Looking forward
The Precision Proton Spectrometer at the LHC

Michele Gallinaro
michgall@cern.ch

LIP Lisbon

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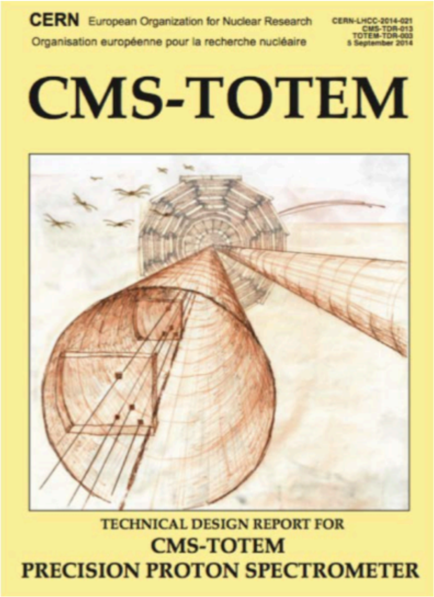
- ✓ The PPS project
- ✓ Physics motivations
- ✓ Tracking and timing detectors
- ✓ Detector performance and physics prospects
- ✓ Summary

CERN-LHC-2014-021

The PPS project

- It is a joint CMS and TOTEM project that aims at measuring the surviving scattered protons on both sides of CMS in standard running conditions
- Tracking and timing detectors inside the beam pipe at ~210m from IP5
- Project approved in Dec. 2014 by LHCC
- Exploratory phase already begun, data taking foreseen for second half of 2016 (beginning of 2017)



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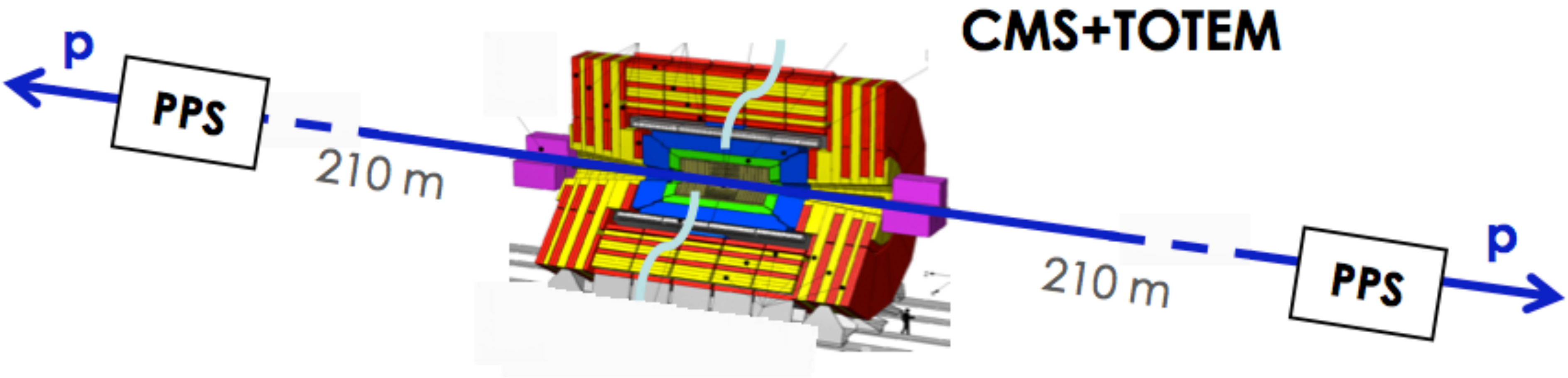
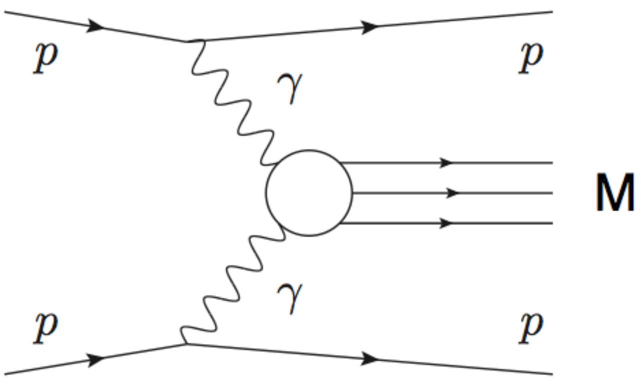
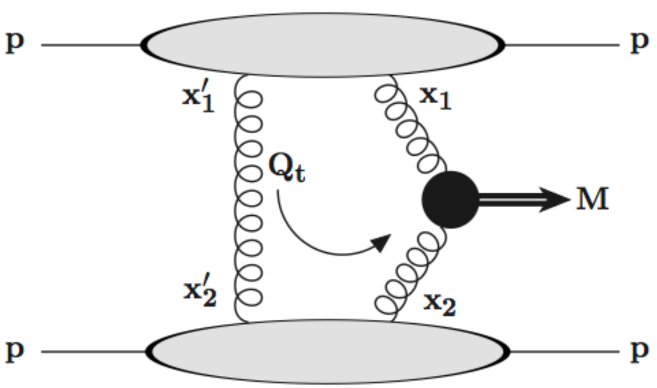


Physics motivations

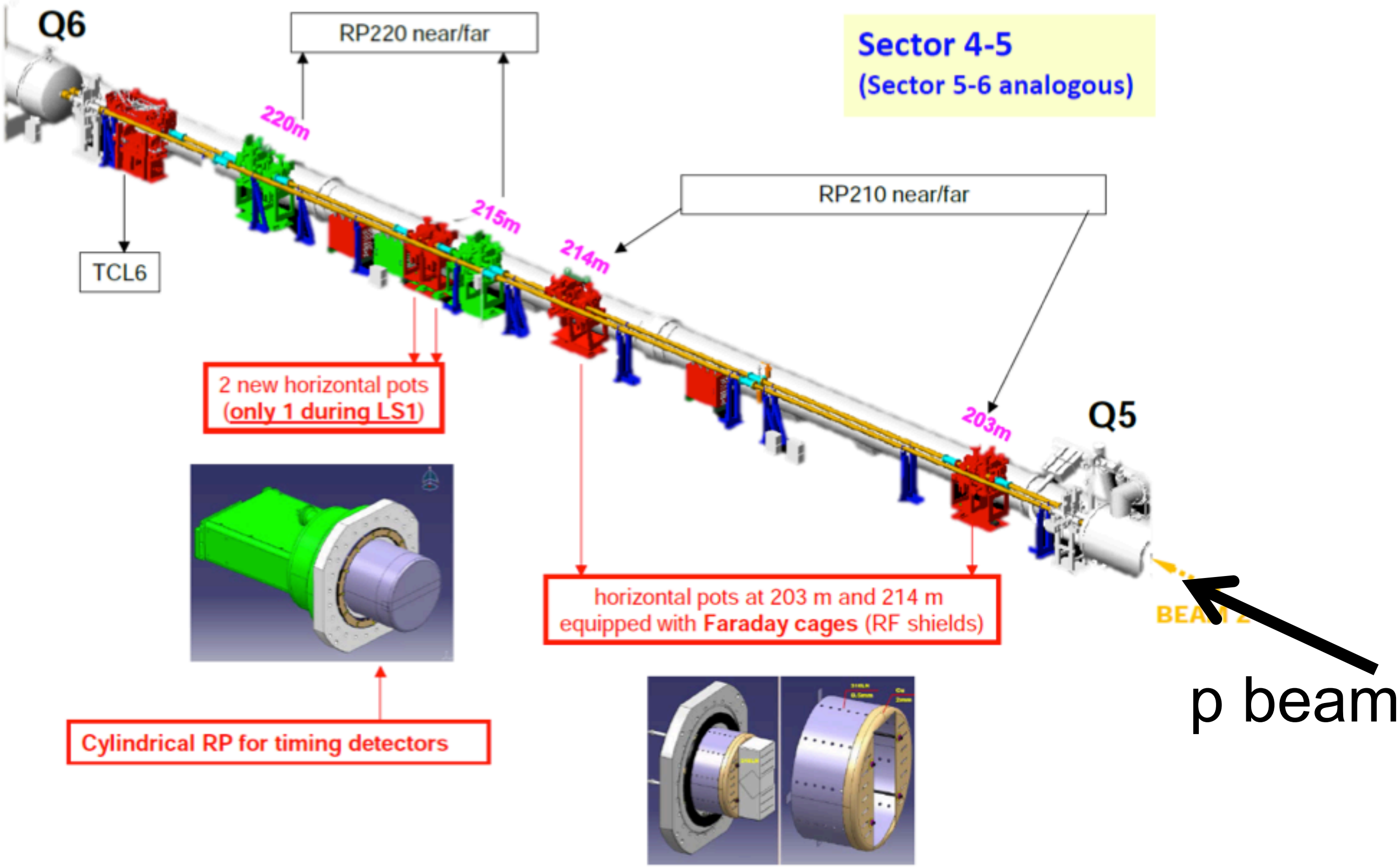
- Central Exclusive Production
  - photon-photon fusion
  - gluon-gluon fusion in color singlet, $J^{PC}=0^{+}$
- High-p_T system in central detector, together with very forward protons in PPS
  - Require momentum balance between central system and forward protons, provides strong kinematical constraints
  - Mass of central system measured by momentum loss of the two leading protons
- Gauge boson production by photon-photon fusion and anomalous couplings ($\gamma\gamma WW$, $\gamma\gamma ZZ$, and $\gamma\gamma\gamma\gamma$)
- Search for new BSM resonances
- Study of QCD in a new domain





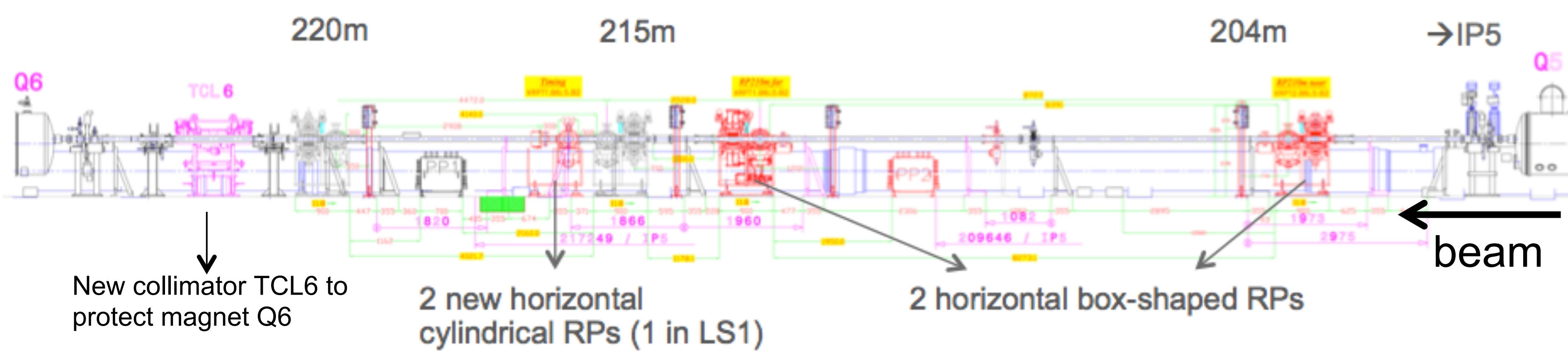
Experimental apparatus

- Roman Pot stations into beampipe secondary vacuum
  - Tracking: 2 horizontal pots at 204m and 214m
  - Timing: 2 (1 for now) horizontal pots at 215m



