Looking forward:
The Precision Proton Spectrometer

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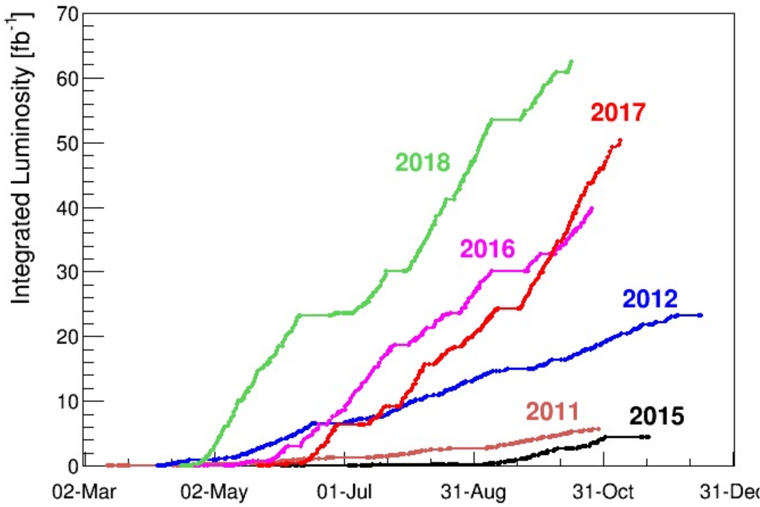
- ✓ Overview
- ✓ Physics motivations
- ✓ Tracking and timing detectors
- ✓ Exclusive dileptons, WW, and prospects
- ✓ Summary

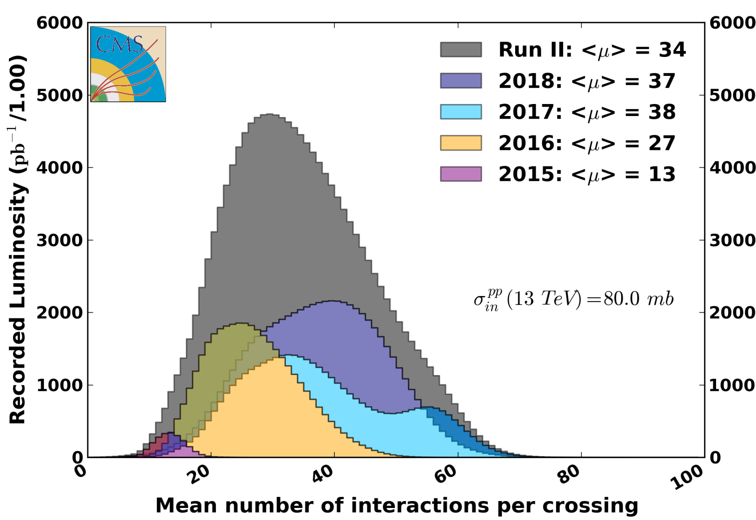
CERN-LHC-2014-021

LHC: from searches to precision

- A hadron collider at full throttle
  - Reaching the energy limit
  - Large datasets
- Moving from searches to precision measurements and rare processes
  - Top quarks and rare decays
  - Higgs couplings and rare decays
  - Anomalous couplings etc.
- Preparing for High-Luminosity (2027 and beyond) with improved detectors
  - Several technological challenges ahead as complexity increases

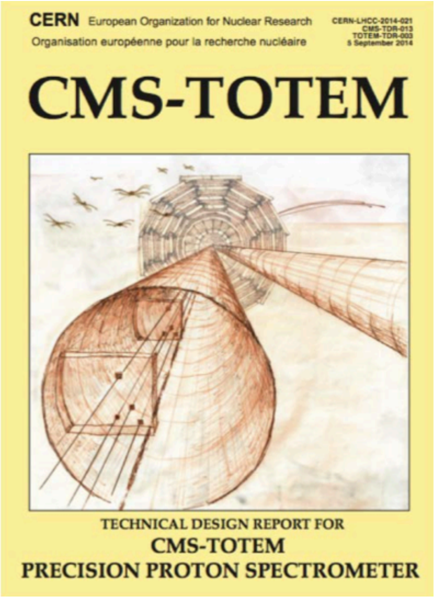


CMS Average Pileup (pp, $\sqrt{s}$=13 TeV)

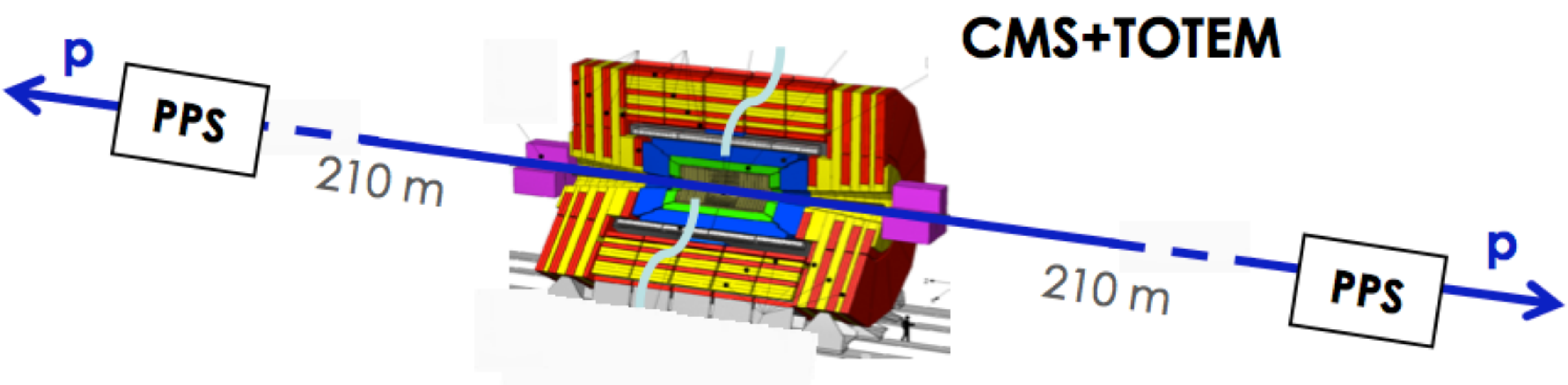


Overview

- 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
- Approved (2014), exploratory phase in 2015, data taking started in 2016, pixels installed from 2017, full detectors in 2018

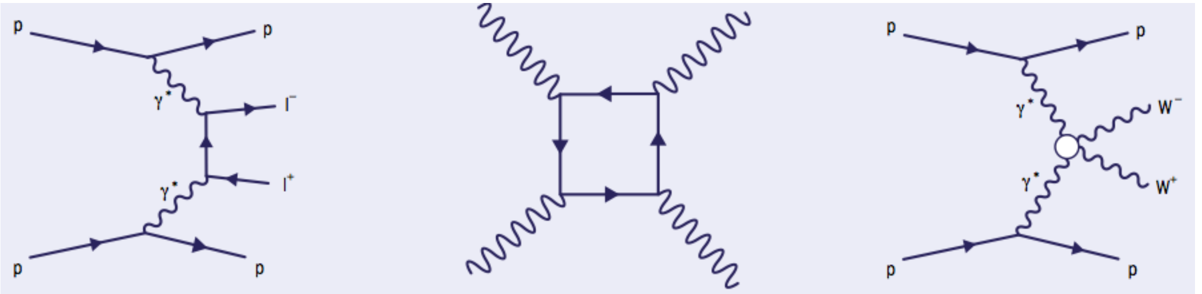


CERN-LHC-2014-021



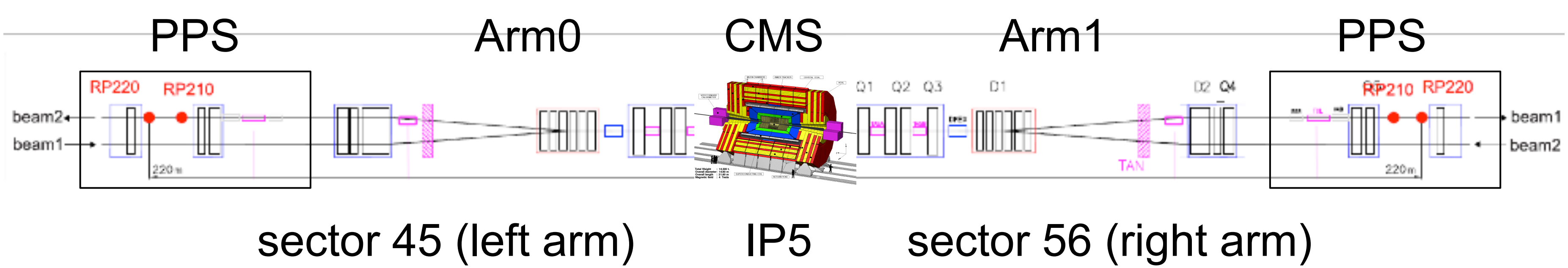
Physics motivations

- Central Exclusive Production
  - photon-photon collisions
  - gluon-gluon fusion in color singlet, $J^{PC}=0^{+}$
- High-mass system in central detector, together with very forward protons in PPS
  - 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 challenges

- Ability to operate the detectors close to beam (15-20σ, i.e. ~1-3 mm) to maximize acceptance for low momentum loss (ξ) protons
- Limit impedance introduced by beam pockets
  - improved RF shielding of RPs
- 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



Data taking

- Successful RP insertions in 2016 at 15σ
- Regular near-beam operation at high-luminosity

2016 – collected ~15/fb

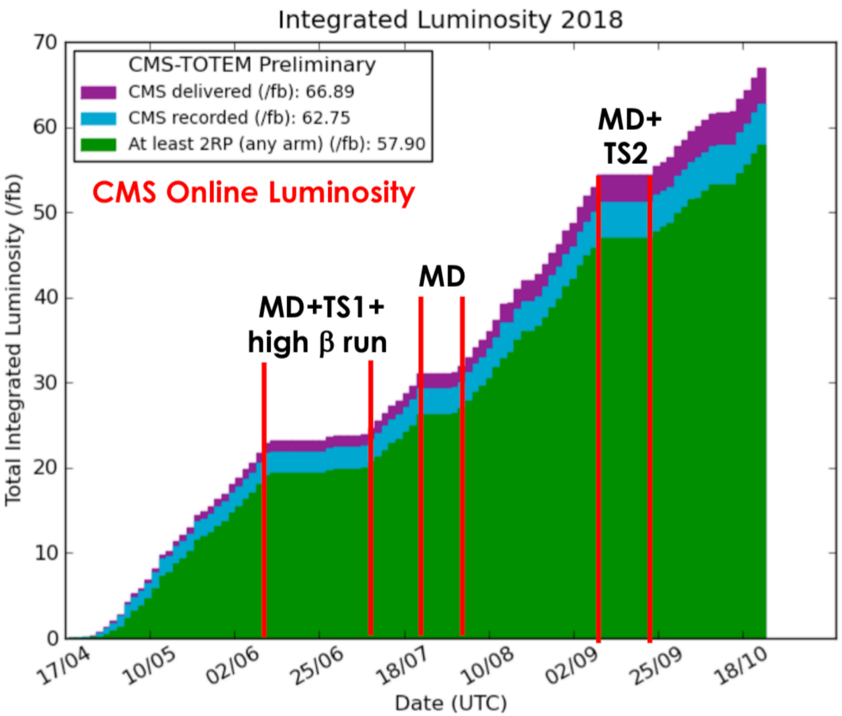
- Silicon strips+diamond

2017 – collected ~40/fb

- Tracking: silicon strips + 3D silicon pixels (first installation in CMS)
- Timing: diamond+UFSD (1[st] time in HEP)
- Detectors fully integrated in central DAQ from first fill

2018 – collected ~60/fb

- full scope with Si pixels+diamonds

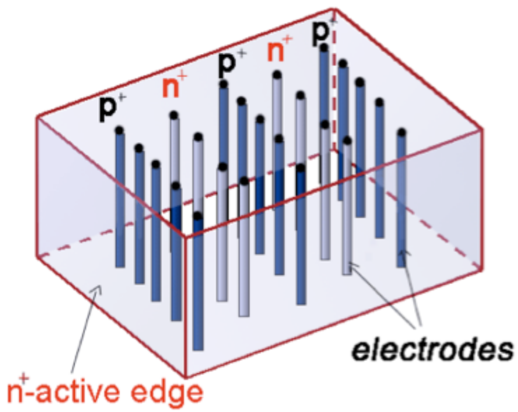


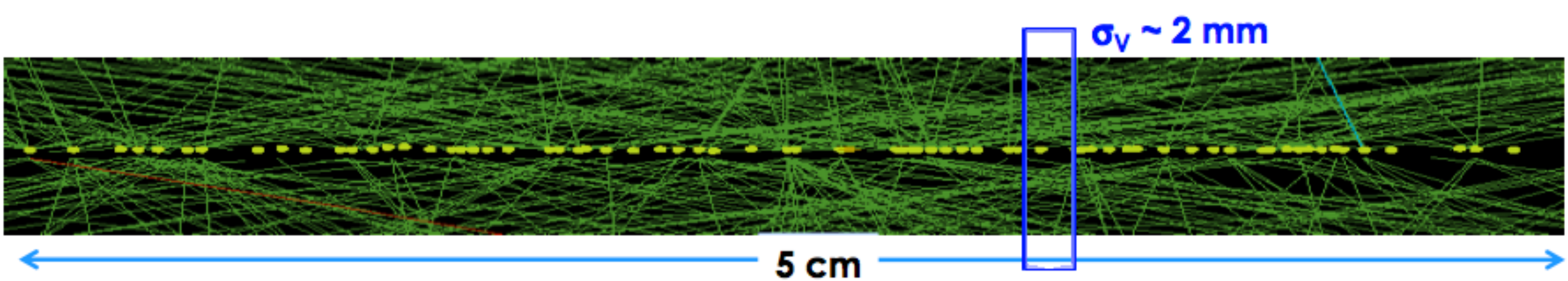
Good stability in 2017/2018 ⇒ integrated luminosity in Run2 ~115 fb^{-1}

