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

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June, 2017

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

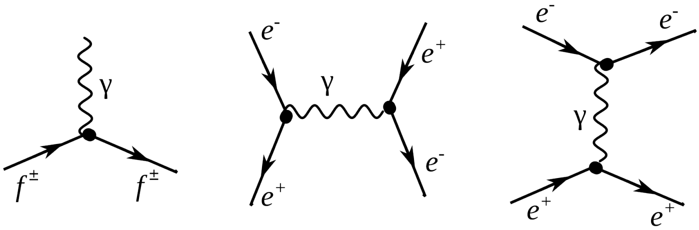
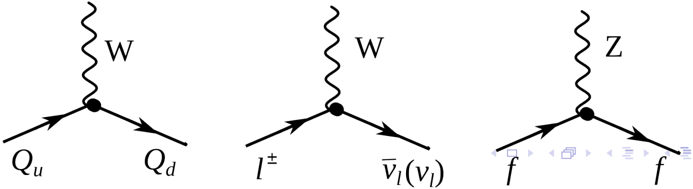


Figure:

Electromagnetic interactions.



Theory. Anomalous Gauge Couplings

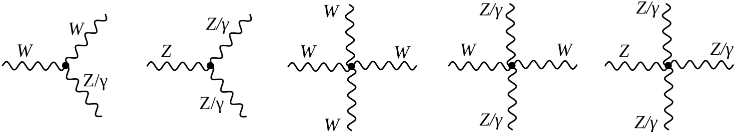


Figure:

Charged TGC (first), neutral TGC (second), charged QGC (third and fourth), and neutral QGC (fifth) vertices.

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

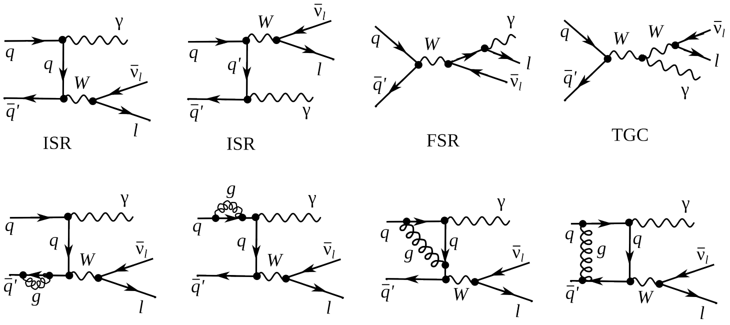
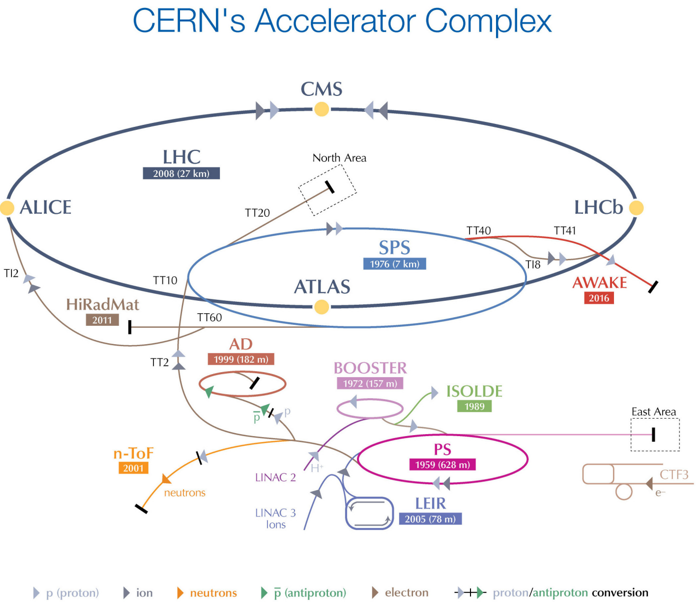


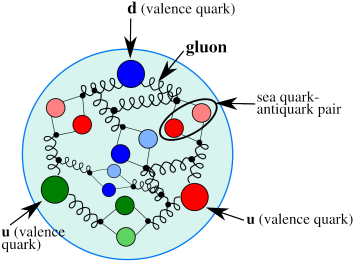
Figure: The Feynman diagrams. ISR(x2), FSR, and TGC.

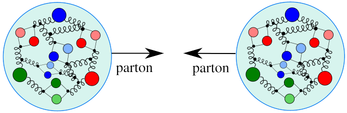
- test Standard Model;
- search for aTGC.

