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

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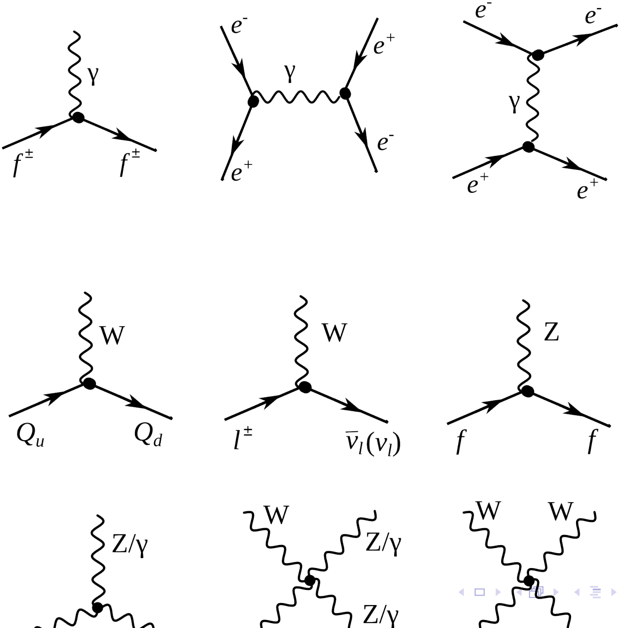
Talk Outline

- **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
- **Conclusions**

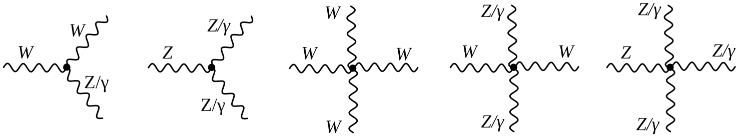
Introduction. The Standard Model

About the Standard Model

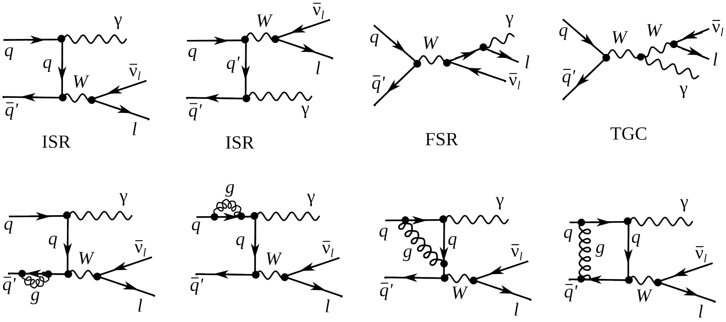
Theory. EWK Interactions



Theory. Anomalous Gauge Couplings

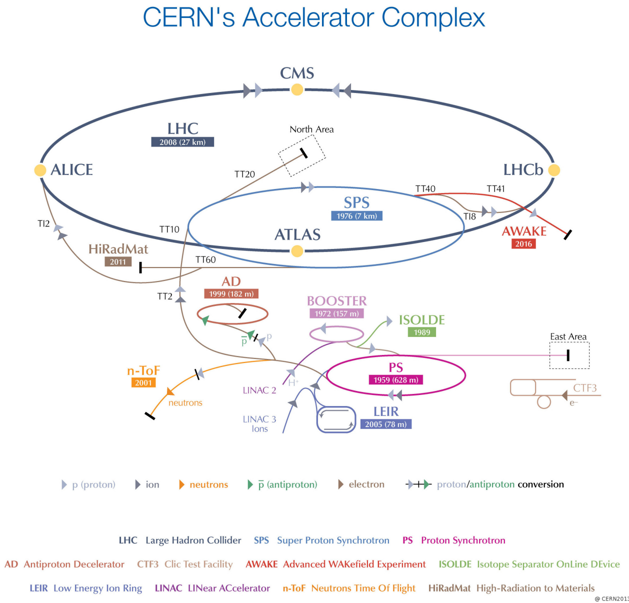


Theory. $W\gamma \to l\nu\gamma$

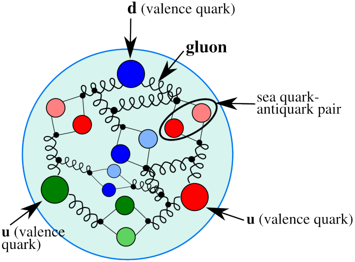


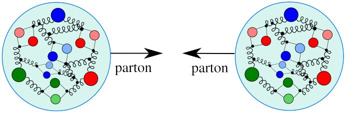
- test Standard Model;
- search for aTGC.

