CMS-TOTEM Precision Proton Spectrometer: Status and Physics Prospects

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September 10, 2015

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

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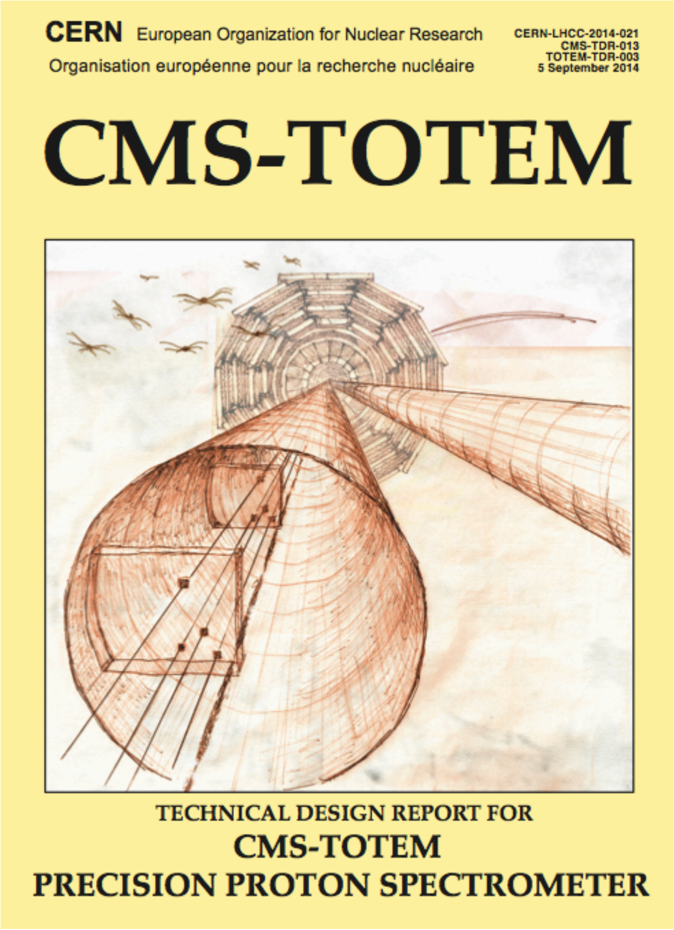
Introduction

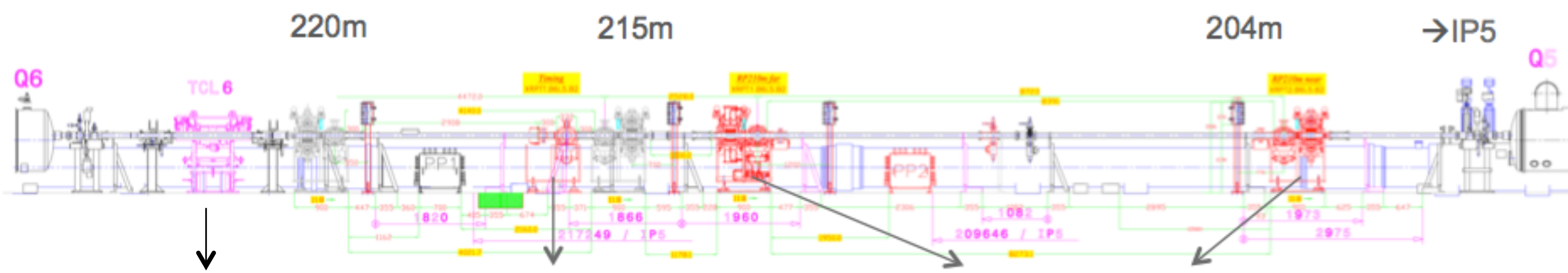


https://indico.cern.ch/event/334693/

- 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)

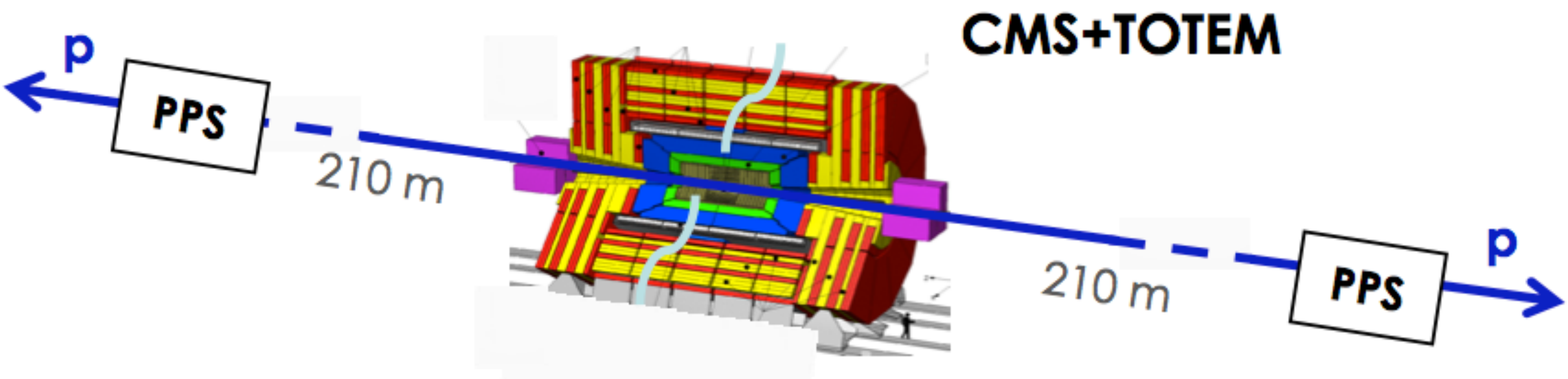
2 horizontal box-shaped RPs

timing detectors

tracking detectors

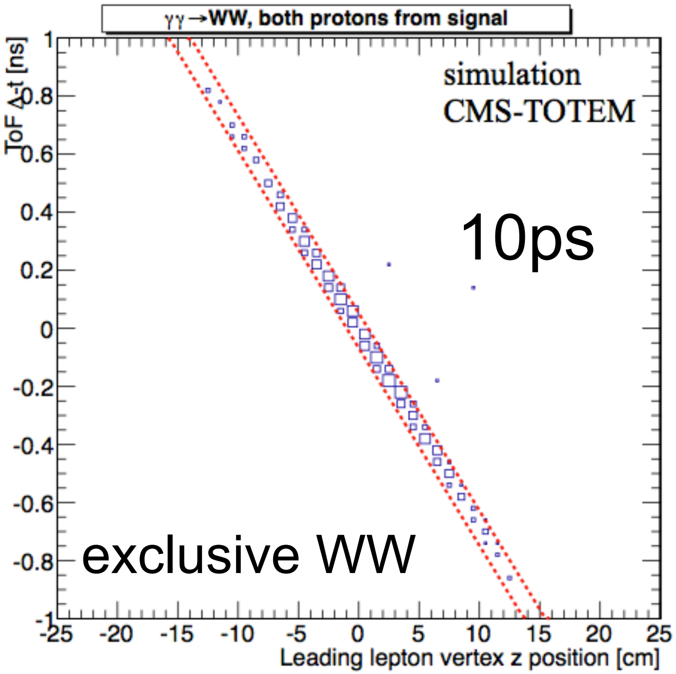
Experimental challenges

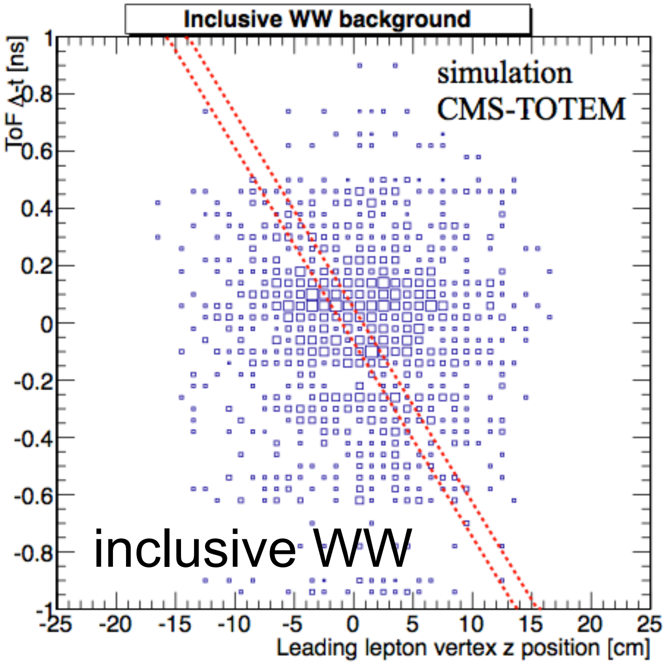
- Ability to operate the detectors close to beam (15-20σ) to maximize acceptance for low momentum loss (ξ) protons
- Limit RF impedance introduced by beam pockets
  - improved RF shielding of RPs
  - R&D on Movable Beam Pipe as future option
- Sustain high radiation levels
  - For 100/fb, proton flux 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

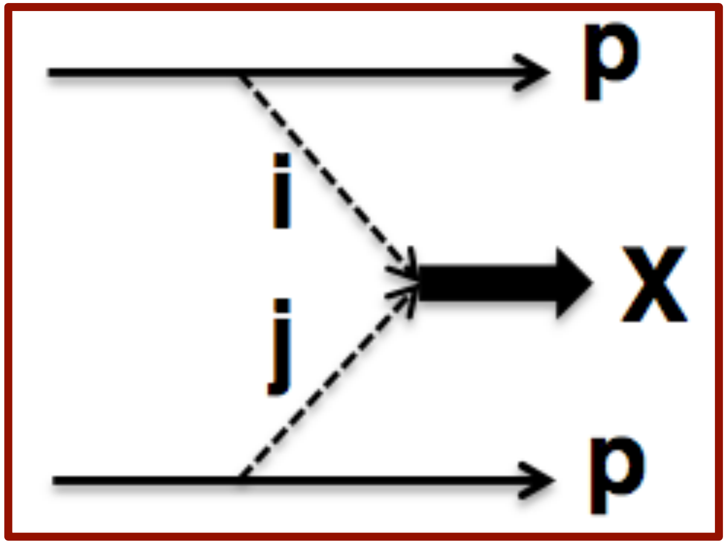




⇒use timing information to reject pileup

(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

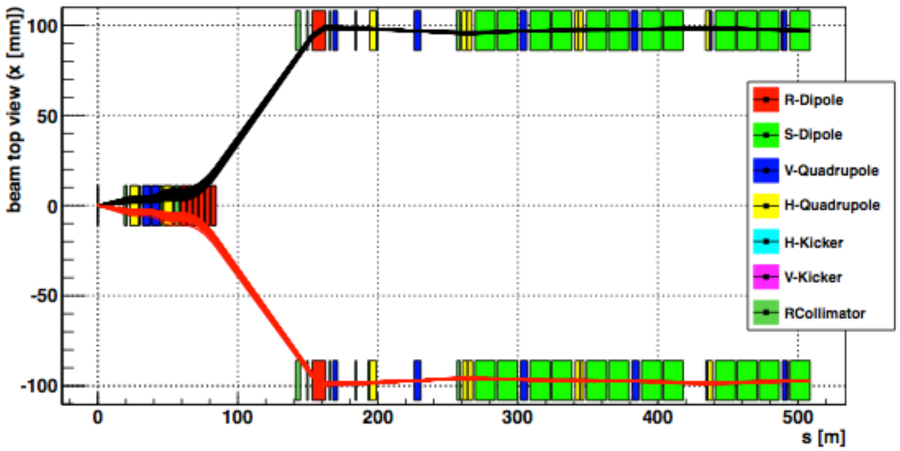
t: 4-momentum transferred squared

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

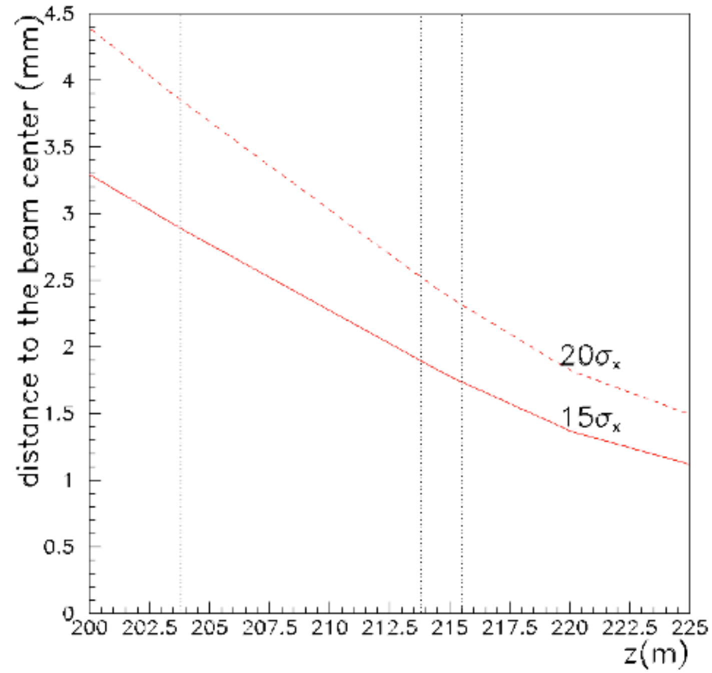
Detector performance

Beam optics



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

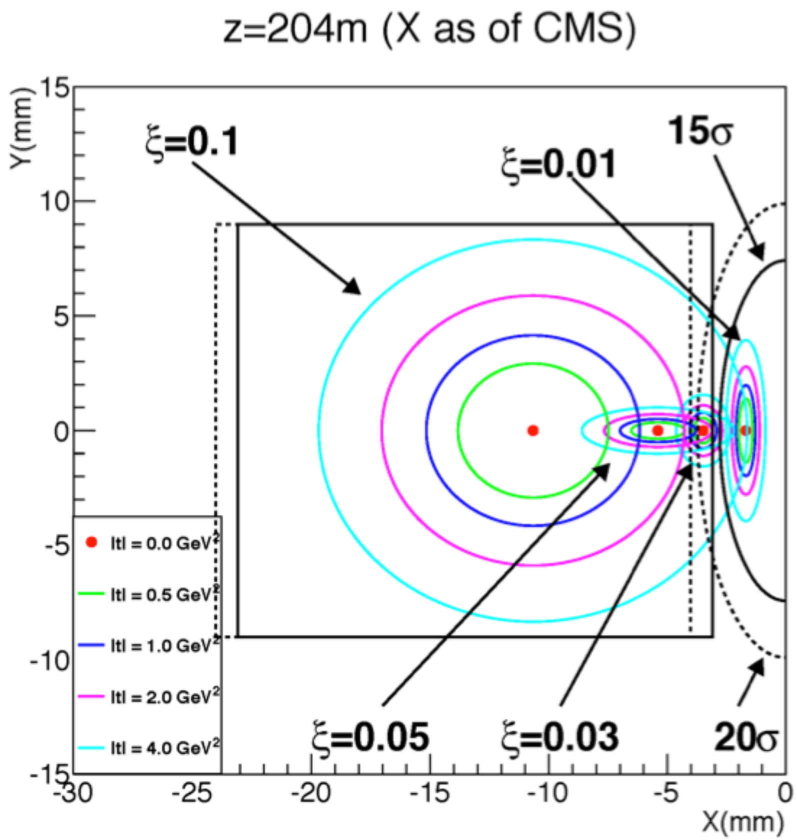
Horizontal distance to beam center in the z-range of the PPS detectors



Detector acceptance

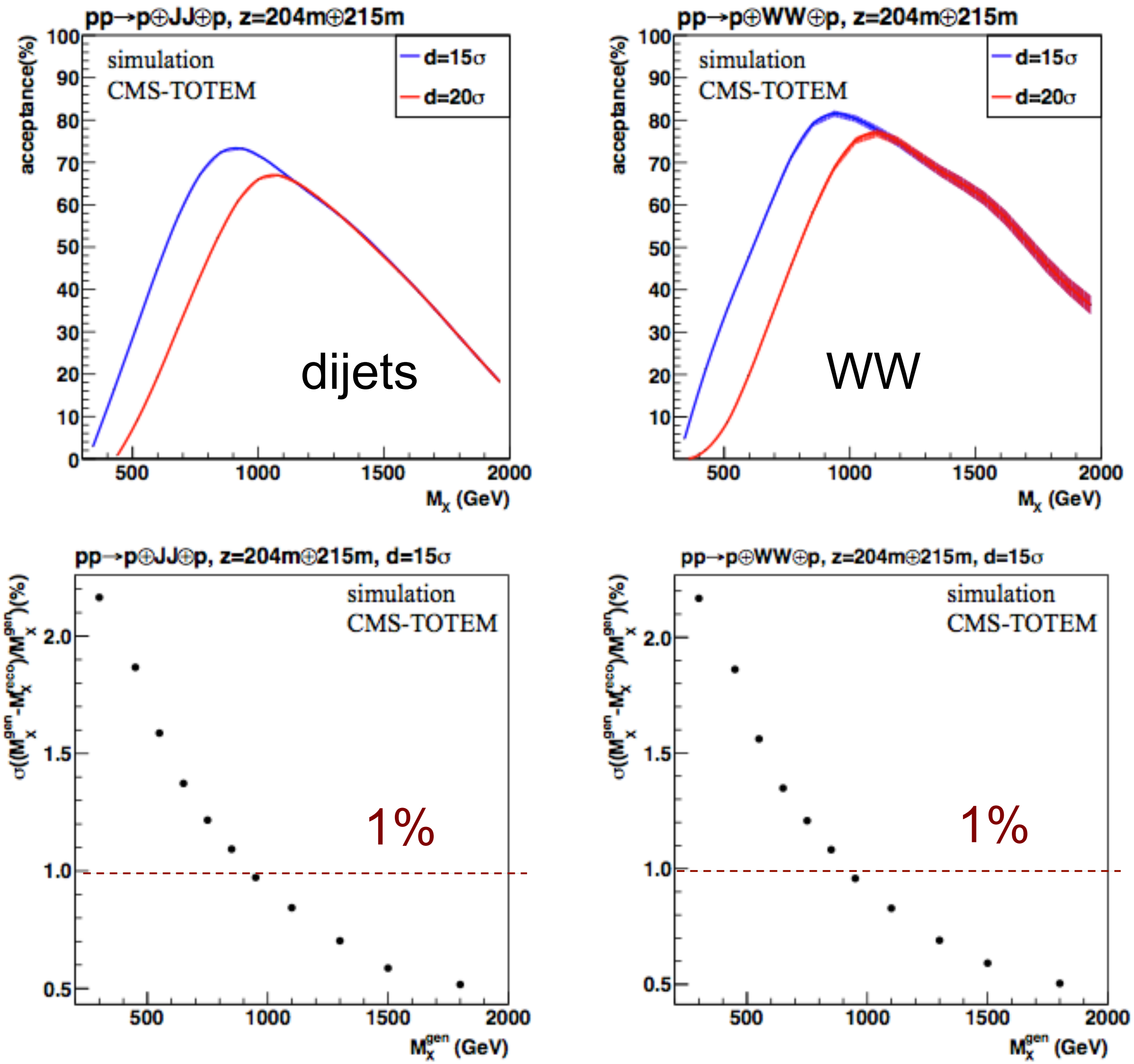
Acceptance: X vs Y (includes ξ,t ellipses)

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



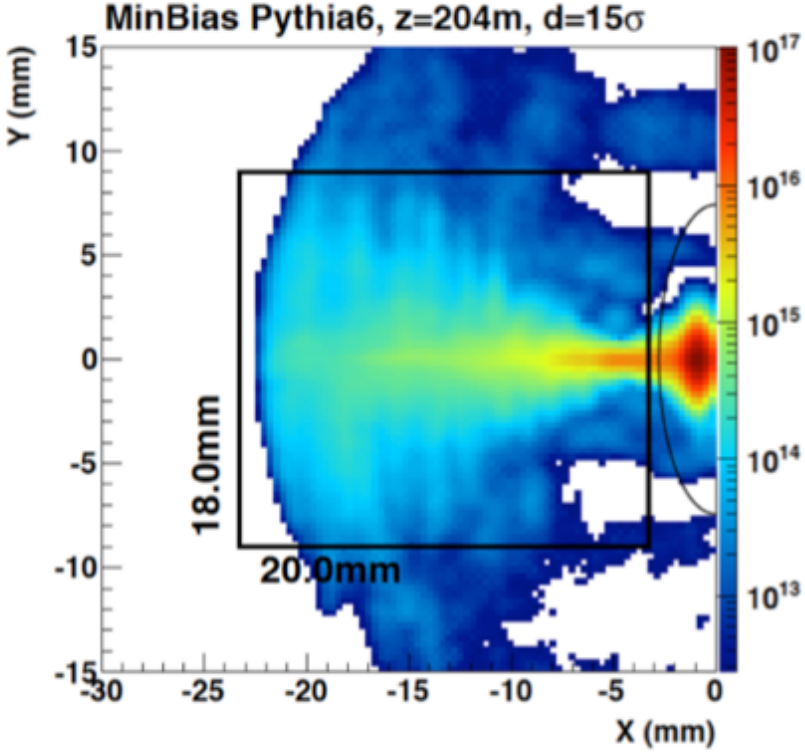
Detector: mass resolution

- 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



Radiation levels

- Radiation levels in detector studied using Totem data and simulation



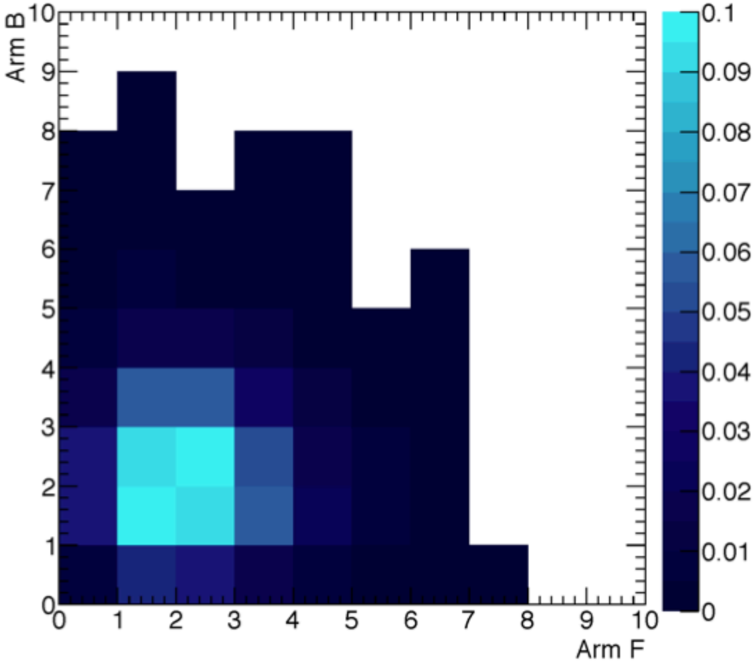
Per 100 fb^{-1}:

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

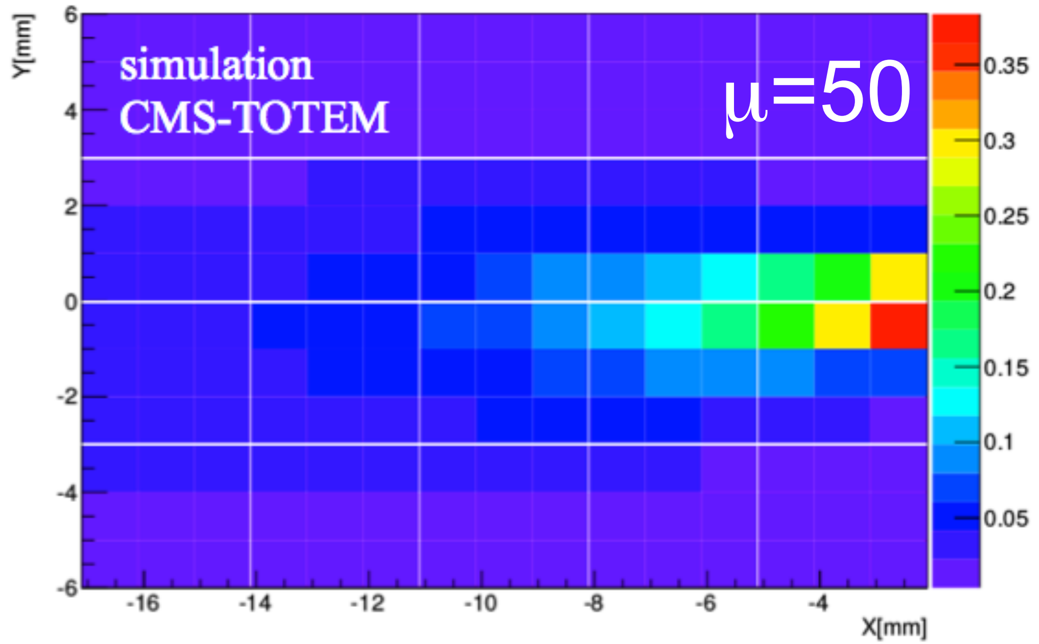
Detector occupancy

- 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

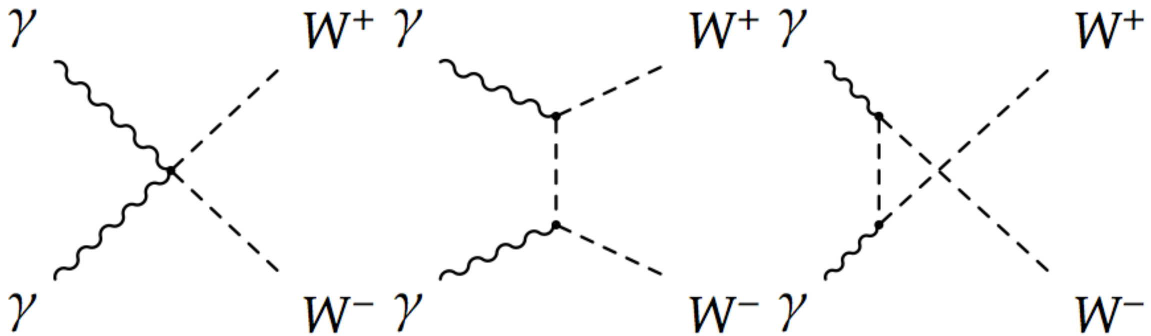


Expected occupancy



Physics prospects

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

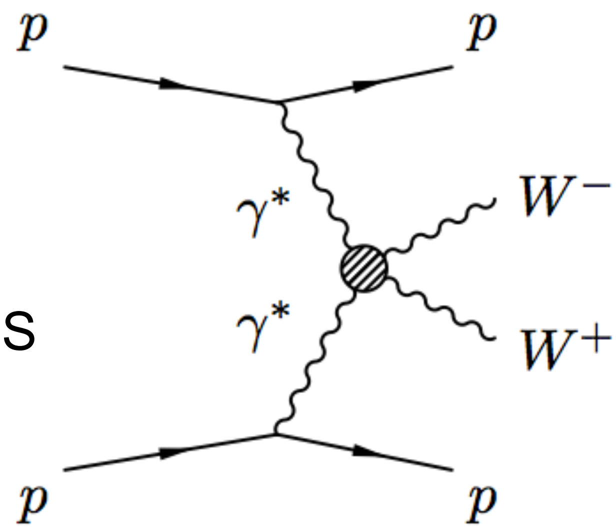


- Measurements can show deviation from SM

WW production

CMS-FSQ-13-008

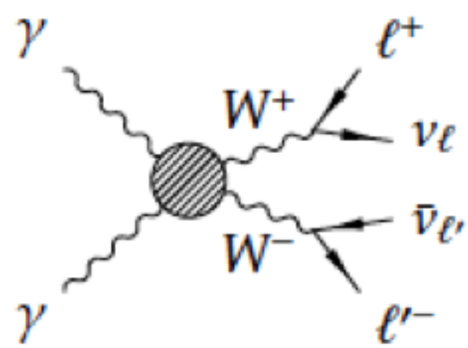
- Study of process: pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Backgrounds:
  - inclusive WW, ττ, exclusive two-photon γγ→ll, etc.
- 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

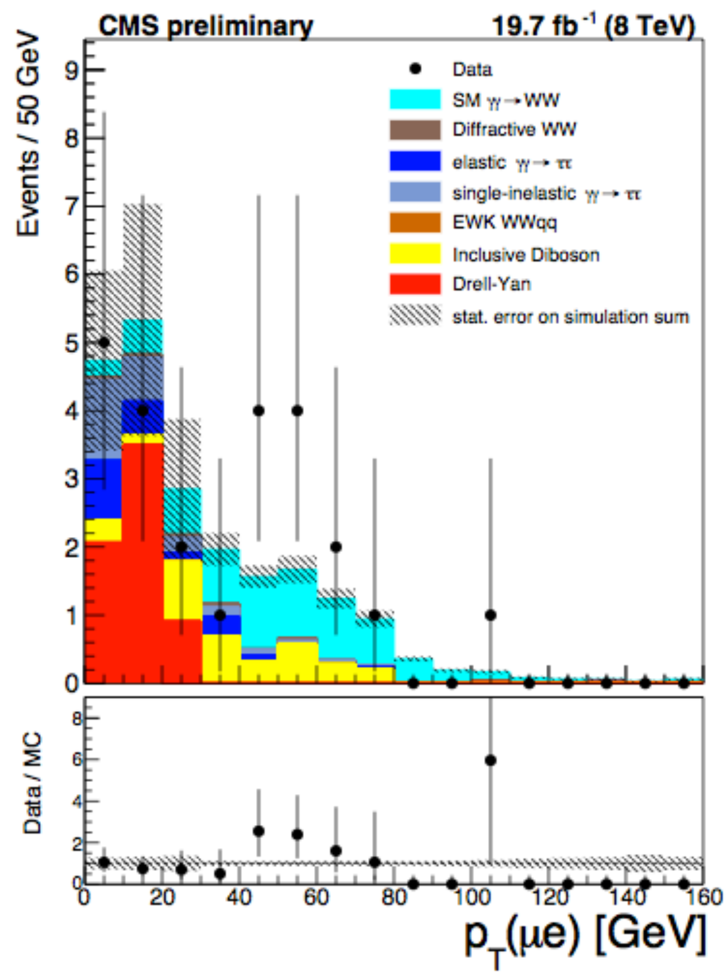


WW production: Selection

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

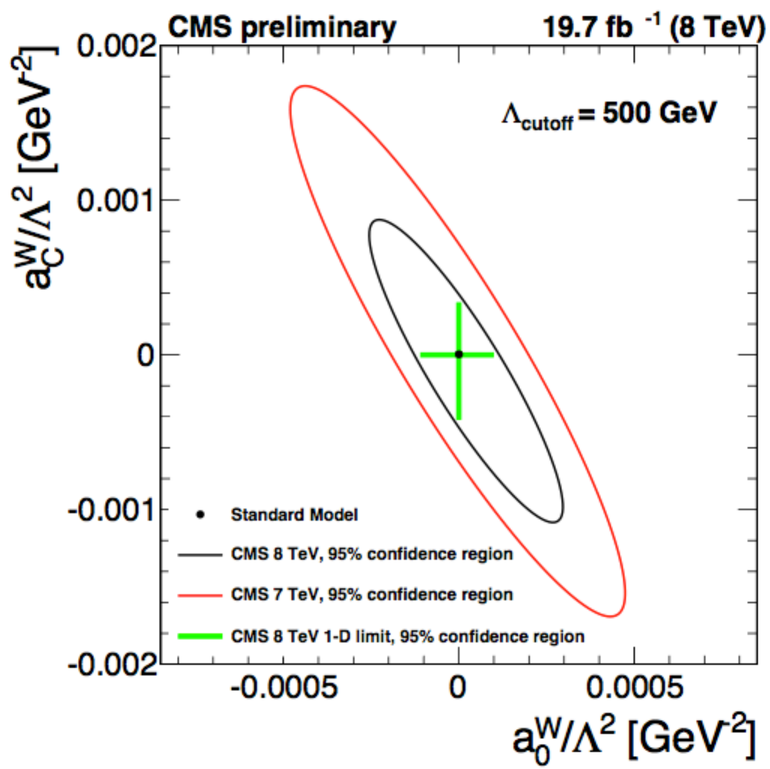
CMS-FSQ-13-008

- Cross section measurement

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

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

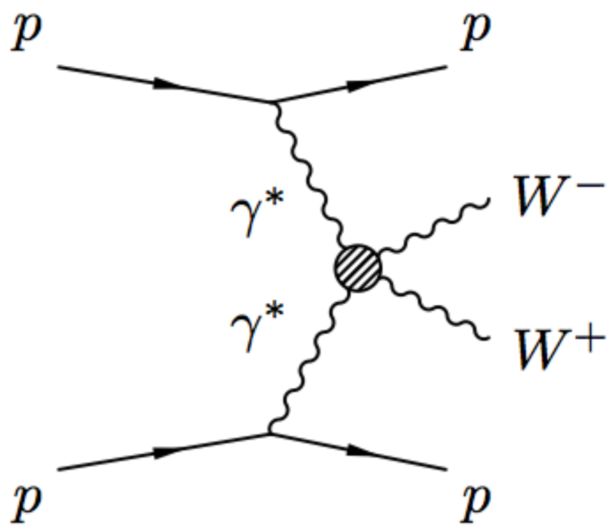
sample	yields
inclusive WW	2.0±0.4
$\gamma\gamma \to \tau\tau$	0.9±0.2
DY$\to \tau\tau$	0
diffractive WW	0.1±0.1
others	0.5±0.2
total backgrounds	3.5±0.5
signal (SM exclusive pp$\to$WW)	5.3±0.1
data	13



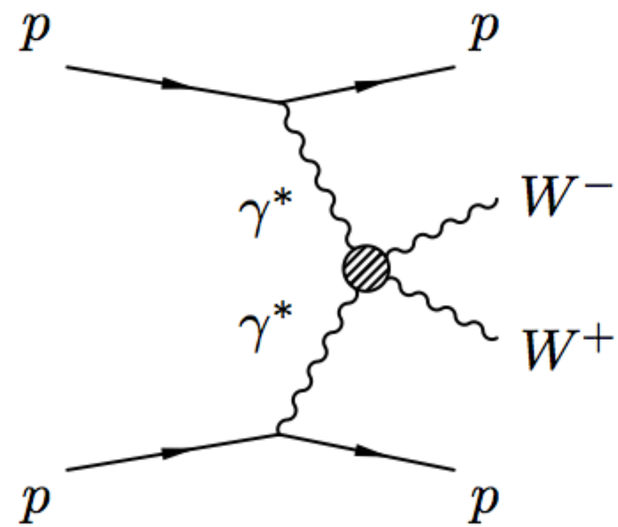
- AQGC results
  - 95%CL limits on a^W_C/Λ^2, a^W_C/Λ^2
  - Improvement of two orders of magnitude over LEP/Tevatron

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



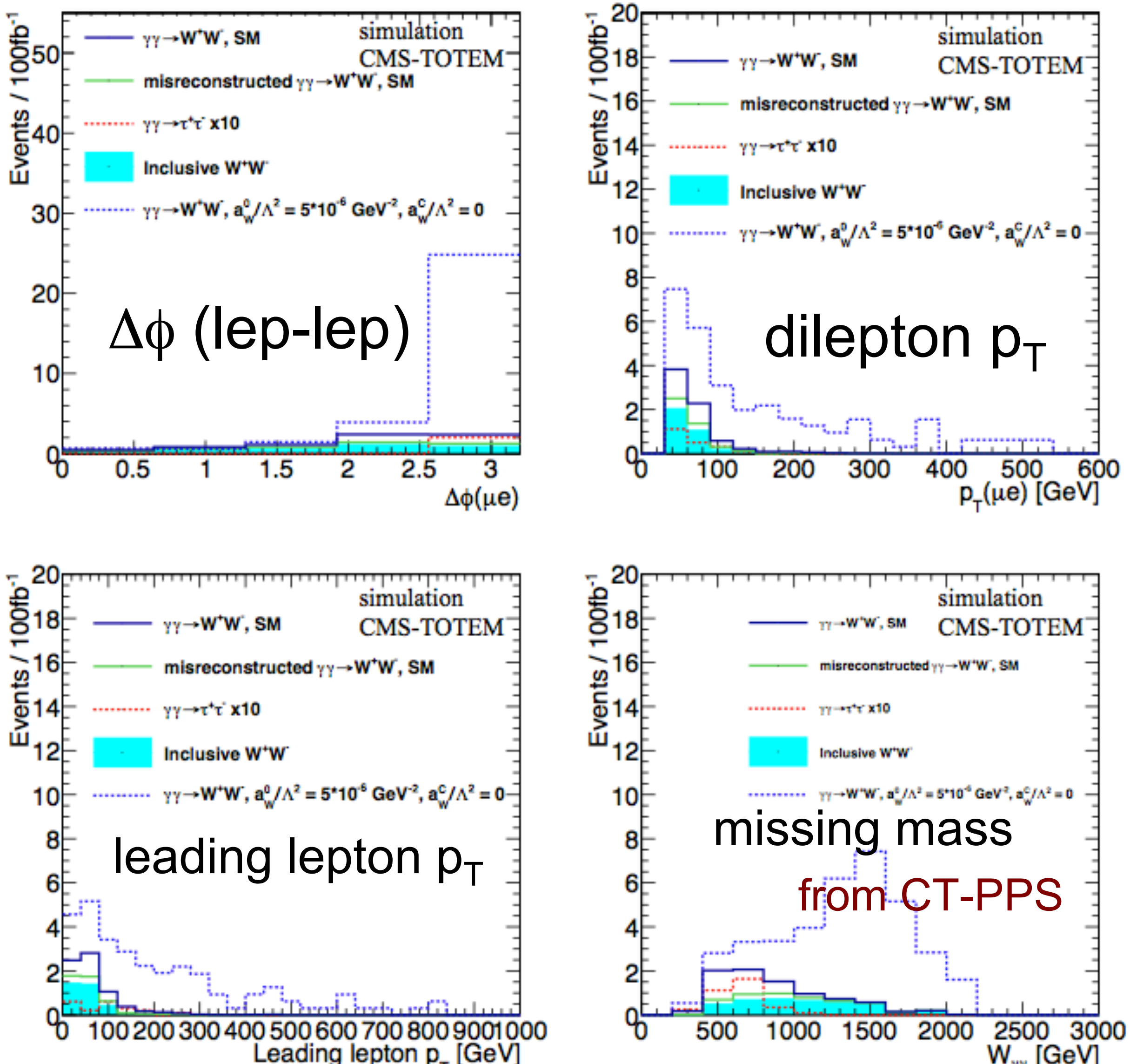
Study of WW production



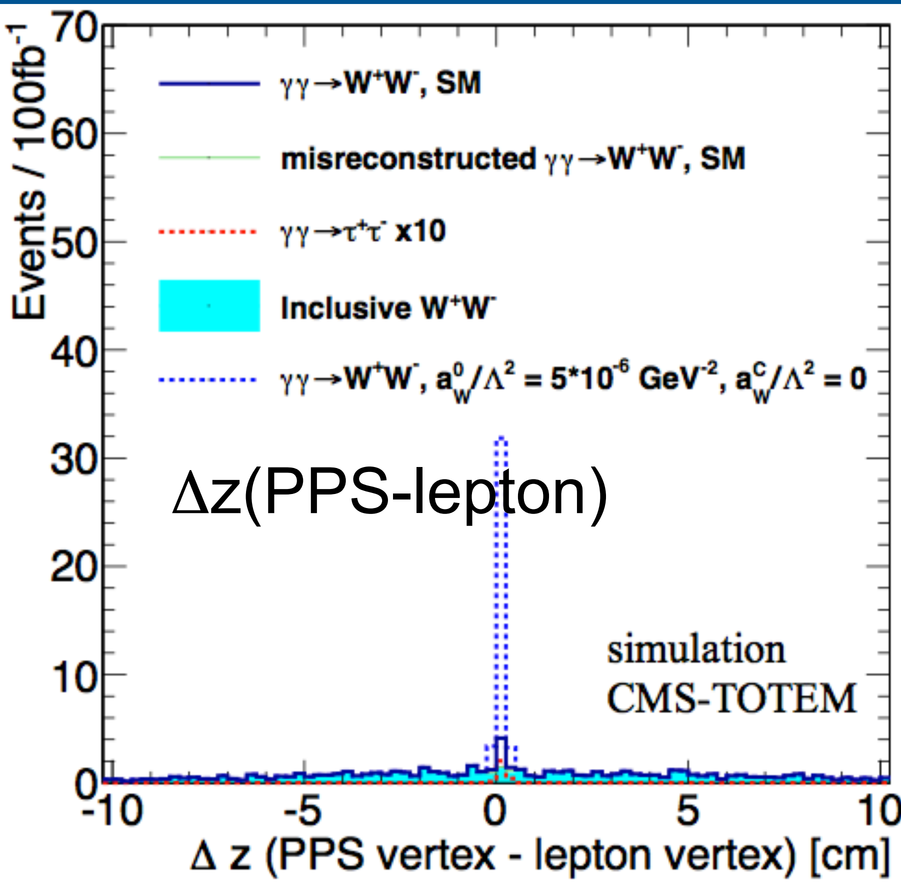
- Event selection
  - W pair in central detector
  - leading protons in PPS
  - study eμ final state
- Two steps:
  - SM production of WW production
  - Anomalous couplings
- Simulation/framework
  - Signal: FPMC generator
  - Backgrounds: incl. WW, SD, DPE, multijet QCD, excl. $\gamma\gamma \rightarrow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

Kinematical distributions

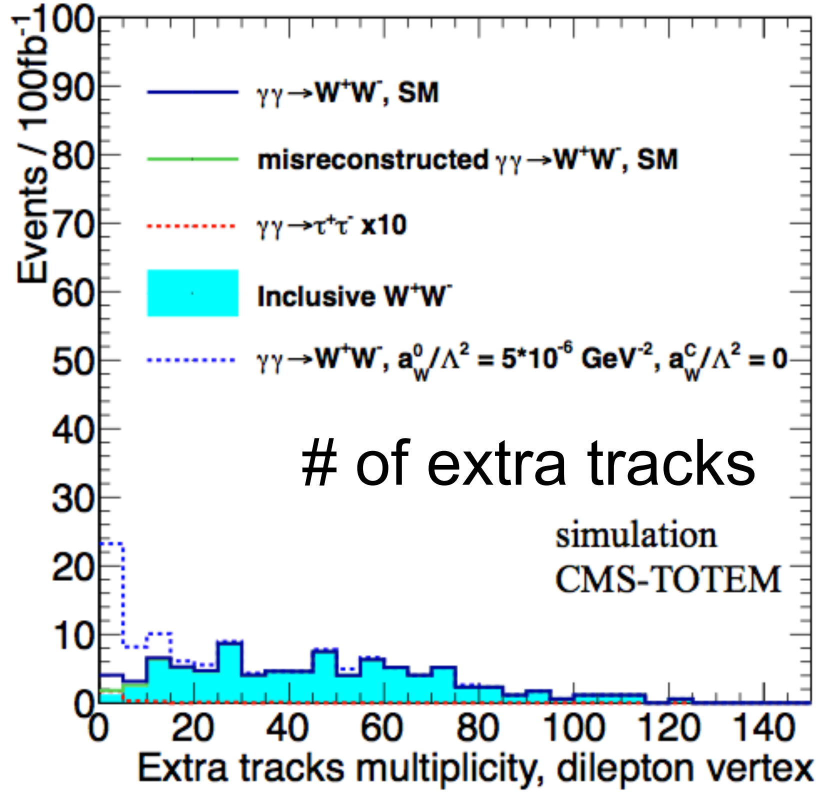
- SM vs AQGC: missing mass provides good separation
- Information from PPS



Kinematical distributions (cont.)



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

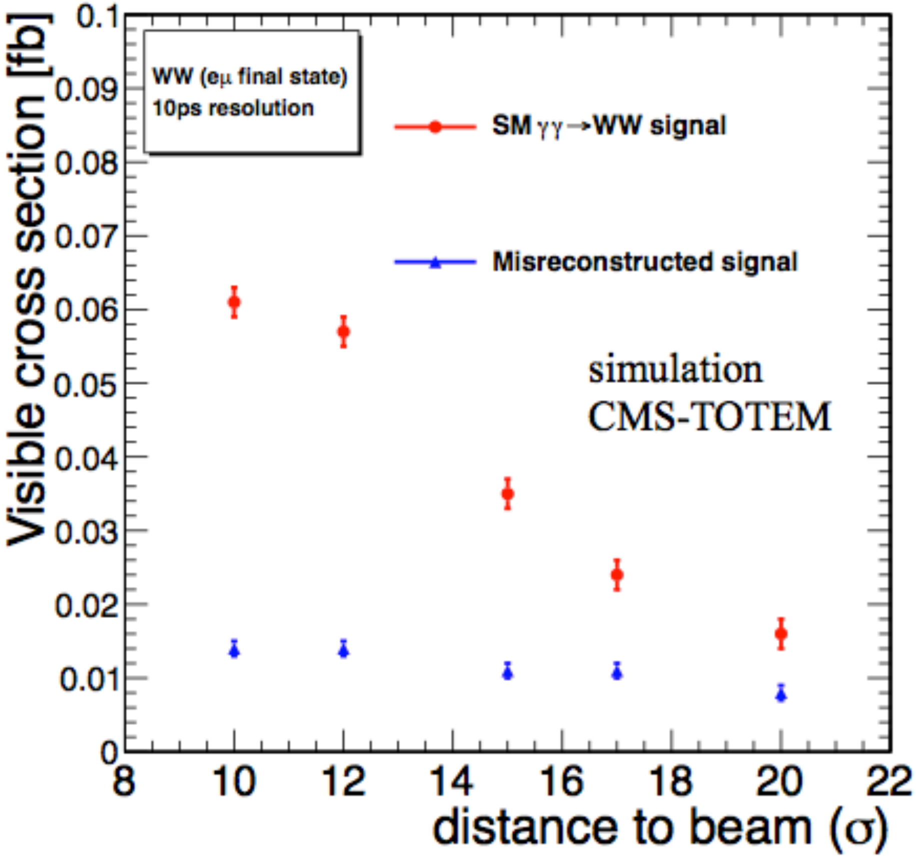


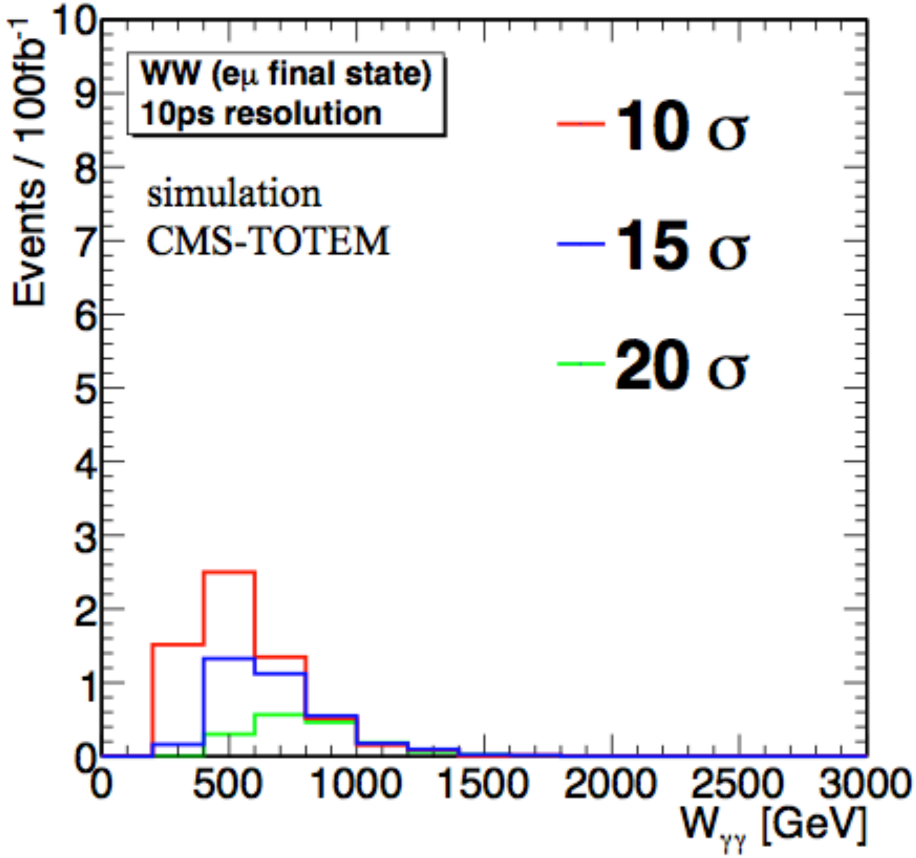
Yields (in fb)

