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

Ekaterina Avdeeva

University of Nebraska - Lincoln

September, 2017

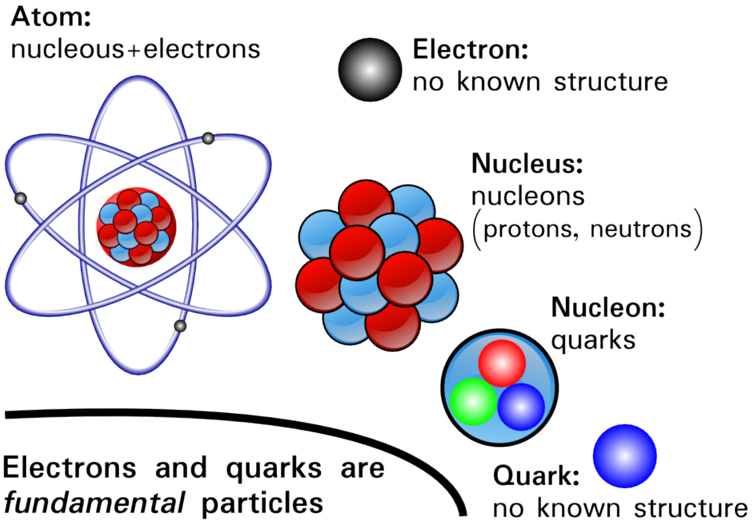
Talk Outline

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

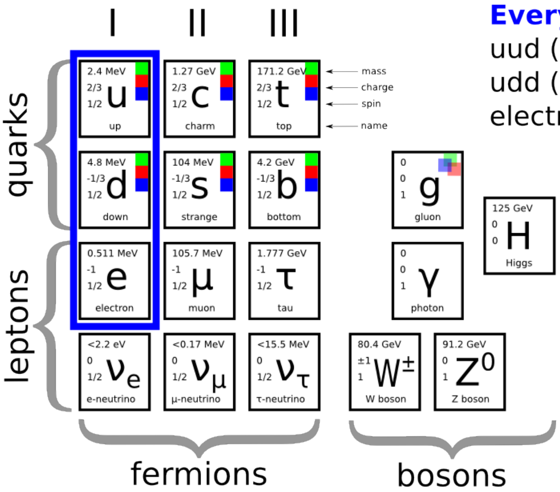
More details about each subject are available in the dissertation:

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

Theory. Atom Structure



Theory. The Standard Model

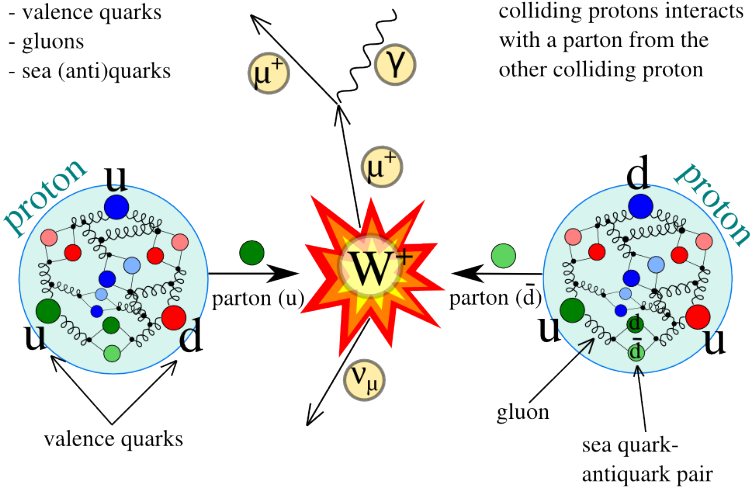


Everyday matter:
uud (proton)
udd (neutron)
electron

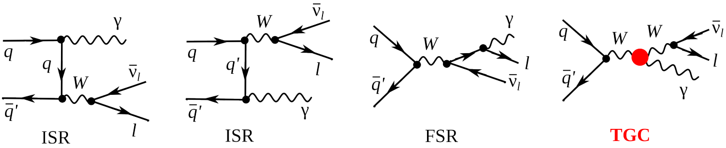
Theory. Proton-Proton Collisions

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

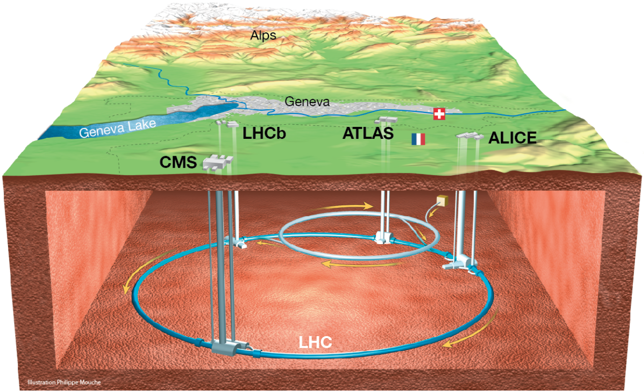


$q\bar{q}' \to W$ or $q\bar{q}' \to W\gamma$

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

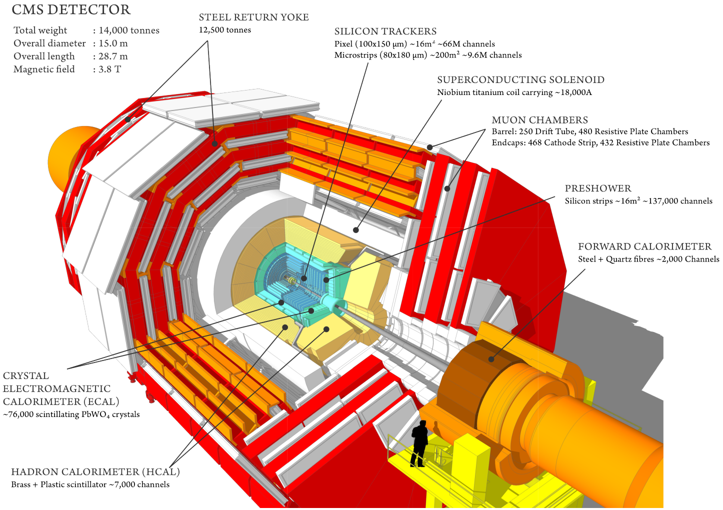
Three mechanisms:	**Measurement goals:**
ISR: initial state radiation; FSR: final state radiation; TGC: triple gauge coupling.	Test the Standard Model; Provide a precise cross section measurement; Search for anomalous TGC (aTGC).

Large Hadron Collider (LHC)



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

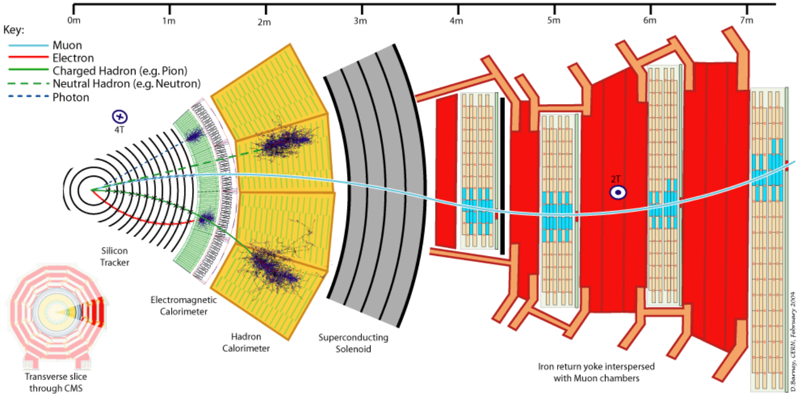
Compact Muon Solenoid (CMS)



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 detected particles).

Observables to Measure

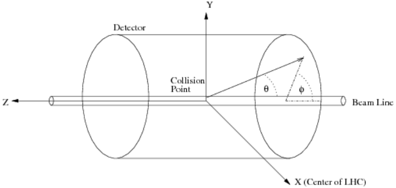
Total (σ) and the differential ($\frac{d\sigma}{dP_T^\gamma}$) cross sections of $W\gamma \to l\nu\gamma$.

$\sigma = \frac{N}{L}$, $\frac{d\sigma}{dP_T^\gamma} = \frac{N}{L\Delta P_T^\gamma}$,
where N is a number of $W\gamma$ events produced during a given period of time, L is an integrated LHC luminocity during the same period of time, ΔP_T^γ is a P_T^γ bin width.

