



# Exclusive processes in *pp* collisions in CMS

**Gustavo Silveira**

[gustavo.silveira@cern.ch](mailto:gustavo.silveira@cern.ch)

on behalf of the CMS Collaboration

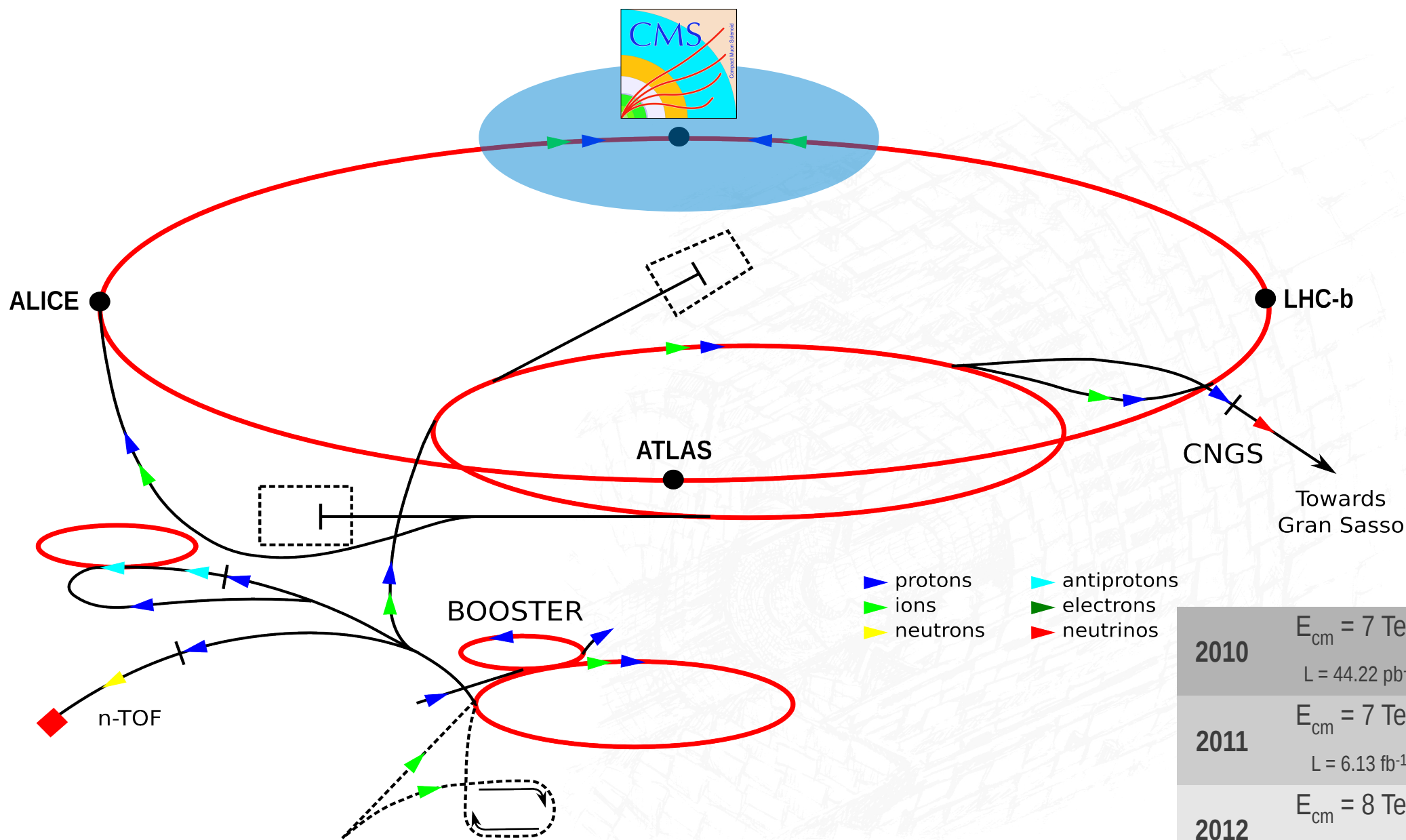
Centre for Cosmology, Particle Physics and Phenomenology (CP3)  
Universite catholique de Louvain (UCL), Belgium

# Outline



- CMS detector and capabilities for forward physics;
- Probing central exclusive processes at high-energies;
  - Limits on central exclusive  $IPIP \rightarrow \gamma\gamma$  production;
  - Measurement of exclusive  $\gamma\gamma \rightarrow e^+e^-$ ;
  - Measurement of exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$ .
- Exclusive production of massive electroweak boson pairs;
  - Cross-checks with exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$  at large masses;
  - Search for exclusive  $\gamma\gamma \rightarrow W^+W^-$  production;
  - Limits on anomalous quartic gauge couplings.

# Large Hadron Collider



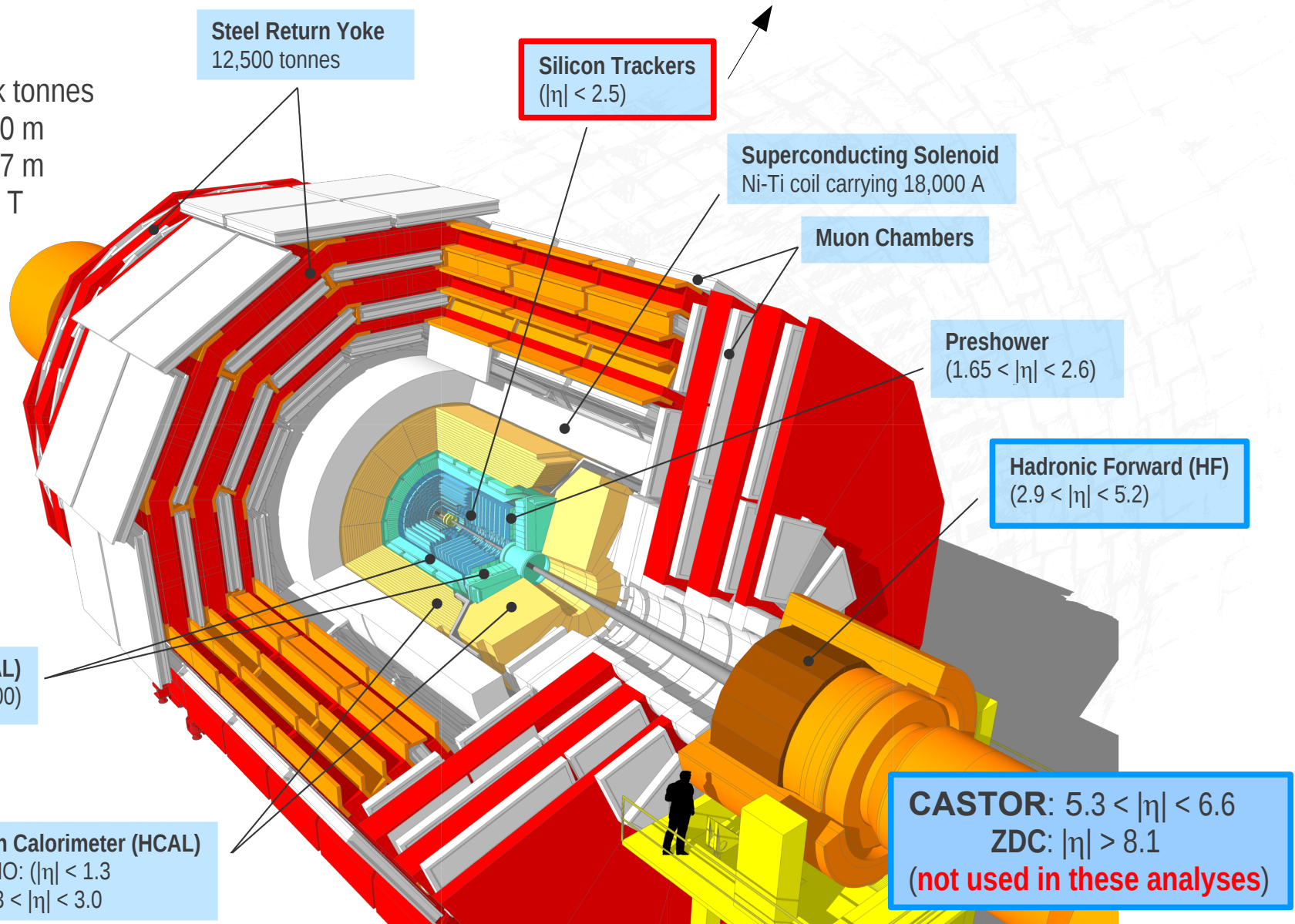
- ▶ protons
- ▶ antiprotons
- ▶ ions
- ▶ electrons
- ▶ neutrons
- ▶ neutrinos

<b>2010</b>	$E_{cm} = 7 \text{ TeV}$ $L = 44.22 \text{ pb}^{-1}$
<b>2011</b>	$E_{cm} = 7 \text{ TeV}$ $L = 6.13 \text{ fb}^{-1}$
<b>2012</b>	$E_{cm} = 8 \text{ TeV}$ $L = 23.30 \text{ fb}^{-1}$

# The CMS experiment

**Exclusivity selection:** Tracker info to select **no** other tracks apart of the two leptons/bosons

Total weight : 14k tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T





# Outline



- CMS detector and capabilities for forward physics;
- Probing central exclusive processes at high-energies;
  - Limits on central exclusive  $IPIP \rightarrow \gamma\gamma$  production;
  - Measurement of exclusive  $\gamma\gamma \rightarrow e^+e^-$ ;
  - Measurement of exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$ .
- Exclusive production of massive electroweak boson pairs;
  - Cross-checks with exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$  at large masses;
  - Search for exclusive  $\gamma\gamma \rightarrow W^+W^-$  production;
  - Limits on anomalous quartic gauge couplings.

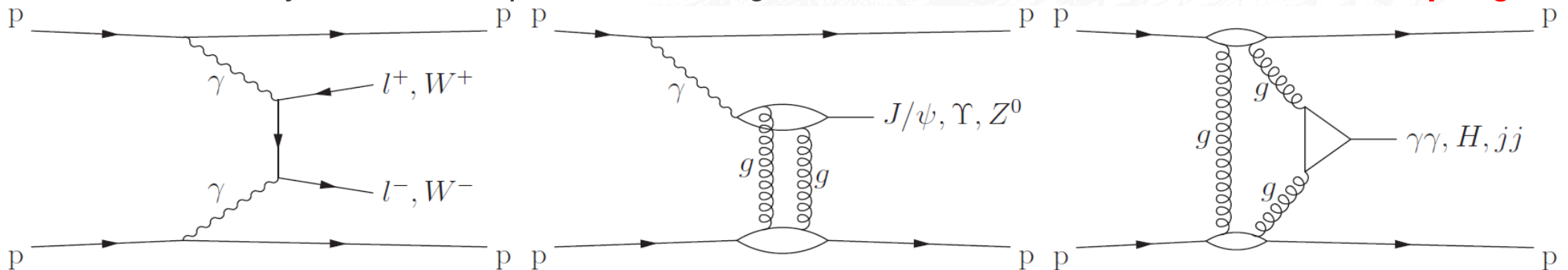
# Exclusive processes at LHC



- The central exclusive production of light and heavy pairs is represented by:

$$pp \rightarrow p^{(*)} + (\gamma\gamma, \ell^+\ell^-, W^+W^-) + p^{(*)}$$

- Intact protons in the final states, however also accounting for **proton dissociation**;
- No other particles in the final states**;
- $\gamma\gamma$ : tests for theoretical prediction for **exclusive Higgs production** and to measure **gluon density at small- $x$** ;
- $\ell^+\ell^-$ : comparison to precision QED predictions and to study of **proton dissociation**;
- $W^+W^-$ : study of exclusive processes at high mass and constraint of **anomalous couplings**.



