

# The Measurement of the $W\gamma$ Cross Section at 8 TeV (PhD thesis defense)

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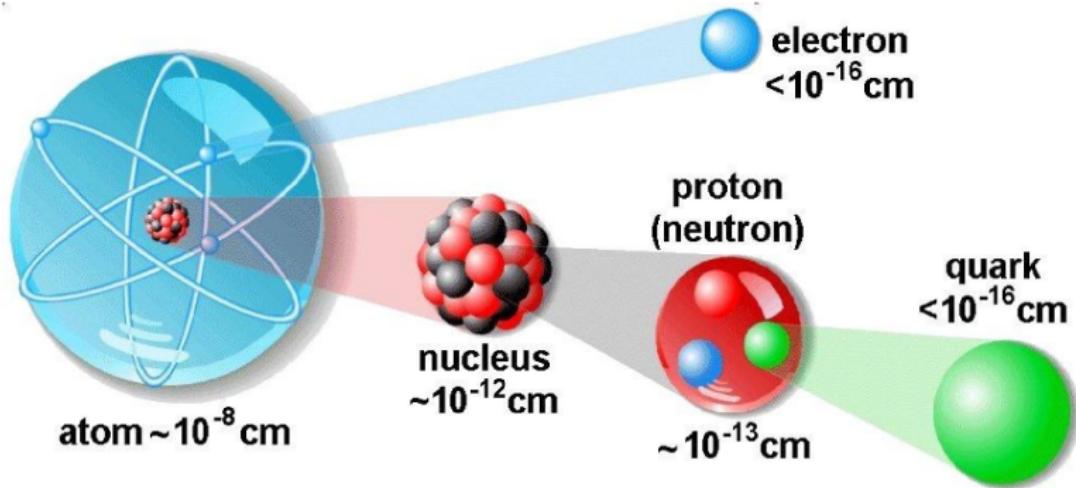
# Talk Outline

- ▶ **Introduction to theory**
  - ▶ Standard Model
  - ▶ Proton-proton collisions
  - ▶  $W\gamma \rightarrow l\nu\gamma$  process
- ▶ **Experimental setup**
  - ▶ Large Hadron Collider (LHC)
  - ▶ Compact Muon Solenoid (CMS)
  - ▶ Particle reconstruction in CMS
- ▶  **$W\gamma$  cross section measurement**
  - ▶ Measurement goal and strategy
  - ▶ Data and simulation (MC) samples
  - ▶ Measurement steps
  - ▶ **Main challenge:** jets  $\rightarrow \gamma$  background estimation
  - ▶ Systematic uncertainties
  - ▶ Results
- ▶ **Conclusions**

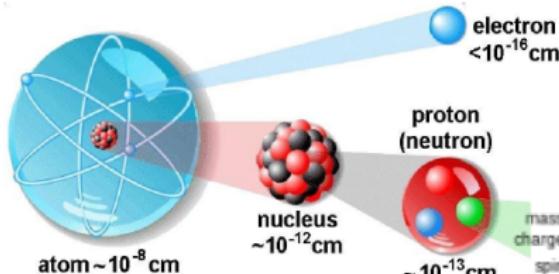
More details about each subject are available in the dissertation:

<https://github.com/eavdeeva/ThesisTextWg/blob/master/nuthesis/examples/nuthesis.pdf>

# Theory. Atom Structure



# Theory. The Standard Model

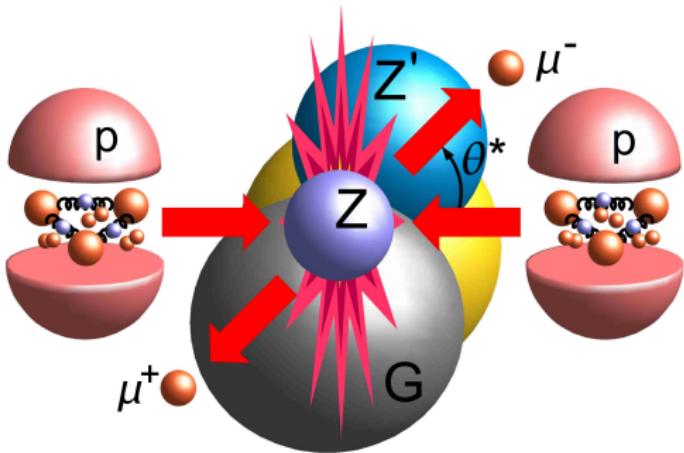


## First generation (everyday matter):

uud (proton)  
udd (neutron)  
electron

Three generations of matter (fermions)		
I	II	III
$2.4 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$1.27 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$171.2 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top
$4.8 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$104 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$4.2 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom
$<2.2 \text{ eV}/c^2$ $0$ $\frac{1}{2}$ e electron neutrino	$<0.17 \text{ MeV}/c^2$ $0$ $\frac{1}{2}$ $\nu_\mu$ muon neutrino	$<15.5 \text{ MeV}/c^2$ $0$ $\frac{1}{2}$ $\nu_\tau$ tau neutrino
$0.511 \text{ MeV}/c^2$ $-1$ $\frac{1}{2}$ e electron	$105.7 \text{ MeV}/c^2$ $-1$ $\frac{1}{2}$ $\mu$ muon	$1.777 \text{ GeV}/c^2$ $-1$ $\frac{1}{2}$ tau tau
		$80.4 \text{ GeV}/c^2$ $\pm 1$ $W^\pm$ W boson
Leptons		Gauge bosons
		Higgs

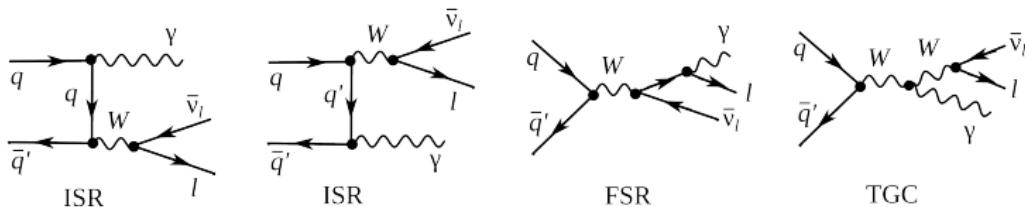
# Theory. Proton-Proton Collisions



- ▶ Quarks u,u,d within a proton interact and produce gluons and quark-antiquark pairs;
- ▶ In a  $p\bar{p}$  collision, any “parton” from one proton can interact with any parton from another proton.

