

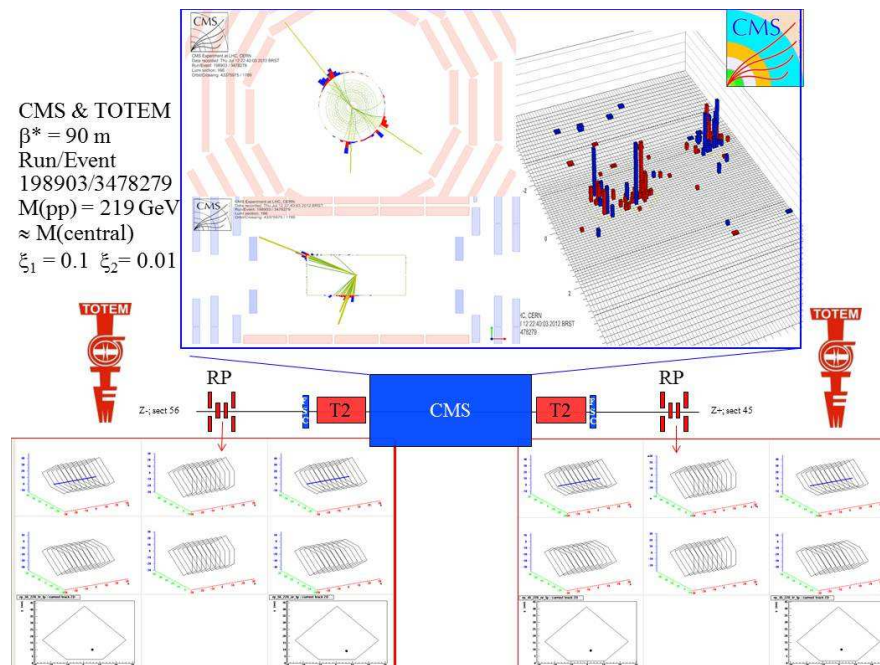
# Timing detectors in particle physics at the LHC

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Workshop on timing detectors and applications, Kansas City, USA,  
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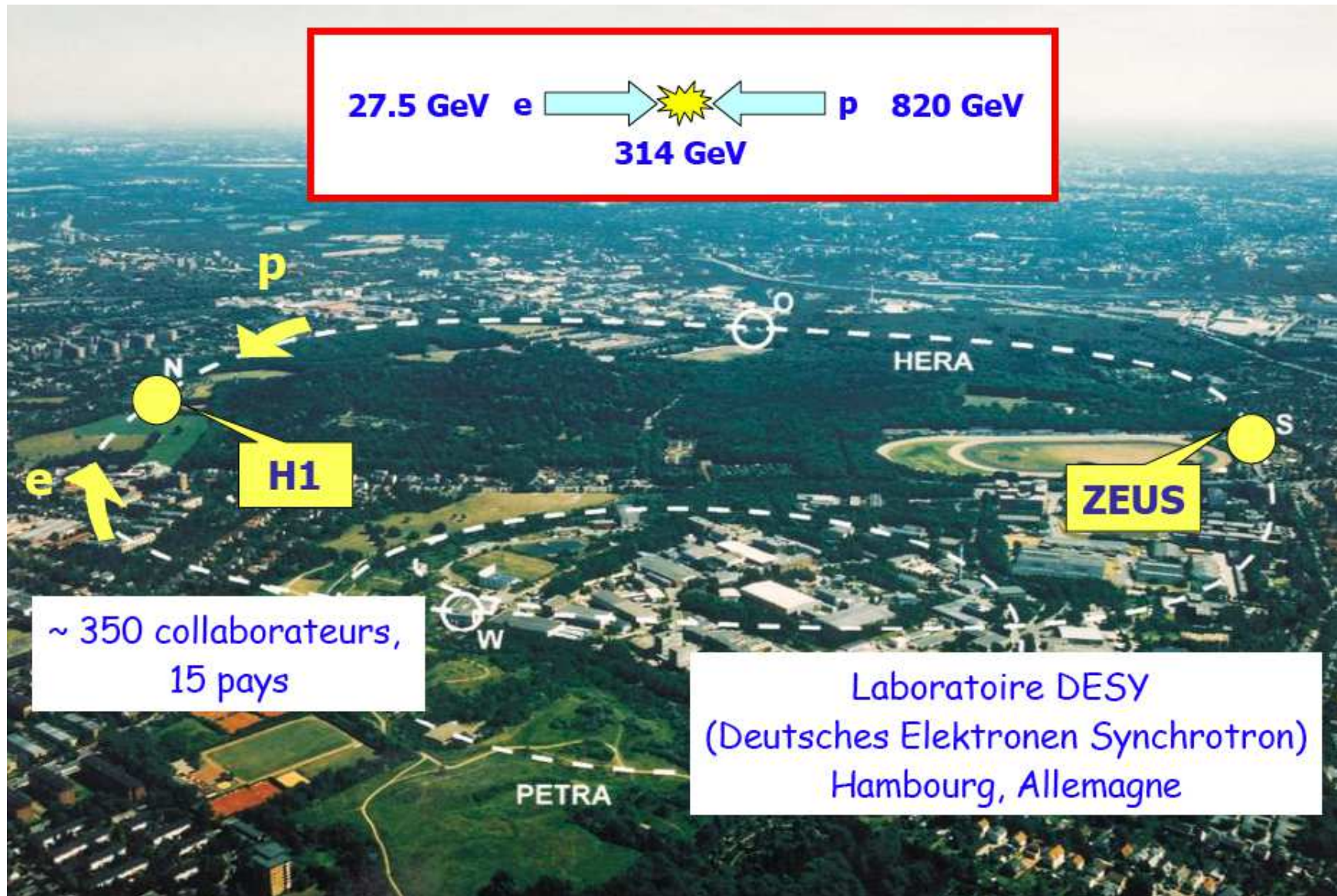
## Contents:

- Definition of diffraction
- CT\_PPS and CMS-TOTEM
- Pile up and timing
- Physics motivation at the LHC: QCD and beyond standard model

