Results (and future prospects) of the CMS experiment in photon-induced collisions in pp collisions

PhotonLHC2014, CERN

L. Forthomme (CMS collaboration)

CP3, UCLouvain

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(Central) exclusive processes

Motivations

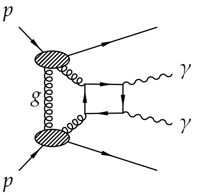
Study of the reactions

$$pp \to p^{(*)} X p^{(*)}$$

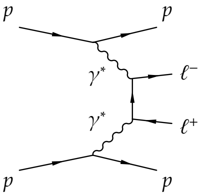
where many production mechanisms ($\gamma\gamma, \gamma\mathbb{P}, \mathbb{P}\mathbb{P}, \ldots$) can produce the central system.

Very **rare**, but very **clean events** to study the QED at high energies :

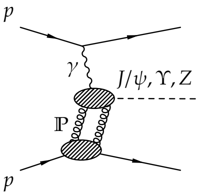
- Large **rapidity gaps** between the central system and the outgoing remnants or scattered protons (forward regions)
- Few tracks from the considered vertex, very **low activity** in the central detector



$\mathbb{P}\mathbb{P}$ exchanges

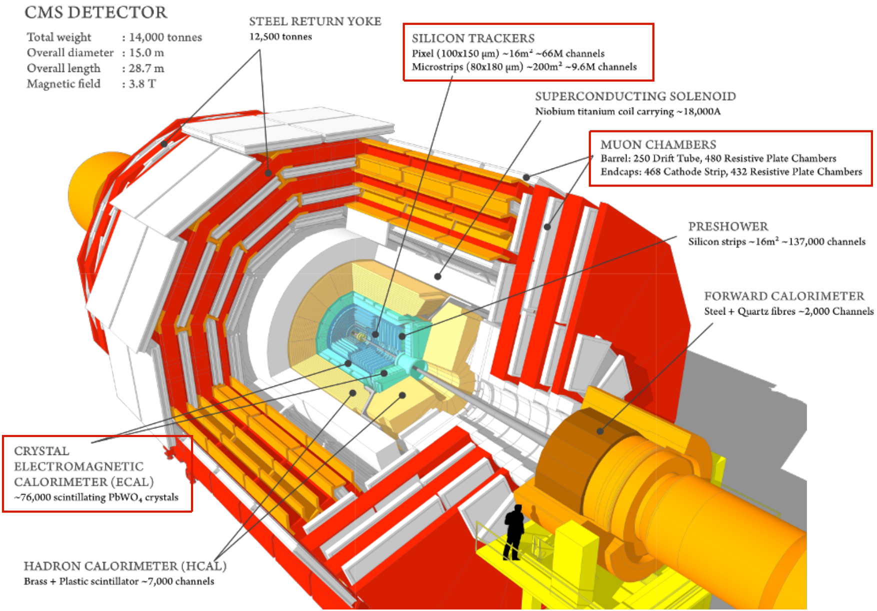


$\gamma\gamma$ interactions



$\gamma\mathbb{P}$ fusions

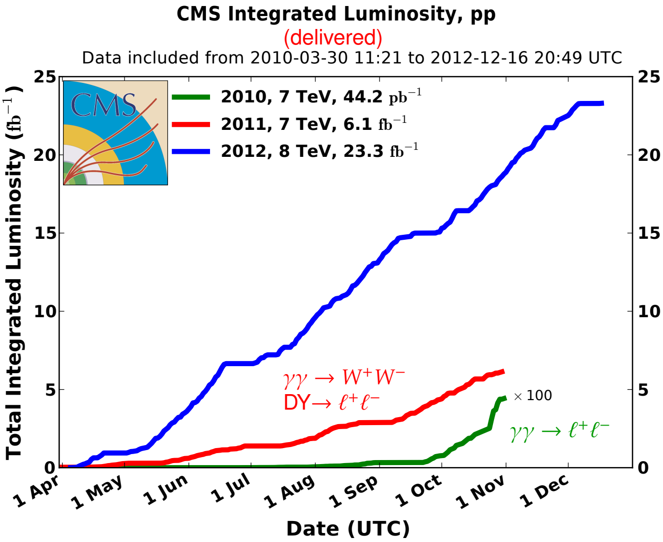
The CMS experiment



Outline

1. Exclusive 2-photon production of lepton pairs
   - $\gamma\gamma \to e^+e^-$
   - $\gamma\gamma \to \mu^+\mu^-$
2. Search for AQGCs in $\gamma\gamma \to W^+W^-$
   - Inelastic yield
   - Search for $\gamma\gamma \to W^+W^-$
   - Limits on anomalous quartic gauge couplings
3. Differential DY cross-section in pp collisions
4. The CMS-TOTEM Precision Proton Spectrometer

The datasets



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Exclusive $\gamma\gamma \to \ell^+\ell^-$ production

JHEP 11 (2012) 080 ($\gamma\gamma \to e^+e^-$) & JHEP 11 (2012) 052 ($\gamma\gamma \to \mu^+\mu^-$)

Search for two-photon production of dileptons (electrons and muons)

Key features

Pure QED process (perfectly described by theory)