Experimental challenges

- Ability to operate the detectors close to beam (15-20σ) to maximize acceptance for low momentum loss (ξ) protons
- Limit 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 $5\times10^{15}\text{cm}^{-2}$ in tracking detectors, $10^{12}n_{eq}/\text{cm}^2$ and 100Gy in photosensors and readout electronics
- Reject background in the high-pileup (μ=50) of normal LHC running



timing detectors

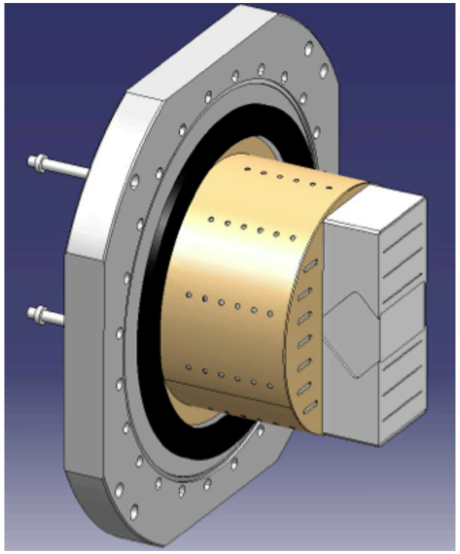
tracking detectors

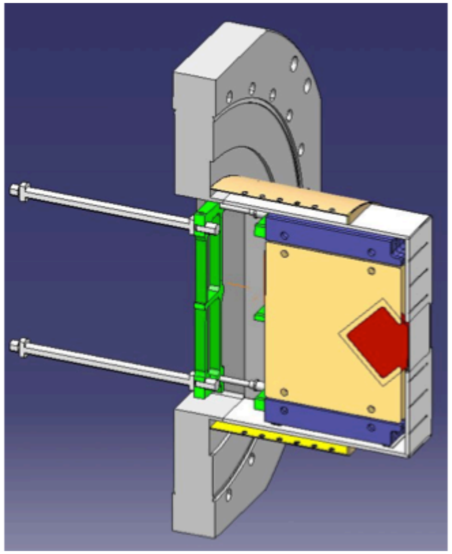
LHC tunnel @ PPS location

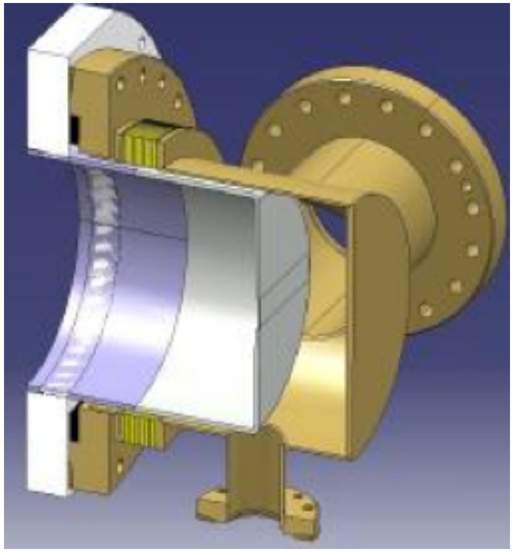
All services are installed (cables, cooling, etc.)

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

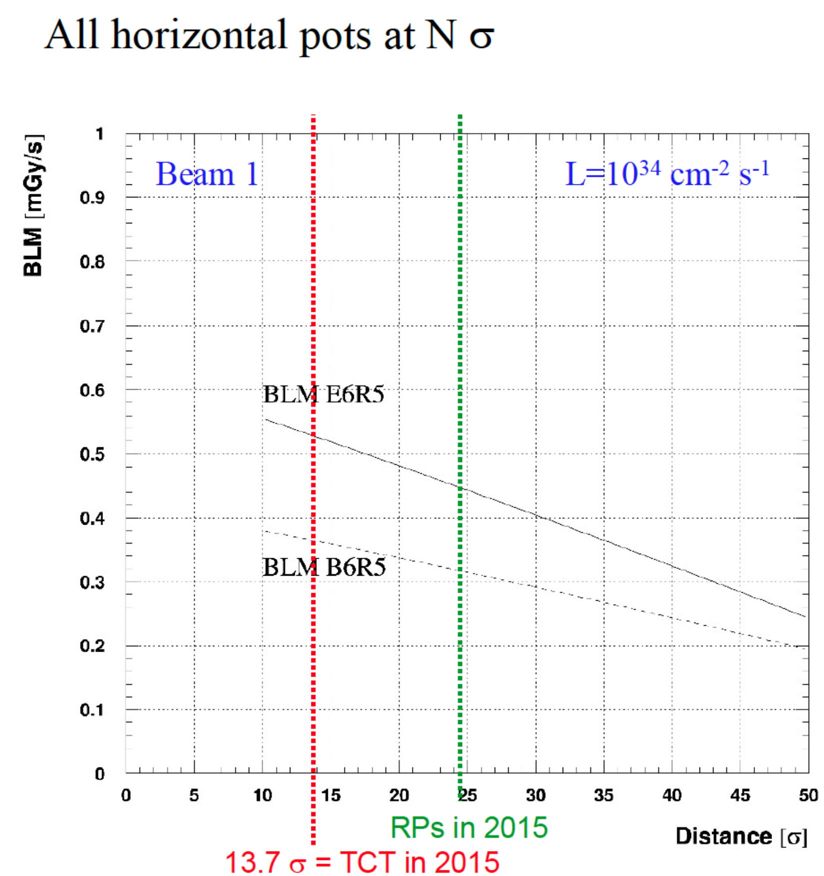






RP insertion tests

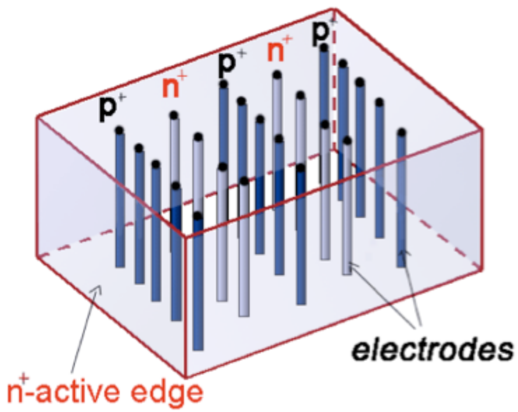
- RP insertions to 25σ in 2015
  - Tests up to L=4x10^{33}cm^{-2}s^{-1}
  - No beam instabilities introduced
  - BLM response well below threshold
  - Vacuum pressure: no problems observed
  - Temperature in RP increases with luminosity. No problems expected.
- Extrapolations to 10^{34} and closer distance to beam look promising



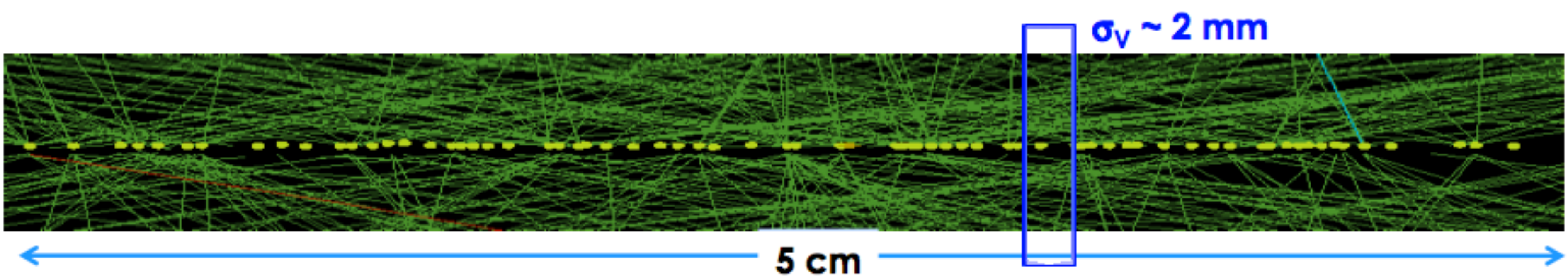
Detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels (6 planes per pot)

"3D" pixel sensors with columnar electrodes

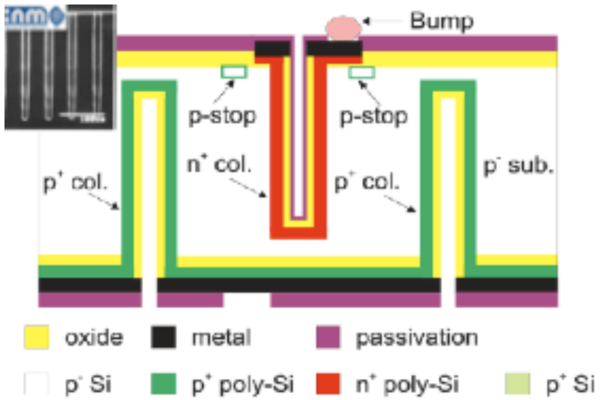


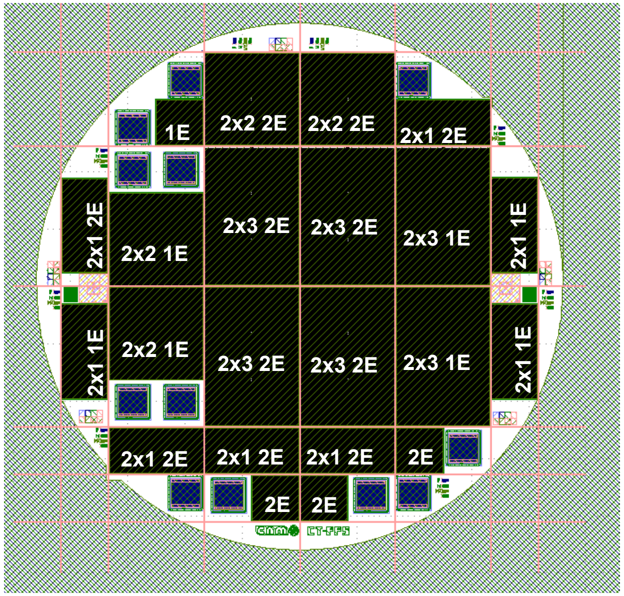
- Timing detectors
  - Goal: identify primary vertex, reject "pileup"
  - σ_{time}~10ps ⇒ σ_z~2mm
  - Technology: silicon/diamond



Tracking detectors

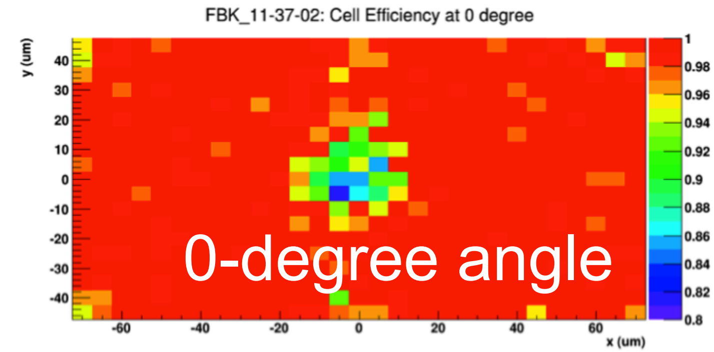
- 3D sensor technology
- Intrinsic radiation hardness (to withstand overall integrated flux of $5x10^{15}$ protons/cm^2
- 200μm slim edges (small dead edge to approach beam as close as possible)
- Spatial resolution <30μm
- Front-end chip: latest version of PSI46dig, same as CMS Pixel Phase I upgrade

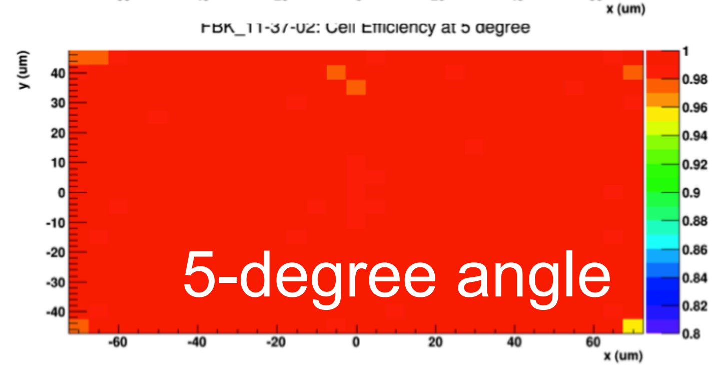


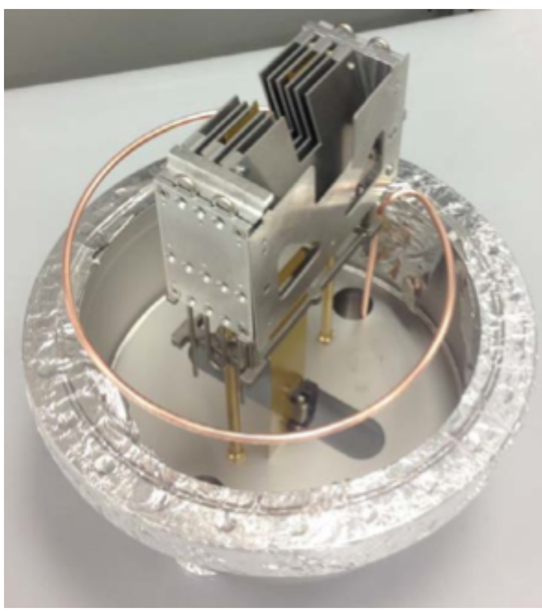


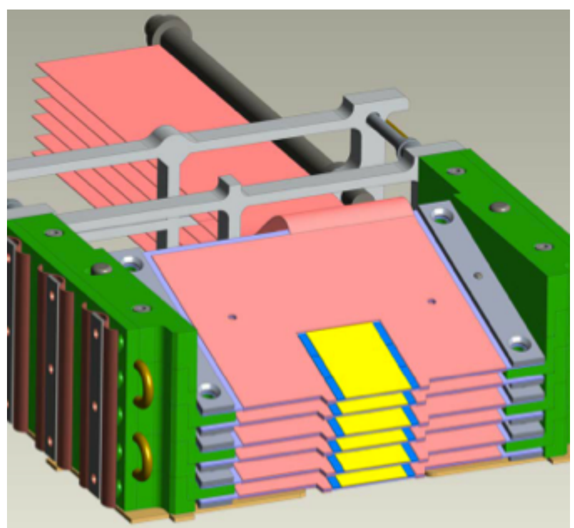
Tracking detectors (cont.)