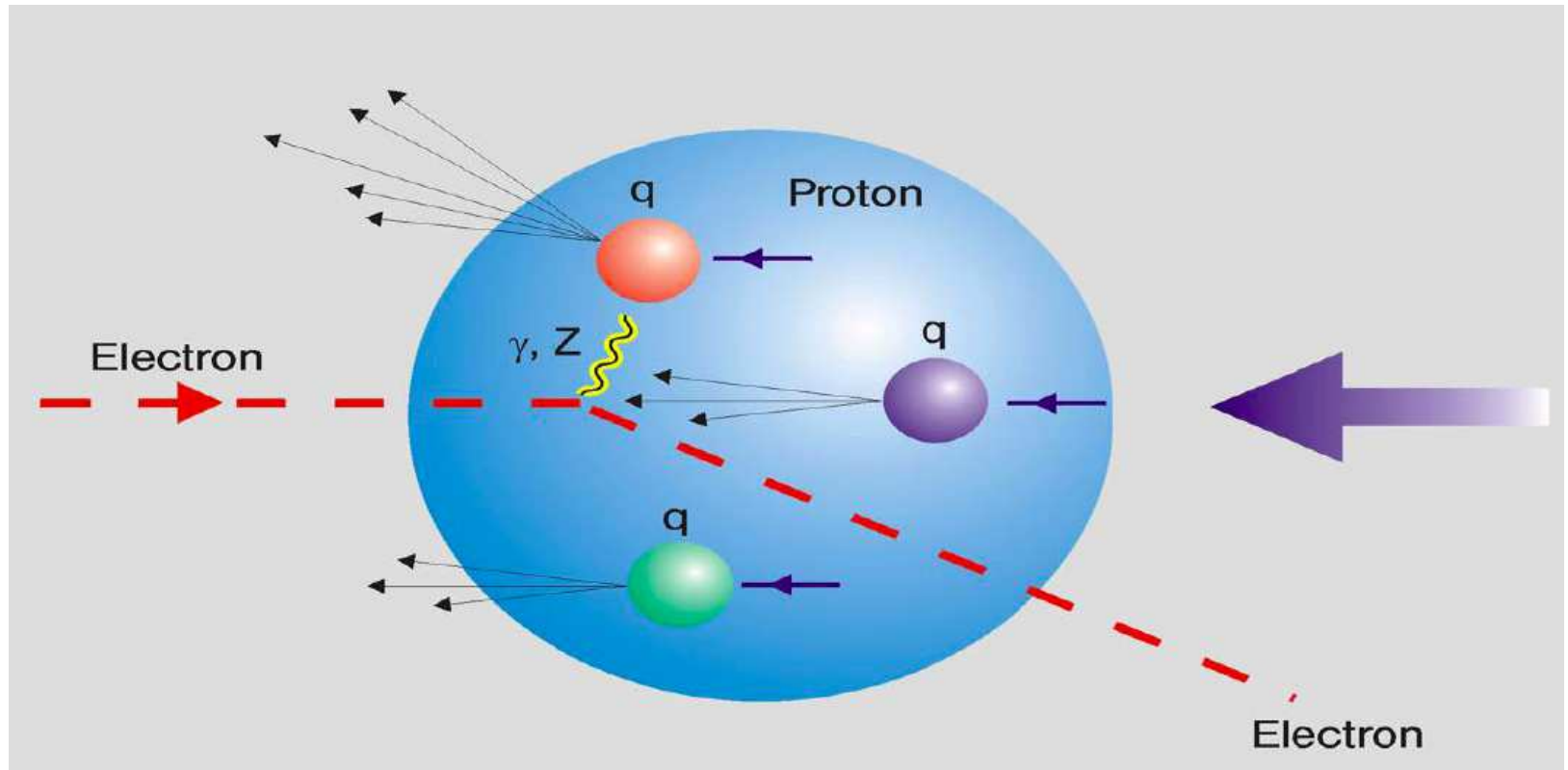


## Definition of diffraction: the example of HERA

HERA: ep collider in DESY, Hamburg, Germany

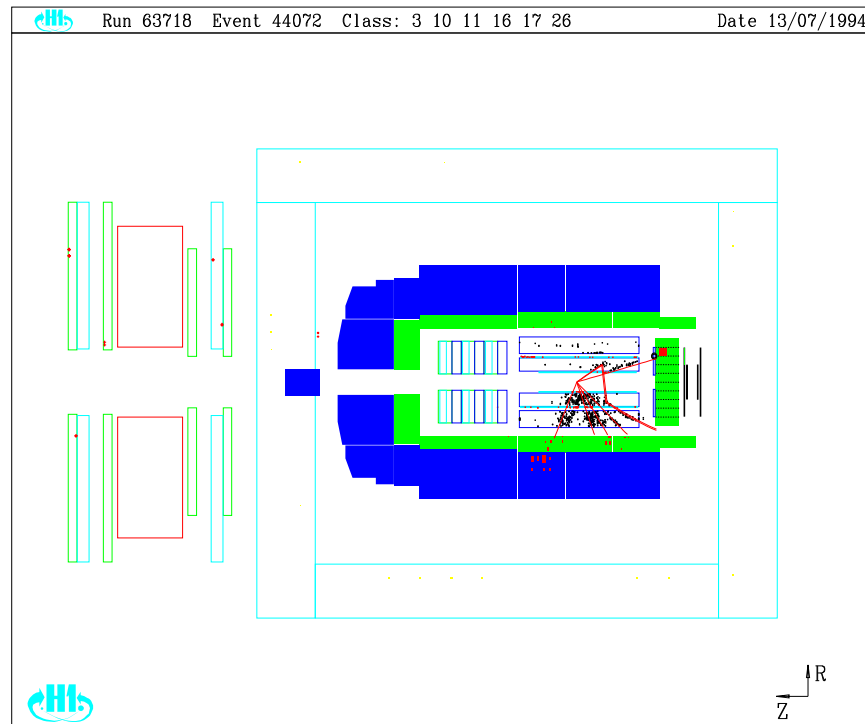
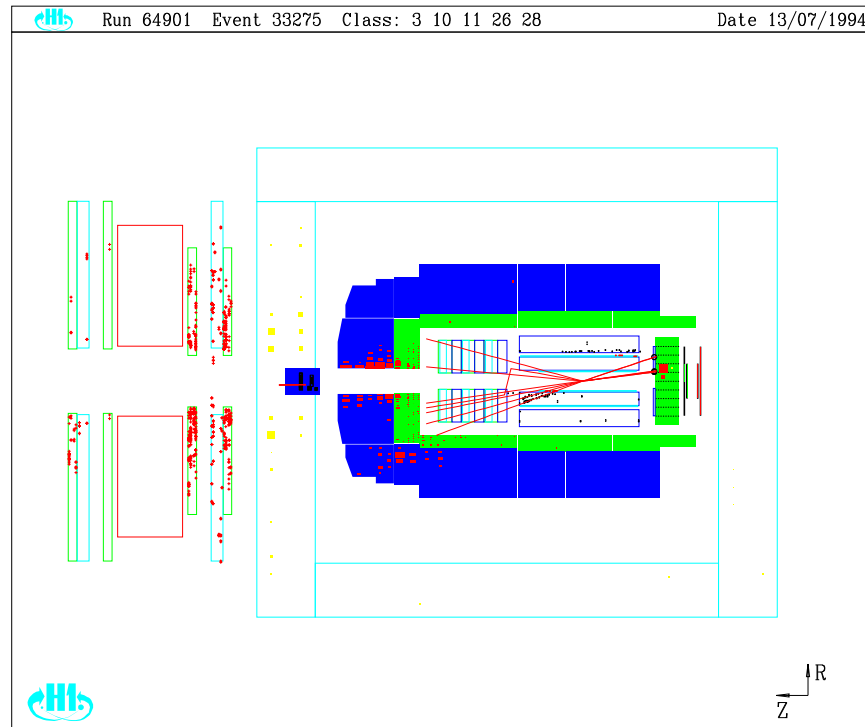


## Why an electron-proton collider?



- In most cases, the proton is “broken” after interaction
- The electron allows to probe the proton substructure (the electron is an elementary particle): proton structure in terms of quarks and gluons
- The interaction allows to test strong interaction
- The example of HERA:  $ep$  collider at DESY, Hamburg, with a center-of-mass energy of  $\sim 300$  GeV: allows us to define diffraction

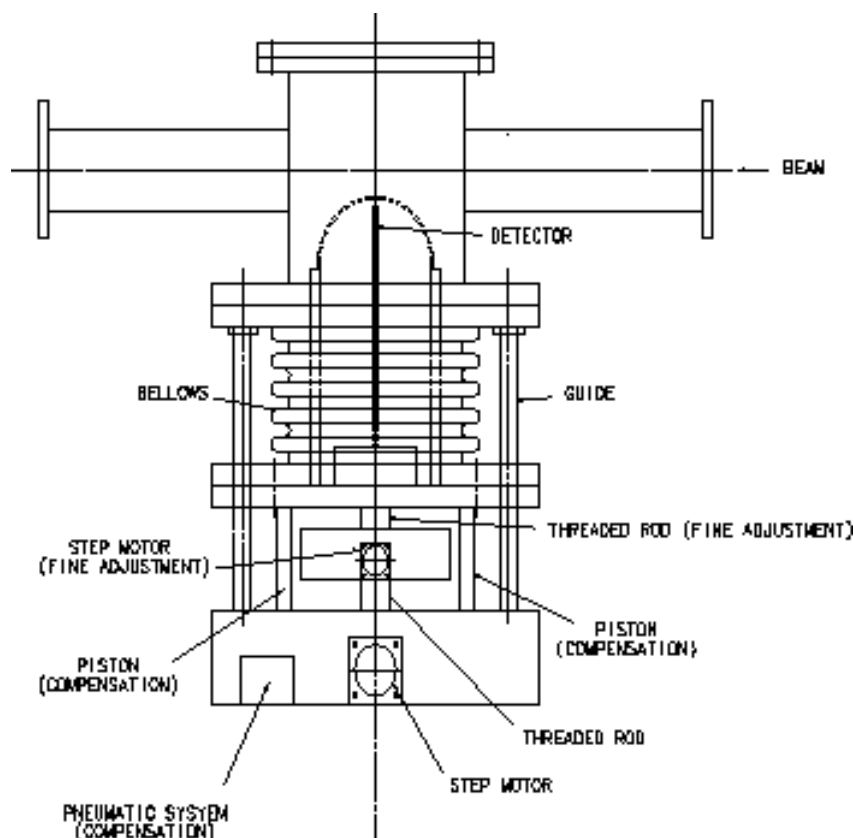
# Definition of diffraction





## Definition of diffraction: example of HERA

- **Typical DIS event:** part of proton remnants seen in detectors in forward region (calorimeter, forward muon...)
- **HERA observation:** in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction
- **Leads to the first experimental method to detect diffractive events:** **rapidity gap in calorimeter:** difficult to be used at the LHC because of pile up events
- **Second method to find diffractive events:** Tag the proton in the final state, method to be used at the LHC (example of AFP project)

