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

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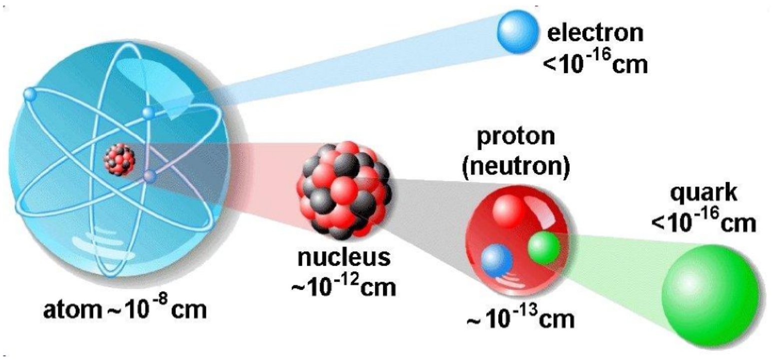
Talk Outline

- **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:

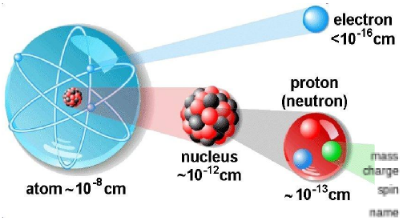
https://github.com/eavdeeva/ThesisTextWg/blob/master/nuthesis/examples/nuthesis.pdf

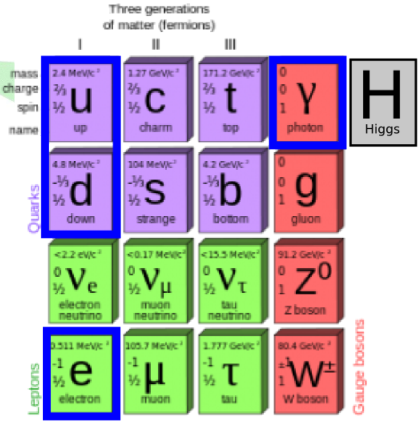
Theory. Atom Structure



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

Theory. The Standard Model





First generation (everyday matter):

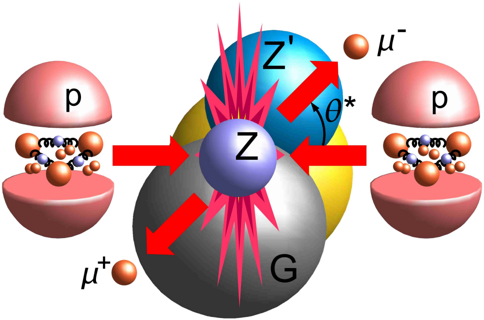
uud (proton)

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.

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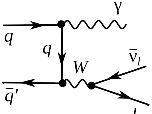
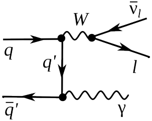
http://cms.web.cern.ch/news/weak-mixing-light-and-heavy

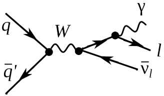
Theory. $W\gamma \to l\nu\gamma$



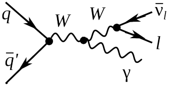
ISR



ISR



FSR

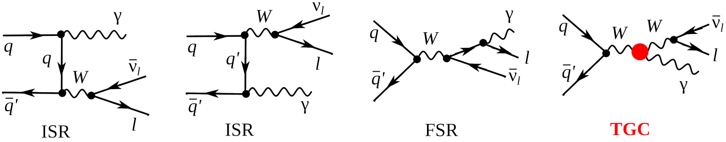


TGC

$q_1\bar{q}_2 \to W$ 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. $W\gamma \to l\nu\gamma$



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

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

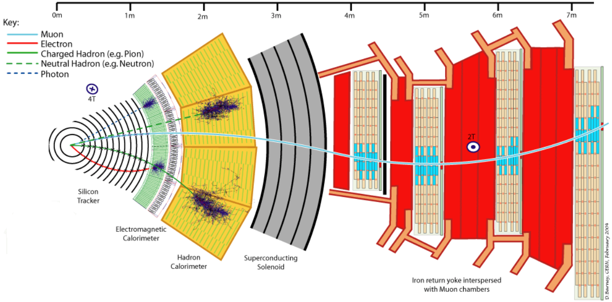
Three mechanisms:	**Measurement goals:**
ISR: initial state radiation; FSR: final state radiation; TGC: triple gauge coupling.	Test the Standard Model; Provide a precise cross section measurement; Search for anomalous TGC (aTGC).

