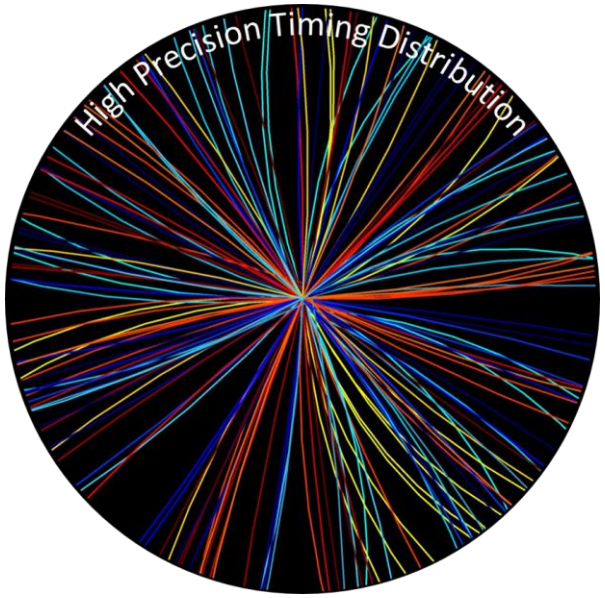
# High-Precision Timing Distribution Systems for LHC experiments



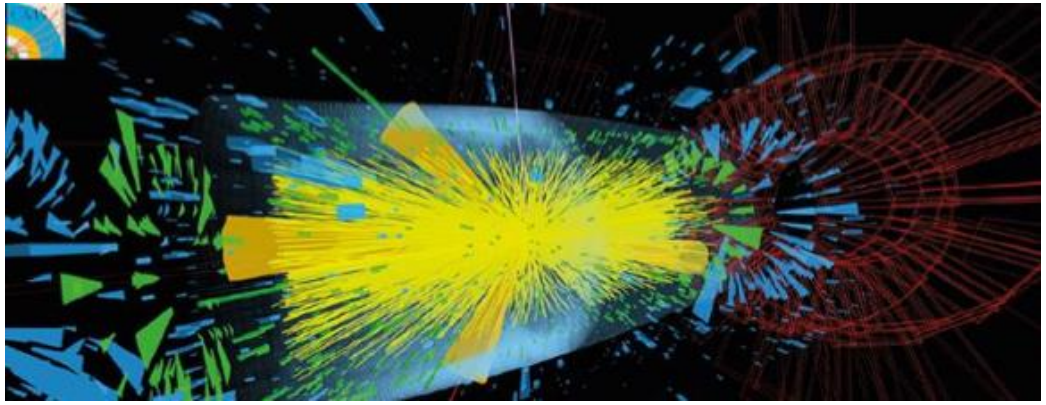

Eduardo Mendes

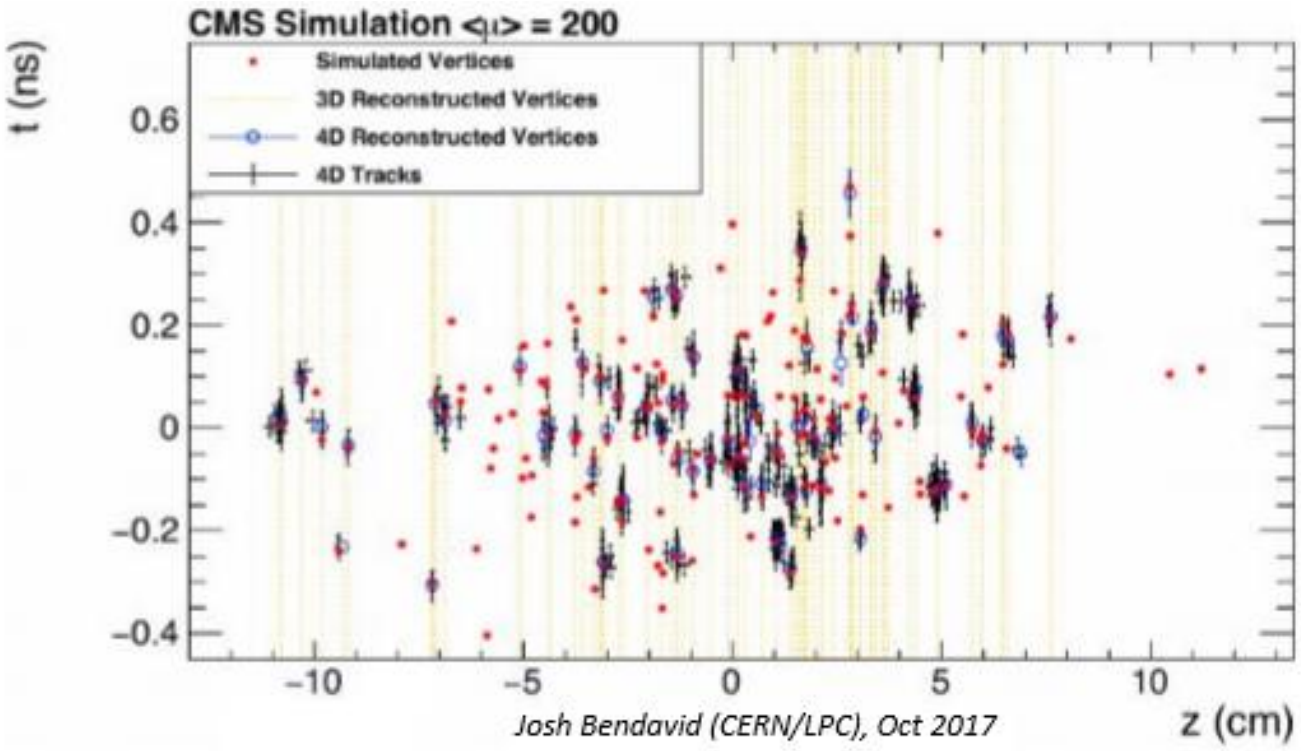
CERN EP-ESE

- Thanks to the many colleagues who contributed directly or indirectly to this talk

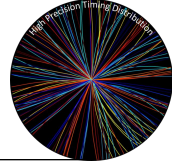
# New playing rules of the HL-LHC

- High Pile-up expected for HL-LHC
  - From 20 (LHC nominal) to ~200 (HL-LHC)
- Adding a timing-layer to the event reconstruction can reduce the effective pile-up
- CMS and ATLAS experiments will adopt such strategy





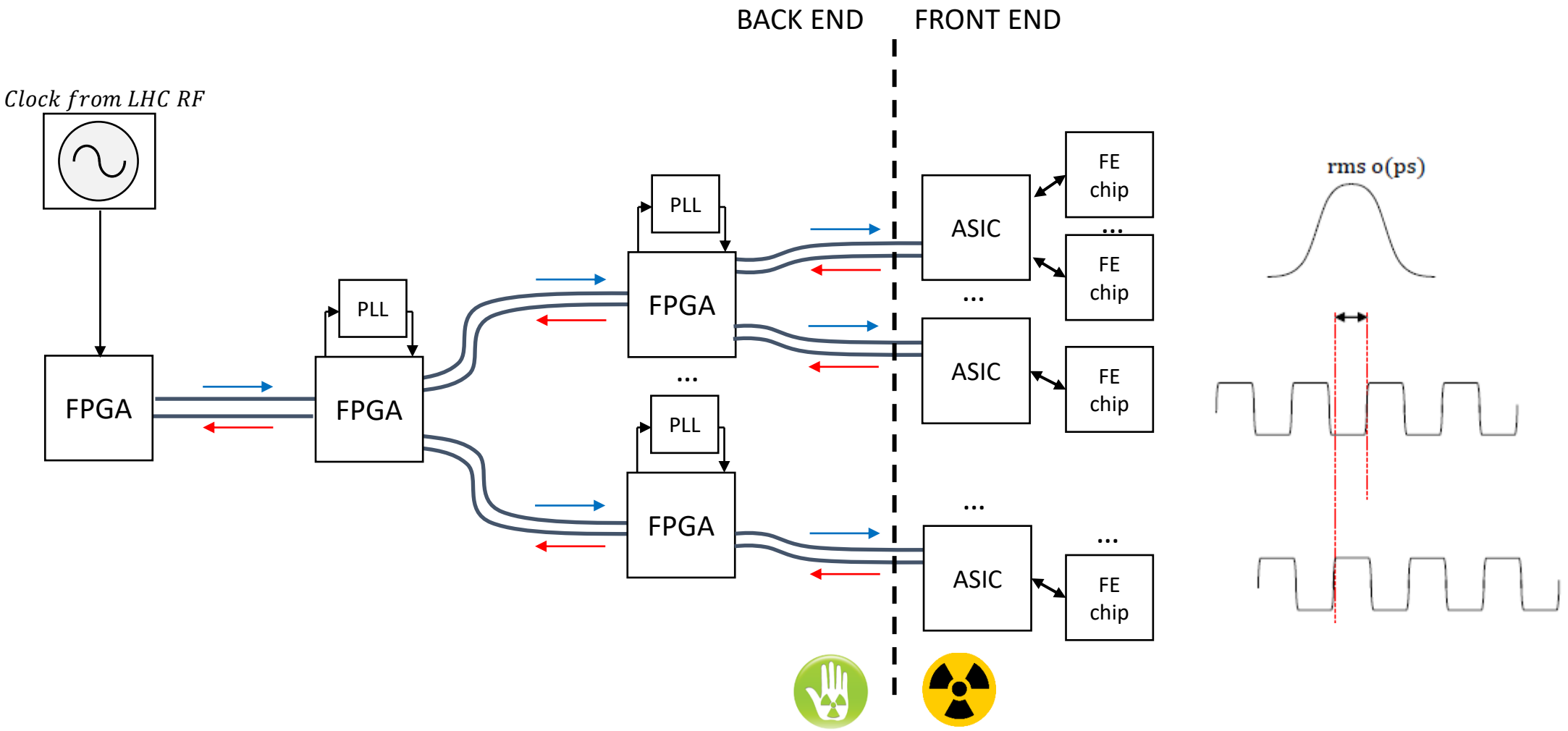
# Agenda




- **Introduction**
- Timing distribution systems
  - Front-end
  - Back-end
- Conclusions