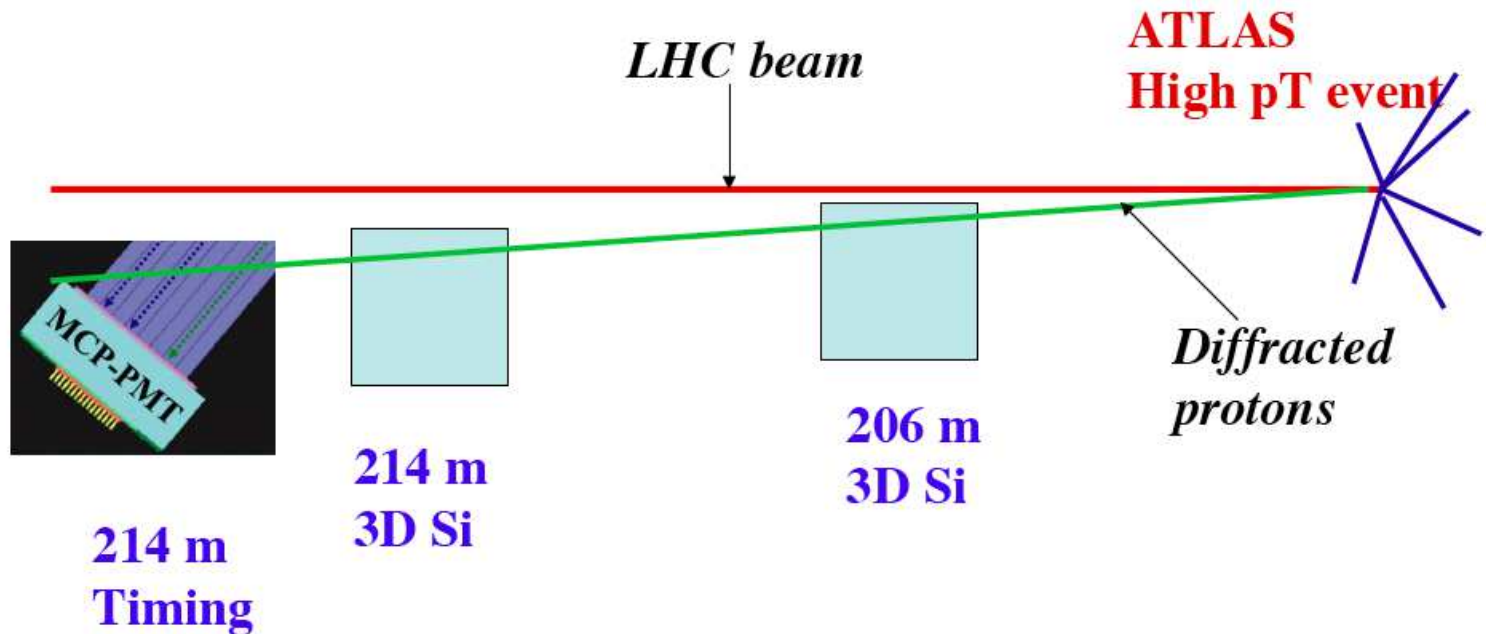


## LHC: Tagging intact protons in CMS-Totem/ATLAS

- Large Hadron Collider at CERN: proton proton collider with 13 TeV center-of-mass energy restarting in 2015
- Tagging intact protons at the LHC



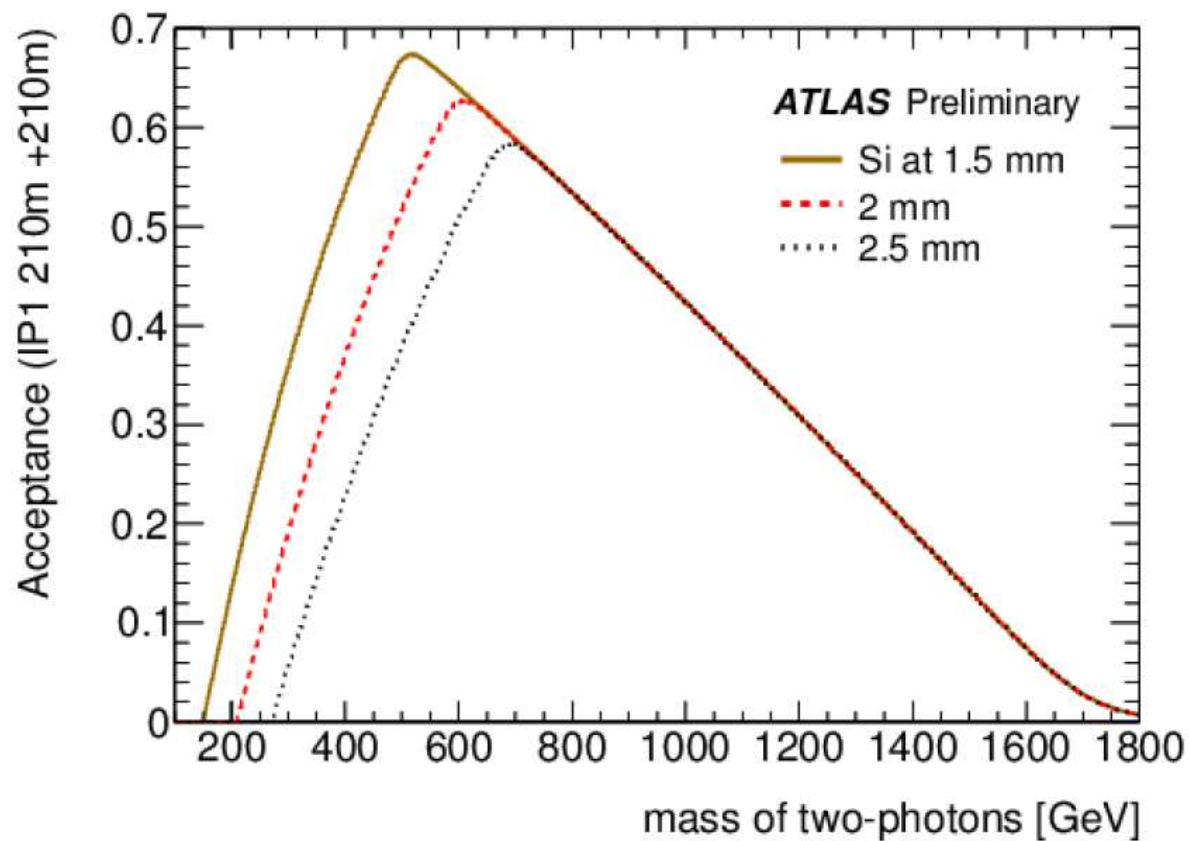
## Proton detectors in CMS-TOTEM/ATLAS



- Tag and measure protons at  $\pm 210$  m: AFP (ATLAS Forward Physics) in ATLAS, CT-PPS (CMS TOTEM - Precision Proton Spectrometer) in CMS/Totem
- **AFP/CT-PPS detectors:** measure proton position (Silicon detectors) and time-of-flight (timing detectors) (we will see later why this is important!)
- **Many applications of timing detectors:** medicine, drones....

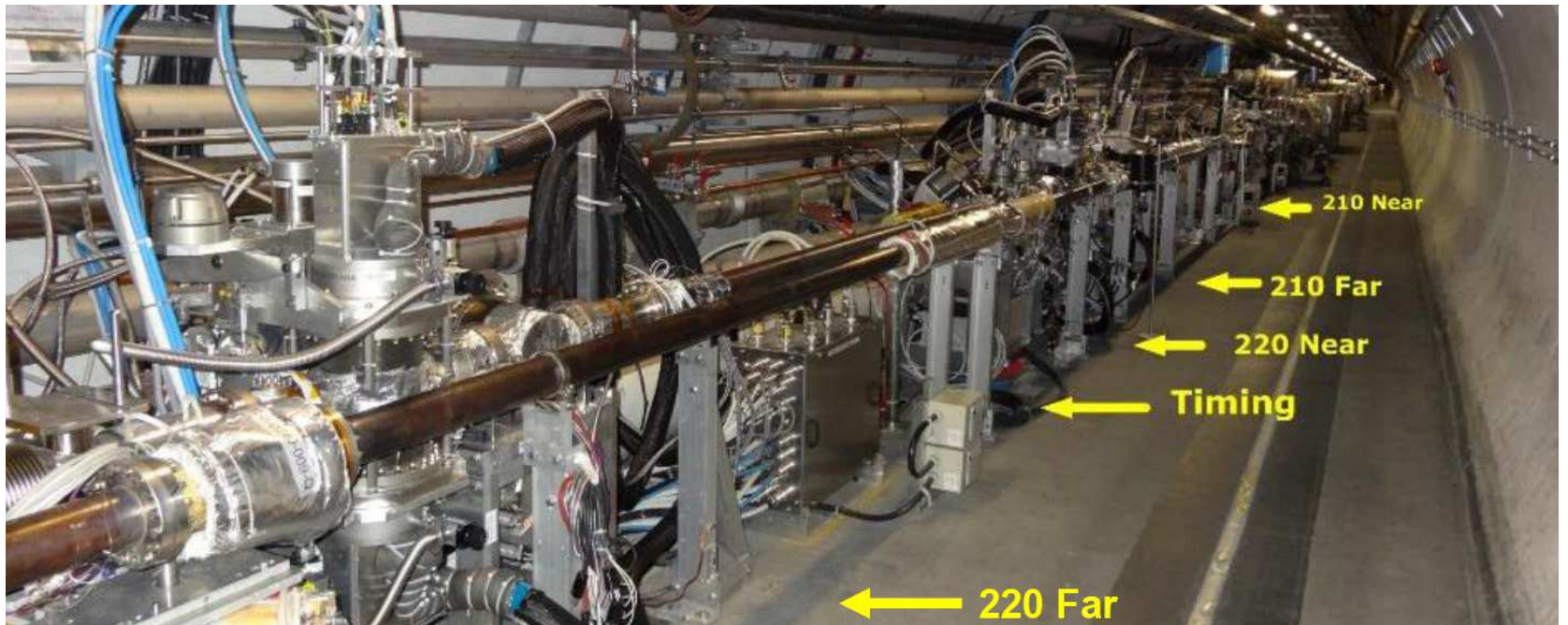
## The AFP/CT-PPS detector

- Tag and measure intact protons at  $\pm 210$  m at the LHC
- Allows to access masses of produced object in ATLAS between 350 and 1.4 TeV: constrain the kinematics/mass of the produced object by measuring final state protons (system fully constrained)