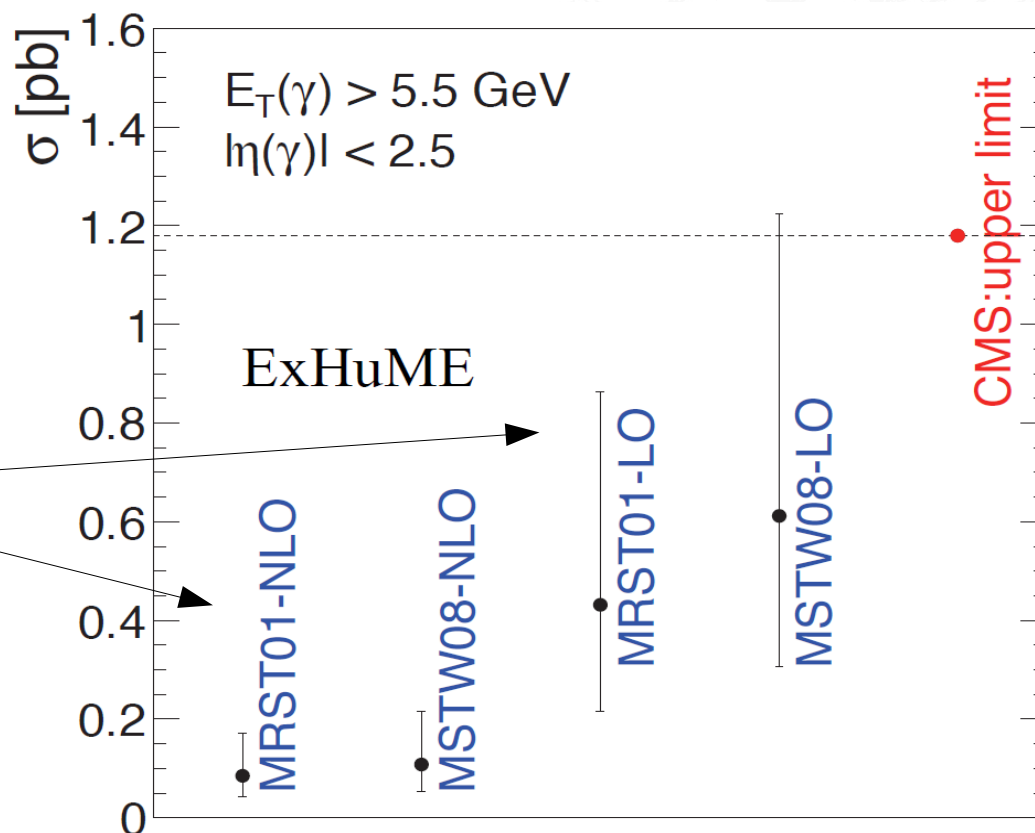
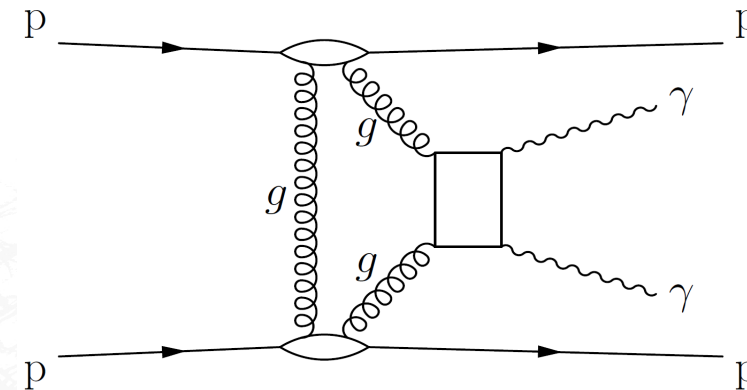
# Central exclusive $\gamma\gamma$ production

CMS-FWD-11-004  
JHEP 11 (2012) 080



- Data collected on 2010 with **36 pb<sup>-1</sup>**;
- With the data collected in CMS it is possible to determine an upper limit cross section with **95% CL**:

$$\sigma(E_T(\gamma) > 5.5 \text{ GeV}, |\eta(\gamma)| < 2.5) < 1.18 \text{ pb}$$



No observed candidates  
with bkg. of  $1.79 \pm 0.40$  evt

Theoretical predictions (pb)				
PDFs	MRST01		MSTW08	
	LO	NLO	LO	NLO
Accuracy				
ExHuMe	0.432	0.086	0.612	0.109
SuperCHIC	-	0.103	0.472	-
New results <sup>†</sup>	-	0.039	0.18	-

<sup>†</sup> Harland-Lang, L.A.; Khoze, V.A.; Ryskin, M.G.; Stirling, W.J.; Eur. Phys. J. C 72 (2012) 2110; arXiv:1204.4803v2 [hep-ph] (2012)

# Exclusive production of $\ell^+ \ell^-$ pairs

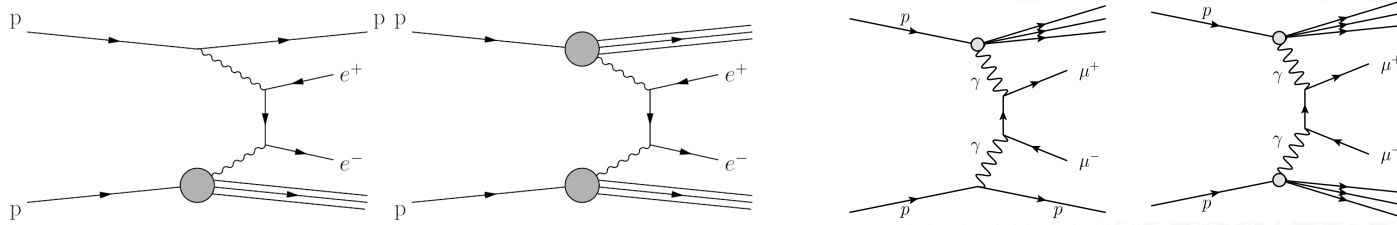


- Selection requires vertex with two leptons tracks & **nothing else**;

- $E_T(e) > 5.5$  GeV and  $|\eta(e)| < 2.5$ ; **electron/positron**

- $p_T(\mu) > 4$  GeV,  $|\eta(\mu)| < 2.1$  and  $m(\mu^+ \mu^-) > 11.5$  GeV; **muons**

- MC predictions include **elastic** processes and contribution from **proton dissociation**:

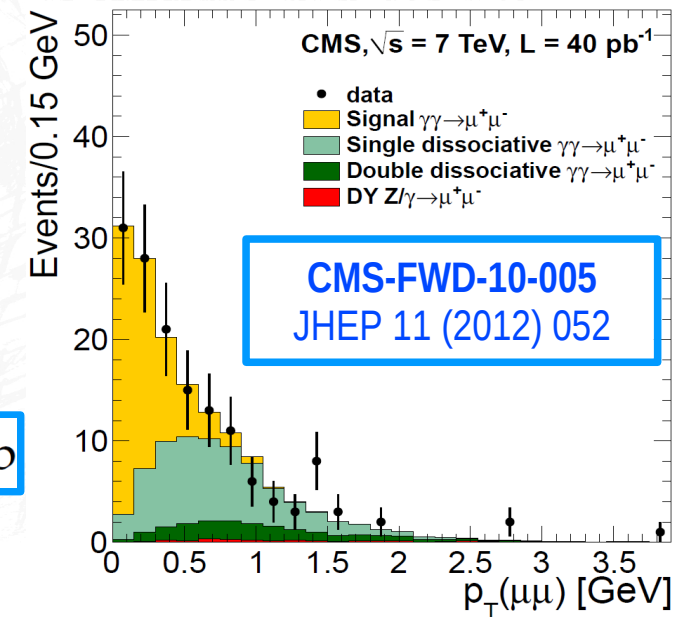
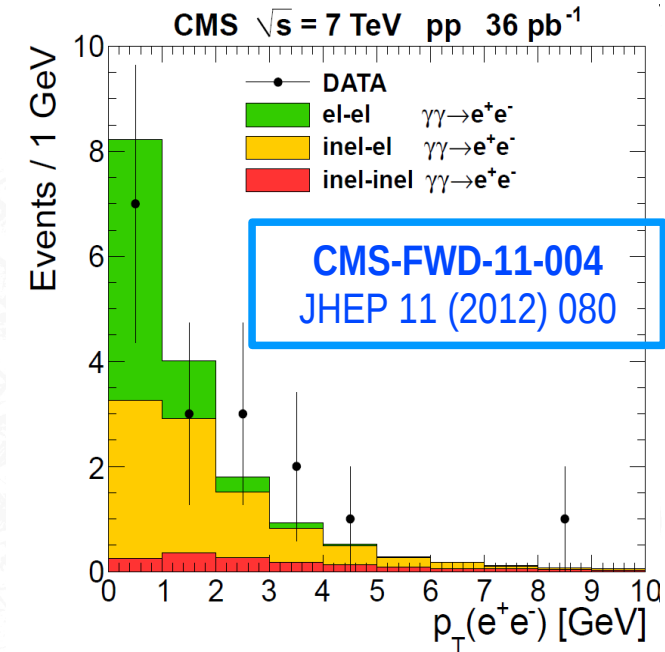


- In the exclusive production of  $e^+ e^-$  pairs, it has been observed **17** (semi-)exclusive events ( $36 \text{ pb}^{-1}$ );

- Measurement of exclusive  $\mu^+ \mu^-$  pairs results in ( $40 \text{ pb}^{-1}$ ):

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

- **Good agreement** between LPAIR and the data.





# Outline

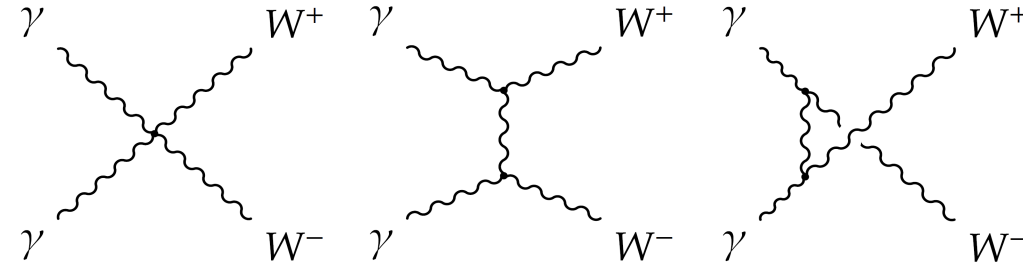


- CMS detector and capabilities for forward physics;
- Probing central exclusive processes at high-energies;
  - Limits on central exclusive  $IPIP \rightarrow \gamma\gamma$  production;
  - Measurement of exclusive  $\gamma\gamma \rightarrow e^+e^-$ ;
  - Measurement of exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$ .
- Exclusive production of massive electroweak boson pairs;
  - Cross-checks with exclusive  $\gamma\gamma \rightarrow \mu^+\mu^-$  at large masses;
  - Search for exclusive  $\gamma\gamma \rightarrow W^+W^-$  production;
  - Limits on anomalous quartic gauge couplings.

