CMS-TOTEM Precision Proton Spectrometer: Status and Physics Prospects

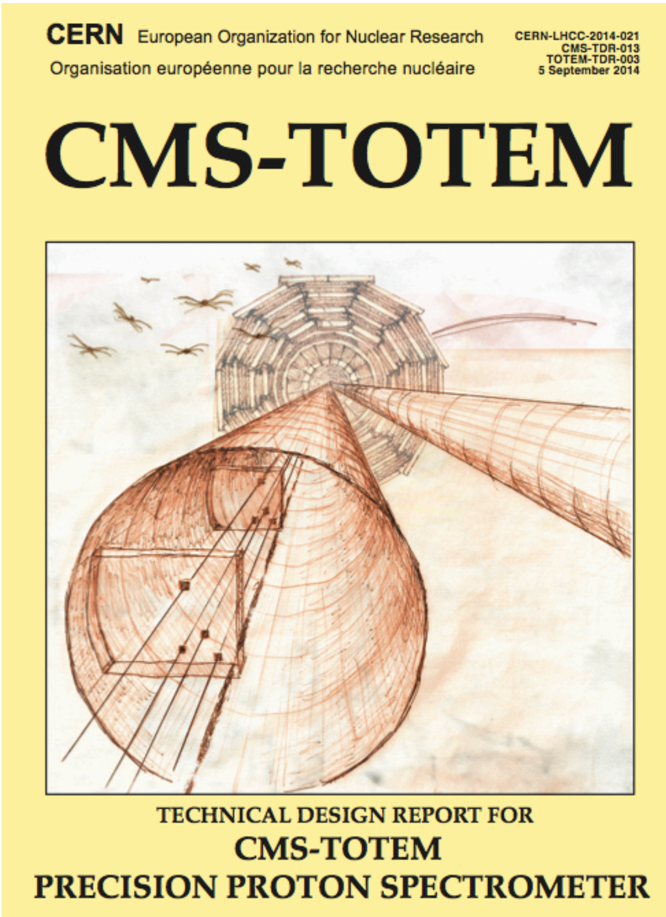
Michele Gallinaro

LIP Lisbon

October 28, 2015

- ✓ Introduction
- ✓ Physics motivation
- ✓ Detector performance
- ✓ Physics case: WW production
- ✓ Tracking and timing detectors
- ✓ Summary

Introduction

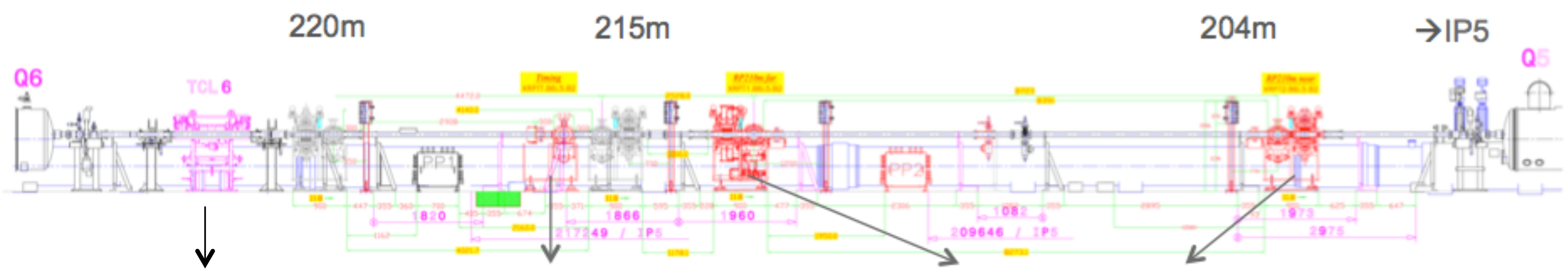


https://indico.cern.ch/event/334693/

- Sep. 2013: CMS approves PPS program
- Dec. 2013: Approval of CMS-TOTEM MoU
- Sep. 2014: TDR published
  - baseline design and alternative future solutions
- Dec. 2014: Project approved by LHCC and Cern Research Board

Detector concept

- The CMS-Totem Precision Proton Spectrometer (CT-PPS) will allow precision proton measurement in the very forward region on both sides of CMS in standard LHC running conditions
- Proton spectrometer uses machine magnets to bend protons
- Two stations for tracking detectors and two stations for timing detectors installed at ~205-215 m from the IP (on both sides)



New collimator TCL6 to protect magnet Q6

2 new horizontal cylindrical RPs (1 in LS1)

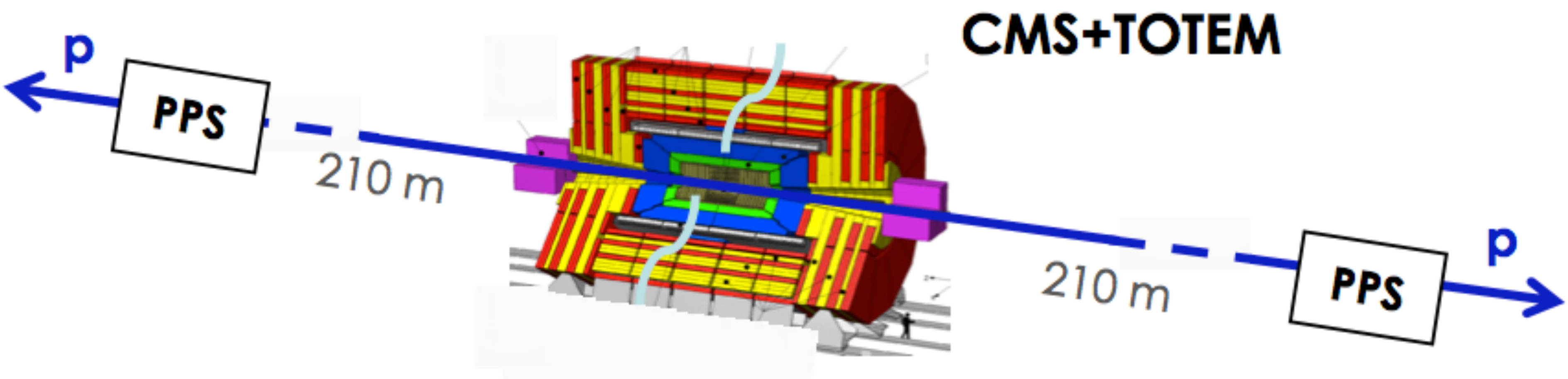
2 horizontal box-shaped RPs

timing detectors

tracking detectors

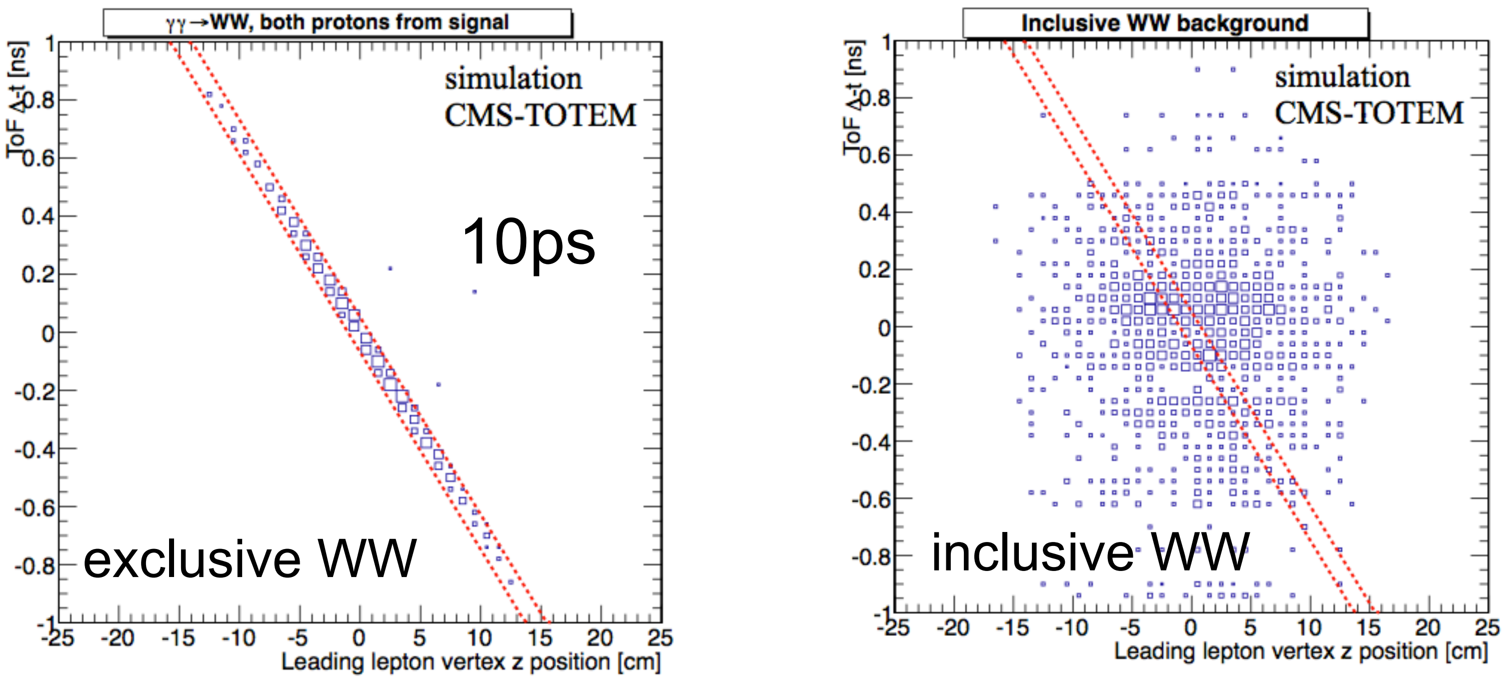
Experimental challenges

- Ability to operate the detectors close to beam (15-20σ) to maximize acceptance for low momentum loss (ξ) protons
- Limit RF impedance introduced by beam pockets
  - improved RF shielding of RPs
  - R&D on Movable Beam Pipe as future option
- Sustain high radiation levels
  - For 100/fb, proton flux up to 5×10^{15} cm^{-2} in tracking detectors, $10^{12} n_{eq}/cm^2$ and 100Gy in photosensors and readout electronics
- Reject background in the high-pileup (μ=50) of normal LHC running



Experimental challenges (cont.)