Dielectron channel :

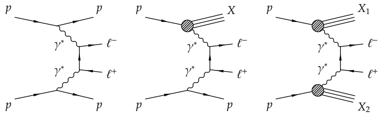
$E_T(e^\pm) > 5.5$ GeV, $|\eta(e^\pm)| < 2.1$

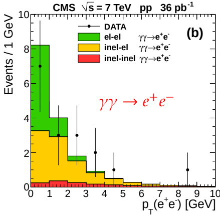
Dimuon channel :

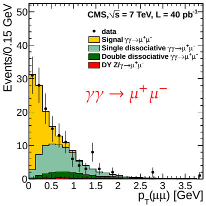
$p_T(\mu^\pm) > 4$ GeV, $|\eta(\mu^\pm)| < 2.5$,
$m(\mu^+\mu^-) > 11.5$ GeV, $\Delta\phi(\mu^+\mu^-)/\pi > 0.9$,
$\Delta p_T(\mu^+\mu^-) < 1$ GeV

One vertex with two leptons and **no additional tracks**

Signal generated using LPAIR







- **17 observed candidates** for the $\gamma\gamma \to e^+e^-$ process, SM expectations : 16.3 ± 1.3 (syst.) signal and 0.85 ± 0.28 (syst.) background events
- Production cross-section for the $\gamma\gamma \to \mu^+\mu^-$ signal with 40 pb^{-1} at 7 TeV :

$$\sigma^{\text{prod}} = 3.38^{+0.58}_{-0.55}\ (\text{stat.}) \pm 0.16\ (\text{syst.}) \pm 0.14\ (\text{lumi.})\ \text{pb}$$

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Search for two-photon production of W pairs

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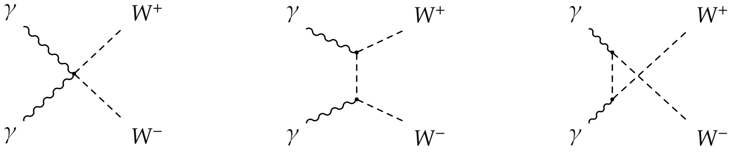

Quartic coupling — t-channel — u-channel

Motivations

- observe (or set limits on the production rate...)
- search for anomalous behaviours : *Anomalous Quartic Gauge Couplings* (AQGCs)

AQGC model

Effective Lagrangian (dimension-6 operators) : G. Belanger *et al.*, Eur.Phys.J. **C13** (2000) 283293

$$\mathcal{L}_{\mathrm{AQGC}} \ni \begin{cases} \mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c^W}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}\left(W^{+\alpha}W^-{}_\beta - W^{-\alpha}W^+{}_\beta\right) - \frac{e^2}{16\cos^2\theta_W}\frac{a_c^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta \\ \mathcal{L}_6^0 = -\frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-{}_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha \end{cases}$$