- -

Phase space definition:

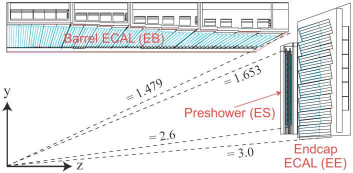
- $P_T^\gamma > 15$ GeV;
- $\Delta R(\gamma, lep) >$0.7;
- several more requirements related to geometric and kinematic limitations



- -

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



- -

Two channels: muon ($W\gamma \to \mu\nu_\mu\gamma$) and electron ($W\gamma \to e\nu_e\gamma$). **Will mostly talk about the muon channel.**

Measurement Strategy

$$\sigma = \frac{N}{L} \;\rightarrow\; \sigma = \frac{N_{sel} - N_{bkg}}{A\epsilon L} \tag{1}$$

$$\frac{d\sigma}{dP_T^\gamma} = \frac{N}{L\Delta P_T^\gamma} \;\rightarrow\; \frac{N^i_{sel} - N^i_{bkg}}{(A\epsilon)^i L \Delta P_T^{\gamma\, i}} \tag{2}$$

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

Requirements for Selection of $W\gamma \to \mu\nu\gamma$ Candidates

Selection requirements	Comment
Event level selection criteria:	
Exactly one muon + at least one photon	process signature
M_T^W =>40 GeV	process signature
$\Delta R(\mu, \gamma)$ >0.7	theory consideration
Photon selection:	
P_T^γ >15 GeV	theory considerations
η^γ: ECal barrel (EB) or endcap (EE)	acceptance
Photon ID	POG**-recommended
Muon selection:	
p_T^μ >25 GeV;	trigger
$\|\eta^\mu\| < 2.1$	trigger
Muon ID	POG-recommended
Second muon veto:	rejects Z+jets, $Z\gamma$
$p_T^{\mu 2} > 10$ GeV;	
$\|\eta^{\mu 2}\| < 2.4$	

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

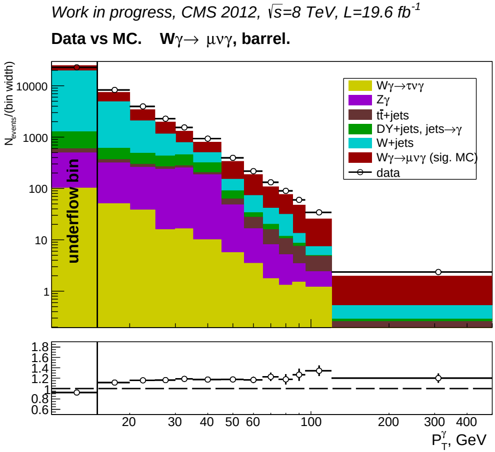
* ID - identification criteria

** POG - Particle Object Group (in CMS)

\- - - - - - - -

$$M_T^W = \sqrt{2P_T^l E_T^{miss}(1 - \cos(\phi^l - \phi^{miss}))}, \ \Delta R(\mu, \gamma) = \sqrt{(\phi_\mu - \phi_\gamma)^2 + (\eta_\mu - \eta_\gamma)^2}$$

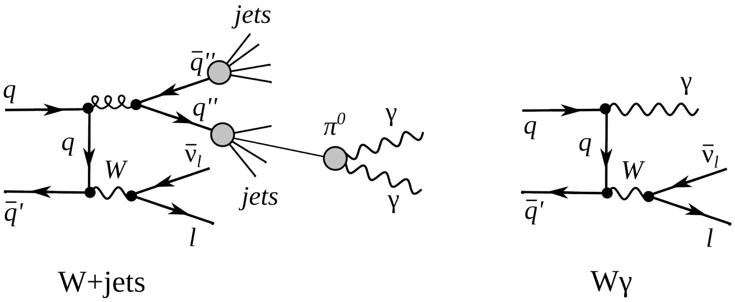
P_T^γ Spectrum of $W\gamma \to \mu\nu\gamma$ Candidates



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

* jets are hadronic jets (explained more later)
** DY+jets is Drell-Yan+jets process, can be understood as Z+jets