Detectors

- Tracking detectors
  - Goal: measure proton momentum
  - Technology: silicon 3D pixels
- Timing detectors
  - Goal: identify primary vertex, reject “pileup”
  - σ_{time}~10ps ⇒ σ_z~2mm
  - Technology: silicon/diamond

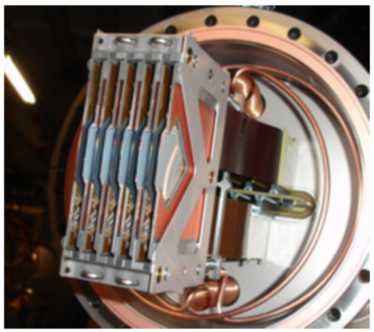
“3D” pixel sensors with columnar electrodes

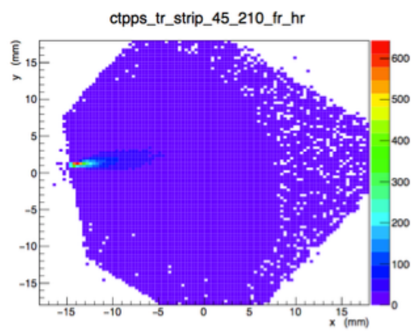




Tracking detectors

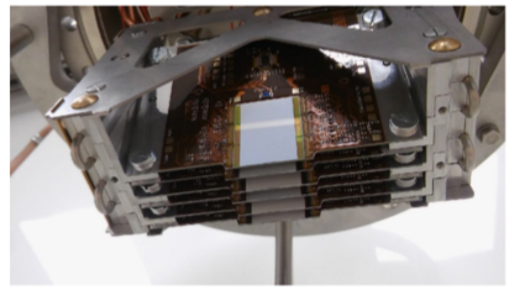
Silicon strips

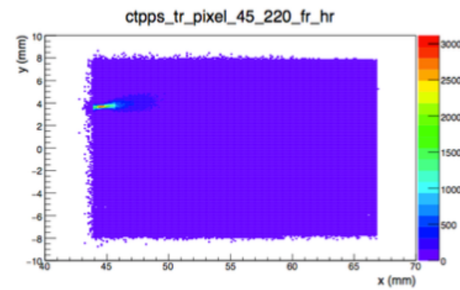




- 10 planes per station of “edgeless” silicon strip detectors (5U+5V)
- Pitch 66μm; track resolution ~12μm
- Designed for low-lumi running
- Used in 2016 and 2017

Silicon pixels

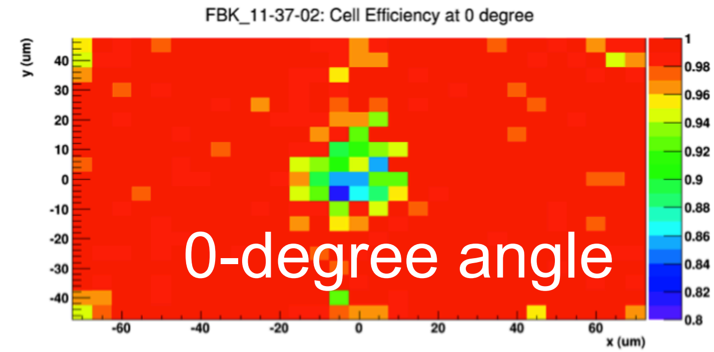


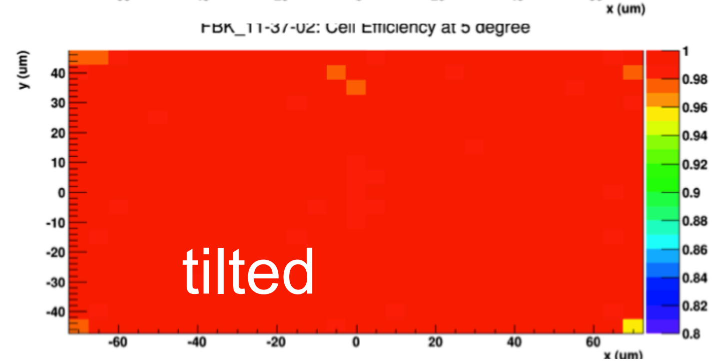


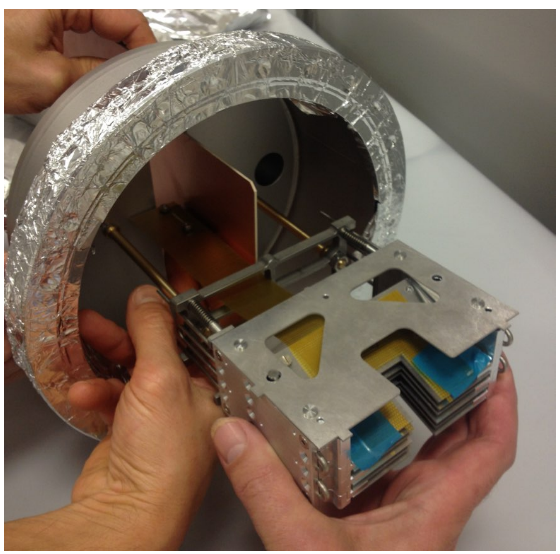
- 6 planes per station of “slim-edge” tilted silicon 3D pixel detectors
- Pixel size 100μm x 150μm; track resolution ~20μm
- Designed for high-lumi running
- Multi-track capability

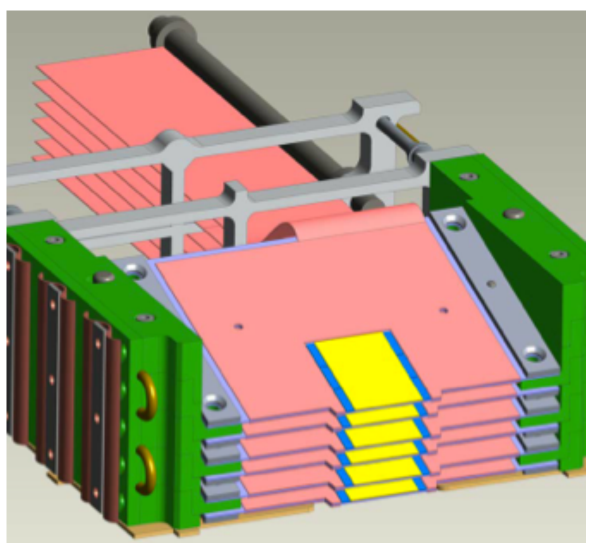
Tracking detectors

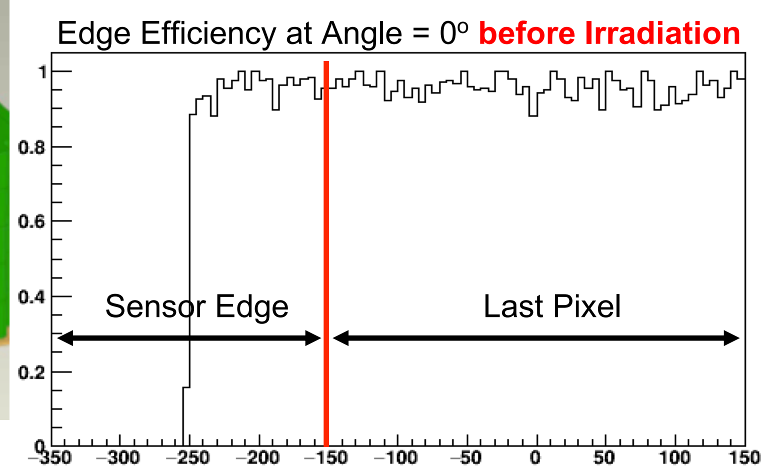
- 3D silicon pixel detectors
- 2 stations per side, 6 detector planes each RP
- Planes tilted to optimize efficiency and resolution
- Thin design studied to minimize impact on beam, insertion in pot, approach to beam
- Designed for high-luminosity running
- Multi-track capability



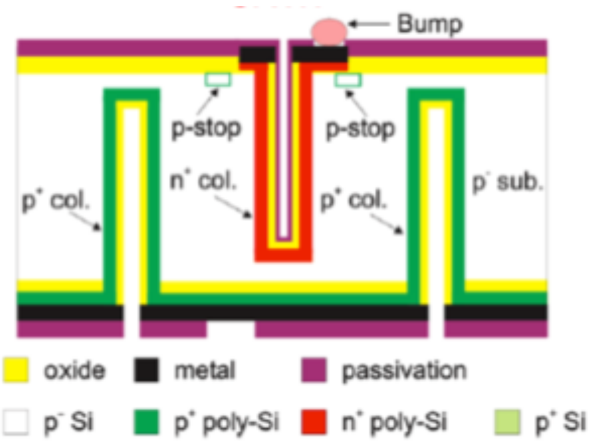






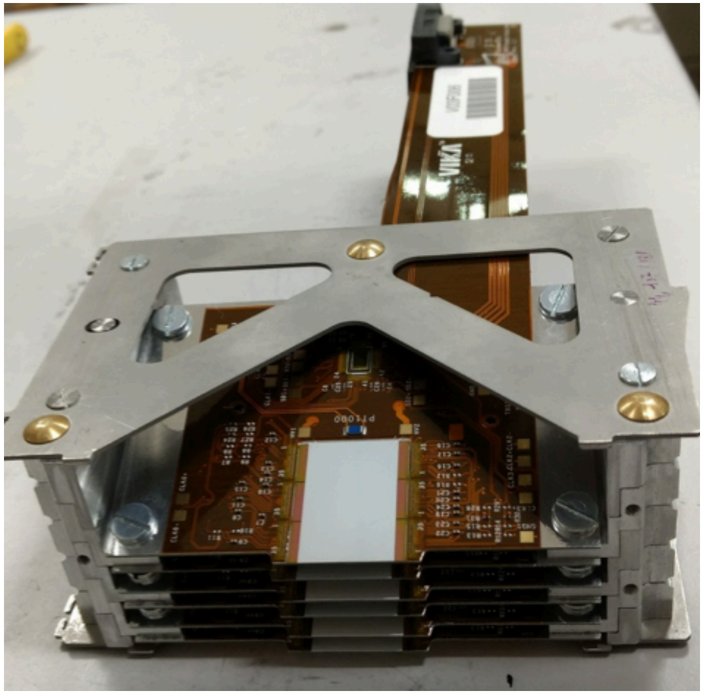


Tracking detectors (cont.)



Sensors:
- 3D sensor technology
- Intrinsic radiation hardness (to withstand overall integrated flux of 5×10^{15} protons/cm^2
- Pixel size 100μm x150μm
- 150μm slim edges (small dead edge to approach beam as close as possible)
- Spatial resolution <30μm

Front-end:
- PSI46dig, same as CMS Pixel Phase 1 upgrade
- Phase 1 DAQ components

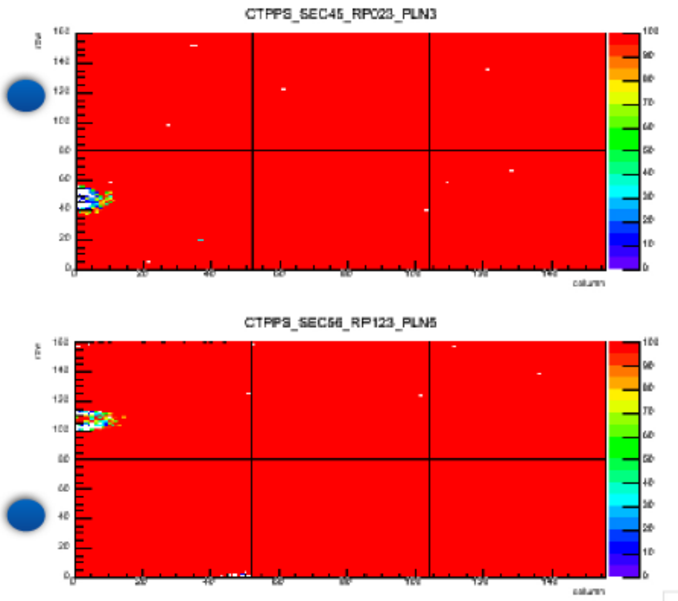


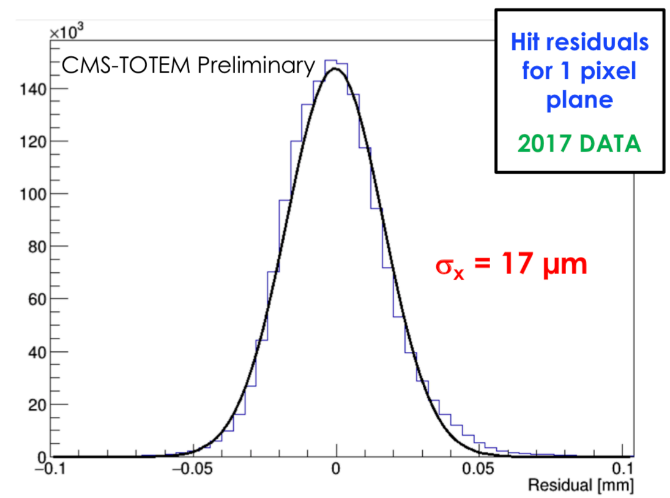
Tracking: status and performance

- Excellent performance of pixel detectors in 2017/2018
  - Track resolutions compatible with expectations
  - Average efficiency above 99%
  - Less than 0.05% bad/noisy pixels
- RP movement and BX shift to cope with radiation
- New detectors installed in 2018 (replacing strip detectors)
- Detector packages swapped btw 45 and 56 to minimize inefficiency