Large Hadron Collider (LHC)

Compact Muon Solenoid (CMS). Components

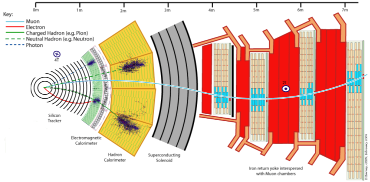
Compact Muon Solenoid (CMS). Particle Reconstruction

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



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.

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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 efficiency	$N^i_{true} = \frac{N^i_{A\times\epsilon}}{(A\times\epsilon)^i}$	$N_{true} = \frac{N_{sign}}{A\times\epsilon}$
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 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
$W\gamma \rightarrow l\nu\gamma$	signal	554
W+jets$\rightarrow l\nu$+jets	background	36257
DY+jets$\rightarrow ll$+jets	background	3504
$t\bar{t}$+jets$\rightarrow 1l$+X	background	99
$t\bar{t}$+jets$\rightarrow 2l$+X	background	24
$Z\gamma \rightarrow ll\gamma$	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
- - - - - - $W\gamma \rightarrow \mu\nu\gamma$ - - - - - -	- - - - - - $W\gamma \rightarrow e\nu\gamma$ - - - - - -	
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
$\lvert\eta^{\mu}\rvert < 2.1$	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

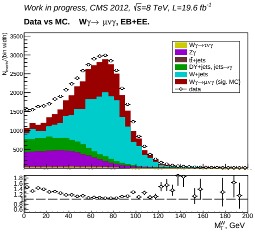
If we have several candidates in an event, we choose one with the highest P_T^{γ}

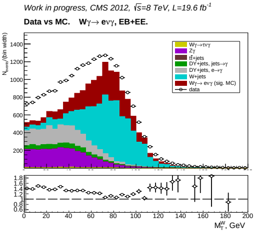
-

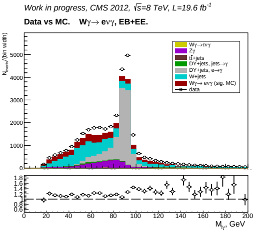
*POG - Particle Object Group (in CMS)

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

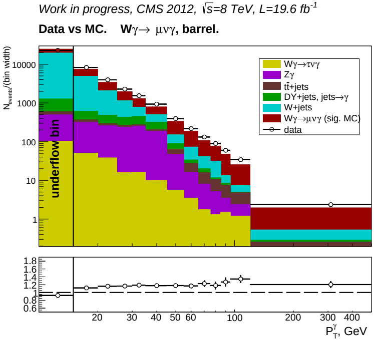


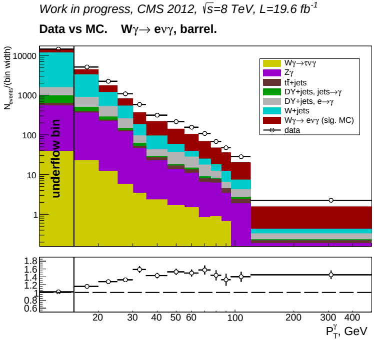




Data vs MC. P_T^{γ}

- Selected datasets are dominated by W+jets events in low P_T^{γ} bins;
- Fraction of signal increases with P_T^{γ};
- Data disagree with MC.



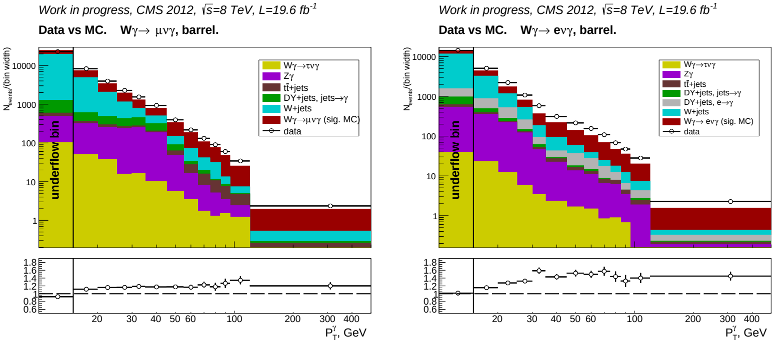


All MC samples are normalized to the luminosity of data.

