

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**
 - ▶ Data
 - ▶ Measurement steps
 - ▶ **Main challenge:** jets $\rightarrow \gamma$ background estimation
 - ▶ Systematic uncertainties
 - ▶ Results
- ▶ **Conclusions**

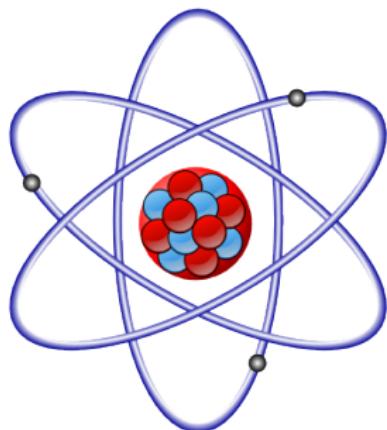
More details about each subject are available in the dissertation:

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

Theory. Atom Structure

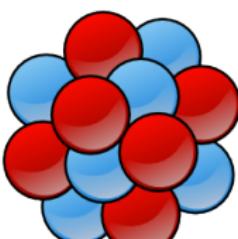
Atom:

nucleus+electrons



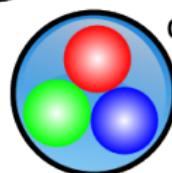
Electron:

no known structure



Nucleus:

nucleons
(protons, neutrons)



Nucleon:
quarks

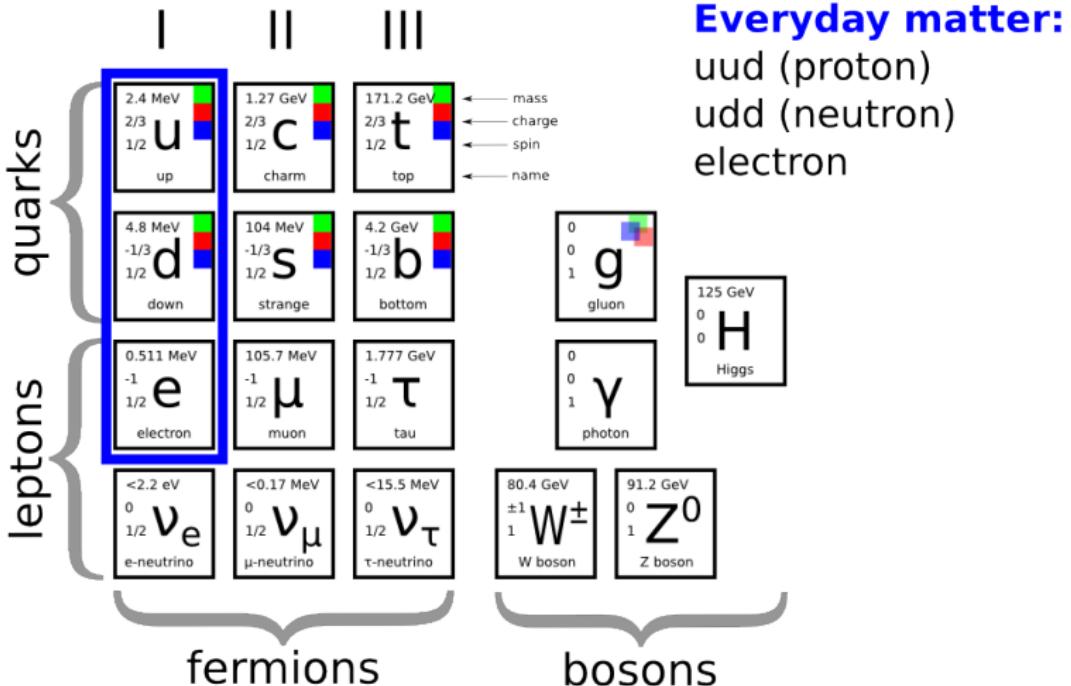


Quark:

no known structure

Electrons and quarks are
fundamental particles

Theory. The Standard Model

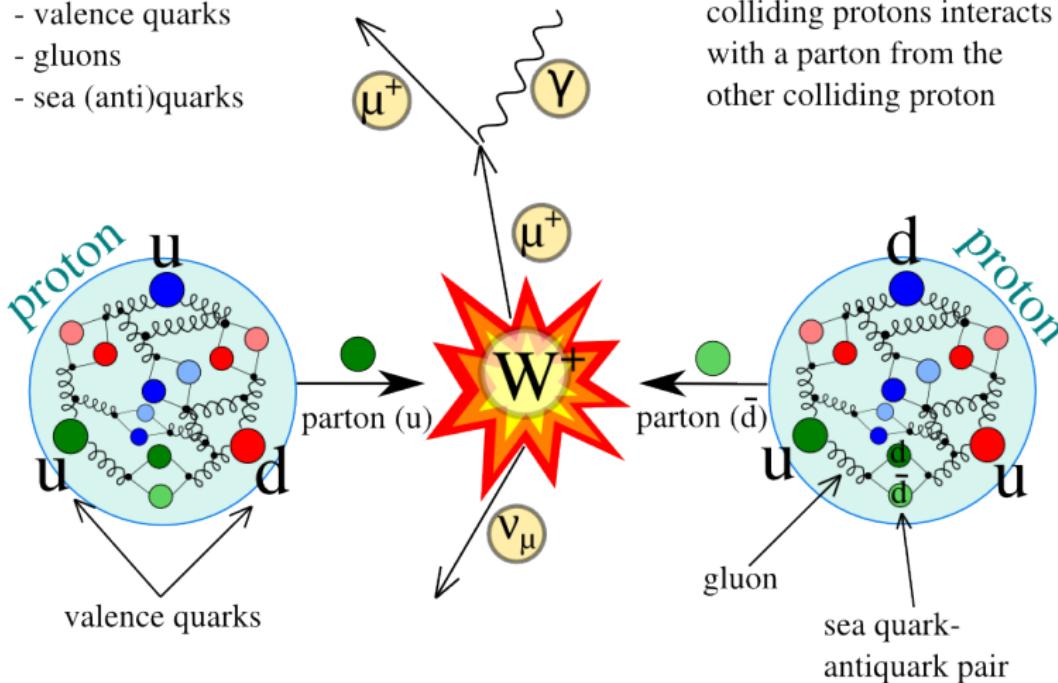


Everyday matter:
uud (proton)
udd (neutron)
electron

Theory. Proton-Proton Collisions

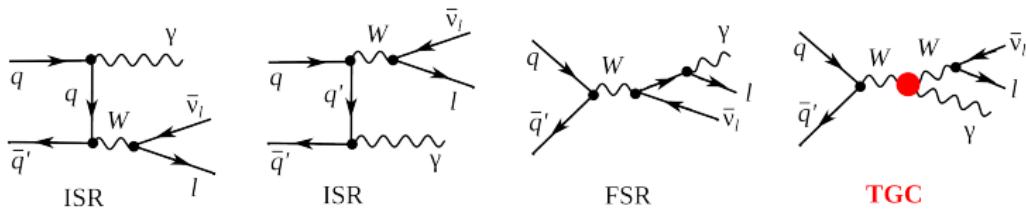
Partons in a proton:

- valence quarks
- gluons
- sea (anti)quarks



A parton from one of the colliding protons interacts with a parton from the other colliding proton

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



$q\bar{q}' \rightarrow W$ or $q\bar{q}' \rightarrow W\gamma$

-
Usually $q\bar{q}' = u\bar{d}$ or $q\bar{q}' = d\bar{u}$

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).

Large Hadron Collider (LHC)

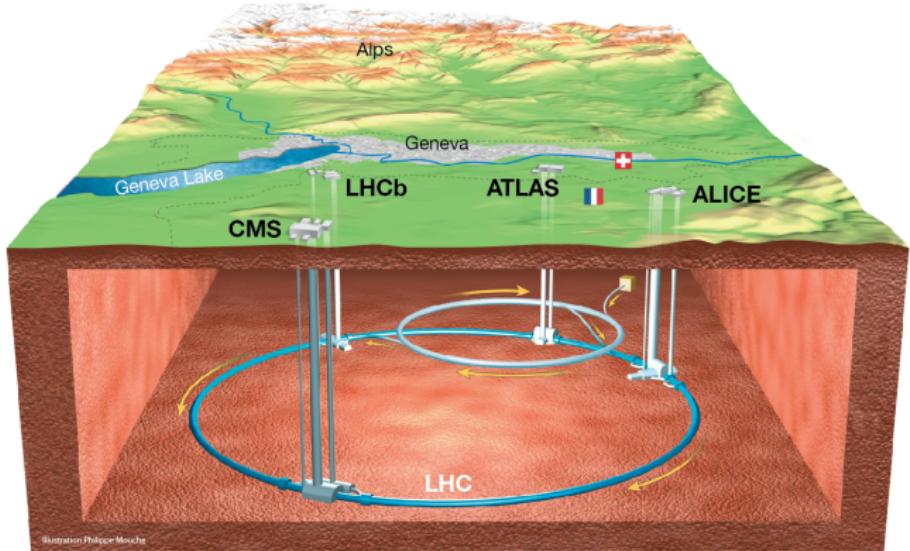


Illustration: Philippe Moretti

<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

STEEL RETURN YOKE

12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER

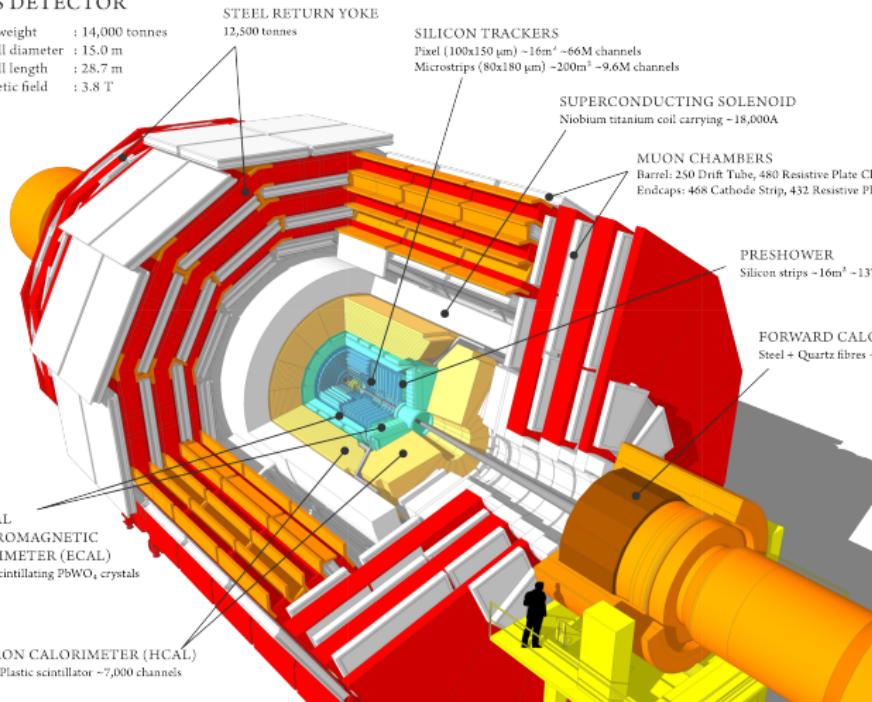
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER

Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

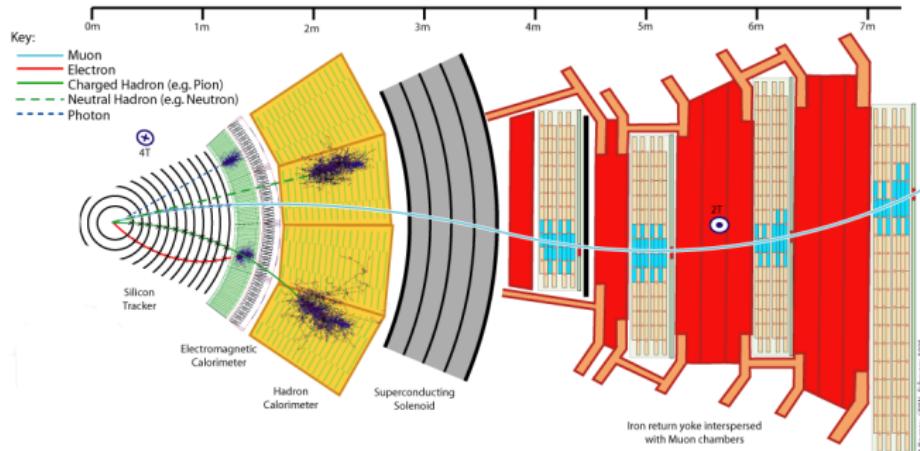
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



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.

Measurement Goal

Total (σ) and the differential ($\frac{d\sigma}{dP_T^\gamma}$) cross sections of $W\gamma \rightarrow l\nu\gamma$.

$$\sigma = \frac{N}{L}, \quad \frac{d\sigma}{dP_T^\gamma} = \frac{N}{L\Delta P_T^\gamma},$$

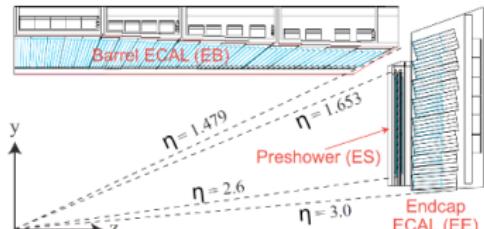
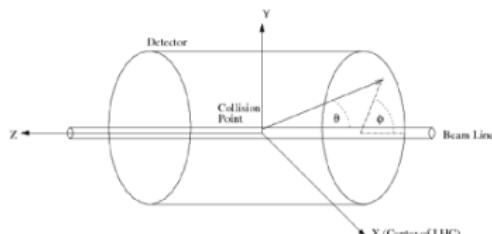
where N is a number of $W\gamma$ events produced during a given period of time, L is an integrated LHC luminosity during the same period of time, ΔP_T^γ is a P_T^γ bin width. - - - - -

Phase space definition:

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

- - - - -
Notations:

- ▶ Transverse momentum (P_T): a photon momentum component transverse to the proton beamline
- ▶ Cone separation: $\Delta R(a, b) = \sqrt{((\phi_a - \phi_b)^2 + (\eta_a - \eta_b)^2)}$;
- ▶ Pseudorapidity: $\eta = -\ln[\tan(\theta/2)]$
- ▶ EB and EE: ECal barrel and ECal endcap



Measurement Strategy

$$\sigma = \frac{N}{L} \rightarrow \sigma = \frac{N_{sel} - N_{bkg}}{A\epsilon L}$$
$$\frac{d\sigma}{dP_T^\gamma} = \frac{N}{L\Delta P_T^\gamma} \rightarrow \frac{N_{sel}^i - N_{bkg}^i}{(A\epsilon)^i L\Delta P_T^{\gamma i}}$$

Step	Algebraic representation for the measurement of $d\sigma/dP_T^\gamma$	σ
select events	N_{sel}^i	N_{sel}
subtract background	$N_{sign}^i = N_{sel}^i - N_{bkg}^i$	$N_{sign} = N_{sel} - N_{bkg}$
correct for eff X acc	$N_{ph.sp.}^i = \frac{N_{sign}^i}{(A \times \epsilon)^i}$	$N_{ph.sp.} = \frac{N_{sign}}{A \times \epsilon}$
compute cross section	$\left(\frac{d\sigma}{dP_T^\gamma}\right)^i = \frac{N_{ph.sp.}^i}{L \cdot (\Delta P_T^{\gamma i})^i}$	$\sigma = N_{ph.sp.}/L$
estimate systematic uncertainties		