Preliminary statement : fraction of inelastic cross-section

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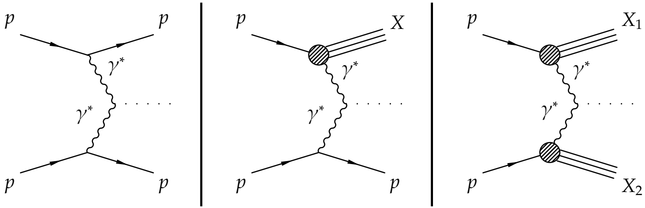
Problematic

Currently, no kinematic information for the outgoing protons (or remnants)

→ How to quote a prediction for the single- and double-dissociative **inelastic contributions**, given the **pure elastic** scenario ?



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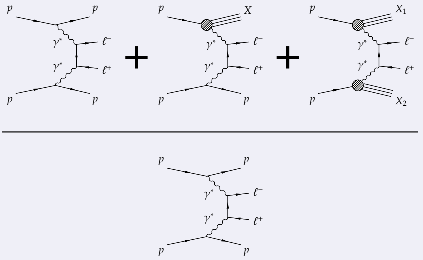
Inelastic contributions

Given the high statistics of the **dilepton channel**, inelastic part of the signal can be extracted from data for **any given phase space region** :

$F =$



signal kinematic region

A look (back) at $\gamma\gamma \rightarrow \mu^+\mu^-$

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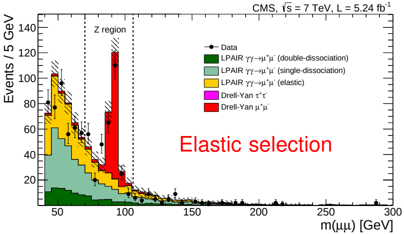
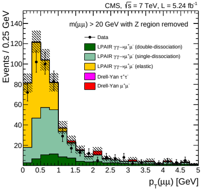
Key features

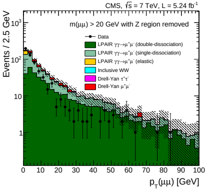
- “**High-statistics**”, well-theoretically described channel
- Single lepton selection :
  $p_T(\mu) > 20$ GeV, $|\eta(\mu)| < 2.4$
- Two kinematic regions
  - **Elastic**-enhanced :
    $\Delta p_T < 1$ GeV and $\Delta\phi/\pi > 0.9$
  - **Dissociation**-enhanced : ”anti-elastic”
- Dilepton primary vertex with no additional tracking activity

Region	Data	Data/MC
Elastic	820 ± 28.6	0.905 ± 0.044
Dissociative	1312 ± 36.2	0.717 ± 0.026





Elastic, no Z peak



Inelastic, no Z peak

Overall agreement in the elastic region, **deficit** of data observed in the **dissociative region** (mainly at high $p_T(\mu\mu)$ values)
→ phenomenology of the rescattering effects not implemented in `LPAIR` so far...

Search for two-photon production of W pairs and ...

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Search strategy

Look for events with :

- **Two high-energy** well-reconstructed **leptons** associated to **one single vertex**
- **No extra tracks** on the primary vertex (exclusivity condition)

Extract prediction for the **observation cross-section** for the $\gamma\gamma \rightarrow W^+W^-$ process

Inelastic yield

Data-driven "inelastic scaling factor" F defined using the region :

$$m(\ell^\pm \ell^\mp) > 160 \text{ GeV} \simeq 2 \times M_W$$

Overall **signal scaling** to take into account **inelastic contributions** for $\gamma\gamma \rightarrow W^+W^-$:

$$F = 3.23 \pm 0.53 \text{ (stat. + syst.)}$$

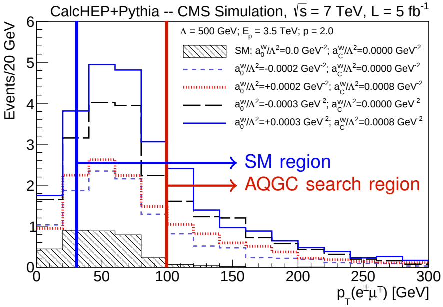
Preselection

- $e - \mu$ triggers with **asymmetric p_T thresholds** ($H \to W^+W^-$ searches)
- $m(e\mu) > 20$ GeV
- **Single lepton** identification :
  - $p_T(\mu), E_T(e) > 20$ GeV
  - $|\eta(\mu)|, |\eta(e)| < 2.4$
- **No additional tracks** on dilepton vertex