# Exclusive $\gamma\gamma \rightarrow W^+W^-$ : theory



- The  $\gamma\gamma \rightarrow W^+W^-$  coupling is present in the SM Lagrangian: quartic coupling plus  $t$ - and  $u$ -channel  $W$  exchange;



- Extension to consider the **anomalous quartic gauge couplings** (aQGC):

$\Lambda$ : scale for new physics

$$L_6^0 = \frac{-e^2 a_0^W}{8 \Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W^-_{\alpha} - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha},$$

$$L_6^C = \frac{-e^2 a_C^W}{16 \Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W^-_{\beta} - W^{-\alpha} W^+_{\beta}) - \frac{e^2}{16 \cos^2 \Theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta},$$

Parameters for the genuine aQGC<sup>†</sup>

- Form factors are included in order to tame the rising of the cross section:

$$a_{0,C}^W(W_{\gamma\gamma}^2) = \frac{a_{0,C}^W}{\left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda^2}\right)^p}$$

$W_{\gamma\gamma}$ :  $\gamma\gamma$  c.m. energy

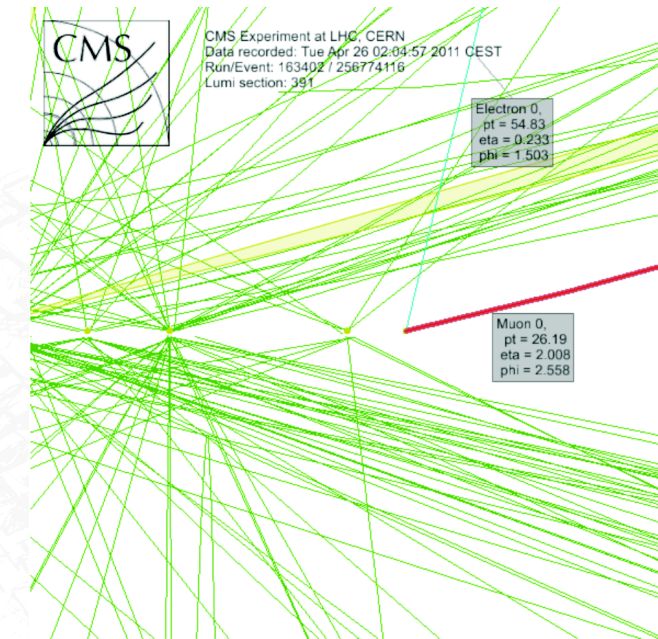
$p = 2$   
(dipole form factor)

- For  $a_0^W / \Lambda^2, a_C^W / \Lambda^2 \sim 10^{-5}$ : unitary bound reached, so  **$\Lambda = 500$  GeV**.

<sup>†</sup> Belanger, G.; Boudjema, F.; Phys. Lett. B 288 (1992) 201

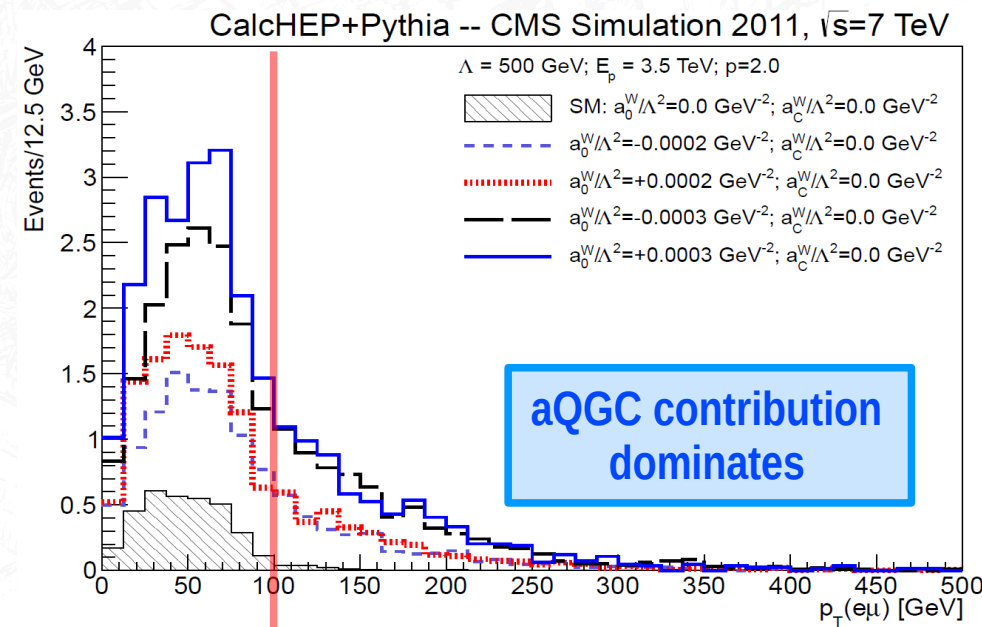
# Event selection

- Data collected in 2011 at 7 TeV:
  - Opposite-sign and flavor  $\mu e$  events in **5.05 fb<sup>-1</sup>**;
  - $\mu^+\mu^-$  events in **5.24 fb<sup>-1</sup>**.
  - Asymmetric triggers with thresholds of 17 & 8 GeV;
  - No extra tracks at the vertex apart of the leptons;



- Selection requires leptons and pairs with:
  - $p_T(\ell) > 15$  GeV and  $|\eta(\ell)| < 2.4$ ;
  - $m(\ell^+\ell^-) > 20$  GeV and  $p_T(\ell^+\ell^-) > 30$  GeV.

- aQGC are studied in a kinematical region with  **$p_T(\mu e) > 100$  GeV**.



# Benchmark with $\gamma\gamma \rightarrow \mu^+\mu^-$ (I)

CMS-FSQ-12-010

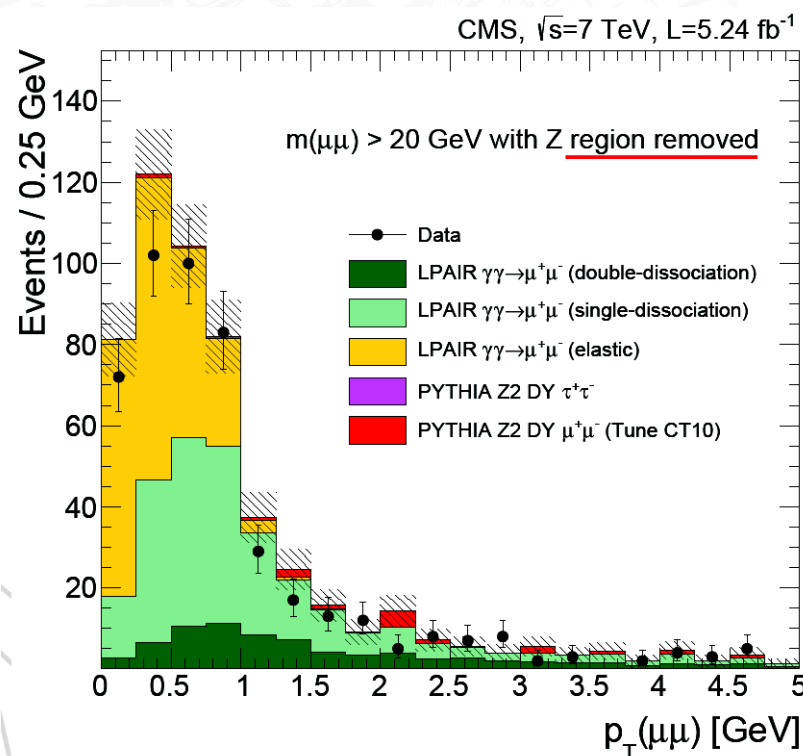
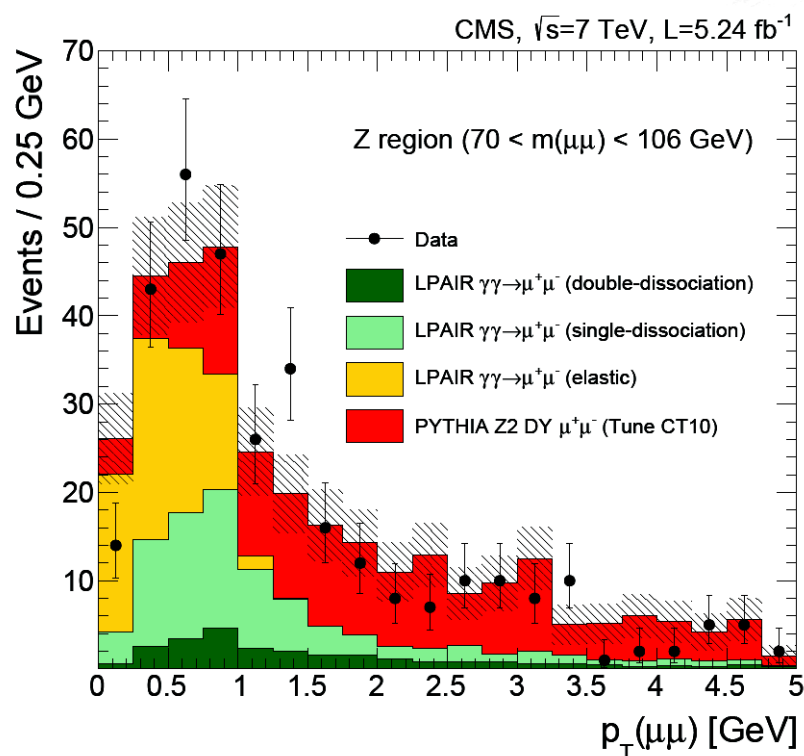


- The dimuon channel is used as a benchmark to **validate** the exclusivity criteria;
- Kinematic regions:  $\longrightarrow$

Good agreement with LPAIR

Elastic	Inelastic (quasi-exclusive)
$1 -  \Delta\phi(\ell^+\ell^-) /\pi < 0.1$	$1 -  \Delta\phi(\ell^+\ell^-) /\pi > 0.1$
$ \Delta p_T(\ell^+\ell^-)  < 1.0$	$ \Delta p_T(\ell^+\ell^-)  > 1.0$

Dissociation dominates



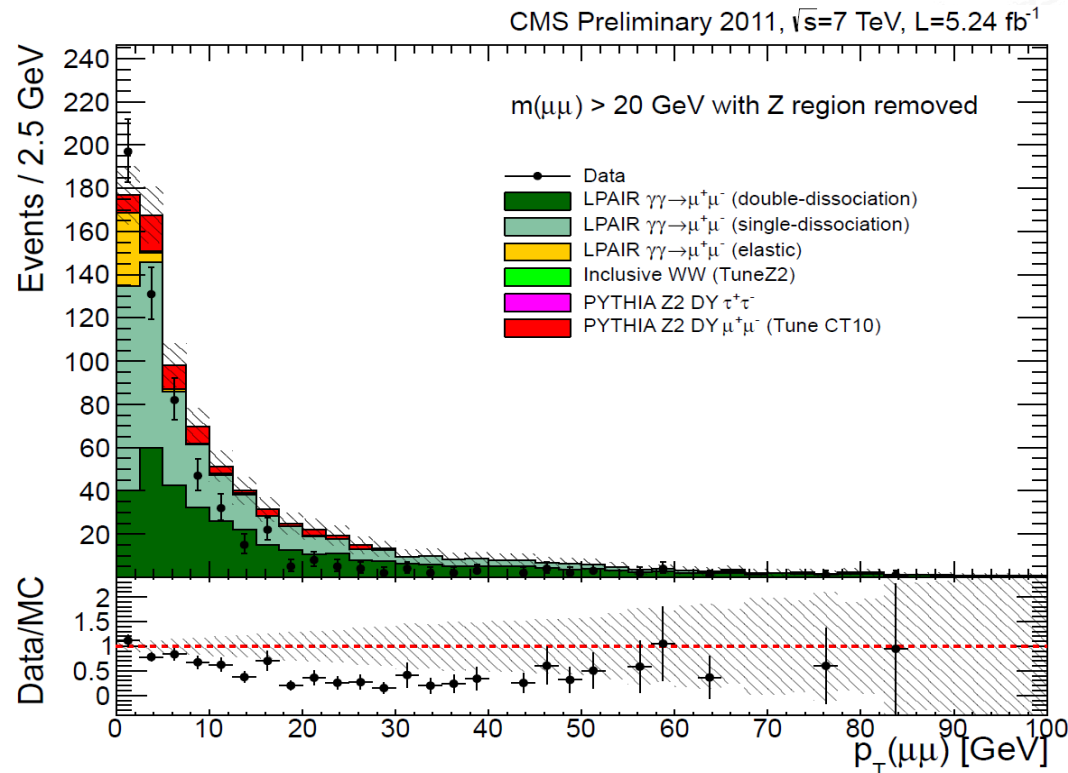
Region	Data	Simulation	Data/Simulation
Elastic	$820 \pm 28.6$	$906.2 \pm 30.1$	$0.905 \pm 0.044$
Dissociation	$1312 \pm 36.2$	$1829.5 \pm 42.8$	$0.717 \pm 0.026$
Total	$2132 \pm 46.2$	$2735.7 \pm 52.3$	$0.779 \pm 0.023$

