

CMS-TOTEM Precision Proton Spectrometer

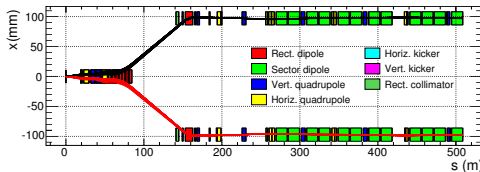
Laurent Forthomme (University of Kansas)

on behalf of the CMS and TOTEM collaborations

Low-x workshop, Gyöngyös, Hungary

June 6-10, 2016

- Joint **CMS-TOTEM** project
- **measurement of outgoing, scattered protons** on both sides of the CMS interaction point ($z_{\text{CMS}} \sim \pm 210$ m)
- Proton spectrometer using LHC magnets



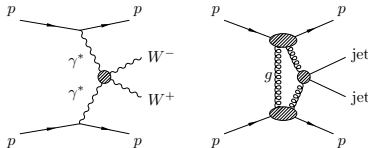
(beamline optics response around CMS' IP ($s = 0$), **Hector**)

- 2 subdetector types:
 - timing components: pileup reduction
 - tracking detectors: measurement of protons momentum



Running in “production mode” with the tracking component since 3rd June!

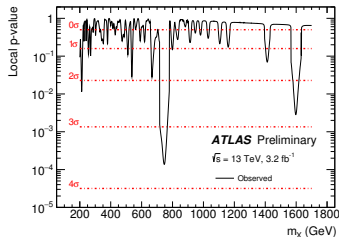
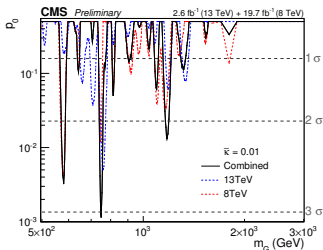
- Study the **colourless interactions**, where large **rapidity gaps** are expected (e.g. the $\gamma\gamma$, $\gamma\mathbb{P}$, $\mathbb{P}\mathbb{P}$ processes)



- In particular, two-photon interactions:
 - Precision measurement of the $\gamma\gamma \rightarrow \ell^+\ell^-$ process
 - Search for anomalous behaviours of the $\gamma\gamma VV$ couplings (anomalous triple- and quartic gauge couplings)
 - Probe the **750 GeV** two-photon mass region (e.g. [arXiv:1512.05751](https://arxiv.org/abs/1512.05751))
- New resonances searches through CEPs
 - CoM system precisely known (overconstrained central system)
- LHC as a two-pomeron collider:
 - Study the pQCD behaviour of exclusive productions

Hints for an excess at $m_{\gamma\gamma} \simeq 750$ GeV in inclusive two-photon events

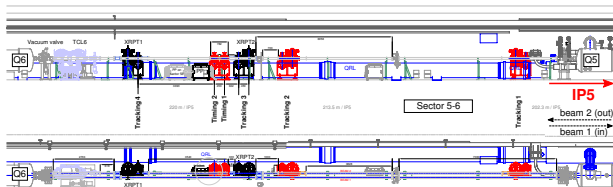
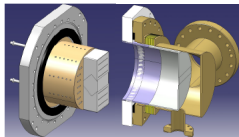
- Observed both in CMS ([CMS-PAS-EXO-15-004](#)) and ATLAS ([ATLAS-CONF-2015-081](#)) with data collected in 2015 at $\sqrt{s} = 13$ TeV