Beam in SEC45

Beam in SEC56

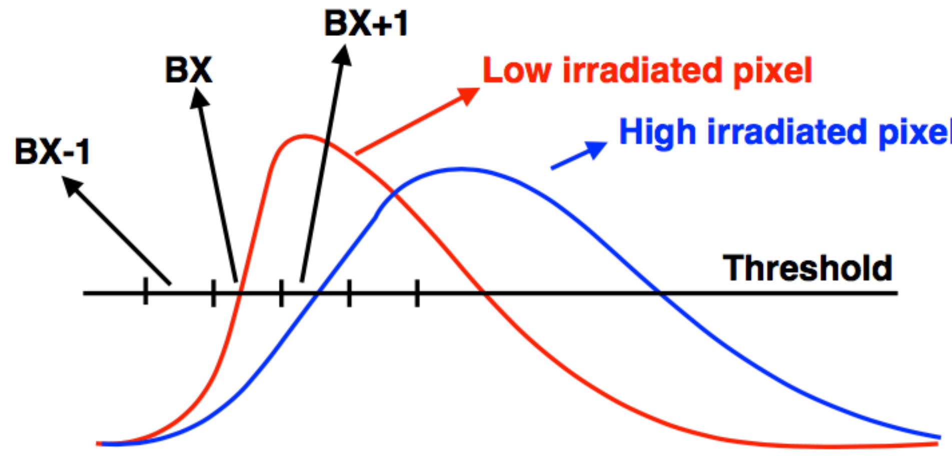


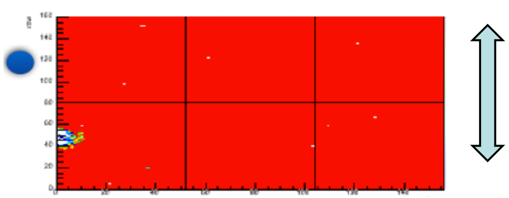


- Excellent spatial resolution, consistent with beam tests
- Single track events ~40%

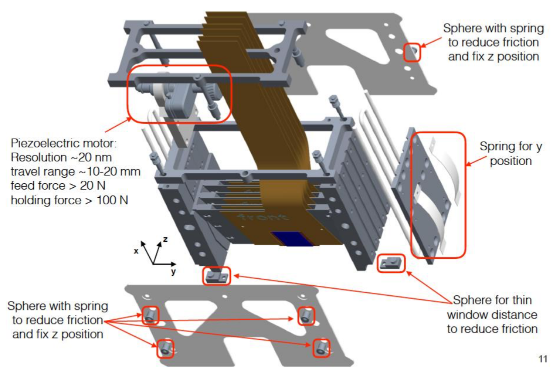
Tracking: Radiation

- Non-uniform irradiation
- Pixels not responding in same BX
- Effect due to readout chip





move up/down

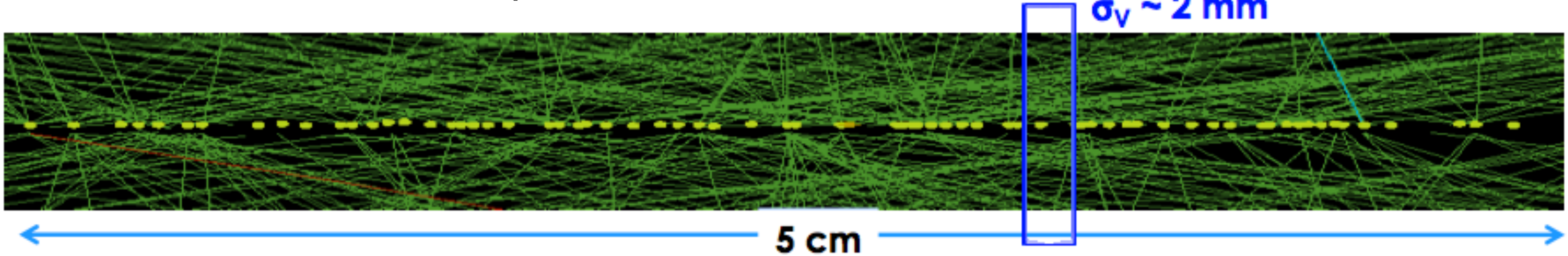


- Localized radiation damage near beam spot after ~10/fb
- Shift detector package to cope with radiation
- New stations with piezoelectric motor connected to detector package

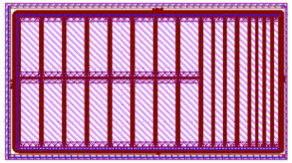
Timing detectors

Time-of-flight measurement to reject pileup bkg (uncorrelated proton tracks)

- Goal: time resolution 20ps ⇒ 4mm

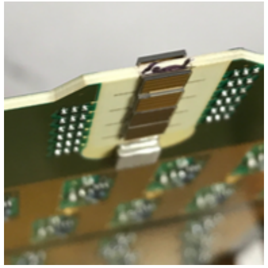


LGAD Silicon



- 1 plane (in 2017) per station
- Pixels of different sizes
- From test beam: single plane resolution ~30ps
- R&D to improve radiation hardness

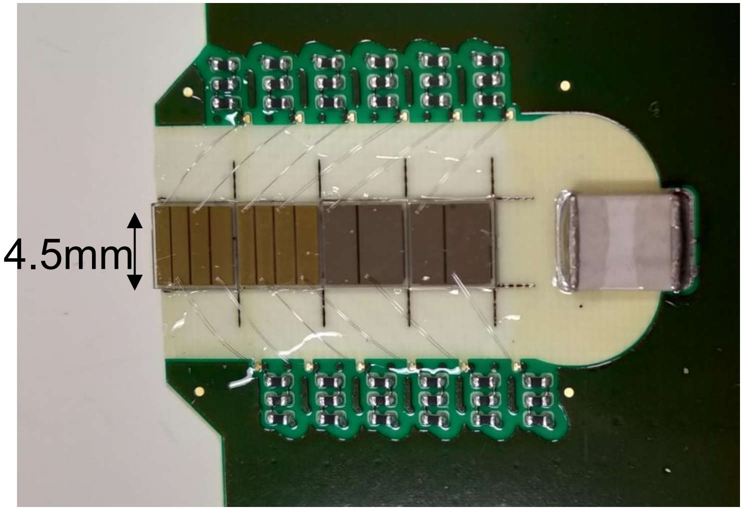
Diamonds

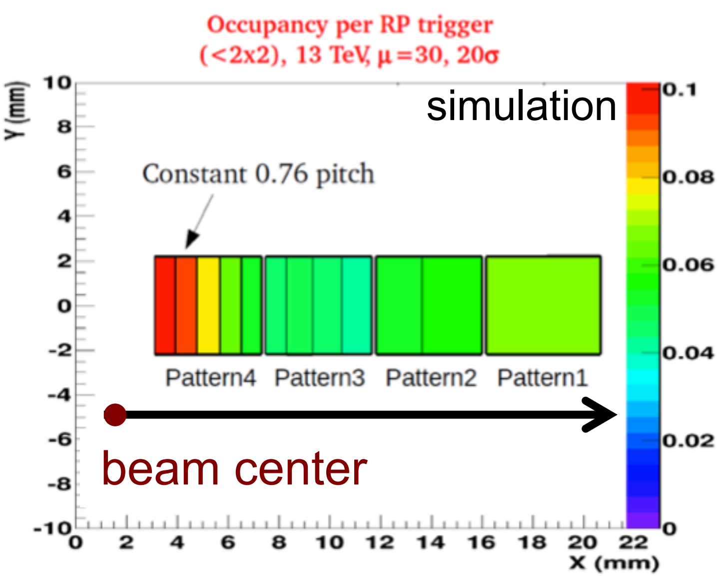


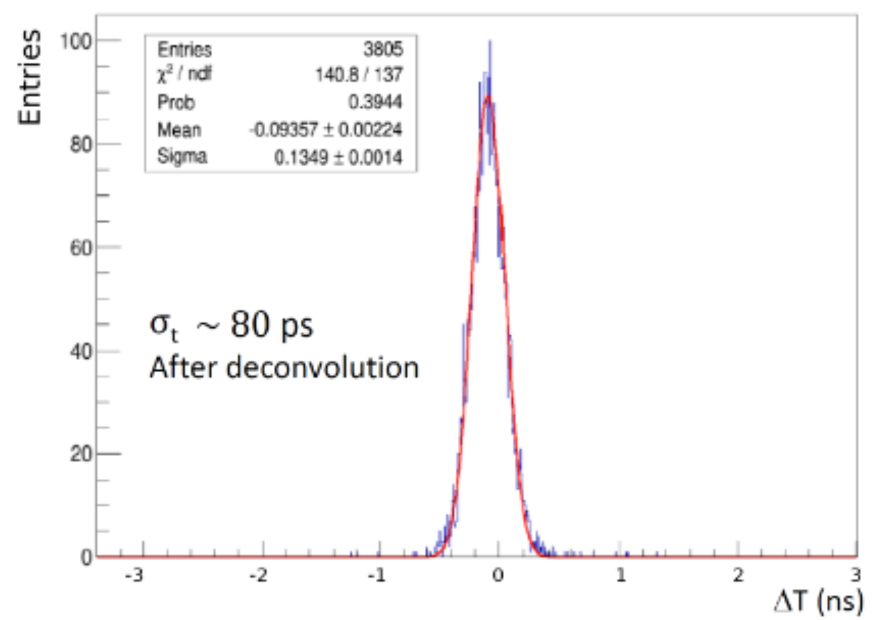
- 4 planes per station
- Pixels of different sizes
- Single plane resolution ~80ps
- Radiation hard

Diamond detectors

- Diamond detectors
  - Sensors based on single crystal CVD diamonds
  - σ_T~80ps per plane, i.e. ~50ps with 4 planes
  - Four 4x4mm^2 sensors per plane
  - Variable pad dimensions to optimize occupancy
- Custom-made readout electronics
- Intrinsic radiation hardness



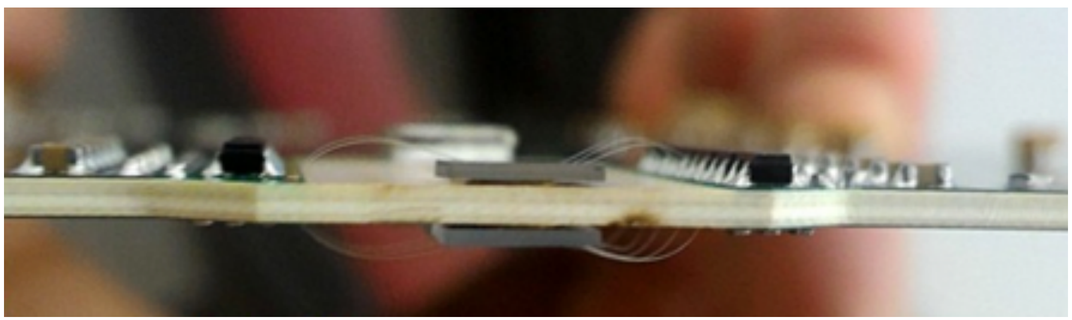


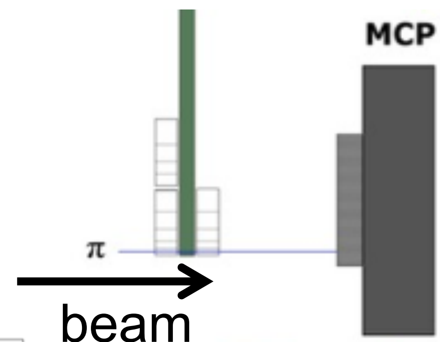


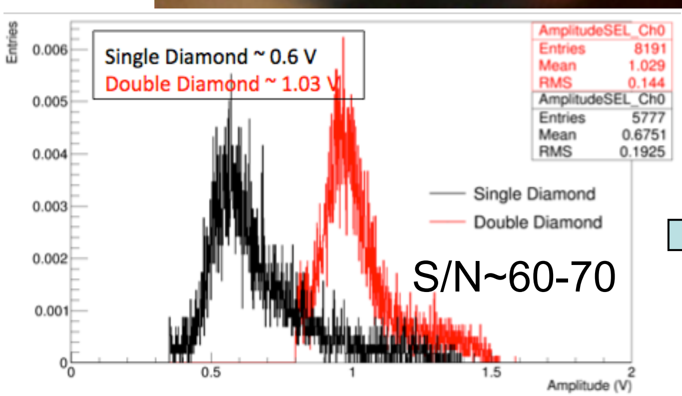
Double diamond layer

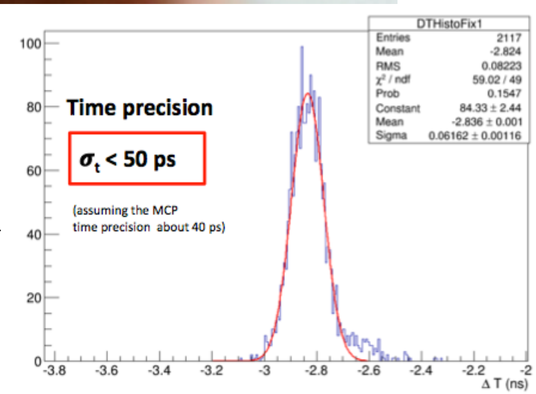
JINST12(2017)P03026

- Connected “sandwich” with two diamond sensors
- Beam tests in 2016/2017
- Performance improved (a factor of 1.7 wrt SD)
  - Larger signal amplitude dominant over extra capacitance
- With 4 diamond sandwich-planes could reach 25 ps



