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

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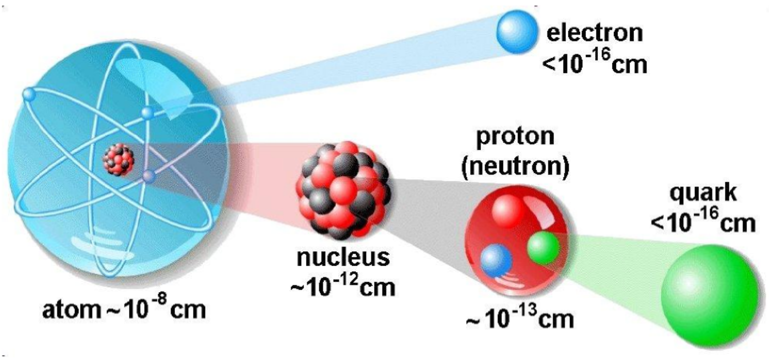
Talk Outline

- **Introduction to theory**
  - Standard Model
  - Proton-proton collisions
  - $W\gamma \to l\nu\gamma$ process
- **Experimental setup**
  - Large Hadron Collider (LHC)
  - Compact Muon Solenoid (CMS)
  - Particle reconstruction in CMS
- **$W\gamma$ cross section measurement**
  - Measurement goal and strategy
  - Data and simulation (MC) samples
  - Measurement steps
  - **Main challenge:** jets$\to\gamma$ background estimation
  - Systematic uncertainties
  - Results
- **Conclusions**

More details about each subject are available in the dissertation:

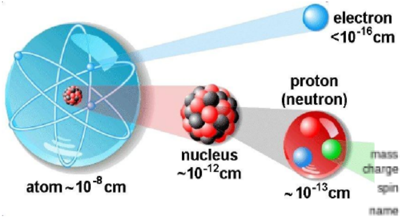
https://github.com/eavdeeva/ThesisTextWg/blob/master/nuthesis/examples/nuthesis.pdf

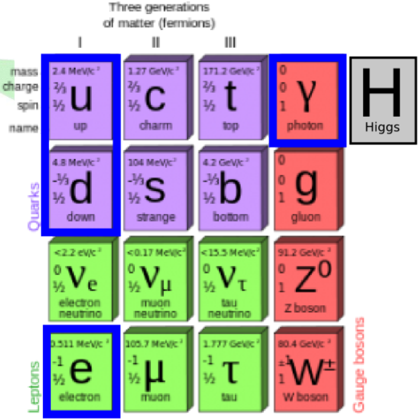
Theory. Atom Structure



http://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/

Theory. The Standard Model





First generation (everyday matter):

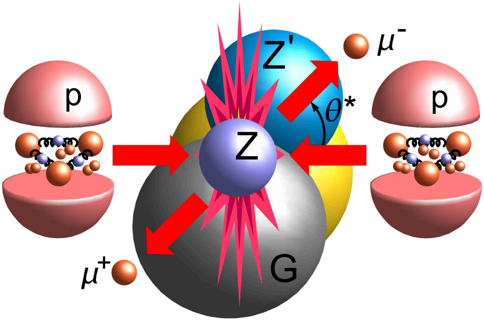
uud (proton)

udd (neutron)

electron

http://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/

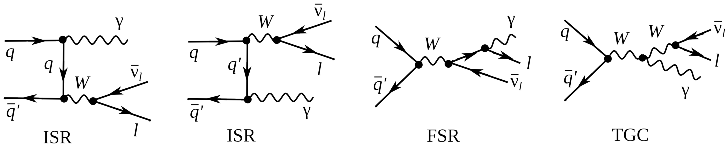
Theory. Proton-Proton Collisions



- Quarks u,u,d within a proton interact and produce gluons and quark-antiquark pairs;
- In a *pp* collision, any "parton" from one proton can interact with any parton from another proton.

