Current Experience
with Precision Timing Distribution

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With many thanks to Jan Troska, Sophie Baron, and everybody else who recognizes their slides

ACES 2018

Experience with Precision Timing Distribution...

Currently there only a few *dedicated* and/or *precise* timing distribution systems in place in and around ATLAS and CMS and friends.

Of the above, not all have been understood and characterized well enough yet to publish figures or numbers.

I have taken some liberties with the original title, and tried to bring something informative nevertheless.

Overview

- A bit of background
- Dedicated clock distribution systems
  - TTC (from LHC RF to experiments)
  - TOTEM/CTPPS
  - ATLAS Forward Detectors
- Looking towards LHC Phase-2

Background

Where exactly does this precision clock matter?

Different 'qualities' matter in different places:

- Single sensors/channels: require reasonably low jitter and stable phase for optimal energy resolution
- Detectors: require low jitter, and coherent phase across channels for pileup suppression
- High-speed serial links: require stable clock frequency (esp. when multiplying clocks for Tx)

In the end it is the detector resolution and physics performance that matters.
The clock system contribution just has to be (quadratically) sub-leading to the detector performance itself.

More detail, esp. on the detector side, in L. Gray's presentation.

Precision Timing Distribution

There are two things to be distributed:
(Ignoring the synchronization part of the timing, for the moment.)

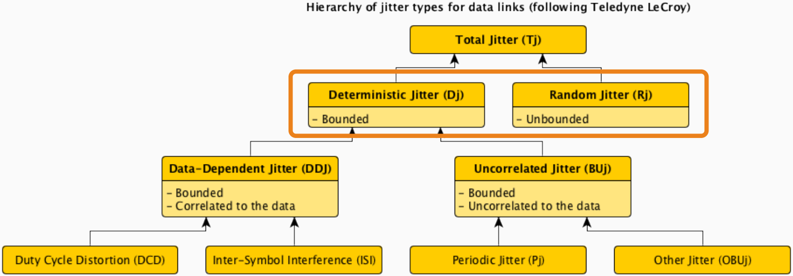
- Clock frequency
- Clock (i.e., sampling) phase

Clock frequency precision/quality can be characterized in terms of *jitter*.

Phase alignment, absolute as well as between channels, in addition to low jitter also requires precise and careful distribution.

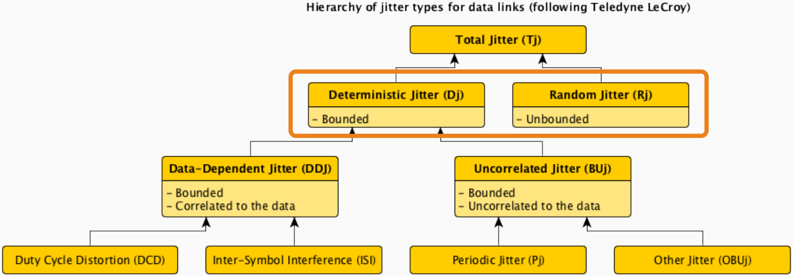
→ What is needed is both a precise clock and a precise distribution system.

Clock Quality - Jitter



- Deterministic jitter is defined as *bounded*, with a *well-defined minimum and maximum*.
- Random jitter is assumed to be (and it typically is) Gaussian-distributed.

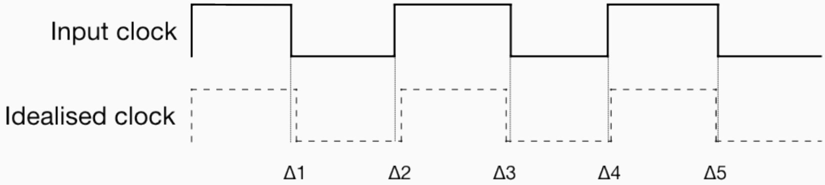
Clock Quality - Jitter



- If there are many sources of deterministic jitter, the result can become random (Gaussian) jitter.
- The true shape of the overall jitter distribution will vary, but in many cases a Gaussian can be a good approximation. (Whether such an approximation is conservative or not depends on the case at hand.)

