Standard Model tests and searches with photons at the LHC

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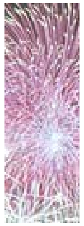
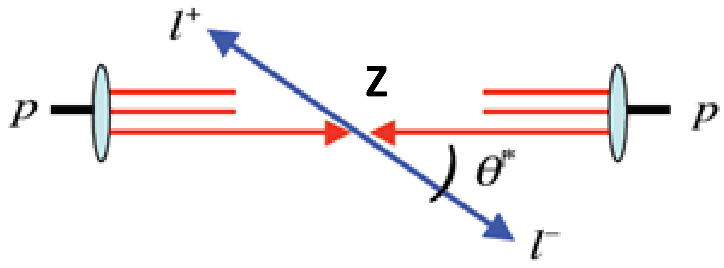
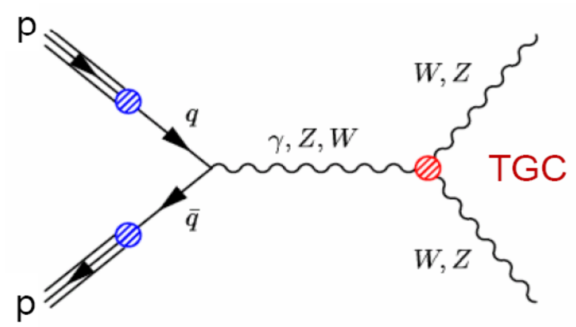


Electroweak with photon @LHC

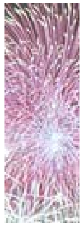
- **Single boson, W, Z production**
  candles for lepton ID, calibrations,
  precision SM measurements to **NNLO**



- **Di-boson production with photons: Wγ, Zγ**
  large cross sections
  detect Triple gauge coupling of **WWγ**
  search for anonymous coupling of **ZZγ, Zγγ**



- **Wγ, Zγ are background to**
  Di-boson : **WW, WZ**
  Higgs search : **H → γγ**

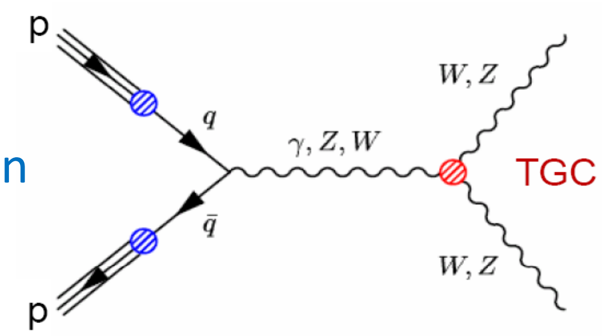


Triple gauge boson coupling (TGC)

Lagrangian for Charged TGC

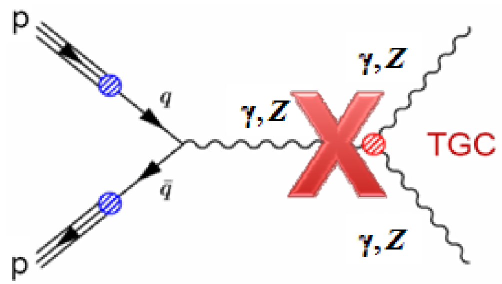
$$L_{WWV}/g_{WWV} = \boxed{g_V^1}(W^{\dagger}_{\mu\nu}W^{\mu}V^{\nu} - W^{\dagger}_{\mu}V_{\nu}W^{\mu\nu}) + \boxed{\kappa_V}W^{\dagger}_{\mu}W_{\nu}V^{\mu\nu} + \frac{\boxed{\lambda_V}}{M_W^2}W^{\dagger}_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$$

- **Charged TGC WWγ**
  predicted for Wγ production
  sensitive to anomalous coupling
  $\lambda_\gamma=\lambda_Z=0$ (SM) λ terms couple to ***s*** of di-boson
  $g^1_Z=\kappa_\gamma=\kappa_Z=1$ (SM) $\Delta\kappa_\gamma=\kappa_\gamma-1$ couples to $\sqrt{s}$

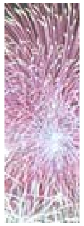


- **Anomalous coupling for new physics:**
  enhancement in high p_T(g, λ type)
  changes in angular distributions (κ type)

- **Neutral TGC ZZγ, Zγγ is forbidden for Zγ**
  Z, γ has no charge nor weak isospin

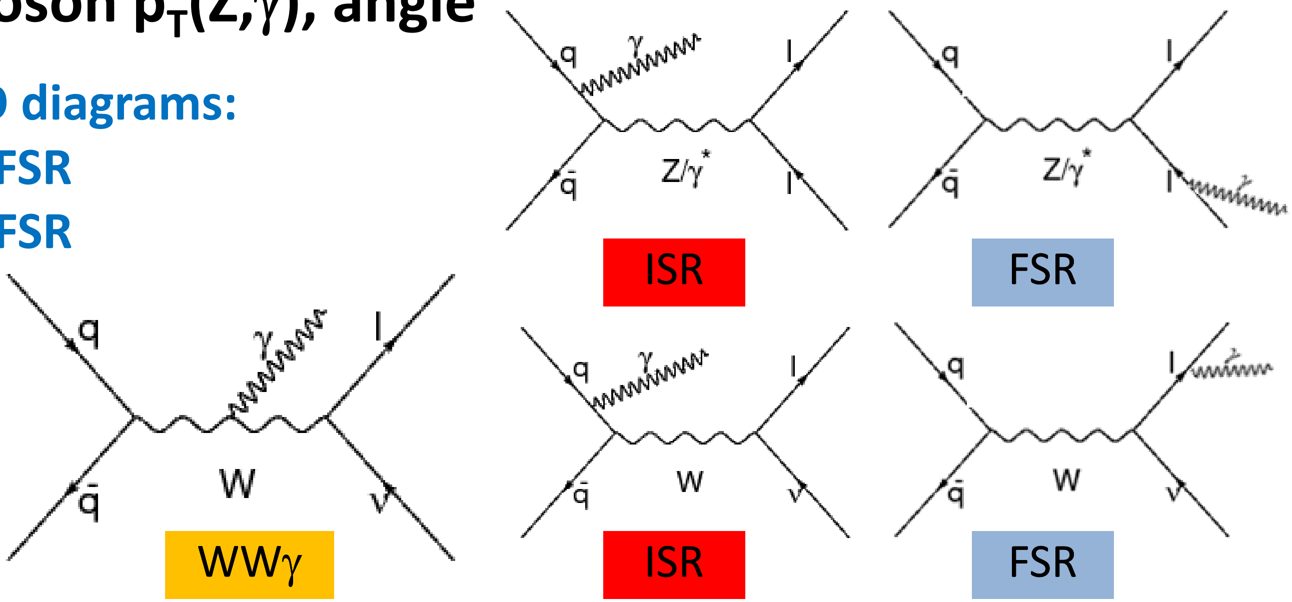


Process	WW	WZ	Wγ
TGC vertex	WWZ, WWγ	WWZ	**WWγ**
Parameters	$\Delta\kappa_Z, \lambda_Z, \Delta g_Z^1$ $\Delta\kappa_\gamma, \lambda_\gamma$	$\Delta\kappa_Z, \lambda_Z, \Delta g_Z^1$	$\boldsymbol{\Delta\kappa_\gamma, \lambda_\gamma}$