→ **December 2015/January 2016:**

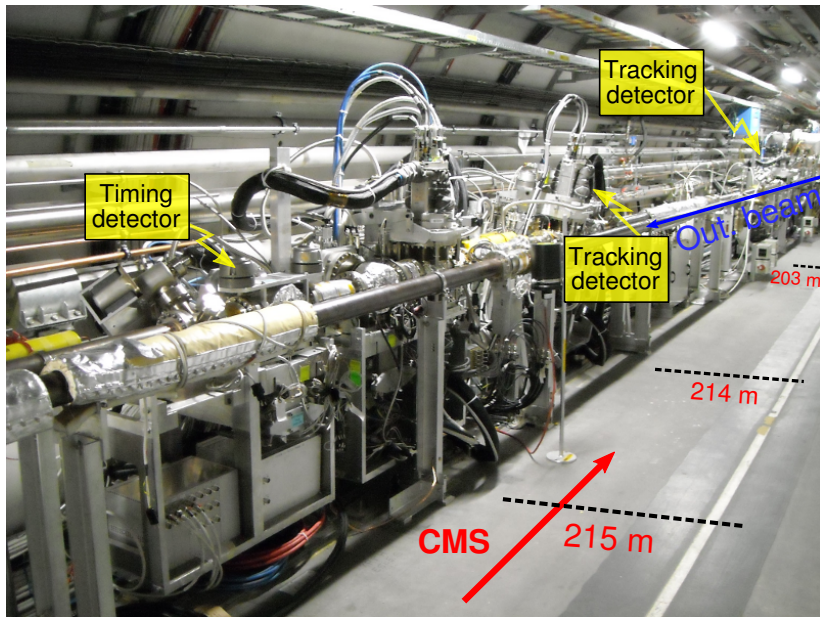
- decision to accelerate CT-PPS given this observation
- start of data taking in 2016 (originally foreseen for 2017)

The apparatus



- Horizontal **Roman Pots** (RPs) installed in the very forward regions
 - 2 for the *tracking* detectors (~ 204 and 215 m)
 - 2 for the *timing* detectors (1 currently installed, 215 m)
- Tested in **real beam conditions** in 2015
 - Operating with *no beam instabilities* up to $4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 - No vacuum pressure, nor temperature issues encountered
 - *Promising extrapolations* to $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and low- σ
- Inserted in *intensity ramp-up* in May 2016
 - Successful insertions up to 1700 bunches intensities at 15σ (+ 0.5 mm margin)
 - **Successful insertions with 49, 600, and 1700 bunches at 15σ (no margin)**

In the tunnel

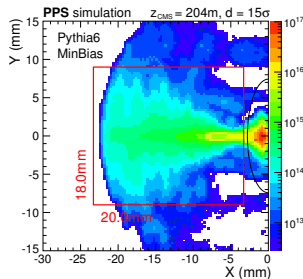


Requirement for **radiation-hard**, high-(timing/spatial) resolution detectors:

Radiation levels in the detector volume studied using TOTEM Run-1 data and simulations

Per 100 fb^{-1} :

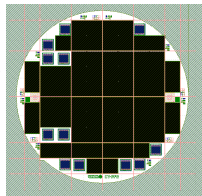
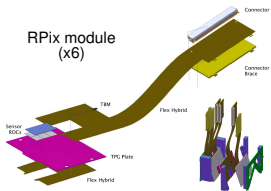
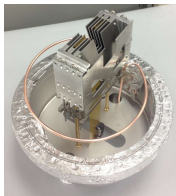
- Proton flux up to $5 \times 10^{15} \text{ cm}^{-2}$ in the **pixel detectors**
- 10^{12} neutron-equivalents $/\text{cm}^2$ and 100 Gy in **off-beam readout electronics**



Since Dec 2015/Jan 2016, two timescales defined for the installation of the detectors:

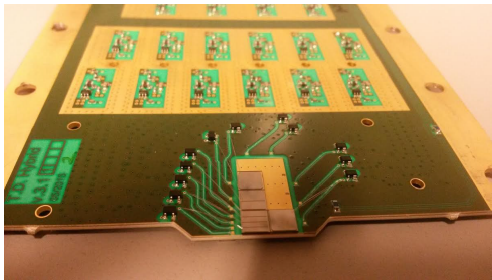
- **Baseline components** (mid- to long-term timescale)
 - R&D programme on both components still ongoing
- **Accelerated programme**
 - Use of TOTEM tracking and timing detectors
 - Closely following the 750 GeV bump
 - Approved by CMS and TOTEM Collaborations

- *Accelerated plan*: TOTEM silicon strip detectors
 - Sustain high trigger rates (lifetime: 10 to 20 fb⁻¹)
 - Already part of CMS data-taking
- 3D silicon pixels (PSI46dig readout chain, same as CMS Pixel Phase 1 upgrade)
 - 200 μm thin edges for minimal beam distance of approach
 - radiation-hard (expected fluence: 5×10^{15} protons /cm²)
 - 6 planes in each station (tilted by 18.4°)
 - baseline: full spatial resolution under 30 μm
 - Available in \sim fall 2016



