The Measurement of the Wγ Cross Section at 8 TeV (PhD thesis defense)

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Talk Outline

- **Introduction to the Standard Model**
- **Theory**
  - Electroweak interactions
  - Triple and quartic gauge couplings
  - $W\gamma \to l\nu\gamma$ process
- **Experimental setup**
  - Large Hadron Collider (LHC)
  - Proton-proton collisions
  - Compact Muon Solenoid (CMS)
  - Particle reconstruction in CMS
- **$W\gamma$ cross section measurement**
  - Measurement goal and strategy
  - Data and simulation (MC) samples
  - Event selection
  - Background estimation
    - Methods and results
    - Challenges and cross checks
  - Selected corrections
  - Systematic uncertainties
  - Cross section
- **Acknowledgements**
- **Conclusions**

Introduction. The Standard Model

About the Standard Model

Theory. EWK Interactions

Theory. Anomalous Gauge Couplings

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

W decay channels:

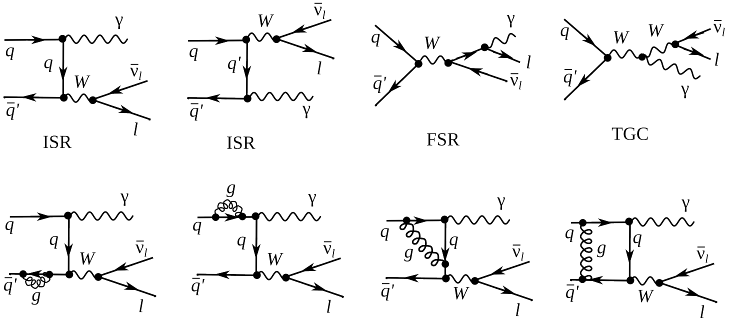


Figure: The Feynman diagrams. ISR(x2), FSR, and TGC.

- test Standard Model;
- search for aTGC.

Large Hadron Collider (LHC)

Proton-Proton Collisions

Compact Muon Solenoid (CMS). Components

Compact Muon Solenoid (CMS). Particle Reconstruction

Neutrino. Missing Transverse Energy

Measurement Goal

- Process: $W\gamma \rightarrow \mu\nu\gamma$ and $W\gamma \rightarrow e\nu\gamma$.
- Observables: the total and the differential ($\frac{d\sigma}{dP_T^\gamma}$) cross sections.
- Data: CMS, 2012, $\sqrt{s}$ =8 TeV (datasets are discussed later).

Phase space definition:

- $p_T^\gamma > 15$ GeV
- $\Delta R(\gamma, lep) > 0.7$
- $|\eta^\gamma| < 2.5$, $|\eta^{lep}| < 2.5$
- $p_T^{lep} > 20$ GeV
- $Iso^\gamma < 5$ GeV
- for differential cross section, P_T^γ binning: 15-20-25-30-35-45-55-65-75-85-95-120-500 GeV

Measurement Strategy

Step	$d\sigma/dP_T$	σ
select events	N^j_{sel}	N_{sel}
subtract background	$N^j_{sign} = N^j_{sel} - N^j_{bkg}$	$N_{sign} = N_{sel} - N_{bkg}$
unfold	$N^i_{A\times\epsilon} = U_{ij} \cdot N^j_{sign}$	$-$
correct for the acceptance and efficiency	$N^i_{true} = \frac{N^i_{A\times\epsilon}}{(A\times\epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A\times\epsilon}$
divide by luminosity and bin width	$\left(\frac{d\sigma}{dP^\gamma_T}\right)^i = \frac{N^i_{true}}{L\cdot(\Delta P^\gamma_T)^i}$	$\sigma = N_{true}/L$
estimate systematic uncertainties		

Data Samples and Triggering

The data sample we use in this measurement was recorded by the CMS experiment in 2012 in LHC pp collisions at $\sqrt{s}$ =8 TeV. Integrated luminosity of the dataset is L =19.6 fb^{-1}.

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

MC Samples and Luminosity Reweighting

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

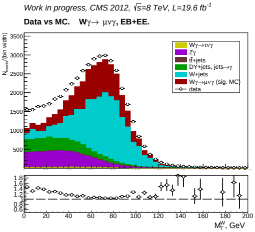
All MC samples are normalized to the data luminosity of L =19.6 fb^{-1} in all studies and plots.