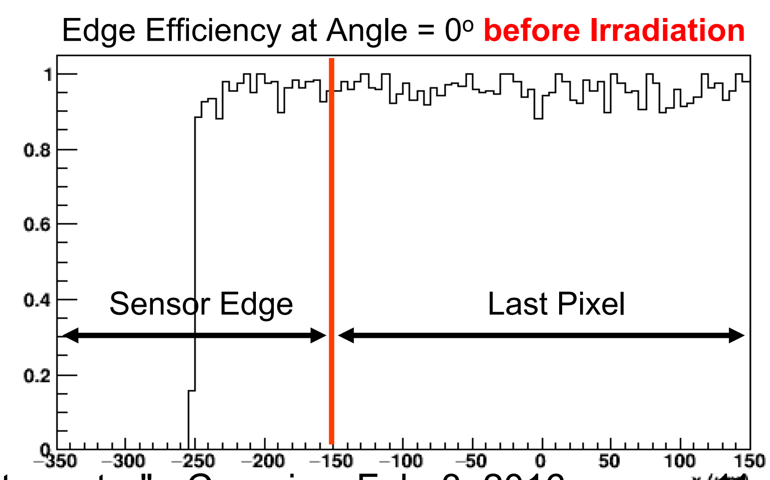
- 2 stations per side, 6 detector modules each pot
- Planes tilted by 18.4° to optimize efficiency and resolution
- Thin design studied to minimize impact on beam, insertion in pot, approach to beam





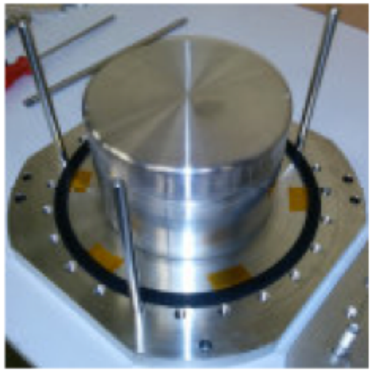


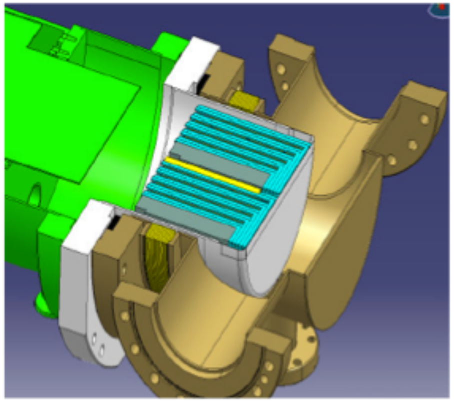


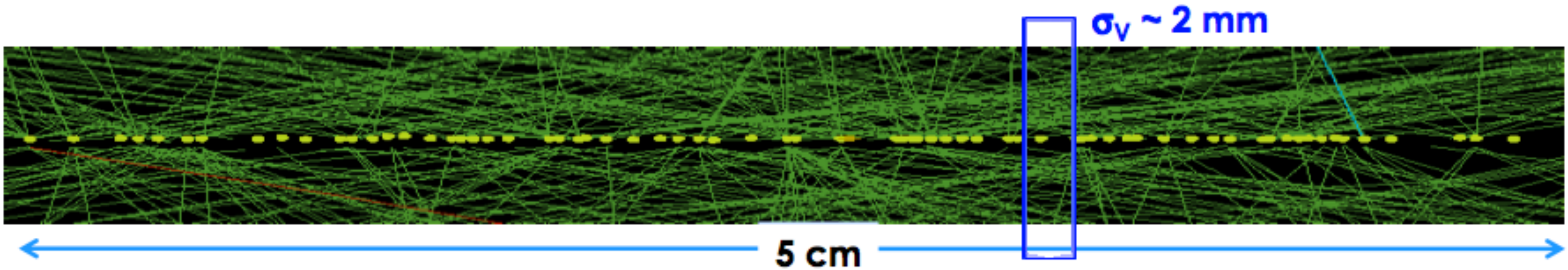


Timing detectors

- Proton timing measurement from both sides of IP5 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

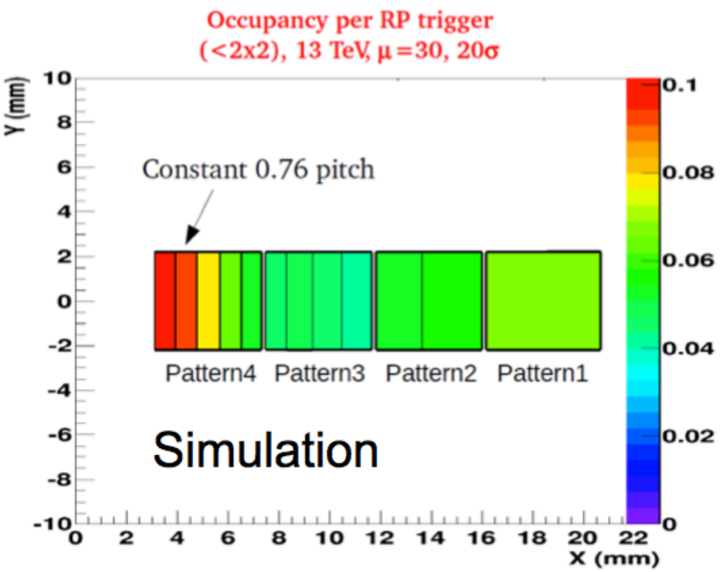


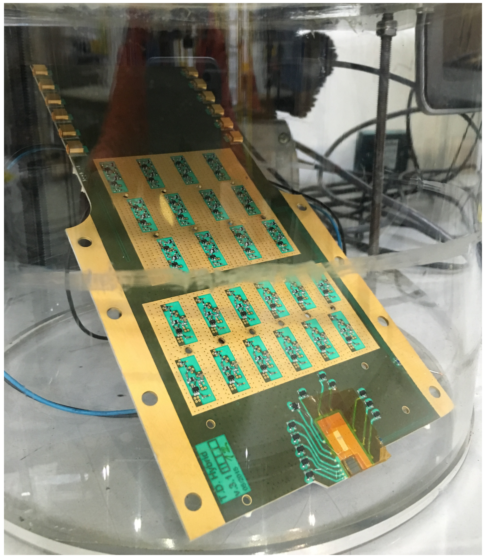


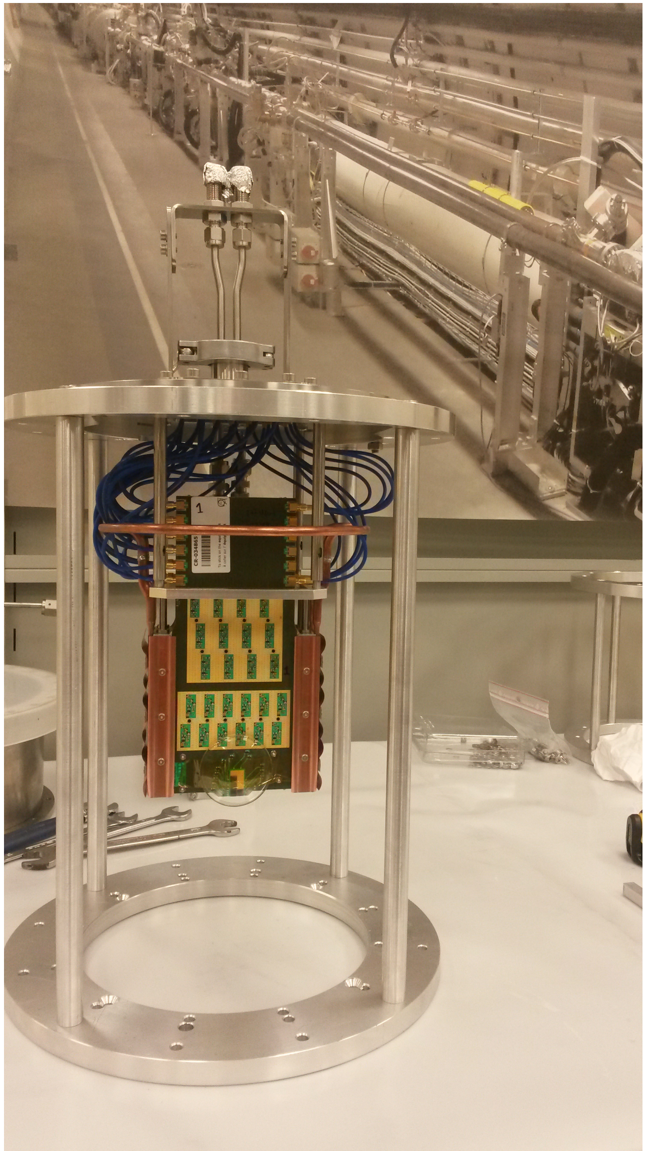


Timing detectors (cont.)

- Diamond detectors
  - σ_T~80ps per plane, i.e. ~50ps with 4 planes
  - Variable pad dimensions to optimize occupancy
- Custom-made readout electronics
  - NINO (discriminator)+HPTDC
- Test detector package installed in Oct. 2015
- Preparing for installation in 2016







Timing detector R&D

Pursuing R&D to improve performance

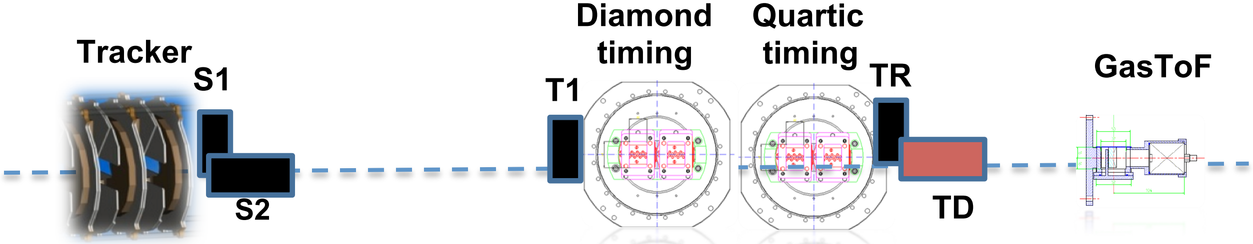
- Diamonds, silicon-based, quartz, etc.

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)

Test beam @ CERN in 2015

H8C Beam

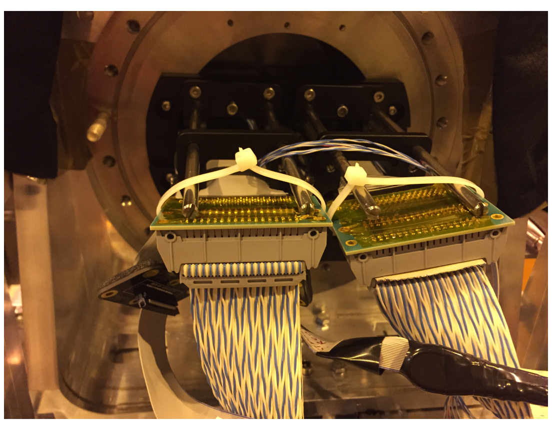


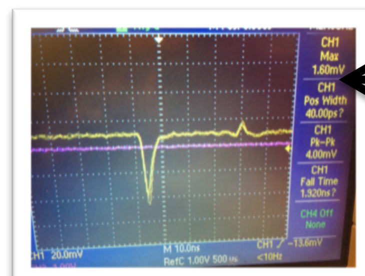
SPS beam:
- E=180 GeV protons
- Divergence: 40-250 mrad
- Rate 5-10KHz/cm²/spill

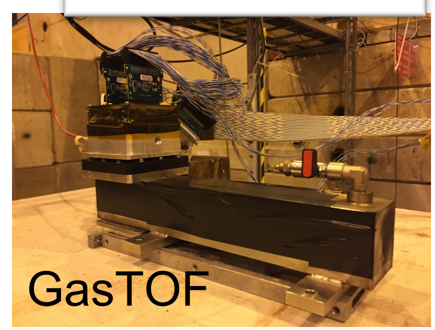
Tracker externally triggered by S1 and S2 (trigger area ~2x2 cm²)