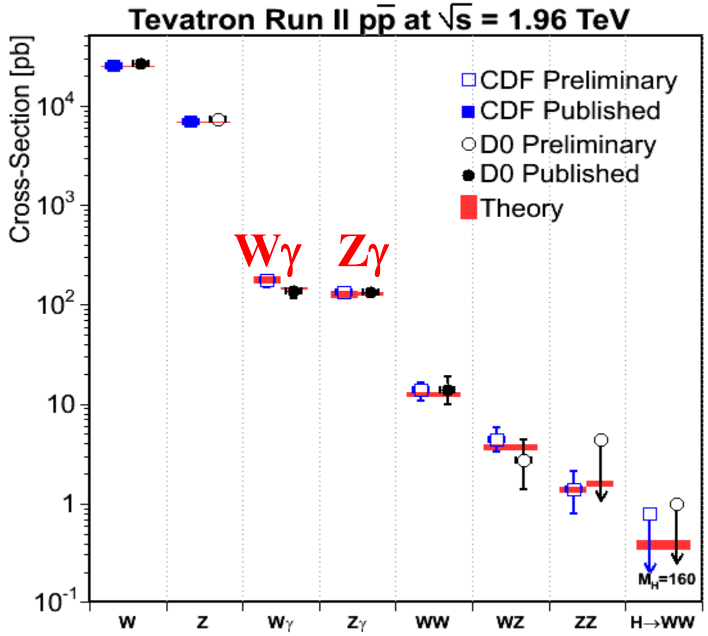


Measurables for Wγ and Zγ

- We report on sensitivity for lepton (e, μ) channels
  $W^{\pm}(\rightarrow \ell^{\pm}\nu)\gamma$, $Z(\rightarrow \ell^{+}\ell^{-})\,\gamma$
- Physics interests are the **ISR photon production** and the **Triple Gauge boson Coupling**
  NLO calculations : Baur et al., Madgraph, Sherpa, ..
- Variables sensitive to TGC:
  cross section; boson $p_T(Z,\gamma)$, angle
- **Standard Model LO diagrams:**
  Zγ : ISR + FSR
  Wγ : WWγ +ISR + FSR



Di-boson from the Tevatron to the LHC



http://www-cdf.fnal.gov/physics/ewk/

http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm

Production rate @LHC is orders of magnitudes higher than Tevatron:

- 10x higher cross section;
- >10x higher luminosity

Probing ***anomalous TGCs***
In higher energy region @LHC

NLO CTEQ6M Cross section σ(pb)

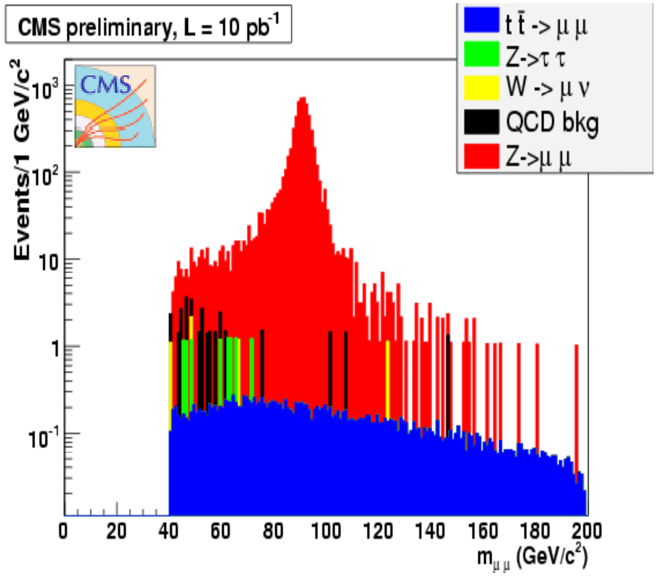
	conditions	√s=1.96 TeV	√s=14 TeV
$W^{\pm}\gamma$	E_T^{γ}>7 GeV, ΔR(ℓ,γ)>0.7	19.3	**451**
$Z^0\gamma$	E_T^{γ}>7 GeV, ΔR(ℓ,γ)>0.7	4.7	**219**
W^+W^-	W width inlcuded	12.4	112
$W^{\pm}Z^0$	Z, W on mass shell	3.7	48
Z^0Z^0	Z on mass shell	1.4	15

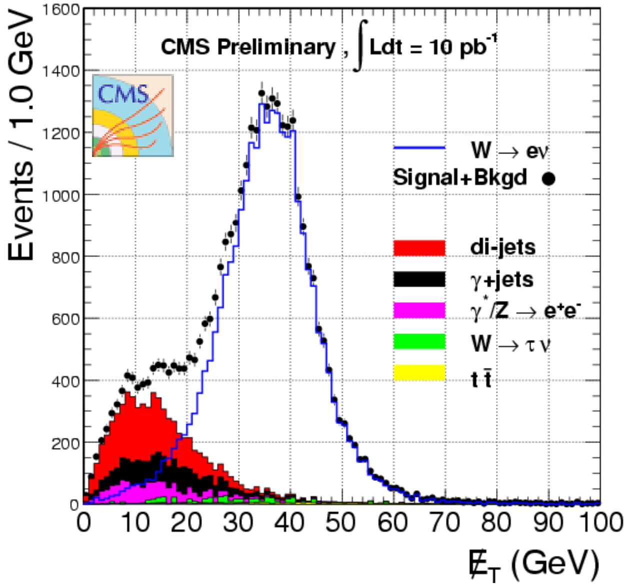
U. Baur et al.; PRD 53 1098, PRD 57 2823

