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

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June, 2017

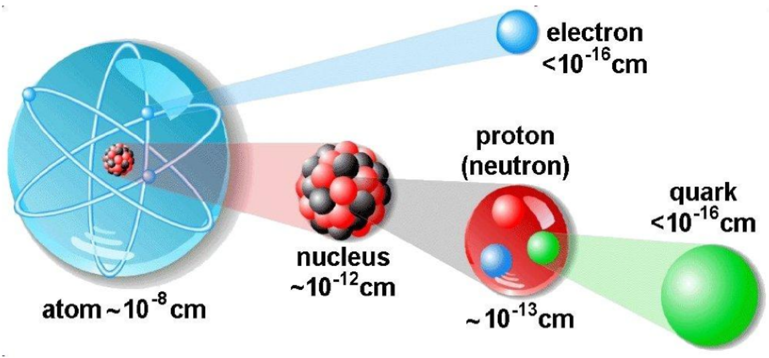
Talk Outline

- **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:

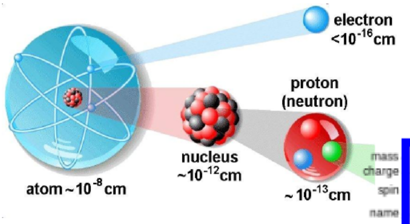
https://github.com/eavdeeva/ThesisTextWg/blob/master/nuthesis/examples/nuthesis.pdf

Theory. Atom Structure



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

Theory. The Standard Model

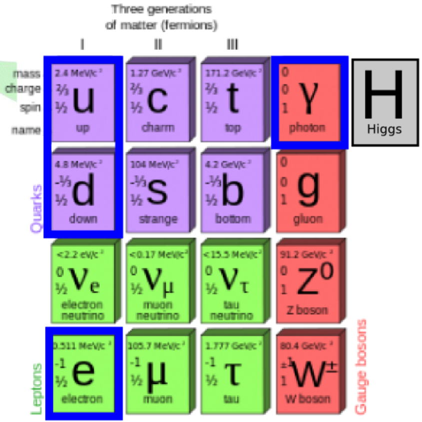


First generation (everyday matter):

uud (proton)

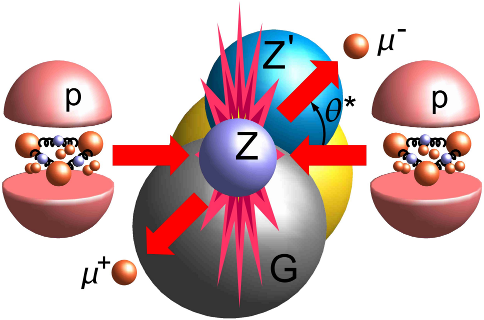
udd (neutron)

electron



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

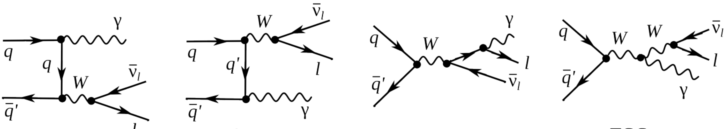
Theory. Proton-Proton Collisions



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

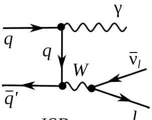


ISR ISR FSR TGC

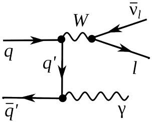
$q_1\bar{q}_2 \to W$ or $q_1\bar{q}_2 \to W\gamma$
Usually $q_1\bar{q}_2 = u\bar{d}$ or $q_1\bar{q}_2 = d\bar{u}$

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).