Data

- ▶ Collisions: LHC pp collisions
- ▶ Protons center-of-mass energy: $\sqrt{s} = 8$ TeV
- ▶ Detector: CMS
- ▶ Year of data collection: 2012
- ▶ 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

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 selection criteria:		
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* [one change in ID]		theory considerations acceptance POG**-recommended $W\gamma\gamma$ -recommended
Lepton selection:		
$p_T^\mu > 25$ GeV; $ \eta^\mu < 2.1$ Muon ID	$p_T^e > 30$ GeV; η^e : EB or EE Electron ID	trigger trigger, acceptance POG-recommended
Second lepton veto:		
$p_T^{\mu^2} > 10$ GeV; $ \eta^{\mu^2} < 2.4$	$p_T^{e^2} > 10$ GeV; η^{e^2} : 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

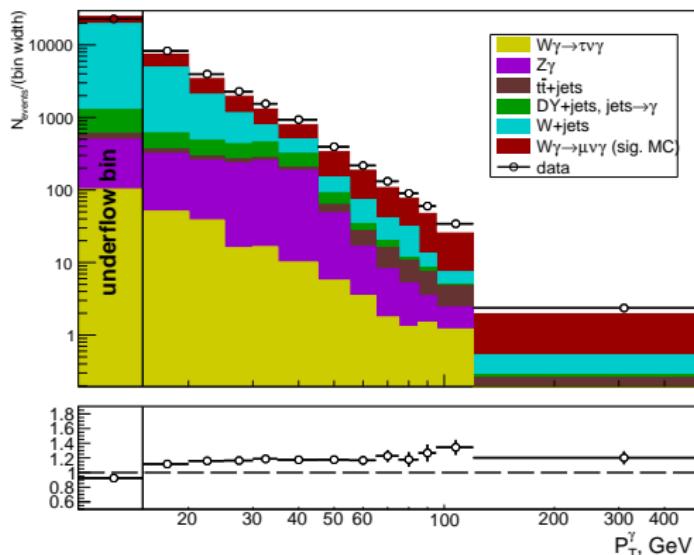
* ID - identification criteria

** POG - Particle Object Group (in CMS)

P_T^γ Spectrum of $W\gamma \rightarrow \mu\nu\gamma$ 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.



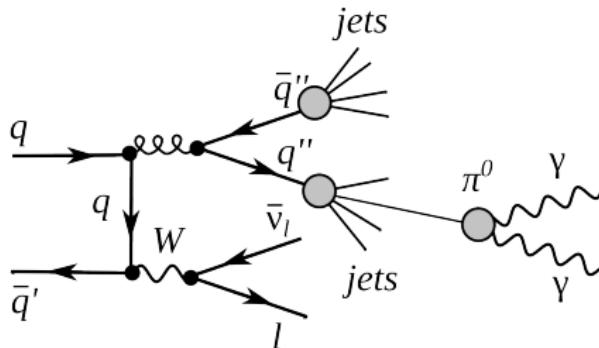
Dominated by $W + \text{jets}^*$ events in low P_T^γ bins;
Fraction of signal increases with P_T^γ ;
Data disagree with MC.

Backgrounds:
Jets $\rightarrow \gamma$: $W + \text{jets}$, $DY + \text{jets}^{**}$, $t\bar{t} + \text{jets}$;
Real- γ : $Z\gamma$, $W\gamma \rightarrow \tau\nu\gamma$.

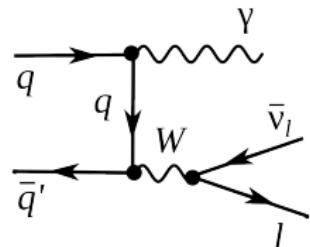
* jets are hadronic jets (explained more later)

** DY+jets is Drell-Yan+jets process, can be understood as $Z + \text{jets}$

Jets $\rightarrow \gamma$ Background



$W + \text{jets}$



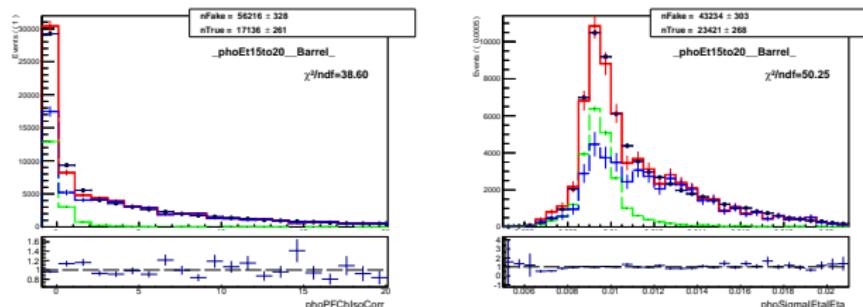
$W\gamma$

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 (next slide);
- ▶ Fit V_{fit} distribution in data by: $F(V_{fit}) = N_{true} \cdot T_{true}(V_{fit}) + N_{fake} \cdot T_{fake}(V_{fit})$.