S. Frixione et al., JHEP 0206 029, JHEP 0308 007

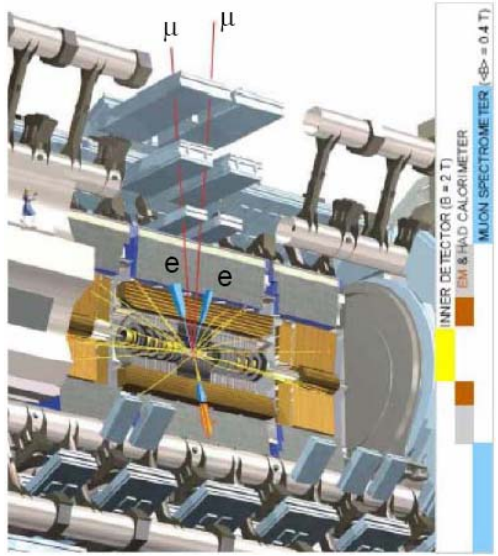
μ/e/γ detection

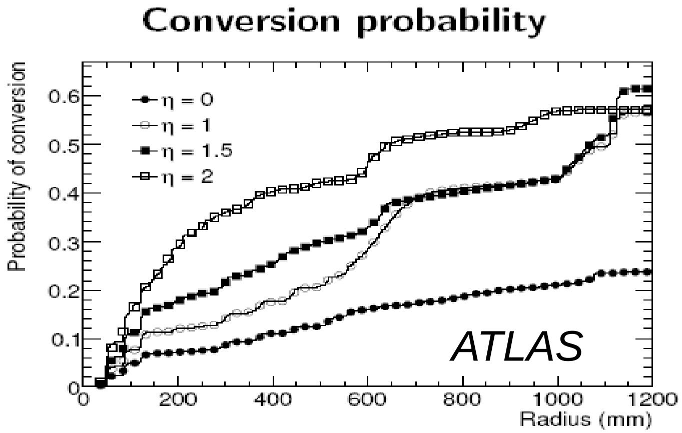
- **Z(ℓℓ), W(ℓν) events are candles for μ, e/γ ID**

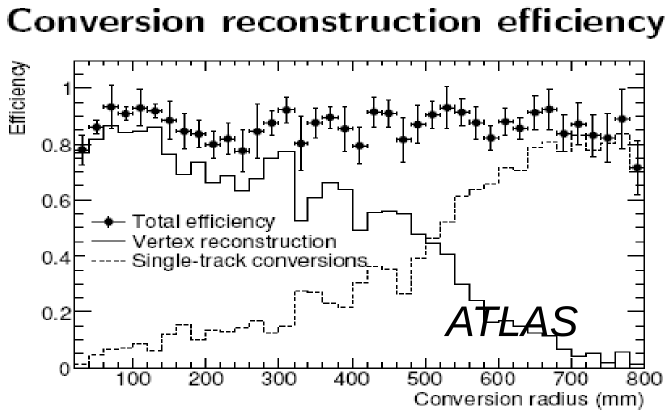




- **e/γ systematics:**
  - bremsstrahlung,
  - γ conversion
  - Jet faking photon, π^0/γ

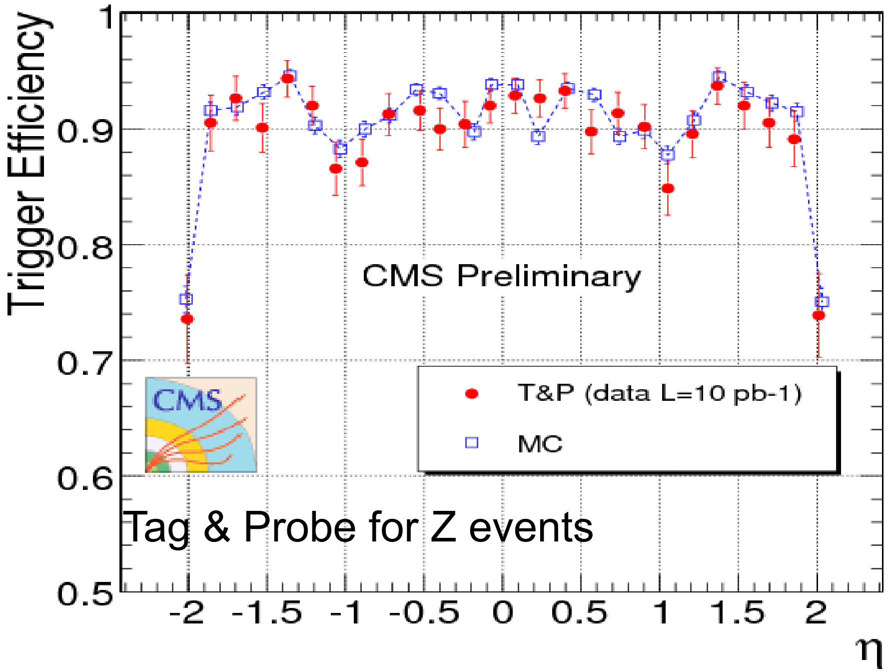




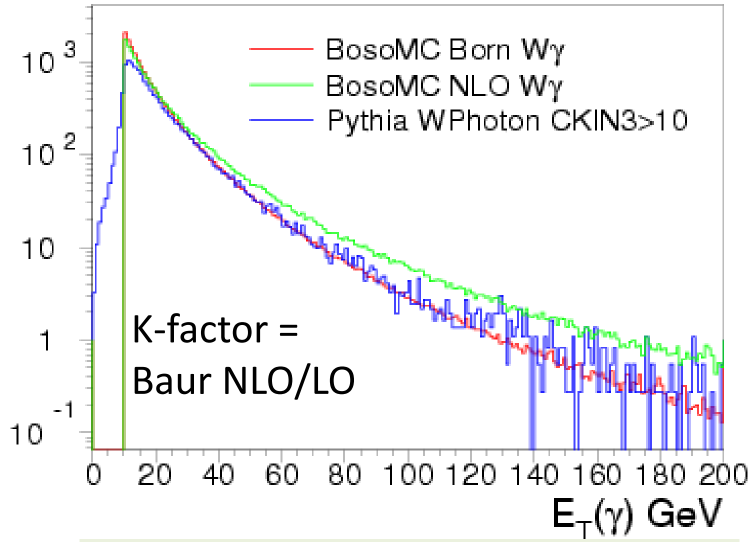


Wγ, Zγ study samples

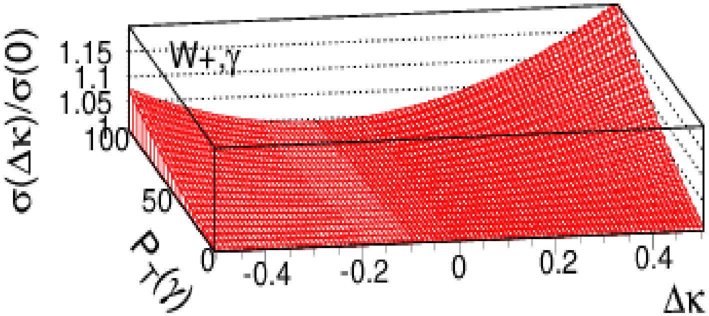
- **SM generators:**
  - **pythia** for LO and full simulations,
  - **Baur** et al. for NLO calculations
- **Full detector simulation data:**
  - for pp at **√s=14 TeV**, with **trigger**

