

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

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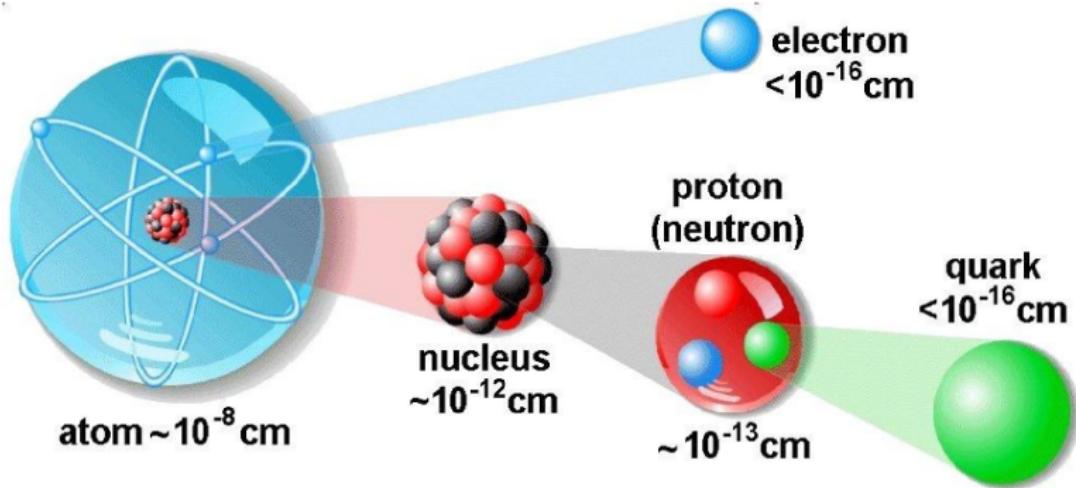
Talk Outline

- ▶ **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**

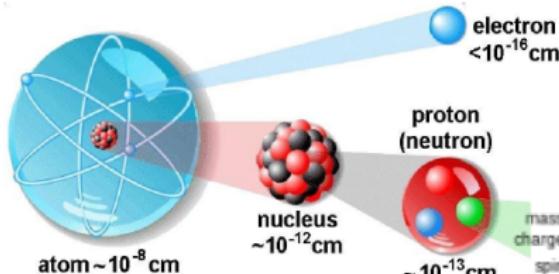
More details about each subject are available in the dissertation:

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

Theory. Atom Structure



Theory. The Standard Model

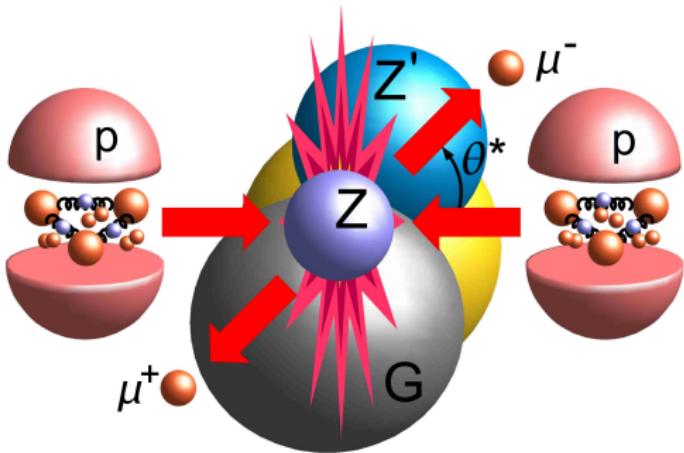


Three generations of matter (fermions)			
I	II	III	
$2.4 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$1.27 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$171.2 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	0 0 1 γ photon
$4.8 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$104 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$4.2 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
$<2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ e electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$<15.5 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$91.2 \text{ GeV}/c^2$ 0 1 Z^0 Z boson
$0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$105.7 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$80.4 \text{ GeV}/c^2$ ± 1 1 W^\pm W boson
Leptons			Gauge bosons

