Timing for DAQ

ISOTDAQ 2024

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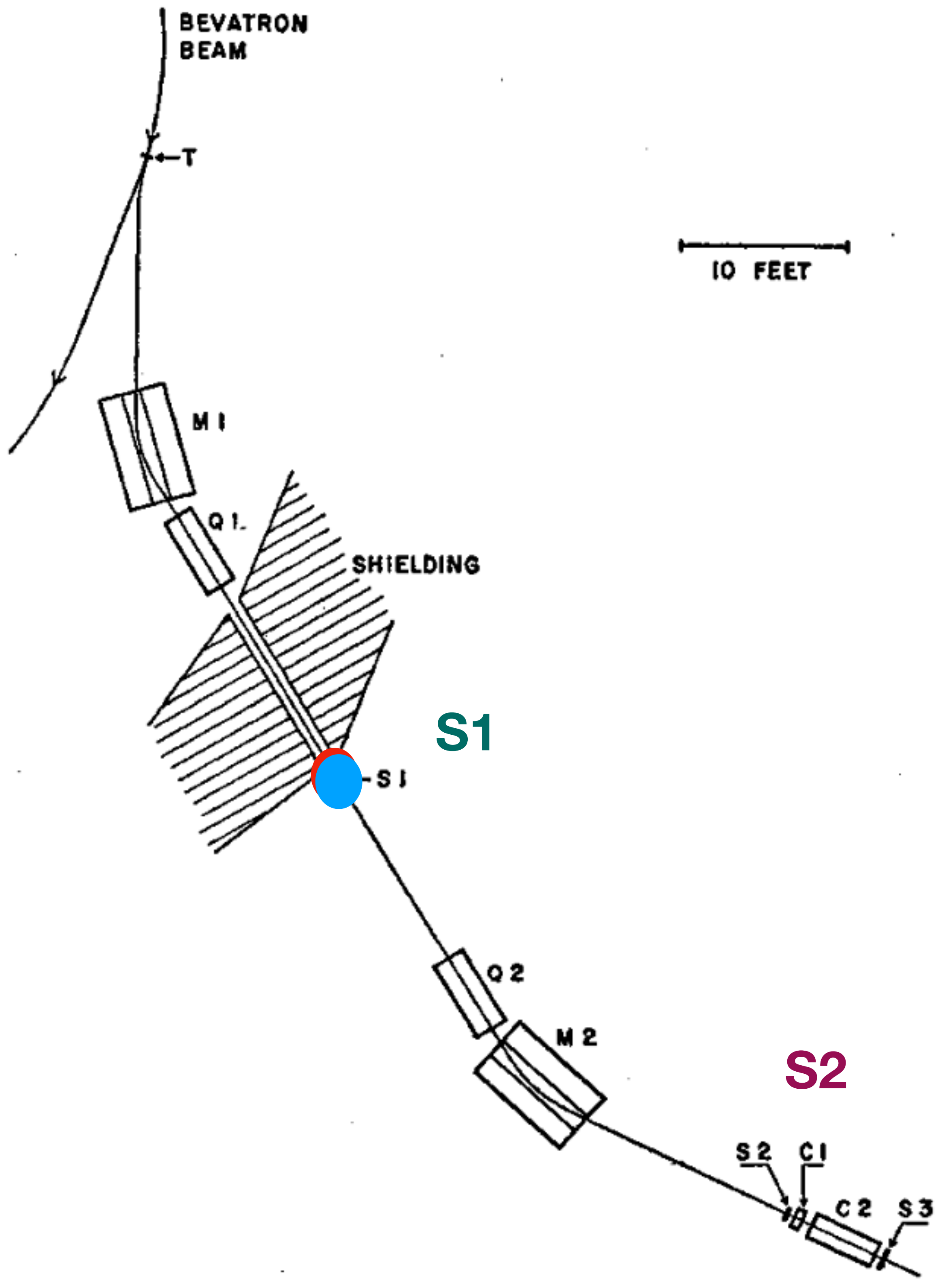
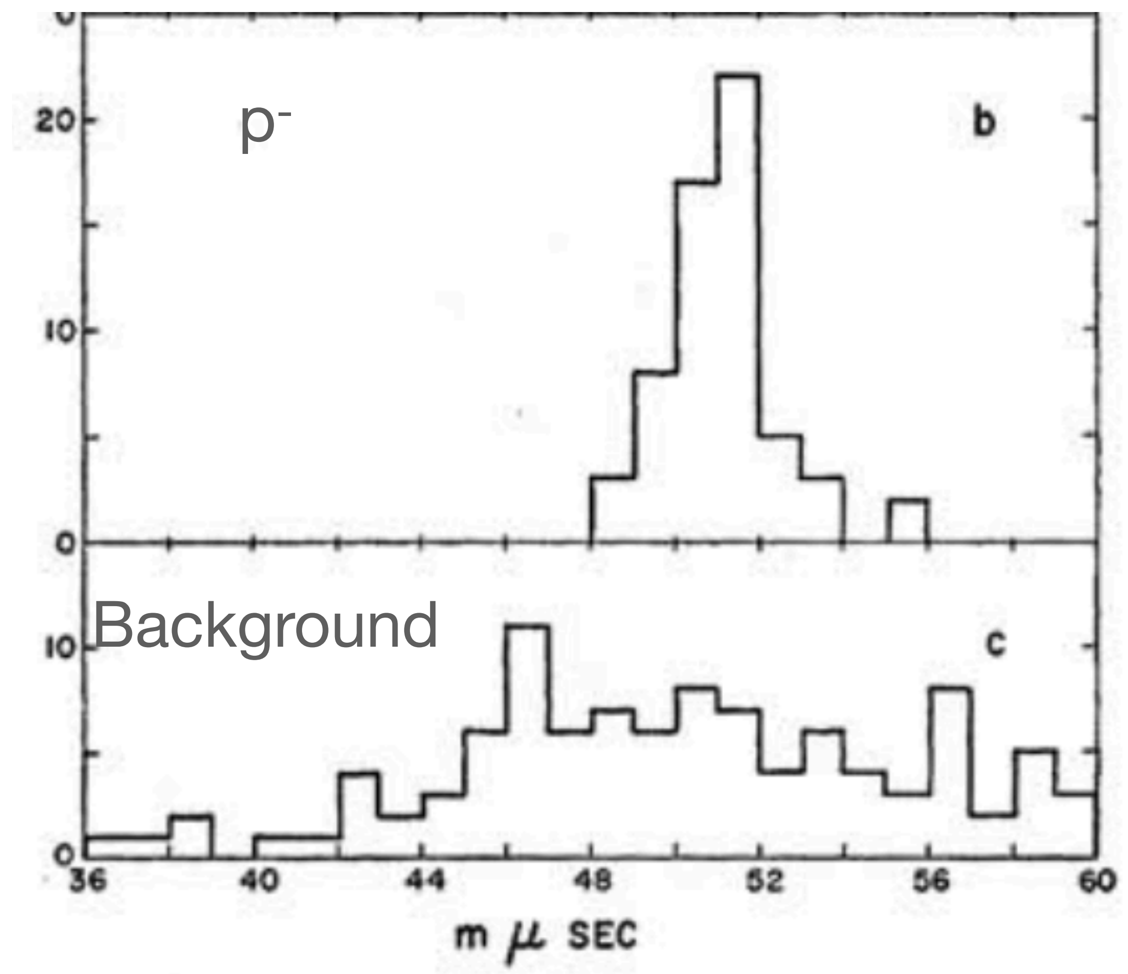
Timing: anti-proton observation

- Timing measurement: Observation of antiproton in 1955

- For the same momentum (1.19 BeV)
  $\beta = 0.99 \rightarrow \pi^-$
  $\beta = 0.76 \rightarrow \mathrm{p}^-$

- 2 scintillators with a resolution of ~1mμs and Δt = t_{S2} - t_{S1}
  $\Delta t = 40 \mathrm{m}\mu s \rightarrow \pi^-$
  $\Delta t = 51 \mathrm{m}\mu s \rightarrow \mathrm{p}^-$





Phys. Rev. 100, 947 (1955) - Observation of Antiprotons
Chamberlain et al

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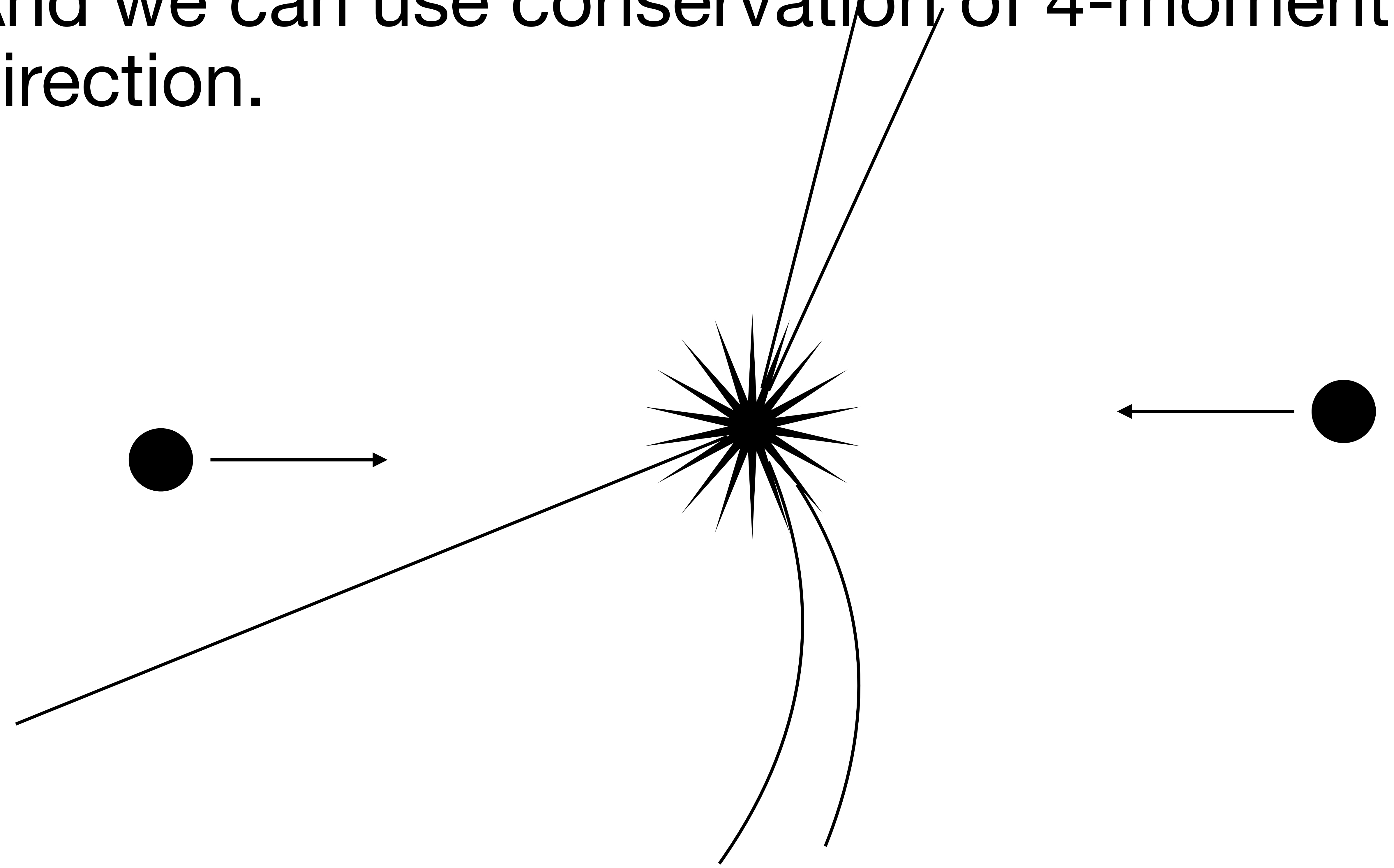
mμs and BeV

- Conférence générale des poids et mesures in 1960
  - 10^{-9} nano
  - 10^{-12} pico
  - The same for Giga and Tera
  - Antiproton was observed in 1955: so 1 mμs -> 1 ns and 1 BeV -> 1 GeV

Why do we need precision timing at the LHC?

- 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 in the transverse direction.



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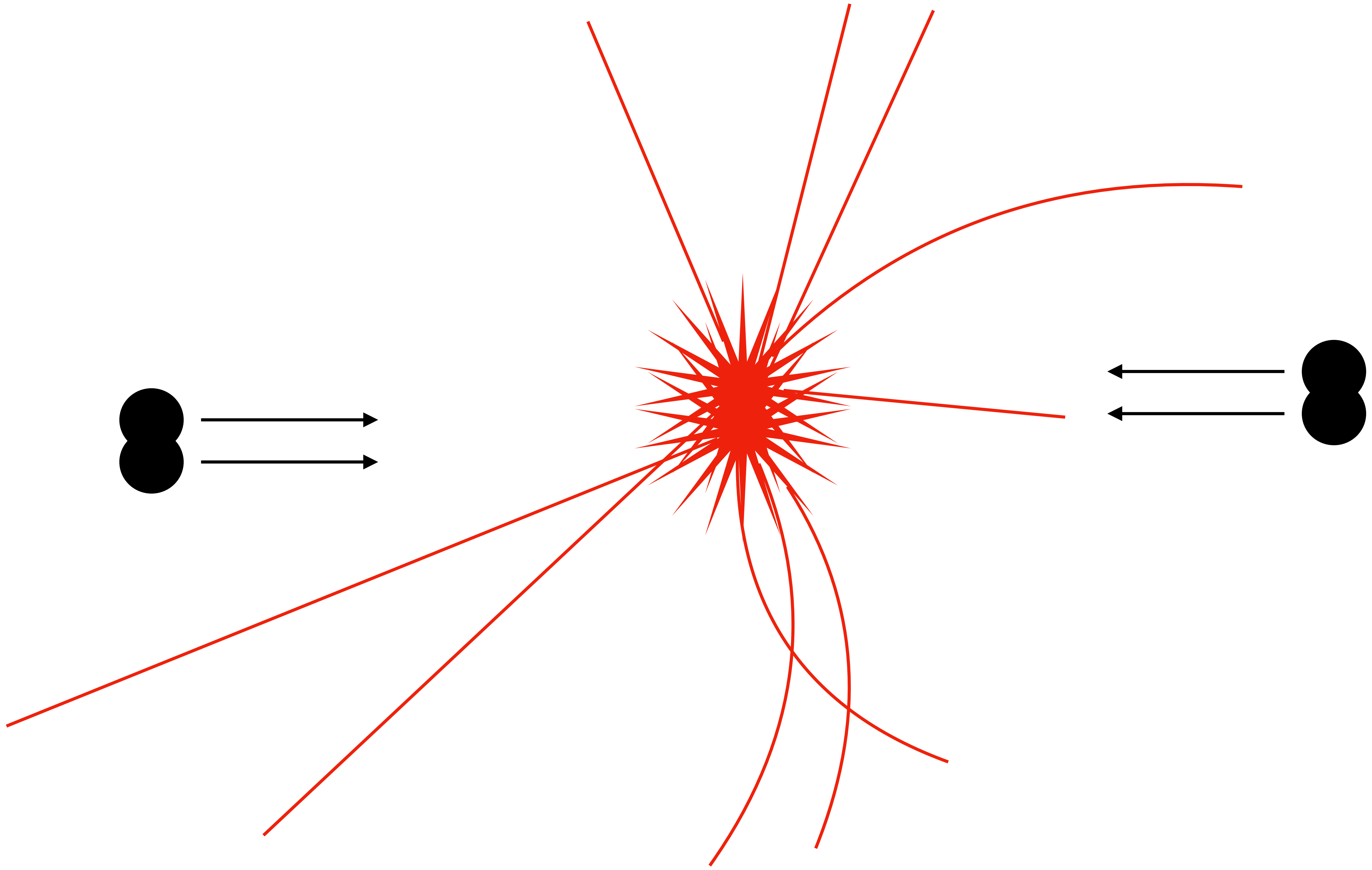
Why do we need precision timing at the LHC?

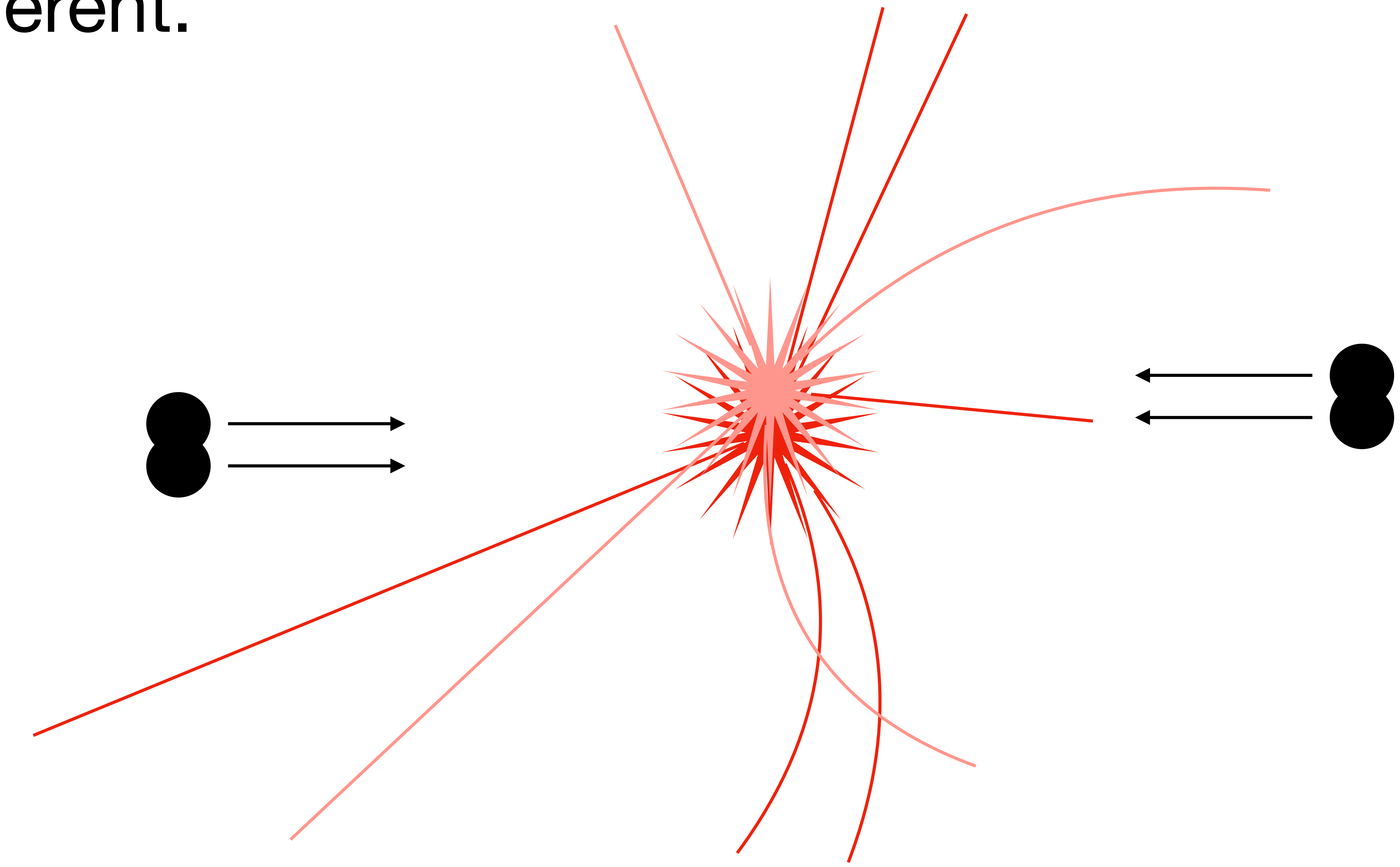
- Now we want to increase our chance of observing collisions.
    - Increase luminosity, more dense beams!



Why do we need precision timing at the LHC?

