Electroweak Measurements at the LHC

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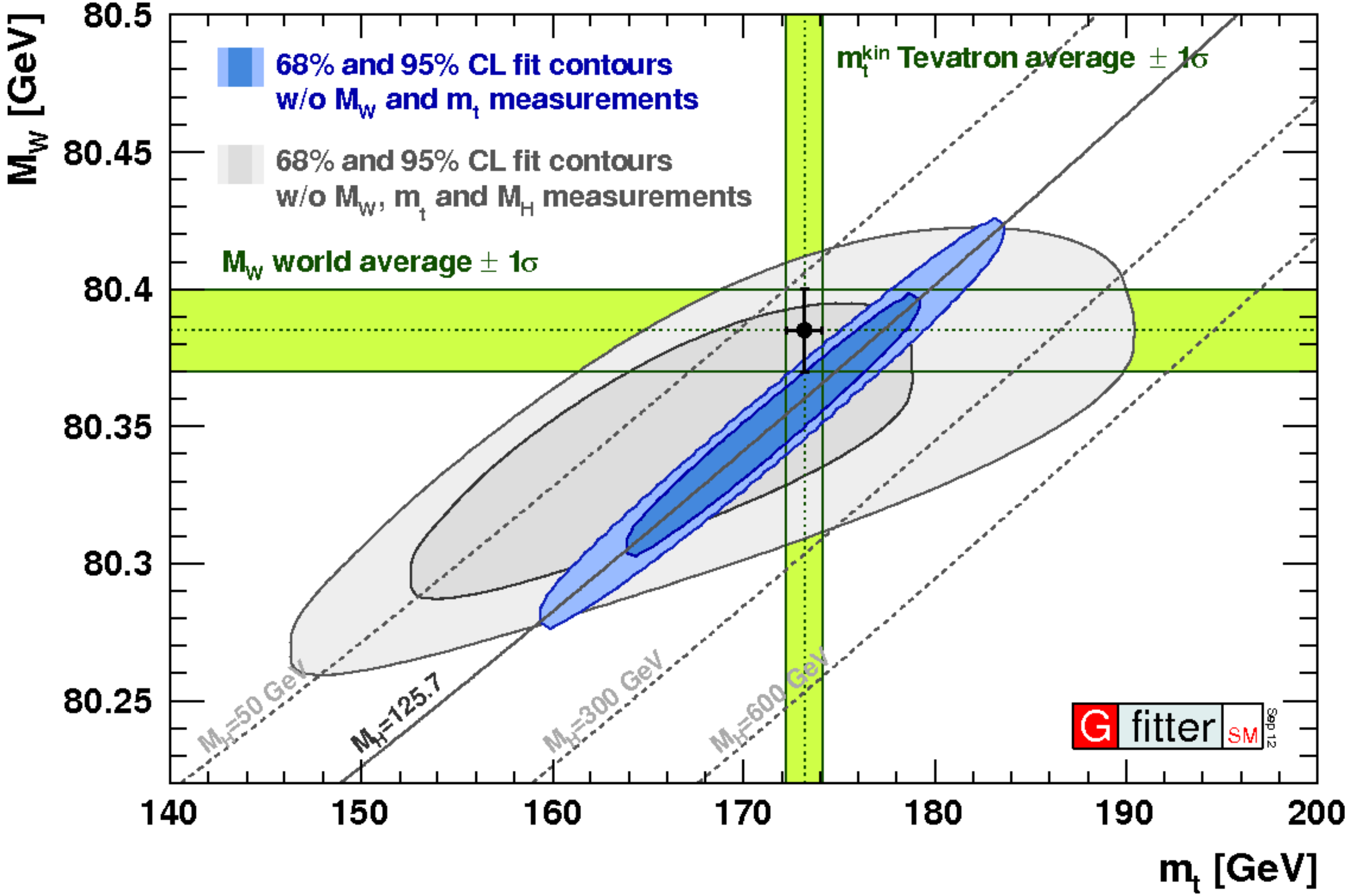
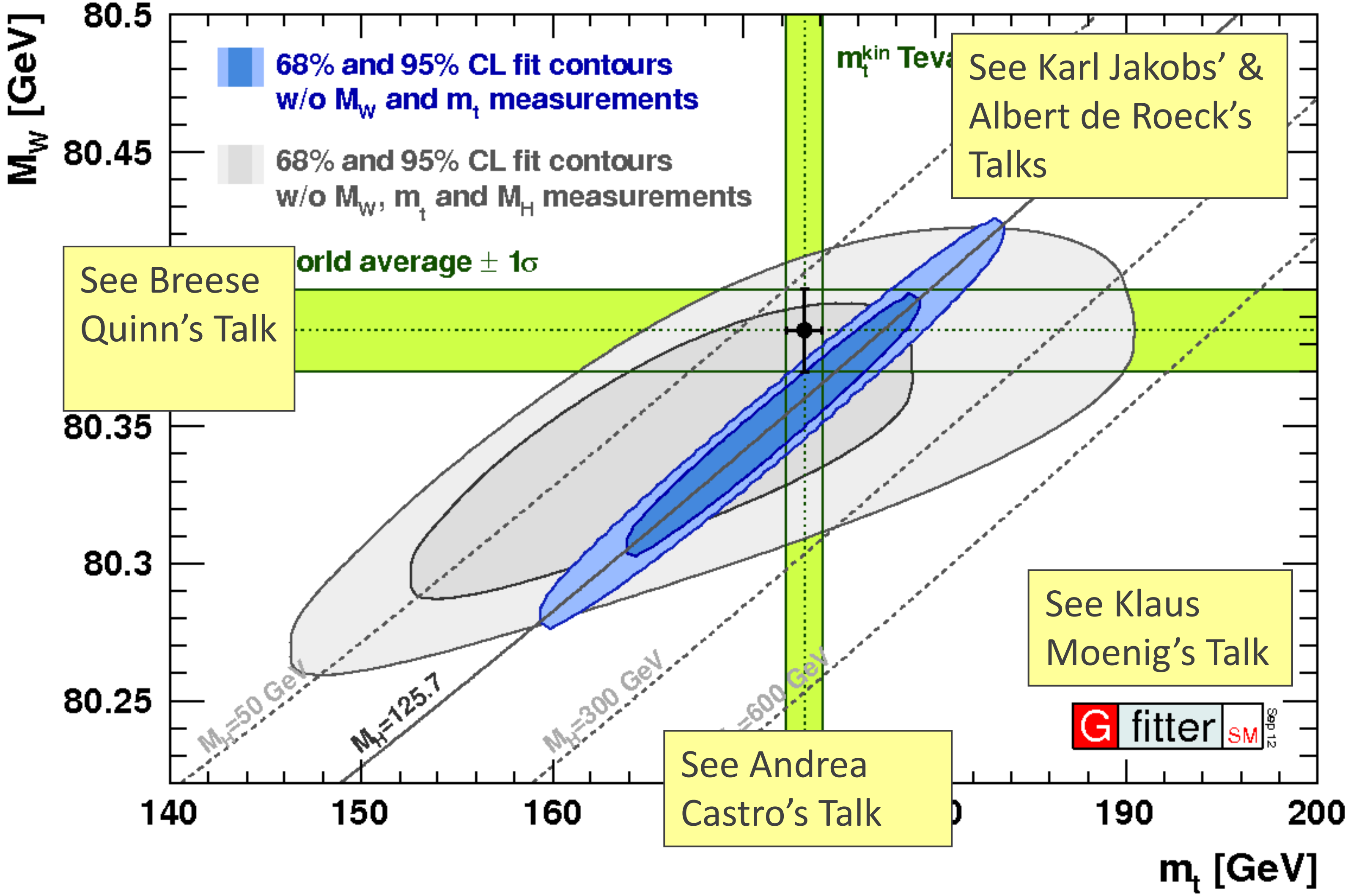
A Grand Success of Electroweak Theory



A Grand Success of Electroweak Theory



Remaining Questions Post-July 4th

- Does the recently observed Higgs boson unitarize the WW scattering cross-section?
  - i.e. It looks like a Higgs boson, but does it do the job of one?
    - In analogy with the “imposter Higgs” do we have a “goldbricking Higgs”?
- Is the electroweak force merely the remnant of a stronger, shorter-ranged force?
  - Like van der Waals forces in atomic physics?
- Are there any surprises?

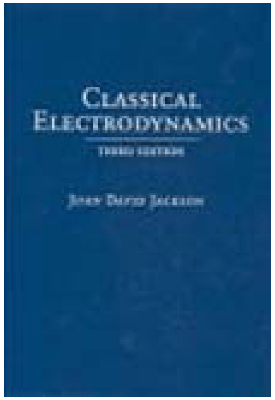
Diboson production touches on all of these issues.

This is a long-term process; this talk will be a status report.

Let’s start with the W+photon interaction

The Semiclassical W

- The interaction between the W and the electromagnetic field can be completely determined by three numbers:
  - The W's electric charge
    - Effect on the E-field goes like $1/r^2$
  - The W's magnetic dipole moment
    - Effect on the H-field goes like $1/r^3$
  - The W's electric quadrupole moment
    - Effect on the E-field goes like $1/r^4$



- Measuring the Triple Gauge Couplings ($WW\gamma$) is equivalent to measuring the 2nd and 3rd numbers
  - Because of the higher powers of 1/r, these effects are largest at small distances
  - Small distance = short wavelength = high energy ($\hat{s}$)

Couplings In More Detail

$$L = g\left(W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W^{\dagger}_{\mu}A_{\nu}W^{\mu\nu}\right) + (1+\Delta\kappa_{\gamma})\left(W^{\dagger}_{\mu}W_{\nu}F^{\mu\nu}\right) + \frac{\lambda_{\gamma}}{M_W^2}\left(W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}F^{\nu\rho}\right)$$

(with)

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - gW_\mu \times W_\nu$$

+ three similar terms for the Z

+ nine other terms that do evil things (violate CP and/or EM gauge invariance)

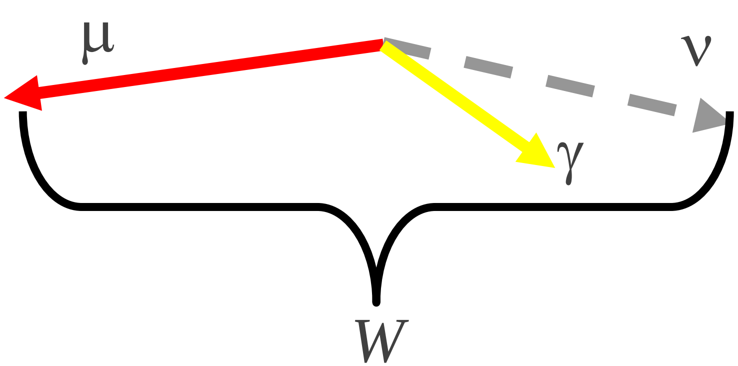
- The convention for this talk is that every parameter you'll see (e.g. Δg_1^Z, $\Delta\kappa_\gamma$, λ_γ) is zero in the Standard Model.
  - This is a slight deviation from the literature
- Dimension 4 operators alter Δg_1^Z, $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$: effects grow as $\hat{s}^{1/2}$
- Dimension 6 operators alter λ_γ and λ_Z :effects grow as $\hat{s}$.