Large Hadron Collider (LHC)

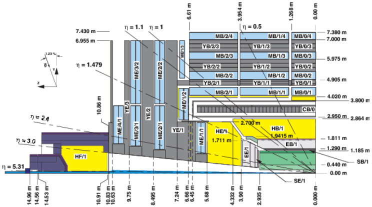


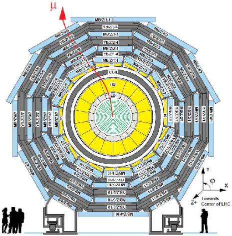
Proton-Proton Collisions



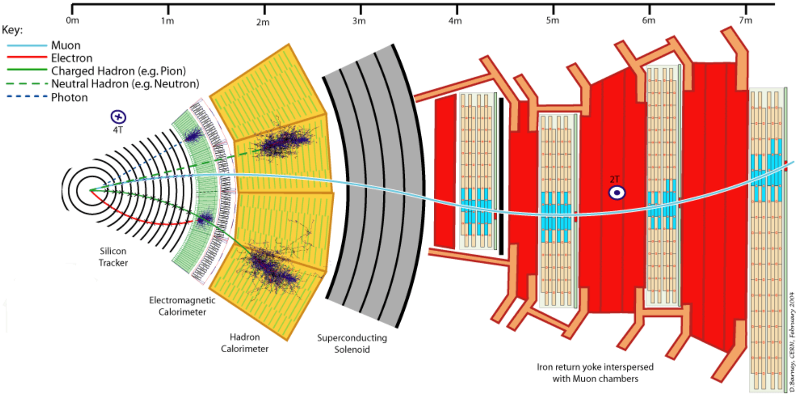


Compact Muon Solenoid (CMS). Components





Compact Muon Solenoid (CMS). Particle Reconstruction



Neutrino. Missing Transverse Energy

When all particles in the event are reconstructed and identified, the algorithm determines missing transverse energy E_T^{miss} as

$$E_T^{miss} = -|\sum \mathbf{P_T}|, \tag{1}$$

where the summation covers all visible particles in the event. For precise measurement of E_T^{miss} it is important to capture the full energy release of all visible particles.

Measurement Goal

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

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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
- P_T^γ ranges for $\frac{d\sigma}{dP_T^\gamma}$: 15-20-25-30-35-45-55-65-75-85-95-120-500 GeV

Measurement Strategy

Step	Algebraic representation for the measurement of $d\sigma/dP_T^{\gamma}$	Algebraic representation for the measurement of 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 the acceptance and efficiency	$N_{true}^{i} = \frac{N_{A\times\epsilon}^{i}}{(A\times\epsilon)^{i}}$	$N_{true} = \frac{N_{sign}}{A\times\epsilon}$
divide by luminosity and bin width	$\left(\frac{d\sigma}{dP_T^{\gamma}}\right)^{i} = \frac{N_{true}^{i}}{L\cdot(\Delta P_T^{\gamma})^{i}}$	$\sigma = N_{true}/L$
estimate systematic uncertainties		

Data 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

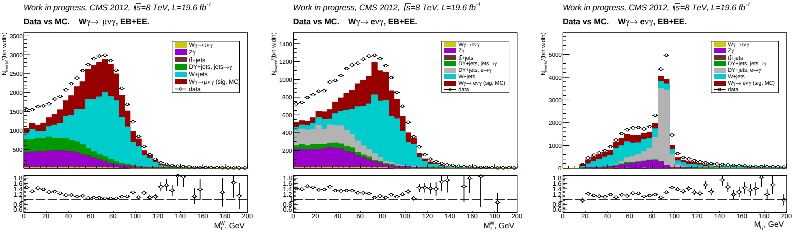
All MC samples are normalized to the data luminosity of $L=$19.6 fb^{-1} in all studies and plots.

Requirements for Selection of $W\gamma$ Candidates

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

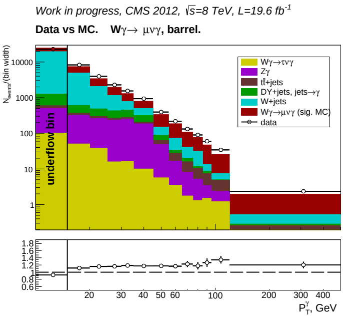
Data vs MC. M_T^W and $M_{l\gamma}$

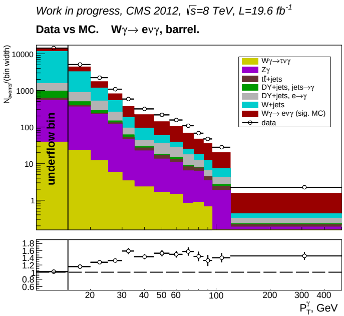
$M_T^W > 40$ **GeV** is applied in both channels
$M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ **GeV** is applied in the **electron channel** only



Data vs MC. P_T^γ

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





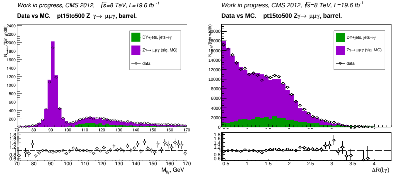
Jets$\rightarrow \gamma$ Background. Sources

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

Jets$\rightarrow \gamma$ Background. Template Method

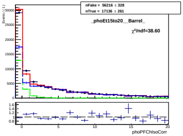
- Fit function: $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$