Clock Quality - Jitter

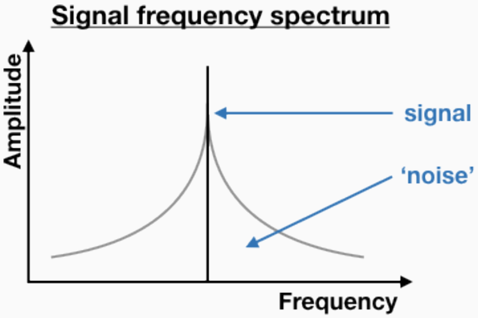
Time Interval Error (TIE): When do the edges arrive, compared to when they should arrive?
→ A fairly intuitive measure, supported by many oscilloscopes nowadays.



- Generate an 'ideal clock' with the same frequency as the input clock
- Calculate the deviations of the input clock edges w.r.t. their ideal positions
- The average $\overline{\Delta_i}$ is the Time Interval Error

Clock Quality - Phase Noise

Phase noise: Shows how much power is present in the signal at frequencies *different* from the desired frequency.



Phase noise integrated over an *appropriate* frequency window gives the RMS jitter.

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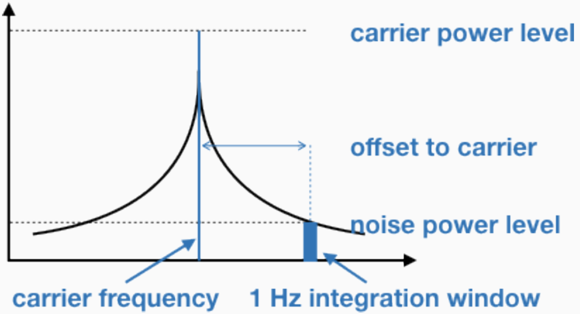

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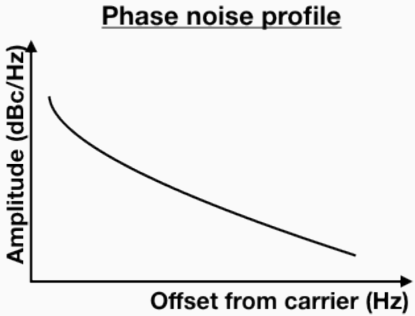

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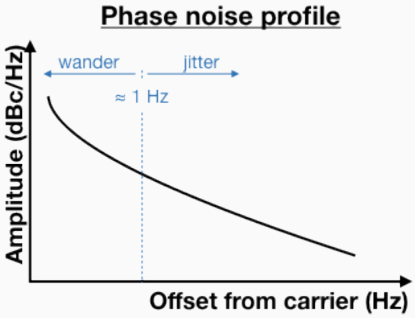

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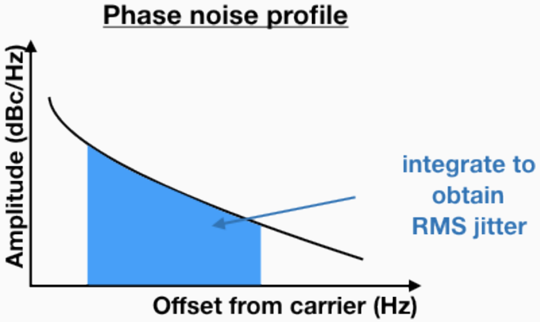

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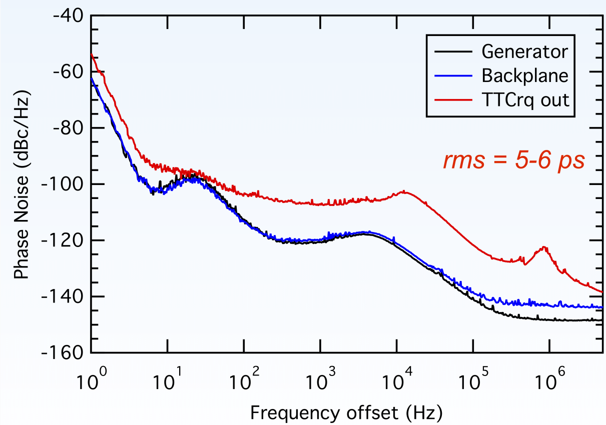
Phase Noise and RMS jitter



True spec must be defined in terms of frequency

J. Troska, *Precision clock in CMS*, `https://indico.cern.ch/event/616181/contributions/2493561/attachments/1421102/2177831/TCDS_TimingDetector_2March2017.pdf`