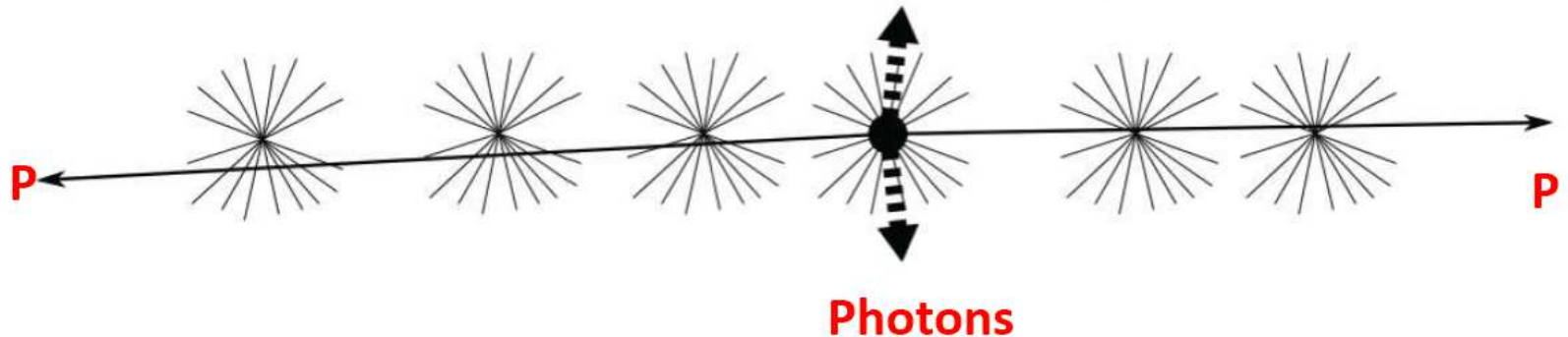
## 26 roman pots installed by TOTEM on both sides of CMS



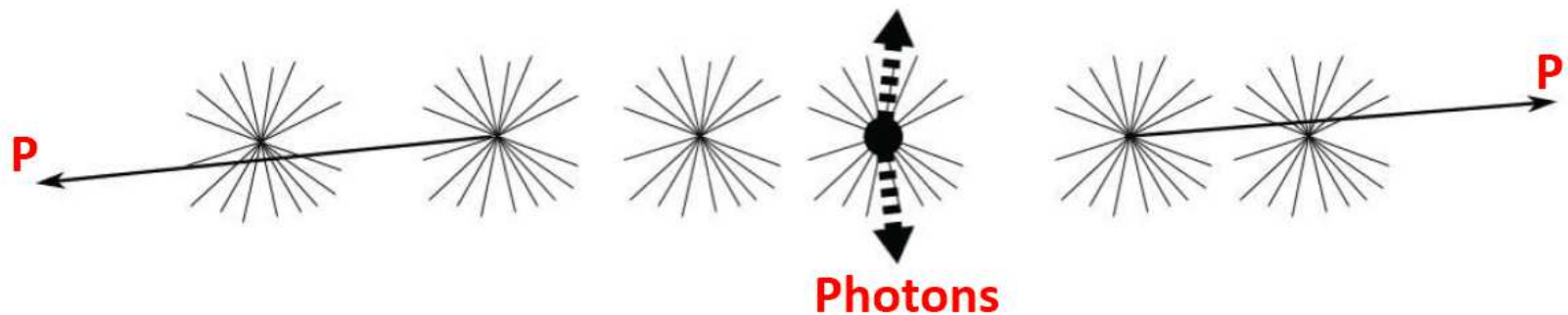
- 26 roman pots installed on both sides of CMS by the TOTEM collaboration!
- Combination of vertical (CMS-TOTEM) and horizontal (CT-PPS) roman pots
- Different physics topics: low and high mass diffraction (QCD), sensitivity to new physics

## One aside: what is pile up at LHC?

### A collision with 2 protons and 2 photons



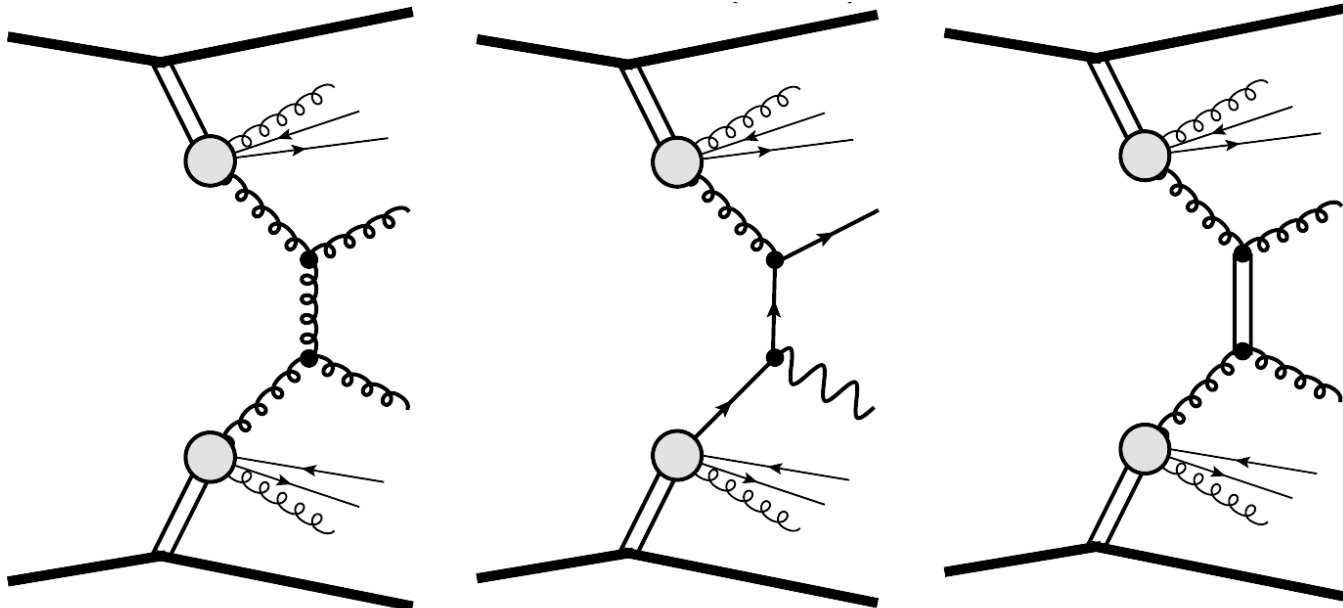
can be faked by one collision with 2 photons and protons from different collisions



- The LHC machine collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events in Run II