Jets$\to\gamma$ Background

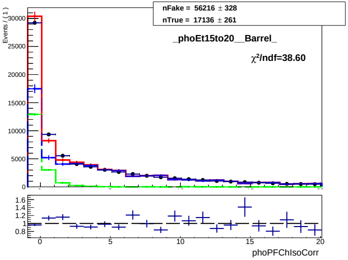


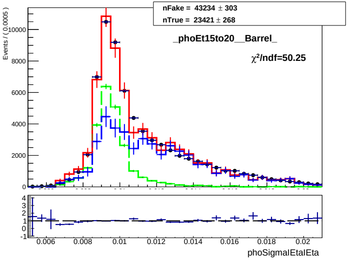
Jets$\to\gamma$: jets misidentified as photons. Jets$\to\gamma$ background estimation is the most challenging part of this measurement and also the source of the largest systematic uncertainties (discussed later).

Jets$\rightarrow\gamma$ Background. Template Method

- Choose a variable that has a significant discriminative power between the true-γ and fake-γ (jets$\rightarrow\gamma$) candidates V_{fit};
- Prepare true-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 true-γ and fake-γ in the $W\gamma$-selected dataset.





$V_{fit} = I_{ch}^{\gamma}$ (charged hadron isolation):
$I_{ch}^{\gamma} = \sum P_T^{ch.had.}$, $\Delta R(\gamma,\text{ch.had.}) < 0.3$

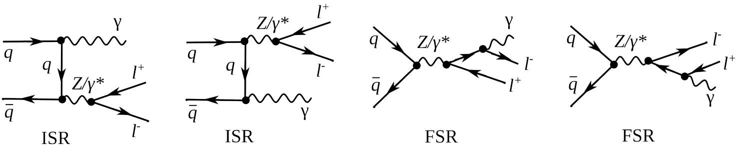
$V_{fit} = \sigma_{i\eta i\eta}$: an ECal shower shape variable

- - - - - - - - - - -

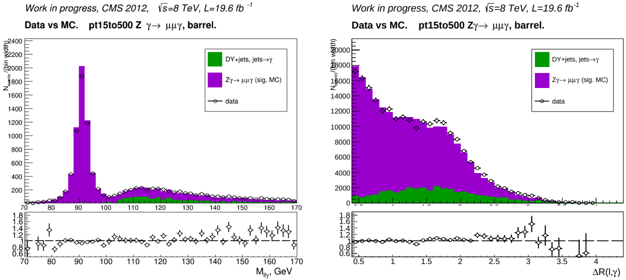
Both I_{ch}^{γ} and $\sigma_{i\eta i\eta}$ are used in photon ID.

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

Jets$\rightarrow \gamma$. True-γ Templates from $Z\gamma \rightarrow \mu^+\mu^-\gamma$



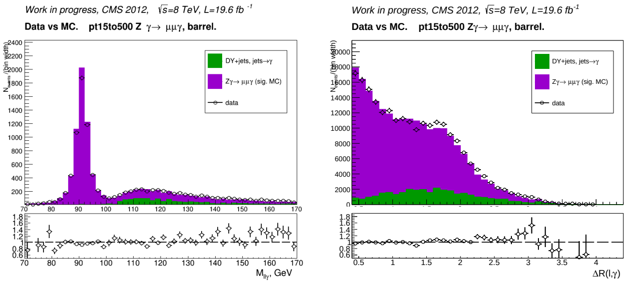
FSR: final state radiation; ISR: initial state radiation



$Z\gamma$-selected sample: $Z\gamma$ and Z+jets

True-γ templates: $M_{\mu\mu\gamma}$ <101 GeV and $\Delta R(\mu_1, \gamma)$ >0.4 ($Z\gamma \rightarrow \mu^+\mu^-\gamma$ FSR)

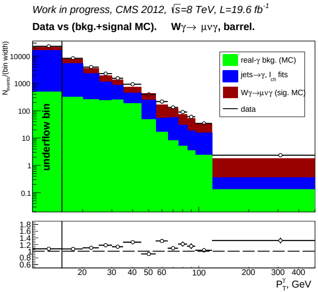
Jets$\to \gamma$. Fake-γ Templates from $Z\gamma \to \mu^+\mu^-\gamma$