28% deficit observed in the data compared to MC



# Benchmark with $\gamma\gamma \rightarrow \mu^+\mu^-$ (II)

- Comparing the data to the simulation, we observe a deficit in data that is **not** predicted by the Monte Carlo event generation;



- We estimate a scale factor for masses larger than the W-pair mass as:

$$F = \frac{N_{\mu\mu \text{ data}} - N_{DY}}{N_{\text{elastic}}} \Big|_{m(\mu^+\mu^-) > 160 \text{ GeV}} = 3.23 \pm 0.50 \text{ (stat.)} \pm 0.36 \text{ (syst.)}$$

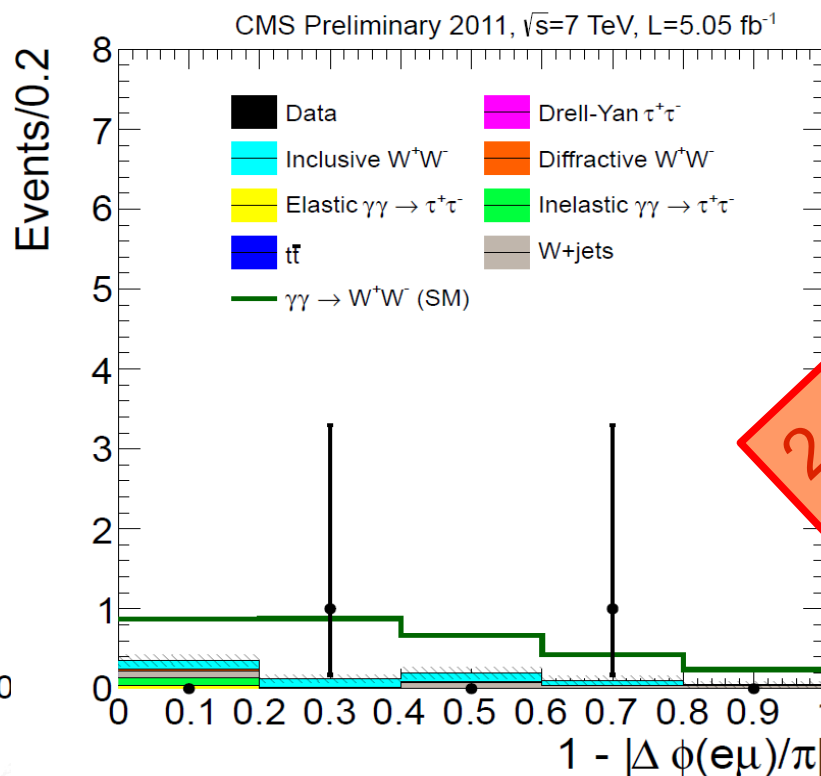
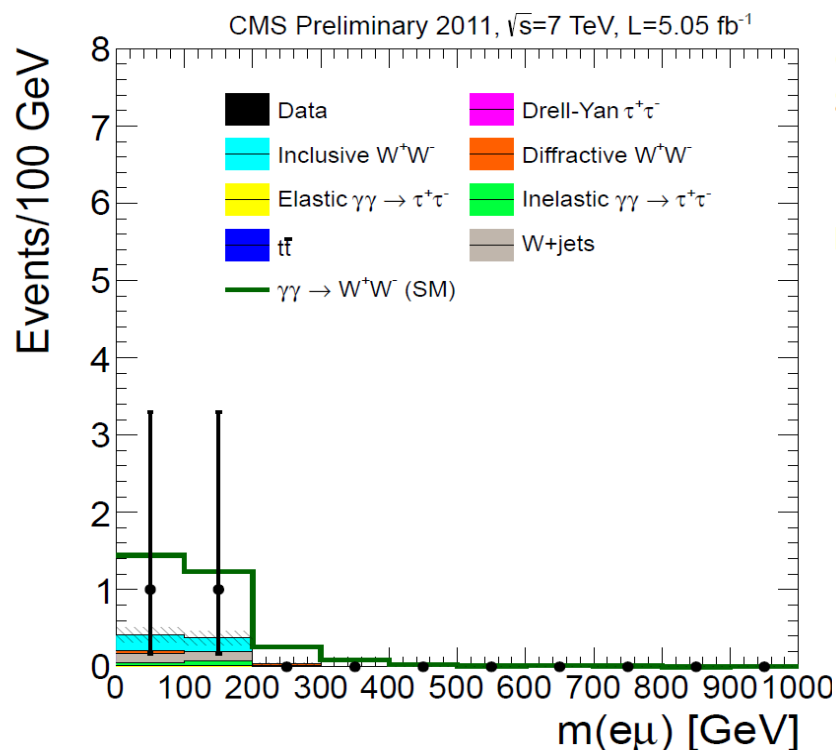
# Signal from $W^+W^- \rightarrow \mu^\pm e^\mp \nu\bar{\nu}$

CMS-FSQ-12-010

- Events passing all the requirements:

Signal:  $2.2 \pm 0.5$  evt  
 Bkg:  $0.84 \pm 0.13$  evt

Selection step	Signal $\epsilon \times A$	Events in data
Trigger and preselection	28.5%	9086
$m(\mu^\pm e^\mp) > 20$ GeV	28.0%	8200
Muon ID and Electron ID	22.6%	1222
$\mu^\pm e^\mp$ vertex with 0 extra tracks	13.7%	6
$p_T(\mu^\pm e^\mp) > 30$ GeV	10.6%	2 <span style="color:red">←</span>



2.2 evt expected  
2 observed

SM:  $3.8 \pm 0.6$  fb

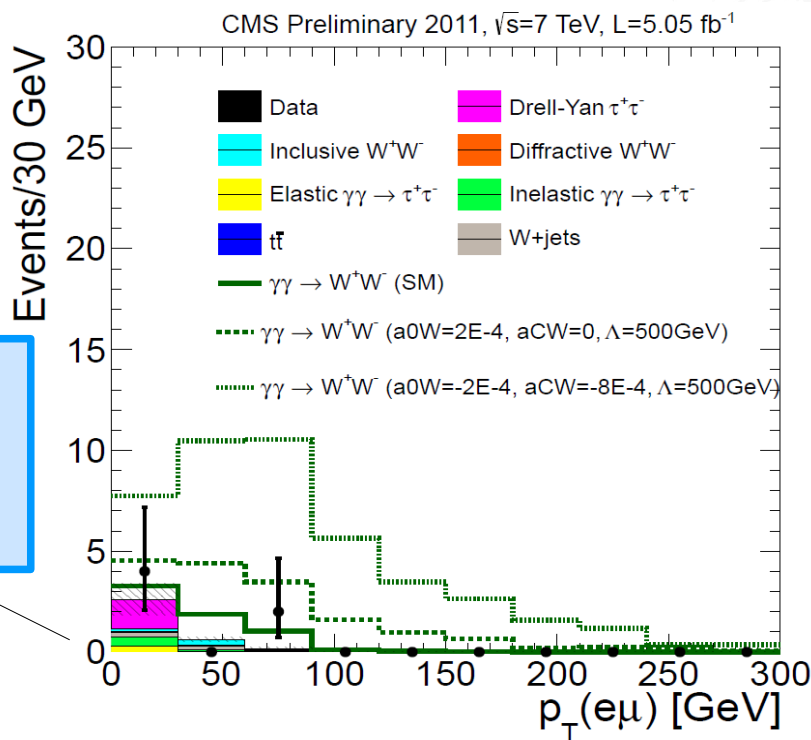
$\sigma \cdot \text{BR}$  with **95% CL**:  $\sigma(pp \rightarrow p^{(*)} W^+ W^- p^{(*)} \rightarrow p^{(*)} \mu^\pm e^\mp p^{(*)}) = 2.1_{-1.9}^{+3.1}$  fb

# Limits on aQGC

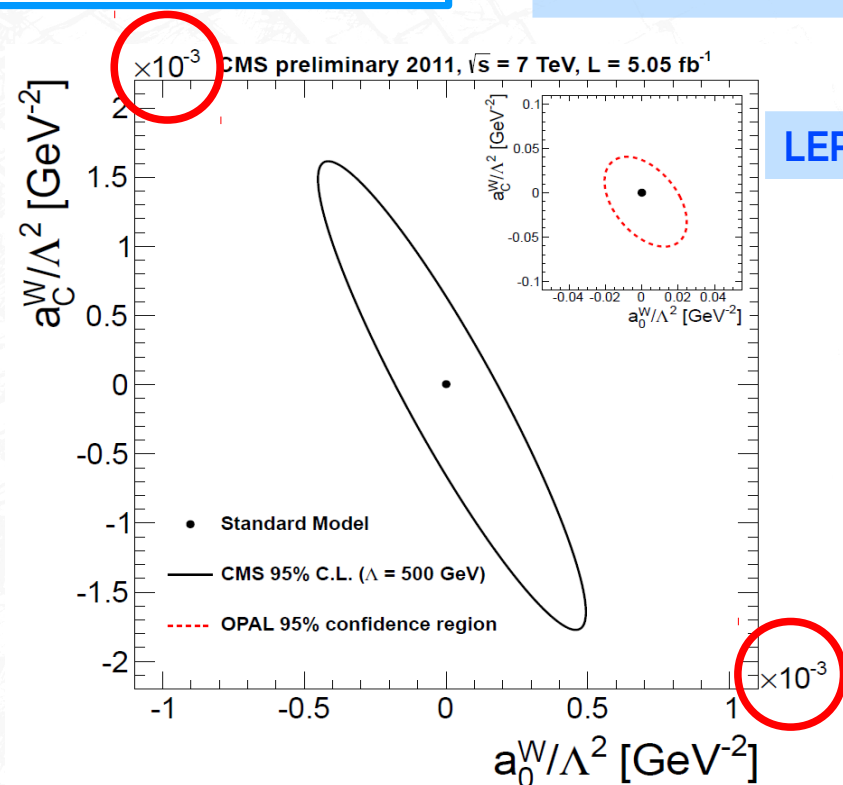
- The upper limit on the cross section times Branching fraction is found as

$$\sigma(pp \rightarrow p^{(*)} W^+ W^- p^{(*)} \rightarrow p^{(*)} \mu^\pm e^\mp p^{(*)}) < 1.9 \text{ fb}$$

Upper limit of 3 events



aQGC would increase yields at high  $p_T(\mu^+\mu^-)$ .  
No extra event found.



$$-0.00017 < a_0^W / \Lambda^2 < 0.00017 \text{ GeV}^{-2} \quad (a_C^W / \Lambda^2 = 0, \Lambda = 500 \text{ GeV})$$

$$-0.0006 < a_C^W / \Lambda^2 < 0.0006 \text{ GeV}^{-2} \quad (a_0^W / \Lambda^2 = 0, \Lambda = 500 \text{ GeV})$$

$$-2.80 \times 10^{-6} < a_0^W / \Lambda^2 < 2.80 \times 10^{-6} \text{ GeV}^{-2} \quad (a_C^W / \Lambda^2 = 0, \text{no form factor}),$$

$$-1.02 \times 10^{-5} < a_C^W / \Lambda^2 < 1.02 \times 10^{-5} \text{ GeV}^{-2} \quad (a_0^W / \Lambda^2 = 0, \text{no form factor})$$

Limits 2 orders of magn. more stringent than those from LEP

# Summary



- CMS has successfully measured exclusive processes at **low** and **high** masses;
- The observed cross sections are in agreement with the theoretical QED predictions for the exclusive  $\gamma\gamma \rightarrow \ell^+\ell^-$  production:

**17** (semi-)exclusive events in exclusive production of  $e^+e^-$  pairs

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

- **Upper limit** cross section on the exclusive central  $IP IP \rightarrow \gamma\gamma$  production with **95% CL**:

$$\sigma(E_T(\gamma) > 5.5 \text{ GeV}, |\eta(\gamma)| < 2.5) < 1.18 \text{ pb}$$

- **Two potential candidates** for the exclusive production of  $W$  pairs with observed cross section in agreement with the SM expectation:

$$\sigma(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.1_{-1.9}^{+3.1} \text{ fb}$$

- aQGC limits:  $-0.00017 < a_0^W / \Lambda^2 < 0.00017 \text{ GeV}^{-2}$  ( $a_C^W / \Lambda^2 = 0, \Lambda = 500 \text{ GeV}$ ),  
 $-0.0006 < a_C^W / \Lambda^2 < 0.0006 \text{ GeV}^{-2}$  ( $a_0^W / \Lambda^2 = 0, \Lambda = 500 \text{ GeV}$ )

- **Two orders of magnitude** more stringent than those determined by the LEP results.