Large Hadron Collider (LHC)

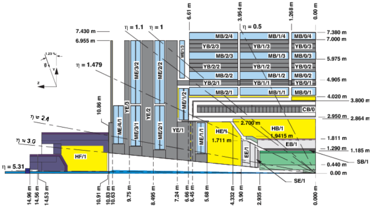


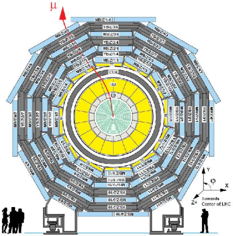
Proton-Proton Collisions



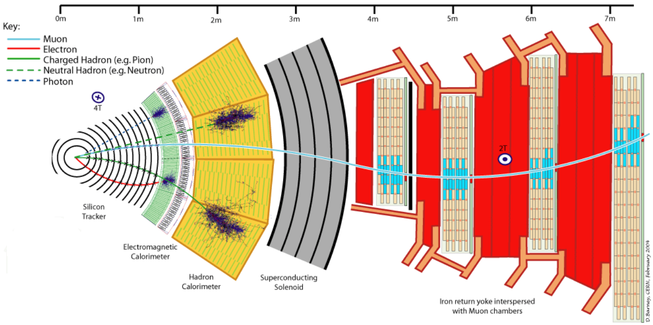


Compact Muon Solenoid (CMS). Components





Compact Muon Solenoid (CMS). Particle Reconstruction



Process to study: $W\gamma \to \mu\nu\gamma$, $W\gamma \to e\nu\gamma$.
Final state particles: muons, electrons, photons, neutrinos.
Neutrino is not detected. Described by the **missing transverse energy**:

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

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 $W\gamma \rightarrow l\nu\gamma$ at $\sqrt{s}$ =8 TeV.

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Phase space definition:

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

Data: CMS experiment, 2012, pp collisions at $\sqrt{s}$ =8 TeV
Integrated luminosity: 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

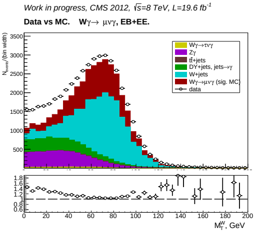
All MC samples are normalized to the data luminosity of L =19.6 fb^{-1} in all studies and plots.

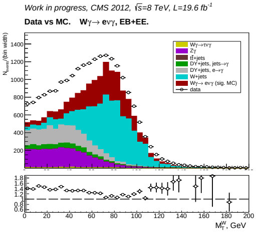
Requirements for Selection of $W\gamma$ Candidates

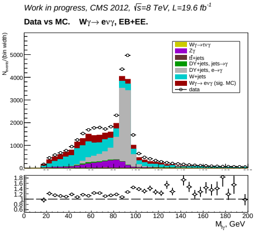
Selection requirements for candidates		Reject
- - - - - - $W\gamma \to \mu\nu\gamma$ - - - - - -	- - - - - - $W\gamma \to e\nu\gamma$ - - - - - -	
Exactly one lepton + at least one photon		
Photon selection: Photon ID; $p_T > 15$; EB or EE	[one change in ID]	
Muon ID	Electron ID	
$p_T^{\mu} > 25$ GeV; $\|\eta^{\mu}\| < 2.1$	$p_T^{e} > 30$; EB or EE	
Second lepton veto: $p_T^{\mu 2} > 10$ GeV; $\|\eta^{\mu 2}\| < 2.4$	$p_T^{e2} > 10$ GeV; EB or EE [veto] ID	
M_T^W >40 GeV		
	$110 > M_{e\gamma} > 70$ GeV excl.	
$\Delta R(lep, \gamma) > 0.7$		

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

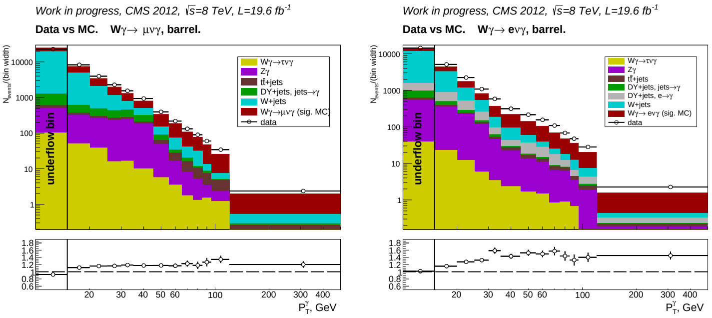






Data vs MC. P_T^γ

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



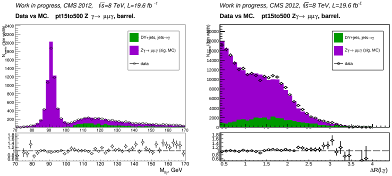
Jets$\rightarrow\gamma$ Background. Sources

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

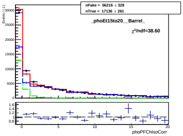
- Fit function: $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$

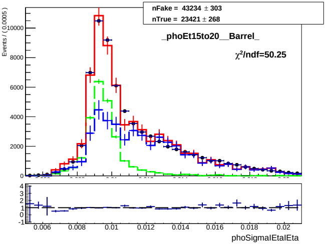
Jets$\rightarrow \gamma$ Background. Templates from $Z\gamma \rightarrow \bar{\mu}\mu\gamma$



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

$Jets \to \gamma$ Background. $V_{fit} = I_{ch}^{\gamma}$ 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