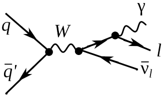
Theory. $W\gamma \to l\nu\gamma$



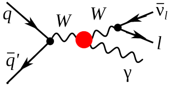
ISR



ISR



FSR



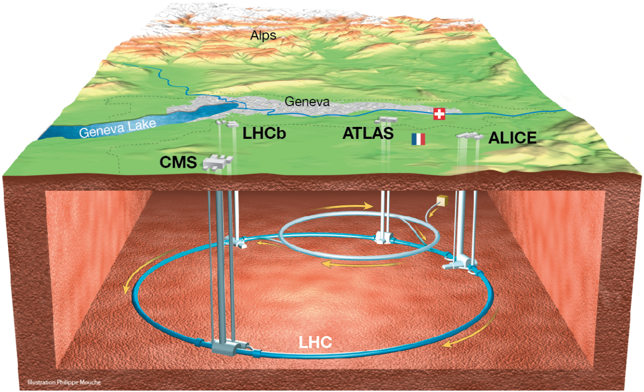
TGC

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

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

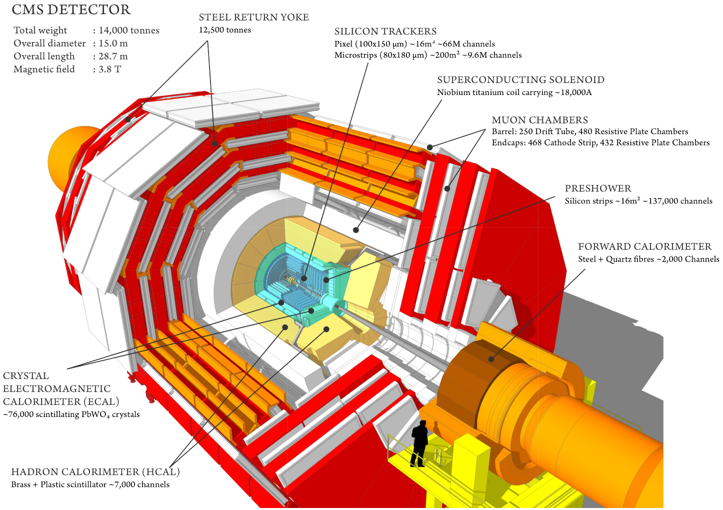
Three mechanisms:	**Measurement goals:**
ISR: initial state radiation; FSR: final state radiation; TGC: triple gauge coupling.	Test the Standard Model; Provide a precise cross section measurement; Search for anomalous TGC (aTGC).

Large Hadron Collider (LHC)



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

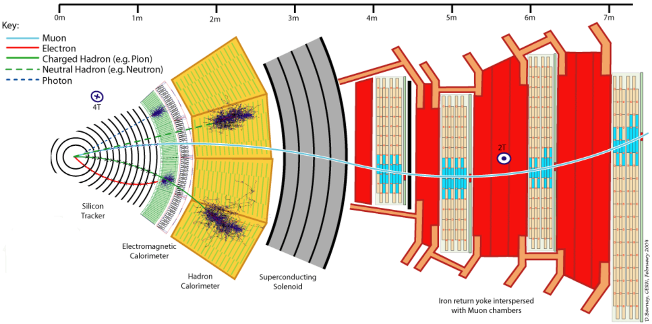
Compact Muon Solenoid (CMS)



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

Compact Muon Solenoid (CMS). Particle Reconstruction

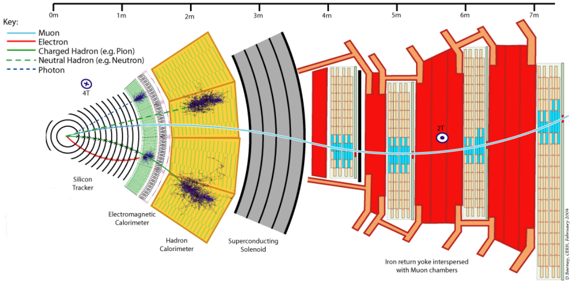
Process to study: $W\gamma \to \mu\nu\gamma$, $W\gamma \to e\nu\gamma$.
Final state particles: muons, electrons, photons, neutrinos.



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.

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.

- - - - - - - - - - - - - - - - -

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_{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		Comment
- - - - - - $W\gamma \to \mu\nu\gamma$ - - - - - -	- - - - - - $W\gamma \to e\nu\gamma$ - - - - - -	
Event level:		
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
$\|\eta^\mu\| < 2.1$	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;	
$\|\eta^{\mu 2}\| < 2.4$	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

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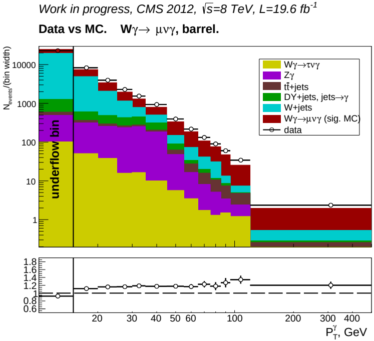
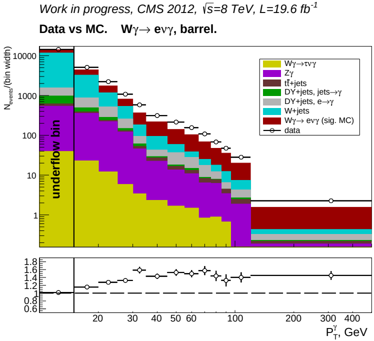
*POG - Particle Object Group (in CMS)

