CMS-TOTEM
Precision Proton Spectrometer

F. Ferro - INFN Genova
on behalf of the CMS and TOTEM collaborations

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Outlook

- Project overview
- Experimental apparatus
- Physics motivations and performance
- Status and latest news
• Project overview
• Experimental apparatus
• Physics motivations and performance
• Status and latest news
CT-PPS institutes

CMS

Belgium
   Louvain
Brazil
   CBPF
   UERJ
Italy
   Genova
   Torino/Novara
Iran
   IPM
Portugal
   LIP
Russia
   IHEP Protvino
US
   Fermilab
   Iowa
   Kansas
   Livermore
   Rockefeller

TOTEM

CERN
   TOTEM group
Czech Republic
   Pilsen
   Prague
Finland
   Helsinki
Italy
   Bari
   Pisa/Siena
CT-PPS project

CT-PPS is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons in both sides of CMS in standard running conditions
- PPS: precision proton spectrometer using LHC magnets

- Tracking and timing detectors inside the beam pipe at ~210m from IP5
  - Tracking to measure proton momentum
  - Timing to disentangle pile-up

- Project TDR approved in Dec.2014 by LHCC

- CT-PPS already taking data with an “accelerated program” configuration
  - Use already available Si strip detectors from TOTEM experiment

- Data taking with the baseline detector configuration foreseen for beginning 2017
Physics motivations

Experimental strategy
- High-pT system detected by the central detector together with very low angle scattered protons detected by CT-PPS
- Requiring the momentum balance between the central system and the detected protons creates strong kinematical constraints
- Central system mass is measured via the momentum loss of the two protons

Physics
- **EWK**: LHC as $\gamma\gamma$ collider with tagged protons
  - Measurement of $\gamma\gamma \to W^+W^-, \, e^+e^-, \, \mu^+\mu^-, \, \tau^+\tau^-$
  - Search for aQGC with high sensitivity
  - Search for SM forbidden $ZZ\gamma\gamma, \, \gamma\gamma\gamma$ couplings
- **QCD**: LHC as $gg$ collider with tagged protons
  - Exclusive two and three jet events.
  - Test of pQCD mechanisms of exclusive production.
  - Gluon jet samples with small component of quark jets
- **BSM**
  - Clean events (no underlying pp event)
  - Independent mass measurement by pp system
  - $J^{PC}$ quantum numbers $0^{++}, \, 2^{++}$
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Experimental apparatus

- Roman Pot stations to get into LHC vacuum pipe
  - 2 horizontal pots at 203m and 214m for tracking
  - 2 (1 for the time being) horizontal pots at 215m for timing
How they look like in reality
Roman Pot insertion

- The insertion of Roman Pots inside the LHC beam pipe is a delicate procedure which needs to be tested and approved by the machine.
- The minimum distance of approach to the beam dramatically affects the detector acceptance and therefore the physics reach.
- CT-PPS goal: RP’s at $15\sigma_{\text{beam}}$ from the beam in nominal runs at the maximum available luminosity. **Achieved.**

To be monitored during the tests:

- beam losses / showers and interplay with collimators
- impact on impedance:
  - heating
  - vacuum stability
  - beam orbit stability

Tests successful $\Rightarrow$ Data taking at $15\sigma_{\text{beam}}$
Detectors

- Tracking detectors
  - Aim: Measure the proton momentum
    - Detailed knowledge of the LHC optics required
  - Technology: Silicon 3D pixel (6 planes per pot)
    - rad-hard and “edgeless”

- Timing detectors
  - Aim: Disentangle pileup primary vertices
    - $\sigma_{\text{Time}} \sim 10\text{ ps} \rightarrow \sigma_Z \sim 2\text{ mm}$
  - Technology:
    - Diamond detectors
    - R&D also pursued
      - Cherenkov quartz bars (QUARTIC)
      - Ultra fast silicon detectors (UFSD)
Tracking detectors (1)

- 6 detector modules per pot
  - planes tilted by $18.4^\circ$ to optimize efficiency and resolution
  - design optimizes material budget, insertion in the pot, approach to the beam
  - installation foreseen at the end of the year to replace the Si strips used now in the “accelerated program”
Tracking detectors (2)

- **3D sensor technology**
  - intrinsic **radiation hardness** (to withstand overall integrated flux of $5 \times 10^{15}$ protons/cm$^2$ corresponding to an integrated luminosity of $\sim 100$/fb)
  - 200 $\mu$m **slim edges** (small dead edge to approach the beam as much as possible)
  - pixel dimensions: 100x150$\mu$m$^2$
  - resolution <30$\mu$m (goal $\sim 10\mu$m)
  - front-end chip: latest version of the PSI46dig, same as for CMS Pixel Phase I upgrade

**Testbeam results (preliminary)**

![Graphs showing efficiency and resolution](image-url)
Timing detectors: Diamonds