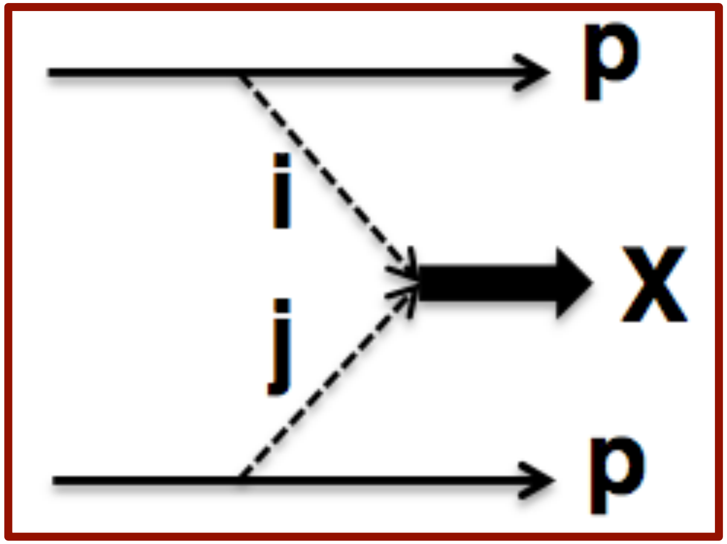
Time of flight vs z-vertex



⇒use timing information to reject pileup

(time difference of two protons is correlated with vertex position)

Central Exclusive Production (CEP)



pp→ p+X+p

X is a state measured in the central region

X: $\mu^+\mu^-$, Z, ZZ, jets

+: rapidity gap

i,j: only photon and gluon exchanges are allowed

4-momentum of X fully constrained by the two proton kinematics

ξ: proton fractional momentum loss

t: 4-momentum transferred squared

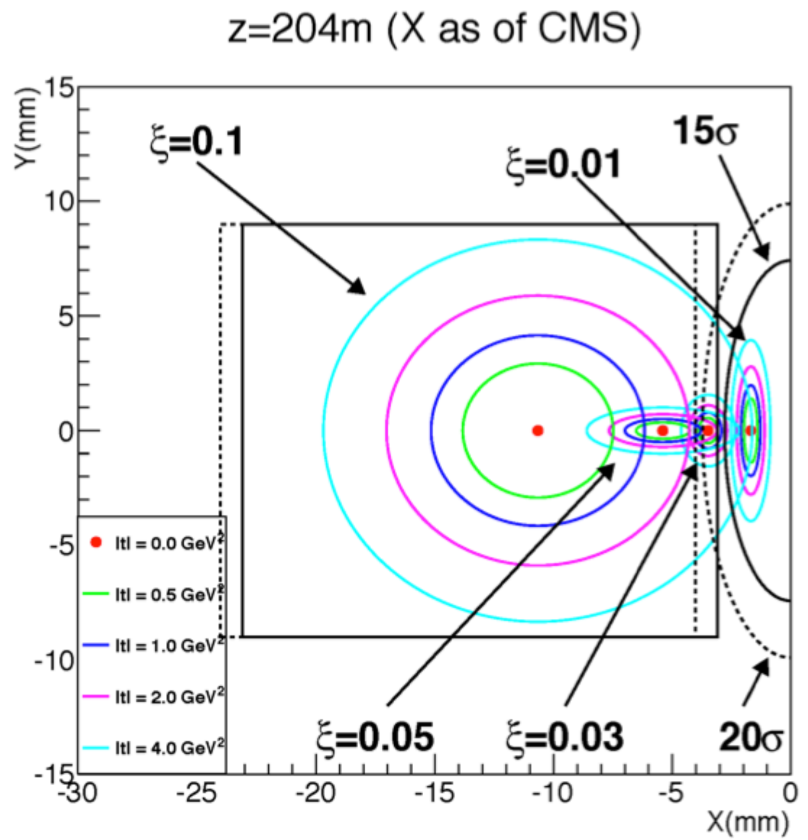
Physics motivations

- LHC used as photon-photon collider
  - Measure $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
  - Search for anomalous quartic gauge couplings (AQGCs) with improved sensitivity
  - Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings
- QCD physics
  - Exclusive 2- and 3-jet events, M up to ~700-800 GeV
  - Tests of pQCD mechanisms of exclusive production
  - Gluon jet samples with small component of quark jets
- BSM: search for New Physics
  - Clean events (no underlying pp event)
  - Independent mass measurement from pp system
  - Search for new resonances

Detector performance: acceptance

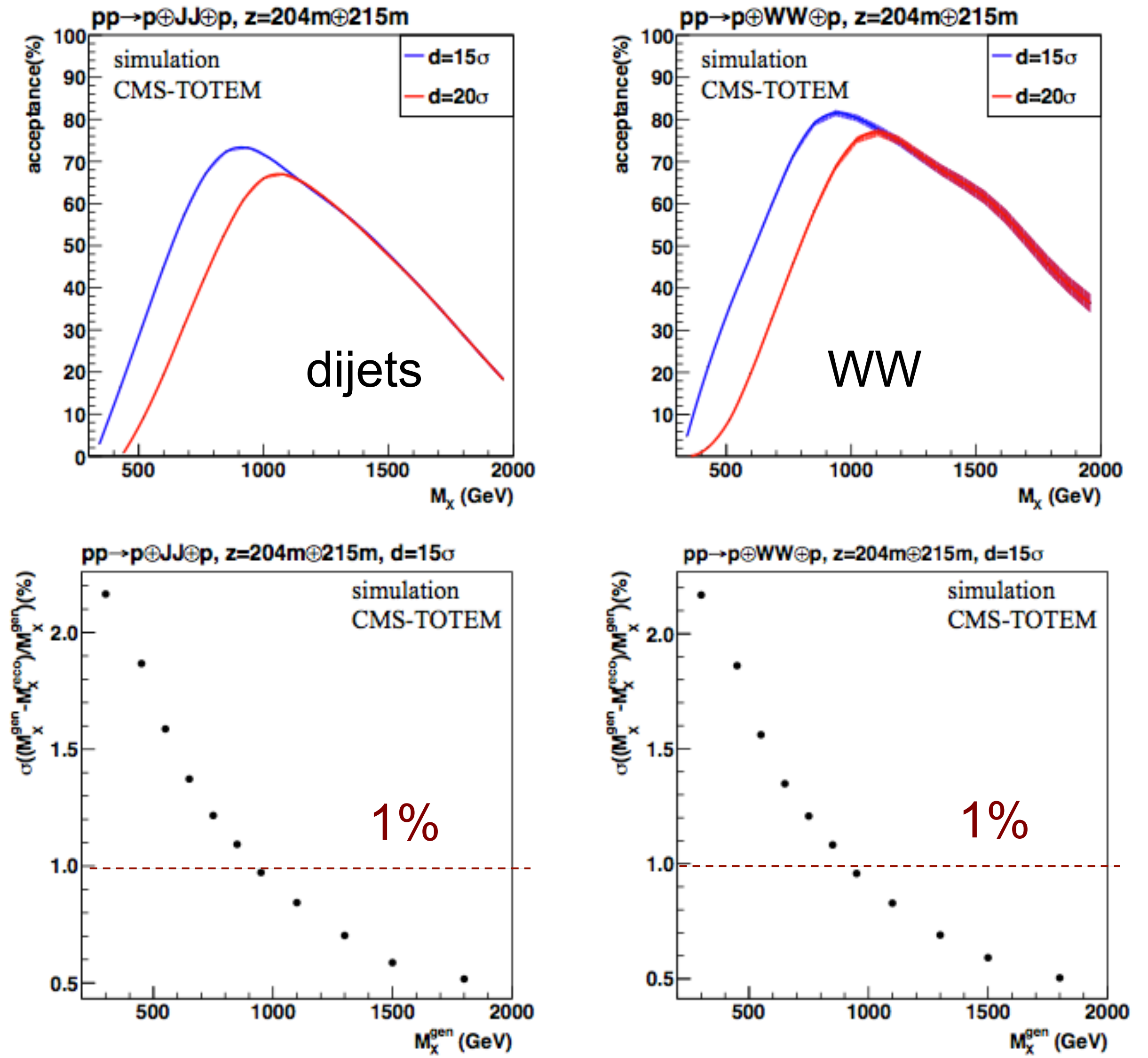
Acceptance: X vs Y (includes ξ,t ellipses)

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



Detector: mass resolution

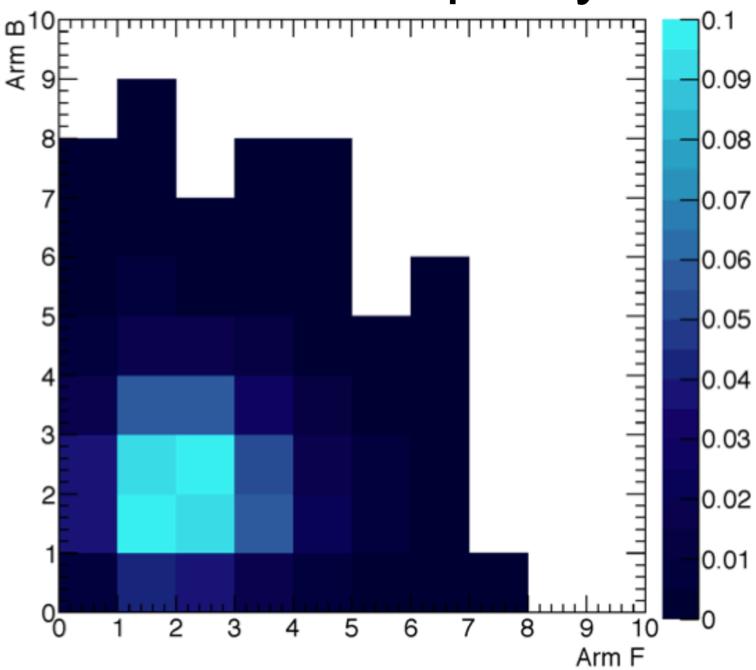
- Mass acceptance and resolution vs M_X
- PPS selects exclusive systems in 300-1700 GeV range (ε>5%)
- At 15σ acceptance larger by a factor of two (wrt 20σ) for lower masses
- Mass resolution ~1.5% at 500 GeV



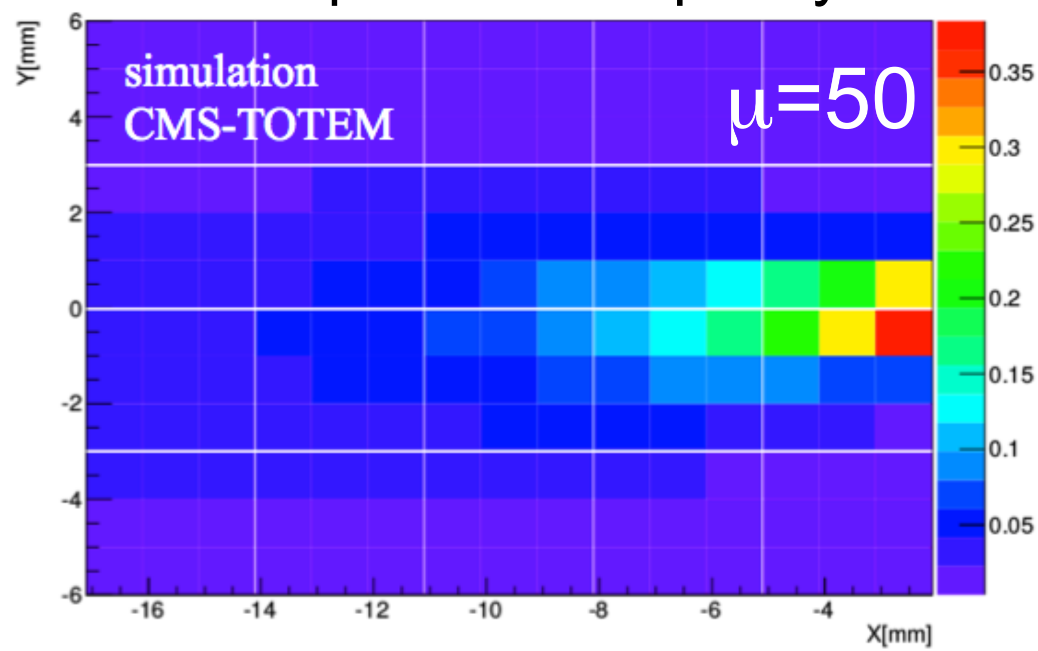
Detector occupancy

- Occupancy of time-of-flight detectors at 15σ
  - Inefficiency due to overlapping hits (of up to ~40%)
  - Beam related bkg and pileup interactions included
- Particle multiplicity (WW signal including pileup μ=50)