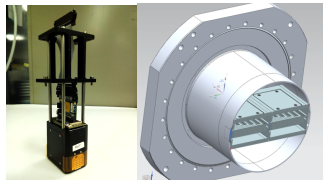
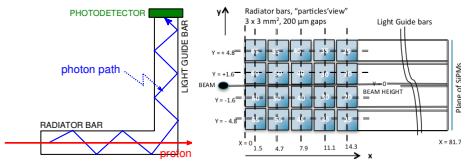
– *Accelerated plan*: TOTEM diamond detectors

- Hybrid design produced and tested in Jan-Feb 2016
- $\sigma_t \sim 80$ ps/plane \rightarrow combined timing resolution of ~ 50 ps with 4 planes
- plane geometry optimised for increased spatial resolution (~ 150 μ m, optimum for $M_{\gamma\gamma} = 750$ GeV)
- Currently being **installed during TS1** (54 hours, starting this 7 Jun @ 6am GVA time. . .)



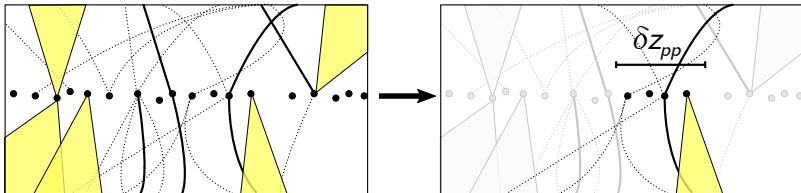
Several parallel R&D tracks:

- Ultra Fast Silicon Detectors
 - goal: 30 ps per plane for 50 μm thickness
 - mature to be installed at the end of 2016
- **QUARTIC** (quartz Cherenkov detector)



- Grid of 4×5 quartz bars, $3 \times 3 \text{ mm}^2$
- Timing resolution (early TB): $\sigma_t \sim 30 \text{ ps}$ (2 bars: $\sim 20 \text{ ps}$)
- Readout: SiPM \oplus NINO discriminator \oplus HPTDC digitizer
- Other R&D projects: GasTof (gas Cherenkov detector), ...

Reduction of the events pileup through addition of timing information on the outgoing two-proton system

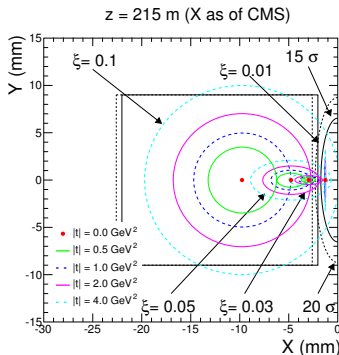
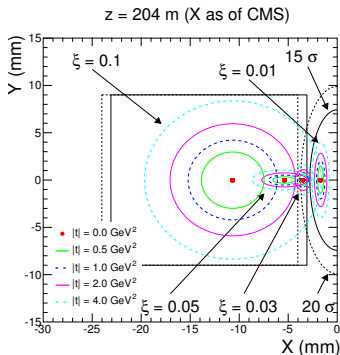


– Relation between detectors *timing resolution* and **longitudinal resolution**:

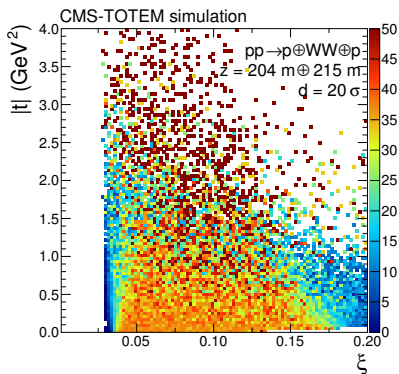
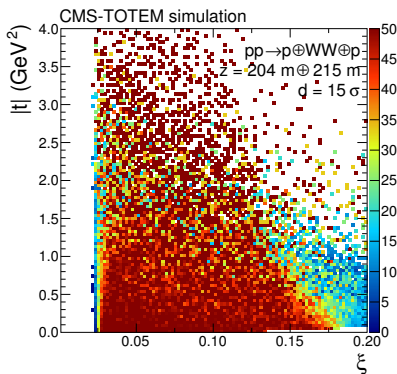
$$\delta z_{pp} = \frac{c}{\sqrt{2}} \delta t \Rightarrow \begin{cases} \delta t = 30 \text{ ps} \rightarrow \delta z_{pp} \simeq 6 \text{ mm} \\ \delta t = 10 \text{ ps} \rightarrow \delta z_{pp} \simeq 2 \text{ mm} \end{cases}$$