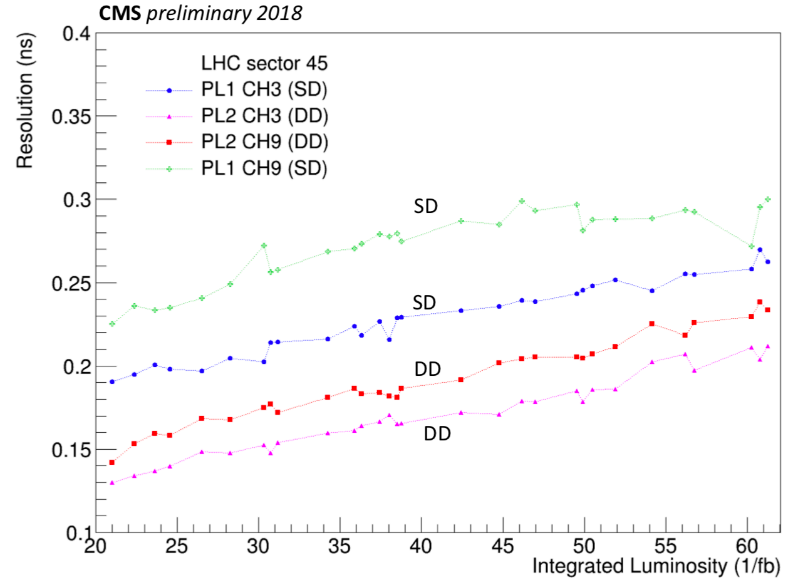


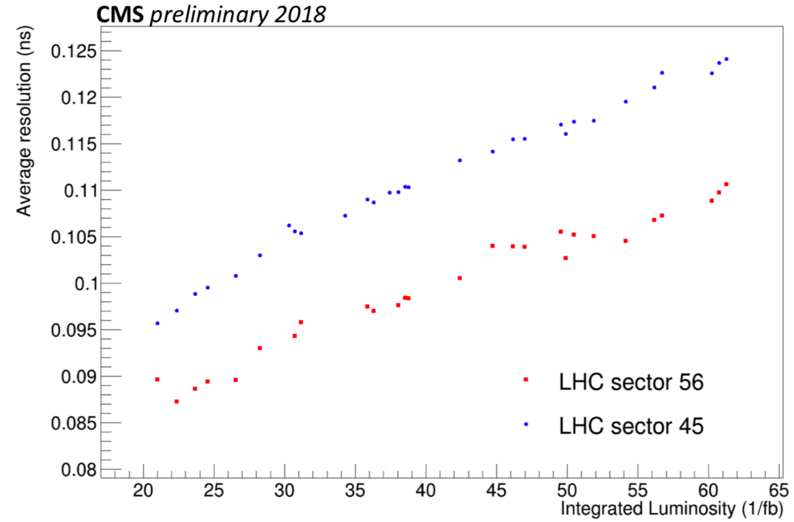




Timing: operation & calibration

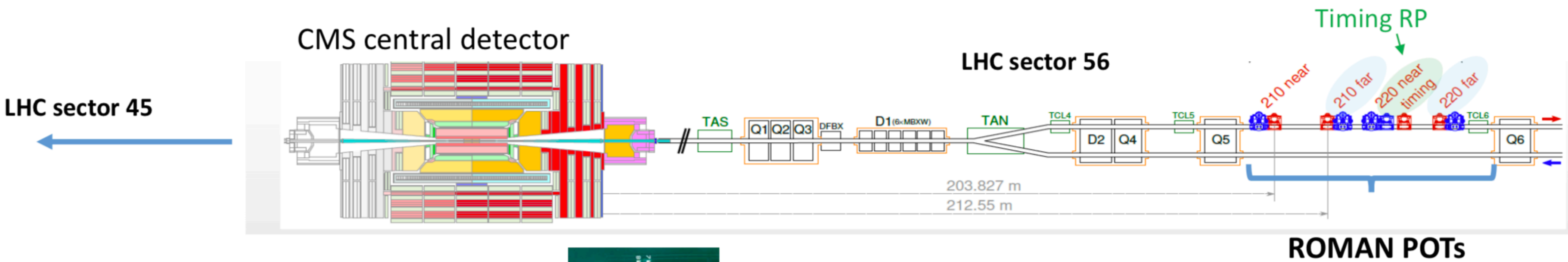
- Timing detectors installed in late 2016
  - Integrated luminosity in Run2 with timing ~100/fb
- Calibration
  - Correction of measured arrival time wrt ToT for each channel, independently
- Two types of degradation identified
  - due to radiation damage on sensors and electronics (pre-amp stage) close to beam
  - Localized damage on sensor in the most irradiated area (~1mm^2)
  - Can recover by raising LV on pre-amp stage (remote)
- Better resolution of DD by a factor of 1.7





The PPS detector

Symmetric experimental setup wrt interaction point



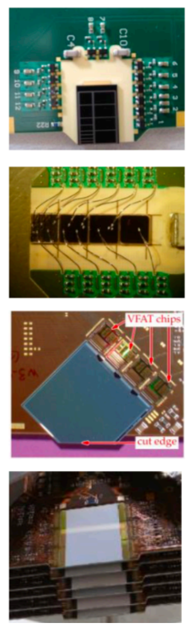
Sensors in Run 2

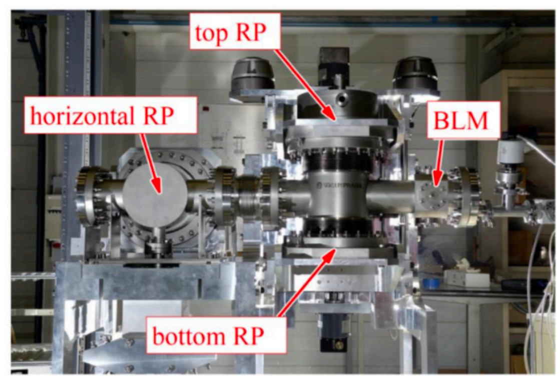
Timing

2016: 4 single diamond planes(SD)
2017: 3 single diamond and 1 UFSD planes
2018: 2 single and 2 double (DD) diamond planes

Tracking

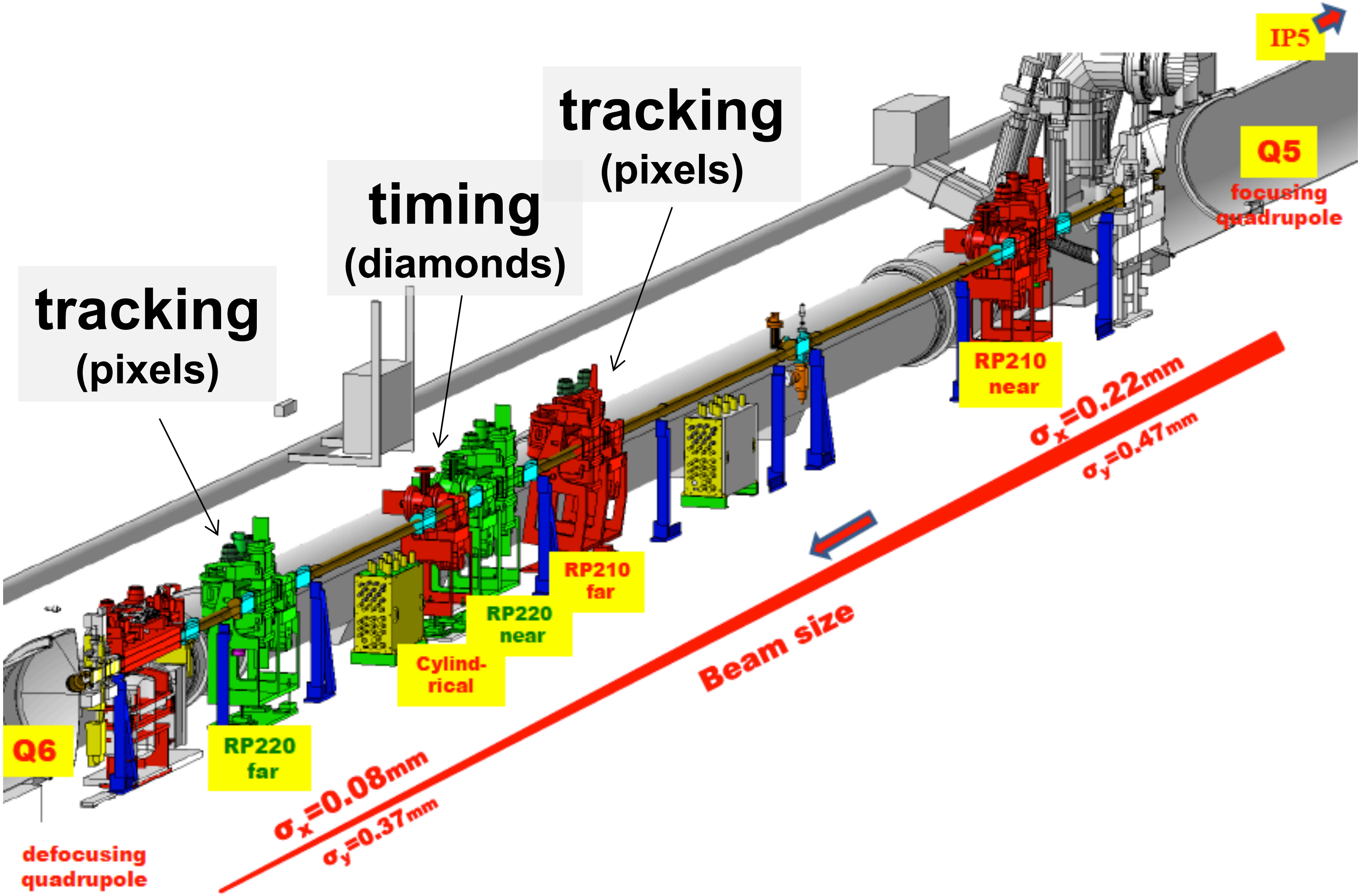
2016: 2 TOTEM strip detector stations
2017: 1 strip and 1 3D pixel stations
2018: 2 3D pixel stations



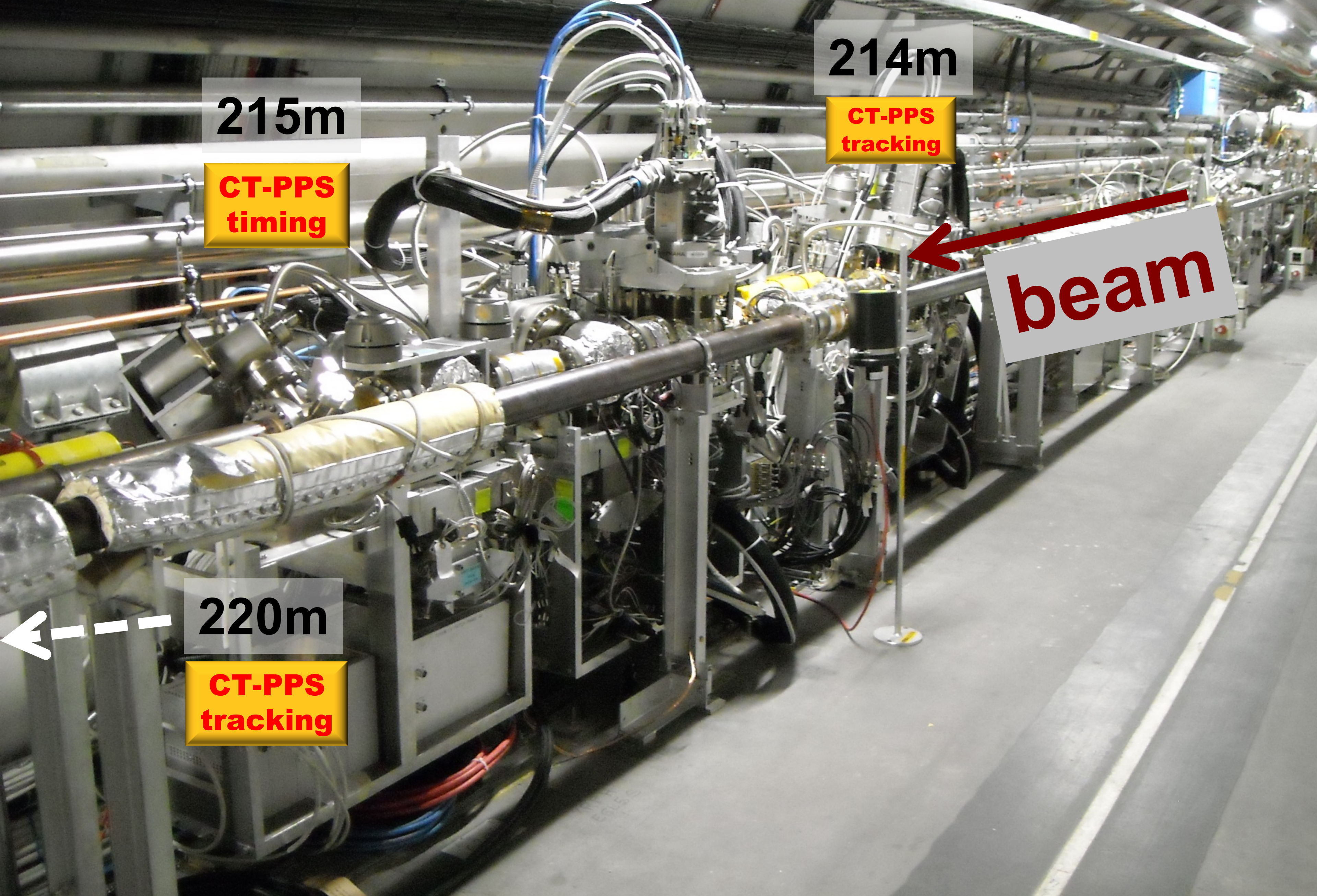


RP: Vacuum vessel entering the beam pipe, can be equipped with many types of detectors. Hosted detectors brought to few mm from LHC beam center.