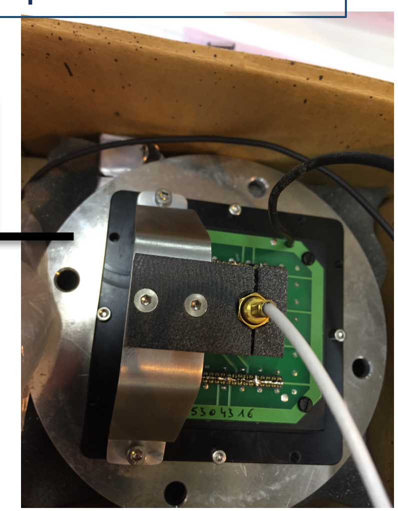
- **Quartic:**
  - Integration of two Quartic modules in RPs
  - 1st test of electronics readout chain

- GasToF: Cherenkov detector MCPMT+(Nino+HPTDC)
- Diamond: scope readout









Timing detector R&D

GasToF system

- Prototype test ongoing

Quartz (Quartic bars)

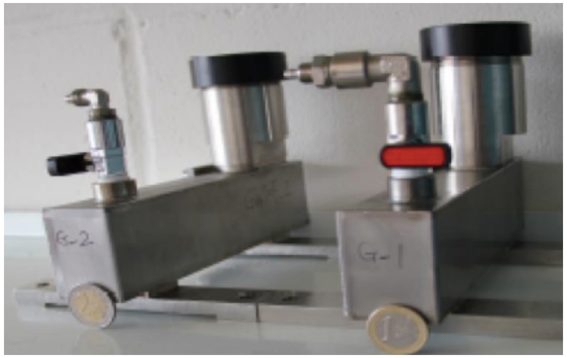
- ~40ps resolution

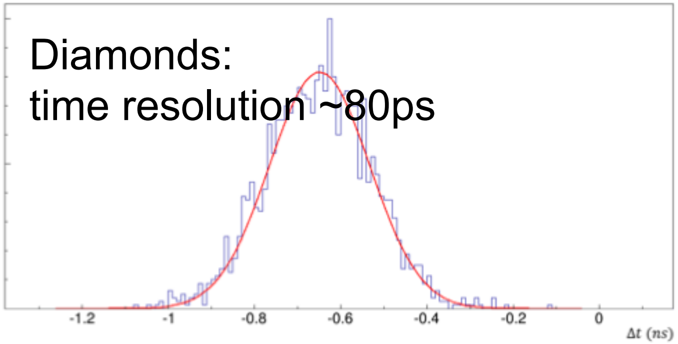
Diamond detectors

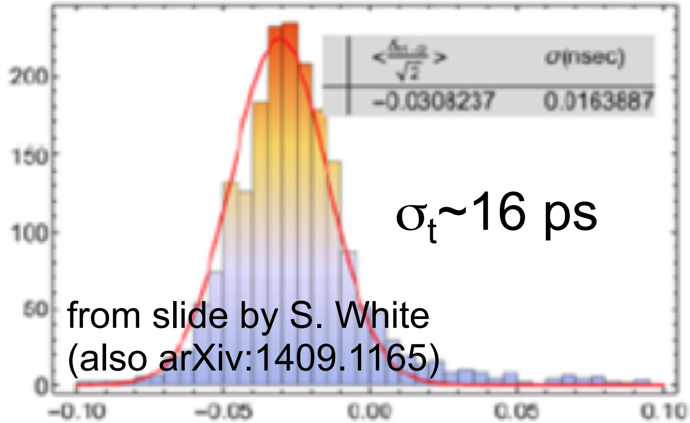
- ~50 ps resolution with 4 planes

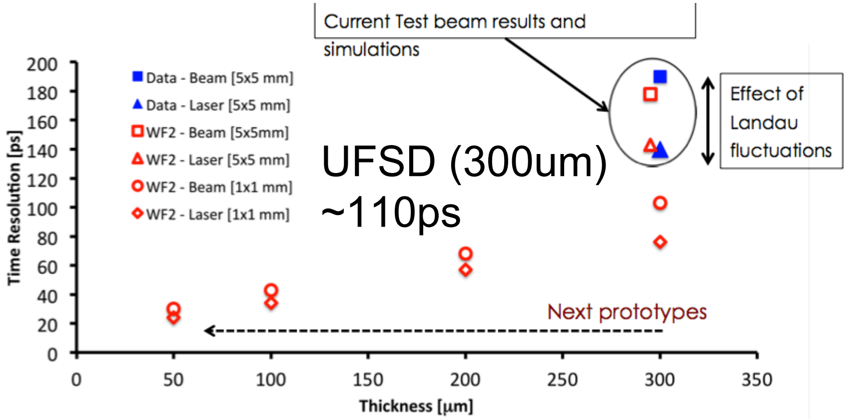
Silicon detectors

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





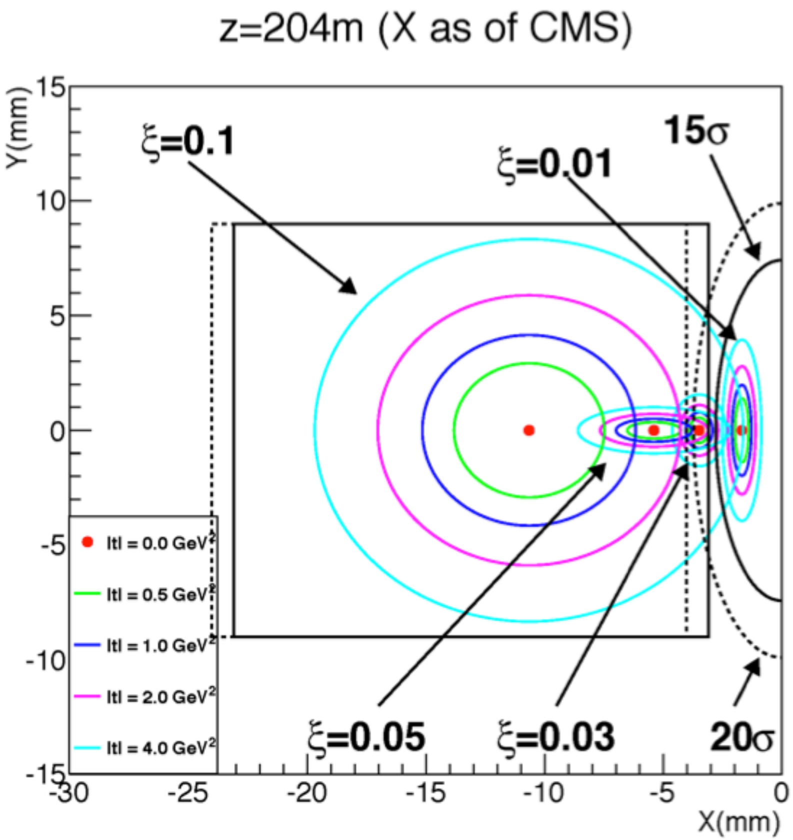




Detector acceptance

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

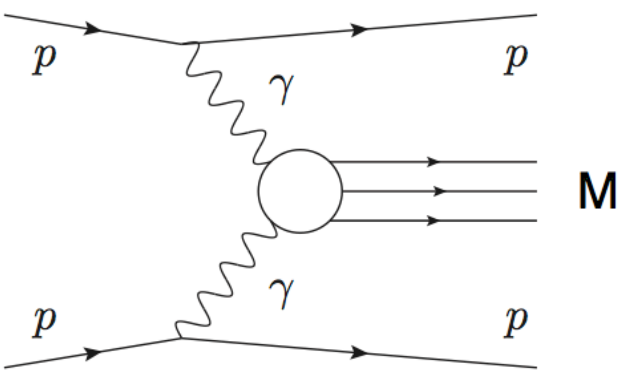
- Particle gun (t,ξ,φ) based on HECTOR at √s = 13 TeV