Signal regions

Defined by the lower bound on $p_T(e\mu)$:

- "**SM-enhanced region**" : $p_T(e\mu) > 30$ GeV
- "**AQGC-enhanced region**" : $p_T(e\mu) > 100$ GeV



Cut	Visible cross-section	Rem. data events
Trigger	1.1 fb	9086
$m(e\mu) > 20$ GeV	1.1 fb	8200
μ, e identification	0.9 fb	724
Exclusivity condition	0.6 fb	6
$p_T(e\mu) > 30$ GeV	0.4 fb	2

Signal generated using `CalcHEP` 2.5.4, W decay with `Pythia` 6.422

Search for two-photon production of W pairs and ...

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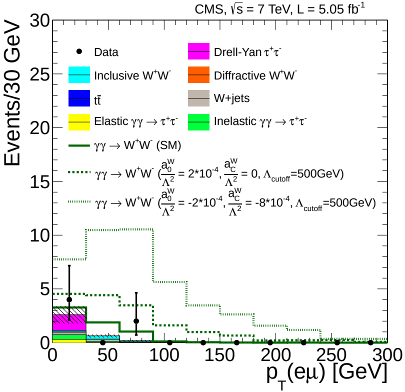
Region	SM	AQGCs
Background	0.84 ± 0.15	0.14 ± 0.02
Signal	2.2 ± 0.4	
Observed	2	0



- **SM region** ($p_T(e\mu) > 30$ GeV) Observed production cross-section

$$\sigma_{\text{obs}}\left(pp \to p^{(*)}(\gamma\gamma \to W^+W^-)p^{(*)}\right) \times BR(W^\pm \to \mu^\pm\nu,\ e^\pm\nu) = 2.2^{+3.3}_{-2.0}\ \text{fb}$$

(SM prediction = 4.0 ± 0.7 fb)

- **AQGC region** ($p_T(e\mu) > 100$ GeV) Upper limit on production cross-section at 95% C.L. :

$$\sigma\left(pp \to p^{(*)}(\gamma\gamma \to W^+W^-)p^{(*)}\right) \times BR(W^\pm \to \mu^\pm\nu,\ e^\pm\nu) < 1.9\ \text{fb}$$

which can be translated into limits on AQGCs...

. . . limits on anomalous quartic gauge couplings

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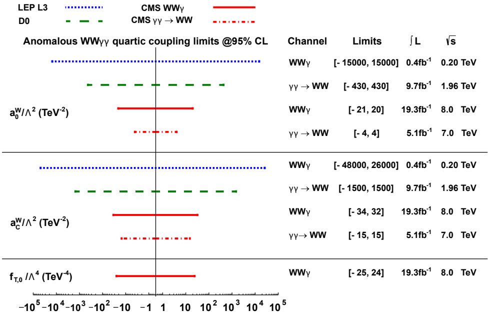
1-D limits at 95% C.L. on the anomalous parameters (in GeV^{-2}) :

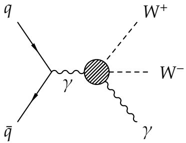
		OPAL (2004)	DØ (2013)	CMS $\gamma\gamma \to WW$ (2013)
a_0^W/Λ^2 [GeV^{-2}]	no form factor	$\pm 2 \times 10^{-2}$	$\pm 4.3 \times 10^{-4}$	$\pm 4.0 \times 10^{-6}$
	Λ_{cutoff} = 500 GeV		$\pm 2.5 \times 10^{-3}$	$\pm 1.5 \times 10^{-4}$
a_c^W/Λ^2 [GeV^{-2}]	no form factor	${}^{+3.7}_{-5.2} \times 10^{-2}$	$\pm 1.5 \times 10^{-3}$	$\pm 1.5 \times 10^{-5}$
	Λ_{cutoff} = 500 GeV		$\pm 9.2 \times 10^{-3}$	$\pm 5.0 \times 10^{-4}$