PPS in 2018

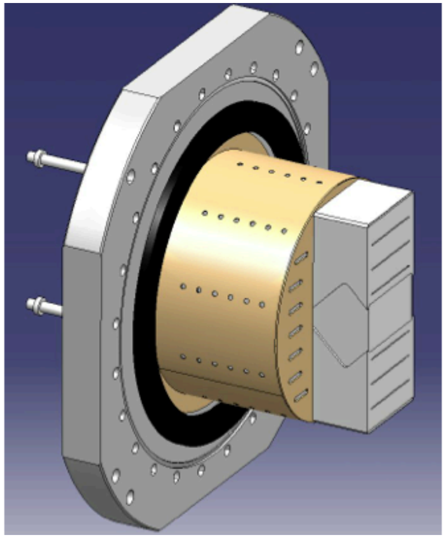
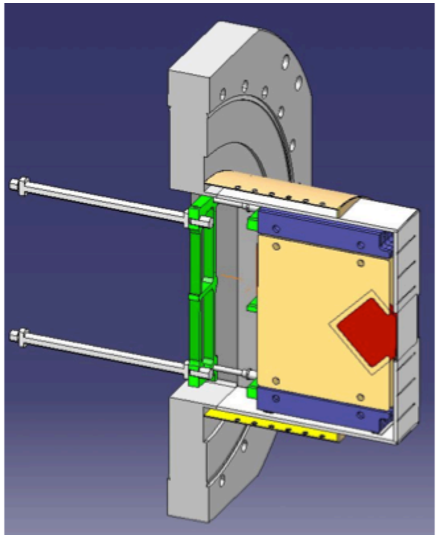
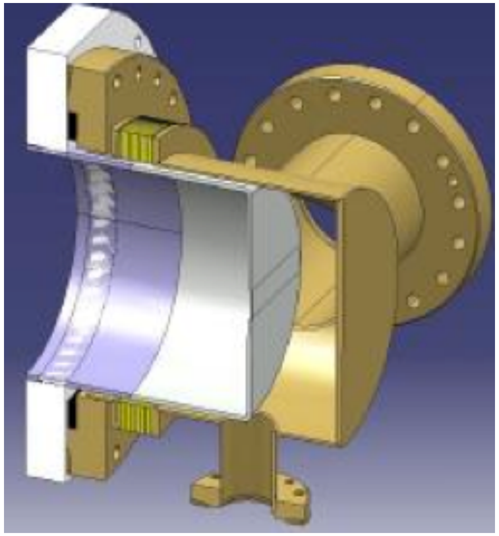

IP5
Q5
focusing quadrupole
tracking
(pixels)
timing
(diamonds)
tracking
(pixels)
RP210
near
RP210
far
RP220
near
Cylind-
rical
RP220
far
Q6
defocusing quadrupole
σx=0.22mm
σy=0.47mm
Beam size
σx=0.08mm
σy=0.37mm

LHC tunnel @ PPS location

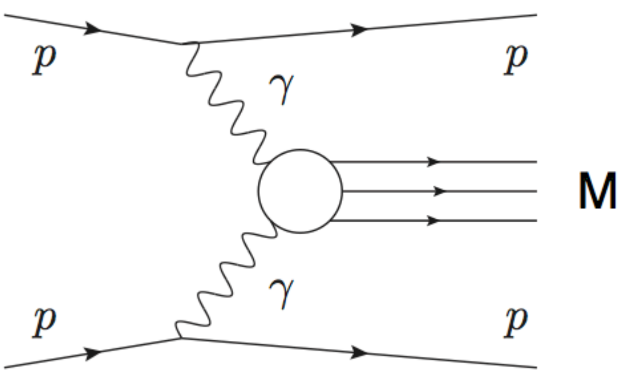


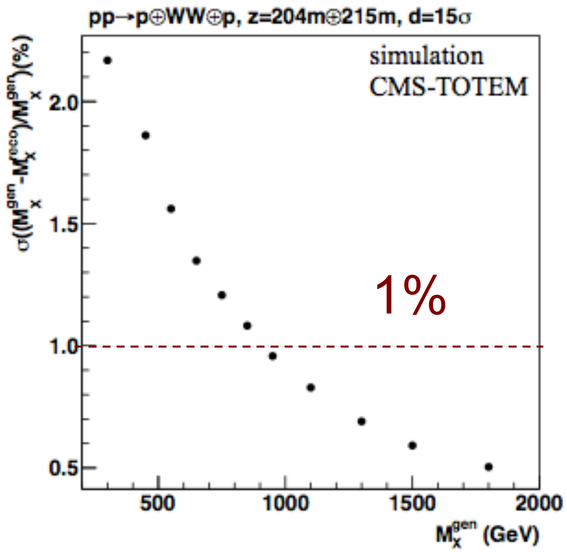
Roman Pot insertion

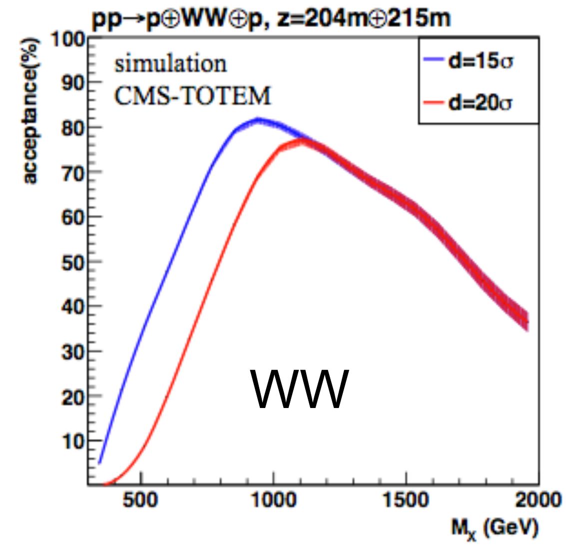
- Insertion procedure validated in 2016 by the LHC
  - Improvements carried out wrt earlier versions (RF shielding, cylindrical pots, ferrite, copper coating)
- Minimum distance of approach dramatically affects detector acceptance and physics reach
- A few mm (~15σ) from beam in nominal high-luminosity runs
  - Monitor beam losses, showers, interplay with collimators, beam impedance (heating, vacuum and beam orbit stability)

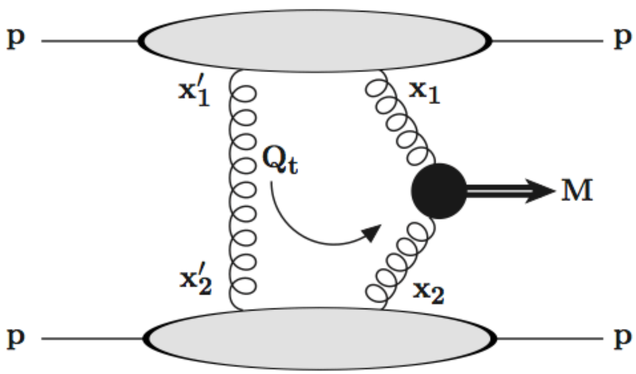




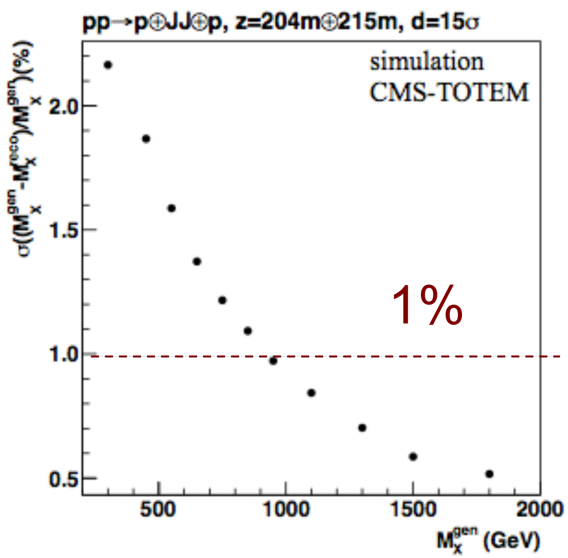
Mass acceptance and resolution

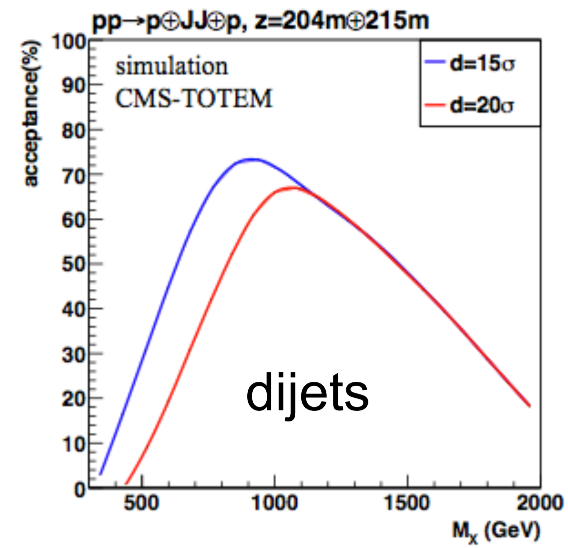




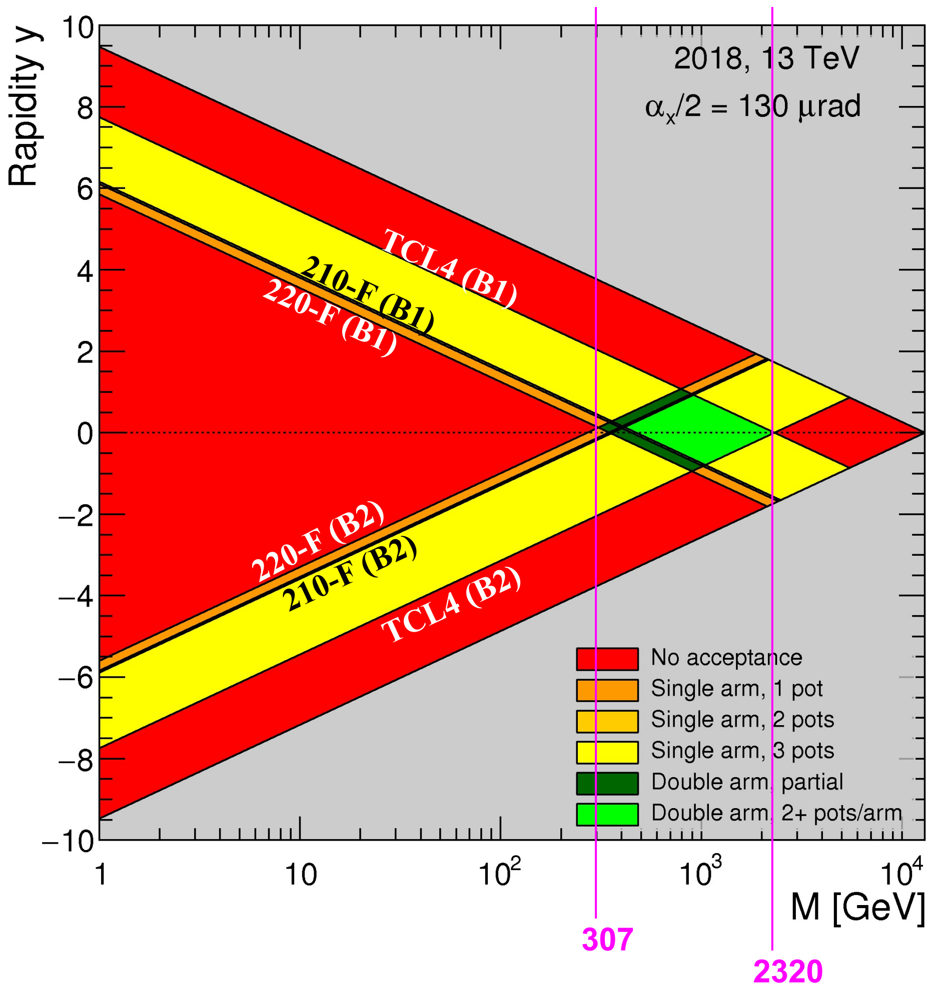


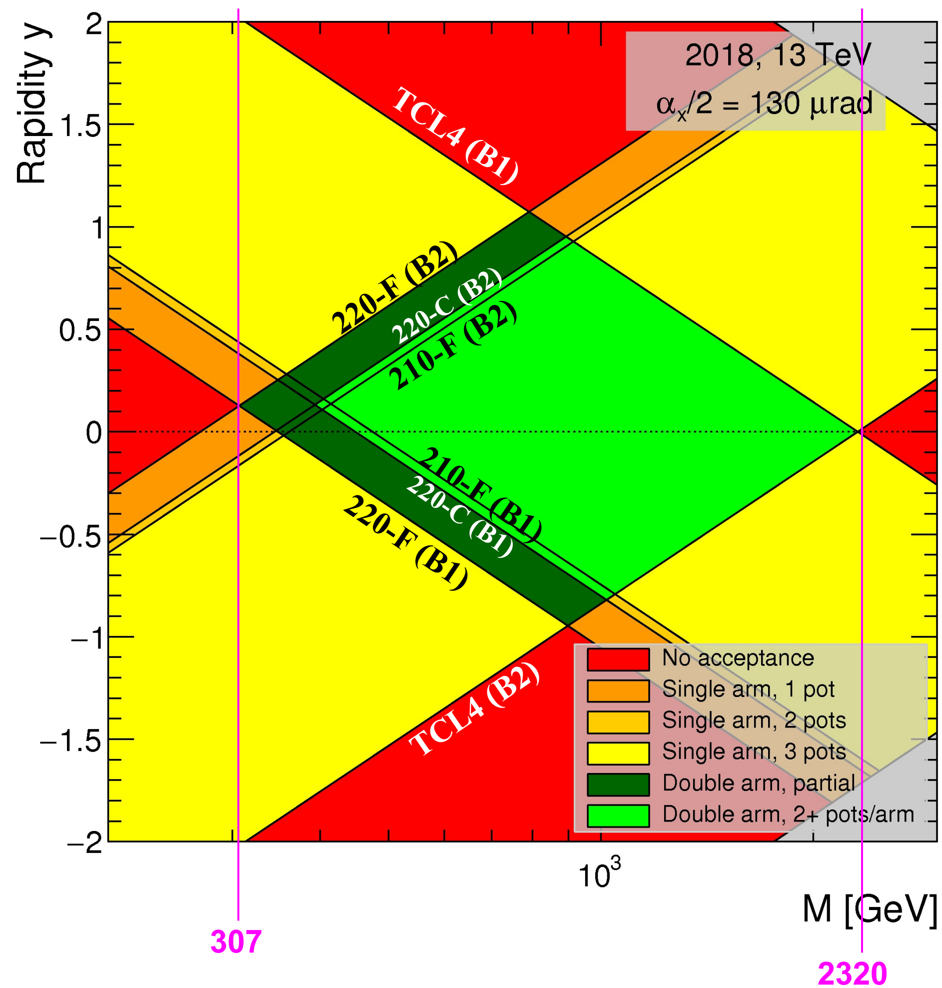






RP Acceptance in 2018



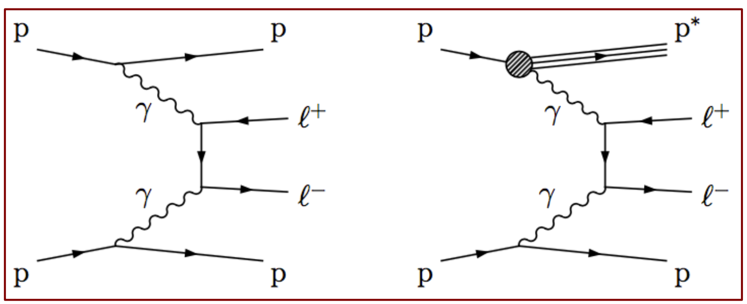


Exclusive dilepton production

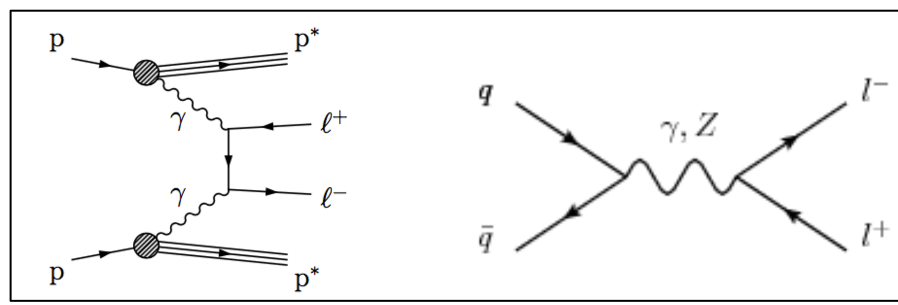
arXiv:1803.04496

- Exclusive processes at the EWK scale
- Study SM candle process: $\gamma\gamma\rightarrow\ell\ell$
- Observation of $\gamma\gamma$ interaction with proton tag
  - Single arm selection to enhance statistics at low m($\ell\ell$)
  - Signal includes both exclusive and SD production

