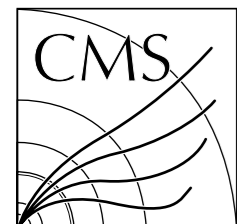
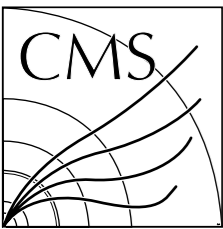


# Neutral and Charged Anomalous Triple Gauge Couplings At CMS

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On behalf of the CMS Collaboration



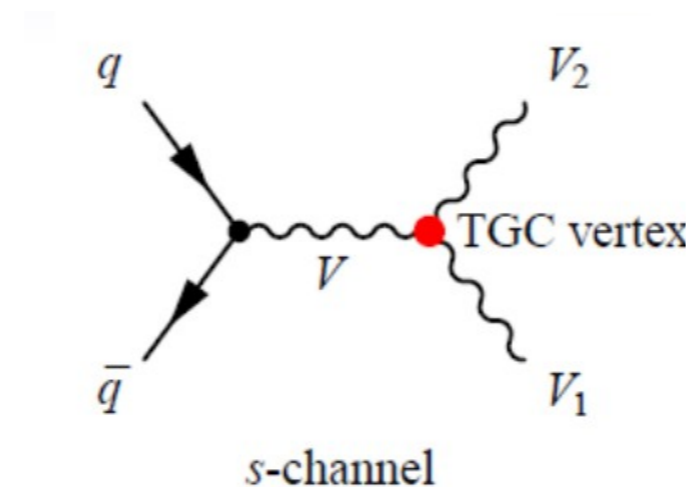


# Outline

- Introduction to Anomalous Triple Gauge Coupling (aTGC) Measurements at CMS
  - Parameterizations used by CMS
  - Measurement strategy used in 2010/2011 analyses
- Results from CMS:  $WW$ ,  $W\gamma$  &  $Z\gamma$
- Case study using CLs for aTGC Limit Setting
  - SM and non-SM settings

# Anomalous Triple Gauge Couplings

- Probing of anomalous triple gauge boson couplings provide a **stringent test of the standard model**.



- This can be used as a robust, generalized search for new physics.
- Search for excess of s-channel diboson production
  - **$Z\gamma$ ,  $W\gamma$ ,  $WW$ ,  $ZZ$  ...**
- High center of mass energies enhance sensitivity to aTGCs

# Charged TGCs

● The most general charged TGC Lagrangian contains 14 anomalous couplings

- Reduce this using physically motivated assumptions
- Charge, Parity, and Gauge invariance reduces this to 3 independent couplings in the ‘HISZ’ parameterization:

$$L/g_{WWV} = ig_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) + i\kappa^V W_\mu^* W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W_{\rho\mu}^* W_\nu^\mu V^{\nu\rho}$$

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W \quad \text{and} \quad \lambda \equiv \lambda_Z = \lambda_\gamma.$$

$$\Delta g_1^V = g_1^V - 1$$

$$\Delta\kappa_V = \kappa_V - 1$$

- SM predicts  $\Delta\kappa_\gamma, \Delta g_1^Z, \lambda$  all to be zero

● Different diboson channels have access to different couplings:

- $WW : WW\gamma$  and  $WWZ$  vertices :  $\Delta\kappa_{\gamma/Z}, \Delta g_1^Z, \lambda$  (Depends on choice of parameterization!)
- $WZ : WWZ$  vertex :  $\Delta\kappa_{\gamma/Z}, \Delta g_1^Z, \lambda$
- $W\gamma : WW\gamma$  vertex :  $\Delta\kappa_\gamma, \lambda$

# Neutral TGCs

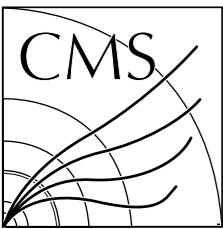
● In a similar way, one arrives at the neutral anomalous couplings for  $Z\gamma$  and  $ZZ$

- $Z\gamma$ :  $\Gamma_{Z\gamma V}^{\alpha\beta\mu} = ie \frac{q_V^2 - m_V^2}{m_Z^2} \left[ \begin{aligned} & h_1^V [q_\gamma^\mu g^{\alpha\beta} - q_\gamma^\alpha g^{\beta\mu}] \\ & + h_2^V \frac{q_V^\alpha}{m_Z^2} [q_\gamma q_V g^{\beta\mu} - q_\gamma^\mu g_V^\beta] \\ & + h_3^V \epsilon^{\alpha\beta\mu\rho} q_{\gamma\rho} \\ & + h_4^V \frac{q_V^\alpha}{m_Z^2} \epsilon^{\mu\beta\rho\sigma} q_{V\sigma} q_{\gamma\sigma} \end{aligned} \right]$
- $ZZ$ :  $g_{ZZV} \Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - M_V^2}{M_Z^2} \left[ i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right]$

$$V = Z, \gamma$$

● These couplings probe on-shell final states coming from initial states that are completely absent in the SM

- This results in possibly large sensitivity to various types of new physics.