- 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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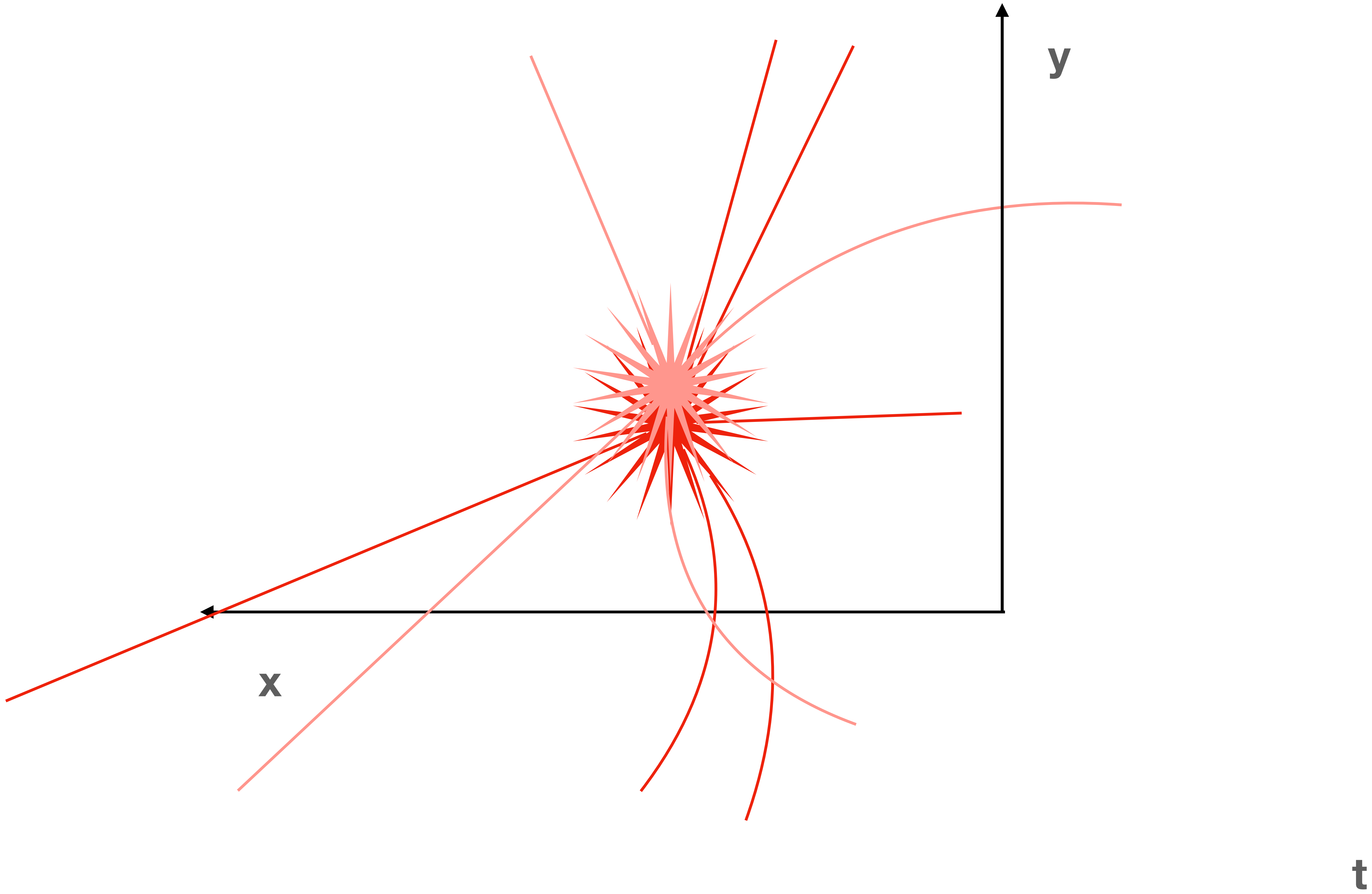
Why do we need precision timing at the LHC?

- In other words, when the position resolution is not enough:



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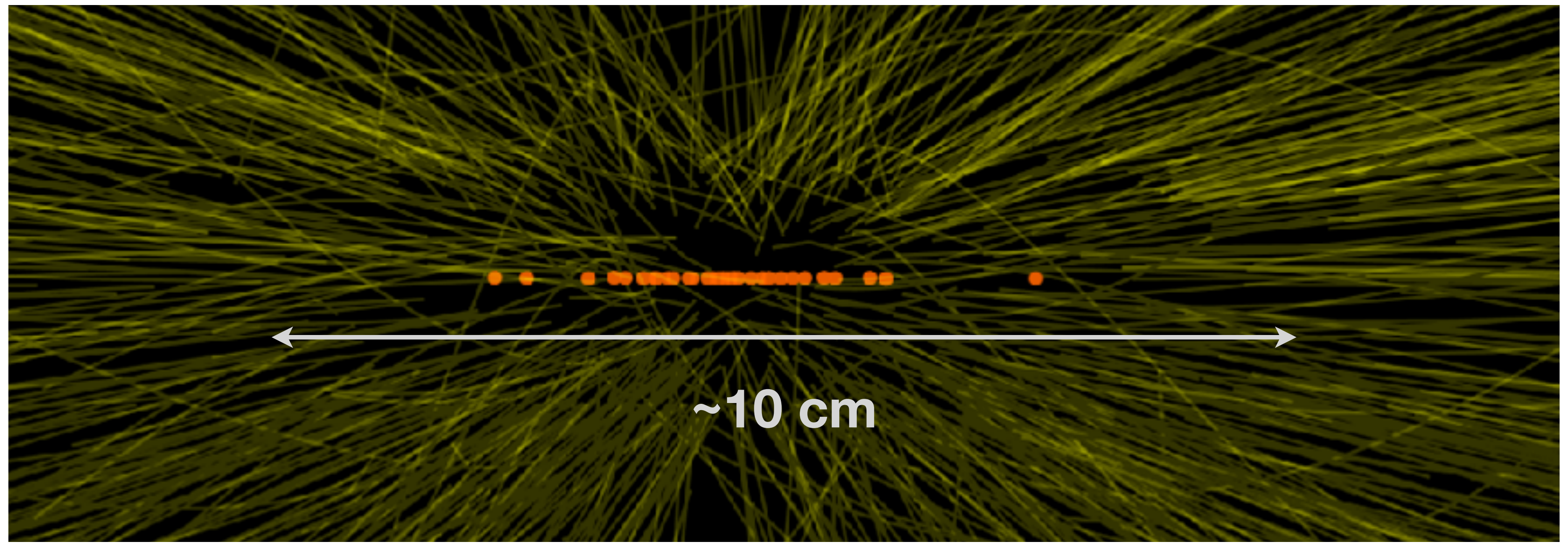
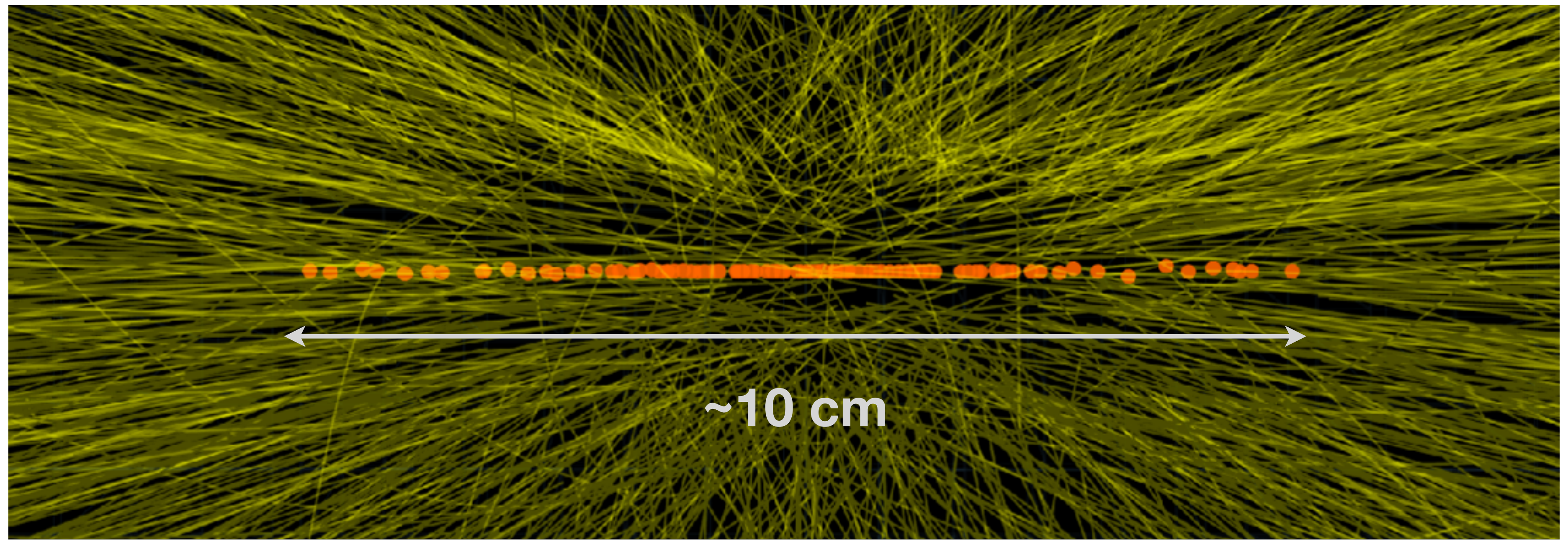
Materializing the concept

- 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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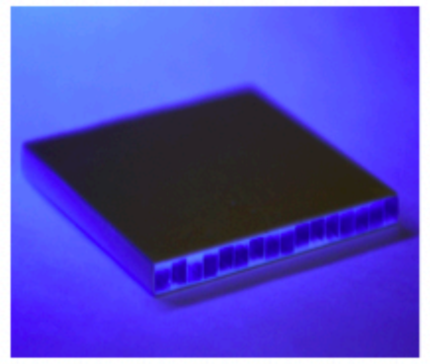
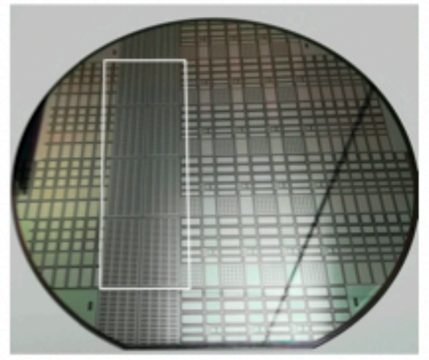
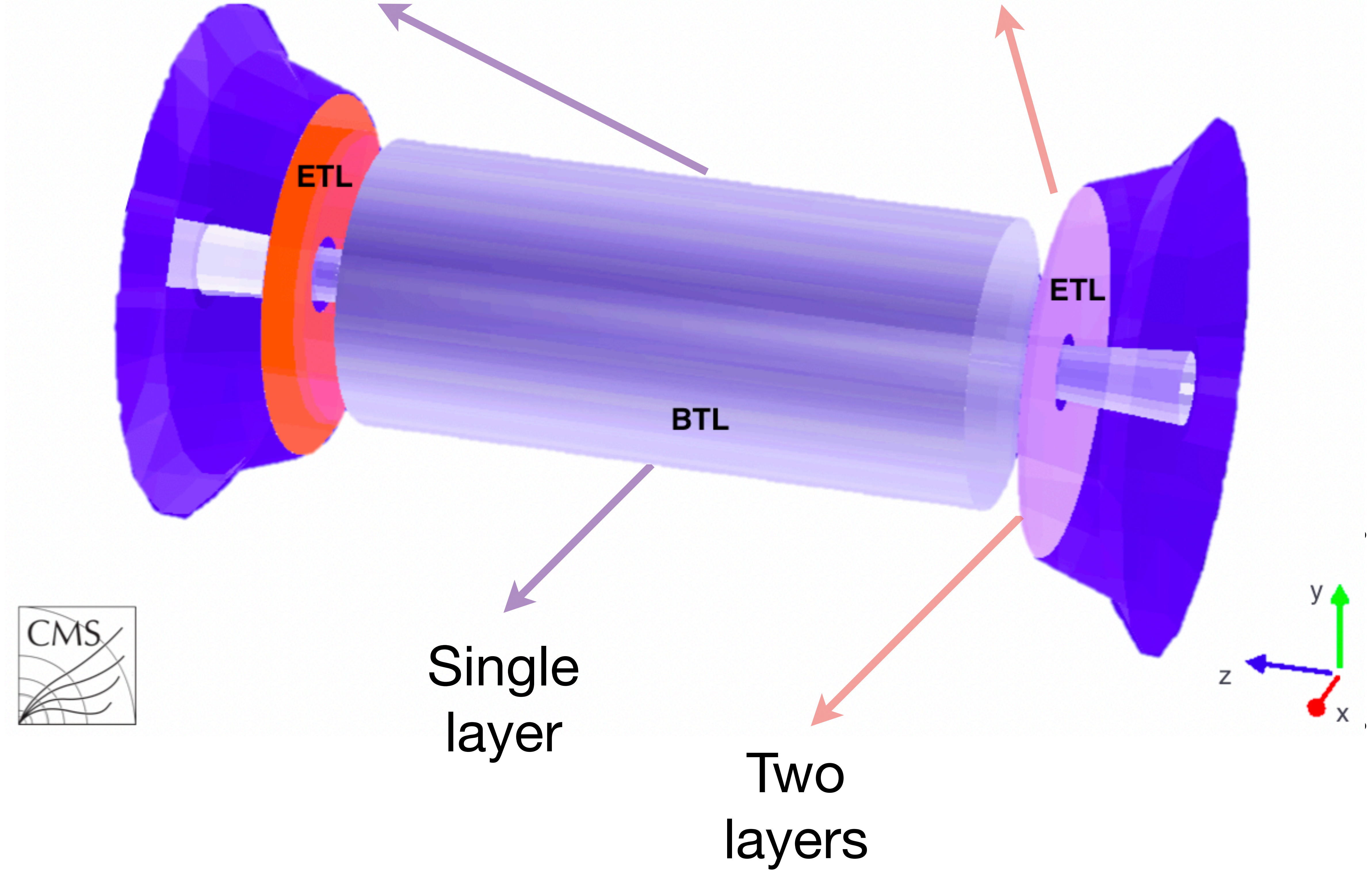
An example solution

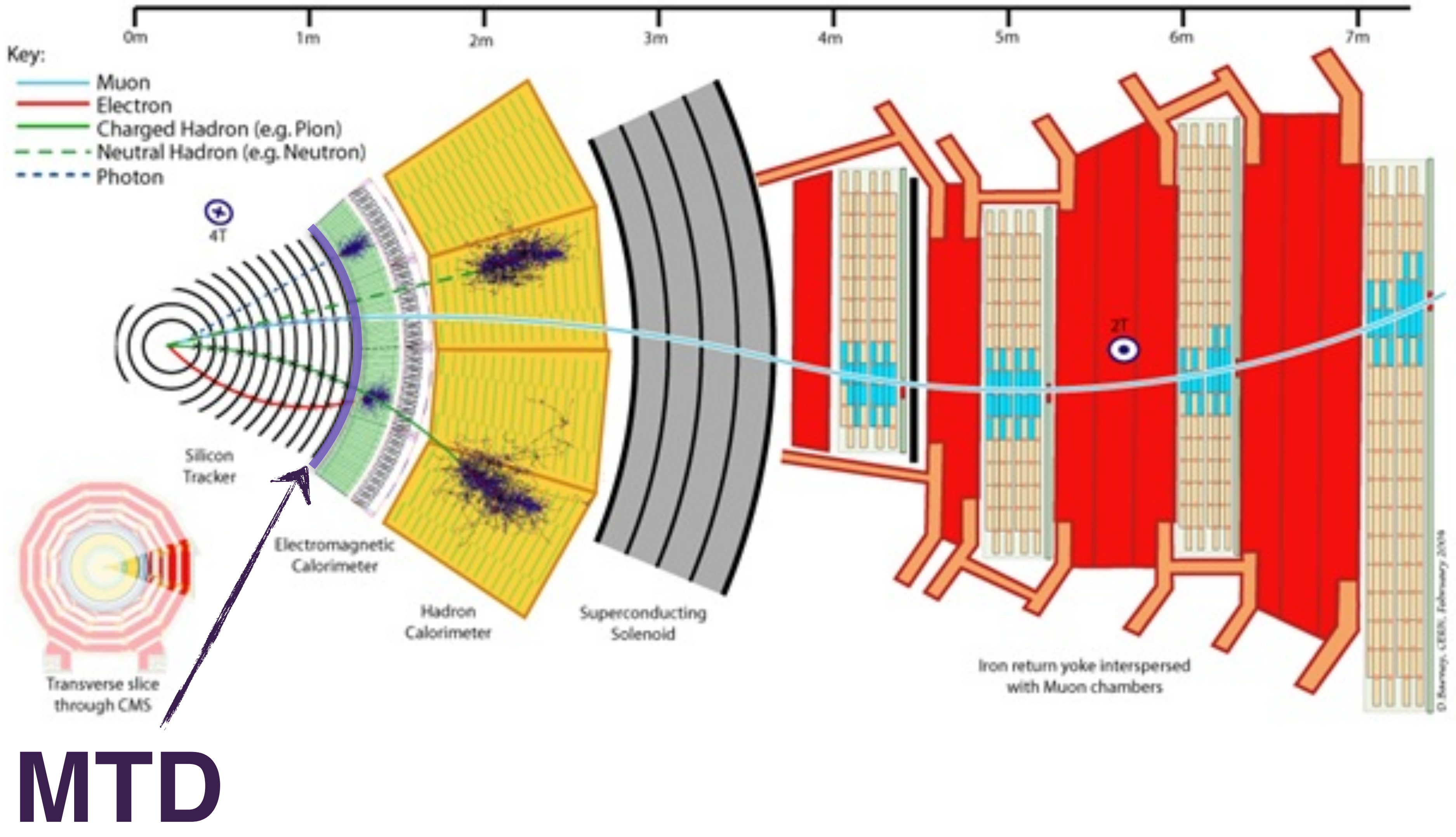
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 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 2x10^{15} n_{eq}/cm^2







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

It will have an hermetic coverage up to η=3.