- 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
$N_{\mathrm{tracks}} < 10$	0.028 (0.025)±0.002	0.009 (0.020)±0.001	0.03 (0.14)±0.01	0.002±0.001

Yields vs distance to beam





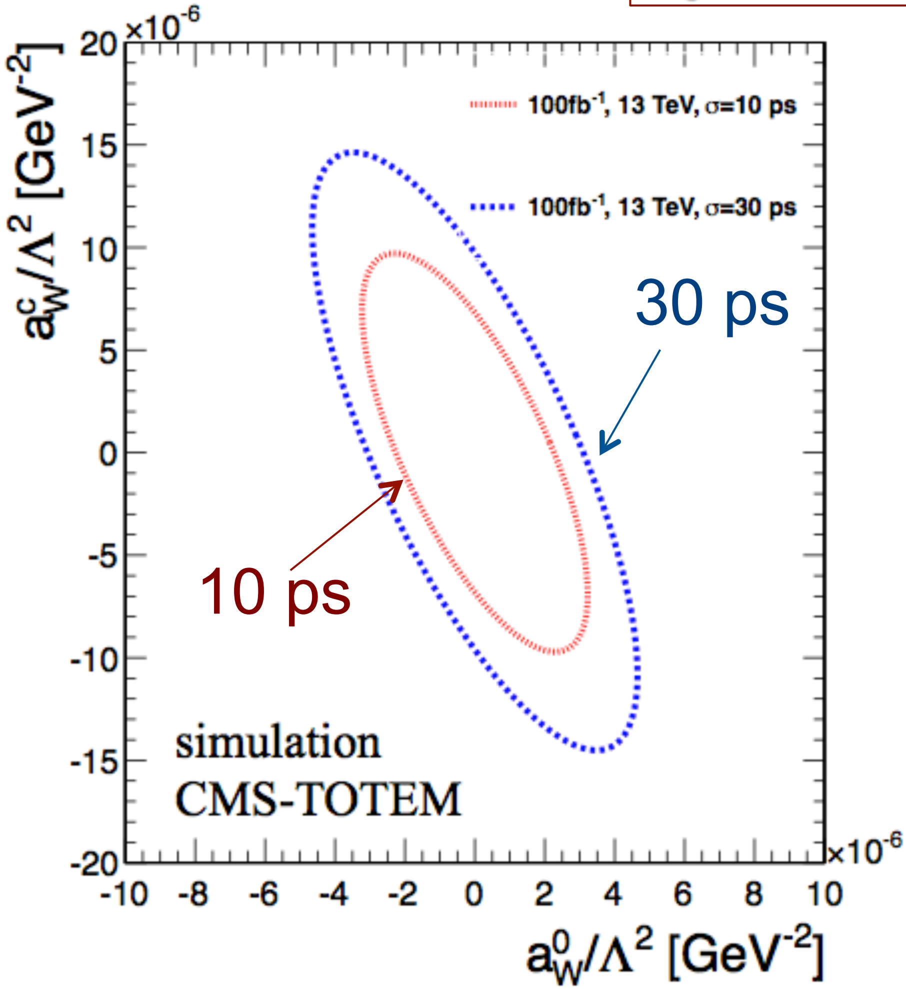
Potential enhancement of sensitivity with closer approach:

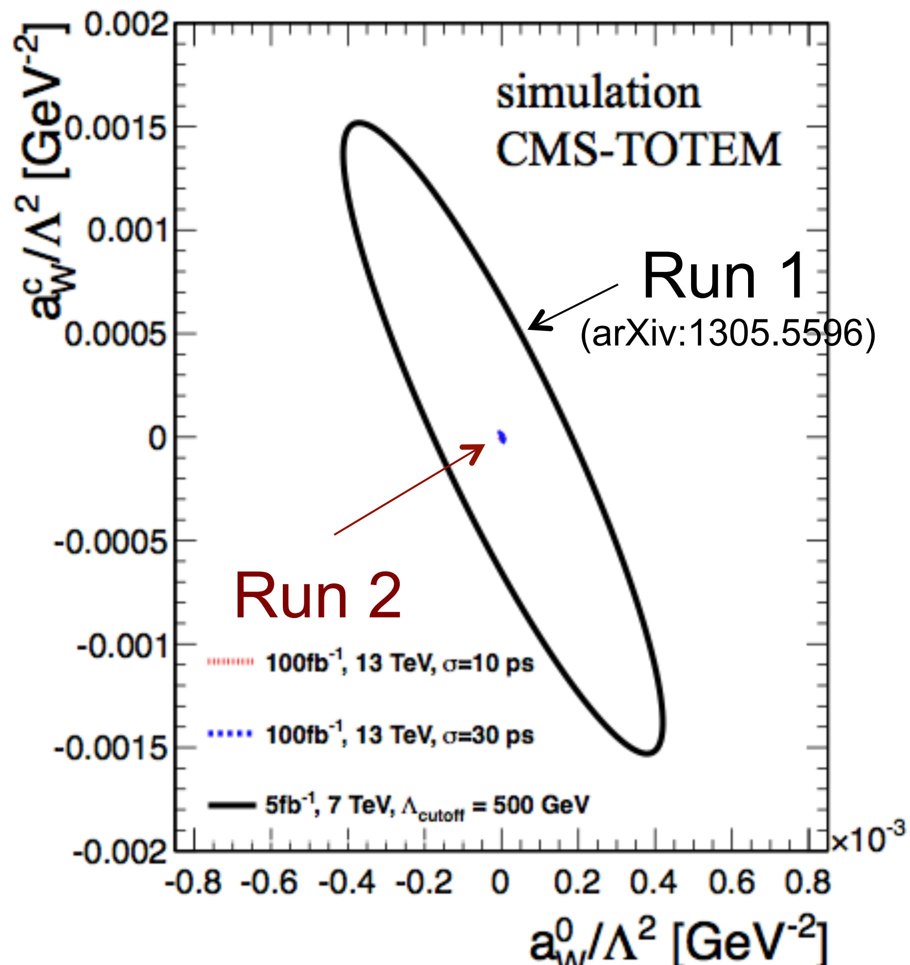
- Signal yield grows by ~x2 when going from 15σ to 10σ
- Background is more or less flat

AQGC expected limits

Expected limits @95%CL:

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



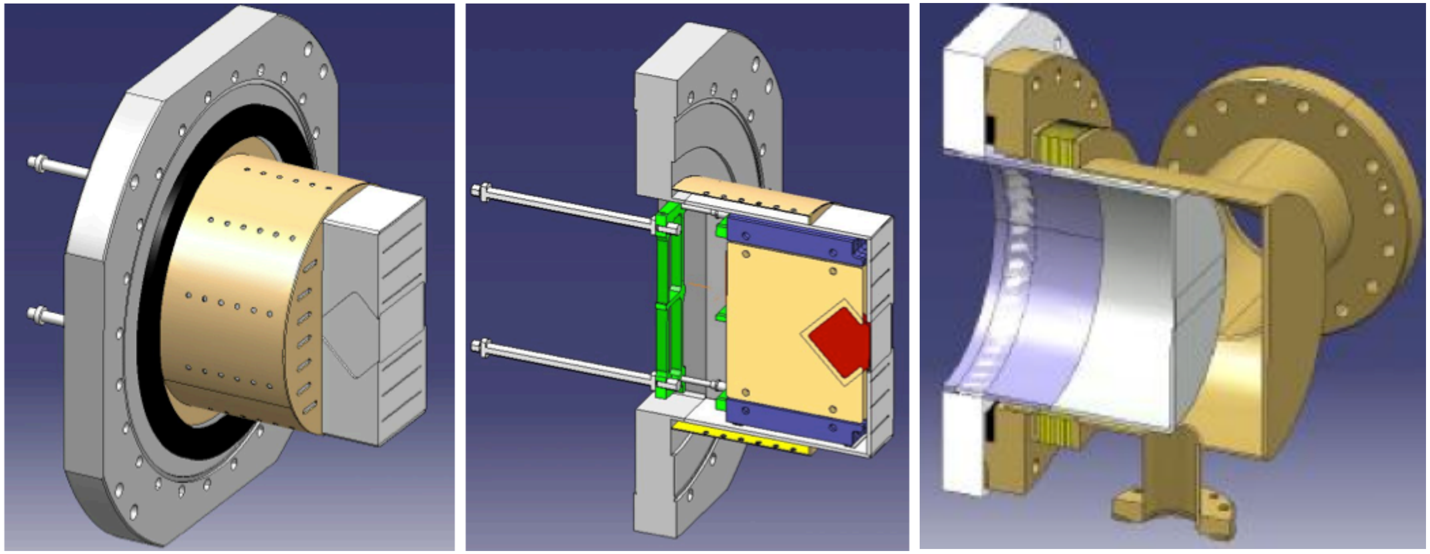


CT-PPS project

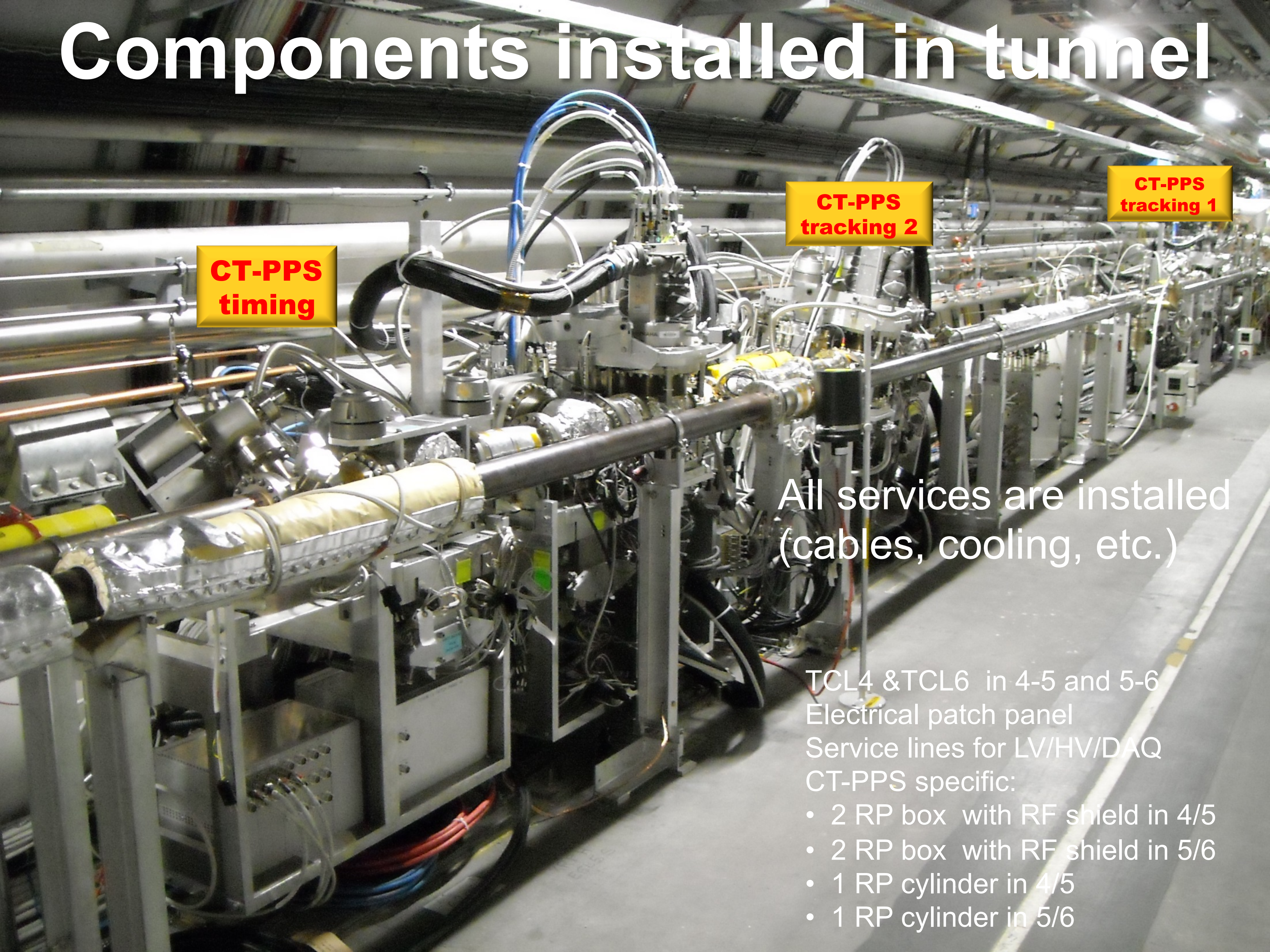
- Exploratory phase (2015-2016)
  - RP insertions commissioning at lowβ^* and high beam intensity
  - Establish regular RP insertions for physics during fills
  - Install detectors, commissioning
- Demonstrate that CT-PPS does not prevent stable operation of LHC beams, does not affect luminosity performance

Roman Pots

- Tests in 2012 of TOTEM RPs at high luminosity revealed issues (vacuum, beam dumps, heating)
- Improvements carried out
  - New RF shielding in standard box-shaped RPs
  - New cylindrical RP for timing detectors
  - 10 μm thick copper coating
  - New ferrites



Components installed in tunnel

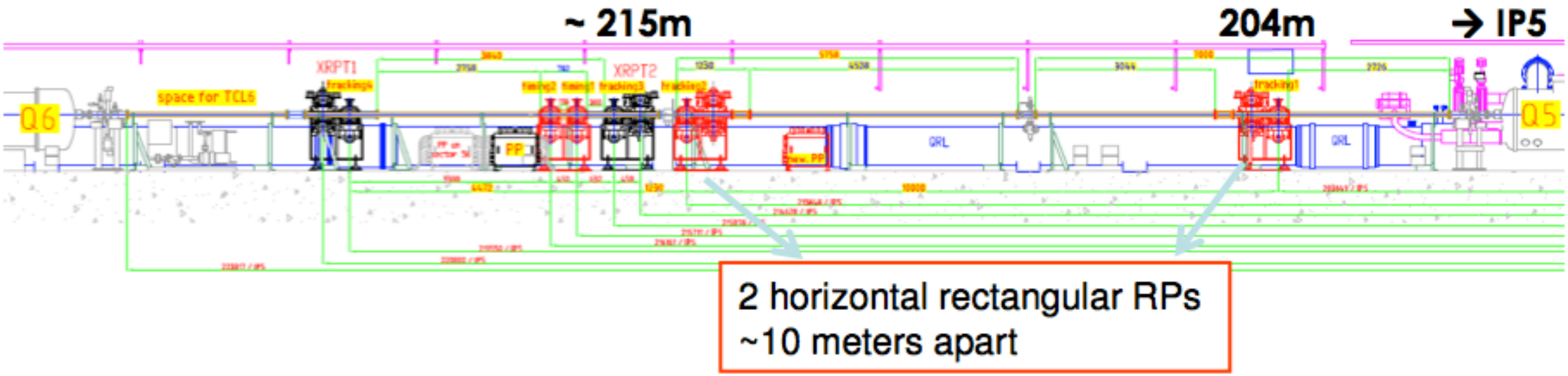


All services are installed (cables, cooling, etc.)

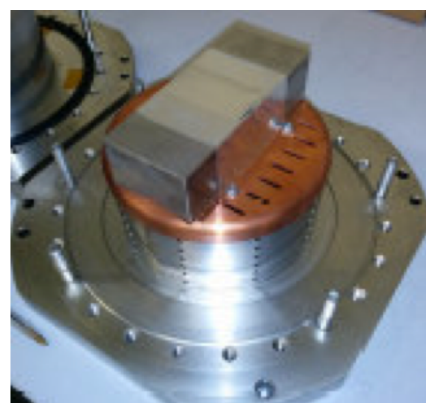
TCL4 &TCL6 in 4-5 and 5-6
Electrical patch panel
Service lines for LV/HV/DAQ
CT-PPS specific:

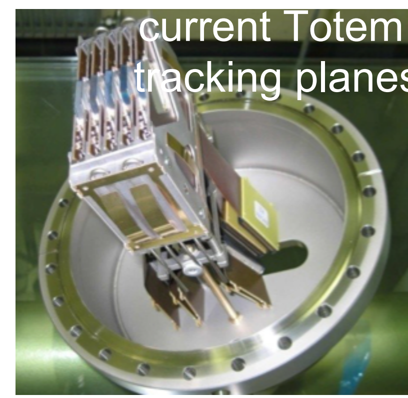
- 2 RP box with RF shield in 4/5
- 2 RP box with RF shield in 5/6
- 1 RP cylinder in 4/5
- 1 RP cylinder in 5/6

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: ~100 μm
- Tolerance to inhomogeneous irradiation
  - ~2x10^{15} n_{eq}/cm^2 close to beam (for 100/fb)
- Baseline: 3D silicon pixel detectors

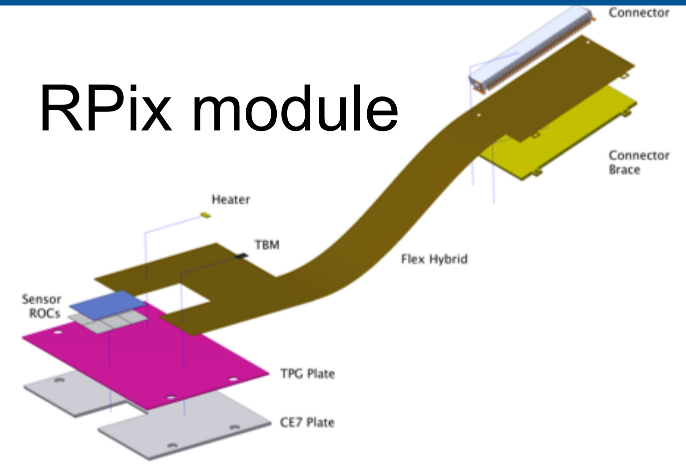




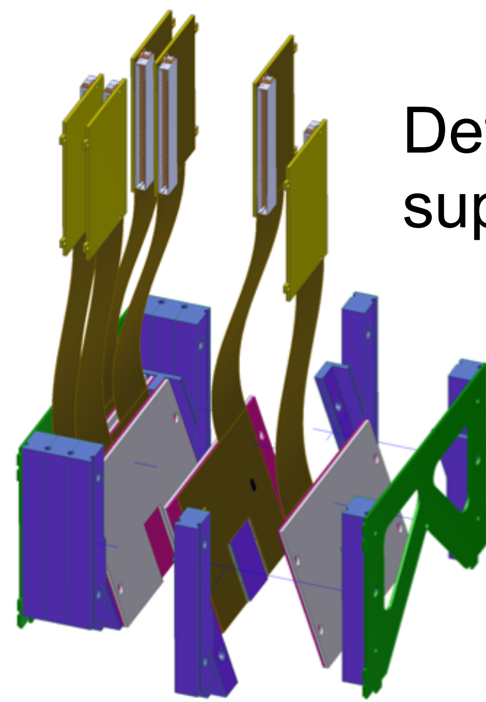
Tracking detectors (cont.)

- 3D silicon sensors
  - slim edges 100um
  - 2 readout electrodes per pixel (2E)
  - in production at CNM
- 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
  - number of planes provide redundancy

RPix module

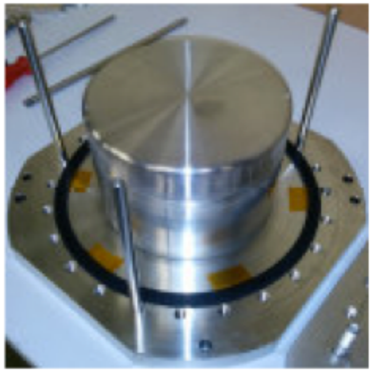


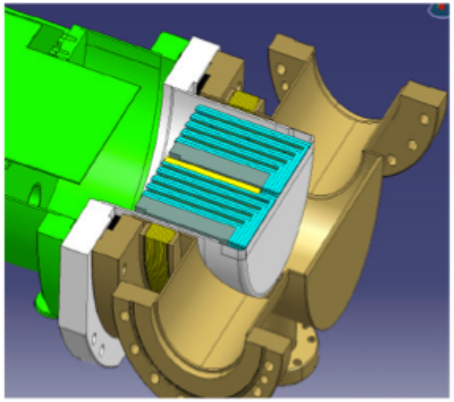
Detector support

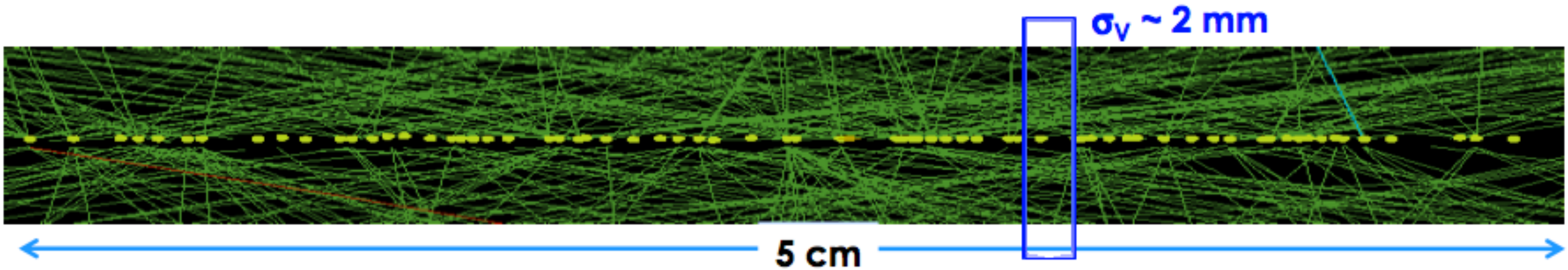


Timing detectors

- 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

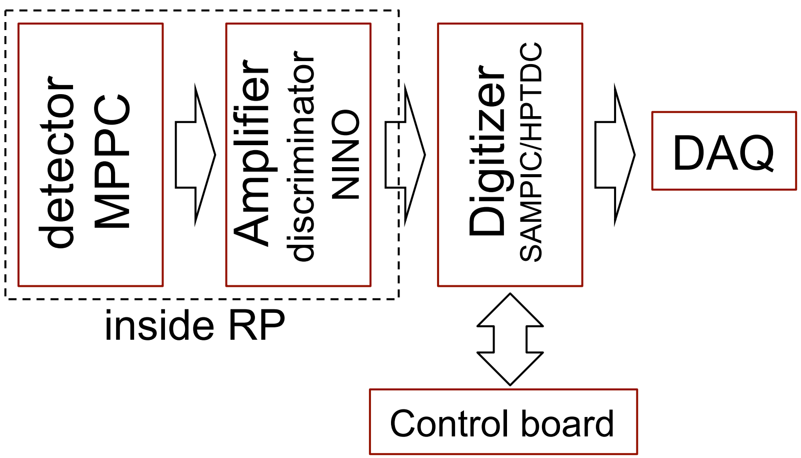


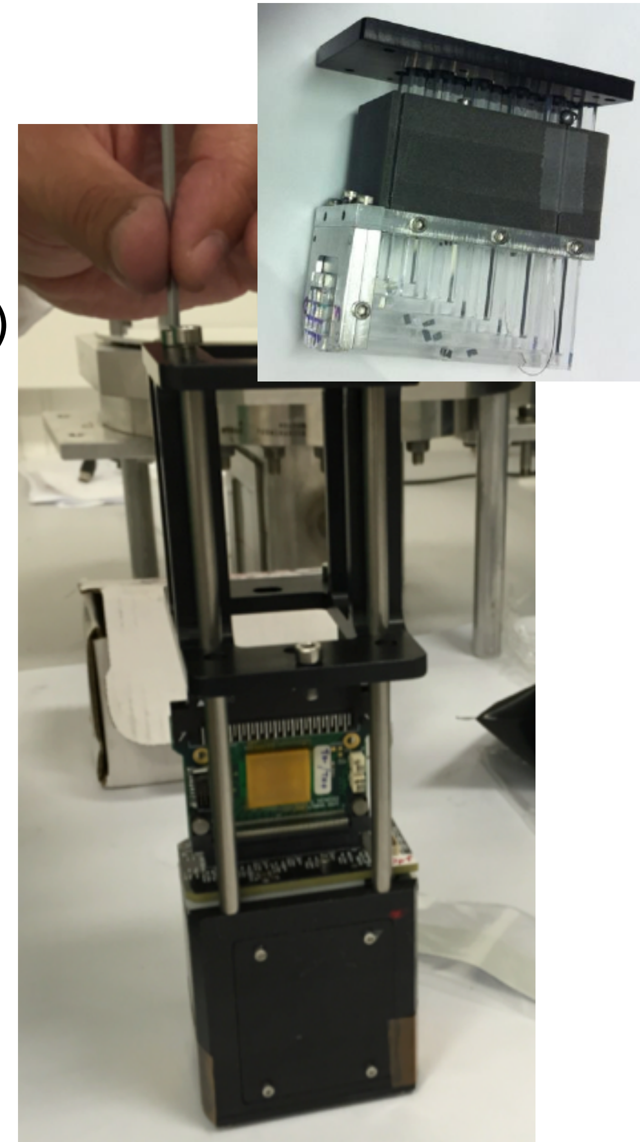




Timing detectors (cont.)