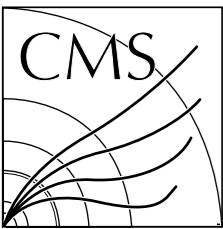
# CMS 2010 aTGC Fitting Strategy

- Follow Tevatron-style aTGC yield extrapolation grid model
  - Use MxM course grid of aTGC values to predict yields at intermediate points using Fermi's Golden Rule.
- For each bin in some diboson observable calculate the poisson probability of observing N events given expectation
  - The expectation is aTGC model + background estimates
  - Allow expectation to fluctuate within systematic errors
    - ➔ Both signal and background have systematics
    - ➔ This means we can account for incorrect measurement of background and theory errors when performing the fit of the aTGC values
  - Re-minimize likelihood with respect to systematic fluctuations at each point in the aTGC parameter space evaluated to set limit (a.k.a. profile likelihood)
    - ➔ Set limits which take into account possible fluctuations from systematics

$$L = G(f_{Bkg.}^{Syst.}, 1, \sigma_{Bkg.}^{Syst.}) \cdot G(f_{\mathcal{L}}, 1, \sigma_{\mathcal{L}}) \cdot G(f_{Sig.}^{Syst.}, 1, \sigma_{Sig.}^{Syst.}) \prod_{i=1} Poisson(N_i, \mu_i(\alpha_j))$$

Lognormal Description of Systematic Fluctuations

Per-bin expectation PDF



# Differences With Respect to Tevatron Method

## ● Treatment of TGC parameters

- Tevatron limits use 'form factor' to enforce unitarity
- CMS limits are LEP-style in the sense that there is no form factor applied
- Tevatron limits are set in a **binned** parameter space
- CMS limits set in **unbinned** parameter space
  - Both parameter spaces are created from a coarse input grid
  - Yield in each  $E_T$  bin assumed to have quadratic dependence on anomalous couplings

## ● Determination of limits

- Tevatron analysis creates a likelihood that is binned in the anomalous couplings
  - Systematic fluctuations are integrated out as opposed to using profile likelihood
- The binned likelihood is then fit with a parabola and limits extracted by taking contours on the parabola
  - This assumes high statistics and cannot be trusted in our analysis
- CMS analysis determines limits using MINOS and makes no assumption on the shape of the likelihood

# Charged aTGC Results: $W\gamma$ 2010

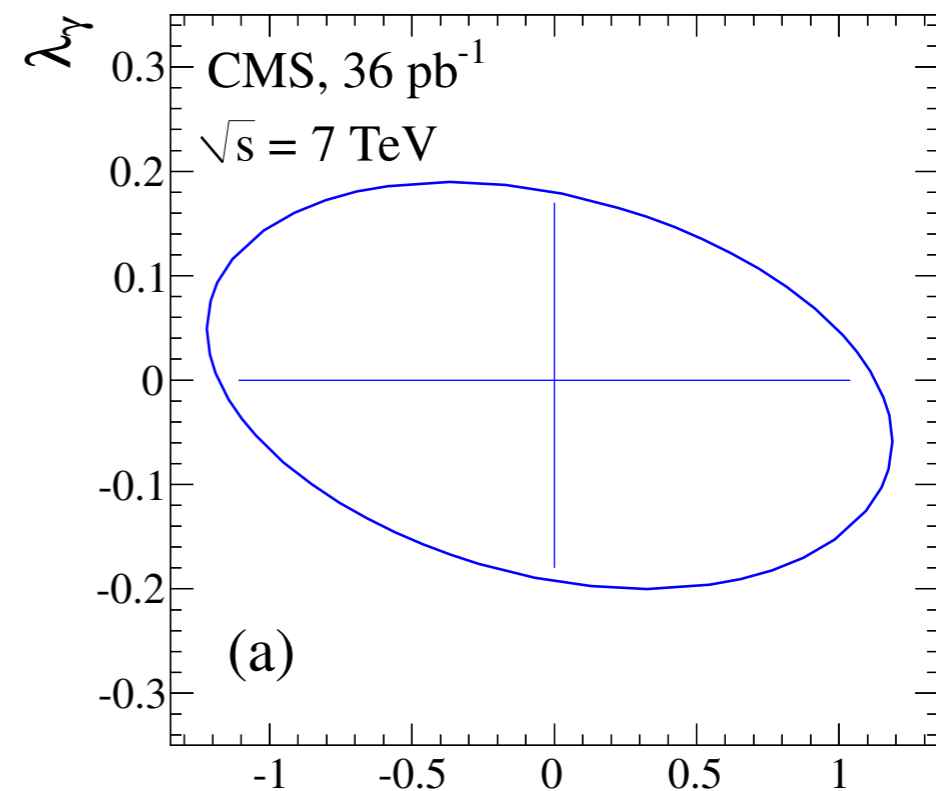
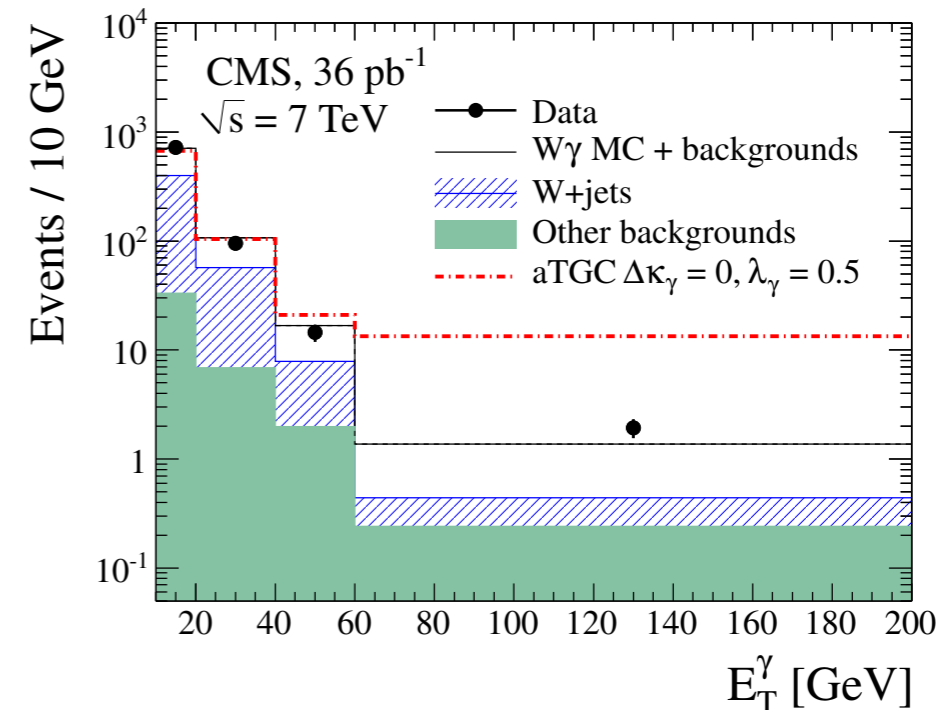
## ● Used profile likelihood based limits