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

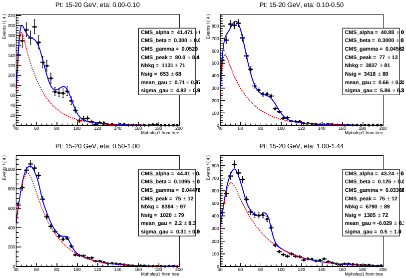


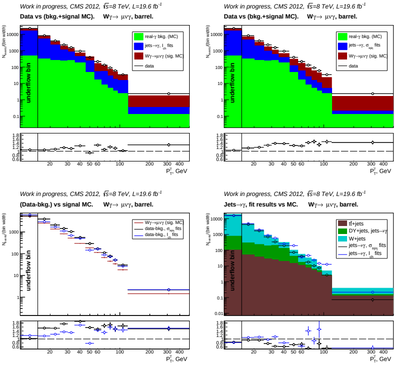
Figure: $M_{e,\gamma}$ fits, Wγ, electron channel, 15-20 GeV, barrel, 4 eta bins

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

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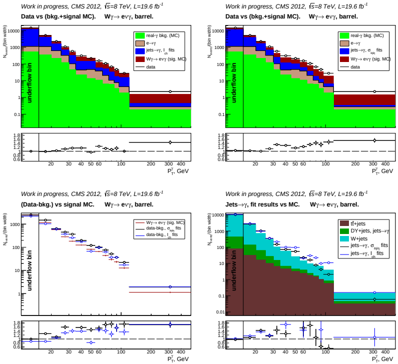

Cross Checks for Jets$\rightarrow \gamma$ Background Estimation

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 $W\gamma$

Uncertainties. Introduction

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

Diagonal elements of error matrices only

P_T^γ, GeV	stat. unc.	systematic uncertainties: related to jets$\to\gamma$: N_{Ich} vs $N_{\sigma i\eta i\eta}$	related to jets$\to\gamma$: $Z\gamma$ MC norm.	related to jets$\to\gamma$: templ. stat.	SFs	lumi	other	total syst.
>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 $W\gamma \to e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

P_T^γ, GeV	stat. unc.	systematic uncertainties							
		related to jets $\to \gamma$							
		N_{Ich} **vs** $N_{\sigma i\eta i\eta}$	$Z\gamma$ **MC norm.**	templ. stat.	SFs	lumi	$e \to \gamma$	other	total syst.
$>$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 $W\gamma \to e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

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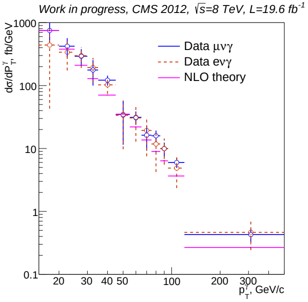
30-35	5	**35**	14	12	14	3	3	8	42
35-45	3	14	13	8	**18**	3	2	7	28
45-55	8	**53**	20	22	36	3	7	11	71
55-65	7	17	12	30	**44**	3	5	10	58
65-75	7	23	15	32	**44**	3	4	11	61
75-85	8	32	17	27	**44**	3	6	13	64
85-95	9	9	7	9	**40**	3	8	14	44
95-120	7	19	9	14	**44**	3	5	11	51
120-500	4	12	6	24	**39**	3	1	9	48

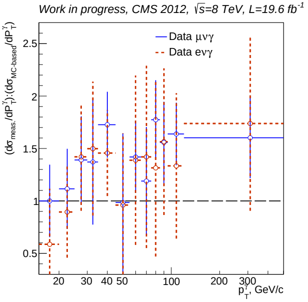
Major Sources of the Systematic Uncertainties

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):

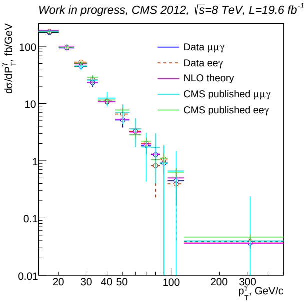
Total and Differential Cross Section

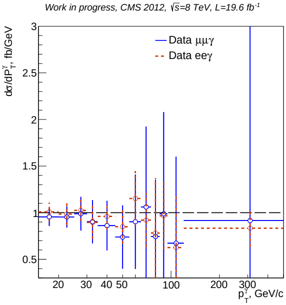
	σ ($P_T^\gamma > 15$ GeV), fb
NLO theory	9101
Data, muon channel	10949 $\pm$91 $\pm$ 1463
Data, electron channel	9146 $\pm$185 $\pm$ 2213





$Z\gamma$ Check. Differential Cross Section





- Cross section of $Z\gamma \to ll\gamma$ 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$\to \gamma$ background estimation have been used;
- $Z\gamma \to \mu\mu\gamma$: template data **significantly overlap** with analyzed data $\to$ **closure check**;
- $Z\gamma \to ee\gamma$: template data **do not overlap** with analyzed data $\to$ **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.