First generation (everyday matter):

uud (proton)
udd (neutron)
electron

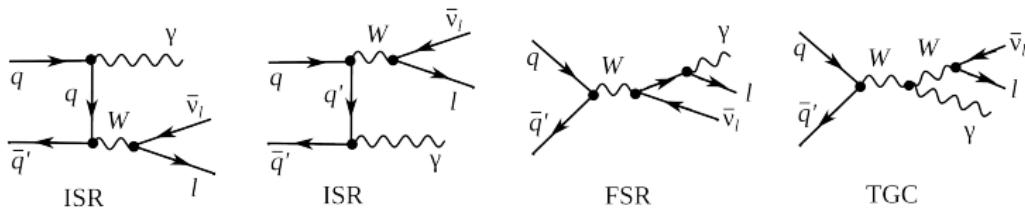
Theory. Proton-Proton Collisions



- ▶ 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 $q_1\bar{q}_2 = d\bar{u}$

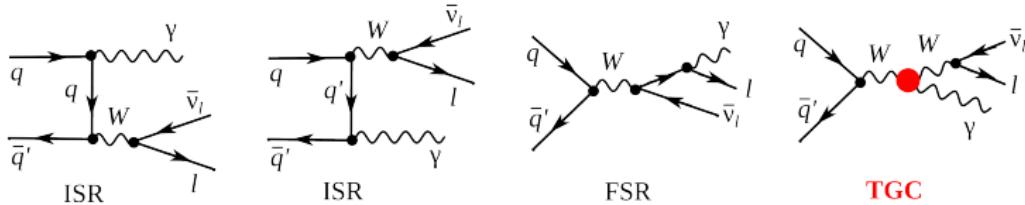
Three mechanisms:

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).

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



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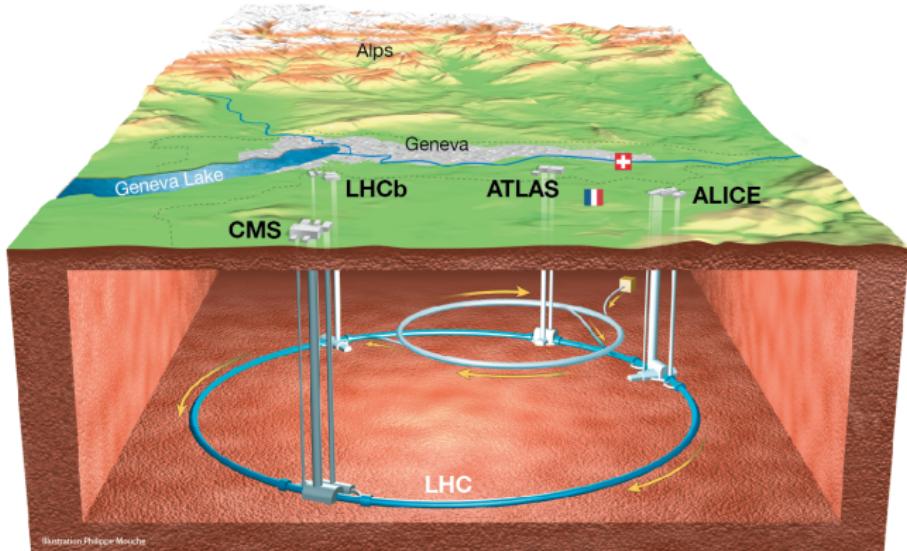
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Large Hadron Collider (LHC)