Up to **two orders of magnitude** improvements to previously fixed limits

- OPAL (LEP2, e^+e^-) [arXiv:0402021]
- DØ (Tevatron, $p\bar{p}$) [arXiv:1305.1258]

Still tighter than the **fully inclusive** CMS $WW\gamma$ study [arXiv:1404.4619] :



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Differential and double-differential DY cross-sections

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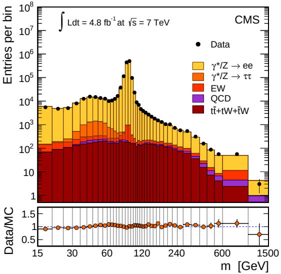
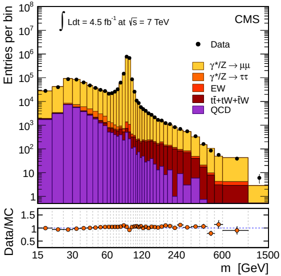
Study of the **differential** ($m_{\ell\ell}$) and **double-differential** ($m_{\ell\ell}, |y|$) Drell-Yan cross-sections :

$$\frac{d\sigma_{DY}}{dm_{ee}}, \quad \frac{d\sigma_{DY}}{dm_{\mu\mu}}, \quad \text{and} \quad \frac{d^2\sigma_{DY}}{dm_{\mu\mu}\, d|y|}$$





Key features

- Di-muons, di-electron, and combined mass ranges :

  $15\text{ GeV} < m_{\ell\ell} < 1500\text{ GeV}$ (sing.-differ. $ee, \mu\mu$)

  $20\text{ GeV} < m_{\mu\mu} < 1500\text{ GeV}$ (doub.-differ. $\mu\mu$)

- **Single lepton** acceptance :

  $|\eta(e)| < 2.5,\ E_T(e) > 10,\ 20\text{ GeV}$

  $|\eta(\mu)| < 2.4,\ p_T(\mu) > 9,\ 14\text{ GeV}$

- **Normalisation** to the Z-peak region ($60\text{ GeV} < m_{\ell\ell} < 120\text{ GeV}$)

Differential and double-differential DY cross-sections

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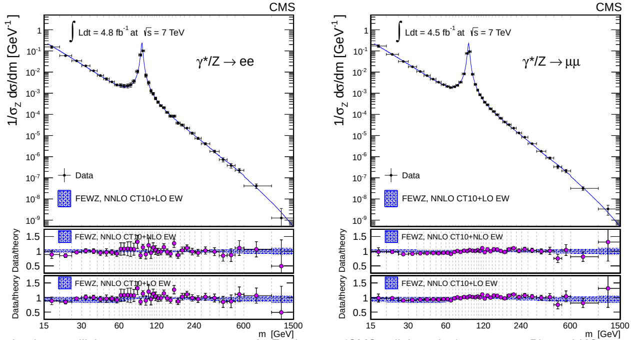
- Comparison to NLO (`Powheg-Pythia`), NNLO (`Fewz`) predictions for **various PDF sets** : `CT10`, `NNPDF2.1`, `MSTW2008`, `HERAPDF15`, `JR09`, `ABKM09`, and `CT10W`
- **Unfolding** to extract the differential (and double-differential) cross-sections
- **Total cross-section** (combined channels) :

$$\sigma_{\text{obs}}^{\text{total}} = 986.4 \pm 0.6\ (\text{stat.}) \pm 5.9\ (\text{exp. syst.}) \pm 21.7\ (\text{th. syst.}) \pm 21.7\ (\text{lum.})\ \text{pb}$$

