Physics Prospects with the CT-PPS Forward Proton Spectrometer

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CT-PPS project

CMS-TOTEM Precision Proton Spectrometer:

A new tool increasing the CMS potential in the search for New Physics

CMS-TOTEM Memorandum of Understanding:

CMS and TOTEM jointly undertake the PPS project

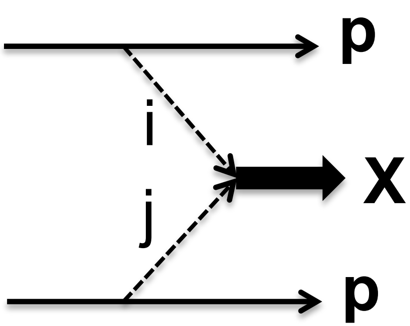
CT-PPS project approval:

CERN Research Board, December 2014

Central exclusive production

CEP : $p\,p \rightarrow p\,p\,X$

where X is a state measured in the central detector



X = high E_T jets, Z, WW, ZZ, …

i, j = photon or gluon exchanges

Four-momentum of X is fully constrained by the two protons kinematics:

- ξ – proton fractional momentum loss
- t – proton Mandelstam invariant

Physics motivations

BSM

Search for new physics

- Clean events (no underlying pp event)
- Independent energy-momentum measurement by pp system
- Search for new resonances and invisible states

EWK

LHC as a photon-photon collider

- Measure $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for AQGC with high sensitivity
- Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings

QCD

QCD physics

- Test of pQCD mechanisms of exclusive production.
- Gluon jet samples with small component of quark jets

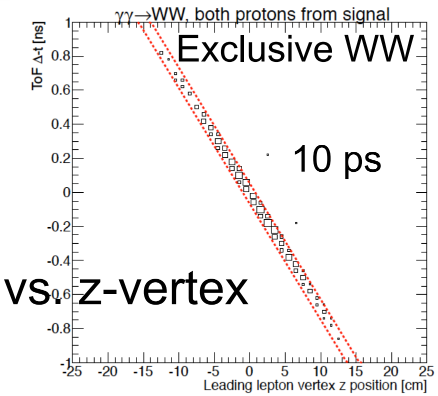
Detector concept

CT-PPS concept:

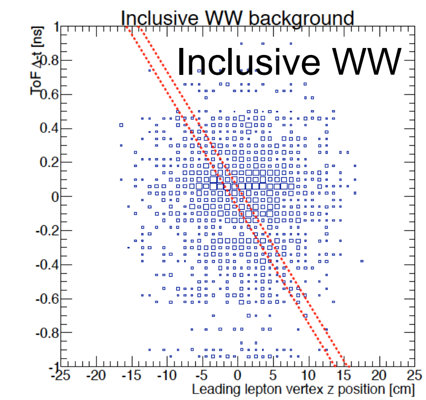
1) Proton spectrometer making use of **machine magnets**
2) Two tracking stations with **3D pixel detectors**
3) One stations with **10 ps timing detectors**

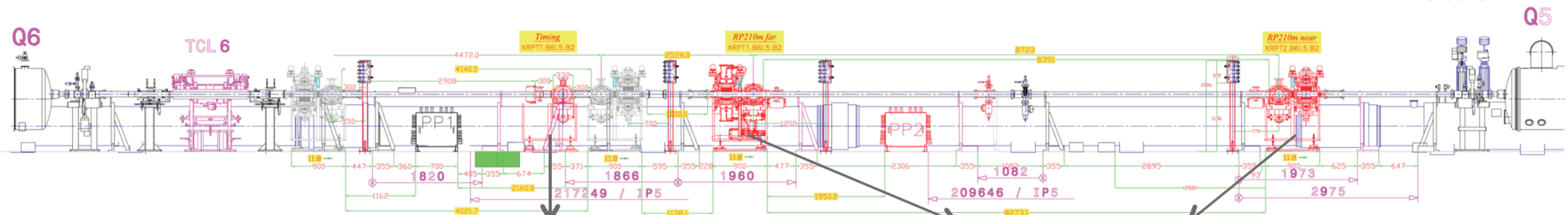
Use timing to reject pileup background

– time difference of two protons is correlated to collision vertex



ToF vs. z-vertex





2 new horizontal cylindrical RPs (1 in LS1)

2 horizontal box-shaped RPs

Main experimental issues

- Physics performance at high luminosity (2.10^{34} cm^{-2} s^{-1})
  - pileup background, beam background
- Detector operation close to the LHC beam
  - RF impedance, showers originated in the detectors
- Radiation levels
  - in detectors and front-end electronics
- Timing detectors
  - challenge is 10 ps resolution and high rates
- Tracking detectors
  - challenge is fluence 5.10^{15} $protons.cm^{-2}$ (100 fb^{-1})

Project phases

- The CT-PPS plan includes an **exploratory phase** in 2015-16 followed by a **production phase**.

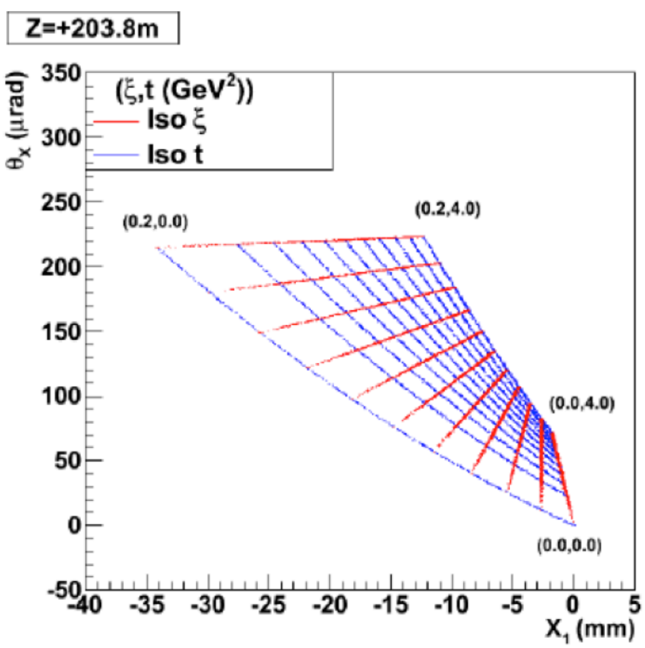
- **Exploratory phase (2015-16):**

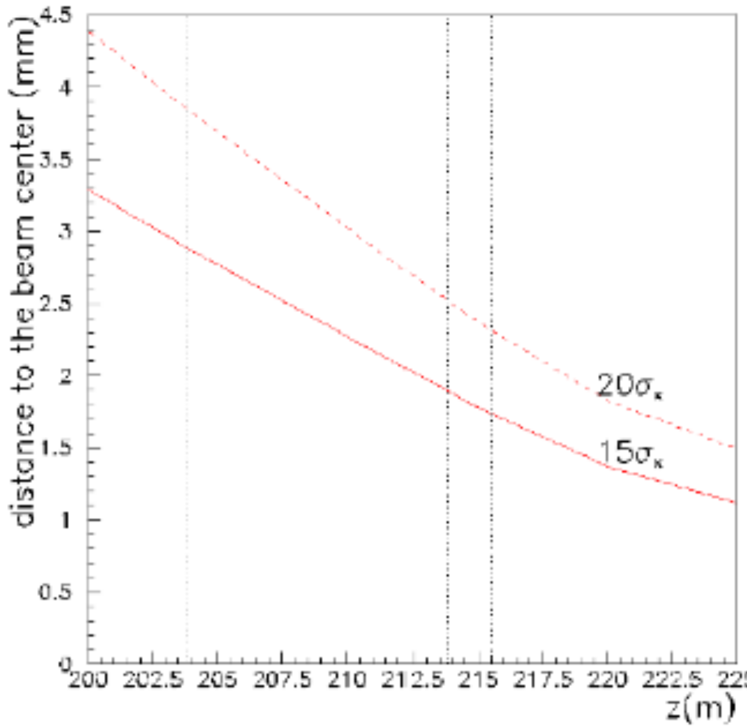
  Show that CT-PPS does not prevent the stable operation of the LHC beams and does not affect significantly the luminosity performance of the machine.