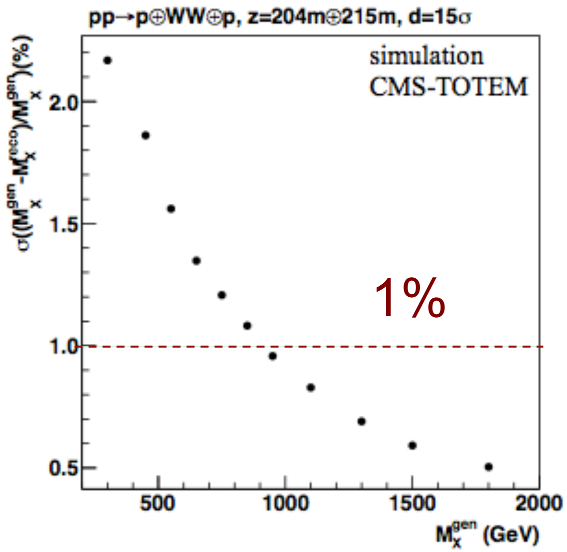


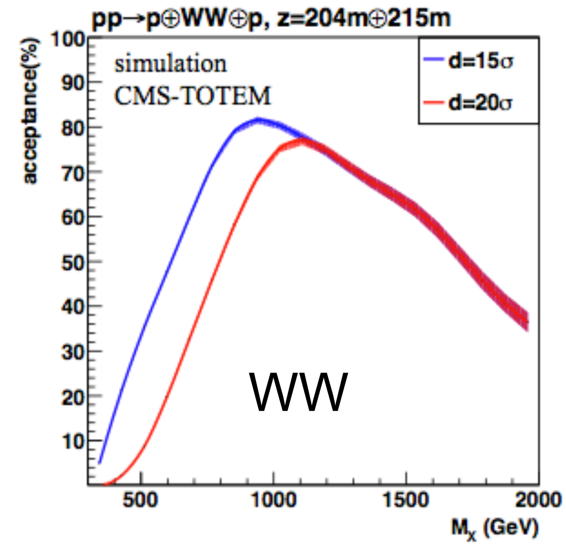
ξ: proton fractional momentum loss

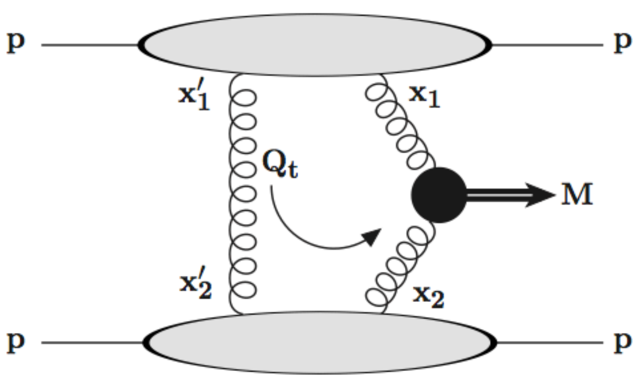
t: 4-momentum transferred squared

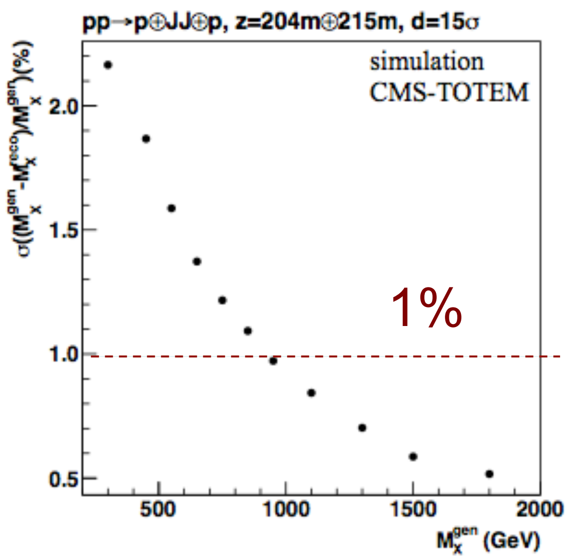
Mass acceptance and resolution

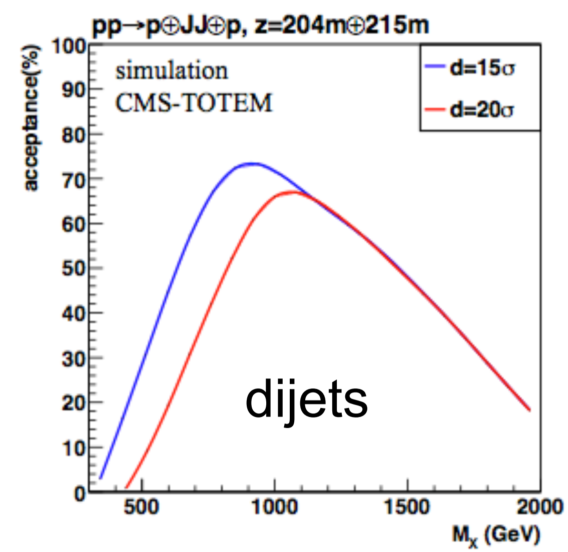






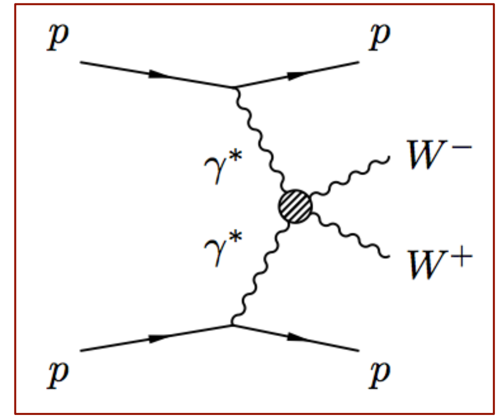


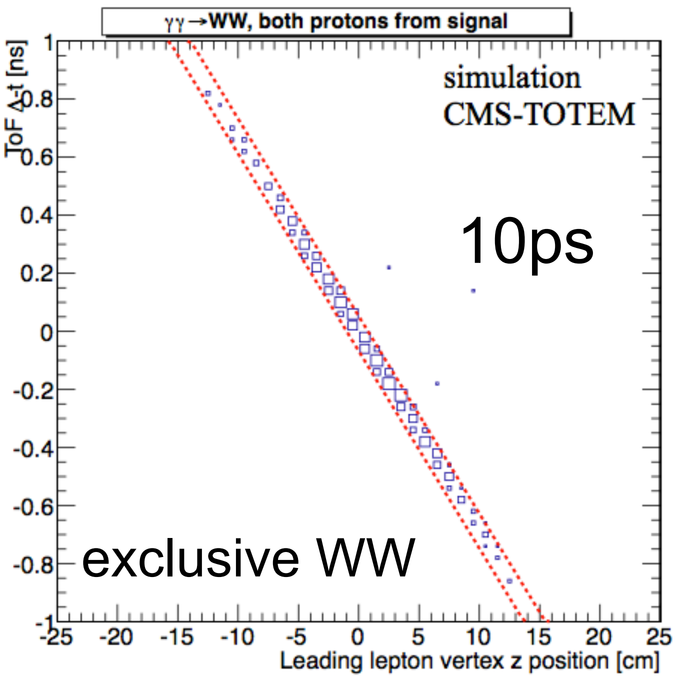


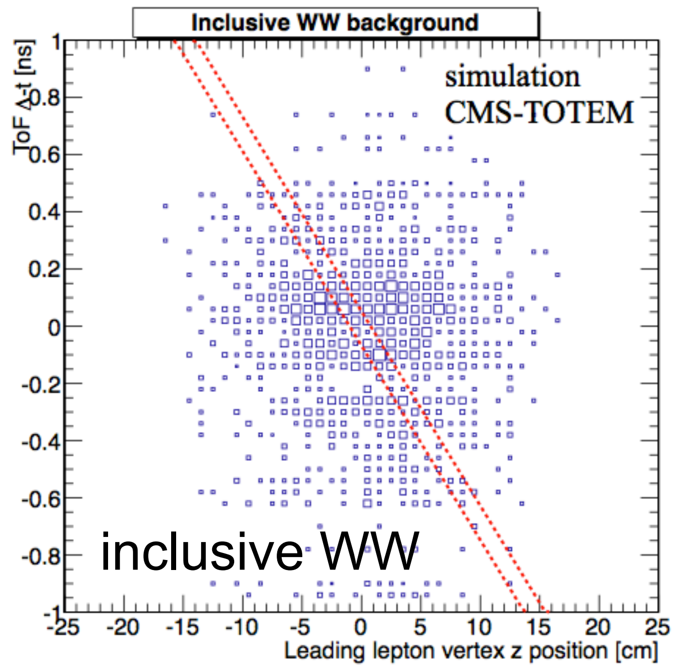


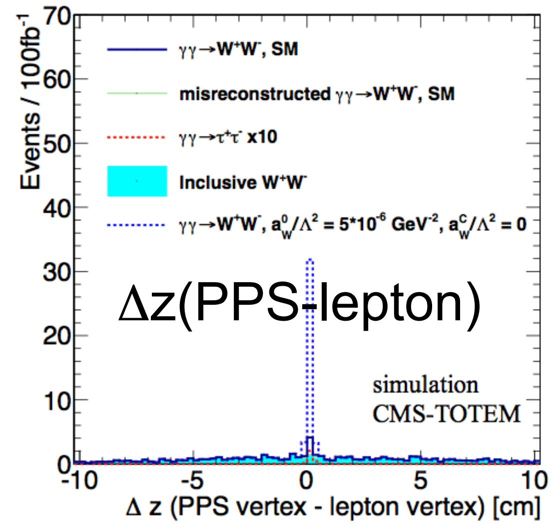
Expected performance

- Study exclusive WW production
- Time-of-flight vs z-vertex







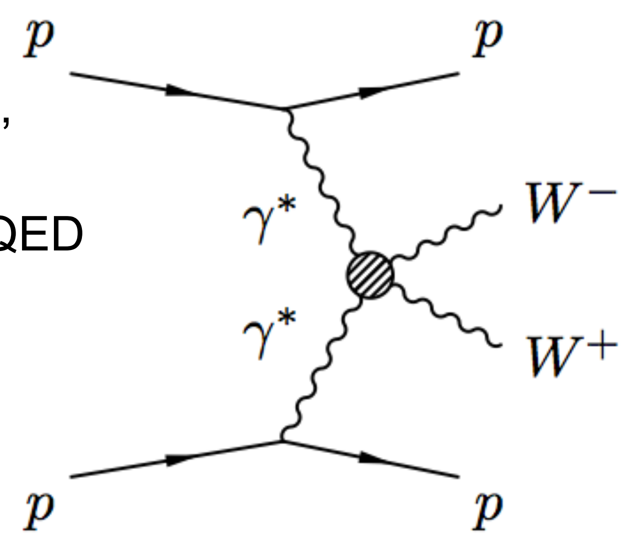


⇒use timing information to reject pileup

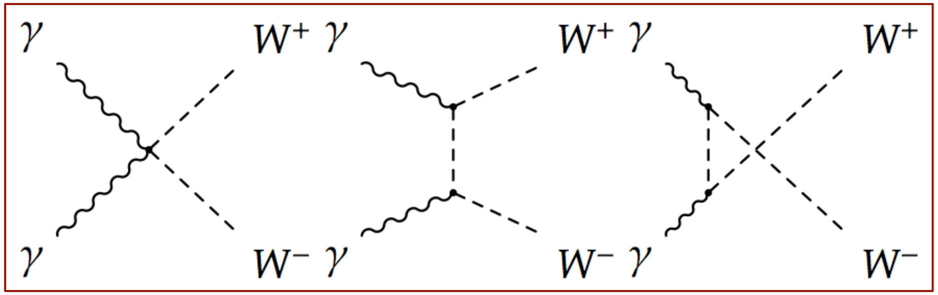
(time difference of two protons is correlated with vertex position)

WW production

CMS-FSQ-13-008



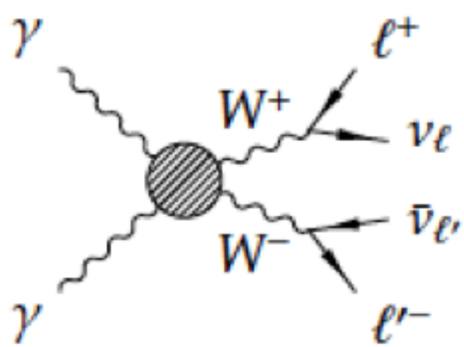
- Study of process: pp→pWWp
  - Clean process: W in central detector and "nothing" else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Backgrounds:
  - inclusive WW, ττ, exclusive two-photon γγ→ll, etc.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

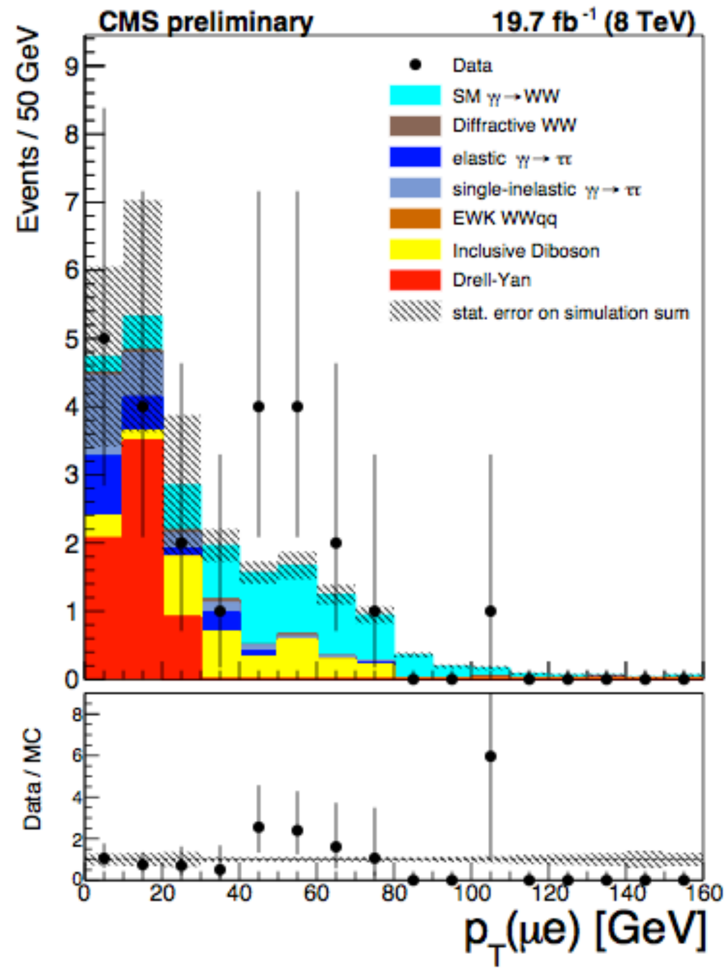


WW production: Selection

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

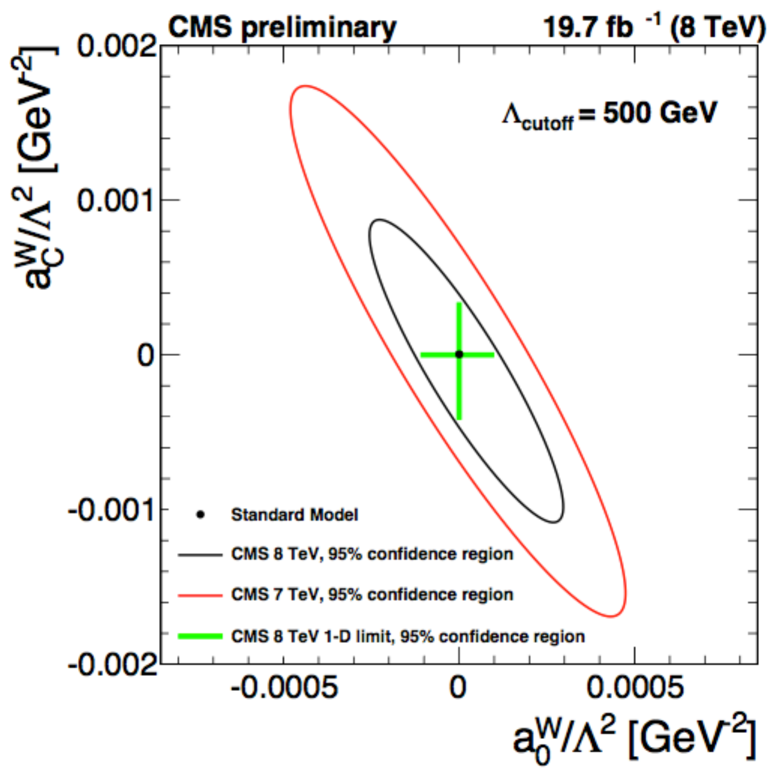
CMS-FSQ-13-008

- Cross section measurement

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

- 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→WW)	5.3±0.1
data	13



- AQGC results
  - 95%CL limits on $a^W{}_C/\Lambda^2$, $a^W{}_C/\Lambda^2$
  - Improvement of two orders of magnitude over LEP/Tevatron

Prospects with PPS: Yields (in fb)

- Select WW events, study eμ final state
- Apply central lepton and PPS acceptance cuts