<http://cms.web.cern.ch/news/weak-mixing-light-and-heavy>

# Theory. $W\gamma \rightarrow l\nu\gamma$



$$q_1\bar{q}_2 \rightarrow W \text{ or } q_1\bar{q}_2 \rightarrow W\gamma$$

Usually  $q_1\bar{q}_2 = u\bar{d}$  or  $q_1\bar{q}_2 = d\bar{u}$

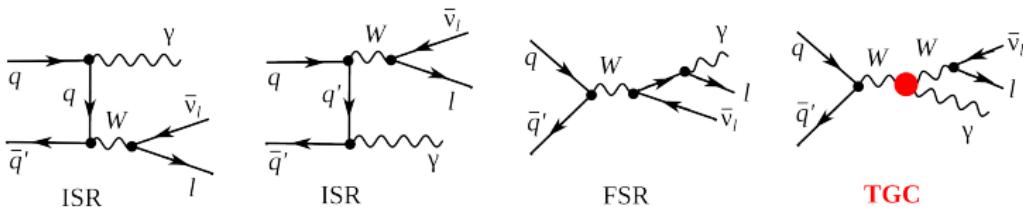
## Three mechanisms:

ISR: initial state radiation;  
FSR: final state radiation;  
TGC: triple gauge coupling.

## Measurement goals:

Test the Standard Model;  
Provide a precise cross section measurement;  
Search for anomalous TGC (aTGC).

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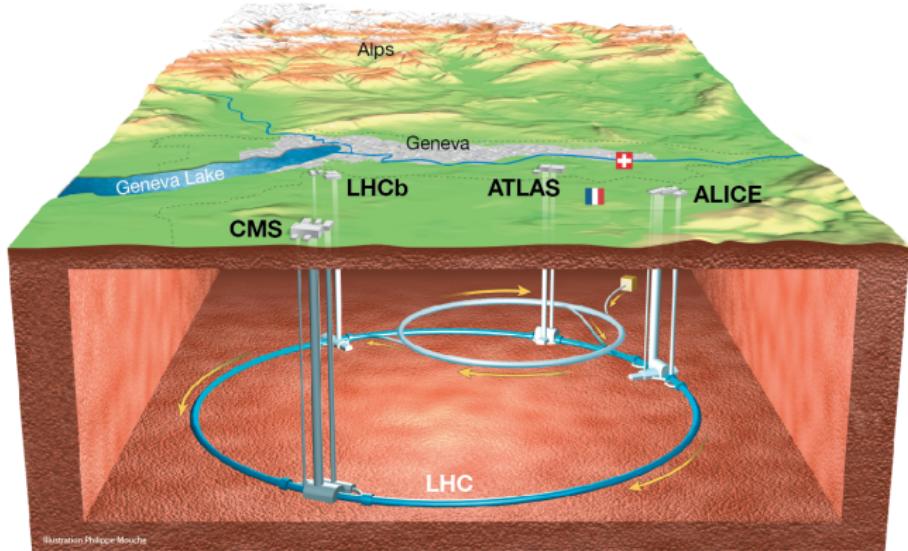
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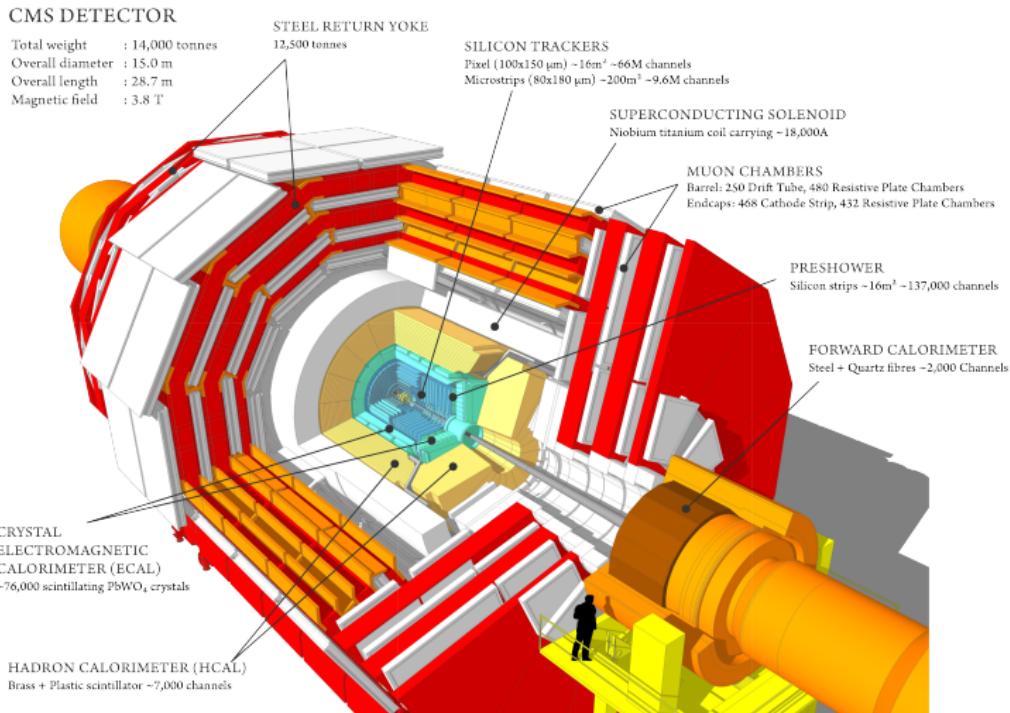
Test the Standard Model;  
Provide a precise cross section measurement;  
**Search for anomalous TGC (aTGC).**

# Large Hadron Collider (LHC)



<http://lhcatome.web.cern.ch/about>

## Compact Muon Solenoid (CMS)

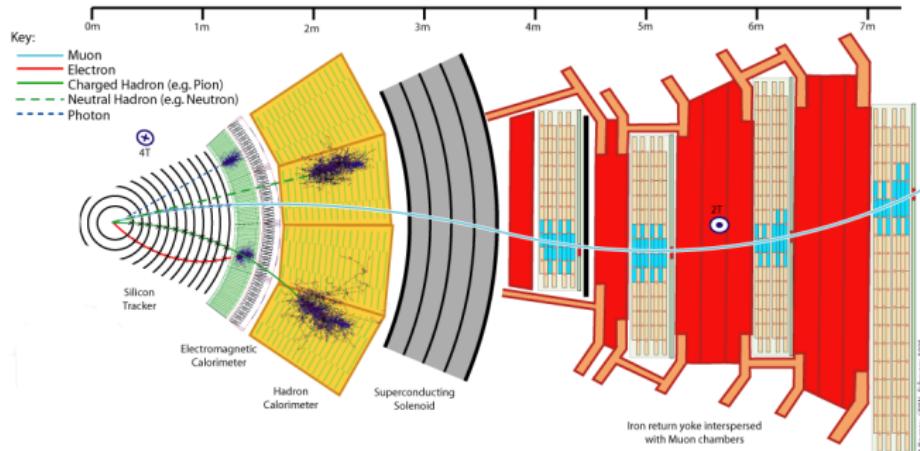


<http://cms.web.cern.ch/news/cms-detector-design>

# Compact Muon Solenoid (CMS). Particle Reconstruction

Process to study:  $W\gamma \rightarrow \mu\nu\gamma, W\gamma \rightarrow e\nu\gamma$ .