CT-PPS detector basics: acceptance and backgrounds

Beam optics

- HECTOR, a fast simulator for particle transport in a beamline
- Full transport line simulation in CMSSW



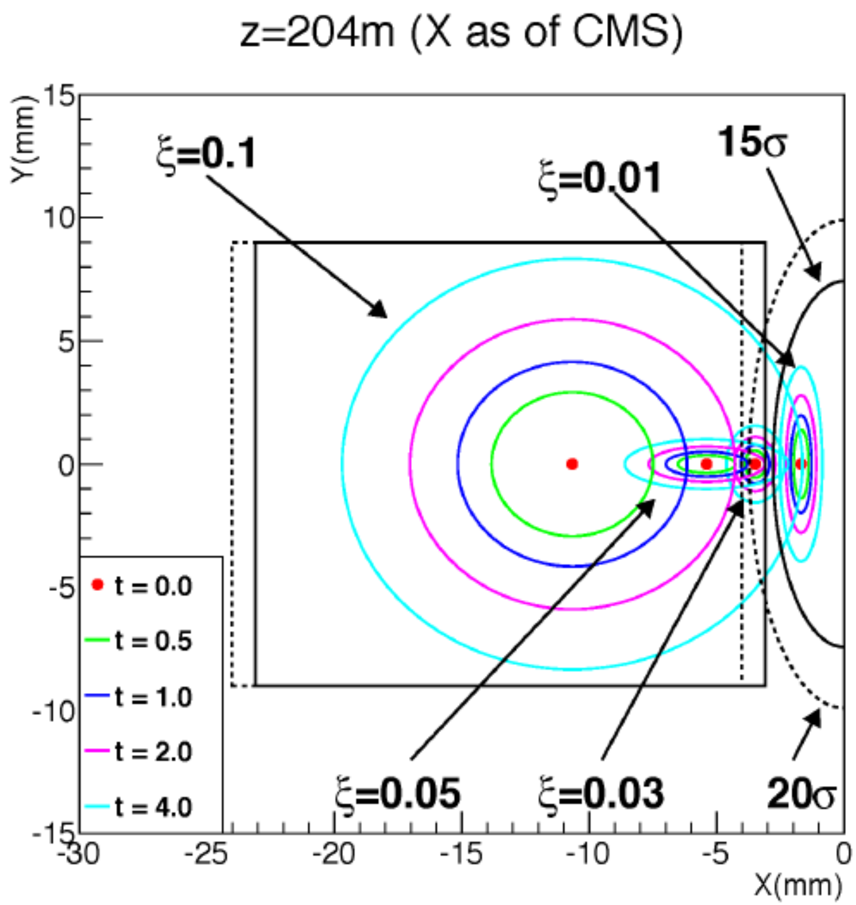


Horizontal distance to beam center in the z-range of the PPS detectors

Detector acceptance

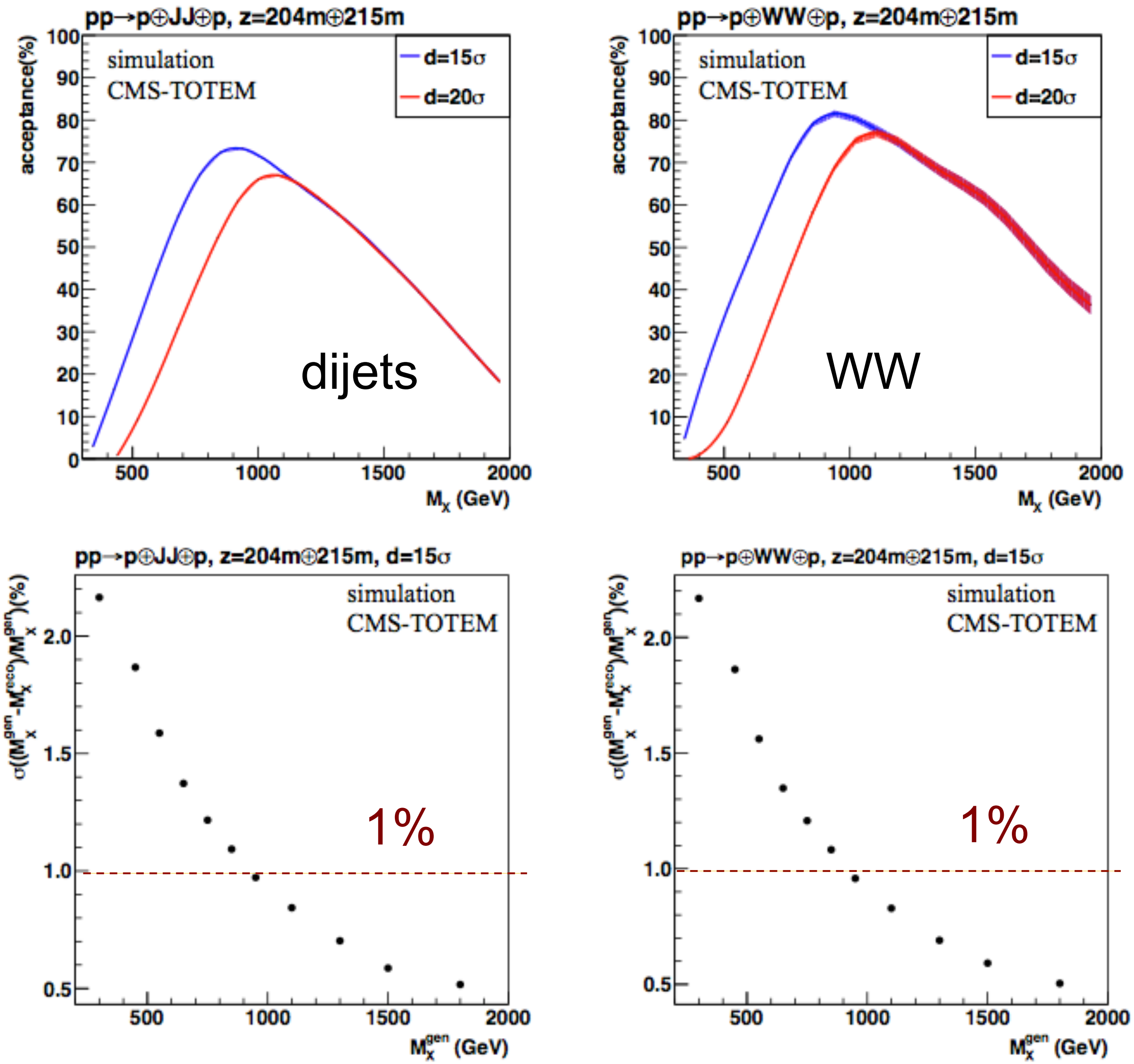
Acceptance ξ-t ellipses in x-y detector plane

- Particle gun (t,ξ,φ) based on HECTOR at √s = 13 TeV



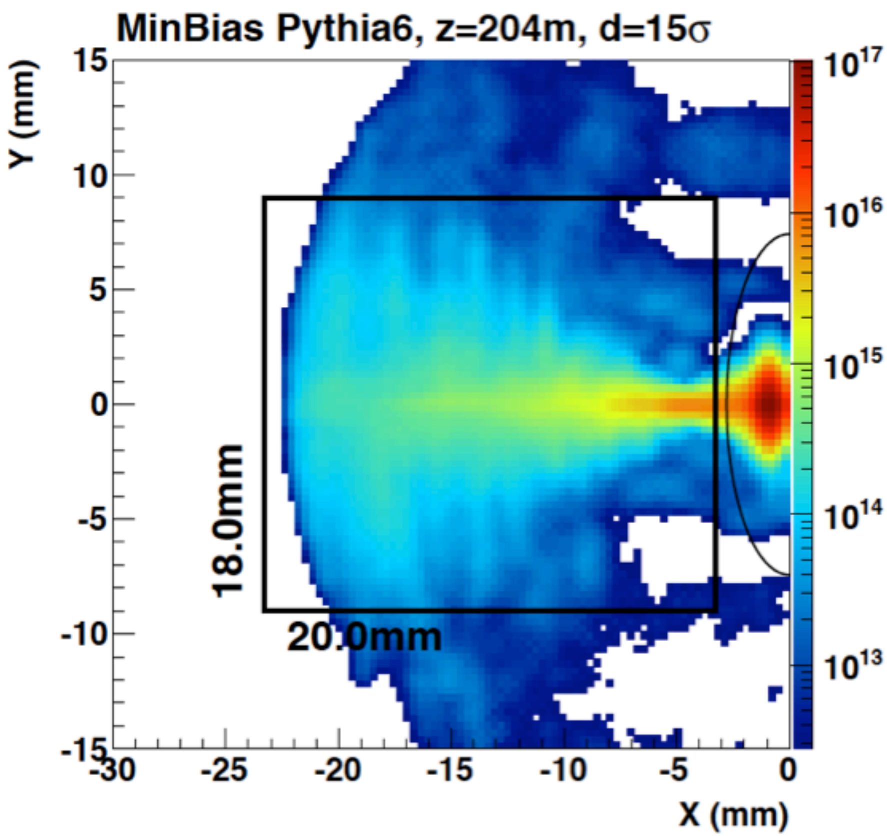
Mass acceptance and resolution

- Mass acceptance and resolution vs M_X
- PPS selects exclusive systems in 300-1700 GeV range (ε>5%)
- At 15σ acceptance larger by a factor of two (wrt 20σ) for lower masses
- Mass resolution ~1.5% at 500 GeV



Radiation levels

Radiation levels in the detector volume were studied using TOTEM data and simulations



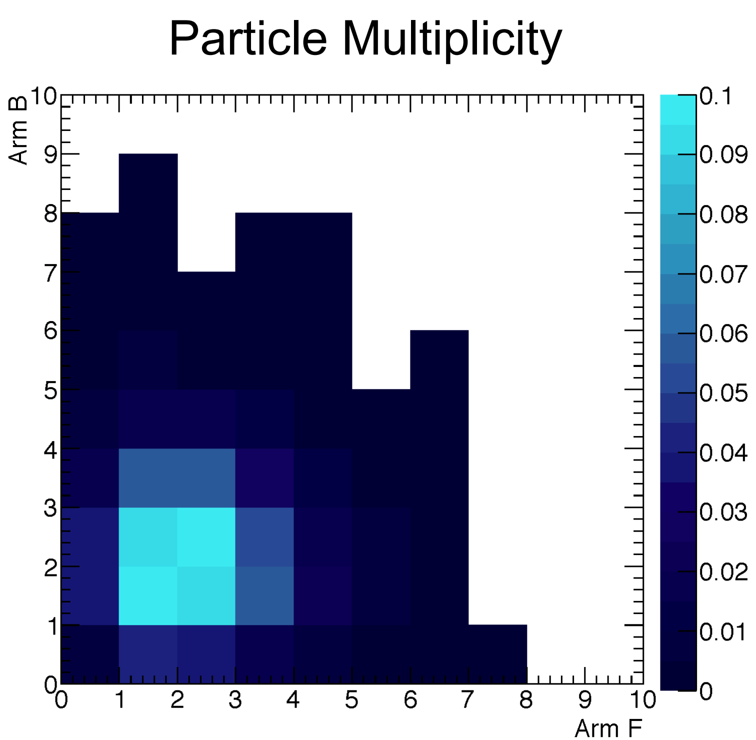
Per 100 fb^{-1}:

- Proton flux up to 5.10^{15} cm^{-2} in the **pixel detectors**
- 10^{12} neq/cm^2 and 100 Gy in **photosensors** and **readout electronics**

Detector occupancy

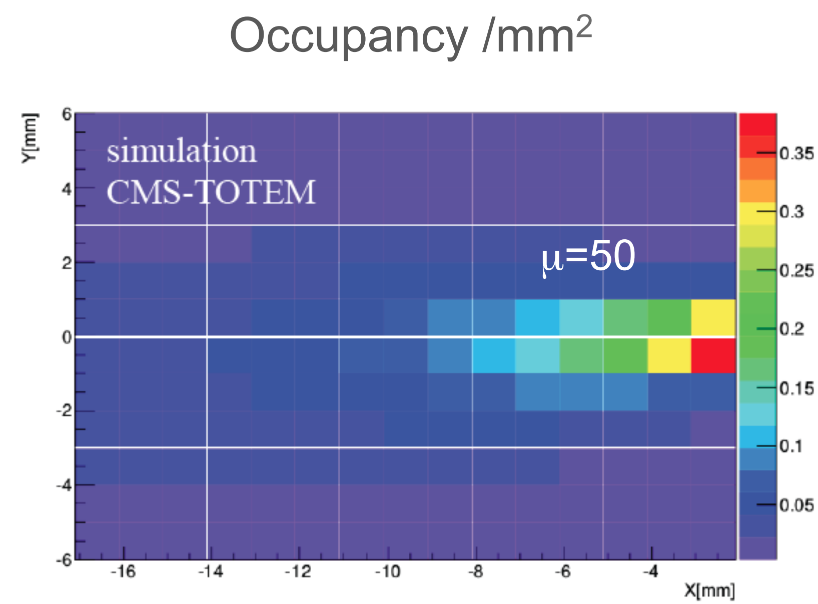
Single diffraction pileup

- Average proton multiplicity in detectors for WW signal with pilup μ =50 is approx. 2

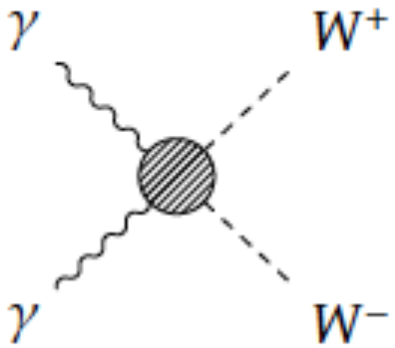


Expected occupancy:

- Beam-related backgrounds and pileup interactions are included.
- Occupancy of detectors at 15 σ from the beam



Physics case:
quartic gauge couplings



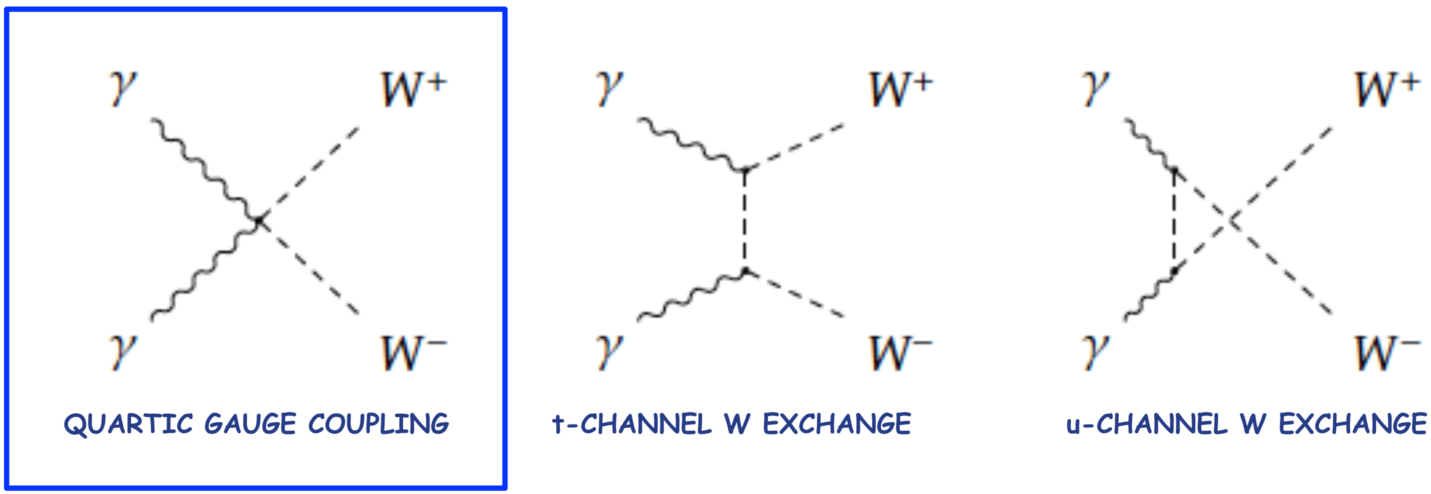
CEP production of W pairs in CMS at 8 TeV

Standard model framework

SM Lagrangian has triple and quartic couplings between γ and W bosons

$$\mathcal{L}^{WW\gamma} = -ie\, F_{\mu\nu} W^{+\mu} W^{-\nu}$$
$$\mathcal{L}^{WW\gamma\gamma} = -e^2 \left(W^+_\mu W^{-\mu} A_\nu A^\nu - W^+_\mu W^-_\nu A^\mu A^\nu \right)$$

SM contribution to $\gamma\gamma \rightarrow W^+W^-$ at leading order:



Measurements of the quartic WWγγ coupling can show deviations from the SM

Anomalous quartic couplings (I)

Formalism adopted in the CMS analysis:

AQGCs introduced via additional dimension-6 operators in the Lagrangian:

$$\mathcal{L}_6^0 = \frac{e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_\alpha^- - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^\alpha Z_\alpha$$

$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_\beta^- + W^{-\alpha} W_\beta^+) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^\alpha Z_\beta$$

containing:

- parameters a_0^W/Λ^2 and a_C^W/Λ^2
- Λ scale for new physics

Anomalous quartic couplings (II)

In the presence of the additional operators the $\gamma\gamma \rightarrow WW$ cross increases rapidly with the $\gamma\gamma$ center of mass energy ($W_{\gamma\gamma}$).

→ dipole form factors introduced to preserve unitarity

$$a_{0,C}^{W} \rightarrow a_{0,C}^{W}\left(W_{\gamma\gamma}^{2}\right) = a_{0,C}^{W}\left(1 + \frac{W_{\gamma\gamma}^{2}}{\Lambda_{\text{cutoff}}^{2}}\right)^{-2}$$

Λ_{cutoff} : energy cutoff scale

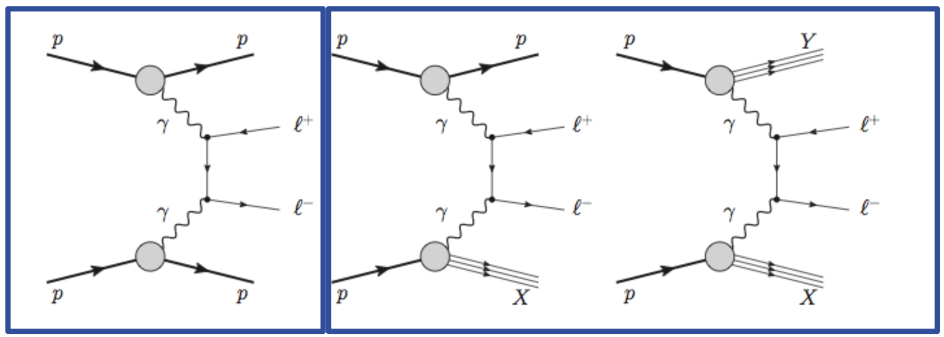
Two scenarios considered:

- $\Lambda_{cutoff} = 500$ GeV
- $\Lambda_{cutoff} \rightarrow \infty$ (no form factor)

Signal and background

Two contributions to signal:

- “elastic”production: pp → pW^+W^-p
- proton-dissociative production: pp → $p^*W^+W^-p^*$,



“ELASTIC" DISSOCIATIVE

Background sources:

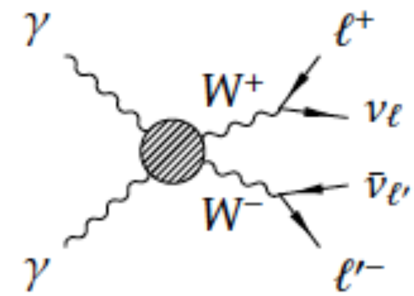
- Inclusive WW, ttbar, W+jets processes
- ττ pairs produced via the Drell-Yan process
- Exclusive two photon processes: γγ→ll
- WW production from single diffractive interactions
- WW→WW scattering (vector boson fusion)

All backgrounds estimated from Monte Carlo after comparison with data in control regions

Event selection

Different flavor dilepton decay channel:

$$\gamma\gamma \rightarrow W^+W^- \rightarrow \mu^\pm e^\mp \nu\bar{\nu}$$



Selection:

- Opposite sign leptons, with p_T>20 GeV and $|\eta|$<2.4, matched to common primary vertex
- **No extra tracks associated to the dilepton vertex**
- Dilepton invariant mass greater than 20 GeV

SM signal region:

$p_T(\mu e)$ > 30 GeV

AQGCs search:

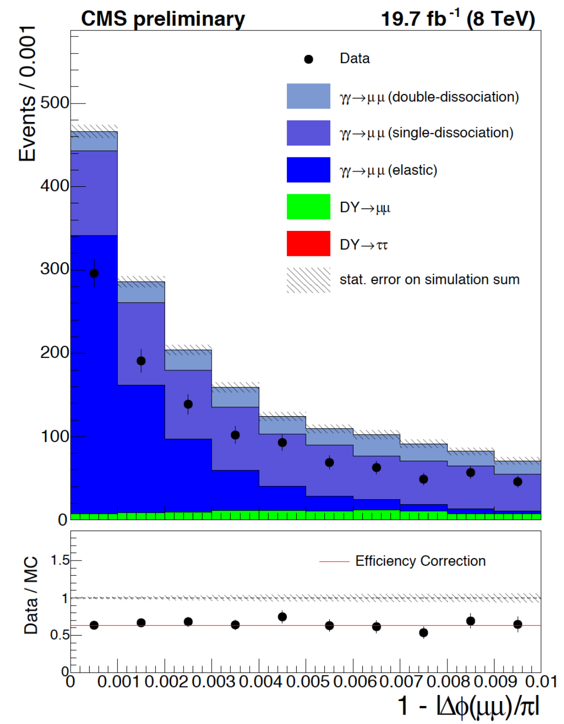
- 2 bins: $p_T(\mu e)$ = 30-130 GeV
  $p_T(\mu e)$>130 GeV

Correction factors from $\gamma\gamma \rightarrow ll$ sample

Control sample dominated by elastic $\gamma\gamma \rightarrow ll$ events:

- dilepton acoplanarity cut: $|1 - \Delta\phi(\ell^+\ell^-)/\pi| < 0.001$
- mass cut (to reject DY)

$$m(\ell^+\ell^-) < 70 \text{ GeV or } m(\ell^+\ell^-) > 106 \text{ GeV}$$



Zero extra-tracks efficiency correction

Data/MC: 0.63±0.04 in $\gamma\gamma \rightarrow \mu\mu$ sample

0.63±0.07 in $\gamma\gamma \rightarrow ee$ sample

Proton dissociation contribution to $\gamma\gamma$ interactions

- Separation of elastic and proton-dissociative events in data not possible without proton tagging (CT-PPS)
- Simulation of single or double dissociation production is not reliable

$$F = \left[\frac{N_{ll\ data} - N_{DY}}{N_{elastic}}\right]_{m(l^+l^-)>160\,GeV}$$

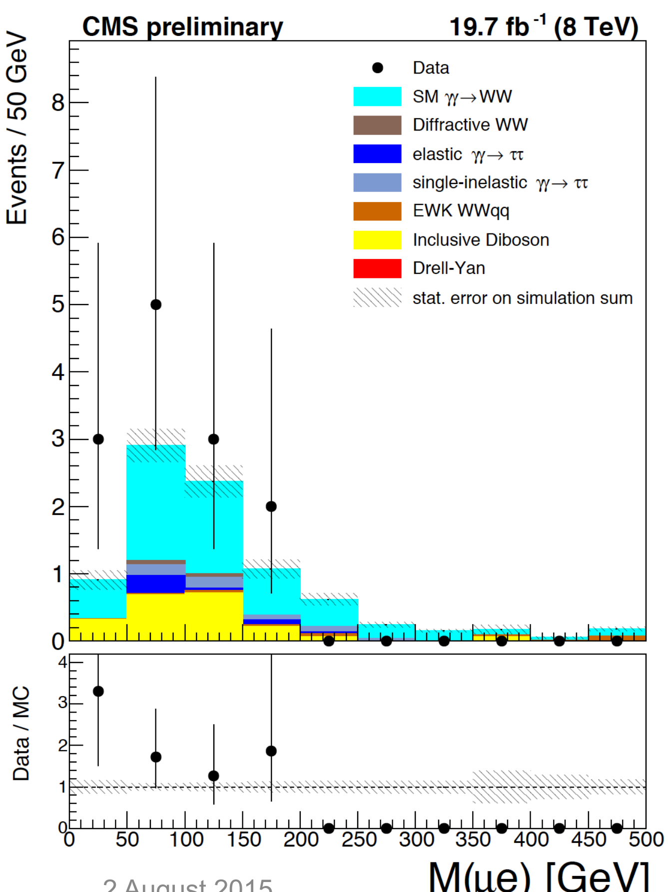
F=4.10±0.43

F used to correct the MC elastic pp → pW^+W^-p prediction to the total pp→$p^{(*)}W^+W^-p^{(*)}$ prediction, including proton dissociation

Results – cross section

Number of expected signal and background events

Signal	All backgrounds	Inclusive WW	γγ→ττ	DY→ττ	Diff. WW	Others
5.3±0.1	**3.5±0.5**	2.0±0.4	0.9±0.2	0	0.1±0.1	0.5±0.2



13 events are observed in data

Cross section measurement:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 12.3^{+5.5}_{-4.4}\text{fb}$$

SM prediction: 6.9 ± 0.6 fb

Observed significance above the background-only hypothesis: 3.6σ

Results – anomalous WWγγ coupling

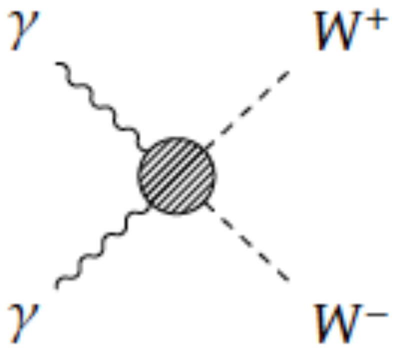
95% CL limits on a^W_0/Λ^2 and a^W_C/Λ^2, for two scenarios:

		OPAL (2004)	DØ (2013)	CMS (2013)	CMS(2015)
$a_0^W/\Lambda^2[GeV^{-2}]$	no form factor	$\pm 2\times 10^{-2}$	$\pm 4.3\times 10^{-4}$	$\pm 4.0\times 10^{-6}$	$\pm 1.2\times 10^{-6}$
	$\Lambda_{cutoff} = 500$ GeV		$\pm 2.5\times 10^{-3}$	$\pm 1.5\times 10^{-4}$	$(-1.1\ -\ 1.0)\times 10^{-4}$
$a_C^W/\Lambda^2[GeV^{-2}]$	no form factor	$^{+3.7}_{-5.2}\times 10^{-2}$	$\pm 1.5\times 10^{-3}$	$\pm 1.5\times 10^{-5}$	$\pm 4.4\times 10^{-6}$
	$\Lambda_{cutoff} = 500$ GeV		$\pm 9.2\times 10^{-3}$	$\pm 5.0\times 10^{-4}$	$(-4.2\ -\ 3.4)\times 10^{-4}$
				$\sqrt{s} = 7\ TeV$	$\sqrt{s} = 8\ TeV$

- Up to two orders of magnitude improvement to limits set by LEP and Tevatron

- One order of magnitude more stringent than CMS limits from tri-boson production:

  "A Search for WWγ and WZγ production in pp Collisions at √s = 8 TeV", CMS-PAS-SMP-13-009



CEP production of W pairs with CT-PPS

Simulation

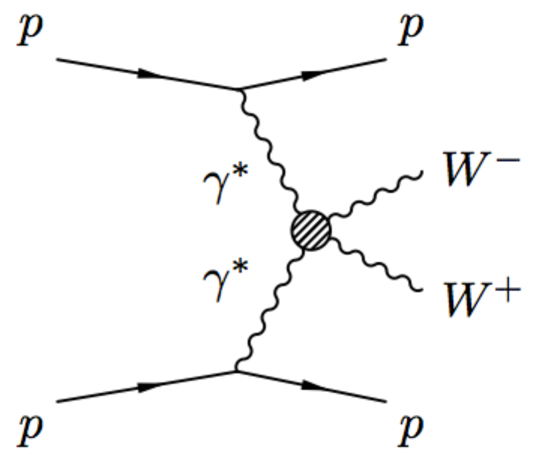
- Signal
  - FPMC generator
- Backgrounds
  - WW inclusive, Single Diffractive (SD) and Double Pomeron Exchange (DPE), multijet QCD, exclusive $\gamma\gamma \rightarrow \tau\tau$
- Pileup
  - 50 and 25 pileup samples.
- Simulation
  - GEANT4 simulation of the CMS central detector
  - Protons are tracked through the beam-line
  - Fast simulation of CT-PPS detectors
  - Beam induced backgrounds included

Study of WW production

- Study of process: **pp→pWWp**
  - Exclusive production of W pairs via photon exchange at 13 TeV