- **Cross-section in Z region** (combined, $60 < m_{\ell\ell} < 120$ GeV, $|y| < 2.4$)

$$\sigma_{\text{obs}}^{\text{Z region}} = 524.7 \pm 0.4\ (\text{stat.}) \pm 5.1\ (\text{exp. syst.}) \pm 1.2\ (\text{th. syst.}) \pm 11.5\ (\text{lum.})\ \text{pb}$$



Differential and double-differential DY cross-sections

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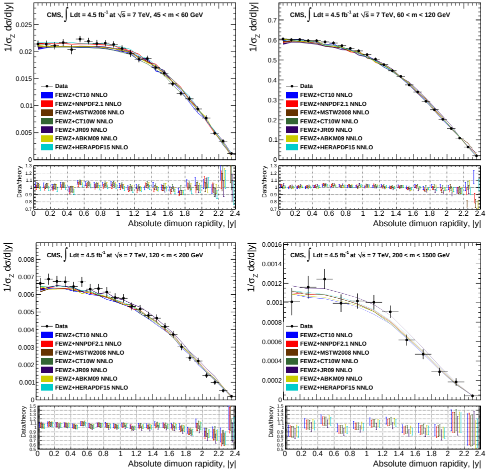
- **Double-differential** cross-section knowledge enables the probe of $|y|$ for **each mass bin**
- `NNPDF2.1` describes well for low $m_{\mu\mu}$, and `JR09` overshoots data for high masses

What about the $\gamma\gamma$ processes ?

- $pp \to p^{(*)}\gamma\gamma p^{(*)} \to p^{(*)}\ell^+\ell^- p^{(*)}$ treated as a background
- Taken into account in the LO-NLO differences of the **EW corrections**
- Yield : up to **10% differences** in **high-mass regions**
- Generator : `Fewz` v3.1.b2



Double-diff. cross-sections ranges (μ channel) probing : ($|y| < 2.4$ and $20 < m_{\ell\ell} < 1500$ GeV)

$$3 \times 10^{-4} < x < 0.5,$$

$$500\ \text{GeV}^2 < Q^2 < 9 \times 10^4\ \text{GeV}^2$$

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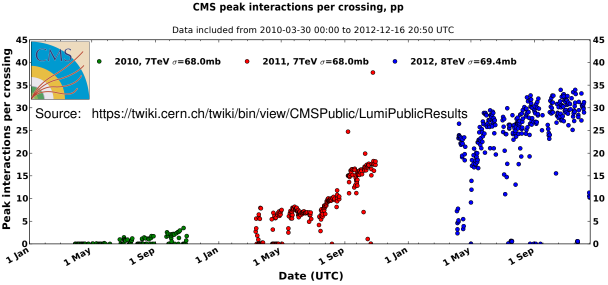
A look forward – The CMS-TOTEM Precision Proton Spectrometer



General motivations

With **increasing number** of **primary vertices** in each event, (track-based) selection efficiency drops for exclusive $\gamma\gamma \to \ell^+\ell^-$, $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to \ldots$ searches

2 solutions

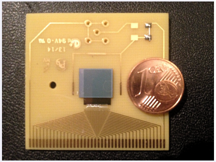
- loosen the exclusivity condition (no extra tracks)
- add information on the primary vertex location

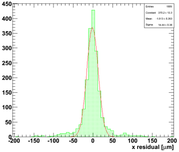
A look forward – The Precision Proton Spectrometer

Key points

Set of detectors to be installed in the (very-)forward region of CMS (220-240 m) to :

- **Tag** the unfragmented protons at high luminosity / low β^*
- Reconstruct their kinematics (embedded **tracking** system)
  - 3D silicon sensors (+ CMS `PSI46Dig readout`)
  - Preliminary tests : $\sigma_{x,y} \sim$ 11-13 μm





