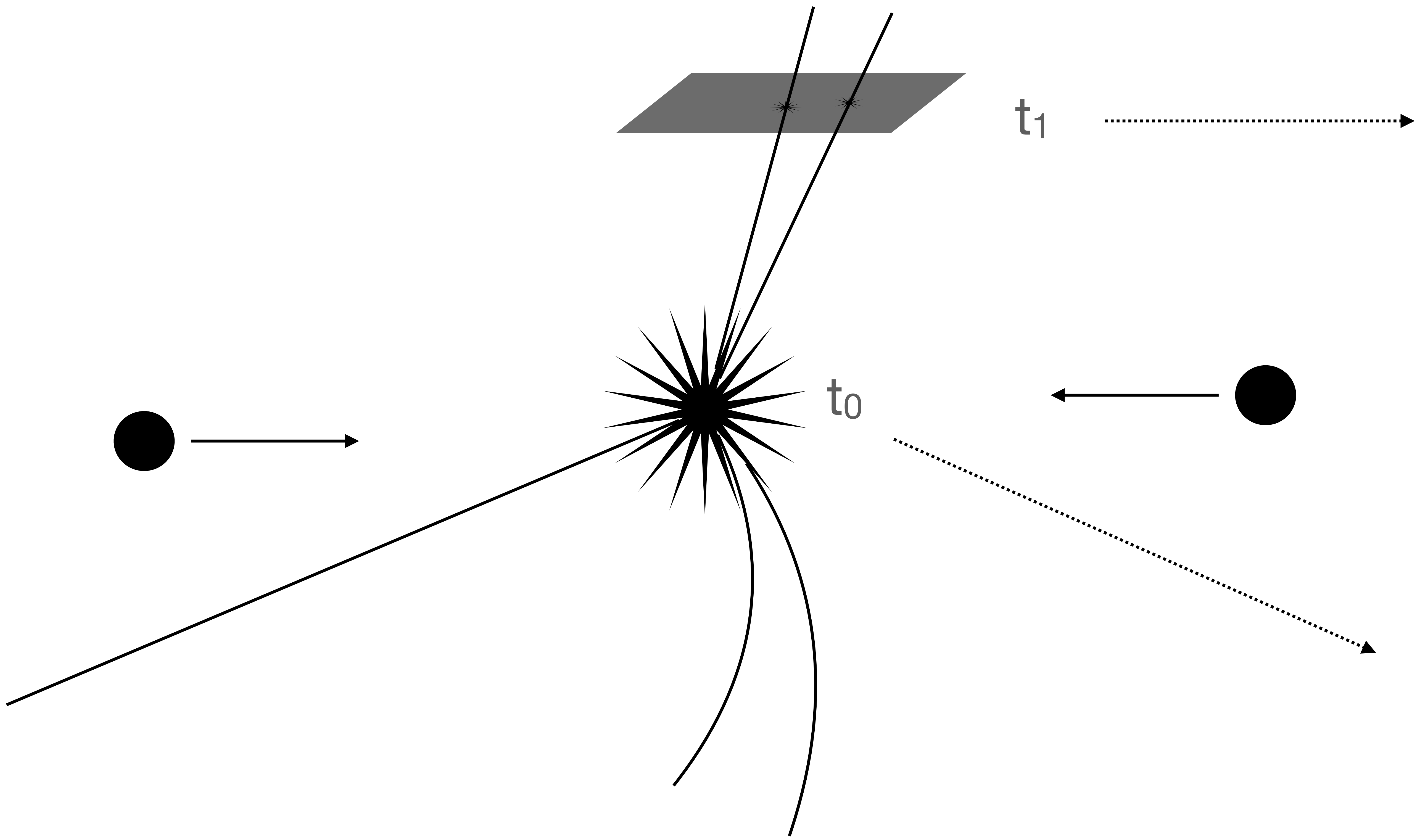
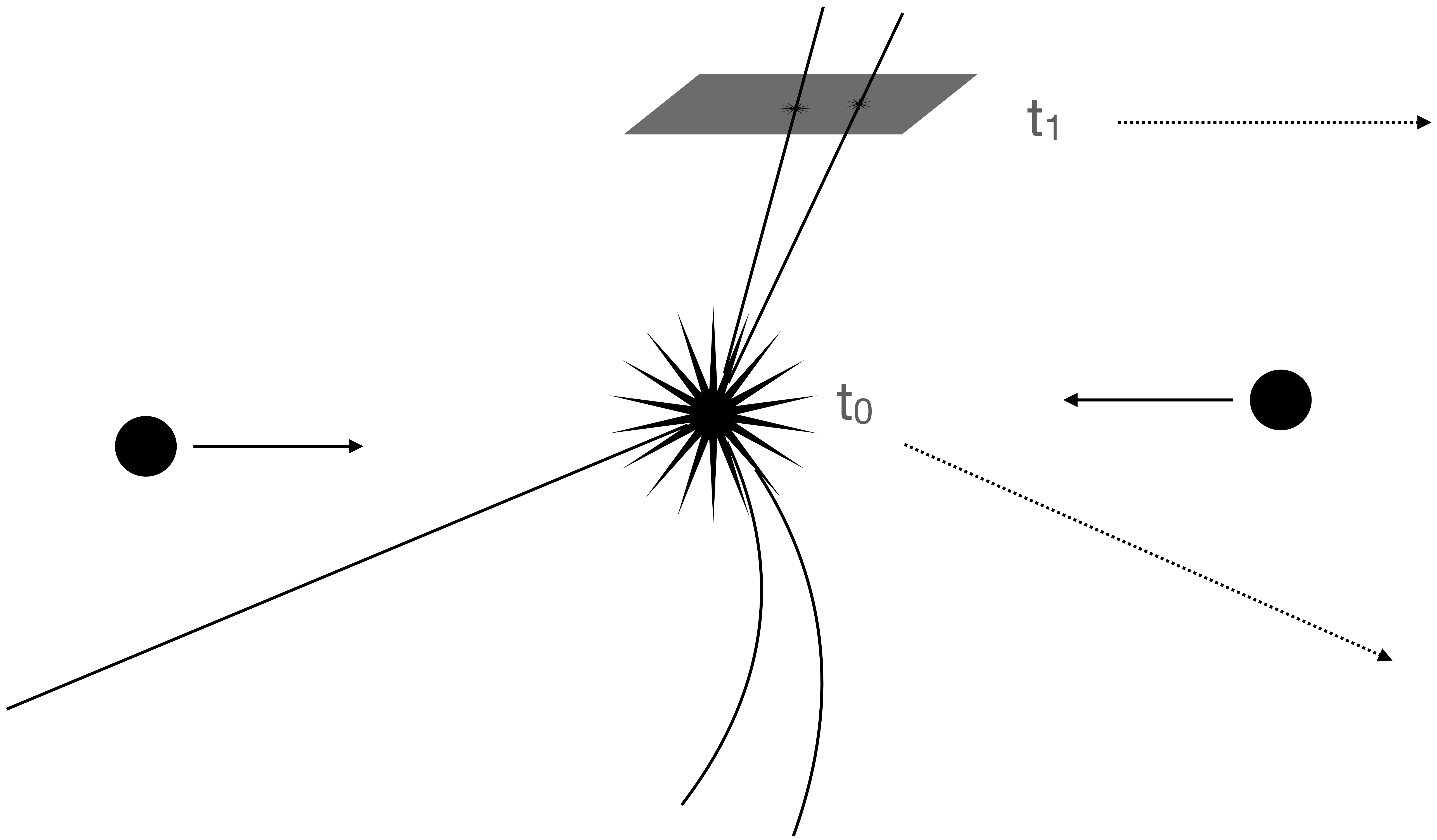
# How do we measure the timing?




- T1 is estimated by converting the analog sensor data to timing information using TDCs.
  - LYSO crystals with SiPMs, LGAD silicon sensors, MAPS…
- Estimation of t0, on the other hand, should be provided by the accelerator.

# How do we measure the timing?

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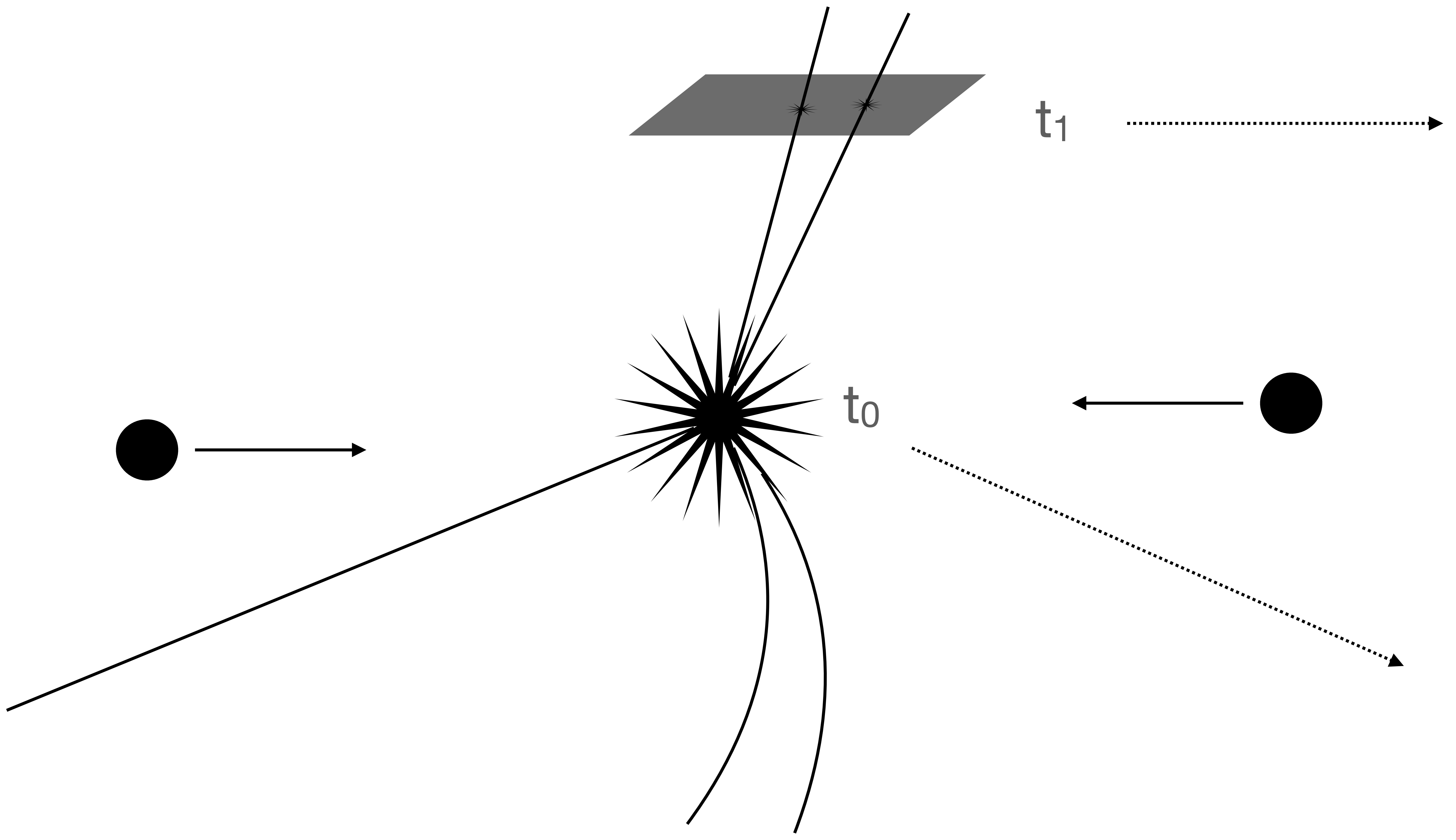
# This lecture