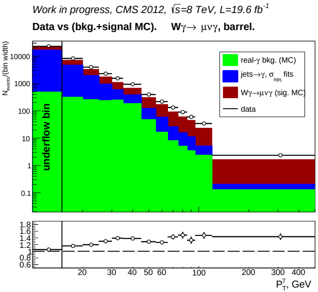


$Z\gamma$-selected sample: $Z\gamma$, Z+jets
$W\gamma$-selected sample: $W\gamma$, W+jets, Z+jets, $t\bar{t}$+jets, and more

- Need V_{fit} distributions of jets selected as photons, same as distributions of jets from W+jets in the $W\gamma$-selected sample;
- **Cannot find a pure sample of such jets in data;**
- Use jets selected as photons from $Z\gamma \to \mu^+\mu^-\gamma$-selected sample;
- Increase fake-γ fraction: $M_{\mu\mu\gamma}$ >101 GeV and $\Delta R(\mu_1, \gamma)$ >1.0 ($Z\gamma \to \mu^+\mu^-\gamma$ ISR);
- **Sample is still dominant by true-γ from $Z\gamma$ events**;
- Subtract the true-γ contribution using $Z\gamma \to \mu^+\mu^-\gamma$ simulation.

P_T^γ Distribution of $W\gamma \to \mu\nu\gamma$ Candidates (ECal Barrel Only)

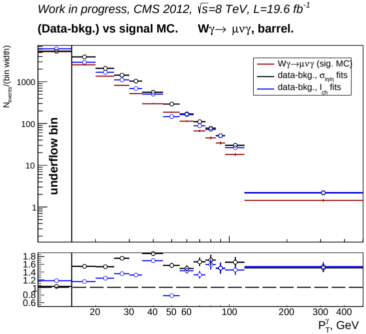




Left: P_T^γ distribution **before** the background subtraction. Jets$\to\gamma$ background is estimated using fits of I_{ch}^γ (top) and $\sigma_{i\eta}^\gamma$ (bottom) templates.

-

Right: P_T^γ distribution **after** the background subtraction. Signal P_T^γ distributions obtained using fits of I_{ch}^γ vs $\sigma_{i\eta}^\gamma$ templates vs signal MC simulation.



Efficiency and Acceptance Correction

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

Selection criteria are tighter than the measurement phase space.

- - - - - - - - -

Efficiency and acceptance correction: from the number of signal ($W\gamma$) events in the selected sample to the number of signal events in the measurement phase space.

- - - - - - - - -

$$(A\times\epsilon)^i = \frac{N^i_{passed(MC)}}{N^i_{passed(MC)} + N^i_{failed(MC)}},$$

where N^i_{passed} and N^i_{failed} are calculated using signal MC simulation sample ($W\gamma$)

- - - - - - - - - -

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

Uncertainties

Statistical: limited statistical power of the $W\gamma$-selected dataset
Systematic: all other effects including limited stat. of control datasets and MC datasets

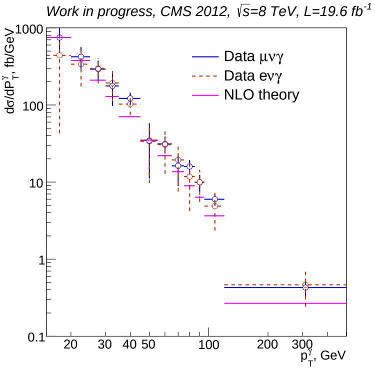
Step	Statistical uncertainty propagation for the measurement of $d\sigma/dP_T^\gamma$	Statistical uncertainty propagation for the measurement of σ
select events	$N^i_{sel} \pm \Delta N^i_{sel}$ $\Delta N^i_{sel} = \sqrt{N^i_{sel}}$	$N_{sel} \pm \Delta N_{sel}$ $\Delta N_{sel} = \sqrt{N_{sel}}$
subtract background	$N^i_{sign} = N^i_{sel} - N^i_{bkg}$ $\Delta N^i_{sign} = \Delta N^i_{sel}$	$N_{sign} = N_{sel} - N_{bkg}$ $\Delta N_{sign} = \Delta N_{sel}$
correct for eff X acc	$N^i_{ph.sp.} = \frac{N^i_{sign}}{(A\times\epsilon)^i}$ $\Delta N^i_{true} = \frac{\Delta N^i_{A\times\epsilon}}{(A\times\epsilon)^i}$	$N_{ph.sp.} = \frac{N_{sign}}{A\times\epsilon}$ $\Delta N_{true} = \frac{\Delta N_{sign}}{A\times\epsilon}$
compute cross section	$\left(\frac{d\sigma}{dP_T^\gamma}\right)^i = \frac{N^i_{true}}{L\cdot(\Delta P_T^\gamma)^i}$ $\Delta\left[\left(\frac{d\sigma}{dP_T^\gamma}\right)^i\right] = \frac{\Delta N^i_{true}}{L\cdot(\Delta P_T^\gamma)^i}$	$\sigma = N_{true}/L$ $\Delta\sigma =_{true} /L$

