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

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June, 2017

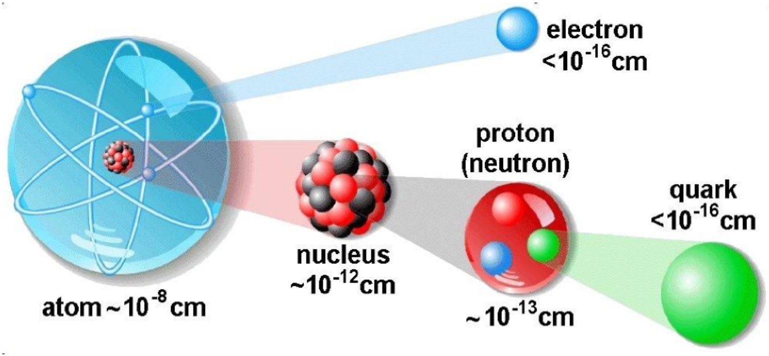
Talk Outline

- **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:

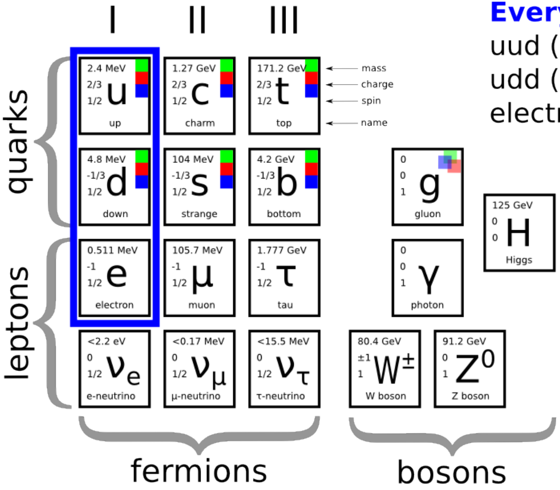
https://github.com/eavdeeva/ThesisTextWg/blob/master/nuthesis/examples/nuthesis.pdf

Theory. Atom Structure



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

Theory. The Standard Model



Everyday matter:

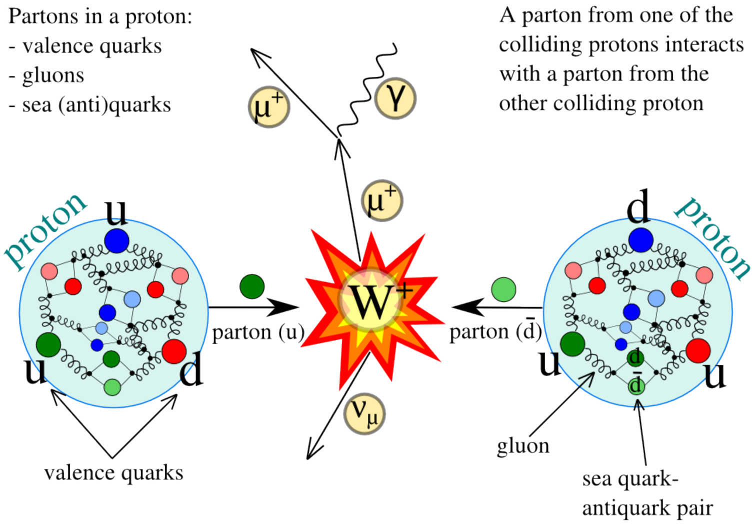
uud (proton)

udd (neutron)