Data vs MC. P_T^γ

Backgrounds:

- jets$\to \gamma$: W+jets, DY+jets, $t\bar{t}$+jets;
- $e \to \gamma$: DY+jets, electron channel only;
- real-γ: $Z\gamma$, $W\gamma \to \tau\nu\gamma$.



Jets$\to\gamma$ Background. Sources

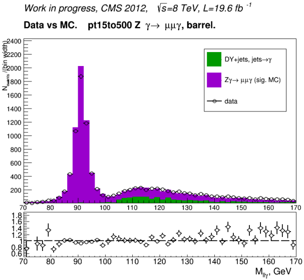
Jets$\to\gamma$ background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed later).

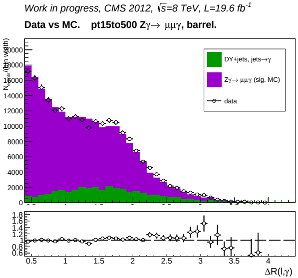
Jets$\rightarrow \gamma$ Background. Template Method

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

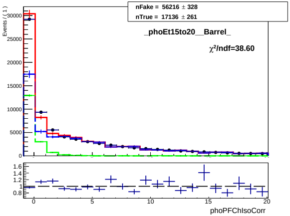


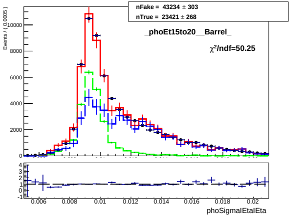


FSR selection: $M_{\mu\mu\gamma}$ <101 GeV and $\Delta R(\mu_1, \gamma)$ >0.4

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 $V_{fit} = \sigma_{i\eta i\eta}$

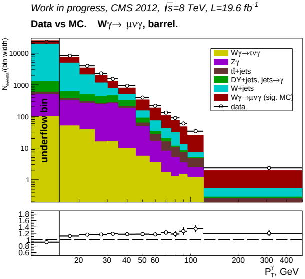




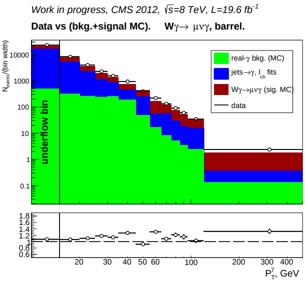
$e \rightarrow \gamma$ Background. Source

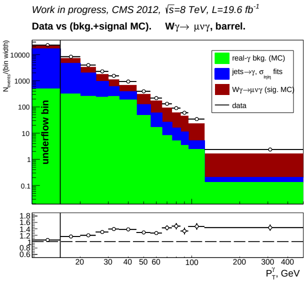
Real-γ Background. Sources

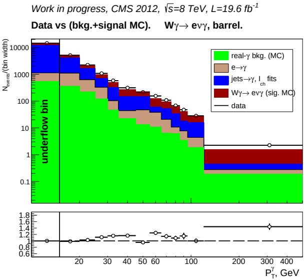
Main sources of true γ background are $Z\gamma$ and $W\gamma \to \tau\nu\gamma$. The MC-based estimation is used to subtract these backgrounds.
MC-based background estimation.

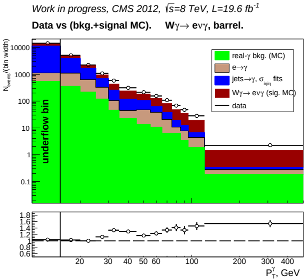


P_T^{γ} Spectrum (EB only)