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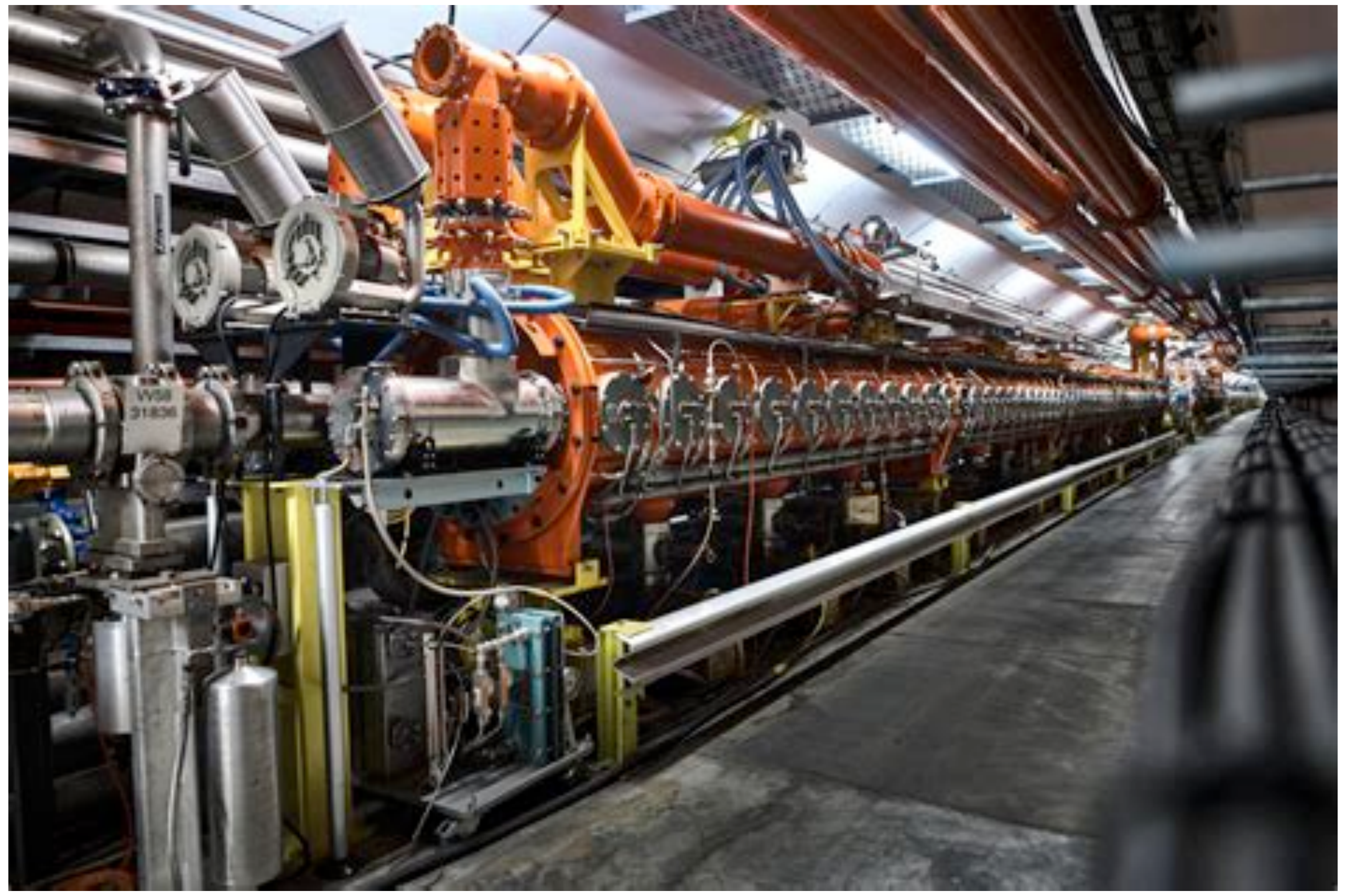
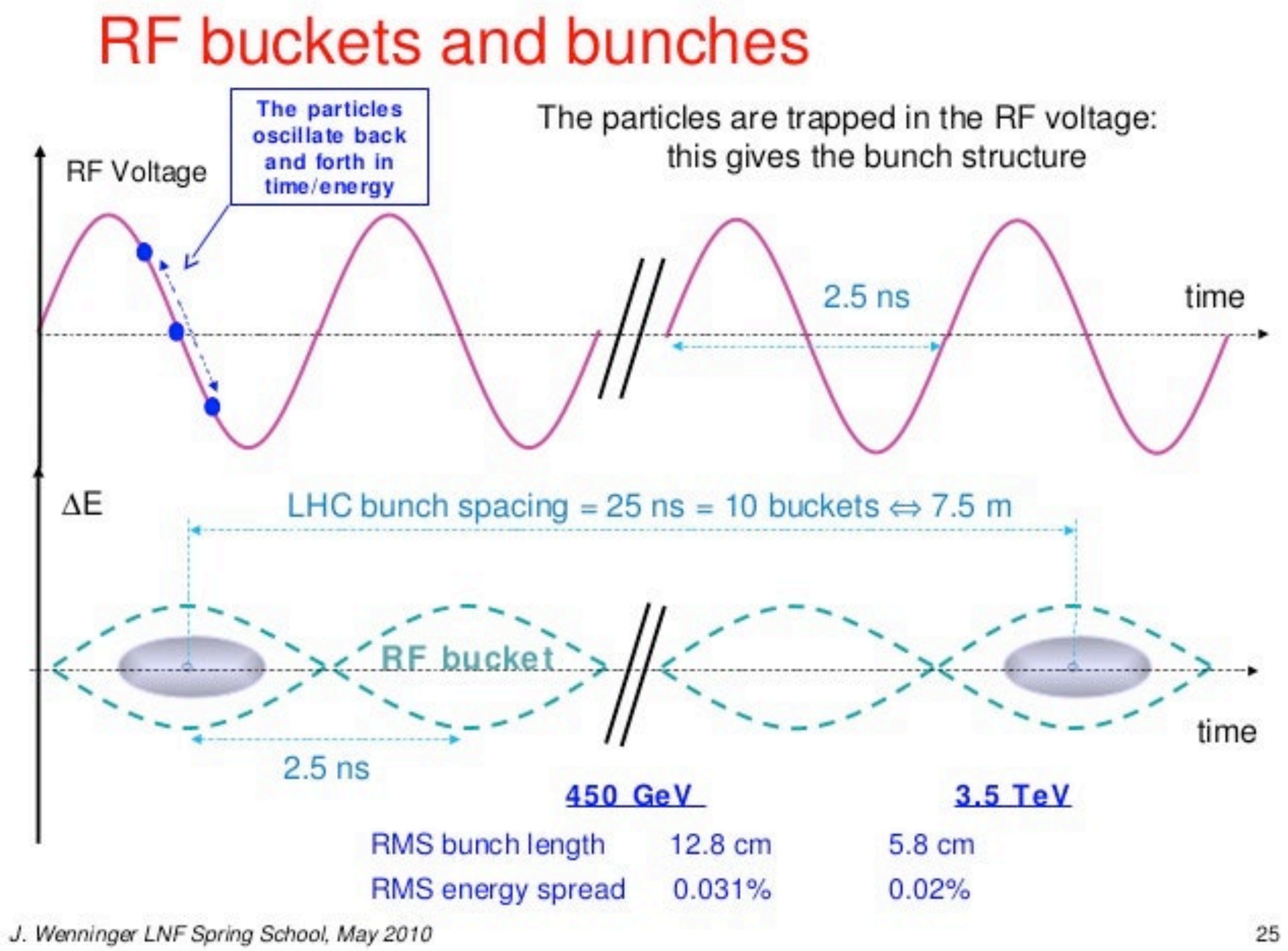
# Collision timing from the LHC

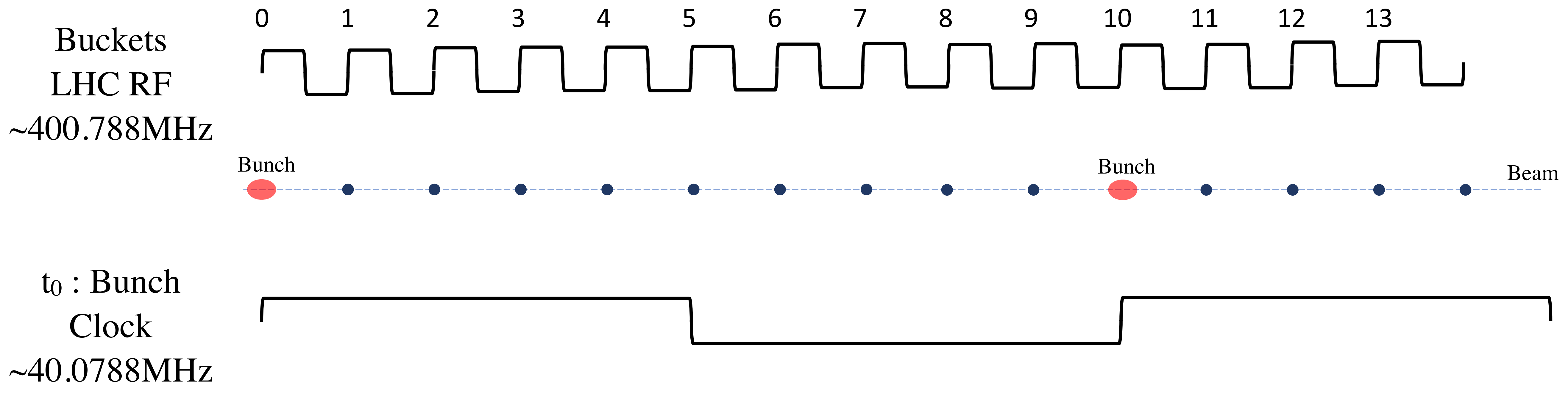
- Bunch of particle are arranged by the RF cavities that are tuned to operate at 400.788 MHz.
- A bunch spacing of approximately 25 ns is achieved in these cavities.





# Collision timing from the LHC

- These neatly spaced bunches are then collide at the interaction points of the LHC.




- Therefore, the readout of the detectors are (and should be) synchronized to this clock.

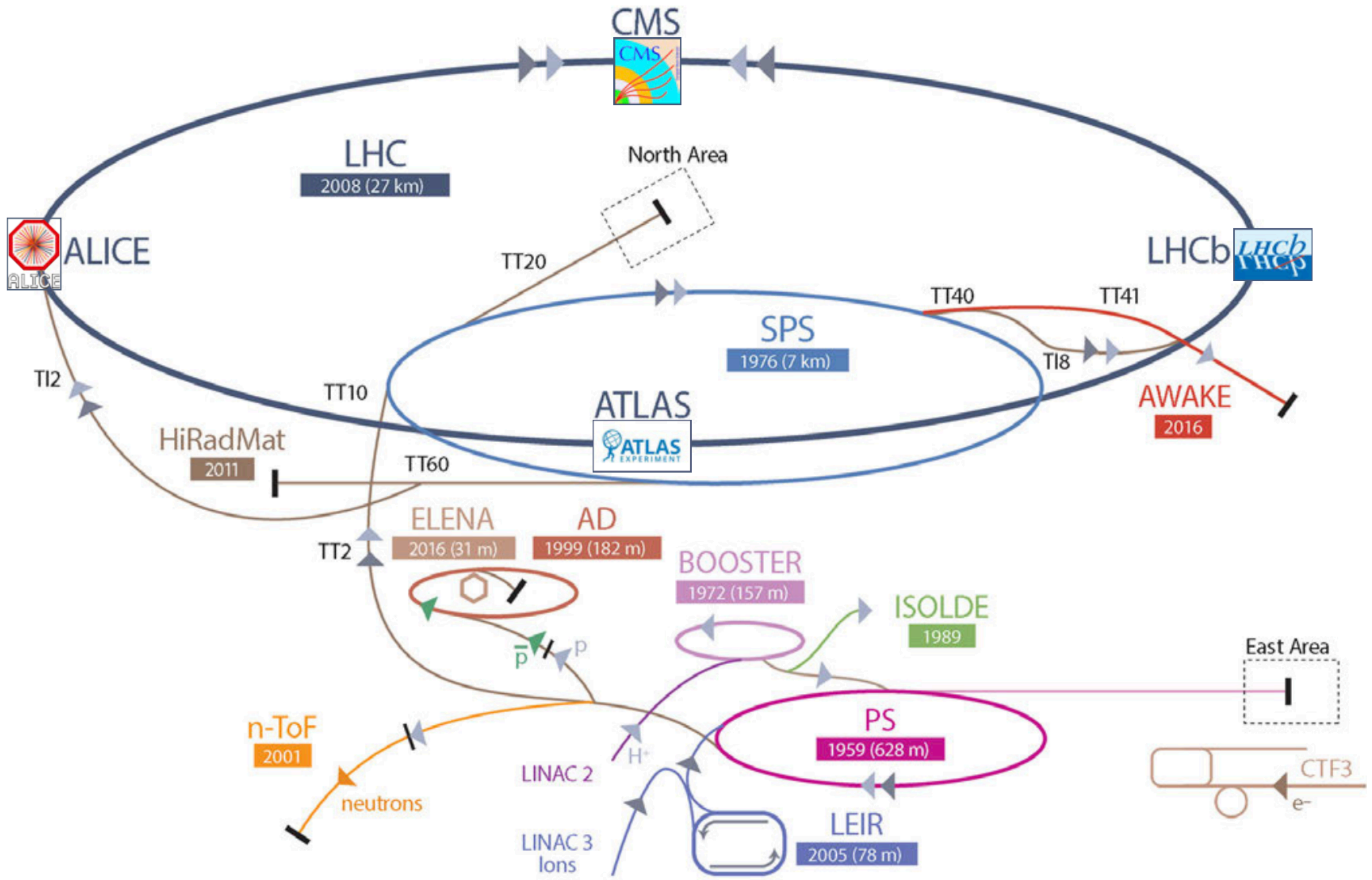
- This the **$t_0$ of the collision** - hence the start of the timing measurement.

# Questions so far?

- After this lengthy introduction we will dive deep into more technical concepts.
  - The slides are heavily inspired from the previous lectures given by the dear colleague E. Mendes (see last year's school).

# Timing distribution to the detectors

- So now we have the collision timing,
  - How do we distribute it to the detectors?
    - Send it as it is - pure clock,
    - Embed it into the data frame.

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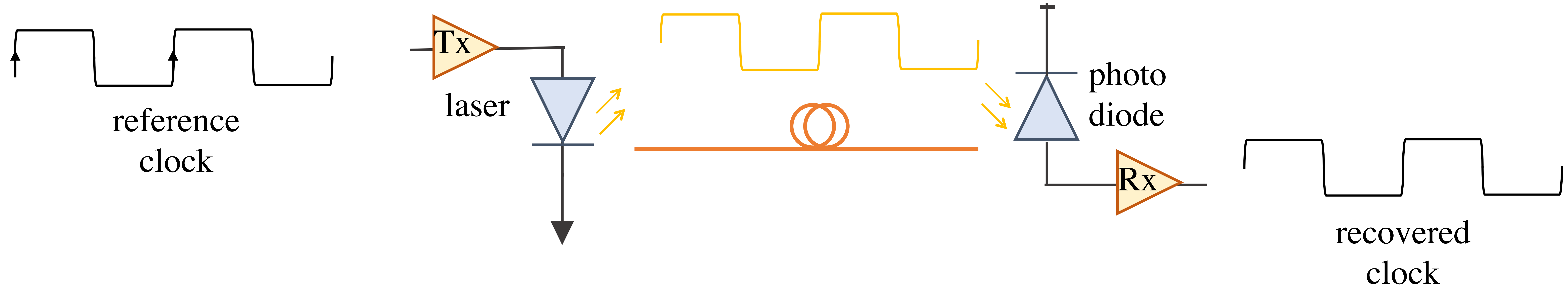
# Pure clock




- The clock is transmitted through different cables in the square wave form.
- This is the simplest way of transmitting the timing information.
  - However, not very efficient.

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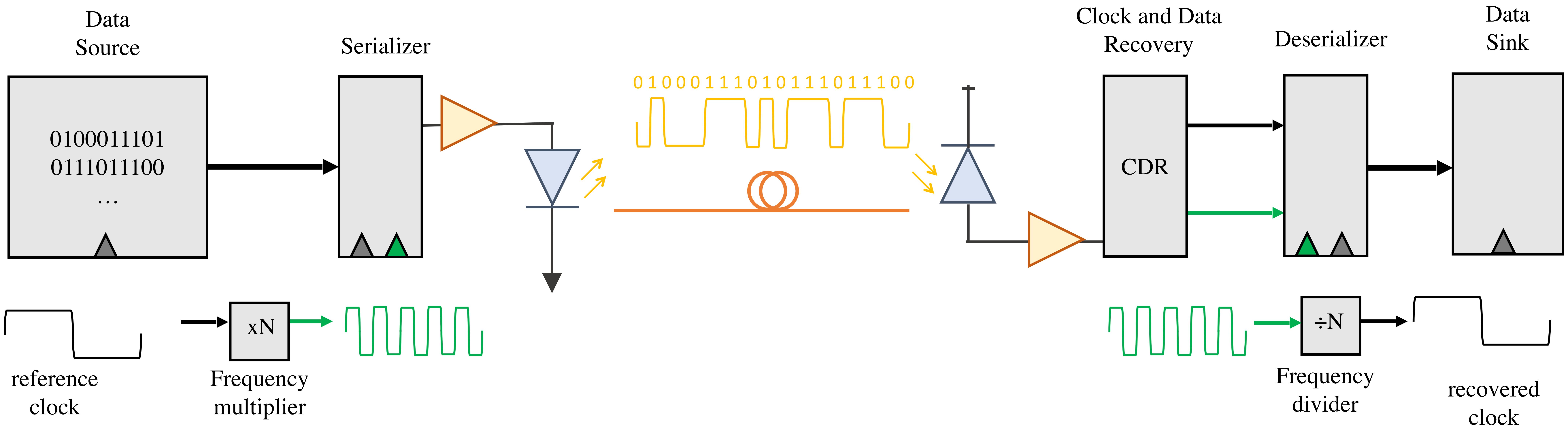
# Embedded clock




- There is a more efficient way of distributing the clock by embedding it to the data stream.
- Here, rather than distributing a square wave clock, the alignment data is transmitted encoded in the data.
- The receiver extracts the alignment information by checking the header bits and reconstructs the clock.

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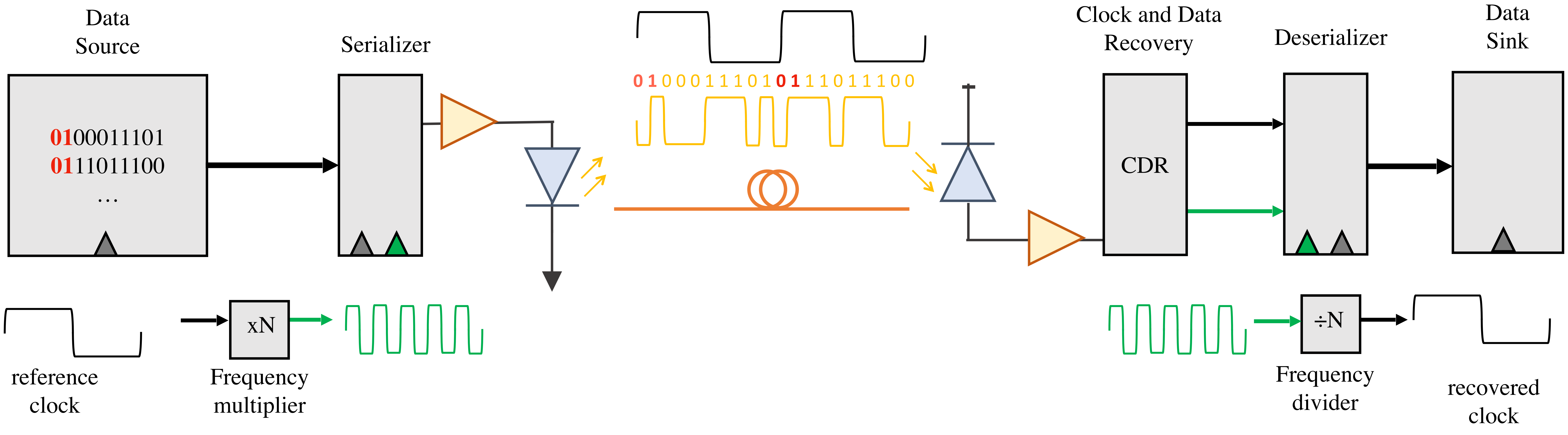
# Embedded clock




- With a rolling window, the logic will check if the header bits (in this example 01) appears at the same frequency.
- After checking it in predefined *n* sequences the logic ‘locks’ to the frame.
- A clock at the frequency of the sequence generation can be reconstructed!
- This allow us to transmit the clock and data in the same link cable.

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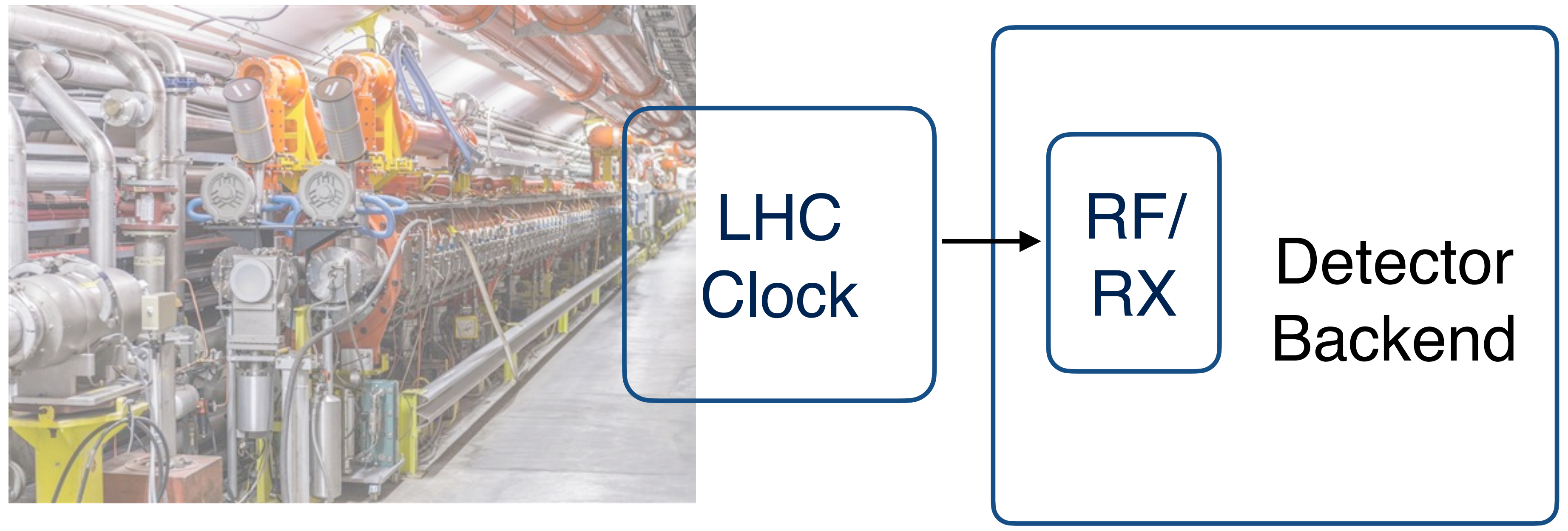
# A typical clock distribution chain




- The clock has a long way to reach to the detector in a large accelerator.
- There may be multiple connection points, opto-electrical conversions, kms to reach to the detector and some of hundred meters to be distributed over thousands of communication links within the detector!

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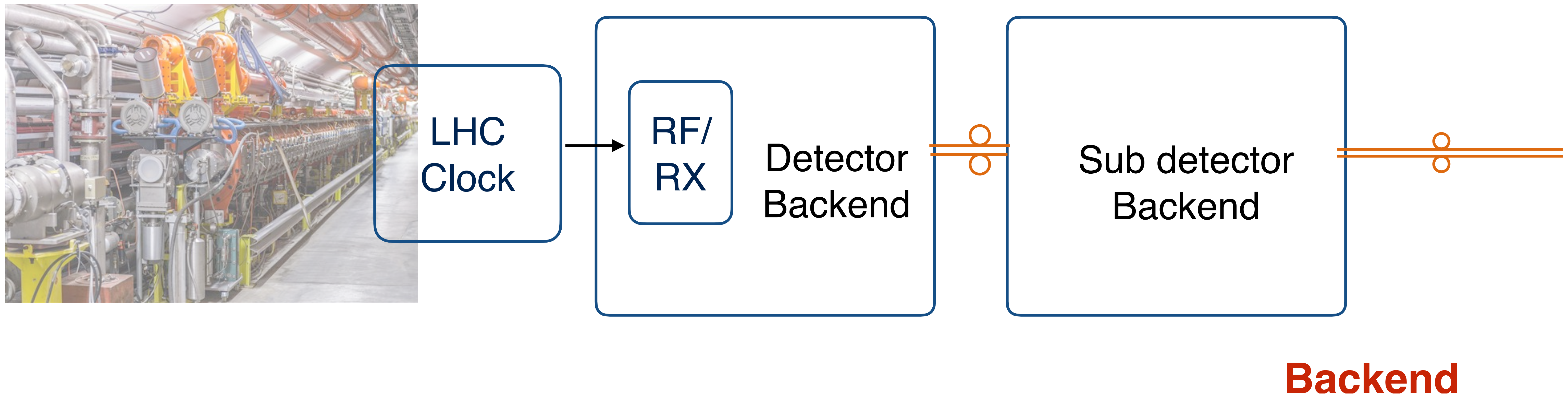
# A typical clock distribution chain

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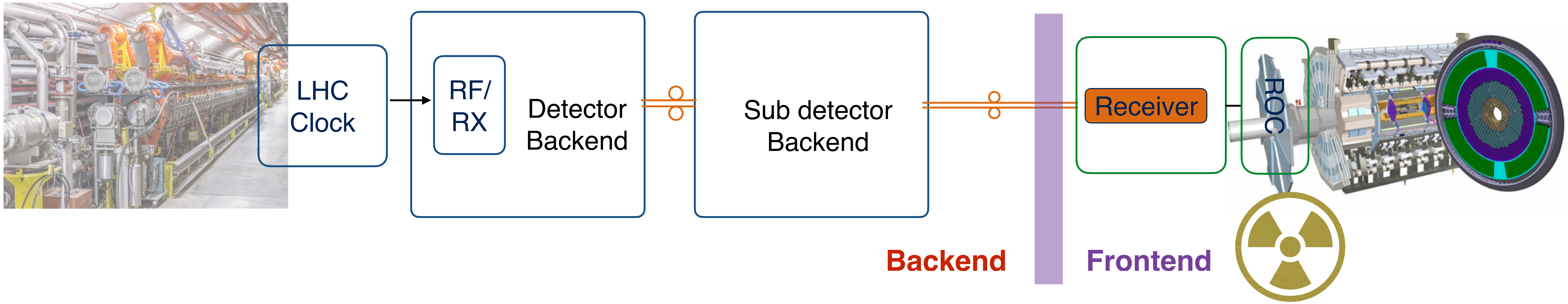


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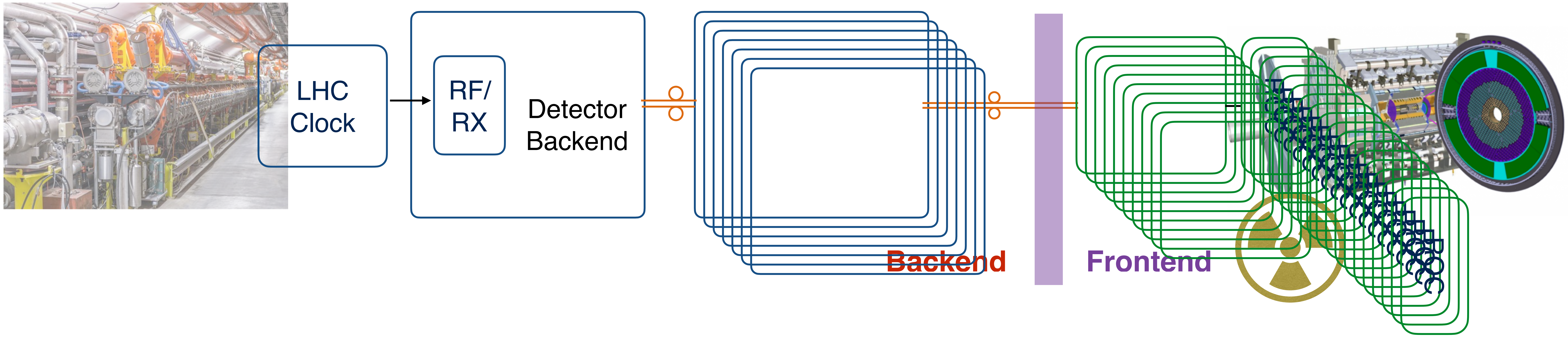
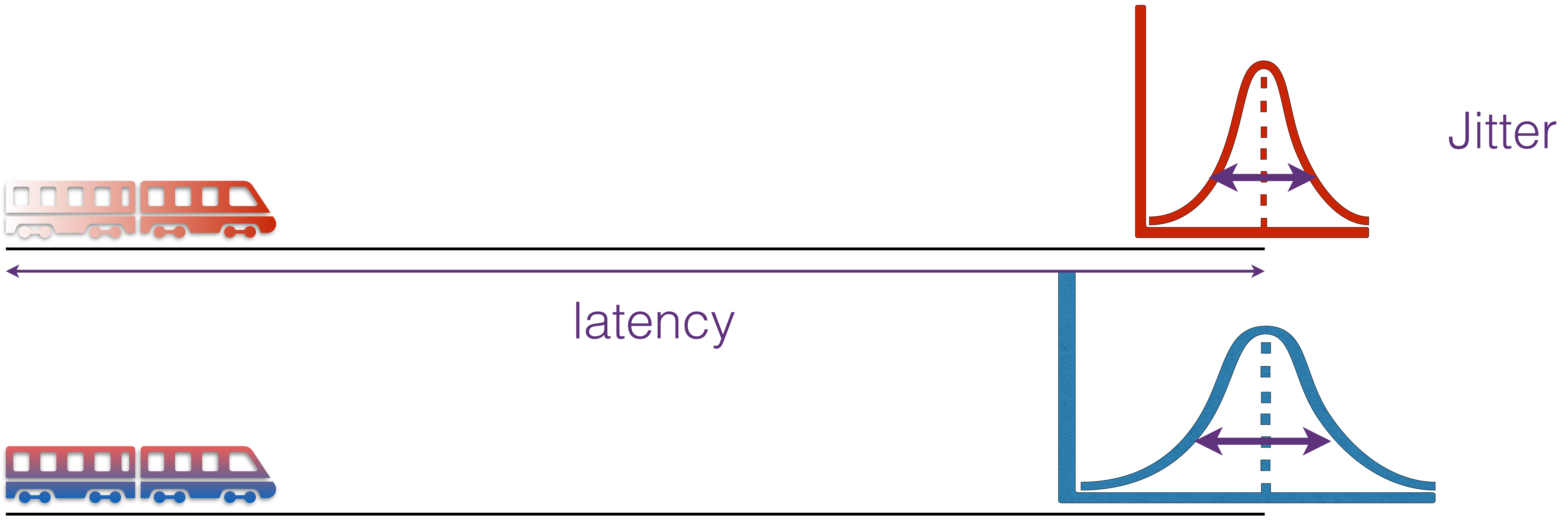



- The clock has a long way to reach to the detector in a large accelerator.
- There may be multiple connection points, opto-electrical conversions, kms to reach to the detector and some of hundred meters to be **distributed over tens of thousands of communication links** within a detector!

# There does not exist a perfect system.

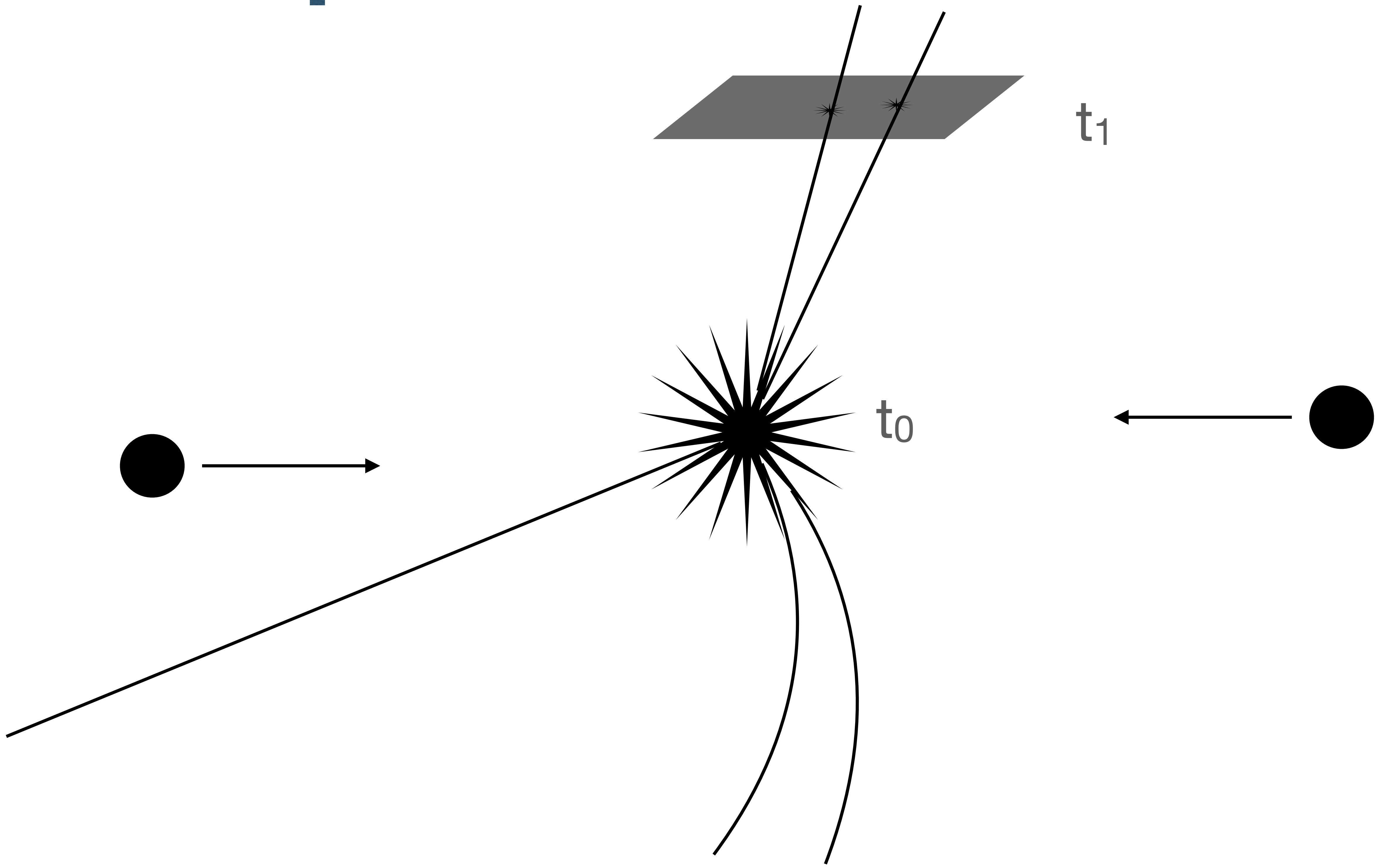
- Any questions so far?

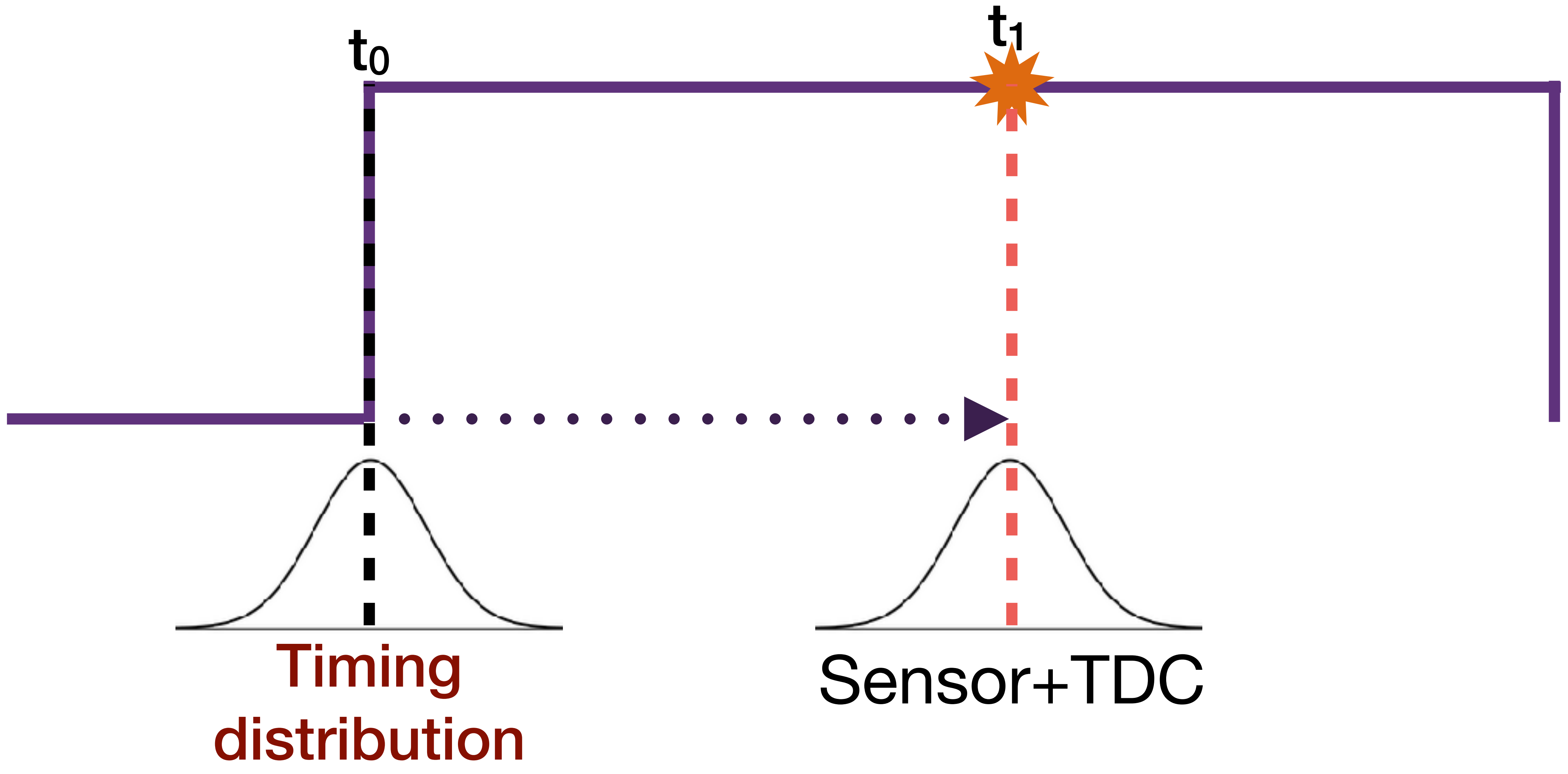
# Delay, wander and jitter




- **Latency** is due to propagation time.
  - **Jitter is the uncertainty** in this propagation time.
  - If it occurs at slow frequencies it is called **wander**.

# Impact on the resolution

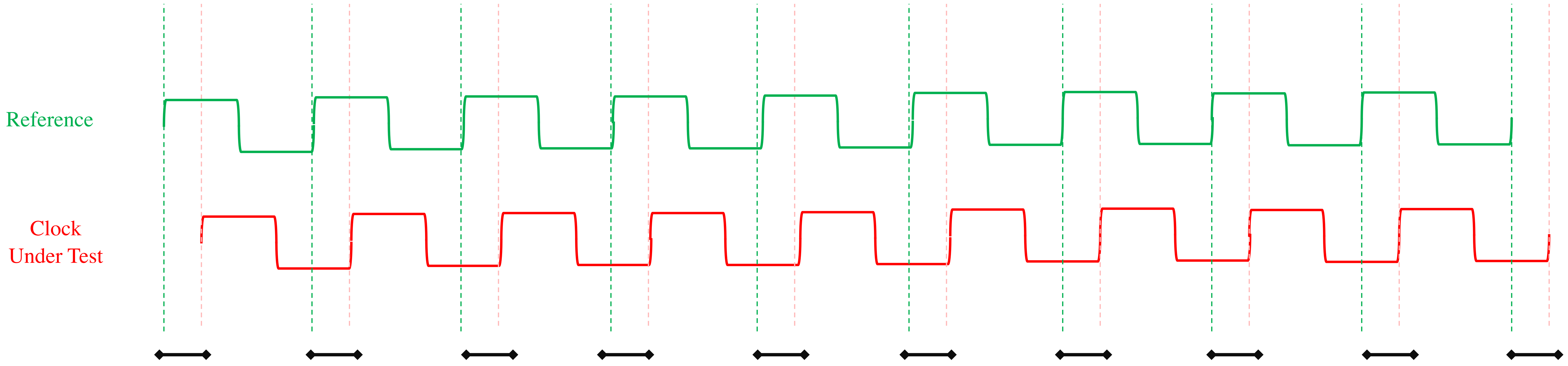



- No matter how good our sensor and readout modules are, the timing resolution **cannot be precise enough if there is too much jitter**!
- Example: even if we achieve 30 ps resolution with the sensor + TDC, a 30 ps RMS jitter will **degrade our resolution to 42ps!**

# How do we measure jitter?

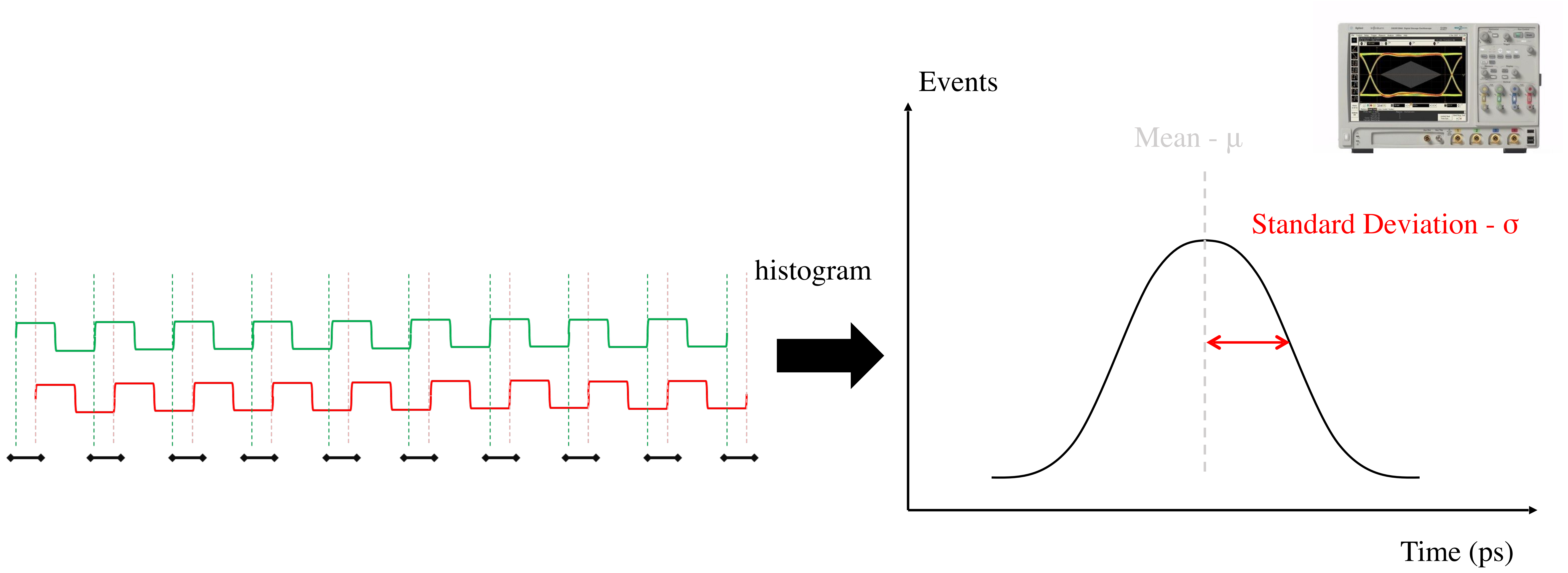
- Finding the difference between the ideal clock or a reference clock and the clock under test!



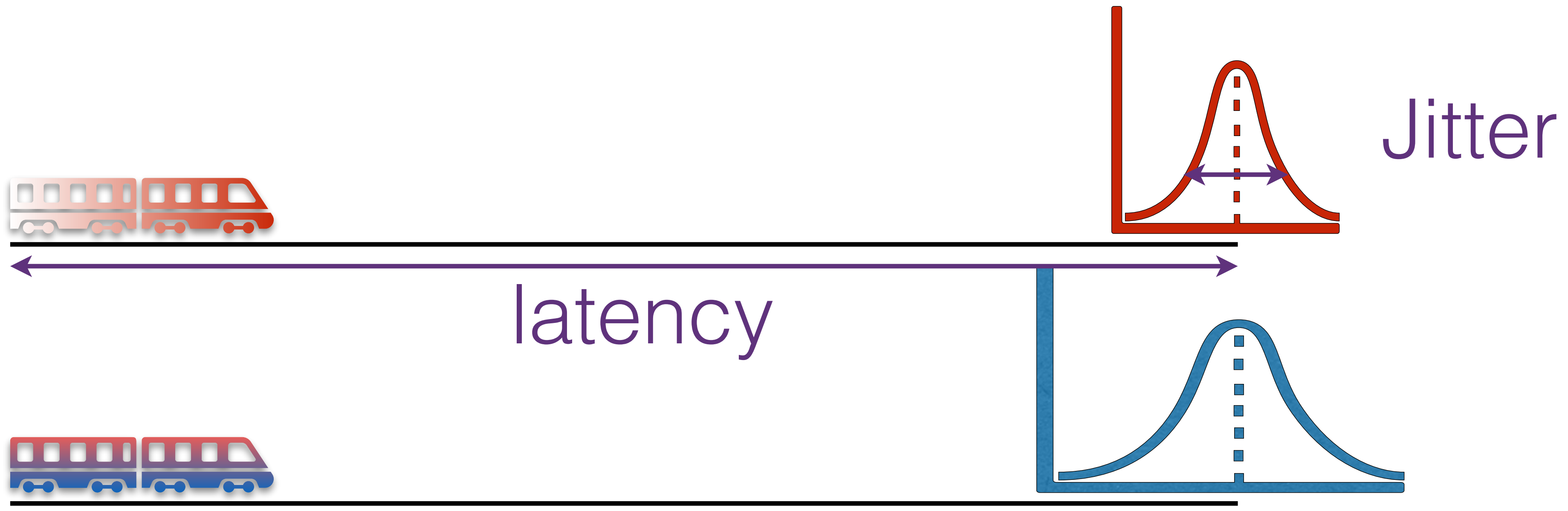

- The measurement is preferably sequential to keep frequency noise correlation.

# Measuring the jitter: TIE

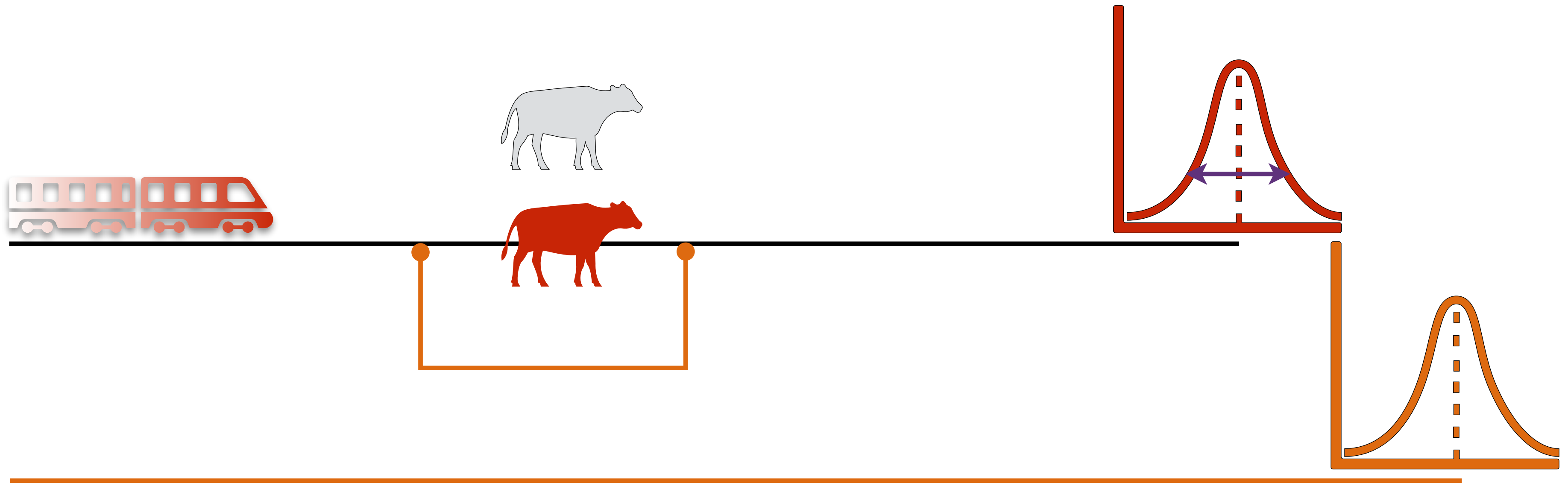
- Time interval error (TIE) is the standard measurement which can be performed using a scope.



# Types of jitter




• The Random Jitter with a Gaussian distribution.



• The Deterministic Jitter with a bimodal Dirac delta distribution.

- The profile of the TIE histogram may tell us what kind of jitter we have in the system.
  - Namely whether it is RJ (unbounded) or DJ (bounded).

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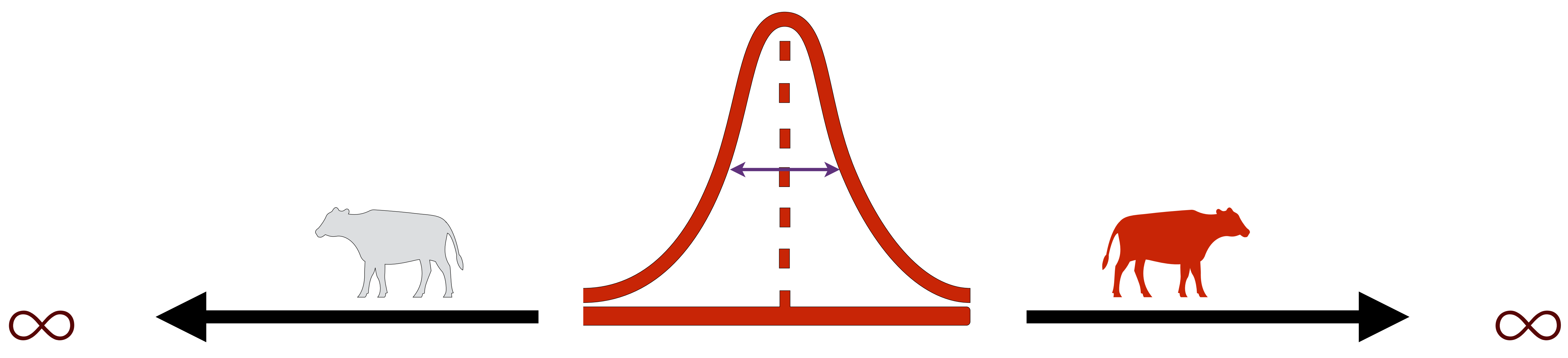
# Worst case?

- Is it possible to provide a worst case scenario?




- RJ is normal distribution, therefore, it is unbounded. As the time progress the worst case will get closer to infinity.
- We need to agree on a convention! (Similar to rejecting a null hypothesis)

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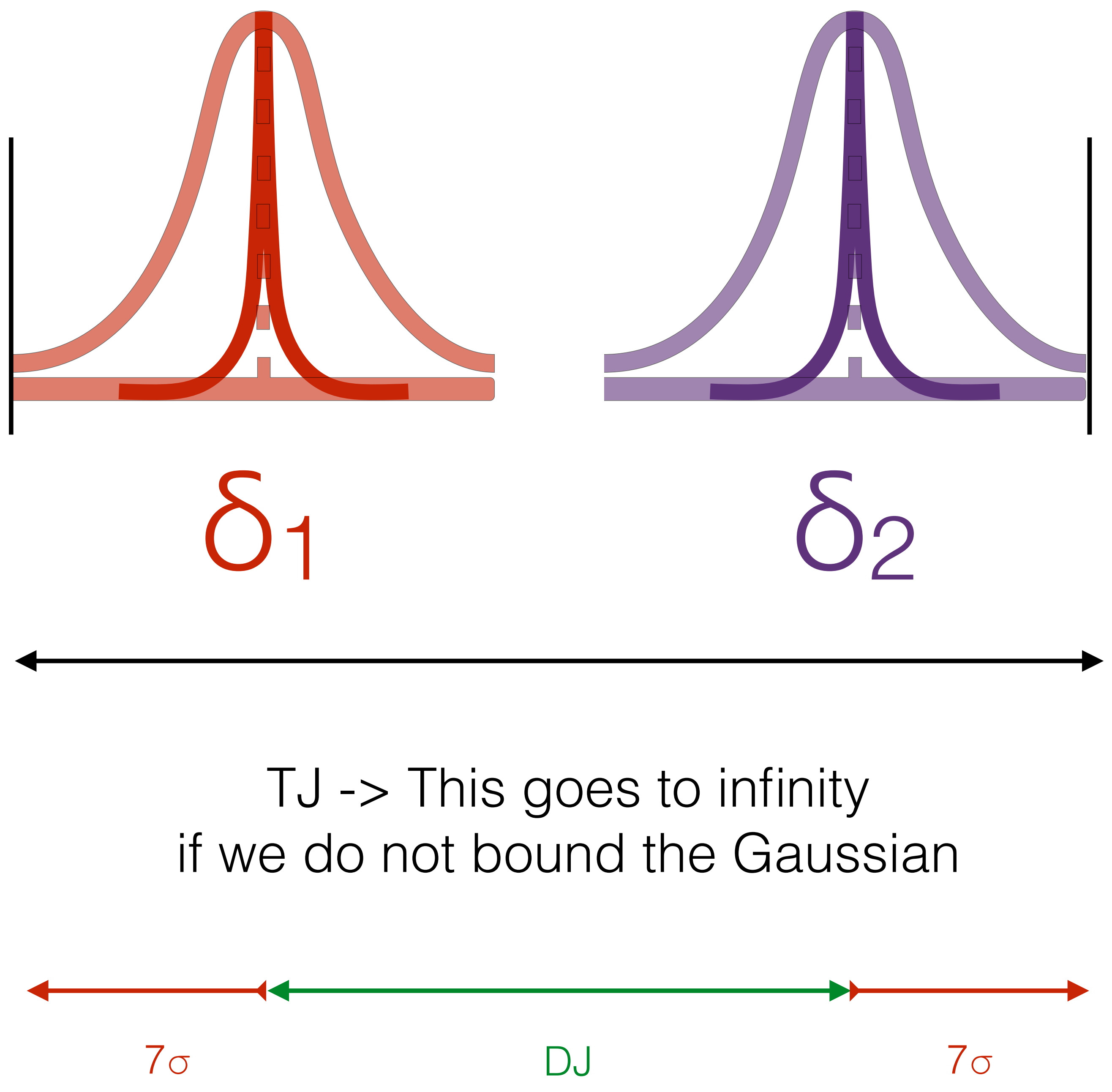
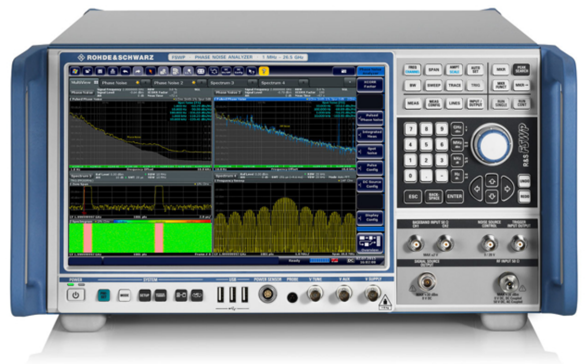
# Total jitter

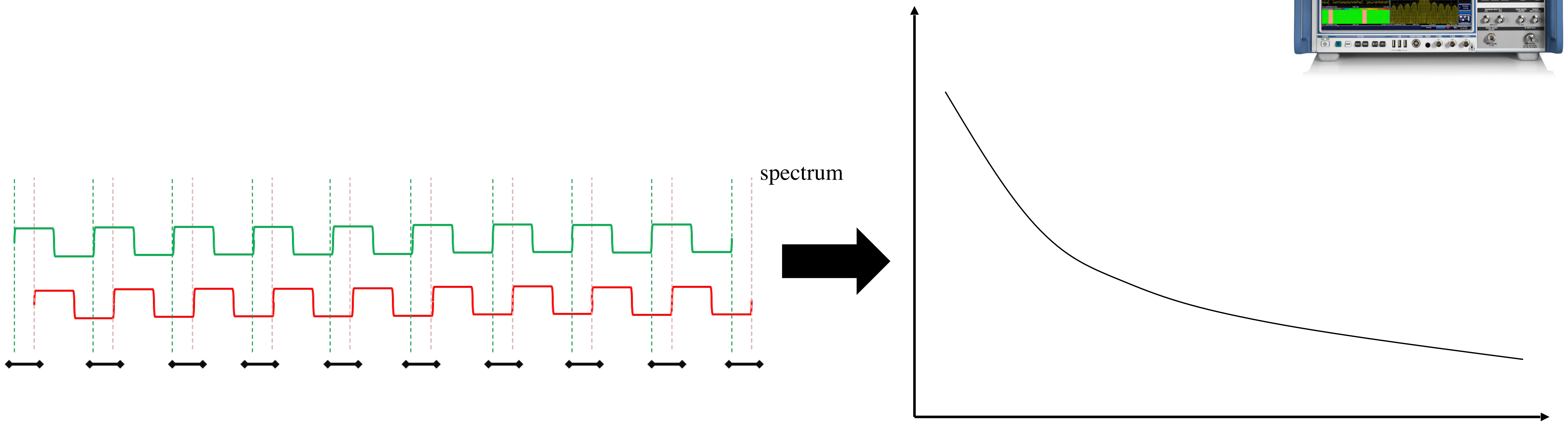



- Convolution of two bounded Gaussian - dirac-delta functions.
- Total Jitter can be modeled as TJ(BER)=2RJ x nσ(BER) + DJ(δδ)
  - The convention is $10^{-12}$ : 14 σ

# Measuring the jitter: phase noise

- TIE will give you the amplitude but not the frequency of the noise components.





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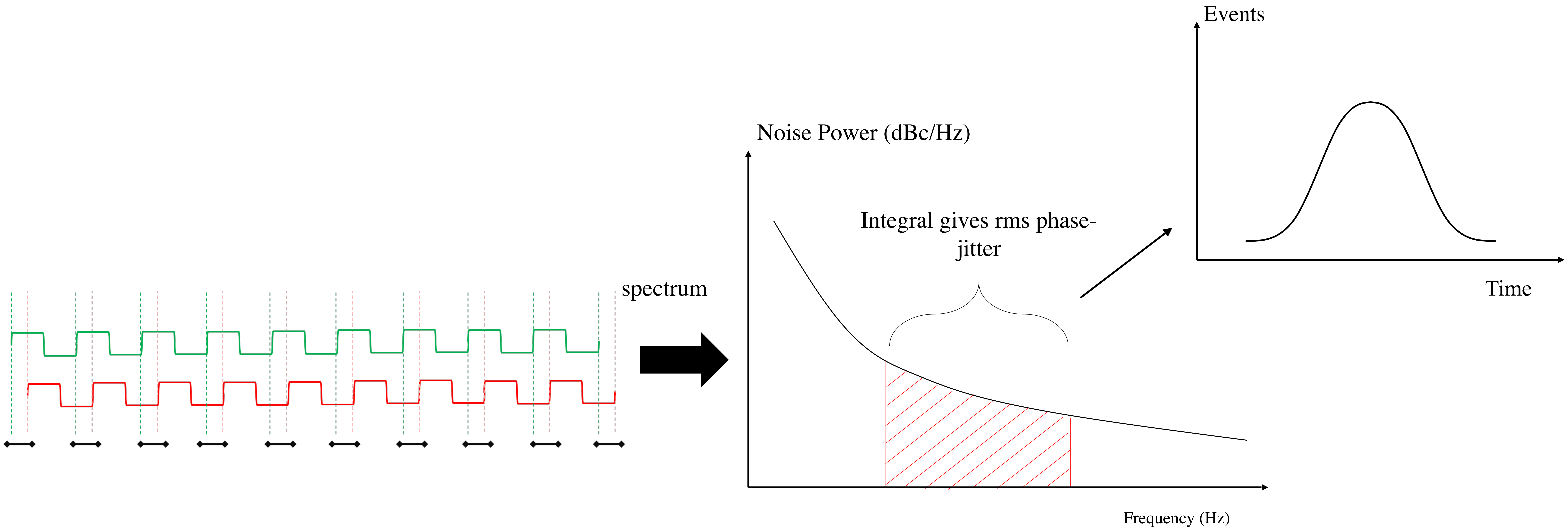
# Noise spectrum to TIE

- It is possible to obtain the TIE from the noise plot



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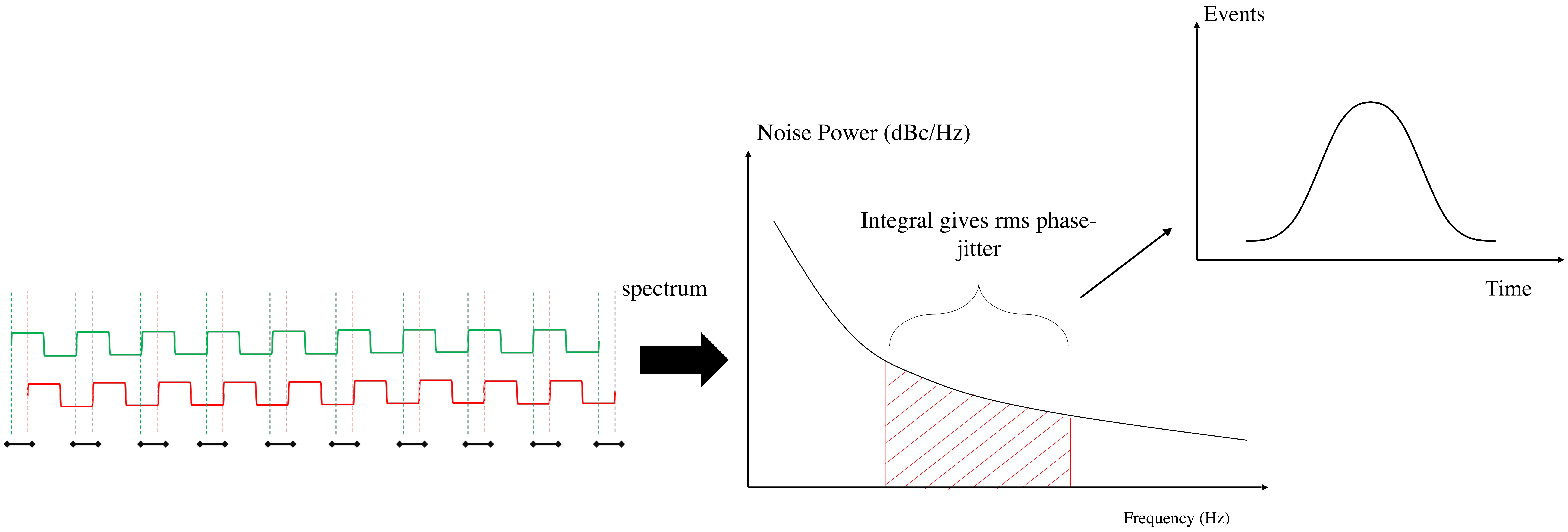
# Noise spectrum to TIE

- The profile of the spectrum gives us hints about the noise type



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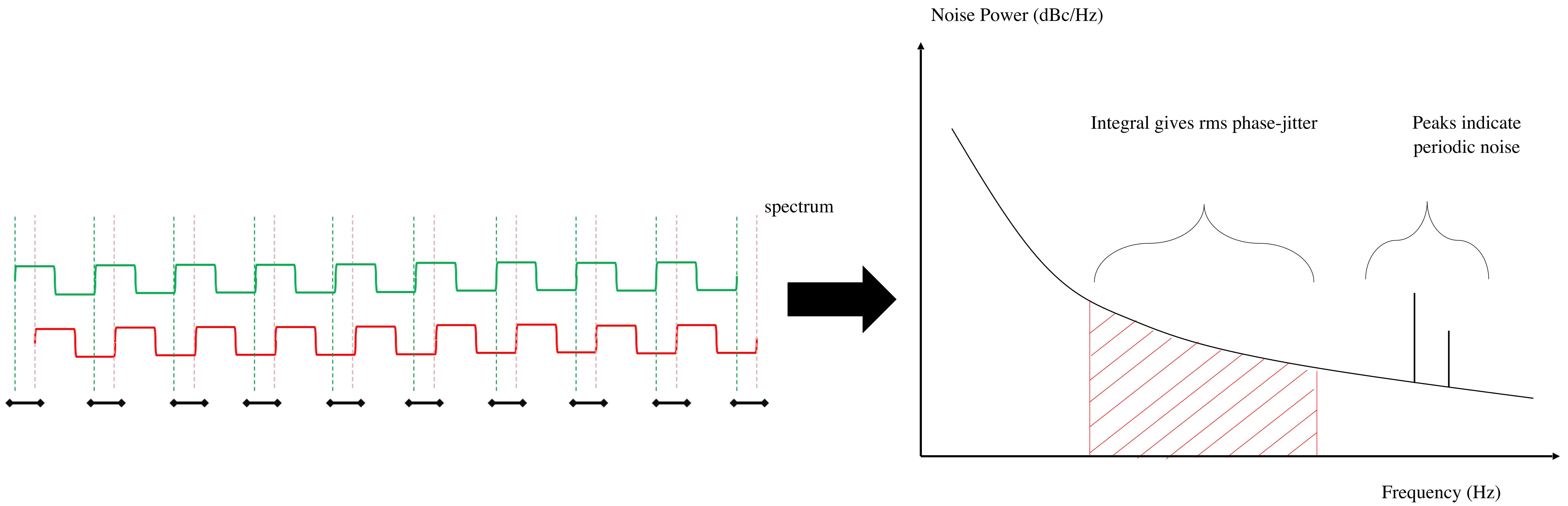
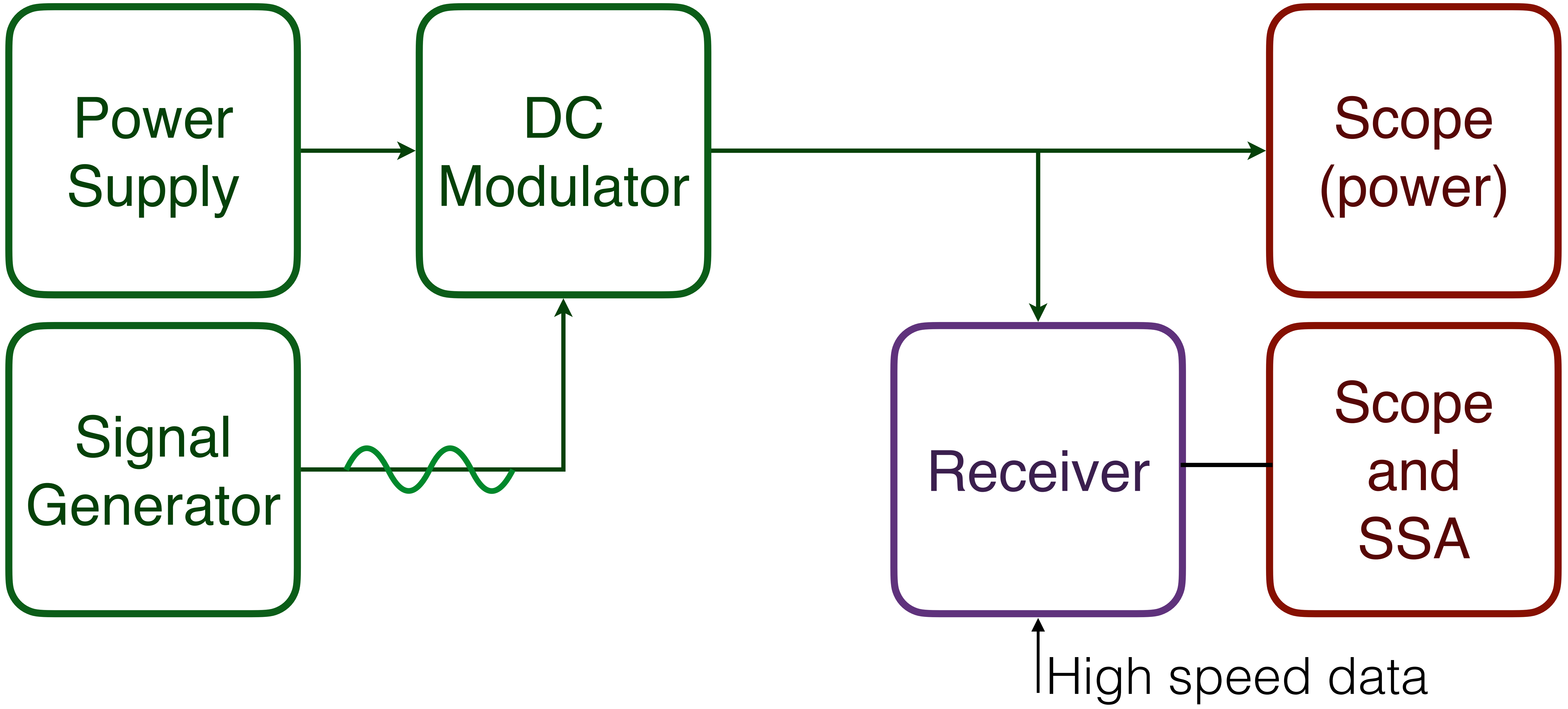


# Jitter sources: an example




- Sine wave noise is generated by the signal generator at three amplitude levels (10 mV, 30 mV, 60 mV) with four different frequencies (500 Hz, 1 kHz, 5 kHz, 10 kHz).
- The generated noise is superposed with the power supply output via the DC modulator. The resulting modulation is measured by the scope.
- We predict this to be a DJ contribution

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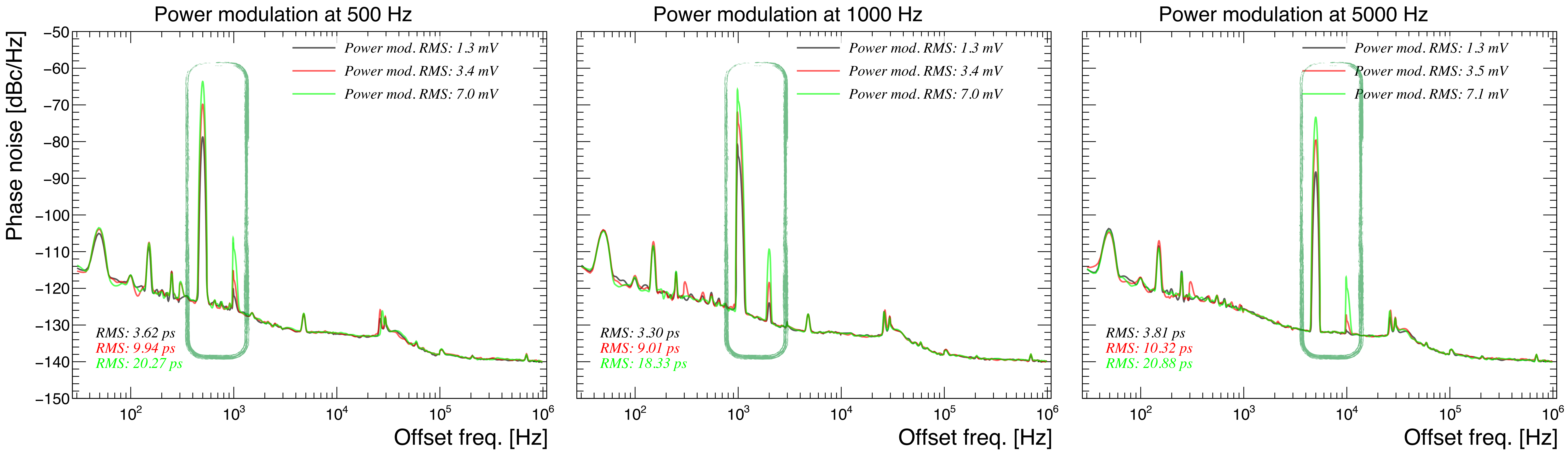
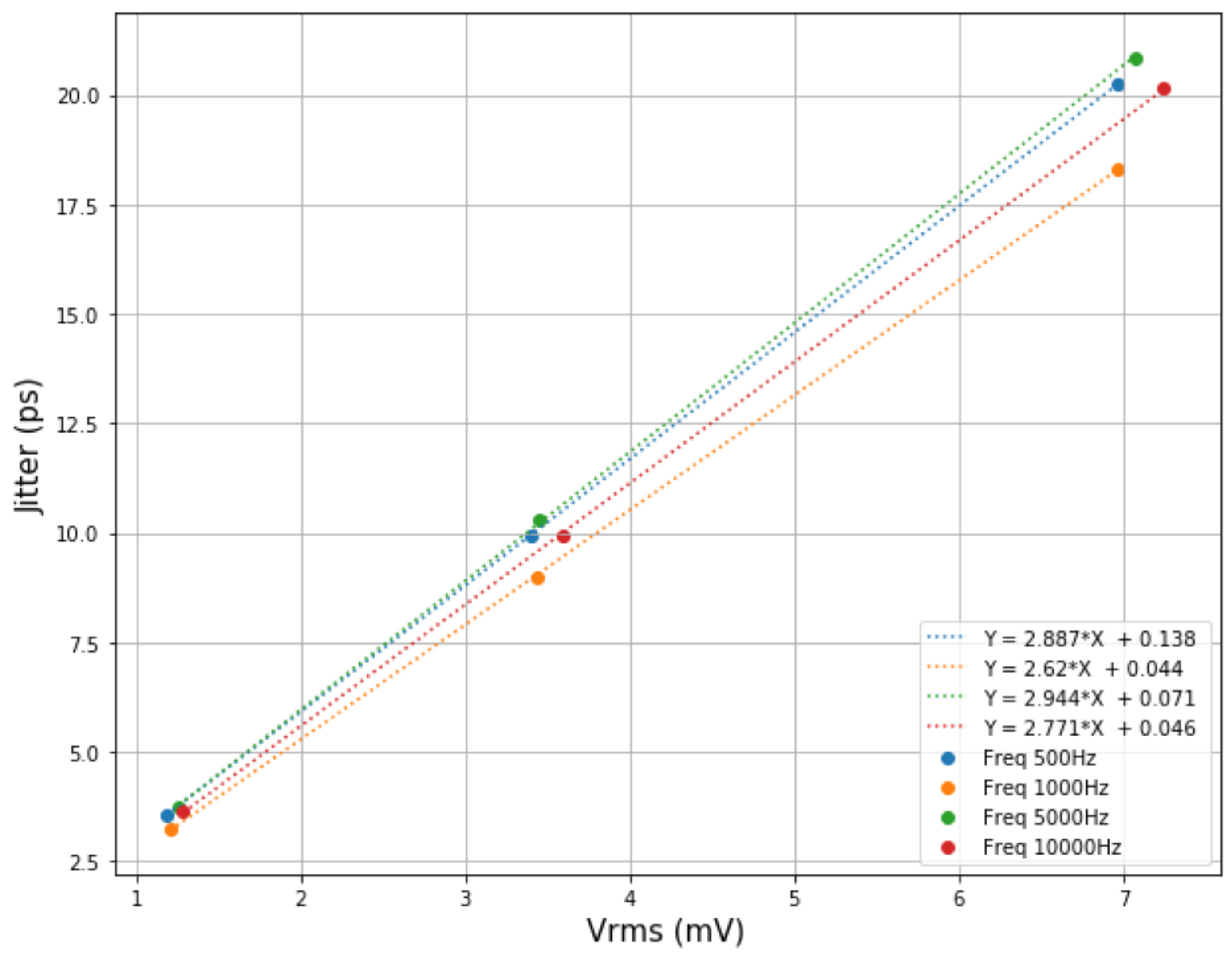
# Jitter sources: an example




- Here the impact of power distribution fluctuations on the timing distribution jitter for an embedded clock distribution chip is quite visible.

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# Rather than having a conclusion

- Phase locked loops
- Digital dual timing mixer (DDMTD)
- Phase monitoring
- Phase stability