- Match the interaction with the central system (**timing** detectors)
  - $\sigma_t \sim$ 10 ps for a 2 mm vertex-z resolution
  - Fine granularity (high hit occupancy)
  - Radiation hardness
  - Several designs under study : Čerenkov (`QUARTIC`, `GasToF`), diamond sensor (R&D)

2 designs under investigation :

- Roman Pots (in collaboration with TOTEM)
- Moveable beam pipe

Prototype to be installed and tested in 2015,
TDR to be released soon

Overview

Precision physics

- **Searches for $\gamma\gamma \to \ell^+\ell^-$**
- Search for $\gamma\gamma \to W^+W^-$
- Differential DY cross-section

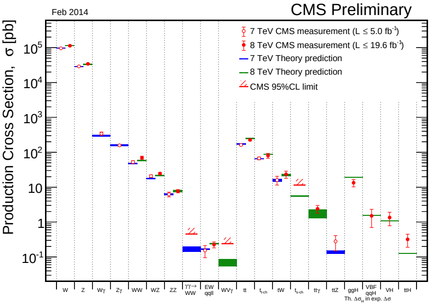
- Observation of **17** exclusive $\gamma\gamma \to e^+e^-$ events
- Exclusive $\gamma\gamma \to \mu^+\mu^-$ production cross-section (40 pb^{-1} at 7 TeV) :

$$\sigma^{\text{prod}} = 3.38^{+0.58}_{-0.55}\ \text{(stat.)} \pm 0.16\ \text{(syst.)} \pm 0.14\ \text{(lumi.) pb}$$

Precision physics

- Searches for $\gamma\gamma \to \ell^+\ell^-$
- **Search for** $\gamma\gamma \to W^+W^-$
- Differential DY cross-section

- Still one of the lowest production cross-section probed at the LHC ($\sim$ 100 fb)
- LEP constraints on AQGCs overshot by two order of magnitude
- Competitiveness of exclusive searches wrt fully inclusive ones



Overview

Precision physics

- Searches for $\gamma\gamma \to \ell^+\ell^-$
- Search for $\gamma\gamma \to W^+W^-$
- **Differential DY cross-section**

- Accurate measurement of differential $\sigma(Z, \gamma^* \to e^+e^-, \mu^+\mu^-)$ with respect to $m_{\ell\ell}$ (and $|y|$ for $\mu\mu$)
- Most precise inclusive Z cross-section observations ($60 < m_{\ell\ell} < 120$ GeV) at a hadron collider
- $\mathrm{d}^2\sigma \big/ \mathrm{d}m_{\mu\mu}\mathrm{d}|y|$ comparison with actual PDF sets provides an efficient probe to update them, first observation at a hadron collider

Backup

$\mathbb{PP} \to \gamma\gamma$ and $\gamma\gamma \to e^+e^-$– Cut flows

$\mathbb{PP} \to \gamma\gamma$ analysis

Cut	Remaining events
Trigger	3023496
Photon reconstruction	1683526
Photon identification	40692
Cosmic rays rejection	34234
Exclusivity condition	0

$\gamma\gamma \to e^+e^-$ analysis

Cut	Remaining events
Trigger	3023496
Electron reconstruction	132271
Electron identification	1668
Cosmic rays rejection	1321
Exclusivity condition	17

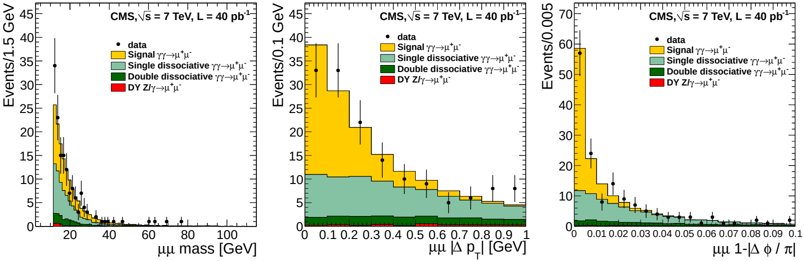
Rapidity gap survival probability

Process	State	S^2
Elastic		1
Single-dissociation	low mass	0.86 ± 0.03
	high mass	0.81 ± 0.03
Double-dissociation	low mass & low mass	0.3–0.45
	low mass & high mass	0.2–0.28
	high mass & high mass	0.08–0.16