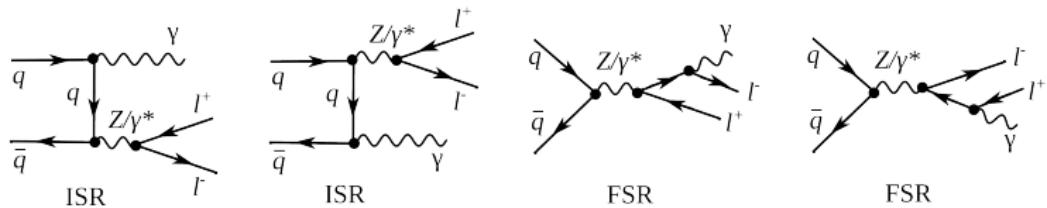
Templates: accurate representations of V_{fit} distributions of real- γ and fake- γ in the $W\gamma$ -selected dataset.



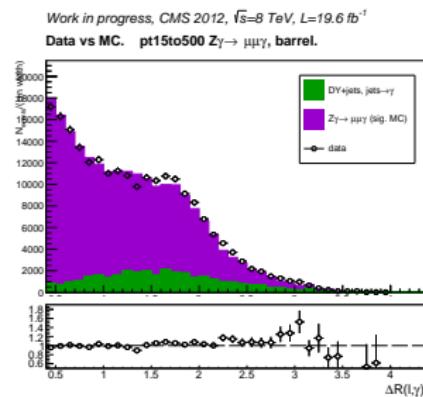
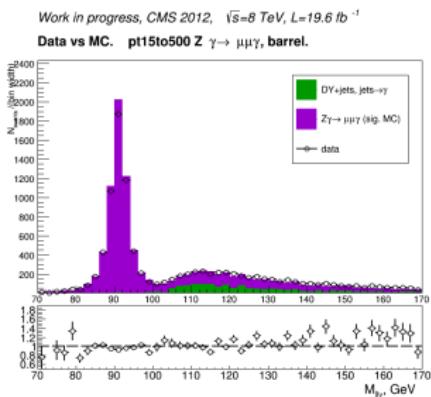
I_{ch}^γ (charged hadron isolation): $I_{ch}^\gamma = \sum P_T^{ch.had.}, \Delta R(\gamma, ch.had.) < 0.3$
 $\sigma_{inj\eta}$: an ECal shower shape variable

black: data; green: real- γ template; blue: fake- γ template; red: fit function

Jets $\rightarrow\gamma$ Background. Templates from $Z\gamma\rightarrow\bar{\mu}\mu\gamma$ - 1

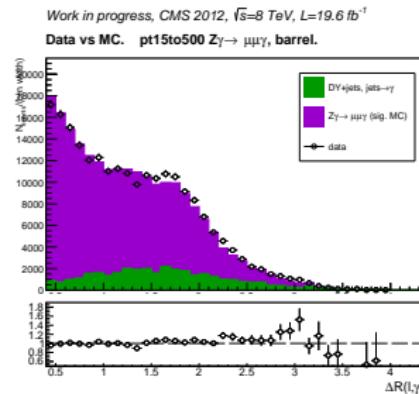
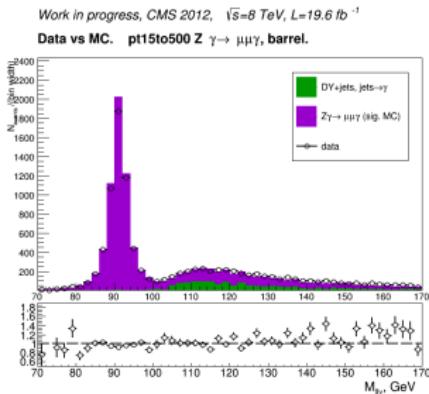


FSR: final state radiation; ISR: initial state radiation



Increase real- γ fraction (FSR): $M_{\mu\mu\gamma} < 101$ GeV and $\Delta R(\mu_1, \gamma) > 0.4$
 Increase fake- γ fraction (ISR): $M_{\mu\mu\gamma} > 101$ GeV and $\Delta R(\mu_1, \gamma) > 1.0$

Jets $\rightarrow\gamma$ Background. Templates from $Z\gamma\rightarrow\bar{\mu}\mu\gamma$ - 2



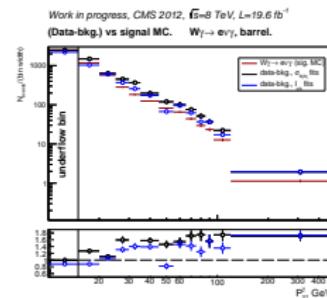
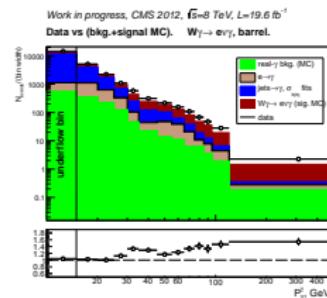
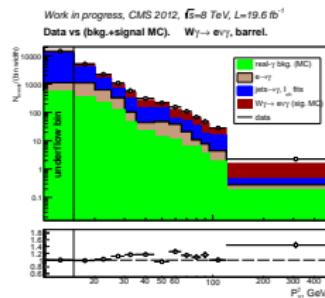
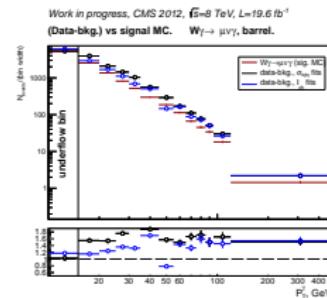
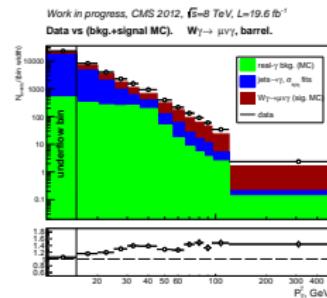
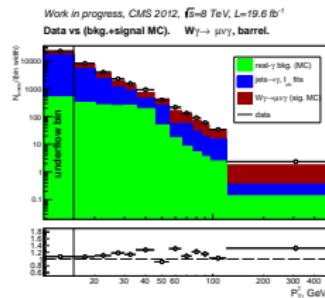
Real- γ templates:

- ▶ Need V_{fit} distributions of photons, the same as distributions of photons in $W\gamma$ candidates in the $W\gamma$ -selected sample;
- ▶ Use photons selected as photons in $W\gamma$ -sample: from $Z\gamma\rightarrow\mu\mu\gamma$ -selected sample with additional selection criteria: $M_{\mu\mu\gamma} < 101$ GeV and $\Delta R(\mu_1, \gamma) > 0.4$.

Fake- γ templates:

- ▶ Need V_{fit} distributions of photon-like jets, the same as distributions of photon-like jets in $W+jets$ candidates in the $W\gamma$ -selected sample;
- ▶ Use jets selected as photons in $W\gamma$ -sample: from $Z\gamma\rightarrow\mu\mu\gamma$ -selected sample with additional selection criteria: $M_{\mu\mu\gamma} > 101$ GeV and $\Delta R(\mu_1, \gamma) > 1.0$;
- ▶ This sample is still dominant by real photons. This real photon contribution is subtracted using $Z\gamma\rightarrow\mu\mu\gamma$ simulation.

P_T^γ Spectrum (ECal Barrel Only)



Efficiency and Acceptance Correction

Step	Algebraic representation for the measurement of $d\sigma / dP_T^\gamma$	
		σ
select events	N_{sel}^i	N_{sel}
subtract background	$N_{sign}^i = N_{sel}^i - N_{bkg}^i$	$N_{sign} = N_{sel} - N_{bkg}$
NEXT MEASUREMENT STEPS:		
correct for eff X acc	$N_{ph.sp.}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{ph.sp.} = \frac{N_{sign}}{A \times \epsilon}$
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		

Effect (main): lose signal events due to selection criteria applied.

$(A \times \epsilon)^i = \frac{N_{passed}^i}{N_{passed}^i + N_{failed}^i} \leftarrow N_{passed}^i$ and N_{failed}^i are calculated using signal MC simulation sample ($W\gamma$)

$$N_{ph.sp.}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$$

Uncertainties

Statistical: limited statistical power of the $W\gamma$ -selected dataset

Systematic: all other effects including limited stat. of control datasets and MC datasets

Step	Statistical uncertainty propagation for the measurement of $d\sigma / dP_T^\gamma$	σ
select events	$N_{sel}^j \pm \Delta N_{sel}^j$ $\Delta N_{sel}^j = \sqrt{N_{sel}^j}$	$N_{sel} \pm \Delta N_{sel}$ $\Delta N_{sel} = \sqrt{N_{sel}}$
subtract background	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$ $\Delta N_{sign}^j = \Delta N_{sel}^j$	$N_{sign} = N_{sel} - N_{bkg}$ $\Delta N_{sign} = \Delta N_{sel}$
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$ $\Delta N_{A \times \epsilon}^i$: diagonal elements of the error matrix	—
correct for eff X acc	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$ $\Delta N_{true}^i = \frac{\Delta N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$ $\Delta N_{true} = \frac{\Delta N_{sign}}{A \times \epsilon}$
compute cross section	$\left(\frac{d\sigma}{dP_T^\gamma} \right)^i = \frac{N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$ $\Delta \left[\left(\frac{d\sigma}{dP_T^\gamma} \right)^i \right] = \frac{\Delta N_{true}^i}{L \cdot (\Delta P_T^\gamma)^i}$	$\sigma = N_{true} / L$ $\Delta \sigma = \text{true} / L$

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.	
		related to jets $\rightarrow \gamma$			templ. stat.	SFs	lumi	other		
		N_{lch} vs $N_{\sigma in in \eta}$	$Z\gamma$ MC norm.	templ. stat.						
>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		