# *Backup slides*

# $IPIP \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow e^+e^-$ : cutflow & efficiency



exclusive diphoton analysis		exclusive dielectron analysis	
selection criterion	events remaining	selection criterion	events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	2 648
Cosmic ray rejection	32 775	Cosmic ray rejection	2 023
Exclusivity requirement	0	Exclusivity requirement	17

exclusive $\gamma\gamma$ analysis		exclusive $e^+e^-$ analysis			
			el-el	inel-el	inel-inel
$\epsilon_{\gamma\gamma}$	$0.485 \pm 0.067$	$\epsilon_{e^+e^-}$	$0.371 \pm 0.037$	$0.438 \pm 0.035$	$0.430 \pm 0.030$
$\epsilon_{\text{cos}}$	$0.979 \pm 0.009$	$\epsilon_{\text{cos}}$	$0.979 \pm 0.009$	$0.822 \pm 0.008$	$0.639 \pm 0.006$
$\epsilon_{\text{fsr}}$	$0.972 \pm 0.003$	$\epsilon_{\text{fsr}}$	$0.927 \pm 0.002$	$0.666 \pm 0.016$	$0.299 \pm 0.009$
$\epsilon_{\text{exc}}$	$0.145 \pm 0.008$	$\epsilon_{\text{exc}}$	$0.145 \pm 0.008$	$0.145 \pm 0.008$	$0.145 \pm 0.008$
$\epsilon$	$0.0669 \pm 0.0100$	$\epsilon$	$0.0488 \pm 0.0056$	$0.0348 \pm 0.0035$	$0.0119 \pm 0.0011$

# $IPIP \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow e^+e^-$ : bkg expectation

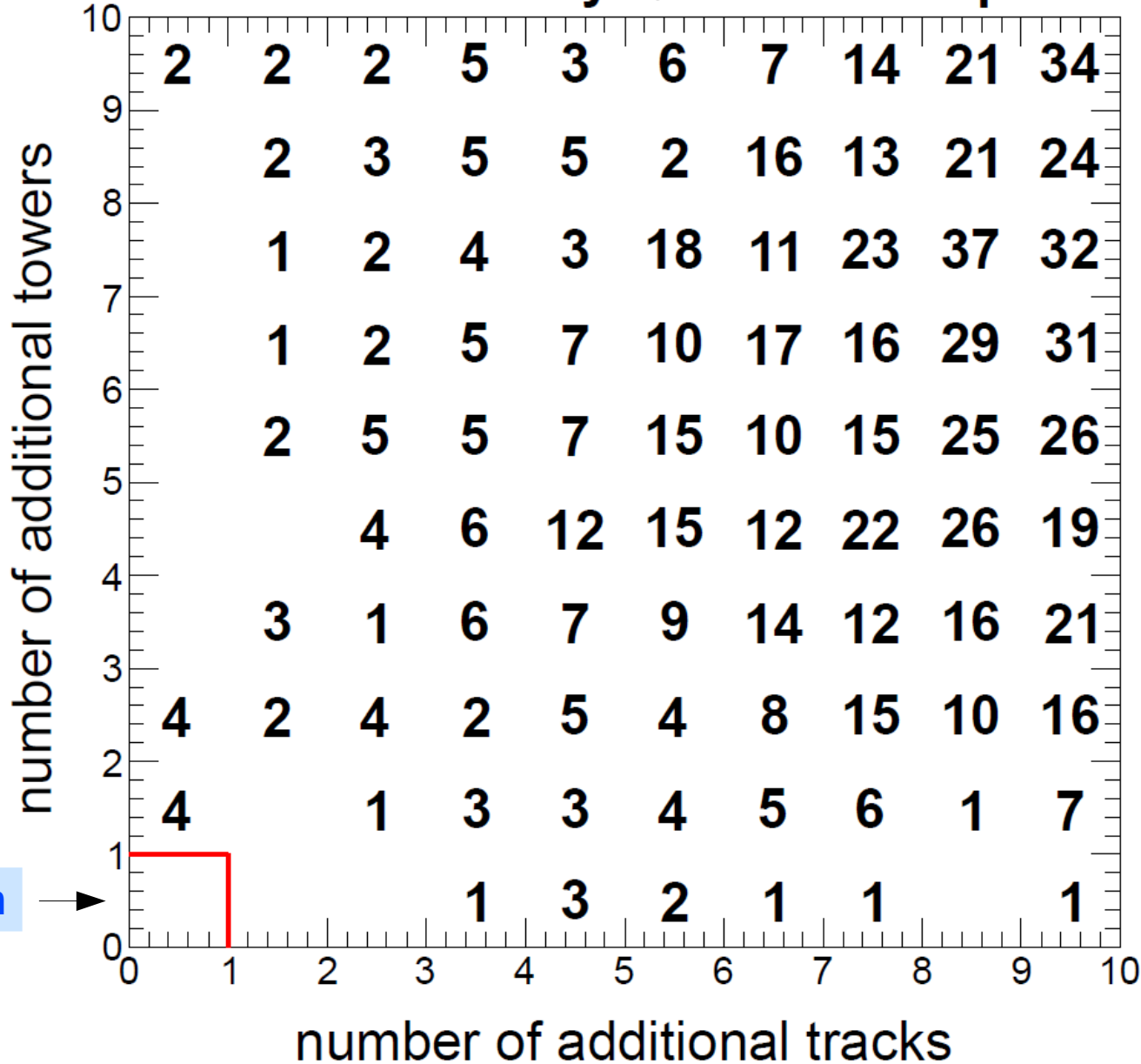


exclusive $\gamma\gamma$ production		exclusive $e^+e^-$ production	
Background	Events	Background	Events
exclusive $e^+e^-$	$0.11 \pm 0.03$	exclusive $Y(1S,2S,3S) \rightarrow e^+e^-$	negligible
cosmic ray	negligible	cosmic ray	$0.04 \pm 0.01$
non-exclusive	$1.68 \pm 0.40$	non-exclusive	$0.80 \pm 0.28$
exclusive $\pi^0\pi^0$ and $\eta\eta$	negligible	exclusive $\pi^+\pi^-$	negligible
Total	$1.79 \pm 0.40$	Total	$0.84 \pm 0.28$

# $IPIP \rightarrow \gamma\gamma$ : extra tracks



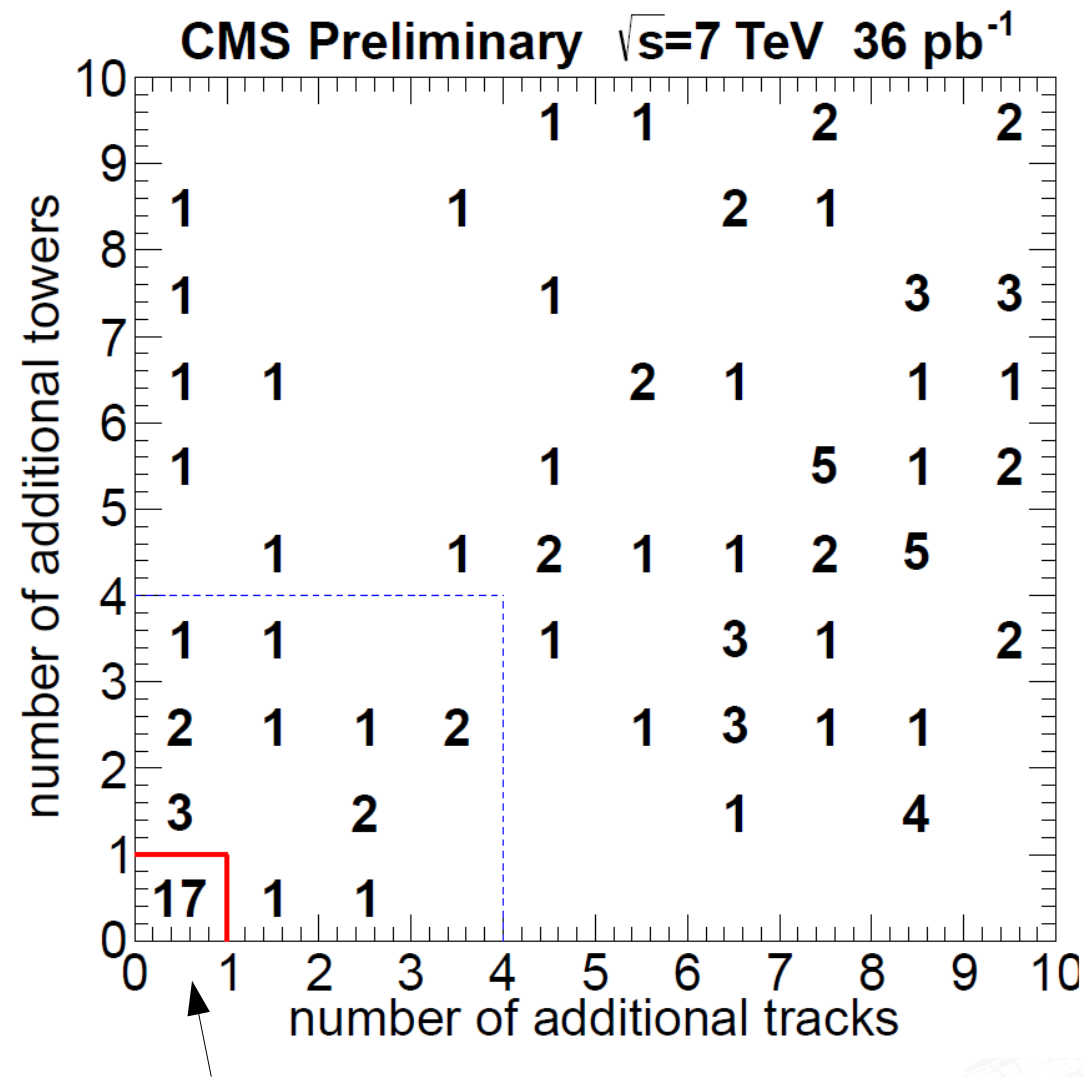
CMS Preliminary  $\sqrt{s}=7$  TeV  $36 \text{ pb}^{-1}$