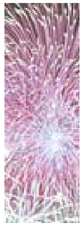


Pythia LO, Baur LO & NLO parton level

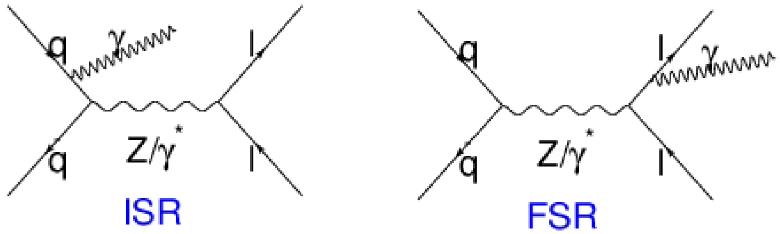


TGC dependence by Baur





$Z\gamma \rightarrow \ell^+\ell^-\gamma$ selection



Event topology:

Z of lepton pairs is clean

Z+ISR photon:

- $\Delta R(\ell,\gamma)$ random, $E_T(\gamma)$ high
- **$m(\ell\ell) = m_Z$**

Z+FSR photon:

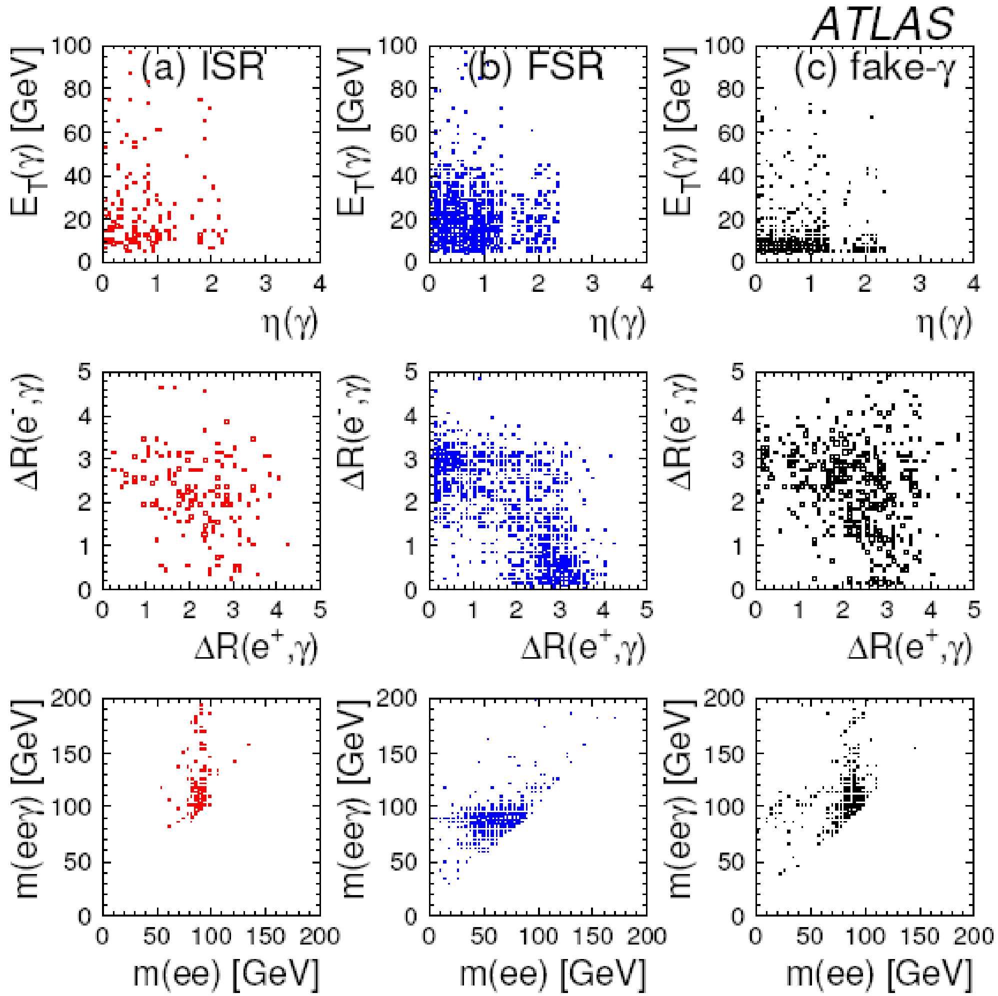
- ***$\Delta R(\ell,\gamma)$ small, $E_T(\gamma)$ low***
- ***$m(\ell\ell\gamma) = m_Z$***

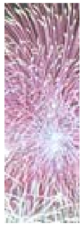
Z+fake photon:

inclusive EM objects in jet: **π^0, η, …**

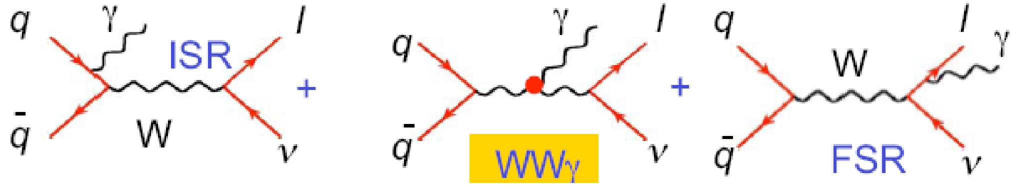
wrongly identified objects: **$e^\pm$, …**

- $\Delta R(\ell,\gamma)$ random, ***$E_T(\gamma)$ low***
- **$m(\ell\ell) = m_Z$**





$W\gamma \to \ell^{\pm}\nu\gamma$ selection



Event topology:

Transverse masses of W, Wγ:

$$m_T(W) = (E_T(W)^2 - p_x(W)^2 - p_y(W)^2)^{1/2} \qquad E_T(W) = E_T(MET) + E_T(\ell)$$

$$m_T(W,\gamma) = (E_T(W,\gamma)^2 - p_x(W,\gamma)^2 - p_y(W,\gamma)^2)^{1/2} \qquad p_i(W) = E_i(MET) + p_i(\ell)$$

W+ISR,WWγ photon:

- $\Delta R(\ell,\gamma)$ random, $E_T(\gamma)$ high
- $m_T(W)$, $m_T(W\gamma)$ high

W+FSR photon:

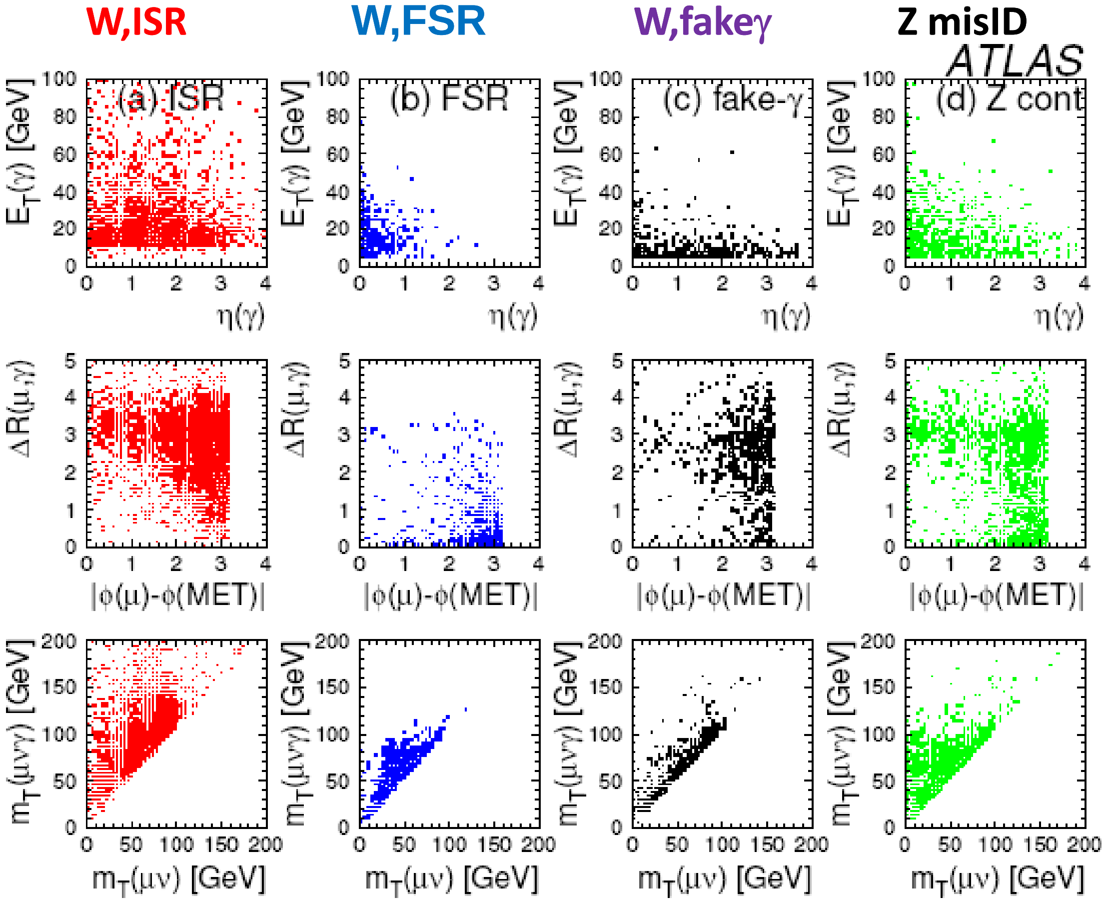
- $\Delta R(\ell,\gamma)$ small, $E_T(\gamma)$ low
- $m_T(W)$, $m_T(W\gamma)$ low

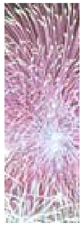
W+fake photon:

- $\Delta R(\ell,\gamma)$ random, $E_T(\gamma)$ low
- $m_T(W)$, $m_T(W\gamma)$ high

Z, Zjet, Zγ mis-ID:

- $\Delta R(l,\gamma)$ back-to-back
- $E_T(\gamma)$ high
- $m_T(W)$ low, $m_T(W\gamma)$ high

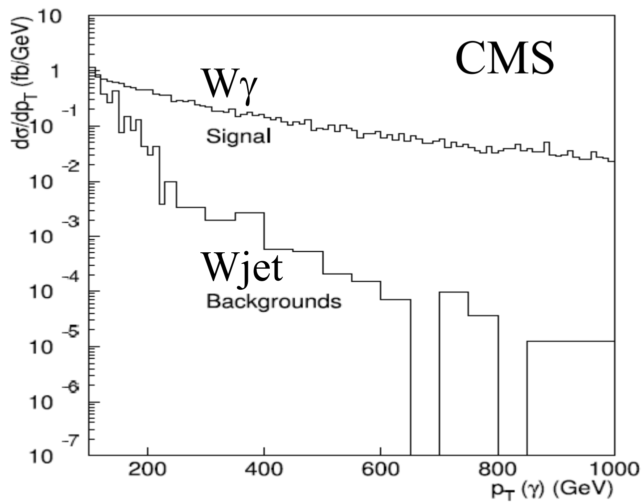




Cut-based and BDT for Zγ, W±γ

CMS cut-based ZγX, WγX selection

Variable	Cut value
Pseudo-rapidity Photon/Lepton	$\vert\eta_{l,\gamma}\vert < 2.4$
Transverse Momentum Photon	$P_{T,\gamma} > 100$ GeV/c
Transverse Momentum Lepton	$P_{T,l} > 25$ GeV/c
Photon-Lepton Separation	$\Delta R_{l,\gamma} > 0.7$
Transverse Missing Energy	$\not{E}_T > 50$ GeV
Wγ Cluster Transverse Mass	$M_{TC}^{W\gamma} > 90$ GeV/c^2
Zγ Three-body Mass	$M_{ll\gamma} > 100$ GeV/c^2



ATLAS Boosted Decision-Tree for Zγ, Wγ

Multiple trainings & tests for

Z+ISRγ to 1) **Z+FSRγ**; 2) **Z+fakeγ**

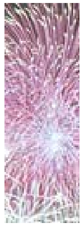
W+ISRγ to 1) **W+FSRγ**; 2) **W+fakeγ**; 3) **Z-misID**