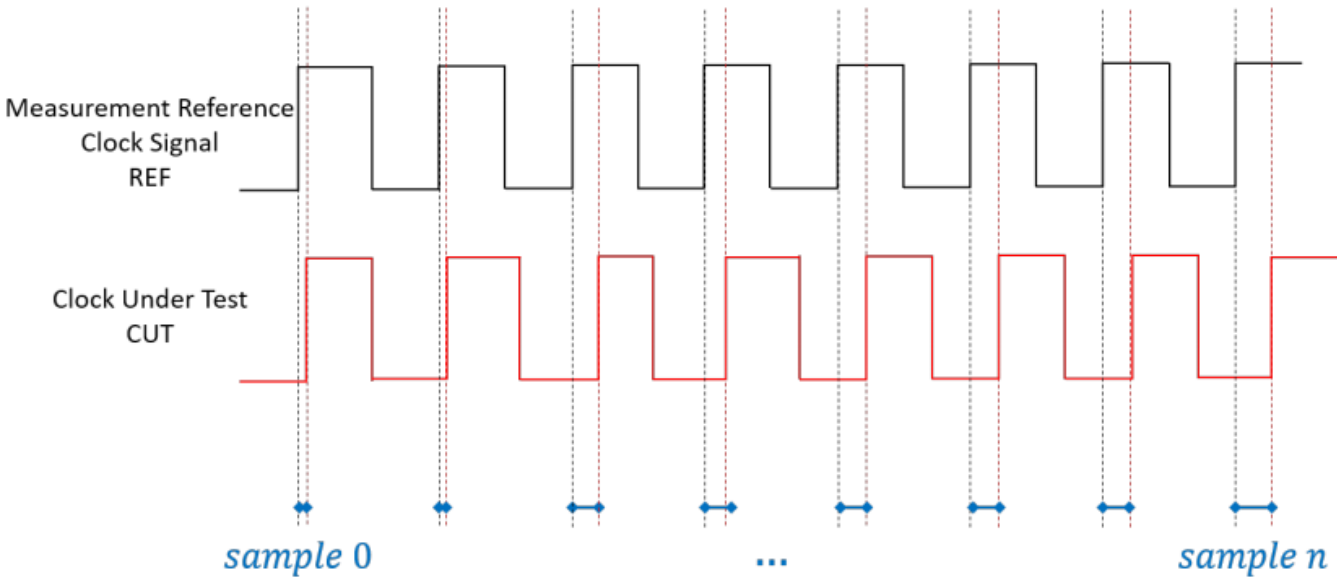
# Timing distribution for LHC experiments

- Baseline **Timing**, trigger and control system based on high-speed optical links

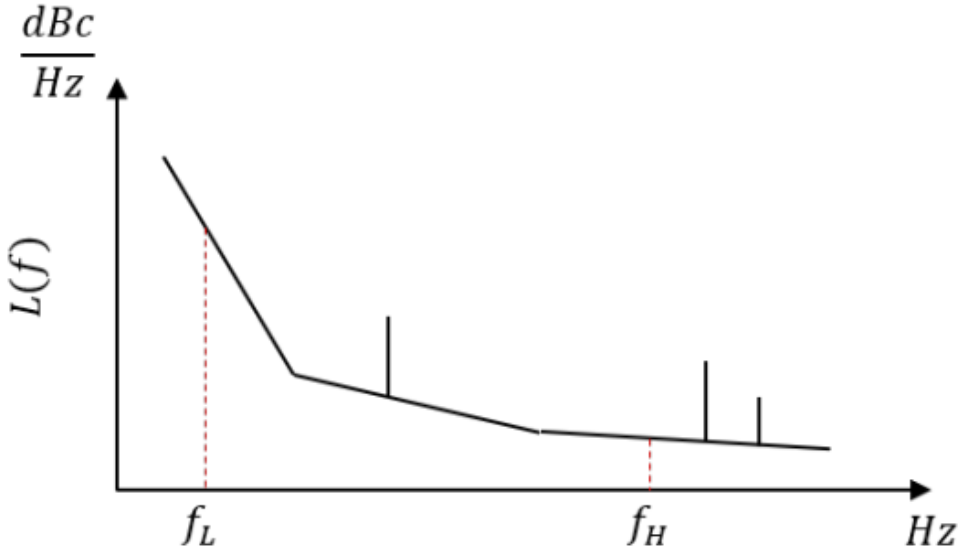


# Measuring clock stability

- Jitter - fast phase variations




Time Interval Error

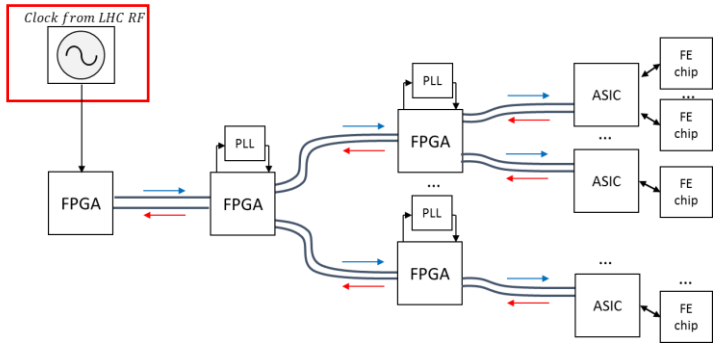


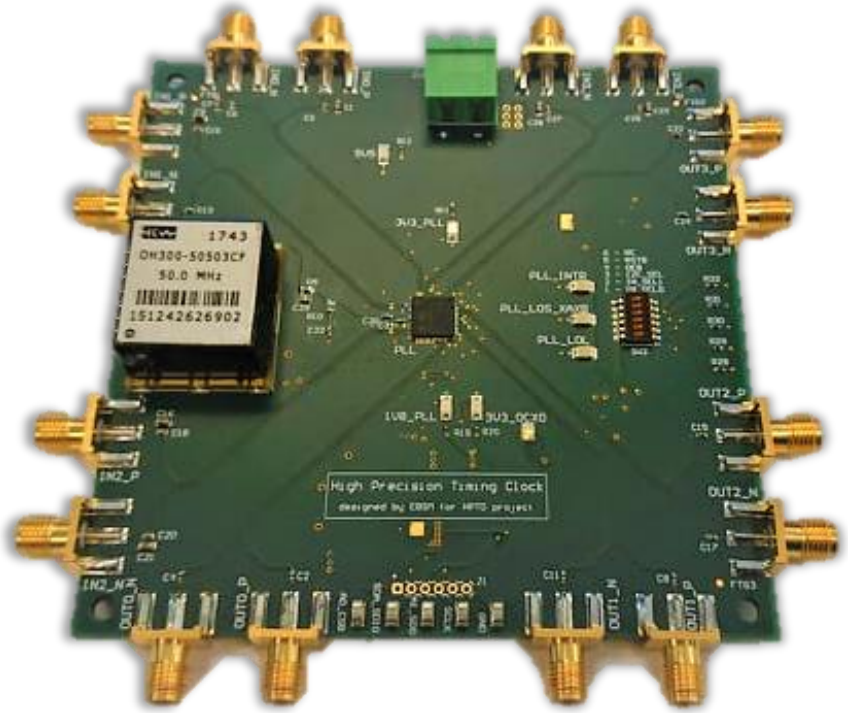

Phase-noise

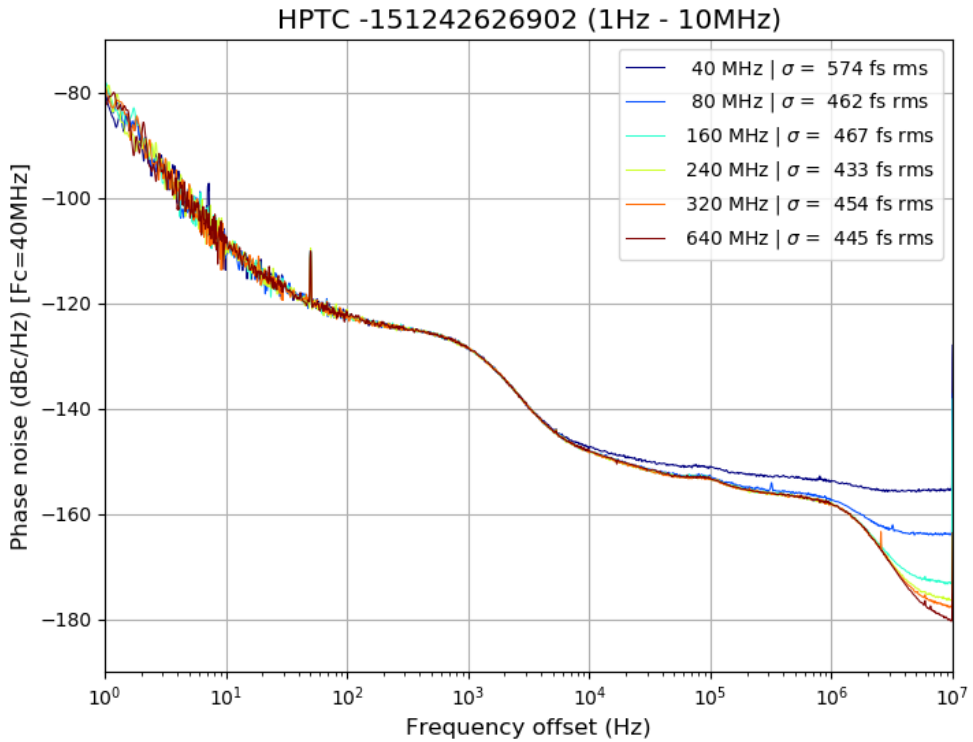
- Wander – slow phase variations
  - Heavily depends on environmental conditions (temperature, power supply stability, …)
  - Typically measured in time-domain
- Phase-determinism with resets