Particle multiplicity

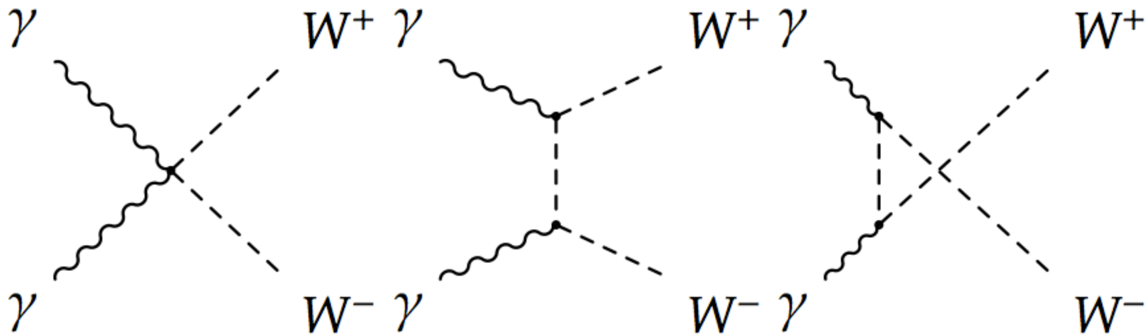


Expected occupancy



Physics prospects

- Study quartic gauge couplings
- CEP production of WW pairs
- Triple ($WW\gamma$) and quartic ($WW\gamma\gamma$) gauge couplings

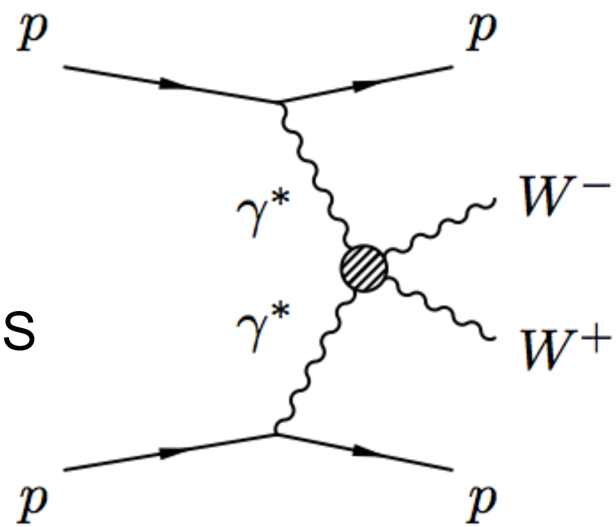


- Measurements can show deviation from SM

WW production

CMS-FSQ-13-008

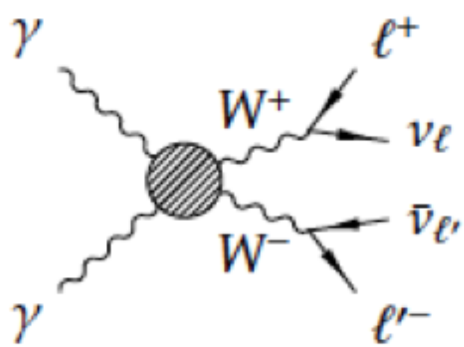
- Study of process: pp→pWWp
  - Clean process: W in central detector and "nothing" else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Backgrounds:
  - inclusive WW, ττ, exclusive two-photon γγ→ll, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_C^W/Λ^2

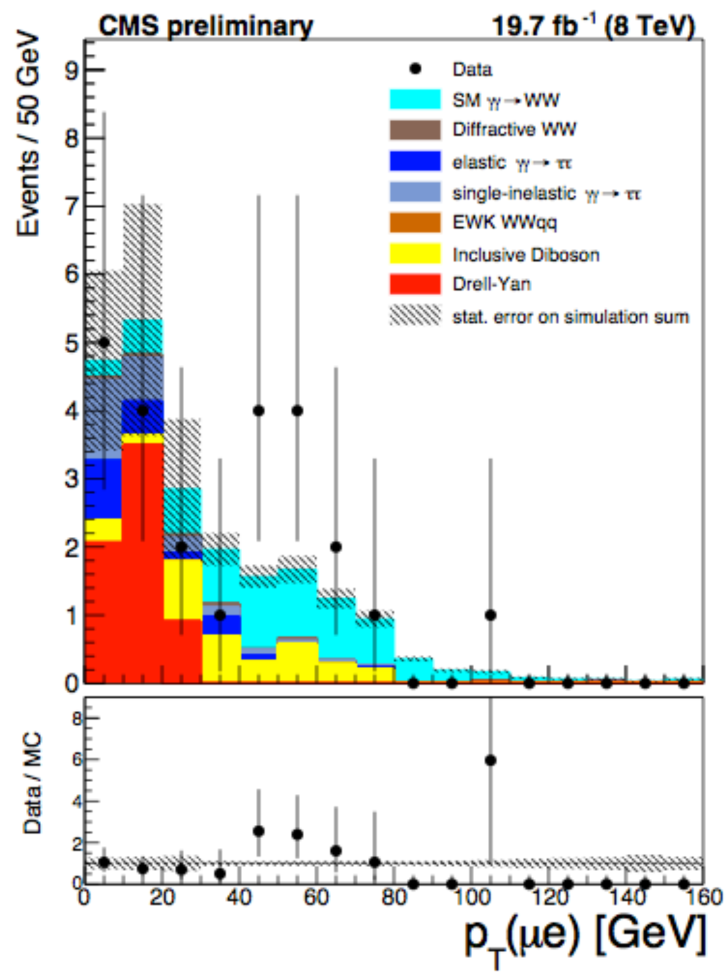


WW production: Selection

CMS-FSQ-13-008

- Dilepton decay channel (diff. flavor)
  - OS leptons (p_T>20GeV, $|\eta|$<2.4)
  - No extra tracks from vertex
  - M_{ll}>20 GeV
  - Use $p_T(\mu e)$ to discriminate
- SM signal region
  - $p_T(\mu e)$>30 GeV
- AGQC search
  - $p_T(\mu e)$=30-130GeV
  - $p_T(\mu e)$>130 GeV





WW production: Results

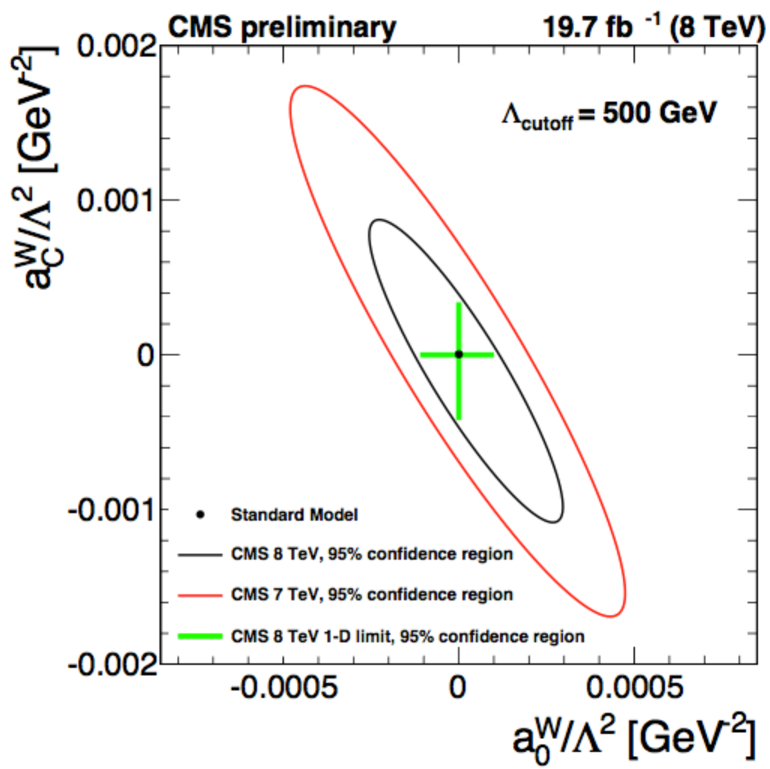
CMS-FSQ-13-008

- Cross section measurement

$$\sigma_{\mathrm{meas}} = 12.3^{+5.5}_{-4.4}\ \mathrm{fb}$$

- SM prediction is σ=6.9±0.6 fb
- Observed significance above background-only hypothesis: 3.6σ

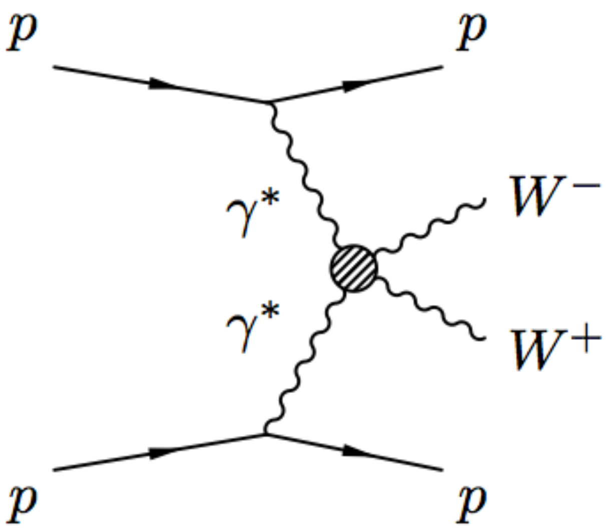
sample	yields
inclusive WW	2.0±0.4
$\gamma\gamma \to \tau\tau$	0.9±0.2
DY$\to \tau\tau$	0
diffractive WW	0.1±0.1
others	0.5±0.2
total backgrounds	3.5±0.5
signal (SM exclusive pp$\to$WW)	5.3±0.1
data	13



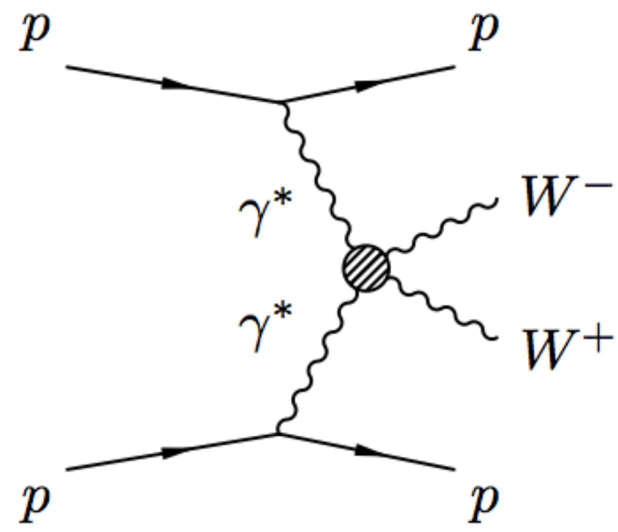
- AQGC results
  - 95%CL limits on a^W_C/Λ^2, a^W_C/Λ^2
  - Improvement of two orders of magnitude over LEP/Tevatron

Prospects with CT-PPS

- Exclusive WW
  - quartic gauge boson coupling $WW\gamma\gamma$
  - sensitivity to anomalous couplings
- Exclusive dijets
  - high jet p_T events (M_{jj} up to~400-500 GeV)
  - test of pQCD mechanism of exclusive production