Final state particles: muons, electrons, photons, neutrinos.

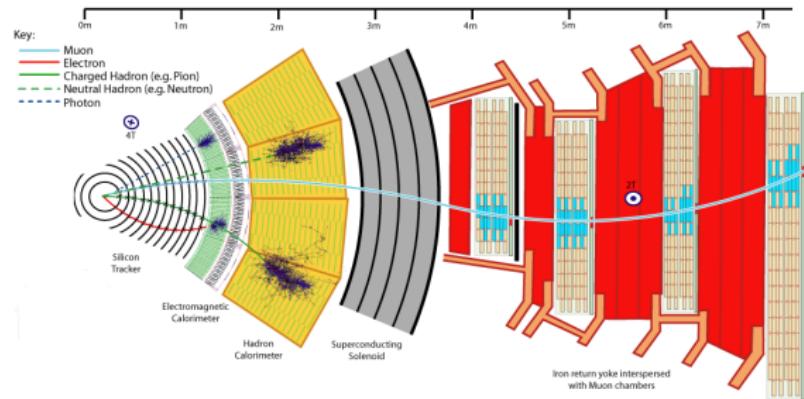


Neutrino is not detected. The measure of  $P_T^\nu$  is missing transverse energy:  $E_T^{\text{miss}} = -|\sum \mathbf{P}_T|$ ,  
Sum over all visible particles in the event.

# Compact Muon Solenoid (CMS). Neutrinos

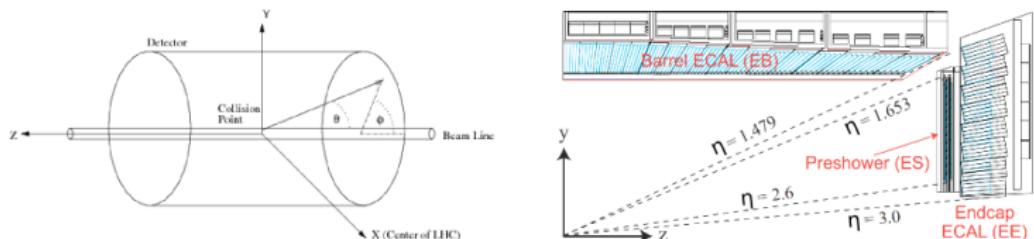
Process to study:  $W\gamma \rightarrow \mu\nu\gamma, W\gamma \rightarrow e\nu\gamma$ .

Final state particles: muons, electrons, photons, **neutrinos**.



**Neutrino is not detected.** The measure of  $P_T^\nu$  is missing transverse energy:  $E_T^{\text{miss}} = -|\sum \mathbf{P}_T|$ ,  
Sum over all visible particles in the event.

# Kinematic Variables and Important Notations



- ▶ Transverse momentum ( $P_T$ ) with respect to the beamline
- ▶ Pseudorapidity ( $\eta = -\ln [\tan(\theta/2)]$ )
- ▶ Cone separation ( $\Delta R(a, b) = \sqrt{((\phi_a - \phi_b)^2 + (\eta_a - \eta_b)^2)}$ )
- ▶ EB (barrel) and EE (endcap)
- ▶ Invariant mass of a particle system ( $M_{ab} = m_a^2 + m_b^2 + 2(E_a E_b - p_a \cdot p_b)$ )
- ▶ Transverse mass of a  $W$  boson ( $M_T^W = \sqrt{2P_T^I E_T^{\text{miss}}(1 - \cos(\phi^I - \phi^{\text{miss}}))}$ )

# Measurement Goal

To measure the total and the differential ( $\frac{d\sigma}{dP_T^\gamma}$ ) cross sections of  $W\gamma \rightarrow l\nu\gamma$  at  $\sqrt{s} = 8$  TeV.

-----  
Phase space definition:

- ▶  $P_T^\gamma > 15$  GeV;
- ▶  $\Delta R(\gamma, lep) > 0.7$ ;
- ▶ several more requirements related to geometric and kinematic limitations

# Measurement Strategy

Step	Algebraic representation for the measurement of $d\sigma/dP_T^\gamma$	$\sigma$
<b>select events</b>	$N_{sel}^j$	$N_{sel}$
<b>subtract background</b>	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$	$N_{sign} = N_{sel} - N_{bkg}$
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$	—
correct for eff X acc	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$
compute cross section	$\left( \frac{d\sigma}{dP_T^\gamma} \right)^i = \frac{N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$	$\sigma = N_{true}/L$
<b>estimate systematic uncertainties</b>		

# Data and Simulation Samples

Data: CMS experiment, 2012,  $pp$  collisions at  $\sqrt{s} = 8$  TeV  
Integrated luminosity:  $L = 19.6 \text{ fb}^{-1}$

Dataset	Candidates	Purpose	Size, T
Single muon	$W\gamma \rightarrow \mu\nu\gamma$	target process	1.2
Single electron	$W\gamma \rightarrow e\nu\gamma$	target process	2.0
Double muon	$Z\gamma \rightarrow \mu\mu\gamma$	background estimation	0.4
Double electron	$Z\gamma \rightarrow ee\gamma$	background estimation	0.5

Monte Carlo Simulation (MC) samples:

Process	Type	$\sigma, \text{ pb}$
$W\gamma \rightarrow l\nu\gamma$	signal	554
$W+\text{jets} \rightarrow l\nu+\text{jets}$	background	36257
$DY+\text{jets} \rightarrow l\bar{l}+\text{jets}$	background	3504
$t\bar{t}+\text{jets} \rightarrow 1l+X$	background	99
$t\bar{t}+\text{jets} \rightarrow 2l+X$	background	24
$Z\gamma \rightarrow ll\gamma$	background	172