# Clock source: emulating LHC RF

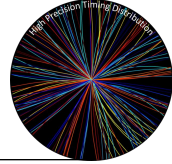
- High-Precision Timing Clock
  - Low-cost high-quality generator designed at CERN
  - Based on a commercial PLL and OCXO
  - Used by several members of the CERN High Precision timing community - comparable reference for timing measurements



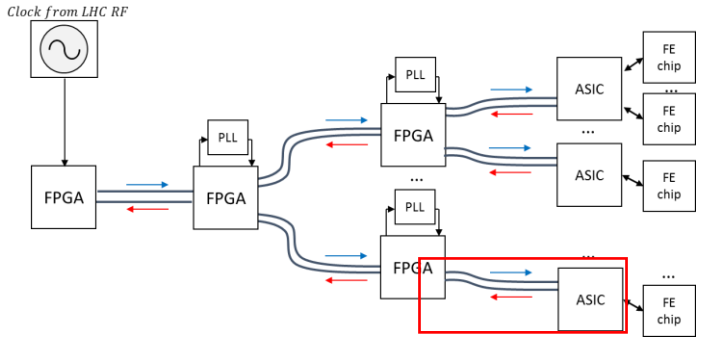
# Agenda

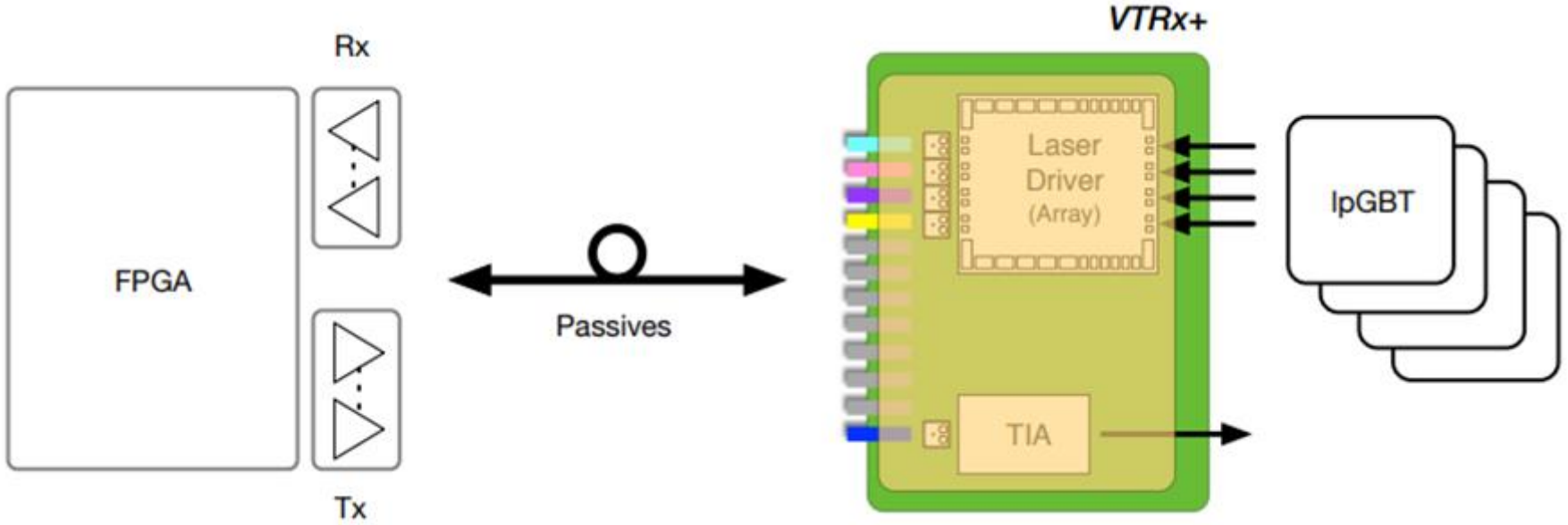



- Introduction
- **Timing distribution systems**
  - Front-end
  - Back-end
- Conclusions

# Front-end: Versatile Link Plus and lpGBT

- Radiation Hard Optical Link and SerDes
- Fixed-latency and low-jitter (<5ps)
- Common project developped by CERN and partner institutes