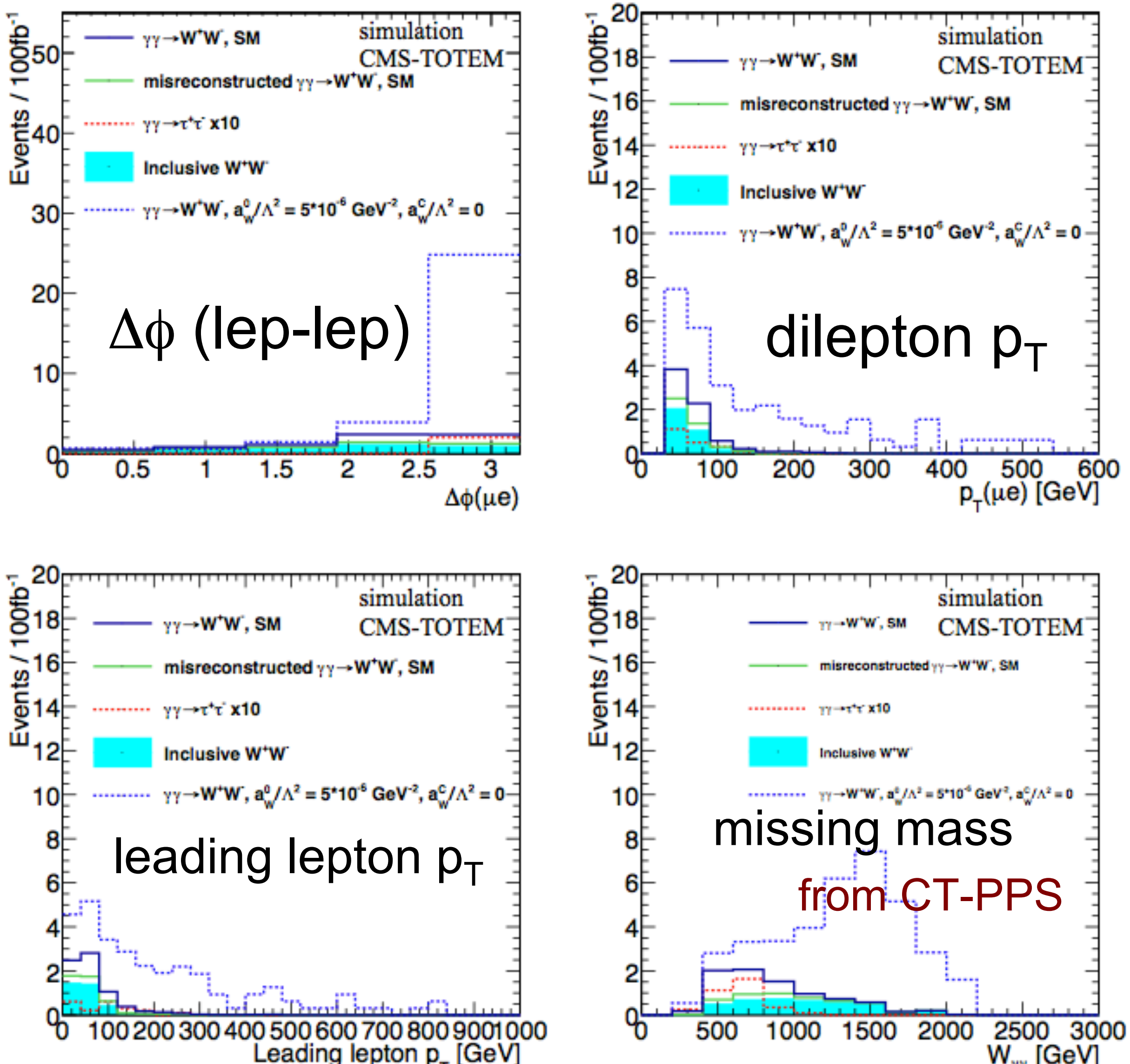
Study of WW production



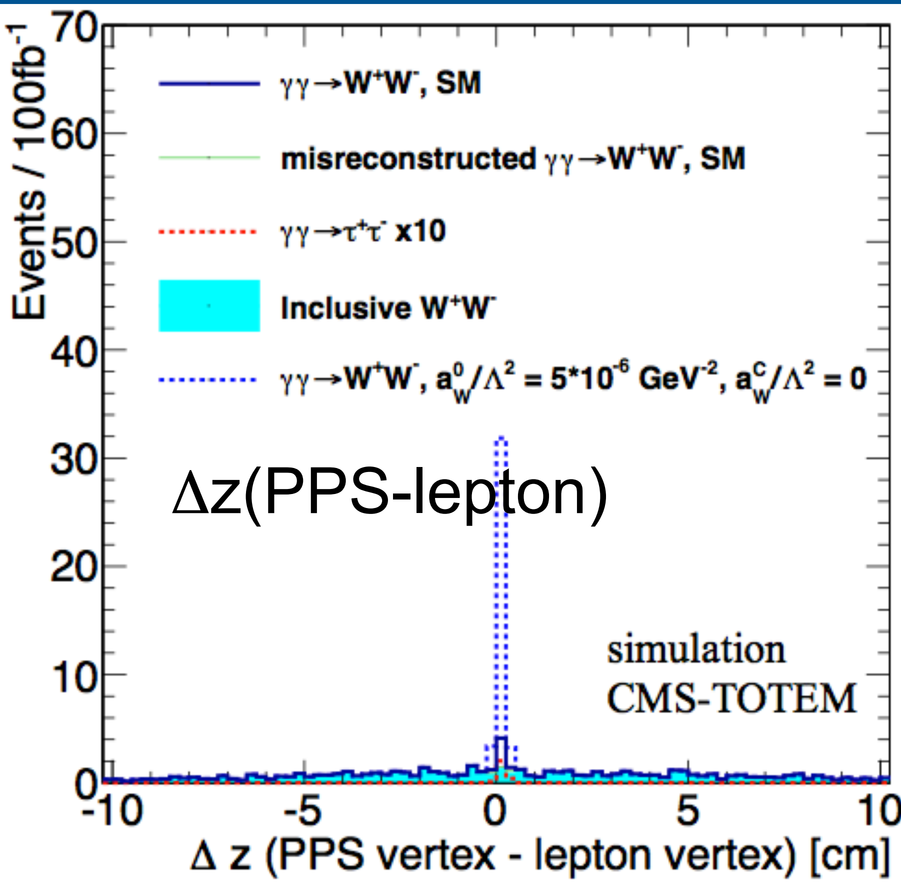
- Event selection
  - W pair in central detector
  - leading protons in PPS
  - study eμ final state
- Two steps:
  - SM production of WW production
  - Anomalous couplings
- Simulation/framework
  - Signal: FPMC generator
  - Backgrounds: incl. WW, SD, DPE, multijet QCD, excl. $\gamma\gamma\to\tau\tau$
  - Pileup (25 and 50 PU)
  - GEANT4 simulation (central detector)
  - Fast simulation of CT-PPS
  - Beam induced backgrounds

Kinematical distributions

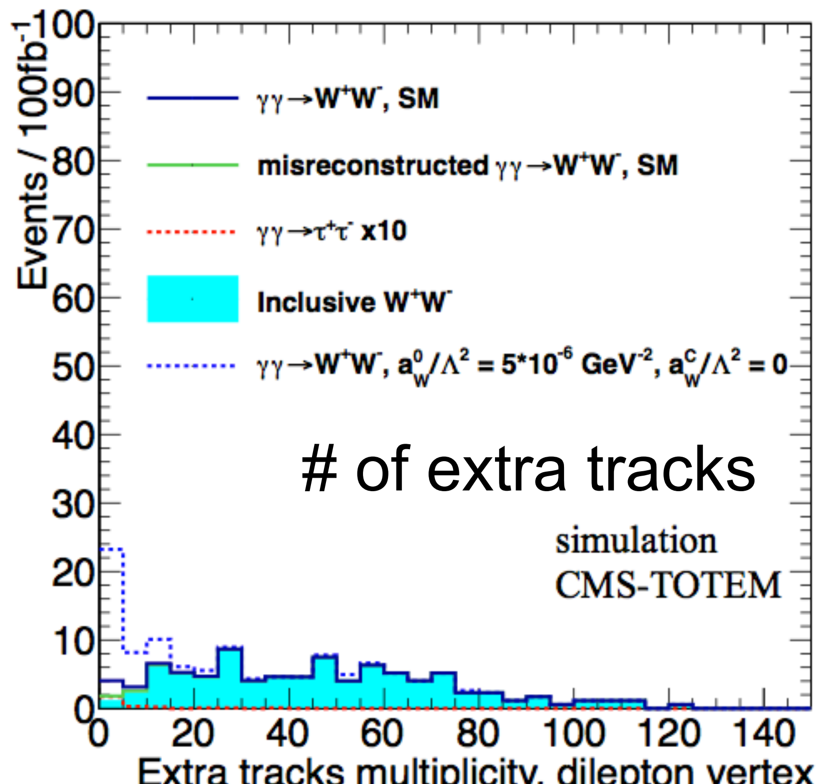
- SM vs AQGC: missing mass provides good separation
- Information from PPS



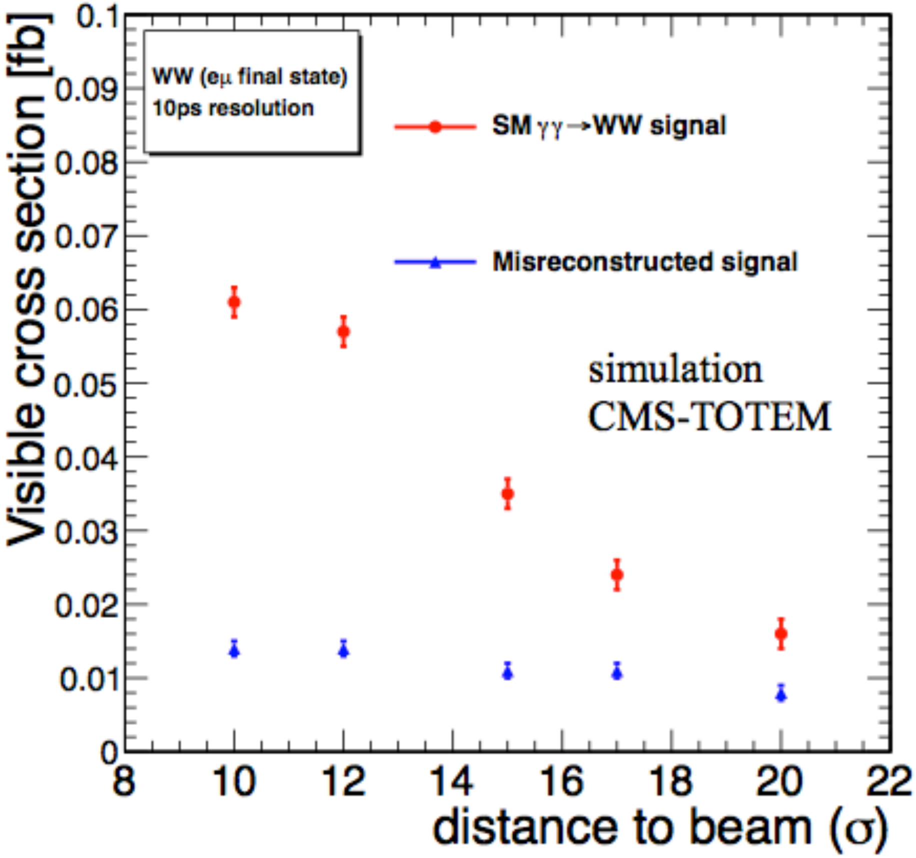
Kinematical distributions (cont.)