http://cms.web.cern.ch/news/weak-mixing-light-and-heavy

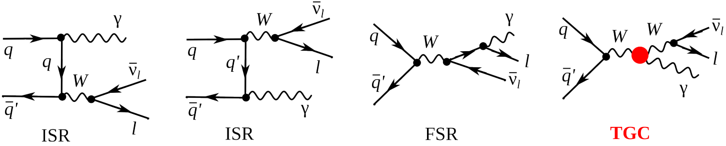
Theory. $W\gamma \to l\nu\gamma$



$q_1\bar{q}_2 \to W$ or $q_1\bar{q}_2 \to W\gamma$
Usually $q_1\bar{q}_2 = u\bar{d}$ or $q_1\bar{q}_2 = d\bar{u}$

Three mechanisms:	**Measurement goals:**
ISR: initial state radiation; FSR: final state radiation; TGC: triple gauge coupling.	Test the Standard Model; Provide a precise cross section measurement; Search for anomalous TGC (aTGC).

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



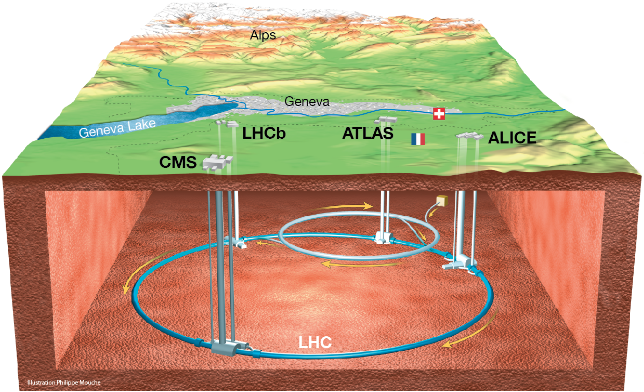
$q\bar{q}' \to W$ or $q\bar{q}' \to W\gamma$

-

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

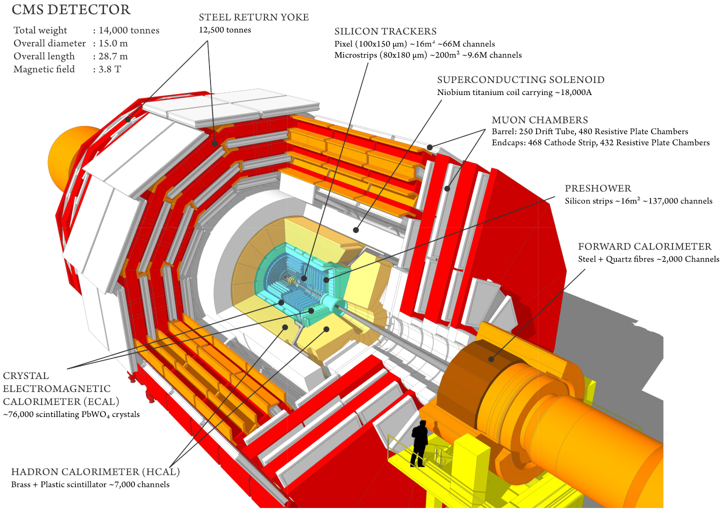
Three mechanisms:	**Measurement goals:**
ISR: initial state radiation; FSR: final state radiation; TGC: triple gauge coupling.	Test the Standard Model; Provide a precise cross section measurement; Search for anomalous TGC (aTGC).

Large Hadron Collider (LHC)



http://lhcathome.web.cern.ch/about

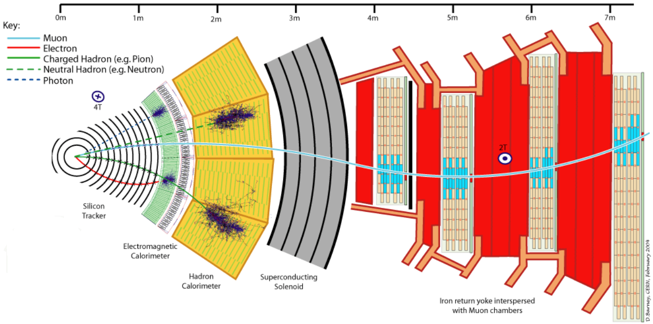
Compact Muon Solenoid (CMS)