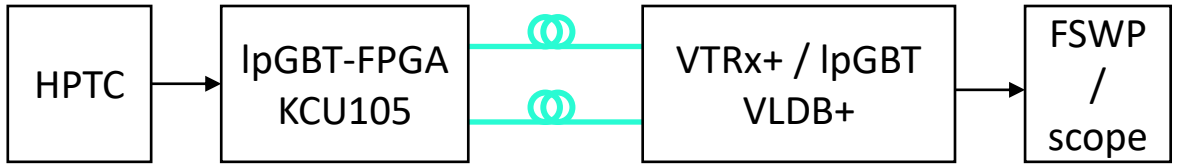


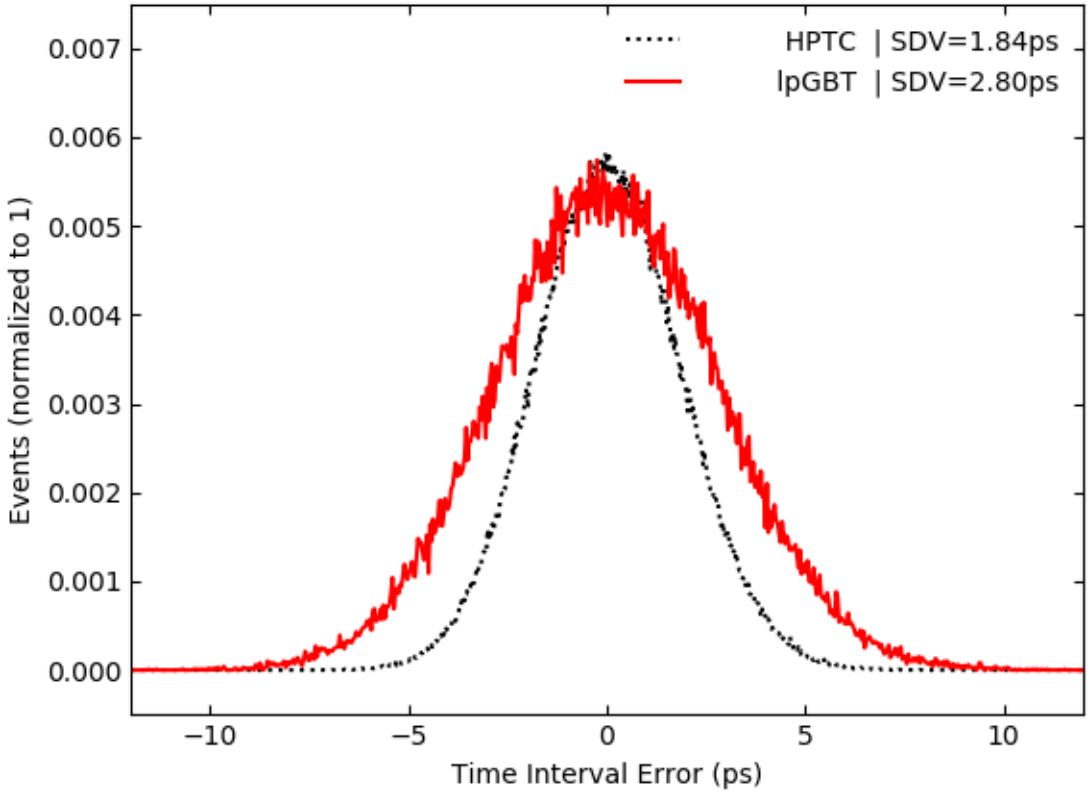



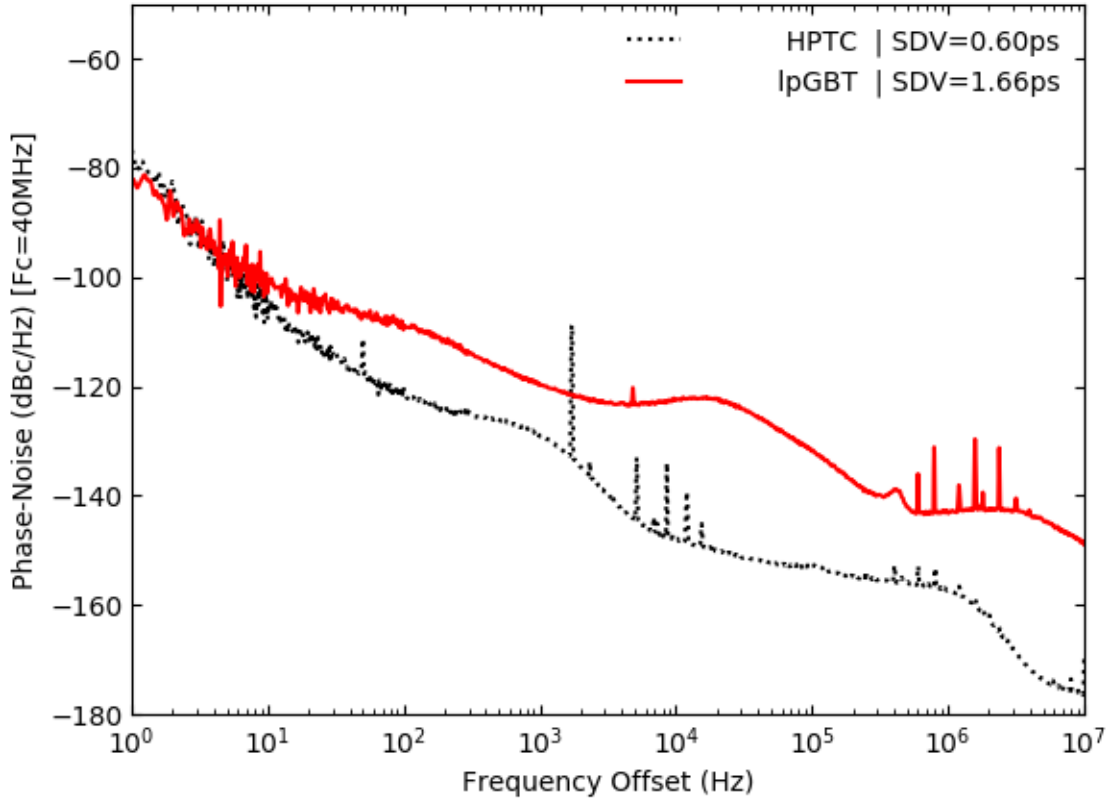

- For more information: https://pos.sissa.it/313/048/pdf

# Front-end: Versatile Link Plus and lpGBT

- Link timing performance
  - TIE and phase-noise



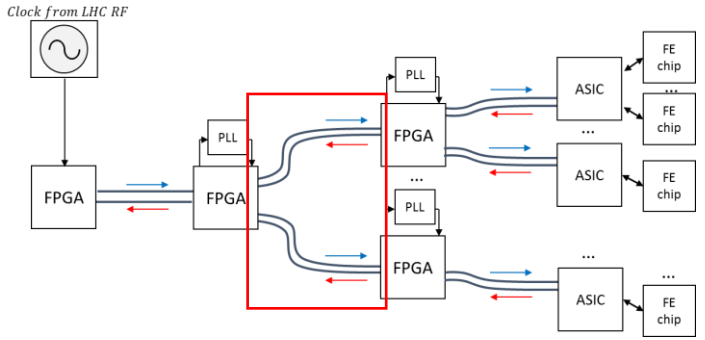



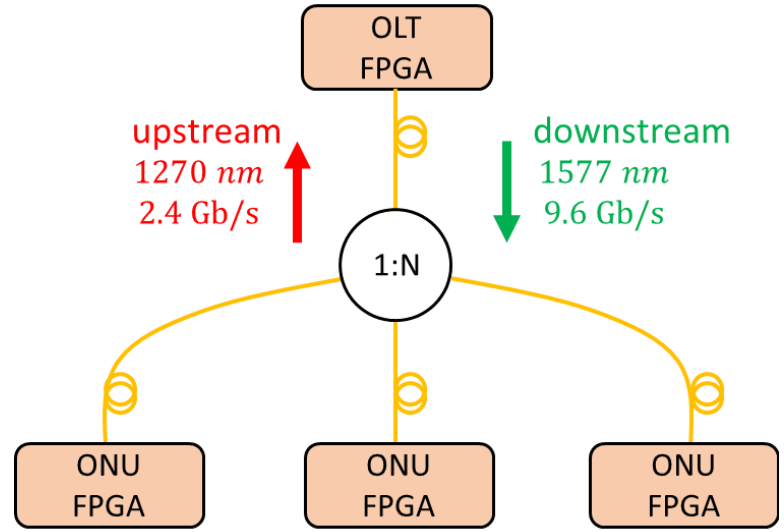

- Excellent performance achieved within the specifications of the LHC experiments

# Back-end: TTC-PON

- Back-end timing distribution system adopted by ALICE and LHCb experiments




- Point-to-multipoint optical network inspired on current TTC
  - Based on Passive Optical Networks
  - Single-fiber using WDM and TDM
  - Low-cost for a high split-ratio (1:64)

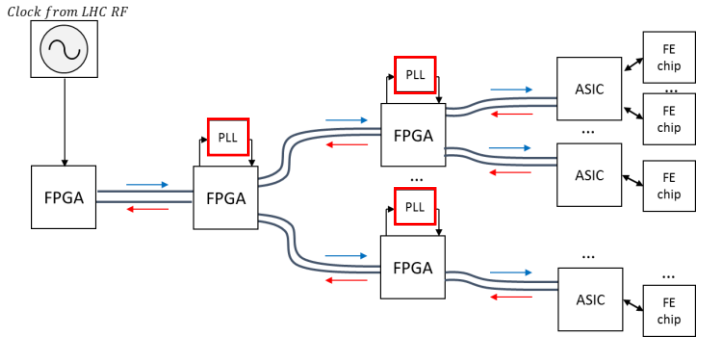



- Phase-monitoring based on system bidirectionality

- Can achieve TIE jitter < 5ps with a careful system design
  - More details in [NSS 2020]

# Back-end: COTS

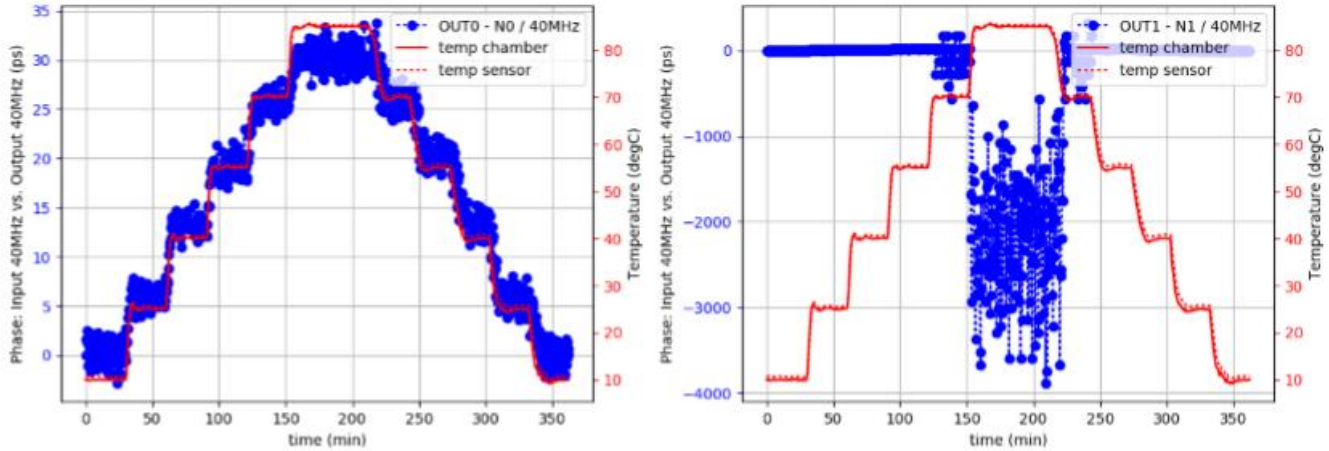
- Heavily based on commercial components and custom links
- CERN started a R&D program to study the timing performance of the different components in a timing distribution system (FPGA, PLLs, LDO, …)
  - Steered by the LHC experiments designers




Technical evaluation

Phase determinism (between reconfiguration cycles) over temperature of Silicon Labs PLLs (Si5344, Si5345, Si5395, Si5391)

Abstract



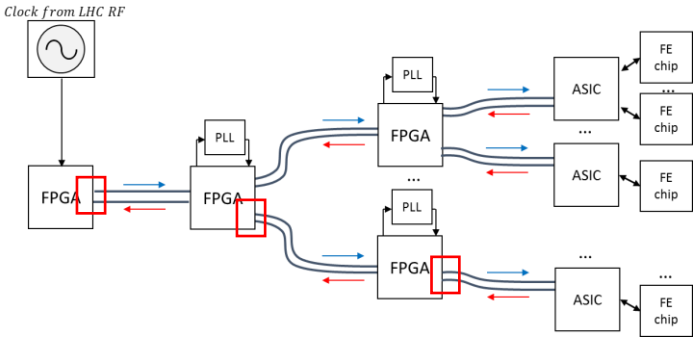

(a) N0 / OUT 40MHz (b) N1 / OUT 40MHz

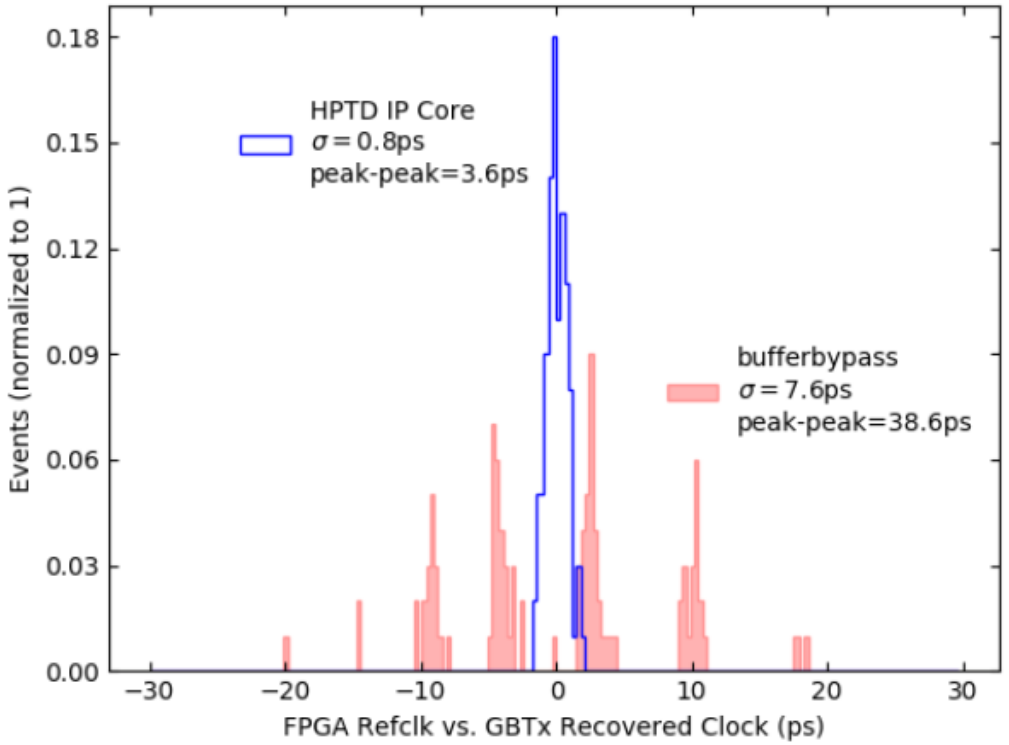
Example: recommendation on how to use Si5344 PLL to avoid phase-jumps