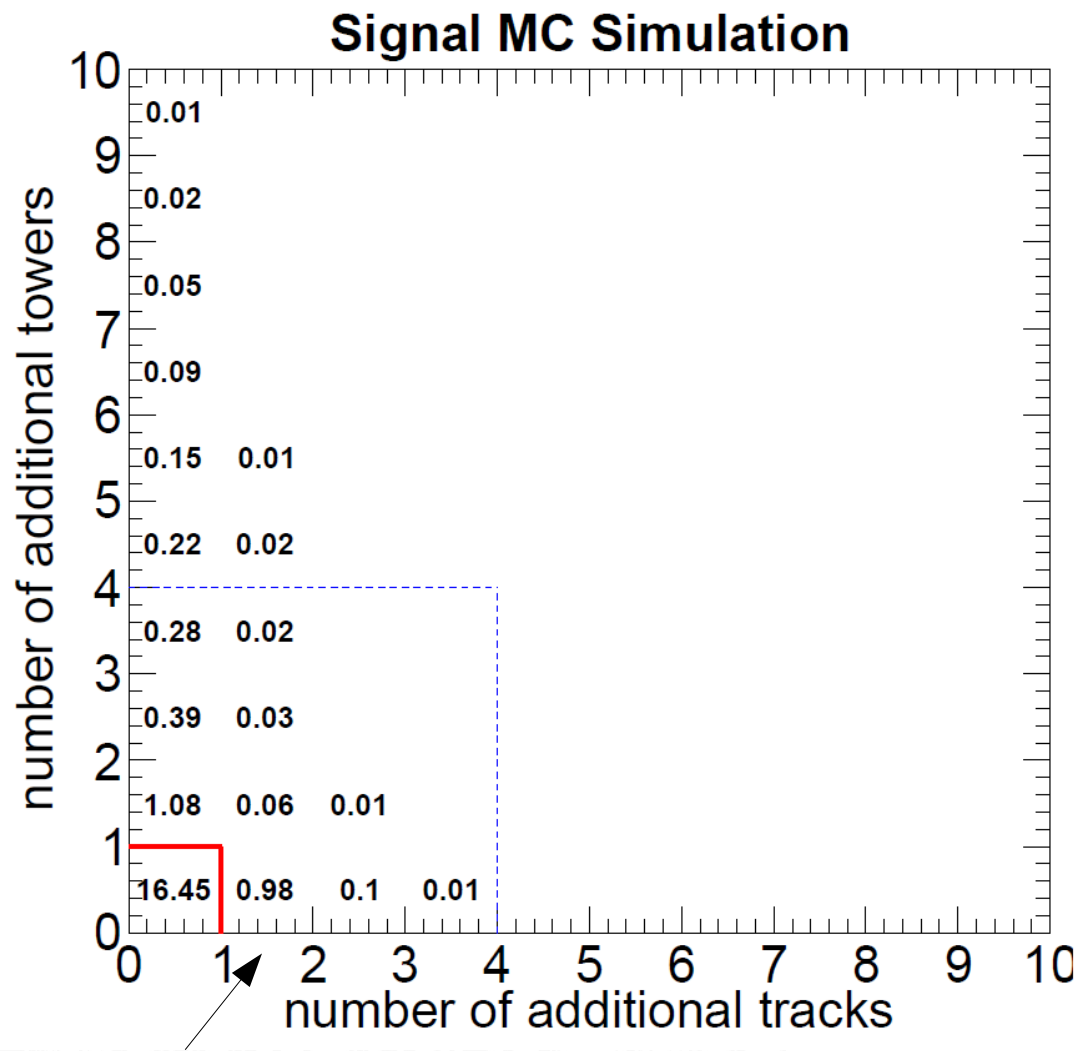
Signal region



# $\gamma\gamma \rightarrow e^+e^-$ : extra tracks



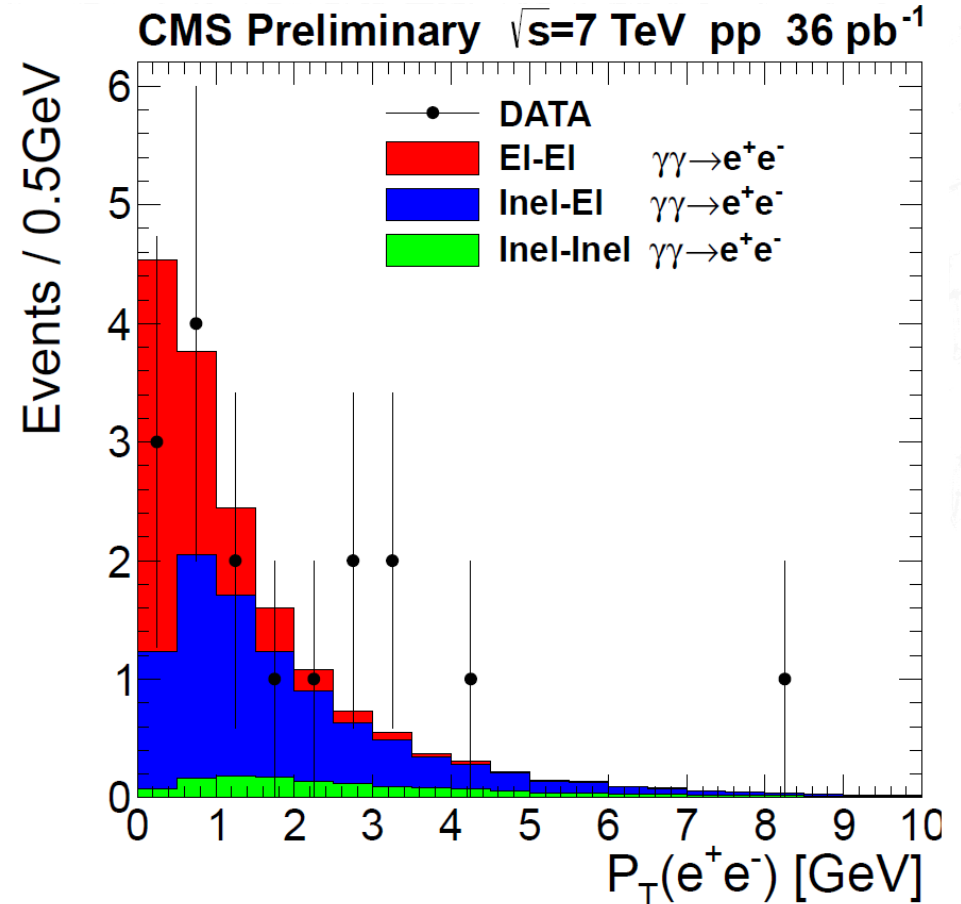
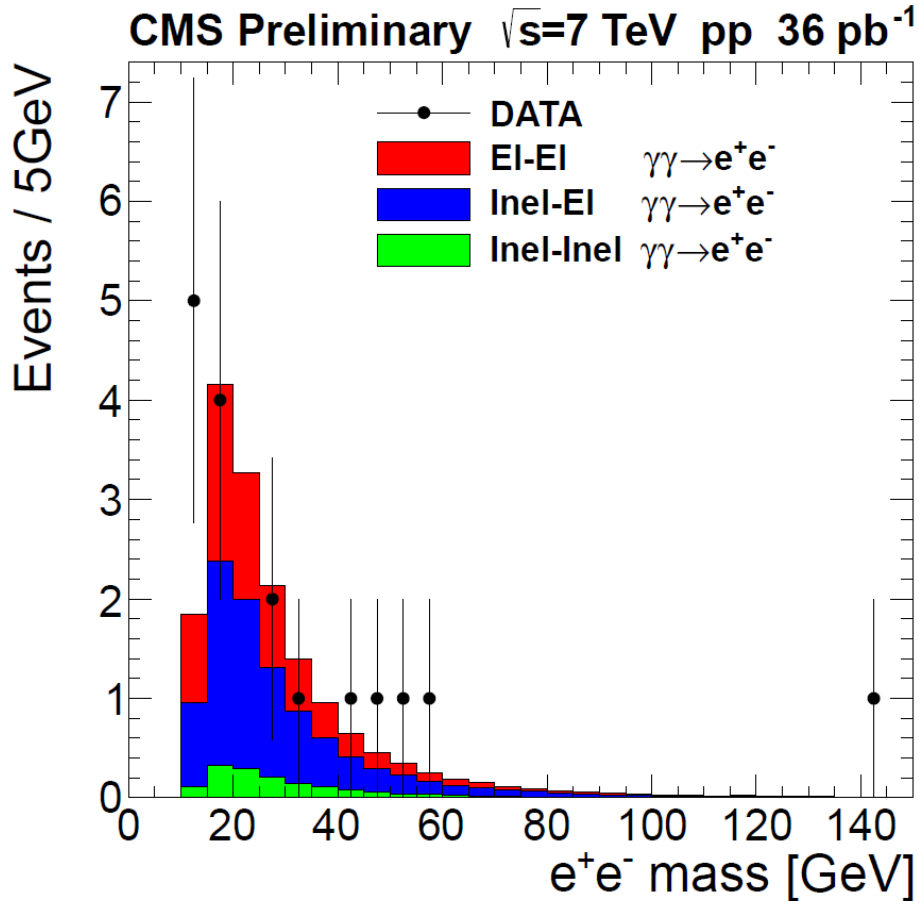
Signal region



15 bins for the Non-exclusive bkg

# $\gamma\gamma \rightarrow e^+e^-$ : observed events

Process	$\mathcal{L}$	$\sigma$	$\varepsilon$	nEvents
el-el	$36 \pm 1.4 \text{ pb}^{-1}$	$3.74 \pm 0.04 \text{ pb}$	$0.0488 \pm 0.0056$	$6.57 \pm 0.07 \text{ (theo.)} \pm 0.80 \text{ (syst.)}$
inel-el	$36 \pm 1.4 \text{ pb}^{-1}$	$3.34 \pm 0.67 \text{ pb} \times 2$	$0.0348 \pm 0.0035$	$8.37 \pm 1.68 \text{ (theo.)} \pm 0.90 \text{ (syst.)}$
inel-inel	$36 \pm 1.4 \text{ pb}^{-1}$	$3.52 \pm 0.70 \text{ pb}$	$0.0119 \pm 0.0011$	$1.51 \pm 0.30 \text{ (theo.)} \pm 0.15 \text{ (syst.)}$
Total				$16.5 \pm 1.7 \text{ (theo.)} \pm 1.2 \text{ (syst.)}$



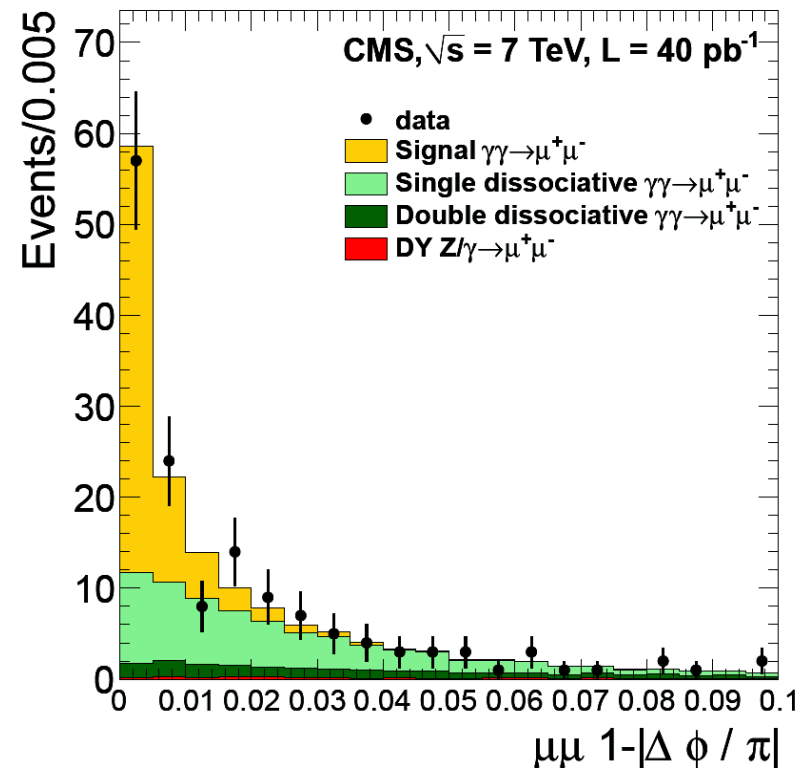
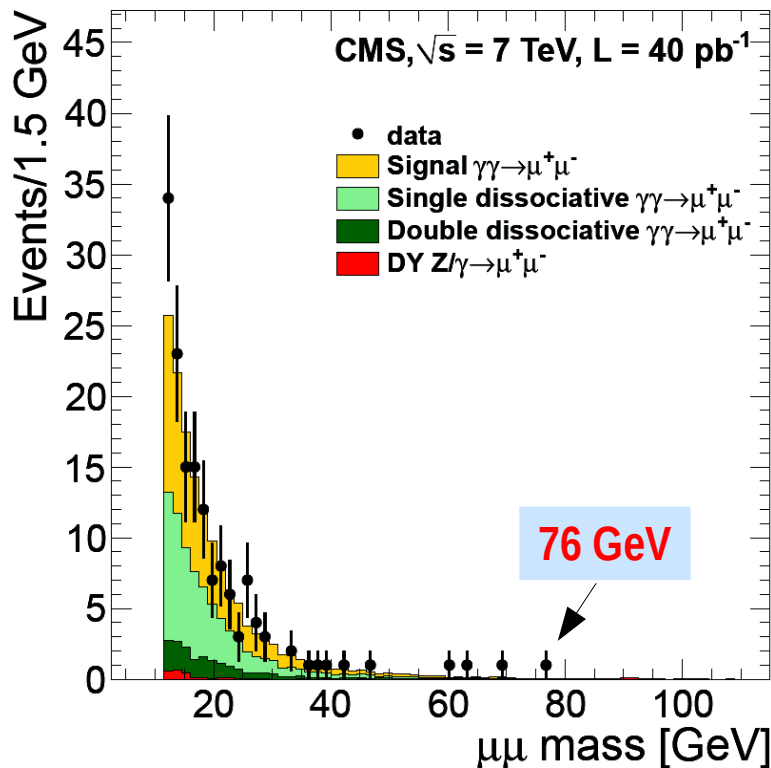
# $\gamma\gamma \rightarrow \mu^+\mu^-$ : cutflow