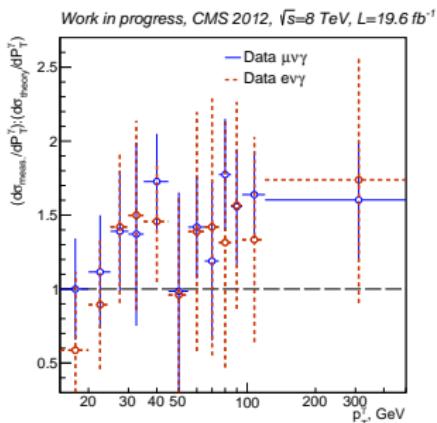
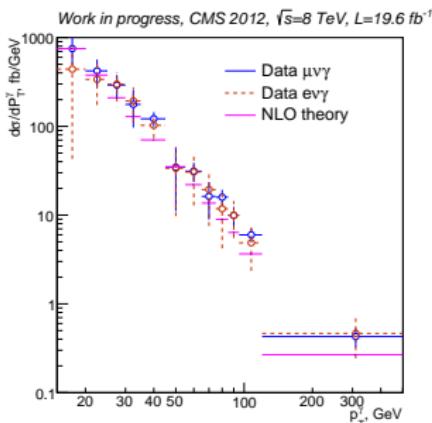
Relative Uncertainties [%] on the $W\gamma \rightarrow e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

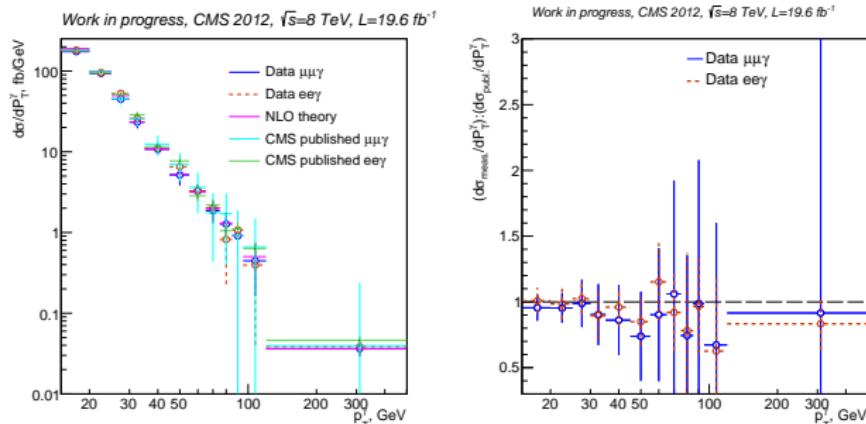
P_T^γ , GeV	stat. unc.	systematic uncertainties							
		related to jets $\rightarrow \gamma$		templ. stat.	SFs	lumi	$e \rightarrow \gamma$	other	total syst.
		N_{lch} vs $N_{\sigma in in}$	$Z\gamma$ MC norm.						
>15	2	15	35	5	19	3	4	5	44
15-20	8	80	27	19	17	3	18	11	90
20-25	7	38	20	14	12	3	11	10	48
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

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.

BACKUP

Kinematic Variables and Important Notations

- ▶ Invariant mass of a particle system ($M_{ab} = m_a^2 + m_b^2 + 2(E_a E_b - p_a \cdot p_b)$)
- ▶ Transverse mass of a W boson ($M_T^W = \sqrt{2P_T^I E_T^{miss}(1 - \cos(\phi^I - \phi^{miss}))}$)

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

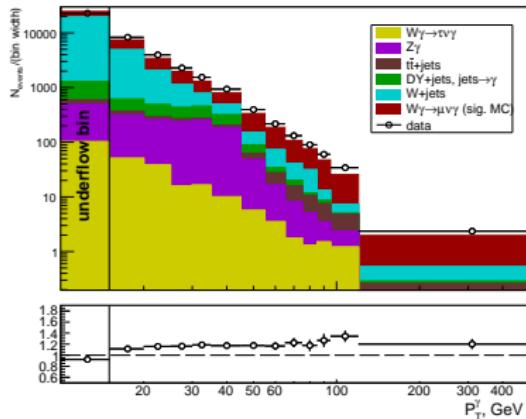
Monte Carlo Simulation (MC) samples:

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

P_T^γ Spectrum of $W\gamma$ Candidates, Two Channels

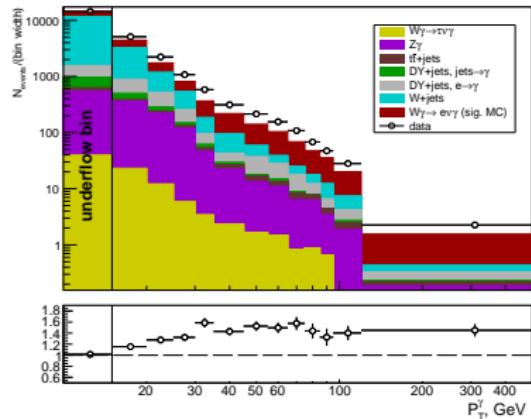
Work in progress, CMS 2012, $\sqrt{s}=8$ TeV, $L=19.6 \text{ fb}^{-1}$

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:

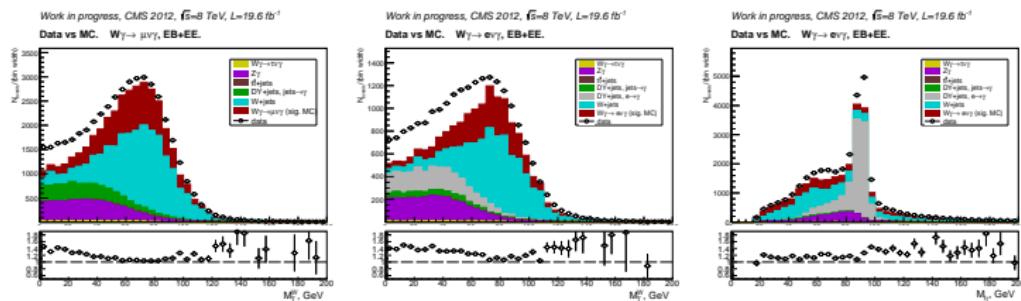
Dominated by $W+\text{jets}$ events in low P_T^γ bins;
Fraction of signal increases with P_T^γ ;
Data disagree with MC.