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Timing detectors at the HL-LHC

- 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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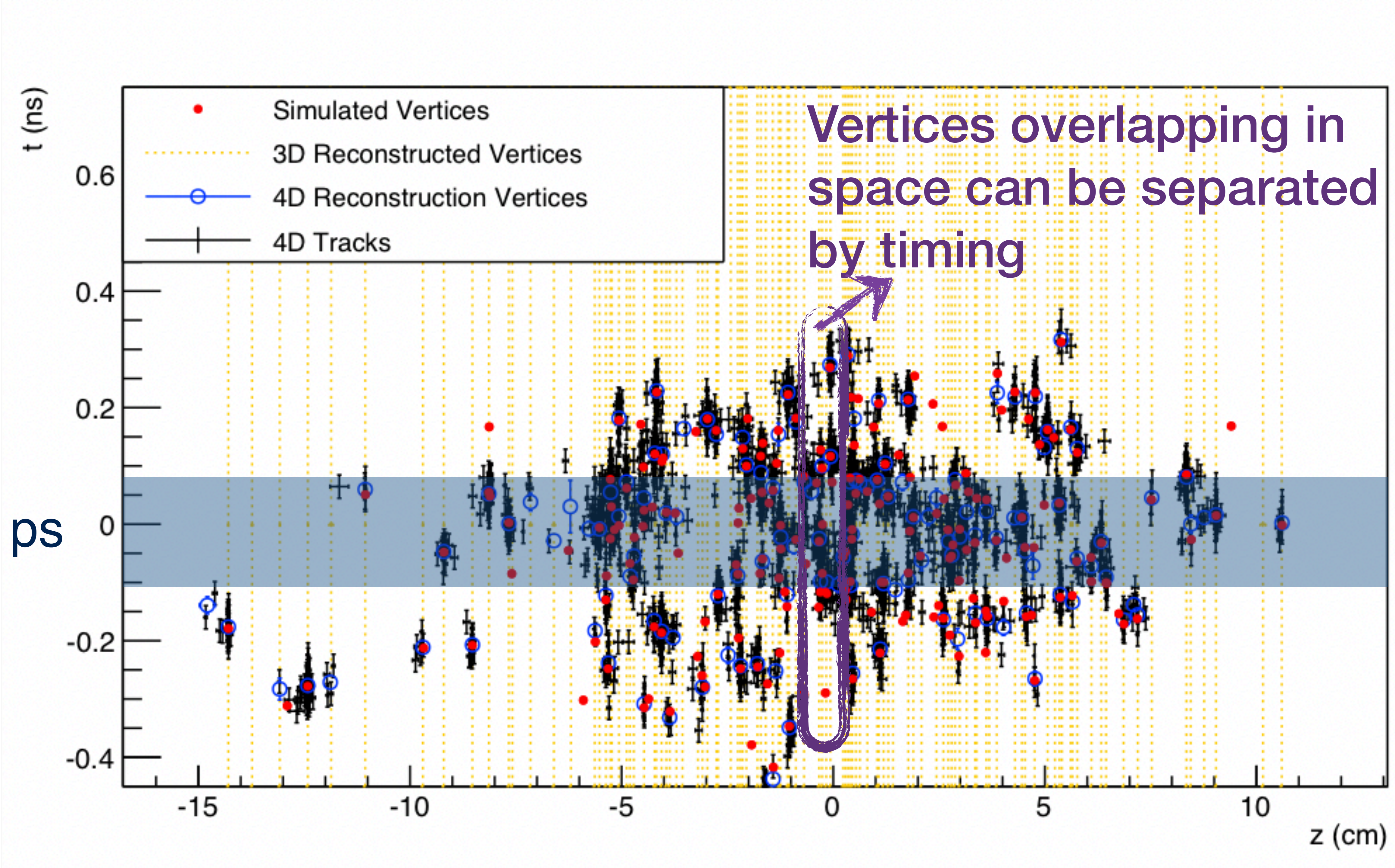
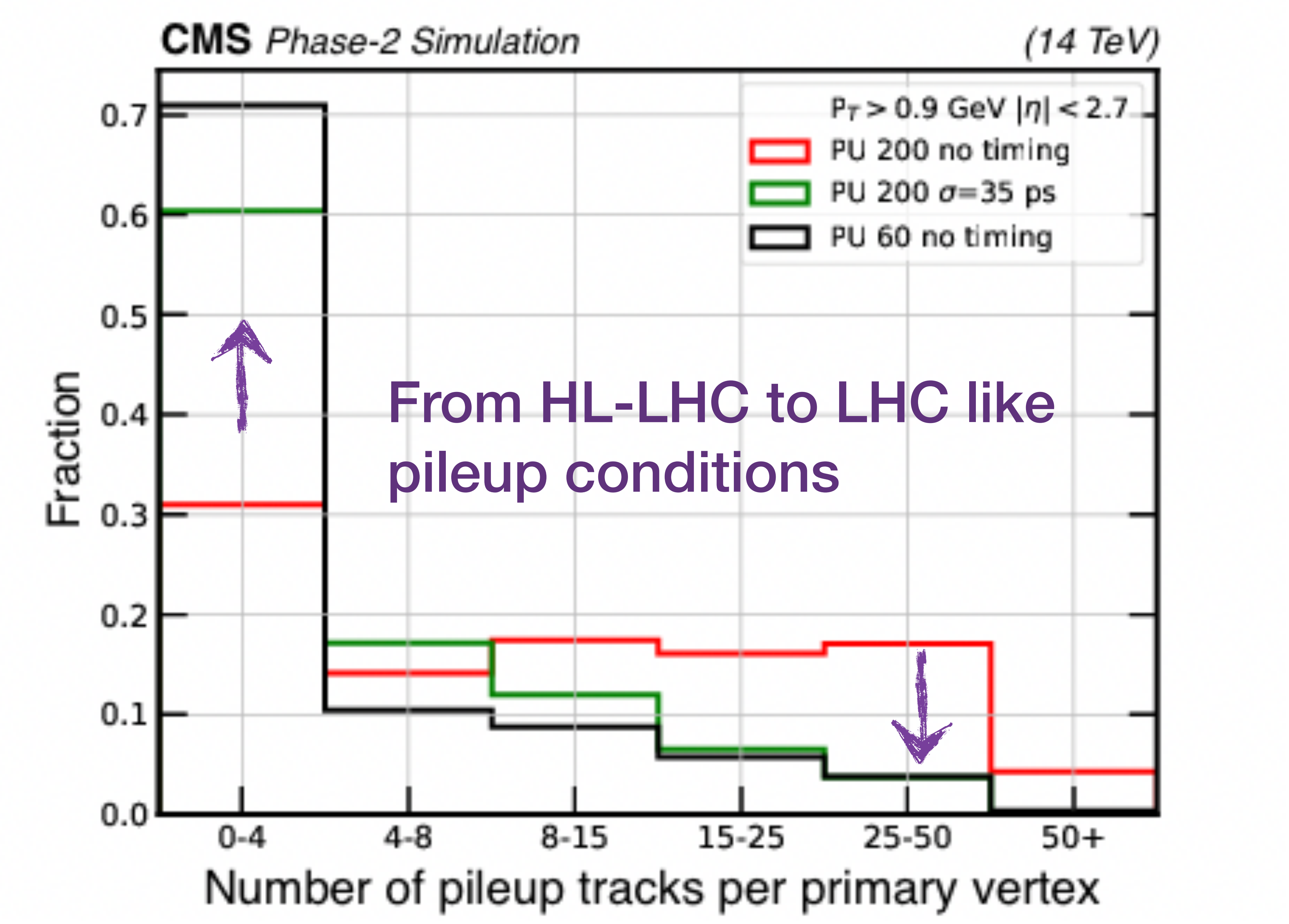
Mitigating the pile up

σ 30 ps





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

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Questions so far?

- After understanding the motivation for timing, we will discuss how to measure timing at the modern colliders.

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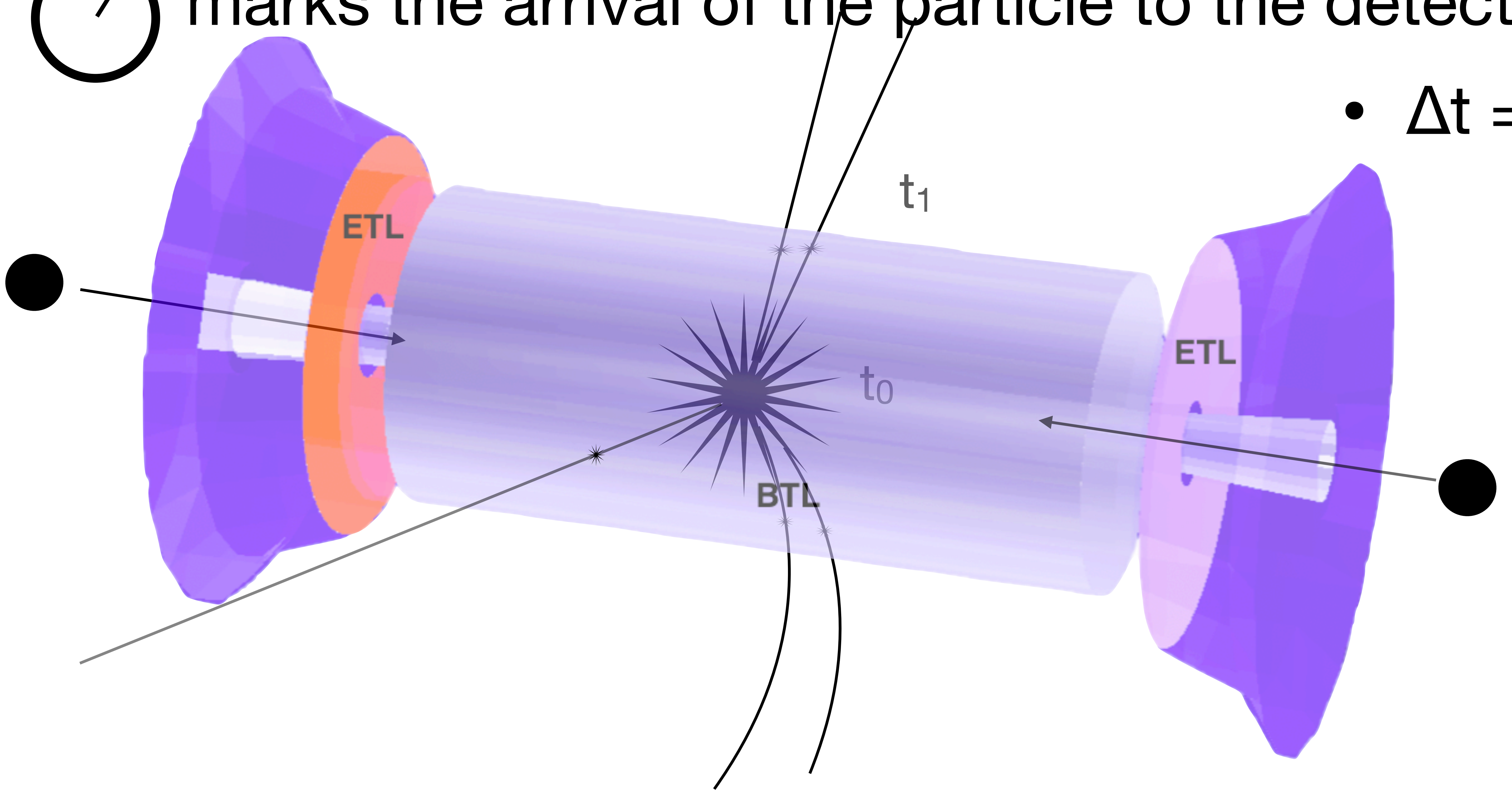
How do we measure the timing?

- 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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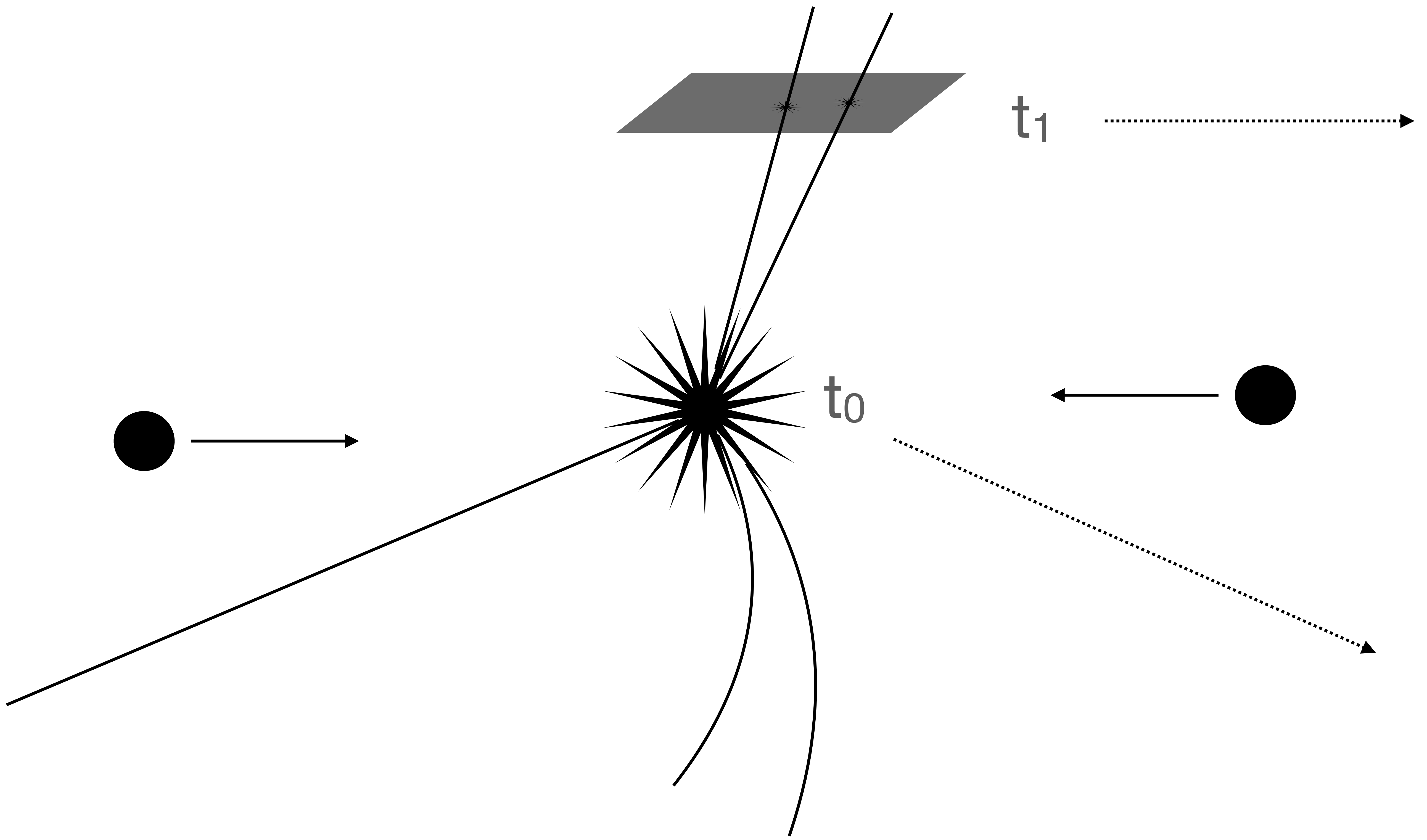
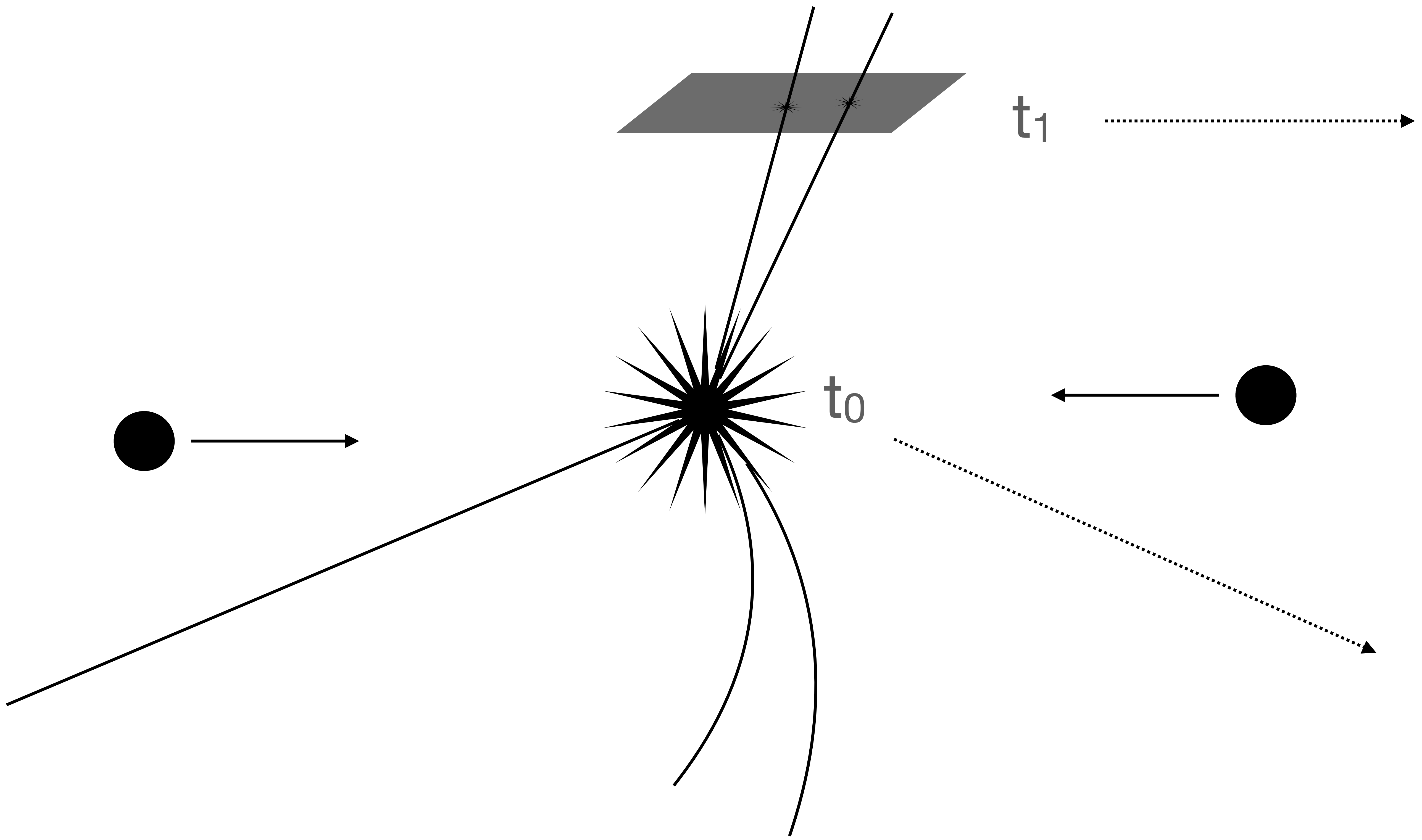
How do we measure the timing?



- **t_1** is estimated by converting the analog sensor data to timing information using TDCs.
  - LYSO crystals with SiPMs, LGAD silicon sensors, MAPS…
- Estimation of **t_0**, on the other hand, should be provided by the accelerator.

How do we measure the timing?