Physics performances

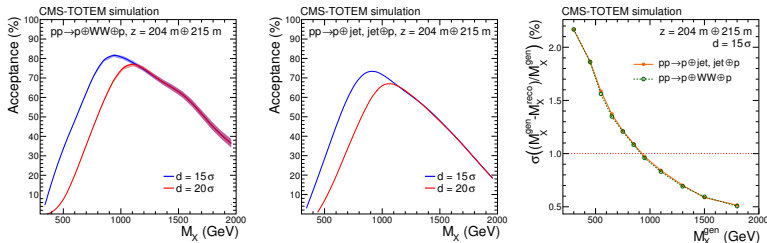
- Full constraint of the central exclusive system kinematics through measurement of outgoing protons
- Proton kinematics:
 - $\xi \equiv \Delta p/p$, and
 - $t \equiv (p_{p,in}^\mu - p_{p,out}^\mu)^2$
- Acceptances, first tracking station, and timing detectors positions:



- Double-arm detector acceptance for $\gamma\gamma \rightarrow W^+W^-$ events ($|t| - \xi$ plane):
 - Events **accepted in $z > 0$ arm** if **detected in $z < 0$ arm**, for $d = 15\sigma$ and 20σ distances of approach
 - LHC optics: $\beta^* = 0.6$ m (**PPS TDR**, 2014)

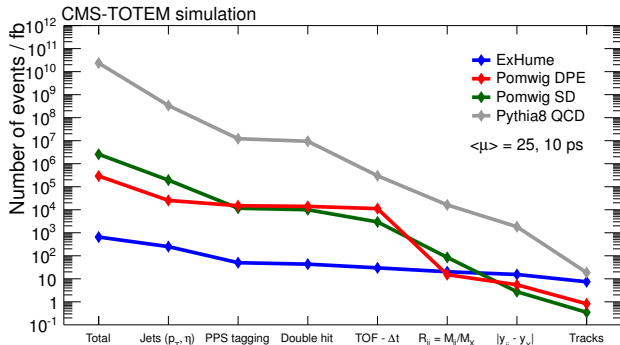
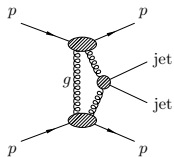


Central system acceptance and relative resolution as a function of its invariant mass:



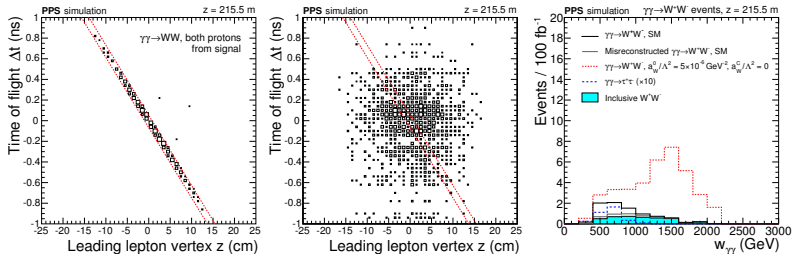
- PPS efficiency $> 5\%$ for exclusive systems in mass range:
 $300 < M_X < 1700 \text{ GeV}$
- Mass resolution:
 - $\sim 1.5\%$ at $M_X = 500 \text{ GeV}$
 - $\sim 1.2\%$ at $M_X = 750 \text{ GeV}$
- LHC optics: $\beta^* = 0.6 \text{ m}$ (PPS TDR, 2014)

Eg. 1: CE dijet production with the PPS

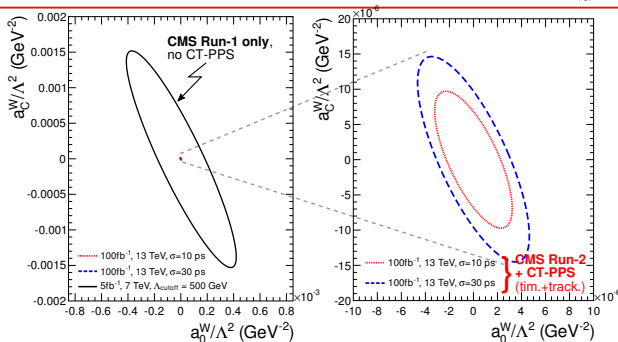


- Timing resolution: $\sigma_t = 10 \text{ ps}$, average pileup multiplicity: $\mu = 25$
- Expected signal/background ratio: $\sim 1/3$

