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
  - $W\gamma \rightarrow l\nu\gamma$ 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. $W\gamma \to l\nu\gamma$

Process signature:

- prompt, energetic, and isolated muon/electron
- prompt isolated photon
- significant missing energy due to neutrino

Goals:

- measure total and differential $\frac{d\sigma}{dp_T^{\gamma}}$ cross section

Motivation:

- test Standard Model

Large Hadron Collider (LHC)

Proton-Proton Collisions

Compact Muon Solenoid (CMS). Components

Compact Muon Solenoid (CMS). Particle Reconstruction

Neutrino. Missing Transverse Energy

Measurement Goal

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

Table: Measurement steps. The first column is the name of the step, the second and the third columns are algebraic representations of the steps for the differential and total cross section measurements, respectively.

Step	$d\sigma/dP_T$	σ
select events	N^j_{sel}	N_{sel}
subtract background	$N^j_{sign} = N^j_{sel} - N^j_{bkg}$	$N_{sign} = N_{sel} -$
unfold	$N^i_{A\times\epsilon} = U_{ij} \cdot N^j_{sign}$	$-$
correct for the acceptance and efficiency	$N^i_{true} = \frac{N^i_{A\times\epsilon}}{(A\times\epsilon)^i}$	$N_{true} = \frac{N}{A}$
divide by luminosity and bin width	$\left(\frac{d\sigma}{dP^\gamma_T}\right)^i = \frac{N^i_{true}}{L\cdot(\Delta P^\gamma_T)^i}$	$\sigma = N_{true}$
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}. To select $W\gamma$ events, we use data collected by single muon and single electron triggers.

Table: Summary of simulated samples used in the measurement.

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

MC Samples and Luminosity Reweighting

Table: Summary of simulated samples used in the measurement.

Process	Type	σ, pb
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$t\bar{t}$+jets$\to$ 1l+X	background	99
$t\bar{t}$+jets$\to$ 2l+X	background	24
$Z\gamma \to ll\gamma$	background	172

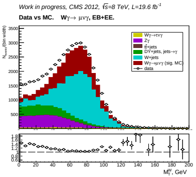
* Other weights and corrections that are not discussed (SFs have to be discussed, I believe)

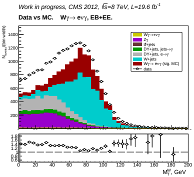
Requirements for Selection of $W\gamma$ Candidates

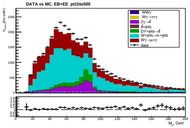
- - - - - - - **Muon Channel** - - - - - - -	- - - - - - **Electron Channel** - - - - - -
Exactly one lepton + at least one photon	
Photon selection: medium ID; $p_T > 15$; $\vert\eta\vert < 1.4442$ or $1.566 < \vert\eta\vert < 2.5$	ElectronConversionVeto$\rightarrow$PixelSeedVeto
Muon tight ID	Electron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

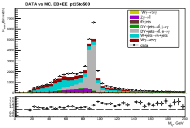
Data vs MC. M_T^W and $M_{l\gamma}$

The selection requirement of $M_T^W > 40$ **GeV** is applied. The selection requirement of $M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ **GeV** is applied in the **electron channel** only.



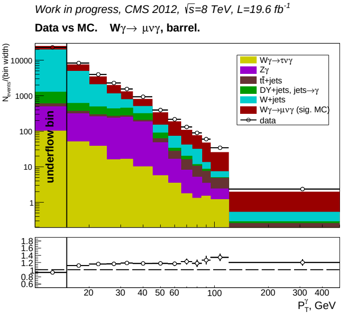


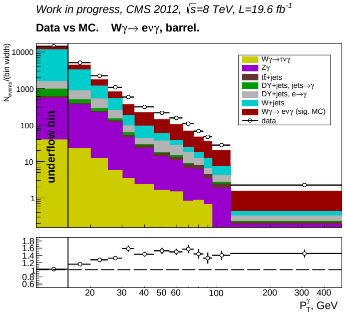




Data vs MC. P_T^γ

The sample composition:





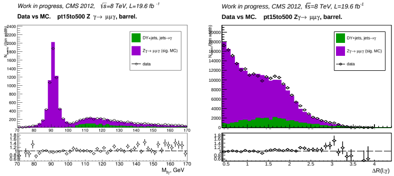
Jets$\rightarrow \gamma$ Background. Sources

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$\to \gamma$ Background. General Description of the Template Method

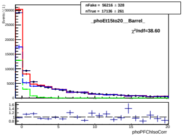
- Fit function: $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$

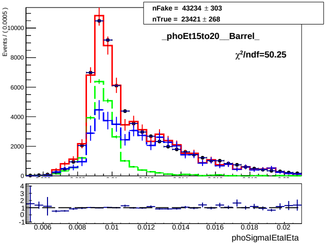
Jets$\to \gamma$ Background. Templates from $Z\gamma \to \bar{\mu}\mu\gamma$, FSR and ISR