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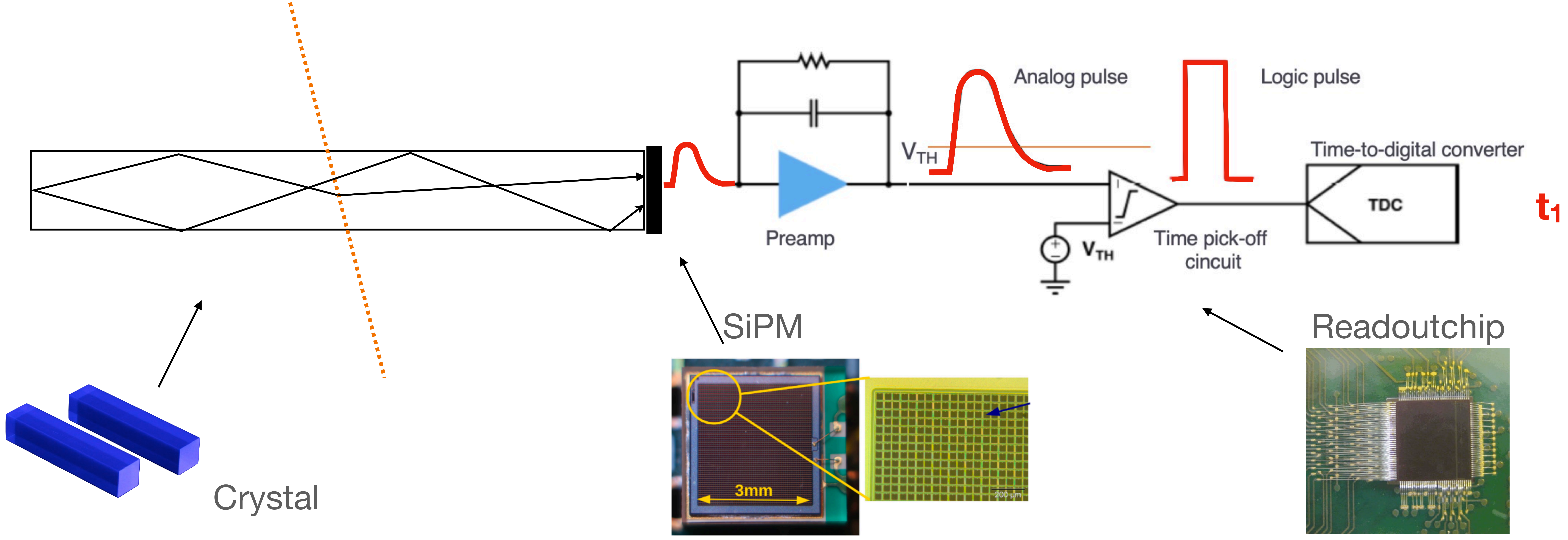
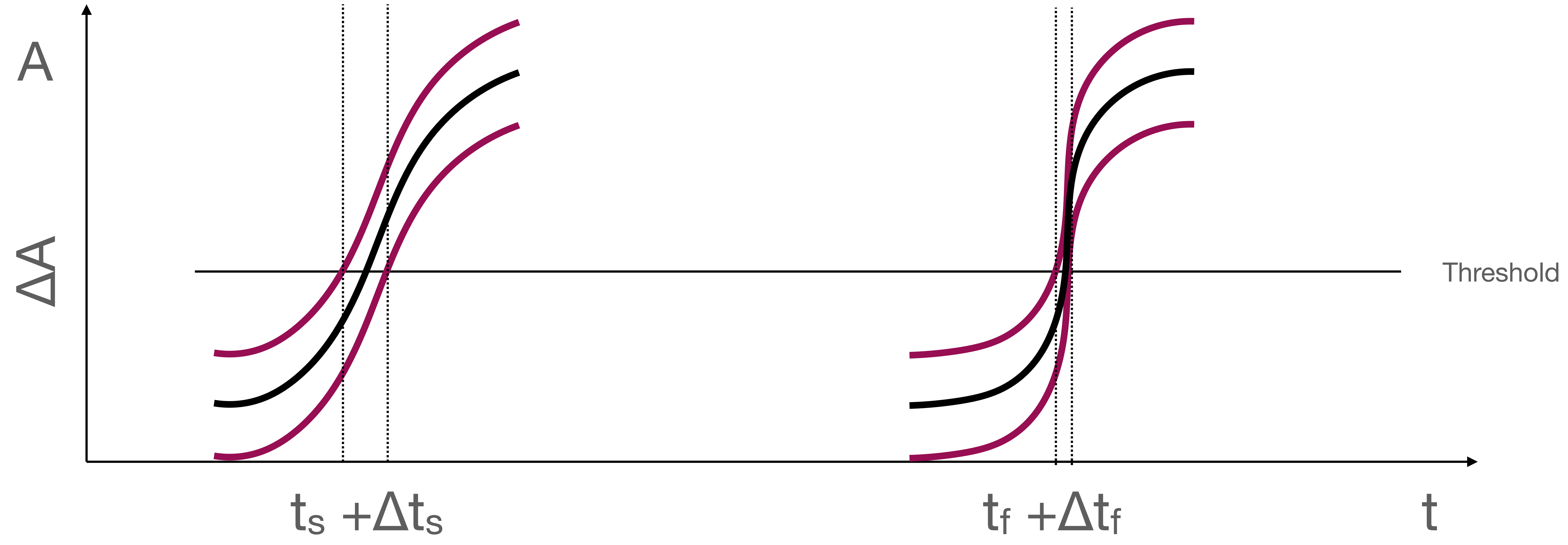
Sensor and electronics

- Let's have a look at scintillators with silicon photomultipliers (SiPM)



Signal requirements

- We need fast rising edge signal out of crystal + SiPM: a simple demonstration.



- For the same ΔA -> **$\Delta t_s > \Delta t_f$**

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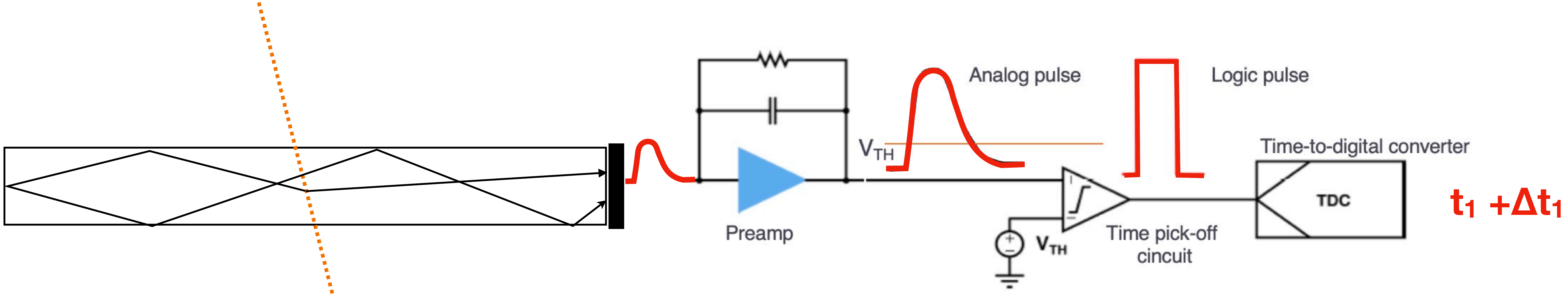
Sensor and electronics noise

- Various elements affect timing resolution:



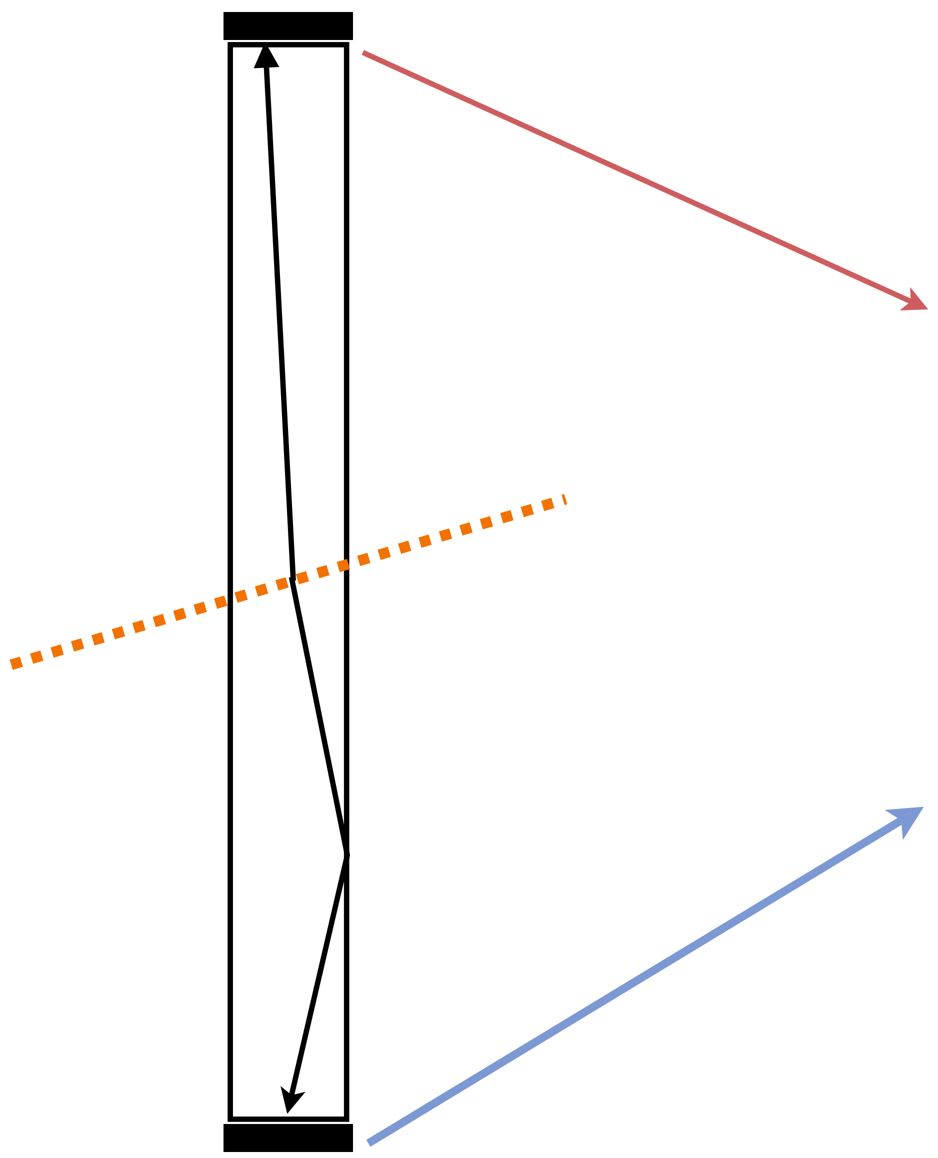
Position uncertainty
PDE
Timing resolution of the TDC
Loss of photon
Electronics jitter

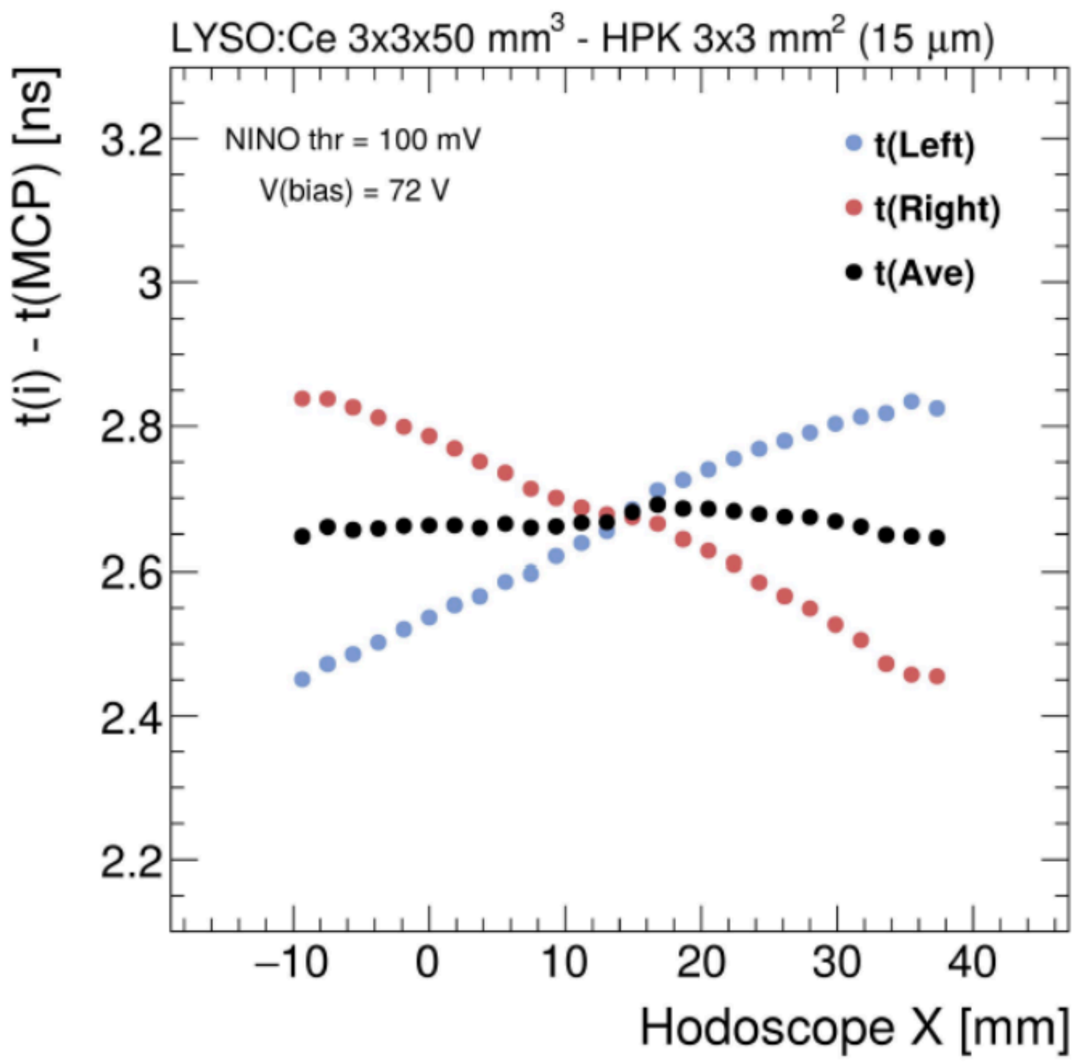
…

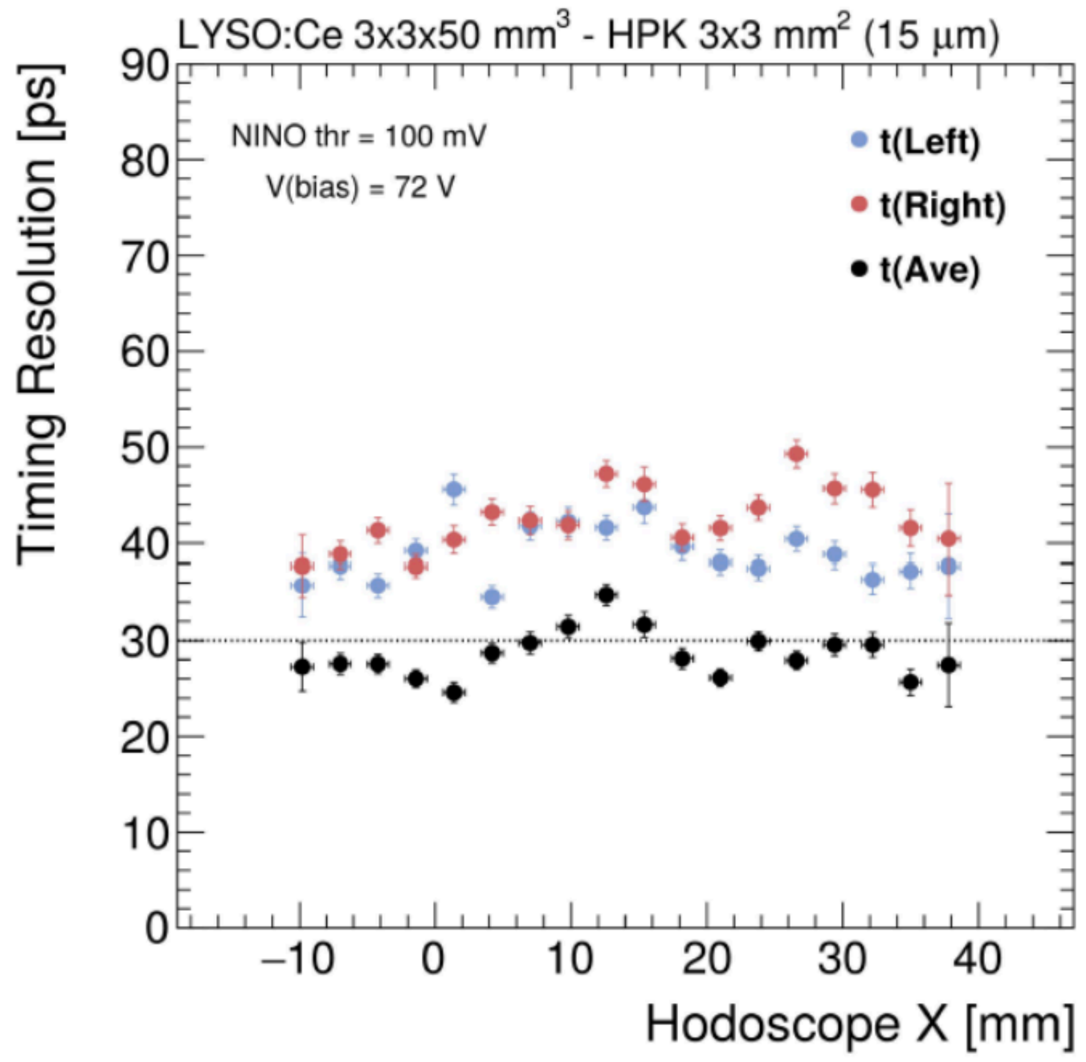
- Can be improved by material choice, different readout schemes, more advanced electronics.

BTL: sensor and electronics

- For BTL, two SiPMs measure the signals from both ends of LYSO crystals.

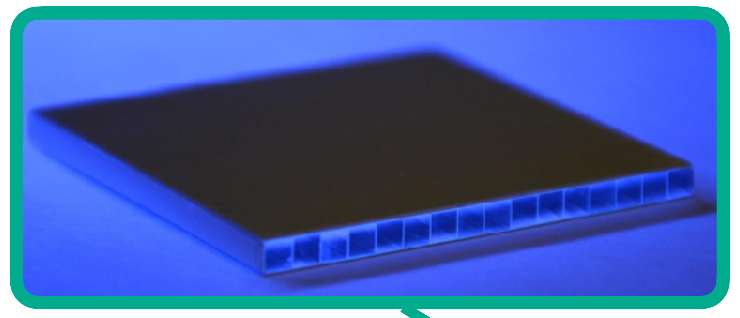


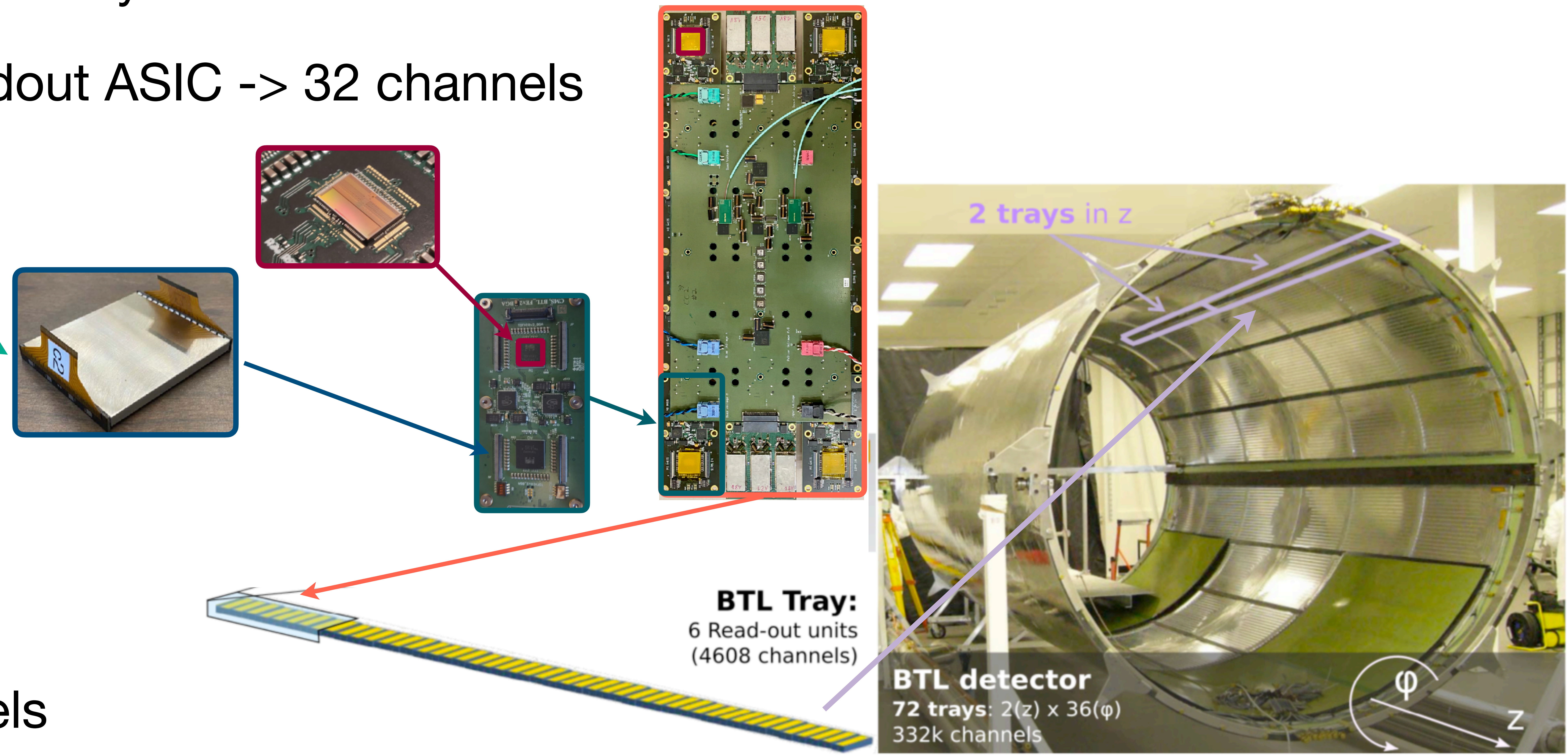




Realizing the detector

- 16 3x3x20 mm crystals -> 32 SiPM
- TOFHIR readout ASIC -> 32 channels





- 332k channels

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Questions so far?