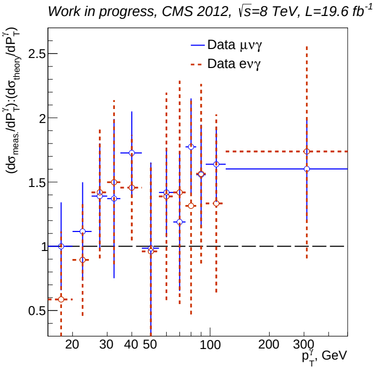
Relative Uncertainties [%] on the $W\gamma \to \mu\nu\gamma$ Cross Section

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.**	lumi	other	total syst.
>15	1	10	**24**	4	3	4	27
15-20	2	**31**	12	10	3	7	35
20-25	2	**29**	13	11	3	6	34
25-30	2	**24**	13	11	3	5	30
30-35	3	**40**	15	13	3	7	45
35-45	2	11	**12**	8	3	6	19
45-55	4	**62**	19	20	3	8	68
55-65	3	**15**	12	14	3	7	24
65-75	6	**36**	19	17	3	10	44
75-85	4	6	11	**16**	3	10	21
85-95	5	2	9	**23**	3	13	25
95-120	5	10	8	**12**	3	9	18
120-500	3	4	11	**21**	3	9	24

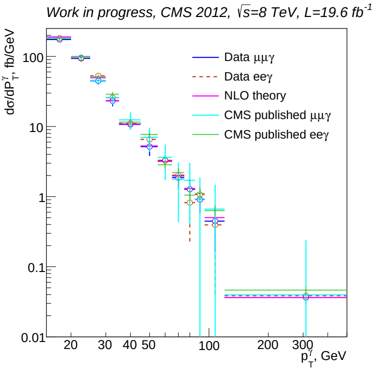
Total and Differential Cross Section

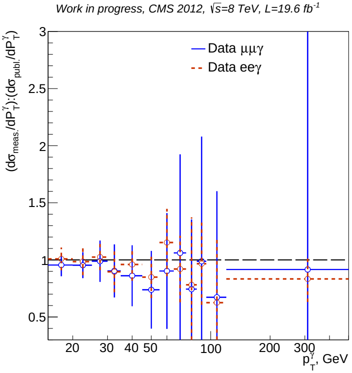
	σ ($P_T^\gamma > 15$ GeV), fb
NLO theory	9101
Data, muon channel	10949 $\pm$91 $\pm$ 1463
Data, electron channel	9146 $\pm$185 $\pm$ 2213





$Z\gamma$ 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...

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

- Ilya Kravchenko (UNL), Yurii Maravin (KSU), Lovedeep Saini (KSU);
- Joshua Kunkle (UMD), Senka Duric (WISC), Dmytro Kovalskyi (UCSD);
- Kuo Chia-Ming (NCU), Sachiko Toda McBride (KSU), Yutaro Iiyama (CMU);
- whole CMS collaboration.

Conclusions

$W\gamma$ cross sections in the muon and electron channels at 8 TeV are measured;

This is the first ever measurement of the differential $W\gamma$ cross section with CMS;
The first total $W\gamma$ cross section measurement at 8 TeV;

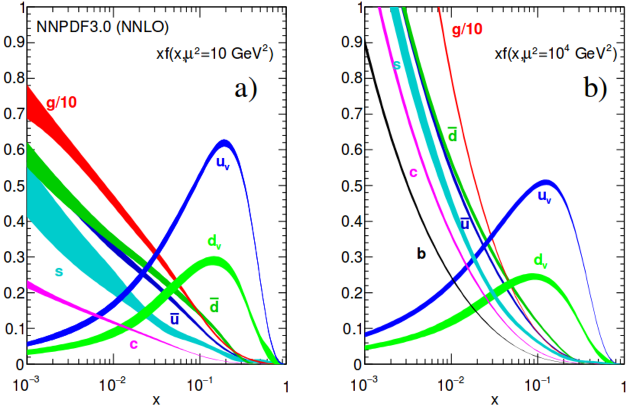
Results agree with the NLO Standard Model prediction;
Results between the two channels agree;