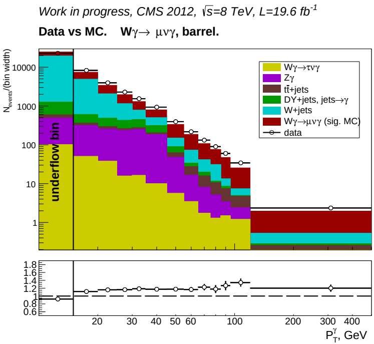
P_T^γ Spectrum of $W\gamma$ Candidates

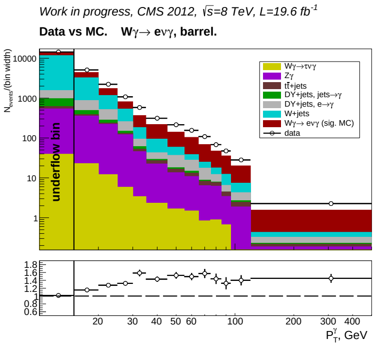




Comments:
Dominated by W+jets events in low P_T^γ bins;
Fraction of signal increases with P_T^γ;
Data disagree with MC.

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

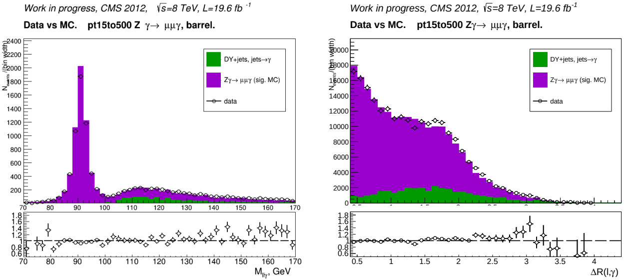
Jets$\rightarrow \gamma$ background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed later).

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

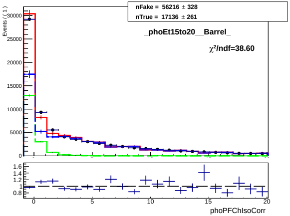
*Templates: binned histograms of V_{fit}, which should be accurate representations of V_{fit} distributions of real and fake photons in the $W\gamma$-selected dataset.

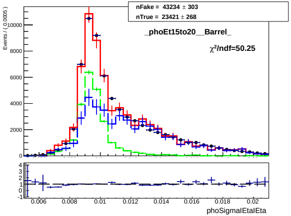
Jets$\rightarrow \gamma$ Background. Templates from $Z\gamma \rightarrow \bar{\mu}\mu\gamma$



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

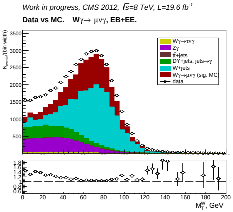
$Jets \rightarrow \gamma$ Background. $V_{fit} = I^{\gamma}_{ch}$ and $V_{fit} = \sigma_{i\eta i\eta}$

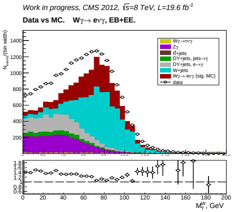


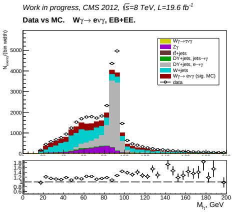


$e \to \gamma$ and Real-γ Backgrounds

Type	Source	Comment	Estimation
$e \to \gamma$	DY+jets$\to$ ee+jets	no track for e; fake E_T^{miss}	semi data driven
Real-γ	$Z\gamma \to ll\gamma$	pass second lepton veto; fake E_T^{miss}	MC-based
Real-γ	$W\gamma \to \tau\nu\gamma$	$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ and $\tau^- \to e^-\bar{\nu}_e\nu_\tau$	MC-based

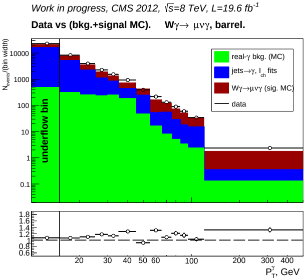


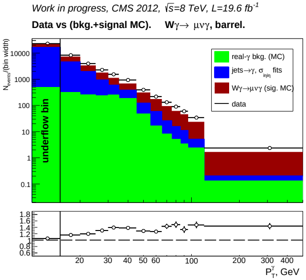


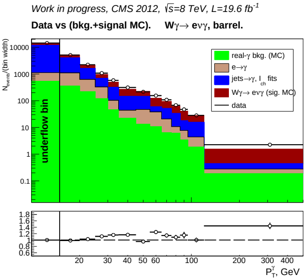


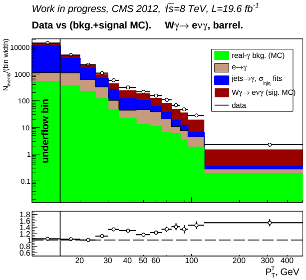
$M_T^W > 40$ GeV in both channels: rejects events without E_T^{miss}
$M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ GeV in the electron channel: rejects events from DY+jets$\to$ ee+jets
Non-negligible amount remains