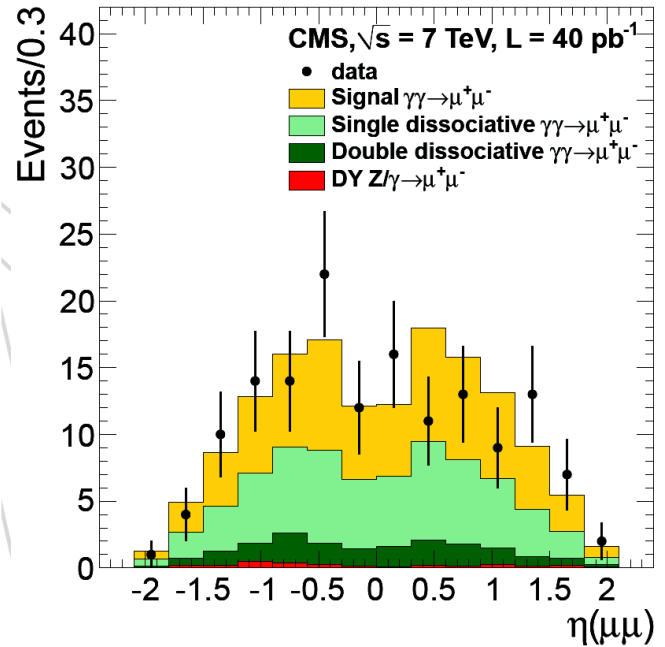
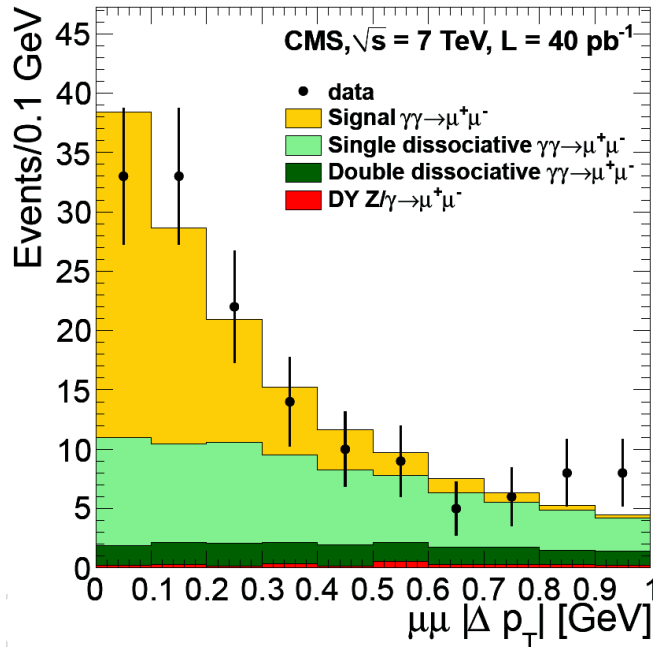
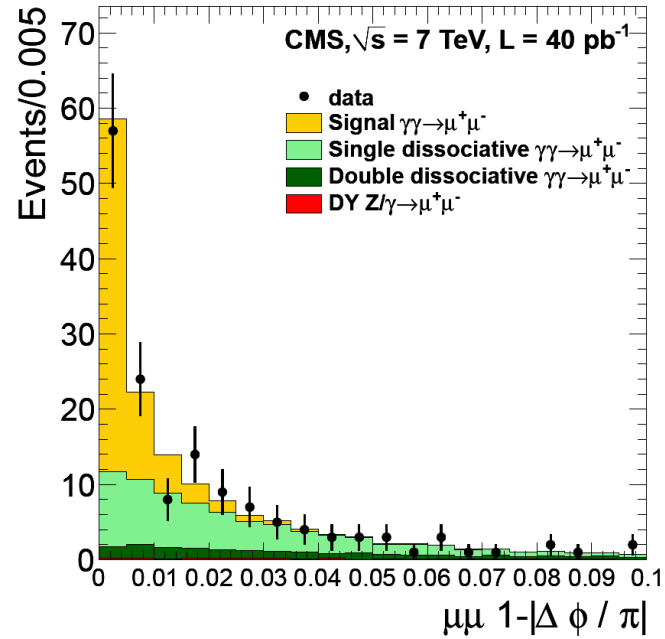
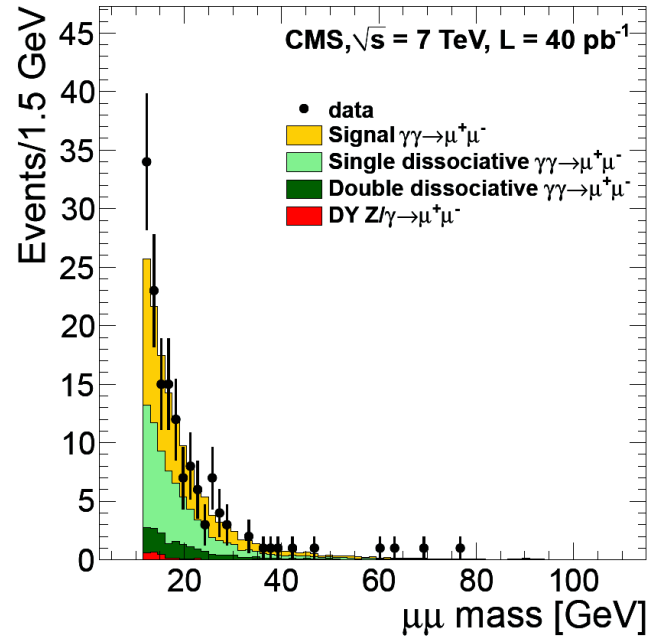
Corrections included:

Event pileup  
Muon ID  
Trigger eff.  
Tracker eff.

Selection	Data	Signal	Single-pdiss.	Double-pdiss.	DY	Total
Vertex and track-exclusivity	921	247	437	197	56	937
Muon ID	724	193	336	160	53	741
$p_T > 4 \text{ GeV},  \eta  < 2.1$	438	132	241	106	20	499
$m(\mu^+\mu^-) > 11.5 \text{ GeV}$	270	95	187	86	13	380
3D angle $< 0.95\pi$	257	87	178	83	12	361
$1 -  \Delta\phi/\pi  < 0.1$	203	87	126	41	8	263
$ \Delta p_T  < 1.0 \text{ GeV}$	148	86	79	16	3	184

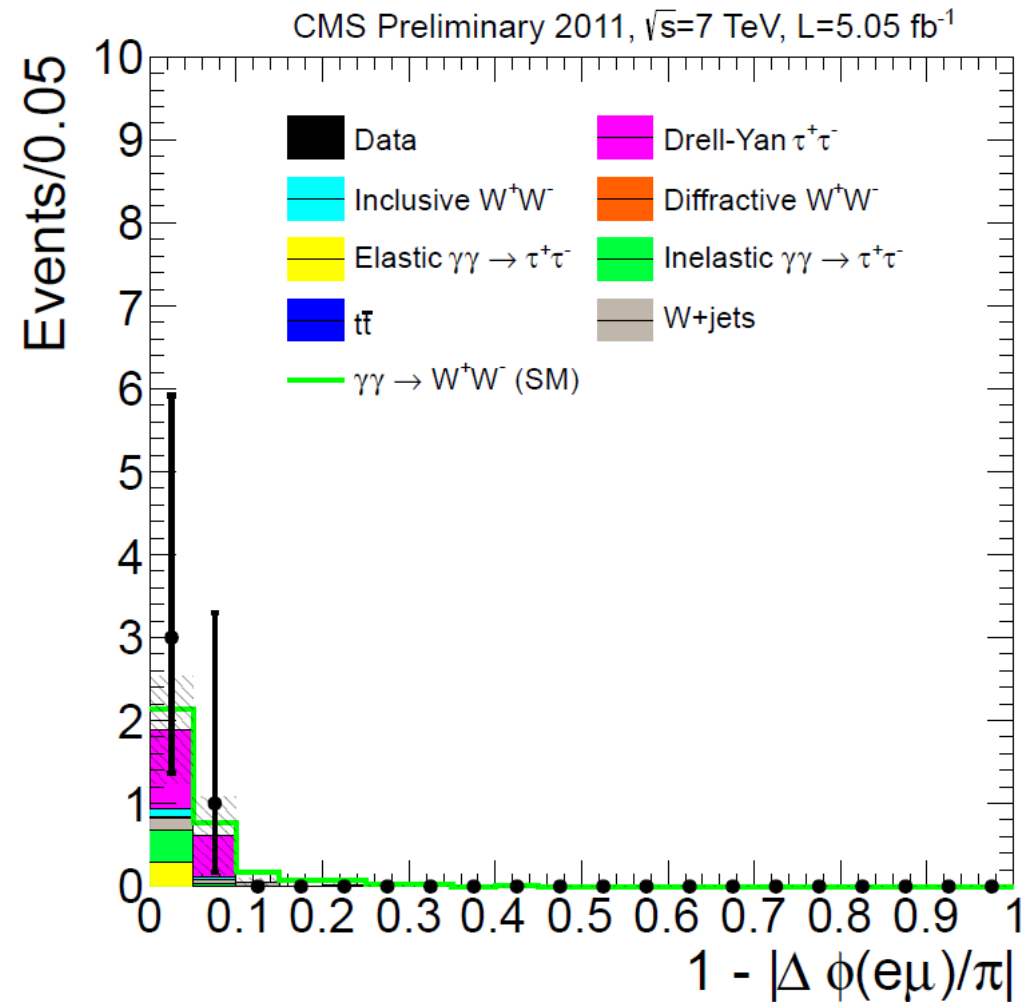
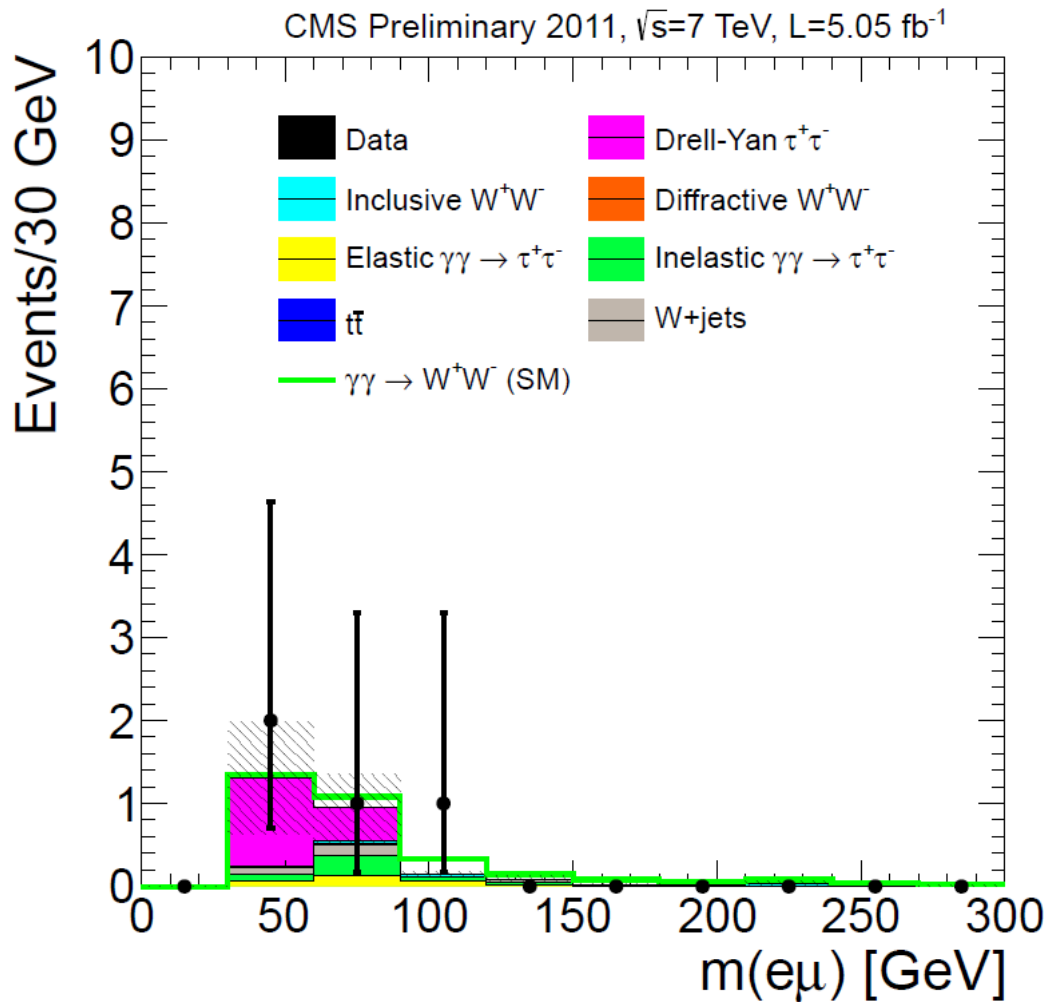