- 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

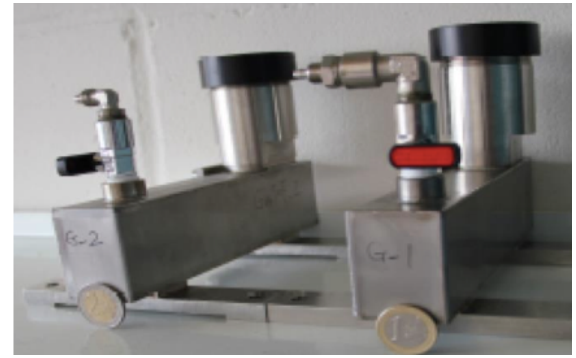
- Prototype test ongoing

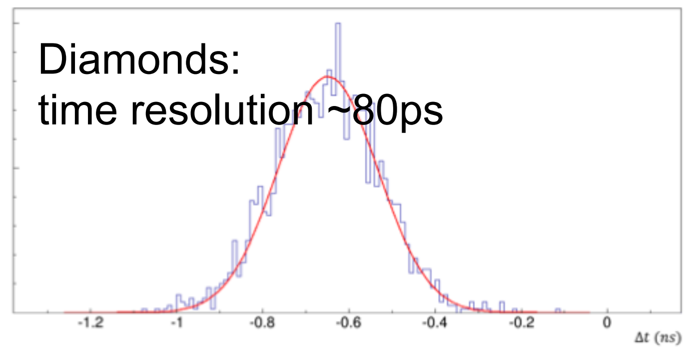
Diamond detectors

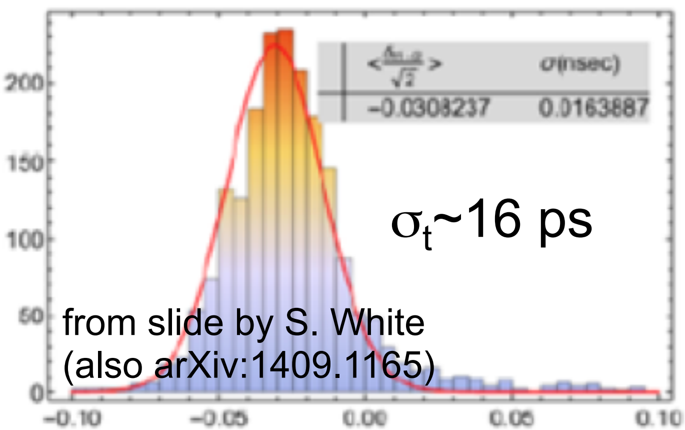
- 50 ps resolution with 4 planes

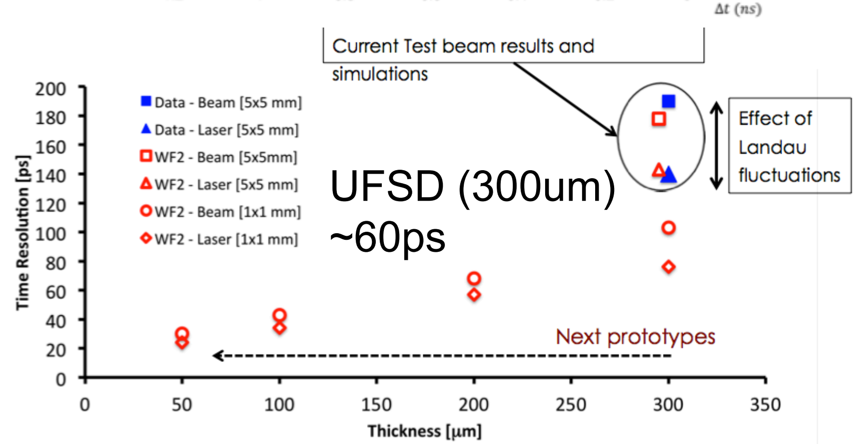
Silicon detectors

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









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

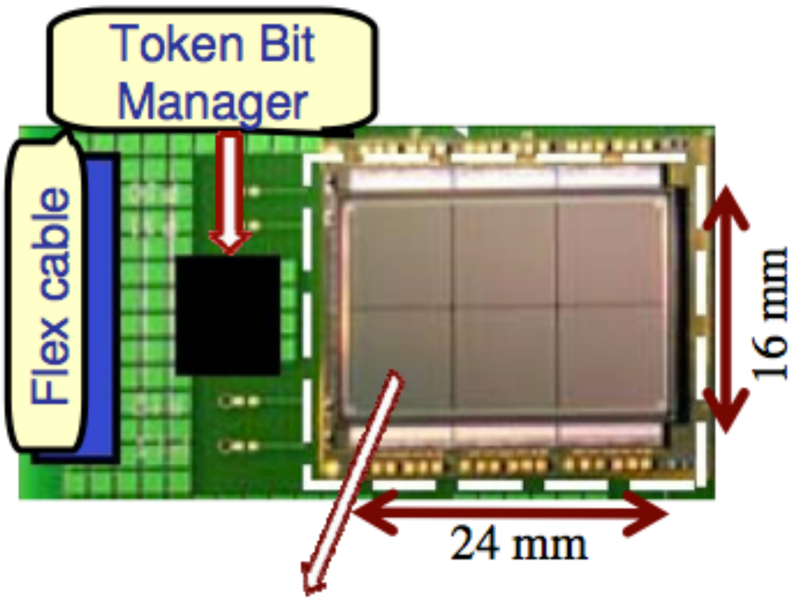
⇒Rich physics program with emphasis on BSM searches

backup

Tracking detectors (cont.)

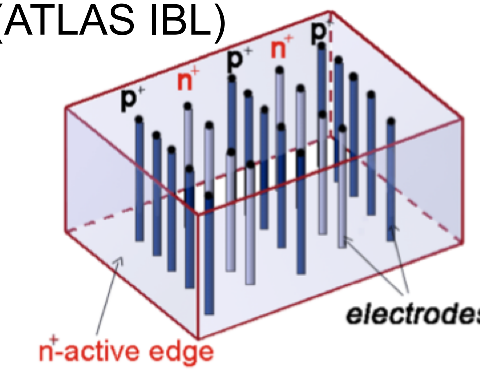
6 detector planes per station

For each plane:



- 16x24 mm^2 3D silicon pixel sensors
- 150(x) x 100(y) μm^2 pixel pattern (same as CMS pixel detectors)
- 6 PSI46dig ROC (52x80 pixels each)

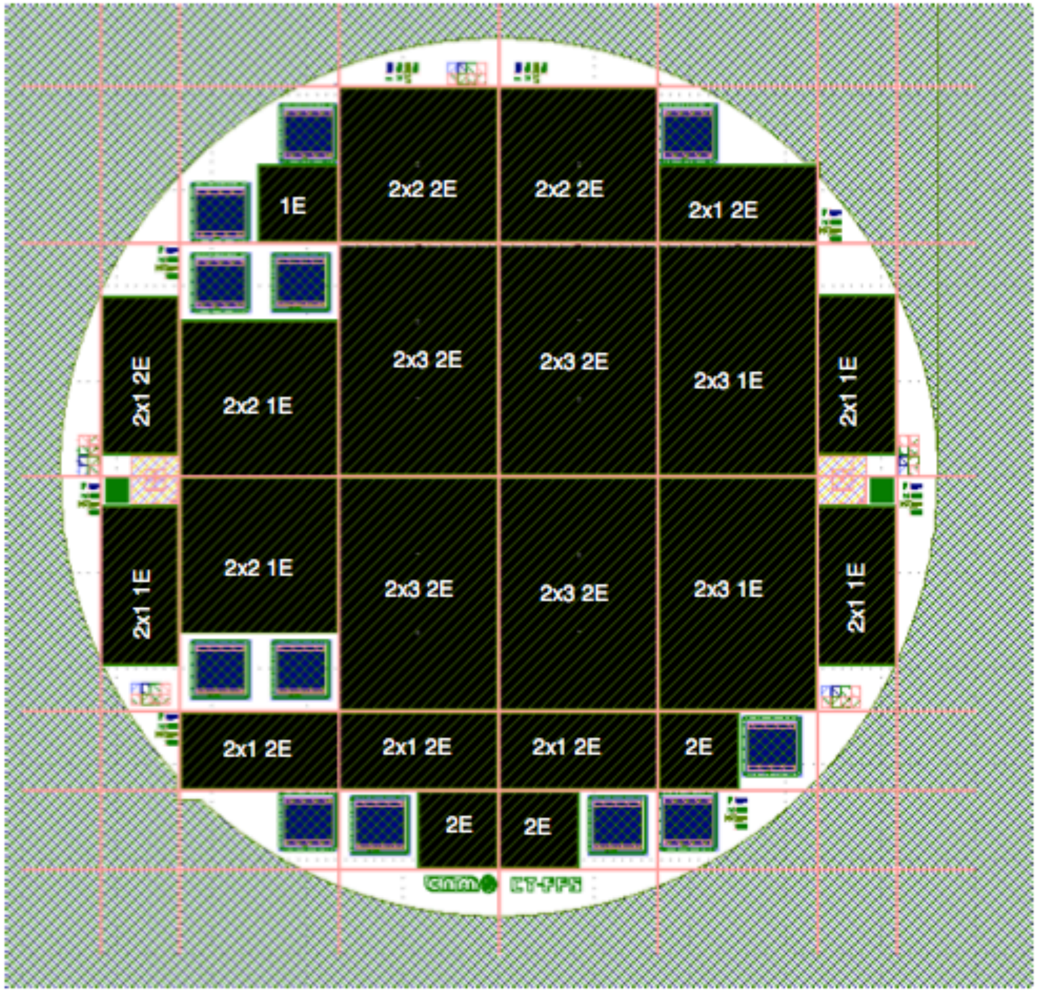
- 3D sensors consist of array of columnar electrodes
  - Mature technology (ATLAS IBL)



Features wrt to planar sensors:

- Low depletion voltage (~10V)
- Fast charge collection time
- High radiation hardness
- Slim edges (dead area of ~100-200μm); active edges with dead area reduced to few μm
- Good spatial resolution

Wafer layout in production



Wafer thickness 230μm

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 detector R&D (cont.)

GasToF system

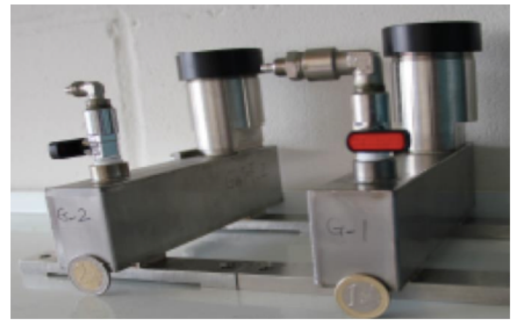
- Prototype test ongoing

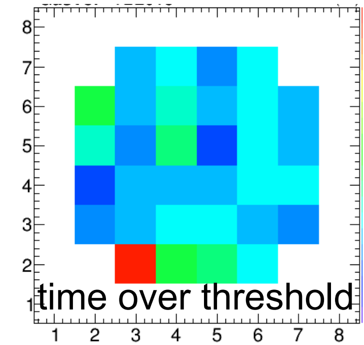
Diamond detectors

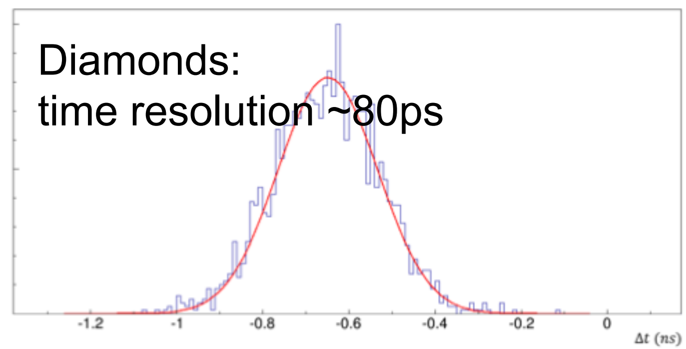
- 50 ps resolution with 4 planes

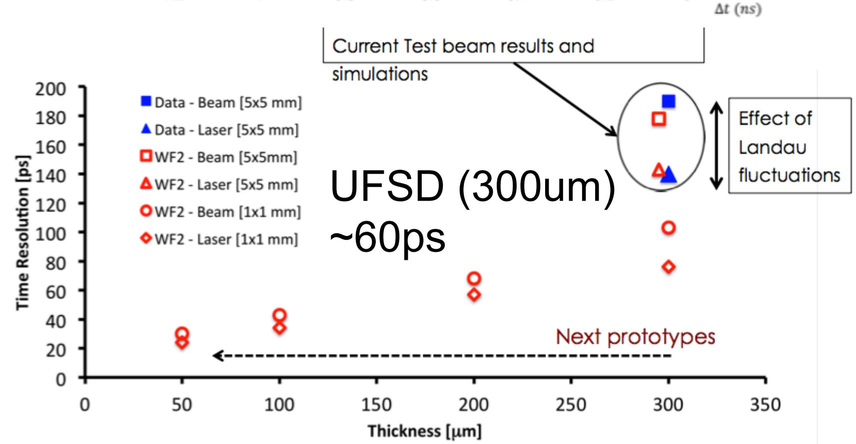
Silicon detectors

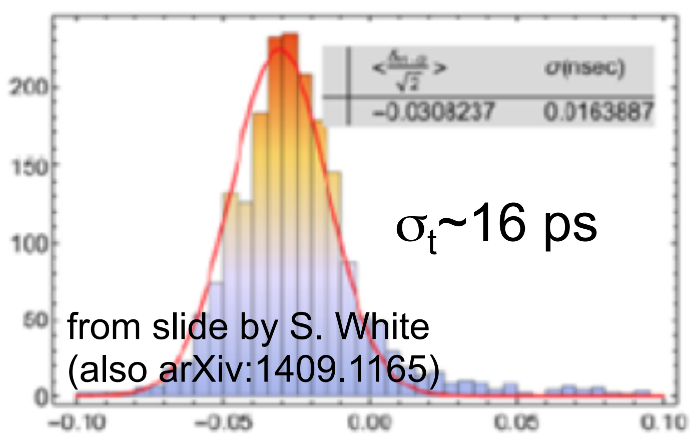
- Ultra-Fast Silicon Detectors
- Hyper-Fast Silicon detectors











Experimental challenge (cont.)

- Physics performance at high luminosity (2×10^{34} cm^{-2} s^{-1})
  - background from pileup/beam
- Detector operation close to the beam
  - expected performance
  - RF impedance, showers originated in the detectors
- Radiation levels
  - in detector and front-end electronics (for 100/fb, proton flux up to $5 \times 10^{15} cm^{-2}$ in detectors, $10^{12} n_{eq}/cm^2$ and 10Gy)
- Timing detectors
  - Challenge is good time resolution, 10/30 ps
- Tracking detectors
  - 10μm, 1μrad, fluence 5×10^{15} protons cm^{-2} ($100\ fb^{-1}$)

Experimental challenge (cont.)

- Physics performance at high luminosity ($2x10^{34}$ cm^{-2} s^{-1})
  - background from pileup/beam
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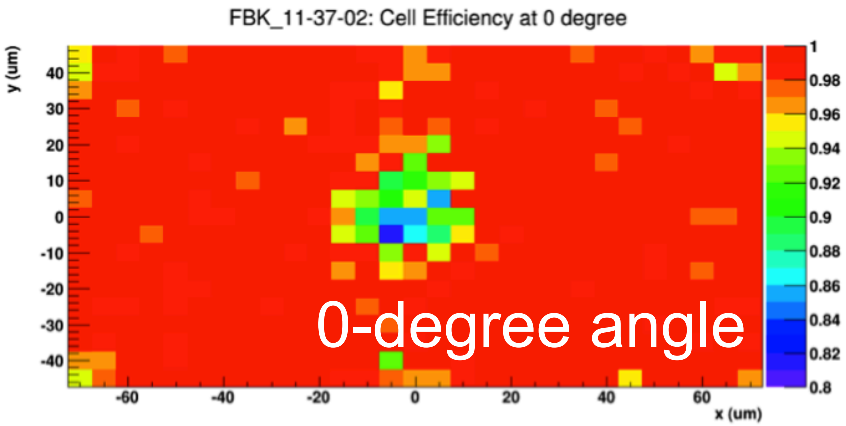
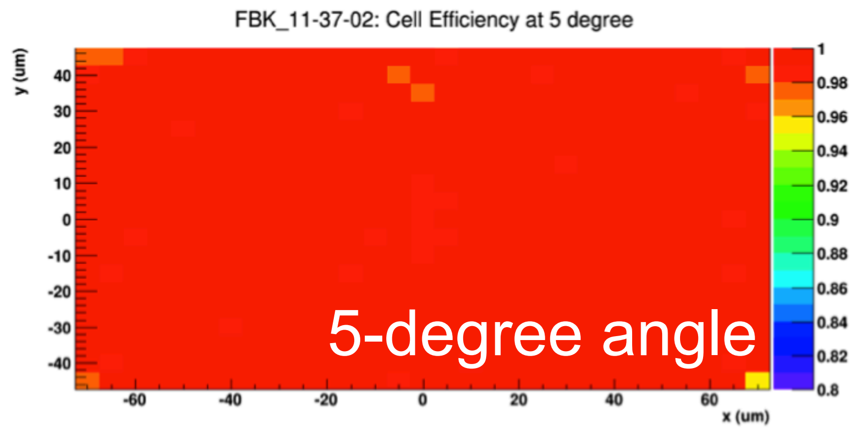
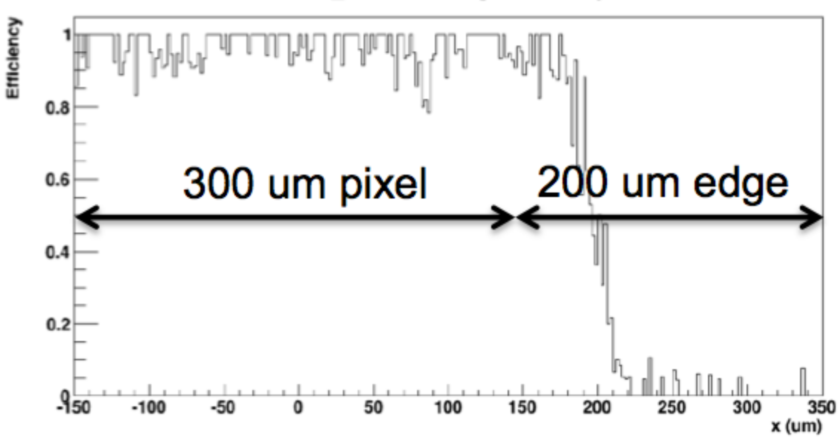
  - expected performance
  - RF impedance, showers originated in the detectors
- Radiation levels
  - In detector and front-end electronics
- Timing detectors
  - Challenge is good time resolution, 10/30 ps
- Tracking detectors
  - 10μm, 1μrad, fluence $5x10^{15}$ protons cm^{-2} (100 fb^{-1})

Beam tests: preliminary results

- FBK 3D sensors with 200μm slim edges coupled to new PSI46dig ROC tested at Fermilab
- Measurements with irradiated detectors (from 1×10^{15} to 1×10^{16} n_{eq}/cm^2) ongoing, results promising

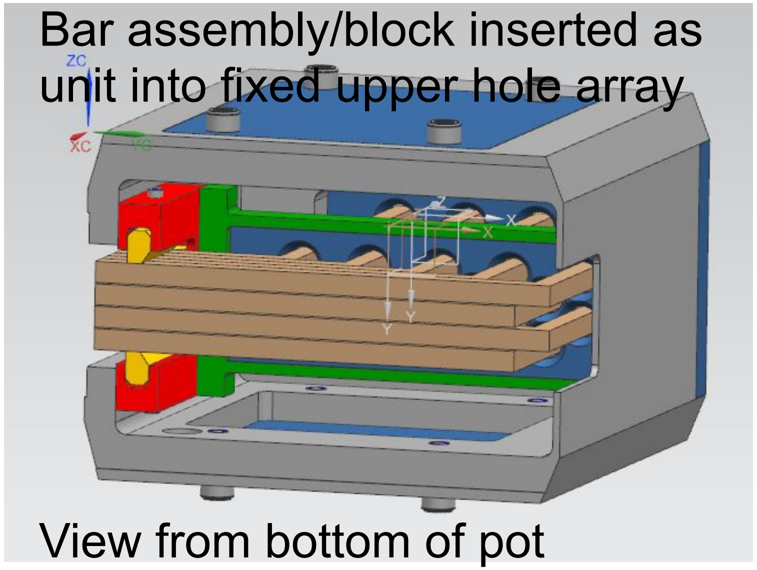






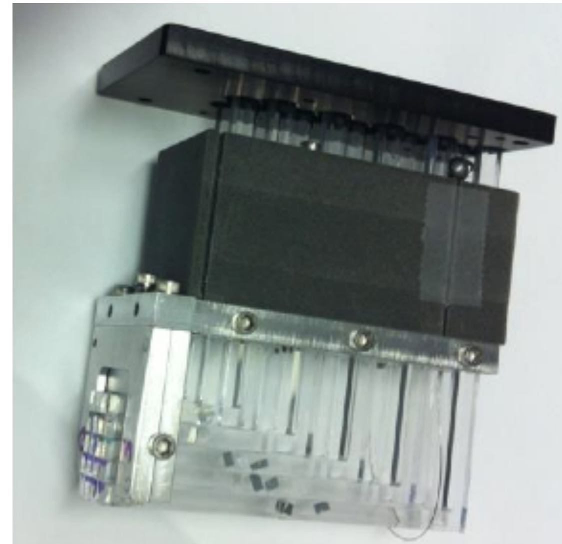
edge efficiency

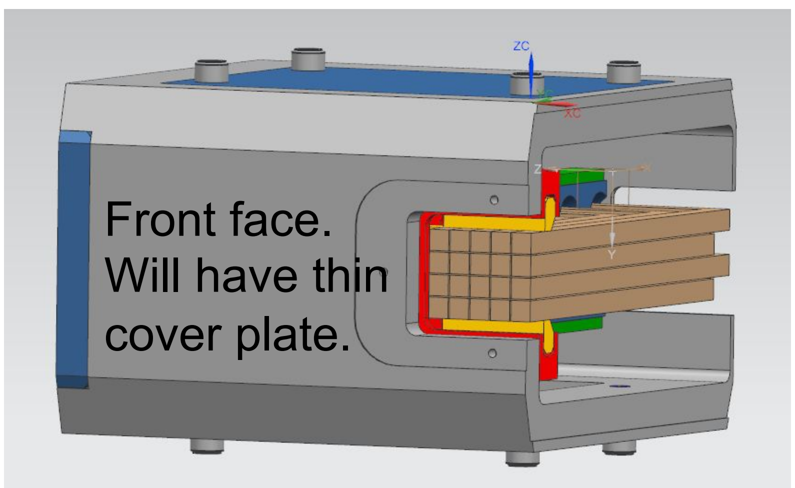
Timing detectors (cont.)