# Requirements for Selection of $W\gamma$ Candidates

Selection requirements for candidates		Comment
$W\gamma \rightarrow \mu\nu\gamma$	$W\gamma \rightarrow e\nu\gamma$	
<b>Event level selection criteria:</b>		
Exactly one lepton + at least one photon $M_T^W > 40$ GeV $ 110 > M_{e\gamma} > 70$ GeV excl. $\Delta R(\text{lep}, \gamma) > 0.7$		process signature rejects DY+jets, $Z\gamma$ rejects DY+jets theory consideration
<b>Photon selection:</b>		
$P_T^\gamma > 15$ GeV $\eta^\gamma$ : EB or EE Photon ID* [one change in ID]		theory considerations acceptance POG**-recommended $W\gamma\gamma$ -recommended
<b>Lepton selection:</b>		
$p_T^\mu > 25$ GeV; $ \eta^\mu  < 2.1$ Muon ID	$p_T^e > 30$ GeV; $\eta^e$ : EB or EE Electron ID	trigger trigger, acceptance POG-recommended
<b>Second lepton veto:</b>		
$p_T^{\mu^2} > 10$ GeV; $ \eta^{\mu^2}  < 2.4$	$p_T^{e^2} > 10$ GeV; $\eta^{e^2}$ : EB or EE [veto] ID	rejects DY+jets, $Z\gamma$ very loose

If we have several candidates in an event, we choose one with the highest  $P_T^\gamma$

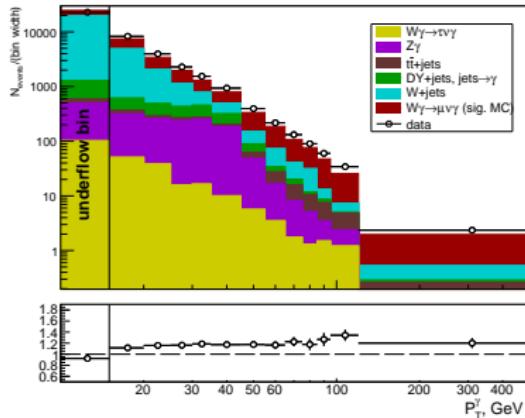
\* ID - identification criteria

\*\* POG - Particle Object Group (in CMS)

# $P_T^\gamma$ Spectrum of $W\gamma$ Candidates

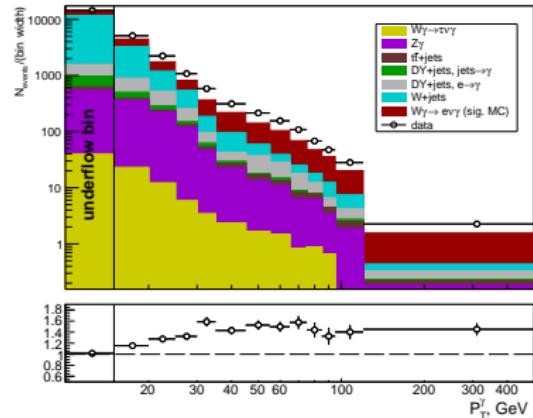
Work in progress, CMS 2012,  $\sqrt{s}=8$  TeV,  $L=19.6 \text{ fb}^{-1}$

Data vs MC.  $W\gamma \rightarrow \mu\nu\gamma$ , barrel.



Work in progress, CMS 2012,  $\sqrt{s}=8$  TeV,  $L=19.6 \text{ fb}^{-1}$

Data vs MC.  $W\gamma \rightarrow e\nu\gamma$ , barrel.



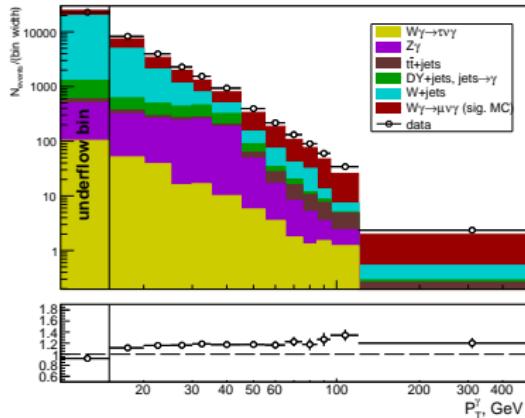
## Comments:

- Dominated by  $W+\text{jets}$  events in low  $P_T^\gamma$  bins;
- Fraction of signal increases with  $P_T^\gamma$ ;
- Data disagree with MC.

# $P_T^\gamma$ Spectrum of $W\gamma$ Candidates

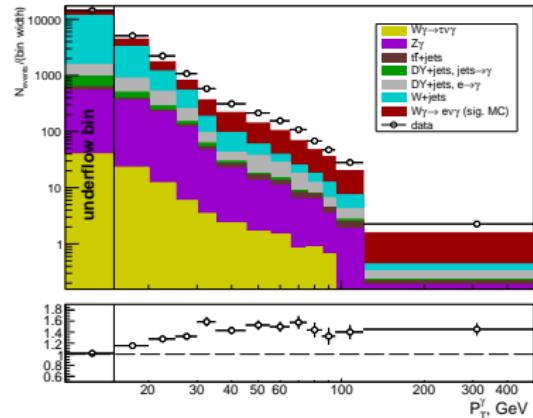
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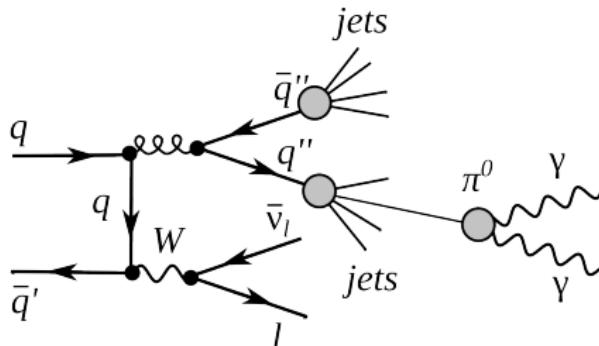
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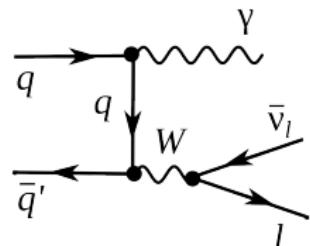
## Backgrounds:

$\text{Jets} \rightarrow \gamma$ :  $W+\text{jets}$ ,  $DY+\text{jets}$ ,  $t\bar{t}+\text{jets}$ ;  
 $e \rightarrow \gamma$ :  $DY+\text{jets}$  (electron channel only);  
 $\text{Real-}\gamma$ :  $Z\gamma$ ,  $W\gamma \rightarrow \tau\nu\gamma$ .