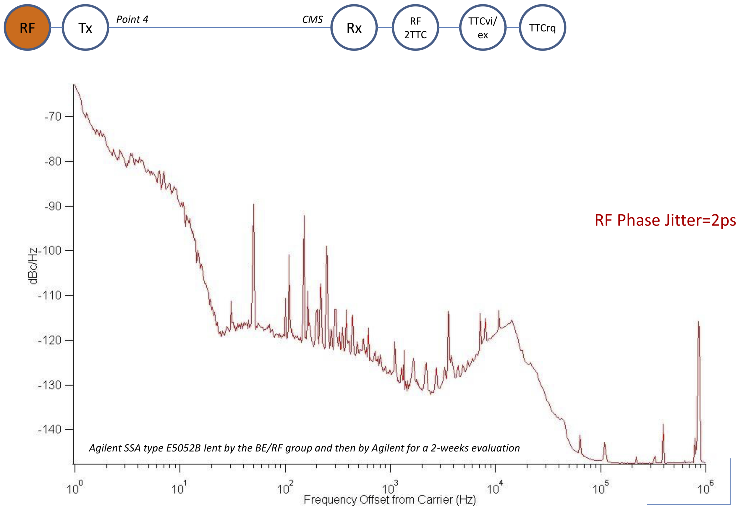
Timing Distribution – TTC

The Good Old TTC

- Sinusoidal optical signal at bunch clock frequency distributed from LHC RF at P4 to experiments. (CMS direct, others after regeneration at the CCC.)
- TTC machine interface electronics (RFRXD, RF2TTX):
  - Performs optical-to-electrical conversion
  - Allows selection and delay/phase adjustment
  - Performs fan-out (as AC-couped ECL)
- TTCvi/TTCci, TTCex, etc. handle distribution throughout experiment as TTC stream (two-channel, biphase-Mark encoded)
- TTCrx ASIC handles decoding and clock recovery
- QPLL ASIC handles clock cleaning and serves as auto-locking PLL

More detail on TTC architecture in presentation by E. Brandao De Souza Mendes.