$Z\gamma$ cross sections are also measured and compared to CMS published result;
Good agreement in the $Z\gamma$ check validates most measurement steps;

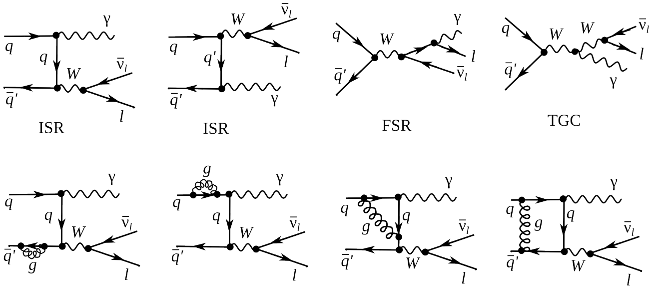
Measurements at higher energies have more opportunities for a discovery..

BACKUP

Parton Distribution Functions



WGamma, LO and NLO Feynman diagrams



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

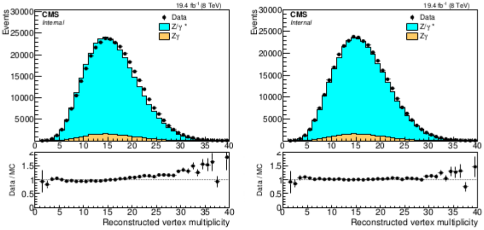
Monte Carlo Simulation (MC) samples:

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

Comment about PU from Wgg CMS Analysis Note

5.1 Pileup multiplicity correction

The simulation samples overlay the hard scatter event with additional min-bias events to simulate the affect of pileup interactions. When the simulation samples were generated the distribution of pileup vertices in data were unknown, so the distribution was generated to cover for the expected range in data. In order for the simulation to correctly predict the vertex multiplicity distribution and other quantities that are correlated with the number of pileup vertices the pileup multiplicity distribution in simulation is corrected to the measured distribution in data. Figure 5 shows the reconstructed vertex multiplicity in data and simulation before and after the pileup corrections are applied for a selection $Z \to \mu\mu$ events.



(a) (b)

Figure 5: Reconstructed vertex multiplicity in data and simulation before (a) and after (b) pileup corrections are applied to a selection of $Z \to \mu\mu$ events.

The uncertainty in the pileup distribution arises mainly from the uncertainty in the minimum-bias cross section. The distribution of pileup vertices associated with the data is determined by scaling a measurement of the luminosity, calculated for each lumi-block, by the min-bias cross section. The standard luminosity measurement used for data taken during the 2012 run was based on pixel seed counting [23]. To assess this uncertainty, the minimum-bias cross section is varied up and down by 5% which shifts the pileup multiplicity correspondingly. The effect on the predicted yield from the up and down variations is used as the pileup uncertainty.

Requirements for Selection of $W\gamma$ Candidates

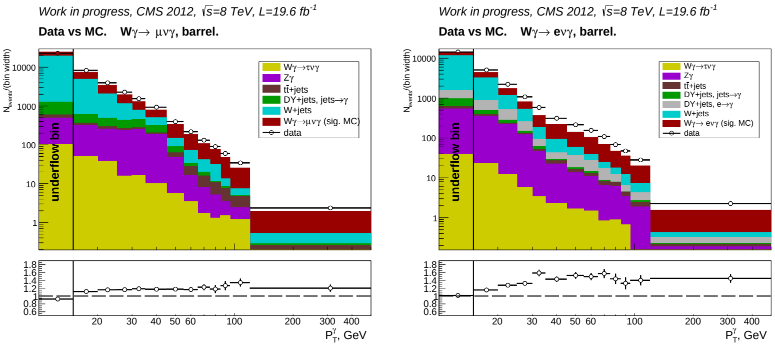
Selection requirements for candidates		Comment
- - - - - - $W\gamma \rightarrow \mu\nu\gamma$ - - - - - -	- - - - - - $W\gamma \rightarrow e\nu\gamma$ - - - - - -	
Event level selection criteria:		
Exactly one lepton + at least one photon		process signature
M_T^W >40 GeV		rejects DY+jets, $Z\gamma$
	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)