# Jets $\rightarrow \gamma$ Background



$W + \text{jets}$



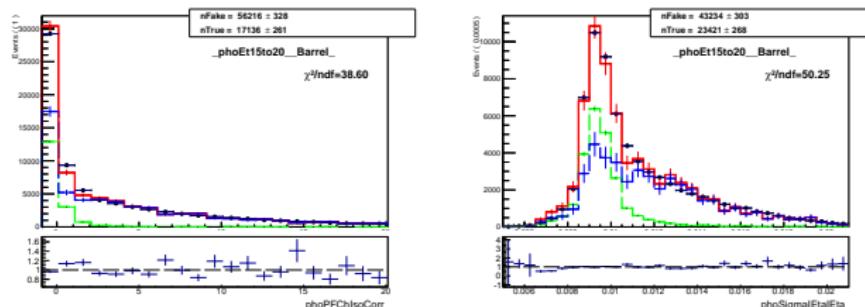
$W\gamma$

Jets $\rightarrow \gamma$  background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed later).

# Jets $\rightarrow\gamma$ Background. Template Method

- ▶ Choose a variable that has a significant discriminative power between the true and fake photon candidates  $V_{fit}$ ;
- ▶ Prepare real- $\gamma$  ( $T_{true}$ ) and fake- $\gamma$  ( $T_{fake}$ ) templates (next slide);
- ▶ Fit  $V_{fit}$  distribution in data by:  $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$ .

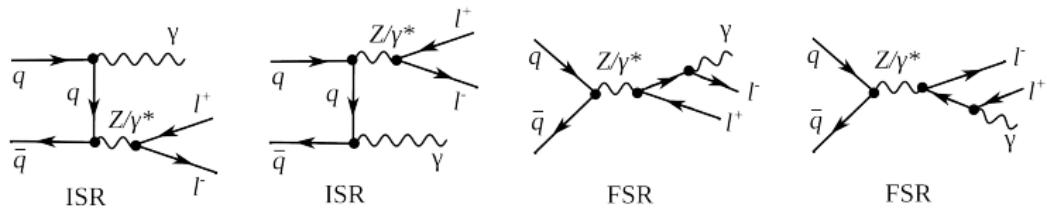
Templates: accurate representations of  $V_{fit}$  distributions of real- $\gamma$  and fake- $\gamma$  in the  $W\gamma$ -selected dataset.



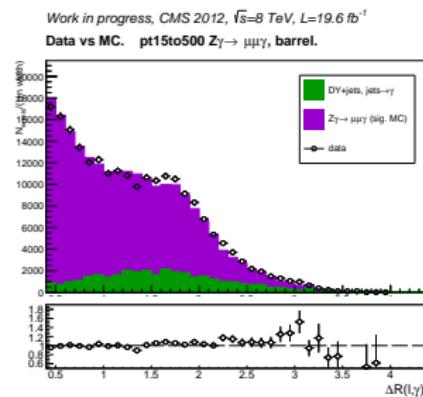
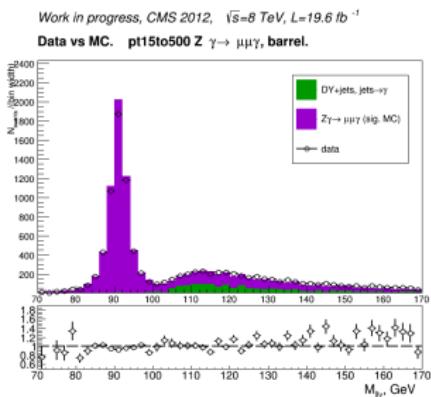
$I_{ch}^\gamma$  (charged hadron isolation):  $I_{ch}^\gamma = \sum P_T^{ch.had.}, \Delta R(\gamma, ch.had.) < 0.3$   
 $\sigma_{inj\eta}$ : an ECal shower shape variable

black: data; green: real- $\gamma$  template; blue: fake- $\gamma$  template; red: fit function

# Jets $\rightarrow\gamma$ Background. Templates from $Z\gamma\rightarrow\bar{\mu}\mu\gamma$



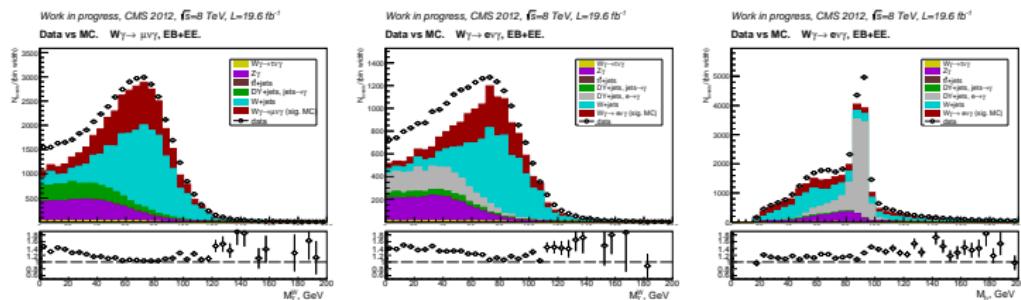
FSR: final state radiation; ISR: initial state radiation



Increase real- $\gamma$  fraction (FSR):  $M_{\mu\mu\gamma} < 101$  GeV and  $\Delta R(\mu_1, \gamma) > 0.4$   
 Increase fake- $\gamma$  fraction (ISR):  $M_{\mu\mu\gamma} > 101$  GeV and  $\Delta R(\mu_1, \gamma) > 1.0$

# $e \rightarrow \gamma$ and Real- $\gamma$ Backgrounds

Type	Source	Comment	Estimation
$e \rightarrow \gamma$	DY+jets $\rightarrow ee + jets$	no track for $e$ ; fake $E_T^{miss}$	semi data driven
Real- $\gamma$	$Z\gamma \rightarrow ll\gamma$	pass second lepton veto; fake $E_T^{miss}$	MC-based
Real- $\gamma$	$W\gamma \rightarrow \tau\nu\gamma$	$\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$ and $\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$	MC-based