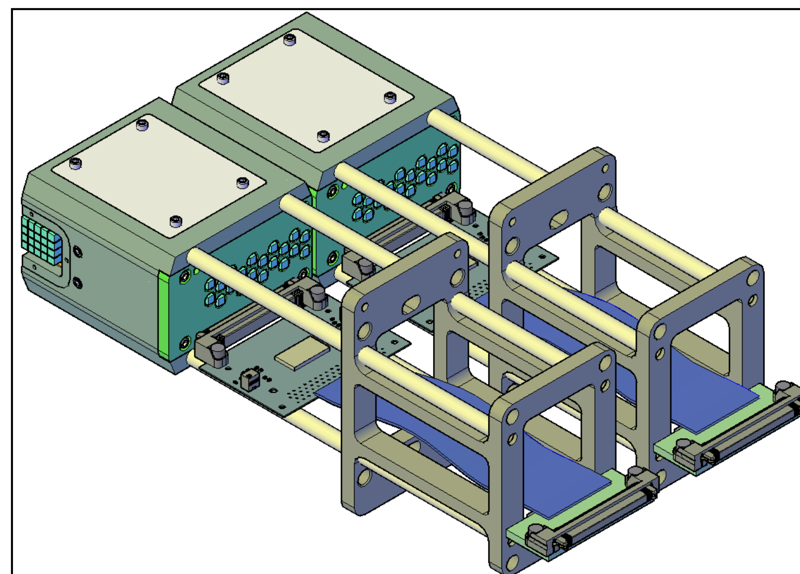
Bar assembly/block inserted as unit into fixed upper hole array

View from bottom of pot



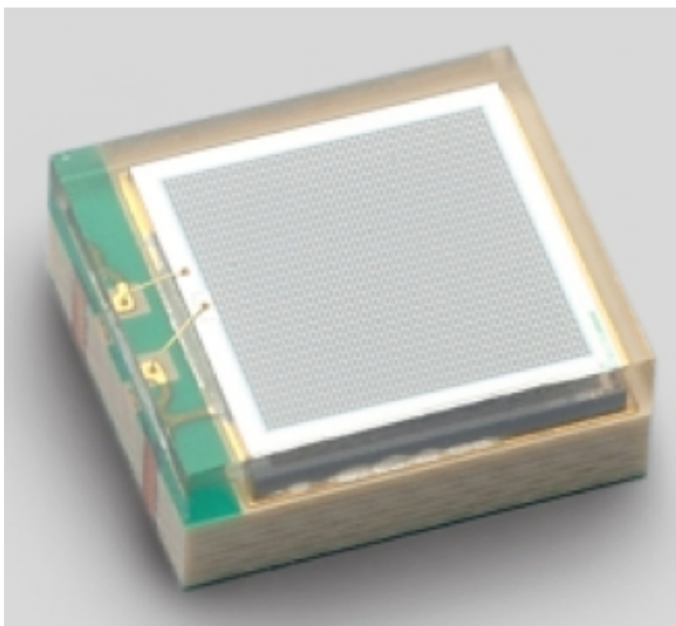


Front face. Will have thin cover plate.

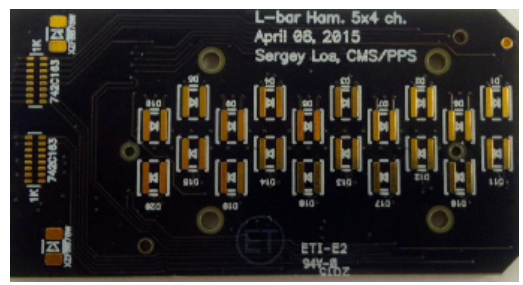


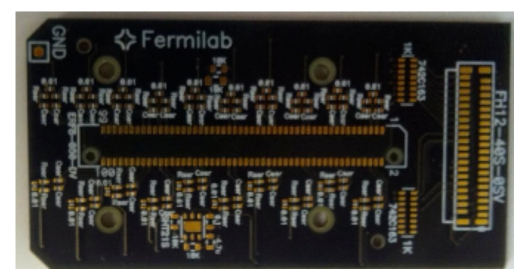
Photosensors

- SiPMs Hamamatsu MPPC S12572-050
  - Qualified for 10^{12} n/cm^2 (CMS HCAL)
  - Low afterpulse
  - Increased leakage current may impact time resolution
- Possible use of GInP photosensors (Shashlik Phase2 option)



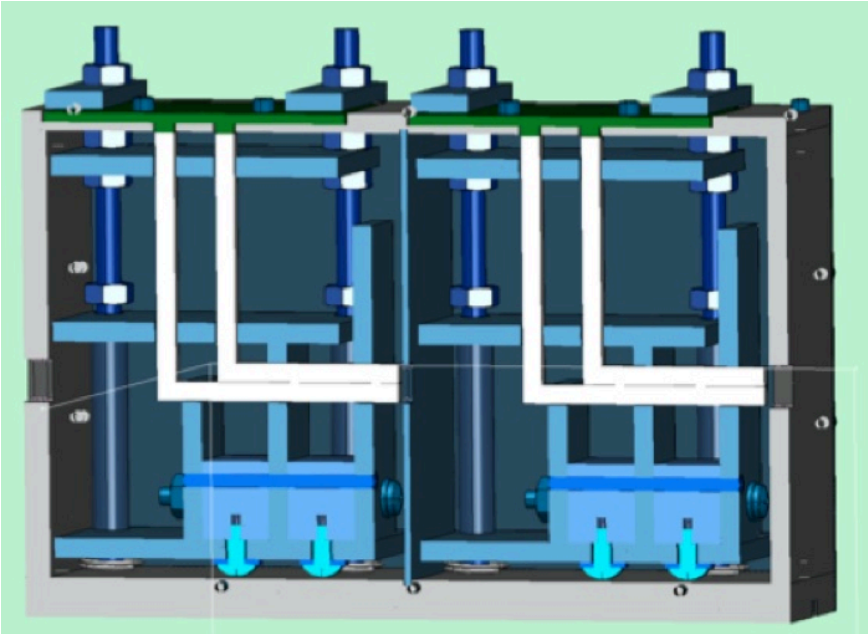
SiPM readout board

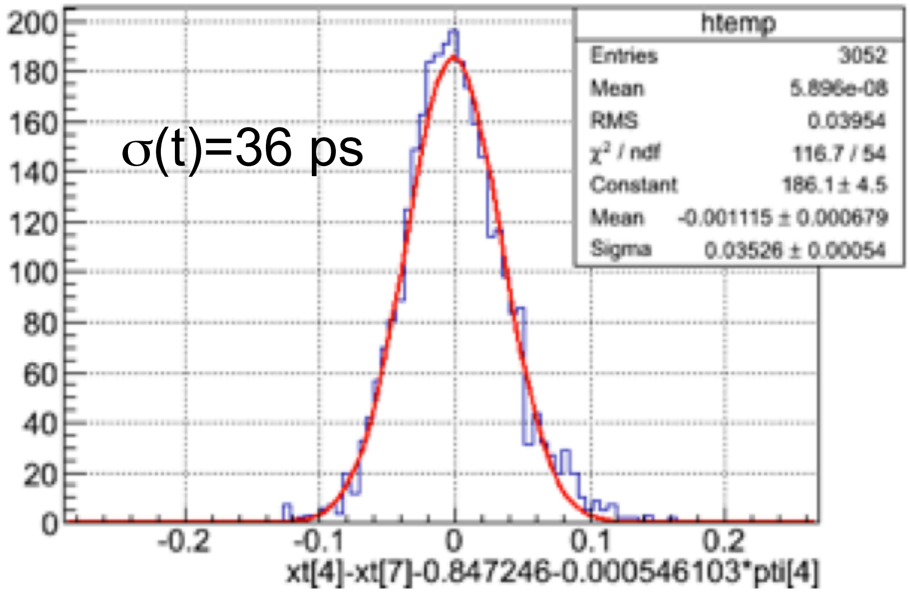




Beam tests

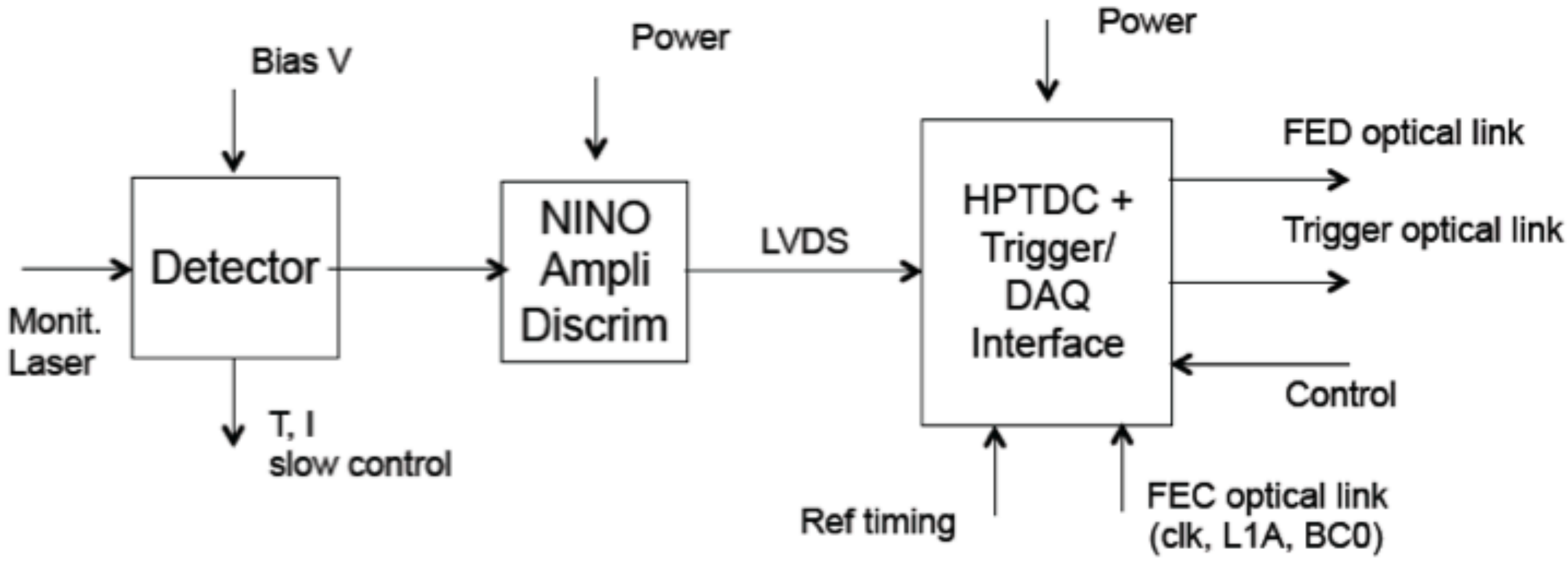
- Test modules with 30 and 40 mm radiator bars
- Time resolution σ=36 ps (30 mm bar)
  - Time difference between L-bar and reference signal
  - 2-in-line ⇒ 25ps (improvements possible)



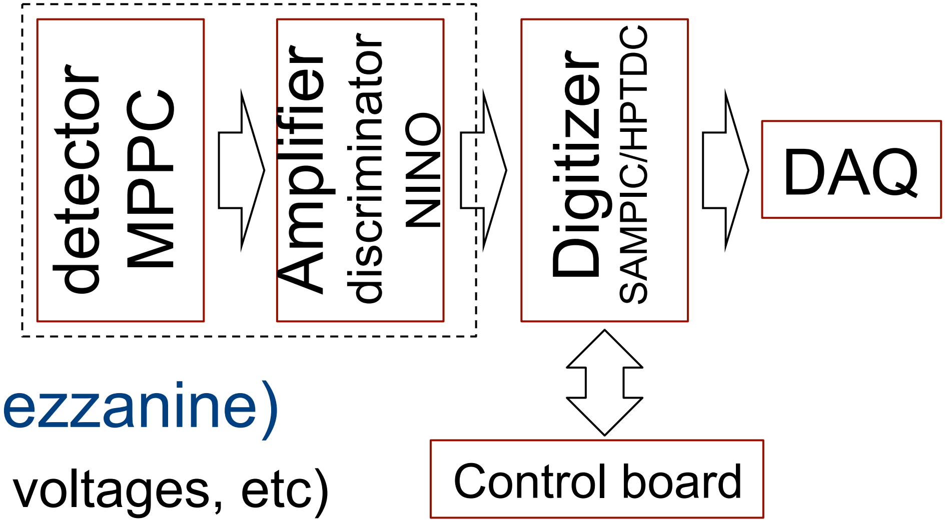


Readout system

- Amplifier & discriminator NINO and high resolution HPTDC chips
- Time resolution of readout is 20 ps
- Integrated with PPS DAQ (tracking+timing)
- Readout rate limit is 5 MHz/channel
  - Quartic 3x3mm^2 rate too high above PU=25

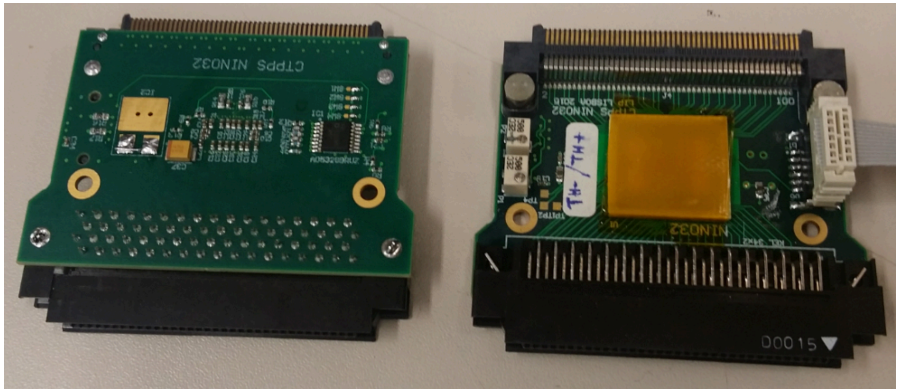


Electronics



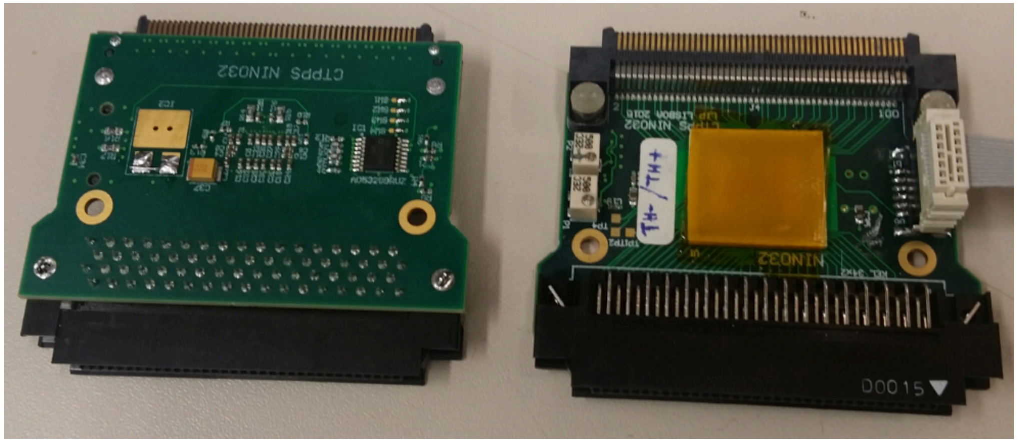
Electronics read-out chain

- Front-end/SiPM board
- NINO (amplifier-discriminator)
- Digitizer board (motherboard+mezzanine)
  - control of SiPM control board (bias voltages, etc)

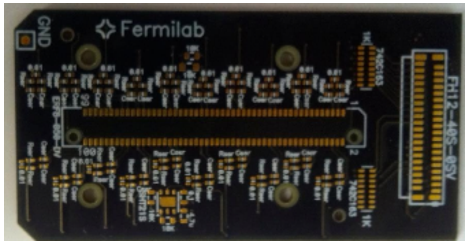


First electronics produced for PPS

- NINO32 board (ampl/disc)
  - Produced, assembled, tested OK
  - Ongoing tests

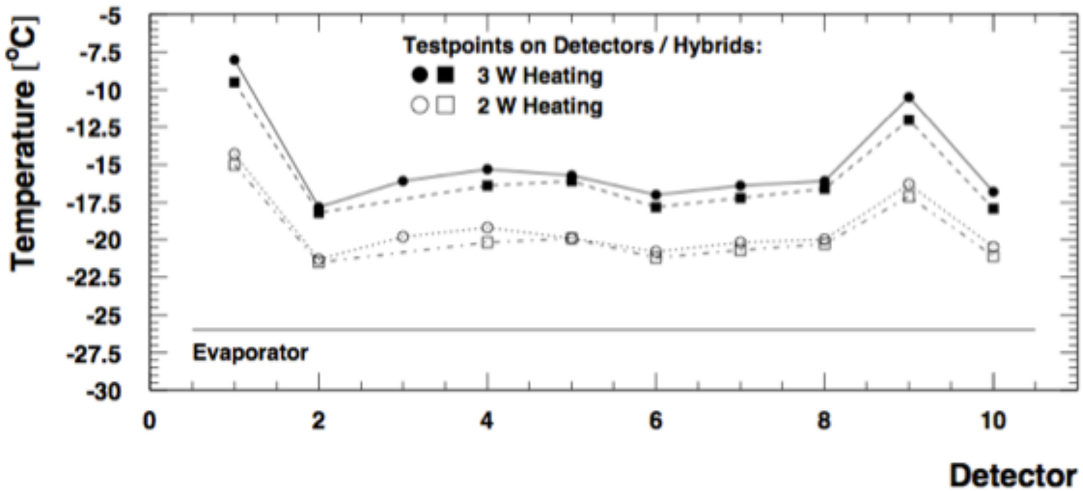


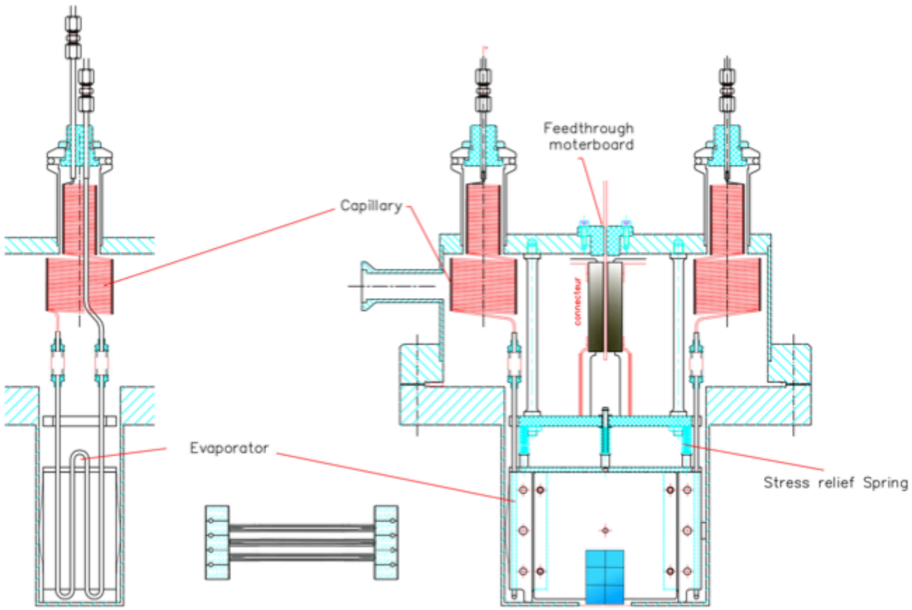
- SiPM front end board
  - Produced, assembled, tested OK
  - Ongoing tests



RP cooling system

- RP cooling system may handle up to 50W of heat released by on-detector electronics
- RPix estimate: <10W per package
- Use existing TOTEM cooling system

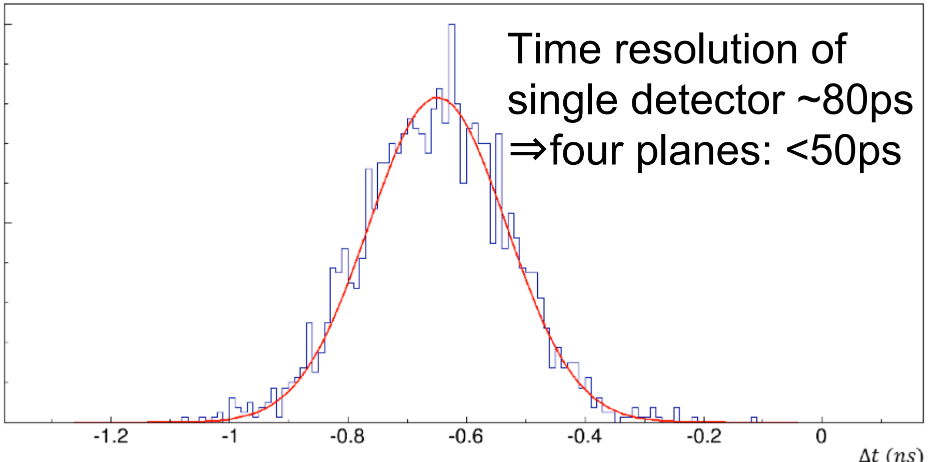




- Temperature measured on test-points on the detectors (circles) and on the hybrids (square) for a heating power of 2W and 3W (open and solid markers)