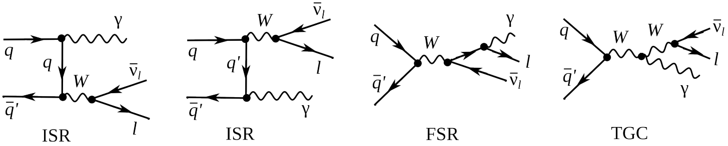
electron

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

Theory. Proton-Proton Collisions



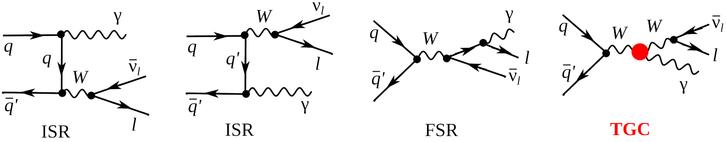
Theory. $W\gamma \to l\nu\gamma$



$q_1\bar{q}_2 \to W$ 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:**
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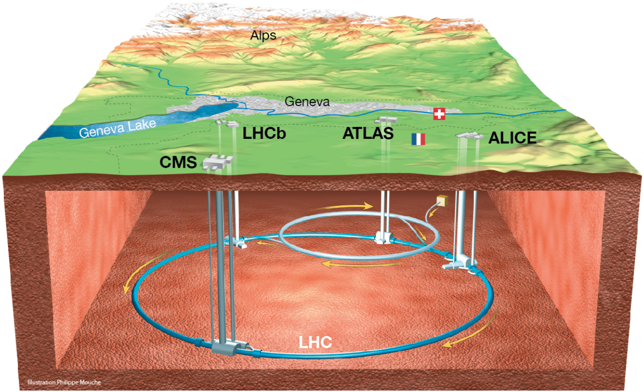
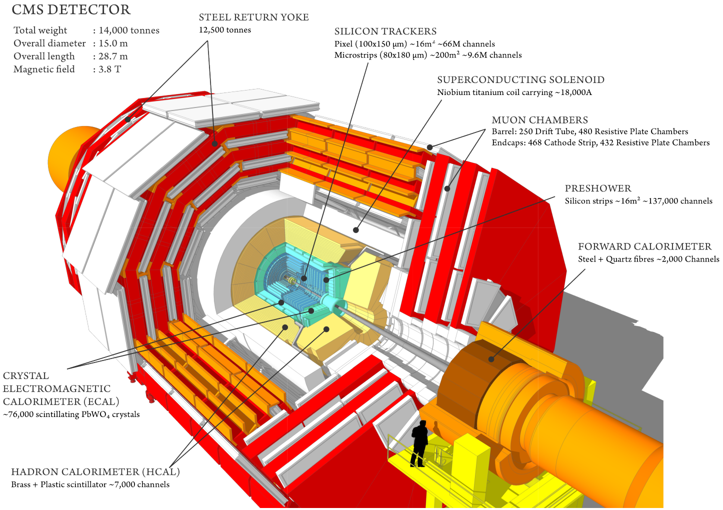
Large Hadron Collider (LHC)



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

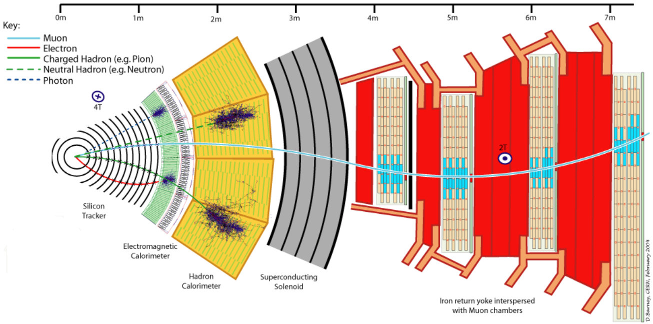
Compact Muon Solenoid (CMS)



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

Compact Muon Solenoid (CMS). Particle Reconstruction

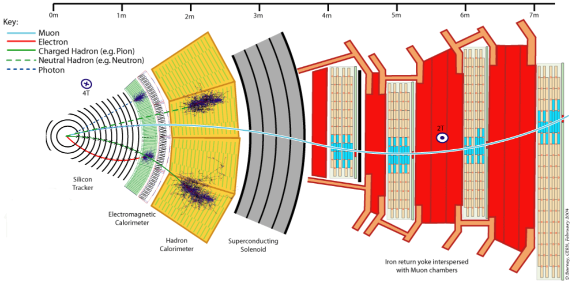
Process to study: $W\gamma \to \mu\nu\gamma$, $W\gamma \to e\nu\gamma$.
Final state particles: muons, electrons, photons, neutrinos.



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.

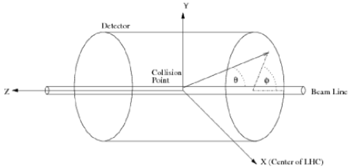
Compact Muon Solenoid (CMS). Neutrinos

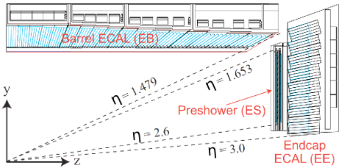
Process to study: $W\gamma \to \mu\nu\gamma$, $W\gamma \to e\nu\gamma$.
Final state particles: muons, electrons, photons, **neutrinos**.