http://cms.web.cern.ch/news/cms-detector-design

Compact Muon Solenoid (CMS). Particle Reconstruction

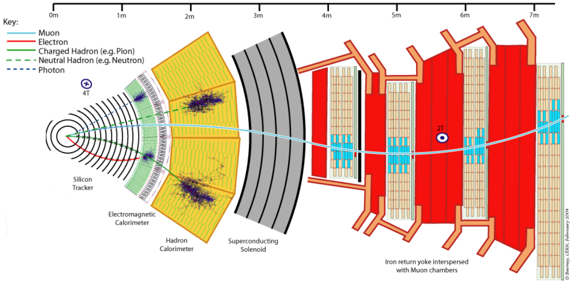
Process to study: $W\gamma \to \mu\nu\gamma$, $W\gamma \to e\nu\gamma$.
Final state particles: muons, electrons, photons, neutrinos.



Neutrino is not detected. The measure of P_T^{ν} is missing transverse energy: $E_T^{miss} = -|\sum \mathbf{P_T}|$,
Sum over all visible particles in the event.

Compact Muon Solenoid (CMS). Neutrinos

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. The measure of P_T^{ν} is **missing transverse energy**: $E_T^{miss} = -|\sum \mathbf{P_T}|$,
Sum over all visible particles in the event.

Kinematic Variables and Important Notations

Transverse momentum (P_T)
Pseudorapidity (η)
Cone separation ($\Delta R(a, b)$)
EB (barrel) and EE (endcap)
Invariant mass of a particle system ($M_{a,b}$)
Transverse mass of a W boson (M_T^W)

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

Measurement Strategy

Step	Algebraic representation for the measurement of $d\sigma/dP_T^{\gamma}$	Algebraic representation for the measurement of 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 eff X acc	$N^i_{true} = \frac{N^i_{A\times\epsilon}}{(A\times\epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A\times\epsilon}$
compute cross section	$\left(\frac{d\sigma}{dP_T^{\gamma}}\right)^i = \frac{N^i_{true}}{L\cdot(\Delta P_T^{\gamma})^i}$	$\sigma = N_{true}/L$
estimate systematic uncertainties		

Data and Simulation Samples

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

Monte Carlo Simulation (MC) samples:

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

Requirements for Selection of $W\gamma$ Candidates

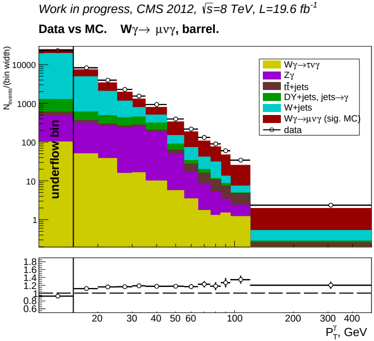
Selection requirements for candidates		Comment
------ $W\gamma \rightarrow \mu\nu\gamma$ ------	------ $W\gamma \rightarrow e\nu\gamma$ ------	
Event level selection criteria:		
Exactly one lepton + at least one photon		process signature
M_T^W >40 GeV		rejects DY+jets, $Z\gamma$
	110> $M_{e\gamma}$ >70 GeV excl.	rejects DY+jets
$\Delta R(lep, \gamma)$ >0.7		theory consideration
Photon selection:		
P_T^γ >15 GeV		theory considerations
η^γ: EB or EE		acceptance
Photon ID*		POG**-recommended
	[one change in ID]	$W\gamma\gamma$-recommended
Lepton selection:		
p_T^μ >25 GeV;	p_T^e >30 GeV;	trigger
$\lvert\eta^\mu\rvert < 2.1$	η^e: EB or EE	trigger, acceptance
Muon ID	Electron ID	POG-recommended
Second lepton veto:		rejects DY+jets, $Z\gamma$
$p_T^{\mu 2} > 10$ GeV;	$p_T^{e2} > 10$ GeV;	
$\lvert\eta^{\mu 2}\rvert < 2.4$	η^{e2}: EB or EE	
	[veto] ID	very loose