P_T^γ Spectrum (EB only)

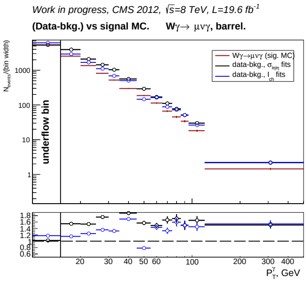


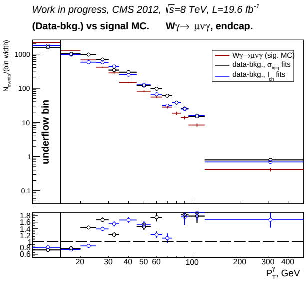


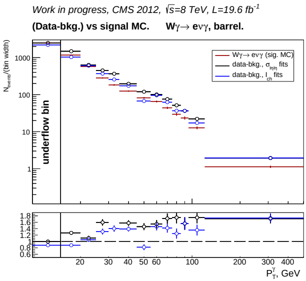


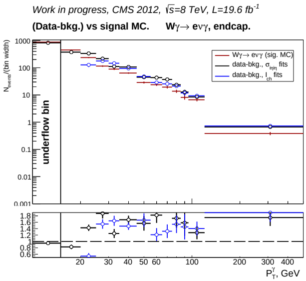


P_T^γ Spectrum after Background Subtraction (EB and EE)









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

Checks$\rightarrow$	- - - **Simple MC closure** - - -	- - - - - **MC realistic** - - - - -	- - - - - - - - $Z\gamma$ **data** - - - - - - - -
Templates	MC samples $W\gamma$ and W+jets	 $Z\gamma$ and DY+jets	$Z\gamma$ FSR and ISR data (same as for $W\gamma$ meas.)
Data-to-fit	Mix MC samples $W\gamma$ and W+jets	 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 bis on the fit machinery.

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 $W\gamma \rightarrow \mu\nu\gamma$ Cross Section

Diagonal elements of error matrices only

P_T^γ, GeV	stat. unc.	systematic uncertainties						
		related to jets$\rightarrow \gamma$						
		N_{Ich} vs $N_{\sigma i\eta i\eta}$	**$Z\gamma$ MC norm.**	**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 $N_{\sigma i\eta i\eta}$	related to jets$\to \gamma$: $Z\gamma$ 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
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45-55	8	**53**	20	22	36	3	7	11	71
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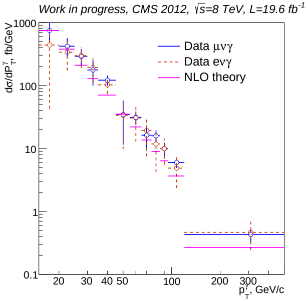
85-95	9	9	7	9	**40**	3	8	14	44
95-120	7	19	9	14	**44**	3	5	11	51
120-500	4	12	6	24	**39**	3	1	9	48

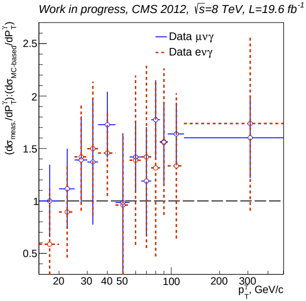
Major Sources of the Systematic Uncertainties

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):

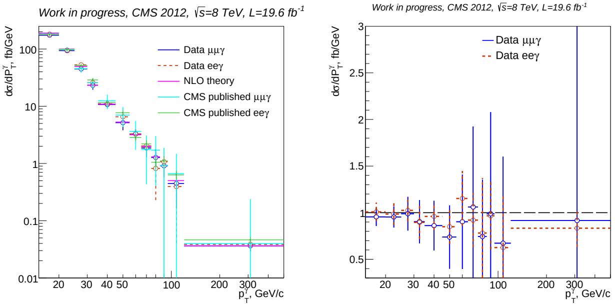
Total and Differential Cross Section

	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 $Z\gamma \rightarrow ll\gamma$ 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.