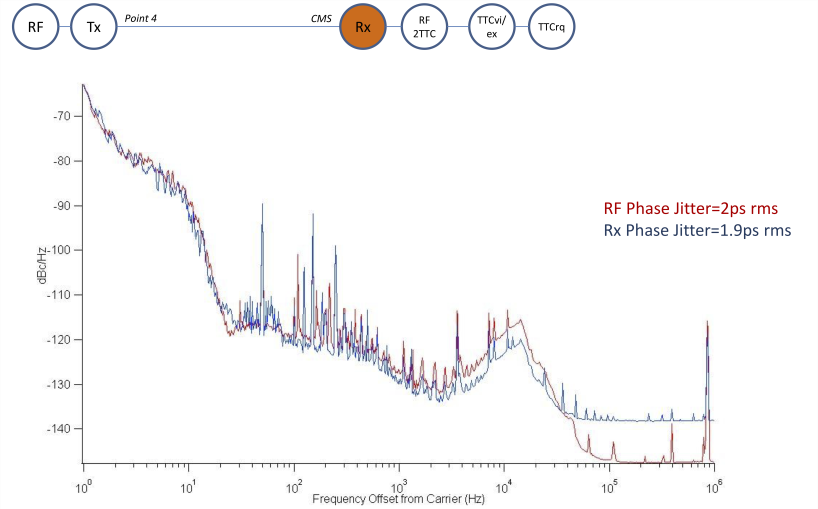
The Good Old TTC



RF Phase Jitter=2ps rms

S. Baron, *TTC system and jitter in LHC experiments*, `https://indico.cern.ch/event/202454/`

The Good Old TTC



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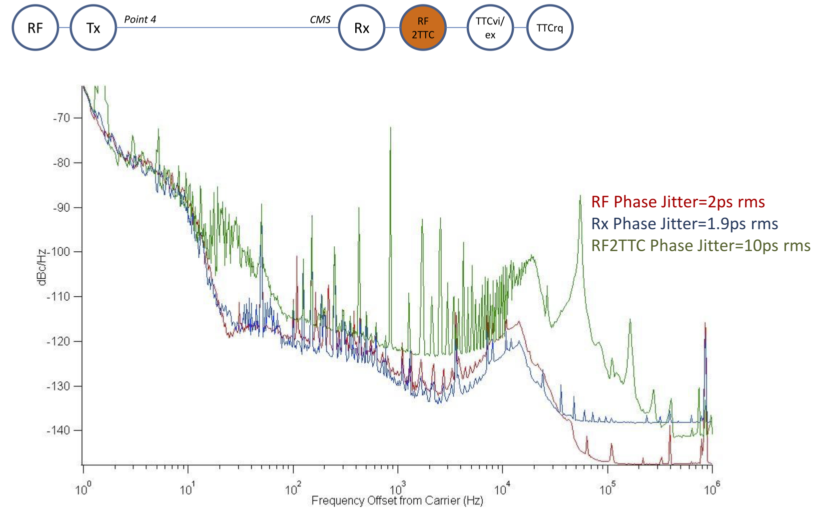

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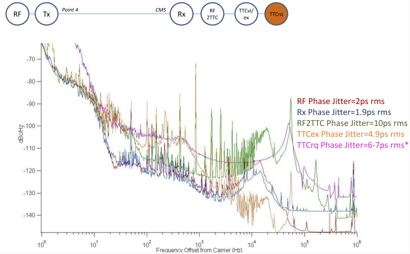
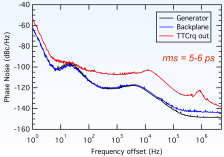
The Good Old TTC

ATLAS (and CMS Run-1)



CMS Run-2

- Current system jitter performance not degraded by TCDS system
  - Dominated by the receiver TTCrx/QPLL
    - where we care about low power, for example



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S. Baron, *TTC system and jitter in LHC experiments*, `https://indico.cern.ch/event/202454/`

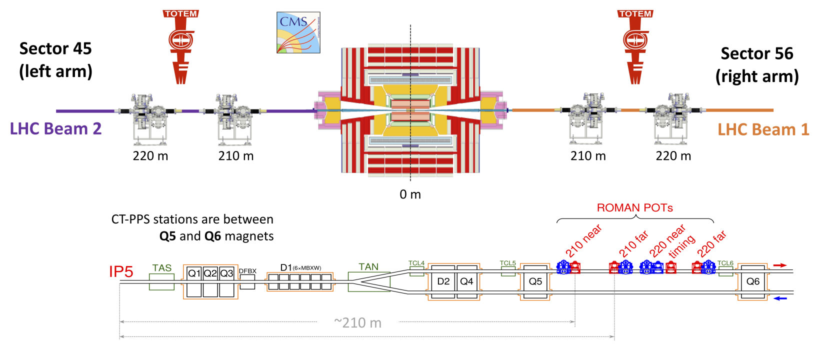
Review of capabilities of existing Clock Distribution System , `https://indico.cern.ch/event/575572/contributions/2328970/`

The Good Old TTC

- The TTC system as a whole is *still* performing admirably
- The top of the distribution tree is already cleaner than most of our sub-detectors can benefit from
- Remaining bottlenecks could probably be easily fixed

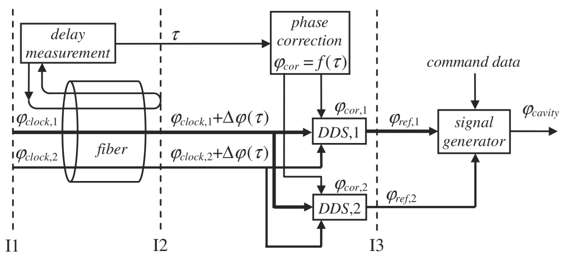
Timing Distribution – TOTEM/PPS

CTPPS/TOTEM



- Hunting for Central Exclusive Production: a central event in CMS, together with coincidence of scattered protons in the very forward region
- Uses artificial single-crystal diamonds as timing detectors
    - to reject pileup, and
    - to identify the CEP vertex in CMS

FAIR inspiration



Solves the problem of serving geographically distinct locations with phase-aligned clocks of different frequencies

Universal picosecond timing system for the Facility for Antiproton and Ion Research
`http://link.aps.org/doi/10.1103/PhysRevSTAB.12.042801`