- CMS “Central detector” analysis details: see **CMS Exclusive measurements** talk this afternoon
 - Search for $pp \rightarrow p^{(*)}(\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\mp \nu \bar{\nu})p^{(*)}$ events at the LHC
 - Major background sources: inclusive $DY \rightarrow W^+W^-, \tau^+\tau^-, \gamma\gamma \rightarrow \tau^+\tau^-$
- Addition of PPS timing and tracking information for pileup mitigation



Eg. 2: AQGCs in $\gamma\gamma \rightarrow W^+W^-$ with the PPS



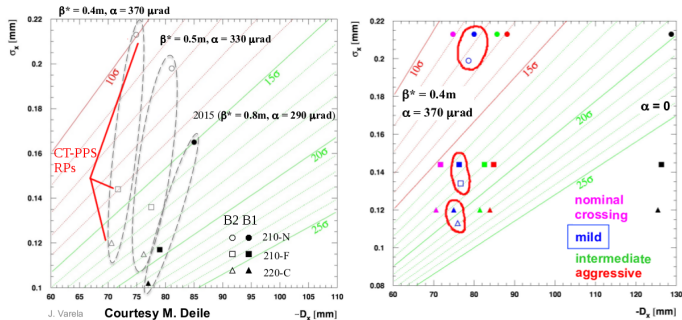
- Up to 2 orders of magnitude improvements on the current Run-1 95% C.L. limits on Anomalous Quartic Gauge Couplings
 - Extracted with the $\gamma\gamma \rightarrow W^+W^-$ searches
 - 2 CT-PPS timing resolution scenarios covered: $\sigma_t = 30$ and 10 ps

Anom. param.	No PPS	PPS, 30 ps	PPS, 10 ps
a_0^W/Λ^2	$[-0.9, 0.9] \times 10^{-4}$	$\pm 3 \times 10^{-6}$	$\pm 2 \times 10^{-6}$
a_C^W/Λ^2	$[-3.6, 3.0] \times 10^{-4}$	$\pm 10 \times 10^{-6}$	$\pm 7 \times 10^{-6}$

Prospects for 2016 – ...

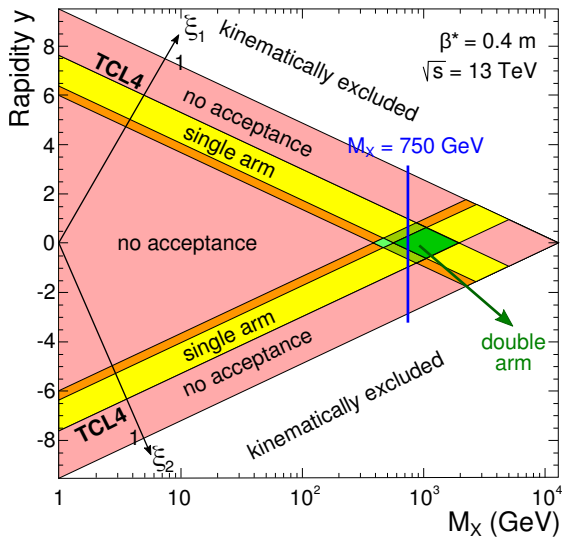
Strong influence of LHC optics on PPS acceptance at $M_X = 750$ GeV

- Post-LS1, 2016 optics optimisations resulted in **significant loss of acceptance** compared to the CT-PPS TDR expectations
- New LHC orbit configuration proposed to **LHC machine coordination** to **increase the dispersion** at RPs location (“**mild**” beam configuration)
- Higher rapidity reach expected with dispersion increase ($y_{\max} = \ln \frac{M_X}{\xi_{\min} \sqrt{s}}$)
 - RP approach needed to reach $y_{\max} = 0.5$ ($\xi_{\min} = 3.5\%$): before (left) vs after (right)