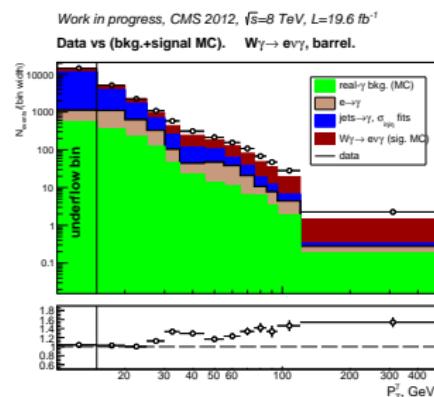
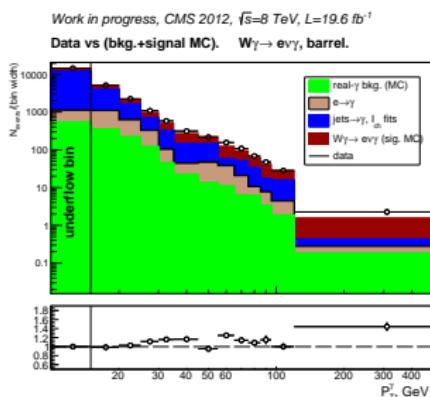
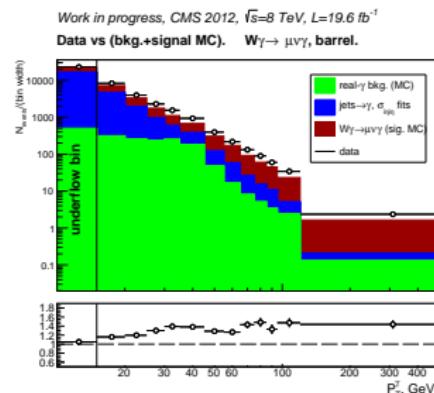
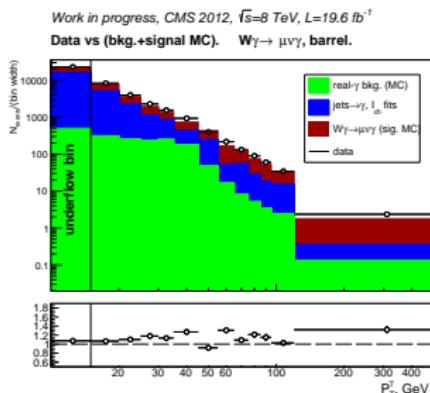


$M_T^W > 40$  GeV in both channels: rejects events without  $E_T^{miss}$

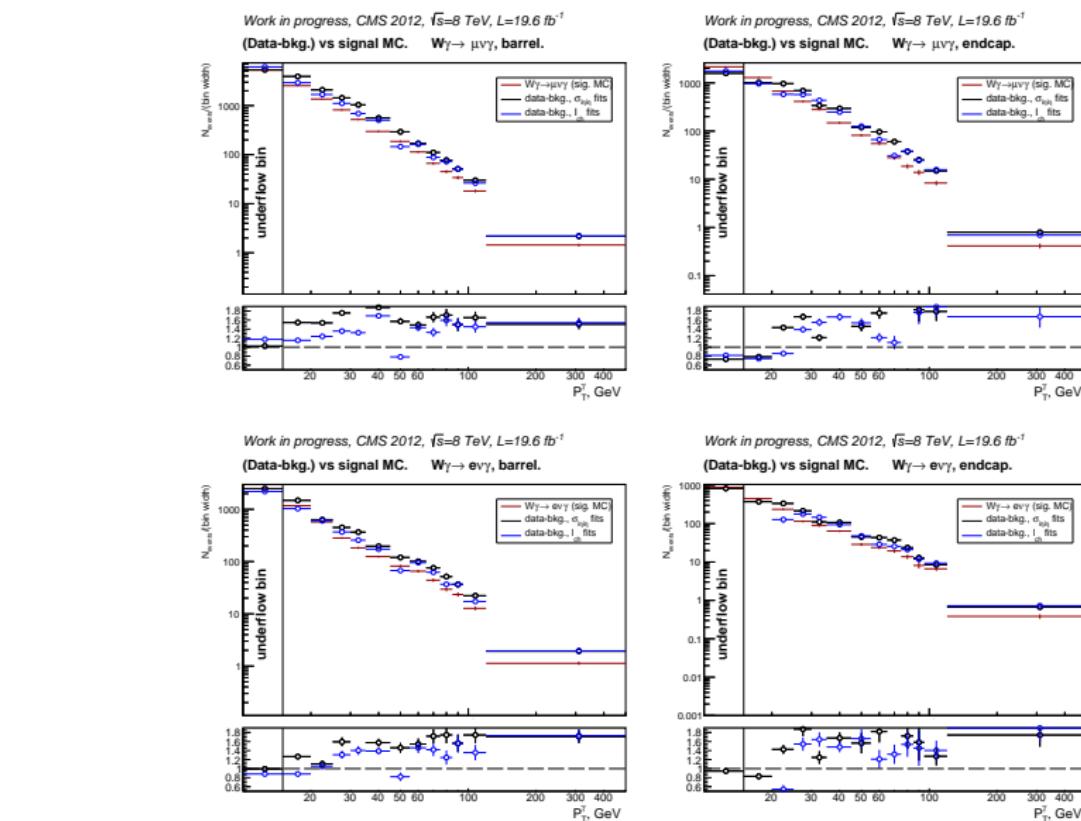
$M_{l,\gamma} < 70$  or  $M_{l,\gamma} > 110$  GeV in the electron channel: rejects events from DY+jets  $\rightarrow ee + jets$

Non-negligible amount remains

# $P_T^\gamma$ Spectrum (EB only)



# $P_T^\gamma$ Spectrum after Background Subtraction (EB and EE)



# Cross Checks for Jets $\rightarrow\gamma$ Background Estimation

Checks $\rightarrow$	- - - Simple MC closure - - -	- - - - MC realistic - - - -	- - - - - $Z\gamma$ data - - - - -
Templates	$W\gamma$ and $W+jets$	MC samples $Z\gamma$ and $DY+jets$	$Z\gamma$ FSR and ISR data (same as for $W\gamma$ meas.)
Data-to-fit	$W\gamma$ and $W+jets$	Mix MC samples All $W\gamma$ -selected	$Z\gamma$ -selected data
Check		Compare fit results of two methods to each other and to MC predictions	Compute cross section and compare to CMS published
Agreement	mostly good	slightly better than in data	excellent

## Reasons of discrepancies in the $W\gamma$ measurement:

- ▶ Not accurate shape of templates;
- ▶ Effect of a bias on the fit machinery.

# Other Corrections

Step	Algebraic representation for the measurement of $d\sigma / dP_T^\gamma$	
select events	$N_{sel}^j$	$N_{sel}$
subtract background	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$	$N_{sign} = N_{sel} - N_{bkg}$
NEXT MEASUREMENT STEPS:		
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$	—
correct for eff X acc	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$
compute cross section	$\left( \frac{d\sigma}{dP_T^\gamma} \right)^i = \frac{N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$	$\sigma = N_{true} / L$
estimate systematic uncertainties		

**Detector resolution unfolding (step “unfold”):**

- ▶ Effect: bin-to-bin migration during the  $P_T^\gamma$  reconstruction;
- ▶ Method: D'Agostini, signal MC sample is used;
- ▶ Note: uncertainties across different  $P_T^\gamma$  bins become correlated.