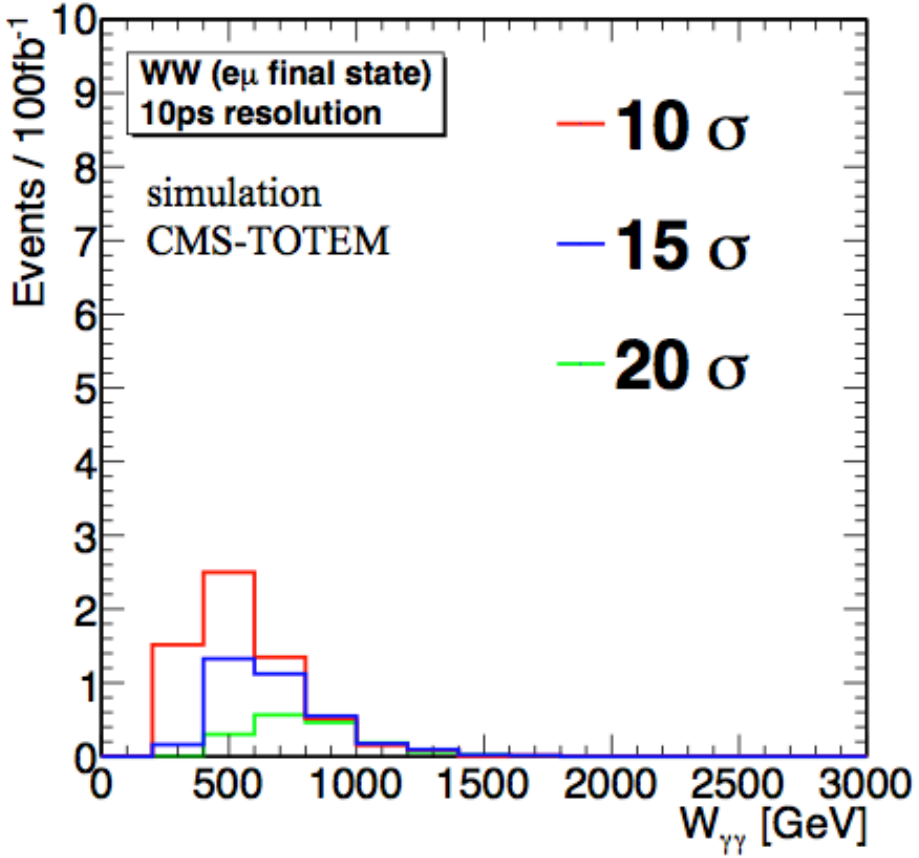


- Multiplicity of "extra tracks" associated to dilepton vertex
- Requiring <10 tracks keeps 80% of signal, 5% of bkg



Yields vs distance to beam





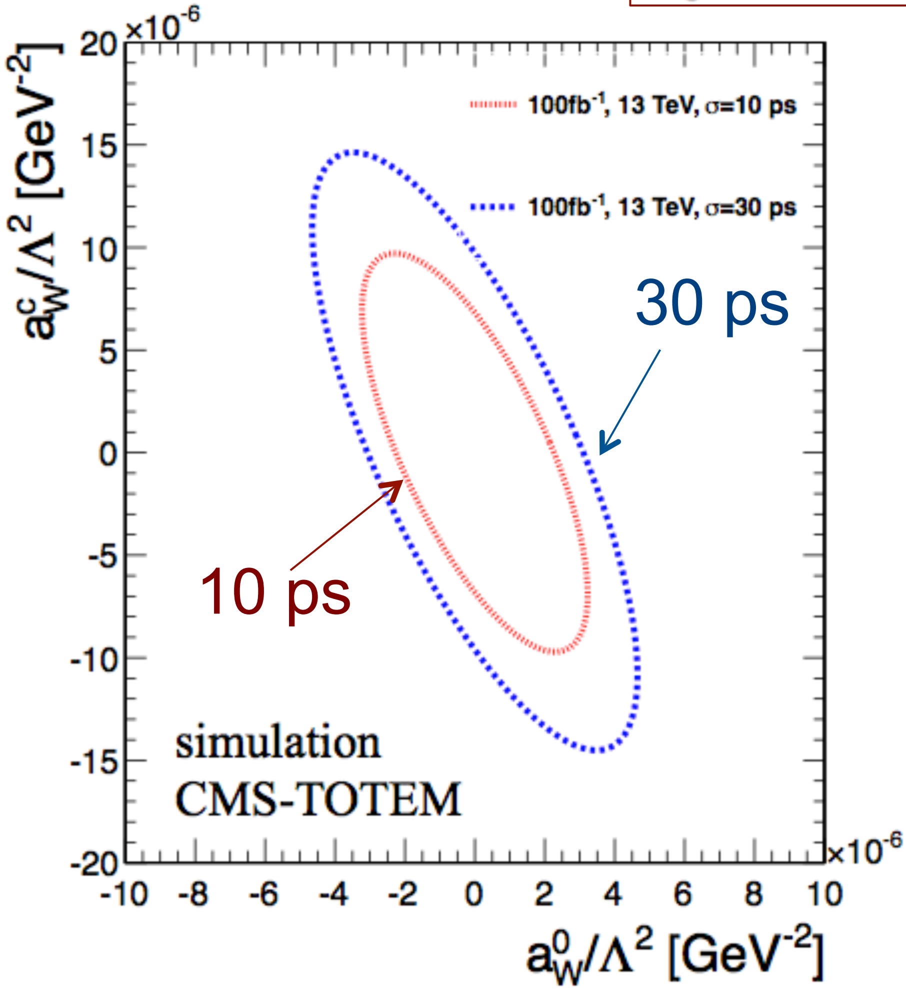
Potential enhancement of sensitivity with closer approach:

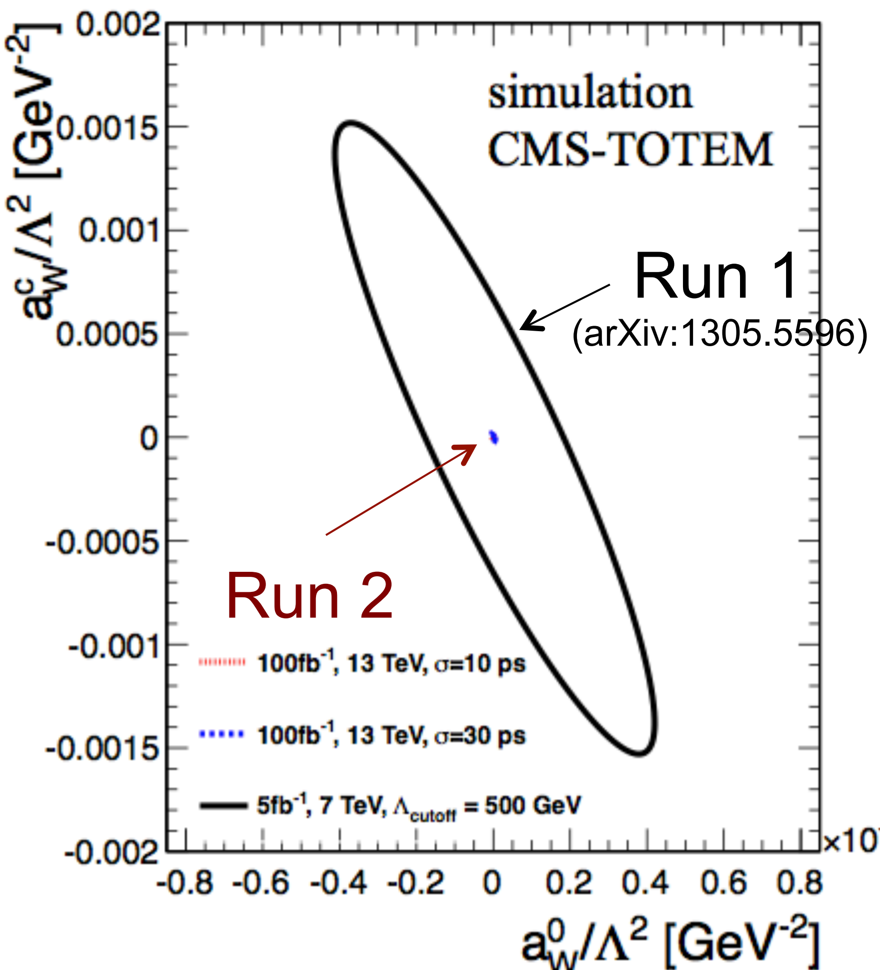
- Signal yield grows by ~x2 when going from 15σ to 10σ
- Background is more or less flat

AQGC expected limits

Expected limits @95%CL:

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

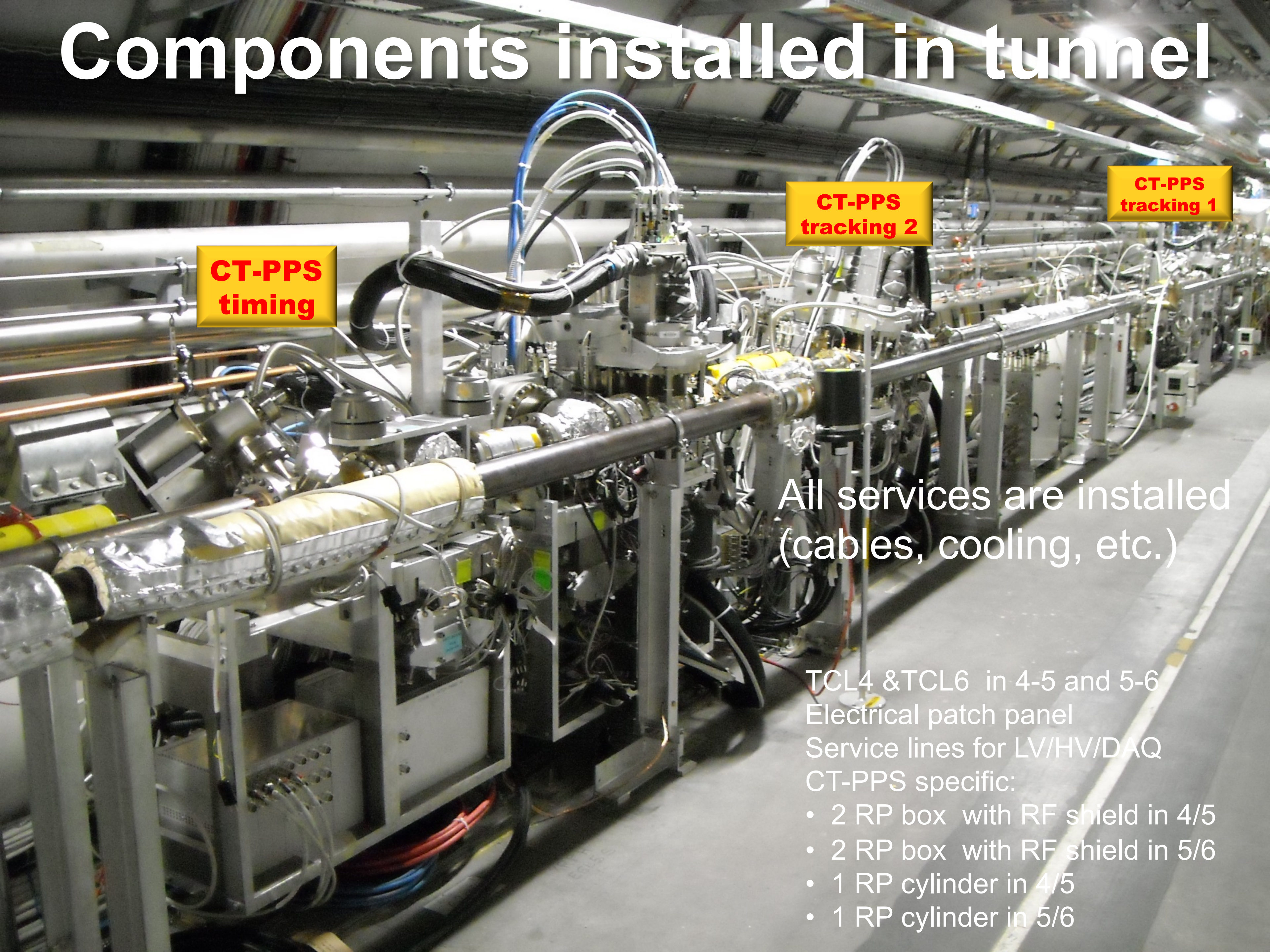




CT-PPS project

- Exploratory phase (2015-2016)
  - RP insertions commissioning at lowβ^* and high beam intensity
  - Establish regular RP insertions for physics during fills
  - Install detectors, commissioning
- Demonstrate that CT-PPS does not prevent stable operation of LHC beams, does not affect luminosity performance

Components installed in tunnel



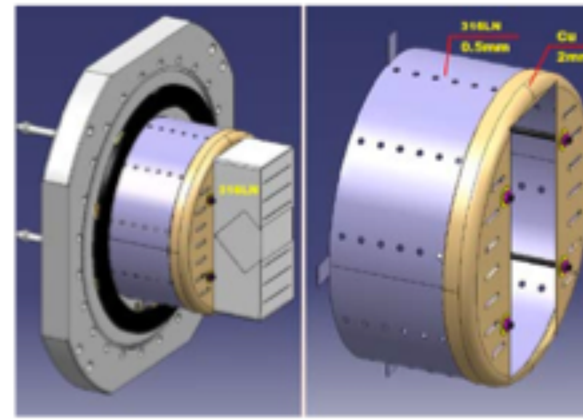
All services are installed (cables, cooling, etc.)