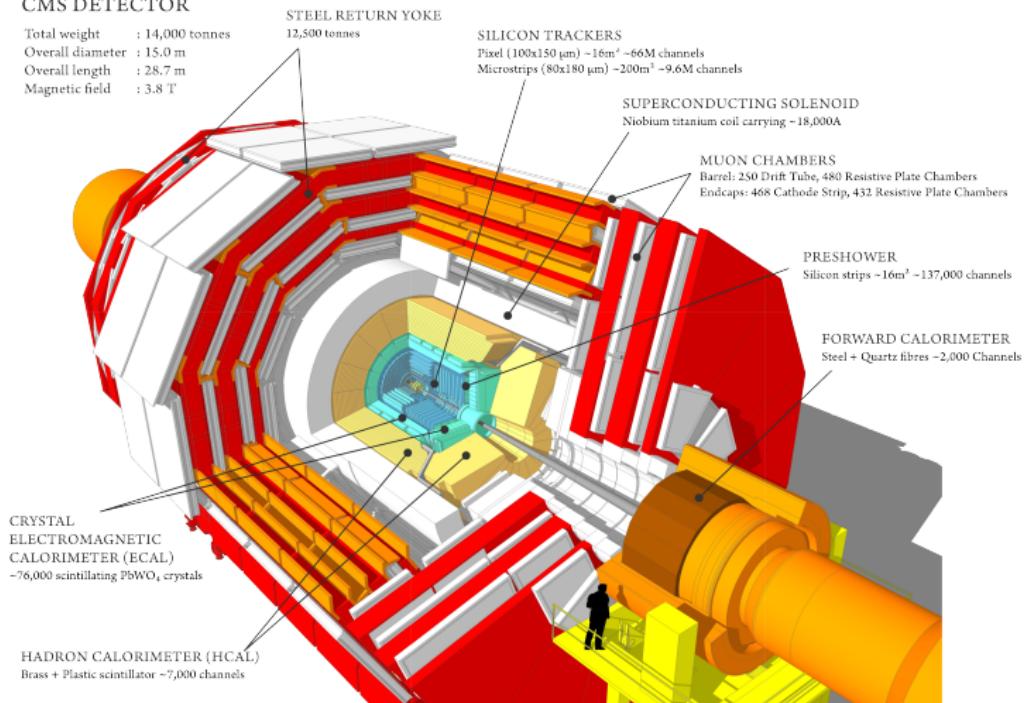


<http://lhcatome.web.cern.ch/about>

Compact Muon Solenoid (CMS)

CMS DETECTOR

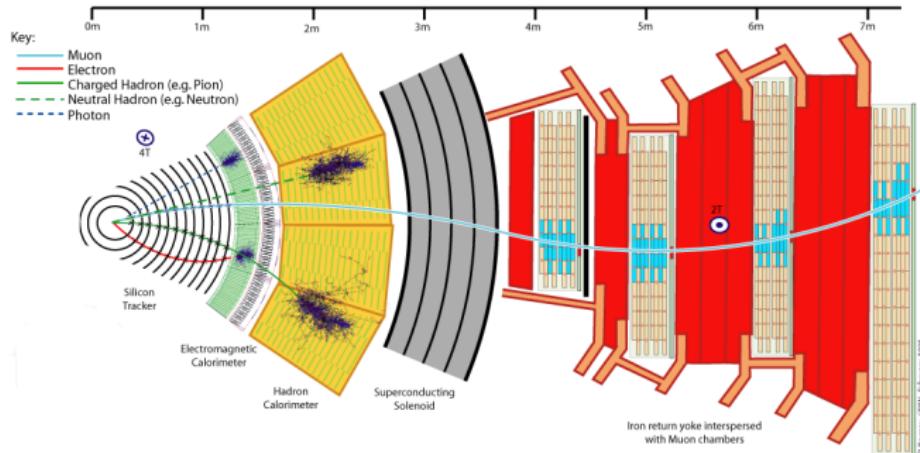
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



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.