**Efficiency and Acceptance (step “correct for eff X acc”):**

- ▶ Effect (main): lose signal events due to selection criteria applied;
- ▶ Method: bin-by-bin correction by  $A \times \epsilon$ , constants prepared using signal MC sample;
- ▶ Note: efficiencies between data and MC differ (next slide).

# Efficiency Scale Factors

The scale factors (SF)  $\rho = \frac{\epsilon_{data}}{\epsilon_{MC}}$ . SF are applied as weights on each event in each MC sample.

type of candidate	full event SF
$W\gamma \rightarrow \mu\nu\gamma$	$\rho_{ID\_iso}^\mu \times \rho_{ID}^\gamma$
$W\gamma \rightarrow e\nu\gamma$	$\rho_{ID}^e \times \rho_{ID}^\gamma \times \rho_{PSV}^\gamma$

Provided by POG:  $\rho_{ID\_iso}^\mu$ ,  $\rho_{ID}^\gamma$ ,  $\rho_{ID}^e$ ; provided by  $W\gamma\gamma\gamma$  measurement:  $\rho_{PSV}^\gamma$

$$\rho_{ID}^\gamma:$$

$P_T^\gamma$	$ \eta^\gamma  \leq 0.80$	$0.80 <  \eta^\gamma  \leq 1.44$	$1.57 <  \eta^\gamma  \leq 2.00$	$ \eta^\gamma  > 2.00$
15-20	$0.95 \pm 0.02$	$0.99 \pm 0.02$	$1.00 \pm 0.02$	$1.02 \pm 0.02$
20-30	$0.96 \pm 0.01$	$0.97 \pm 0.01$	$0.98 \pm 0.01$	$1.00 \pm 0.01$
30-40	$0.98 \pm 0.01$	$0.98 \pm 0.01$	$0.99 \pm 0.01$	$1.00 \pm 0.01$
40-50	$0.98 \pm 0.01$	$0.98 \pm 0.01$	$1.00 \pm 0.01$	$1.01 \pm 0.01$
>50	$0.98 \pm 0.01$	$0.98 \pm 0.01$	$1.00 \pm 0.01$	$1.01 \pm 0.01$

$$\rho_{PSV}^\gamma:$$

$P_T^\gamma$	barrel	endcap
15-20	$0.996 \pm 0.020$	$0.960 \pm 0.041$
20-25	$0.994 \pm 0.024$	$0.977 \pm 0.051$
25-30	$0.996 \pm 0.030$	$0.951 \pm 0.062$
30-40	$0.999 \pm 0.033$	$1.029 \pm 0.081$
40-50	$1.009 \pm 0.073$	$0.971 \pm 0.150$
50-70	$0.993 \pm 0.128$	$0.965 \pm 0.294$
>70	$1.047 \pm 0.111$	$1.145 \pm 0.371$

# Uncertainties

**Statistical:** limited statistical power of the  $W\gamma$ -selected dataset

**Systematic:** all other effects including limited stat. of control datasets and MC datasets

Step	Statistical uncertainty propagation for the measurement of $d\sigma / dP_T^\gamma$	$\sigma$
select events	$N_{sel}^j \pm \Delta N_{sel}^j$ $\Delta N_{sel}^j = \sqrt{N_{sel}^j}$	$N_{sel} \pm \Delta N_{sel}$ $\Delta N_{sel} = \sqrt{N_{sel}}$
subtract background	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$ $\Delta N_{sign}^j = \Delta N_{sel}^j$	$N_{sign} = N_{sel} - N_{bkg}$ $\Delta N_{sign} = \Delta N_{sel}$
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$ $\Delta N_{A \times \epsilon}^i$ : diagonal elements of the error matrix	—
correct for eff X acc	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$ $\Delta N_{true}^i = \frac{\Delta N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$ $\Delta N_{true} = \frac{\Delta N_{sign}}{A \times \epsilon}$
compute cross section	$\left( \frac{d\sigma}{dP_T^\gamma} \right)^i = \frac{N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$ $\Delta \left[ \left( \frac{d\sigma}{dP_T^\gamma} \right)^i \right] = \frac{\Delta N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$	$\sigma = N_{true} / L$ $\Delta \sigma = \text{true} / L$

# Relative Uncertainties [%] on the $W\gamma \rightarrow \mu\nu\gamma$ Cross Section

Diagonal elements of error matrices only

$P_T^\gamma$ , GeV	stat. unc.	systematic uncertainties							total syst.
		$N_{lch}$ vs $N_{\sigma in in \eta}$	$Z\gamma$ MC norm.	templ. stat.	SFs	lumi	other		
>15	1	10	24	4	2	3	4	27	
15-20	2	31	12	10	3	3	6	35	
20-25	2	29	13	11	1	3	6	34	
25-30	2	24	13	11	1	3	5	30	
30-35	3	40	15	13	2	3	7	45	
35-45	2	11	12	8	2	3	6	19	
45-55	4	62	19	20	2	3	8	68	
55-65	3	15	12	14	1	3	7	24	
65-75	6	36	19	17	1	3	10	44	
75-85	4	6	11	16	1	3	10	21	
85-95	5	2	9	23	1	3	13	25	
95-120	5	10	8	12	1	3	9	18	
120-500	3	4	11	21	2	3	9	24	

# Relative Uncertainties [%] on the $W\gamma \rightarrow e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

$P_T^\gamma$ , GeV	stat. unc.	systematic uncertainties							
		related to jets $\rightarrow \gamma$		templ. stat.	SFs	lumi	$e \rightarrow \gamma$	other	total syst.
		$N_{lch}$ vs $N_{\sigma in in}$	Z $\gamma$ MC norm.						
>15	2	15	35	5	19	3	4	5	44
15-20	8	80	27	19	17	3	18	11	90
20-25	7	38	20	14	12	3	11	10	48
25-30	5	25	16	12	14	3	8	8	36
30-35	5	35	14	12	14	3	3	8	42
35-45	3	14	13	8	18	3	2	7	28
45-55	8	53	20	22	36	3	7	11	71
55-65	7	17	12	30	44	3	5	10	58
65-75	7	23	15	32	44	3	4	11	61
75-85	8	32	17	27	44	3	6	13	64
85-95	9	9	7	9	40	3	8	14	44
95-120	7	19	9	14	44	3	5	11	51
120-500	4	12	6	24	39	3	1	9	48