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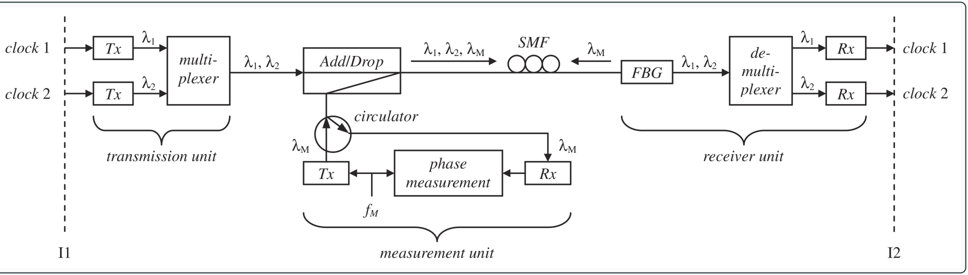

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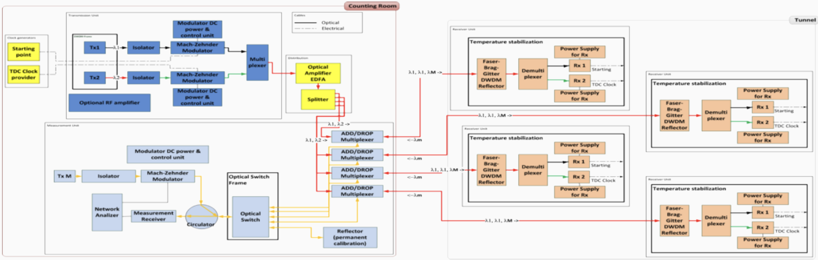
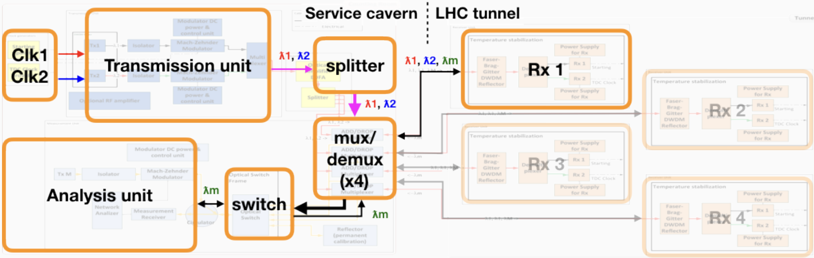
CTPPS/TOTEM timing



- Contrary to the FAIR original, the delay measurement is not used for correction, only for monitoring.
- Preliminary results indicate this approach provides sufficient stability.

F. Cafagna, *The TOTEM precision clock distribution system*, NSS/MIC 2017

CTPPS/TOTEM timing



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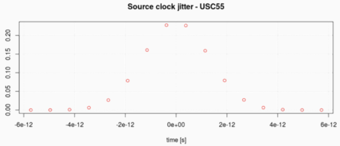
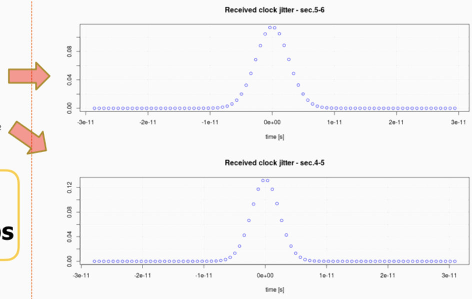
F. Cafagna, *The TOTEM precision clock distribution system*, NSS/MIC 2017