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) with respect to the beamline
- Pseudorapidity ($\eta = -ln\,[tan(\theta/2)]$)
- Cone separation ($\Delta R(a,b) = \sqrt((\phi_a - \phi_b)^2 + (\eta_a - \eta_b)^2)$)
- EB (barrel) and EE (endcap)
- 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 ($M_T^W = \sqrt{2P_T^l E_T^{miss}(1 - \cos(\phi^l - \phi^{miss}))}$)

Measurement Goal

To measure the total and the differential $\left(\frac{d\sigma}{dP_T^{\gamma}}\right)$ 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 $d\sigma/dP_T^{\gamma}$	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 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		

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

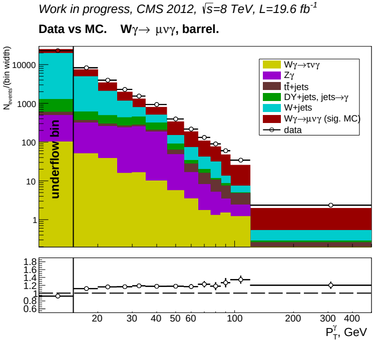
Selection requirements for candidates: $W\gamma \to \mu\nu\gamma$	Selection requirements for candidates: $W\gamma \to e\nu\gamma$	Comment
Event level selection criteria:		
Exactly one lepton + at least one photon	Exactly one lepton + at least one photon	process signature
M_T^W >40 GeV	M_T^W >40 GeV	rejects DY+jets, $Z\gamma$
	110> $M_{e\gamma}$ >70 GeV excl.	rejects DY+jets
$\Delta R(lep,\gamma)$ >0.7	$\Delta R(lep,\gamma)$ >0.7	theory consideration
Photon selection:		
P_T^γ >15 GeV	P_T^γ >15 GeV	theory considerations
η^γ: EB or EE	η^γ: EB or EE	acceptance
Photon ID*	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

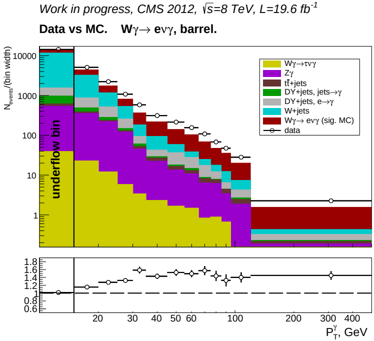
If we have several candidates in an event, we choose one with the highest P_T^γ

* ID - identification criteria

** POG - Particle Object Group (in CMS)

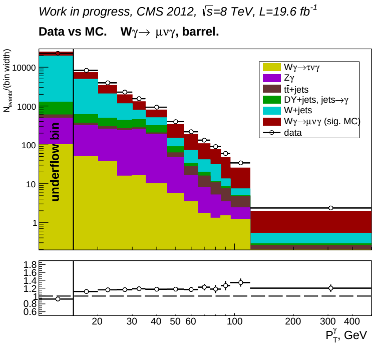
P_T^γ Spectrum of $W\gamma$ Candidates

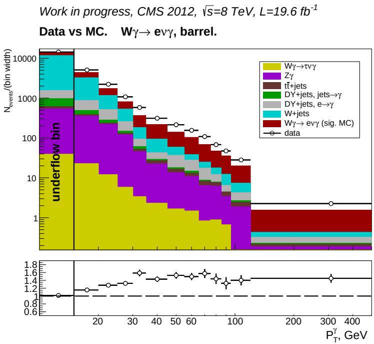




Comments: Dominated by W+jets events in low P_T^γ bins; Fraction of signal increases with P_T^γ; Data disagree with MC.	