signal



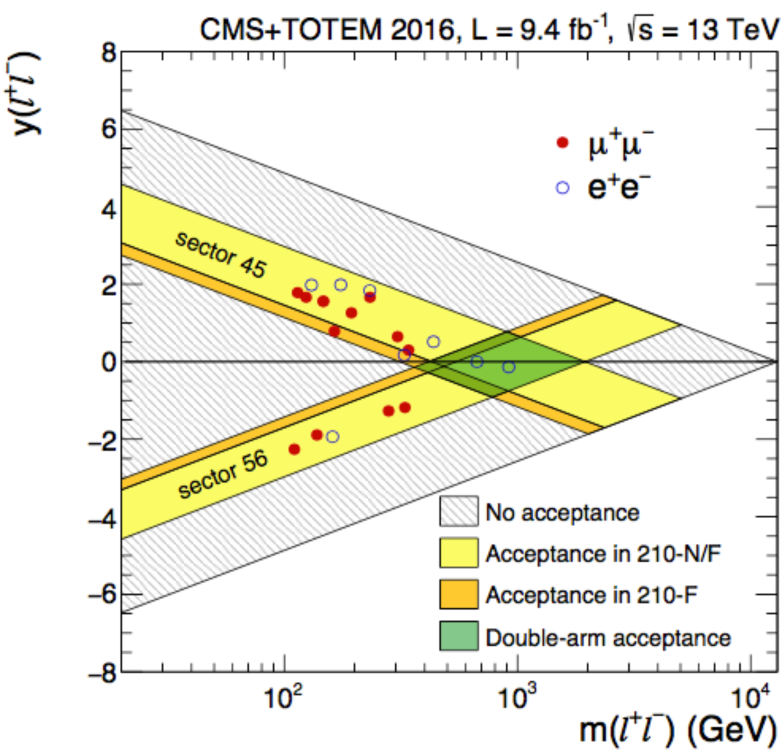
bkg: overlapping with PU protons or beam bkg

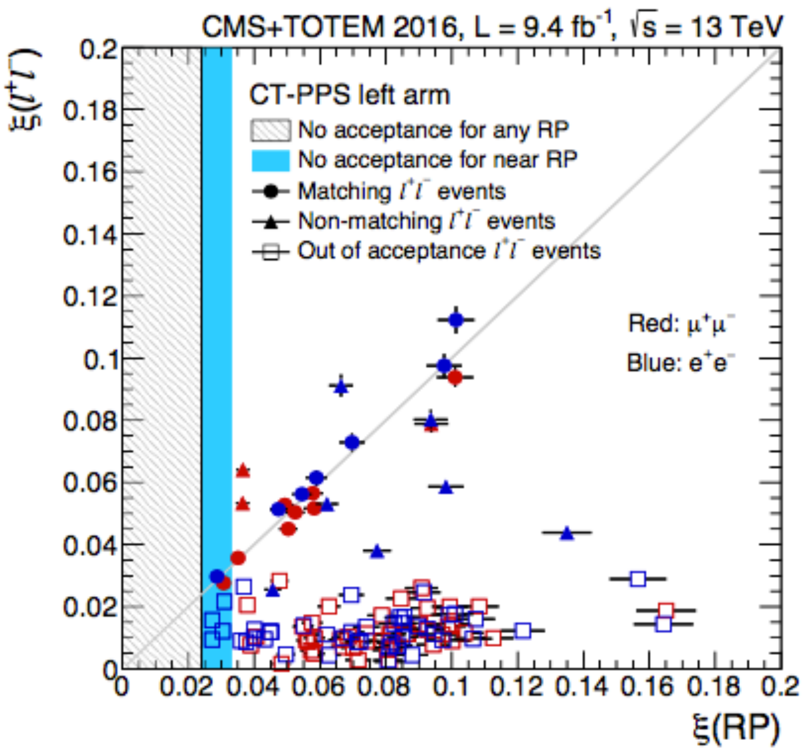


Exclusive dilepton production

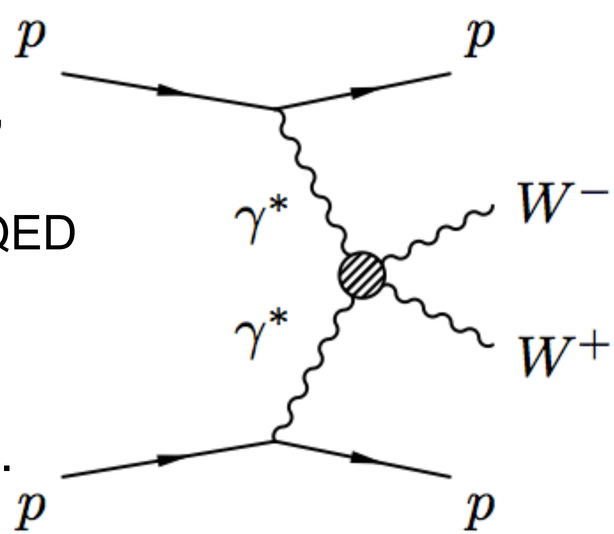
arXiv:1803.04496

- Correlation between the ξ values in central system vs PPS
- 12 μμ, 8 ee candidates observed (>5σ over expected bkg)
  - Mass and rapidity distribution consistent with single-arm acceptance
  - Highest mass candidate >900 GeV

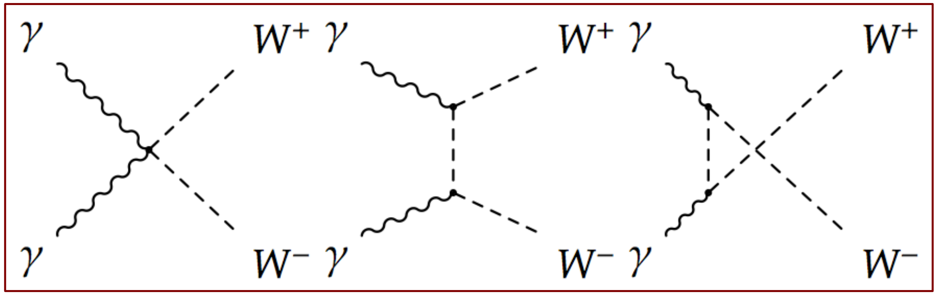




Prospects: WW production

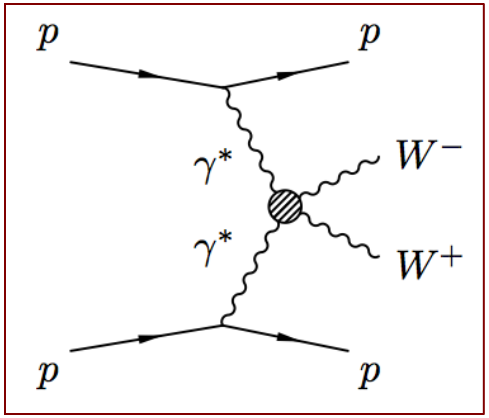


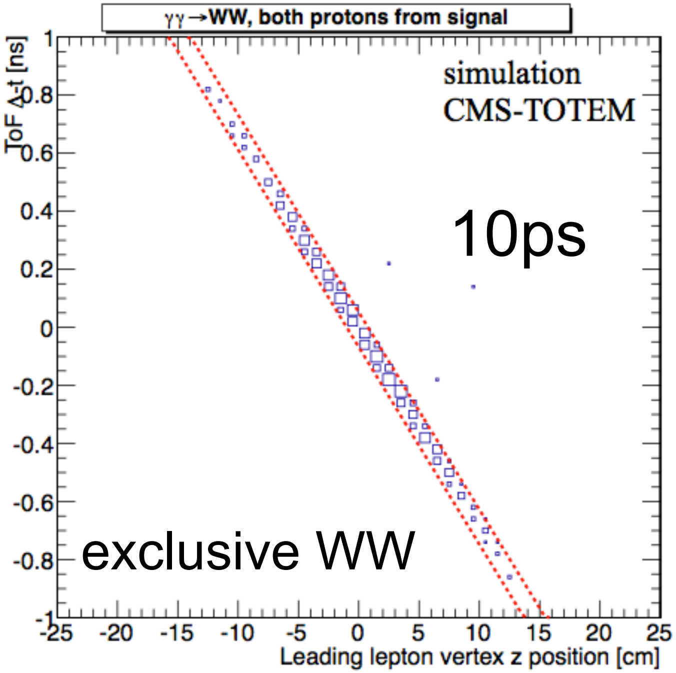
- pp→pWWp
  - Clean process: W in central detector and “nothing” else, intact protons can be detected far away from IP
  - Exclusive production of W pairs via photon exchange: QED process, cross section well known
- Backgrounds:
  - inclusive WW, $\tau\tau$, exclusive two-photon $\gamma\gamma \rightarrow \ell\ell$, etc.
- Events:
  - WW pair in central detector, leading protons in PPS
- SM observation of WW events
- Anomalous couplings
  - predicted in BSM theories
  - parameters: a_0^W/Λ^2, a_C^W/Λ^2
- Deviations from SM can be large

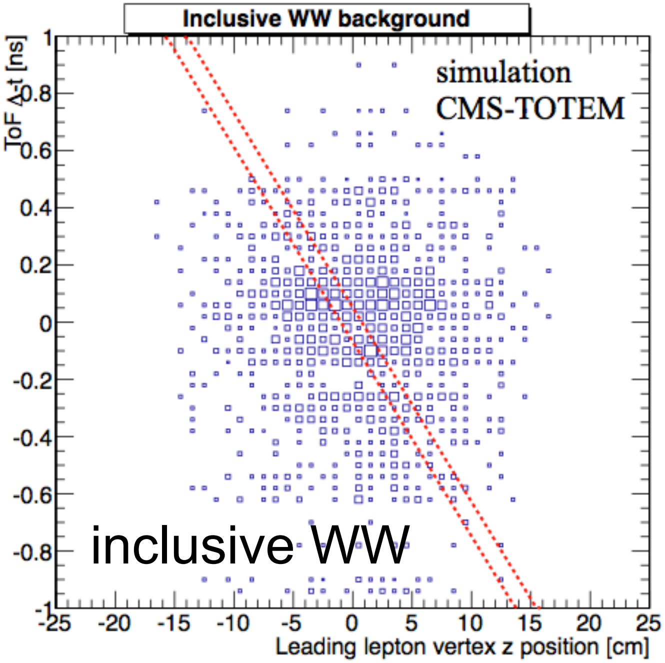


Prospects: anomalous couplings

- Allowed in SM via charged triple and quartic gauge couplings
- Sensitive to BSM contributions in high-mass tails







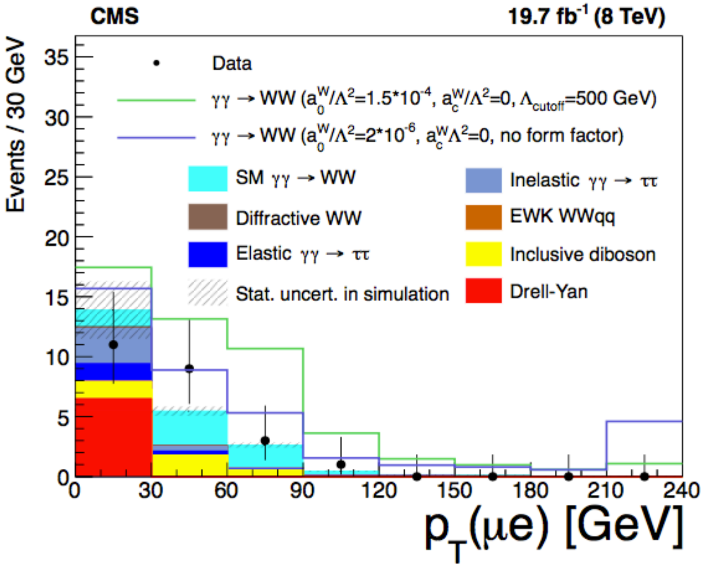
- Leptonic channels cleanest, but neutrinos prevent clear mass/rapidity matching
- time difference of two protons correlated with vertex position