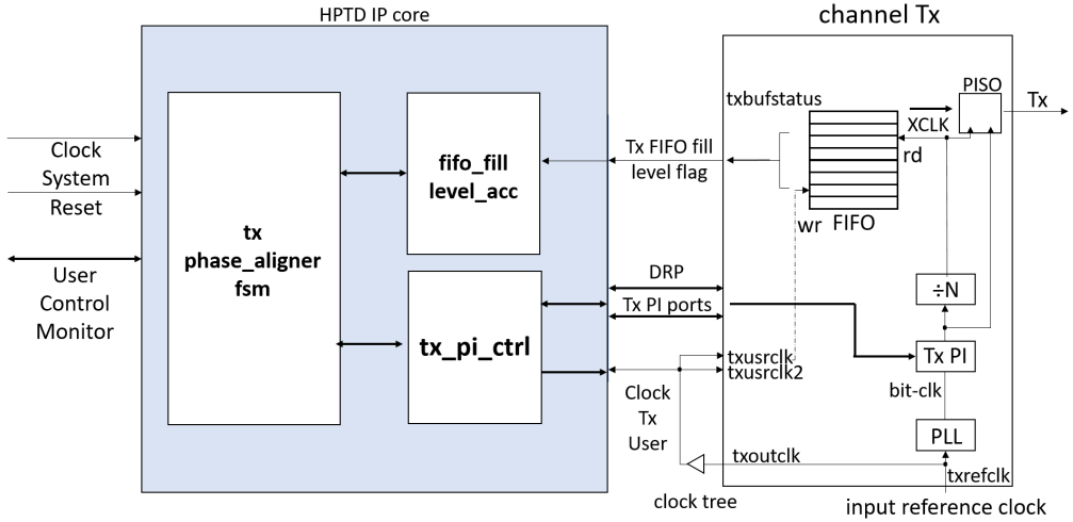
- Some results can be found here

# Back-end: HPTD IP

- Higher Phase-determinism for Ultrascale transmitters
- Results presented in IEEE TNS

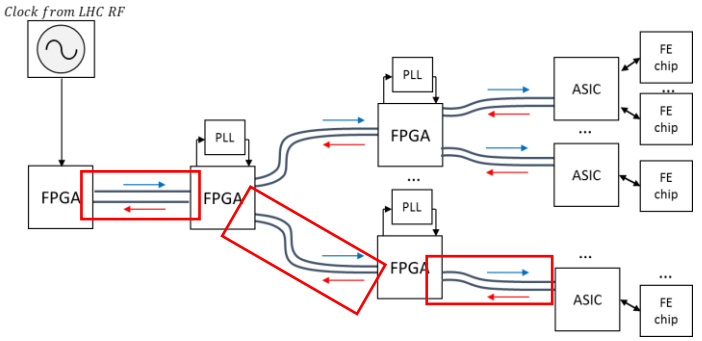


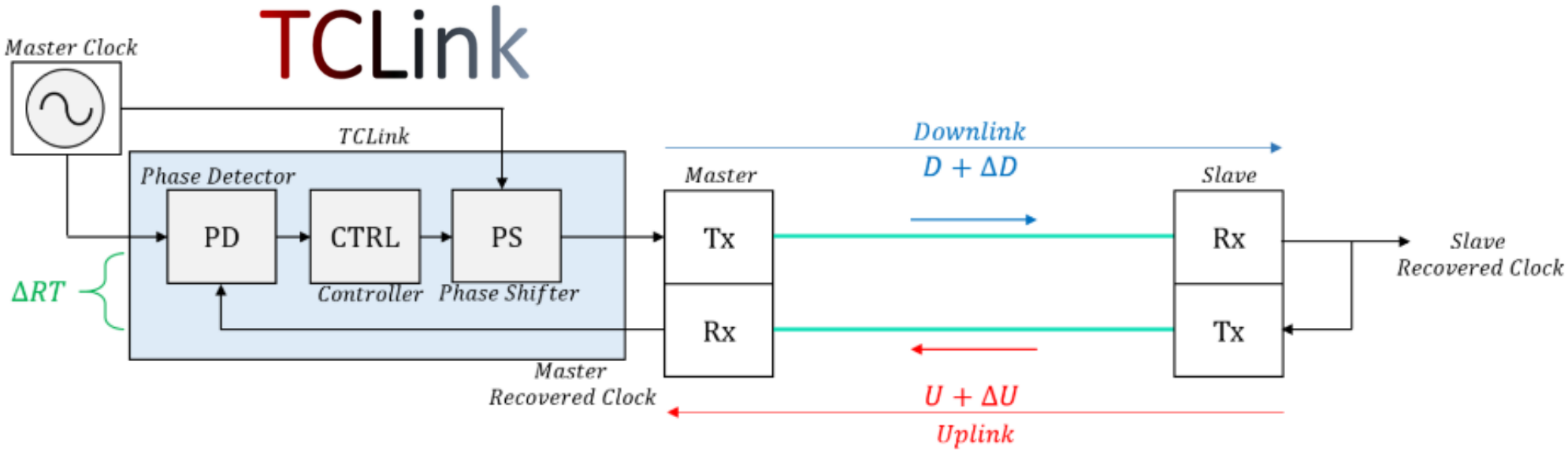



# Back-end: Timing Compensated link (TCLink)

- CERN developped an FPGA-IP to implement timing monitoring and compensation in FPGA-based links
  - Protocol-agnostic
  - Presented in TWEPP-19

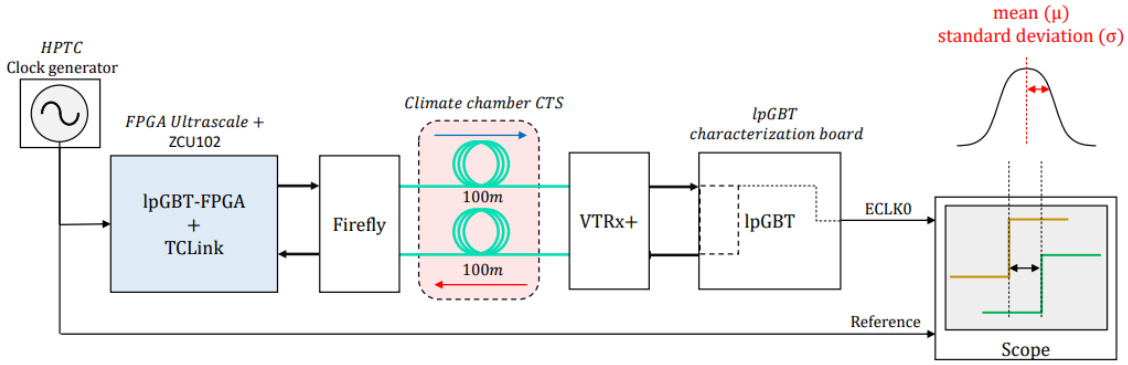


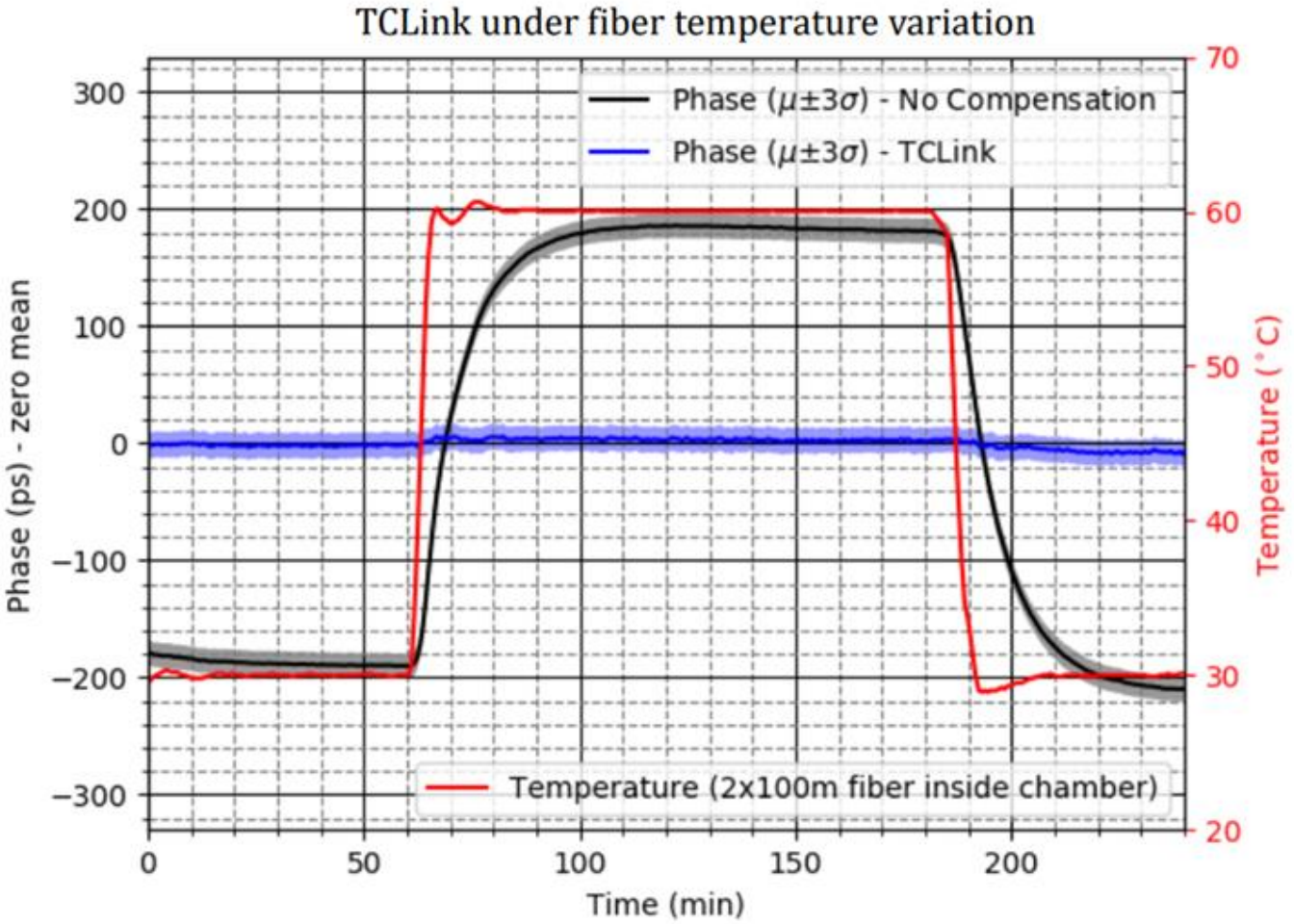




- Unique feature: fully integrated (no need of external components)