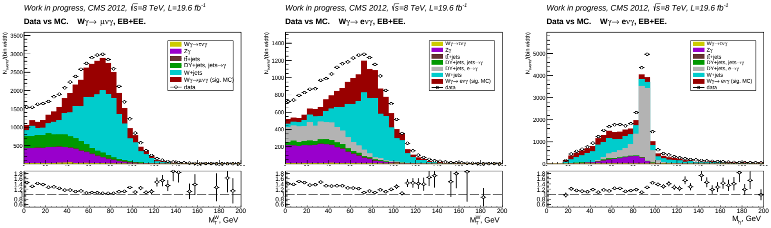
P_T^γ Spectrum of $W\gamma$ Candidates, Two Channels



Comments:	**Backgrounds:**
Dominated by W+jets events in low P_T^γ bins;	Jets$\rightarrow\gamma$: 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: $Z\gamma$, $W\gamma\rightarrow\tau\nu\gamma$.

$e \to \gamma$ and Real-γ Backgrounds

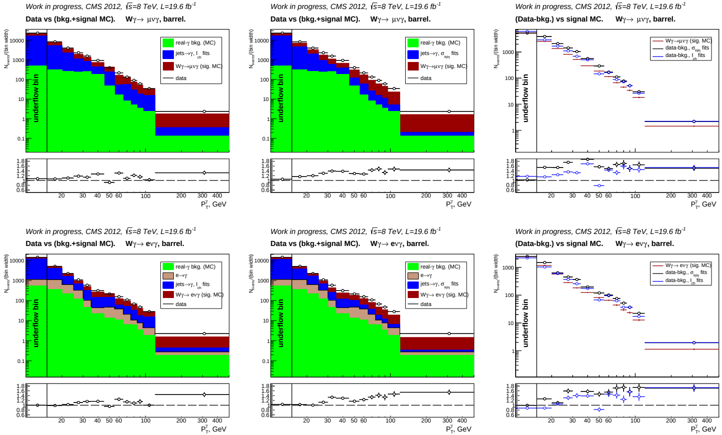
Type	Source	Comment	Estimation
$e \to \gamma$	DY+jets$\to$ ee+jets	no track for e; fake E_T^{miss}	semi data driven
Real-γ	$Z\gamma \to ll\gamma$	pass second lepton veto; fake E_T^{miss}	MC-based
Real-γ	$W\gamma \to \tau\nu\gamma$	$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ and $\tau^- \to e^- \bar{\nu}_e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

- 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 ($M_T^W = \sqrt{2P_T^l E_T^{miss}(1 - \cos(\phi^l - \phi^{miss}))}$)

P_T^γ Spectrum (ECal Barrel Only). Both channels



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^{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 (Including “unfolding” step)

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

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 $N_{\sigma i\eta i\eta}$	systematic uncertainties: 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

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.

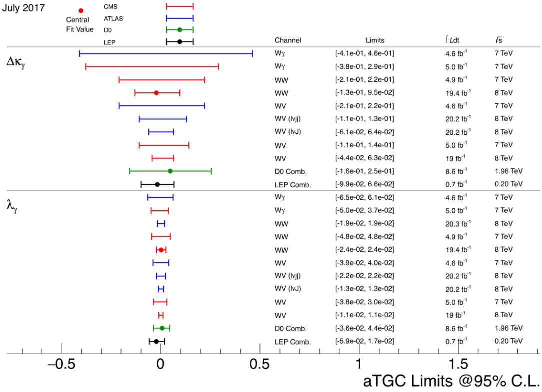
Cross Checks for Jets$\to \gamma$ Background Estimation

Checks$\to$	- - - **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 bias on the fit machinery.

Limits on aTGC constants



WW: $pp \to W^+W^- \to l^+\nu l^-\bar{\nu}$

WV: $(pp \to WW \to l\nu\text{+jets}) + (pp \to WZ \to l\nu\text{+jets})$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC