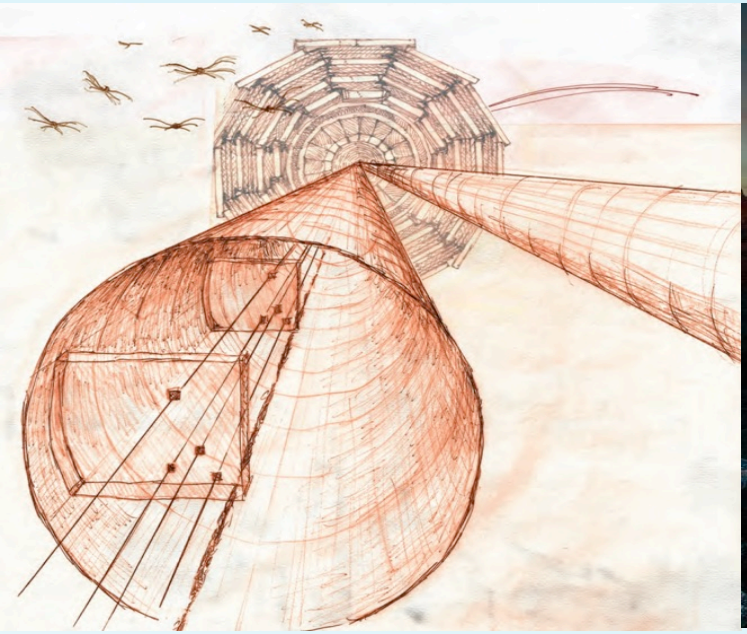
CMS-TOTEM
Precision Proton Spectrometer

F.Ferro - INFN Genova

on behalf of the CMS and TOTEM collaborations



Diffraction 2016

Outlook

- Project overview
- Experimental apparatus
- Physics motivations and performance
- Status and latest news

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CT-PPS institutes

CMS

Belgium
- **Louvain**

Brazil
- **CBPF**
- **UERJ**

Italy
- **Genova**
- **Torino/Novara**

Iran
- **IPM**

Portugal
- **LIP**

Russia
- **IHEP Protvino**

US
- **Fermilab**
- **Iowa**
- **Kansas**
- **Livermore**
- **Rockefeller**

TOTEM

CERN
- **TOTEM group**

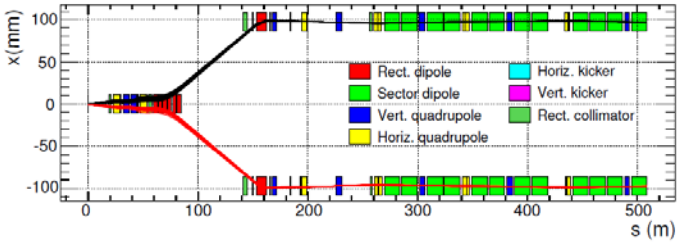
Czech Republic
- **Pilsen**
- **Prague**

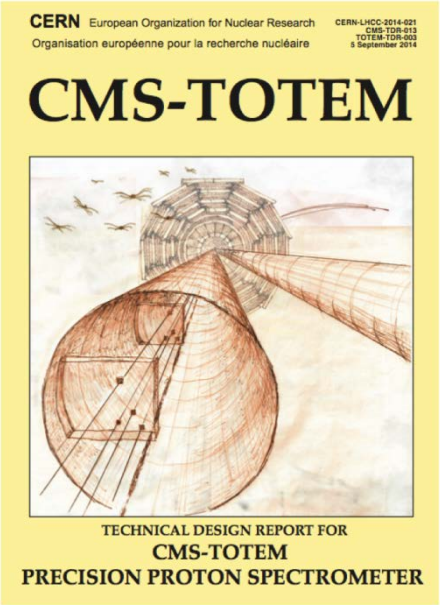
Finland
- **Helsinki**

Italy
- **Bari**
- **Pisa/Siena**

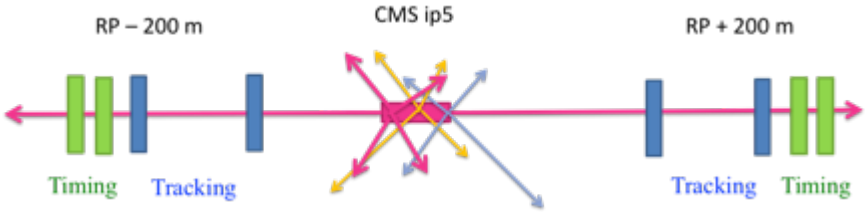
CT-PPS project

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





- Tracking and timing detectors inside the beam pipe at ~210m from IP5
  - Tracking to measure proton momentum
  - Timing to disentangle pile-up
- Project TDR approved in Dec.2014 by LHCC
- CT-PPS already taking data with an “accelerated program” configuration
  - Use already available Si strip detectors from TOTEM experiment
- Data taking with the baseline detector configuration foreseen for beginning 2017



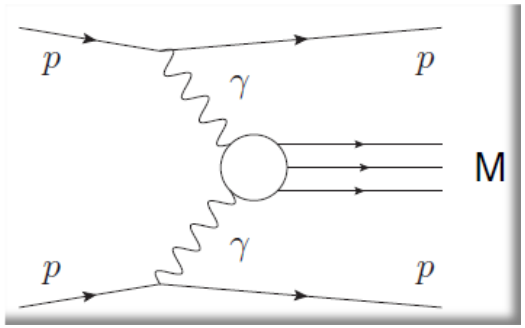
Physics motivations

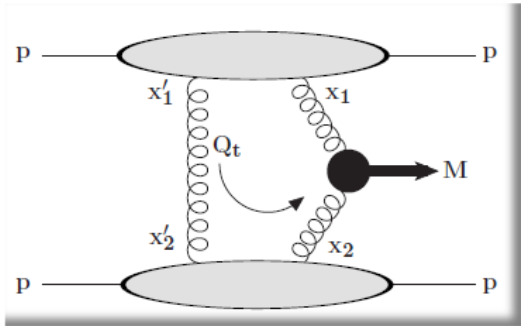
Experimental strategy

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

Physics

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





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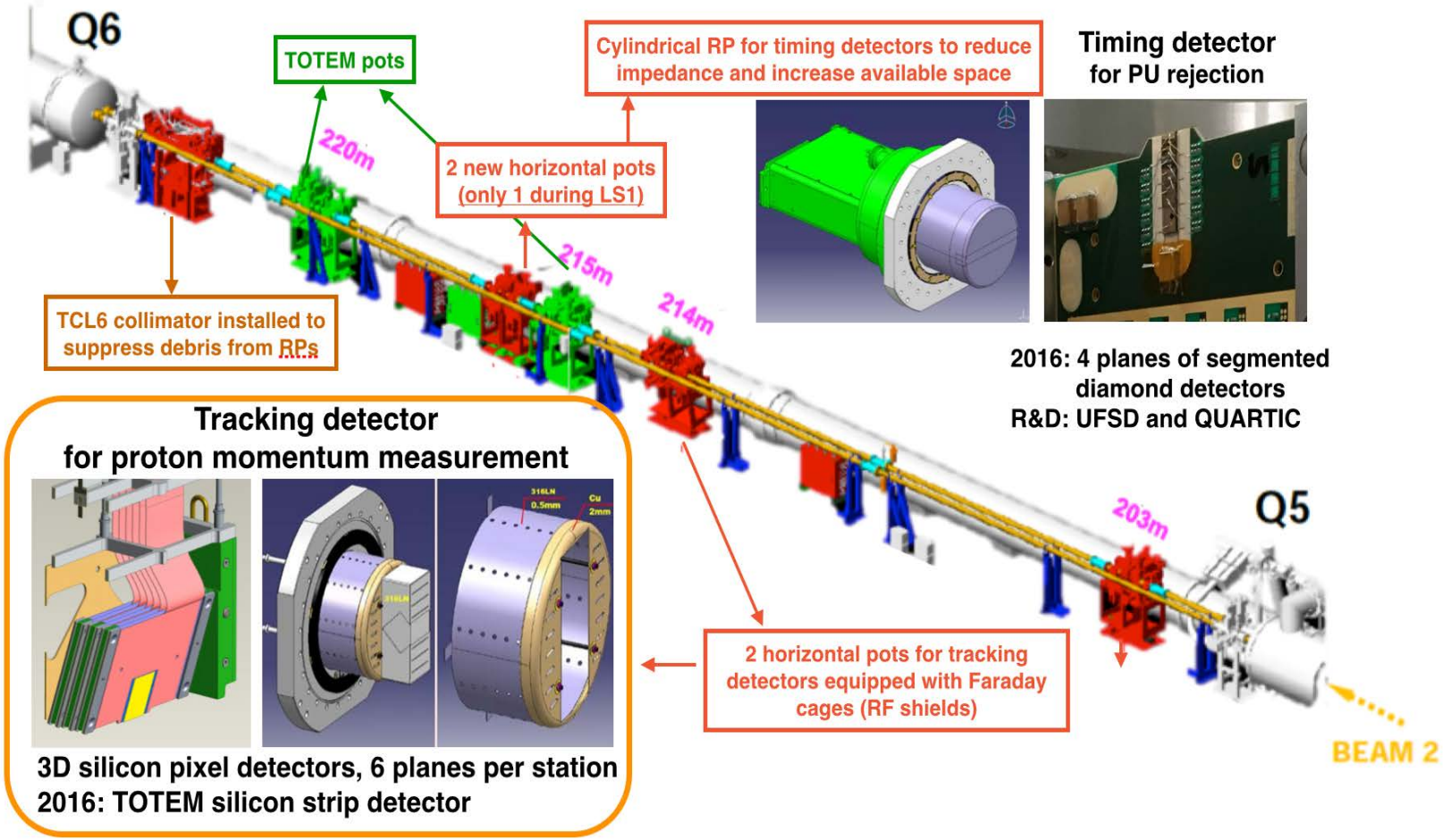
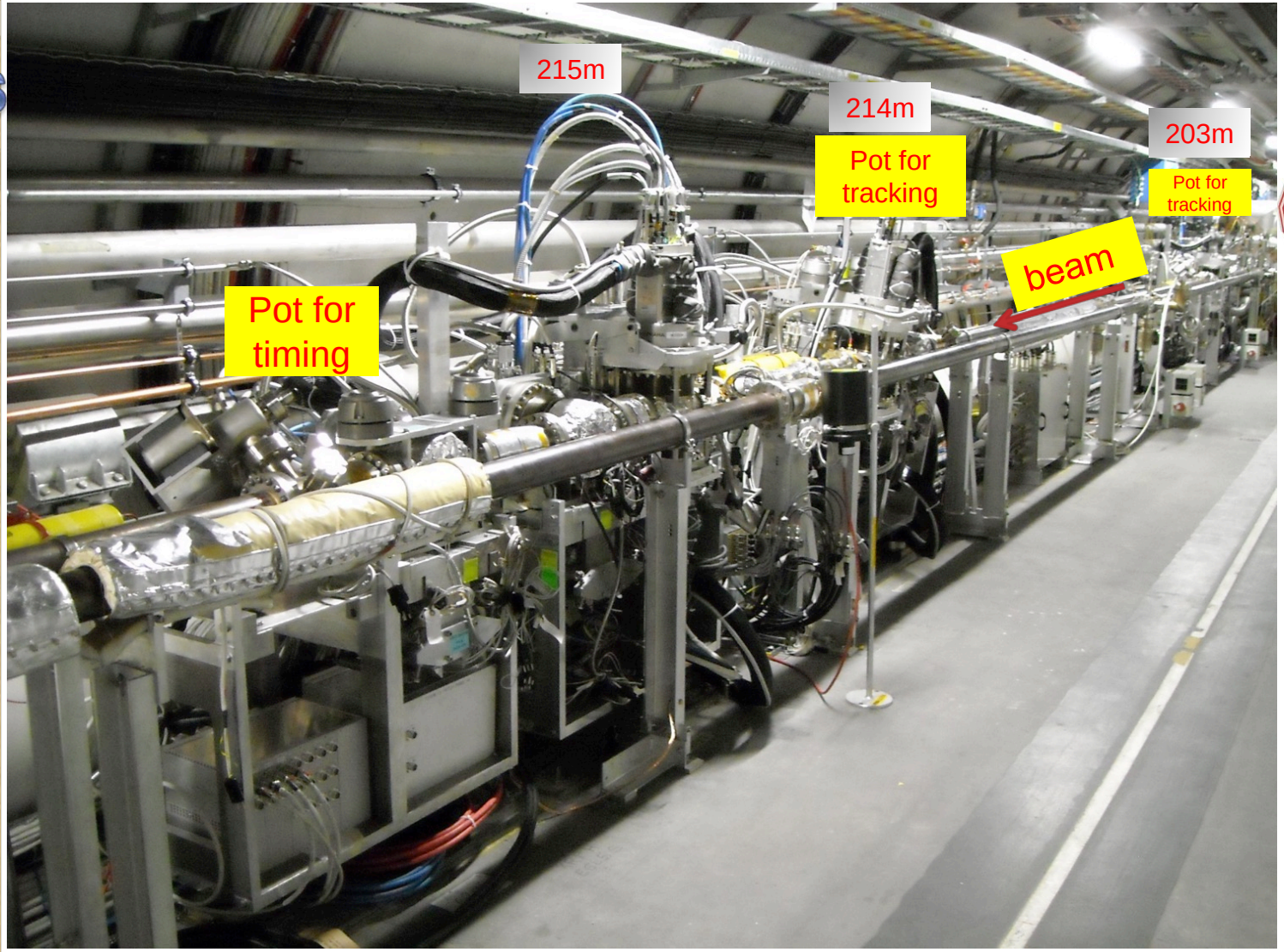
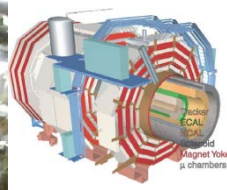
Experimental apparatus

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



How they look like in reality





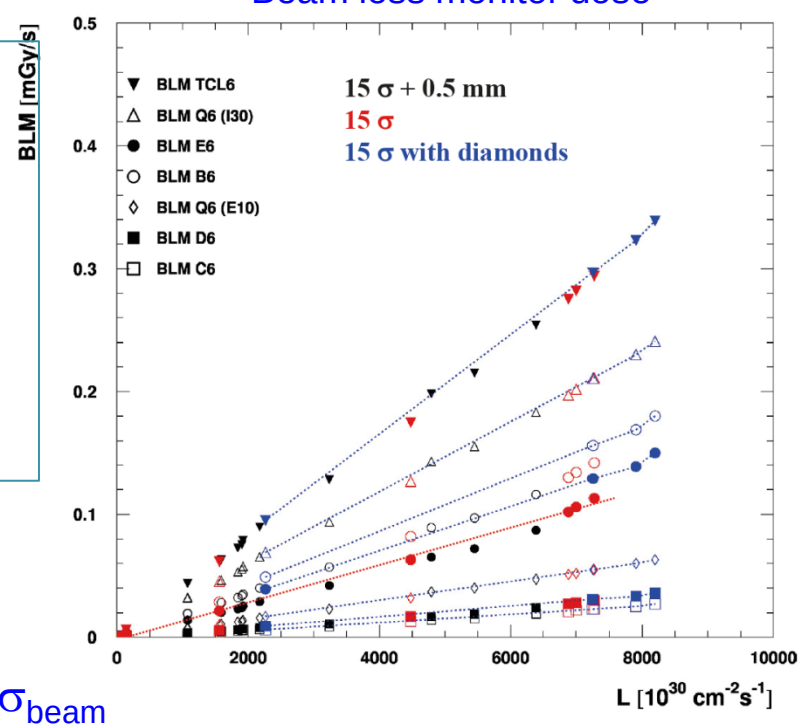
Roman Pot insertion

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

To be monitored during the tests

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

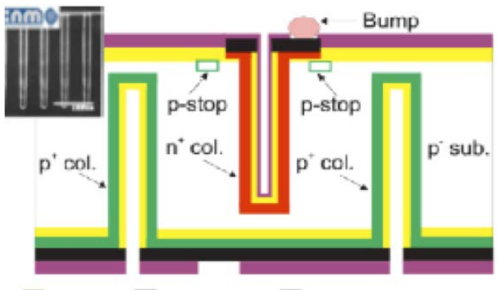
Beam loss monitor dose



Tests successful ⇒ Data taking at $15\sigma_{beam}$

Detectors

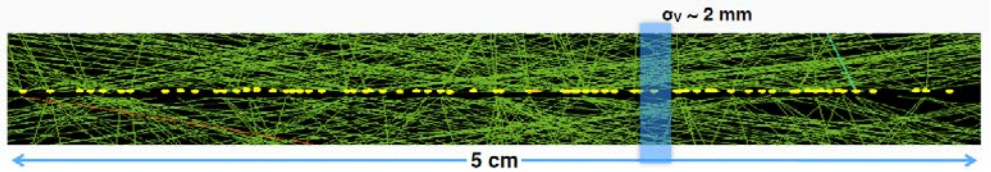
- Tracking detectors
  - Aim: Measure the proton momentum
    - Detailed knowledge of the LHC optics required
  - Technology: Silicon 3D pixel (6 planes per pot)
    - rad-hard and “edgeless”



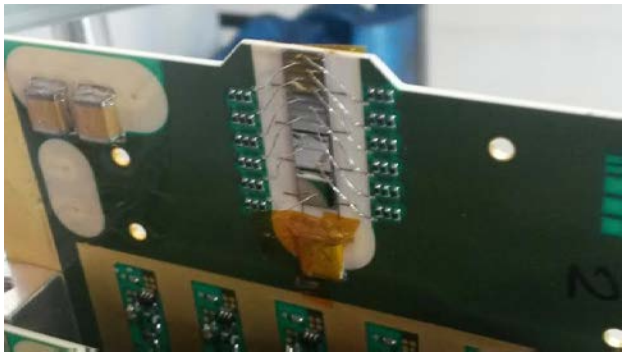
- Timing detectors
  - Aim: Disentangle pileup primary vertices
    - $\sigma_{Time} \sim 10$ ps $\rightarrow$ $\sigma_Z \sim 2$ mm

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

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

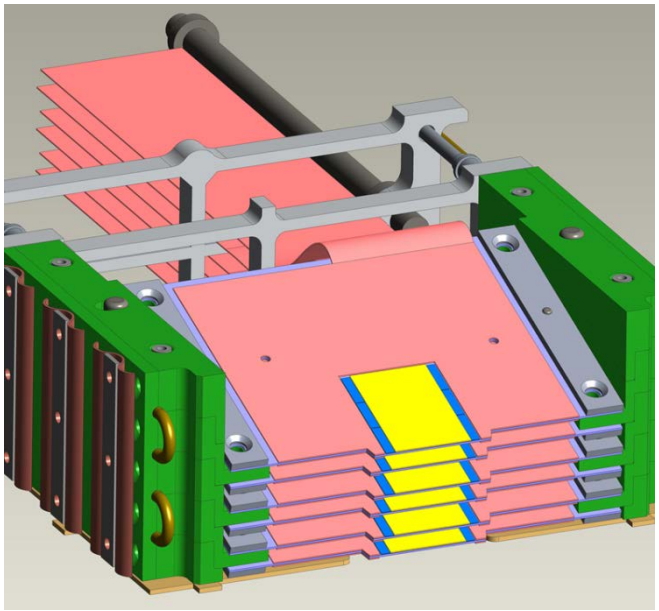


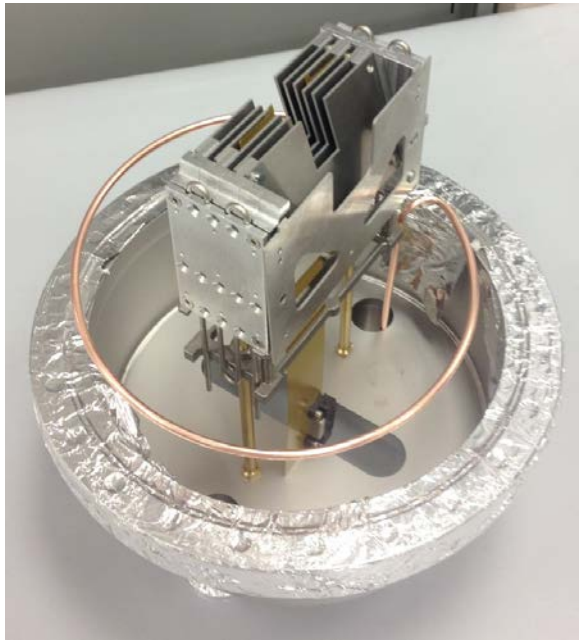
  - Technology:
    - Diamond detectors
    - R&D also pursued
      - Cherenkov quartz bars (QUARTIC)
      - Ultra fast silicon detectors (UFSD)



Tracking detectors (1)

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

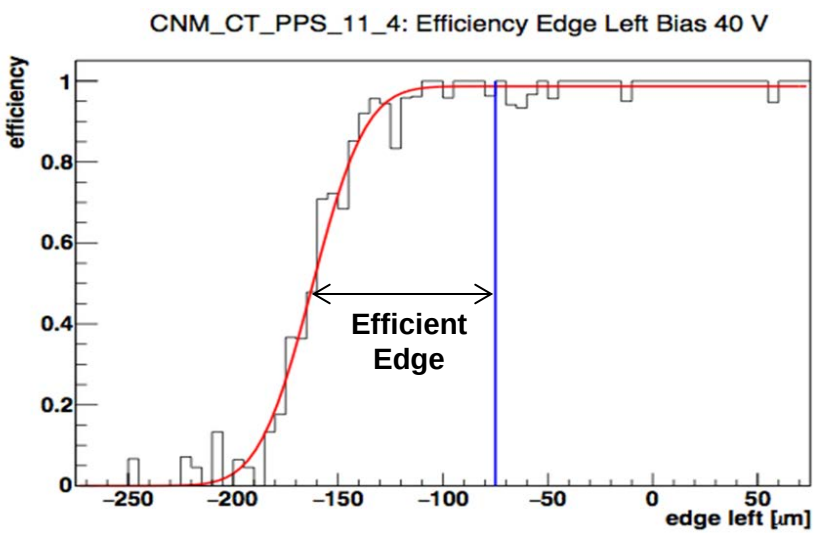


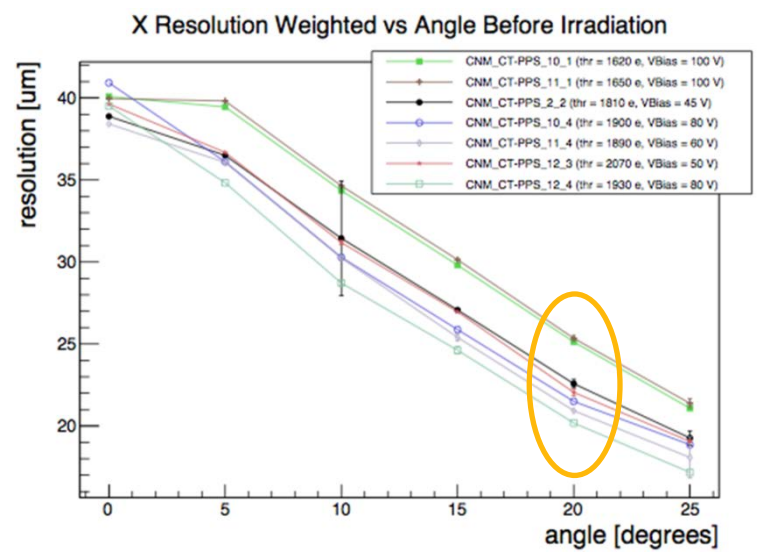


Tracking detectors (2)

- **3D sensor** technology
  - intrinsic **radiation hardness** (to withstand overall integrated flux of $5 \cdot 10^{15}$ protons/cm^2 corresponding to an integrated luminostity of ~100/fb)
  - 200 μm **slim edges** (small dead edge to approach the beam as much as possible)
  - pixel dimensions: 100x150μm^2
  - resolution <30μm (goal ~10μm)
  - front-end chip: latest version of the PSI46dig, same as for CMS Pixel Phase I upgrade

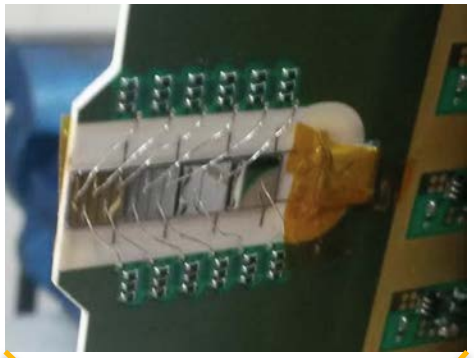
Testbeam results (preliminary)

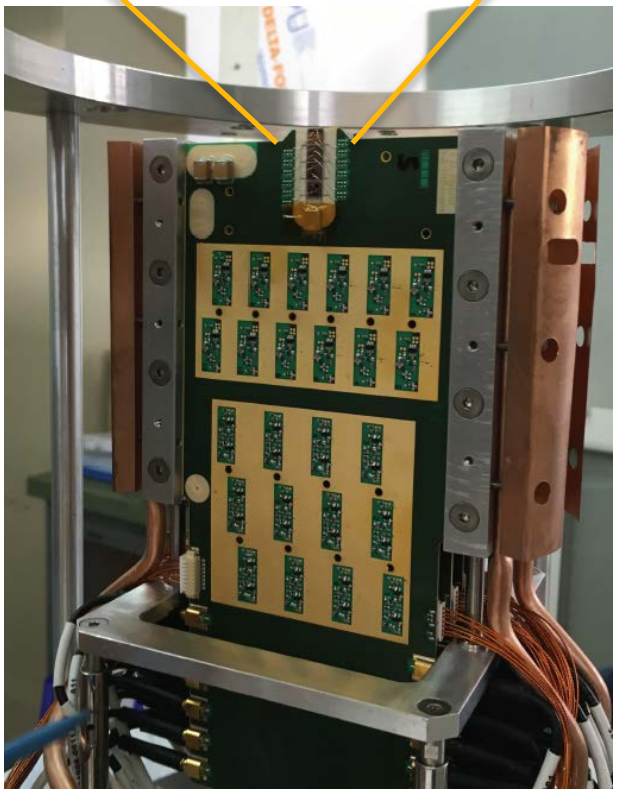


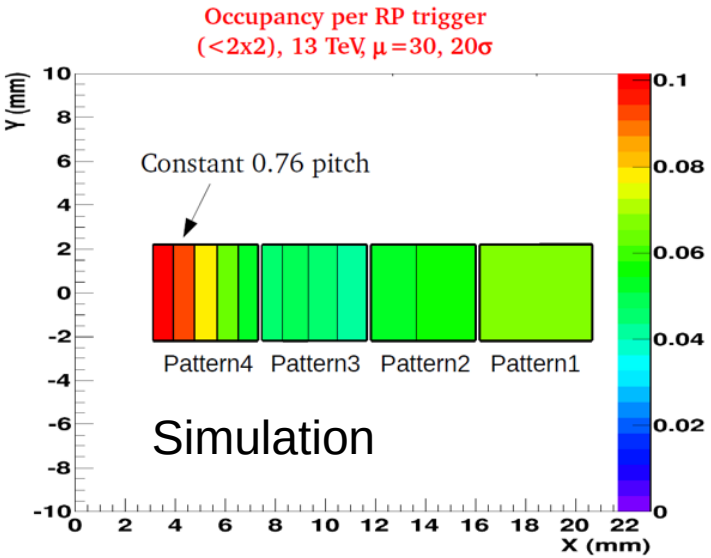


Timing detectors: Diamonds

- σ_T ~ 80 ps per plane, better than 50 ps with a package of 4 planes
- variable pad dimensions to optimize occupancy
- Readout with NINO + HPTDC
- A detector package installed in the cylindrical pots during TS1
- Data taking expected for September (together with the Si strip, in the "accelerated program" configuration)







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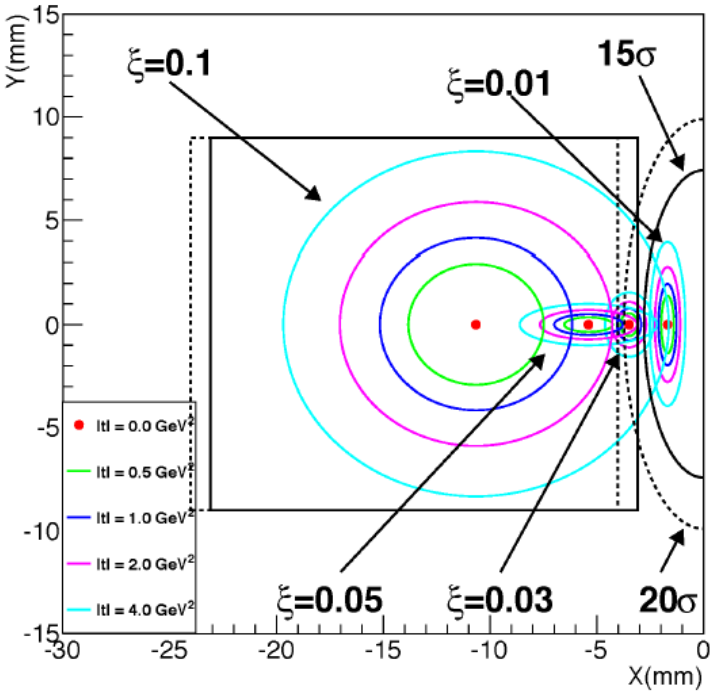
Detector acceptance and resolution

Proton kinematics (t and ξ)

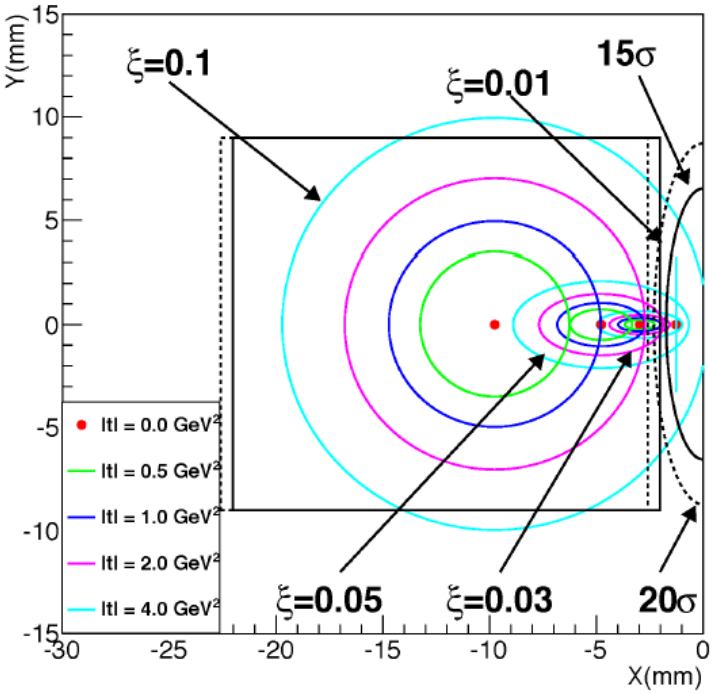
Near pot

z=204m (X as of CMS)



Far pot

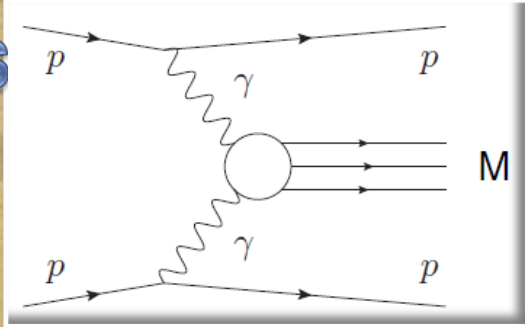
z=215m (X as of CMS)

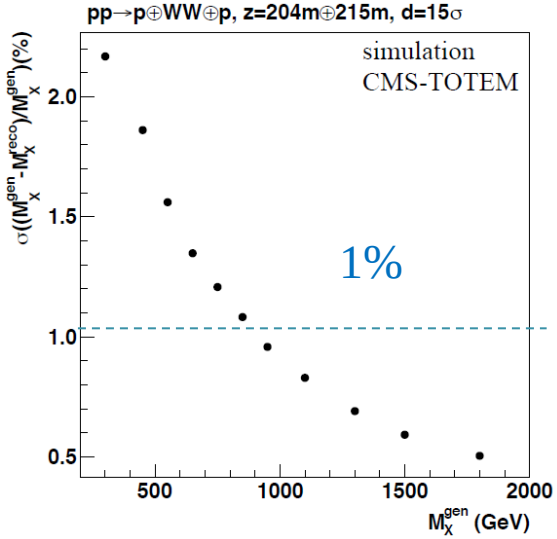


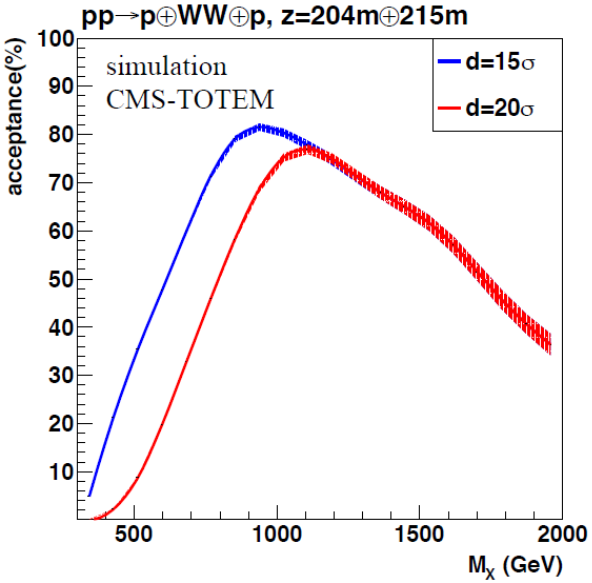
N.B.: all acceptance plots done with optics (slightly) different wrt the current one

Mass acceptance and resolution

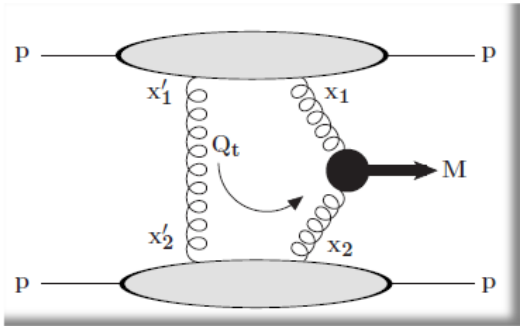
WW

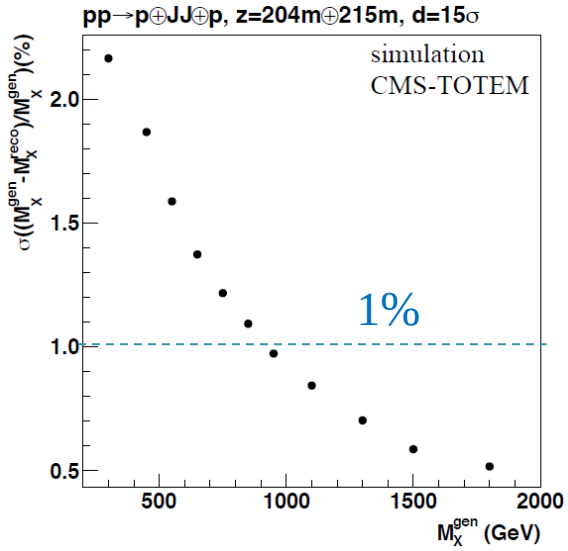


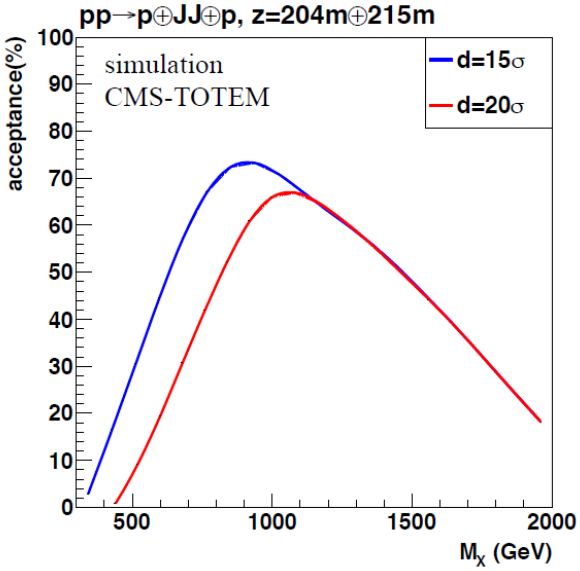




jet jet



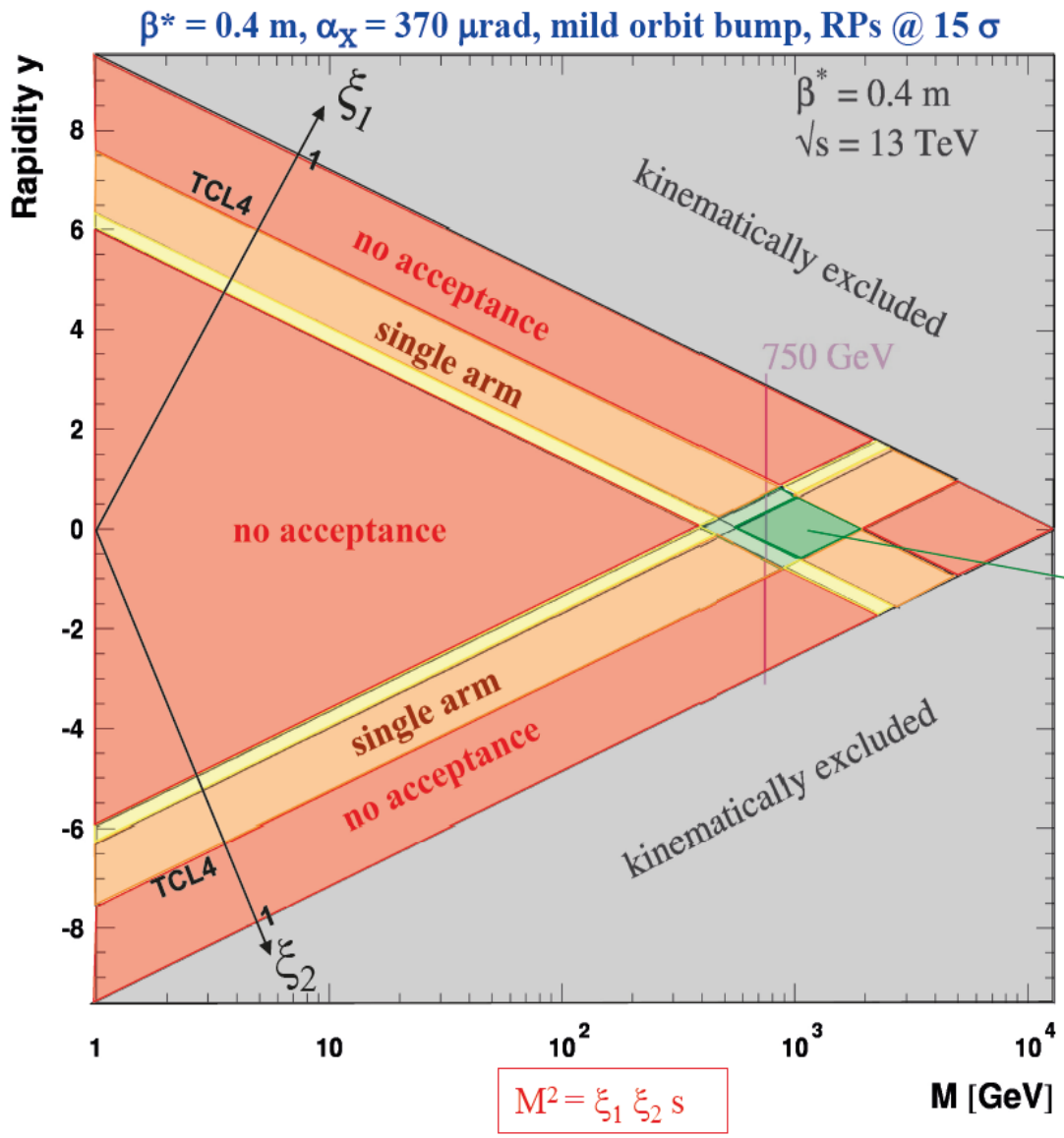




Mass-rapidity space

Recent studies with actual optics

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



$$M^2 = \xi_1 \, \xi_2 \, s$$

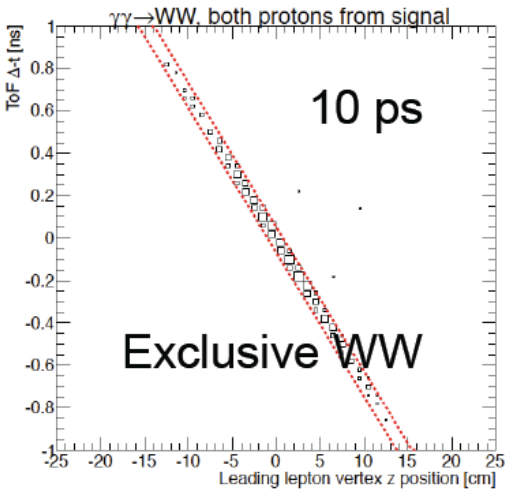
light green,
light orange:
acceptance only
in 210-F and 220-C

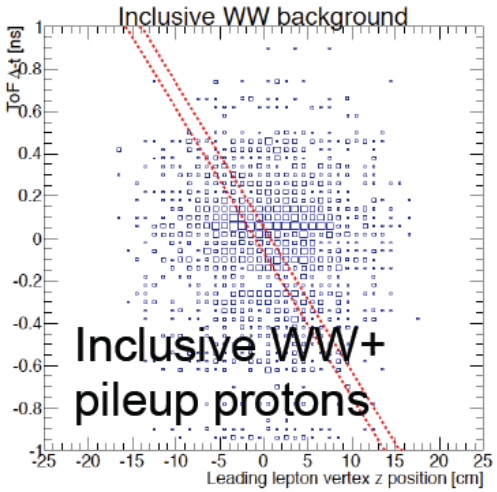
Exclusive WW production

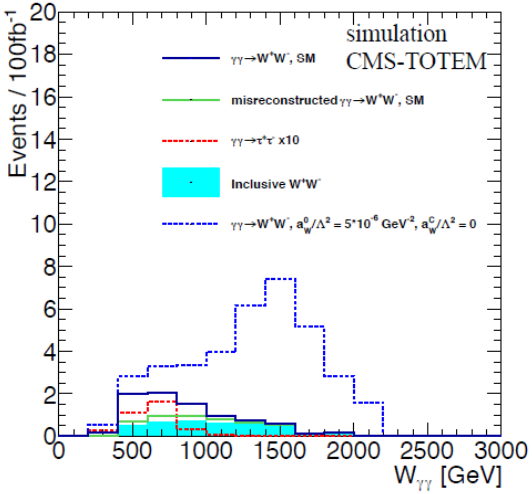
Studied only eμ channel

Main background from inclusive WW and ττ exclusive production

- Proton timing: an important tool to reject background
- SM contribution small in the tail of $W_{\gamma\gamma}=\sqrt{s}\xi_1\xi_2$
  - aQGC events clearly separated

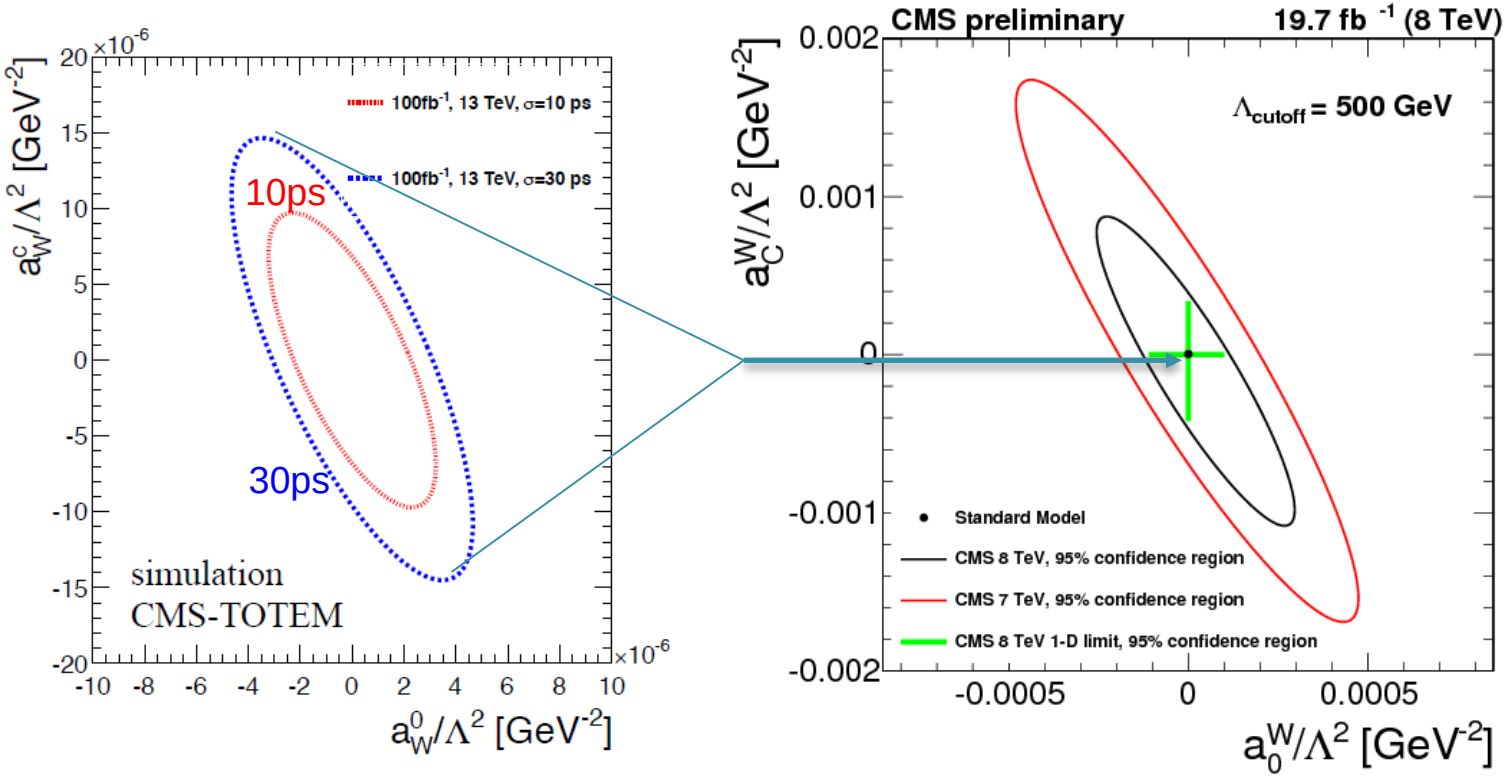






Exclusive WW production

Expected new limits on aQGC couplings at 95% CL



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

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

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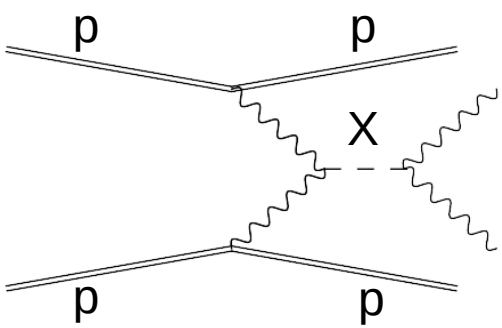
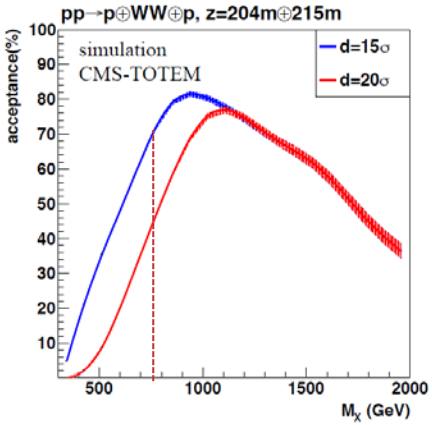
CT-PPS accelerated program

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

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



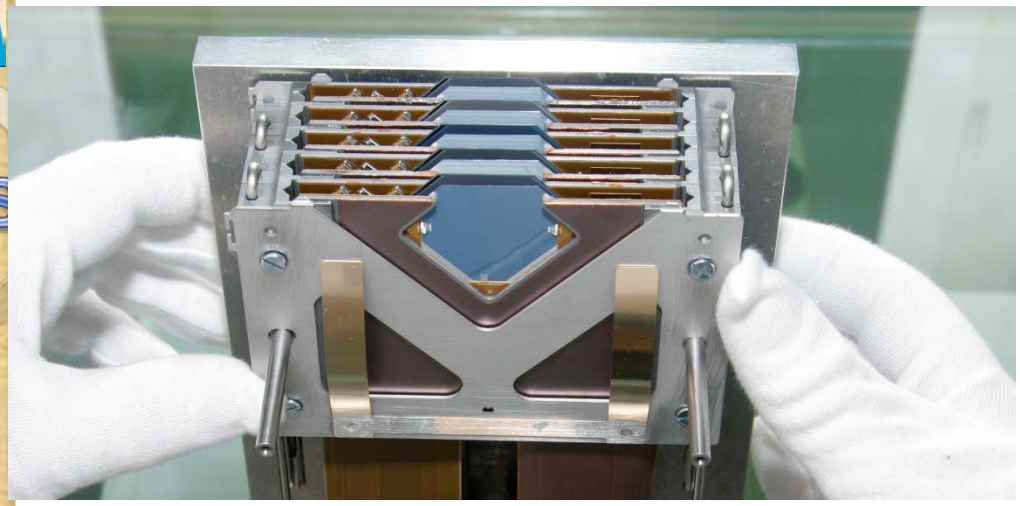


At the beginning of the year it was decided to make an effort to have:

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

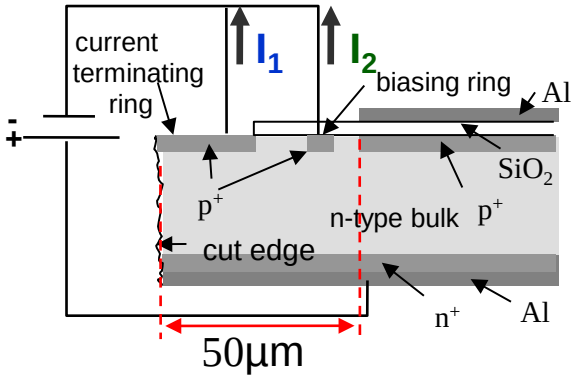
The resonance was not there, nevertheless CT-PPS has already taken precious data with the TOTEM Si strips and is going to take data with the diamonds

TOTEM Si strips

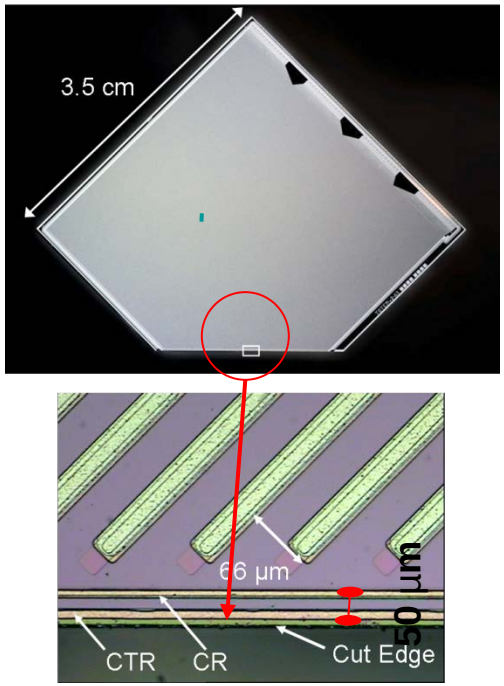


- 10 planes of Si detectors
- 512 strips at ± 45°
- Pitch: 66 μm
- Resolution: ~ 20 μm

Planar technology + CTS
(Current Terminating Structure)



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



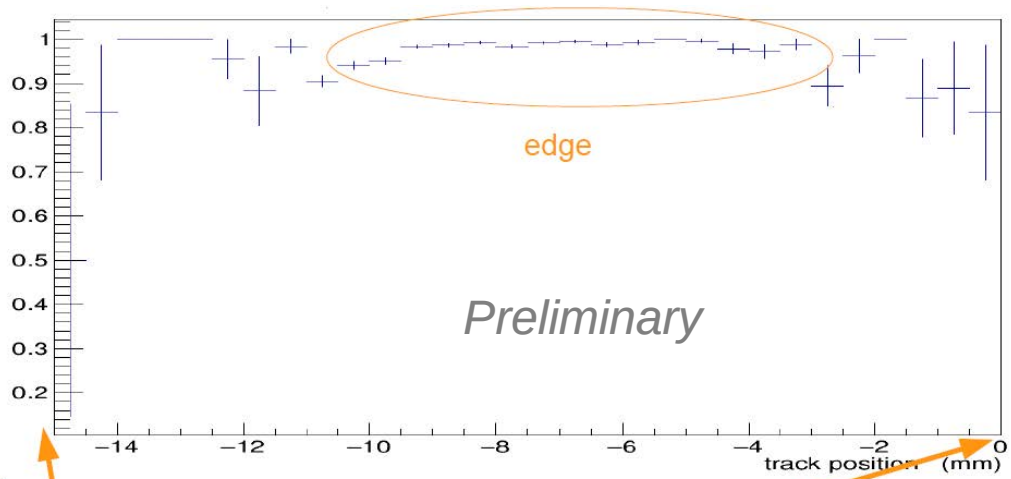
Si strip integration and performance

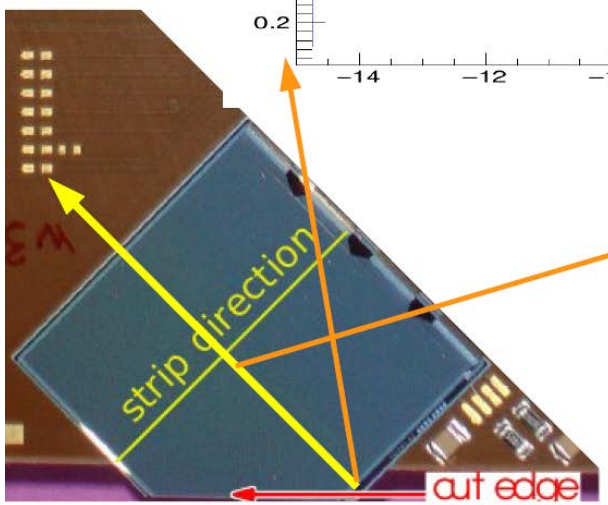
- Si strips integrated in the CMS DAQ

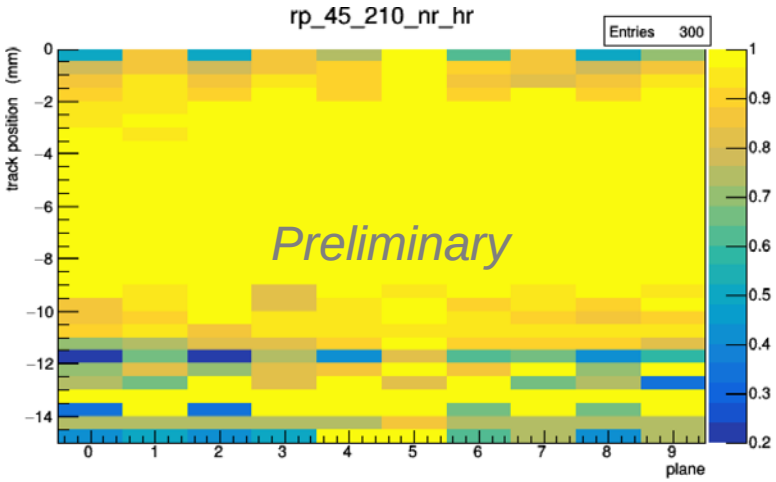
DQM screenshot (example)

Si strip integration and performance

Si strips efficiency



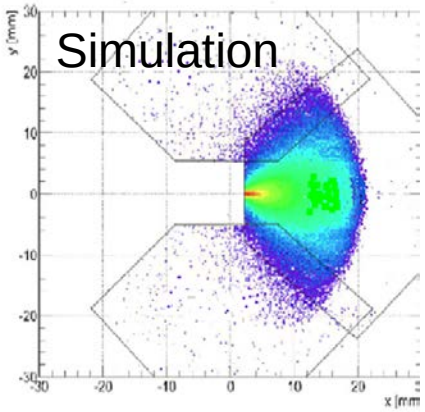


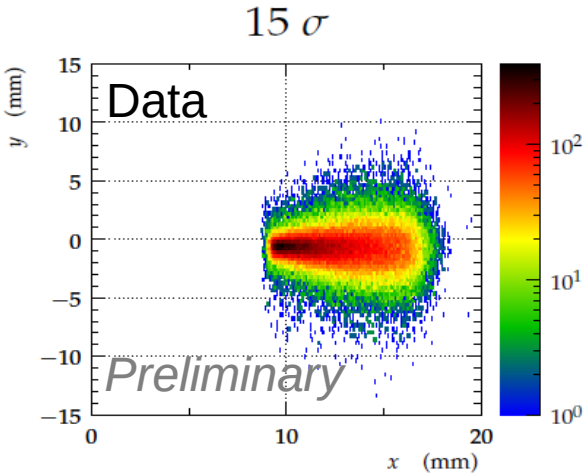


Very good efficiency

Si strip integration and performance

- ~8fb^{-1} data taken
  - Data taking stopped due to radiation damage in the high occupancy region (as expected)
- Hit/track reconstruction performed using consolidated Totem algorithms (software fully integrated in CMS official software)





- Alignment algorithms under test
- Proton kinematics reconstruction still preliminary
  - Alignment
  - Detailed optics knowledge

Current status of the project

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

Towards full CT-PPS

- Tracking
  - 3D pixel tracker on schedule. Installation foreseen during winter shutdown (EYETS)
- Timing
  - Diamond detectors installed
  - UFSD expected to be ready for installation at the end of the year
- Full DAQ and Software integration within the winter shutdown

Conclusions

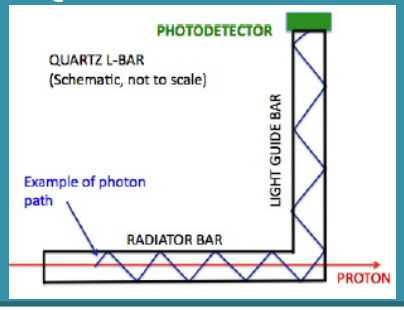
- CT-PPS accelerated program was successful even if there is no 750 GeV resonance
- The integration of Si strips is paying in terms of useful data and expertise
- 8/fb data useful for commissioning and hopefully for physics
- The new detectors are on schedule and expected to be operational beginning 2017
- Data analysis ongoing

Back up

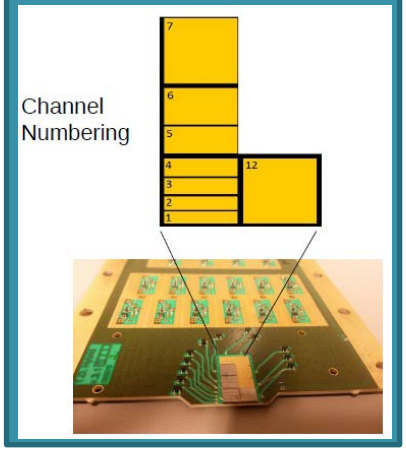
Timing detectors

- QUARTIC detectors
  - Quartz L-bar Cherenkov detectors
  - 3x3 mm^2 bars in a 4x5 array
  - resolution from early test beams σ_T~30 ps (needs to be confirmed)
- Diamond detectors
  - 500 μm thick sensors, 5 mm^2 pads, σ_T ~ 80 ps per plane, better than 50 ps with a package of 4 planes (TOTEM group)
  - variable pad dimensions to optimize occupancy
- Ultra Fast Silicon Detectors
  - Recent beam test results achieve σ_T ~115 ps with 300 μm thickness (N. Cartiglia et al, 2015)
  - expect σ_T ~ 40 ps per plane with 50 μm thick silicon
- Diamonds and UFSD wrt Cherenkov
  - Finer segmentation and hence lower occupancy
  - Thin and light detectors: reduces nuclear interactions and allow for a larger number of layers (which enhances timing resolution)

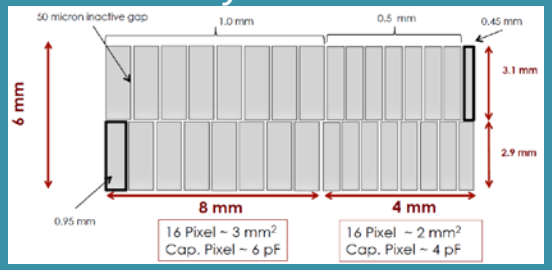
QUARTIC L-bar



Diamond prototype

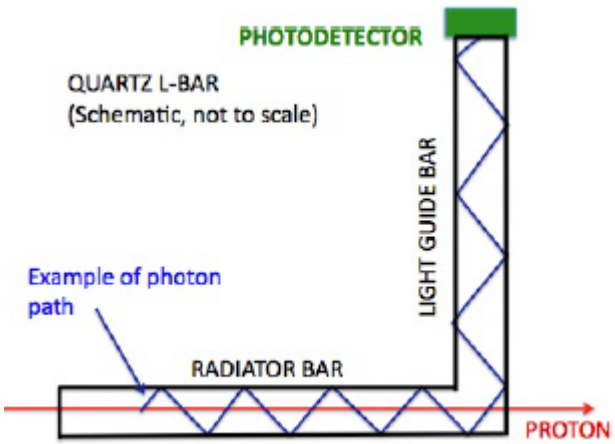


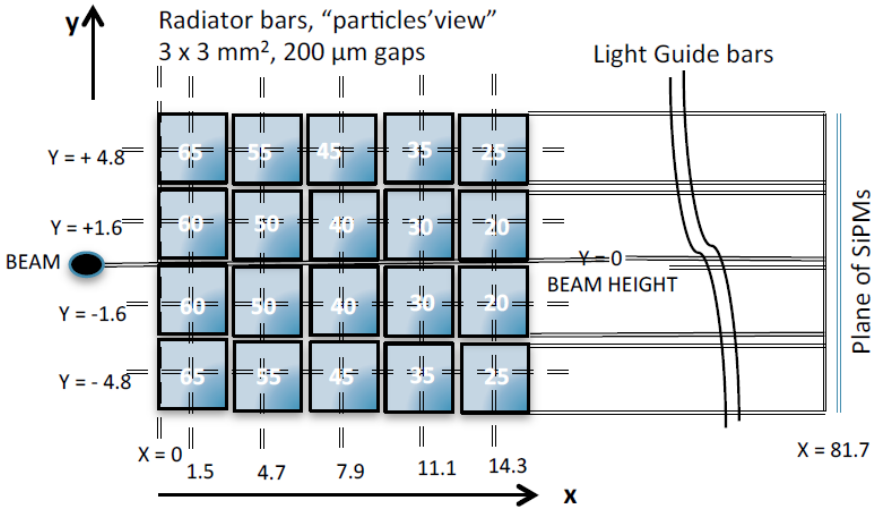
Possible layout of an UFSD

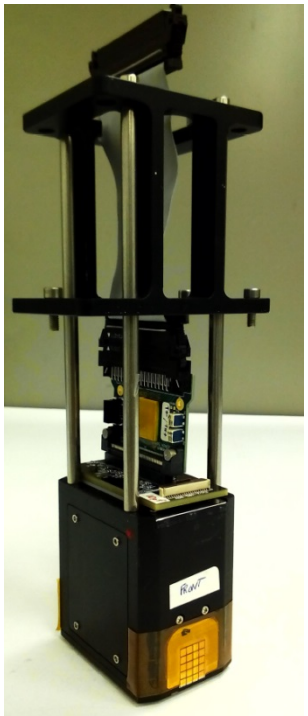


Timing detectors: QUARTIC

- L-bar Cherenkov detectors
- 3x3 mm^2 bars in a 4x5 array
- resolution from early test beams σ_T~30 ps (needs to be confirmed)
- Readout with SiPM, NINO discriminator and HPTDC digitizer







Exclusive WW production

Cuts and cross sections (fb)

Selection	Cross section (fb)			
SM	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

aQGC	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6}\text{GeV}^{-2}$ ($a_C^W = 0$)	$a_C^W/\Lambda^2 = 5 \times 10^{-6}\text{GeV}^{-2}$ ($a_0^W = 0$)
generated $\sigma \times \mathcal{B}(WW \to e\mu\,\nu\bar{\nu})$	3.10±0.14	1.53±0.07
$\geq$ 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
$N_{\text{tracks}} < 10$	0.27 (0.24)±0.03	0.11 (0.10)±0.01