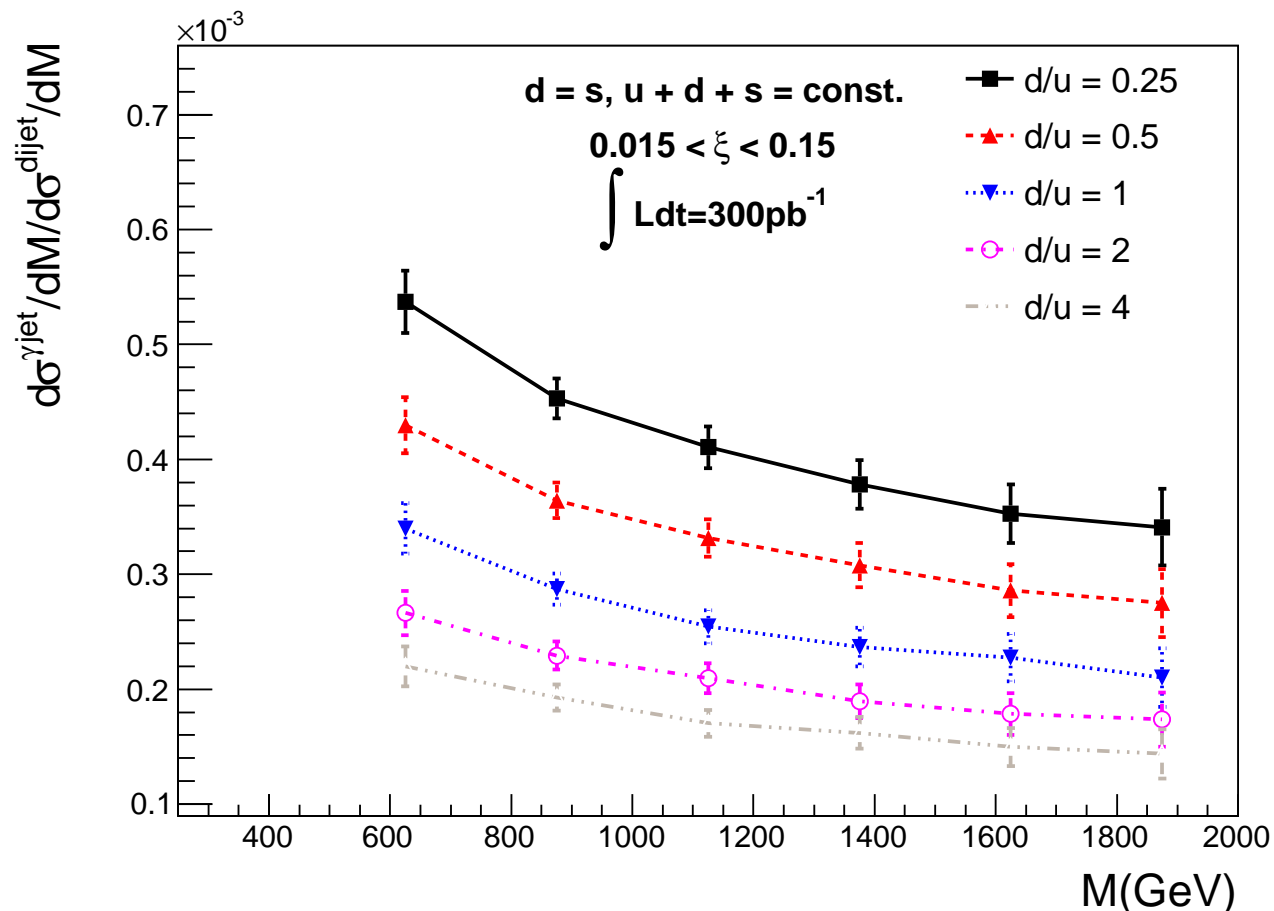
## Hard diffraction at the LHC

- Dijet production: dominated by  $gg$  exchanges;  $\gamma$ +jet production: dominated by  $qg$  exchanges (C. Marquet, C. Royon, M. Saimpert, D. Werder, arXiv:1306.4901)
- Jet gap jet in diffraction: Probe BFKL (C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, Phys. Rev. D 87 (2013) 034010; O. Kepka, C. Marquet, C. Royon, Phys. Rev. D79 (2009) 094019; Phys.Rev. D83 (2011) 034036 )
- Three aims
  - Is it the same object which explains diffraction in  $pp$  and  $ep$ ?
  - Further constraints on the structure of the Pomeron as was determined at HERA
  - Survival probability: difficult to compute theoretically, needs to be measured, inclusive diffraction is optimal place for measurement



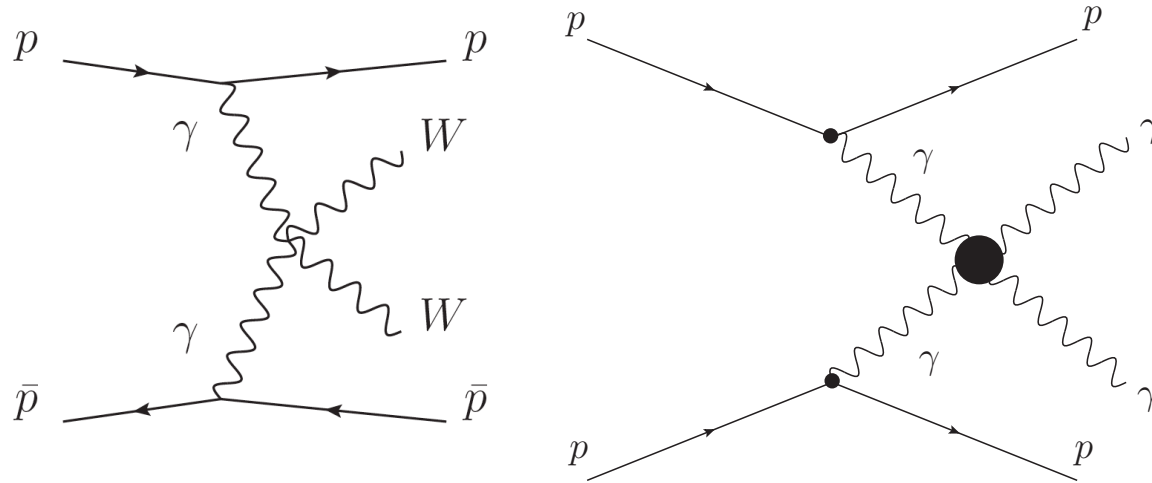
## Inclusive diffraction at the LHC: sensitivity to quark densities

- Predict DPE  $\gamma$ +jet divided by dijet cross section at the LHC
- Sensitivity to universality of Pomeron model
- Sensitivity to quark density in Pomeron, and of assumption:  
 $u = d = s = \bar{u} = \bar{d} = \bar{s}$  used in QCD fits at HERA





## Search for $\gamma\gamma WW$ , $\gamma\gamma\gamma\gamma$ quartic anomalous coupling



- Study of the process:  $pp \rightarrow ppWW$ ,  $pp \rightarrow ppZZ$ ,  $pp \rightarrow pp\gamma\gamma$
- Standard Model:  $\sigma_{WW} = 95.6 \text{ fb}$ ,  $\sigma_{WW}(W = M_X > 1\text{TeV}) = 5.9 \text{ fb}$
- Process sensitive to anomalous couplings:  $\gamma\gamma WW$ ,  $\gamma\gamma ZZ$ ,  $\gamma\gamma\gamma\gamma$ ; motivated by studying in detail the mechanism of electroweak symmetry breaking, predicted by extradim. models
- Rich  $\gamma\gamma$  physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys.Rev. D89 (2014) 114004 ; S.Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 1502 (2015) 165; S. Fichet, G. von Gersdorff, C. Royon Phys. Rev. Lett. 116 (2016) no 23, 231801 and Phys. Rev. D93 (2016) no 7, 075031; J. de Favereau et al., arXiv:0908.2020.

## Warped extra-dimensions

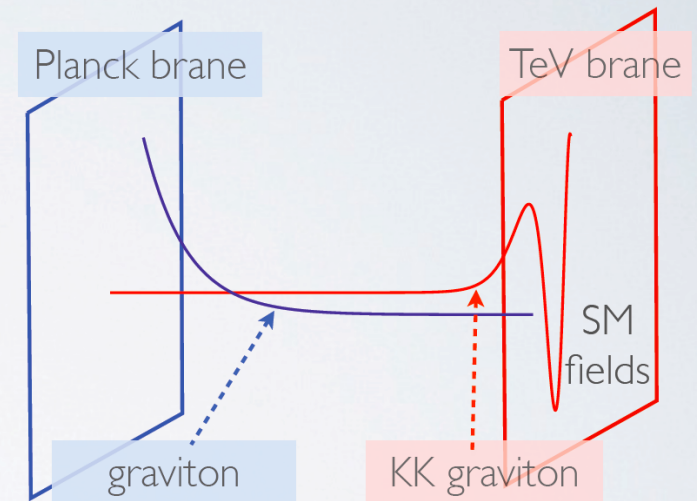
- ✗ Warped Extra Dimensions **solve hierarchy problem** of SM
- ✗ 5<sup>th</sup> dimension bounded by two branes
- ✗ SM on the visible (or TeV) brane

- ✗ The **Kaluza Klein** modes of the graviton couple with **TeV** strength

$$\mathcal{L}^{\gamma\gamma h} = f^{-2} h_{\mu\nu}^{\text{KK}} \left( \frac{1}{4} \eta_{\mu\nu} F_{\rho\lambda}^2 - F_{\mu\rho} F_{\rho\nu} \right)$$

$$f \sim \text{TeV} \quad m_{\text{KK}} \sim \text{few TeV}$$

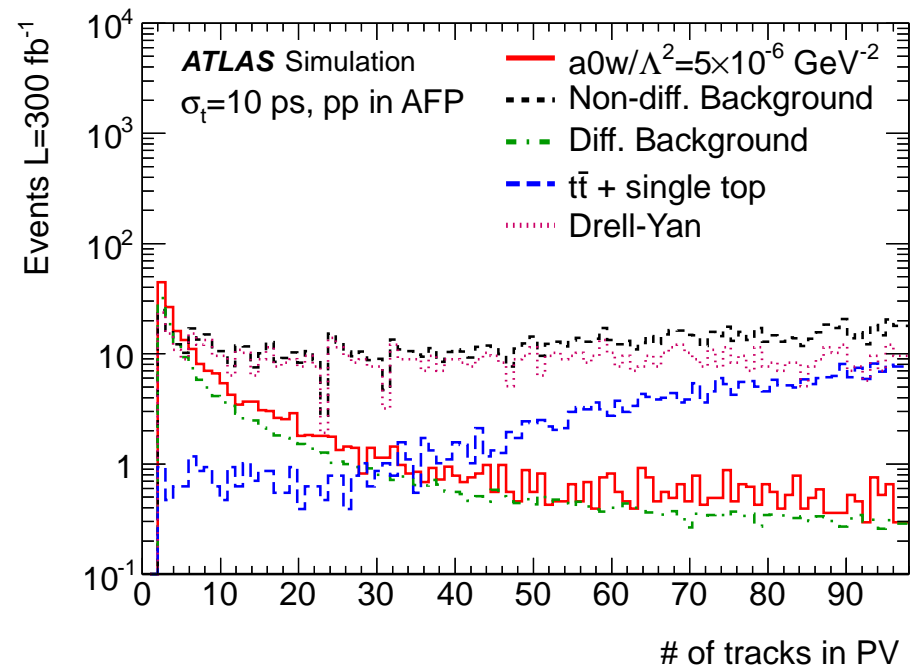
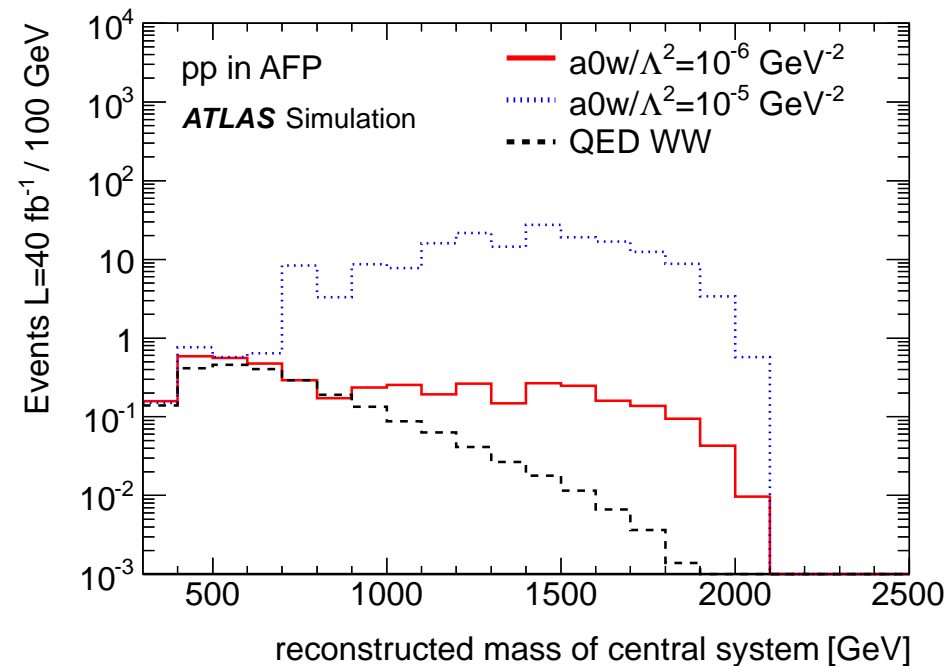
- ✗ Effective 4-photon couplings  $\zeta_i \sim 10^{-14} - 10^{-13} \text{ GeV}^{-2}$  possible
- ✗ The **radion** can produce similar effective couplings