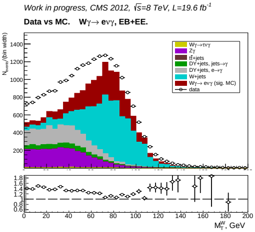
Requirements for Selection of $W\gamma$ Candidates

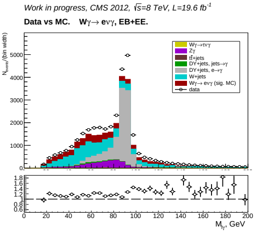
- - - - - - - **Muon Channel** - - - - - - -	- - - - - - - **Electron Channel** - - - - - - -
Exactly one lepton + at least one photon	
Photon selection: medium ID; $p_T > 15$; $\|\eta\| < 1.4442$ or $1.566 < \|\eta\| < 2.5$	ElectronConversionVeto→PixelSeedVeto
Muon tight ID	Electron tight ID
$p_T^{\mu} > 25$ GeV; $\|\eta^{\mu}\| < 2.1$	$p_T^{ele} > 30$; $\|\eta^{ele}\| < 1.4442$ or $1.566 < \|\eta^{ele}\| < 2.5$
Second lepton veto: $p_T^{\mu 2} > 10$ GeV; $\|\eta^{\mu 2}\| < 2.4$	$p_T^{ele2} > 10$; $\|\eta^{ele2}\| < 1.4442$ or $1.566 < \|\eta^{ele2}\| < 2.5$; veto ID for ele2
M_T^W >40 GeV (discussed later)	
	$110\ GeV > M_{e\gamma} > 70\ GeV$ excluded (discussed later)
$\Delta R(lep, \gamma) > 0.7$	

Data vs MC. M_T^W and $M_{l\gamma}$

$M_T^W > 40$ **GeV** is applied in both channels
$M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ **GeV** is applied in the **electron channel** only

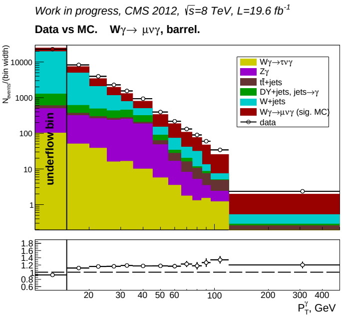


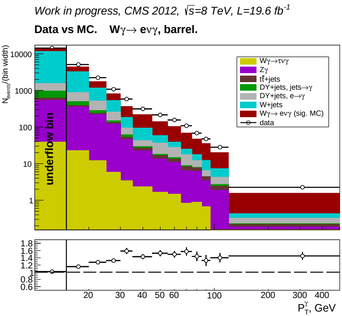




Data vs MC. P_T^{γ}

- selected datasets in both channels are dominated by W+jets events





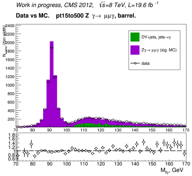
Jets$\rightarrow \gamma$ Background. Sources

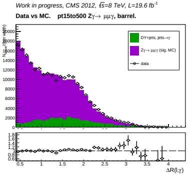
Jets$\rightarrow \gamma$ background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed lated).

Jets$\rightarrow \gamma$ Background. Template Method

- Fit function: $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$

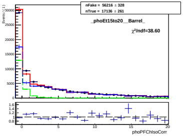
Jets$\rightarrow\gamma$ Background. Templates from $Z\gamma\rightarrow\bar{\mu}\mu\gamma$

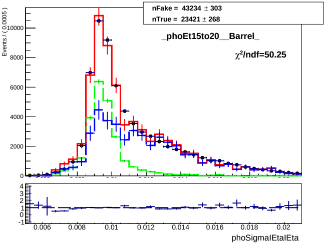




FSR selection: $M_{\mu\mu\gamma} < 101$ GeV and $\Delta R(\mu_1, \gamma) > 0.4$
ISR selection: $M_{\mu\mu\gamma} > 101$ GeV and $\Delta R(\mu_1, \gamma) > 1.0$

$Jets \to \gamma$ Background. $V_{fit} = I^{\gamma}_{ch}$ and $V_{fit} = \sigma_{i\eta i\eta}$





$e \to \gamma$ Background. Source

$e \to \gamma$ Background. Method Description

Method Description

- Get $N^{e\to\gamma}_{MC-Zpeak}$ (number of $e \to \gamma$ events under the Z-peak based on the MC prediction); done by counting
- Get $N^{e\to\gamma}_{data-Zpeak}$ (number of $e \to \gamma$ events under the Z-peak from data); done by fitting
- Get $N^{e\to\gamma}_{MC-nom}$ (number of $e \to \gamma$ events in the nominal range based on the MC prediction); done by counting
- Get $N^{e\to\gamma}_{data-nom}$ (number of $e \to \gamma$ events in the nominal range based on the MC predictionfrom data); done by scaling $N^{e\to\gamma}_{data-nom} = N^{e\to\gamma}_{MC-nom} \cdot N^{e\to\gamma}_{data-Zpeak} / N^{e\to\gamma}_{MC-Zpeak}$

$M_{e,\gamma}$ Fit Model and Fit Plots. 15-20 GeV, barrel

$$N_{sig} \cdot (RooNDKeysPdf \;\; x \;\; Gaussian) + N_{bkg} \cdot (RooCMSShapePdf)$$

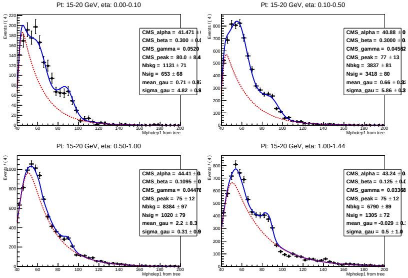


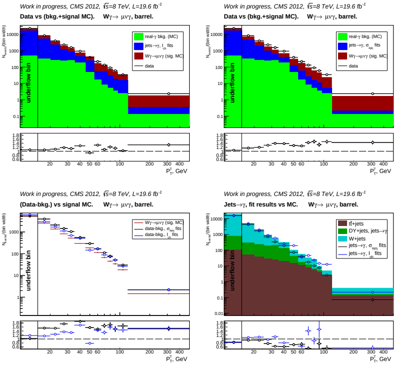
Figure: $M_{e,\gamma}$ fits, Wγ, electron channel, 15-20 GeV, barrel, 4 eta bins

Real-γ Background

Main sources of true γ background are $Z\gamma$ and $W\gamma \to \tau\nu\gamma$. The MC-based estimation is used to subtract these backgrounds. MC-based background estimation.

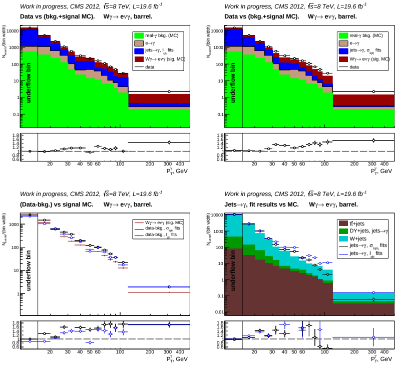
P_T^{γ} Spectrum before and after Background Subtraction. Muon Channel, Barrel

Top: data vs fake-γ background derived from the template method + real-γ background predicted by dedicated MC samples + signal MC, with I_{ch} and $\sigma_{i\eta i\eta}$ used as fit variables. Bottom: left: data yields after full background subtraction vs signal MC. I_{ch} vs $\sigma_{i\eta i\eta}$ fit results. Right: fake-γ data driven background prediction vs MC. Plotted with the stat error only. Disagreement



P_T^γ Spectrum before and after Background Subtraction. Electron Channel, Barrel

Top: data vs fake-γ background derived from the template method + real-γ background predicted by dedicated MC samples + signal MC, with I_{ch} and $\sigma_{i\eta i\eta}$ used as fit variables. Bottom: left: data yields after full background subtraction vs signal MC. I_{ch} vs $\sigma_{i\eta i\eta}$ fit results. Right: fake-γ data driven background prediction vs MC. Plotted with the stat error only.



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

Simple MC closure check:
MC realistic check:
$Z\gamma$ **check:**
Conclusions:

Other Corrections

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

Efficiency Scale Factors

POG

Special SF from $W\gamma$

Systematic Uncertainties. Introduction

Relative Systematic Uncertainties [%] in the Muon Channel. Table

P_T^{γ}, GeV	err stat	syst $\lvert N_{Ich} - N_{\sigma i \eta i \eta} \rvert$	$Z\gamma$ MC norm	templ stat	SFs err	syst lumi	syst other	syst total
total	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

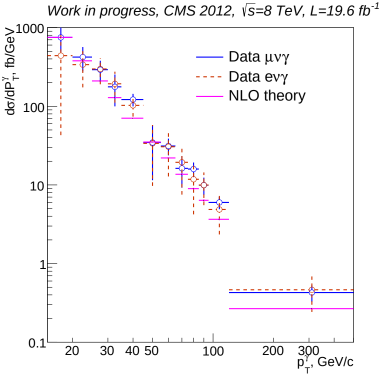
Relative Systematic Uncertainties [%] in the Electron Channel. Table

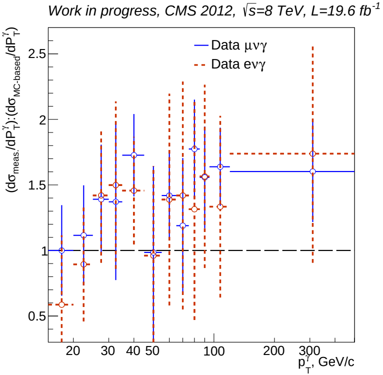
P_T^γ, GeV	err stat	syst $\lvert N_{Ich} - N_{\sigma i\eta i\eta}\rvert$	$Z\gamma$ MC norm	templ stat	SFs err	syst lumi	$e \to \gamma$	syst other	syst total
total	2	15	35	5	19	3	4	5	44
15-20	8	80	27	19	17	3	18	11	90
20-25	7	38	20	14	12	3	11	10	48
25-30	5	25	16	12	14	3	8	8	36
30-35	5	35	14	12	14	3	3	8	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

Bias in Template Shape and Fit Machinery:$|N_{Ich} - N_{\sigma i\eta i\eta}|$
$Z\gamma$ **MC Normalization:**
Statistical Power of Templates:
PixelSeedVeto SFs (electron channel only):

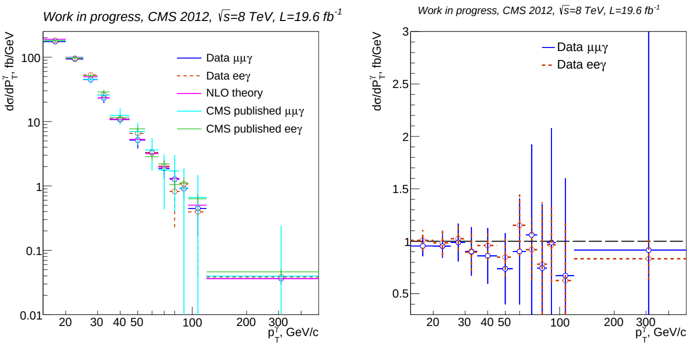
Total and Differential Cross Section





Total cross section ($P_T^\gamma > 15$ GeV):
MC-based: $\sigma = 9101$ fb
Measured, muon channel: $\sigma = 10949 \pm 91 \pm 1463$ fb
Measured, electron channel: $\sigma = 9146 \pm 185 \pm 2213$ fb

ZGamma check. Differential Cross Section



- Total and differential cross section of $Z\gamma \to ll\gamma$ is measured and agrees well with the 8 TeV published CMS result as well as with the theory prediction;
- The workflows for the $Z\gamma$ and $W\gamma$ are very similar, and we used the same procedures of the jets$\to \gamma$ background estimation;
- For the muon channel, data used for preparing templates significantly overlap with the dataset, thus, the result is a closure test rather that a valid physics measurement;
- For the electron channel, templates and the dataset are independent, thus, the result is a valid physics measurement.

Acknowledgements

Before drawing conclusions...

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