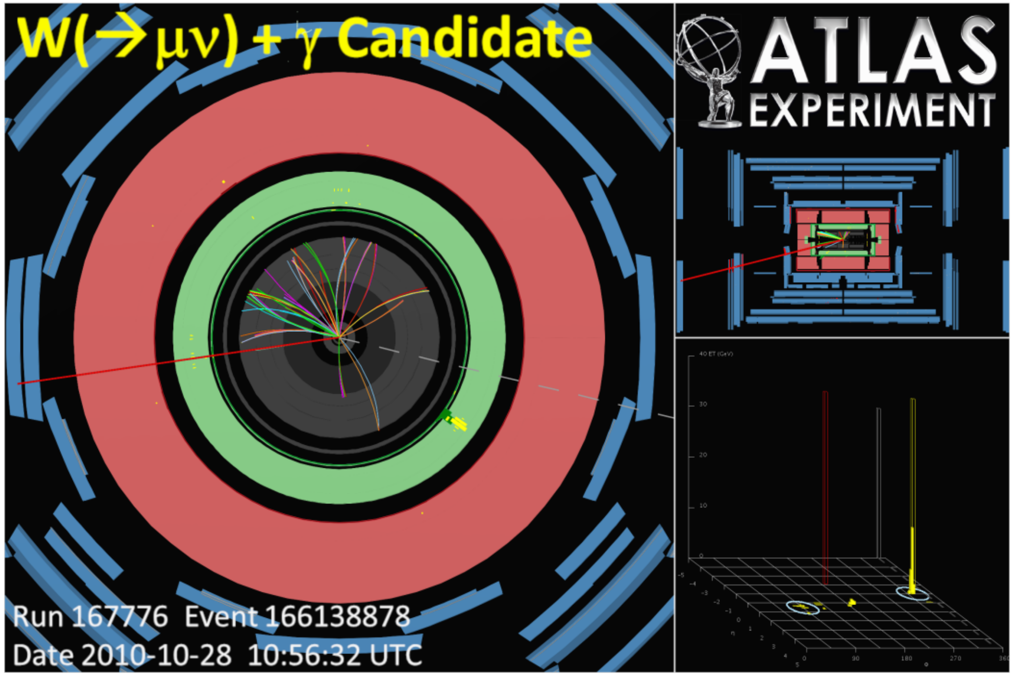
$$\mu_W = e\frac{2+\Delta\kappa_\gamma+\lambda_\gamma}{2M_W}$$

$$Q_W = -e\frac{1+\Delta\kappa_\gamma-\lambda_\gamma}{M_W^2}$$

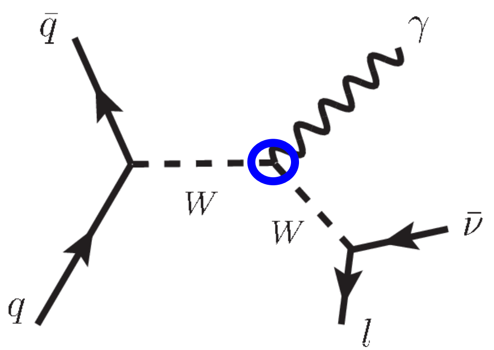
W+γ Production

The experiments are looking for events like this:

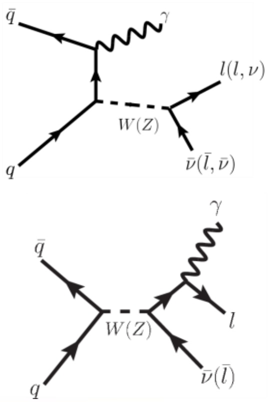




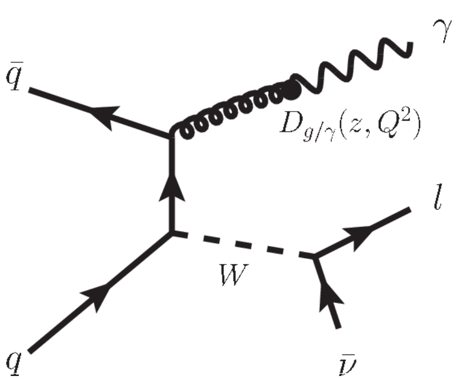
Which includes triple gauge couplings,



interfering amplitudes,



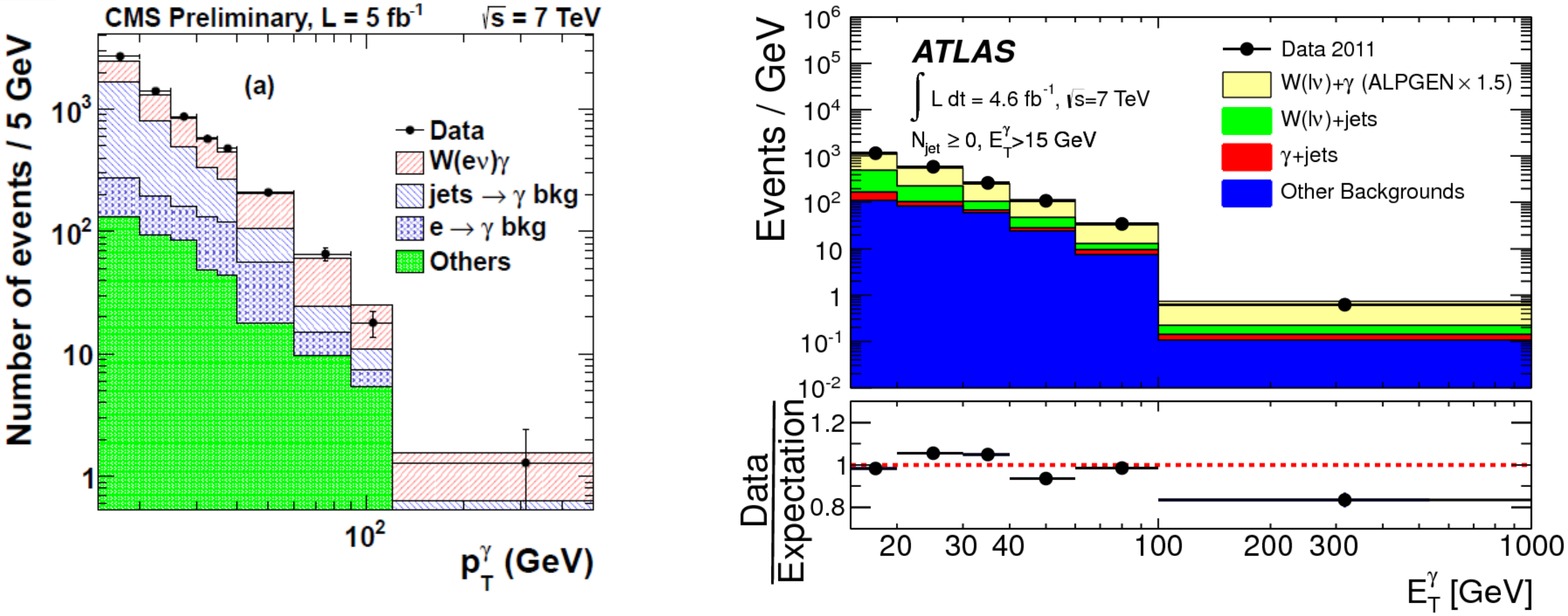
and backgrounds.



W+γ :What The Experiments See

CMS EWK-11-009-PAS

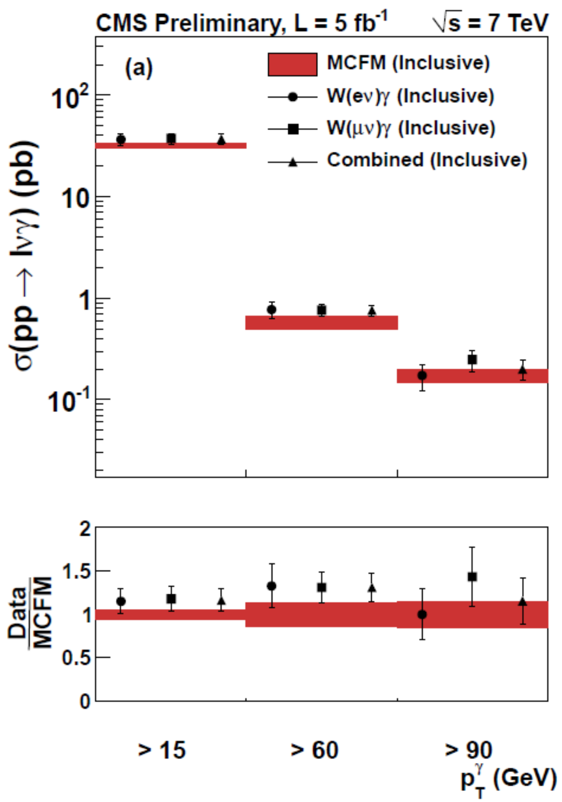
ATLAS Phys. Rev. D 87, 112003 (2013)

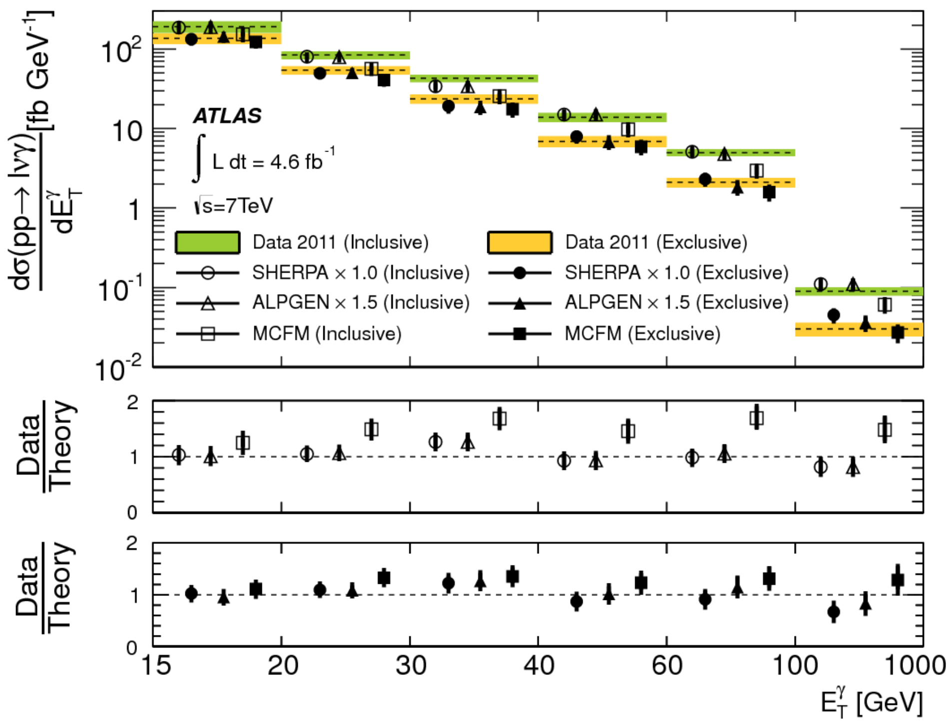


A sample dominated by real W+γ, with the largest background being W+jets, with a jet misidentified as a photon. This is controlled with template fits, ratio correction and ABCD two-dimensional sideband subtraction.