Wγ selection at 67% efficiency (1fb^{-1})

		Signal $W^{\pm}\gamma$	Background W+FSR_γ	W+fake_γ	$Z(\ell\ell)\gamma$
$\ell = e$	Pre-selected	1710	11440	7890	32480
	BDT selection	1145	242	791	101
	Triggered	966	188	628	93
	NLO scaled	1604 (k=1.66)			
$\ell = \mu$	Pre-selected	2680	28410	10250	3950
	BDT selection	1793	413	961	409
	Triggered	1305	177	595	260
	NLO scaled	2166 (k=1.66)			

Zγ selection at 67% efficiency (1fb^{-1})

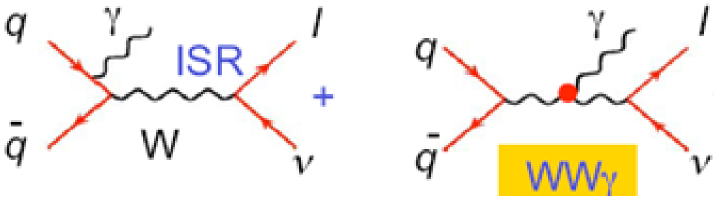
		Signal $Z\gamma$	Background Z+FSR_γ	Z+fake_γ	$W(l\nu)\gamma$
$\ell = e$	Pre-selected	430	2760	490	44
	BDT selection	288	70	74	0
	Triggered	282	65	79	0
	NLO scaled	367 (k=1.3)			
$\ell = \mu$	Pre-selected	950	7500	790	930
	BDT selection	636	173	186	0
	Triggered	578	164	165	0
	NLO scaled	751 (k=1.3)			



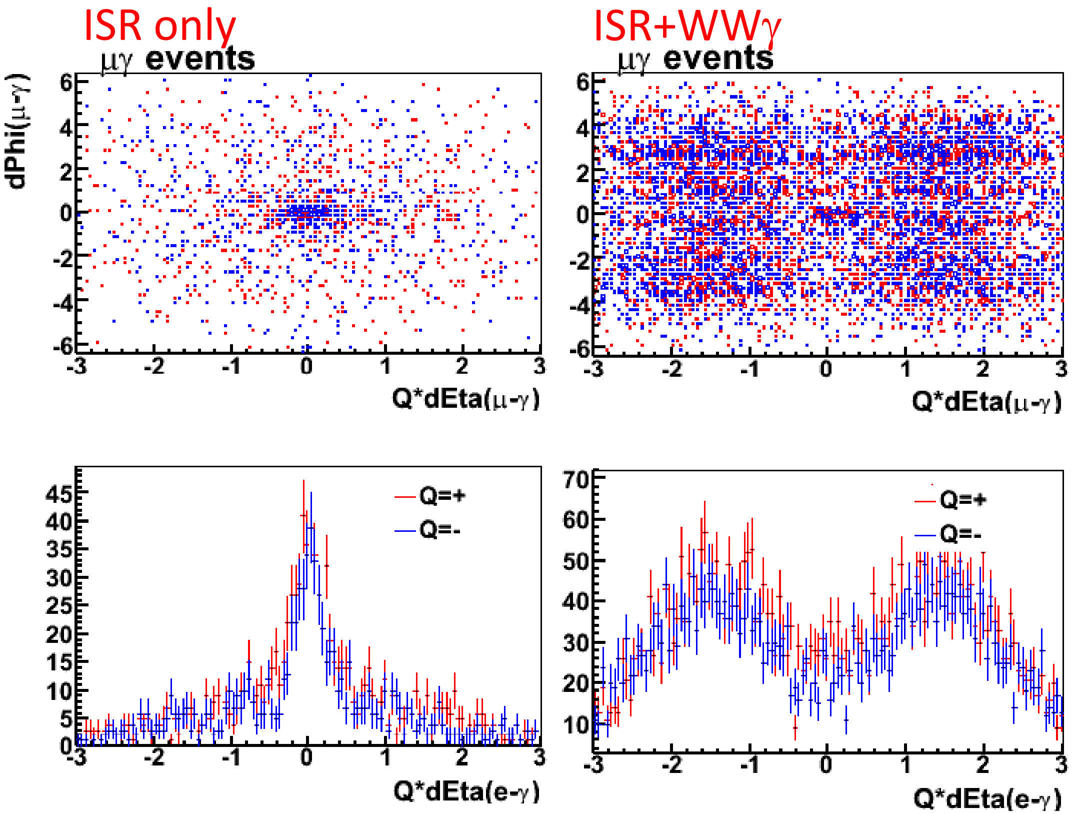
$W^{\pm}\gamma$ Radiation Zero Amplitude

$WW\gamma$ suppresses ISR production amplitude zero at

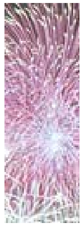
$\cos\theta_{\bar{q}\gamma'} = \pm 1/3$ for $W^{\pm}$



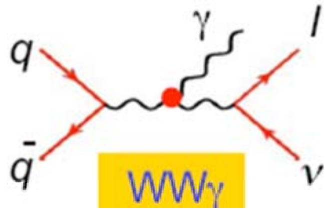
Comparison: ISR, ISR+WWγ of Pythia LO
parton level distributions



1) NLO,
2) Anomalous coupling
change cross section
and fill up the gap



WWγ anomalous coupling



Sensitivity to WWγ & Anomalous Coupling

Evaluated with $E_T(\gamma)$ of Wγ selected

$$\Delta\kappa_\gamma = \Delta\kappa_{\gamma 0}/(1+\frac{m_{W\gamma}^2}{\Lambda_{FF}^2})^n, \qquad \lambda_\gamma = \lambda_{\gamma 0}/(1+\frac{m_{W\gamma}^2}{\Lambda_{FF}^2})^n,$$