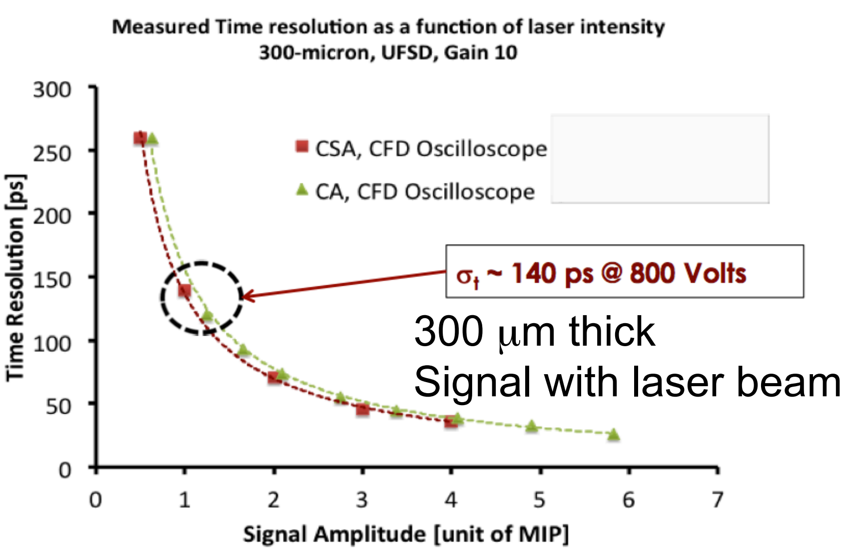
Diamond detectors

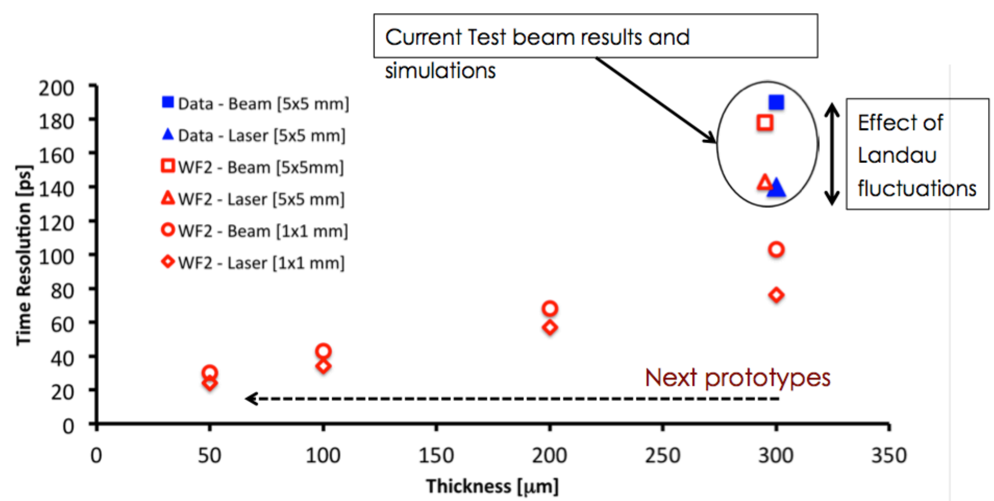
- Appropriate characteristics
  - Fast signals
  - Detector pixel size does not affect signal response
  - Adjustable geometry
- Requires R&D on frontend electronics
  - Small charge signal from diamond sensor (6k e) implies very low noise electronics
  - Good timing requires fast electronics
- Requires R&D on radiation and rate effects



Timing silicon detectors

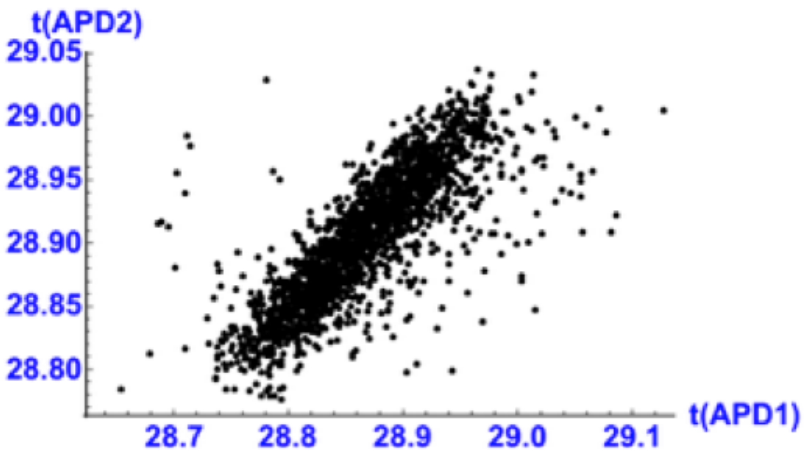
- Based on Low-Gain Avalanche Diodes (LGAD)
  - Output signals 10 times larger than traditional silicon sensors
- Requires R&D on frontend electronics
- Requires R&D to improve radiation resistance

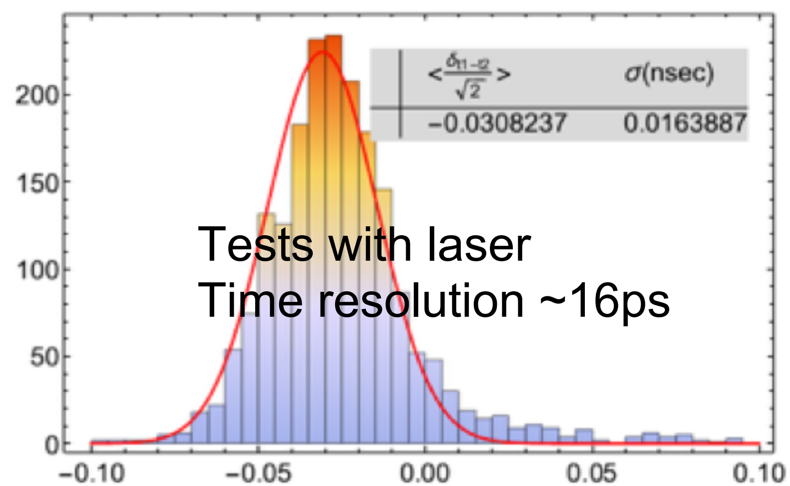




Avalanche Photo Diodes

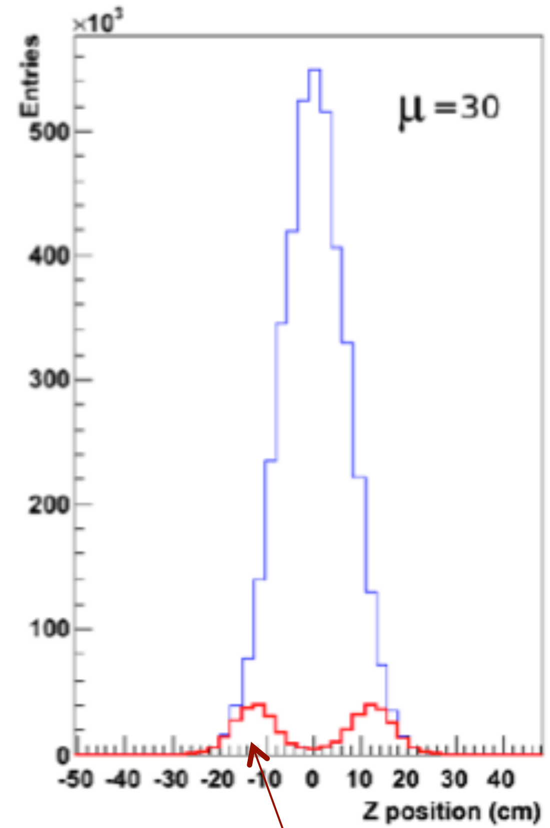
- Avalanche Photo Diodes (APDs)
  - preliminary tests show good time resolution
- Requires R&D on frontend electronics
- Requires R&D to improve radiation resistance
  - tests ongoing
- Requires improved characterization/understanding





Trigger strategy

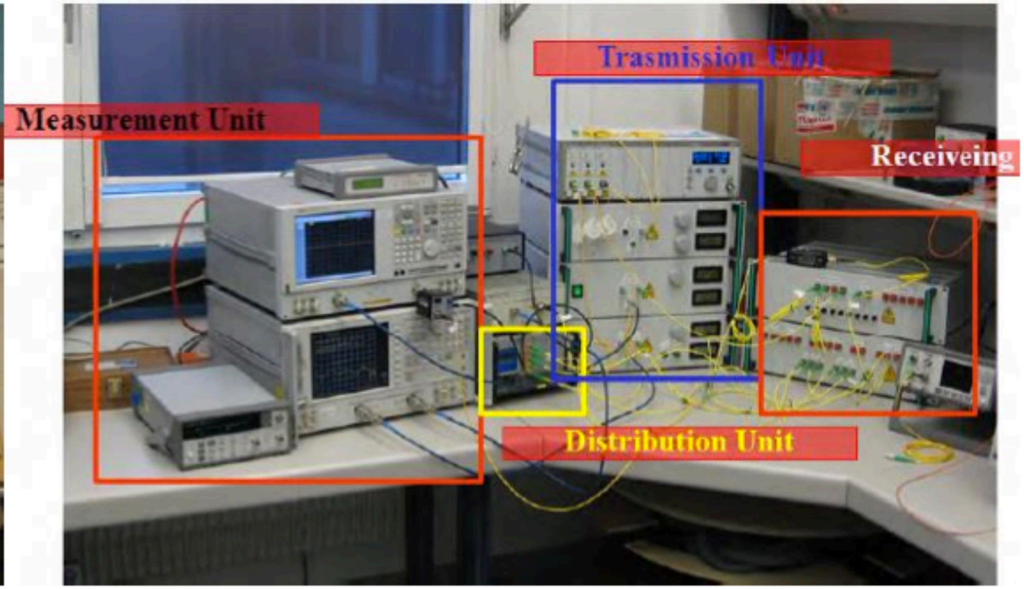
- Two photon physics
  - Lepton final states captured by lepton triggers
  - Trigger efficiency expected to be high, as lepton thresholds are 30 GeV or below
  - Final states with hadronic decays of one W or one tau accessible using lepton+jet triggers
- Hadronic physics
  - Large inclusive QCD jet background
  - L1 timing trigger selecting events in the tails of the z-vertex distribution



Vertices separated by at least 1cm (in red)

Timing system

- PPS will be integrated in the CMS Trigger Control and Distribution System (TCDS) as additional partition
- It requires a complementary timing system with low jitter (<1 ps) replica of master clock
  - System developed in CMS based on system at SLAC Linac Coherent Light Source (LCLS)
  - System developed in Totem (FAIR at GSI)



Planning

- Exploratory phase followed by a production phase until LS2
- Exploratory phase (2015-16)
  - Prove ability to operate detectors close to beam-line at high luminosity
  - Show that PPS does not prevent stable operation of LHC beams, does not affect luminosity performance of machine
- In 2015:
  - Evaluate RPs in 204-215 m region
  - Demonstrate timing performance of Quartic baseline
  - Use Totem silicon strip detectors
  - Integrate PPS detectors into CMS trigger/DAQ system
- In 2016:
  - Upgrade tracking to pixel detectors
  - Upgrade timing detectors if required/possible
  - Evaluate MBP option

CT-PPS project phases

Main goals

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

Collimators TCL 4, 5, 6

- TCL6 (downstream of CT-PPS)
  - New collimators TCL6 between RP220 and Q6 installed
  - To absorb showers produced by the RPs and protect quadrupole Q6
- TCL4 and TCL5 (upstream of CT-PPS)
  - New collimators TCL4 installed
  - TCL4 closed to 15σ and TCL5 closed to 35σ
  - Both collimators would set cut-off at ξ_{max}=0.11

Roman Pot insertion at low β^*

Final goal

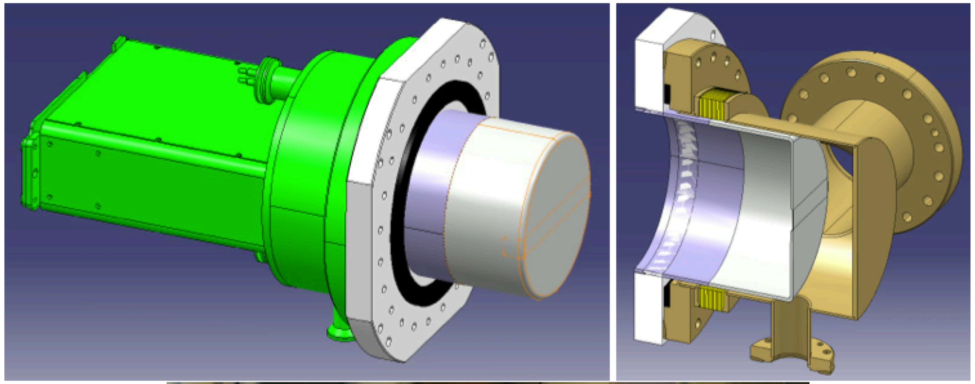
- Establish regular RP insertion for physics operation in regular fills from 2016
- RP insertion commissioning
- Insertions at low beta* and high beam intensities during 2015 exploratory phase

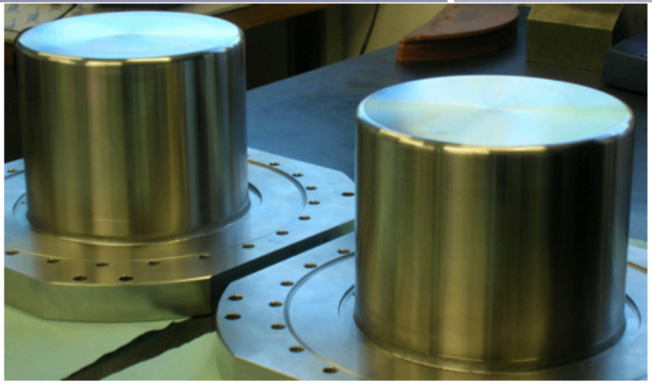
Experience from tests in 2012

- Showers of collisions debris from IP
- Impedance heating combined with ferrite outgassing
- Measured temperature rise despite active cooling
- Vacuum deterioration

Beam pockets

- Approaching the beam:
  - Roman Pots (RPs)
  - Movable Beam Pipe (MBP)
- RP is more mature solution
  - To be tested in 2015 exploratory phase
- MBP pursued in parallel
  - Low impedance
  - Joint project of LHC/experiments





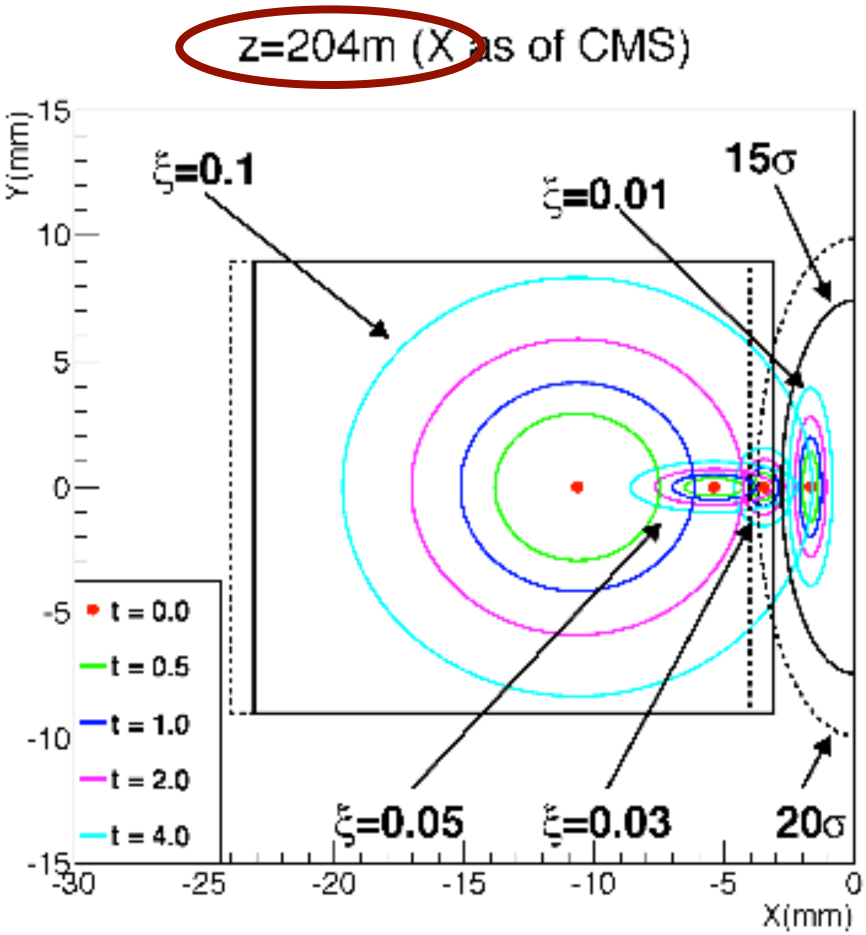
Simulation

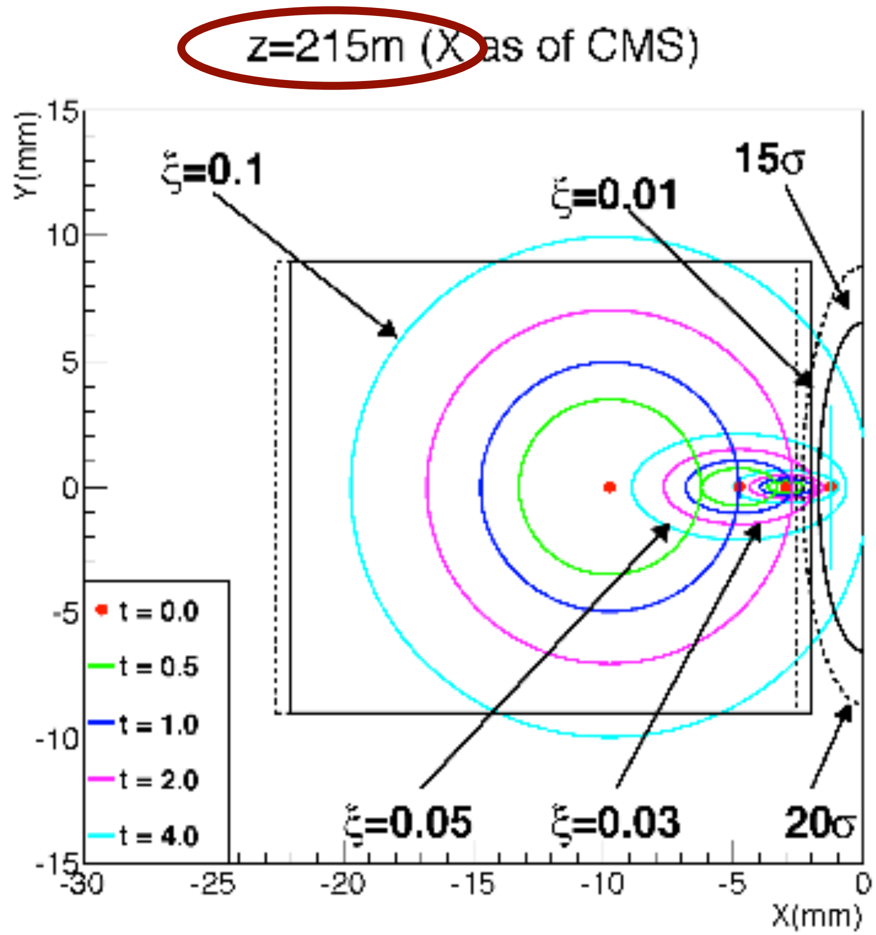
- Generated events are processed through GEANT4 simulation of CMS central detector, and standard reconstruction chain
- Protons are tracked through the beam-line to tracking and timing detector position
  - Simulation includes beam energy dispersion, beam crossing angle, smearing due to beam divergence, vertex smearing
- Fast simulation of PPS detectors takes into account detector segmentation and resolution
  - Time resolution of 10ps (baseline) and 30ps (conservative) considered
  - Tracking detectors: position resolution of 10μm at z=204-214m
- Beam induced background is included
  - Simulated event-by-event simulation based on data at PU=9 and extrapolated to PU=25,50

Detector acceptance

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

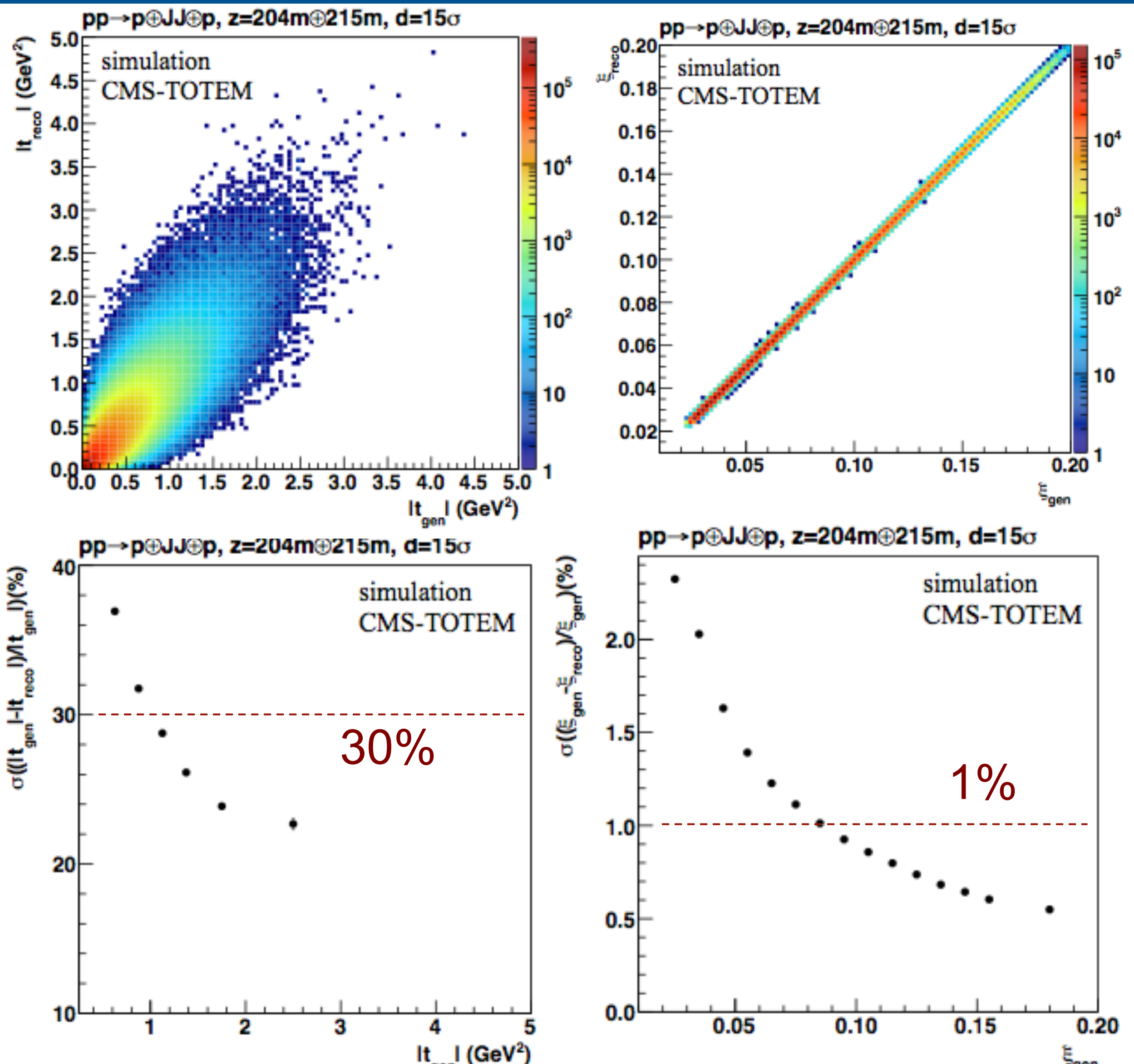
- Particle gun (t,ξ,φ) based on HECTOR at √s = 13 TeV





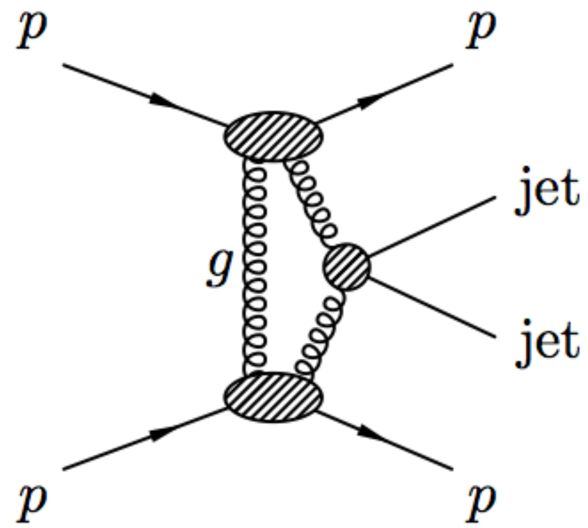
Detector resolution: t, ξ

- Compare generated and reconstructed values
- Resolution of the t and ξ variables



Physics processes

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



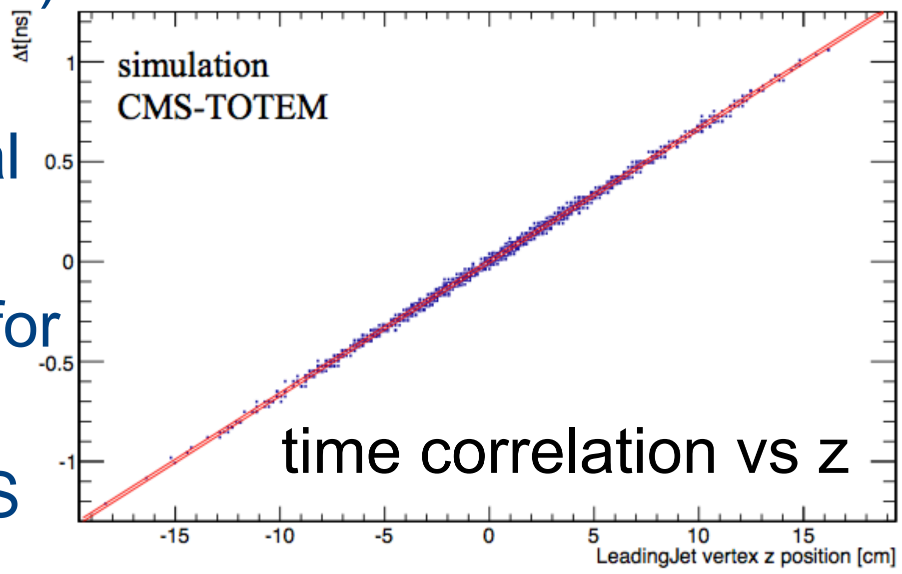
AQGC yields (in fb)

Table 7: Cross section (in fb) for the expected exclusive WW events due to anomalous quartic gauge couplings, for different values of anomalous coupling parameters (a_0^W and a_C^W) after each selection cut (for a timing resolution of 10 ps). In case of different values, numbers in parentheses are for a timing resolution of 30 ps. Only the $e\mu$ final state is considered. Statistical uncertainties are shown.