CTPPS/TOTEM timing

CMS USC55

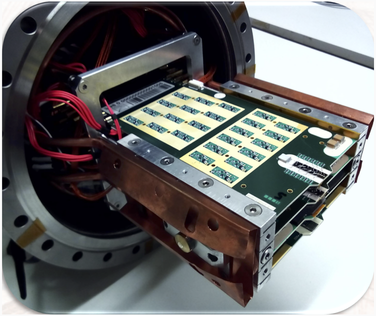


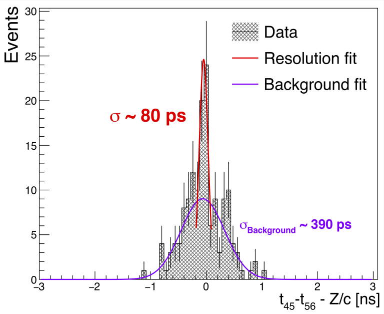
LHC tunnel



- RMS jitter at source **~1ps**
- RMS jitter at receivers **~2ps**

CTPPS/TOTEM timing



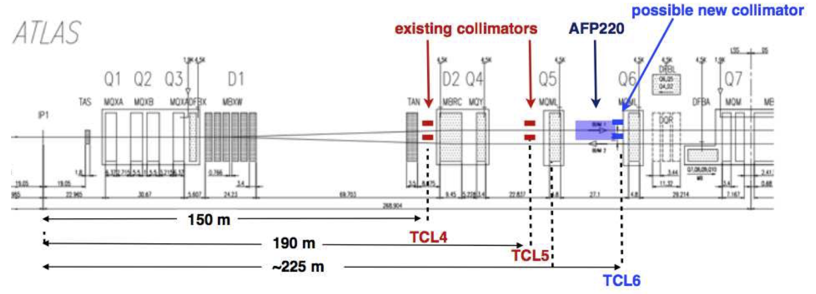


- Diamond sensors (cvCVD) provide timing resolution of ≈ 55 ps per detector arm
- Timing resolution completely dominated by sensors and front-end

D. Figueiredo, *Operation and performance of the new detectors in the CMS-TOTEM Precision Proton Spectrometer in 2017*, LHCC Feb. 2018, `https://indico.cern.ch/event/705390/`

Timing Distribution – AFD

ATLAS Forward Detectors



- Physics compatriot of TOTEM/CTPPS
- Aiming for a timing resolution of < 10 ps
- Timing detectors based on Cerenkov radiator with a microchannel plate PMT:
    - QUARTIC (quartz) radiators, timing resolution $O(35\,\text{ps})$ per measurement
    - GASTOF (gas) radiators, timing resolution $O(20\,\text{ps})$

ATLAS Forward Detectors

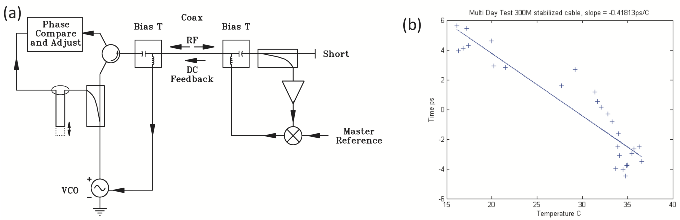


Figure 5.3: (a) Schematic of the Reference timing system as described in text.(b) Results of temperature stabilization test showing a mild drift with temperature (about 4 ps for 10 degrees C).

- Timing system based on a design developed at SLAC, by Joe Frisch and Jeff Gronberg (LLNL)
- PLL stabilizing the 400 MHz LHC RF clock, then converting to 40 MHz
- Preliminary tests show:
    - a jitter of ≈ 150 fs over a 100 m cable(!)
    - Temperature stability improved from ≈ 80 ps/degree C to ≈ 4 ps/degree C

AFP technical proposal , `https://atlas-project-lumi-fphys.web.cern.ch/atlas-project-lumi-fphys/AFP_TP.pdf`

Both forward timing systems

Both the TOTEM/CTPPS and the AFD timing systems are currently being commissioned, together with their detectors. Looking forward to seeing a comparison of their performance vs. expectations. Especially for long(er)-term stability.

Looking towards LHC Phase-2

Phase-2: lpGBT

lpGBT promises:

- 4 Programmable clocks:
    - Frequency and phase programmable
    - Frequencies: 40/80/160/320/640/1280 MHz
    - Clock jitter: < 5 ps
    - Phase resolution: 50 ps
- 28 eLink clocks:
    - Frequency programmable, phase fixed
    - Clock jitter: < 5 ps

The above is a very good start, but 'the other half' of the job remains:

- Careful system design, validation, and characterization
- Implementation of system-wide phase stability monitoring (and determining how to use the resulting data)

https://espace.cern.ch/GBT-Project/LpGBT/Specifications/LpGbtxSpecifications.pdf

Food for discussion (after Eduardo's talk)

- In the HEP community there is plenty of expertise around on precision timing, RF systems, high-speed data links, etc.
- Precision timing, a somewhat niche subject until now, will be of utmost importance for the hi-lumi LHC experiments.
- As is the case in many aspects, the timing requirements for the Phase-2 LHC detectors are challenging partly due to their lack of significant margins.
- For future experiments, it is just as important to characterize the timing distribution performance as the sensors themselves.
- For ultimate trust in system stability, timing distribution monitoring should be built in, just like sensor calibration.

$\rightarrow$ Expect that everybody will benefit from participating in the common project on precision timing