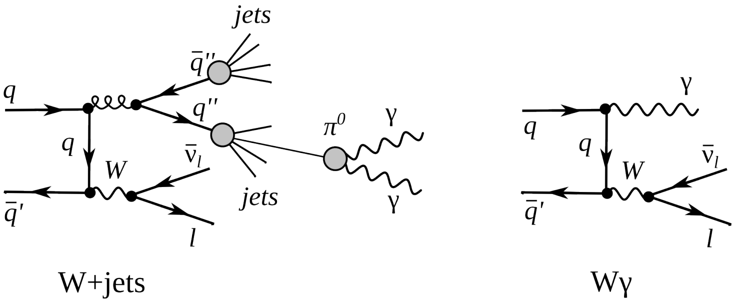
P_T^γ Spectrum of $W\gamma$ Candidates





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

Jets$\rightarrow \gamma$ Background



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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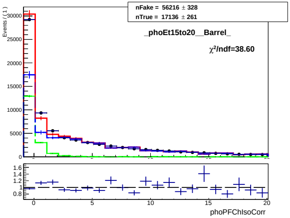
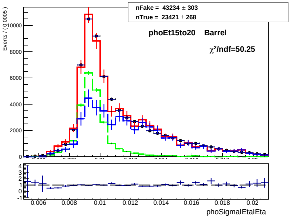
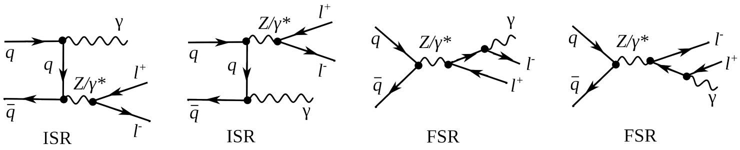




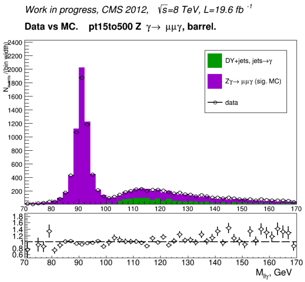
I_{ch}^{γ} (charged hadron isolation): $I_{ch}^{\gamma} = \sum P_T^{ch.had.}$, $\Delta R(\gamma,\text{ch.had.}) < 0.3$
$\sigma_{i\eta i\eta}$: an ECal shower shape variable

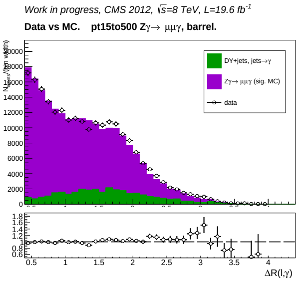
black: data; **green**: real-γ template; **blue**: fake-γ template; **red**: fit function

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



FSR: final state radiation; ISR: initial state radiation

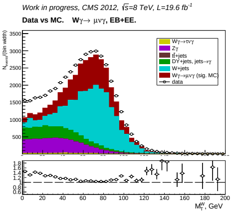


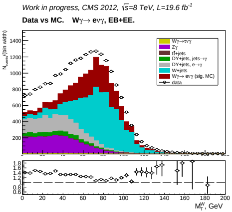


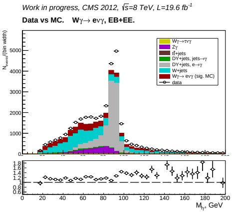
Increase real-γ fraction (FSR): $M_{\mu\mu\gamma}$ <101 GeV and $\Delta R(\mu_1,\gamma)$ >0.4
Increase fake-γ fraction (ISR): $M_{\mu\mu\gamma}$ >101 GeV and $\Delta R(\mu_1,\gamma)$ >1.0

$e \to \gamma$ 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

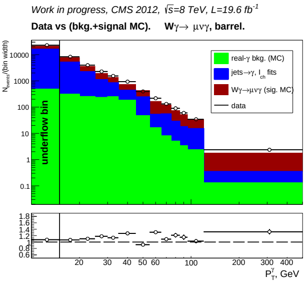


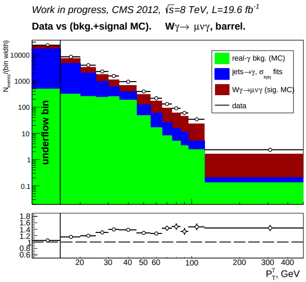


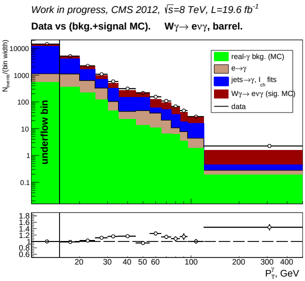


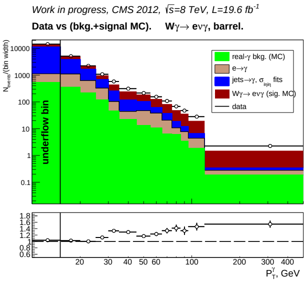
$M_T^W > 40$ GeV in both channels: rejects events without E_T^{miss}
$M_{l,\gamma} < 70$ *or* $M_{l,\gamma} > 110$ GeV in the electron channel: rejects events from DY+jets$\to$ ee+jets
Non-negligible amount remains

P_T^γ Spectrum (EB only)

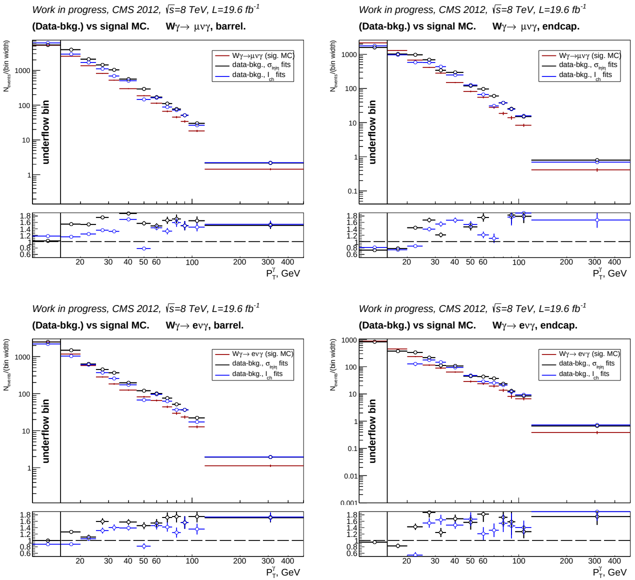








P_T^{γ} Spectrum after Background Subtraction (EB and EE)



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	MC samples $Z\gamma$ 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	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.

Other Corrections

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	$N^j_{sign} = N^j_{sel} - N^j_{bkg}$	$N_{sign} = N_{sel} - N_{bkg}$
NEXT MEASUREMENT STEPS:		
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		

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

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	$\left(\frac{d\sigma}{dP_T^{\gamma}}\right)^{i} = \frac{N_{true}^{i}}{L \cdot (\Delta P_T^{\gamma})^{i}}$ $\Delta \left[\left(\frac{d\sigma}{dP_T^{\gamma}}\right)^{i}\right] = \frac{\Delta N_{true}^{i}}{L \cdot (\Delta P_T^{\gamma})^{i}}$	$\sigma = N_{true} / L$ $\Delta\sigma =_{true} / L$

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 $W\gamma \to e\nu\gamma$ 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$\to\gamma$ background estimation:

- **Bias in Template Shape and Fit Machinery:**
  - Estimate as $|N_{Ich} - N_{\sigma i\eta i\eta}|$.
- **$Z\gamma$ 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.
- **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.

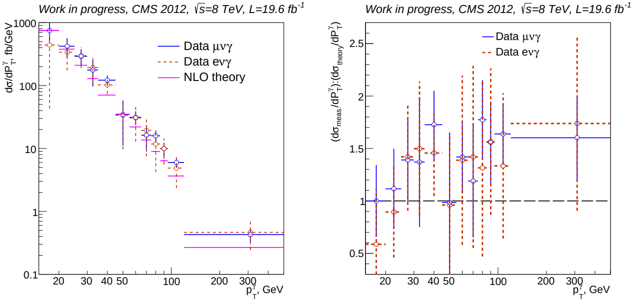
- -

Related to PixelSeedVeto SF (electron channel only):

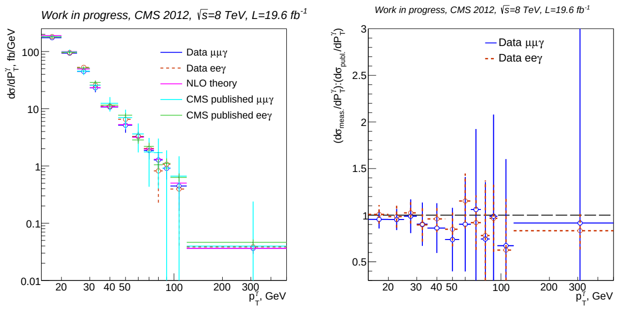
- Change SF by $\pm\Delta[SF]$;
- From signal MC, obtain new constants for $A \times \epsilon$ and unfolding corrections;
- Compute two new cross section values corresponding to $\pm\Delta[SF]$;
- Assign the spread among three cross section values as an uncertainty.

Total and Differential Cross Section

	σ (P_T^γ > 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.