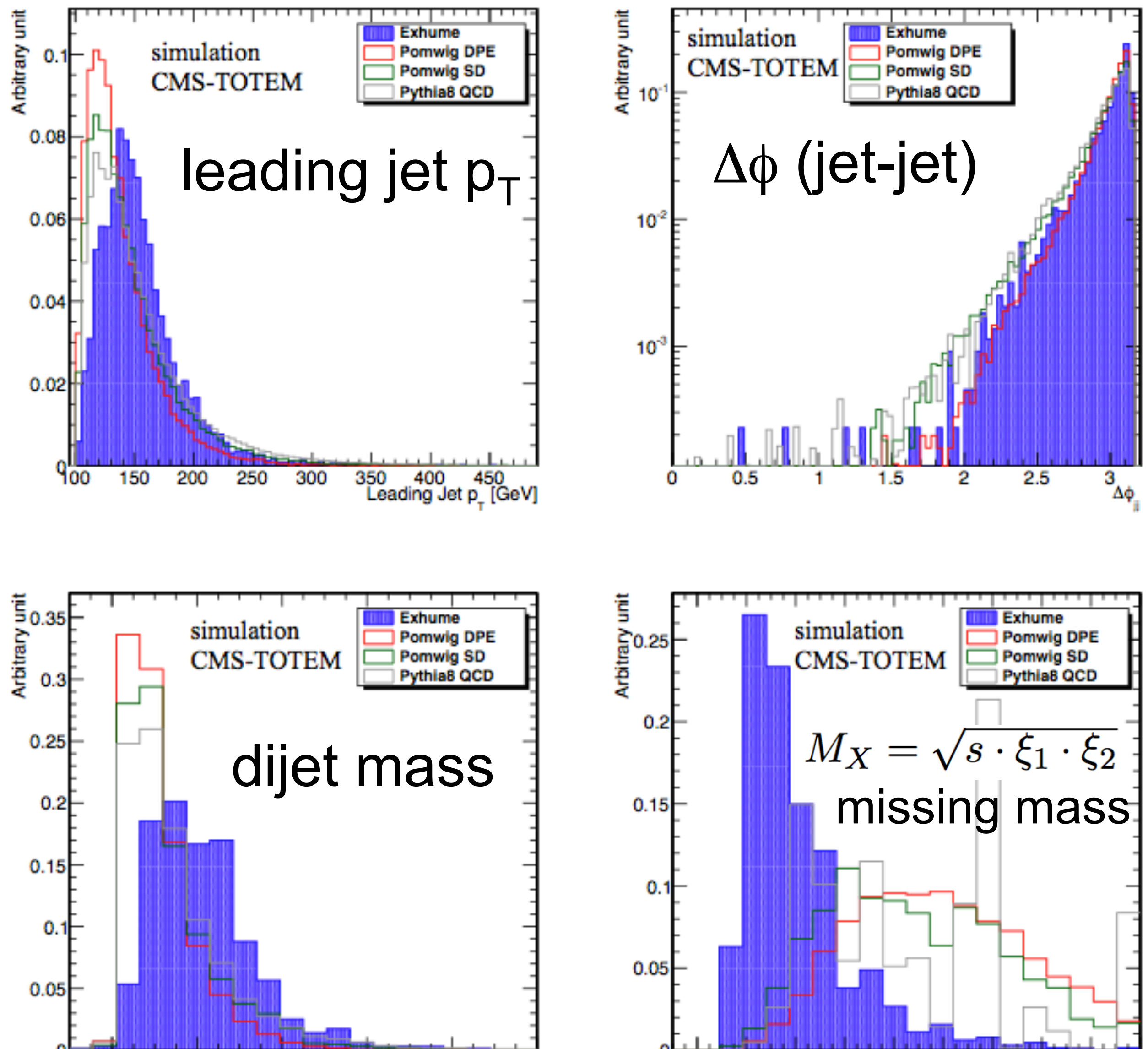
Selection	Cross section (fb)	
	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}\mathrm{GeV}^{-2}$ ($a_C^W = 0$)	$a_C^W/\Lambda^2 = 5 \times 10^{-6}\mathrm{GeV}^{-2}$ ($a_0^W = 0$)
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	3.10±0.14	1.53±0.07
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	2.33±0.08	1.00±0.04
opposite sign leptons, "tight" ID	1.82±0.08	0.78±0.03
dilepton pair $p_T > 30$ GeV	1.69±0.07	0.68±0.03
protons in both PPS arms (ToF and TRK)	0.52 (0.50)±0.04	0.18 (0.17)±0.02
no overlapping hits in ToF detectors	0.35 (0.32)±0.03	0.12 (0.11)±0.01
ToF difference, $\Delta t = (t_1 - t_2)$	0.35 (0.32)±0.03	0.12 (0.11)±0.01
$N_{\mathrm{tracks}} < 10$	0.27 (0.24)±0.03	0.11 (0.10)±0.01

Exclusive dijets

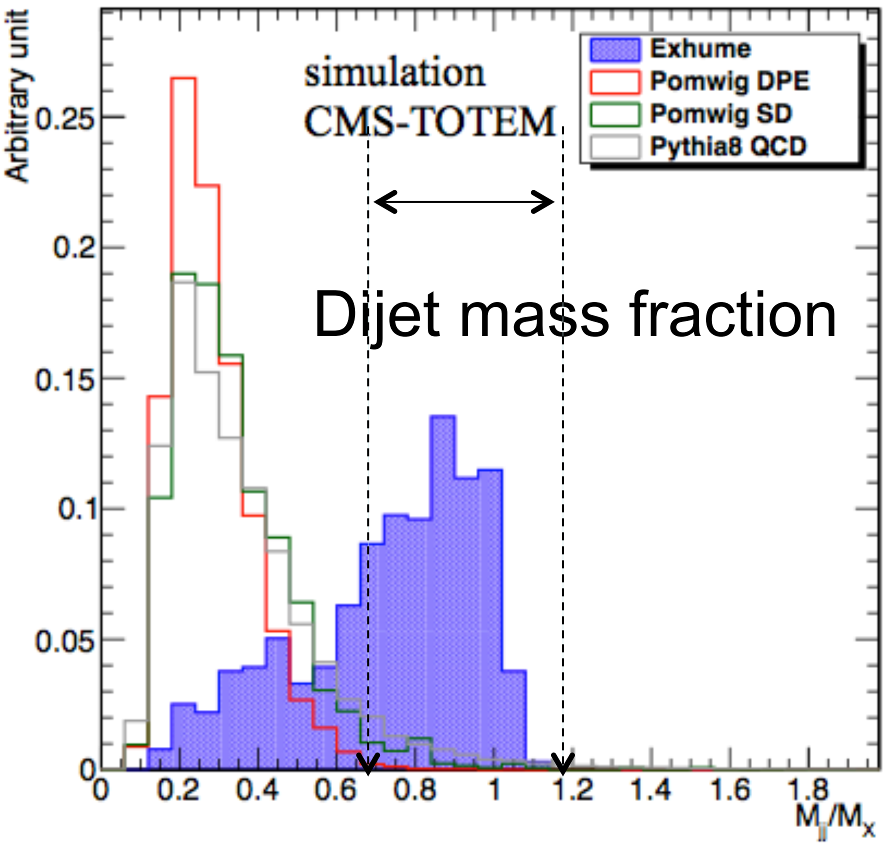
- Require 2 jets (p_T>100 GeV, $|\eta|$<2)
- Leading protons tagged by PPS
- Sensitivity to high mass of central system M_X (from PPS)
- Timing as powerful discriminant for exclusive states
- Kinematical constraints from PPS measurements
- Signal: ExHuME (pp→gg→dijets)
- PU: Pythia 8 (MB, PU50, PU25)

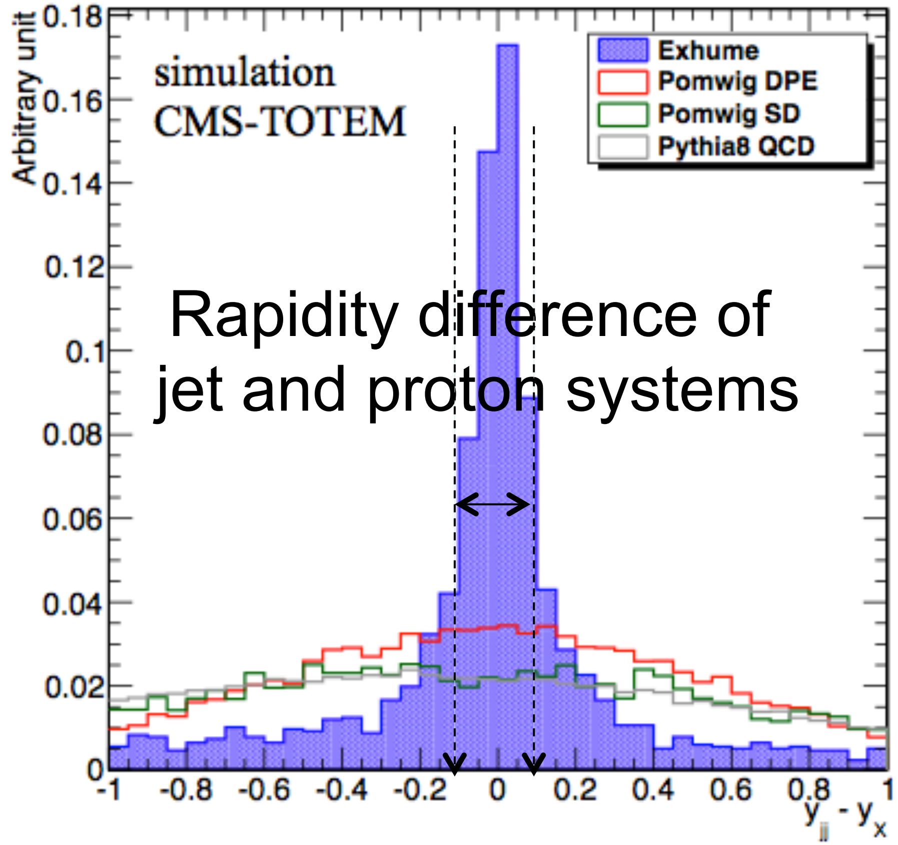


Kinematical distributions



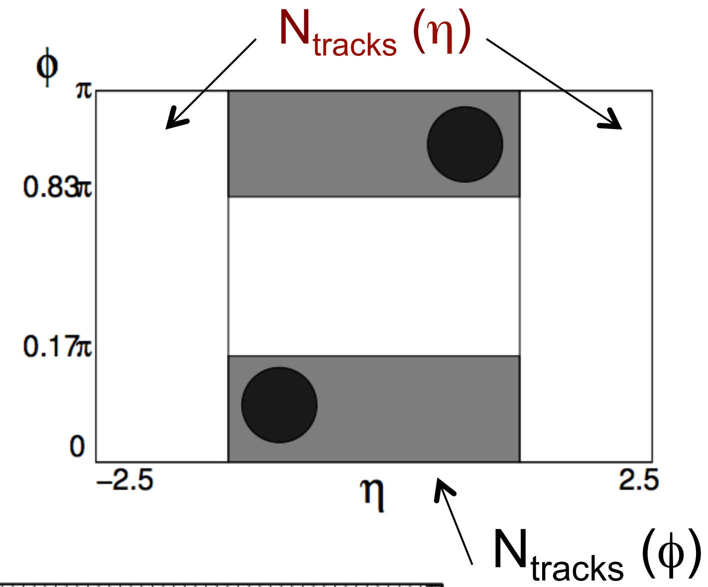
Kinematical distributions (cont.)

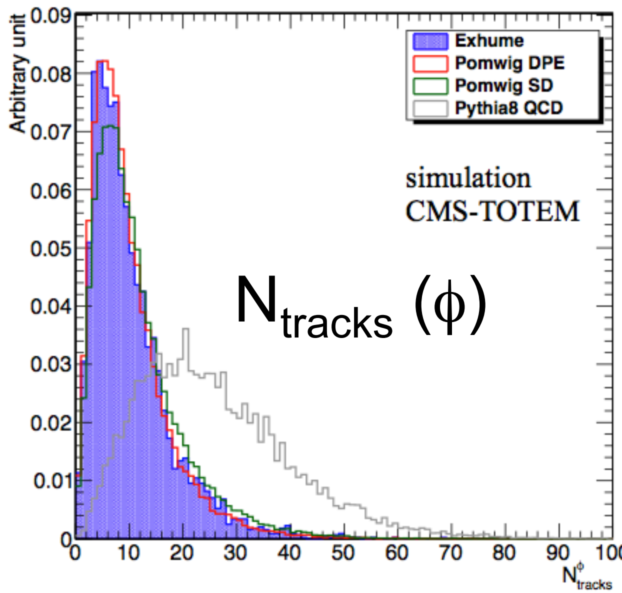


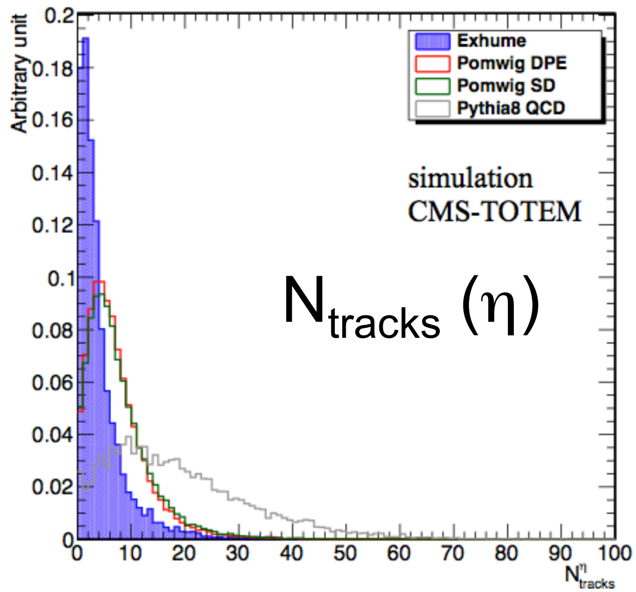


Track multiplicity

- Exploit the exclusivity of signal events to discriminate against large QCD multijet background
- Count number of tracks in regions of η/ϕ around the jet system







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)±2	5	$14\ (11) \times 10^3$	4.8	6×10^3	0.3	$95\ (180) \times 10^4$	4×10^{-3}
$0.70 < [R_{jj} = (M_{jj}/M_X)] < 1.15$	20 (16)±1	3.1	43 (39)±8	0.01	200 (250)±40	0.01	$45\ (85) \times 10^3$	2×10^{-4}
$\Delta(y_{jj} - y_X) < 0.1$	15 (12)±1	2.3	10 (11)±4	-	12±10	-	$5\ (9) \times 10^3$	-
N_{tracks}	5 (4)±1	0.8	1.3 (1.5)±0.5	-	1±1	-	40 (77) ± 1	-
≥ 2 jets (p_T > 150 GeV, $\lvert\eta\rvert < 2.0$)	2.5 (1.9)±0.2	0.4	0.4±0.2	-	0±1	-	20 (36) ± 1	-

⇒ S/B ~ 1/8

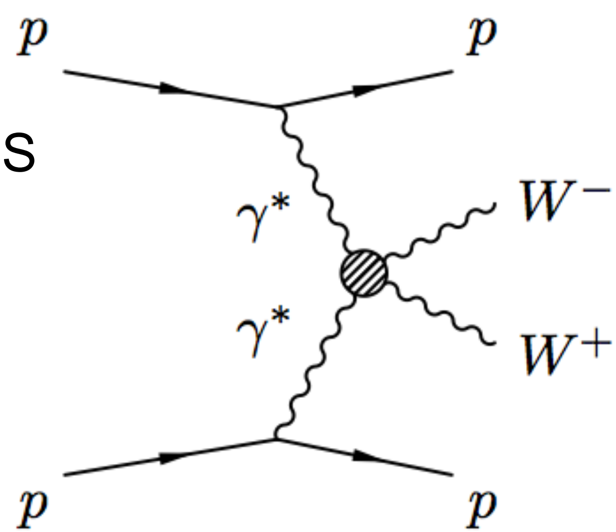
Yields per 1/fb – Pileup=25

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

WW production

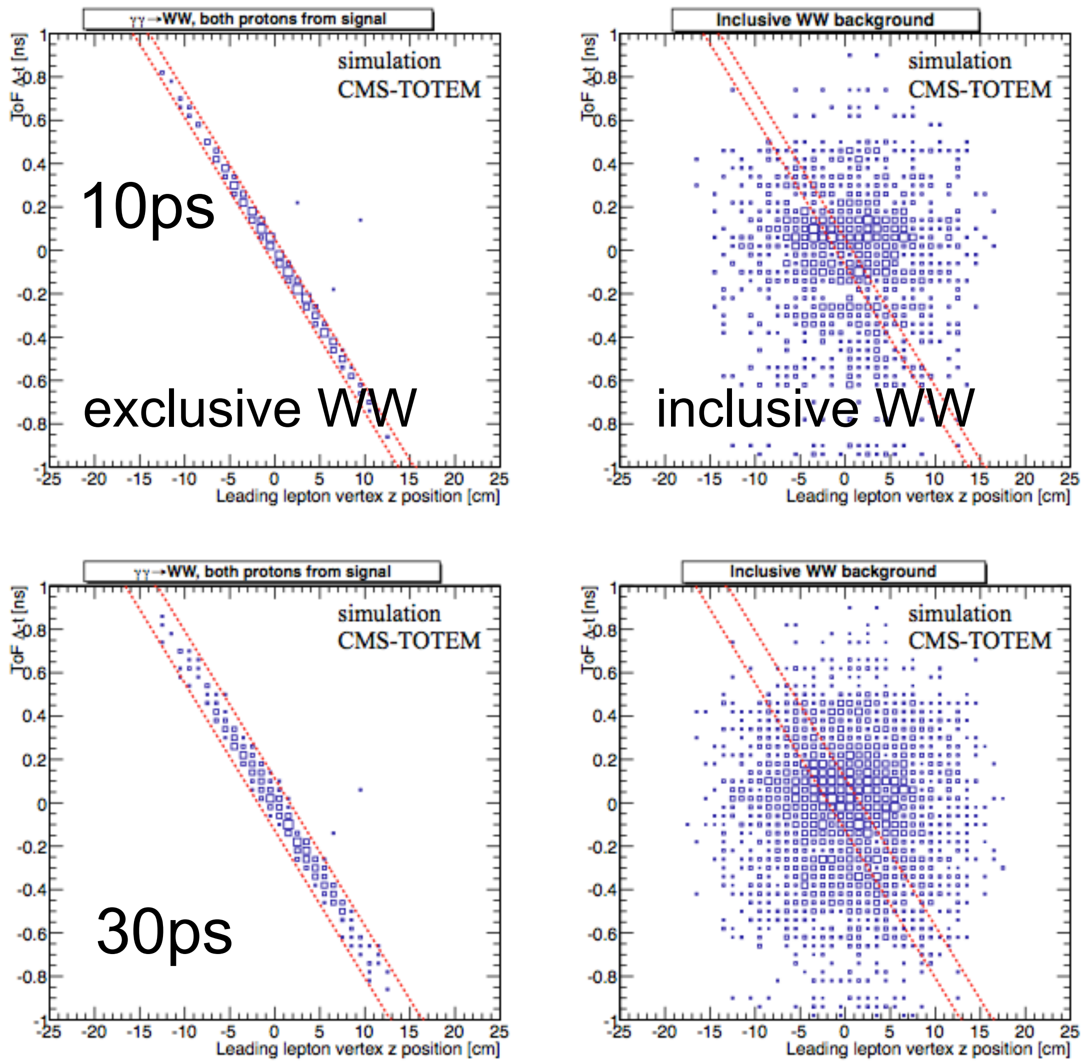
- Study of process: pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Events:
  - WW pair in central detector, leading protons in PPS
  - Studied only eμ final state



- SM observation of WW events
  - σ_{WW}=95.6 fb, σ_{WW} (W>1TeV)=5.9 fb
- Anomalous coupling study
  - AQGCs predicted in BSM theories
  - Two points: $a_0^W/\Lambda^2=5\times10^{-6}$, $a_C^W/\Lambda^2=5\times10^{-6}$