$M_X - y$ space – “mild” orbit bump

$\alpha_X = 370 \mu\text{rad}$, mild orbit bump, **RP@15 σ**



Light green/orange:
Acceptance at 210-F
and 220-C only

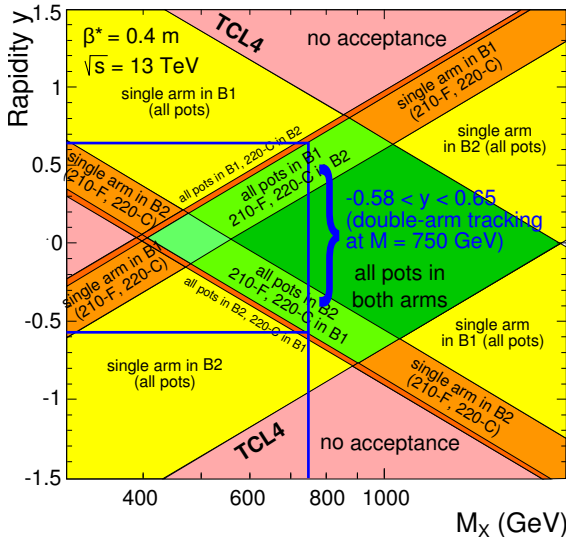
$$y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2},$$

$$M_X = \sqrt{\xi_1 \xi_2} \cdot \sqrt{s}$$

Plot: courtesy M. Deile

$M_X - y$ space – “mild” orbit bump (zoom)

$\alpha_X = 370 \mu\text{rad}$, mild orbit bump, **RP**s @ 15σ



Zoom on double-arm acceptance region

$$y = \frac{1}{2} \ln \frac{\xi_1}{\xi_2},$$

$$M_X = \sqrt{\xi_1 \xi_2} \cdot \sqrt{s}$$

Plot: courtesy M. Deile

- Success data taking with RPs at 15σ with 1700 bunches
- Installation of diamond detectors in RPs during TS1
- Integration of detector readout in CMS Central DAQ (and DCS)
 - Integration of TOTEM Strips and Diamonds
- Integration of software in the full CMS simulation framework
 - TOTEM strips and track reconstruction
 - Timing detectors software
- Other areas being developed:
 - Data quality monitoring, alignment studies, calibration, online and offline databases

Same analysis scheme as 2015 inclusive $\gamma\gamma$ searches by CMS and ATLAS

Running conditions: $20 - 30 \text{ fb}^{-1}$ LHC luminosity expected in 2016, $\beta^* = 0.6 \text{ m}$

- Excl. $\gamma\gamma \rightarrow X(750) \rightarrow \gamma\gamma$ production cross-section fusion: $\sim 0.3 - 0.6 \text{ fb}$ (resonance dominantly produced in $\gamma\gamma$ fusion)
- Main **background sources**: incl. $\gamma\gamma + \text{PU}$ ($\lesssim 0.1$), incl. $\gamma + j/j + j$, excl. $\gamma\gamma$ ($< 10^{-4}$), $\gamma\gamma \rightarrow \gamma\gamma$ continuum, ...

→ Few (4 – 7) \sim **background-free** events expected in an early run

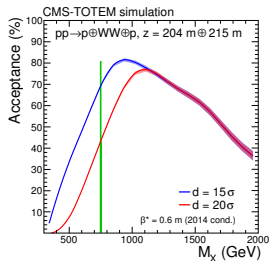


Figure source: **PPS TDR**

Combined CT-PPS ($A \times \epsilon$) for signal events (as a function of the distance of approach):

- 29% for 20σ
- 41% for 15σ

Can be carried out with PPS **tracking-only information** (unlike $\gamma\gamma \rightarrow W^+W^-$ and dijet channels)

Old optics parameters! (more information [here](#))

- Rich physics programme to be expected with the CT-PPS
 - Sensitivity to AQGCs increased by 2 orders of magnitude
 - Direct probe to the diphoton excess at ~ 750 GeV
- Many experimental challenges
 - Low- β^* , high-pileup collection mode
 - High granularity tracking in a radiation-hard environment
 - Picosecond-scale timing resolution to be achieved
- Some subsystems already integrated into the CMS DAQ
 - Data collection started in 2016 for tracking component,
 - Diamonds timing detectors being integrated during this TS, data collection within the next week(s)...