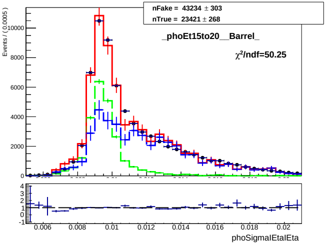
Jets$\rightarrow\gamma$ Background. Templates from $Z\gamma \rightarrow \bar{\mu}\mu\gamma$



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 $\Delta R(\mu_1, \gamma) > 1.0$

$Jets \rightarrow \gamma$ 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

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

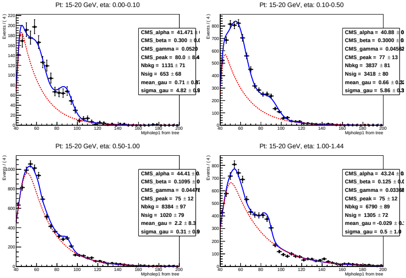


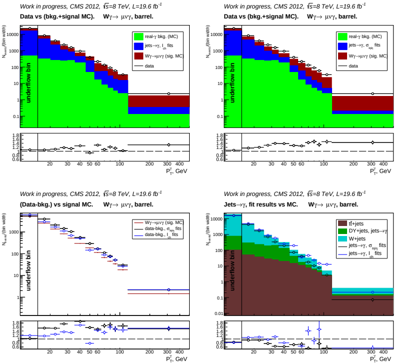
Figure: $M_{e,\gamma}$ fits, Wγ, electron channel, 15-20 GeV, barrel, 4 eta bins

Real-γ Background

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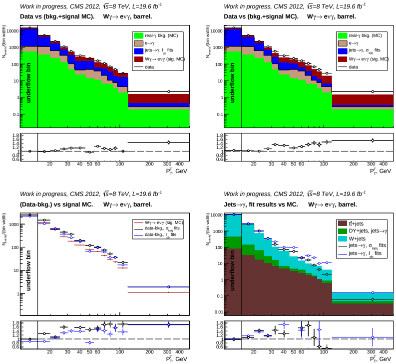


Cross Checks for Jets$\rightarrow \gamma$ Background Estimation

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

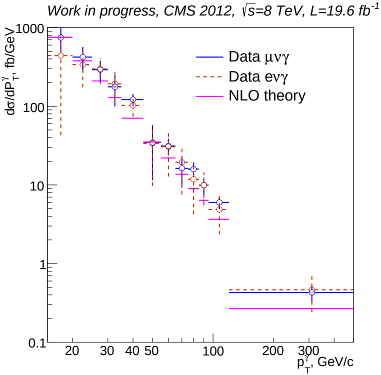
Relative Systematic Uncertainties [%] in the Electron Channel. Table

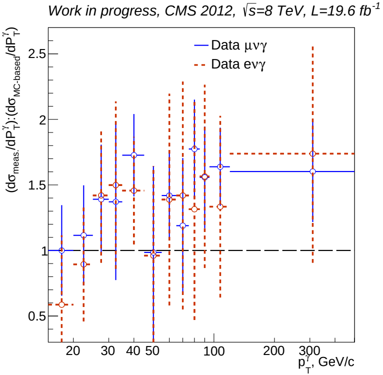
P_T^{γ}, GeV	err stat	syst $\lvert N_{Ich} - N_{\sigma i \eta i \eta}\rvert$	$Z\gamma$ MC norm	templ stat	SFs err	syst lumi	$e \to \gamma$	syst other	syst total
total	2	15	35	5	19	3	4	5	44
15-20	8	80	27	19	17	3	18	11	90
20-25	7	38	20	14	12	3	11	10	48
25-30	5	25	16	12	14	3	8	8	36
30-35	5	35	14	12	14	3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

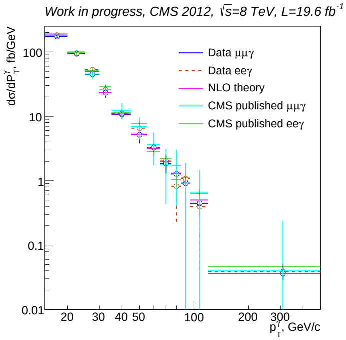
Total and Differential Cross Section

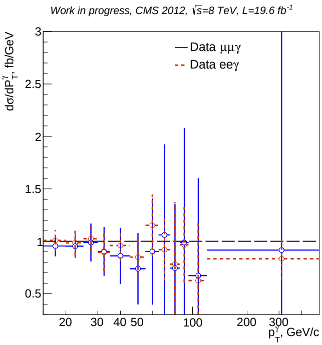




Total cross section ($P_T^{\gamma} > 15$ GeV):
MC-based: $\sigma = 9101$ fb
Measured, muon channel: $\sigma = 10949 \pm 91 \pm 1463$ fb
Measured, electron channel: $\sigma = 9146 \pm 185 \pm 2213$ fb

ZGamma check. Differential Cross Section





- Total and differential cross section of $Z\gamma \rightarrow ll\gamma$ 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$\rightarrow \gamma$ 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;
- 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.