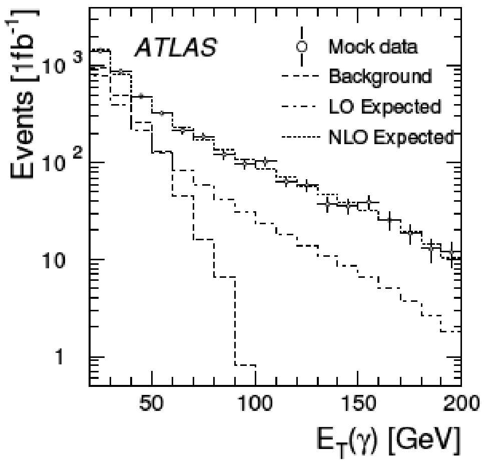
ATLAS W(μν)γ, W(eν)γ combined

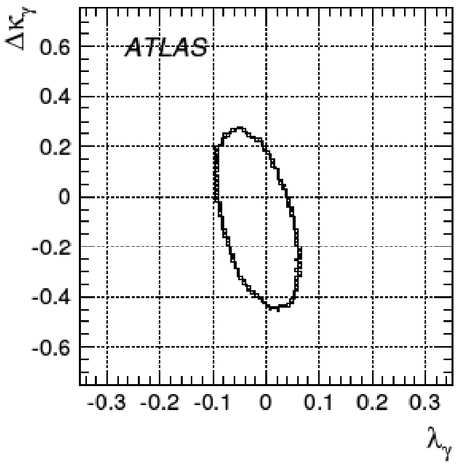
- reweight to **ds(AC)/ds(SM)**
- Binned likelihood 95% CL intervals
- **Λ=2 TeV, n=2**

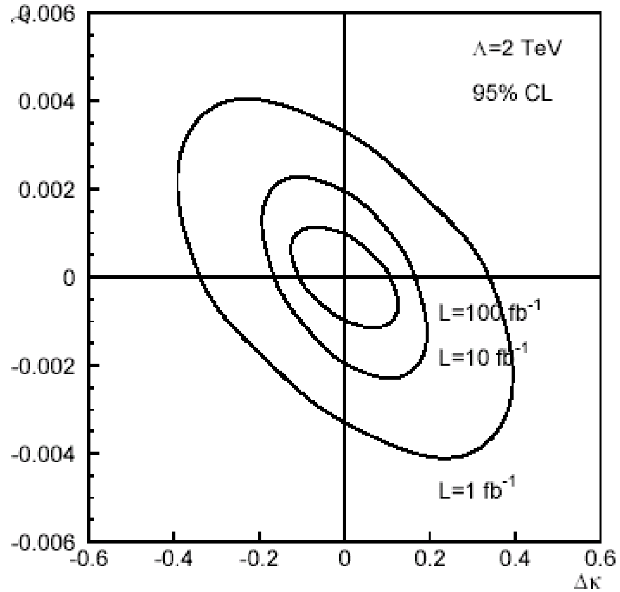
CMS sensitivity to WWγ

95% CL limits for 100 fb^{-1} , Λ=2 TeV

$\Delta\kappa_\gamma < 0.1$, $\lambda_\gamma < 0.0009$





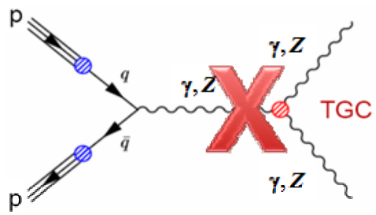


$W(\ell\nu)+ISR\gamma$			
	1 fb^{-1}	10 fb^{-1}	30 fb^{-1}
λ_γ	[-0.09, 0.04]	[-0.05, 0.02]	[-0.02,0.01]
$\Delta\kappa_\gamma$	[-0.43, 0.20]	[-0.26, 0.07]	[-0.11,0.05]

Zγ Neutral Triple Gauge boson Couplings

NTGC Anomalous Couplings

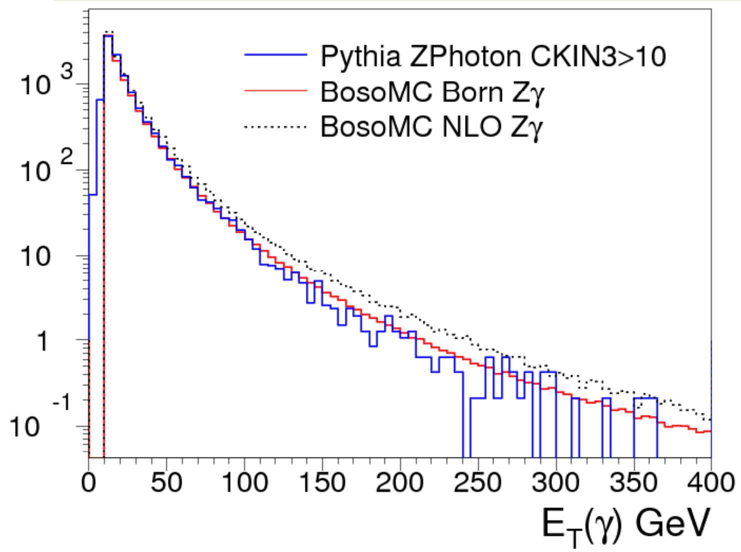
$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = \frac{i(P^2-M_V^2)}{M_Z^2}\Big[h_1^V(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{M_Z^2}P^\alpha((P.q_2)q^{\mu\beta}-q_2^\mu P^\beta)$$
$$-h_3^V\epsilon_{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{M_Z^2}P^\alpha\epsilon\mu\beta\rho\sigma P_\rho q_{2\sigma}\Big]$$



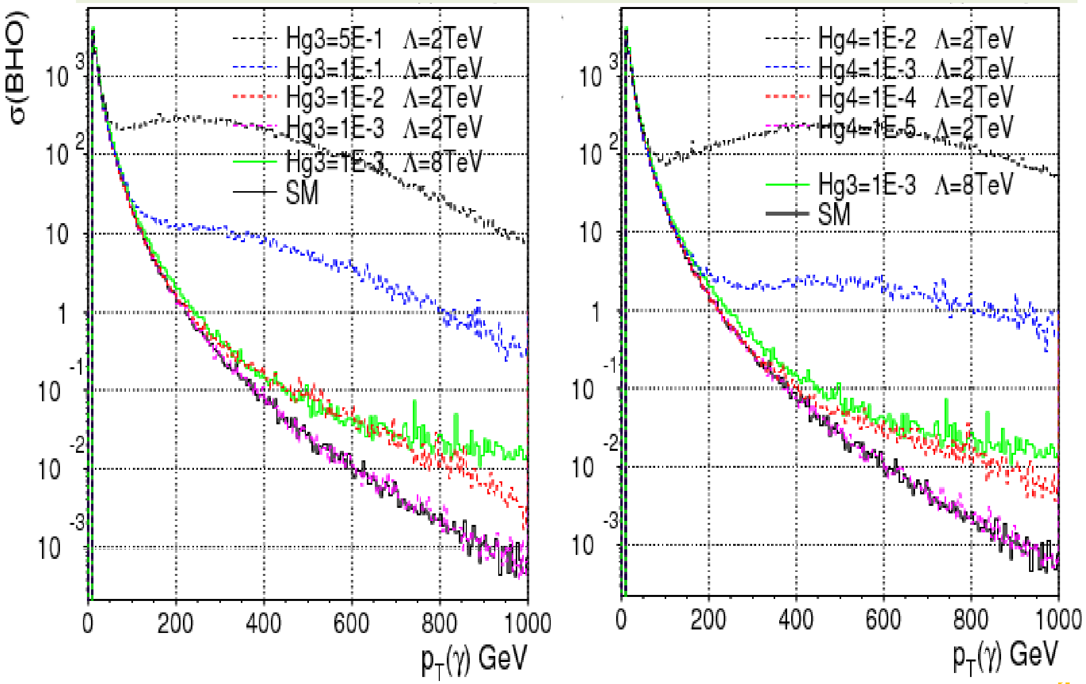
h_1^V, h_2^V, are P-even, violating CP
h_3^V, h_4^V, are CP conserving