- $\sigma_T \sim 80$ ps per plane, better than 50 ps with a package of 4 planes
- Variable pad dimensions to optimize occupancy
- Readout with NINO + HPTDC
- A detector package installed in the cylindrical pots during TS1
- Data taking expected for September (together with the Si strip, in the “accelerated program” configuration)
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Detector acceptance and resolution

Proton kinematics (t and $\xi$)

Near pot

$z=204m$ (X as of CMS)

Far pot

$z=215m$ (X as of CMS)

N.B.: all acceptance plots done with optics (slightly) different wrt the current one
Mass acceptance and resolution

WW

jet jet
Mass-rapidity space

Recent studies with actual optics

$\beta^* = 0.4 \text{ m}, \alpha_X = 370 \mu\text{rad}, \text{mild orbit bump, RPs @ 15 } \sigma$

$\sqrt{s} = 13 \text{ TeV}$

$\beta^* = 0.4 \text{ m}$

$\xi_1, \xi_2$

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

$M^2 = \xi_1 \xi_2 s$

kinematically excluded

750 GeV

single arm

no acceptance

double arm

light green, light orange: acceptance only in 210-F and 220-C

F. Ferro - INFN Genova
Studied only $e\mu$ channel
Main background from inclusive WW and $\tau\tau$ exclusive production

- Proton timing: an important tool to reject background
- SM contribution small in the tail of $W_{\gamma\gamma} = \sqrt{s} \xi_1 \xi_2$
  - $aQGC$ events clearly separated
Expected new limits on aQGC couplings at 95% CL

\[ \mathcal{L}_6^0 = -\frac{e^2 a_W^0}{8 \Lambda^2} F_{\mu\nu} F_{\mu\nu} W^+ W^- - \frac{e^2}{16 \cos^2 \theta_W} \frac{a^Z_0}{\Lambda^2} F_{\mu\nu} F_{\mu\nu} Z^\alpha Z_\alpha \]

\[ \mathcal{L}_6^C = -\frac{e^2 a_C^0}{16 \Lambda^2} F_{\mu\alpha} F_{\mu\beta}(W^+ W^- + W^- W^+) - \frac{e^2}{16 \cos^2 \theta_W} \frac{a^Z_0}{\Lambda^2} F_{\mu\alpha} F_{\mu\beta} Z^\alpha Z_\beta \]
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CT-PPS accelerated program

CMS and ATLAS reported last year an excess of events in the 750 GeV region in the $\gamma\gamma$ channel:

- possible production by $\gamma\gamma$ fusion
- possible observation by CT-PPS in events with 2 surviving protons

At the beginning of the year it was decided to make an effort to have:

- the TOTEM Si strips fully integrated in the CMS DAQ to get data already at the beginning of 2016 LHC operations in high luminosity runs
- the Diamond detectors installed in the cylindrical pots as soon as available to provide additional tracking information

The resonance was not there, nevertheless CT-PPS has already taken precious data with the TOTEM Si strips and is going to take data with the diamonds.
TOTEM Si strips

- 10 planes of Si detectors
- 512 strips at ± 45°
- Pitch: 66 µm
- Resolution: ~ 20 µm

Micro-strip Si detectors designed to reduce the inefficiency at the edge.
Inefficient edge ~ 50 µm
Si strip integration and performance

- Si strips integrated in the CMS DAQ

DQM screenshot (example)
Si strip integration and performance

Si strips efficiency

Very good efficiency
Si strip integration and performance

- ~8fb\(^{-1}\) data taken
  - Data taking stopped due to radiation damage in the high occupancy region (as expected)

- Hit/track reconstruction performed using consolidated Totem algorithms (software fully integrated in CMS official software)

- Alignment algorithms under test
- Proton kinematics reconstruction still preliminary
  - Alignment
  - Detailed optics knowledge
Current status of the project

- Roman Pots regularly inserted at $15 \, \sigma_{\text{beam}}$ without problems
- Si strips fully integrated in CMS (DAQ, slow-control, data quality monitoring, offline software, etc.)
- $\sim 8/\text{fb}$ data taken with Si strips at high (nominal) luminosity
- Si strips damaged by radiation (as expected). Data taking temporarily stopped. Detector packages to be replaced (detectors already available)
- Diamond detectors installed but not yet operational. Data taking start expected in September (just after TS2 or if possible earlier)
- Data are being analyzed
Towards full CT-PPS

- **Tracking**
  - 3D pixel tracker on schedule. Installation foreseen during winter shutdown (EYETS)

- **Timing**
  - Diamond detectors installed
  - UFSD expected to be ready for installation at the end of the year

- **Full DAQ and Software integration within the winter shutdown**
Conclusions

- CT-PPS accelerated program was successful even if there is no 750 GeV resonance

- The integration of Si strips is paying in terms of useful data and expertise

- 8/fb data useful for commissioning and hopefully for physics

- The new detectors are on schedule and expected to be operational beginning 2017

- Data analysis ongoing
Back up
Timing detectors

- QUARTIC detectors
  - Quartz L-bar Cherenkov detectors
  - 3x3 mm² bars in a 4x5 array
  - resolution from early test beams $\sigma_T \sim 30$ ps (needs to be confirmed)