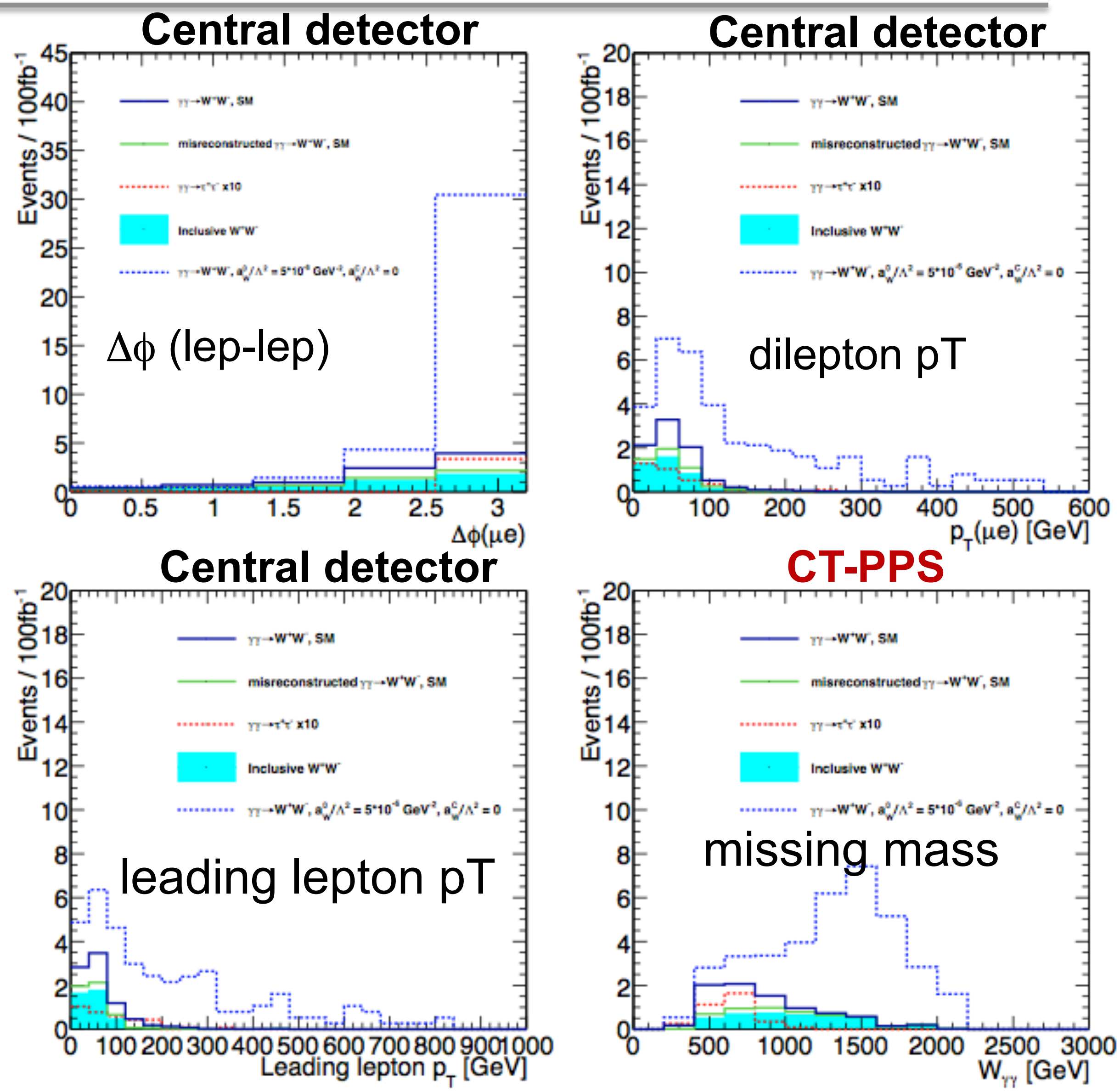
- **Events:** W pair in central detector, intact protons detected in CT-PPS
  Study only **eμ final state**

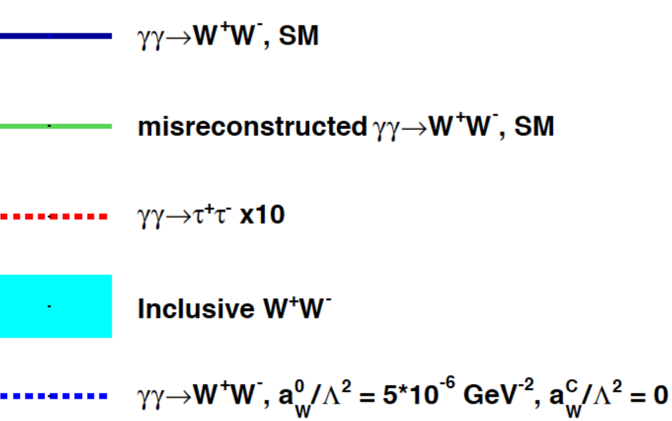
- **Two steps:**
  1. SM observation of WW events
     - σ_{WW}=95.6 fb
  2. Study of anomalous coupling
     - Two points: $a_0^W/\Lambda^2=5\text{x}10^{-6}$, $a_C^W/\Lambda^2=5\text{x}10^{-6}$



Kinematical distributions

Missing mass distributions provide a very clear separation of AQGC events





Yields (in fb)

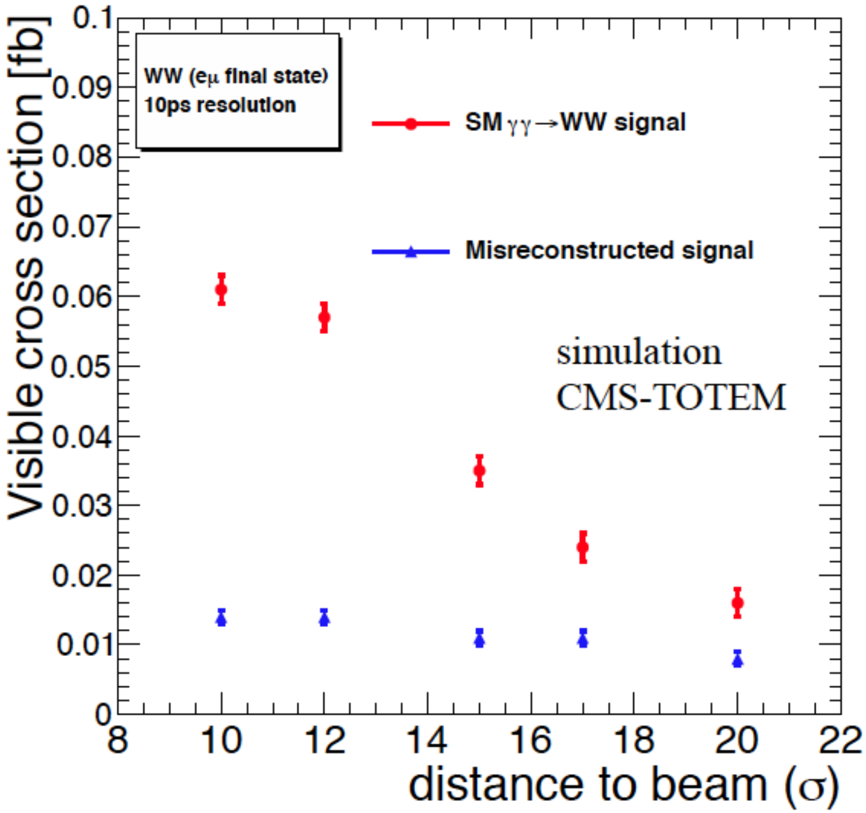
- Select WW events
- Apply central lepton and PPS acceptance cuts
- Additional timing and track multiplicity cuts
- Numbers in parenthesis are for time resolution of 30 ps

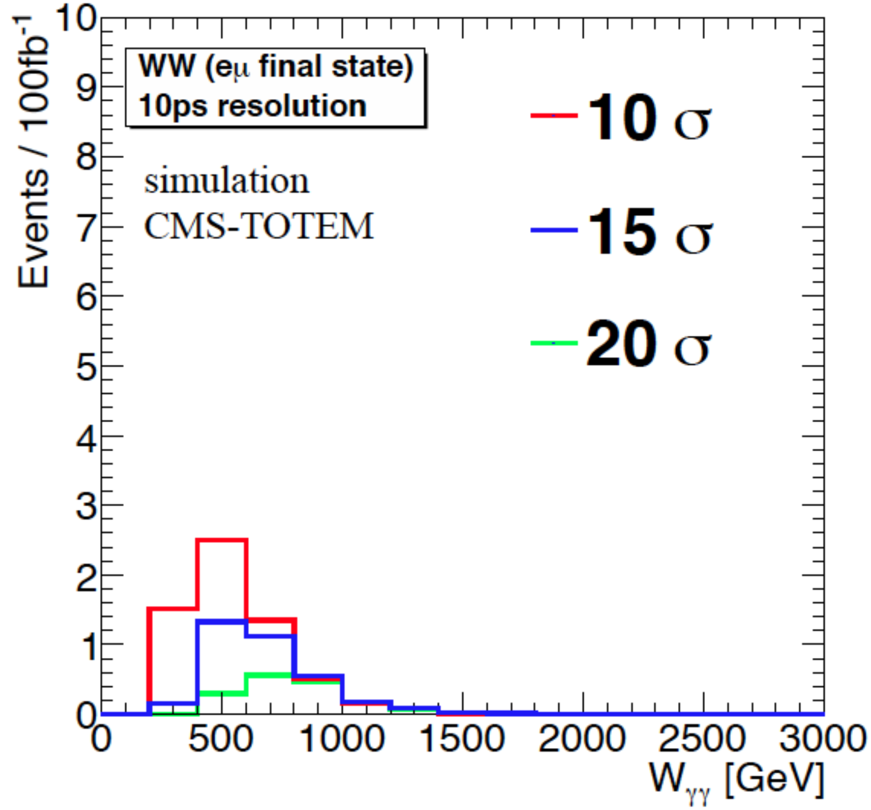
selection	cross section (fb)			
	exclusive WW	exclusive WW (incorrectly reconstructed)	inclusive WW	exclusive $\tau\tau$
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	0.86±0.01	N/A	2537	1.78±0.01
$\geq$ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	0.47±0.01	N/A	1140±3	0.087±0.003
opposite sign leptons, "tight" ID	0.33±0.01	N/A	776±2	0.060±0.002
dilepton pair $p_T > 30$ GeV	0.25±0.01	N/A	534±2	0.018±0.001
protons in both PPS arms (ToF and TRK)	0.055 (0.054)±0.002	0.044 (0.085)±0.003	11 (22)±0.3	0.004±0.001
no overlapping hits in ToF + vertex matching	0.033 (0.030)±0.002	0.022 (0.043)±0.002	8 (16)±0.2	0.003 (0.002)±0.001
ToF difference, $\Delta t = (t_1 - t_2)$	0.033 (0.029)±0.002	0.011 (0.024)±0.001	0.9 (3.3)±0.1	0.003 (0.002)±0.001
$N_{\text{tracks}} < 10$	0.028 (0.025)±0.002	0.009 (0.020)±0.001	0.03 (0.14)±0.01	0.002±0.001