These plots show $p_T(\gamma)=E_T(\gamma)$. Later plots in the talk will show other variables, but all are measurements of or proxies for the diboson system invariant mass, $\hat{s}$.

W+γ :What The Experiments See II



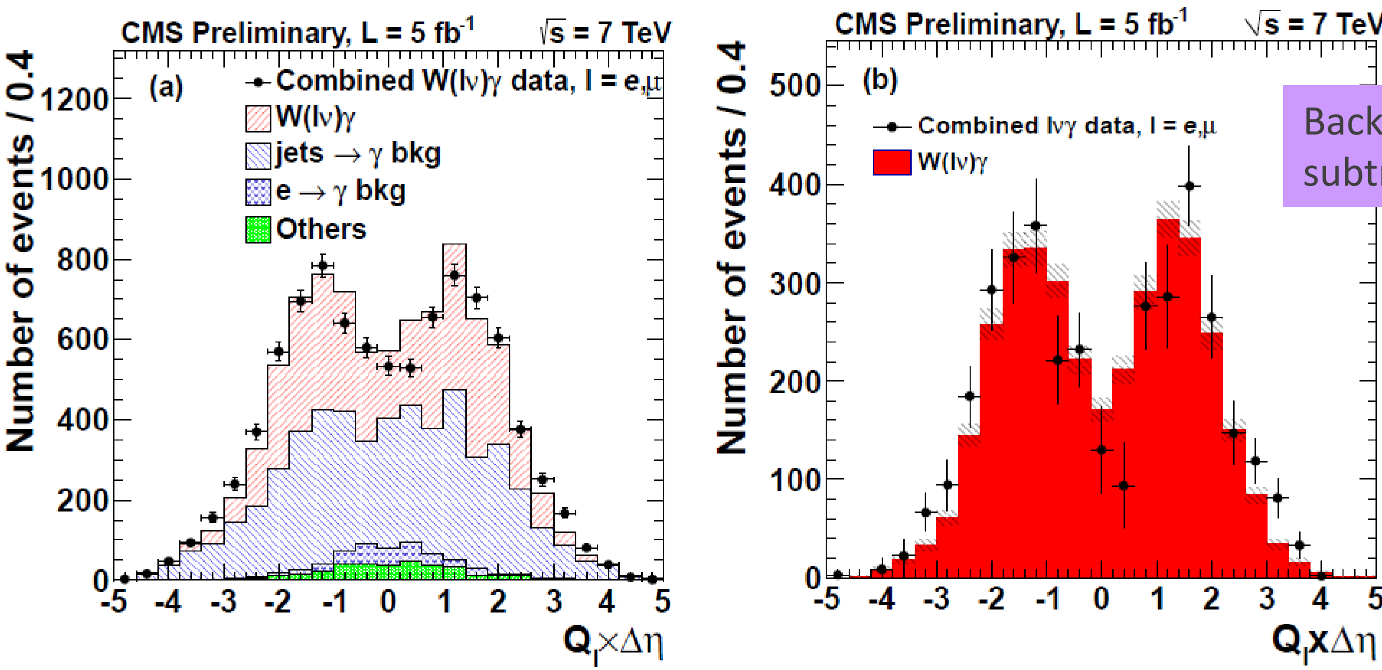


The agreement between data (both experiments) and theory is smaller than the range of variation between theoretical models.

"Exclusive" here means exactly zero jets

(which is why MCFM works better here, as expected)

Additional Evidence for Wγ: the RAZ

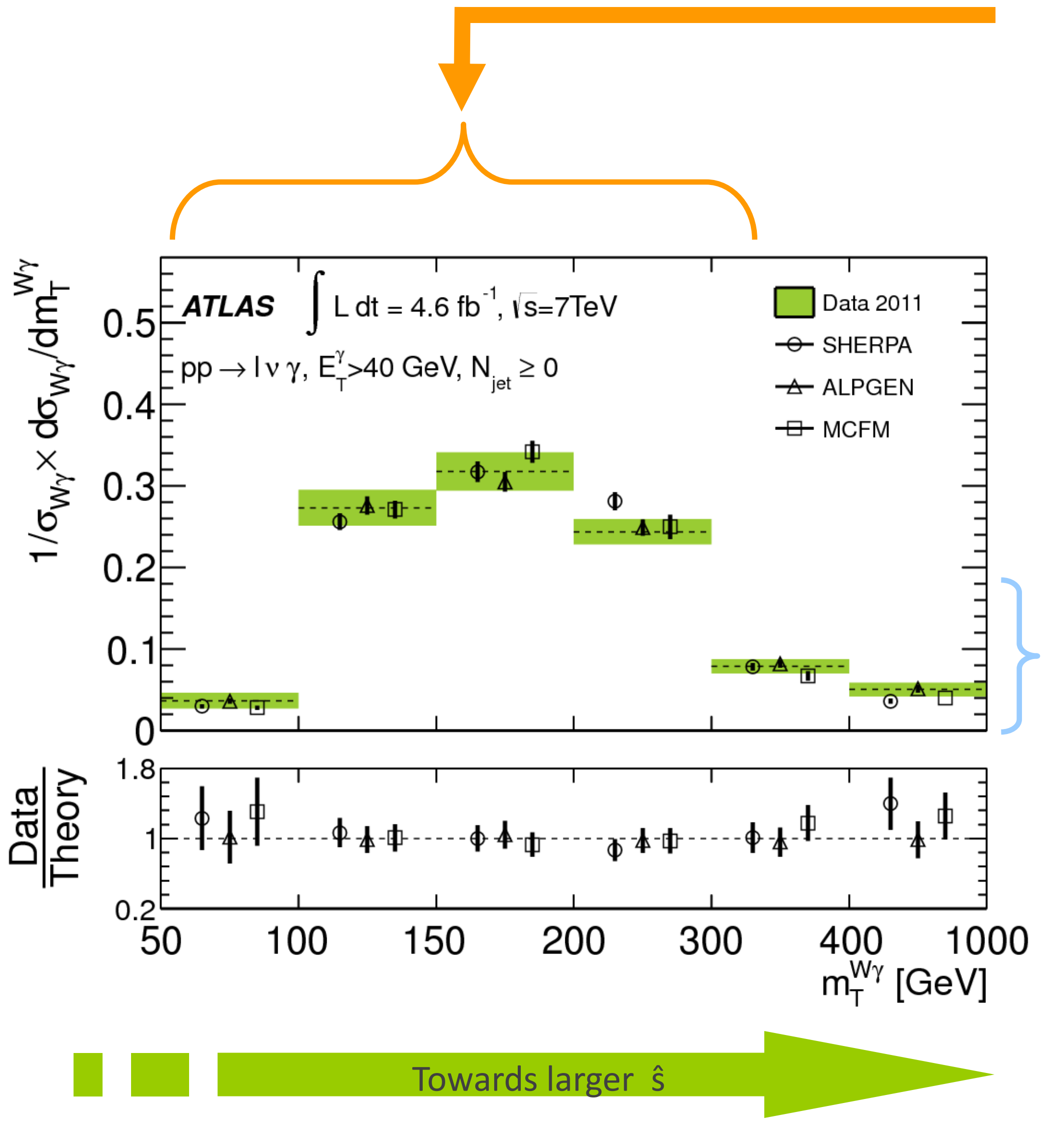


Background subtracted

- This is the "Radiation Amplitude Zero", caused by the interference between the TGC and ISR/FSR amplitudes.
- Note that the dip at η=0 exists for the signal, but not for the background.
- First seen at the Tevatron

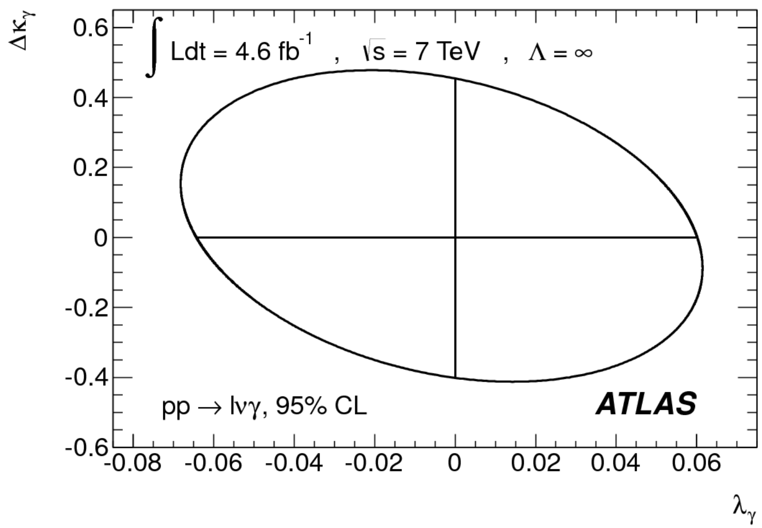
What Does This Tell Us?

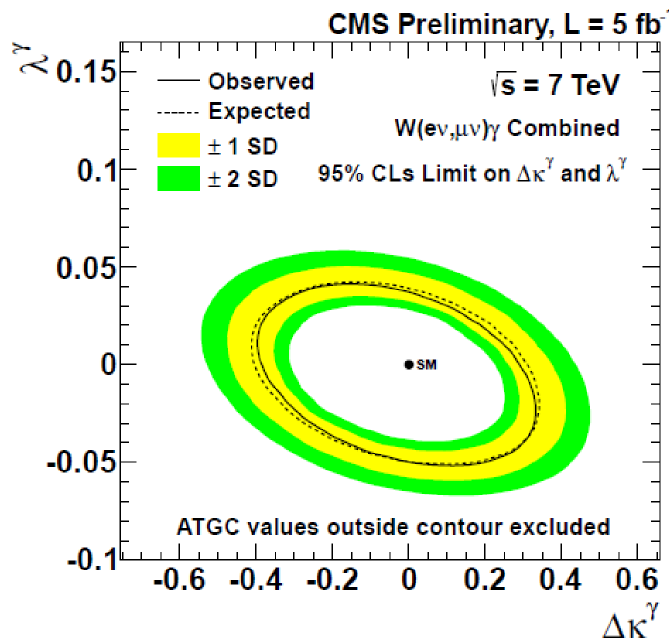
This region is dominated by the dipole radiation from the W's motion. It's essentially a not-very-good measurement of the W charge.

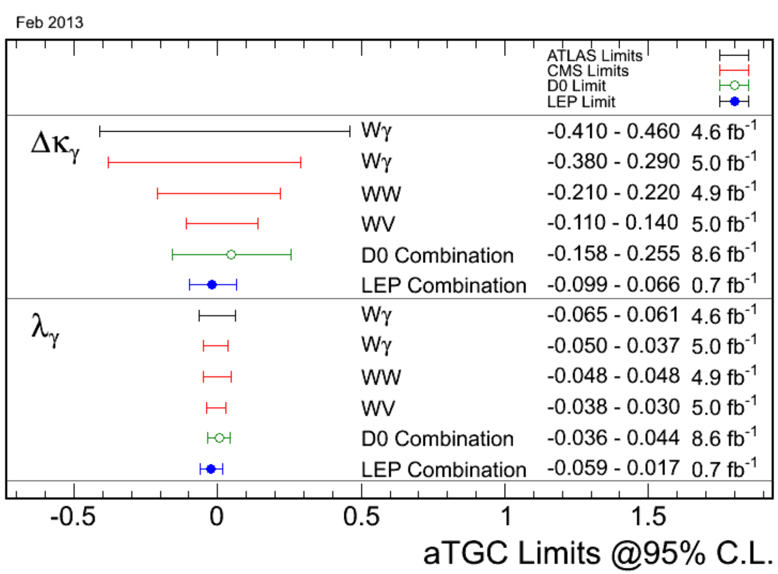


This region, however, is sensitive to the higher (magnetic dipole and electric quadrupole) moments of the W, and is where new physics can show up.