# Back-end: Timing Compensated link (TCLink)

- Tracks and correct slow-phase variations with sub-ps resolution

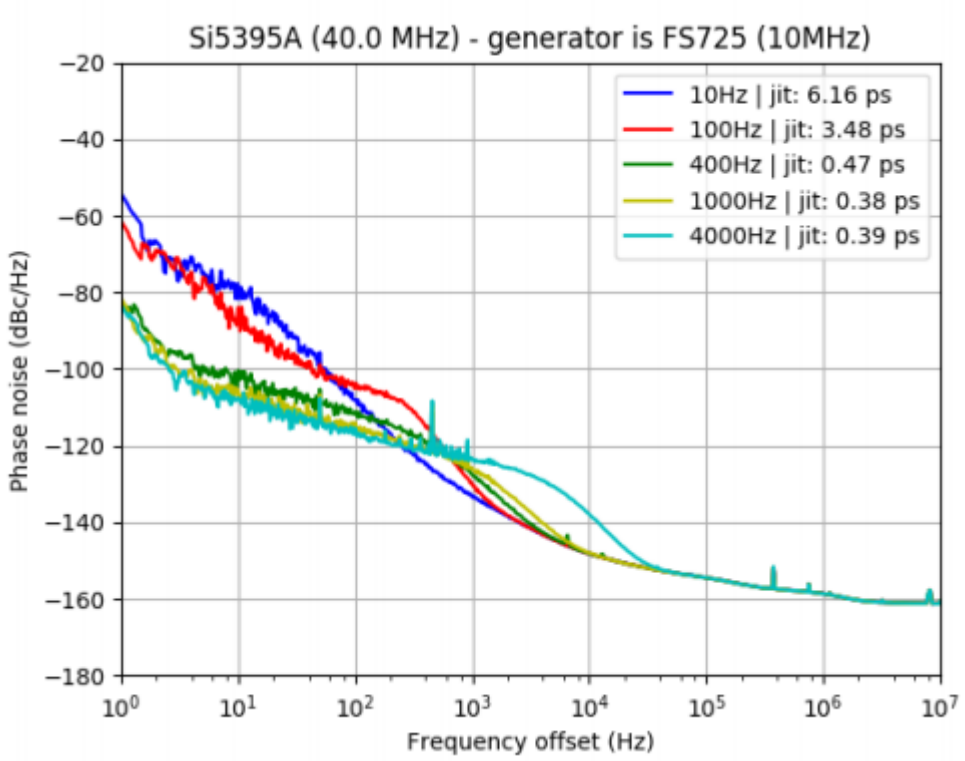


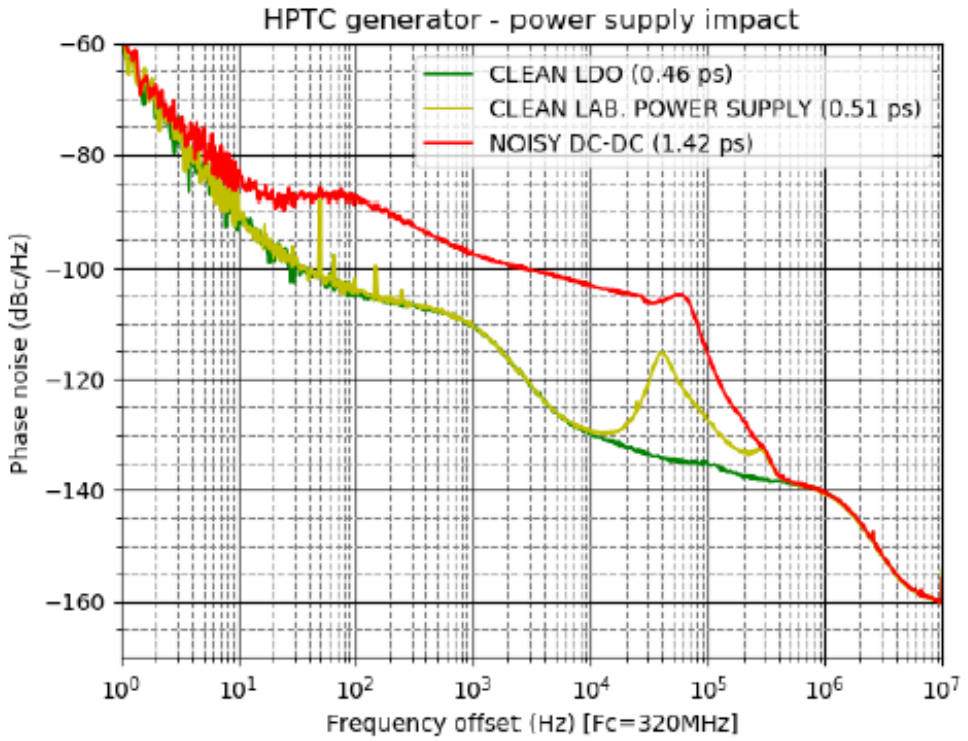




- Adopted by CMS designers

# Timing distribution

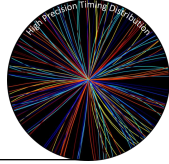
- It is possible to achieve a high timing performance with our current systems but…




… any design mistake can greatly jeopardize the performance of a timing distribution network

# Conclusions



- To achieve the high-performance required for HL-LHC…
  - CERN and external institutes are undergoing an extensive R&D program on the different components of a timing distribution system
  - Some weak-points were identified and solutions proposed

- Early system prototypes helped in gaining confidence that such a system can meet the specifications
  - See this talk of Jeroen Hegeman from CMS-DTH

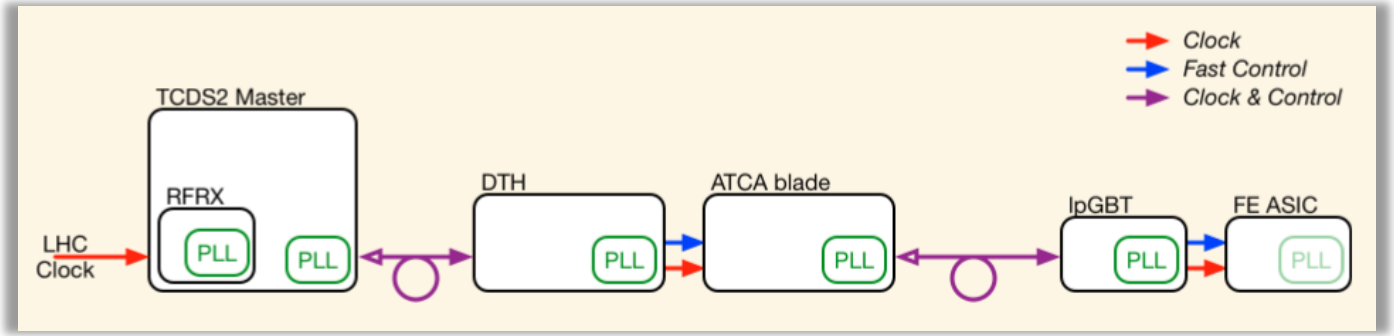
- It is possible to achieve a high timing performance for our needs with our current systems but a **careful system design** has to be carried out