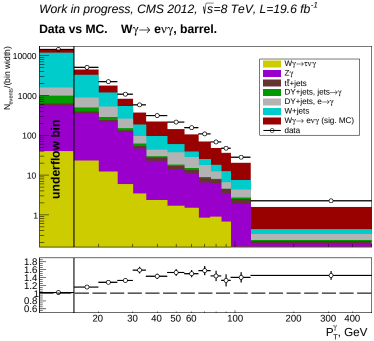
If we have several candidates in an event, we choose one with the highest P_T^γ

* ID - identification criteria

** POG - Particle Object Group (in CMS)

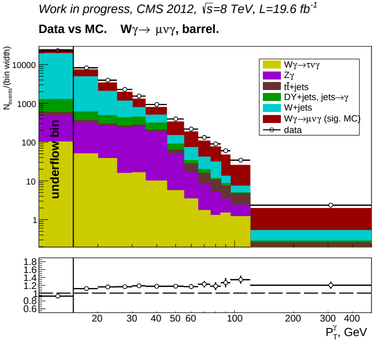
P_T^γ Spectrum of $W\gamma$ Candidates

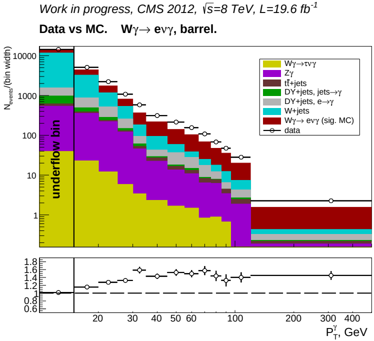




Comments: Dominated by W+jets events in low P_T^γ bins; Fraction of signal increases with P_T^γ; Data disagree with MC.	

P_T^γ Spectrum of $W\gamma$ Candidates





Comments:	**Backgrounds:**
Dominated by W+jets events in low P_T^γ bins;	Jets$\rightarrow$ γ: W+jets, DY+jets, $t\bar{t}$+jets;
Fraction of signal increases with P_T^γ;	$e \rightarrow \gamma$: DY+jets (electron channel only);
Data disagree with MC.	Real-γ: $Z\gamma$, $W\gamma \rightarrow \tau\nu\gamma$.

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

- 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.

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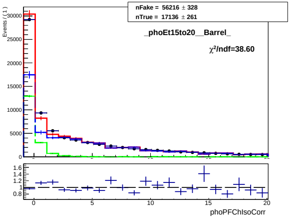
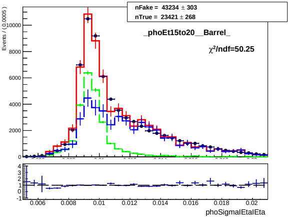
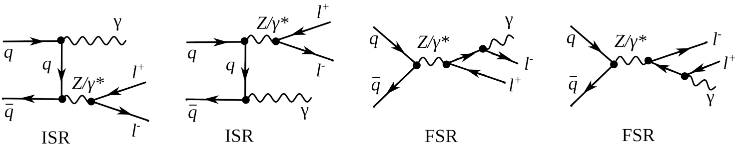




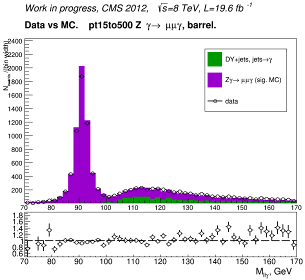
I^{γ}_{ch} (charged hadron isolation): $I^{\gamma}_{ch} = \sum P_T^{ch.had.}$, $\Delta R(\gamma,\text{ch.had.}) < 0.3$
$\sigma_{i\eta i\eta}$: an ECal shower shape variable

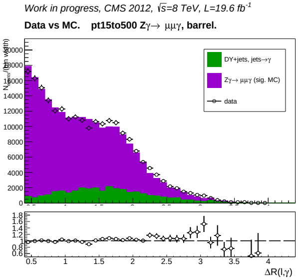
black: data; **green**: real-γ template; **blue**: fake-γ template; **red**: fit function