Limits on Δκ and λ







- **ATLAS and CMS have comparable** limits today
- They are closing in on the **Tevatron in** λ (Dimension-6, where the LHC is at its best).
- LEP is still driving the Δκ bounds
- 8 **TeV data will of course make a** **substantial improvement.**

$\mu_W = e(2 + \Delta\kappa_\gamma + \lambda_\gamma)/2M_W \quad Q_W = -e(1 + \Delta\kappa_\gamma - \lambda_\gamma)/M^2_W$

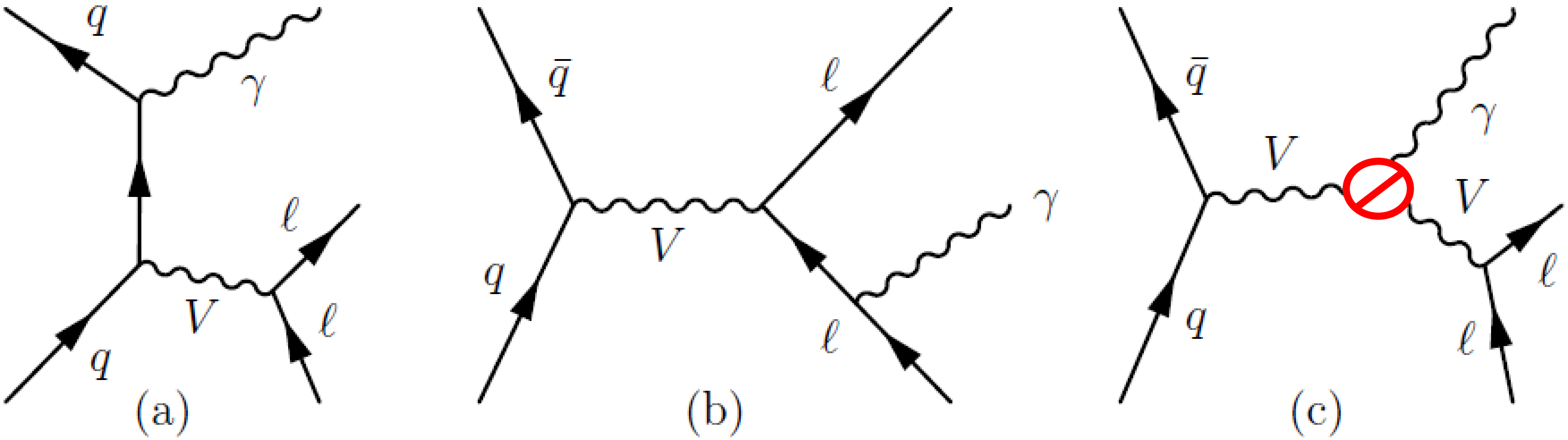
Beyond $\Delta\kappa$ and λ

- The $\Delta\kappa$-λ formalism has its problems:
  - Changing $\Delta\kappa$ or λ increases the cross-section at high p_T. The problem is, it doesn't stop, so one needs to put in a form-factor cutoff Λ to keep things finite.
    - This same cutoff is what allows one to mix Dimension 4 and 6 operator coefficients: if $\mu_W = e(2 + \Delta\kappa_\gamma + \lambda_\gamma)/2M_W$ and $Q_W = -e(1 + \Delta\kappa_\gamma - \lambda_\gamma)/2M^2_W$,that's exactly what we are doing.
  - Tevatron experiments historically set the cut-off to 2 TeV: beyond their ability to measure
  - This is too low for LHC experiments
    - Setting Λ = 6 TeV only postpones the inevitable
    - Setting Λ = Infinity solves the postponment problem, but we're left with an inconsistent model

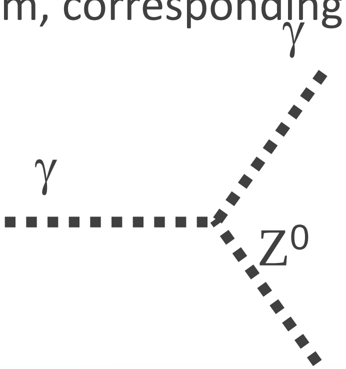
- An alternative exists based on Effective Field Theories:
  - arXiv 1205.4231 (Degrande, Greiner, Kilian, Mattelaer, Mebane, Stelzer, Willenbrock and Zhang) casts this in the form of an effective field theory and avoids having to include a form-factor. Cut-off effects are smaller and less relevant.

- "Tradition" (i.e. ease of comparison with prior experiments) keeps us from switching, but it has also led us to a baseline framework that is consistent only in the SM limit.
  - Ironically, we can't directly compare anyway, since different experiments use different cut-offs.

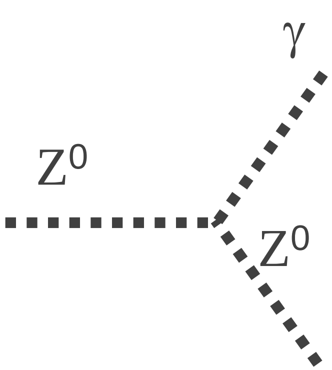
Z+γ Production



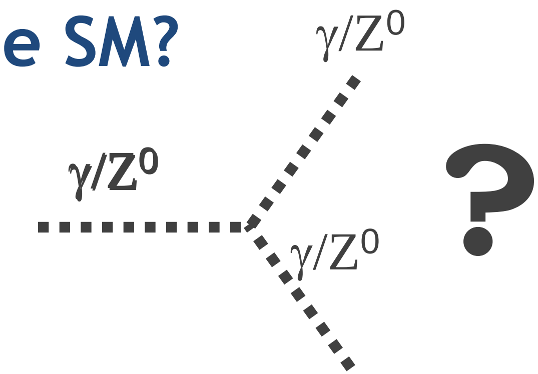
- Unlike the W-γ case, there is no TGC here in the SM (see next slide)
- There is still ISR, and FSR for Z → ee and μμ.
- The BSM couplings probed here are named h_3 and h_4, rather than $\Delta\kappa$ and λ, and there are two sets of them, corresponding to:



and



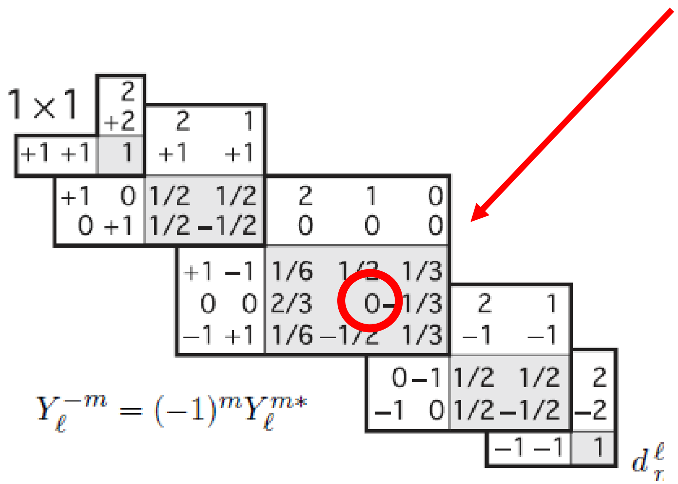
Why No All-Neutral Couplings in the SM?



Here's where thinking about the unbroken SU(2) X U(1) symmetry helps.

- Trilinear Coupings
  - B-B-B: zero because U(1)'s are Abelian
  - B-B-w_3
  - B-w_3-w_3
  - w_3-w_3-w_3
    - The Clebsch-Gordon coefficient for (1,0)+(1,0)=(1,0) is **zero**.
    - This is the SU(2) symmetry in action

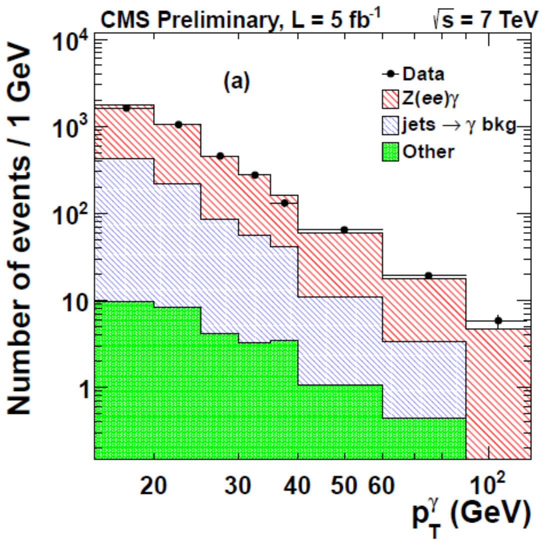
The w's don't carry hypercharge, and the B doesn't carry isospin. So the "mixed couplings" are zero

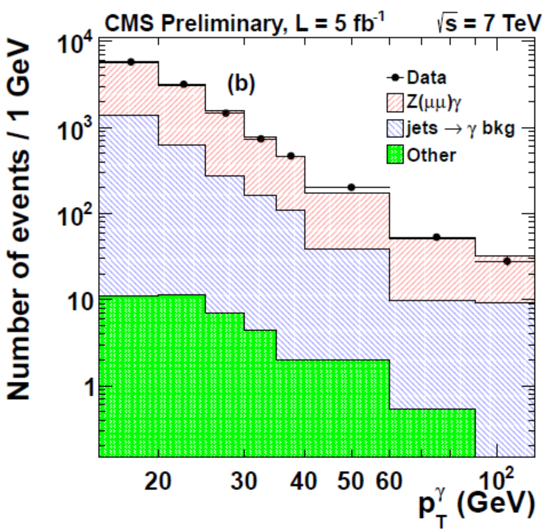


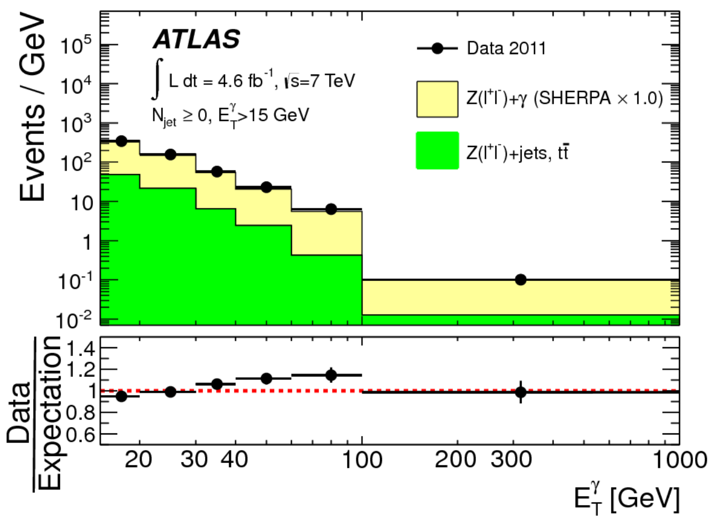
These are all zero. Any linear combination (like the γ and Z) of zeros is still zero.

A similar argument holds for the quartic couplings.

(Z → ll)+γ :What The Experiments See







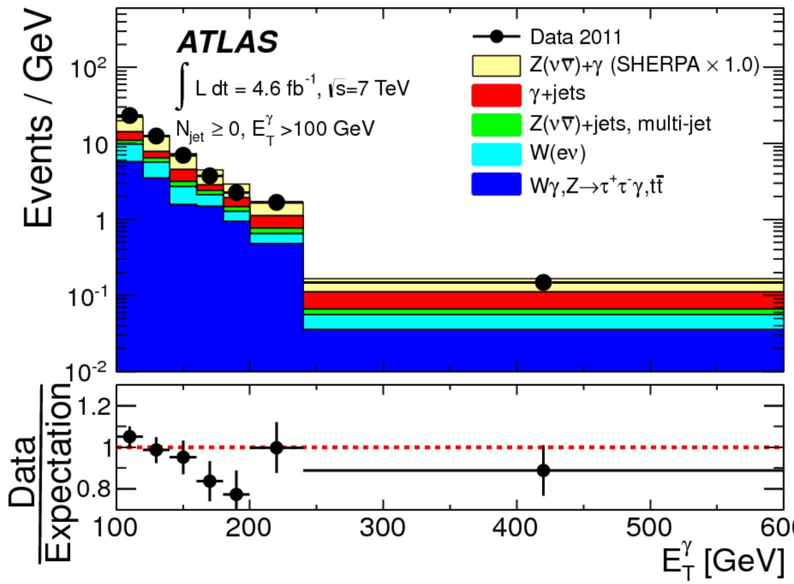
- Same story as before
  - Good signal to background (which is dominated by jets misidentified as photons)
  - In this case the Z+γ signal is pure ISR and FSR
  - No significant excess
    - Particularly at large $p_T(\gamma)$ – a proxy for $\hat{s}$: characteristic of an anomalous TGC

CMS EWK-11-009-PAS

ATLAS Phys. Rev. D 87, 112003 (2013)

$(Z \rightarrow \nu\nu)+\gamma$:What The Experiments See

- ATLAS & CMS have added the $Z \rightarrow \nu\nu$ channel
- Pros:
  - Branching Fraction is 6-7x larger
  - You never miss a neutrino
  - No FSR
  - Pushes out to higher energy → where the signal would be
- Cons:
  - Backgrounds are larger (but not too large)
  - Blind to low p_T



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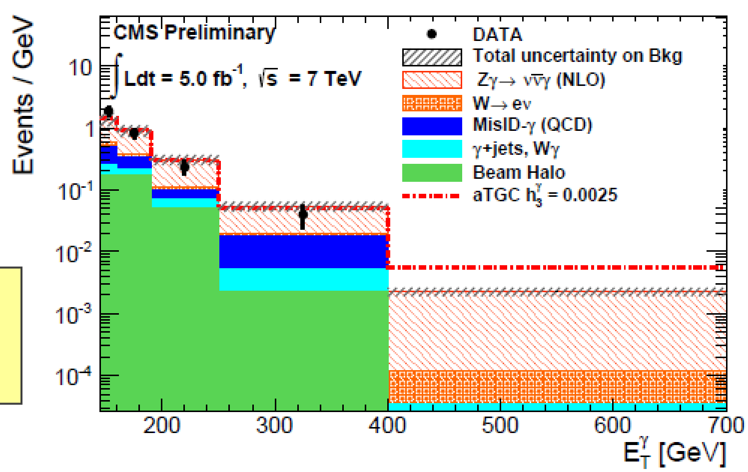
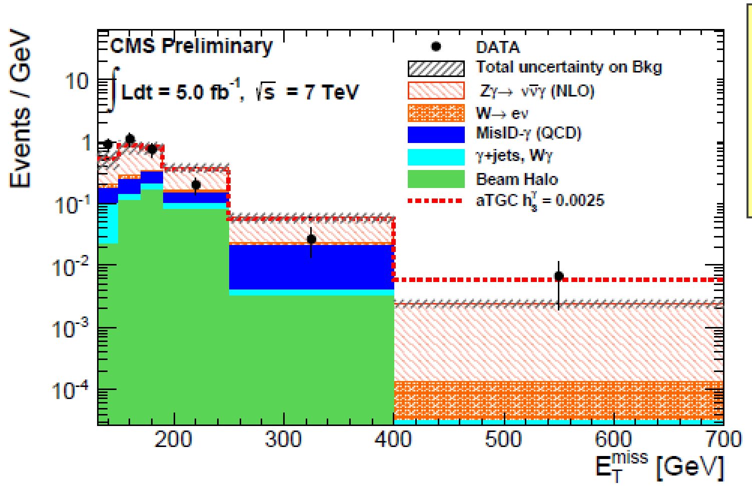
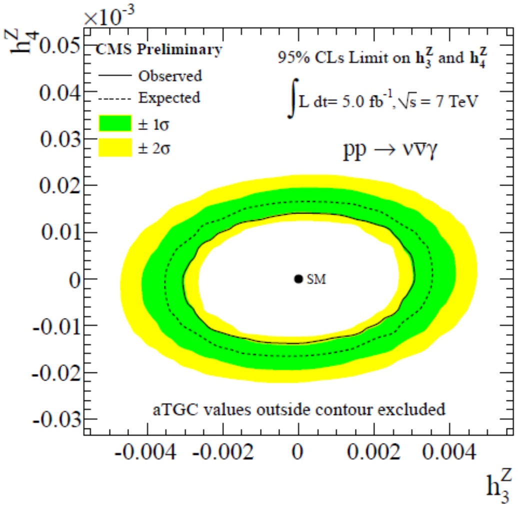


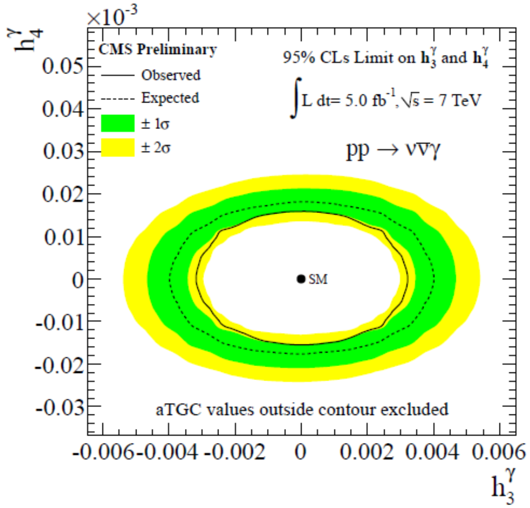


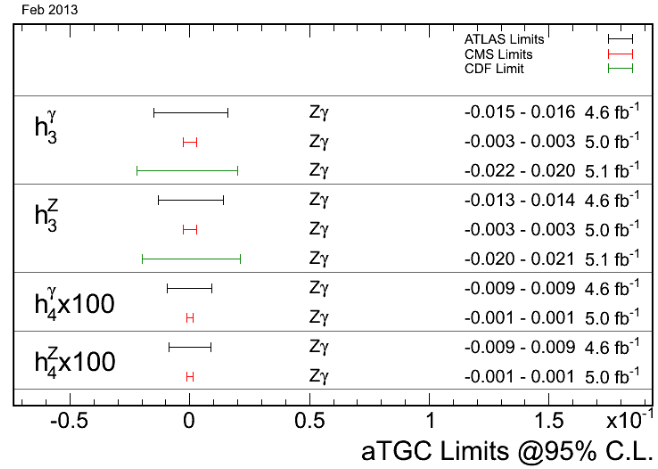
CMS-PAS-SMP-12-020

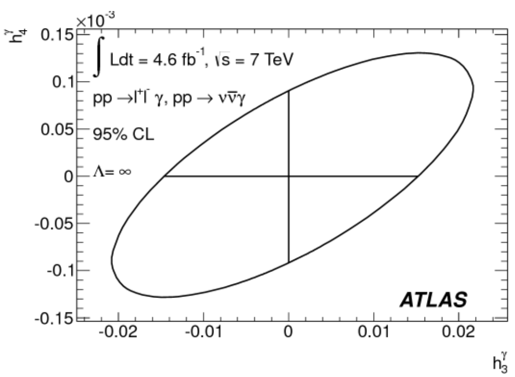
No significant excess observed.

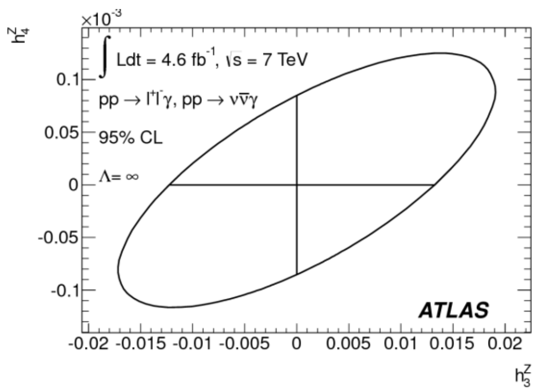
Limits on h^{γ}_{3}, h^{Z}_{3}, h^{γ}_{4}, h^{Z}_{4}











ATLAS and CMS results are consistent with each other and with the SM.

- Here the LHC does much better than the Tevatron
  - Discussion in 2 slides
- The choice of cutoff is much more important here than in the W+γ case.

Why Are The CMS/ATLAS Results Different?

- Both experiments have comparably sized datasets
- Both see about what they expect given the SM
- What's different?

Binning!

Sensitivity to new physics is driven by the high mass events.

It matters how your events are distributed at high mass:

Gives a very different limit than:

- CMS uses a binning from 250-400 and 400-700 GeV
- ATLAS uses a binning from 250-600 GeV
  - They set the limit based on the number of events above 100 GeV
- This is probably a good argument to switch to unbinned fits

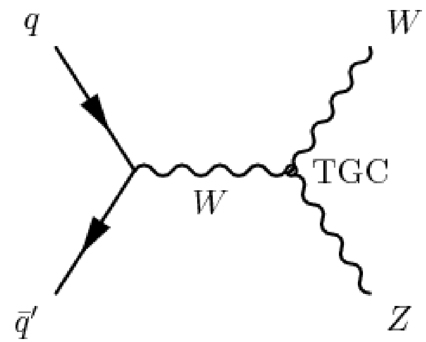
Summary for W/Z+γ

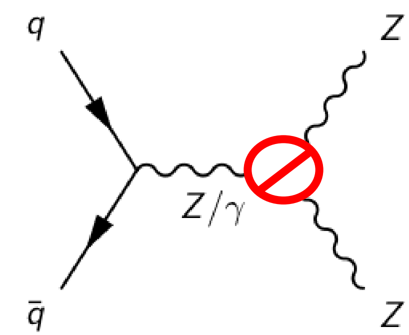
- The Standard Model remains intact
  - No evidence of anomalous W/Z+γ interactions
  - The W's MDM and EQM are measured to be within about 20% of the SM values
- The LHC experiments are more sensitive to Z+γ than W+γ
  - For the h's, these are the world's most sensitive; for $\Delta\kappa$ and λ, they are competitive with the Tevatron (at twice the data) and LEP, LEP remains most sensitive for $\Delta\kappa$.
  - Operators are of Dimension 6 and 8 rather than 4 and 6, so the extra reach in $\hat{s}$ pays off
- 14 TeV running will be even better in this regard (as will 8!)
- The cutoff Λ introduces a complication
  - A 2 TeV cutoff is no longer enough
  - It makes a factor of ~2 difference on the limits on h
  - Theoretical alternatives exist

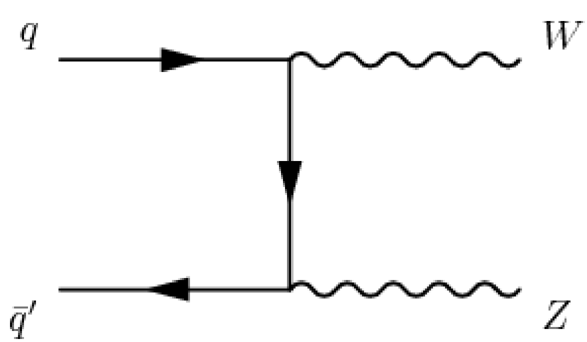
Next: multiple heavy bosons.

Heavy Diboson Production: WW, WZ and ZZ

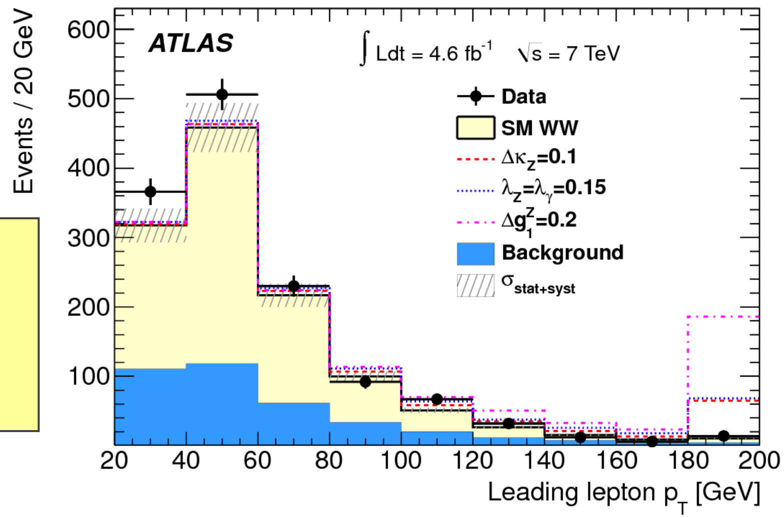
- Qualitatively, the same story as W/Z + gamma
  - Sensitivity to new physics is at short distances/high mass scales
  - The rate is a mix of TGC processes and ISR/FSR (in this case, ISR)
  - There are no all-neutral couplings
- Rates are much smaller
  - Handfuls of events, not thousands
- The WW and ZZ channels are a by-product of the Higgs search
  - I will therefore spend more time on WZ



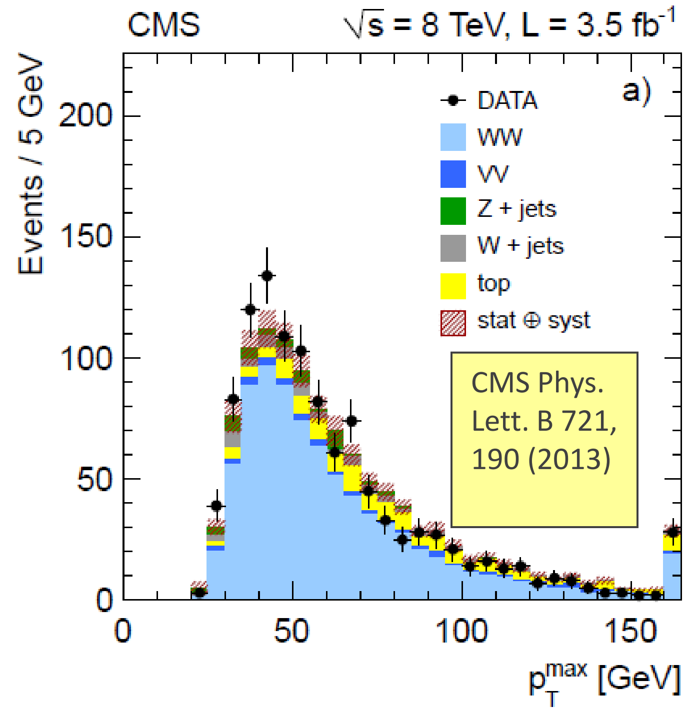




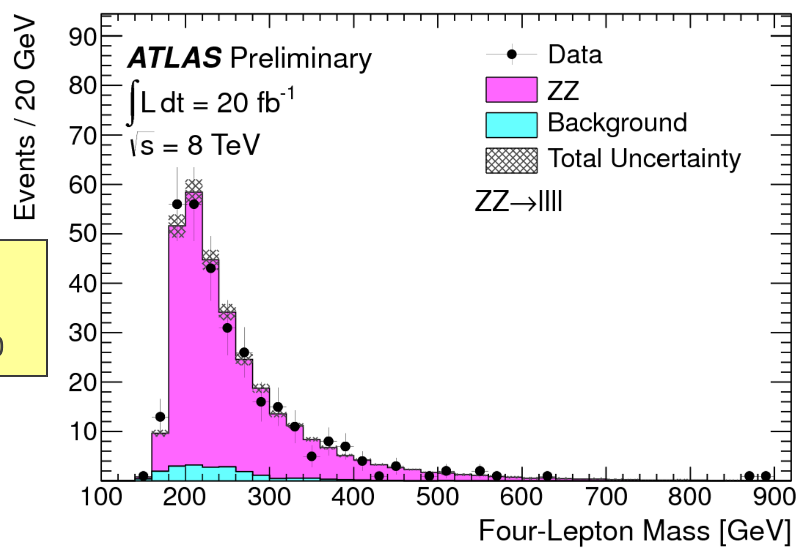
WW & ZZ To Leptons



ATLAS Phys. Rev. D 87, 112001 (2013)



CMS Phys. Lett. B 721, 190 (2013)



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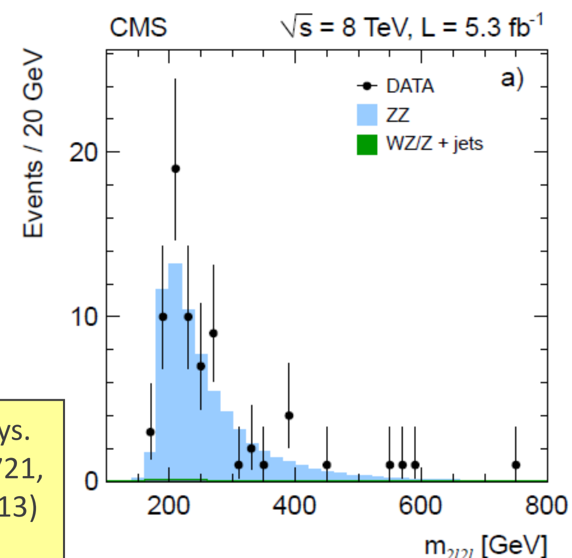
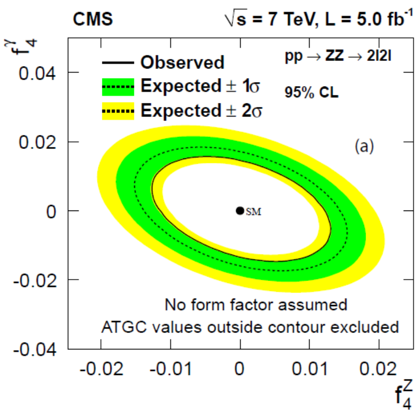
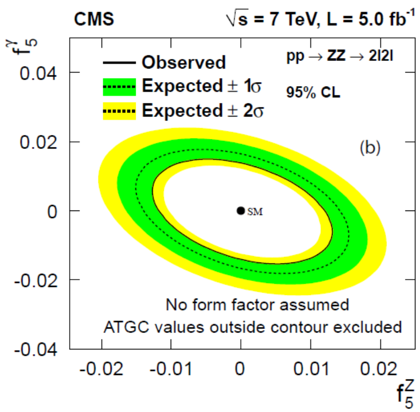
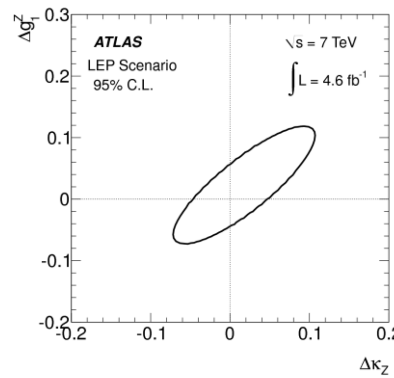


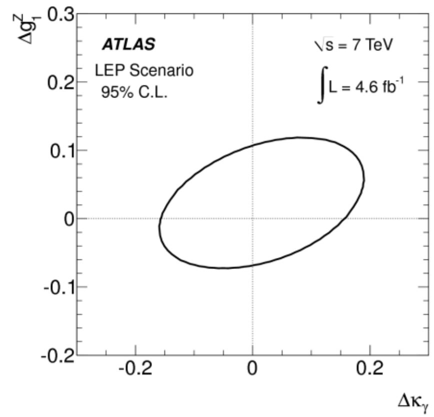
CMS Phys. Lett. B 721, 190 (2013)

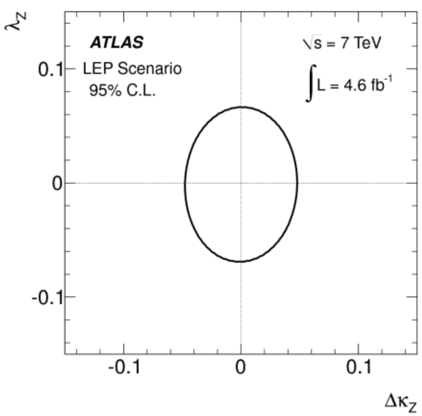
WW & ZZ Limits

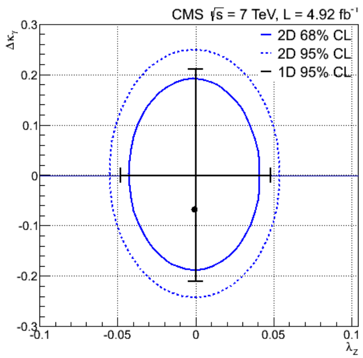


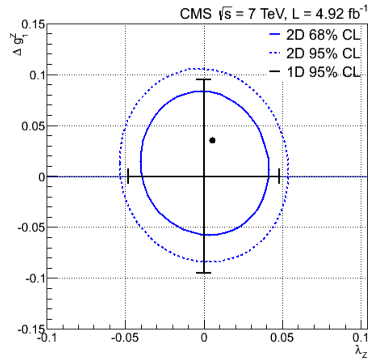








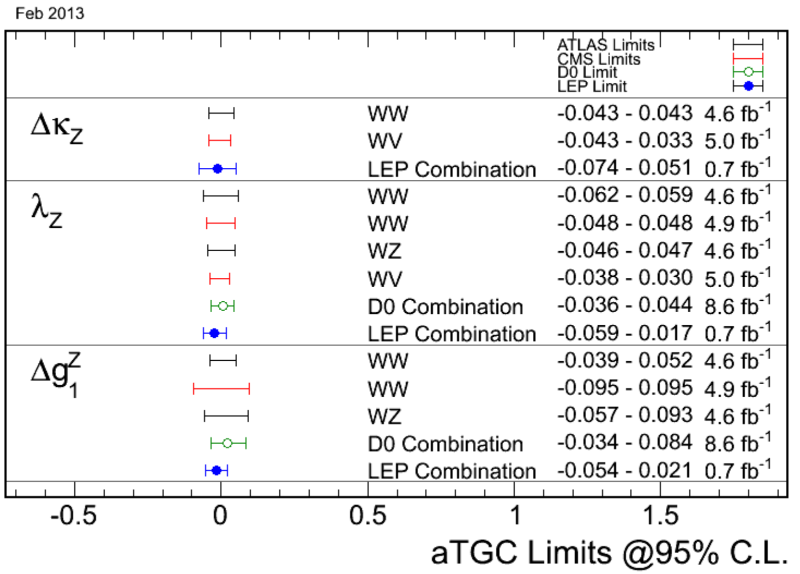


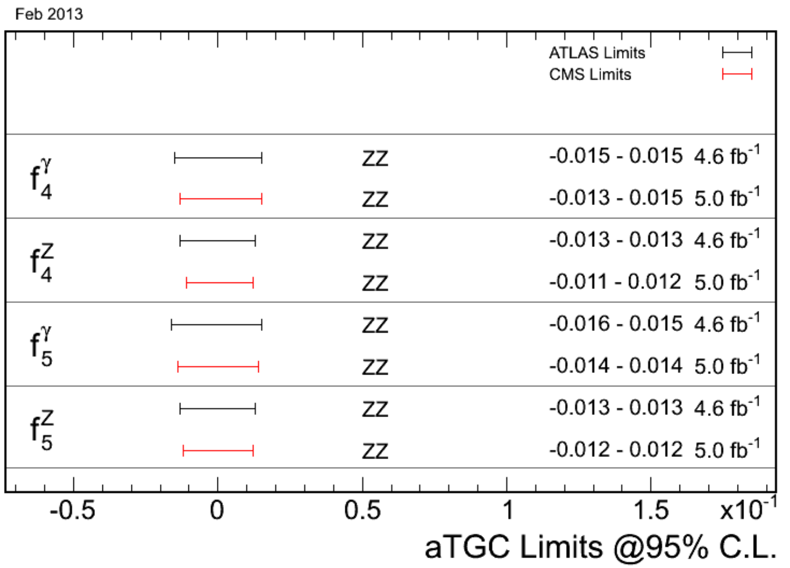


PLB 712 (2012) 239, PRL 108 (2012) 041804 (ATLAS)
arXiv:1306.1126, JHEP 1301 (2013) 063 (CMS)

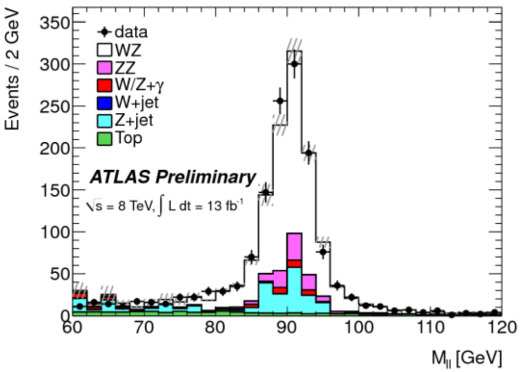
Putting Meaning to These Limits

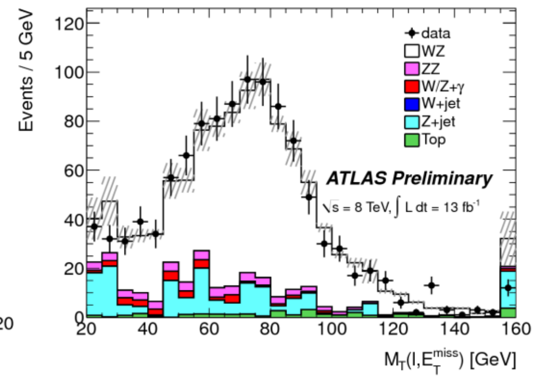
- For $\Delta\kappa$ and Δg (Dimension 4 operators) results are comparable among experiments
- For λ (Dimension 6) results are also comparable
  - Note that D0 has twice the data; this shows the interplay between luminosity and energy.
- For the all-neutral couplings (Dimensions 6 and 8) , we are setting limits at the 10^{-2} level.
  - Energy helps twice: the LHC makes more ZZ events, and it makes many more at high m(ZZ) where the sensitivity is.





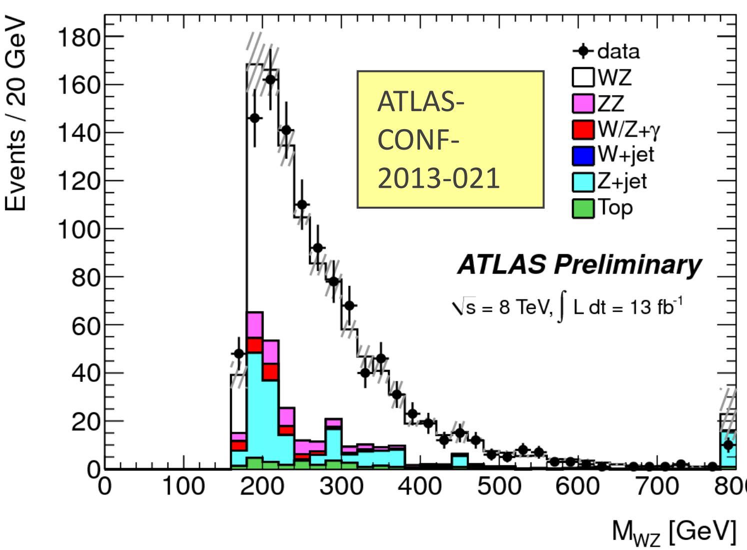
WZ Production with Trileptons

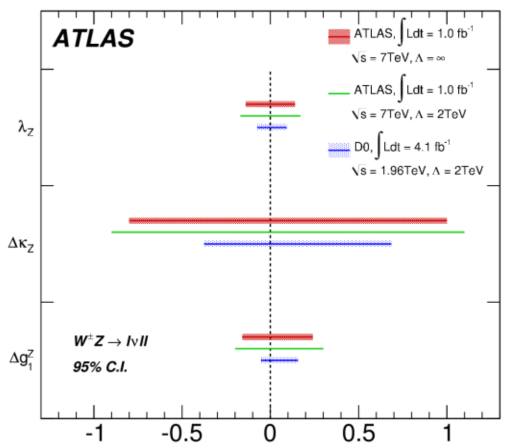


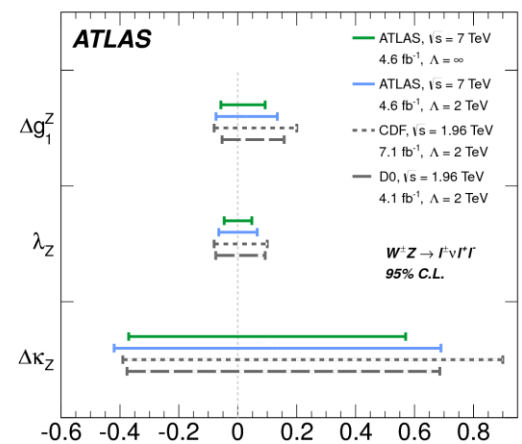


- ATLAS' 1 fb^{-1} 7 TeV results are a bit worse than D0's
  - Partly because they used 25% of the data D0 did
  - However, the ATLAS limits were set based on the total cross section.
  - D0 used the shape – more information
- With the 5 fb^{-1} results, datasets are comparably sized, six p_T bins are used, and the sensitivity improves.
- Recurring theme: it's what's going on at the high end that drives the sensitivity.

Each boson is required to decay leptonically.
Very low background.



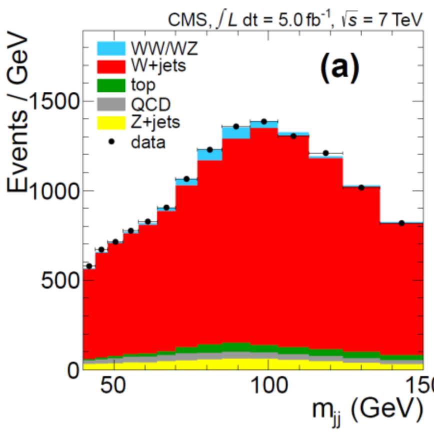


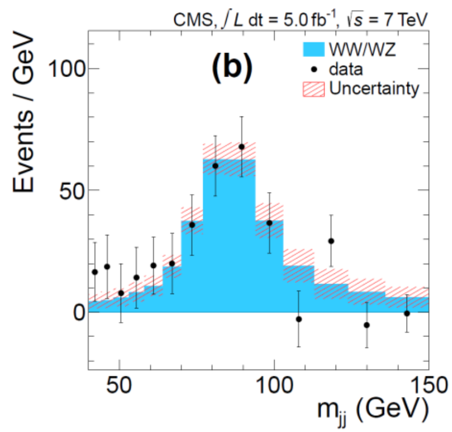


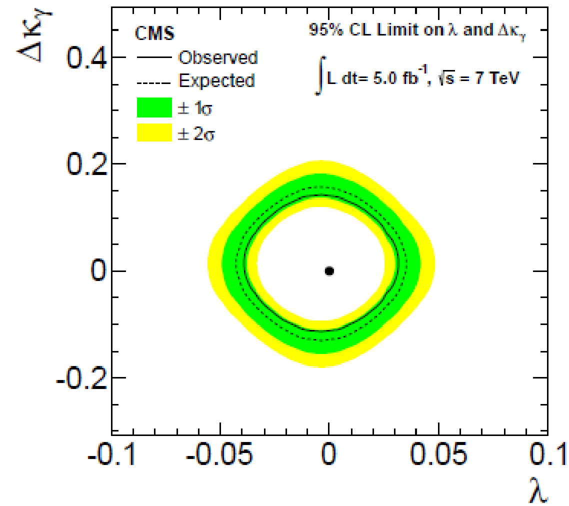
ATLAS EPJ C72 (2011) 2173 & Phys. Lett. B709 (2012) 341

A Different Handle on WW/WZ Production

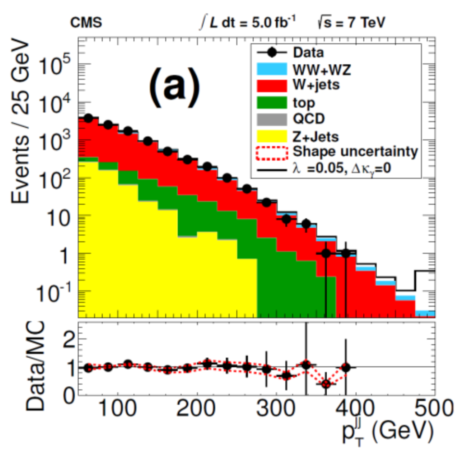
The idea: trigger on a W (lepton + MET) and look at the dijet spectrum to find another W or Z.

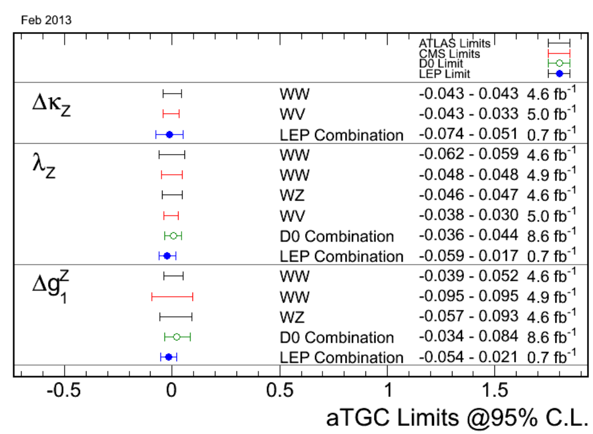






- Pros:
  - A lot of signal, and lets you push to high p_T, where the sensitivity is.
- Cons:
  - A good deal of background
  - Cannot distinguish WW from WZ





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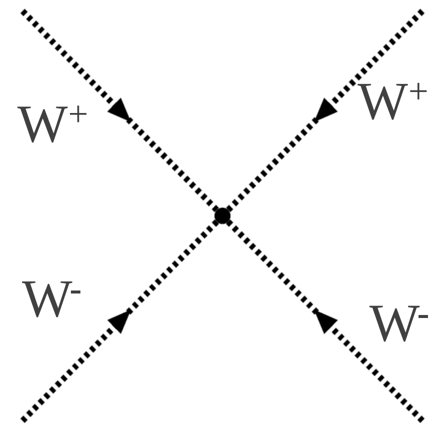
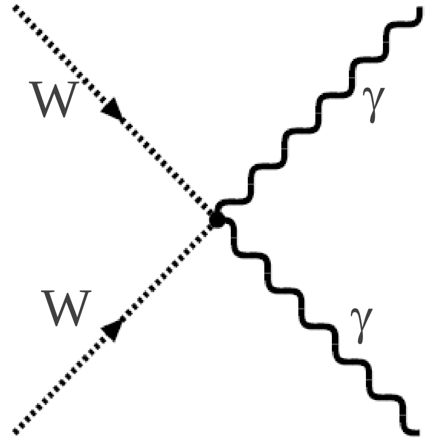
c.f. ATLAS CONF-2013-021

Quartic Gauge Couplings

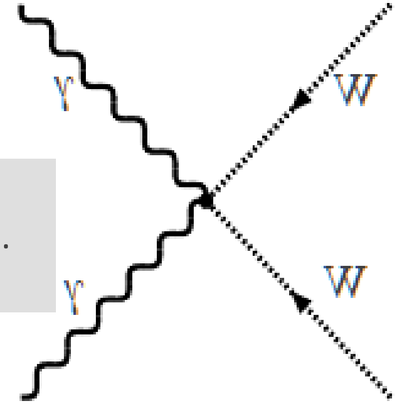
- This is a high priority – we need to understand QGCs to tell if the Higgs unitarizes the process WW → WW
- The highest rate process (and thus the first we are likely to see) is $W\gamma\gamma$
  - Both the signal and the irreducible background are down relative to $W\gamma$ by a factor of $\sim\alpha$
  - This happens because of the SU(2) part of the photon, not the U(1): an electroweak correction to electromagnetism
- If I set the TGCs to zero, the cross-section blows up
  - In some sense, makes them easy to see
- The same thing does not happen with QGCs
  - Unlike TGCs, I can write down a completely consistent theory without QGCs





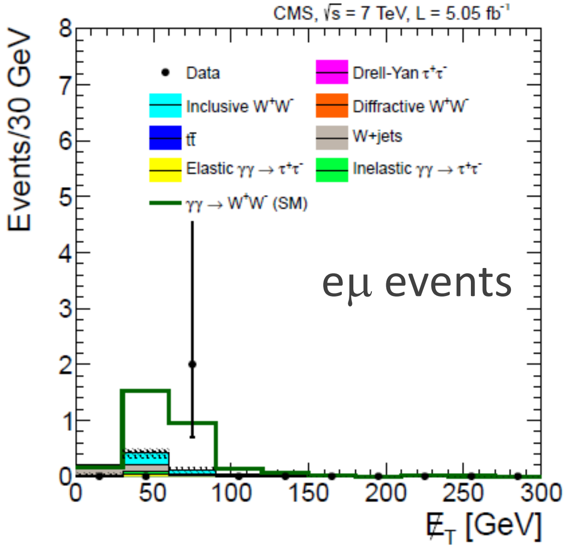
A Very Clever Idea From CMS

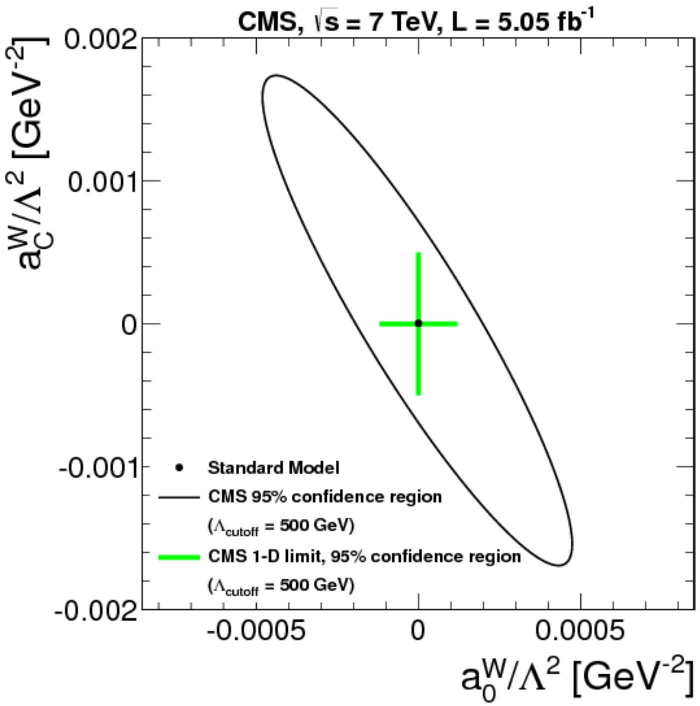
CMS arXiv: 1305.5596



- Look at the mirror image:
  - Semi-exclusive production:
    - **(Mostly) empty events**
  - Photon VBF to produce WW pairs
  - pp → $p^{(*)}W^+W^-p^{(*)}$

In VBF processes, one needs to infer or calculate the initial state. In this case, $\gamma\gamma$ dominates.





Background is 0.84 ± 0.15 events, with comparable contributions from inclusive WW and $\gamma\gamma$ → $\tau\tau$. Expected signal is 2.2 ± 0.2 events. 2 events are observed.

CP Violation

- With the particle content of the SM, there are three sources of CP violation
  - The CKM matrix of the quark sector
  - The PMNS matrix of the neutrino sector
  - A electric dipole moment or magnetic quadrupole moment of the W
    - A consequence of CP-violating triple gauge couplings $\tilde{\kappa}$ and $\tilde{\lambda}$.

- If the W had an EDM, it would induce a neutron EDM as well
  - c.f. Marciano and Queijeiro Phys.Rev. D33 (1986) 3449
  - Neutron EDM limits are so strict, we would need a trillion W's to be competitive

- The neutron, being spin-½, cannot support a quadrupole moment
  - So while we know that $\tilde{\kappa}$+$\tilde{\lambda}$ must be small, that argument doesn't hold for $\tilde{\kappa}$-$\tilde{\lambda}$

- A CP-violating observable needs to be constructed from at least three vectors
  - The momenta of the W and γ provide only two

The Third Vector

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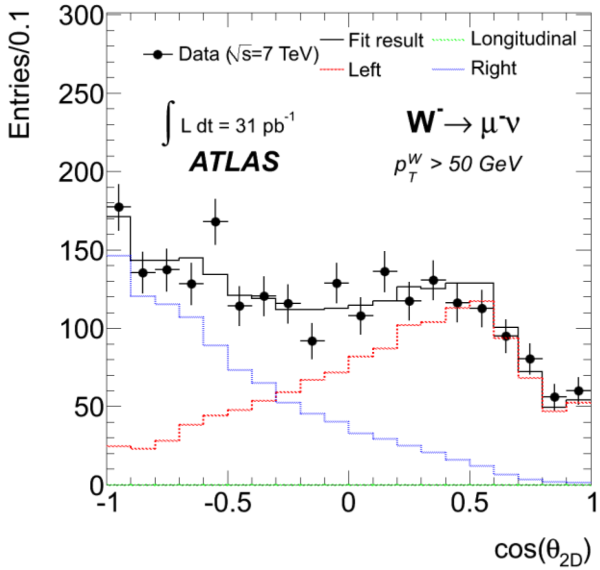
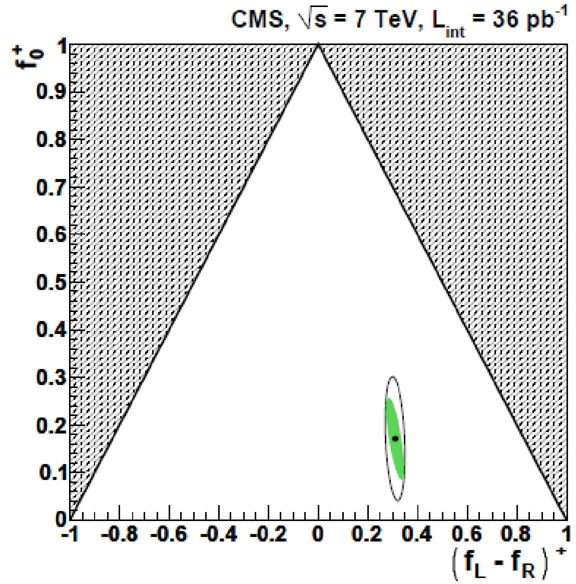


- The W decay "remembers" the W polarization
  - The three vectors are then p(W), p(γ) and J(W)
- We can now construct CP-sensitive observables and constrain $\tilde{\kappa}$-$\tilde{\lambda}$
- Aside: the W magnetic quadrupole moment cannot be too big, or we would see it in the W+γ *rate*.
  - We wouldn't know that it is CP-violating without a measurement like this however.
- A few 100 fb^{-1} 14 TeV sample is where this becomes interesting: a few thousand W+γ events at high p_T



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Conclusions

- The SM stubbornly refuses to make a prediction falsified by experiment
  - Dibosons are no exception
  - These are TeV-scale limits: unlike for the muon, our understanding of "g-2" for the W is at the 0.1 level
- New ideas are starting to realize their potential
  - $Z \rightarrow \nu\nu$ decays in $Z + \gamma$
  - VBF production to constrain QGC
  - Self-analyzing nature of the W polarization
- The higher the dimension operator being probed, the better the LHC does, both in absolute terms and relative to its peers
  - Limits on h_4 (D8) are better than h_3 and λ (D6) which in turn are better than κ (D4)
  - Expected because of different powers of $\hat{s}$.
- Which is why 14 TeV running is so important to the program