THANK YOU

# BACK-UP

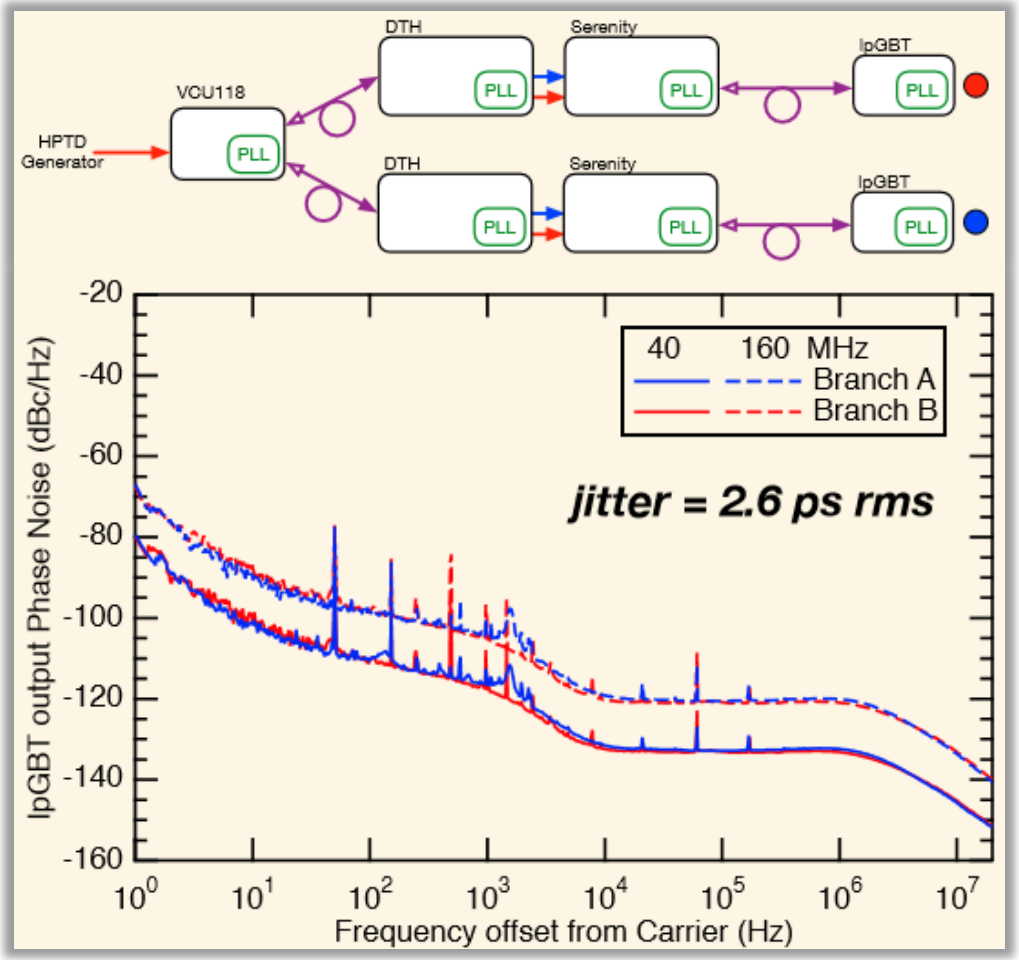
# CMS DTH

- Baseline system distributes clock and fast control



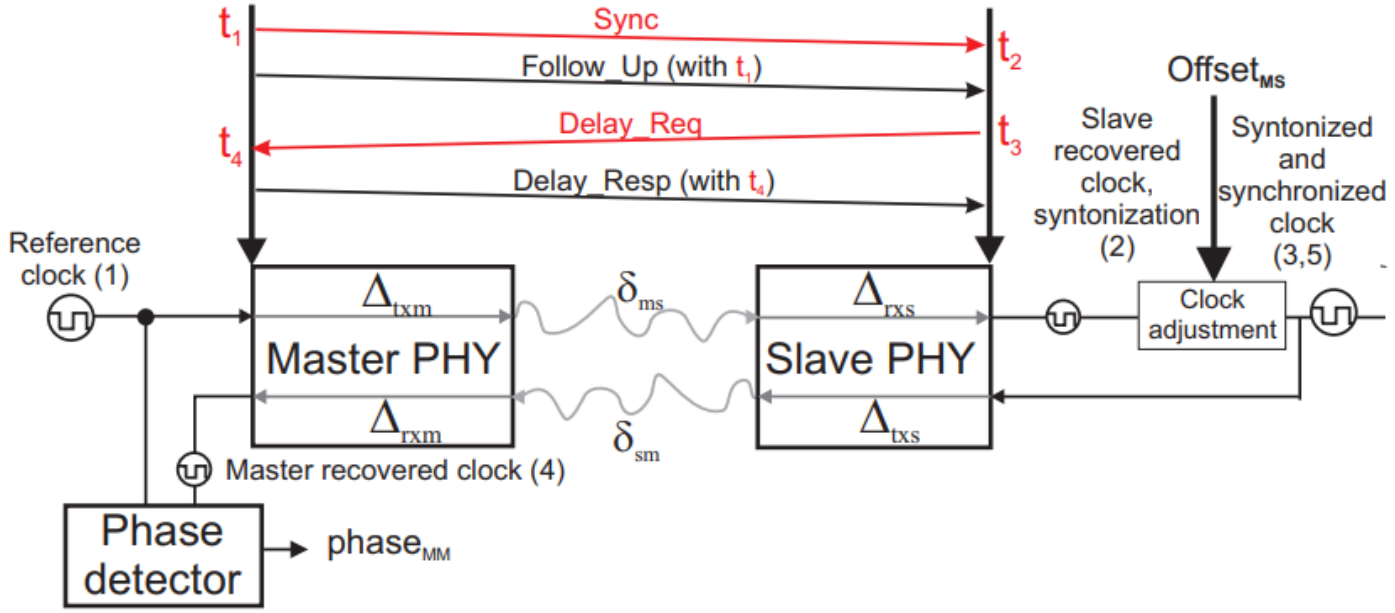

- Excellent performance achieved in the first full-chain prototype

- For more information see this talk from Jeroen



# White-Rabbit

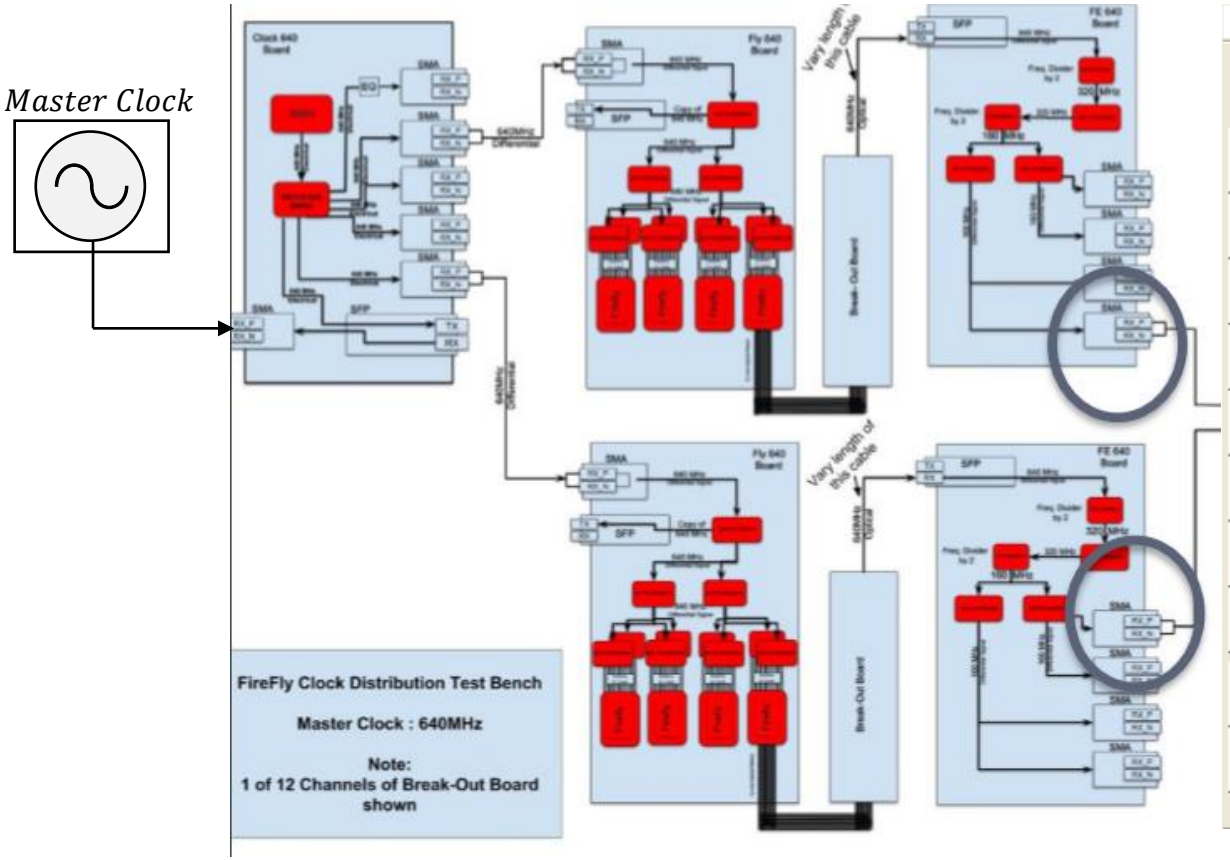
- High-accuracy (sub-ns) time transfer using an enhanced version of the Precision Time Protocol (PTP)

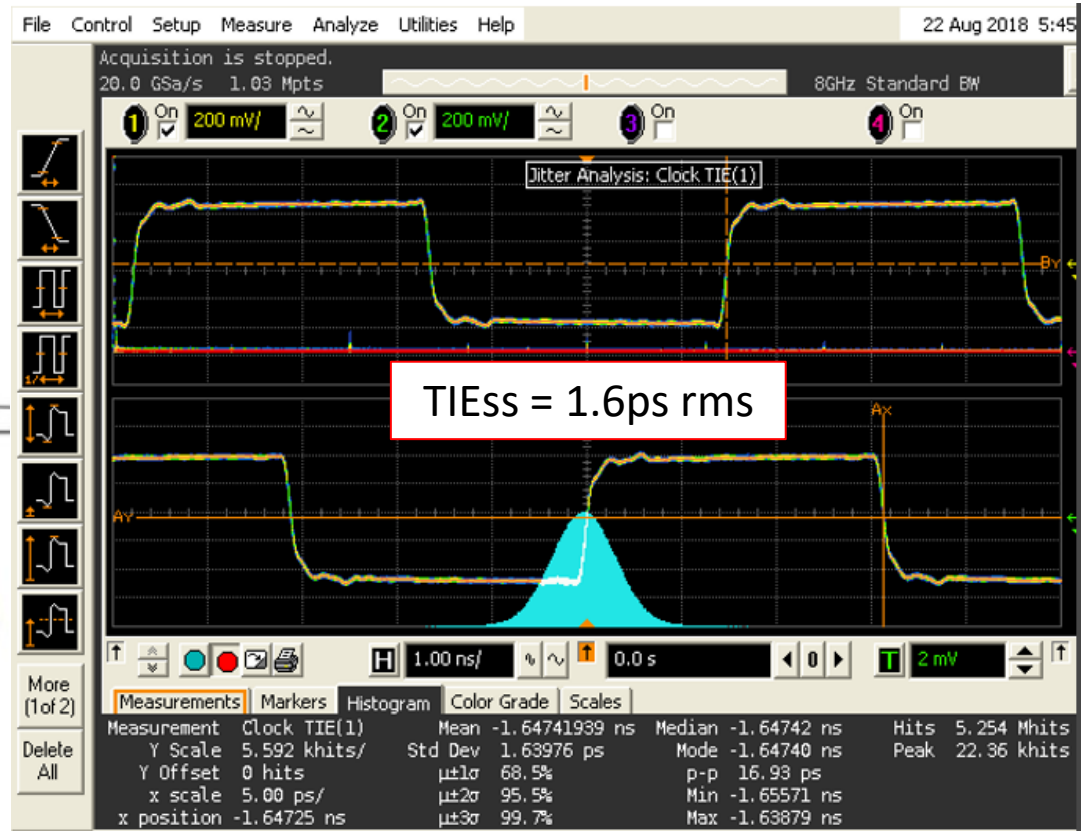



- The high accuracy of synchronization achieved in White Rabbit was standardized.
- Can be used to distribute RF signals: currently being implemented at CERN SPS-RF
  - Prototype shows better than 100fs jitter and phase-determinism over resets below 10ps