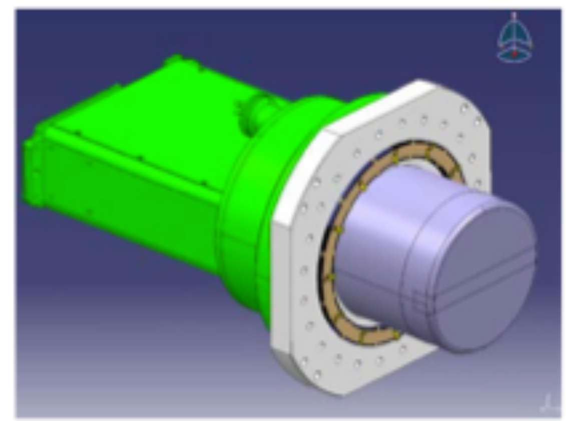
TCL4 &TCL6 in 4-5 and 5-6
Electrical patch panel
Service lines for LV/HV/DAQ
CT-PPS specific:

- 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

RP insertion tests

- RP insertion tests at high luminosity in preparation for 2016
- Goal: establish RP insertions for physics operation in all regular fills
- Problems experienced in 2012
  - Impedance heating, outgassing, vacuum deterioration, amplification of collision debris
- Improvements:
  - New ferrite material (higher Curie temperature)
  - Ferrite bake-out at 1,000C (less outgassing)
  - RF shielding (impedance reduction)
  - Cylindrical RP geometry
- Study beam losses and interplay with TCLs



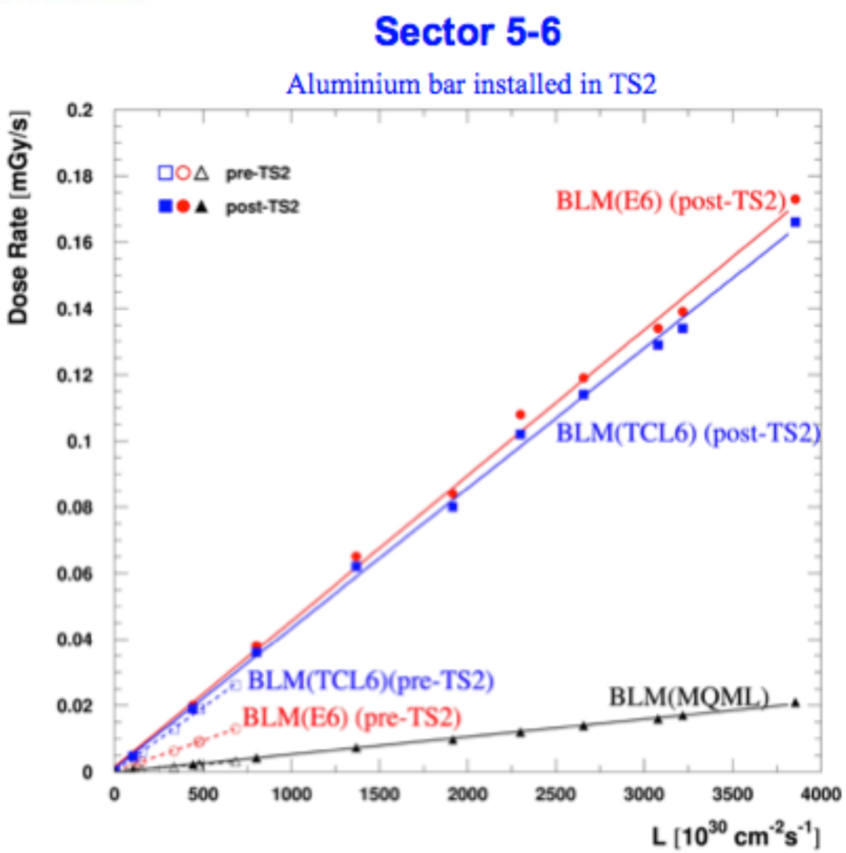


RP insertion tests (cont.)

- Several insertions up to 25σ
  - BLM response: linear with luminosity
  - Vacuum pressure and temperature
  - No beam instabilities introduced

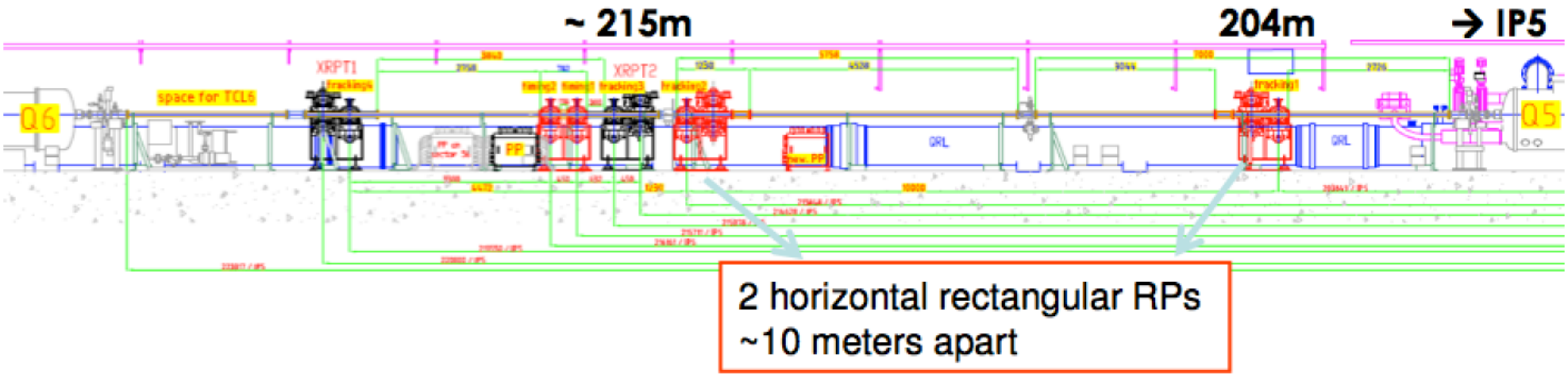
⇒extrapolation to 10^{34}: no problems expected

- Next challenge is to go closer 20σ

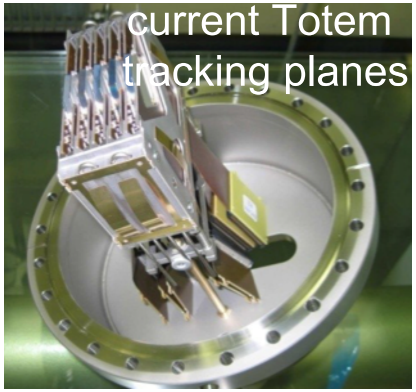


(see M. Deile's presentation)

Tracking detectors



- Position and angle, combined with beam magnets, allow to determine momentum of scattered proton
  - Position resolution: ~10 μm
  - Angular resolution: ~1-2 μrad
- Slim edges on side facing beam
  - dead region: ~200 μm
- Tolerance to inhomogeneous irradiation
  - approx 2×10^{15} n_{eq}/cm^2 close to beam (for 100/fb)
- Baseline: 3D silicon pixel detectors



Tracking detectors (cont.)

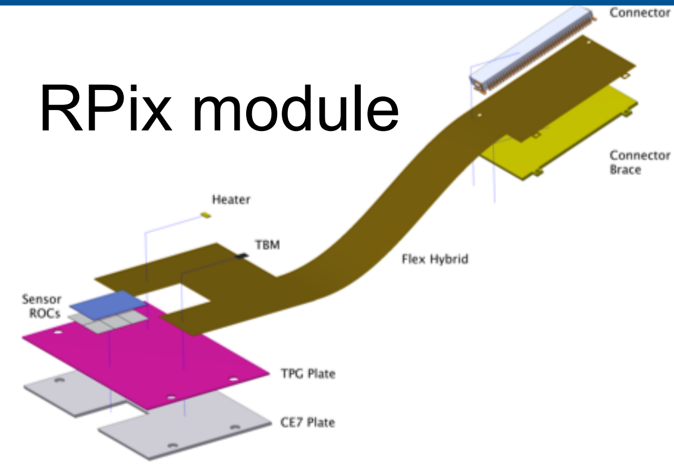
Sensors

- 3D silicon pixel sensors
  - slim edges 200um
  - 2 readout electrodes per pixel (2E)

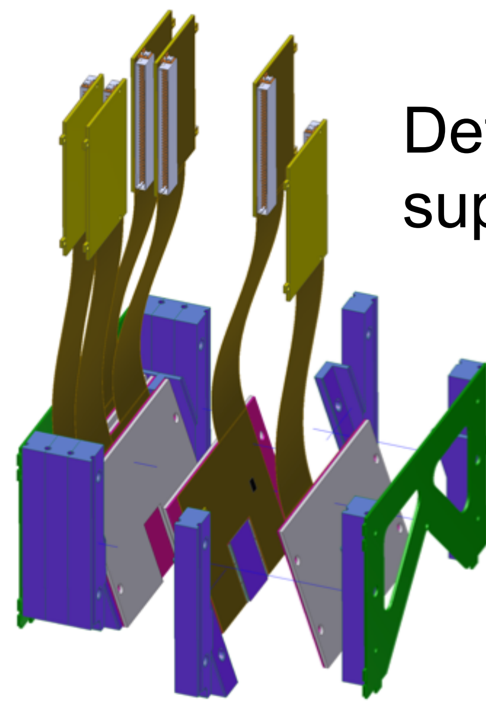
Front-end readout chip

- PSI46dig ROC, with same readout as Phase I CMS upgrade pixel system
  - existing CMS DAQ components and software can be reused
- 6 detector planes per station
  - detectors are tilted (reduce inefficiency)
  - number of planes provide redundancy

RPix module



Detector support



Tracking detectors: schedule

Sensors:

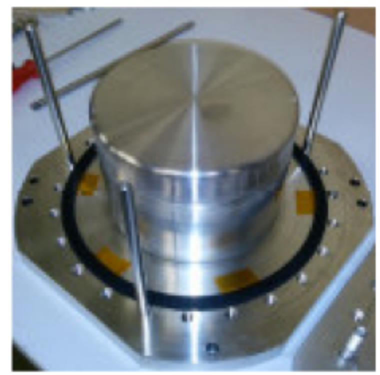
- 3D silicon pixel sensors in production
- To be delivered soon (4wks, year-end)

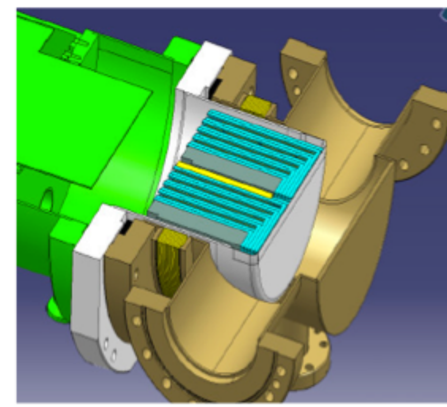
Front-end chips:

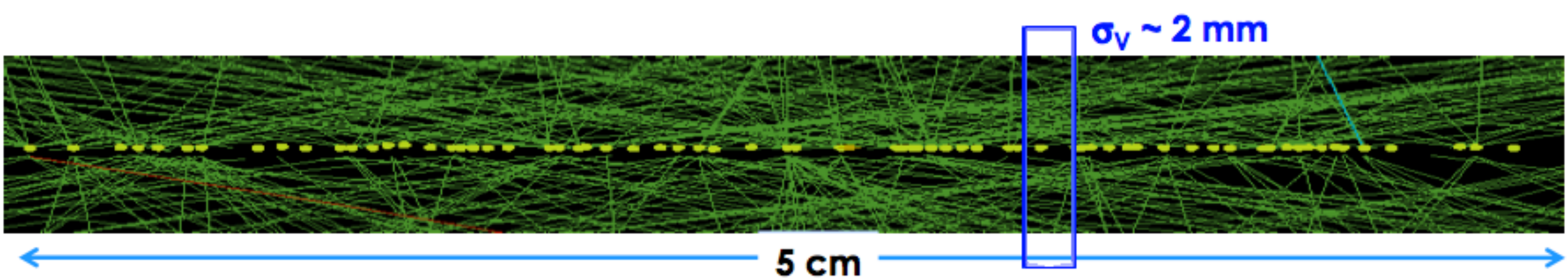
- Two wafers of ROCs sent: mean yield ~91%, a total of ~400 good ROCs. Bonding soon to start.
- Delivery expected 3 months later

Timing detectors

- Proton timing measurement from both sides of CMS allows to determine the primary vertex, correlate it with the central detector's, reject pileup
  - Time resolution 10ps→2mm
  - Reasonable segmentation
  - Radiation hard
  - Minimize impact on beam

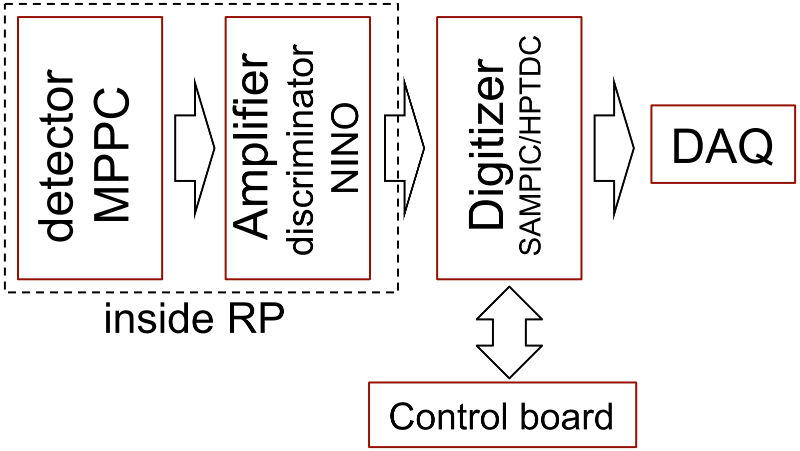


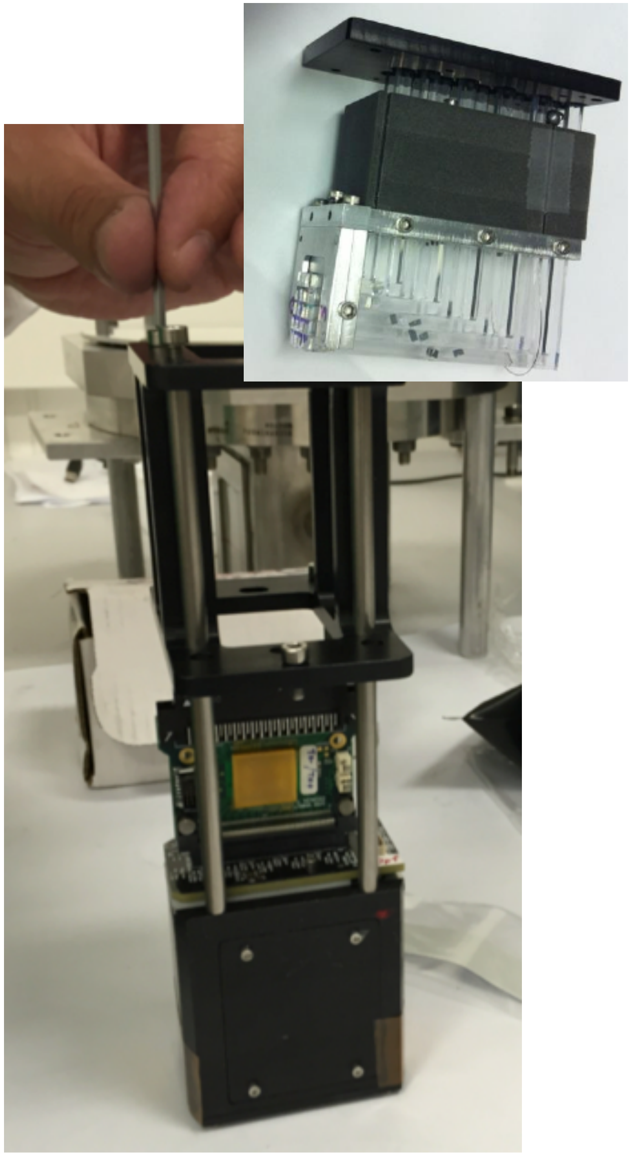




Timing detectors (cont.)

- Cerenkov light in quartz radiator bars
- Quartic module:
  - 20 (4x5) 3x3 mm^2 L-shaped bar elements
  - bars separated by100 μm (total internal reflection)
- Two modules in one RP
- Beam tests: σ~30ps (~20ps for two in-line)
- Readout electronics:





Timing detector R&D

Solid state as possible alternative

- Diamonds, silicon-based, etc.

Challenges

- Radiation-hardness
- Fast signals
- Finer segmentation reducing channel occupancy
- Thin and light, allow multiple layers N
  - reducing nuclear interaction
  - Time resolution ~1/sqrt(N)

Timing detector R&D (cont.)

GasToF system

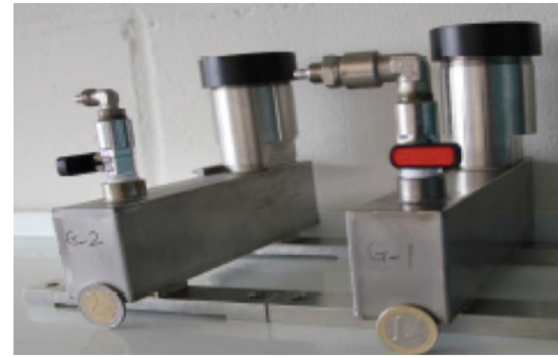
- Prototype test ongoing

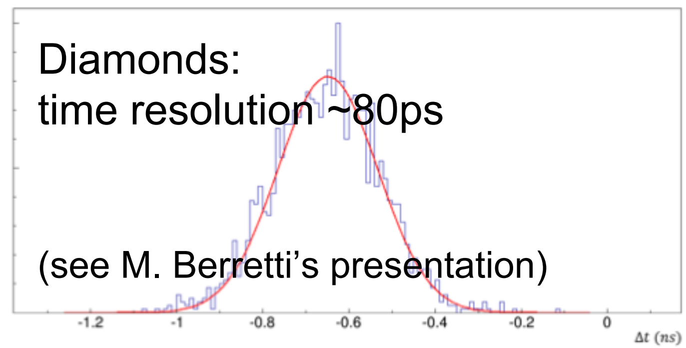
Diamond detectors

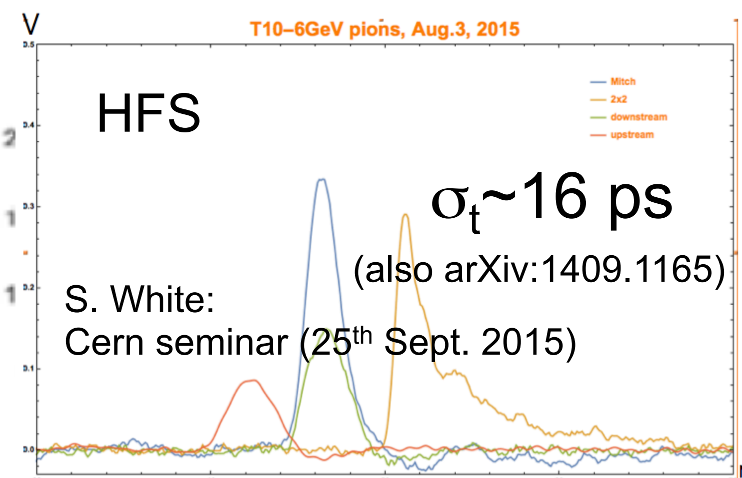
- 50 ps resolution with 4 planes

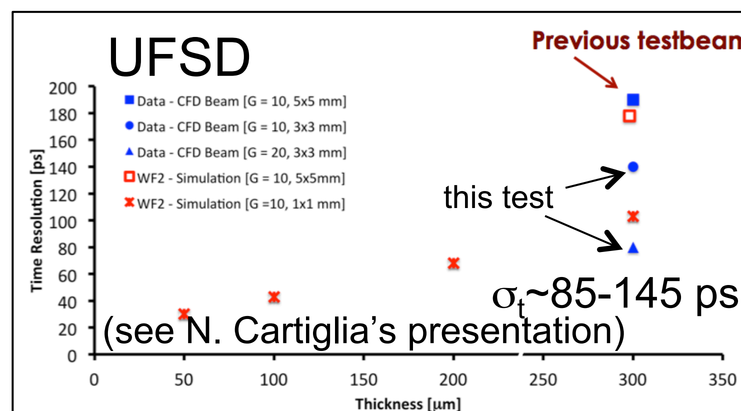
Silicon detectors

- Ultra-Fast Silicon Detectors
- Hyper-Fast Silicon detectors





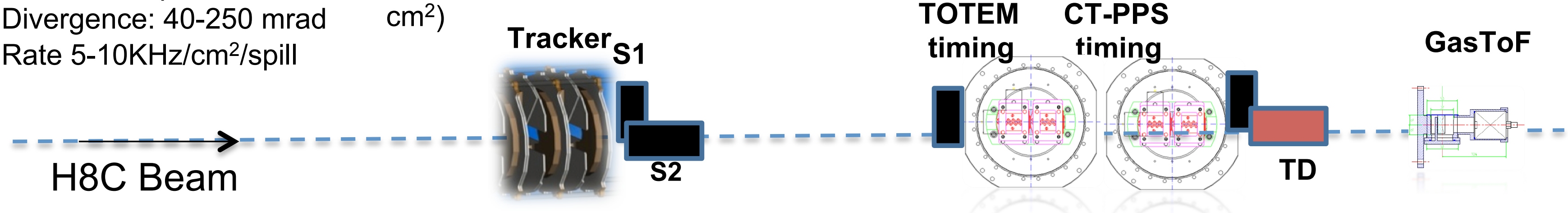




Test beam

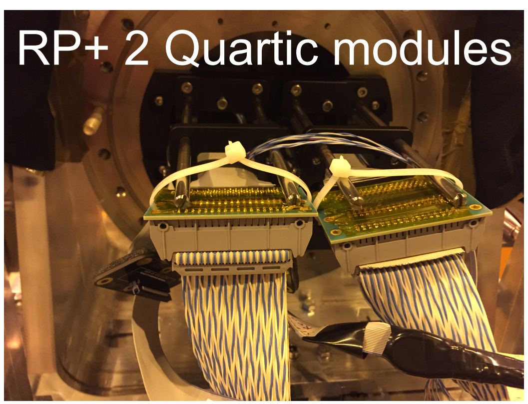
SPS beam:
- E=180 GeV protons
- Divergence: 40-250 mrad
- Rate 5-10KHz/cm^2/spill