Low mass : $M_X < 2.0$–2.5 GeV

$\gamma\gamma \to \mu^+\mu^-$ – Cut flows and control plots

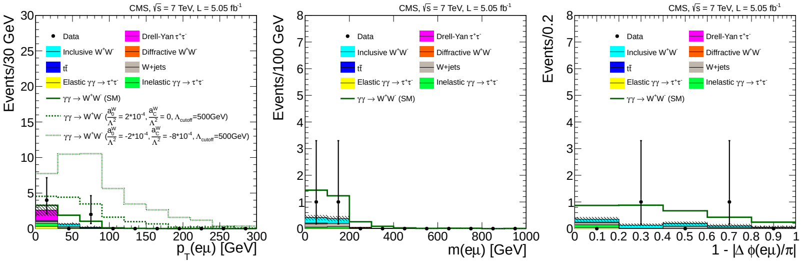
Cut	Remaining events
Trigger	7.87×10^6
Exclusivity condition	921
Muon identification	724
$p_T(\mu) > 4$ GeV, $\lvert\eta(\mu)\rvert < 2.1$	438
$m(\mu\mu) > 11.5$ GeV	270
3D angle $< 0.95\pi$	257
1-$\lvert\Delta\phi(\mu\mu)/\pi\rvert < 0.1$	203
$\Delta p_T(\mu\mu) < 1$ GeV	148



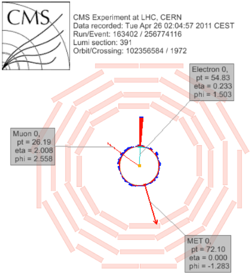
$\gamma\gamma \to W^+W^-$ – Cut flows and signal events distributions

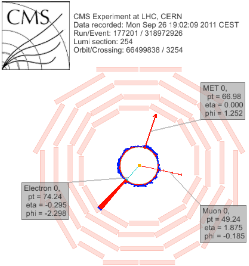
Cut	Remaining events
Trigger	9086
$m(\mu\mu) > 20$ GeV	8200
Muon, electron identification	724
Exclusivity condition	6
$p_T(\mu\mu) > 30$ GeV	2

Signal region



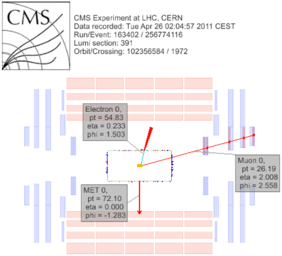
$\gamma\gamma \to W^+W^-$– Event displays

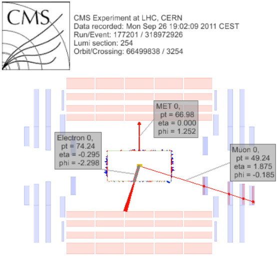




First candidate events

Only tracks from the $e\mu$ primary vertex, pileup events hidden





	σ_{obs} in the Z-peak region in det. acceptance (60 $< m <$ 120 GeV, $\|y\|$ ¡ 2.4)
Data	524.7 ± 0.4 (stat.) ± 5.1 (exp. syst.) ± 1.2 (th. syst.) ± 11.5 (lum.) pb
CT10 NNLO	534.29 ± 0.36 (stat) ± 16.60 (PDF) pb
NNPDF2.1 NNLO	524.76 ± 0.68 (stat) ± 6.38 (PDF) pb
MSTW2008 NNLO	524.02 ± 0.38 (stat.) ± 17.46 (PDF) pb
JR09 NNLO	485.97 ± 0.36 (stat.) ± 11.78 (PDF) pb
ABKM09 NNLO	534.69 ± 0.43 (stat.) ± 9.30 (PDF) pb
HERAPDF15 NNLO	531.92 ± 0.23 (stat.) ± 6.25 (PDF) pb