- After measuring t_1 we will discuss how can do we obtain and distribute t_0 at the LHC.

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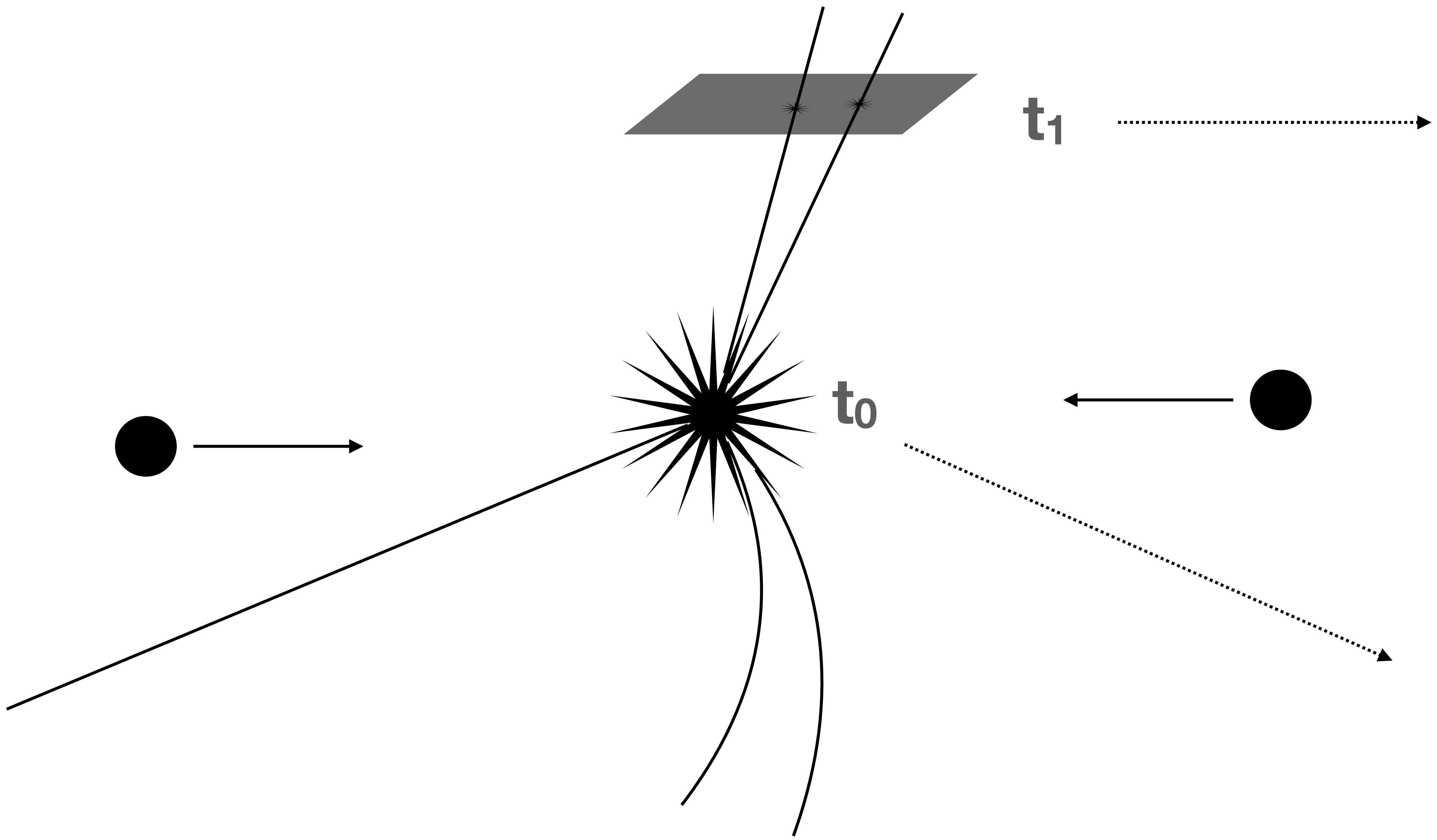
How do we measure the timing?



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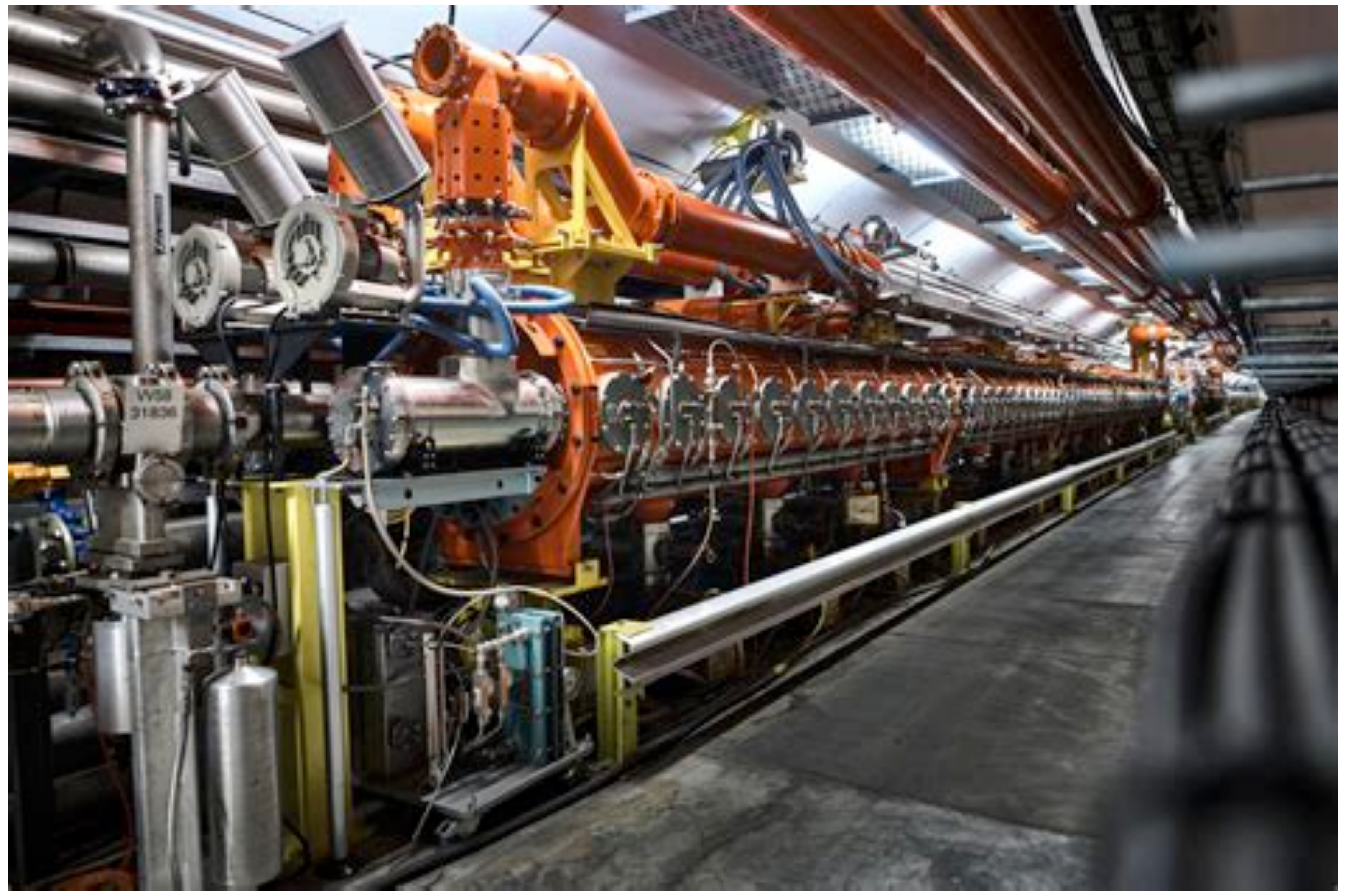
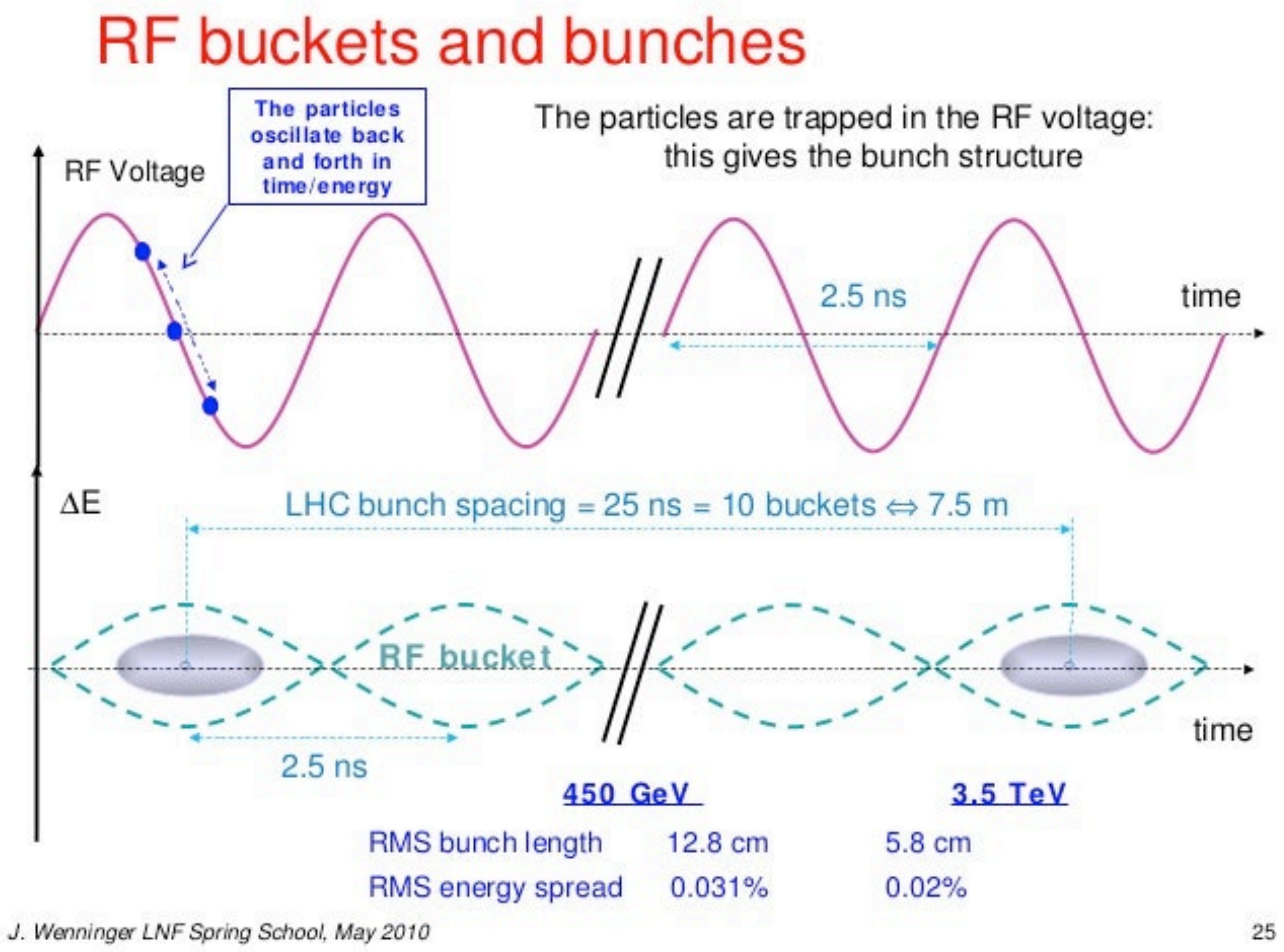
Collision timing from the LHC

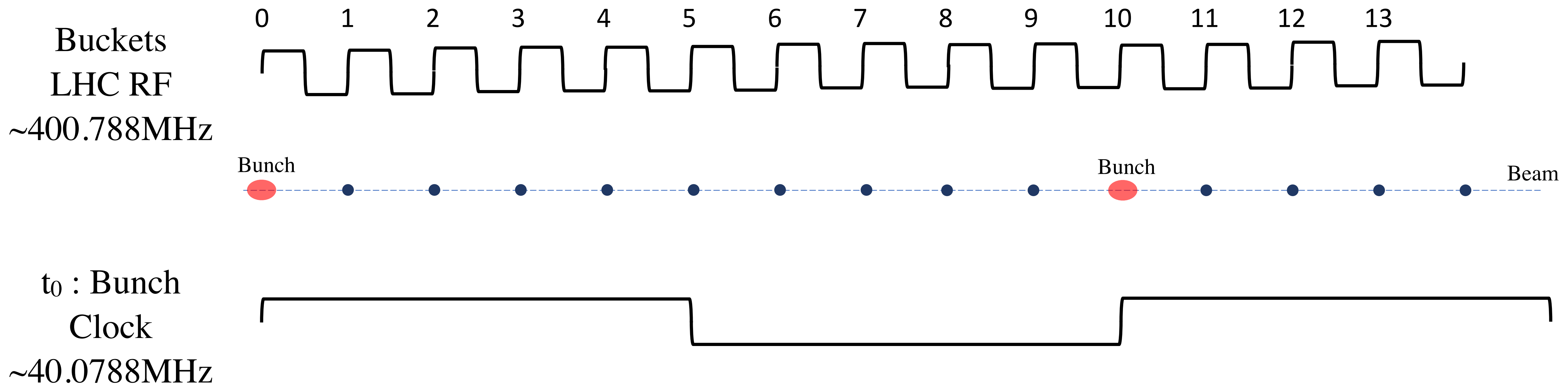
- Bunch of particle are arranged by the RF cavities that are tuned to operate at 400.788 MHz.
- A bunch spacing of approximately 25 ns is achieved in these cavities.





Collision timing from the LHC

- These neatly spaced bunches are then collide at the interaction points of the LHC **at 40.0788 MHz**.

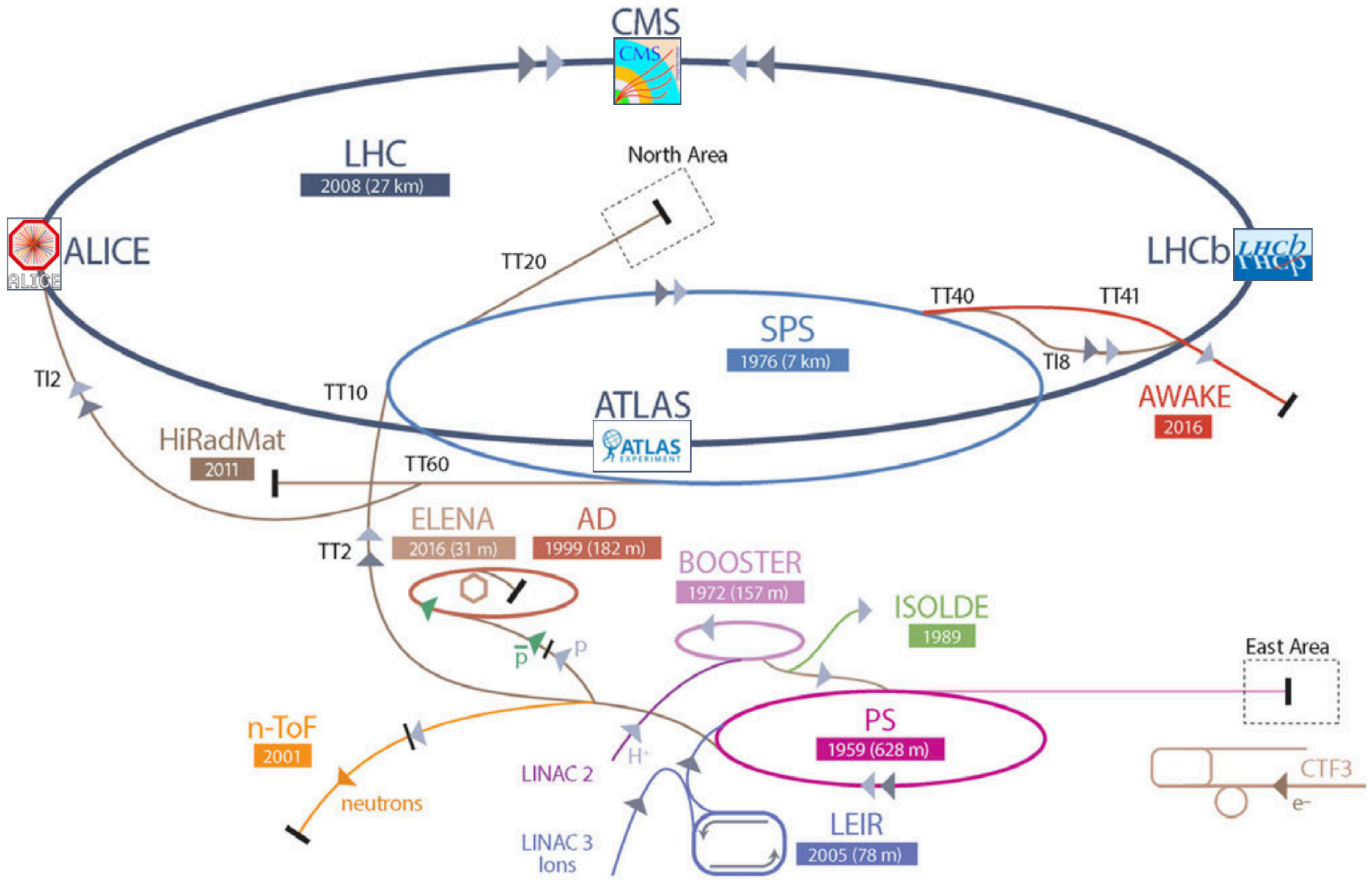


- Therefore, the readout of the detectors are (and should be) synchronized to this clock.

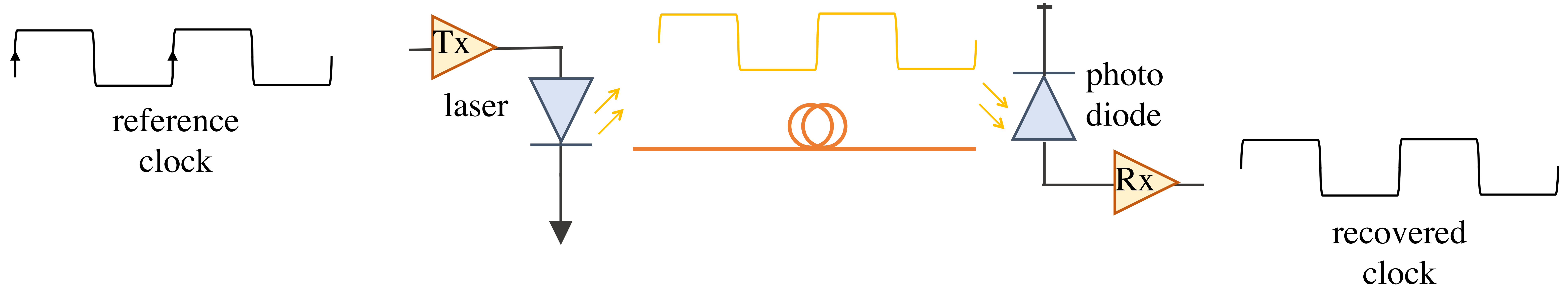
- This the **t_0 of the collision** - hence the start of the timing measurement.

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.