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





$e \to \gamma$ Background. Source

$e \rightarrow \gamma$ Background. Method Description

Method Description

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

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

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

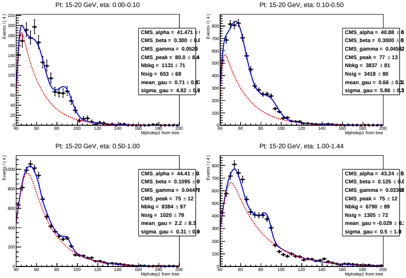


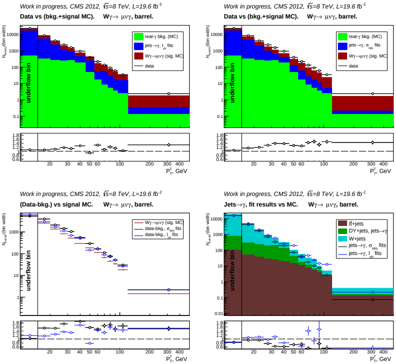
Figure: $M_{e,\gamma}$ fits, Wγ, electron channel, 15-20 GeV, barrel, 4 eta bins

Real-γ Background

Main sources of true γ background are $Z\gamma$ and $W\gamma \rightarrow \tau\nu\gamma$. 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

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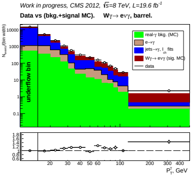
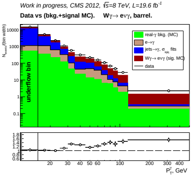
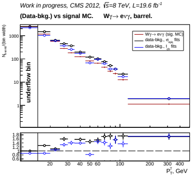
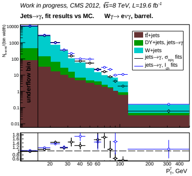








Cross Checks for Jets$\rightarrow \gamma$ Background Estimation

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

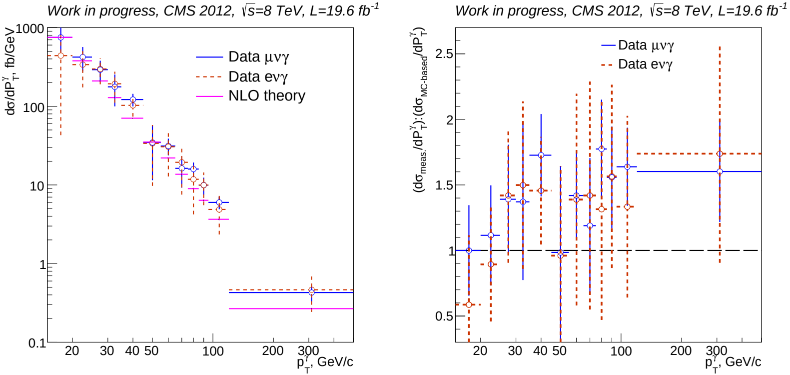
Relative Systematic Uncertainties [%] in the Electron Channel. Table

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

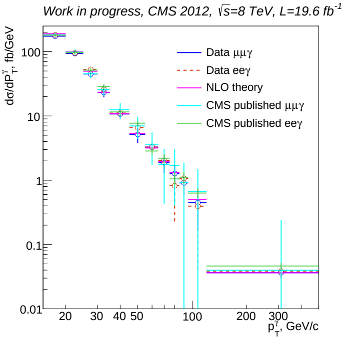
Bias in Template Shape and Fit Machinery:$|N_{Ich} - N_{\sigma i \eta i \eta}|$
$Z\gamma$ **MC Normalization:**
Statistical Power of Templates:
PixelSeedVeto SFs (electron channel only):

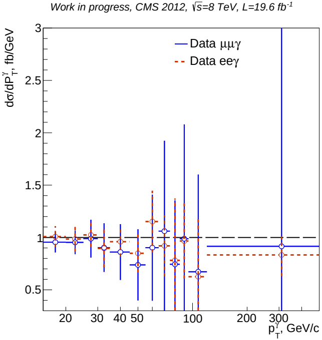
Total and Differential Cross Section



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





- Double-mu and double-ele datasets are used to perform the Zγ check (the same samples as used to prepare templates for jets$\rightarrow$ γ background estimation)
- Total and differential cross section of Z$\gamma\gamma$ is measured and compared to the 8 TeV published CMS result
- The workflow for Zγ is the same as Wγ except different selection criteria and also Zγ has only jets$\rightarrow$ γ background
- For the muon channel, templates significantly overlay with the dataset, so, the result for the muon channel is a closure test rather that an actual measurement
- For the electron channel, templates and dataset are independent
- Intermediate plots are available in the AN (template fits, yields, data vs MC)
- The result agrees well with the 8 TeV published CMS result

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 MC prediction;
- Results between the two channels agree;
- Relative systematic uncertainties on total cross section are larger than those reported by the CMS 7 TeV measurement;
- Good agreement in the $Z\gamma$ check validates most parts of the analysis (those which are the same for the muon and electron channels).