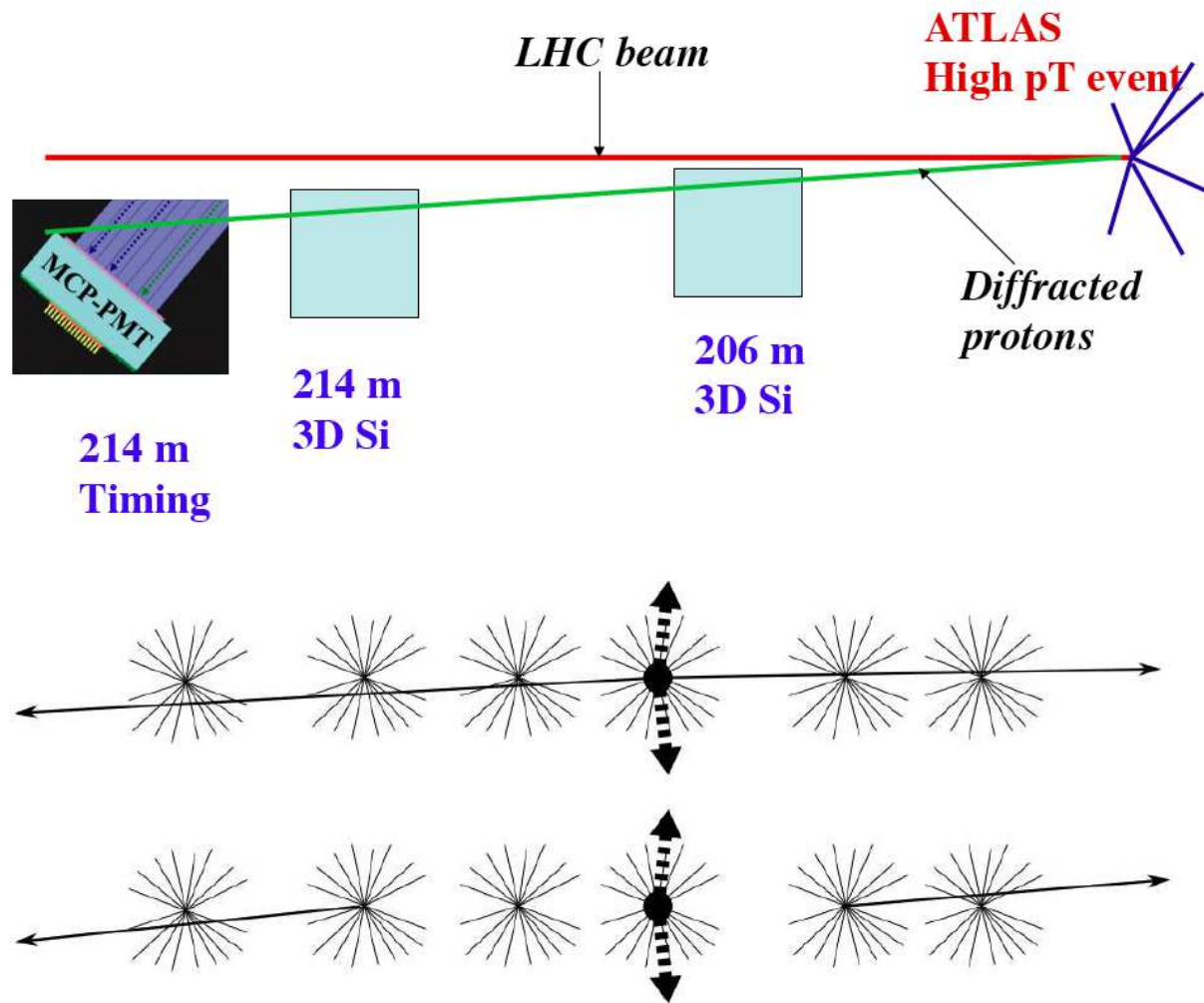
- Which models/theories are we sensitive to using AFP/CT-PPS
- Beyond standard models predict anomalous couplings of  $\sim 10^{-14}$ - $10^{-13}$
- Work in collaboration with Sylvain Fichet, Gero von Gersdorff

## Anomalous couplings studies in $WW$ events

- Reach on anomalous couplings studied using a full simulation of the ATLAS detector, including all pile-up effects; only leptonic decays of  $W$ s are considered
- Signal appears at high lepton  $p_T$  and dilepton mass (central ATLAS) and high diffractive mass (reconstructed using forward detectors)
- Cut on the number of tracks fitted to the primary vertex: very efficient to remove remaining pile-up after requesting a high mass object to be produced (for signal, we have two leptons coming from the  $W$  decays and nothing else)



## Removing pile up: measuring proton time-of-flight

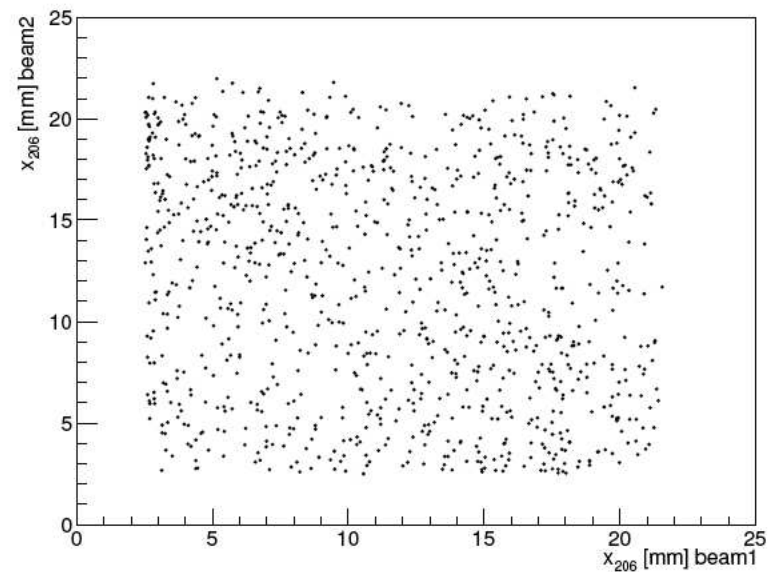
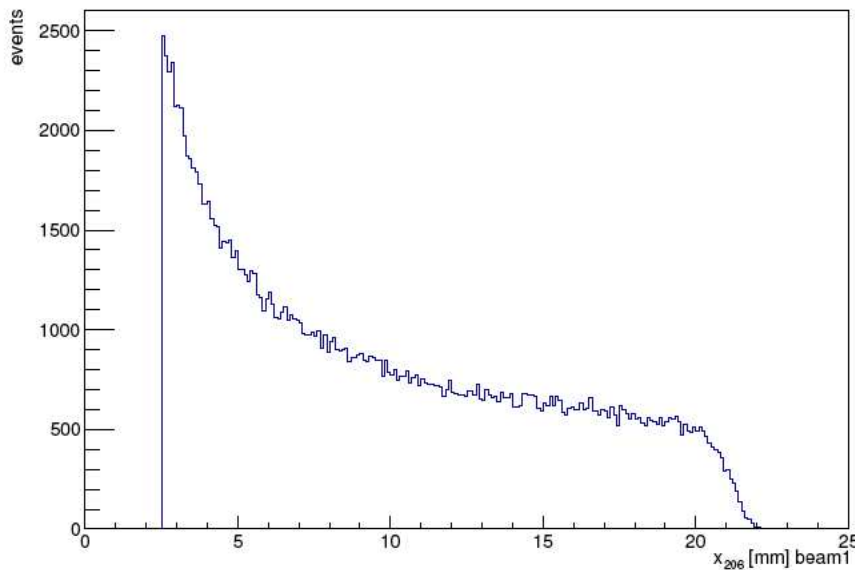