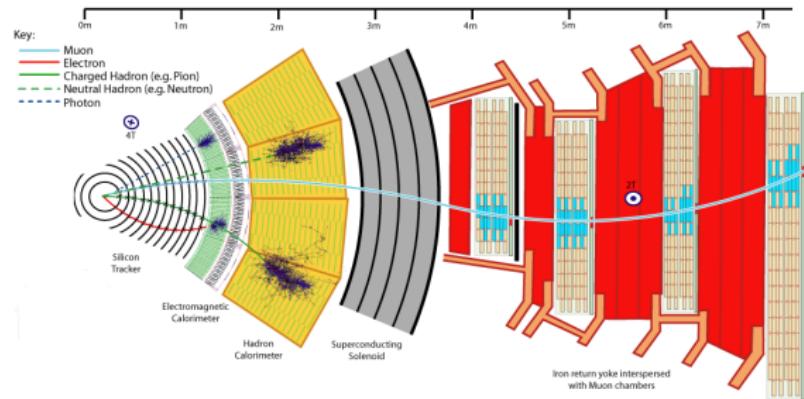


Neutrino is not detected. The measure of P_T^ν is missing transverse energy: $E_T^{\text{miss}} = -|\sum \mathbf{P}_T|$,
Sum over all visible particles in the event.

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^ν is missing transverse energy: $E_T^{\text{miss}} = -|\sum \mathbf{P}_T|$,
Sum over all visible particles in the event.

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 $d\sigma/dP_T^\gamma$	σ
select events	N_{sel}^j	N_{sel}
subtract background	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$	$N_{sign} = N_{sel} - N_{bkg}$
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$	—
correct for efficiency	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$
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		

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
$W\gamma \rightarrow \mu\nu\gamma$	$W\gamma \rightarrow e\nu\gamma$	
Event level: 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
Photon selection: $P_T^\gamma > 15$ GeV η^γ : EB or EE Photon ID \quad [one change in ID]		theory considerations acceptance POG*-recommended $W\gamma\gamma$ -recommended
$p_T^\mu > 25$ GeV; $ \eta^\mu < 2.1$ Muon ID	$p_T^e > 30$ GeV; η^e : EB or EE Electron ID	trigger trigger, acceptance POG*-recommended
$p_T^{\mu 2} > 10$ GeV; $ \eta^{\mu 2} < 2.4$	$p_T^{e2} > 10$ GeV; η^{e2} : EB or EE [veto] ID	rejects DY+jets, $Z\gamma$ very loose

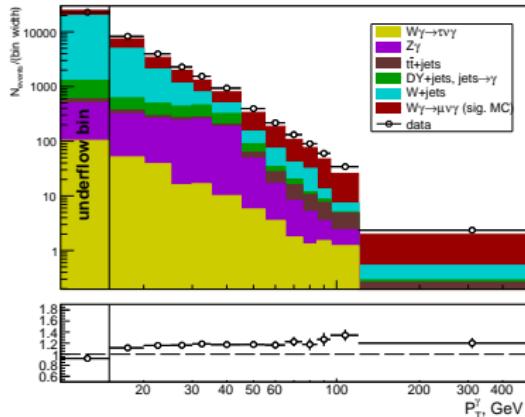
If we have several candidates in an event, we choose one with the highest P_T^γ

*POG - Particle Object Group (in CMS)

P_T^γ Spectrum of $W\gamma$ Candidates

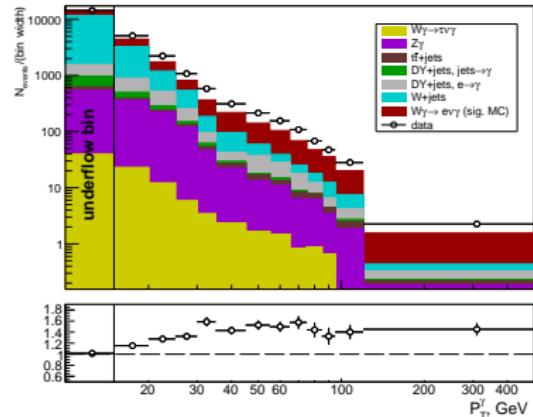
Work in progress, CMS 2012, $\sqrt{s}=8$ TeV, $L=19.6 \text{ fb}^{-1}$

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.