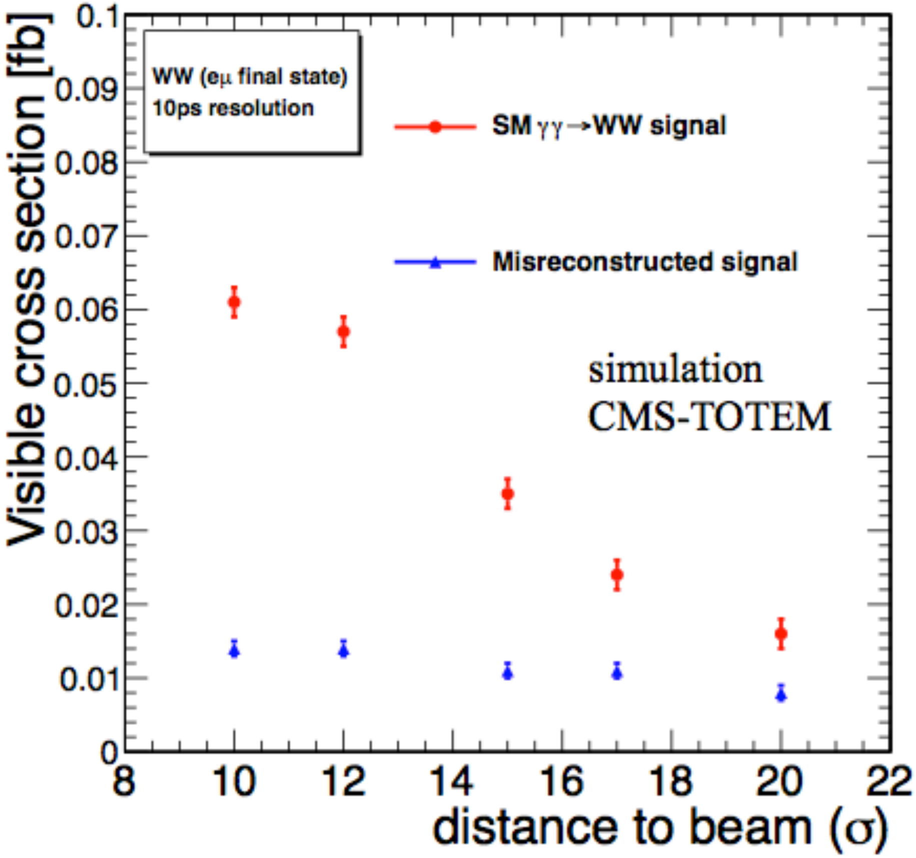
σ=10ps (30ps)

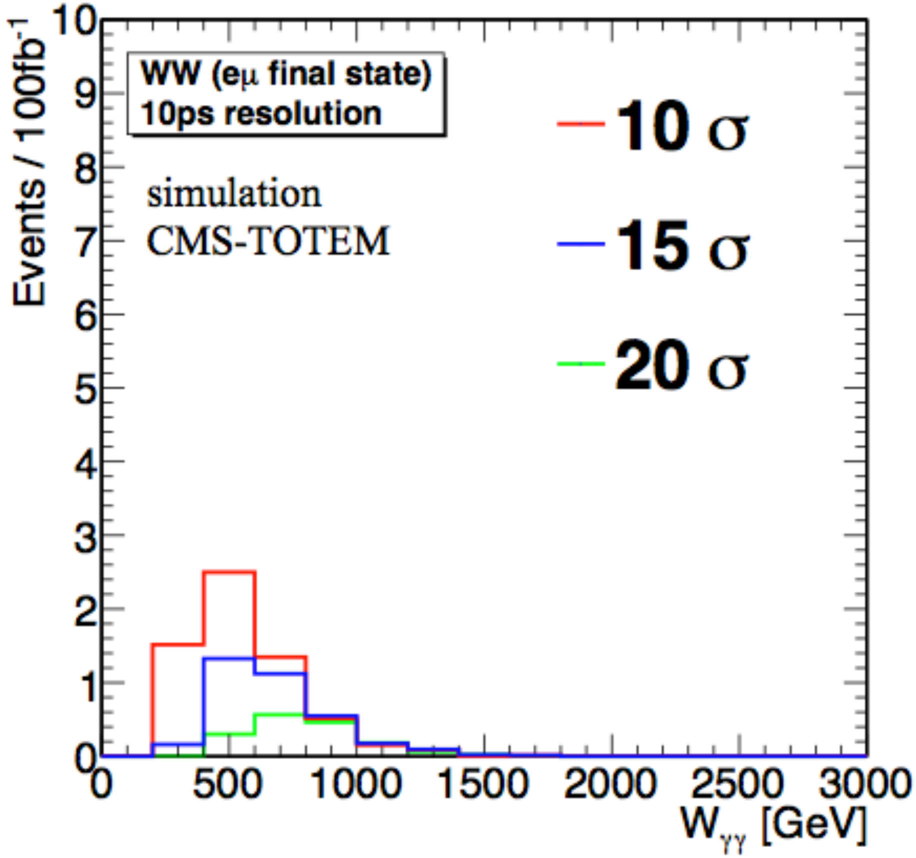
Selection	Cross section (fb)			
	exclusive WW	exclusive WW (incorrectly reconstructed)	inclusive WW	exclusive $\tau\tau$
generated $\sigma \times \mathcal{B}(WW \to e\mu\, \nu\bar{\nu})$	0.86±0.01	N/A	2537	1.78±0.01
≥ 2 leptons ($p_T > 20$ GeV, $\eta < 2.4$)	0.47±0.01	N/A	1140±3	0.087±0.003
opposite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

	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}\text{GeV}^{-2}$ ($a_C^W = 0$)	$a_C^W/\Lambda^2 = 5 \times 10^{-6}\text{GeV}^{-2}$ ($a_0^W = 0$)
opposite sign leptons, "tight" ID		
dilepton pair $p_T > 30$ GeV		
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
$N_{\text{tracks}} < 10$	0.27 (0.24)±0.03	0.11 (0.10)±0.01

AQGC x10 larger

Yields vs distance to beam





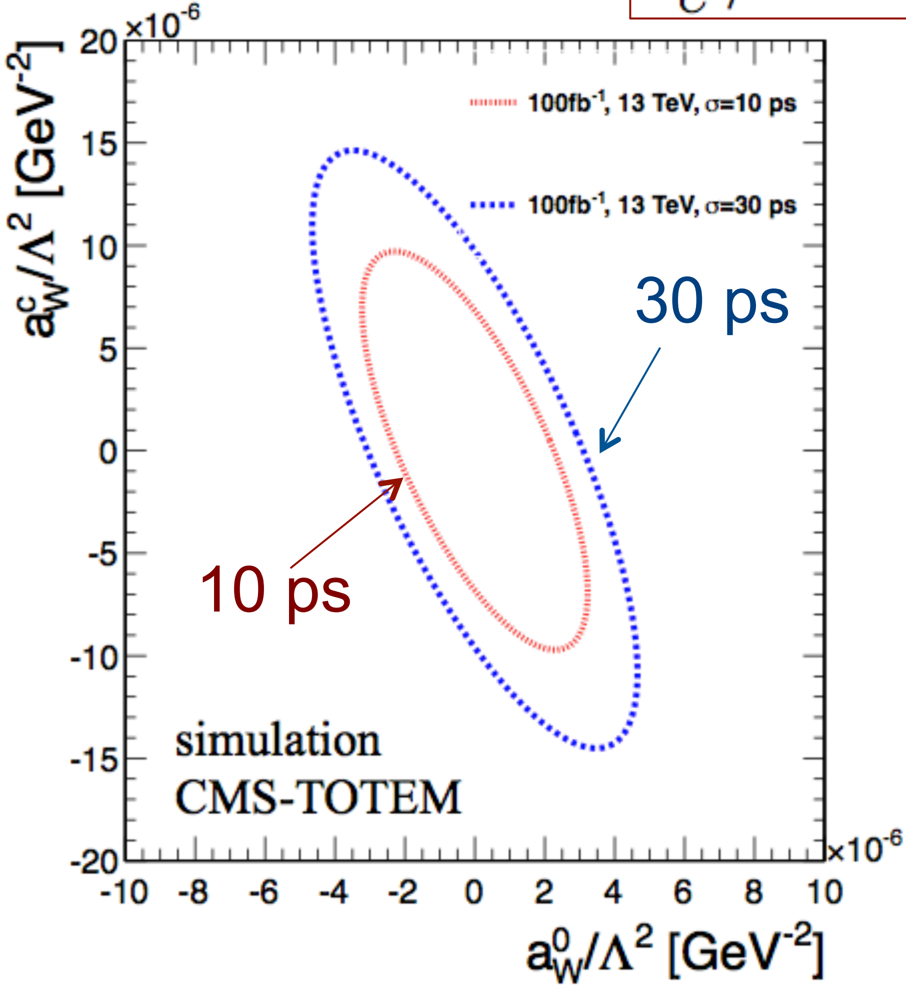
Potential enhancement of sensitivity with closer approach:

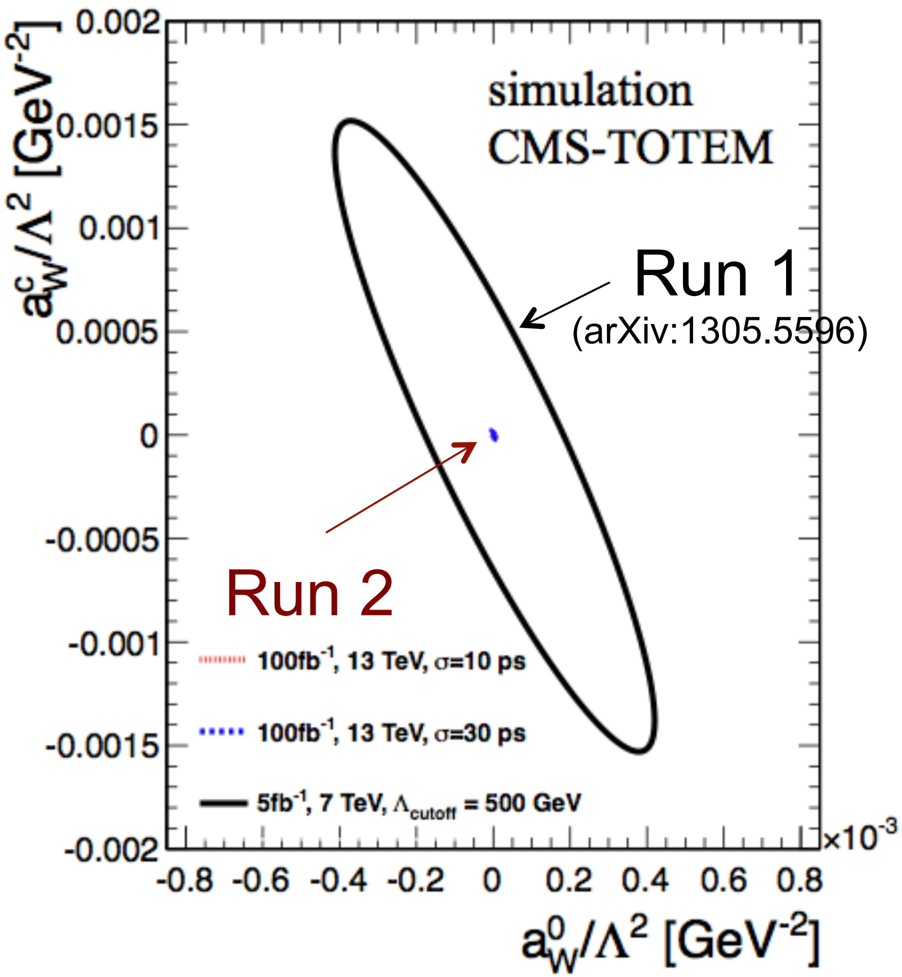
- Signal yield grows by ~x2 when going from 15σ to 10σ
- Background is more or less flat

AQGC expected limits

Expected limits @95%CL:

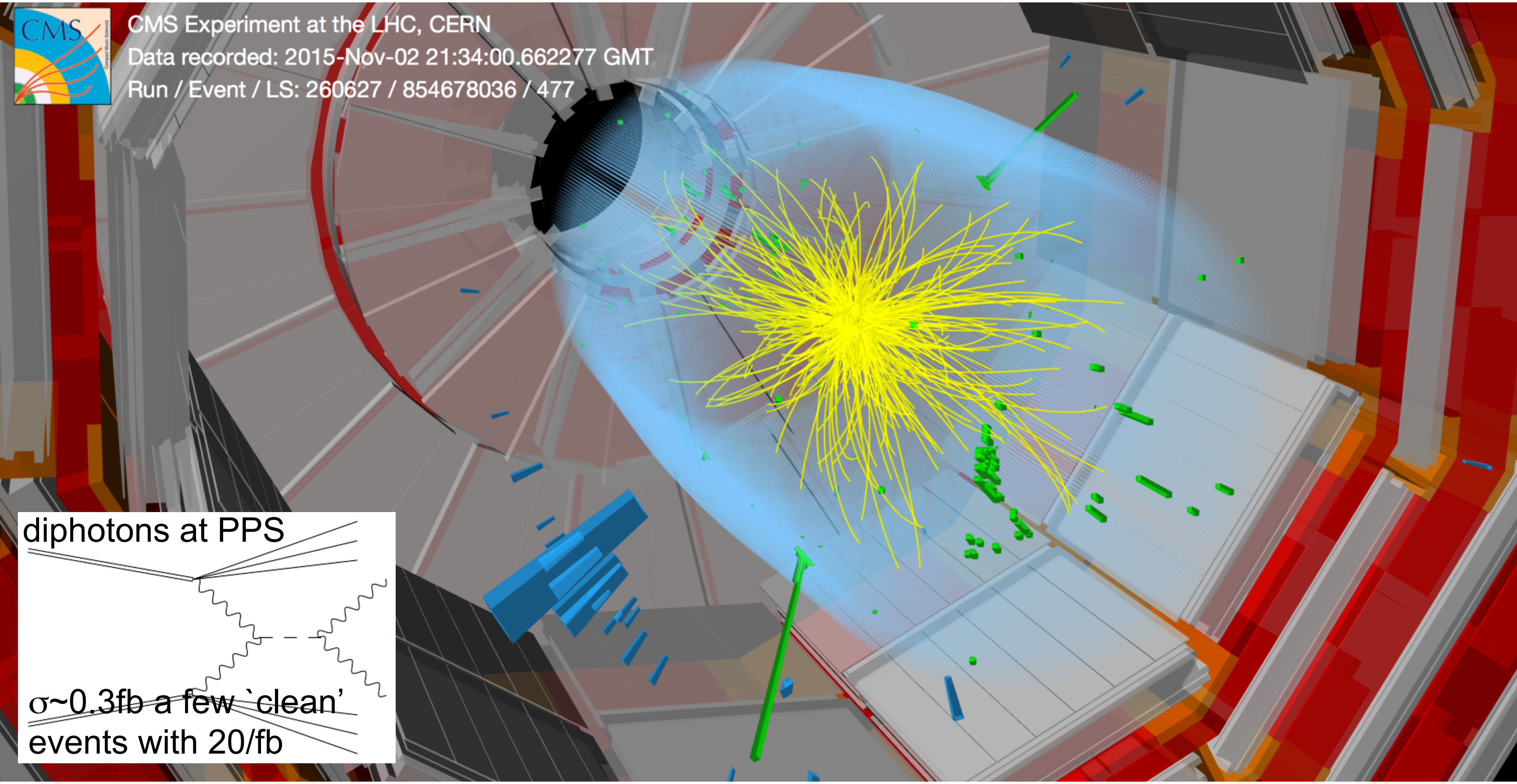
$$a_0^W/\Lambda^2 = 2 \times 10^{-6}\ (3 \times 10^{-6}),$$
$$a_C^W/\Lambda^2 = 7 \times 10^{-6}\ (10 \times 10^{-6}),$$





BSM searches: diphoton resonance

CMS-EXO-15-004, arXiv:1512.0575



Diphoton event with m($\gamma\gamma$) = 745 GeV

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
- Studied physics and detector performance
- Tracking and timing detector options
- Experimental challenges are being addressed
- Consolidation phase in 2016 and beyond

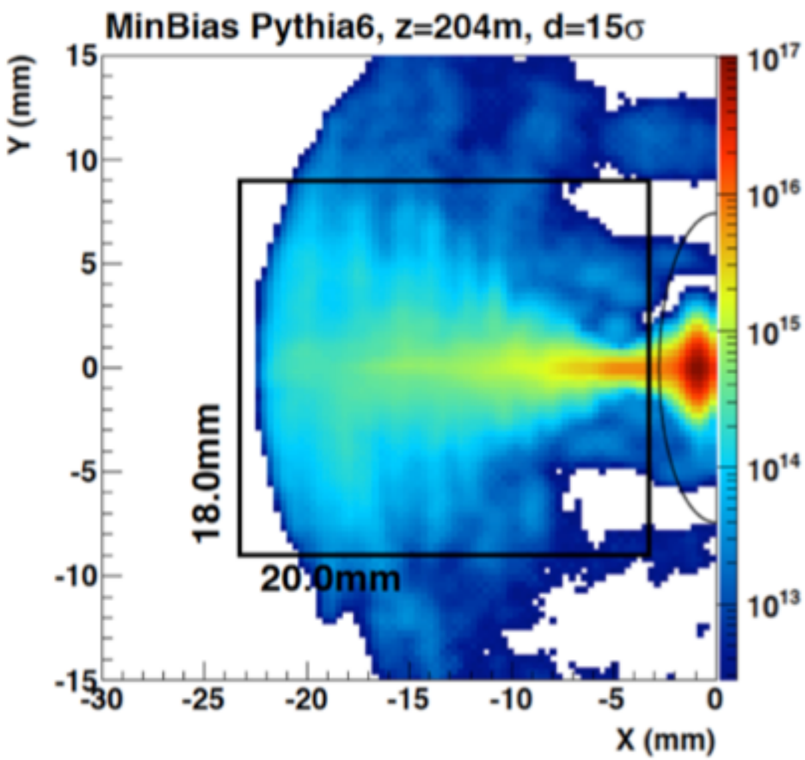
⇒Rich physics program with emphasis on BSM searches

Thesis proposal: ``Development of high-performance timing detectors for the forward proton spectrometer''

backup

Expected radiation doses

- Radiation levels in detector studied using Totem data and simulation



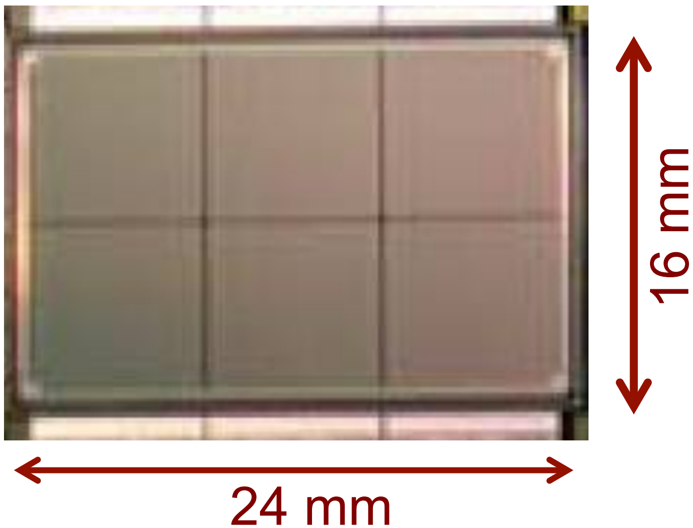
Per 100 fb^{-1}:

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

Tracking detectors (cont.)

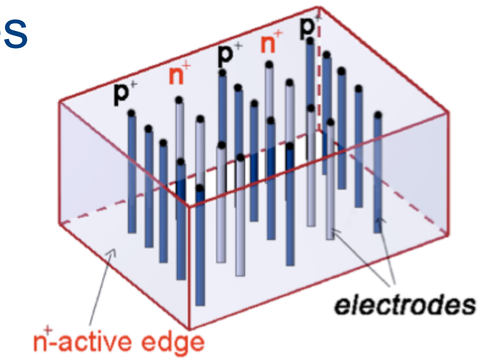
6 detector planes per station

- For each plane:



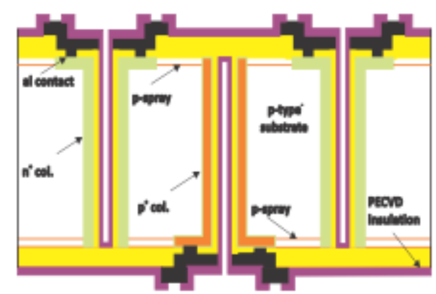
- 16 x 24mm^2 3D silicon pixel sensors
- 150(x) x 100 (y) μm^2 pixel pattern
- 6 PSI46dig readout chips (52x80 pixels each)

3D sensors consist of an array of columnar electrodes



Interesting features w.r.t. planar sensors:

- Low depletion voltage (~10V)
- Fast charge collection time
- Reduced charge trapping probability and high-radiation hardness
- Slim edges, dead area of 100-200mm
- Spatial resolution comparable to planar sensors

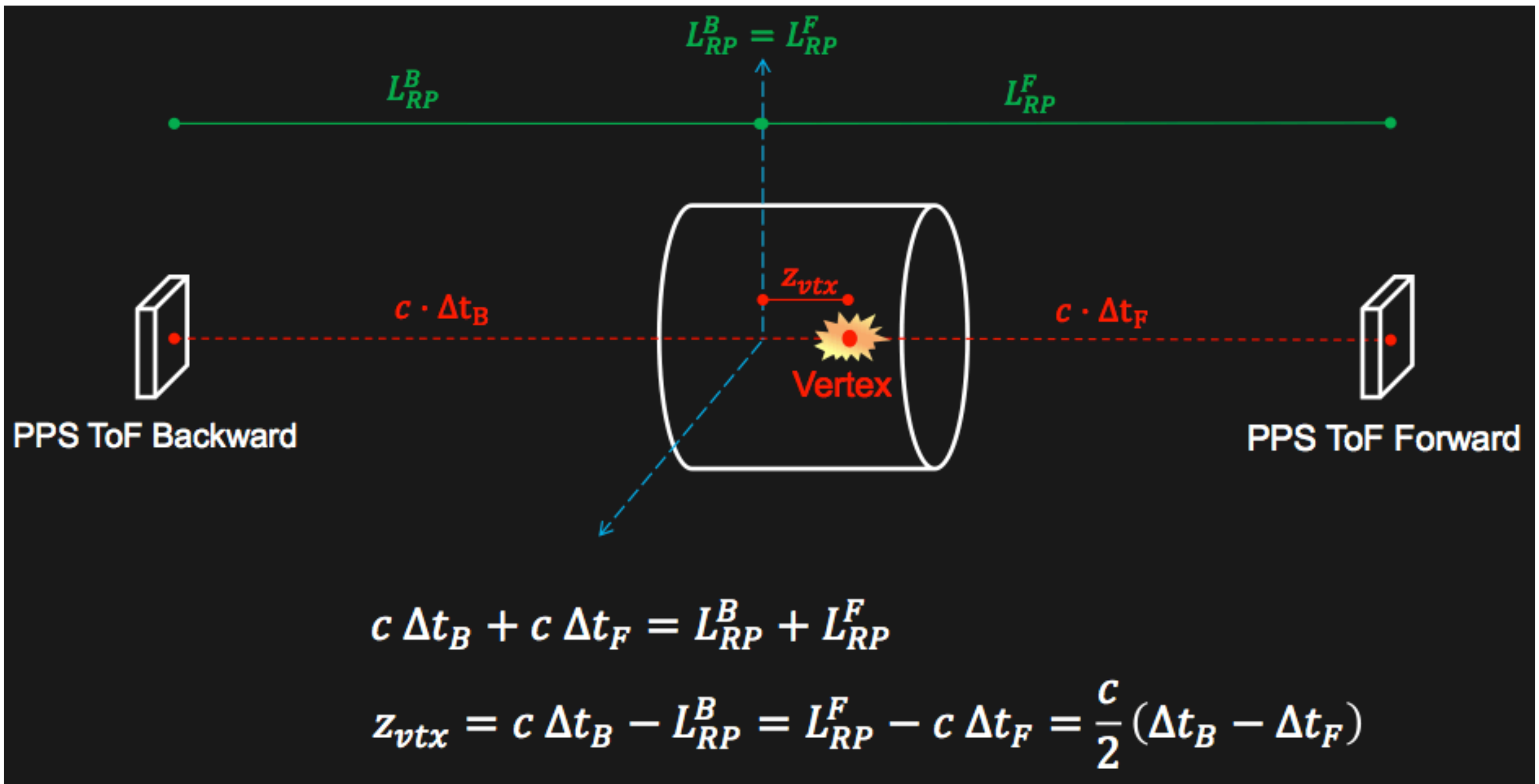


Inter-electrode distance 62.5μm

Pileup rejection: timing

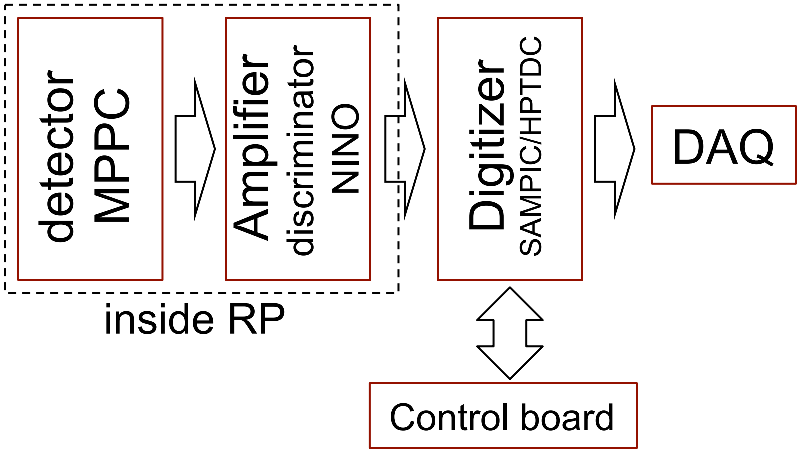
$$\sigma_{z_{vtx}} = \frac{c}{2}\sqrt{2\sigma^2_{\Delta t}} \overset{\sigma_{\Delta t}=10\mathrm{ps}}{\approx} 2\ \mathrm{mm}$$