- Measure the proton time-of-flight in order to determine if they originate from the same interaction as our  $W$ s
- Typical precision: 10 ps means 2.1 mm



## Pile up treatment and Proton distribution in AFP

- Generation of 7 TeV protons (Single diffractive and Double Pomeron Exchange events) with PYTHIA 8
- Transport at AFP/CT-PPS position from the Interaction Point (IP) with FPTRACKER/MADX (program from the LHC beam division allowing transport through the magnets)

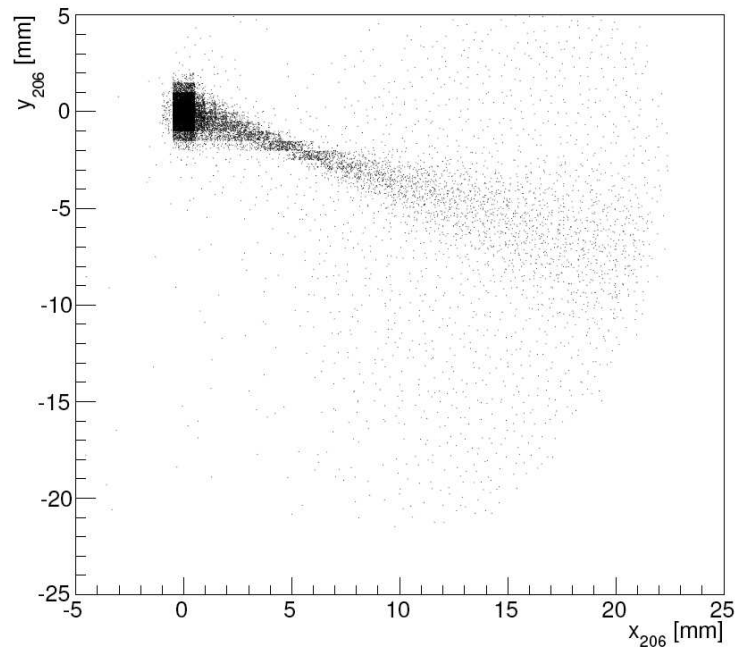


- Proton distribution ( $X$  distance from the horizontal axis on one side for SD, and correlations between both  $x$  on each side of ATLAS for DPE events)
- Probability for a proton to be tagged (taking into account SD/DPE cross sections) for one bunch crossing: 0.01% (double tag on each side), 1.6% (single tag on one side), 97% (no tag)

## Probability to detect intact protons

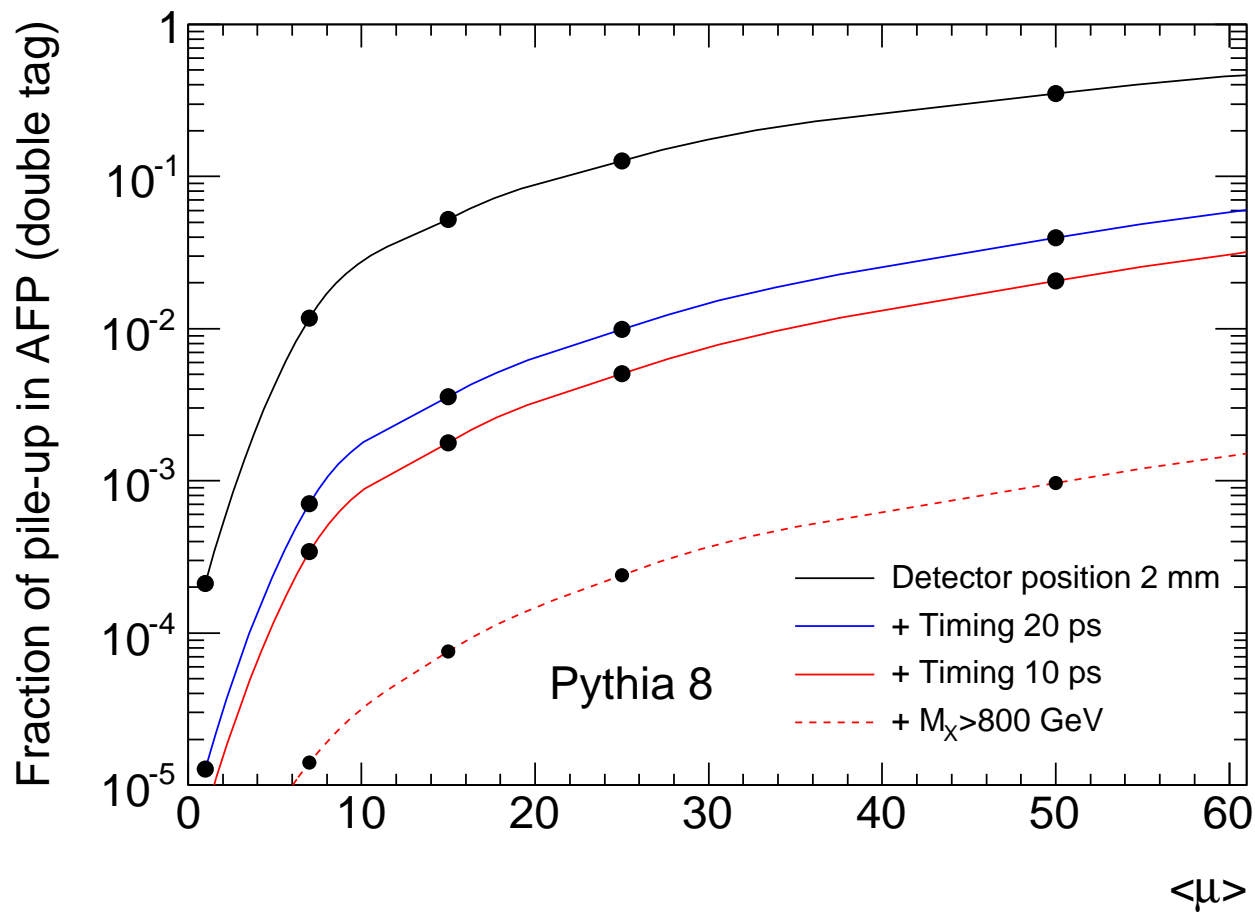
- 3 different kinds of pile up conditions to be considered: 50, 100 and 300
- Probability to detect intact proton on one side or on both sides

$\mu$	$P_N$	$P_{S,left}$	$P_{S,right}$	$P_D$
0	0.97	0.016	0.016	9.9e-05
50	0.189	—	0.248	0.316
100	0.036	—	0.155	0.655
300	0.	—	0.007	0.986



## Background reduction as a function of pile up

- Measurement of the arrival times of protons with a 10-20 ps precision
- allows to constrain the vertex position from where protons are originating: 10 ps interval corresponds to  $\Delta z = 2.1$  mm
- Reduction of background independent of process: factor 12 for 20 ps resolution, 25 for 10 ps



## Results from full simulation on $WW$ production

- Effective anomalous couplings correspond to loops of charged particles,  
Reaches the values expected for extradim models

Cuts	Top	Dibosons	Drell-Yan	W/Z+jet	Diff.	$a_0^W/\Lambda^2 = 5 \cdot 10^{-6} \text{ GeV}^{-2}$
timing < 10 ps $p_T^{lep1} > 150 \text{ GeV}$ $p_T^{lep2} > 20 \text{ GeV}$	5198	601	20093	1820	190	282
M(l $\bar{l}$ )>300 GeV	1650	176	2512	7.7	176	248
nTracks $\leq 3$	2.8	2.1	78	0	51	71
$\Delta\phi < 3.1$	2.5	1.7	29	0	2.5	56
$m_X > 800 \text{ GeV}$	0.6	0.4	7.3	0	1.1	50
$p_T^{lep1} > 300 \text{ GeV}$	0	0.2	0	0	0.2	35

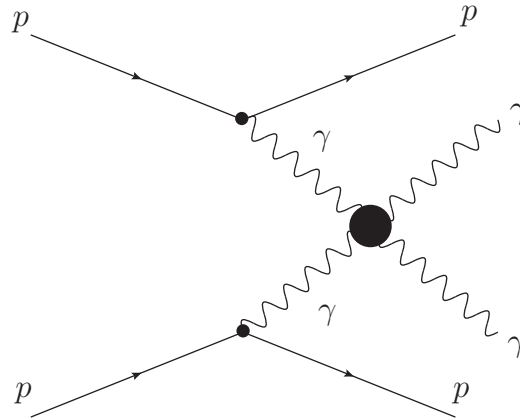
**Table 9.5.** Number of expected signal and background events for  $300 \text{ fb}^{-1}$  at pile-up  $\mu = 46$ . A time resolution of 10 ps has been assumed for background rejection. The diffractive background comprises production of QED diboson, QED dilepton, diffractive WW, double pomeron exchange WW.