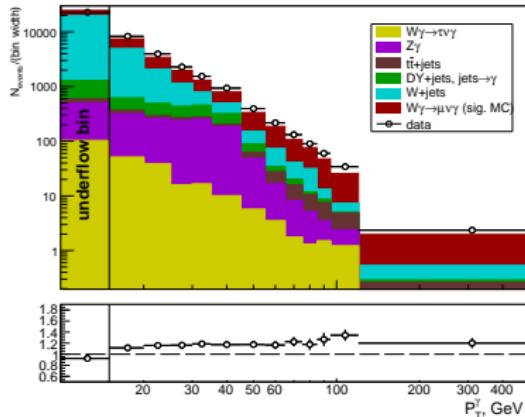
Comments:

Dominated by $W+jets$ events in low P_T^γ bins;
Fraction of signal increases with P_T^γ ;
Data disagree with MC.

P_T^γ Spectrum of $W\gamma$ Candidates

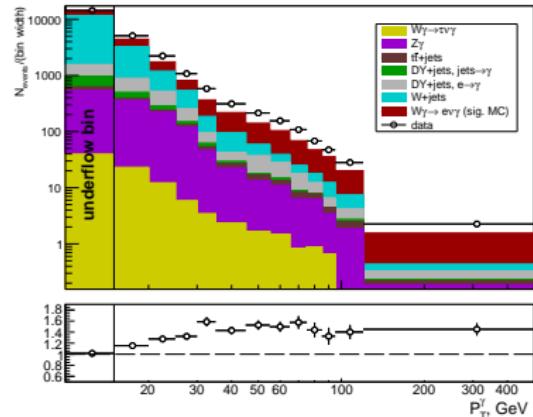
Work in progress, CMS 2012, $\sqrt{s}=8$ TeV, $L=19.6 \text{ fb}^{-1}$

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^γ bins;
Fraction of signal increases with P_T^γ ;
Data disagree with MC.

Backgrounds:

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

Jets $\rightarrow\gamma$ Background. Sources

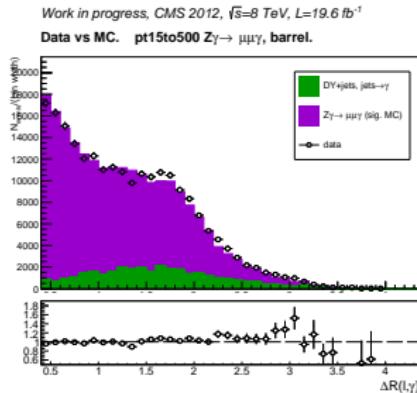
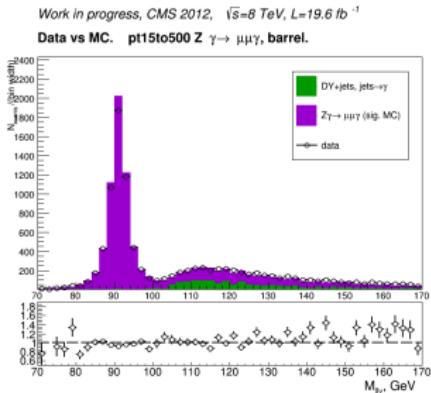
Jets $\rightarrow\gamma$ background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed later).

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- γ (T_{true}) and fake- γ (T_{fake}) templates*;
- ▶ 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: binned histograms of V_{fit} , which should be accurate representations of V_{fit} distributions of real and fake photons in the $W\gamma$ -selected dataset.

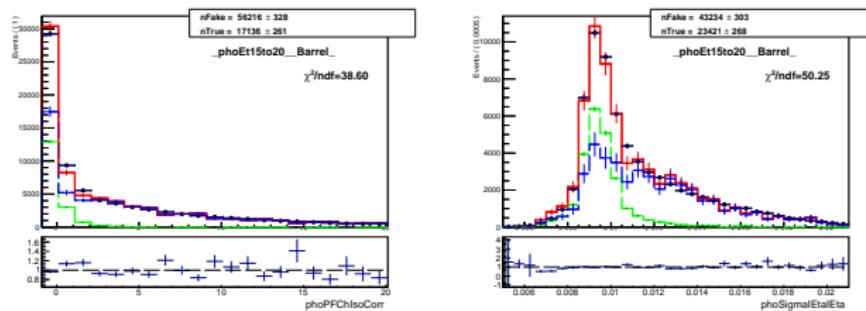
Jets $\rightarrow\gamma$ Background. Templates from $Z\gamma\rightarrow\bar{\mu}\mu\gamma$



FSR selection: $M_{\mu\mu\gamma} < 101$ GeV and $\Delta R(\mu_1, \gamma) > 0.4$

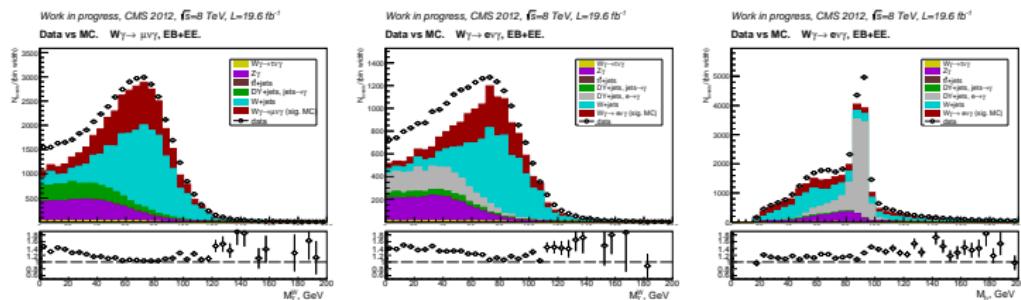
ISR selection: $M_{\mu\mu\gamma} > 101$ GeV and $\Delta R(\mu_1, \gamma) > 1.0$

Jets $\rightarrow \gamma$ Background. $V_{fit} = I_{ch}^\gamma$ and $V_{fit} = \sigma_{i\eta i\eta}$



$e \rightarrow \gamma$ and Real- γ 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- γ	$Z\gamma \rightarrow ll\gamma$	pass second lepton veto; fake E_T^{miss}	MC-based
Real- γ	$W\gamma \rightarrow \tau\nu\gamma$	$\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$ and $\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$	MC-based

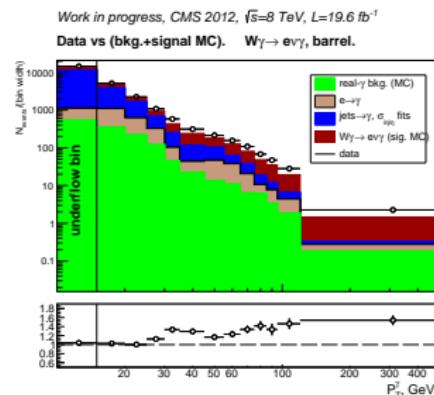
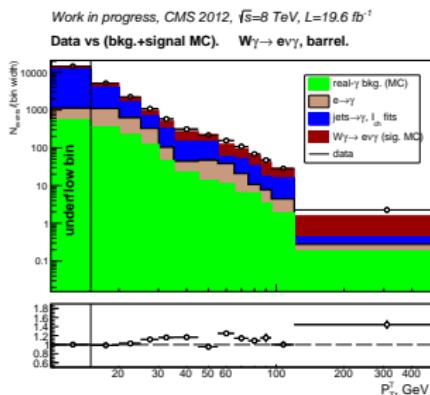
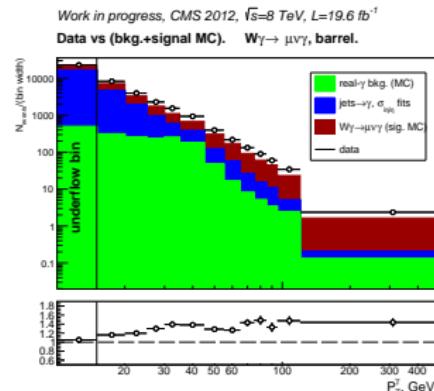
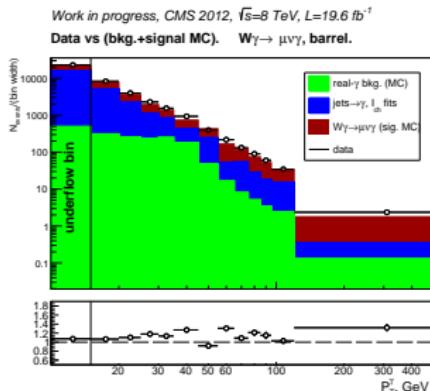


$M_T^W > 40$ GeV in both channels: rejects events without E_T^{miss}

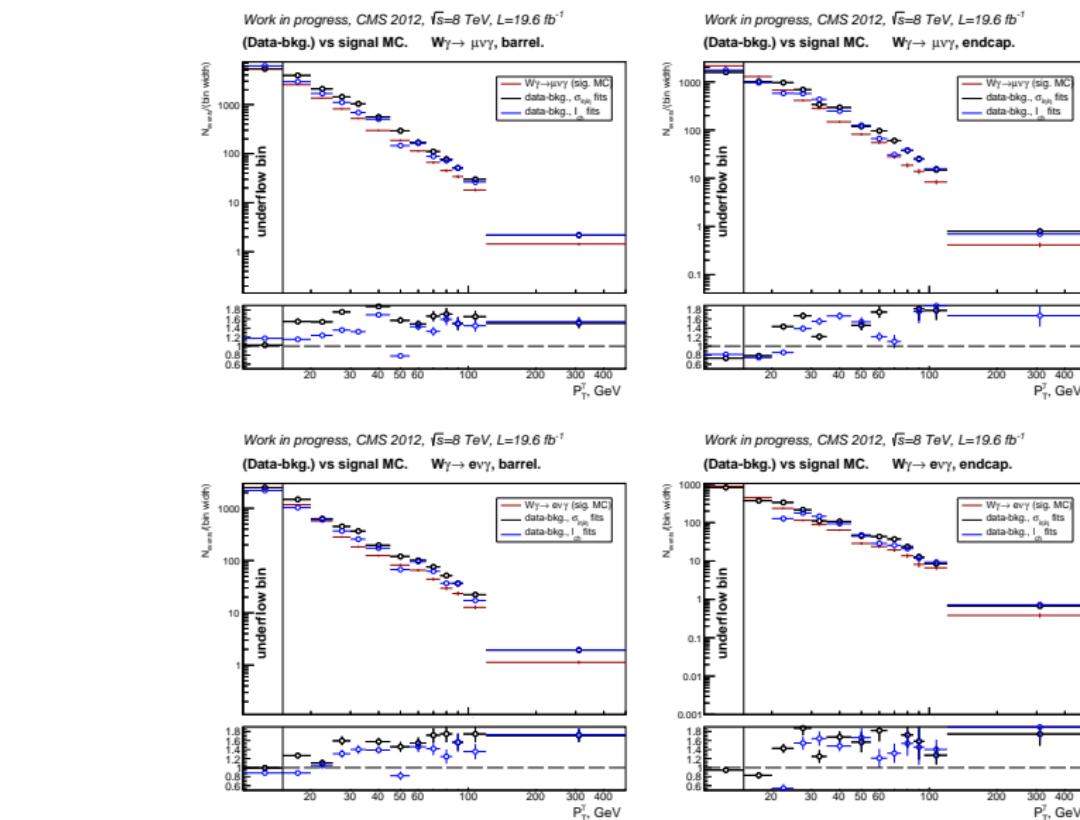
$M_{l,\gamma} < 70$ or $M_{l,\gamma} > 110$ GeV in the electron channel: rejects events from $DY+jets \rightarrow ee+jets$

Non-negligible amount remains

P_T^γ Spectrum (EB only)



P_T^γ 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

Detector resolution unfolding: Important note: errors across different P_T^γ bins become correlated after the unfolding procedure.