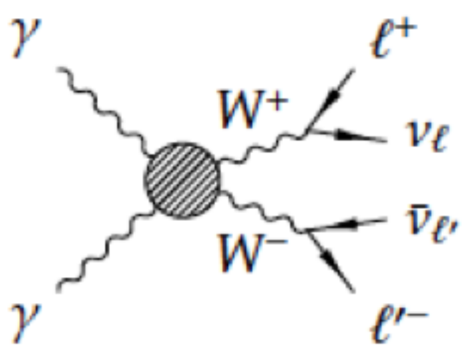
WW production: Selection

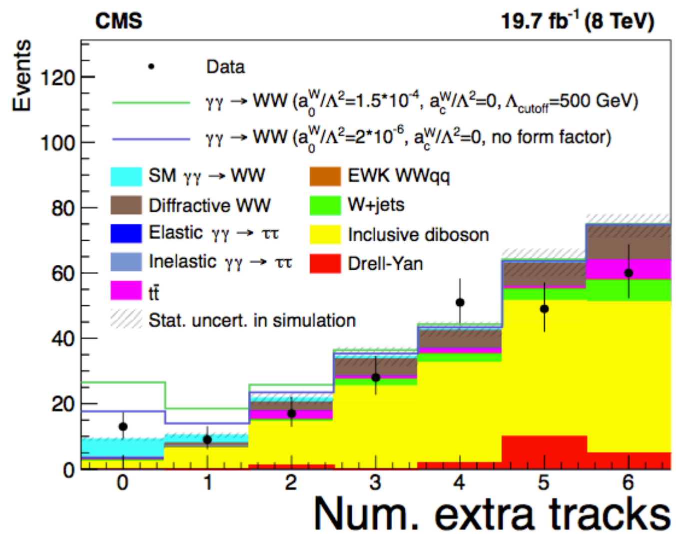
arXiv:1604.04464

Run 1 results w/ no proton tagging

- 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
- AQGC search
  - $p_T(\mu e)$=30-130GeV
  - $p_T(\mu e)$>130 GeV







WW production: Results

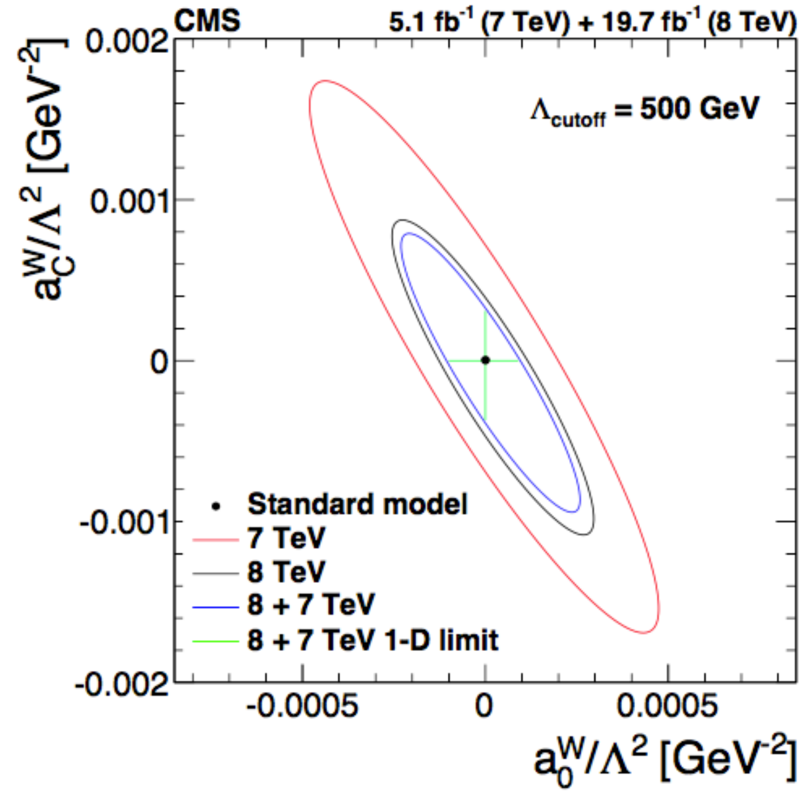
arXiv:1604.04464

- Cross section measurement

$$\sigma_{meas} = 10.8^{+5.1}_{-4.1}\ fb$$

- SM prediction is σ=6.9±0.6 fb
- Observed significance above background-only hypothesis: 3.4σ

process	yields
inclusive dibosons	2.3 ± 0.4
Drell-Yan	0.1 ± 0.1
$\gamma\gamma \to \tau\tau$	0.9 ± 0.2
other backgrounds	0.6 ± 0.1
total backgrounds	3.9 ± 0.5
signal (SM exclusive WW)	5.3 ± 0.1
data	13



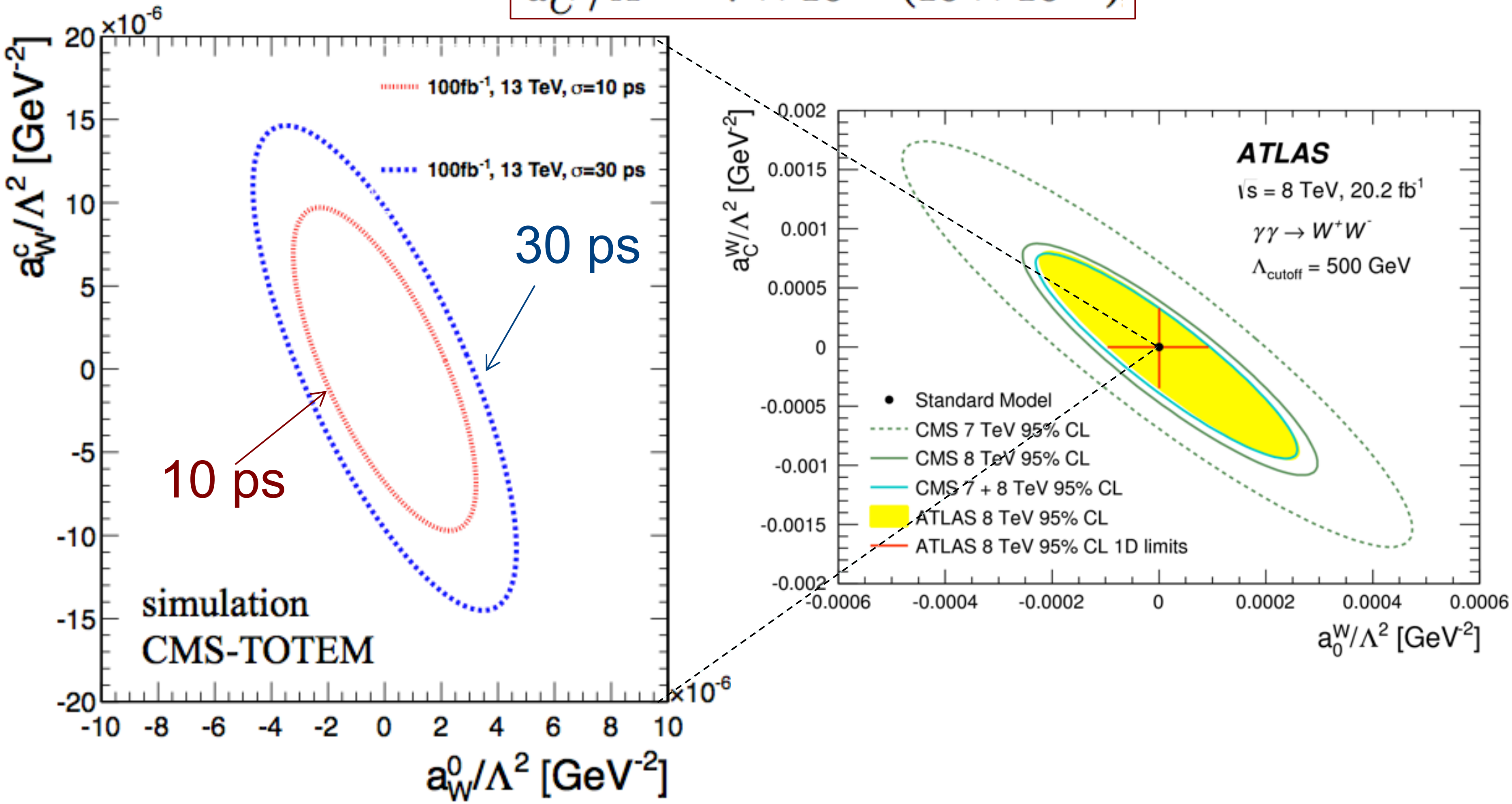
- AQGC results
  - 95%CL limits on a^W_C/Λ^2, a^W_C/Λ^2
  - Improvement of two orders of magnitude over LEP/Tevatron

AQGC expected limits

arXiv:1607.03745

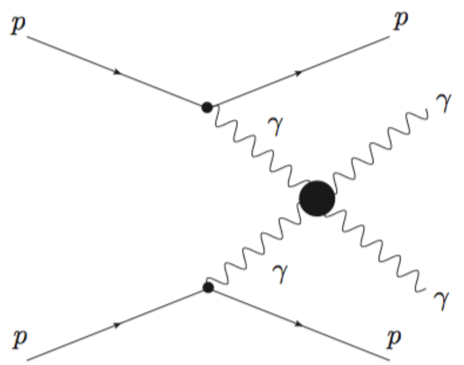
Expected limits @95%CL:

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

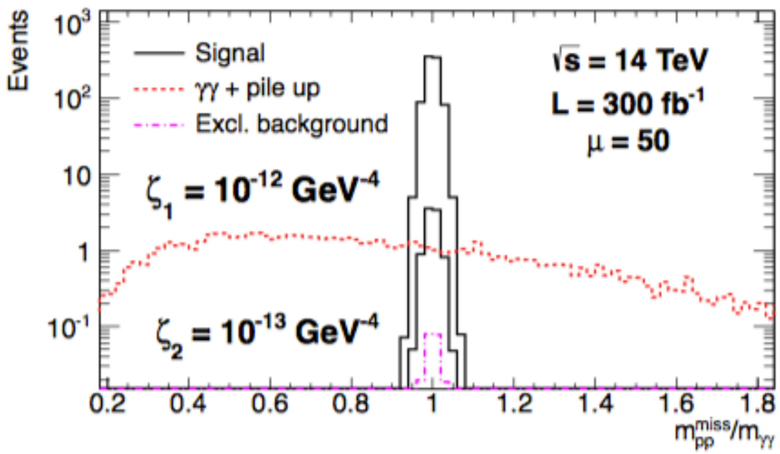


$\gamma\gamma \to \gamma\gamma$: Anomalous couplings, etc.

PRD 89(2014)114004



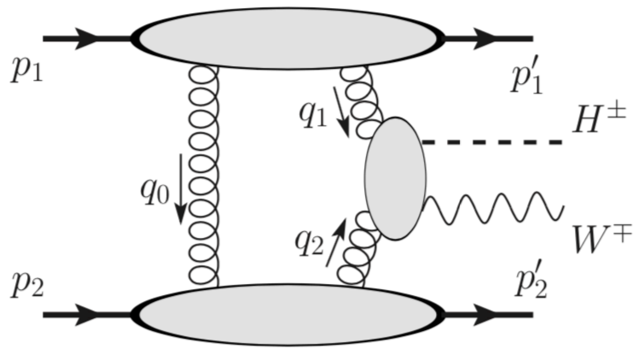
- Indirect search: neutral quartic gauge couplings (forbidden in SM) in $\gamma\gamma \to \gamma\gamma$
- Expect to provide best sensitivity at LHC
- Sensitive to axion-like particles

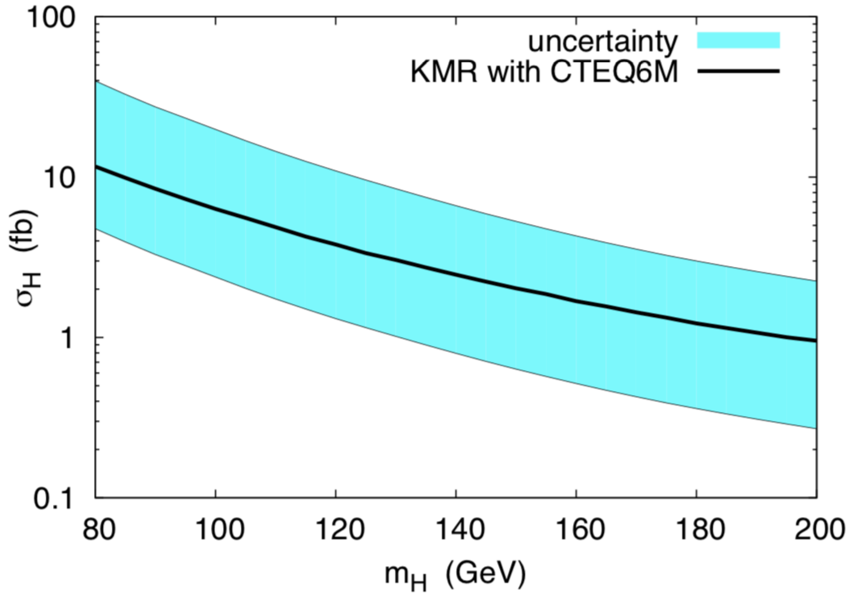


Associated $W^{\mp} H^{\pm}$

arXiv:1104.0889

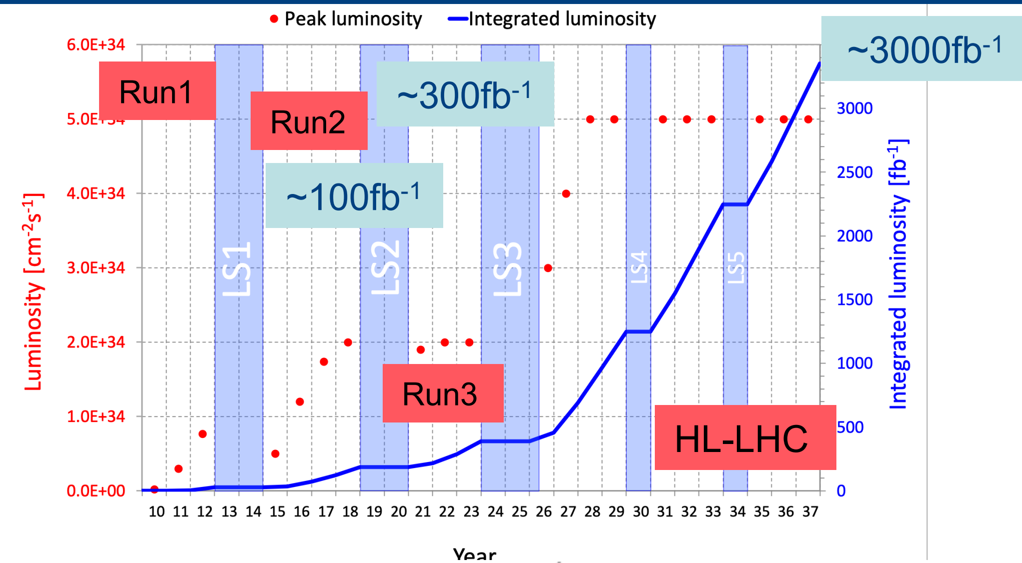
- Central exclusive production of a charged Higgs boson in association with a W boson as a possible signature of certain types of extended Higgs sectors
- $W^{\mp}$ and $H^{\pm}$ expected to be back-to-back