# Relative Uncertainties [%] on the $W\gamma \rightarrow e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

$P_T^\gamma$ , GeV	stat. unc.	systematic uncertainties							
		related to jets $\rightarrow \gamma$		templ. stat.	SFs	lumi	$e \rightarrow \gamma$	other	total syst.
		$N_{lch}$ vs $N_{\sigma in in}$	$Z\gamma$ MC norm.						
>15	2	15	35	5	19	3	4	5	44
15-20	8	80	27	19	17	3	18	11	90
20-25	7	38	20	14	12	3	11	10	48
25-30	5	25	16	12	14	3	8	8	36
30-35	5	35	14	12	14	3	3	8	42
35-45	3	14	13	8	18	3	2	7	28
45-55	8	53	20	22	36	3	7	11	71
55-65	7	17	12	30	44	3	5	10	58
65-75	7	23	15	32	44	3	4	11	61
75-85	8	32	17	27	44	3	6	13	64
85-95	9	9	7	9	40	3	8	14	44
95-120	7	19	9	14	44	3	5	11	51
120-500	4	12	6	24	39	3	1	9	48

# Major Sources of the Systematic Uncertainties

Related to jets →  $\gamma$  background estimation:

- ▶ Bias in Template Shape and Fit Machinery:
  - ▶ Estimate as  $|N_{lch} - N_{\sigma i \eta i \eta}|$ .
- ▶  $Z\gamma$  MC Normalization:
  - ▶ Assign uncertainty on the  $Z\gamma$  normalization of  $\Delta N = 4.6\%$  (CMS published  $Z\gamma$  measurement);
  - ▶ Prepare fake- $\gamma$  templates with  $Z\gamma$  MC normalizations of  $N \pm \Delta N$ ;
  - ▶ Perform fits with such deviated templates;
  - ▶ Assign the spread among the three results as an uncertainty.
- ▶ Statistical Power of Templates:
  - ▶ Randomize fake- $\gamma$  templates 100 times with Gaussian distribution;
  - ▶ Perform fits with such deviated templates;
  - ▶ Take the Standard deviation of 100 fit results as an uncertainty;
  - ▶ Same for real- $\gamma$  templates (except randomize 20 times, not 100).
- ▶ Propagate each of three uncertainties through unfolding and other corrections.

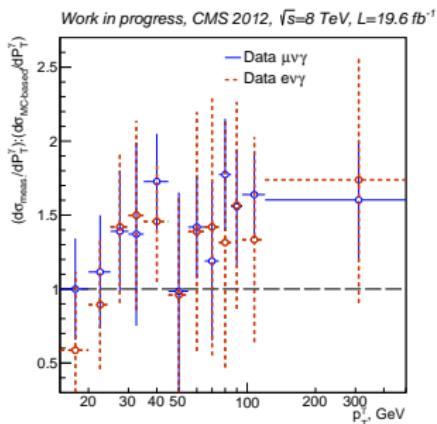
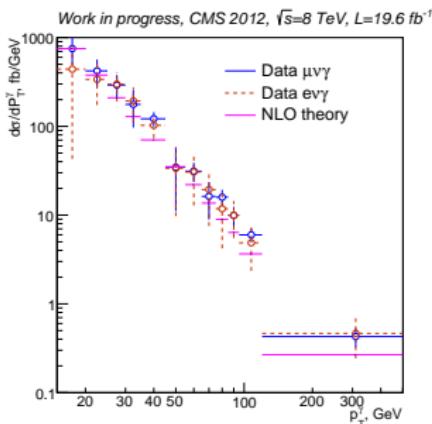
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Related to PixelSeedVeto SF (electron channel only):

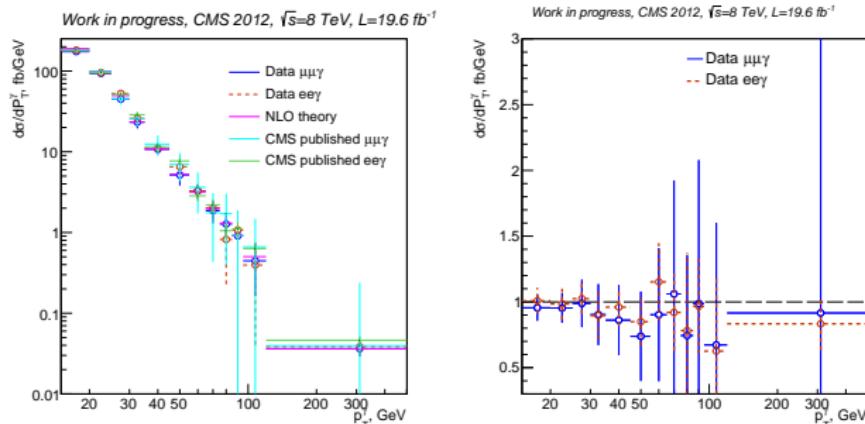
- ▶ Change SF by  $\pm \Delta[SF]$ ;
- ▶ From signal MC, obtain new constants for  $A \times \epsilon$  and unfolding corrections;
- ▶ Compute two new cross section values corresponding to  $\pm \Delta[SF]$ ;
- ▶ Assign the spread among three cross section values as an uncertainty.

# Total and Differential Cross Section

	$\sigma (P_T^\gamma > 15 \text{ GeV}), \text{fb}$
NLO theory	9101
Data, muon channel	$10949 \pm 91 \pm 1463$
Data, electron channel	$9146 \pm 185 \pm 2213$



# $Z\gamma$ Check. Differential Cross Section



- ▶ Cross section of  $Z\gamma \rightarrow ll\gamma$  agrees well with the 8 TeV published CMS result and with the theory prediction;
- ▶ The workflows for the  $Z\gamma$  and  $W\gamma$  measurements are very similar;
- ▶ The same procedures of the jets $\rightarrow \gamma$  background estimation have been used;
- ▶  $Z\gamma \rightarrow \mu\mu\gamma$ : template data **significantly overlap** with analyzed data  $\rightarrow$  **closure check**;
- ▶  $Z\gamma \rightarrow ee\gamma$ : template data **do not overlap** with analyzed data  $\rightarrow$  **valid physics measurement**.

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- ▶ Joshua Kunkle, Senka Duric, Dmytro Kovalskyi;
- ▶ Kuo Chia-Ming, Sachiko Toda McBride, Yutaro Iiyama;
- ▶ whole CMS collaboration.

# Conclusions

- ▶ Cross section for muon and electron channels are computed;
- ▶ This is the first measurement of the differential  $W\gamma$  cross section with CMS;
- ▶ Results agree with the theory;
- ▶ Results between the two channels agree;
- ▶ Good agreement in the  $Z\gamma$  check validates most parts of the measurement.