- Improvement of “standard” LHC methods by studying  $pp \rightarrow l^\pm \nu \gamma \gamma$  by more than 2 orders of magnitude
- Timing detectors are crucial

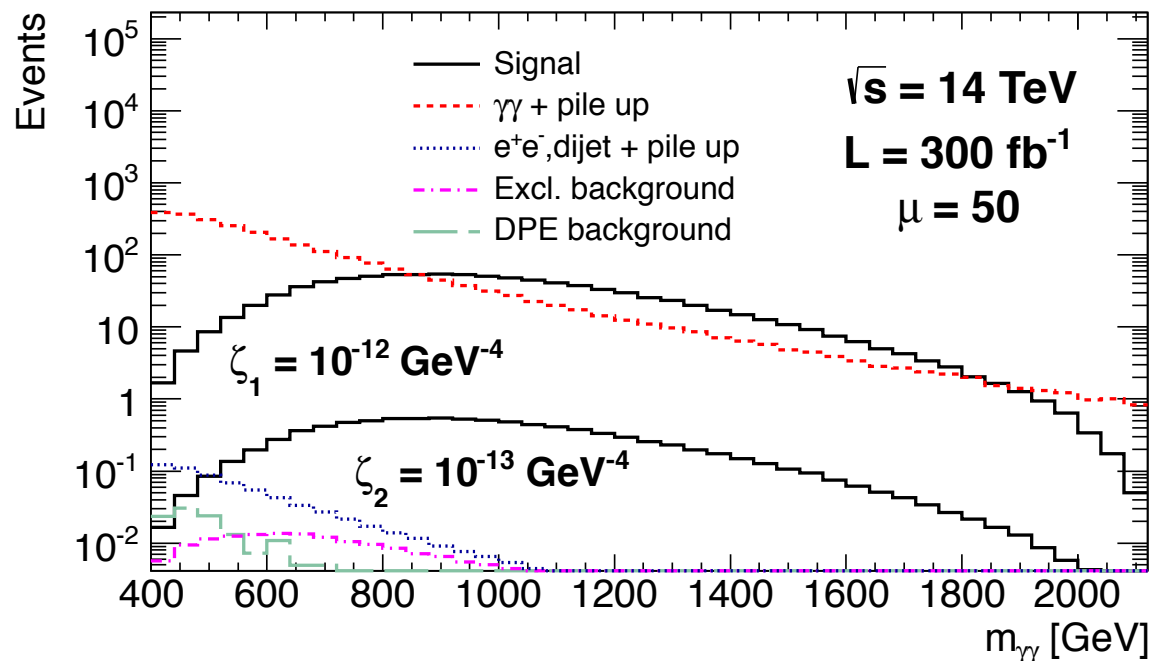
	$5\sigma$	95% CL
$\mathcal{L} = 40 \text{ fb}^{-1}, \mu = 23$	$5.5 \cdot 10^{-6}$	$2.4 \cdot 10^{-6}$
$\mathcal{L} = 300 \text{ fb}^{-1}, \mu = 46$	$3.2 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$



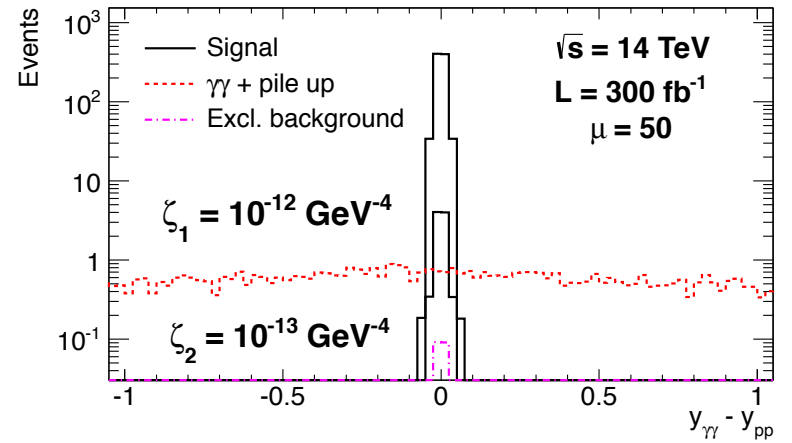
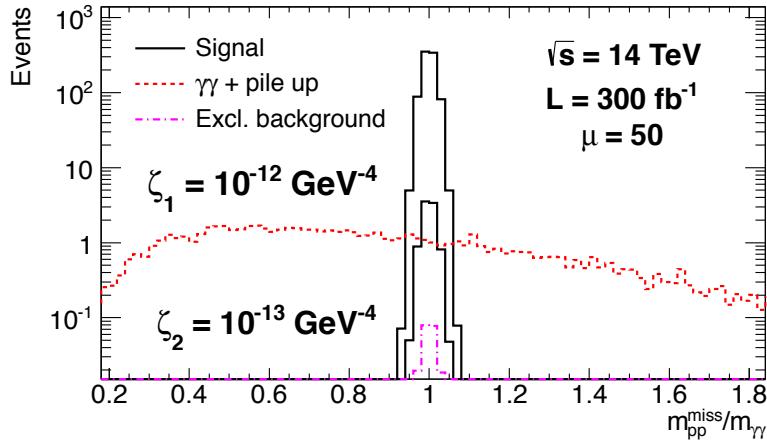
## Search for quartic $\gamma\gamma$ anomalous couplings



- Search for  $\gamma\gamma\gamma\gamma$  quartic anomalous couplings
- Couplings predicted by extra-dim, composite Higgs models
- Analysis performed at hadron level including detector efficiencies, resolution effects, pile-up...



# Search for quartic $\gamma\gamma$ anomalous couplings



Cut / Process	Signal (full)	Signal with (without) f.f (EFT)	Excl.	DPE	DY, di-jet + pile up	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15,$ $p_{T1,(2)} > 200, (100) \text{ GeV}]$	130.8	36.9 (373.9)	0.25	0.2	1.6	2968
$m_{\gamma\gamma} > 600 \text{ GeV}$	128.3	34.9 (371.6)	0.20	0	0.2	1023
$[p_{T2}/p_{T1} > 0.95,$ $ \Delta\phi  > \pi - 0.01]$	128.3	34.9 (371.4)	0.19	0	0	80.2
$\sqrt{\xi_1 \xi_2 s} = m_{\gamma\gamma} \pm 3\%$	122.0	32.9 (350.2)	0.18	0	0	2.8
$ y_{\gamma\gamma} - y_{pp}  < 0.03$	119.1	31.8 (338.5)	0.18	0	0	0

- No background after cuts for  $300 \text{ fb}^{-1}$  **without needing timing detector information**
- Exclusivity cuts using proton tagging needed to suppress backgrounds
- When all particles are measured in the final state with good mass/rapidity resolution, timing is not crucial

## Search for quartic $\gamma\gamma$ anomalous couplings:

Luminosity	300 fb <sup>-1</sup>	300 fb <sup>-1</sup>	300 fb <sup>-1</sup>	3000 fb <sup>-1</sup>
pile-up ( $\mu$ )	50	50	50	200
coupling (GeV <sup>-4</sup> )	$\geq 1$ conv. $\gamma$ 5 $\sigma$	$\geq 1$ conv. $\gamma$ 95% CL	all $\gamma$ 95% CL	all $\gamma$ 95% CL
$\zeta_1$ f.f.	$8 \cdot 10^{-14}$	$5 \cdot 10^{-14}$	$3 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$
$\zeta_1$ no f.f.	$2.5 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$	$9 \cdot 10^{-15}$	$7 \cdot 10^{-15}$
$\zeta_2$ f.f.	$2 \cdot 10^{-13}$	$1 \cdot 10^{-13}$	$6 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$
$\zeta_2$ no f.f.	$5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1.5 \cdot 10^{-14}$

- **Unprecedented sensitivities at hadronic colliders:** no limit exists presently on  $\gamma\gamma\gamma\gamma$  anomalous couplings
- Reaches the values predicted by extra-dim or composite Higgs models
- Introducing form factors to avoid quadratical divergences of scattering amplitudes due to anomalous couplings in conventional way:  

$$a \rightarrow \frac{a}{(1+W\gamma\gamma/\Lambda_{cutoff})^2}$$
with  $\Lambda_{cutoff} \sim 2$  TeV, scale of new physics
- **Full amplitude calculation leads to similar results:** avoids using a form factor and parameters dependence of the results
- **Conclusion: background free experiment**

## Conclusion

- AFP/CT-PPS and CMS-TOTEM aim at detecting intact protons: QCD (structure of Pomeron...), search for extra-dimensions in the universe via anomalous couplings between  $\gamma$ ,  $W$ ,  $Z$ ...
- Timing detectors: used to reject pile up background
- Timing detectors not essential when one detects all particles in the final state with good mass/rapidity resolution:  $\gamma\gamma$ ,  $Z\gamma$ ,  $ZZ$  when  $Z$  decays leptonically...
- Timing detectors are crucial when not all particles are detected (example of  $WW$  production because of neutrinos or when we have a worse resolution on mass in ATLAS/CMS (for instance jets))
- Many applications especially in PET imaging, drones...