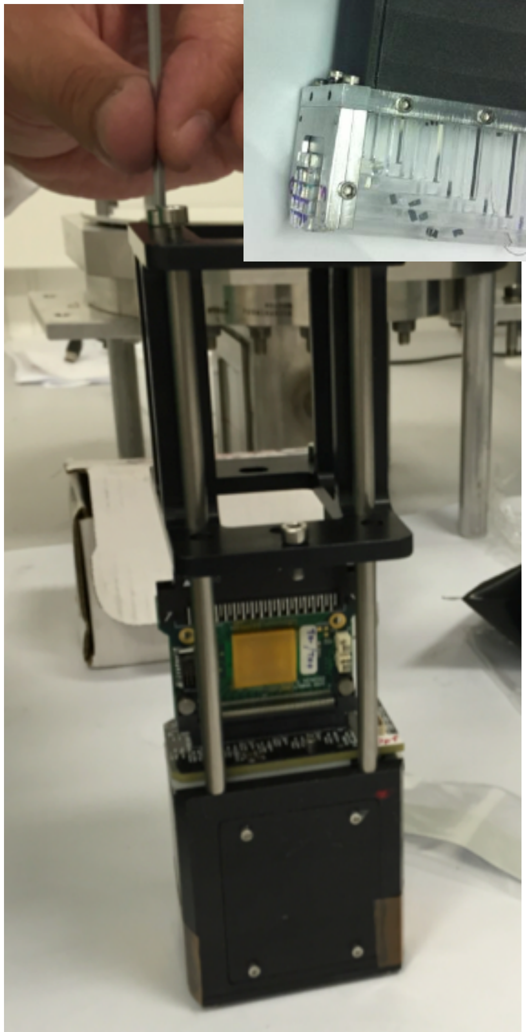
$$\overset{\sigma_{\Delta t}=30\mathrm{ps}}{\approx} 6\ \mathrm{mm}$$

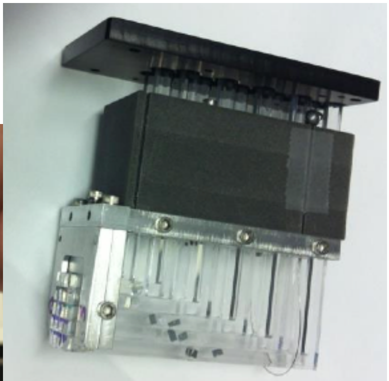


Timing detectors (cont.)

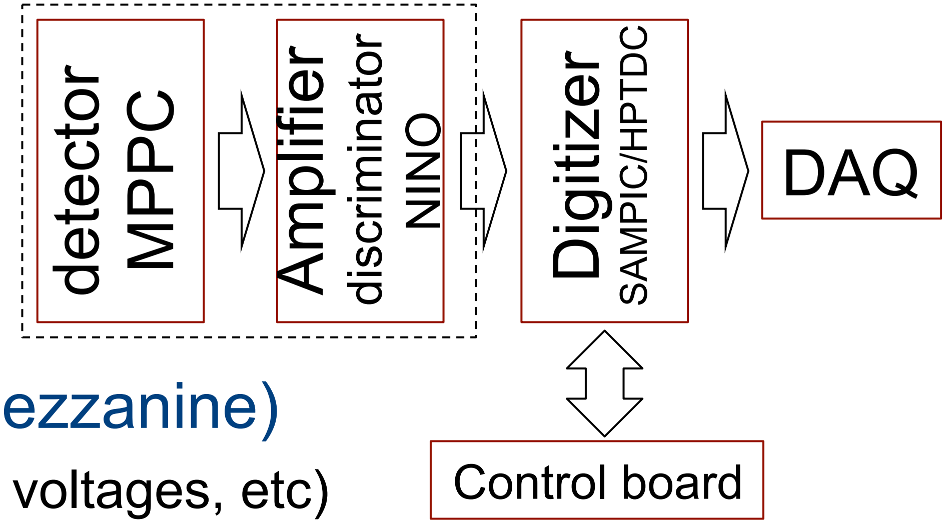
- Cerenkov light in quartz radiator bars
- Quartic module:
  - 20 (4x5) 3x3 mm^2 L-shaped bar elements
  - bars separated by100 μm (total internal reflection)
- Two modules in one RP
- Beam tests: σ~30ps (~20ps for two in-line)
- Readout electronics:





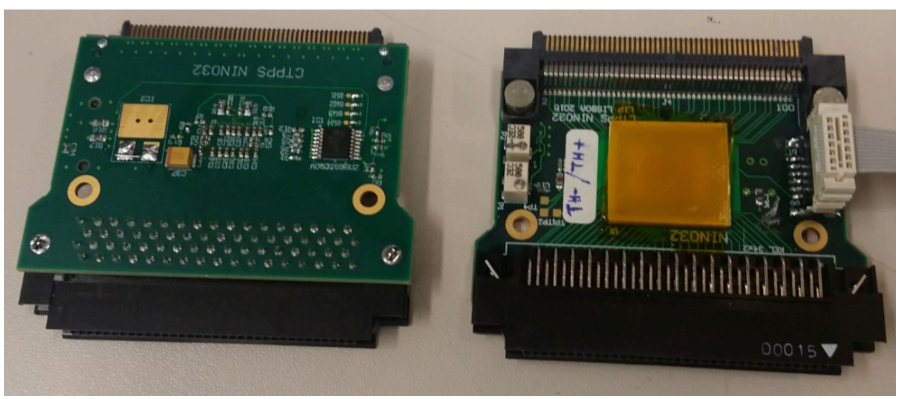


Electronics



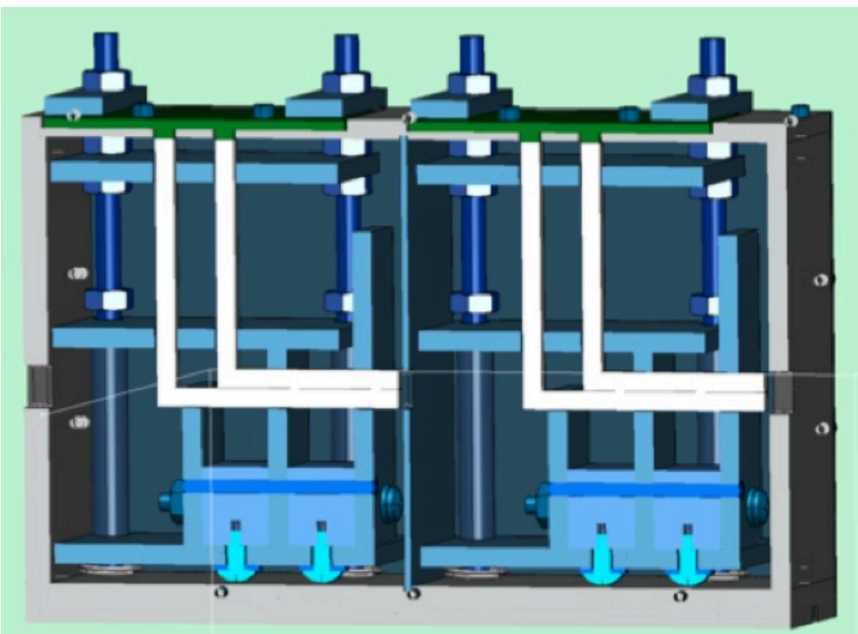
Electronics read-out chain

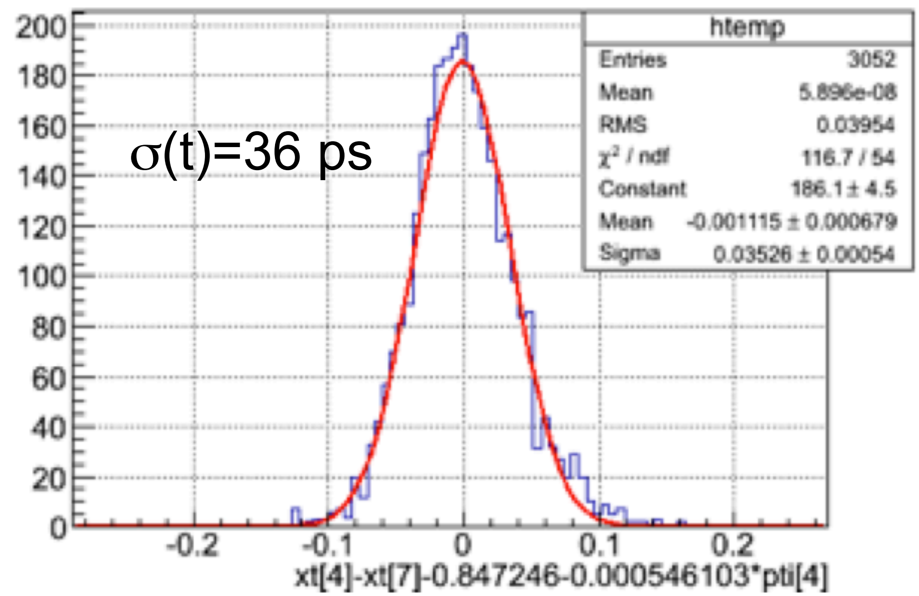
- Front-end/SiPM board
- NINO (amplifier-discriminator)
- Digitizer board (motherboard+mezzanine)
  - control of SiPM control board (bias voltages, etc)



Beam tests

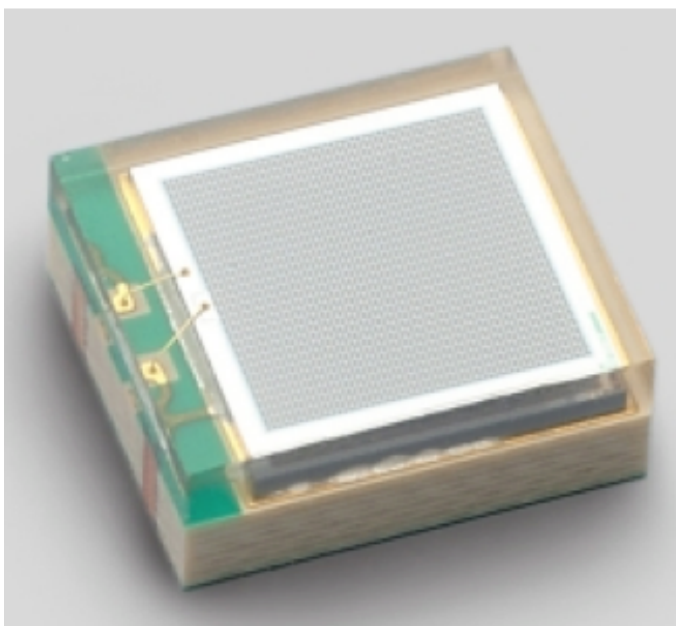
- Test modules with 30 and 40 mm radiator bars
- Time resolution σ=36 ps (30 mm bar)
  - Time difference between L-bar and reference signal
  - 2-in-line ⇒ 25ps (improvements possible)



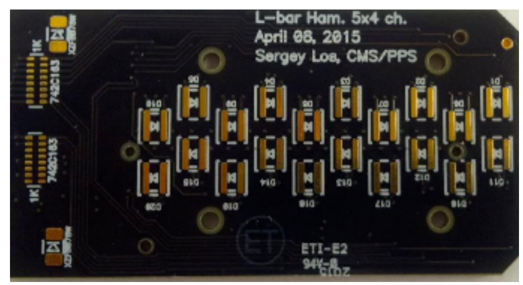


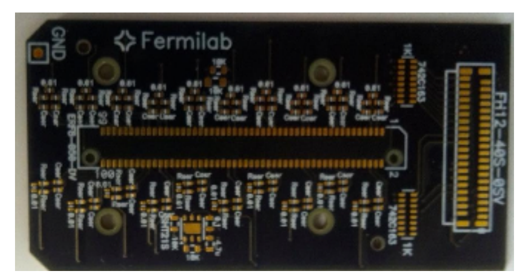
Photosensors

- 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





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