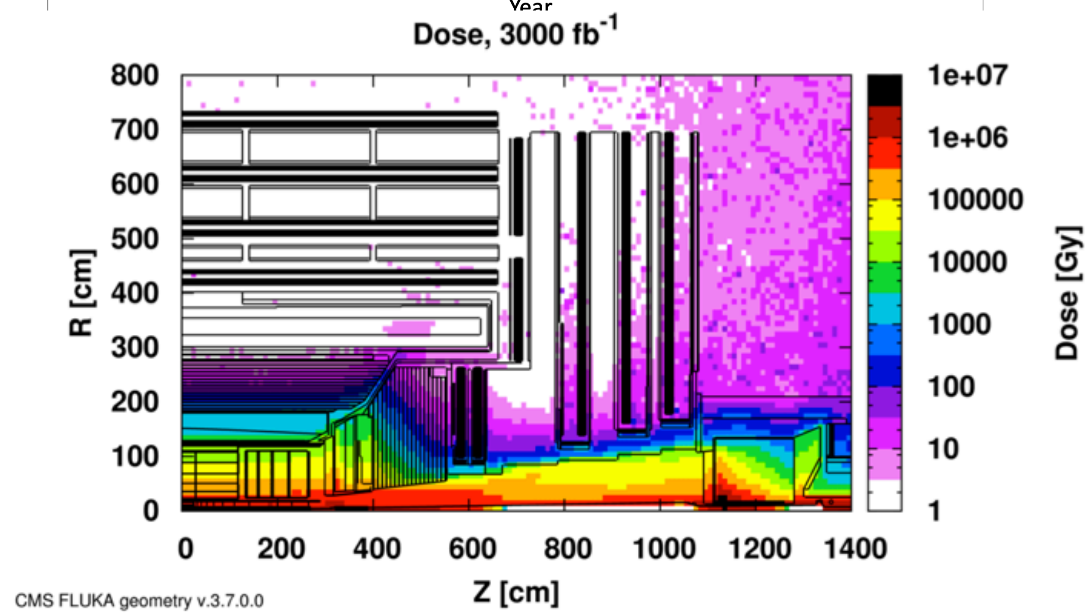




Prospects for Run3 and beyond

- More luminosity in a more challenging environment
- Will enhance the mass reach in the search for new particles
- Need to meet experimental challenges
  - Aging of detector, improve/adapt capability
  - Integrated luminosity: 300-3000/fb
  - peak luminosity of $2 \times 10^{35} cm^{-2} s^{-1}$
  - pileup will be ~150 or higher (Phase2)
  - large radiation doses





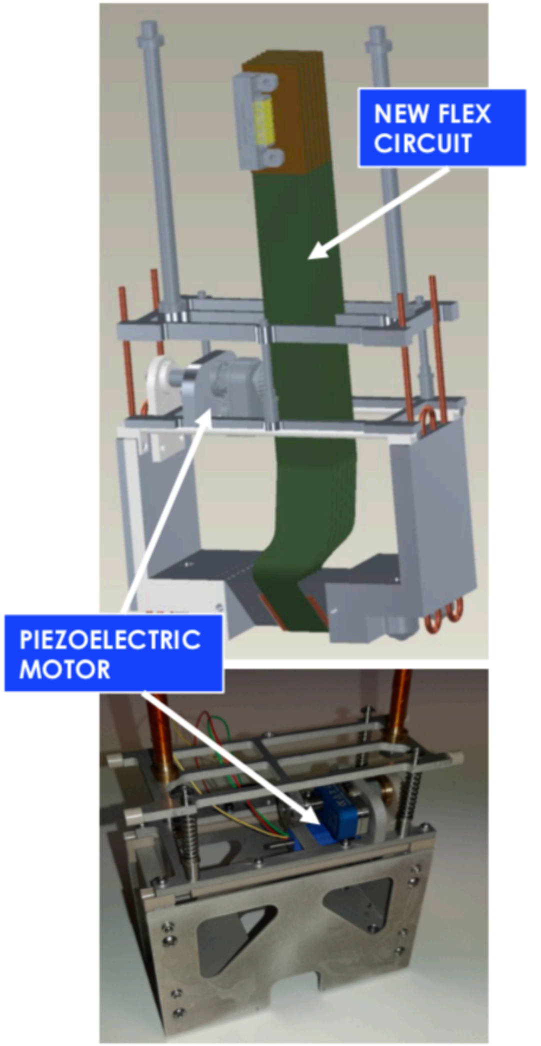
Prospects for Run3 (cont.)

PPS will operate in Run3 (2021-2023)

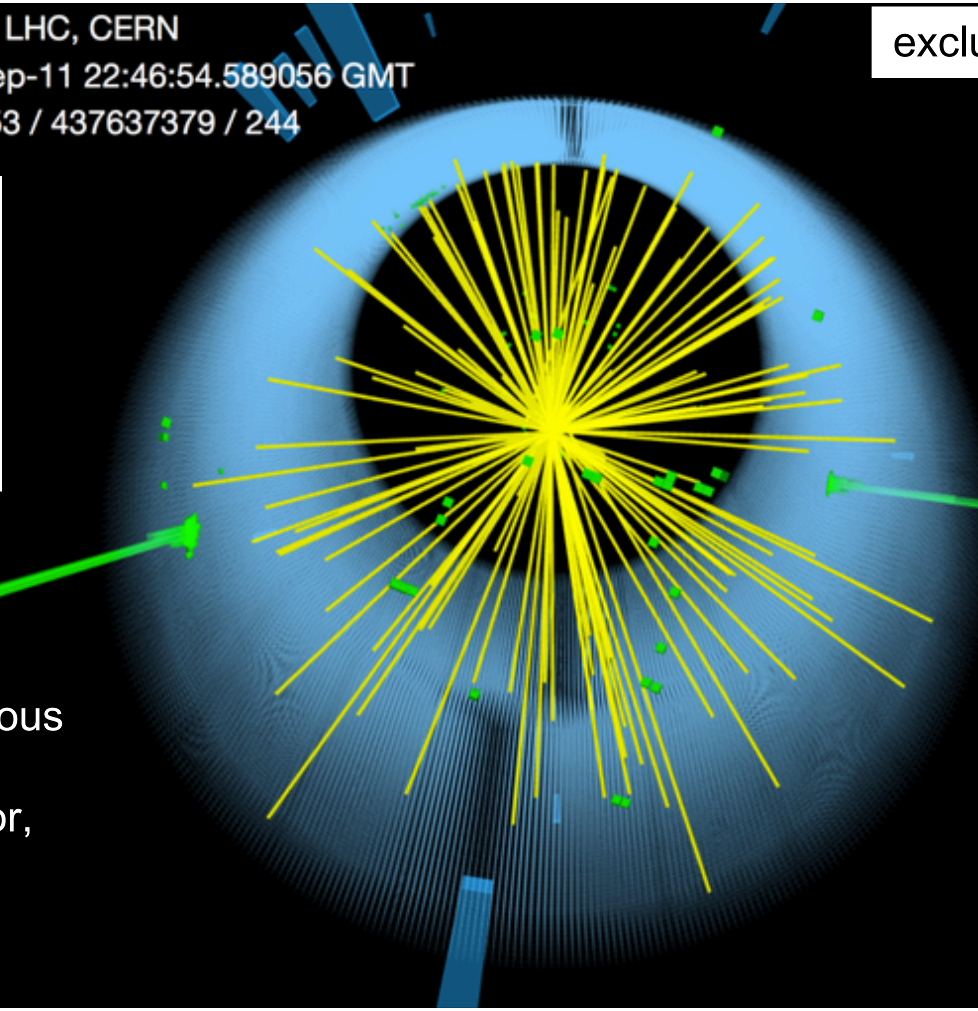
Tracker system in Run3

- 2 RPs per side at 210 m and 220 m
  - 6 detector planes per RP (as in 2018)
- New 3D silicon pixel sensors
  - Single side technology
  - 2x2 sensor geometry
  - 150um thick
  - 2E electrode configuration
- ROC: PROC600 (same as layer 1 of CMS pixel detector)
- New flex circuit design (different “look” but similar design)
- New detector package with internal movement system
  - 12 positions spaced by 500 um to handle radiation damage (more than 50/fb with minimal efficiency loss)

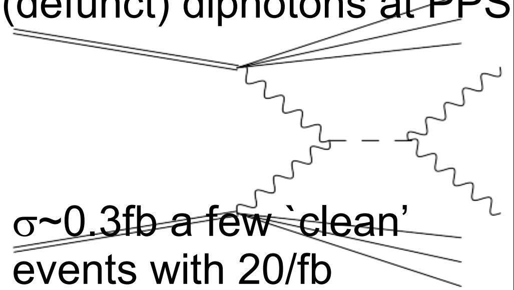
DESIGN AND FIRST PROTITYPE OF THE NEW DETECTOR PACKAGE



BSM searches: resonances, etc.

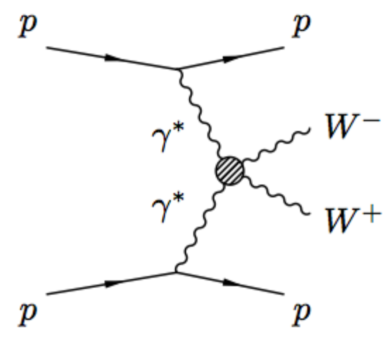


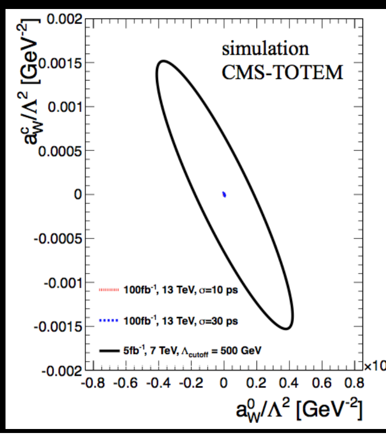
(defunct) diphotons at PPS



σ~0.3fb a few `clean' events with 20/fb

exclusive WW production





Composite Higgs, anomalous gauge-Higgs couplings, excited leptons, technicolor, extra dimensions, axions, heavy exotic states, dark matter candidates, …?

Prospects

Many BSM scenarios can be explored in $\gamma\gamma$ interactions

Composite Higgs, Anomalous gauge-Higgs couplings
JHEP 1407 (2014) 149
Phys.Rev. D90 (2014) no.1, 015035
JHEP 1403 (2014) 102
Nucl.Phys.Proc.Suppl. 179-180 (2008) 104-108

Extra Dimensions
Phys.Rev. D85 (2012) 014006
JHEP 1009 (2010) 042
Phys.Rev. D80 (2009) 075009
Phys.Rev. D84 (2011) 095002
JHEP 1403 (2014) 102

Magnetic monopoles
Eur.Phys.J. C62 (2009) 587-592
Phys.Rev. D57 (1998) 6599-6603
Eur.Phys.J.Plus 127 (2012) 60
Eur.Phys.J. A39 (2009) 213-217

top FCNCs/anomalous couplings
Phys.Rev. D92 (2015) no.1, 014006
Nucl.Phys. B897 (2015) 289-301

SUSY
Phys.Lett. B328 (1994) 369-373
Phys.Rev. D53 (1996) 2371-2379
Phys.Rev. D50 (1994) 2335-2338

Doubly-charged particles
Phys.Rev. D76 (2007) 075013
Phys.Rev. D95 (2017) no.5, 055020
Chin.Phys.Lett. 31 (2014) 021201

Charged Higgs
Phys.Rev. D91 (2015) 095008

Excited leptons
Phys.Rev. D81 (2010) 115002

Technicolor
Phys.Rev. D94 (2016) no.1, 015023

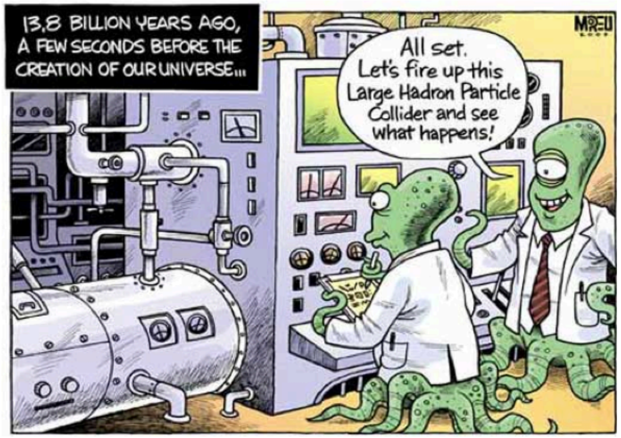
Unparticles
JHEP 0909 (2009) 069

4th generation
Int.J.Mod.Phys. A26 (2011) 3605-3613

τ EDM/anomalous magnetic moment
JHEP 1011 (2010) 060

Summary

- Overall excellent LHC and detector performance
- PPS extends coverage to very forward regions
  - Additional sensitivity to New Physics searches
  - Collected ~115/fb
- Exclusive dilepton production
  - Exclusive process at the EWK scale
  - First physics results published
  - More data to be analyzed



- Regularly taking data in high-luminosity fills
- Preparing with improved detectors and extending sensitivity for high-luminosity phase