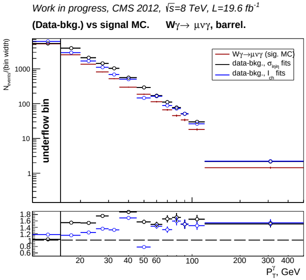


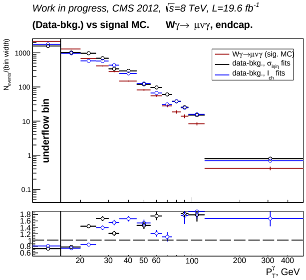


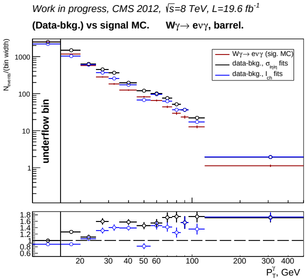


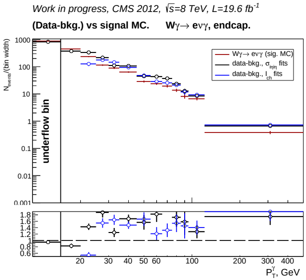


P_T^γ Spectrum after Background Subtraction (EB and EE)









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

Simple MC closure check:

- Mix $W\gamma$ and W+jets MC samples to prepare pseudodata;
- Use $W\gamma$ and W+jets Mc to prepare templates;
- Fit pseudodata and compare fit results with MC predictions;
- Agreement is mostly good.

MC realistic check:

- Mix $W\gamma$, W+jets, DY+jets, $Z\gamma$, $t\bar{t}$+jets MC samples to prepare pseudodata-I;
- Mix $Z\gamma$ and DY+jets MC to prepare pseudodata-II for templates;
- Fit pseudodata-I and compare fit results with MC predictions;
- Agreement is better than in data but generally not very good.

$Z\gamma$ check:

- Apply $Z\gamma$ selection on Double Muon and Double Electron datasets;
- Prepare templates the same way as for the $W\gamma$ measurement;
- Fit $Z\gamma$-selected datasets and compare fit results with MC predictions and I_{ch}^{γ} vs $\sigma_{i\eta}^{\gamma}$;
- Measure $Z\gamma$ cross section and compare to the published CMS 8 TeV result;
- Agreement is very good.

Conclusions: 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 $W\gamma \to \mu\nu\gamma$ Cross Section

Diagonal elements of error matrices only

P_T^γ, GeV	stat. unc.	systematic uncertainties						
		related to jets $\to \gamma$						
		N_{Ich} vs $N_{\sigma i\eta i\eta}$	**$Z\gamma$ 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 $W\gamma \rightarrow e\nu\gamma$ Cross Section

Diagonal elements of error matrices only

P_T^γ, GeV	stat. unc.	systematic uncertainties							
		related to jets$\rightarrow \gamma$							
		N_{Ich} **vs** $N_{\sigma i\eta i\eta}$	$Z\gamma$ **MC norm.**	templ. stat.	SFs	lumi	$e \rightarrow \gamma$	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 $N_{\sigma i\eta i\eta}$	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
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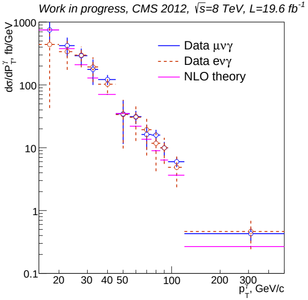
95-120	7	19	9	14	**44**	3	5	11	51
120-500	4	12	6	24	**39**	3	1	9	48

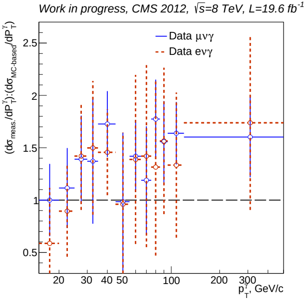
Major Sources of the Systematic Uncertainties

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):

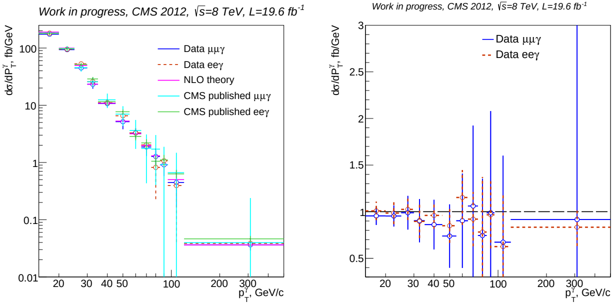
Total and Differential Cross Section

	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.