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



FSR: final state radiation; ISR: initial state radiation

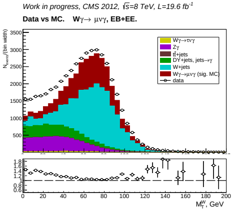


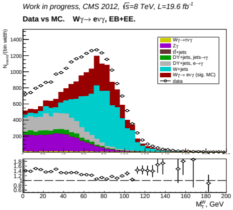


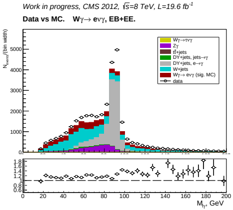
Increase real-γ fraction (FSR): $M_{\mu\mu\gamma}$ <101 GeV and $\Delta R(\mu_1,\gamma)$ >0.4
Increase fake-γ fraction (ISR): $M_{\mu\mu\gamma}$ >101 GeV and $\Delta R(\mu_1,\gamma)$ >1.0

$e \rightarrow \gamma$ 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

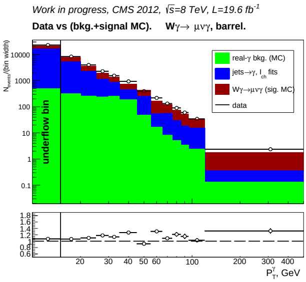


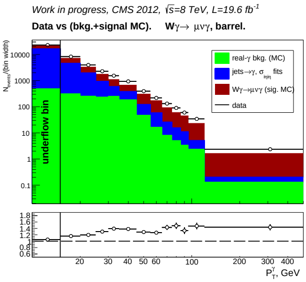


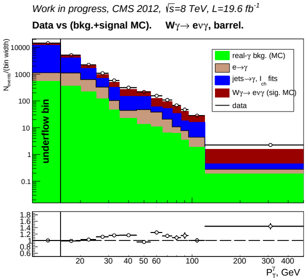


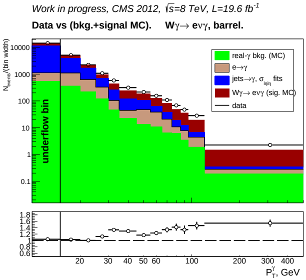
$M_T^W > 40$ GeV in both channels: rejects events without E_T^{miss}
$M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ GeV in the electron channel: rejects events from DY+jets$\rightarrow$ ee+jets
Non-negligible amount remains

P_T^γ Spectrum (EB only)

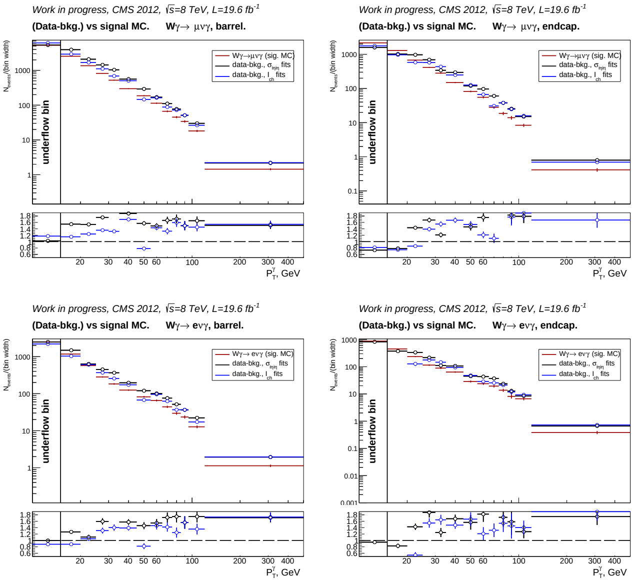








P_T^γ Spectrum after Background Subtraction (EB and EE)



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

<table>
<tr><th>Checks$\rightarrow$</th><th>- - - Simple MC closure - - -</th><th>- - - - - MC realistic - - - - -</th><th>- - - - - - - $Z\gamma$ data - - - - - - -</th></tr>
<tr><td rowspan="2">Templates</td><td colspan="2">MC samples</td><td rowspan="2">$Z\gamma$ FSR and ISR data
(same as for $W\gamma$ meas.)</td></tr>
<tr><td>$W\gamma$ and W+jets</td><td>$Z\gamma$ and DY+jets</td></tr>
<tr><td rowspan="2">Data-to-fit</td><td colspan="2">Mix MC samples</td><td rowspan="2">$Z\gamma$-selected
data</td></tr>
<tr><td>$W\gamma$ and W+jets</td><td>All $W\gamma$-selected</td></tr>
<tr><td rowspan="2">Check</td><td colspan="3">Compare fit results of two methods to each other and to MC predictions</td></tr>
<tr><td></td><td></td><td>Compute cross section
and compare to CMS published</td></tr>
<tr><td>Agreement</td><td>mostly good</td><td>slightly better than in data</td><td>excellent</td></tr>
</table>