# Pure clock distribution

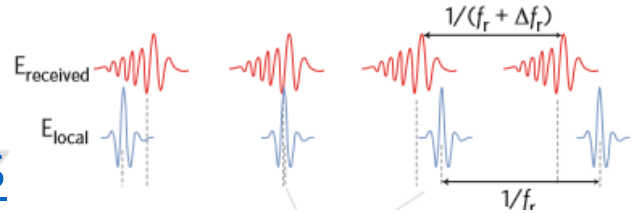
- An alternative to a serial self-synchronous based timing distribution system would be a pure clock distribution link - no data-encoding
- Presented in TWEPP19 by University of Minnesota

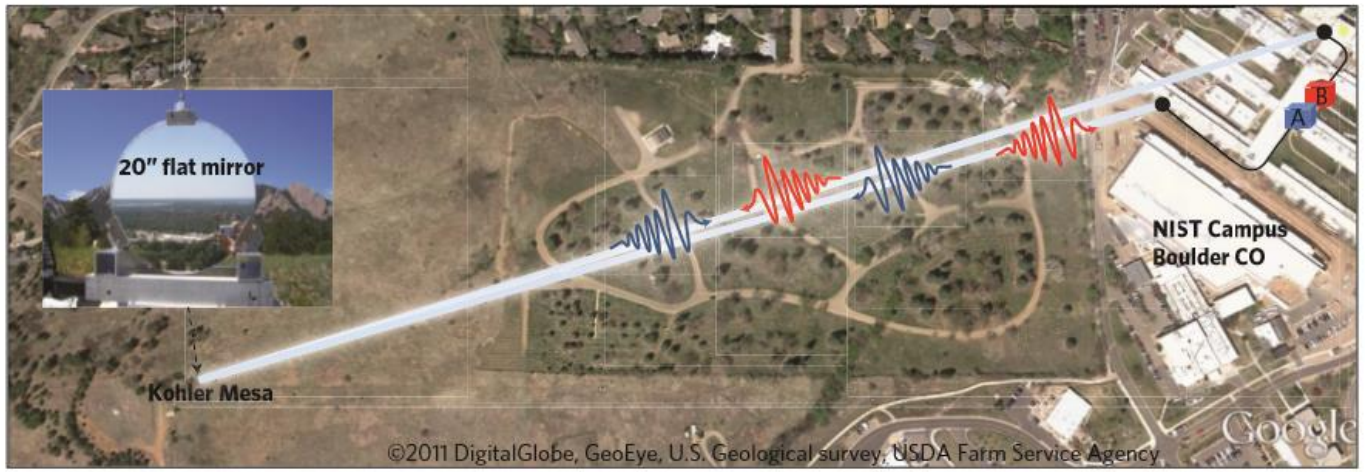


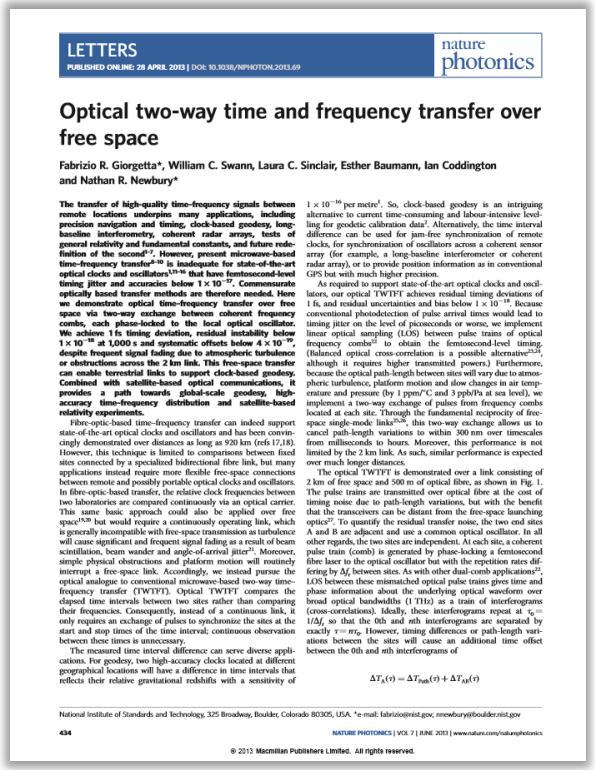



# Time transfer on free-space

- Work developped at NIST for time-frequency transfer in free-space
  - Based on frequency-comb
  - Not directly applicable for a detector-wide timing distribution but some ideas can be inspiring…
- High-performance achieved with accuracy on femto-second level
- Work published in [Nature Photonics]



LETTERS
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nature photonics

**Optical two-way time and frequency transfer over free space**

Fabrizio R. Giorgetta*, William C. Swann, Laura C. Sinclair, Esther Baumann, Ian Coddington and Nathan R. Newbury*

**The transfer of high-quality time–frequency signals between remote locations underpins many applications, including precision navigation and timing, clock-based geodesy, long-baseline interferometry, coherent radar arrays, tests of general relativity and fundamental constants, and future redefinition of the second[1,2]. However, present microwave-based time–frequency transfer[3–10] is inadequate for state-of-the-art optical clocks and oscillators[3,11–16] that have femtosecond-level timing jitter and accuracies below $1\times10^{-17}$. Commensurate optically based transfer methods are therefore needed. Here we demonstrate optical time–frequency transfer over free space via two-way exchange between coherent frequency combs, each phase-locked to the local optical oscillator. We achieve 1 fs timing deviation, residual instability below $1\times10^{-18}$ at 1,000 s and systematic offsets below $4\times10^{-19}$, despite frequent signal fading due to atmospheric turbulence or obstructions across the 2 km link. This free-space transfer can enable terrestrial links to support clock-based geodesy. Combined with satellite-based optical communications, it provides a path towards global-scale geodesy, high-accuracy time–frequency distribution and satellite-based relativity experiments.**

Fibre-optic-based time–frequency transfer can indeed support state-of-the-art optical clocks and oscillators and has been convincingly demonstrated over distances as long as 920 km (refs 17,18). However, this technique is limited to comparisons between fixed sites connected by a specialized bidirectional fibre link, but many applications instead require more flexible free-space connections between remote and possibly portable optical clocks and oscillators. In fibre-optic-based transfer, the relative clock frequencies between two laboratories are compared continuously via an optical carrier. This same basic approach could also be applied over free space[11,19] but would require a continuously operating link, which is generally incompatible with free-space transmission as turbulence will cause significant and frequent signal fading as a result of beam scintillation, beam wander and angle-of-arrival jitter[11]. Moreover, simple physical obstructions and platform motion will routinely interrupt a free-space link. Accordingly, we instead pursue the optical analogue to conventional microwave-based two-way time–frequency transfer (TWTFT). Optical TWTFT compares the elapsed time intervals between two sites rather than comparing their frequencies. Consequently, instead of a continuous link, it only requires an exchange of pulses to synchronize the sites at the start and stop times of the time interval; continuous observation between these times is unnecessary.

The measured time interval difference can serve diverse applications. For geodesy, two high-accuracy clocks located at different geographical locations will have a difference in time intervals that reflects their relative gravitational redshifts with a sensitivity of $1\times10^{-16}$ per metre[1]. So, clock-based geodesy is an intriguing alternative to current time-consuming and labour-intensive levelling for geodetic calibration data[2]. Alternatively, the time interval difference can be used for jam-free synchronization of remote clocks, for synchronization of oscillators across a coherent sensor array (for example, a long-baseline interferometer or coherent radar array), or to provide position information as in conventional GPS but with much higher precision.

As required to support state-of-the-art optical clocks and oscillators, our optical TWTFT achieves residual timing deviations of 1 fs, and residual uncertainties and bias below $1\times10^{-18}$. Because conventional photodetection of pulse arrival times would lead to timing jitter on the level of picoseconds or worse, we implement linear optical sampling (LOS) between pulse trains of optical frequency combs[20] to obtain the femtosecond-level timing. (Balanced optical cross-correlation is a possible alternative[21,24], although it requires higher transmitted powers.) Furthermore, because the optical path-length between sites will vary due to atmospheric turbulence, platform motion and slow changes in air temperature and pressure (by 1 ppm/°C and 3 ppb/hPa at sea level), we implement a two-way exchange of pulses from frequency combs located at each site. Through the fundamental reciprocity of free-space single-mode links[25,26], this two-way exchange allows us to cancel path-length variations to within 300 nm over timescales from milliseconds to hours. Moreover, this performance is not limited by the 2 km link. As such, similar performance is expected over much longer distances.

The optical TWTFT is demonstrated over a link consisting of 2 km of free space and 500 m of optical fibre, as shown in Fig. 1. The pulse trains are transmitted over optical fibre at the cost of timing noise due to path-length variations, but with the benefit that the transceivers can be distant from the free-space launching optics[27]. To quantify the residual transfer noise, the two end sites A and B are adjacent and use a common optical oscillator. In all other regards, the two sites are independent. At each site, a coherent pulse train (comb) is generated by phase-locking a femtosecond fibre laser to the optical oscillator but with the repetition rates differing by $\Delta f_r$ between sites. As with other dual-comb applications[22], LOS between these mismatched optical pulse trains gives time and phase information about the underlying optical waveform over broad optical bandwidths (1 THz) as a train of interferograms (cross-correlations). Ideally, these interferograms repeat at $\tau_0 = 1/\Delta f_r$ so that the 0th and $n$th interferograms are separated by exactly $\gamma = n\tau_0$. However, timing differences or path-length variations between the sites will cause an additional time offset between the 0th and $n$th interferograms of

$$\Delta T_A(\gamma) = \Delta T_{Path}(\gamma) + \Delta T_{AB}(\gamma)$$

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