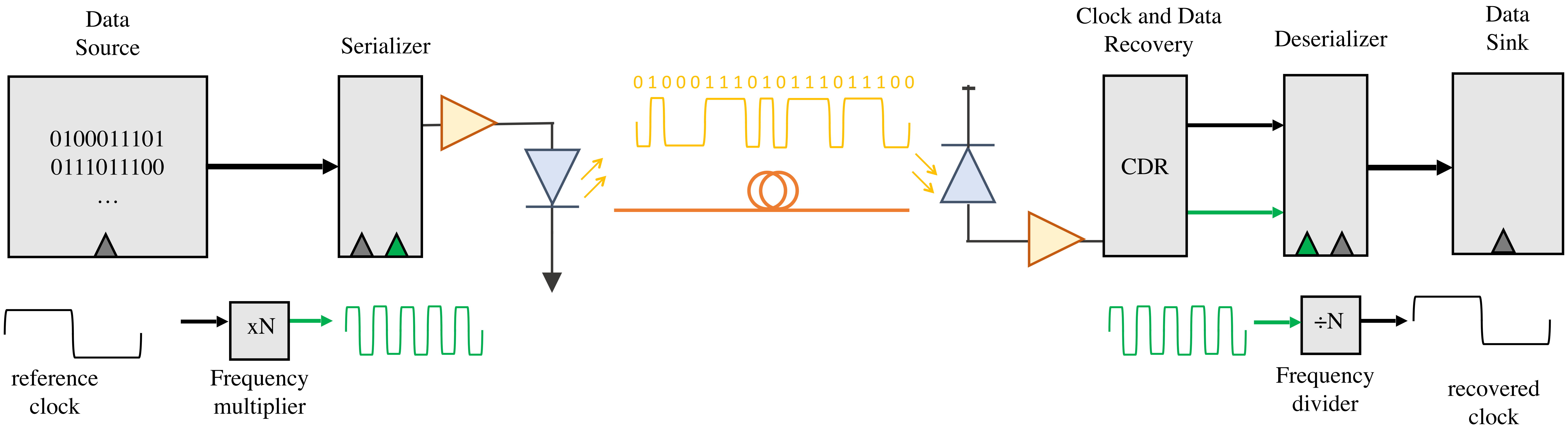


Pure clock



- 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.

Embedded clock



- There is a more efficient way of distributing the clock by embedding it to the data stream.
- In this approach, 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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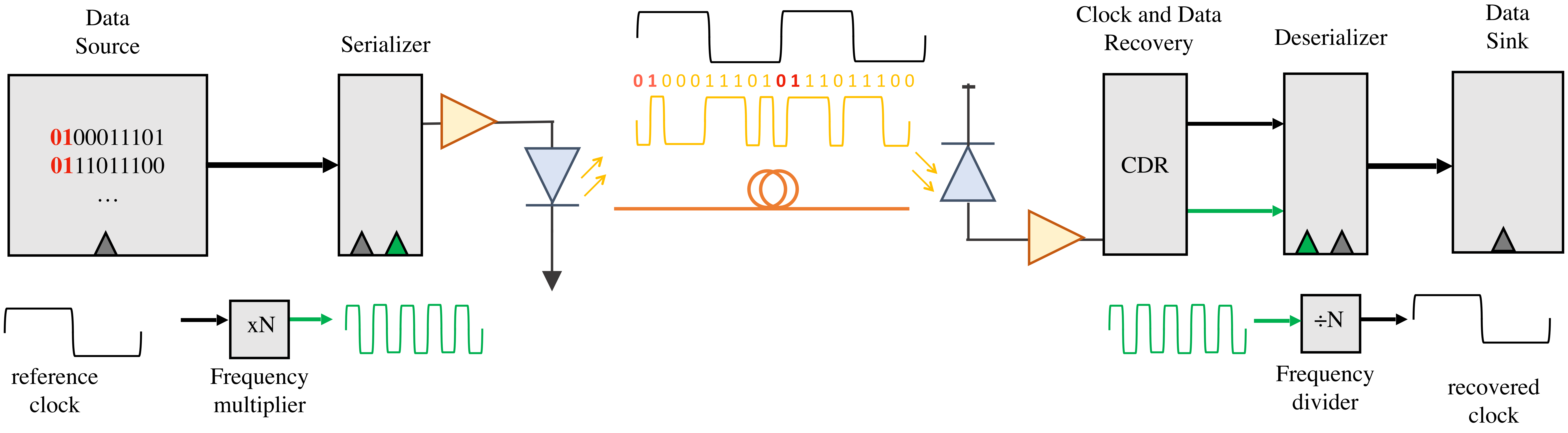
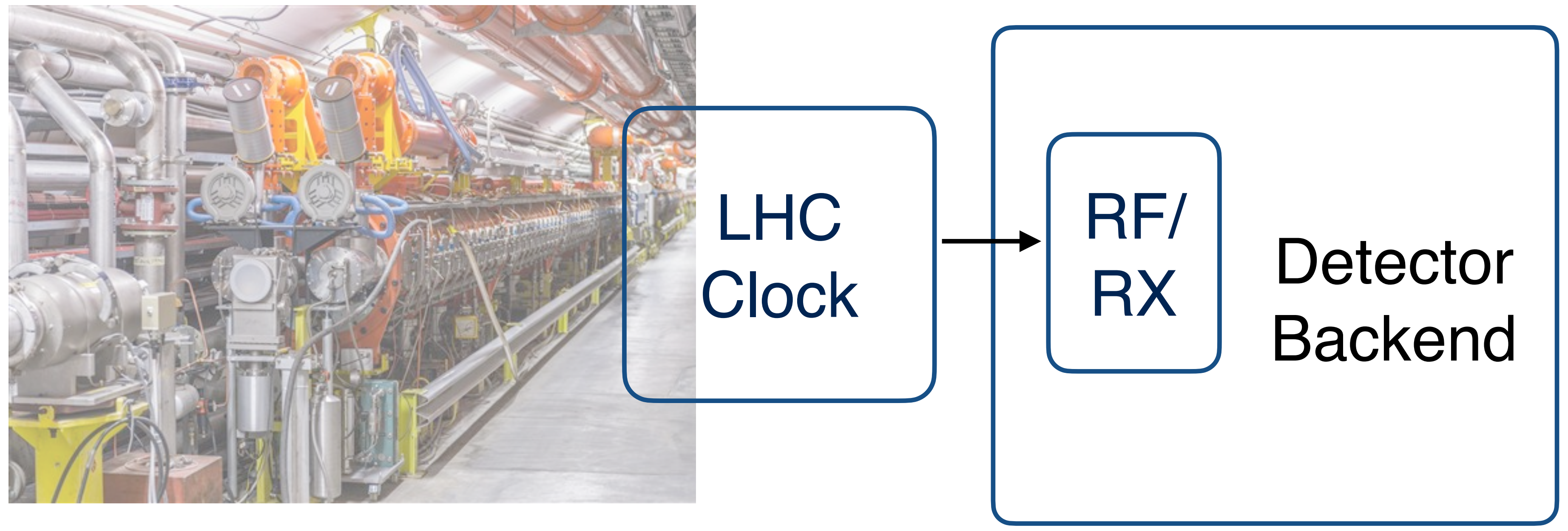
Embedded clock



- 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.

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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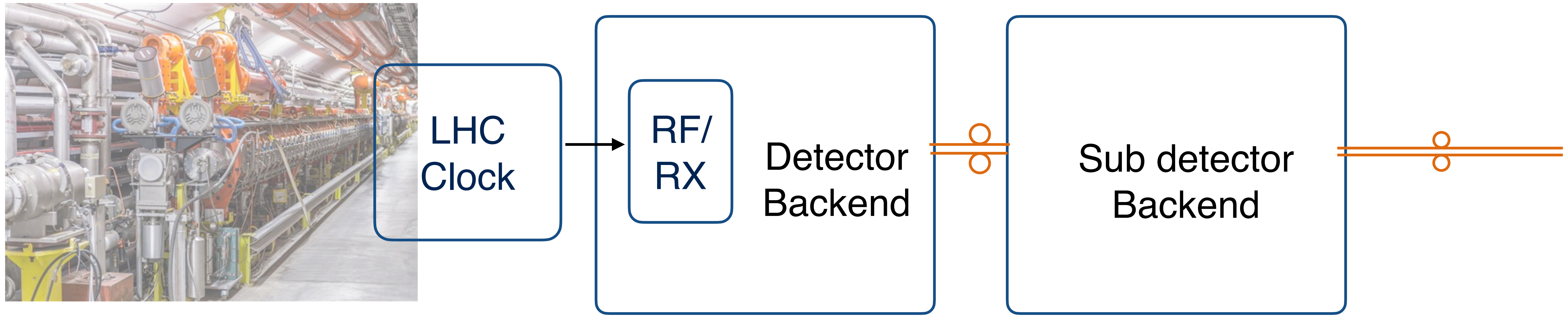
A typical clock distribution chain



Backend

- The clock has a long way to reach to the detector in a large accelerator.
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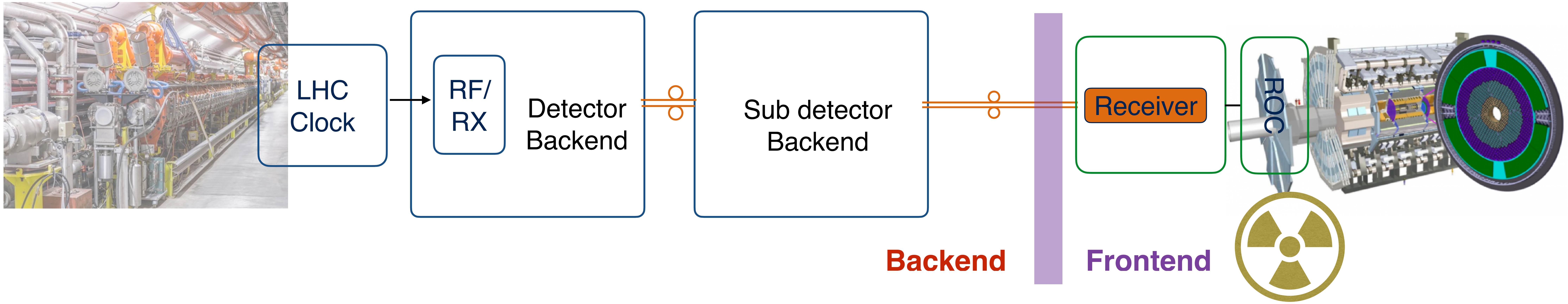

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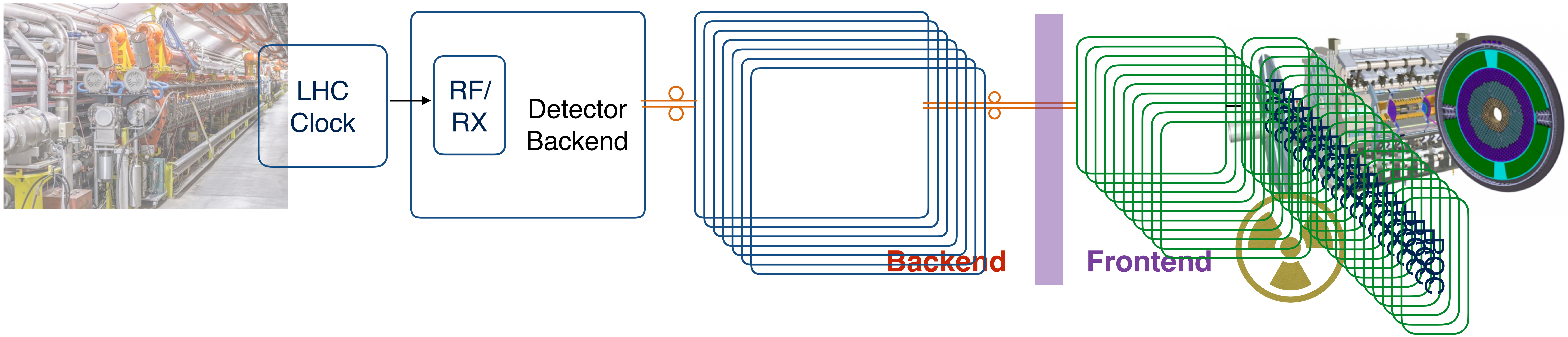

- The clock has a long way to reach to the detector in a large accelerator.
- There may be multiple connection points, opto-electrical conversions, kms to reach to the detector and some of hundred meters to be **distributed over tens of thousands of communication links** within a detector!

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There does not exist a perfect system.

- Any questions so far?

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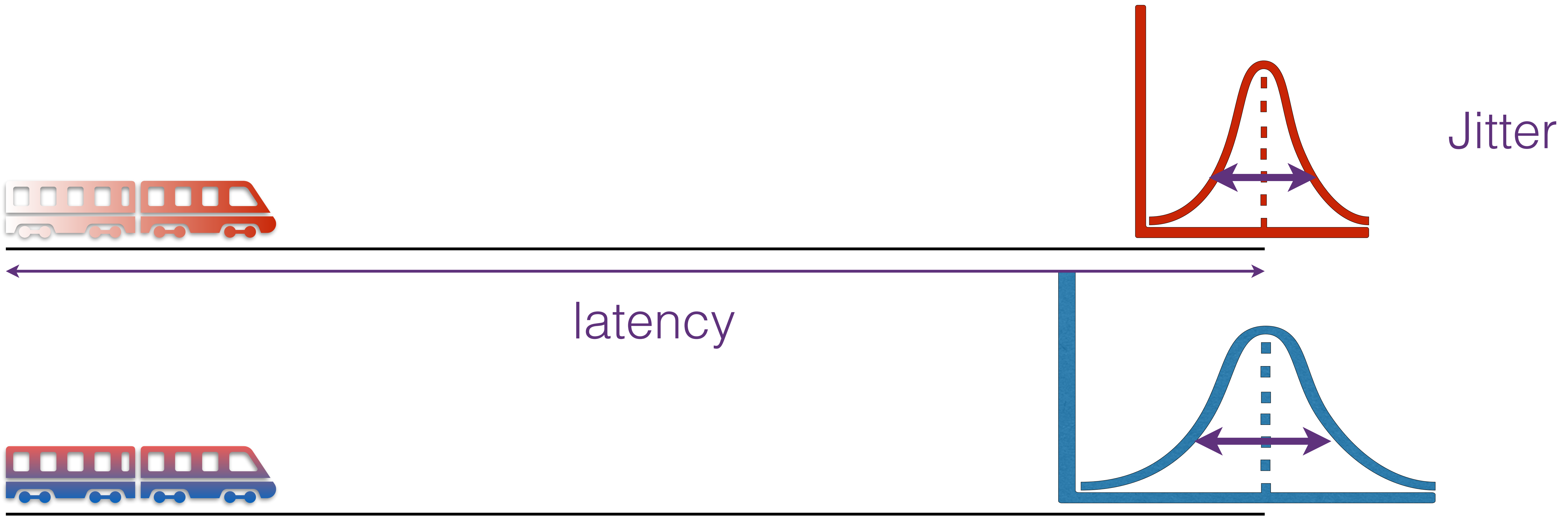
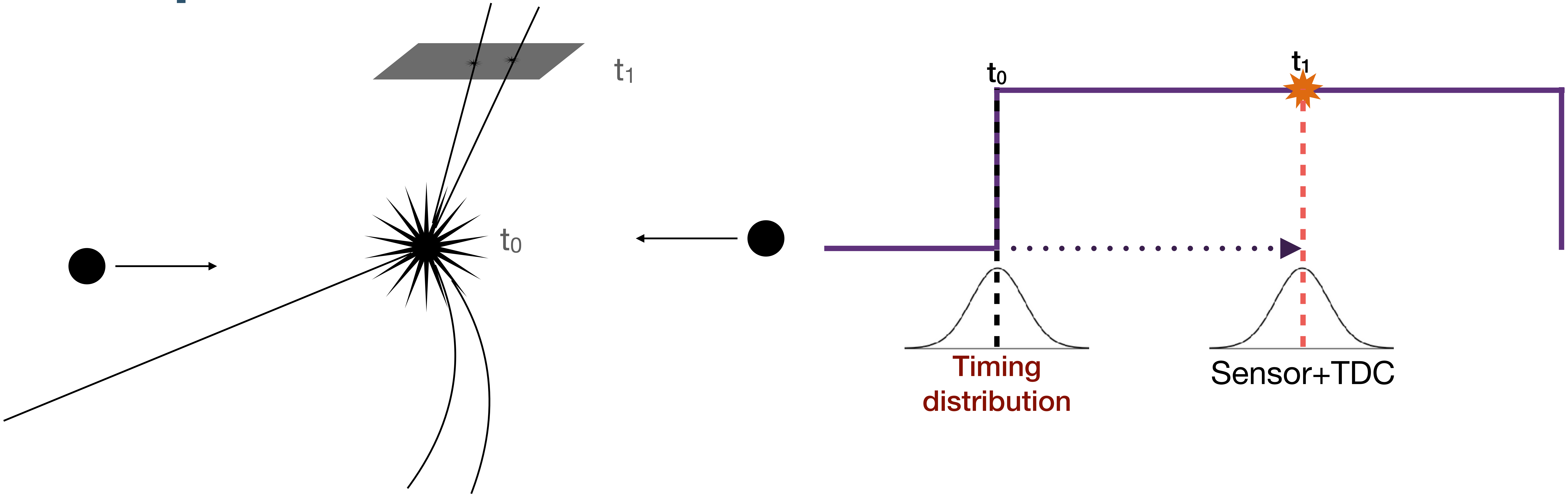
Delay, wander and jitter



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

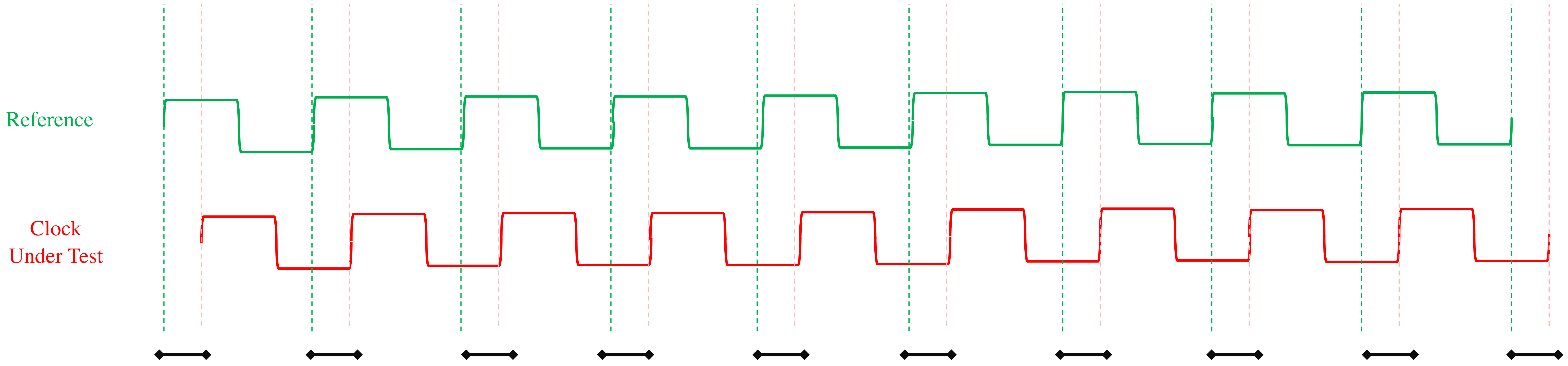
Impact on the resolution



- 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.