Reasons of discrepancies in the $W\gamma$ measurement:

- Not accurate shape of templates;
- Effect of a bias on the fit machinery.

Other Corrections

Step	Algebraic representation for the measurement of $d\sigma/dP_T^{\gamma}$	σ
select events	N_{sel}^{j}	N_{sel}
subtract background	$N_{sign}^{j} = N_{sel}^{j} - N_{bkg}^{j}$	$N_{sign} = N_{sel} - N_{bkg}$
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 difffent 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
$W\gamma \to \mu\nu\gamma$	$\rho^{\mu}_{ID\_iso} \times \rho^{\gamma}_{ID}$
$W\gamma \to e\nu\gamma$	$\rho^{e}_{ID} \times \rho^{\gamma}_{ID} \times \rho^{\gamma}_{PSV}$

Provided by POG: $\rho^{\mu}_{ID\_iso}$, ρ^{γ}_{ID}, ρ^{e}_{ID}; provided by $W\gamma\gamma$ measurement: ρ^{γ}_{PSV}

ρ^{γ}_{ID}:

P^{γ}_{T}	$\lvert\eta^{\gamma}\rvert \leq 0.80$	$0.80 < \lvert\eta^{\gamma}\rvert \leq 1.44$	$1.57 < \lvert\eta^{\gamma}\rvert \leq 2.00$	$\lvert\eta^{\gamma}\rvert > 2.00$
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

ρ^{γ}_{PSV}:

P^{γ}_{T}	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**

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
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

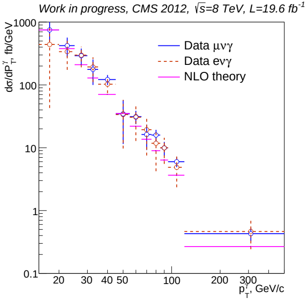
Related to jets$\rightarrow \gamma$ background estimation:

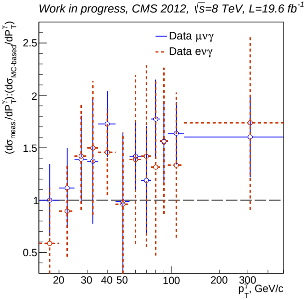
- **Bias in Template Shape and Fit Machinery:**
  - estimate as $|N_{Ich} - N_{\sigma i \eta i \eta}|$;
  - propagate through unfolding and other corrections.
- **$Z\gamma$ MC Normalization:**
  - assign uncertainty on the $Z\gamma$ normalization of ΔN =4.6% (CMS published $Z\gamma$ measurement);
  - 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;
  - propagate through unfolding and other corrections.
- **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 through unfolding and other corrections.

Related to PixelSeedVeto SF (electron channel only):

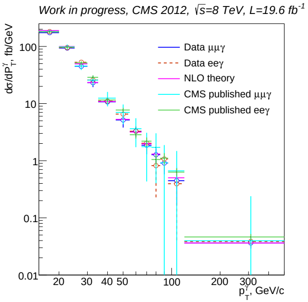
Total and Differential Cross Section

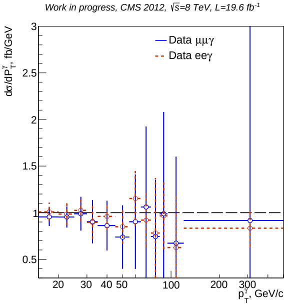
	σ ($P_T^\gamma > 15$ GeV), fb
NLO theory	9101
Data, muon channel	10949 $\pm$91 $\pm$ 1463
Data, electron channel	9146 $\pm$185 $\pm$ 2213





$Z\gamma$ 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...

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- 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.