Backgrounds:

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

$e \rightarrow \gamma$ 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

Other Corrections

Step	Algebraic representation for the measurement of $d\sigma / dP_T^\gamma$	
select events	N_{sel}^j	N_{sel}
subtract background	$N_{sign}^j = N_{sel}^j - N_{bkg}^j$	$N_{sign} = N_{sel} - N_{bkg}$
NEXT MEASUREMENT STEPS:		
unfold	$N_{A \times \epsilon}^i = U_{ij} \cdot N_{sign}^j$	—
correct for eff X acc	$N_{true}^i = \frac{N_{A \times \epsilon}^i}{(A \times \epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A \times \epsilon}$
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		

Detector resolution unfolding (step “unfold”):

- ▶ Effect: bin-to-bin migration during the P_T^γ reconstruction;
- ▶ Method: D'Agostini, signal MC sample is used;
- ▶ Note: uncertainties across different P_T^γ bins become correlated.

Efficiency and Acceptance (step “correct for eff X acc”):

- ▶ Effect (main): lose signal events due to selection criteria applied;
- ▶ Method: bin-by-bin correction by $A \times \epsilon$, constants prepared using signal MC sample;
- ▶ Note: efficiencies between data and MC differ (next slide).

Efficiency Scale Factors

The scale factors (SF) $\rho = \frac{\epsilon_{data}}{\epsilon_{MC}}$. SF are applied as weights on each event in each MC sample.

type of candidate	full event SF
$W\gamma \rightarrow \mu\nu\gamma$	$\rho_{ID_iso}^\mu \times \rho_{ID}^\gamma$
$W\gamma \rightarrow e\nu\gamma$	$\rho_{ID}^e \times \rho_{ID}^\gamma \times \rho_{PSV}$

Provided by POG: $\rho_{ID_iso}^\mu$, ρ_{ID}^γ , ρ_{ID}^e ; provided by $W\gamma\gamma$ measurement: ρ_{PSV}^γ

$$\rho_{ID}^\gamma:$$

P_T^γ	$ \eta^\gamma \leq 0.80$	$0.80 < \eta^\gamma \leq 1.44$	$1.57 < \eta^\gamma \leq 2.00$	$ \eta^\gamma > 2.00$
15-20	0.95 ± 0.02	0.99 ± 0.02	1.00 ± 0.02	1.02 ± 0.02
20-30	0.96 ± 0.01	0.97 ± 0.01	0.98 ± 0.01	1.00 ± 0.01
30-40	0.98 ± 0.01	0.98 ± 0.01	0.99 ± 0.01	1.00 ± 0.01
40-50	0.98 ± 0.01	0.98 ± 0.01	1.00 ± 0.01	1.01 ± 0.01
>50	0.98 ± 0.01	0.98 ± 0.01	1.00 ± 0.01	1.01 ± 0.01

$$\rho_{PSV}^\gamma:$$

P_T^γ	barrel	endcap
15-20	0.996 ± 0.020	0.960 ± 0.041
20-25	0.994 ± 0.024	0.977 ± 0.051
25-30	0.996 ± 0.030	0.951 ± 0.062
30-40	0.999 ± 0.033	1.029 ± 0.081
40-50	1.009 ± 0.073	0.971 ± 0.150
50-70	0.993 ± 0.128	0.965 ± 0.294
>70	1.047 ± 0.111	1.145 ± 0.371

Major Sources of the Systematic Uncertainties

Related to jets → γ background estimation:

- ▶ Bias in Template Shape and Fit Machinery:
 - ▶ Estimate as $|N_{lch} - N_{\sigma i \eta i \eta}|$.
- ▶ $Z\gamma$ MC Normalization:
 - ▶ Assign uncertainty on the $Z\gamma$ normalization of $\Delta N = 4.6\%$ (CMS published $Z\gamma$ measurement);
 - ▶ Prepare fake- γ templates with $Z\gamma$ MC normalizations of $N \pm \Delta N$;
 - ▶ Perform fits with such deviated templates;
 - ▶ Assign the spread among the three results as an uncertainty.
- ▶ Statistical Power of Templates:
 - ▶ Randomize fake- γ templates 100 times with Gaussian distribution;
 - ▶ Perform fits with such deviated templates;
 - ▶ Take the Standard deviation of 100 fit results as an uncertainty;
 - ▶ Same for real- γ templates (except randomize 20 times, not 100).
- ▶ Propagate each of three uncertainties through unfolding and other corrections.

Related to PixelSeedVeto SF (electron channel only):

- ▶ Change SF by $\pm \Delta[SF]$;
- ▶ From signal MC, obtain new constants for $A \times \epsilon$ and unfolding corrections;
- ▶ Compute two new cross section values corresponding to $\pm \Delta[SF]$;
- ▶ Assign the spread among three cross section values as an uncertainty.

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.