$$h_i^V(\hat{s}) = \frac{h_{i0}^V}{(1+\frac{\hat{s}}{\Lambda_{FF}^2})^n} \qquad (i=1,2,3,4)$$

Pythia, Baur LO & NLO comparison @parton level



Sensitivity to h_3^γ, h_4^γ and Λ



ZZγ, Zγγ Anomalous Couplings

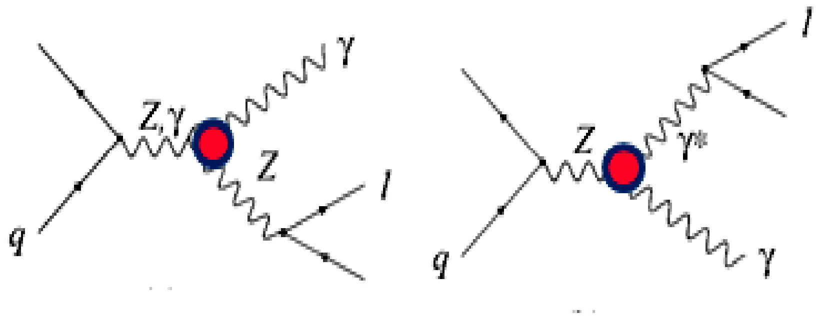
$Z\gamma \rightarrow \ell^+\ell^-\gamma$ BDT selected $E_T(\gamma)$

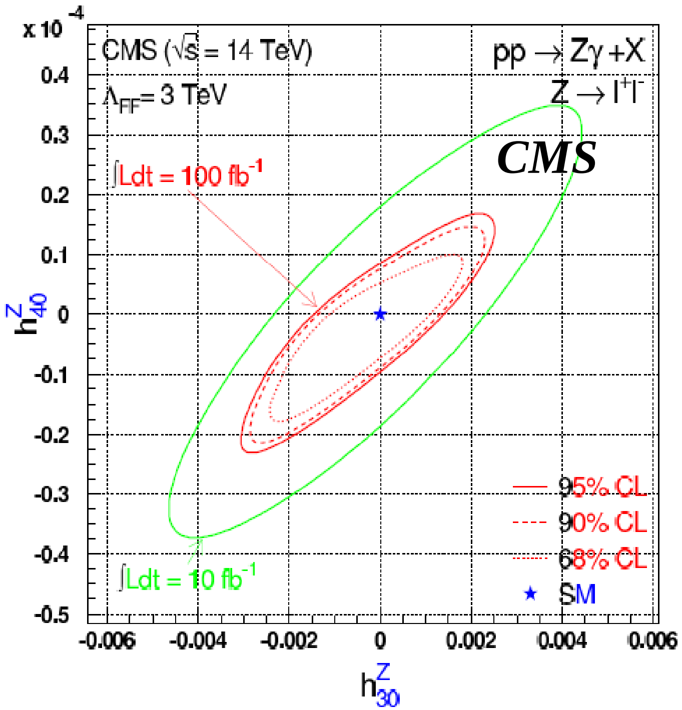
- reweight spectrum by

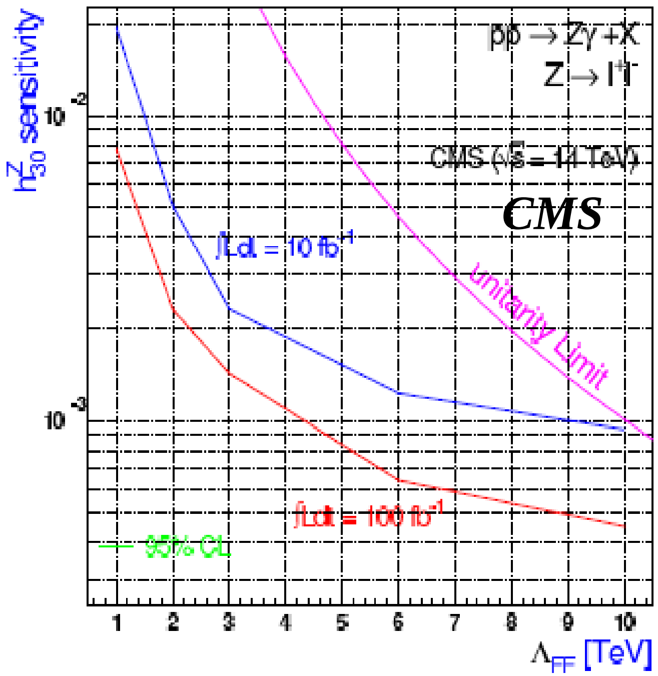
dσ(AC)/dσ(SM)

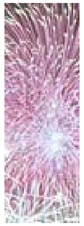
- **Binned likelihood on $E_T(\gamma)$**

95% CL interval for $\mathbf{h_i^Z}, \mathbf{h_i^\gamma}$









Summary

Perspectives for SM with photons @LHC
is investigated for di-boson channels of Wγ, Zγ

→ **Z/W**; **Z/W+γ** are candles for **e/μ/γ**
→ Production rates estimated for **SM σ(Zγ)**, **σ(Wγ)**
→ Sensitivity to new physics
is estimated for **anomalous TGC** of **WWγ, ZZγ, Zγγ**

Assuming 20% systematic uncertainties

→ with 0.1 fb^{-1} to establish Wγ, Zγ detection of significant >5σ
→ Systematic uncertainty will dominate after 5-30 fb^{-1}

On-going investigations:

→ Monte Carlo on PDF assumption, NLO scaling
→ Detector: Luminosity, Particle ID, Calibration, jet energy