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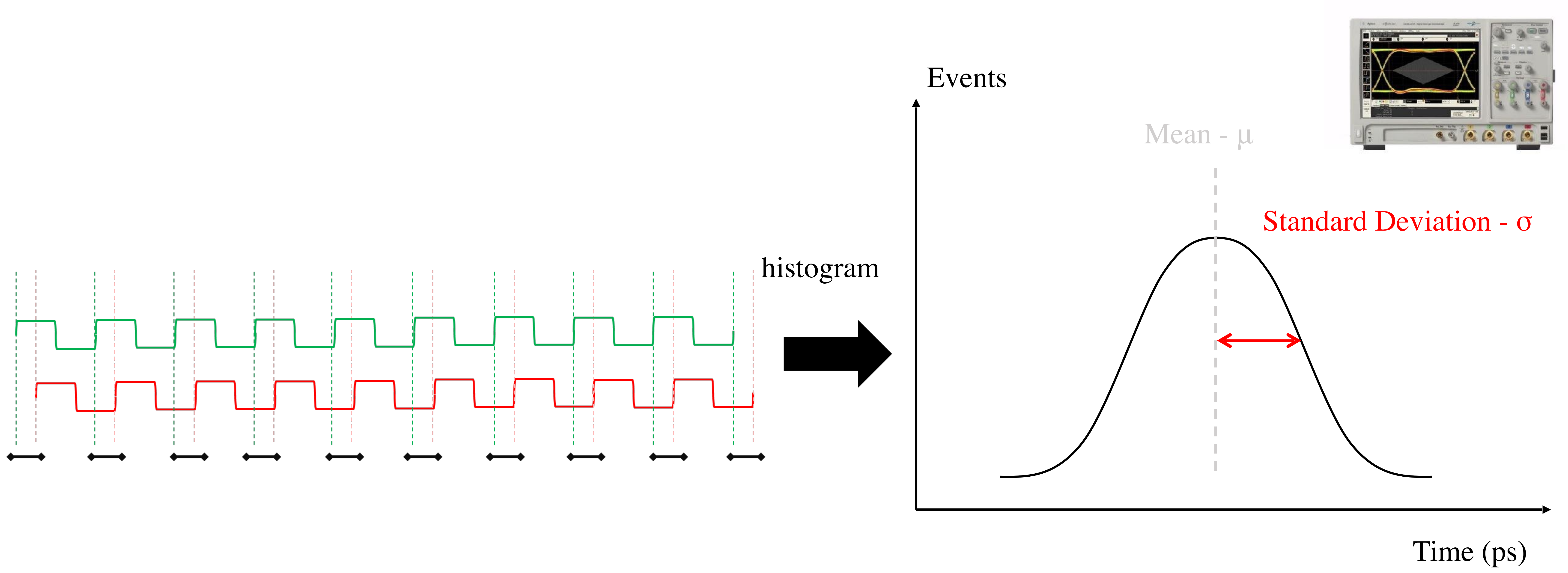
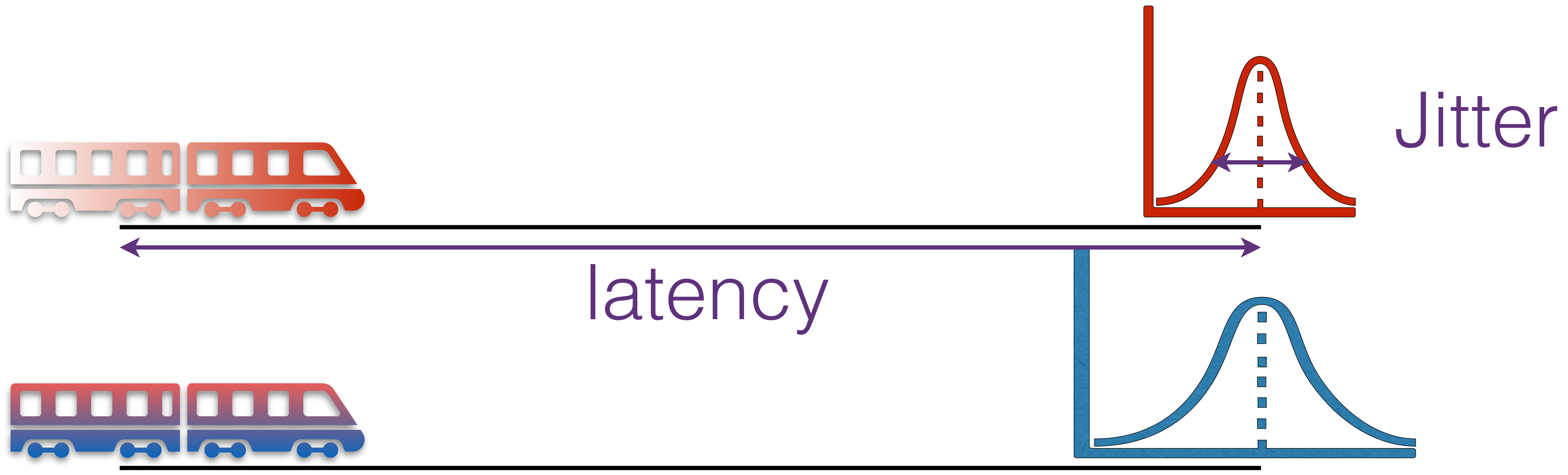
Measuring the jitter: TIE

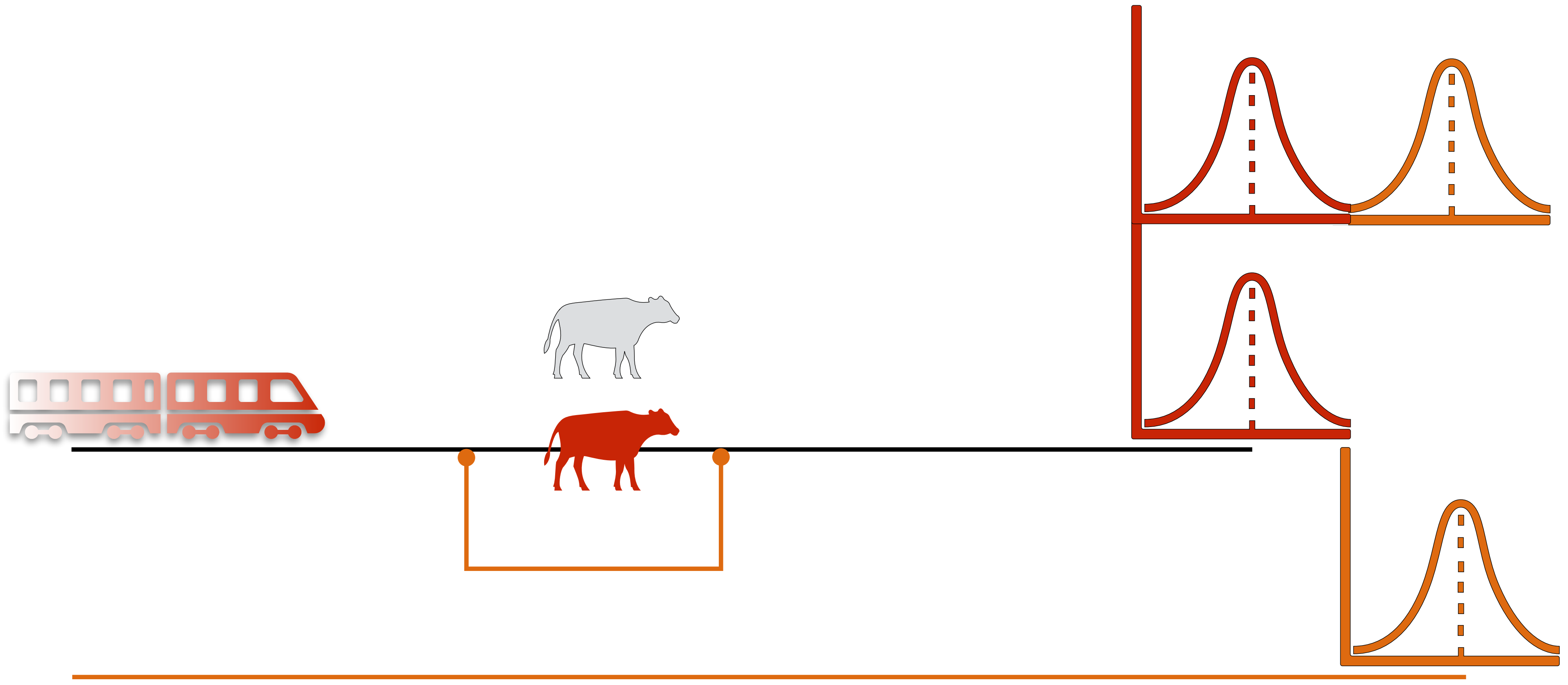
- Time interval error (TIE) is the standard measurement which can be performed using a scope.



Types of jitter



The Random Jitter with a Gaussian distribution.

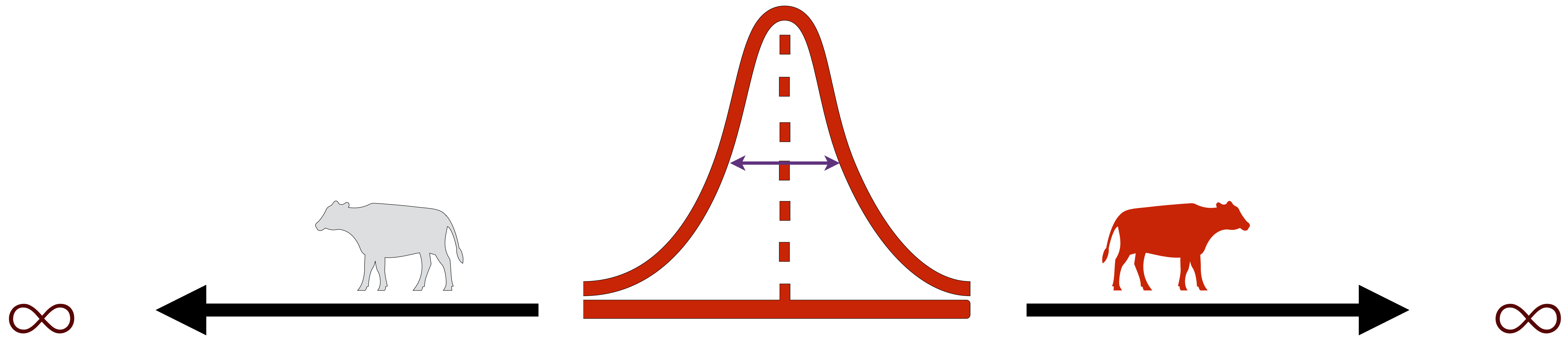


The Deterministic Jitter with a bimodal Dirac delta distribution.

- 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).

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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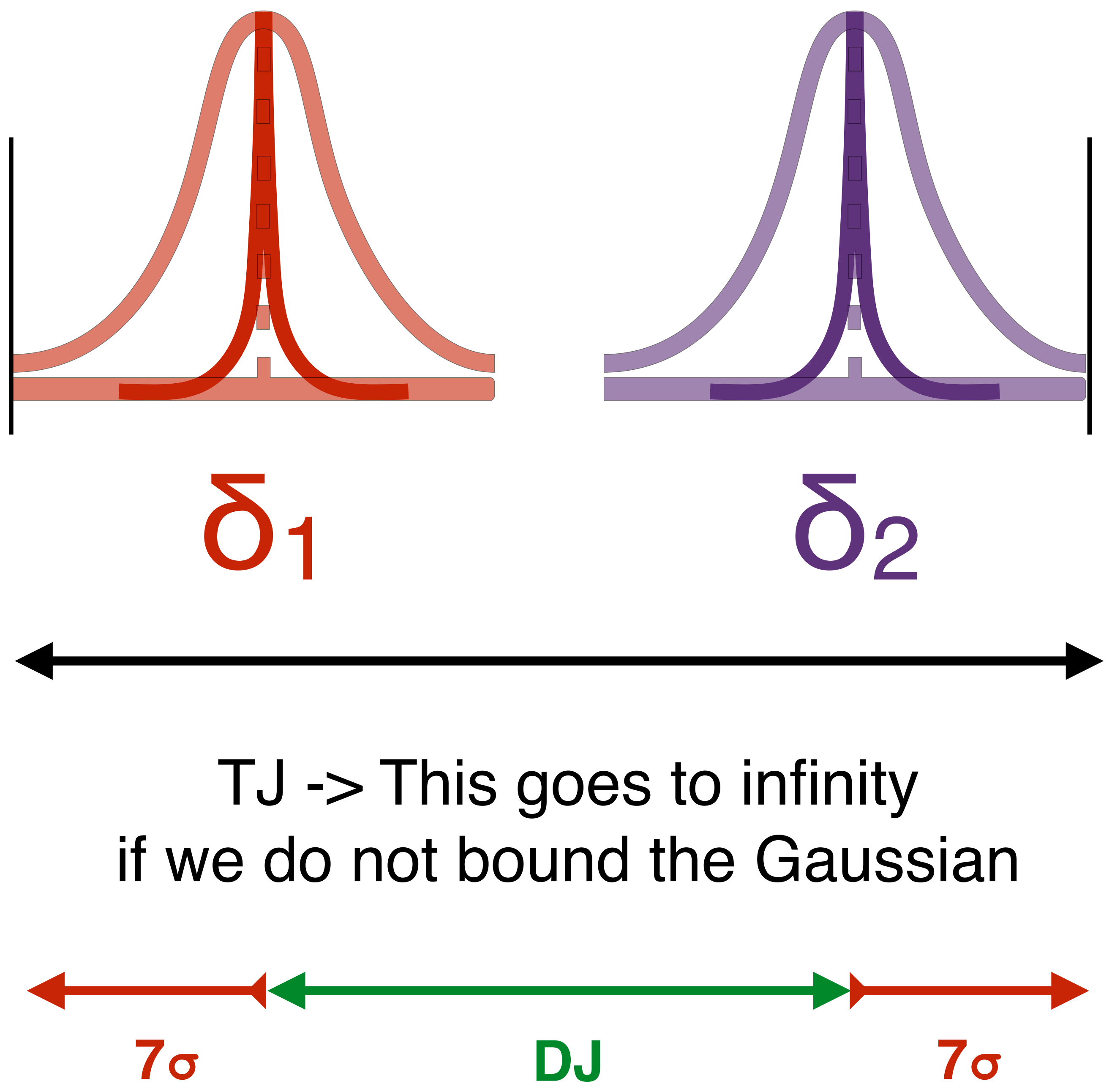
Total jitter



- 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

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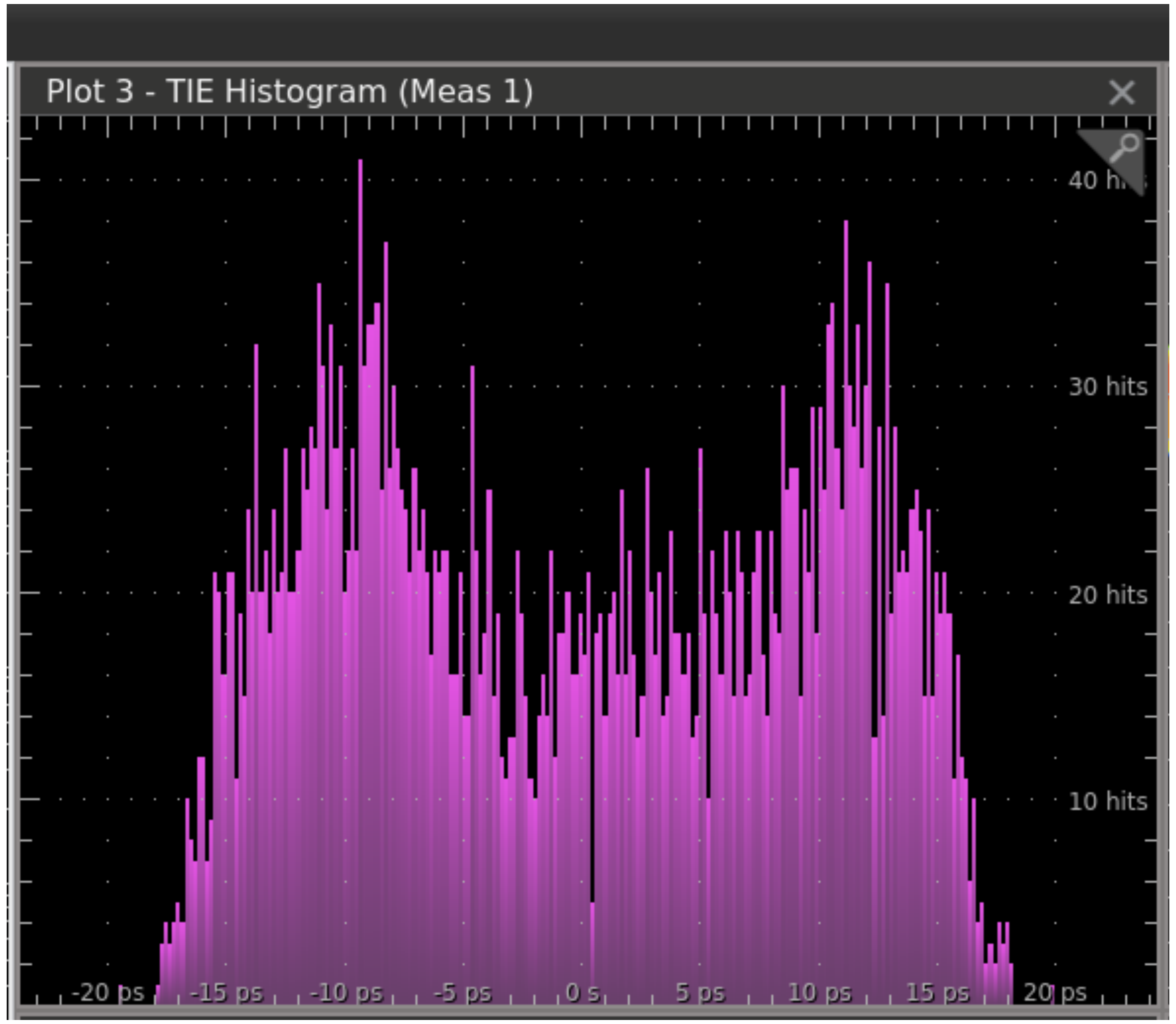
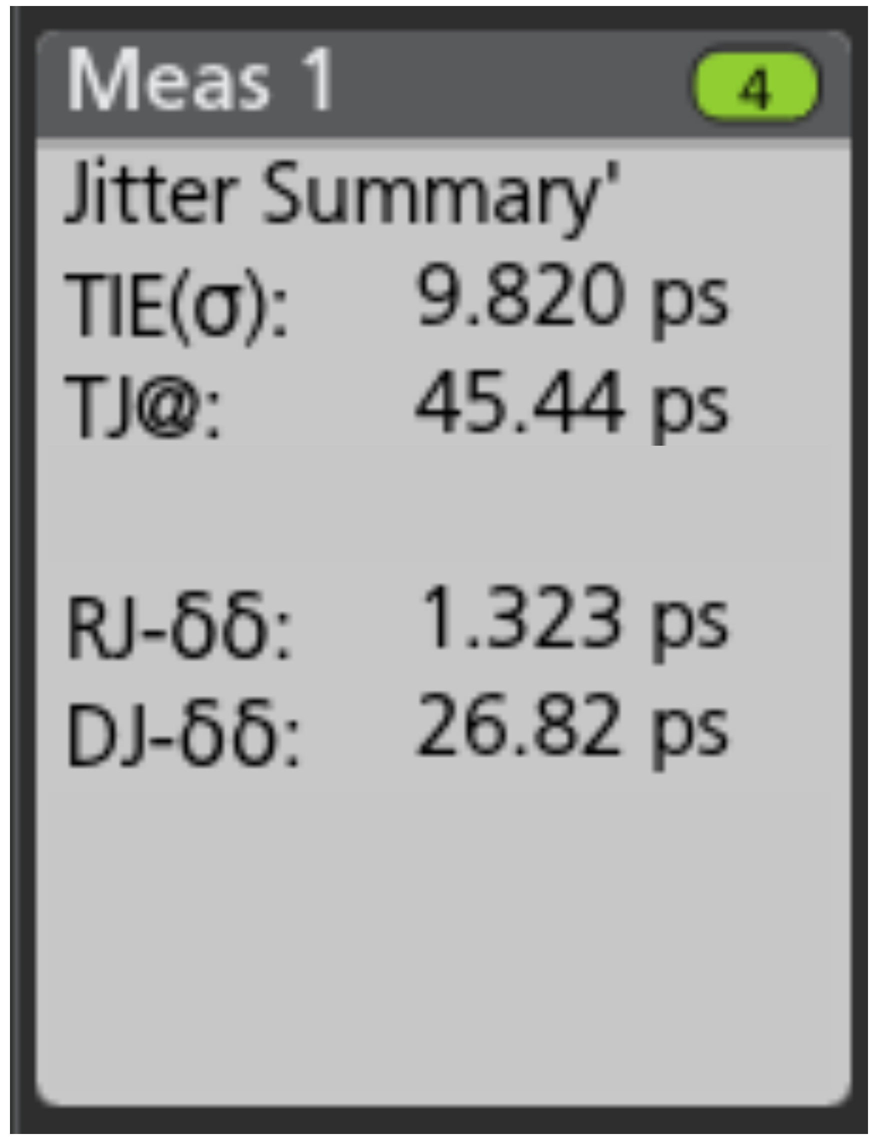
Let’s look at an oscilloscope measurement





- We clearly observe the bimodal TIE jitter distribution.
- Let’s test our understanding: 14*1.3+26.8=~45 ps TJ

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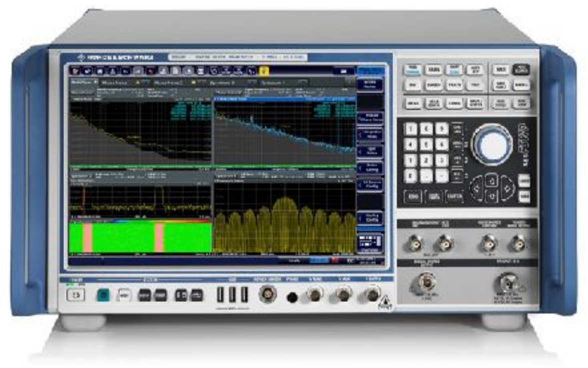
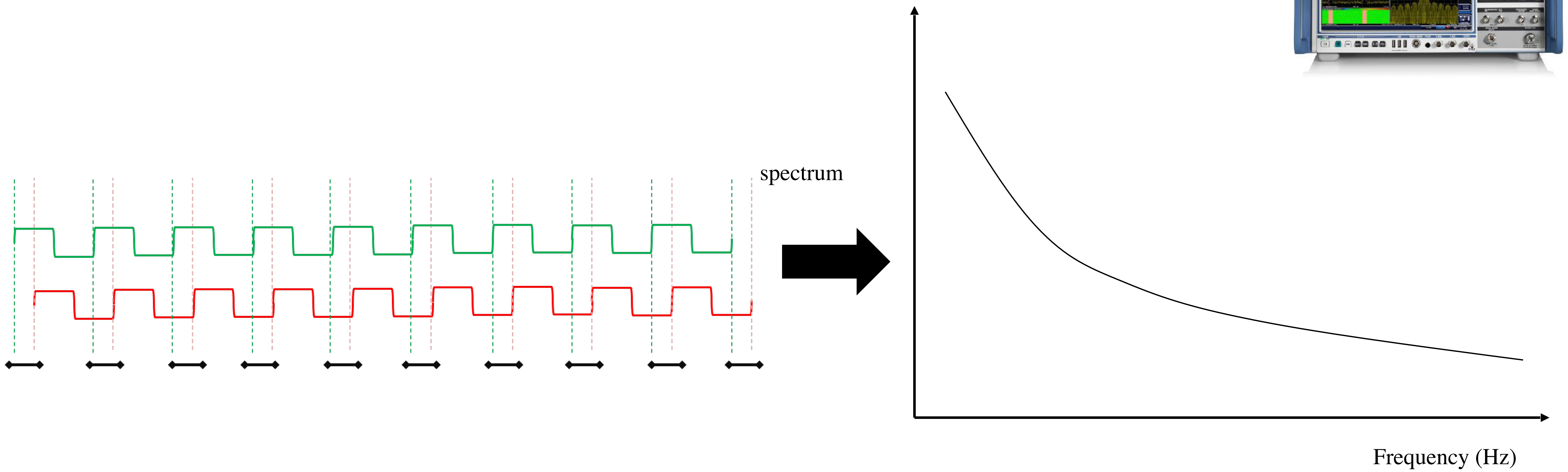
Measuring the jitter: phase noise

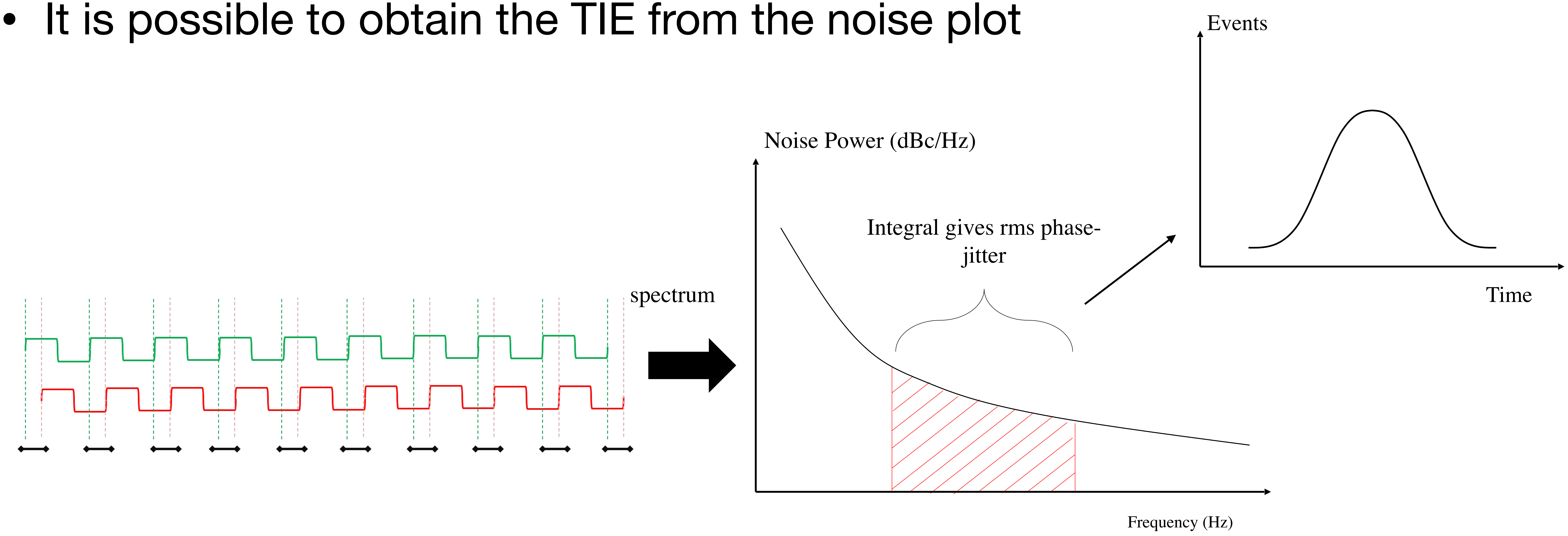
- TIE will give you the amplitude but not the frequency of the noise components.





Noise spectrum to TIE

- The profile of the spectrum gives us hints about the noise type
- It is possible to obtain the TIE from the noise plot



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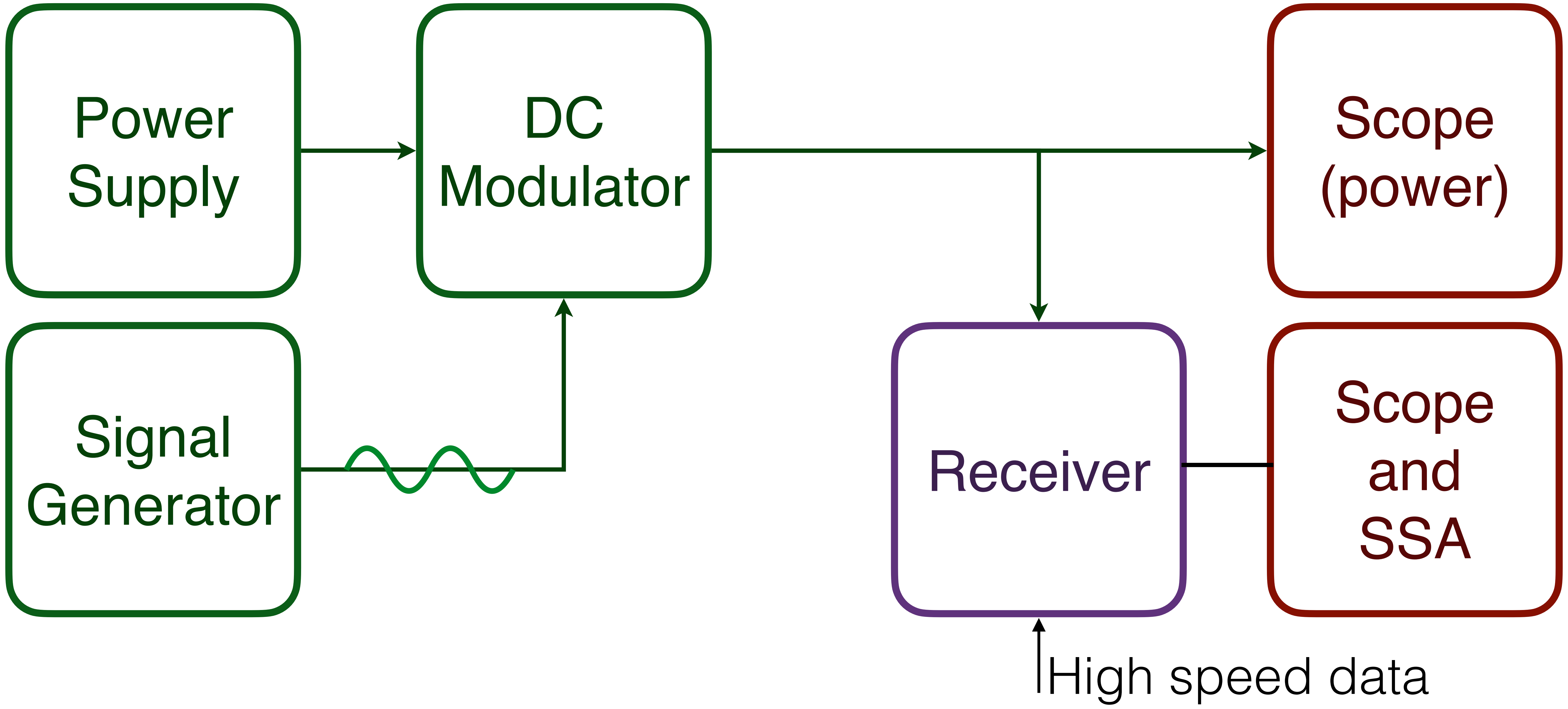
Jitter sources: an example



- **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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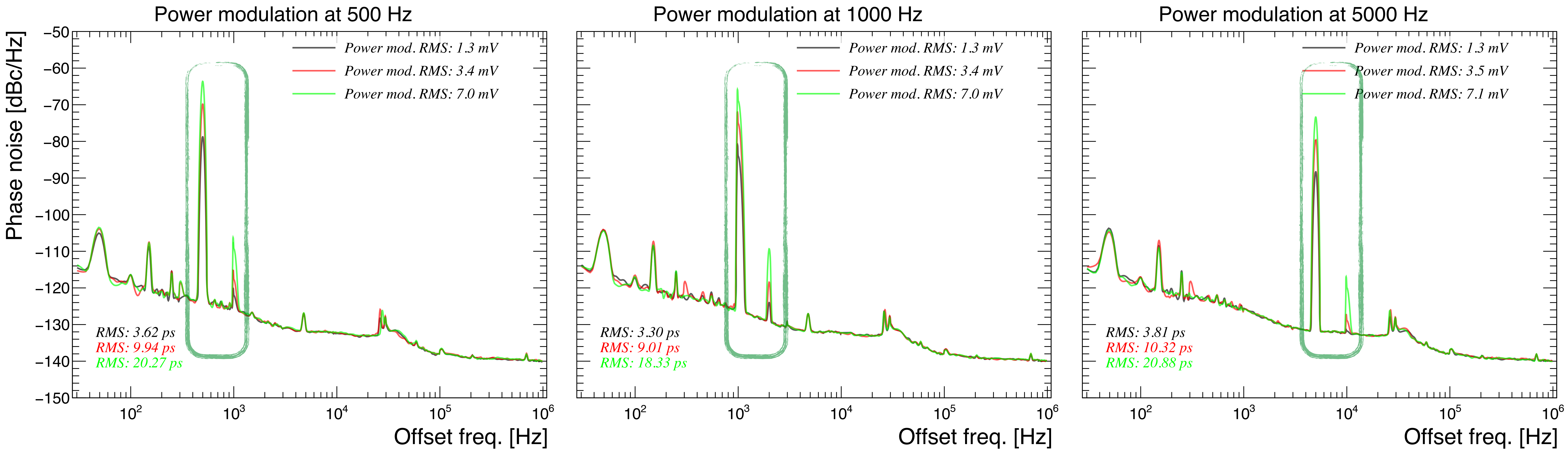
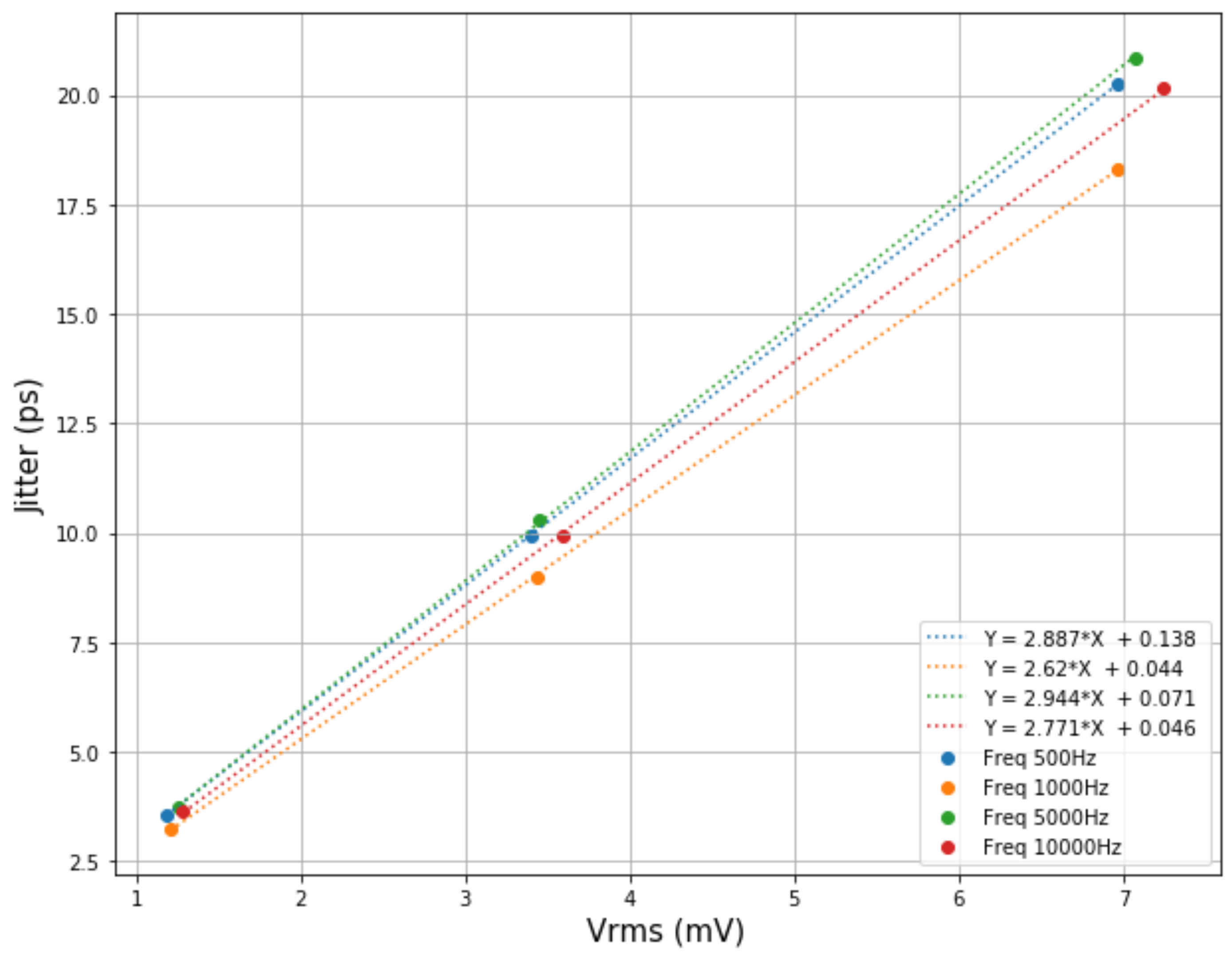
Jitter sources: an example

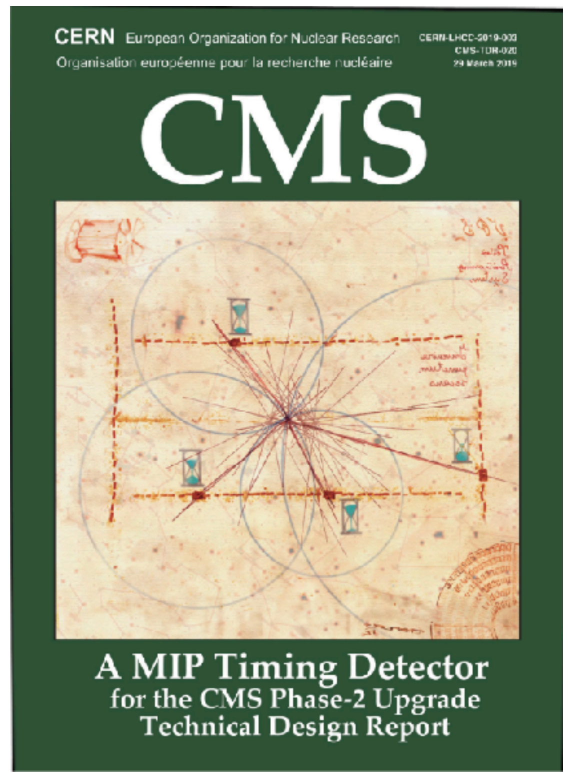




- Here the impact of power distribution fluctuations on the timing distribution jitter for an embedded clock distribution chip is quite visible.

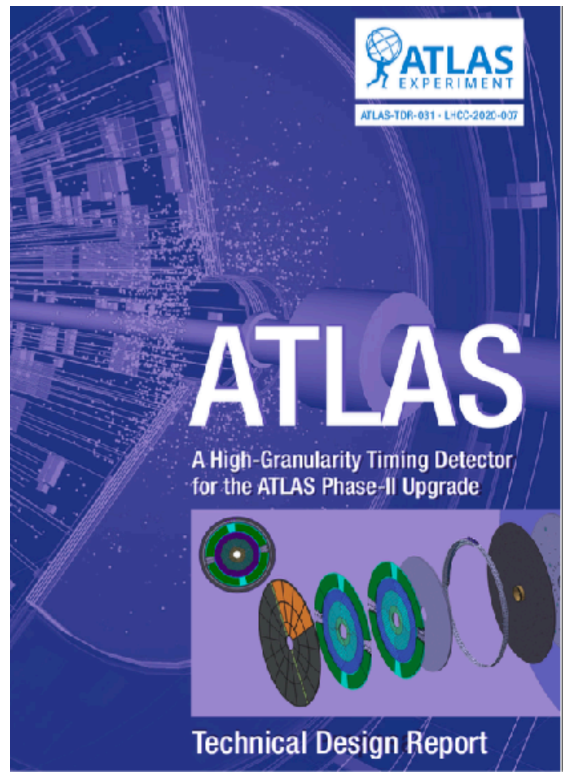
Rather than having a conclusion

- This lecture only scratched the surface of the timing concepts.
- There are various resources:



CMS MTD TDR

ATLAS HGTD TDR



- This material is adapted from large number of references:
  Mainly but not limited to E Mendes ISOTDAQ 22, C Tully CERN Academical Training 17, T Tabarelli de Fatis INFIERI 21, T Niknejad TWEPP 19, A Rivetti TWEPP 15…