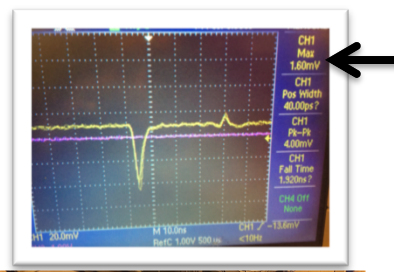
Tracker externally triggered by S1 and S2 (trigger area ~2x2 cm^2)

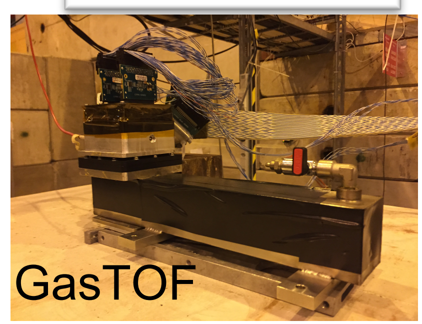


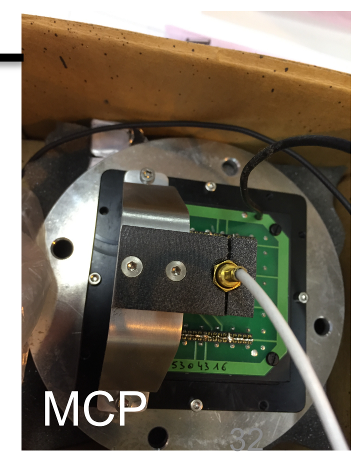
- Triggers:
  - scintillator (4.5x4.5mm^2) and diamond (20x20mm^2)
- Quartic:
  - Integration of two modules in RPs
  - 1st test of electronics readout chain
- GasToF:
  - readout MCP+Nino+HPTDC

- Data-taking
  - With no-beam: threshold scan
  - With beam: threshold voltage, diamond/ scintillator trigger, position scan









Summary

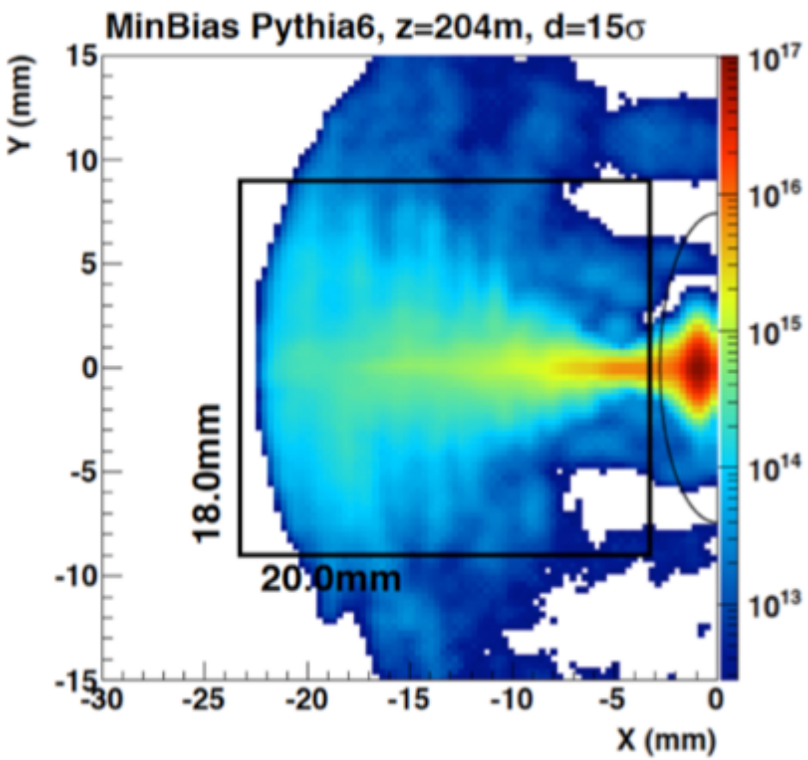
- CT-PPS will allow precision proton measurement in the very forward region on both sides of CMS
- A new tool to enhance the potential for BSM searches
  - Improves sensitivity to SM and BSM physics
- Studied physics and detector performance
  - Timing resolutions of 10ps and 30ps
  - Distance from beam at 15σ and 20σ
- Tracking and timing detector options (baseline vs R&D)
- Experimental challenges are being addressed
- Exploratory/consolidation phase in 2015-2016 and beyond
- Program is progressing

⇒Rich physics program with emphasis on BSM searches

backup

Radiation levels

- Radiation levels in detector studied using Totem data and simulation



Per 100 fb^{-1}:

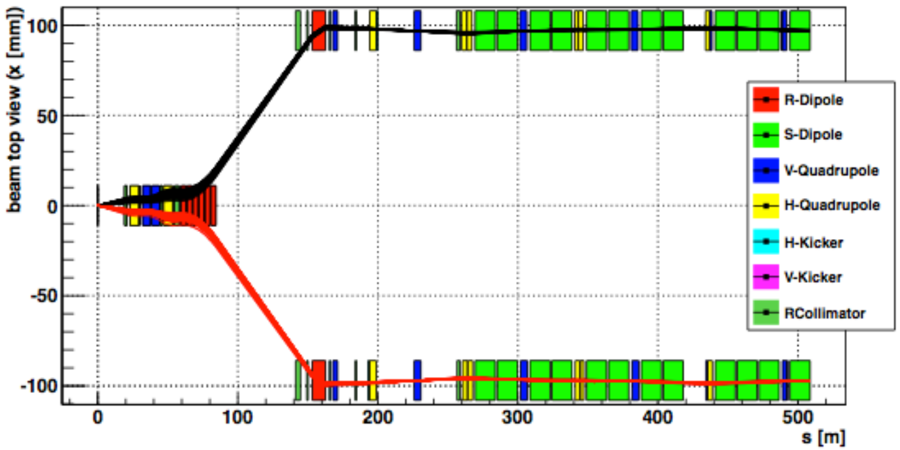
- Proton flux up to $5x10^{15}$ cm^{-2} in pixel detectors
- 10^{12} neq/cm^2 and 100 Gy in photosensors and readout electronics

Yields (in fb)

- Select WW events
- Apply central lepton and PPS acceptance cuts
- Additional timing and track multiplicity cuts
- Inefficiency due to overlapping hits in timing detectors is taken into account
- Number in parenthesis are for time resolution of 30ps

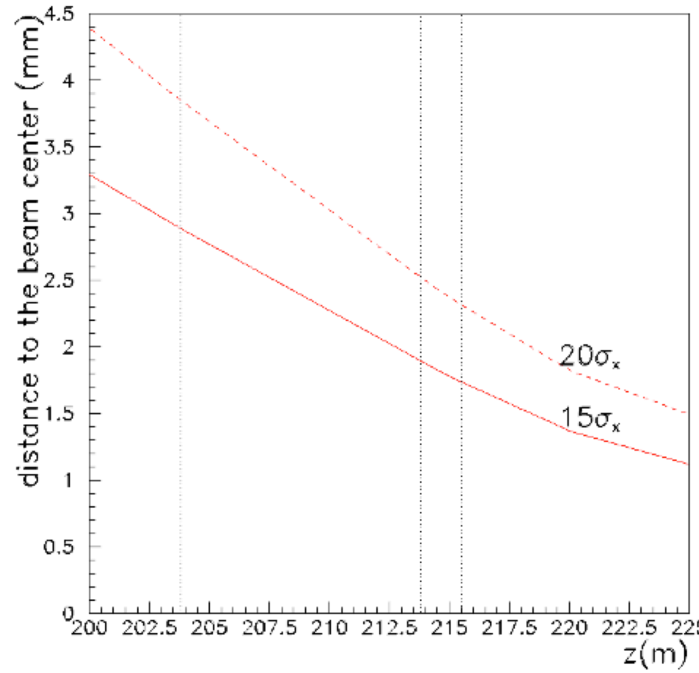
Selection	Cross section (fb)			
	exclusive WW	exclusive WW (incorrectly reconstructed)	inclusive WW	exclusive $\tau\tau$
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	0.86±0.01	N/A	2537	1.78±0.01
$\geq$ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	0.47±0.01	N/A	1140±3	0.087±0.003
opposite 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

Beam optics



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

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



Yields per 1/fb – Pileup=50

Selection	Exclusive dijets		DPE		SD		Inclusive dijets	
	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)
total number of events	652 ± 7	100	290×10^3	100	2.6×10^6	100	2.4×10^{10}	100
≥ 2 jets (p_T >100 GeV, $\lvert\eta\rvert < 2.0$)	287 ± 5	44	36×10^3	12.2	270×10^3	10	4.4×10^8	1.8
PPS tagging (fiducial)	77 ± 3	12	23×10^3	7.8	39×10^3	1.5	0.5×10^8	0.2
no overlap hits in ToF detectors	54 ± 2	8	18×10^3	6.3	25×10^3	1.2	0.3×10^8	0.12
ToF difference, Δt	32 (27)$\pm$2	5	14 (11) $\times10^3$	4.8	6×10^3	0.3	95 (180) $\times10^4$	4×10^{-3}
$0.70 < [R_{jj} = (M_{jj}/M_X)] < 1.15$	20 (16)$\pm$1	3.1	43 (39)$\pm$8	0.01	200 (250)$\pm$40	0.01	45 (85) $\times10^3$	2×10^{-4}
$\Delta(y_{jj} - y_X) < 0.1$	15 (12)$\pm$1	2.3	10 (11)$\pm$4	-	12 ± 10	-	5 (9) $\times10^3$	-
N_{tracks}	5 (4)$\pm$1	0.8	1.3 (1.5)$\pm$0.5	-	1 ± 1	-	40 (77) $\pm$ 1	-
≥ 2 jets (p_T > 150 GeV, $\lvert\eta\rvert < 2.0$)	2.5 (1.9)$\pm$0.2	0.4	0.4 ± 0.2	-	0 ± 1	-	20 (36) $\pm$ 1	-

$\Rightarrow$ S/B ~ 1/8

Yields per 1/fb – Pileup=25

Selection	Exclusive dijets		DPE		SD		Inclusive dijets	
	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)	events	ϵ (%)
total number of events	652±5	100	290×10^3	100	2.6×10^6	100	2.4×10^{10}	100
≥ 2 jets (p_T >100 GeV, $\lvert\eta\rvert < 2.0$)	250±4	38	25×10^3	8.7	190×10^3	7.6	3.4×10^8	1.4
PPS tagging (fiducial)	50±2	8	15×10^3	5.1	12×10^3	0.5	0.1×10^8	0.05
no overlap hits in ToF detectors	43±2	7	14×10^3	4.8	$10\ (18) \times 10^3$	0.4	0.1×10^8	0.04
ToF difference, Δt	30 (23)±2	4.6	$11\ (9) \times 10^3$	3.8	3×10^3	0.1	$0.3\ (0.6) \times 10^6$	1×10^{-3}
$0.70 < [R_{jj} = (M_{jj}/M_X)] < 1.15$	20 (15)±1	3.1	15 (14)±3	0.01	85 (110)±15	-	$16\ (30) \times 10^3$	1×10^{-4}
$\Delta(y_{jj} - y_X) < 0.1$	15 (12)±1	2.4	6 (4)±2	-	3 (11)±3	-	$1.8\ (3.4) \times 10^3$	-
N_{tracks}	7.4 (5.8)±0.4	1.1	0.8 (0.6)±0.3	-	1±1	-	19 (35) ± 1	-
≥ 2 jets (p_T > 150 GeV, $\lvert\eta\rvert < 2.0$)	3.5 (2.6)±0.2	0.5	0.2 (0.1)±0.1	-	1±1	-	9 (17) ± 1	-

⇒ S/B ~ 1/3