- Diamond detectors
  - 500 $\mu$m thick sensors, 5 mm² pads, $\sigma_T \sim 80$ ps per plane, better than 50 ps with a package of 4 planes (TOTEM group)
  - variable pad dimensions to optimize occupancy

- Ultra Fast Silicon Detectors
  - Recent beam test results achieve $\sigma_T \sim 115$ ps with 300 $\mu$m thickness (N. Cartiglia et al, 2015)
  - expect $\sigma_T \sim 40$ ps per plane with 50 $\mu$m thick silicon

- Diamonds and UFSD wrt Cherenkov
  - Finer segmentation and hence lower occupancy
  - Thin and light detectors: reduces nuclear interactions and allow for a larger number of layers (which enhances timing resolution)
Timing detectors: QUARTIC

- L-bar Cherenkov detectors
- 3x3 mm² bars in a 4x5 array
- resolution from early test beams $\sigma_T \sim 30$ ps (needs to be confirmed)
- Readout with SiPM, NINO discriminator and HPTDC digitizer
### Exclusive WW production

#### Cuts and cross sections (fb)

<table>
<thead>
<tr>
<th>Selection</th>
<th>SM exclusive WW (incorrectly reconstructed)</th>
<th>SM inclusive WW</th>
<th>SM exclusive WW (ττ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>generated (\sigma \times B(WW \rightarrow e\mu \nu\bar{\nu}))</td>
<td>0.86±0.01</td>
<td>2537</td>
<td>1.78±0.01</td>
</tr>
<tr>
<td>(\geq 2) leptons ((p_T &gt; 20) GeV, (\eta &lt; 2.4))</td>
<td>0.47±0.01</td>
<td>1140±3</td>
<td>0.087±0.003</td>
</tr>
<tr>
<td>opposite sign leptons, “tight” ID</td>
<td>0.33±0.01</td>
<td>776±2</td>
<td>0.060±0.002</td>
</tr>
<tr>
<td>dilepton pair (p_T &gt; 30) GeV</td>
<td>0.25±0.01</td>
<td>534±2</td>
<td>0.018±0.001</td>
</tr>
<tr>
<td>protons in both PPS arms (ToF and TRK)</td>
<td>0.055 (0.054)±0.002</td>
<td>0.044 (0.085)±0.003</td>
<td>11 (22)±0.3</td>
</tr>
<tr>
<td>no overlapping hits in ToF + vertex matching</td>
<td>0.033 (0.030)±0.002</td>
<td>0.022 (0.043)±0.002</td>
<td>0.004±0.001</td>
</tr>
<tr>
<td>ToF difference, (\Delta t = (t_1 - t_2))</td>
<td>0.033 (0.029)±0.002</td>
<td>0.011 (0.024)±0.001</td>
<td>0.003 (0.002)±0.001</td>
</tr>
<tr>
<td>(N_{\text{tracks}} &lt; 10)</td>
<td>0.028 (0.025)±0.002</td>
<td>0.009 (0.020)±0.001</td>
<td>0.002±0.001</td>
</tr>
</tbody>
</table>

#### aQGC

<table>
<thead>
<tr>
<th>Selection</th>
<th>(a^W_0/\Lambda^2 = 5 \times 10^{-6}) GeV(^{-2}) ((a^W_0 = 0))</th>
<th>(a^W_C/\Lambda^2 = 5 \times 10^{-6}) GeV(^{-2}) ((a^W_0 = 0))</th>
</tr>
</thead>
<tbody>
<tr>
<td>generated (\sigma \times B(WW \rightarrow e\mu \nu\bar{\nu}))</td>
<td>3.10±0.14</td>
<td>1.53±0.07</td>
</tr>
<tr>
<td>(\geq 2) leptons ((p_T &gt; 20) GeV, (\eta &lt; 2.4))</td>
<td>2.33±0.08</td>
<td>1.00±0.04</td>
</tr>
<tr>
<td>opposite sign leptons, “tight” ID</td>
<td>1.82±0.08</td>
<td>0.78±0.03</td>
</tr>
<tr>
<td>dilepton pair (p_T &gt; 30) GeV</td>
<td>1.69±0.07</td>
<td>0.68±0.03</td>
</tr>
<tr>
<td>protons in both PPS arms (ToF and TRK)</td>
<td>0.52 (0.50)±0.04</td>
<td>0.18 (0.17)±0.02</td>
</tr>
<tr>
<td>no overlapping hits in ToF detectors</td>
<td>0.35 (0.32)±0.03</td>
<td>0.12 (0.11)±0.01</td>
</tr>
<tr>
<td>ToF difference, (\Delta t = (t_1 - t_2))</td>
<td>0.35 (0.32)±0.03</td>
<td>0.12 (0.11)±0.01</td>
</tr>
<tr>
<td>(N_{\text{tracks}} &lt; 10)</td>
<td>0.27 (0.24)±0.03</td>
<td>0.11 (0.10)±0.01</td>
</tr>
</tbody>
</table>