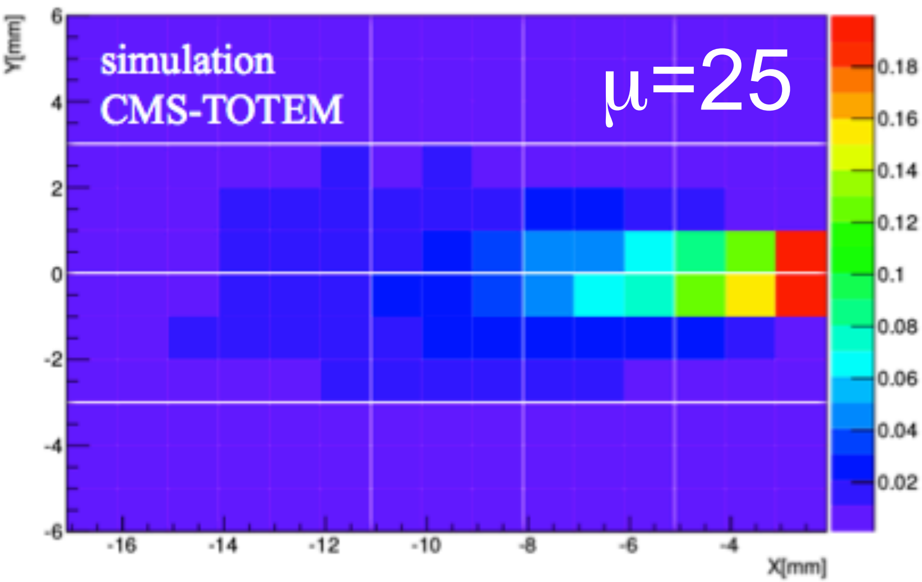
PPS timing vs. z-vertex

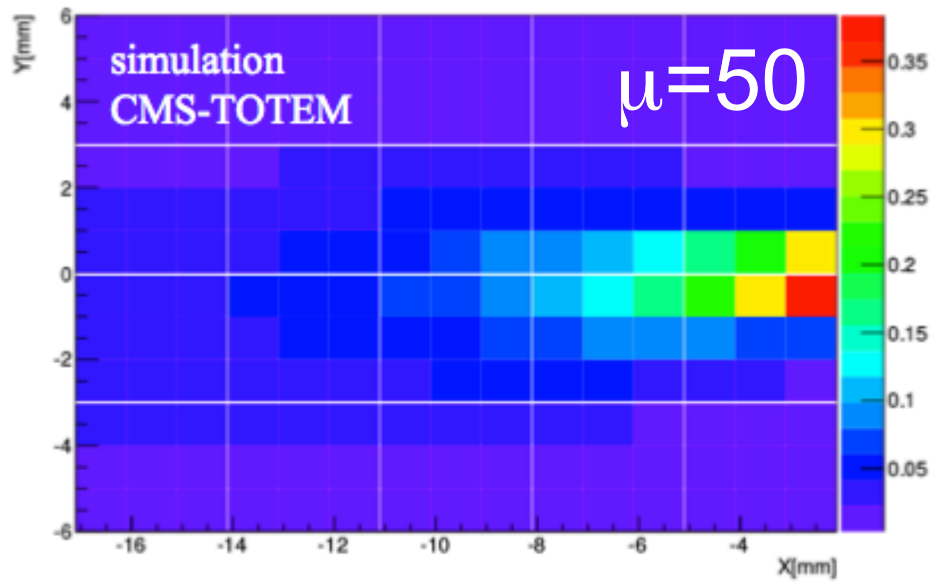
- Use timing to reject background
- Keep:
  - ~99% of signal events
  - ~10% of inclusive WW
- Two scenarios: 10ps and 30ps



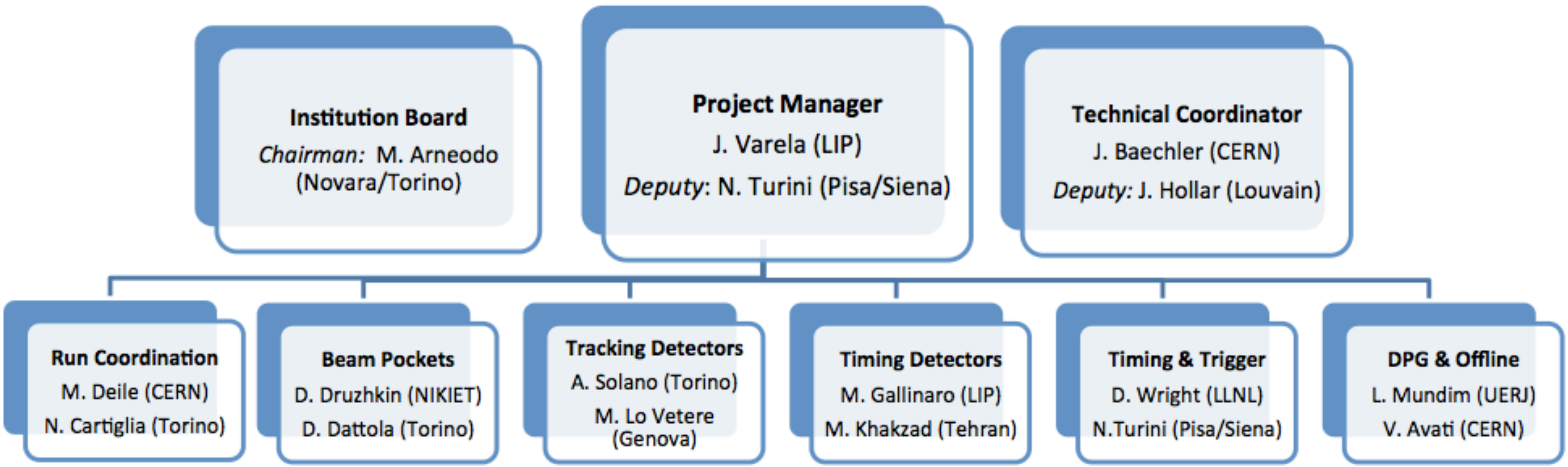
Detector occupancy

- Occupancy of time-of-flight detectors at 15σ
- Inefficiency due to overlapping hits (of up to ~40%)
- Beam related bkg and pileup interactions included



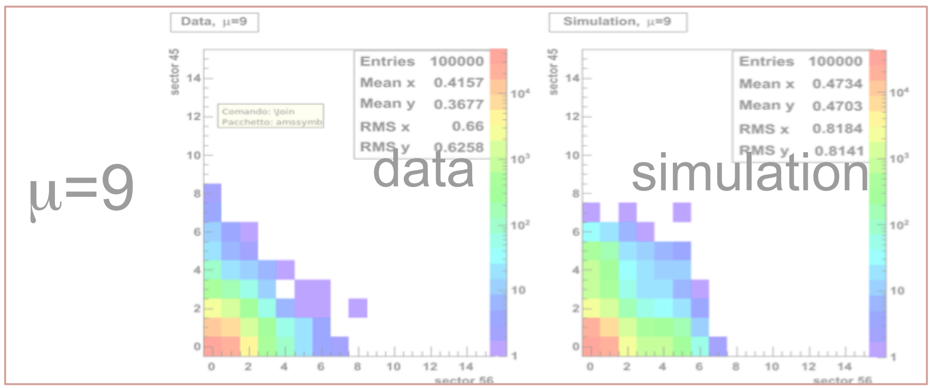


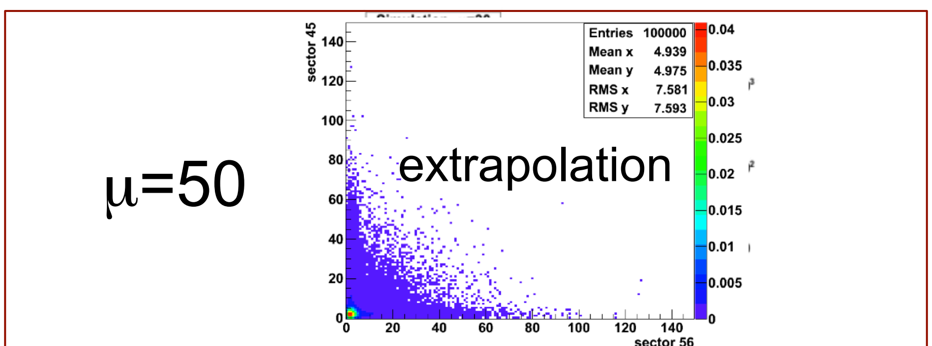
Organizational chart



Machine induced backgrounds

- Use TOTEM data at μ=9
- Account for pileup protons (from simulation) to estimate beam background only
- Extrapolate from μ=9 to μ=50





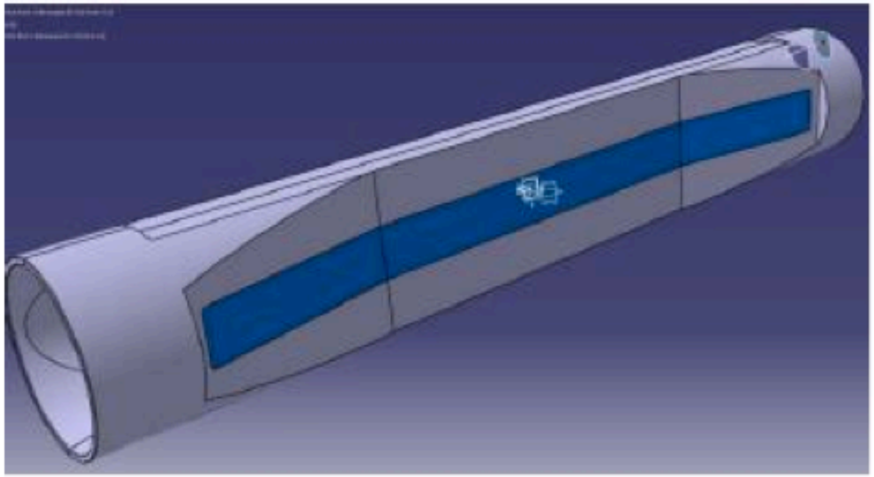
RP studies

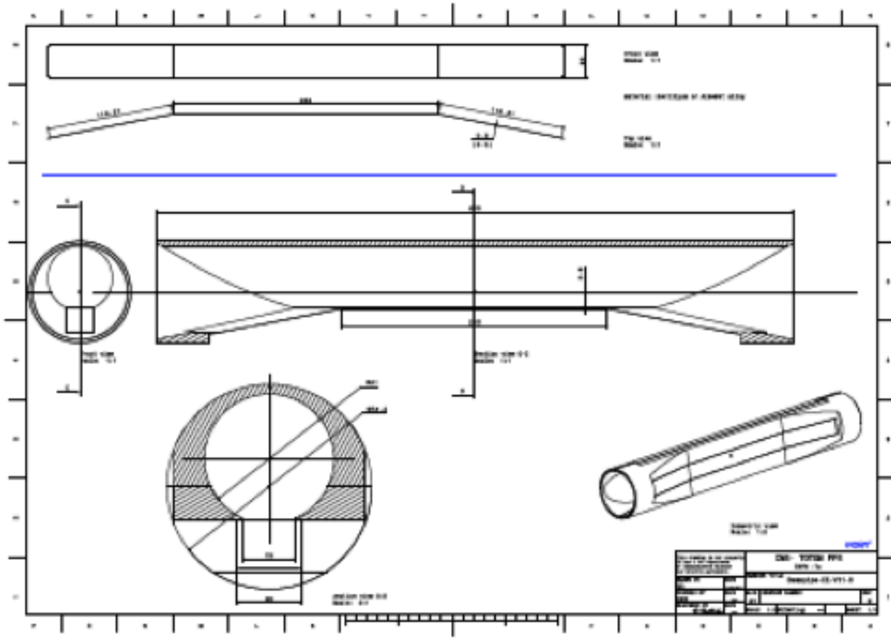
- Impedance simulation
- RF tests in the lab
- GEANT simulation of shower production
- FLUKA simulation of fluence at Q6

	Distance from the beam [mm]	$\frac{\Im Z^0_{\mathrm{long}}}{n}$ [mΩ]	fraction of $(\frac{\Im Z_{\mathrm{long}}}{n})^{\mathrm{eff}}_{\mathrm{LHC}}$ (90 mΩ)	$\overline{\Im Z^{\mathrm{driving}}_{\mathrm{trans}}}$ [MΩ/m]	fraction of $\Im(Z_x)^{\mathrm{eff}}_{\mathrm{LHC}}$ (25 MΩ/m)	Heating [W] I=0.6 A
Box RP	1	1.7	$< 1.9\,\%$	0.15	$< 0.6\,\%$	62
	5	1.3	$< 1.4\,\%$			52
	40 (garage)	0.41	$< 0.45\,\%$			10
Cylindrical RP	1	1.1	$< 1.2\,\%$	0.11	$< 0.5\,\%$	13
	5	0.73	$< 0.81\,\%$			11
	40 (garage)	0.18	$< 0.20\,\%$			4
Shielded RP	1	1.2	$< 1.3\,\%$	0.2	$< 0.8\,\%$	10
	40 (garage)	0.30	$< 0.33\,\%$			2

Movable Beam Pipe

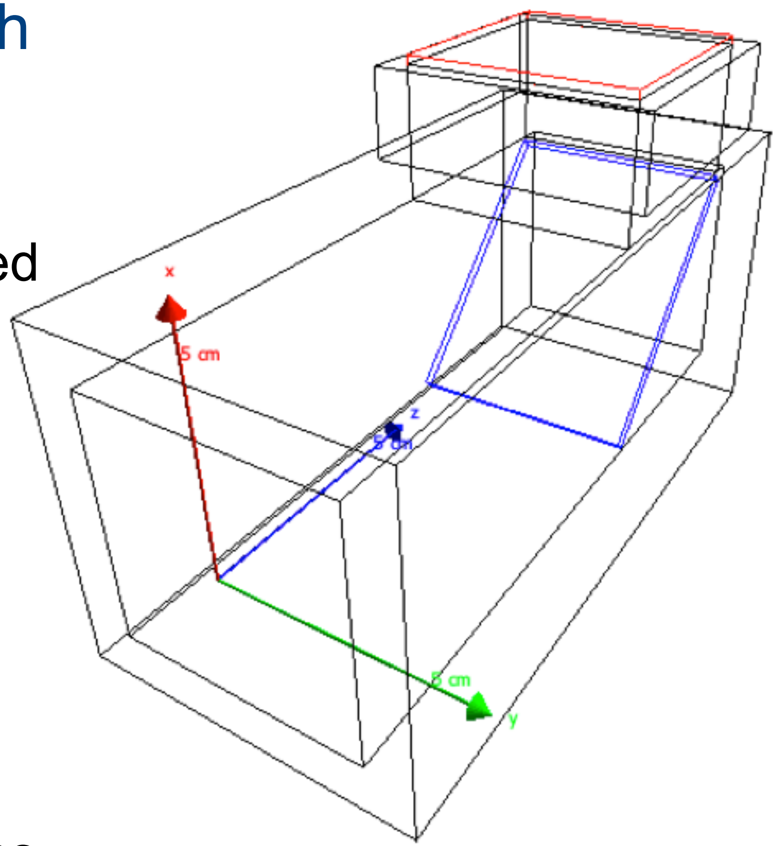
- Main body of MBP in stainless steel
- Copper coated for RF shielding and Non-Evaporative Getter (NEG) coated
- Interior surface tapered into a conical shape to reduce RF impedance effects
- At 1mm, RF impedance estimated at 0.05% (trans) and 0.5% (long)
- Thin-window (0.3mm) in AlBeMet alloy (38% aluminum, 62% beryllium) to minimize multiple scattering





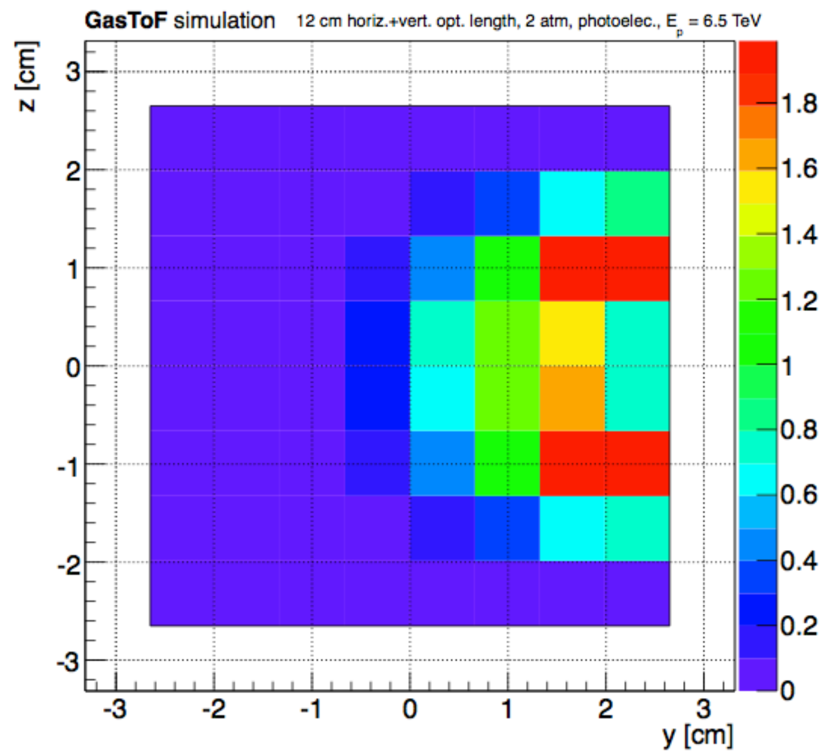
Gas Cherenkov option

- GasToF: gas Cherenkov detector with direct detection of very forward light cone
  - Tests with single-anode MCP-PMTs showed time resolution of ~15 ps for single-photoelectron signals
- GasToF design uses Photonis 8x8 anode MCP-PMTs
  - 12 cm long filled with the C4F10 at 2 atm produce signal of 7 pe’s per proton
  - MCP has transit time spread of 35 ps
  - Expected time resolution per proton of 15 ps



GasToF simulation

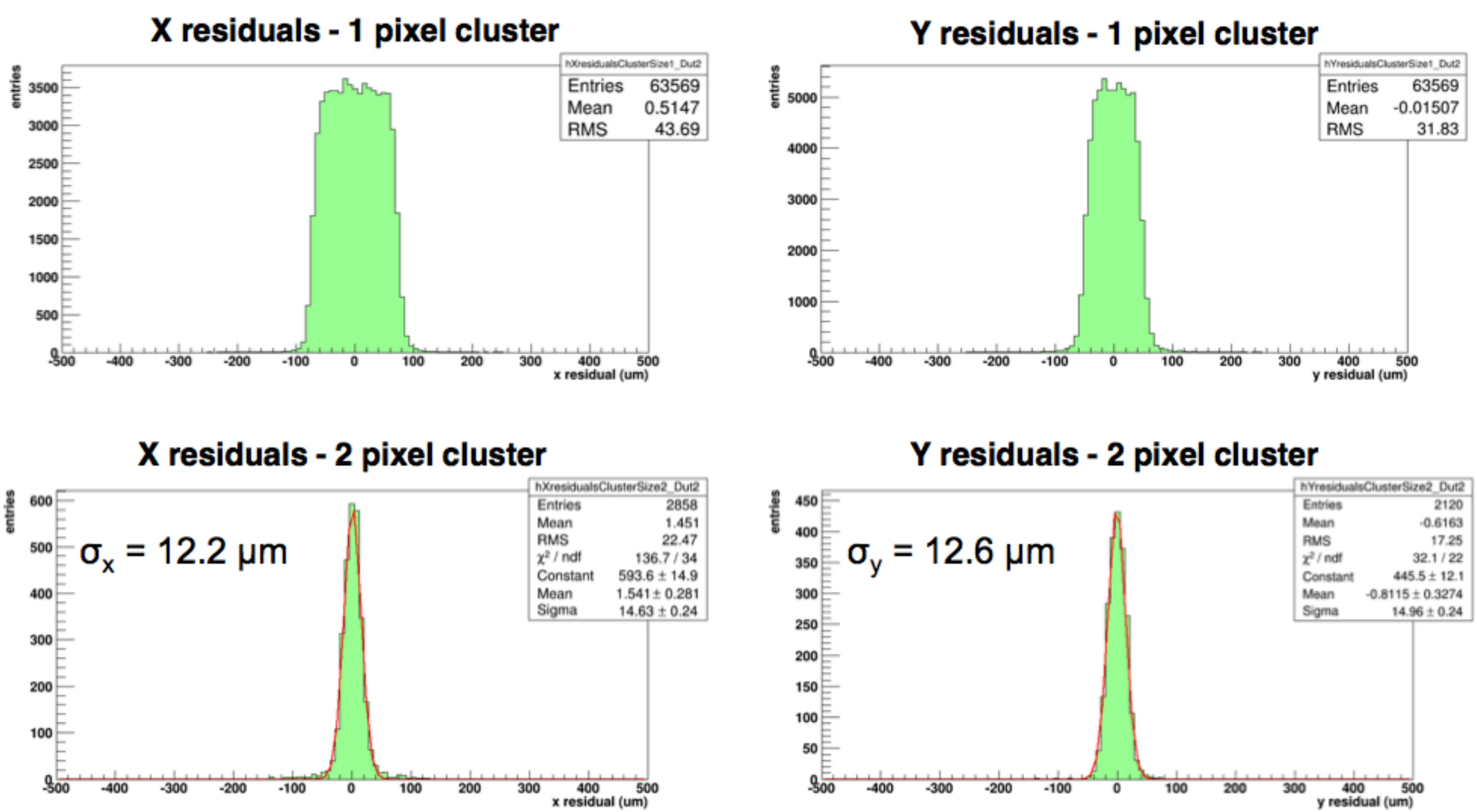
- GEANT study: capability to distinguish two or more protons in the detector
- MCP channel occupancy is expected at 10% for physical protons (after optimization)



Average number of pe's (before collection efficiency) on the MCP PMT 64 ch for protons (μ=50)

Preliminary results

Space Resolution for FBK_11-37-02 (θ = 0°)



Institutes and responsibilities

	Infrastructure	RP	MBP	Tracking sensors	Tracking readout	Timing sensors	Timing readout	Trigger & timing	Offline SW
CMS									
Belgium									
Louvain			x			x			x
Brazil									
UERJ					x		x		x
CBPF									x
CERN									
CMS TC group	x	x	x						
Italy									
Torino			x	x	x	x			
Genova				x	x				x
Iran									
Tehran			x				x		x
Portugal									
LIP						x	x	x	x
Russia									
IHEP Protvino						x			x
US									
Fermilab						x			
Livermore								x	
Kansas									
Iowa						x	x		
Rockefeller									x
TOTEM									
CERN	x	x	x			x		x	x
Czech Republic									
Prague	x	x							
Pilsen						x		x	
Finland									
Helsinki						x			x
Italy (INFN)									
Bari	x					x		x	x
Pisa/Siena	x					x		x	x
Collaboration									
CommonFund	x								

10 countries
20 institutes
93 people

Cost estimate

Cost of baseline detector: 550 kCHF

Area	Item	Cost (kCHF)
Tracking detector	Sensors	150
	Front-end electronics	60
	Back-end system	30
	Mechanics	10
	Services	20
	Tracking detector total	***270***
Timing detector	Sensors & mechanics (Quartic)	40
	Front-end electronics	60
	Back-end system	30
	Services	70
	Timing detector total	***200***
Timing & Trigger	Reference timing system	40
	Trigger system	40
	Timing & Trigger total	***80***
	Grand Total	**550**

Cost of R&D prototypes: 400 kCHF

Area	Item	Cost (kCHF)
Timing detectors	High granularity Quartic	30
	Gastof prototypes *)	70
	Diamond prototypes	50
	Timing silicon prototypes	50
	Timing integrated electronics	50
	Timing R&D total	***250***
Beam pockets	Moving Beam Pipe prototype mechanics	30
	MBP motorization (for one prototype)	50
	Two additional cylindrical RPs	70
	Beam pockets R&D total	***150***
	Grand Total	***400***

*) Cost corresponds to two detectors (2x 35 kCHF). The second detector will be built after results of the TB measurements

RP expenditures in 2013-14: 438 kCHF

Area	Item	Cost (kCHF)
RP Infrastructure *)	Tracking RPs: Relocation of four RP stations. RP Faraday cages.	87
	Timing RPs: Two cylinder RPs stations. Prototypse and final production. Movement system. Infrastructure (cables, cooling, vacuum, LV). Ferrites.	322
	Development	29
	RP Infrastructure total	***438***

*) Cost includes CERN services manpower

Schedule of construction

Timing detectors	
Before 16/01/2015	Complete module design. Order components.
Before 31/03/2015	Assemble prototype module at Fermilab. NINO boards delivered.
Before 17/04/2015	Deliver prototype module for beam tests.
Before 30/05/2015	Beam tests with a reference time counter.
Before 31/7/2015	HPTDC boards delivered.
Before 31/08/2015	Construct four modules and deliver to CERN.
Before 30/09/2015	Beam tests of four modules with readout electronics.
October 2015	Ready for installation.
Tracking detectors	
Before 15/2/2015	Pre-production of sensors at FBK and CNM.
Before 15/5/2015	Test of sensors. Final decision of manufacturer. Delivery of flex-hybrid pre-prod.
Before 15/7/2015	Launch production of final sensors. Delivery of the portcard pre-production.
Before 30/9/2015	Launch production of mechanical supports, flex-hybrids and portcards.
Before 15/12/2015	Delivery of final sensors, mechanical supports, flex-hybrids and portcards.
Before 30/1/2016	Delivery of bump-bonded detectors.
Before 30/3/2016	Ready for installation.