- Best fit aTGC values consistent with SM

## ● Set limits using $\gamma$ $p_T$ shape

## ● 1D limits:

- $-0.96 < \Delta\kappa < 0.91$
- $-0.16 < \lambda < 0.15$

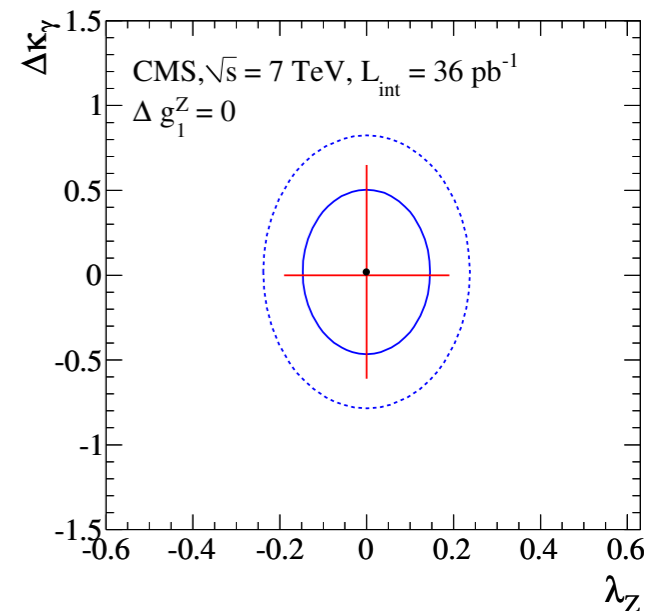
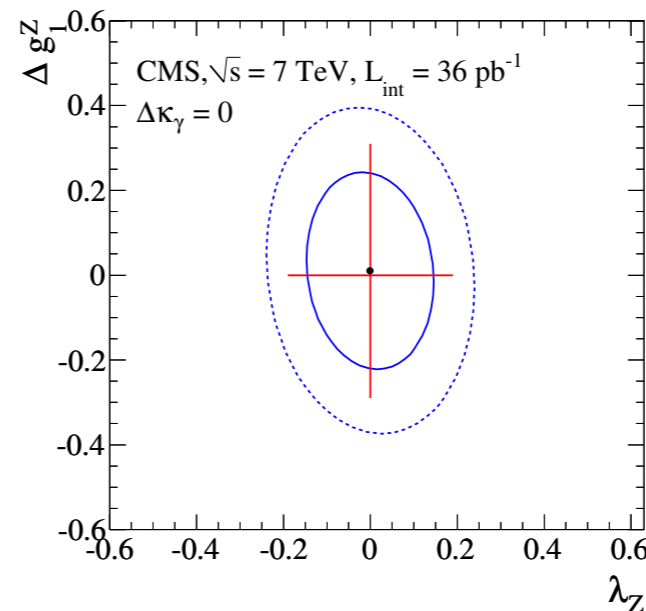
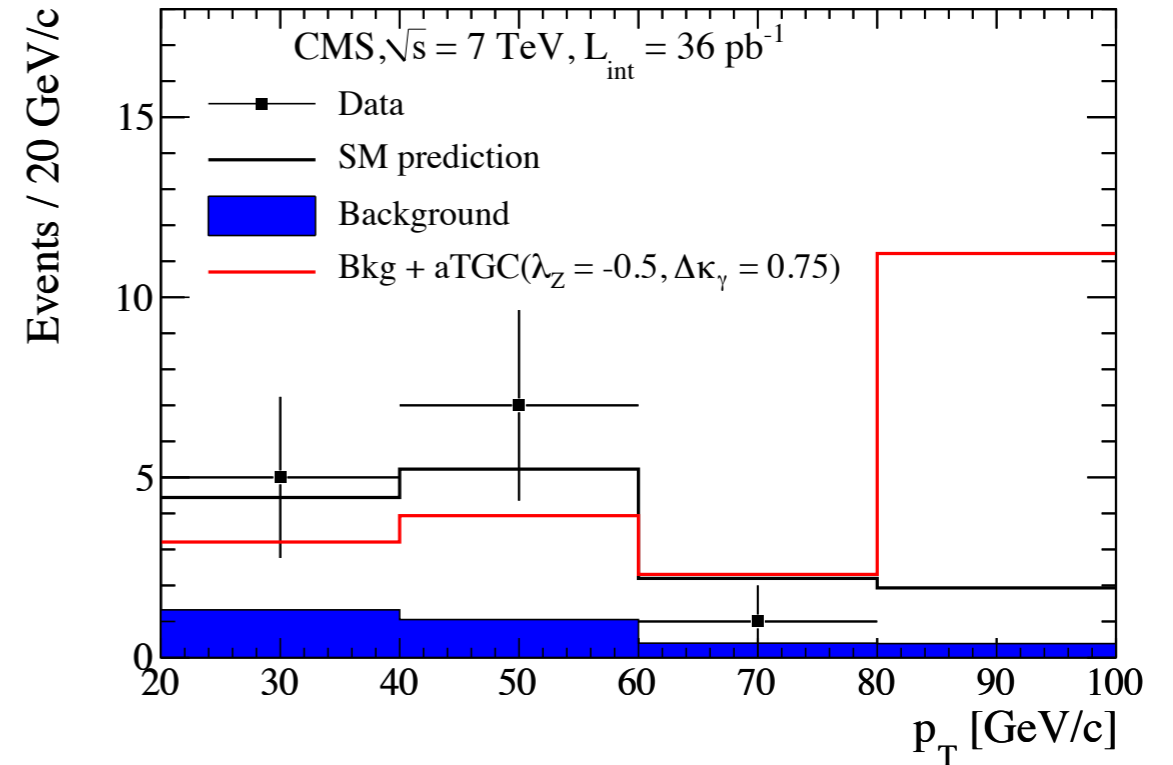