S/B ~ 1

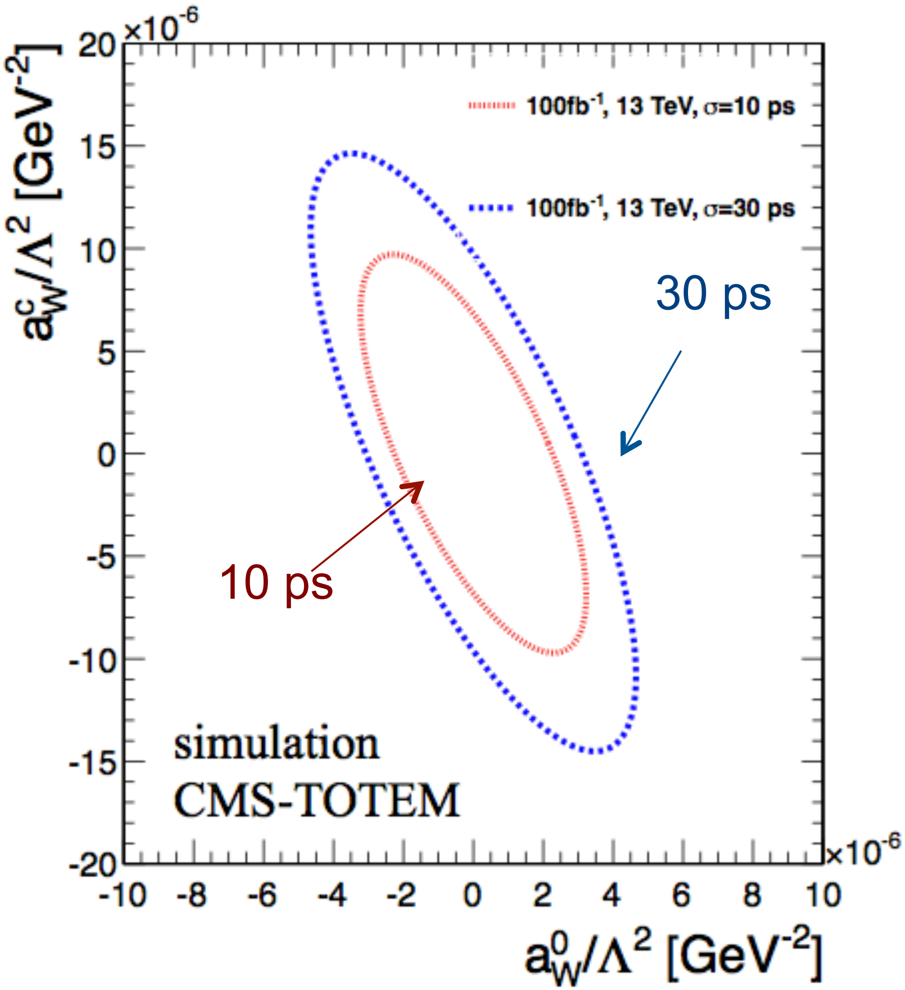
Dependence on distance to beam

Exclusive WW event yields





AQGC expected limits



Expected limits @95%CL:

with CT-PPS, 13 TeV, 100 fb^{-1}

$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6})\ \text{GeV}^{-2}$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6})\ \text{GeV}^{-2}$$

Observed limits @95%CL:

CMS Run 1, 8 TeV, 20 fb^{-1}

$$a_0^W/\Lambda^2 < 1.0 \times 10^{-4}\,\text{GeV}^{-2}$$
$$a_C^W/\Lambda^2 < 3.4 \times 10^{-4}\,\text{GeV}^{-2}$$

Two orders of magnitude improvement is expected

CT-PPS Detectors

Approaching detectors to the beam

Options considered:

- Roman Pots (RP) developed by TOTEM
- Movable Beam Pipe (MBP)

Main goals:

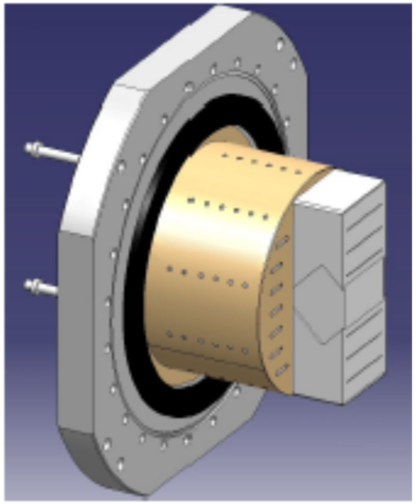
- Establish Roman Pot insertions for physics operation in regular fills from 2016
- Install detectors for run in 2016 and beyond

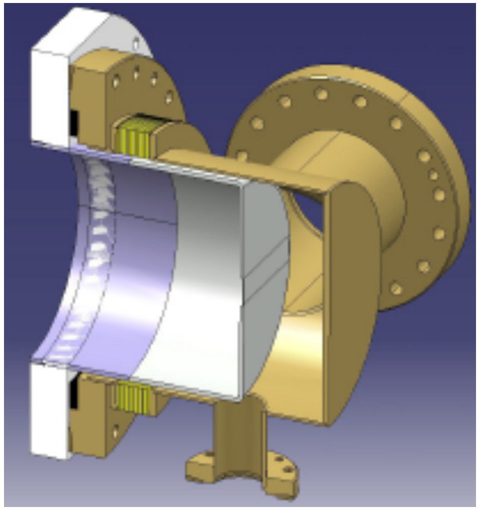
RP insertion commissioning:

- RP insertions at low β^* and highest beam intensities are being tested in the exploratory phase in 2015.

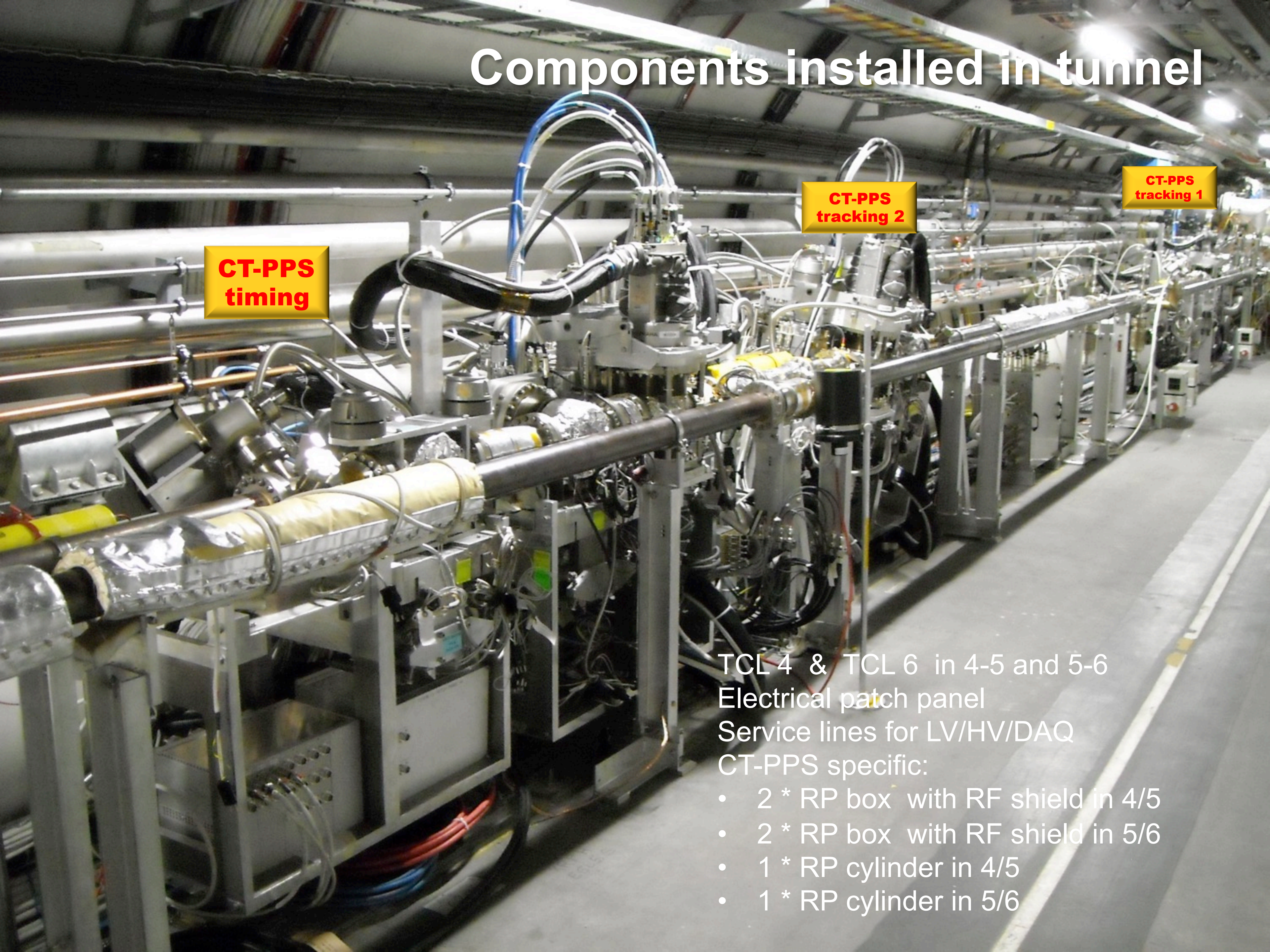
Roman Pots

- Tests of TOTEM RPs at high luminosity revealed important issues (vacuum, beam dumps, heating).
- Several improvements have been carried by TOTEM (and CMS) in collaboration with BE-ABP.
  - New RF shielding in standard box-shaped RPs
  - New cylindrical RP for timing detectors
  - 10 um thick copper coating
  - New ferrites





Components installed in tunnel



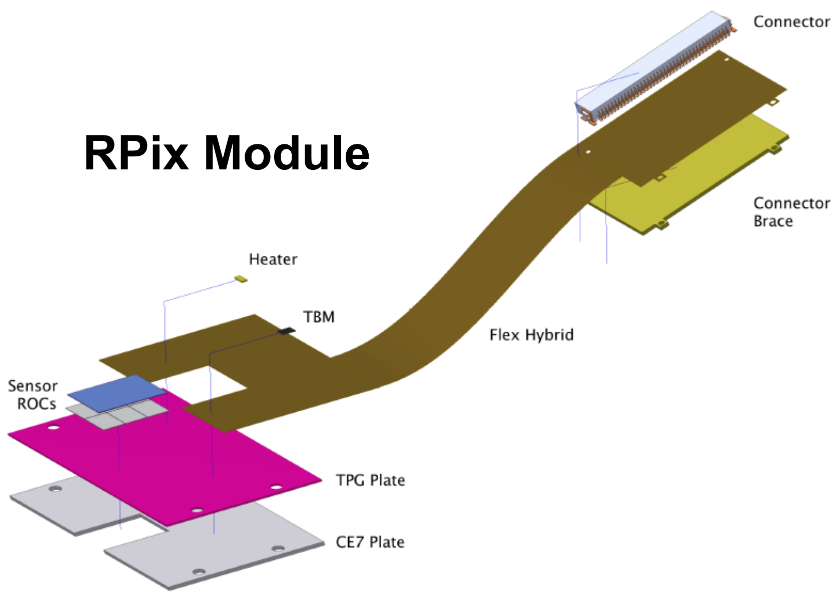
TCL 4 & TCL 6 in 4-5 and 5-6
Electrical patch panel
Service lines for LV/HV/DAQ
CT-PPS specific:

- 2 * RP box with RF shield in 4/5
- 2 * RP box with RF shield in 5/6
- 1 * RP cylinder in 4/5
- 1 * RP cylinder in 5/6

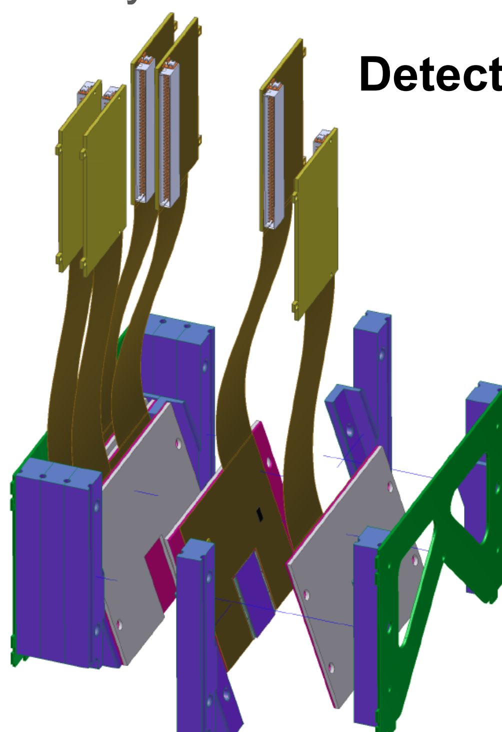
Tracking baseline

- 3D silicon sensors
- PSI46dig ROC, with same readout scheme as for Phase I Upgrade of the CMS pixel system
  - existing CMS DAQ components and software can be reused
- 6 detector planes per station
  - detectors are tilted in one direction
  - number of planes provide adequate redundancy

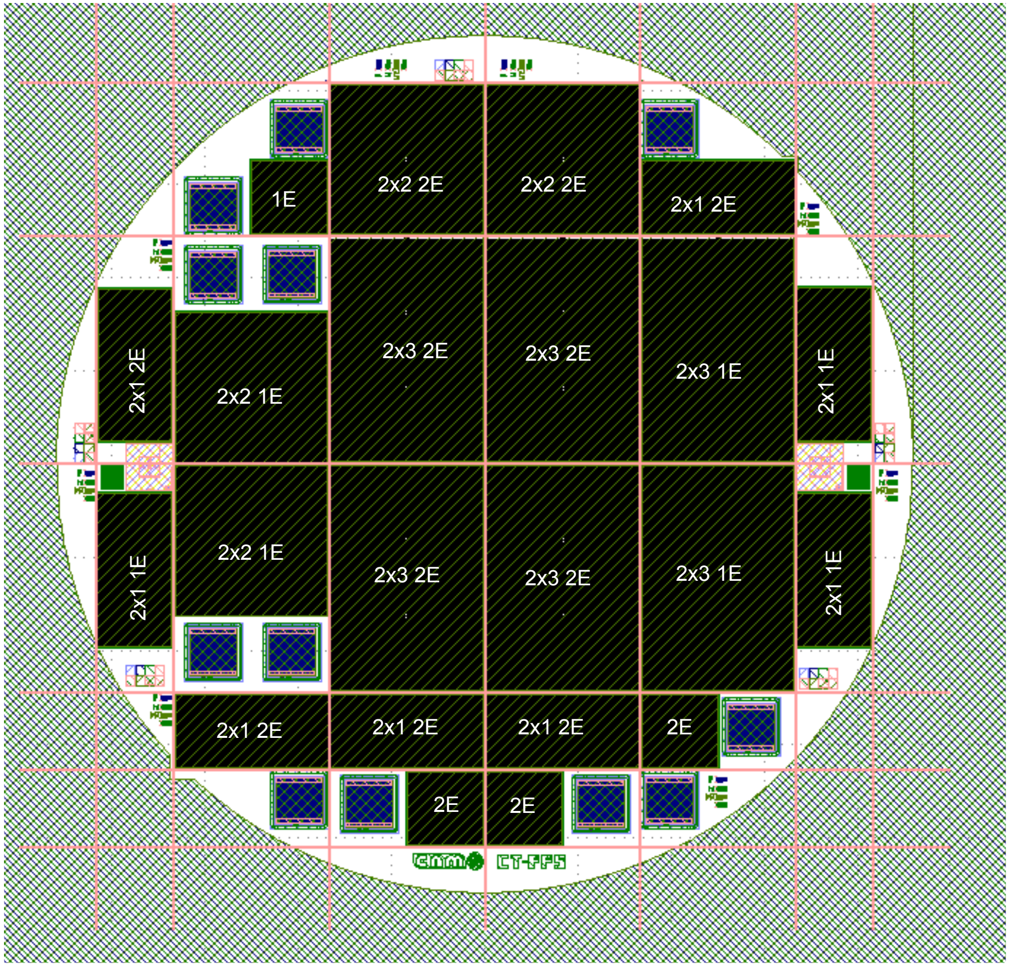
RPix Module



Detector support



3D sensors – wafer layout in production



Wafer thickness 230 μ m

FZ HR <100> silicon
p-type N=10^{12}atm/cm^3
p-stop isolation

	2E	1E
■ 6 detectors 2x3	4	2
■ 4 detectors 2x2	2	2
■ 8 detectors 2x1	5	3
■ 4 single chip	3	1
■ Diodes	6	6

With the first 12 wafers:

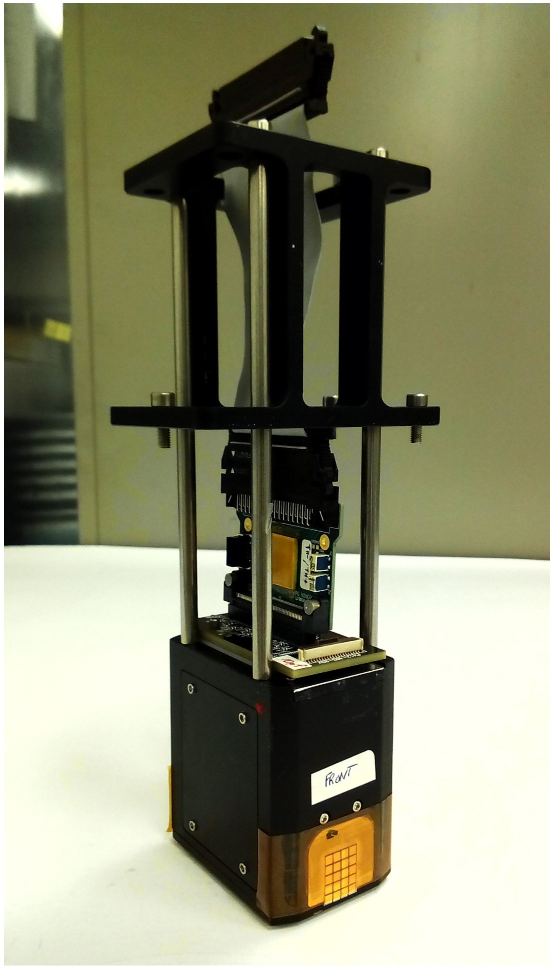
- 48 sensors 2x3 & 2E and we need 24

In case of problems we could still mount 2x2 sensors (+ 2x1 sensors)

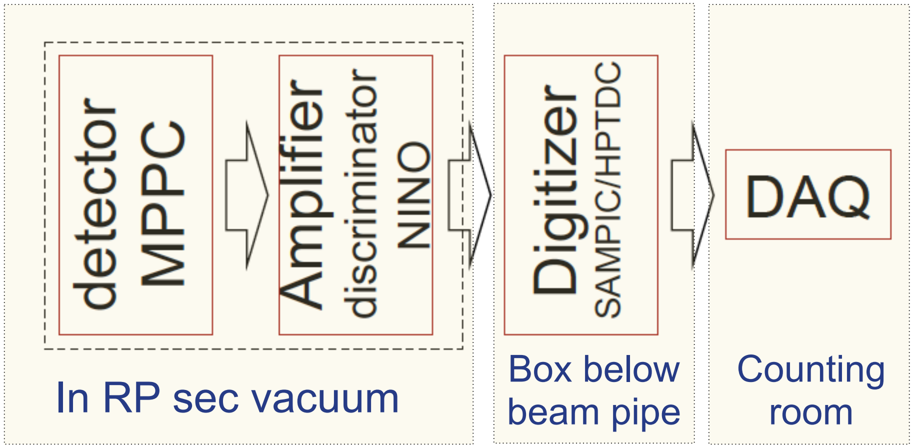
Timing baseline

Quartic detector:

- Detector is a 4 x 5 array of quartz bars, 3 x 3mm^2, SiPM light detection.
- Two such modules in one Roman pot in each arm.
- Radiator bars separated by 100 μm for total internal reflection
- Beam tests achieved $\sigma(t)$ = 30 ps/module (~ 20 ps for 2-in-pot)



Quartic readout chain



Timing R&D

GasTOF system

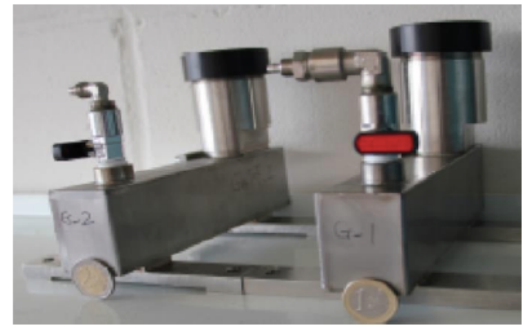
- prototype for test beam is on-going

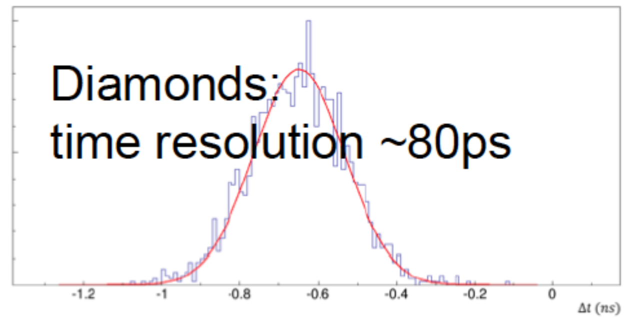
Diamond detectors

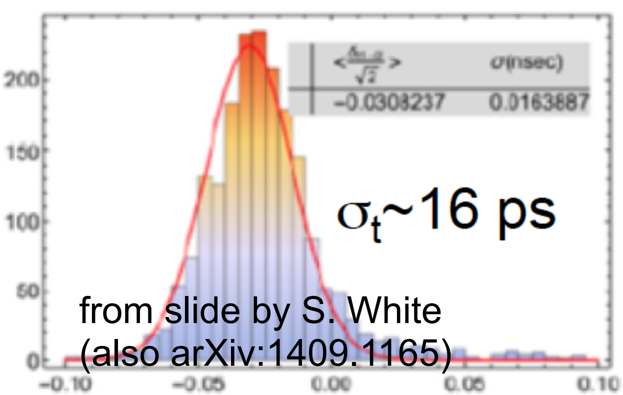
- effort led by TOTEM
- demonstrated 50 ps with 4 planes

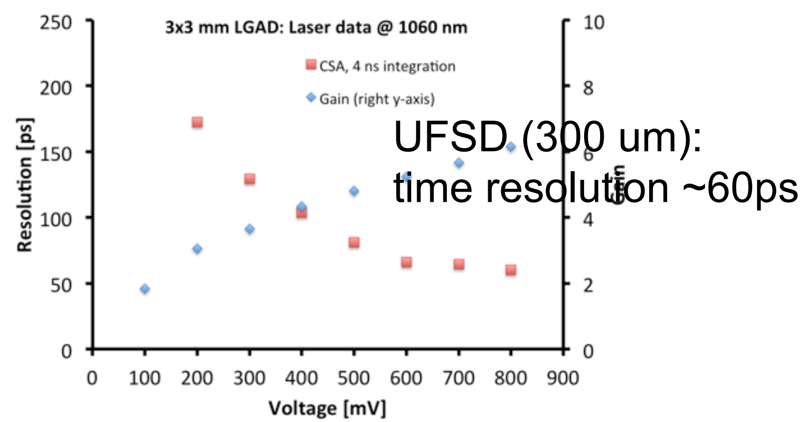
Silicon detectors

- Fast Silicon Detectors (UFSD):
  - 60 ps with new prototypes (laser)
- Plan to exploit Avalanche PhotoDiodes as charged particle timing detectors (Hyperfast Silicon)







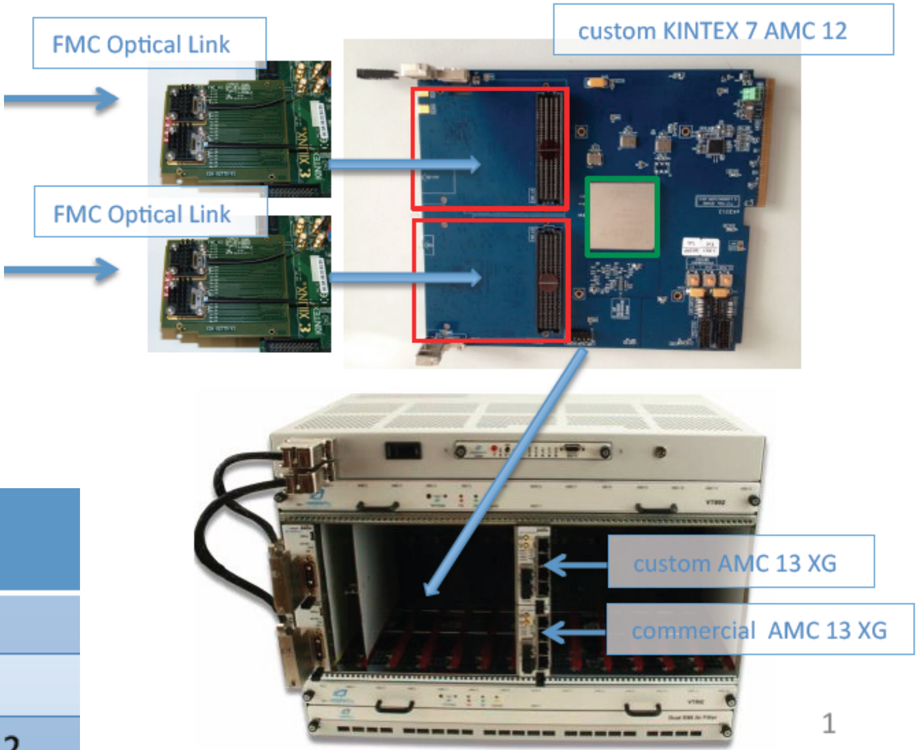


DAQ

Same readout scheme as Phase-1 upgrade of the CMS Pixel Tracker.

MicroTCA crate including:

- 2 CTA-FED, 2 CTA-tkFEC, 1 CTA-pkFEC
- FMC Optical mezzanines



Component	Prod.	Test & Spares	Prelim. Req.
uTCA Crates	1	2	3
AMC13XG	1	2	3
CTA	5	5(*)	10-12
GLIB	0	2(**)	0
FED FMC	3	3-4	6-7
FEC FMC	4	6-8	10-12

Summary

- CT-PPS is a new sub-detector that increases the potential of the CMS experiment
  - joint effort by CMS and TOTEM
- Forward proton tagging allows physics in a LEP like environment:
  - photon-photon and gluon-gluon interactions at precisely known center-of-mass energy
  - no underlying pp event
- Rich physics program with emphasis in the search for New Physics:
  - Sensitivity to anomalous gauge couplings is increased by two orders of magnitude
  - Search for new resonances and invisible states
- Big experimental challenges are being addressed:
  - operation of Roman Pots at the highest LHC luminosity
  - pileup mitigation using timing detectors with 10 ps resolution
  - 3D pixels tracking at very large particle fluence
- Plan to start collecting data in 2016