Efficiency:

Acceptance:

Efficiency Scale Factors

POG

Special SF from $W\gamma$

Uncertainties. Introduction

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

Diagonal elements of error matrices only

P_T^γ , 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^γ , 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 γ 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^γ , GeV	stat. unc.	systematic uncertainties							
		related to jets $\rightarrow \gamma$		templ. stat.	SFs	lumi	$e \rightarrow \gamma$	other	total syst.
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Major Sources of the Systematic Uncertainties

Bias in Template Shape and Fit Machinery: $|N_{lch} - N_{\sigma in \eta}|$

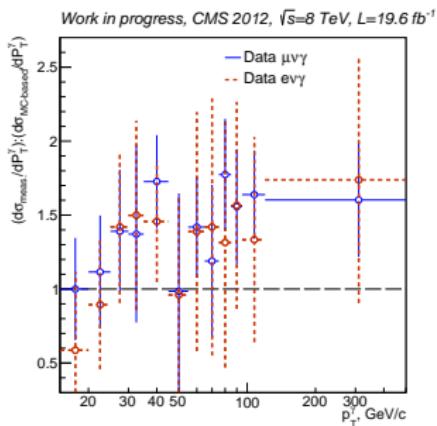
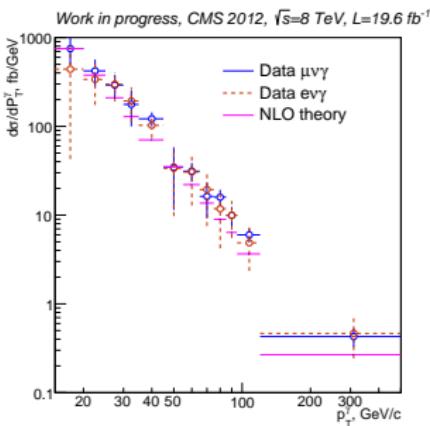
Z γ MC Normalization:

Statistical Power of Templates:

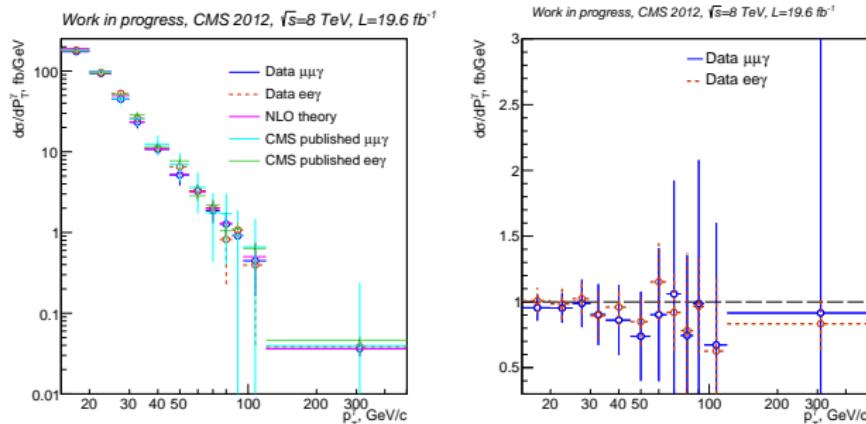
PixelSeedVeto SFs (electron channel only):

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**.

Acknowledgements

Before drawing conclusions...

- ▶ Ilya Kravchenko, Yurii Maravin, Lovedeep Saini;
- ▶ 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.