# $\gamma\gamma \rightarrow \mu^+\mu^-$ : distributions



# Comparing the data with $\gamma\gamma \rightarrow \tau^+\tau^-$

CMS-FSQ-12-010





# $\gamma\gamma \rightarrow W^+W^-$ : summary of uncertainties

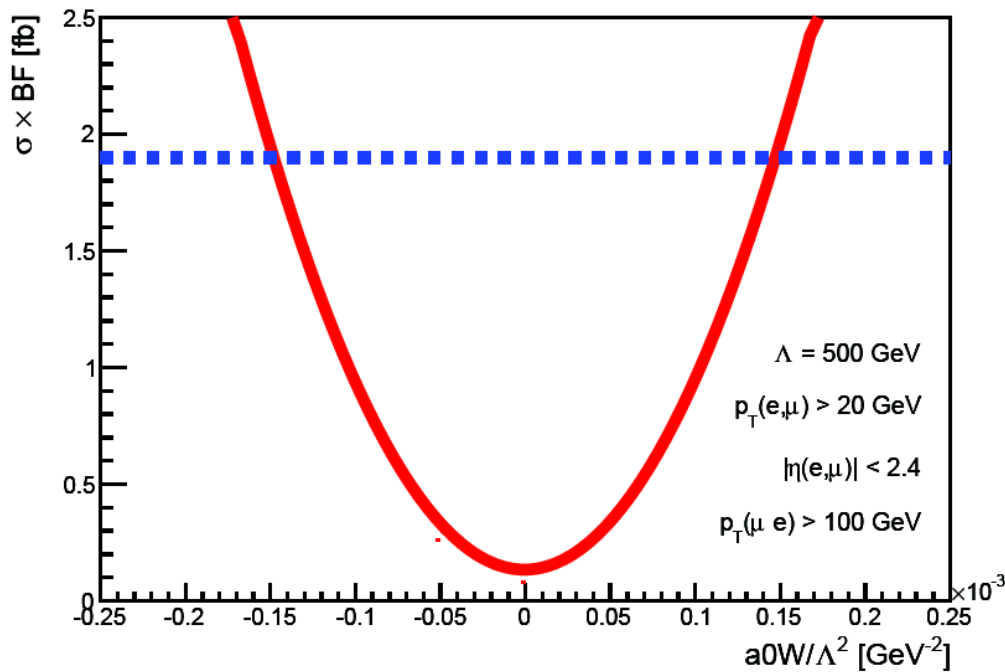


	Uncertainty
Trigger and lepton identification	4.2%
Luminosity	2.2%
Vertexing efficiency	1.0%
Exclusivity and pileup dependence	10.0%
Proton dissociation factor	20.0%

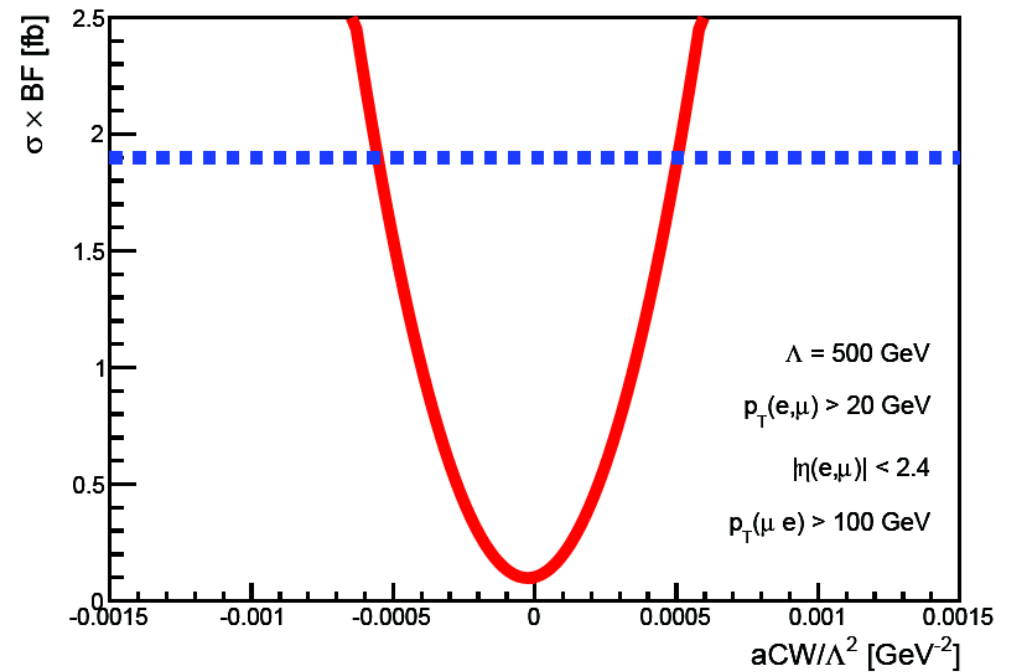
# $\gamma\gamma \rightarrow W^+W^-$ : Exclusion plots



CMS Preliminary 2011,  $\sqrt{s}=7$  TeV,  $L=5.05$  fb $^{-1}$



CMS Preliminary 2011,  $\sqrt{s}=7$  TeV,  $L=5.05$  fb $^{-1}$



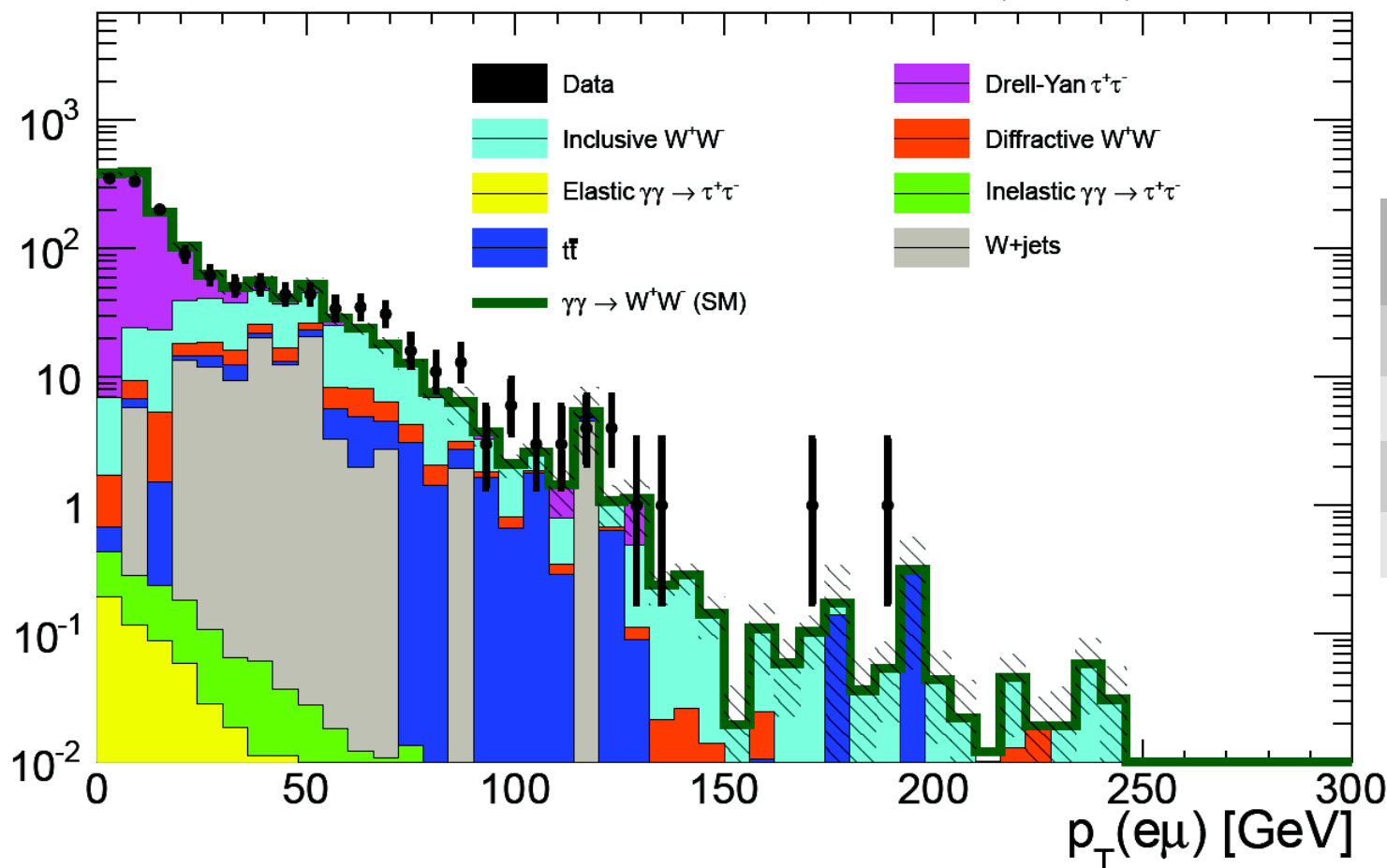
# Signal from $W^+W^- \rightarrow \mu^\pm e^\mp \nu\bar{\nu}$

CMS-FSQ-12-010

- Events are required to pass trigger and preselection requirements, and lepton identification:

Events/6 GeV

CMS 2011,  $\sqrt{s}=7$  TeV,  $L=5.05$  fb $^{-1}$



Process	# extra Tracks	$p_T$ (GeV)
$\gamma\gamma \rightarrow \tau\tau$	0	< 30
Signal	0	> 30
DY $\tau\tau$	1-6	< 30
Incl. WW	1-6	> 30