# Charged aTGC Results: WW 2010

● Limits set using leading lepton  $p_T$  shape as  $W$  boson  $p_T$  isn't directly available

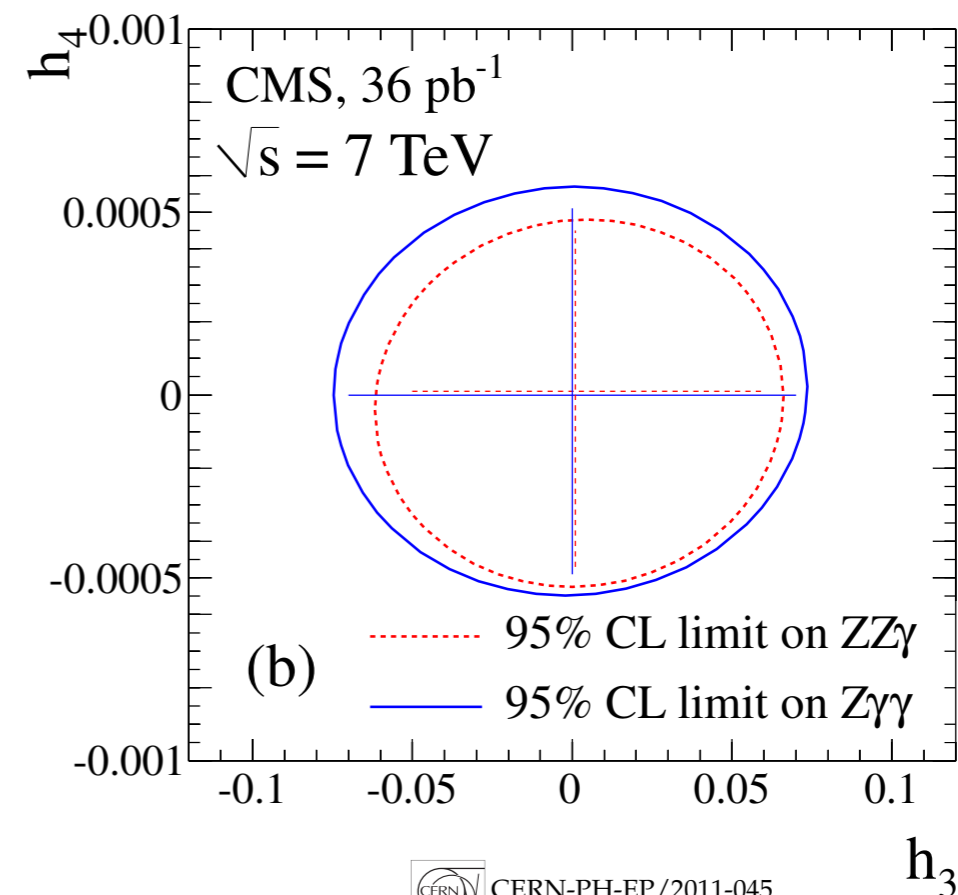
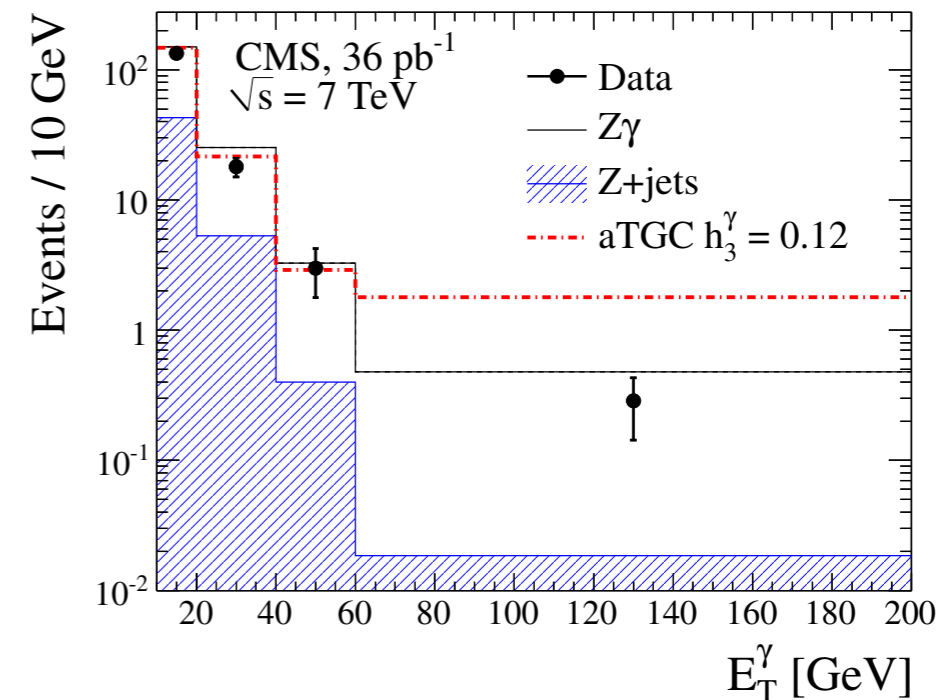
● ID Limits:

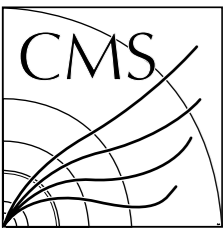
- $-0.75 < \Delta\kappa < 0.72$
- $-0.23 < \lambda < 0.23$
- $-0.33 < \Delta g_1^Z < 0.40$



# Neutral aTGC Results: $Z\gamma$ 2010

- Set limits using  $\gamma$   $p_T$  shape
- Cannot set limits on  $h_1$  or  $h_2$  using  $p_T$  based analysis
  - $p_T$  shape doesn't show CP violating effects
- ID limits:
  - $ZZ\gamma$ 
    - $-0.05 < h_3 < 0.06$
    - $-0.0005 < h_4 < 0.0005$
  - $Z\gamma\gamma$ 
    - $-0.07 < h_3 < 0.07$
    - $-0.0005 < h_4 < 0.0006$





# 2011 MC Case Study: Why Using CLs

- A CMS/ATLAS agreement for last year's Higgs analyses enforced a new rule in the anticipation of combination of results:
  - Analyses without precedent or good reason should adopt CLs limit setting methodology
  - CLs is known to always cover the null hypothesis
    - This is possibly bad behavior in the case of aTGCs since small aTGCs are degenerate with the SM
    - SM never gets excluded!
- How do CLs limits react in the case of a real aTGC signal?
  - Expect observed limits to include SM and injected aTGC value
  - By definition limits are more conservative
    - aTGC information now exists in the comparison between expected and observed limits.
- As a demonstration of the point I have created two semi-realistic MC scenarios using the full CMS limit setting machinery and applying the CLs methodology to set the final limits.
  - Masahiro Morii has already shown in private communication what we are about to see here
- All MC is scaled to 3/fb and backgrounds are taken from the full 2011 run period and scaled to 3/fb
  - Systematics have been scrambled: these limits do not reflect the true sensitivity of CMS

# 2011 MC Case Study: $W\gamma$ Using CLs

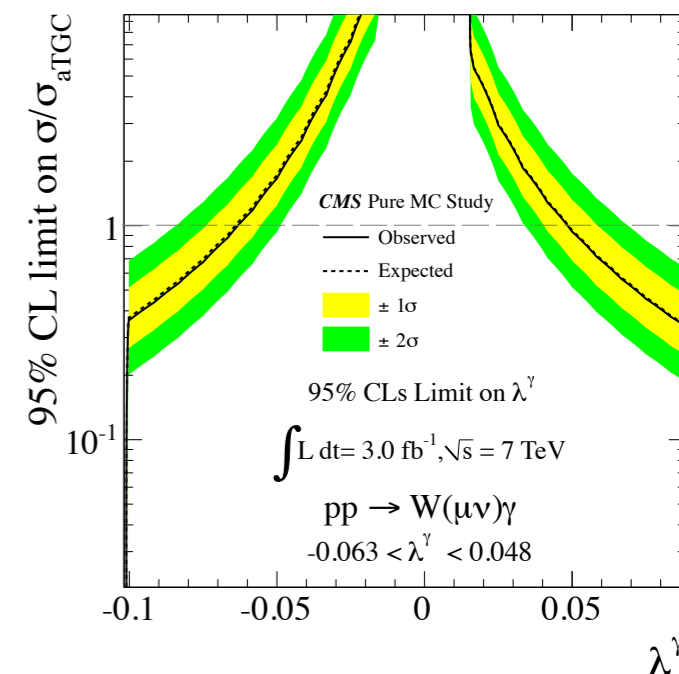
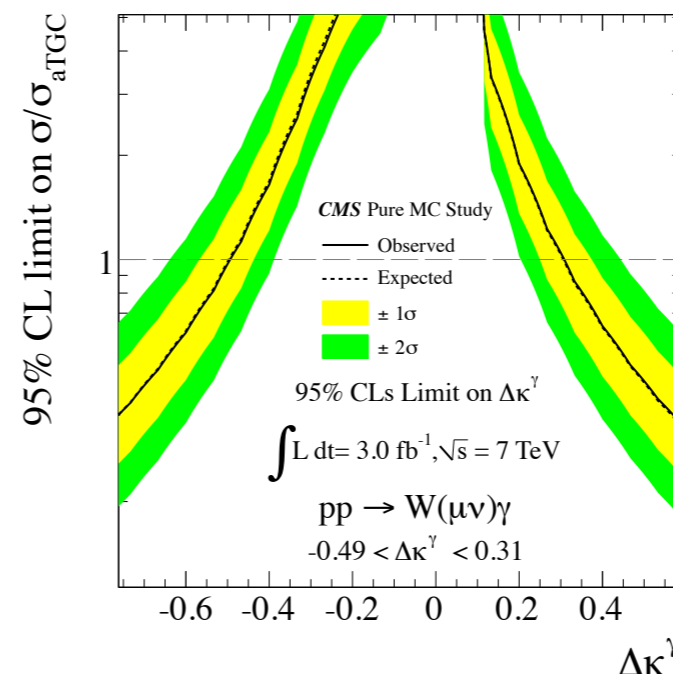
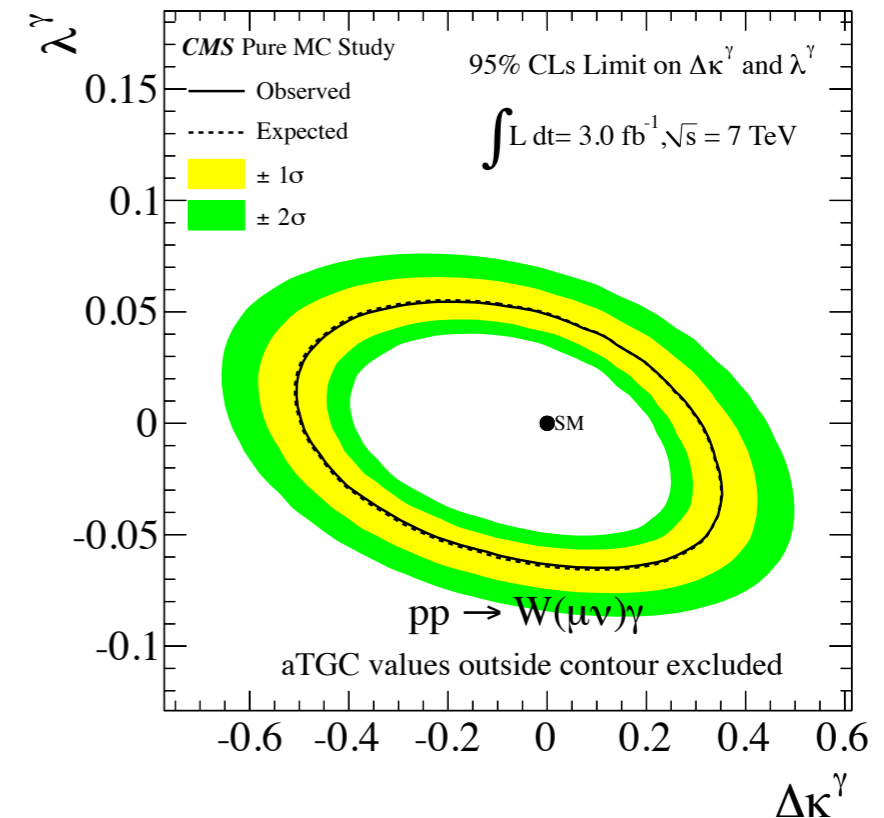
## ● SM MC + Backgrounds

- No aTGC
- Use asymptotic CLs

## ● Observed = Median Expected by definition

- I have not smeared the input data with a poisson
- We see exactly this
- Modulo assumed shapes of systematics affecting the toy dataset

## ● So, when there's no or little signal, the limits make sense



# 2011 MC Case Study: $W\gamma$ Using CLs

## ● Inject large anomalous gauge coupling

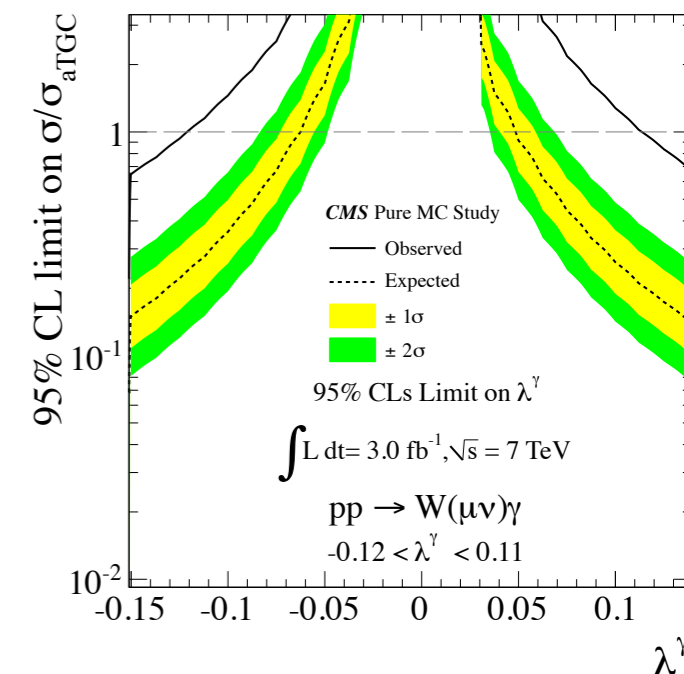
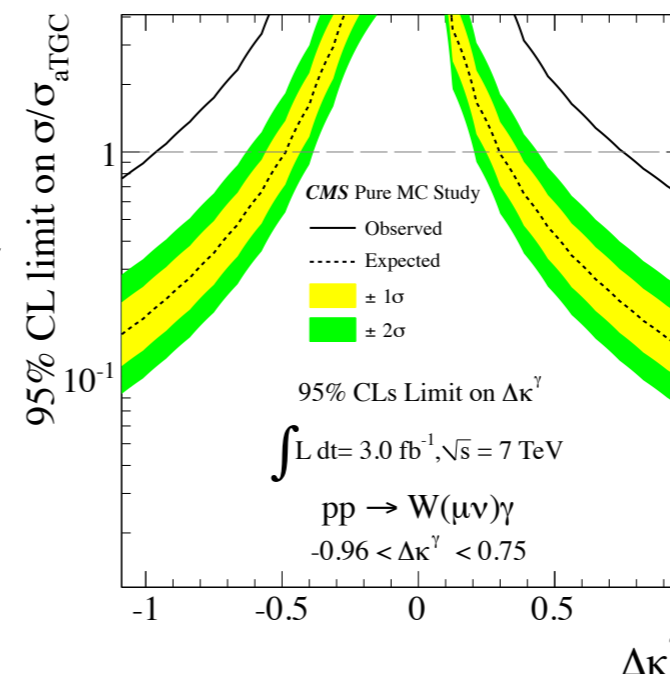
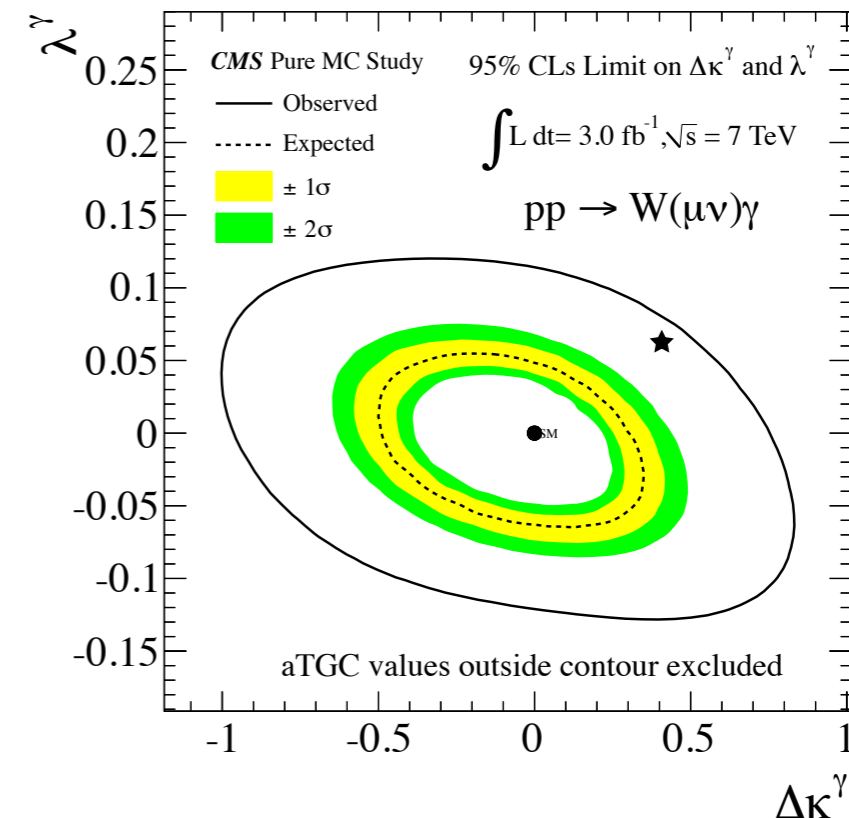
- $\Delta\kappa = 0.4, \lambda = 0.06$

## ● See huge differences between observed and expected

- Limits forced to be conservative by CLs ratio

- Note: ID limits do not become disjoint intervals
  - Should happen due to degeneracy in pt shape on aTGC sign

## ● Is there a better choice than CLs for setting limits in the presence of signal?



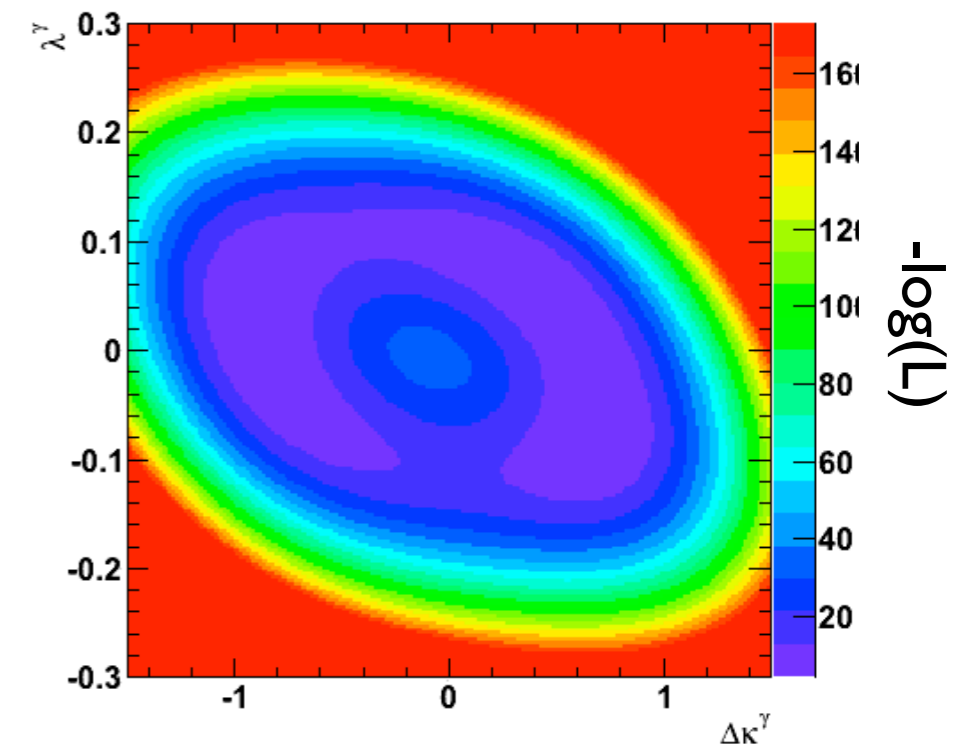
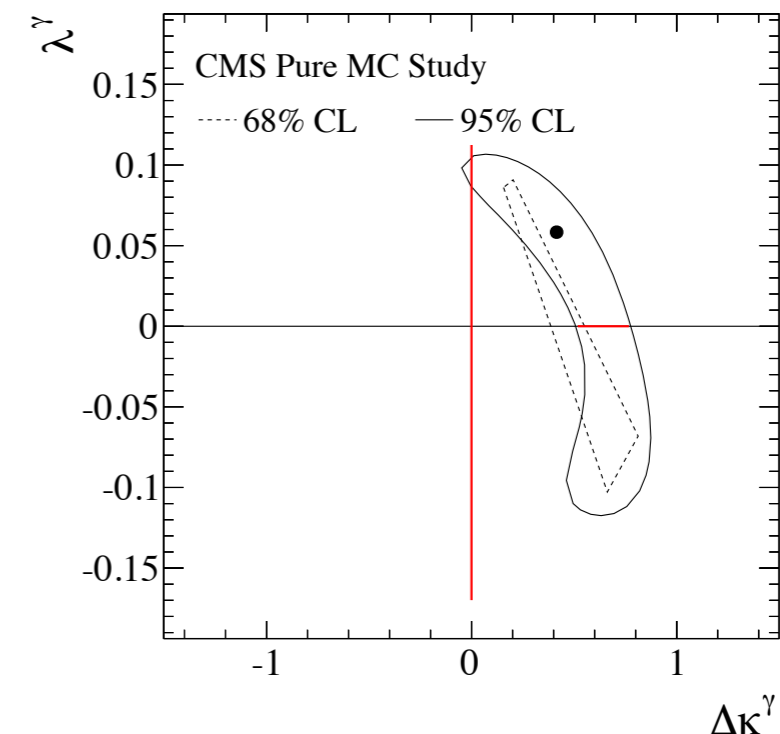
# 2011 MC Case Study: $W\gamma$ Using CLs

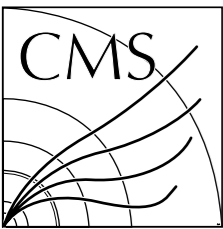
## ● Profile likelihood limits + TGC

- As CMS 2010 analysis
- Exactly the same data as previous slide
- Limit forms disjoint intervals in 2D parameter space
  - Due to quadratic nature of coupling dependence
  - Minuit only picks up one

## ● Profile likelihood limit easily transitions into ‘measurement’ regime

- However, as seen, comes with problems of its own





# Conclusions

## ● Presented CMS's most current results on aTGCs

- All 2010 analyses
- The 2011 analyses are nearing completion
  - $Z\gamma, W\gamma, WW, WZ$  &  $ZZ$

## ● A short case study using CLs was presented

- CLs is fine to use when there is little or no signal
- In the presence of a real signal CLs produces hyper-conservative limits that never exclude the standard model, but which disagree wildly with expected limits
- Obviously we cannot be 'fair weather' limit setters
  - We must choose a methodology that sets accurate limits with presence or lack of signal

# TGC Generator Wishlist

## ● POWHEG ZZ with aTGCs

- WW and WZ exist already

## ● NLO( $\alpha_s$ ) $V\gamma$ unweighted event generation with TGCs

## ● Offshell anomalous triple gauge couplings

- a'la a subset of the LEP results

## ● Quartic Coupling Generators @ NLO